Mass hierarchy and naturalness from TeV scale strong dynamics

Roberto Frezzotti

Physics Department - University of Rome *Tor Vergata*

INFN - Rome *Tor Vergata*

Rome - Italy

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work in preparation (Tor Vergata group + Bonn group + other collaborators)

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Beyond the SM & elementary particle mass puzzle

1. Standard Model (SM): renormalizable QFT, highly successful in describing electroweak (EW) and strong interaction physics ...

2. ... needs be extended anyway to account for observed

- ⋆ neutrino masses and mixings
- ⋆ dark matter
- ⋆ baryogenesis (larger CP violation needed)
- ⋆ dark energy & quantum aspects of gravity

3. SM can describe the masses of elementary particles via SSB $SU(2)_L \times U(1)_Y \stackrel{SSB}{\longrightarrow} U(1)_{em}$, has nothing to say about their magnitude

- ⋆ $m_{W,Z} \sim m_h \sim v \sim 10^{-13}\Lambda_{GUT} \sim 10^{-16}\Lambda_{Planck}$

  no extra symmetry when $m_h \sim v$ gets small $\Rightarrow$ un–naturalness
- ⋆ $m_t \sim 10^5 m_u\,, \quad m_\tau \sim 10^4 m_e\,, \quad m_e > 10^7 m_{\nu_i}$

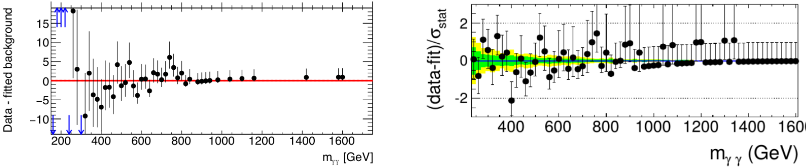
  (even for equal quantum numbers) $\Rightarrow$ huge fermion mass hierarchy

or flavour mixing (e.g. CKM matrix for quarks). Key to New Physics?

Non-Perturbative (NP) dynamics at few TeV scale

- New superstrong forces and particles accessible to experiments
- Possible deeper understanding of elementary particle masses

Hypothesis receiving renewed attention as (if) many SUSY scenarios are ruled out (further) by LHC experiments (testing $m_{gluino} \leq 1.5$ TeV in run2)



... or in case TeV-scale resonances with large widths are found at the LHC

Simplest theory of EW SSB: Technicolor (TC) Weinberg, Susskind - '79

fermion mass via extended-TC interactions problematic: (t, b)-mass & small FCNC not easy together: walking TC, partial compositeness

A mechanism for dynamical elementary particle mass

... will be shortly discussed – based on the following key features:

- a new superstrong interaction at the TeV scale + SM forces in a basic UV-regulated model with a dimensionful UV cutoff
- exact chiral symmetry (χ) acting on fermions, EW-bosons and scalars – corresponding (in a realistic setting) to $SU(2)_L \times U(1)_Y$
- a chiral "symmetry" acting only on fermions + EW-bosons ($\tilde{\chi}$): broken at the UV cutoff scale, recovered at low energy with certain NP "defects" $\leftrightarrow$ mass of elementary fermions & weak bosons!
- NP "defects": NP operator mixings due to $d > 4$ action terms $\Rightarrow$ (NP) universality to be reinterpreted, predictivity preserved
- Higgs resonance: $WW + ZZ$ bound state due to superstrongly interacting d.o.f.'s

New NP mechanism vs. possible realistic models

Masses $\propto \Lambda_T = O(1)$ TeV times appropriate gauge coupling powers

$\Rightarrow$ naturalness & framework suitable for fermion mass hierarchy

$+$ compatibility with FCNC and S-parameter bounds ... not for free

$\Leftarrow$ new QFT feature conjectured: under test by lattice simulation

A possible realistic model Lagrangian should look like

$$\mathcal{L}^{BSMM} = \frac{1}{4}\left(F^B F^B + F^W F^W + F^A F^A + F^G F^G\right) +$$

$$\sum_f \left[\bar{q}^f_L D^{BWA} q^f_L + \bar{q}^{f\,u}_R D^{BA} q^{f\,u}_R + \bar{q}^{f\,d}_R D^{BA} q^{f\,d}_R + \bar{\ell}^f_L D^{BW} \ell^f_L + \bar{\ell}^{f\,u}_R D^{B} \ell^{f\,u}_R + \bar{\ell}^{f\,d}_R D^{B} \ell^{f\,d}_R\right] +$$

$$\bar{Q}_L D^{BWAG} Q_L + \bar{Q}^u_R D^{BAG} Q^u_R + \bar{Q}^d_R D^{BAG} Q^d_R + \bar{L}_L D^{BWG} L_L + \bar{L}^u_R D^{BG} L^u_R + \bar{L}^d_R D^{BG} L^d_R +$$

$+$ $\tilde{\chi}$-breaking terms of $d = 4, 6, 8, 10$ with $\tilde{\chi}$-critical or free/adjusted coeff.s

Gauge coupling unification at $\mu \sim 10^{18}$GeV (Garofalo's talk - May 26)
with non-standard Y-charge assignments for Q, L (arXiv:1602.03684)

Outline

- Introduction: see above!
- Mechanism in toy model at $g_W = g_Y = 0$
- Mechanism in toy model at $g_W \neq 0$ (and $g_Y = 0$: custodial limit)
- Higgs resonance origin and Γ_{LE} for $E < 1$ TeV
- Conclusions

A new NP mechanism for elementary particle masses

... is discussed here by means of a toy basic (renormalizable) model

$$\mathcal{L}_{\rm toy}(Q,A,\Phi) = \mathcal{L}_{kin}(Q,A,\Phi) + \mathcal{V}(\Phi) + \mathcal{L}_{Wil}(Q,A,\Phi) + \mathcal{L}_{Yuk}(Q,\Phi)$$

- $\mathcal{L}_{kin}(Q,A,\Phi) = \frac{1}{4}F^a_{\mu\nu}F^a_{\mu\nu} + \bar{Q}_L\gamma_\mu\mathcal{D}_\mu Q_L + \bar{Q}_R\gamma_\mu\mathcal{D}_\mu\, Q_R + \frac{1}{2}\mathrm{Tr}\big[\partial_\mu\Phi^\dagger\partial_\mu\Phi\big]$
- $\mathcal{L}_{Wil}(Q,A,\Phi) = \frac{b^2}{2}\rho\big(\bar{Q}_L\overleftarrow{\mathcal{D}}_\mu\Phi\mathcal{D}_\mu Q_R + \bar{Q}_R\overleftarrow{\mathcal{D}}_\mu\Phi^\dagger\mathcal{D}_\mu Q_L\big)$
- $\mathcal{L}_{Yuk}(Q,\Phi) = \eta\,\big(\bar{Q}_L\Phi Q_R + \bar{Q}_R\Phi^\dagger Q_L\big)$
- $\mathcal{V}(\Phi) = \frac{\mu_0^2}{2}\mathrm{Tr}\big[\Phi^\dagger\Phi\big] + \frac{\lambda_0}{4}\big(\mathrm{Tr}\big[\Phi^\dagger\Phi\big]\big)^2\,, \qquad \Phi \equiv [\varphi| - i\tau^2\varphi^*]$

A fermion doublet Q is coupled to a non-Abelian SU(N) gauge field and via Yukawa & Wilson-like ($d=6$) terms to a scalar doublet φ

- ⋆ UV cutoff $\sim b^{-1}$; fermion chiral symm. broken if $(\rho,\eta) \neq (0,0)$
- ⋆ exact chiral symmetry acting on Q and Φ: Wigner and NG phases

$\mathcal{L}_{\rm toy}$: renormalizability & $\tilde{\chi}$–symmetry enhancement

- $\mathcal{L}_{\rm toy}$ invariant under: χ global $SU(2)_L \times SU(2)_R$ transformations

$$\chi_L : \tilde{\chi}_L \otimes \chi_L^{\Phi} \qquad \text{and} \qquad \chi_R : \tilde{\chi}_R \otimes \chi_R^{\Phi} \qquad \text{with}$$

$$\tilde{\chi}_L : Q_L \to \Omega_L Q_L \,,\; \bar{Q}_L \to \bar{Q}_L \Omega_L^{\dagger} \,, \quad \chi_L^{\Phi} : \Phi \to \Omega_L \Phi \,, \quad \Omega_L \in SU(2)_L \,,$$

$$\tilde{\chi}_R : Q_R \to \Omega_R Q_R \,,\; \bar{Q}_R \to \bar{Q}_R \Omega_R^{\dagger} \,, \quad \chi_R^{\Phi} : \Phi \to \Phi \Omega_R^{\dagger} \,, \quad \Omega_R \in SU(2)_R \,,$$

and gauge, Poincaré, P, T, C, $\mathcal{D}_d$ ... $\Rightarrow$ power counting renormalizable,

$\chi \;\Rightarrow$ no power-like UV divergencies ... besides $\hat{\mu}_{\Phi}^2 = Z_{\Phi^\dagger\Phi}^{-1}[\mu_0^2 - \tau b^{-2}]$

O(b^2) cutoff effects. Neither $\tilde{\chi}_{L,R}$ nor $\chi_{L,R}^{\Phi}$ are symmetries in general due to

terms $\frac{b^2}{2}\rho(\bar{Q}_L \overleftarrow{\mathcal{D}}_\mu \Phi \mathcal{D}_\mu Q_R + \bar{Q}_R \overleftarrow{\mathcal{D}}_\mu \Phi^\dagger \mathcal{D}_\mu Q_L) + \eta\,(\bar{Q}_L \Phi Q_R + \bar{Q}_R \Phi^\dagger Q_L)$ in $\mathcal{L}_{\rm toy}$

- ⋆ at $\eta = \eta_{cr}(\rho)$ these terms cancel at all orders in PT up to O(b^2)
  $\tilde{\chi}_{L,R}$ recovery $\;\Rightarrow$ no Yukawa coupling in Γ_{LE}, no $m_Q \sim \langle \Phi \rangle$
- ⋆ strong forces $\xrightarrow{\text{in NG phase}}$ $\tilde{\chi}_{L,R}$-SSB & possibly a NP mass term in Γ_{LE}

- Take model with maximal $\tilde{\chi}_{L,R}$–symmetry (charge algebra closure)

$\tilde\chi_L \times \tilde\chi_R$ broken & renormalized WTI's

$$\partial_\mu \langle \tilde J^{L,i}_\mu(x)\, \hat O(0)\rangle = \langle \tilde\Delta^i_L \hat O(0)\rangle \delta(x) - \eta\,\langle D^{L,i}_{Yuk}(x)\,\hat O(0)\rangle - b^2 \langle \underline{O^{L,i}_{Wil}}(x)\,\hat O(0)\rangle$$

$$\tilde J^{L,i}_\mu = \bar Q_L \gamma_\mu \tfrac{\tau^i}{2} Q_L - \tfrac{b^2}{2}\rho\Big(\bar Q_L \tfrac{\tau^i}{2}\Phi \mathcal{D}_\mu Q_R - \bar Q_R \overleftarrow{\mathcal{D}}_\mu \Phi^\dagger \tfrac{\tau^i}{2} Q_L\Big)$$

$$D^{L,i}_{Yuk} = \Big[\bar Q_L \tfrac{\tau^i}{2}\Phi Q_R - \mathrm{hc}\Big]\,, \qquad \underline{O^{L,i}_{Wil}} = \tfrac{\rho}{2}\Big[\bar Q_L \overleftarrow{\mathcal{D}}_\mu \tfrac{\tau^i}{2}\Phi \mathcal{D}_\mu Q_R - \mathrm{hc}\Big]$$

- Operator Mixing

$$b^2 \underline{O^{L,i}_{Wil}} = (Z_{\tilde J}-1)\partial_\mu \tilde J^{L,i}_\mu - \bar\eta\, D^{L,i}_{Yuk} + C_1 \Lambda_S[\bar Q_L \tfrac{\tau^i}{2} U Q_R - hc] + b^2 O^{L,i}_{6\,\mathrm{sub}} + \ldots$$

only in NG phase peculiar NP term possible, with $C_1 = \mathrm{O}(g_S^4)$, due to

$$U = \Phi/\sqrt{\Phi^\dagger\Phi} = [v + \sigma + i\vec\tau\vec\pi]/\sqrt{(v+\sigma)^2 + \vec\pi\vec\pi}$$

- Renormalized $\tilde\chi_L$ WTI's @ $\eta_{cr} = \bar\eta(\eta_{cr})$, NG phase & $x \neq 0$

$$\partial_\mu \langle Z_{\tilde J} \tilde J^{L,i}_\mu(x)\,\hat O(0)\rangle = C_1 \Lambda_S \langle [\bar Q_L \tfrac{\tau^i}{2} U Q_R - hc](x)\hat O(0)\rangle + \mathrm{O}(b^2)$$

$\Rightarrow$ in $\Gamma^{NG}_{\mathrm{loc}}$ <u>a mass term</u> $C_1\Lambda_S[\bar Q_L U Q_R + hc]$ $\neq$ Yukawa term !

NP vertex corrections $\Rightarrow$ fermion mass generation

@ NG phase ($\Phi = v + \sigma + i\vec{\tau}\vec{\pi}$): b^2 [$d \geq 6$ $\tilde{\chi}-$operator] terms in $\mathcal{L}^{cr}_{\rm toy}$

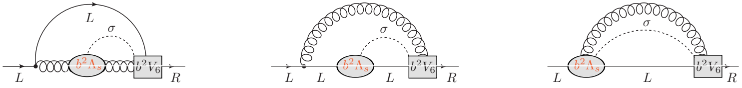
$$\mathcal{L}_{Wil} = \frac{b^2}{2}\rho(\bar{Q}_L \overleftarrow{\mathcal{D}}_\mu \Phi \mathcal{D}_\mu Q_R + \mathrm{hc}) \xrightarrow{b^2 v \to ar} \mathcal{L}^{QCD}_{Wil} = -\frac{ar}{2}(\bar{Q}_L \mathcal{D}^2 Q_R + \mathrm{hc})$$

polarize the vacuum under $\tilde{\chi}$–SSB due to strong interactions $\Rightarrow$

expect NP O(b^2) contributions to $\tilde{\chi}$–invariant vertices $\bar{Q}\not{D}Q\sigma$, $FF\sigma$, ...

$$\Delta\Gamma_{AA\Phi,Q\bar{Q}\Phi,\dots} = b^2\Lambda_s \mathrm{O}(\alpha_s)\, w_{\rm analytic}(\mathrm{mom})\, F_{AA\Phi,Q\bar{Q}\Phi,\dots}\Big(\frac{\Lambda_s^2}{\mathrm{mom}^2}\Big) \quad \Rightarrow$$

NP fermion self-energy contributions (e.g. central panel)



$$\underline{\underline{m_Q^{eff}}} \propto g_s^2\alpha_s(\Lambda_s)\int^{1/b}\frac{d^4k}{k^2}\frac{\gamma_\mu k_\mu}{k^2}\int^{1/b}\frac{d^4\ell}{\ell^2+m_\sigma^2}\frac{\gamma_\nu(k+\ell)_\nu}{(k+\ell)^2}\,\cdot$$

$$\cdot b^2\gamma_\rho(k+\ell)_\rho\, b^2\Lambda_s\gamma_\lambda(2k+\ell)_\lambda \sim \underline{\underline{g_s^2\alpha_s(\Lambda_s)\Lambda_s}}$$

[b^4 factor compensated by the two-loop quartic divergency]

Remarks & analogous evidence in Lattice QCD

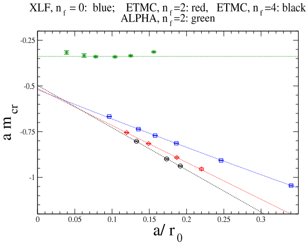
⋆ Goldstones interaction effects ⇔ $(\chi_L \times \chi_R)$–invariant NP mass term

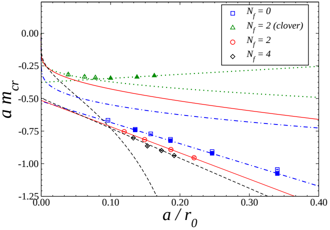
$\Gamma^{NG}_{\rm loc} \supset C_1 \Lambda_s [\bar{Q}_L U Q_R + \bar{Q}_R U^\dagger Q_L]$, $\quad U = \exp\{\frac{i\vec{\zeta}\vec{\tau}}{v}\}$, $\zeta^{1,2,3}$ = GB's

U transforms as Φ under $\chi_{L,R}$; GB's couplings different from σ ones

⋆ $|C_1| = \mathrm{O}(\rho^2 g_s^4)$ ↔ controlled by $d = 6$ $\tilde{\chi}$ terms ↔ universality?

⋆ Similar NP "mass" phenomenon seen in Wilson quark Lattice QCD





$am_{cr} = w(g_0^2) = c_0 + c_1 a\Lambda_{QCD} + \mathrm{O}(a^2)$: $c_1 < 0$, but just one $\tilde{\chi}$ operator:

$\bar{q}q \;\Rightarrow$ NP mass entangled with a^{-1}, neither well defined nor natural

Toy model with weak interactions: symmetries

Add weak interactions ($g_W > 0$; still $g_Y = 0$):

$$\mathcal{L}_{\rm toy}(Q,A,\Phi,W) = \mathcal{L}_{kin}(Q,A,\Phi,W) + \mathcal{V}(\Phi) + \mathcal{L}_{Wil}(Q,A,\Phi,W) + \mathcal{L}_{Yuk}(Q,\Phi)$$

- $\mathcal{L}_{kin}(Q,A,\Phi,W) = \frac{1}{4}F^{A;a}_{\mu\nu}F^{A;a}_{\mu\nu} + \frac{1}{4}F^{W;i}_{\mu\nu}F^{W;i}_{\mu\nu} +$
  $+\bar{Q}_L\gamma_\mu\mathcal{D}^{A,W}_\mu Q_L + \bar{Q}_R\gamma_\mu\mathcal{D}^{A}_\mu Q_R + \frac{1}{2}\mathrm{Tr}\left[\Phi^\dagger\overleftarrow{\mathcal{D}}^{W}_\mu\mathcal{D}^W_\mu\Phi\right]$
- $\mathcal{L}_{Wil}(Q,A,\Phi,W) = \frac{b^2}{2}\rho\left(\bar{Q}_L\overleftarrow{\mathcal{D}}^{A,W}_\mu\Phi\mathcal{D}^A_\mu Q_R + \bar{Q}_R\overleftarrow{\mathcal{D}}^{A}_\mu\Phi^\dagger\mathcal{D}^{A,W}_\mu Q_L\right)$

$SU(2)_L$ gauge symmetry: $W^{1,2,3}_\mu$ bosons & covariant derivatives, e.g.

$$\mathcal{D}^{A,W}_\mu = \partial_\mu - ig_s\lambda^a A^a_\mu - ig_w\frac{\tau^i}{2}W^i_\mu \qquad \overleftarrow{\mathcal{D}}^{A,W}_\mu = \overleftarrow{\partial}_\mu + ig_s\lambda^a A^a_\mu + ig_w\frac{\tau^i}{2}W^i_\mu$$

Global $SU(2)_L \times SU(2)_R$ invariance, if W's transform under $\tilde{\chi}_L$:

$$\chi_L : \tilde{\chi}_L \otimes \chi^\Phi_L \qquad \text{and} \qquad \chi_R : \tilde{\chi}_R \otimes \chi^\Phi_R \qquad \text{with}$$

$$\tilde{\chi}_L : Q_L \to \Omega_L Q_L\,,\ \bar{Q}_L \to \bar{Q}_L\Omega_L^\dagger\,, \qquad \chi^\Phi_L : \Phi \to \Omega_L\Phi\,, \qquad \Omega_L \in SU(2)_L\,,$$

$$W_\mu \to \Omega_L W_\mu \Omega_L^\dagger\,,$$

$$\tilde{\chi}_R : Q_R \to \Omega_R Q_R\,,\ \bar{Q}_R \to \bar{Q}_R\Omega_R^\dagger\,, \qquad \chi^\Phi_R : \Phi \to \Phi\Omega_R^\dagger\,, \qquad \Omega_R \in SU(2)_R\,,$$

Weak interactions & $\tilde{\chi}$–symmetry restoring: ρ_{cr}, η_{cr}

⋆ $\tilde{\chi}_{L,R}$ and $\chi^{\Phi}_{L,R}$ are not symmetries: e.g. $\tilde{\chi}_L$ broken by $\mathrm{Tr}\big[\Phi^\dagger \overleftarrow{\mathcal{D}}^W_\mu \mathcal{D}^W_\mu \Phi\big]$

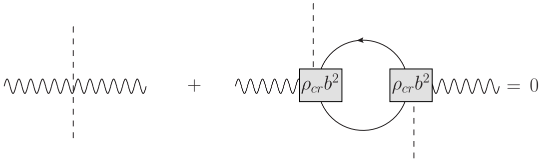
⋆ $\tilde{\chi}_L \otimes \tilde{\chi}_R$ is recovered in PT at $\rho = \rho_{cr}$, $\eta = \eta_{cr}$ – up to O(b^2)

- If $\mathcal{V}(\Phi)$ has a single minimum ($\hat{\mu}^2_\Phi > 0$, Wigner phase of $\chi_L \times \chi_R$) ,

operator mixings are as in PT and the local effective Lagrangian is

$$\Gamma^{Wig}_{\rm loc} = \frac{1}{4}[(F^A F^A) + (F^W F^W)] + \bar{Q}_L \not{\mathcal{D}}^{A,W} Q_L + \bar{Q}_R \not{\mathcal{D}}^A Q_R + \mathcal{V}_{eff}[\Phi]$$

⇒ Determine $\rho_{cr} \sim$ O($1/\sqrt{N_F^{\rm tot}}$) in the Wigner phase from

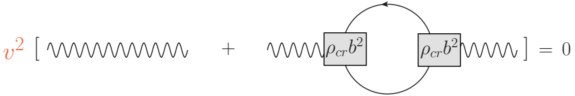


- If $\mathcal{V}(\Phi)$ has Mexican hat shape ($\hat{\mu}^2_\Phi < 0$, NG phase of $\chi_L \times \chi_R$)

⇒ ρ_{cr} kills the O(v^2) W-mass term in the NG phase

$\tilde{\chi}$–charge algebra closure $\Rightarrow$ NP masses $\propto \Lambda_s$

- If $\mathcal{V}(\Phi)$ has Mexican hat shape ($\hat{\mu}_\Phi^2 < 0$, NG phase of $\chi_L \times \chi_R$)

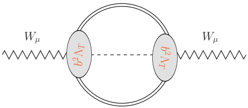


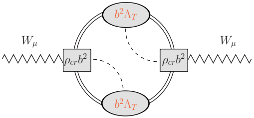
$\Rightarrow$ dynamical $\tilde{\chi}$SB is triggered by residual O($b^2 v$) $\tilde{\chi}$-breaking terms

$\Rightarrow$ $\tilde{\chi}$SB leads to NP vertices and new operator mixings so that

$$\Gamma^{NG}_{\rm loc} = \Gamma^{Wig}_{\rm loc} + C_1 \Lambda_s [\bar{Q}_L U Q_R + \bar{Q}_R U^\dagger Q_L] + C_2 \Lambda_s^2 \, {\rm Tr}\, [U^\dagger \overleftarrow{\mathcal{D}}^W_\mu \mathcal{D}^W_\mu U]$$

hence $M_W^2 = g_w^2 C_2 \Lambda_s^2$ and $m_Q = C_1 \Lambda_s$ from a common mechanism

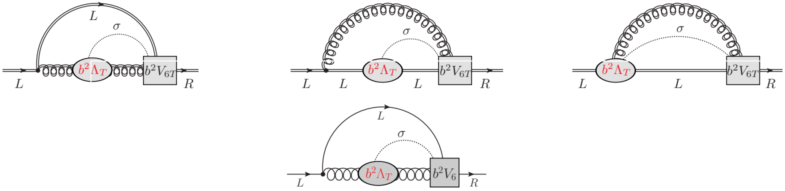




$\star$ Symmetry principle: $\tilde{\chi}$–charge algebra closure – preserved by the NP terms $\propto C_{1,2}$ (but not by $\Lambda_s |\Phi| \, {\rm Tr}\, [U^\dagger \overleftarrow{\mathcal{D}}^W_\mu \mathcal{D}^W_\mu U]$)

Superstrong & strong interactions: mass hierarchy (I)

- Q feel super-strong & strong interactions, L super-strong ones
- $q \to N_g = 3$ generations - feel gauge force $\mathrm{SU}(N_c = 3)$
- $Q, L \to 1, \nu_L$ generations - gauge forces $\mathrm{SU}(N_c = 3) \times \mathrm{SU}(N_T = 3)$
- $\beta_T^0 / \beta_{QCD}^0 = \frac{11N_T - 4(N_c + \nu_L)}{11N_c - 4N_g - 4N_T} = \frac{7}{3} - \frac{4}{9}\nu_L \quad \Rightarrow \quad \Lambda_T \gg \Lambda_{QCD}$



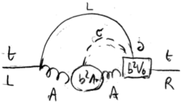
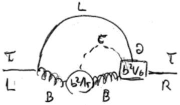
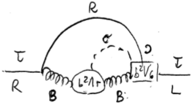
- LO RG-improved estimates at $\mu \simeq$ few times Λ_T [s.t. $\alpha_T(\mu) \sim 1/2$]

$$m_Q(\mu) \simeq k_{\mathrm{LO}}^{(Q)} g_T^2(\mu)\, \alpha_T(\mu)\, \Lambda_T \qquad m_q(\mu) \simeq k_{\mathrm{LO}}^{(q)} g_s^2(\mu)\, \alpha_s(\mu)\, \Lambda_T$$

$$\left.\frac{m_{q=top}}{m_Q}\right|_\mu \sim \frac{\alpha_s^2(\mu)}{\alpha_T^2(\mu)} \sim \frac{1}{20} \quad \Rightarrow \quad m_{Q_T}|_\mu \sim 3 \text{ TeV}, \quad \Lambda_T \simeq \frac{O(1) \text{ TeV}}{k_{\mathrm{LO}}^{(q)}} \sim O(1) \text{ TeV}$$

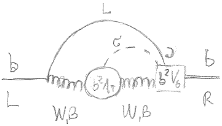
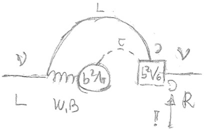
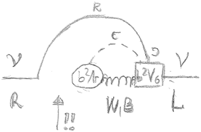
Strong & EW interactions: mass hierarchy (example)

$\frac{b^2}{2}\rho_{t,cr}\big(\bar q_L \overleftarrow{\mathcal{D}}^{BWA}_{\mu} \phi \mathcal{D}^{BA}_{\mu} t_R + \mathrm{h.c.}\big)$ $\qquad$ $\frac{b^2}{2}\rho_{\tau,cr}\big(\bar\ell_L(\mathcal{D}^{BW}_{\mu}\tilde\phi)\mathcal{D}^{B}_{\mu}\tau_R + \mathrm{h.c.}\big)$

$m_t(\mu) \simeq k^{(t)}_{\mathrm{LO}} g_s^2(\mu)\,\alpha_s(\mu)\,\Lambda_T$ $\qquad$ $m_\tau(\mu) \simeq k^{(\tau)}_{\mathrm{LO}} g_Y^2(\mu)\,\alpha_Y(\mu)\,\Lambda_T$

$\frac{b^2}{2}\rho_{b,cr}\big(\bar q_L(\mathcal{D}^{BW}_{\mu}\mathcal{D}^{BW}_{\mu}\tilde\phi) b_R + \mathrm{h.c.}\big)$ $\qquad$ $\frac{b^2}{2}\rho_{\nu,cr}\big(\bar\ell_L \overleftarrow{\mathcal{D}}^{BW}_{\mu} \phi\,\partial_\mu \nu_R + \mathrm{h.c.}\big)$

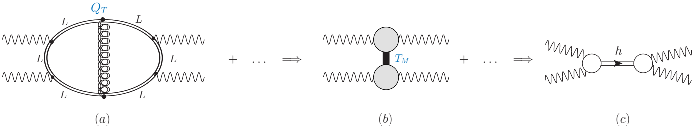




$m_b(\mu) \simeq k^{(b)}_{\mathrm{LO}} g_{W,Y}^2(\mu)\,\alpha_{W,Y}(\mu)\,\Lambda_T$ $\qquad$ $m_\nu(\mu) = 0$ [$\mathrm{O}(\Lambda_T^2/\Lambda_{GUT})$?]

- ⋆ leptonic $\tilde{\chi}$ terms invariant under $\nu_R \to \nu_R + \mathrm{const.}$ [Goltermann-Petcher]

125 GeV Higgs resonance as $WW + ZZ$ bound state

Assume binding force from T-hadron exchange to form h: $M_h < 2M_W$



$$G(\vec{p}, \vec{0}, x_0) = \int d^3x e^{-i\vec{p}\vec{x}} M_W^3 \int d^3z \langle W(\vec{x}, x_0) W(\vec{z} + \vec{x}, x_0) W^\dagger(\vec{0}, 0) W^\dagger(\vec{0}, 0) \rangle$$

in free theory has a cut starting at $p^2 = -4M_W^2$; in interaction due to $g_W > 0$ and superstrong force

$$G(\vec{p}, \vec{0}, x_0) \sim \int \frac{dp_0}{2\pi} \frac{g_{2,analyt}(p^2) e^{ip_0 x_0}}{p^2 + 4M_W^2 - \Delta_0^2}\,, \quad \Delta_0^2 = \# g_W^4 4M_W^2\,, \quad \# = \mathrm{O}(1 \div 10)$$

a pole appears at $p^2 = -M_h^2 = -4M_W^2 + \Delta_0^2 \;\leftrightarrow\; M_h = 2M_W(1 - \# g_W^4)^{1/2}$

Likely just one bound state ... In non-rel. approx. binding given by a potential well with height $V_0 \propto M_W$, width $a \propto \Lambda_T^{-1}$, $8 m_{red} V_0 a^2 \ll 1$

Predictivity of models based on NP $\tilde{\chi}$-breaking

Renormalizable model at the maximal restored $\tilde{\chi}$ symmetry point:

$\partial_\mu \tilde{J}^{L,i}_\mu = O$, (Wigner phase)

$\partial_\mu \tilde{J}^{L,i}_\mu = \sum_f c_{1,f}\Lambda_T \mathcal{D}^{L,i}_f + \frac{ig_W}{2} c_2 \Lambda_T^2 \mathrm{tr}\Big(U^\dagger[\frac{\tau^i}{2}, W_\mu] D^{WB}_\mu U - \mathrm{h.c.}\Big)$, (NG phase)

⋆ RGI of l.h.s. ⇒ RGI (& UV-finite) NP $\tilde{\chi}$-breaking terms on the r.h.s.

with $\mathcal{D}^{L,i}_f = [\bar{Q}_L \frac{\tau^i}{2} U Q_R - \mathrm{h.c.}]$ and $c_{1,f} = \mathrm{O}(\rho^2_{f,cr})\, \alpha^{n(f)}_{c(f)} [1 + \mathrm{O}(\alpha_{...})]$

⋆ effective masses$|_{\mathrm{scale}\ b^{-1}}$: $c_{1,f}\Lambda_T \leftrightarrow m^{dyn}_f$, $c_2 g_W^2 \Lambda_T^2 \leftrightarrow (m^{dyn}_W)^2$

UV cutoff $b^{-1} \to \infty$ at fixed $M_{\mathrm{Tglueball}}$, M_{proton}, G_F, $\sin^2\theta_W$ $(\hat{\alpha}_{T,S,W,Y})$

$\tilde{\chi}$-symmetry ⇒ $\sum_{f=1}^{N^{tot}_{ferm}} \rho^2_{f,cr}(1 + \mathrm{O}(\rho^2_{f,cr})) = O(1)$ bounds the $\rho_{f,cr}$'s

$\to \rho_{Q,cr}$, $\rho_{L,cr}$ control m^{dyn}_Q, m^{dyn}_L, as well as m^{dyn}_W, m^{dyn}_Z

$\to \rho_{t,cr}$ controls m^{dyn}_t, ... $\rho_{\tau,cr}$ controls m^{dyn}_τ, ...

Assuming similar $\rho_{f,cr}$ for all fermions f (GUT?) ⇒ mass hierarchy from relevant gauge couplings and dim./type of $\tilde{\chi}$-breaking terms

NP dynamics and low energy effective theory

At $E < 1$ TeV realistic models based on NP $\tilde{\chi}$-breaking should admit

$$\Gamma_{LE} = \frac{1}{4}F_A F_A + \frac{1}{4}(F_W F_W + F_B F_B) + \sum_f (\bar{f}_R \not{D}_f^{A,B} f_R + \bar{f}_L \not{D}_f^{A,W,B} f_L) +$$
$$+ \frac{1}{2}\partial_\mu h \partial_\mu h + V_{eff}(h) + [\underline{c\Lambda_T^2} + c'\Lambda_T h + c'' h^2]\frac{1}{2}\mathrm{Tr}\,[D_\mu^{W,B} U^\dagger D_\mu^{W,B} U] +$$
$$+ \sum_{f \neq \nu} [\underline{x_f \Lambda_T} + y_f h](\bar{f}_L u_{I_f} f_R + \bar{f}_R u_{I_f}^\dagger f_L) + \mathrm{O}(\frac{1}{\Lambda_T})\,, \qquad \Lambda_T = \mathrm{O}(1)\ \mathrm{TeV}$$

$$U = \exp[i\vec{\zeta}\cdot\vec{\tau}/\sqrt{c}\Lambda_T] = \left[u_{I=\frac{1}{2}} = u \,|\, u_{I=-\frac{1}{2}} = -i\tau_2 u^\star\right] \qquad \mathrm{GB's\ fields}$$

- $m_h < \Lambda_T$ and h-couplings as (to be) measured in experiments
  $x_f = m_f/\Lambda_T \sim y_f$ follows from NP vertex corrections analysis
- flavour changing currents as in the SM (suppressed FCNC)
- loop effects consistent with precise EW data (S-parameter)
- $\mathrm{O}(1/\Lambda_T)$ eff. terms include hF_AF_A, hF_WF_W and hF_BF_B operators

Conclusions & Outlook

⋆ A dynamical mechanism for "naturally small" elementary particle masses: expected to occur in models with "gluons", fermions & scalars in NG phase once hardly broken fermionic $\tilde{\chi}$ symmetries are maximally restored (up to UV-cutoff effects), yields fermion mass O(Λ_T) and scalar-vev independent

⋆ Numerical check of NP mass mechanism (& "universality"): ongoing

- appropriate $d_f = 6, 8, 10$ $\tilde{\chi}$–breaking terms in the basic Lagrangian

$\Rightarrow$ fermion mass hierarchy in Γ_{LE}^{NG}: $m_{q,l}^{eff} \sim \alpha_{S,W/Y}^{1+(d_f-4)/2} \Lambda_T$

- $m_{t,b}$-values $\Rightarrow$ superstrong interactions with $\Lambda_T \sim$ few TeV range and superstrongly interacting T-fermions (having masses $\sim \Lambda_T$) expected
- χ-invariance (χ_L gauged) exact in the presence of EW interactions: same mechanism as for fermion masses gives natural mass to W/Z bosons too
- $h \leftrightarrow WW/ZZ$ bound (by EWly & superstrongly interacting fermions) state
- T-hadron resonances at $E_{CoM} \sim$ 1 to few TeV: clear experimental feature

Backup slides

$\tilde\chi_{L,R}$–WTI's in the Wigner phase [theorem]

- $\tilde\chi_L \times \tilde\chi_R$ WTIs read [Bochicchio *et al.* 1985]
  - $\partial_\mu \langle \tilde J^{L,i}_\mu(x)\,\hat O(0)\rangle = \langle \tilde\Delta^i_L \hat O(0)\rangle\delta(x) - \eta\,\langle O^{L,i}_{Yuk}(x)\,\hat O(0)\rangle - b^2\langle \underline{O^{L,i}_{Wil}}(x)\,\hat O(0)\rangle$
    - $\tilde J^{L,i}_\mu = \bar Q_L \gamma_\mu \frac{\tau^i}{2} Q_L - \frac{b^2}{2}\rho\Big(\bar Q_L \frac{\tau^i}{2}\Phi \mathcal{D}_\mu Q_R - \bar Q_R \overleftarrow{\mathcal{D}}_\mu \Phi^\dagger \frac{\tau^i}{2} Q_L\Big)$
    - $O^{L,i}_{Yuk} = \Big[\bar Q_L \frac{\tau^i}{2}\Phi Q_R - \mathrm{hc}\Big]$
    - $\underline{O^{L,i}_{Wil}} = \frac{\rho}{2}\Big[\bar Q_L \overleftarrow{\mathcal{D}}_\mu \frac{\tau^i}{2}\Phi \mathcal{D}_\mu Q_R - \mathrm{hc}\Big]$
- Mixing
  - $b^2\,\underline{O^{L,i}_{Wil}} = (Z_{\tilde J} - 1)\partial_\mu \tilde J^{L,i}_\mu - \bar\eta(\eta; g_s^2, \rho, \lambda_0)\,O^{L,i}_{Yuk} + \ldots + \mathrm{O}(b^2)$
  - $\partial_\mu \langle Z_{\tilde J}\tilde J^{L,i}_\mu(x)\,\hat O(0)\rangle = \langle \tilde\Delta^i_L \hat O(0)\rangle\delta(x) - (\eta - \bar\eta(\eta))\,\langle O^{L,i}_{Yuk}(x)\,\hat O(0)\rangle + \ldots + \mathrm{O}(b^2)$
- Critical theory $\to \eta - \bar\eta(\eta; g_s^2, \rho, \lambda_0) = 0 \implies \eta_{cr}(g_s^2, \rho, \lambda_0)$
  - $\partial_\mu \langle Z_{\tilde J}\tilde J^{L,i}_\mu(x)\,\hat O(0)\rangle_{\eta_{cr}} = \langle \tilde\Delta^i_L \hat O(0)\rangle_{\eta_{cr}}\delta(x) + \ldots + \mathrm{O}(b^2)$
- All the same with $[L \leftrightarrow R \;\&\; \Phi \leftrightarrow \Phi^\dagger]$
- • Possible NP effects (arising in NG phase) represented here by dots

NP $O(b^2\Lambda_T)$ corrections to vertices [conjecture]

Examples of NP corrections: gluon-gluon-scalar, $Q_{L/R}$-$\bar{Q}_{L/R}$-scalar & $Q_{L/R}$-$\bar{Q}_{L/R}$-gluon-scalar vertices ($p = k, \ell, \ell', \ldots$)

$$\Delta\Gamma^{bc\mu\nu}_{AA\Phi}(k,\ell)\Big|^R = b^2\Lambda_s\alpha_s(\Lambda_s)\frac{\delta^{bc}}{2}\{[k(k+\ell)\delta_{\mu\nu} - k_\mu(k+\ell)_\nu] + [\mu \to \nu]\}F_{AA\Phi}\Big(\frac{\Lambda_s^2}{p^2}\Big)$$

$$\Delta\Gamma_{Q\bar{Q}\Phi}(k,\ell)\Big|^R = b^2\Lambda_s\,\alpha_s(\Lambda_s)\,\frac{i}{2}\gamma_\mu(2k+\ell)_\mu\,F_{Q\bar{Q}\Phi}\Big(\frac{\Lambda_s^2}{p^2}\Big)$$

$$\Delta\Gamma^{b,\mu}_{Q\bar{Q}A\Phi}(k,\ell,\ell')\Big|^R = b^2\Lambda_s\,\alpha_s(\Lambda_s)\,ig_s\lambda^b\gamma_\mu\,F_{Q\bar{Q}A\Phi}\Big(\frac{\Lambda_s^2}{p^2}\Big)$$

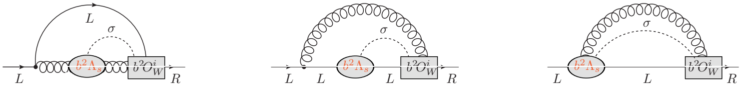
Like in LQCD, we assume NP effects displayed here persist up to $p^2 = O(b^{-2})$, and *conjecture* the asymptotic behaviour

$$F_{AA\Phi}\Big(\frac{\Lambda_s^2}{p^2}\Big) \overset{p^2\to\infty}{\longrightarrow} H_{AA}\,,\quad F_{Q\bar{Q}\Phi}\Big(\frac{\Lambda_s^2}{p^2}\Big) \overset{p^2\to\infty}{\longrightarrow} H_{Q\bar{Q}}\,,\quad F_{Q\bar{Q}A\Phi}\Big(\frac{\Lambda_s^2}{p^2}\Big) \overset{p^2\to\infty}{\longrightarrow} H_{Q\bar{Q}}$$

with H_{AA} & $H_{Q\bar{Q}} \to O(1)$ constants

NG phase: $\tilde{\chi}_{L,R}$–WTI's & conjectured NP term in Γ^{NG}_{LE}

- Similarly to self-energy diagrams one gets mixing diagrams like



- $\rightarrow$ NP mixing terms, "…" $\rightarrow \bar{Q}_L \frac{\tau^i}{2} U\, Q_R - \mathrm{hc}$

- $b^2 \underline{O^{L,i}_{Wil}} = (Z_{\tilde{J}} - 1)\partial_\mu \tilde{J}^{L,i}_\mu - \bar{\eta}(\eta; g_s^2, \rho, \lambda_0)\, O^{L,i}_{Yuk} + C_1 \Lambda_s \Big[\bar{Q}_L \frac{\tau^i}{2} U\, Q_R - \mathrm{hc}\Big] + \mathrm{O}(b^2)$
- same with $[L \leftrightarrow R \;\&\; U \leftrightarrow U^\dagger]$

- hence renormalized $\tilde{\chi}_L \times \tilde{\chi}_R$ WTIs read $[C_1|_{LO} \sim \mathrm{O}(g_s^4)]$

  - $\partial_\mu \langle Z_{\tilde{J}} \tilde{J}^{L\,i}_\mu(x)\, \hat{O}(0)\rangle\Big|_{\eta_{cr}} = \langle \tilde{\Delta}^i_L \hat{O}(0)\rangle\Big|_{\eta_{cr}} \delta(x) \; +$

    $$+ C_1\, \Lambda_s \,\langle\, [\bar{Q}_L \frac{\tau^i}{2} U Q_R - \mathrm{hc}](x)\, \hat{O}(0)\,\rangle\Big|_{\eta_{cr}} + \mathrm{O}(b^2)$$

  - same with $[L \leftrightarrow R \;\&\; U \leftrightarrow U^\dagger]$

- a mass term is generated (just set $U = U^\dagger = 1\!\!1$)

RGI NP mass terms in WTI's & running NP mass

To all orders in g_s^2: $\partial_\mu \langle Z_{\tilde J} \tilde J_\mu^{L\,i}(x)\, \hat O(0)\rangle\Big|_{\eta_{cr}} = \langle \tilde\Delta_L^i \hat O(0)\rangle\Big|_{\eta_{cr}} \delta(x) +$

$+\, k_{\rm LO}\, g_s^2(b^{-1})\, \tilde Z_m(b\Lambda_s)\alpha_s(\Lambda_s)\,\Lambda_s \,\langle\, [\bar Q_L \frac{\tau^i}{2} U Q_R - {\rm hc}\,](x)\, \hat O(0)\,\rangle\Big|_{\eta_{cr}} + {\rm O}(b^2)$

with the radiative corrections in NP fermion mass summarized by

$\tilde Z_m(b\Lambda_s) = 1 + g_s^2(b^{-1})\,(\tilde\gamma_m \log b\Lambda_s + \tilde c_m) + \ldots$

accounting for our conventional choice of the scale in $g_s^2(b^{-1})$ & $\alpha_s(\Lambda_s)$

NP mass at the UV cutoff scale (see also $\Gamma_{\rm loc}^{NG}$ in slide 14):

$C_1\Lambda_s = k_{\rm LO}\, g_s^2(b^{-1})\tilde Z_m(b\Lambda_s)\,\alpha_s(\Lambda_s)\Lambda_s \equiv m_Q^{eff}(b^{-1})$

indeed enters the $\tilde\chi_L$-WTI as the prefactor of $\Sigma^i = [\bar Q_L \frac{\tau^i}{2} U Q_R - {\rm hc}]$

Interpretation above & RG-invariance of $Z_{\tilde J} \tilde J_\mu^{L\,i}$ (at η_{cr}) require

$m_Q^{eff}(b^{-1})\,\Sigma_L^i = m_Q^{eff}(\mu)\,\hat\Sigma_L^i(\mu)\,,$ where

$\hat\Sigma_L^i(\mu) = Z_\Sigma(b\mu)\Sigma_L^i(b^{-1}) \;\rightarrow\;$ renormalized Σ_L^i–density

$m_Q^{eff}(\mu) = k_{\rm LO}\, g_s^2(\mu)\tilde Z_m(\Lambda_s/\mu)\,\alpha_s(\Lambda_s)\Lambda_s \;\rightarrow\;$ running NP fermion mass

Note relation $Z_\Sigma(b\mu) = \dfrac{g_s^2(b^{-1})\tilde Z_m(b\Lambda_s)}{g_s^2(\mu)\tilde Z_m(\Lambda_s/\mu)}$ (following from RG-inv. of $Z_{\tilde J} \tilde J_\mu^{L\,i}$)

Lattice test of mass mechanism: toy model @ $g_W = 0$

$\mathcal{S}^{toy}_{lat} = b^4 \sum_x \Big\{ \mathcal{L}^{YM}_{kin}[U] + \mathcal{L}^{sca}_{kin}(\Phi) + \mathcal{V}(\Phi) + \bar\Psi D_{lat}[U,\Phi]\Psi \Big\}$

$\mathcal{L}^{YM}_{kin}[U]$ = plaquette action, $\quad \Phi = \varphi_0 1\!\!1 + i\varphi_j \tau^j\,, \quad \Psi = (u,d)^t$

$\mathcal{L}^{sca}_{kin}(\Phi) = \frac{1}{2}\,\mathrm{Tr}\,[\Phi^\dagger(-\partial^*_\mu\partial_\mu)\Phi]\,, \quad \mathcal{V}(\Phi) = \frac{\mu_0^2}{2}\,\mathrm{Tr}\,\big[\Phi^\dagger\Phi\big] + \frac{\lambda_0}{4}\big(\,\mathrm{Tr}\,\big[\Phi^\dagger\Phi\big]\big)^2$

Setting $F(x) \equiv [\varphi_0 i + i\gamma_5\tau^j\varphi_j](x)$, use "naive" lattice Dirac operator

$(D_{lat}[U,\Phi]\Psi)(x) = \gamma_\mu\widetilde\nabla_\mu\Psi(x) + \eta F(x)\Psi(x) - b^2\rho\frac{1}{2}F(x)\widetilde\nabla_\mu\widetilde\nabla_\mu\Psi(x) +$
$-b^2\rho\frac{1}{4}\Big[(\partial_\mu F)(x)U_\mu(x)\widetilde\nabla_\mu\Psi(x+\hat\mu) + (\partial^*_\mu F)(x)U^\dagger_\mu(x-\hat\mu)\widetilde\nabla_\mu\Psi(x-\hat\mu)\Big]$

as the mechanism can be tested in quenched approximation: 1st MC study!

Check $\tilde\chi$–WTIs by evaluating two-point correlators at few fixed $b^{-1} > \Lambda_s$

$\langle\partial_\mu\tilde J^{L,i}_\mu\Sigma^{L,i}\rangle = O \quad \Rightarrow \quad$ in Wigner phase determine $\eta_{cr}(\rho)$

$\langle\partial_\mu\tilde J^{L,i}_\mu(x)\Sigma^{L,i}(y)\rangle = \langle\sum_f c_{1,f}\Lambda_T\mathcal{D}^{L,i}_f(x)\Sigma^{L,i}(y)\rangle \quad \Rightarrow \quad$ in NG phase

test NP mass terms – with $\mathcal{D}^{L,i}_f = \bar Q_L\frac{\tau^i}{2}UQ_R - \mathrm{h.c.}\,,\ \Sigma^{L,i} = \bar\Psi_L\frac{\tau^i}{2}\Phi\Psi_R - \mathrm{h.c.}$

Unquenched studies needed later: use Domain Wall (or Overlap) fermions

Toy model at $g_W > 0$: bare $\tilde\chi$–WTI and $\tilde\chi$-restoring

The associated non-conserved currents are

$$\tilde J^{L\,i}_\mu = K^i_\mu + \bar q_L \gamma_\mu \frac{\tau^i}{2} q_L - \frac{b^2}{2}\rho\Big(\bar q_L \frac{\tau^i}{2}\Phi \mathcal{D}^A_\mu q_R - \bar q_R \overleftarrow{\mathcal{D}}^A_\mu \Phi^\dagger \frac{\tau^i}{2} q_L\Big)\,, \qquad (2.18)$$

$$\tilde J^{R\,i}_\mu = \bar q_R \gamma_\mu \frac{\tau^i}{2} q_R - \frac{b^2}{2}\rho\Big(\bar q_R \frac{\tau^i}{2}\Phi^\dagger \mathcal{D}^{A,W}_\mu q_L - \bar q_L \overleftarrow{\mathcal{D}}^{A,W}_\mu \Phi \frac{\tau^i}{2} q_R\Big)\,, \qquad (2.19)$$

and differ from the conserved ones, $J^{L\,i}_\mu$ and $J^{R\,i}_\mu$, only because in the latter a contribution bilinear in the scalar field coming from the Φ-kinetic term appears. The transformations $\tilde\chi_L$ and $\tilde\chi_R$ give rise to the (bare) WTIs

$$\begin{aligned}\partial_\mu \langle \tilde J^{L\,i}_\mu(x)\,\hat O(0)\rangle &= \langle \tilde\Delta^i_L \hat O(0)\rangle\delta(x) - \eta\,\langle\Big(\bar q_L \frac{\tau^i}{2}\Phi q_R - \bar q_R \Phi^\dagger \frac{\tau^i}{2} q_L\Big)(x)\,\hat O(0)\rangle + \\ &- \frac{b^2}{2}\rho\,\langle\Big(\bar q_L \overleftarrow{\mathcal{D}}^{A,W}_\mu \frac{\tau^i}{2}\Phi \mathcal{D}^A_\mu q_R - \bar q_R \overleftarrow{\mathcal{D}}^A_\mu \Phi^\dagger \frac{\tau^i}{2}\mathcal{D}^{A,W}_\mu q_L\Big)(x)\,\hat O(0)\rangle + \\ &+ \frac{i}{2} g_w \langle \mathrm{tr}\,\Big(\Phi^\dagger[\frac{\tau^i}{2}, W_\mu]\mathcal{D}^W_\mu \Phi + \Phi^\dagger \overleftarrow{\mathcal{D}}^W_\mu [W_\mu, \frac{\tau^i}{2}]\Phi\Big)(x)\hat O(0)\rangle\,, \qquad (2.20)\end{aligned}$$

$$\begin{aligned}\partial_\mu \langle \tilde J^{R\,i}_\mu(x)\,\hat O(0)\rangle &= \langle \tilde\Delta^i_R \hat O(0)\rangle\delta(x) - \eta\,\langle\Big(\bar q_R \frac{\tau^i}{2}\Phi^\dagger q_L - \bar q_L \Phi \frac{\tau^i}{2} q_R\Big)(x)\,\hat O(0)\rangle + \\ &- \frac{b^2}{2}\rho\,\langle\Big(\bar q_R \overleftarrow{\mathcal{D}}^A_\mu \frac{\tau^i}{2}\Phi^\dagger \mathcal{D}^{A,W}_\mu q_L - \bar q_L \overleftarrow{\mathcal{D}}^{A,W}_\mu \Phi \frac{\tau^i}{2}\mathcal{D}^A_\mu q_R\Big)(x)\,\hat O(0)\rangle\,, \qquad (2.21)\end{aligned}$$

(ρ_{cr}, η_{cr})–values exist for which $\tilde\chi_L \otimes \tilde\chi_R$ symm. is restored in PT up to O(b^2)

A non-SUSY model with gauge coupling unification (I)

$$\mathcal{L}^{BSMM} = \frac{1}{4}\Big(F^B F^B + F^W F^W + F^A F^A + F^G F^G\Big) +$$

$$+ \sum_{f=1,2,3} \Big[\bar{q}^f_L D^{BWA} q^f_L + \bar{q}^{f\,u}_R D^{BA} q^{f\,u}_R + \bar{q}^{f\,d}_R D^{BA} q^{f\,d}_R +$$

$$+ \bar{\ell}^f_L D^{BW} \ell^f_L + \bar{\ell}^{f\,u}_R D^{B} \ell^{f\,u}_R + \bar{\ell}^{f\,d}_R D^{B} \ell^{f\,d}_R\Big] +$$

$$+ \Big[\bar{Q}_L D^{BWAG} Q_L + \bar{Q}^u_R D^{BAG} Q^u_R + \bar{Q}^d_R D^{BAG} Q^d_R\Big] +$$

$$+ \Big[\bar{L}_L D^{BWG} L_L + \bar{L}^u_R D^{BG} L^u_R + \bar{L}^d_R D^{BG} L^d_R\Big] +$$

$$+ \text{mass terms } + \sum_{h=1}^{N_S} \Big(\bar{\psi}^h D^G \psi^h + m_h \bar{\psi}^h \psi^h\Big)$$

SM particles, T-gluons, one generation of T-quarks & T-leptons

$N_S = 4 \div 6$ fermions (feeling only T-gluon vector forces) of mass $\sim v$

Realistic matter content, inspired to our mechanism + unification

A non-SUSY model with gauge coupling unification (II)

Alternative Y–charges & no gauge anomalies for T-quarks/leptons (separately), R/L-handed fermions SU(2)$_L$-singlets/doublets, and ...

$\ldots y_Q = [\mathcal{Q}_{em} - T_3]_Q$	$\ldots y_L = [\mathcal{Q}_{em} - T_3]_L$
$y_{U_L} = \frac{1}{2} - \frac{1}{2} = 0$	$y_{N_L} = \frac{1}{2} - \frac{1}{2} = 0$
$y_{U_R} = \frac{1}{2} - 0 = \frac{1}{2}$	$y_{N_R} = \frac{1}{2} - 0 = \frac{1}{2}$
$y_{D_L} = -\frac{1}{2} + \frac{1}{2} = 0$	$y_{L_L} = -\frac{1}{2} + \frac{1}{2} = 0$
$y_{D_R} = -\frac{1}{2} - 0 = -\frac{1}{2}$	$y_{L_R} = -\frac{1}{2} - 0 = -\frac{1}{2}$

GUT $\Rightarrow$ $g_1^2 := \frac{4}{3}\, g_Y^2\,, \qquad g_2^2 := g_w^2\,, \qquad g_3^2 := g_s^2\,, \qquad g_4^2 := \frac{8+N_S}{12}\, g_T^2$

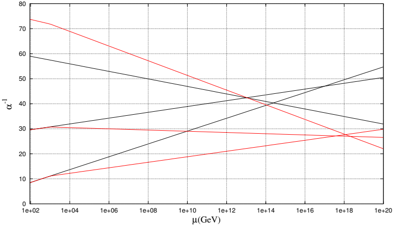
PDG inputs at $\mu = M_Z$ & SM-evolution for $M_Z < \mu < \Lambda_T \sim 5$ TeV

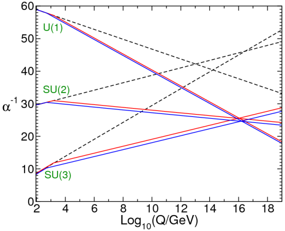
1-loop β-functions for $\Lambda_T < \mu < v$ (with $N_T = 3$, $\nu_Q = \nu_L = 1$, no Φ):

$$\beta_{g_1} = 8\frac{g_1^3}{(4\pi)^2}\,, \quad \beta_{g_2} = \frac{4}{6}\frac{g_2^3}{(4\pi)^2}\,, \quad \beta_{g_3} = -3\frac{g_3^3}{(4\pi)^2}\,, \quad \beta_{g_4} = -\frac{17}{3}\,\frac{12}{8+N_S}\,\frac{g_4^3}{(4\pi)^2}$$

Approximate gauge coupling unification (vs. MSSM)

Excellent strong & EW coupling unification found at 1-loop level





stable under 2-loop corrections, which are numerically similar to GUT threshold effects (unknown) and TeV-scale threshold discontinuities

Setting $\alpha_4^{-1}(\mu = 5\,\text{TeV}) = 1$, need $N_S \sim 4 \div 6$ for unification of α_4 ...