A BSM without Higgs

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Bibliography

- The talk is based on the papers
  R. Frezzotti and G. C. Rossi
  - Phys. Rev. D **92** (2015) no.5, 054505
  - LFC19: Frascati Physics Series Vol. **70** (2019)

  S. Capitani, P. Dimopoulos, R. Frezzotti, M. Garofalo, B. Kostrzewa, F. Pittler, G. C. Rossi and C. Urbach
  - PRL **123** (2019) 061802
- Extensions & theoretical considerations can be found in
  G. C. Rossi
  - EPJ Web Conf. **258** (2022) 06003
  - NPPP **324-329** (2023) 133
  - e-Print: 2306.00115 [hep-ph]
  - e-Print: 2306.00189 [hep-ph]
- See also
  R. Frezzotti, M. Garofalo and G. C. Rossi
  - Phys. Rev. D **93** (2016) no.10, 105030

Outline
&
Take home message

Outline of the talk (take home message)

1. I skip [Introduction - Motivations: SM & its limitations] for lack of time
2. I discuss the construction of an unconventional bSMm with no Higgs
   - exhibiting a NP mechanism yielding "naturally" light quark masses
     $$m_q^{NP} \sim C_q(\alpha_s)\Lambda_{\rm RGI}$$
   - and allowing the introduction of EW interactions, entailing
     $$M_{W,Z}^{NP} \sim g_w C_{w,z}(\alpha)\Lambda_{\rm RGI}$$
   - The above top & W, Z mass formulae require $\Lambda_{\rm RGI} \gg \Lambda_{\rm QCD}$, hence
   - $\exists$ a sector of super-strongly interacting (Tera) particles so that the full SM+Tera-particles theory $\Lambda_{\rm RGI} \equiv \Lambda_T = O(\#\text{TeV}) \leftrightarrow$ EW scale
3. A few consequences
   - Masses NP-ly determined by the dynamics (no Yukawa fitting)
   - Higgs mass "tuning" problem evaporates (no fundamental Higgs)
   - SM + Tera-particles $\rightarrow$ gauge coupling unification (without SUSY)
4. Conjecture 125 GeV boson $h = WW/ZZ$ state bound by Tera-exchanges
5. Encouraging estimates of Λ_T, heaviest family masses and m_h
6. One can prove that the SM Lagrangian is the LEEL of this bSMmodel
7. Conclusions & outlook

The simplest model endowed with NP mass generation

A (toy) model with NP mass generation

Consider a model – where an SU(2) fermion doublet, subjected to non-abelian gauge interactions (of the QCD type), is coupled to a complex scalar doublet via $d=4$ Yukawa and "irrelevant" $d=6$ Wilson-like chiral breaking terms – described by the Lagrangian

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

- $\mathcal{L}_{kin}(q,A,\Phi)=\frac{1}{4}(F^A\cdot F^A)+\bar q_L \not{\mathcal{D}}^A q_L+\bar q_R \not{\mathcal{D}}^A q_R+\frac{1}{2}\mathrm{Tr}\left[\partial_\mu\Phi^\dagger\partial_\mu\Phi\right]$
- $\mathcal{V}(\Phi)=\frac{\mu_0^2}{2}\mathrm{Tr}\left[\Phi^\dagger\Phi\right]+\frac{\lambda_0}{4}\left(\mathrm{Tr}\left[\Phi^\dagger\Phi\right]\right)^2$
- $\mathcal{L}_{Yuk}(q,\Phi)=\eta\left(\bar q_L\Phi q_R+\bar q_R\Phi^\dagger q_L\right)$
- $\mathcal{L}_{Wil}(q,A,\Phi)=\frac{b^2}{2}\rho\left(\bar q_L\overleftarrow{\mathcal{D}}^A{}_\mu\Phi\mathcal{D}^A_\mu q_R+\bar q_R\overleftarrow{\mathcal{D}}^A_\mu\Phi^\dagger\mathcal{D}^A_\mu q_L\right)$

- $\mathcal{L}_{\rm toy}$ key features
  - presence of the "irrelevant" chiral breaking $d=6$ Wilson-like term
  - despite appearance Φ not the Higgs: doesn't enter mass formulae
- $\mathcal{L}_{\rm toy}$ notations
  - $b^{-1}\sim\Lambda_{UV}$=UV cutoff, η=Yukawa coupling, ρ to keep track of $\mathcal{L}_{Wil}$

Theoretical background

1. $\mathcal{L}_{\rm toy}$ is formally power-counting renormalizable (like Wilson LQCD)
2. and exactly invariant under the (global) transformations

$$\chi_L \times \chi_R = [\tilde{\chi}_L \times (\Phi \to \Omega_L \Phi)] \times [\tilde{\chi}_R \times (\Phi \to \Phi\Omega_R^\dagger)]$$

$$\tilde{\chi}_{L/R} : \begin{cases} q_{L/R} \to \Omega_{L/R} q_{L/R} \\ \bar{q}_{L/R} \to \bar{q}_{L/R} \Omega^\dagger_{L/R} \end{cases} \qquad \Omega_{L/R} \in \mathrm{SU}(2)$$

- $\chi_L \times \chi_R$ exact, can be realized
  - *á la* Wigner
  - *á la* Nambu–Goldstone
- $\tilde{\chi}_L \times \tilde{\chi}_R$ ($\sim$ chiral transformations) - broken for generic η and ρ
  - can become symmetries at a "critical" Yukawa coupling, $\eta_{cr}(\rho)$

3. Φ is the $\mathcal{L}_{\rm toy}$ UV completion enforcing $\chi_L \times \chi_R$ invariance (not the Higgs)
4. Standard fermion masses are forbidden because the operator $\bar{q}_L q_R + \bar{q}_R q_L$ is not invariant under the exact $\chi_L \times \chi_R$ symmetry $\Longrightarrow$
   - mass protected against UV linear divergencies, unlike Wilson LQCD
   - a step towards complying with naturalness 't Hooft

- Yukawa and Wilson-like terms break $\tilde{\chi}_L \times \tilde{\chi}_R$ and mix
- At $\eta = \eta_{cr}$ they "compensate", enforcing chiral $\tilde{\chi}_L \times \tilde{\chi}_R$ symmetry
- symmetry enhancement similar to that induced by m_{cr} in LQCD
- Conservation of $\tilde{\chi}_L \times \tilde{\chi}_R$ currents imply at 1-loop Bochicchio et al.
  1. Wigner phase $\langle |\Phi|^2 \rangle = 0 \to$ effective $\bar{q}_R \Phi q_L + \text{hc}$ vertex absent

[box is the Wilson-like vertex]

  2. NG phase $\langle |\Phi|^2 \rangle = v^2 \to$ Higgs mechanism is made ineffective

- Observations
  - b^2 factor from the Wilson-like vertex is compensated by the quadratic loop divergency b^{-2}, yielding a finite 1-loop diagram
- Q: after Higgs-like mass cancellation, any fermion mass term left?
  A: YES!

The road to NP mass generation - II

1. As in QCD (recovered) chiral $\tilde{\chi}_L \times \tilde{\chi}_R$ symmetry is spontaneously broken
2. At O(b^2) besides Symanzik P terms, in NG phase also NP ones occur
3. Cutoff effects of regularized theory are analyzed *á la* Symanzik
   - Standard Symanzik expansion technique allows identifying the O(b^2) operators necessary to describe the peculiar NP cutoff features ensuing from the S$\tilde{\chi}$SB phenomenon. They are

$$O_{6,\bar{q}q} \propto b^2 \Lambda_s \alpha_s |\Phi| \Big[\bar{q} \not{\mathcal{D}}^A q\Big]\,, \qquad O_{6,FF} \propto b^2 \Lambda_s \alpha_s |\Phi| \Big[F^A \cdot F^A\Big]$$

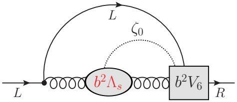
   - $O_{6,\bar{q}q}$ & $O_{6,FF}$ expression fixed by symmetries ($\chi_L \times \chi_R$) & dimension
   - They matter in the limit $b \to 0$, as formally O(b^2) effects can be promoted by UV power divergencies in loops to finite contributions
   - Bookkeeping of NP effects can be standardly described including new diagrams derived from the "augmented" Lagrangian

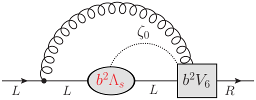
$$\mathcal{L}_{\rm toy} \to \mathcal{L}_{\rm toy} + \Delta \mathcal{L}_{NP}$$

$$\Delta \mathcal{L}_{NP} = b^2 \Lambda_s \alpha_s |\Phi| \Big[c_{FF} F^A \cdot F^A + c_{\bar{q}q} \bar{q} \not{\mathcal{D}}^A q\Big] + \dots$$

A diagrammatic understanding of NP masses - III

- NP fermion masses emerge from new self-energy diagrams like





  - Amputated diagrams at vanishing external momenta (masses)
  - blobs = vertices from the NP Symanzik term, $\Delta\mathcal{L}_{NP}$
  - box = Wilson-like vertex from the fundamental $\mathcal{L}_{\rm toy}$

$$\underline{\underline{m_q^{NP}}} \propto \underline{\underline{\alpha_s^2}} \int^{1/b} \frac{d^4k}{k^2}\frac{\gamma_\mu k_\mu}{k^2} \int^{1/b} \frac{d^4\ell}{\ell^2+m_{\zeta_0}^2}\frac{\gamma_\nu(k+\ell)_\nu}{(k+\ell)^2}\cdot$$

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

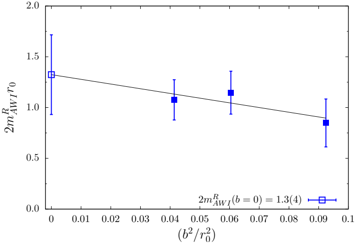
- Diagrams are finite
  - b^4 S$\tilde{\chi}$SB IR effects compensate 2-loop UV quartic divergency
  - Thus masses are a kind of NP anomalies that appear as obstructions to a full recovery of the $\tilde{\chi}_L \times \tilde{\chi}_R$ chiral symmetry
  - This NP mechanism is in line with the ’t Hooft naturalness idea since switching off masses enlarges the symmetry of the theory

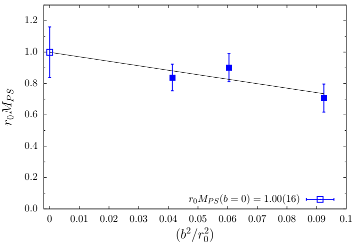
NP mass in NG phase: a lattice confirmation - IV

- At $\eta = \eta_{cr}$, where invariance under $\tilde{\chi}_L \times \tilde{\chi}_R$ is recovered so in the NG phase the Higgs quark mass is killed, we compute the "PCAC mass"

$$m_q^{NP} = m_{PCAC}(\eta_{cr}) = \frac{\sum_{\vec{x}} \partial_\mu \langle \tilde{A}^i_\mu(\vec{x}, x_0) P^i(0) \rangle}{\sum_{\vec{x}} \langle P^i(\vec{x}, x_0) P^i(0) \rangle} \Big|^{NG}_{\eta_{cr}}, \qquad P^i = \bar{q}\gamma_5 \frac{\tau^i}{2} q$$

- Surprisingly we find that neither m_{PCAC} nor M_{PS} vanish
  $\rightarrow$ a NP fermion mass is getting dynamically generated
  $\rightarrow$ together with a non-vanishing PS-meson mass





- $2m^R_{AWI} r_0 \equiv 2 r_0 m_{PCAC} Z_{\tilde{A}} Z_P^{-1}$ (left) and $r_0 M_{PS}$ (right) vs. $(b/r_0)^2$
- straight lines are (linear) extrapolations to the $b \rightarrow 0$ limit

Quantum Effective Lagrangian (QEL) in NG phase

Summarizing we saw that

- it is possible to enforce $\tilde{\chi}_L \times \tilde{\chi}_R$ symmetry by fixing $\eta = \eta_{cr}(\rho)$
- in the NG phase at η_{cr} the "Higgs" fermion mass get cancelled, but (lattice simulations confirm that) the fermion acquires a NP mass

$m_q^{NP} = c_q(g_s^2)\Lambda_s$ - at lowest order for a d=6 Wilson-like term $c_q(g_s^2) = \mathrm{O}(\alpha_s^2)$

1. $m_q^{NP} \neq 0$ can be naturally incorporated in the QEL that describes the physics of the model in the NG phase, Γ^{NG}, by introducing U

$$\Phi = (v + \zeta_0)U\,, \qquad U = \exp[i\vec{\tau}\vec{\zeta}/c\Lambda_s]$$

2. $\Gamma^{Wig}_{d=4}\Big|_{\hat{\mu}^2_\Phi > 0} = \frac{1}{4}(F^A \cdot F^A) + \bar{q}_L \mathcal{D}\!\!\!/^A q_L + \bar{q}_R \mathcal{D}\!\!\!/^A q_R + \frac{1}{2}\mathrm{Tr}\,[\partial_\mu \Phi^\dagger \partial_\mu \Phi] + \mathcal{V}(\Phi)$

3. Include in Γ^{NG} all $\chi_L \times \chi_R$ invariant operators functions of $q, \bar{q}, A, U$. New NP terms can be formed as U transforms like Φ

$$\Gamma^{NG}_{d=4} = \Gamma^{Wig}_{d=4}\Big|_{\hat{\mu}^2_\Phi < 0} + \underline{c_q \Lambda_s [\bar{q}_L U q_R + \bar{q}_R U^\dagger q_L]} + \frac{c^2 \Lambda_s^2}{2}\mathrm{Tr}\,[\partial_\mu U^\dagger \partial_\mu U]$$

4. From $U = 1\!\!1 + i\vec{\tau}\vec{\zeta}/v + \ldots$ we get a fermion mass plus NGBs interactions

Introducing electro-weak interactions
Why super-strong (Tera) interactions?

Why superstrong (Tera) interactions?

Obviously we want EW interactions. But why Tera-interactions?

- In the previous mass formulae $\Lambda_s = \Lambda_{\rm RGI}$ is the RGI scale of the theory
- Let us focus on the top quark. Can we make the NP formula

$$m_q^{NP} = C_q(\alpha_s)\Lambda_{\rm RGI}$$

  compatible with the phenomenological value of the top mass?
- As an order of magnitude, we clearly need to have for $\Lambda_{\rm RGI}$

$$\Lambda_{\rm QCD} \ll \Lambda_{\rm RGI} = \text{O(a few TeV's)}$$

  so as to get a top mass in the 10^2 GeV range $\rightarrow$
- Super-strongly interacting particles must exist hinting at a full theory with

$$\Lambda_{\rm RGI} \equiv \Lambda_T = \text{O(a few TeV's)}$$

- We refer to them as Tera-particles Glashow (to avoid confusion with Techni-particles)

- Revealing Tera-hadrons $\rightarrow$ an unmistakable sign of New Physics

Towards a bSMm: including EW & Tera-interactions

$$\mathcal{L}(q,\ell,Q,L;\Phi;A,G,W,B) = \mathcal{L}_{kin}(q,\ell,Q,L;\Phi;A,G,W,B) + \mathcal{V}(\Phi) + \\ + \mathcal{L}_{Yuk}(q,\ell,Q,L;\Phi) + \mathcal{L}_{Wil}(q,\ell,Q,L;\Phi;A,G,W,B)$$

- $\mathcal{L}_{kin}(q,\ell,Q,L;\Phi;A,G,W,B) =$

$$= \frac{1}{4}\Big(F^A\cdot F^A + F^G\cdot F^G + F^W\cdot F^W + F^B\cdot F^B\Big) + \\ + \Big[\bar{q}_L \not{\mathcal{D}}^{BWA} q_L + \bar{q}_R \not{\mathcal{D}}^{BA} q_R + \bar{\ell}_L \not{\mathcal{D}}^{BW} \ell_L + \bar{\ell}_R \not{\mathcal{D}}^{B} \ell_R\Big] + \\ + \Big[\bar{Q}_L \not{\mathcal{D}}^{BWAG} Q_L + \bar{Q}_R \not{\mathcal{D}}^{BAG} Q_R + \bar{L}_L \not{\mathcal{D}}^{BWG} L_L + \bar{L}_R \not{\mathcal{D}}^{BG} L_R\Big] + \\ + \frac{k_b}{2}\mathrm{Tr}\left[(\mathcal{D}_\mu^{WB}\Phi)^\dagger \mathcal{D}_\mu^{WB}\Phi\right]$$

- $\mathcal{V}(\Phi) = \frac{\mu_0^2}{2} k_b \mathrm{Tr}\left[\Phi^\dagger\Phi\right] + \frac{\lambda_0}{4}\left(k_b \mathrm{Tr}\left[\Phi^\dagger\Phi\right]\right)^2$
- $\mathcal{L}_{Yuk}(q,\ell,Q,L;\Phi) = \sum_{f=q,\ell,Q,L} \eta_f \left(\bar{f}_L \Phi f_R + \mathrm{hc}\right)$
- $\mathcal{L}_{Wil}(q,\ell,Q,L;\Phi;A,G,W,B) =$

$$= \frac{b^2}{2}\rho_q\left(\bar{q}_L \overleftarrow{\mathcal{D}}_\mu^{BWA}\Phi\mathcal{D}_\mu^{BA} q_R + \mathrm{hc}\right) + \frac{b^2}{2}\rho_\ell\left(\bar{\ell}_L \overleftarrow{\mathcal{D}}_\mu^{BW}\Phi\mathcal{D}_\mu^{B}\ell_R + \mathrm{hc}\right) + \\ + \frac{b^2}{2}\rho_Q\left(\bar{Q}_L \overleftarrow{\mathcal{D}}_\mu^{BWAG}\Phi\mathcal{D}_\mu^{BAG} Q_R + \mathrm{hc}\right) + \frac{b^2}{2}\rho_L\left(\bar{L}_L \overleftarrow{\mathcal{D}}_\mu^{BWG}\Phi\mathcal{D}_\mu^{BG} L_R + \mathrm{hc}\right).$$

Covariant derivatives & Symmetries

- Covariant derivatives

$$D_\mu^{BWAG} = \partial_\mu - iYg_Y B_\mu - ig_w \tau^r W_\mu^r - ig_s \frac{\lambda^a}{2} A_\mu^a - ig_T \frac{\lambda_T^\alpha}{2} G_\mu^\alpha$$

- Symmetries ($f = q, Q, \ell, L$)

$$\chi_L \times \chi_R = [\tilde{\chi}_L \times (\Phi \to \Omega_L \Phi)] \times [\tilde{\chi}_R \times (\Phi \to \Phi \Omega_R^\dagger)]$$

$\chi_L \times \chi_R$ is exact

$$\tilde{\chi}_L : \begin{cases} f_L \to \Omega_L f_L & \bar{f}_L \to \bar{f}_L \Omega_L^\dagger\,, \quad f = q, \ell, Q, L \\ W_\mu \to \Omega_L W_\mu \Omega_L^\dagger & \end{cases}$$

$$\tilde{\chi}_R : \quad f_R \to \Omega_R f_R\,, \qquad \bar{f}_R \to \bar{f}_R \Omega_R^\dagger\,, \quad f = q, \ell, Q, L$$

$\tilde{\chi}_L \times \tilde{\chi}_R$ recovered in the critical limit (up to O(b^2)) terms

The critical theory

- Besides the operators
  - $\mathcal{L}_{Yuk}(q, \ell, Q, L; \Phi)$
  - $\mathcal{L}_{Wil}(q, \ell, Q, L; \Phi; A, G, W, B)$

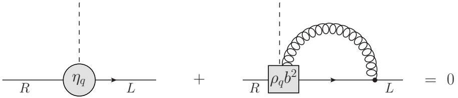
  now also the kinetic term of the scalar
  - $\mathcal{L}_{kin}(\Phi; W, B) = \frac{k_b}{2} \mathrm{Tr}\left[(\mathcal{D}_\mu^{WB}\Phi)^\dagger \mathcal{D}_\mu^{WB}\Phi\right]$

  breaks $\tilde{\chi}_L \times \tilde{\chi}_R$ and mixes with $\mathcal{L}_{Yuk}$ and $\mathcal{L}_{Wil}$

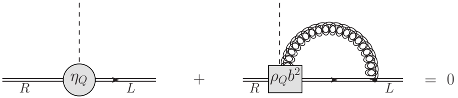
- On top of $\eta_f, f = q, Q, \ell, L$, also k_b needs to be tuned,
- The conditions determining the critical theory (invariant under $\tilde{\chi}_L \times \tilde{\chi}_R$) correspond to a QEL with
  - vanishing Yukawa interactions
  - vanishing scalar kinetic term (Bardeen, Hill & Lindner 1989)

Critical tuning in the Wigner phase $\langle|\Phi|^2\rangle = 0$ at 1-loop

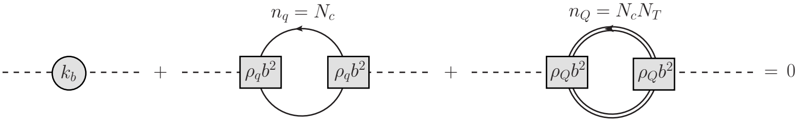
- The η_q tuning condition $\to \eta^{(1)}_{q\,cr} = \rho_q\, \eta_{1q} \alpha_s$



- The η_Q tuning condition $\to \eta^{(1)}_{Q\,cr} = \rho_Q\, \eta_{1Q} \alpha_T$



- The k_b tuning condition $\to k^{(1)}_{b\,cr} = \rho_q^2 N_c k^{(1)}_{b\,q} + \rho_Q^2 N_c N_T k^{(1)}_{b\,Q}$

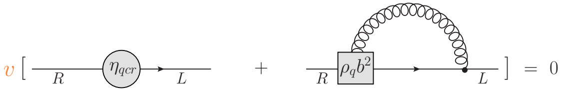


- UV divergencies are exactly compensated by the IR behaviour

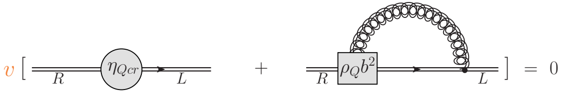
Critical tuning in the NG phase $\langle|\Phi|^2\rangle = v^2$ at 1-loop

Higgs-like masses cancelled in the NG phase of the critical theory

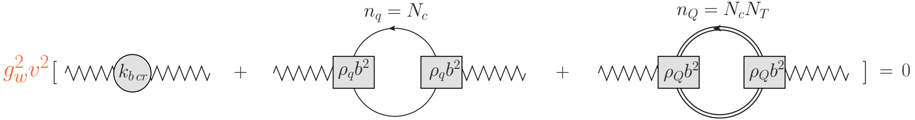
- Cancellation mechanism of the "Higgs-like" quark mass term
  $v\,\bar{q}q$



- Cancellation mechanism of the "Higgs-like" Tera-quark mass term
  $v\,\bar{Q}Q$



- The cancellation mechanism of the "Higgs-like" W mass term
  $g_w^2 v^2 \mathrm{Tr}\,[W_\mu W_\mu]$



- UV divergencies are exactly compensated by the IR behaviour

NP O(b^2) Symanzik operators - I

Since UV divergencies can be compensated by the IR behaviour, we cannot neglect NP O(b^2) Symanzik operators

$$\gamma^{T}_{\bar{Q}Q} O^{T}_{6,\bar{Q}Q} = r^{T}_{\bar{Q}Q} b^2 \Lambda_T \, \alpha_T |\Phi| \Big[\bar{Q}_L \, \not{\mathcal{D}}^{AGBW} Q_L + \bar{Q}_R \, \not{\mathcal{D}}^{BAG} Q_R \Big] \quad (1)$$

$$\gamma^{T}_{\bar{L}L} O^{T}_{6,\bar{L}L} = r^{T}_{\bar{L}L} b^2 \Lambda_T \, \alpha_T |\Phi| \Big[\bar{L}_L \, \not{\mathcal{D}}^{GBW} L_L + \bar{L}_R \, \not{\mathcal{D}}^{GB} L_R \Big] \quad (2)$$

$$\gamma_{AA} O_{6,AA} = r_{AA} b^2 \Lambda_T \, g_s^2 |\Phi| F^A \cdot F^A \quad (3)$$

$$\gamma^{Q}_{GG} O^{Q}_{6,GG} = r^{Q}_{GG} b^2 \Lambda_T \, g_T^2 |\Phi| F^G \cdot F^G \quad (4)$$

$$\gamma^{L}_{GG} O^{L}_{6,GG} = r^{L}_{GG} b^2 \Lambda_T g_T^2 \, |\Phi| F^G \cdot F^G \quad (5)$$

$$\gamma^{Q}_{BB} O^{Q}_{6,BB} = r^{Q}_{BB} b^2 \Lambda_T \, g_Y^2 |\Phi| F^B \cdot F^B \quad (6)$$

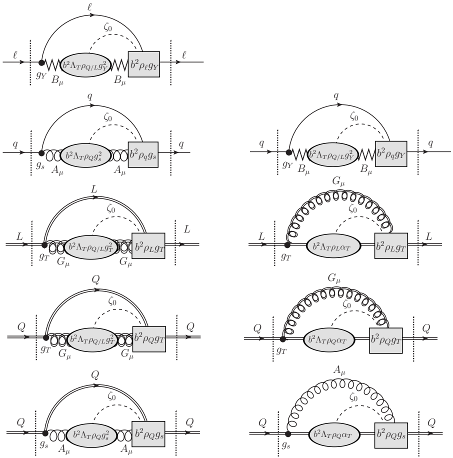
$$\gamma^{L}_{BB} O^{L}_{6,BB} = r^{L}_{BB} b^2 \Lambda_T \, g_Y^2 |\Phi| F^B \cdot F^B \quad (7)$$

The coefficients r's are in principle computable, numerical constants, depending on the ρ_f parameters, N_c and N_T

Fermions & EW bosons NP masses

Amputated self-energy diagrams

Blobs = NP Symanzik operators - **Squares** = Wilson-like terms



$$m_q = C_q\,\Lambda_T\,, \quad C_q = c_q O(\alpha_s^2) \qquad m_\ell = C_\ell\,\Lambda_T\,, \quad C_\ell = c_\ell O(\alpha_Y^2)$$

$$m_Q = C_Q\,\Lambda_T\,, \quad C_Q = c_Q O(\alpha_T^2) \qquad m_L = C_L\,\Lambda_T\,, \quad C_L = c_L O(\alpha_T^2)$$

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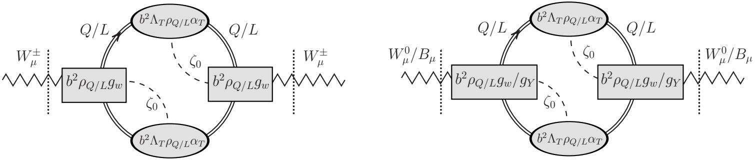


$$M_{W^\pm} = C_{W^\pm}\,\Lambda_T\,, \qquad C_{W^\pm} = g_w c_w\,, \qquad c_w = k_w \mathrm{O}(\alpha_T)$$

$$M_Z = C_{Z^0}\,\Lambda_T\,, \qquad C_Z = \sqrt{g_w^2 + g_Y^2}\,c_w$$

$$M_{A^0} = 0$$

- Custodial symmetry unbroken at leading order in the EW interactions
- Diagonalization of the self-energy matrix yields, exactly like in the SM, a massive Z boson and a massless photon

The critical QEL in the NG phase

Similarly to the case of the toy-model, we obtain now for the QEL

$$\Gamma^{NG}_{cr}(q,\ell,Q,L;\Phi;A,G,W,B) = \frac{1}{4}\Big(F^A\cdot F^A + F^G\cdot F^G + F^W\cdot F^W + F^B\cdot F^B\Big) +$$
$$+\Big[\bar q_L \not{\mathcal{D}}^{BWA} q_L + \bar q_R \not{\mathcal{D}}^{BA} q_R\Big] + C_q\Lambda_T\left(\bar q_L U q_R + \bar q_R U^\dagger q_L\right) +$$
$$+\Big[\bar\ell_L \not{\mathcal{D}}^{BW} \ell_L + \bar\ell_R \not{\mathcal{D}}^{B} \ell_R\Big] + C_\ell\Lambda_T\left(\bar\ell_L U \ell_R + \bar\ell_R U^\dagger \ell_L\right) +$$
$$+\Big[\bar Q_L \not{\mathcal{D}}^{BWAG} Q_L + \bar Q_R \not{\mathcal{D}}^{BAG} Q_R\Big] + C_Q\Lambda_T\left(\bar Q_L U Q_R + \bar Q_R U^\dagger Q_L\right) +$$
$$+\Big[\bar L_L \not{\mathcal{D}}^{BWA} L_L + \bar L_R \not{\mathcal{D}}^{BA} L_R\Big] + C_L\Lambda_T\left(\bar L_L U L_R + \bar L_R U^\dagger L_L\right) +$$
$$+\frac{1}{2}c_w^2\Lambda_T^2 \mathrm{Tr}\left[(\mathcal{D}^{BW}_\mu U)^\dagger \mathcal{D}^{BW}_\mu U\right] + \mathrm{O}(\Lambda_T^{-1})$$

- Expanding $U = 1\!\!1 + i\vec\tau\vec\zeta/v + \ldots$ we get the previous mass identification
- Mass terms are kind of NP anomalies preventing the full recovery of the $\tilde\chi_L \times \tilde\chi_R$ symmetry.
- For consistency
  - weak interactions are needed to decouple Φ
  - hypercharge interactions are needed to give mass to leptons

The 125 GeV resonance
&
comparison with the SM

125 GeV resonance & comparison with the SM

No need for a Higgs $\to$ how do we interpret the 125 GeV resonance?

- At $p^2/\Lambda_T^2 \ll 1$ Tera-dof's can be integrated out
- Tera-forces bind a $|W^+W^- + ZZ\rangle = |h\rangle$ state with $E_{bind} = \mathrm{O}(M_W)$
- $|h\rangle$ resonance with $m_h \sim 125 \ll \Lambda_T$ is left behind
- We need to include this "light" $\chi_L \times \chi_R$ singlet in the QEL
- If we do so, perhaps not surprisingly, one finds that, up to perturbative corrections, $\mathrm{LEEL}_{d=4}$ looks like the SM Lagrangian with $v_H \sim \Lambda_T$
- m_h^2 from Bethe–Salpeter-like iteration

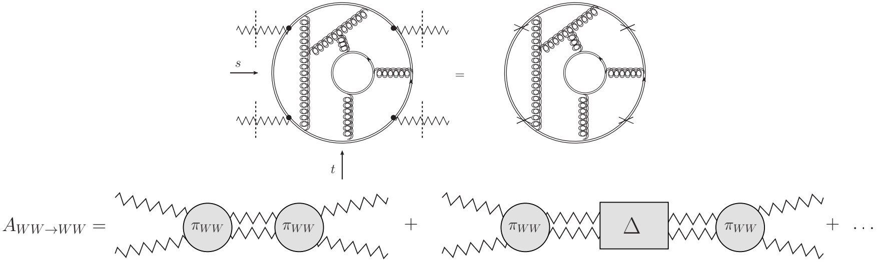


Figure: Upper panel, the Δ kernel. Lower panel, the Bethe–Salpeter iteration

Evaluating m_h

- In the Bethe–Salpeter-like iteration Δ is the energy shift of the initial free state due to the interaction

$$A_{WW\to WW}(s) \;\Rightarrow\; \frac{(\pi_{WW}(s))^2}{s+4M_W^2}\Big[1-\frac{\Delta(s)}{s+4M_W^2}+\dots\Big]=$$

$$=\frac{(\pi_{WW}(s))^2}{s+4M_W^2+\Delta(s)} \stackrel{s\simeq -m_h^2}{\longrightarrow} \frac{g_w^2 M_W^2}{s+m_h^2}$$

  - Price to have two W's sufficiently close to feel Tera-interactions

$$\pi_{WW}(s)|_{s_{pole}} = \mathrm{O}(g_w^2\Lambda_T) = \mathrm{O}(g_w M_W)$$

  - $\Delta(s)$ at the pole has the parametric expression

$$\Delta(p^2)|_{s_{pole}} = c_h\, g_w^4 4M_W^2$$

- We thus get

$$m_h^2 = 4M_W^2 + c_h g_w^4 4M_W^2$$

  At face value, with $g_w = 0.62$, $c_h = \mathrm{O}(1)$ and negative, one obtains

$$E_{bin} = -c_h g_w^4 M_W \sim 12\ \mathrm{GeV}$$

- Lattice QCD simulations can help evaluating c_h

$d=4$ LEEL of the critical NG model vs. SM Lagrangian

- LEEL$_{d=4}$ of the critical NG model for $p^2/\Lambda_T^2 \ll 1$, including h reads [we ignore weak isospin, leptons & U$_Y(1)$]

$$\mathcal{L}^{NG}_{4\,cr}(q;A,W;U,h) = \frac{1}{4}F^A\cdot F^A + \frac{1}{4}F^W\cdot F^W + \Big[\bar{q}_L \not{\mathcal{D}}^{AW} q_L + \bar{q}^u_R \not{\mathcal{D}}^A q^u_R + \bar{q}^d_R \not{\mathcal{D}}^A q^d_R\Big] +$$
$$+\frac{1}{2}\partial_\mu h \partial_\mu h + \frac{1}{2}(k_v^2 + 2k_v k_1 h + k_2 h^2)\mathrm{Tr}\,[(\mathcal{D}^W_\mu U)^\dagger \mathcal{D}^W_\mu U] + \widetilde{\mathcal{V}}(h) +$$
$$+(y_q h + k_q k_v)\left(\bar{q}_L U q_R + \bar{q}_R U^\dagger q_L\right)$$

- $\mathcal{L}^{\mathcal{NG}}_{\triangle\rfloor\triangledown}$ is neither renormalizable nor unitary (unlike the fundamental Lagrangian in slide 15) for generic k_v, k_1, k_2, y_q, k_q. But if in $\mathcal{L}^{NG}_{4\,cr}$ we set

$$k_q/y_q = 1\,, \qquad k_1 = k_2 = 1$$

precisely the combination $\Phi \equiv (k_v + h)U$ appears (except in $\widetilde{\mathcal{V}}(h)$) and we get

$$\mathcal{L}^{NG}_{4\,cr}(q;A,W;\Phi) \to \frac{1}{4}F^A\cdot F^A + \frac{1}{4}F^W\cdot F^W + \Big[\bar{q}_L \not{\mathcal{D}}^{AW} q_L + \bar{q}^u_R \not{\mathcal{D}}^A q^u_R + \bar{q}^d_R \not{\mathcal{D}}^A q^d_R\Big] +$$
$$+\frac{1}{2}\mathrm{Tr}\,[(\mathcal{D}^W_\mu \Phi)^\dagger \mathcal{D}^W_\mu \Phi] + \widetilde{\mathcal{V}}(h) + y_q\left(\bar{q}_L \Phi q_R + \bar{q}_R \Phi^\dagger q_L\right) \sim \mathcal{L}^{\rm SM}$$

$$m_q = y_q k_v = C_q\Lambda_T\,, \quad M_W = g_w k_v = g_w c_w \Lambda_T$$

i.e. a unitary & renormalizable theory

A bit of phenomenology

Estimating Λ_T & heaviest family masses - I

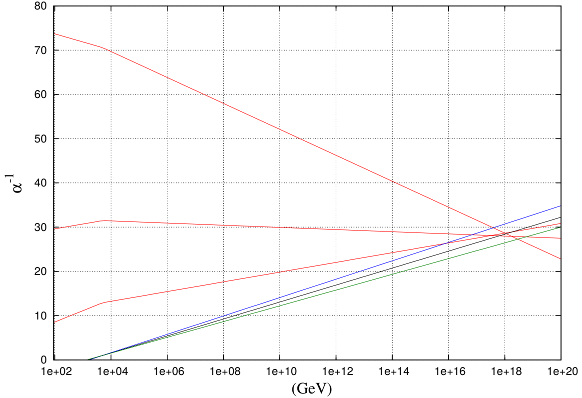
- Assumptions - I
  - Previous formulae for running masses give values at the UV cutoff
  - or better at Λ_{GUT} for a unifying theory, like the one we consider
  - Defining $\overline{\alpha} = \alpha(\Lambda_{GUT})$ we can write

$$m_f(\Lambda_{GUT}) = C_f\,\overline{\alpha}_s^{u_f}\,\overline{g}_s^2\Lambda_T\,, \qquad f = t, b\,,$$
$$m_\tau(\Lambda_{GUT}) = C_\tau\,\overline{\alpha}_Y^{u_\tau}\,\overline{g}_Y^2\Lambda_T\,,$$
$$m_Q(\Lambda_{GUT}) = C_Q\,\overline{\alpha}_T^{u_Q}\,\overline{g}_T^2\Lambda_T\,,$$
$$m_L(\Lambda_{GUT}) = C_L\,\overline{\alpha}_T^{u_L}\,\overline{g}_T^2\Lambda_T$$
$$M_W = k_w\overline{\alpha}_T\,\overline{g}_w\Lambda_T$$

with the "ad hoc" choice $u_t = u_Q = u_L = 1$ & $u_b = u_\tau = 2$

  - The above exponents correspond to take
    - $d = 6$ Wilson-like terms for *top*, Q, L
    - $d = 8$ Wilson-like terms for b, τ

- Assumptions - II
  - The unification plot



  - The unifying couplings (best choice is $N_S = 5$)

$$g_1^2 = \frac{4}{3} g_Y^2 \quad g_2^2 = g_w^2 \, , \quad g_3^2 = g_s^2 \, , \quad g_4^2 = \frac{8 + N_S}{12} g_T^2 = \frac{13}{12} g_T^2$$

Estimating Λ_T & heaviest family masses - III

- At Λ_{GUT}

$$\overline{\alpha}_Y \sim \frac{3}{4}\cdot\frac{1}{28} = \frac{3}{112} \qquad \overline{\alpha}_w \sim \frac{1}{28} \qquad \overline{\alpha}_s \sim \frac{1}{28} \qquad \overline{\alpha}_T \sim \frac{12}{13}\cdot\frac{1}{28} = \frac{12}{364}$$

$$\overline{g}_Y \sim 0.58 \qquad \overline{g}_w \sim 0.67 \qquad \overline{g}_s \sim 0.67 \qquad \overline{g}_T \sim 0.64$$

- At 5 TeV

$$\alpha_3(5\text{ TeV}) = \alpha_s(5\text{ TeV}) \sim \frac{1}{13}$$

$$\alpha_4(5\text{ TeV}) = \frac{13}{12}\,\alpha_T(5\text{ TeV}) \sim \frac{13}{12}\cdot 2$$

- Ignoring EW running, we get for $f =$ top, b, Q, L

$$m_f(5\text{ TeV}) = m_f(\Lambda_{GUT}) \prod_{p=s,T} \left[\frac{\alpha_p(5\text{ TeV})}{\alpha_p(\Lambda_{GUT})}\right]^{\gamma^f_{0p}/2\beta_{0p}}$$

with the 1-loop β and γ coefficients

$$\beta_{0s} = 3\,, \quad \beta_{0T} = \frac{17}{3}\,, \quad \gamma^Q_{0s} = \gamma^L_{0s} = \gamma^q_{0s} = 8\,, \quad \gamma^Q_{0T} = \gamma^L_{0T} = 8$$

Estimating Λ_T & heaviest family masses - IV

- We take $M_W \sim 80$ GeV as the input scale

$$80 = k_w \overline{\alpha}_T \, \overline{g}_w \Lambda_T = k_w \frac{12}{364} \, 0.67 \Lambda_T \quad \to \quad k_w \Lambda_T \sim 3.6 \text{ TeV}$$

k_w has a weak dependence on ρ_f, N_c and N_T

- Tera-fermion mass running

$$m_Q(5 \text{ TeV}) = C_Q \overline{\alpha}_T \, \overline{g}_T^2 \Lambda_T \left(\frac{2}{12/364} \right)^{8 \frac{3}{17} \frac{1}{2}} \left(\frac{1/13}{1/28} \right)^{\frac{8}{3} \frac{1}{2}} \sim$$

$$\sim \frac{C_Q}{k_w} \frac{12}{364} (0.64)^2 \cdot 18.15 \cdot 2.78 \cdot 3600 \sim \frac{C_Q}{k_w} 2500 \text{ GeV}$$

$$m_L(5 \text{ TeV}) = C_L \overline{\alpha}_T \, \overline{g}_T^2 \Lambda_T \left(\frac{2}{12/364} \right)^{8 \frac{3}{17} \frac{1}{2}} \sim \frac{C_L}{k_w} 900 \text{ GeV}$$

Estimating Λ_T & heaviest family masses - V

- Top mass running

$$m_t(5\text{ TeV}) = C_t\,\overline{\alpha}_s\,\overline{g}_s^2\Lambda_T\left(\frac{1/13}{1/28}\right)^{\frac{8}{3}\frac{1}{2}} \sim$$

$$\sim \frac{C_t}{k_w}\,\frac{1}{28}(0.67)^2\cdot 2.78\cdot 3600 \sim \frac{C_t}{k_w}\,160\text{ GeV}$$

- m_b running

$$m_b(5\text{ TeV}) = C_b\,\overline{\alpha}_s\overline{g}_s^2\overline{\alpha}_Y\Lambda_T\left(\frac{1/13}{1/28}\right)^{\frac{8}{3}\frac{1}{2}} \sim$$

$$\sim \frac{C_b}{k_w}\,\frac{1}{28}(0.67)^2\frac{3}{112}\cdot 2.78\cdot 3600 \sim \frac{C_b}{k_w}\,4.3\text{ GeV}$$

- m_τ pole mass

$$m_\tau \sim C_\tau\overline{\alpha}_Y^2\,\overline{g}_Y^2\Lambda_T \sim \frac{C_\tau}{k_w}\left(\frac{3}{112}\right)^2(0.58)^2\cdot 3600 \sim \frac{C_\tau}{k_w}\,0.87\text{ GeV}$$

Conclusions & Epilogue

Conclusions

- I have presented the construction of an elementary particle model where fundamental fermions and electroweak bosons masses are NP-ly determined by the dynamics and not via the Higgs mechanism
- Masses have parametric form $m_f^{NP} \propto C_f(\alpha)\Lambda_{\mathrm{RGI}}$, $M_W^{NP} \propto g_w C_w(\alpha_T)\Lambda_{\mathrm{RGI}}$
  - $m_{top}, M_W \sim 10^2$ GeV call for a Tera-strong interaction
  - in oder to get the full theory with $\Lambda_{\mathrm{RGI}} \equiv \Lambda_T =$ O(a few TeV's)
- We provide an understanding of the
  - EW scale magnitude (as a fraction of Λ_T)
  - fermion mass ranking $(\alpha_y \ll \alpha_s \ll \alpha_T \to m_\ell \ll m_q \ll m_{Q/L})$
  - absence of Higgs mass tuning problem (no fundamental Higgs)
- 125 GeV resonance is an $h = WW/ZZ$ state bound by Tera-exchanges
- Including it makes the LEEL of the model look like the SM Lagrangian
- Conceptually NP masses are “naturally" light ['t Hooft]
  - symmetry enhancement ($\sim$ recovery of $\tilde{\chi}$) of the massless theory
  - encouraging estimates for Λ_T, heaviest family masses and m_h
- One gets gauge coupling unification in SM+Tera-sector (no SUSY)

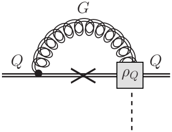
Epilogue

- Phenomenology largely to be still worked out
  - need a good&convincing interpretation of 125 GeV resonance
    - we suggest it's a $|W^+W^- + ZZ\rangle$ bound state
    - indications of a bound state in Bethe–Salpeter and in a non-relativistic potential well approach yielding $E_{bind} = \mathrm{O}(g_w^n M_W)$
  - tera-particles contribution to $g-2$ vacuum polarization amplitude
  - need to study to what extent LEEL of the model deviates from SM
- Moving towards a realistic model
  - need to introduce families
  - need to split quarks & leptons within $\mathrm{SU}(2)_L$ doublets
  - need to give mass to neutrinos that here are massless
- We might have ideas how to deal with some of these issues
  - dimension of Wilson-like terms
  - a natural scale for neutrino masses, $\Lambda_T^2/\Lambda_{GUT}$

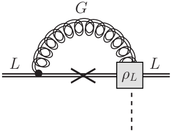
Thanks for your attention

Back-up slides

NP O(b^2) Symanzik operators - II

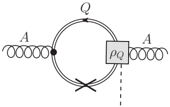


$\rightarrow b^2\Lambda_T\alpha_T|\Phi|\bar{Q}\not{D}^{AGBW}Q$

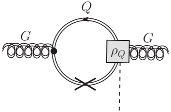


$\rightarrow b^2\Lambda_T\alpha_T|\Phi|\bar{L}\not{D}^{GBW}L$

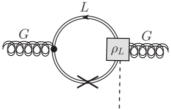
Lowest loop diagrams yielding the dynamically generated operators (1)-(2)



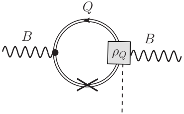
$\rightarrow \quad b^2\Lambda_T g_s^2|\Phi|F^A F^A$



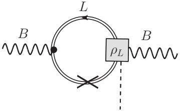
$\rightarrow \quad b^2\Lambda_T g_T^2|\Phi|F^G F^G$



$\rightarrow \quad b^2\Lambda_T g_T^2|\Phi|F^G F^G$



$\rightarrow \quad b^2\Lambda_T g_Y^2|\Phi|F^B F^B$



$\rightarrow \quad b^2\Lambda_T g_Y^2|\Phi|F^B F^B$

Lowest loop diagrams yielding the dynamically generated operators (3)-(7)

Universality

To what extent our mass formulae depend on the choice of the fermionic Wilson-like terms, in particular operator dimension and ρ?

- Dimension of Wilson-like operators
  - Generically, the larger the operator dimension, the higher the leading power of the gauge coupling dependence of $C_f(\alpha)$
  - Exploit this fact to implement mass splitting, like quarks from leptons, up from down (as we did before) and (?) among families
  - We insist that $d_T^{Wil}=6$ and, as we said, $d_t^{Wil}=6$, $d_b^{Wil}=8$, $d_\tau^{Wil}=8$
  - The leading gauge coupling power dependence then is $C_T(\alpha)=\alpha^{1+1}$, $C_t(\alpha)=\alpha^{1+1}$, $C_b(\alpha)=\alpha^{1+2}$, $C_\tau(\alpha)=\alpha^{1+2}$
- ρ dependence
  - Physics only depends on ρ ratios
  - Symmetries can "mitigate" ρ ratio dependence
    - If all ρ are equal, $\rho_f/\rho_{f'}=1, \forall\, f, f'$
  - Weak ρ ratio dependence of M_W & m_Q, none for large N_c and N_T