Elementary particle mass generation 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
- Preliminary simulation results can be found in
  S. Capitani, plus the same Authors as above
  - EPJ Web Conf. **175** (2018) 08008 & 08009
- More extended theoretical considerations can be found in
  G. C. Rossi
  - EPJ Web Conf. **258** (2022), 06003
- See also
  R. Frezzotti, M. Garofalo and G. C. Rossi
  - Phys. Rev. D **93** (2016) no.10, 105030

Prologue & Outline

Prologue

1. I will show that there exists a field theoretical mechanism of non-perturbative (NP) nature capable of dynamically generating mass terms for elementary particles, alternative to the Higgs scenario
2. In this scenario all masses are "naturally light" (no power divergencies) The "Higgs mass tuning problem" is solved as there is no Higgs
3. We get some understanding of the "fermion mass ranking"
4. A super-strongly interacting sector (Tera-sector) is predicted, which provides a physical interpretation of the magnitude of the EW scale
5. We get gauge coupling unification in the SM + Tera-particles model
6. The LEEL of the model is very similar to the SM Lagrangian

Note - The above NP feature was already noticed in LQCD simulations, but no use was made of it for the purpose of giving mass to quarks, because the breaking of chirality induced by the lattice regularization has the well-known effect of generating linearly divergent UV mass terms that completely hide any finite mass contribution

Outline of the talk (take home message)

1. I'll skip [Introduction - Motivations: SM & its limitations] for lack of time
2. I lead you along an unfinished road towards a bSMmodel with no Higgs
   - exhibiting a NP mechanism giving "naturally" light quark masses
     $$m_q^{NP} \sim c_q(\alpha_s)\Lambda_{\rm RGI}\,, \quad c_q(\alpha_s) = O(\alpha_s^2)$$
     confirmed by lattice simulations & diagrammatic understanding
   - allowing the introduction of
     - weak interactions with $M_W^{NP} \sim g_w c_w(\alpha)\Lambda_{\rm RGI}\,, \quad c_w(\alpha) = O(\alpha)\,,$
     - leptons & hypercharge with $m_\ell^{NP} \sim c_\ell(\alpha_Y)\Lambda_{\rm RGI}\,, \quad c_\ell(\alpha_Y) = O(\alpha_Y^2)$
   - top and W mass formulae require $\Lambda_{\rm RGI} \gg \Lambda_{\rm QCD}$, hence $\rightarrow$
   - $\exists$ super-strongly interacting (Tera) particles yielding $\Lambda_{\rm RGI}$ = O(#TeV)
3. A few consequences
   - Fermion mass "ranking" $\alpha_y \ll \alpha_s \ll \alpha_T \;\rightarrow\; m_\ell \ll m_q \ll m_{Q_T}$
   - Higgs mass tuning problem bypassed - no fundamental Higgs!
   - SM + Tera-particles $\rightarrow$ gauge coupling unification (without SUSY)
   - Universe metastability issue should be reconsidered
4. Conjecture: 125 GeV boson a WW/ZZ state bound by Tera-exchanges
5. Comparison with the SM
6. Conclusions

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

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

- $\mathcal{L}_{kin}(q,A,\Phi)=\frac{1}{4}(F^A\cdot F^A)+\bar{q}_L\mathcal{D}\!\!\!\!/^A q_L+\bar{q}_R\mathcal{D}\!\!\!\!/^A q_R+\frac{1}{2}\mathrm{Tr}\left[\partial_\mu\Phi^\dagger\partial_\mu\Phi\right]$
- $\mathcal{V}(\Phi)=\frac{\mu_0^2}{2}\mathrm{Tr}\left[\Phi^\dagger\Phi\right]+\frac{\lambda_0}{4}\left(\mathrm{Tr}\left[\Phi^\dagger\Phi\right]\right)^2$
- $\mathcal{L}_{Yuk}(q,\Phi)=\eta\left(\bar{q}_L\Phi q_R+\bar{q}_R\Phi^\dagger q_L\right)$
- $\mathcal{L}_{Wil}(q,A,\Phi)=\frac{b^2}{2}\rho\left(\bar{q}_L\overleftarrow{\mathcal{D}}^A{}_\mu\Phi\mathcal{D}^A_\mu q_R+\bar{q}_R\overleftarrow{\mathcal{D}}^A_\mu\Phi^\dagger\mathcal{D}^A_\mu q_L\right)$

- $\mathcal{L}_{\rm toy}$ key features
  - presence of the "irrelevant" chiral breaking $d=6$ Wilson-like term
  - Φ, despite the appearances, is not the Higgs boson
- $\mathcal{L}_{\rm toy}$ 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

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

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

- red $\chi_L \times \chi_R$ transformations are invariances and can be realized
  - *á la* Wigner
  - *á la* Nambu–Goldstone
- blue $\tilde{\chi}_L \times \tilde{\chi}_R$ (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
   - mass protected against UV linear divergencies, unlike Wilson LQCD
   - a step towards complying with naturalness ’t Hooft

The road to NP mass generation - I

- Yukawa and Wilson-like terms break $\tilde{\chi}_L \times \tilde{\chi}_R$ and mix
- At a suitable $\eta = \eta_{cr}$ they can be made to "compensate", thus enforcing chiral $\tilde{\chi}_L \times \tilde{\chi}_R$ symmetry, like m_{cr} does in Wilson-LQCD
- Enforcement of chiral $\tilde{\chi}_L \times \tilde{\chi}_R$ symmetry implies
  1. Wigner phase $\langle|\Phi|^2\rangle = 0$ → effective $\bar{q}_R \Phi q_L$ + hc vertex absent

[box is the Wilson-like vertex]

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

Note - For illustration we only draw 1-loop diagrams

- A key observation
  - b^2 factor from the Wilson-like vertex is compensated by the quadratic loop divergency b^{-2}, yielding finite 1-loop diagrams

The road to NP mass generation - II

Q: after Higgs-like mass cancellation, any fermion mass term left out?
A: YES!

1. Like in QCD, chiral $\tilde{\chi}_L \times \tilde{\chi}_R$ Symmetry is Spontaneously Broken
2. At $O(b^2)$ besides Pert 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
$$O_{6,\bar{q}q} \propto b^2 \Lambda_s \alpha_s |\Phi| \left[\bar{q} \not{D}^A q \right] , \qquad O_{6,FF} \propto b^2 \Lambda_s \alpha_s |\Phi| \left[F^A \cdot F^A \right]$$
   - $O_{6,\bar{q}q}$ & $O_{6,FF}$ 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 to finite contributions by UV power divergencies in loops
   - Bookkeeping of NP effects can be standardly described including the new diagrams derived from the "augmented" Lagrangian
$$\mathcal{L}_{\rm toy} \to \mathcal{L}_{\rm toy} + \Delta\mathcal{L}_{NP}$$
$$\Delta\mathcal{L}_{NP} = b^2 \Lambda_s \alpha_s |\Phi| \left[c_{FF} F^A \cdot F^A + c_{\bar{q}q} \bar{q} \not{D}^A q \right] + \ldots$$

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

  - 1PI diagrams at vanishingly small external momenta (masses)
  - blobs = NP vertices from $\Delta\mathcal{L}_{NP}$
  - box = Wilson-like vertex from the fundamental $\mathcal{L}_{\rm toy}$

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

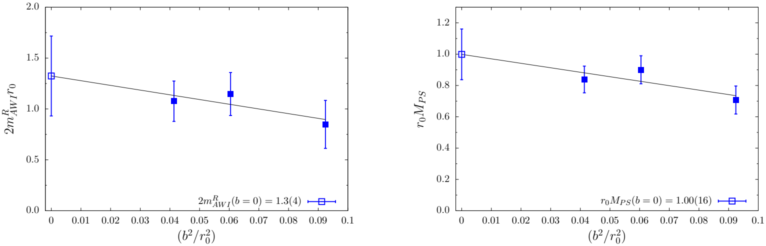
$$\cdot b^2\gamma_\rho(k+\ell)_\rho\, b^2\underline{\underline{\Lambda_s}}\gamma_\lambda(2k+\ell)_\lambda \sim \underline{\underline{\alpha_s^2\Lambda_s}}$$

- 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 as switching off masses enlarges the symmetry of the theory

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



- $2m^R_{AWI} r_0 \equiv 2r_0 m_{PCAC} Z_{\tilde{A}} Z_P^{-1}$ (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

$$m_q^{NP} = c_q(g_s^2)\Lambda_s\,, \quad c_q(g_s^2) = \mathrm{O}(\alpha_s^2)$$

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

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

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

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

$$\Gamma^0_{d=4} = \frac{1}{4}(F^A \cdot F^A) + \bar{q}_L \mathcal{D}\!\!\!/^A q_L + \bar{q}_R \mathcal{D}\!\!\!/^A q_R + \mathcal{V}(\Phi) = \Gamma^{Wig}_{d=4}\Big|_{\hat{\mu}^2_\Phi < 0}$$

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

Introducing weak interactions
Why Tera-interactions?

Why Tera-interactions?

Obviously we want weak 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

$$m_q^{NP} = C_q \Lambda_{\rm RGI}\,, \qquad C_q = \mathrm{O}(\alpha_s^2)$$

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

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

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

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

- We refer to them as Tera-particles Glashow (to avoid confusion with Techni-particles)
- Revealing Tera-hadrons $\to$ an unmistakable sign of New Physics

Towards a BSMm: including weak- & Tera-interactions

- We extend the Lagrangian to include weak and Tera-interactions
  - Tera-particles $\to$ duplicate what was done for quarks
  - Weak bosons $\to$ gauge the exact χ_L symmetry

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

- $\mathcal{L}_{kin}(q, Q; \Phi; A, W) = \frac{1}{4}\Big(F^A \cdot F^A + F^G \cdot F^G + F^W \cdot F^W\Big) + \\ + \Big[\bar{q}_L \not{\mathcal{D}}^{AW} q_L + \bar{q}_R \not{\mathcal{D}}^{A} q_R\Big] + \Big[\bar{Q}_L \not{\mathcal{D}}^{AGW} Q_L + \bar{Q}_R \not{\mathcal{D}}^{AG} Q_R\Big] + \frac{k_b}{2}\mathrm{Tr}\,\big[(\mathcal{D}^W_\mu \Phi)^\dagger \mathcal{D}^W_\mu \Phi\big]$
- $\mathcal{V}(\Phi) = \frac{\mu_0^2}{2} k_b \mathrm{Tr}\,\big[\Phi^\dagger \Phi\big] + \frac{\lambda_0}{4}\big(k_b \mathrm{Tr}\,\big[\Phi^\dagger \Phi\big]\big)^2$
- $\mathcal{L}_{Yuk}(q, Q; \Phi) = \eta_q \left(\bar{q}_L \Phi\, q_R + \bar{q}_R \Phi^\dagger q_L\right) + \eta_Q \left(\bar{Q}_L \Phi\, Q_R + \bar{Q}_R \Phi^\dagger Q_L\right)$
- $\mathcal{L}_{Wil}(q, Q; \Phi; A, G, W) = \frac{b^2}{2}\rho_q \left(\bar{q}_L \overleftarrow{\mathcal{D}}^{AW}_\mu \Phi \mathcal{D}^A_\mu q_R + \bar{q}_R \overleftarrow{\mathcal{D}}^{A}_\mu \Phi^\dagger \mathcal{D}^{AW}_\mu q_L\right) + \\ + \frac{b^2}{2}\rho_Q \left(\bar{Q}_L \overleftarrow{\mathcal{D}}^{AGW}_\mu \Phi \mathcal{D}^{AG}_\mu Q_R + \bar{Q}_R \overleftarrow{\mathcal{D}}^{AG}_\mu \Phi^\dagger \mathcal{D}^{AGW}_\mu Q_L\right)$

Covariant derivatives & Symmetries

$$\begin{cases} \mathcal{D}_\mu^{AGW} = \partial_\mu - ig_s\lambda^a A_\mu^a - ig_T T^\alpha G_\mu^\alpha - ig_w \frac{\tau^i}{2} W_\mu^i \\ \overleftarrow{\mathcal{D}}_\mu^{AGW} = \overleftarrow{\partial}_\mu + ig_s\lambda^a A_\mu^a + ig_T T^\alpha G_\mu^\alpha + ig_w \frac{\tau^i}{2} W_\mu^i \\ \mathcal{D}_\mu^{AG} = \partial_\mu - ig_s\lambda^a A_\mu^a - ig_T T^\alpha G_\mu^\alpha \\ \overleftarrow{\mathcal{D}}_\mu^{AG} = \overleftarrow{\partial}_\mu + ig_s\lambda^a A_\mu^a + ig_T T^\alpha G^\alpha \end{cases}$$

- χ_L : $\tilde{\chi}_L \times (\Phi \to \Omega_L \Phi)$ exact

$$\tilde{\chi}_L : \begin{cases} q_L \to \Omega_L q_L \\ \bar{q}_L \to \bar{q}_L \Omega_L^\dagger \\ W_\mu \to \Omega_L W_\mu \Omega_L^\dagger \\ Q_L \to \Omega_L Q_L \\ \bar{Q}_L \to \bar{Q}_L \Omega_L^\dagger \end{cases} \qquad \Omega_L \in \mathrm{SU}_L(2)$$

- χ_R : $\tilde{\chi}_R \times (\Phi \to \Phi \Omega_R^\dagger)$ exact

$$\tilde{\chi}_R : \begin{cases} q_R \to \Omega_R q_R \\ \bar{q}_R \to \bar{q}_R \Omega_R^\dagger \\ \\ Q_R \to \Omega_R Q_R \\ \bar{Q}_R \to \bar{Q}_R \Omega_R^\dagger \end{cases} \qquad \Omega_R \in \mathrm{SU}_R(2)$$

The critical theory

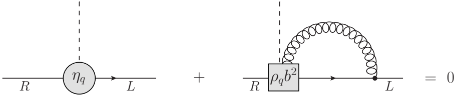
- Besides the Yukawa and Wilson-like operators
  - $\mathcal{L}_{Yuk}(q,Q;\Phi) = \eta_q \left(\bar{q}_L \Phi\, q_R + \bar{q}_R \Phi^\dagger q_L\right) + \eta_Q \left(\bar{Q}_L \Phi\, Q_R + \bar{Q}_R \Phi^\dagger Q_L\right)$
  - $\mathcal{L}_{Wil}(q,Q;\Phi;A,G,W) = \frac{b^2}{2}\rho_q \left(\bar{q}_L \overleftarrow{\mathcal{D}}^{AW}_\mu \Phi \mathcal{D}^A_\mu q_R + \bar{q}_R \overleftarrow{\mathcal{D}}^{A}_\mu \Phi^\dagger \mathcal{D}^{AW}_\mu q_L\right) + $
    $+ \frac{b^2}{2}\rho_Q \left(\bar{Q}_L \overleftarrow{\mathcal{D}}^{AGW}_\mu \Phi \mathcal{D}^{AG}_\mu Q_R + \bar{Q}_R \overleftarrow{\mathcal{D}}^{AG}_\mu \Phi^\dagger \mathcal{D}^{AGW}_\mu Q_L\right)$

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

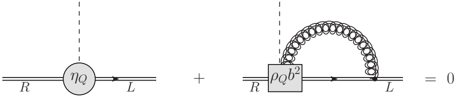
  breaks $\tilde{\chi}_L \times \tilde{\chi}_R$ and mixes with $\mathcal{L}_{Yuk}$ and $\mathcal{L}_{Wil}$
- in addition to η_q & η_Q, a further parameter needs to be tuned, k_b
- The critical theory (invariant under $\tilde{\chi}_L \times \tilde{\chi}_R$) has
  - vanishing effective Yukawa interactions
  - vanishing scalar kinetic term (Bardeen, Hill & Lindner 1989)

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

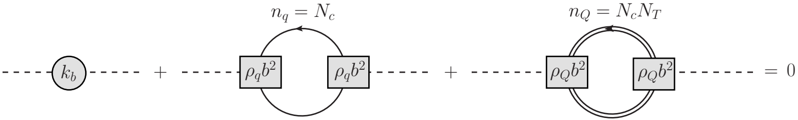
- The η_q tuning condition $\to \eta^{(1)}_{q\,cr} = \rho_q\,\eta_{1q}\alpha_s$



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



- The k_b tuning condition $\to k^{(1)}_{b\,cr} = [\rho_q^2 N_c + \rho_Q^2 N_c N_T] k_1$

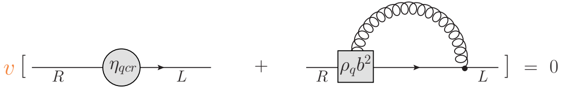


- UV divergencies are exactly compensated by the IR behaviour

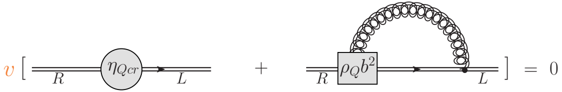
Critical tuning in the NG phase $\langle|\Phi|^2\rangle = v^2$ at 1-loop

In the NG phase of the critical theory Higgs-like masses get cancelled

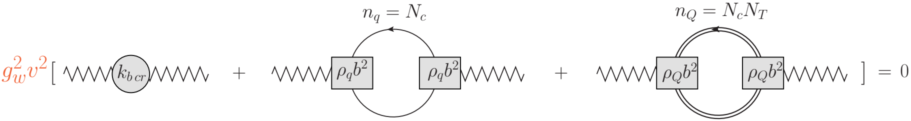
- The cancellation mechanism of the “Higgs-like” quark mass term $v\,\bar{q}q$



- The cancellation mechanism of the “Higgs-like” Tera-quark mass term $v\,\bar{Q}Q$



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



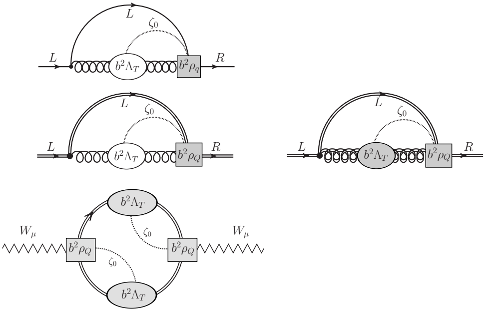
- UV divergencies are exactly compensated by the IR behaviour

NP elementary particle masses: fermions & W-bosons

NP Symanzik operators (white and gray ovals) come to rescue masses

- $O^{T}_{6,\bar{Q}Q} = b^2\alpha_T\rho_Q\Lambda_T|\Phi|\Big[\bar{Q}_L\tilde{\mathcal{D}}^{AGW}Q_L + \bar{Q}_R\tilde{\mathcal{D}}^{AG}Q_R\Big]$
- $O^{s}_{6,\bar{Q}Q} = b^2\alpha_s\rho_Q\Lambda_T|\Phi|\Big[\bar{Q}_L\tilde{\mathcal{D}}^{AGW}Q_L + \bar{Q}_R\tilde{\mathcal{D}}^{AG}Q_R\Big]$
- $O_{6,GG} = b^2\alpha_T\rho_Q\Lambda_T|\Phi|F^G\cdot F^G$ • $O_{6,AA} = b^2\alpha_s\rho_Q\Lambda_T|\Phi|F^A\cdot F^A$

combine with Wilson-like vertices (boxes) leading to 1PI self-energy graphs



quark

Tera-quark

W

Finite diagrams, owing to UV-IR compensation, yielding O(Λ_T) masses

The critical QEL in the NG phase

Following the same line of arguments as in the case of the toy-model, we get for the $d = 4$ piece of the QEL

$$\Gamma^{NG}_{4\,cr}(q, Q; \Phi; A, G, W) = \frac{1}{4}\Big(F^A \cdot F^A + F^G \cdot F^G + F^W \cdot F^W\Big) +$$

$$+\Big[\bar{q}_L \not{\mathcal{D}}^{WA} q_L + \bar{q}_R \not{\mathcal{D}}^{A} q_R\Big] + C_q \Lambda_T \left(\bar{q}_L U q_R + \bar{q}_R U^\dagger q_L\right) +$$

$$+\Big[\bar{Q}_L \not{\mathcal{D}}^{WAG} Q_L + \bar{Q}_R \not{\mathcal{D}}^{AG} Q_R\Big] + C_Q \Lambda_T \left(\bar{Q}_L U Q_R + \bar{Q}_R U^\dagger Q_L\right) +$$

$$+\frac{1}{2} c_w^2 \Lambda_T^2 \mathrm{Tr}\left[(\mathcal{D}^W_\mu U)^\dagger \mathcal{D}^W_\mu U\right]$$

$$U = \frac{\Phi}{\sqrt{\Phi^\dagger \Phi}} = \exp\left(i \frac{\vec{\tau} \cdot \vec{\zeta}}{c_w \Lambda_T}\right) = 1\!\!1 + i \frac{\vec{\tau} \cdot \vec{\zeta}}{c_w \Lambda_T} + \dots$$

implying

$$m_q^{NP} = C_q \Lambda_T \,, \qquad C_q = \mathrm{O}(\alpha_s^2)$$

$$m_Q^{NP} = C_Q \Lambda_T \,, \qquad C_Q = \mathrm{O}(\alpha_T^2, \dots)$$

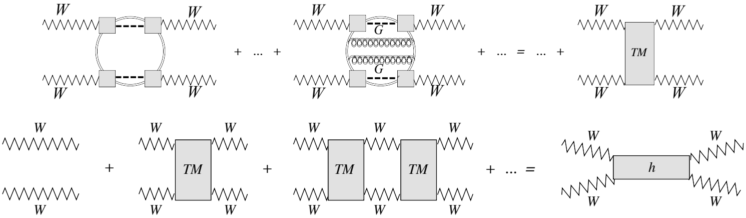
$$M_W^{NP} = C_w \Lambda_T \,, \qquad C_w = g_w c_w \,, \; c_w = k_w \mathrm{O}(\alpha_T, \dots)$$

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 Bethe–Salpeter



- $|h\rangle$ 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 LEEL
- If we do so, perhaps not surprisingly, one finds that, up to small corrections, $\text{LEEL}_{d=4}$ resembles very much the SM with $v_H \sim \Lambda_T$

- $d = 4$ LEEL of the critical NG model for $p^2/\Lambda_T^2 \ll 1$, including h reads [we ignore families, leptons & $U_Y(1)$]

$$\mathcal{L}^{\rm LEEL}_{4\,cr}(q;A,W;U,h) = \frac{1}{4}F^A\cdot F^A + \frac{1}{4}F^W\cdot F^W + \left[\bar q_L \not{\mathcal{D}}^{AW} q_L + \bar q^u_R \not{\mathcal{D}}^A q^u_R + \bar q^d_R \not{\mathcal{D}}^A q^d_R\right] +$$

$$+\frac{1}{2}\partial_\mu h \partial_\mu h + \frac{1}{2}(k_v^2 + 2k_v k_1 h + k_2 h^2){\rm Tr}\left[(\mathcal{D}^W_\mu U)^\dagger \mathcal{D}^W_\mu U\right] + \widetilde{\mathcal{V}}(h) +$$

$$+(y_q h + k_q k_v)\left(\bar q_L U q_R + \bar q_R U^\dagger q_L\right)$$

- Above $\mathcal{L}^{\rm LEEL}_{4\,cr}$ is neither renormalizable nor unitary (unlike the fundamental Lagrangian in slide 16) for generic k_v, k_1, k_2, y_q, k_q. But if in $\mathcal{L}^{\rm LEEL}_{4\,cr}$ 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

$$\mathcal{L}^{\rm LEEL}_{4\,cr}(q;A,W;\Phi) \to \frac{1}{4}F^A\cdot F^A + \frac{1}{4}F^W\cdot F^W + \left[\bar q_L \not{\mathcal{D}}^{AW} q_L + \bar q^u_R \not{\mathcal{D}}^A q^u_R + \bar q^d_R \not{\mathcal{D}}^A q^d_R\right] +$$

$$+\frac{1}{2}{\rm Tr}\left[(\mathcal{D}^W_\mu \Phi)^\dagger \mathcal{D}^W_\mu \Phi\right] + \widetilde{\mathcal{V}}(h) + y_q\left(\bar q_L \Phi q_R + \bar q_R \Phi^\dagger q_L\right) \sim \mathcal{L}^{\rm SM}$$

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

with the standard coupling between the composite Φ field and the fermions

Conclusions & Epilogue

Conclusions

- We have identified a NP mechanism for elementary particle mass generation successfully confirmed by lattice simulations
- yielding $m_f^{NP} \propto \alpha_f^2 \Lambda_{\rm RGI}$ & $M_W \propto g_w \alpha \Lambda_{\rm RGI}$ (to lowest loop order)
  - $m_{top}, M_W \sim 10^2$ GeV call for a Tera-strong interaction
  - so as to get a whole theory with $\Lambda_{\rm RGI} \equiv \Lambda_T =$ O(a few TeV's)
- We provide an understanding of the
  - EW scale magnitude (as a fraction of Λ_T)
  - fermion mass ranking $\alpha_y \ll \alpha_s \ll \alpha_T \rightarrow m_\ell \ll m_q \ll m_{Q_T}$
  - Higgs mass tuning problem as there is no fundamental Higgs
- NP masses are “naturally" light ['t Hooft]
  - symmetry enhancement ($\sim$ recovery of $\tilde{\chi}$) in the massless theory
- LEEL of the model very similar to the SM Lagrangian
- 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 with $E_{bind} = \mathrm{O}(g_w^n M_W)$
    - indications of a bound state in a non-relativistic potential well
  - need to study to what extent LEEL of the model deviates from SM
  - compute Tera-particle contribution to S, T, U parameters
- Moving towards a realistic model
  - introduce families
  - split quarks & leptons within $\mathrm{SU}(2)_L$ doublets
  - give mass to neutrinos that are here (naturally) massless
  - reconsider the Universe metastability problem
- We might have ideas how to deal with some of these issues

Thanks for your attention

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