Towards a beyond the Standard Model model with elementary particle non-perturbative mass generation

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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
- 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

Outline of the talk (take home message)

1. I'll jump [Introduction & Motivation: SM and its limitations]
2. I'll lead you along a yet unfinished road towards a bSMm 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, yielding
     $$M_W \sim g_w c_w(\alpha)\Lambda_{\rm RGI}\,, \quad c_w(\alpha) = O(\alpha)\,,$$
   - as well as leptons and hypercharge
   - top and W mass formulae require $\Lambda_{\rm RGI} \gg \Lambda_{\rm QCD}$, hence $\to$
   - $\exists$ super-strongly interacting (Tera) particles yielding $\Lambda_{\rm RGI}$ = O(#TeV)
3. Some consequences
   - Fermion mass "ranking" $\alpha_y \ll \alpha_s \ll \alpha_T \;\to\; m_\ell \ll m_q \ll m_{Q_T}$
   - Mass "hierarchy" problem bypassed - no fundamental Higgs!
   - SM + Tera-particles $\to$ gauge coupling unification (without SUSY)
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

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

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

- $\mathcal{L}_{\rm toy}$ key features
  - presence of the "irrelevant" chiral breaking $d=6$ Wilson-like term
  - Φ, despite the appearances, is not the Higgs
- $\mathcal{L}_{\rm toy}$ notations
  - $b^{-1} \sim \Lambda_{UV}$ =UV cutoff, $\eta =$ 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

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

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

   - $\chi_L \times \chi_R$ 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 <u>forbidden</u> 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 - at 1-loop we have
  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
  - symmetry enhancement similar to that triggered by m_{cr} in LQCD
- Q: after Higgs-like mass cancellation, any fermion mass term left?

  A: YES!

The road to NP mass generation - II

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

$$O_{6,\bar{q}q} \propto b^2 \Lambda_s \alpha_s |\Phi| \left[\bar{q} \not{D}^A q \right]$$

$$O_{6,FF} \propto b^2 \Lambda_s \alpha_s |\Phi| \left[F^A \cdot F^A \right]$$

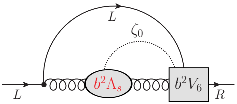
   - $O_{6,\bar{q}q}$ & $O_{6,FF}$ expression fixed by symmetries $(\chi_L \times \chi_R)$ & dimension
   - They matter in the limit $b \to 0$, as formally $O(b^2)$ effects can be promoted by UV power divergencies in loops to finite contributions
   - Bookkeeping of NP effects can be standardly described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

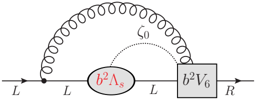
$$\mathcal{L}_{\rm toy} \to \mathcal{L}_{\rm toy} + \Delta \mathcal{L}_{NP}^{Sym}$$

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

A diagrammatic understanding of NP masses - III

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





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

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

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

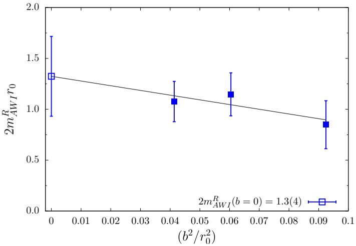
- Diagrams are finite
  - b^4 S$\tilde{\chi}$SB IR effects compensate 2-loop UV quartic divergency
  - Thus masses are a kind of NP anomalies that appear as obstructions to a full recovery of the $\tilde{\chi}_L \times \tilde{\chi}_R$ chiral symmetry
  - This NP mechanism is in line with the 't Hooft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

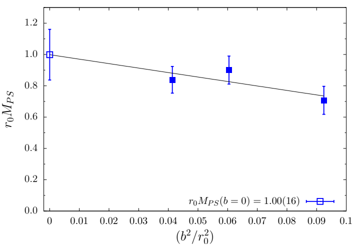
NP mass in NG phase: a lattice confirmation - IV

- At $\eta = \eta_{cr}$, where invariance under $\tilde{\chi}_L \times \tilde{\chi}_R$ is recovered and the quark Higgs mass is killed, we compute in the NG phase 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
  $\to$ a NP fermion mass is getting dynamically generated
  $\to$ 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 $b \to 0$ 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

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

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

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 $\to$ we duplicate what we did for quarks
  - Weak bosons $\to$ we gauge the exact χ_L symmetry

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

- $\mathcal{L}_{kin}(q,Q;\Phi;A,W)=\frac{1}{4}\Big(F^A\cdot F^A+F^G\cdot F^G+F^W\cdot F^W\Big)+$

$$+\Big[\bar{q}_L \not{\mathcal{D}}^{AW} q_L+\bar{q}_R\not{\mathcal{D}}^{A}q_R\Big]+\Big[\bar{Q}_L\not{\mathcal{D}}^{AGW}Q_L+\bar{Q}_R\not{\mathcal{D}}^{AG}Q_R\Big]+\frac{k_b}{2}\mathrm{Tr}\,\big[(\mathcal{D}^W_\mu\Phi)^\dagger\mathcal{D}^W_\mu\Phi\big]$$

- $\mathcal{V}(\Phi)=\frac{\mu_0^2}{2}k_b\mathrm{Tr}\,\big[\Phi^\dagger\Phi\big]+\frac{\lambda_0}{4}\big(k_b\mathrm{Tr}\,\big[\Phi^\dagger\Phi\big]\big)^2$
- $\mathcal{L}_{Yuk}(q,Q;\Phi)=\eta_q\,(\bar{q}_L\Phi\, q_R+\bar{q}_R\Phi^\dagger q_L)+\eta_Q\,(\bar{Q}_L\Phi\, Q_R+\bar{Q}_R\Phi^\dagger Q_L)$
- $\mathcal{L}_{Wil}(q,Q;\Phi;A,G,W)=\frac{b^2}{2}\rho_q\,(\bar{q}_L\overleftarrow{\mathcal{D}}^{AW}_\mu\Phi\mathcal{D}^A_\mu q_R+\bar{q}_R\overleftarrow{\mathcal{D}}^{A}_\mu\Phi^\dagger\mathcal{D}^{AW}_\mu q_L)+$

$$+\frac{b^2}{2}\rho_Q\,(\bar{Q}_L\overleftarrow{\mathcal{D}}^{AGW}_\mu\Phi\mathcal{D}^{AG}_\mu Q_R+\bar{Q}_R\overleftarrow{\mathcal{D}}^{AG}_\mu\Phi^\dagger\mathcal{D}^{AGW}_\mu Q_L)$$

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 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) + $
    $+\frac{b^2}{2}\rho_Q\left(\bar{Q}_L\overleftarrow{\mathcal{D}}^{AGW}_\mu\Phi\mathcal{D}^{AG}_\mu Q_R + \bar{Q}_R\overleftarrow{\mathcal{D}}^{AG}_\mu\Phi^\dagger\mathcal{D}^{AGW}_\mu Q_L\right)$

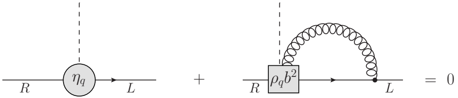
  now also the kinetic term of the scalar
  - $\mathcal{L}_{kin}(\Phi;W) = \frac{k_b}{2}\mathrm{Tr}\left[(\mathcal{D}^W_\mu\Phi)^\dagger\mathcal{D}^W_\mu\Phi\right]$

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

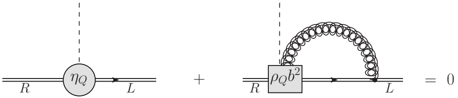
- On top of η_q and η_Q, a further parameter needs to be tuned, k_b
- The conditions determining the critical theory (invariant under $\tilde{\chi}_L \times \tilde{\chi}_R$) correspond to have
  - vanishing effective Yukawa interactions
  - vanishing scalar kinetic term (Bardeen, Hill & Lindner 1989)

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

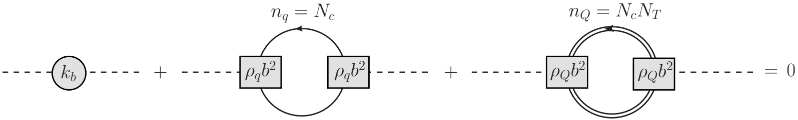
- The η_q tuning condition $\rightarrow \eta^{(1)}_{q\,cr} = \rho_q\, \eta_{1q}\alpha_s$



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



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

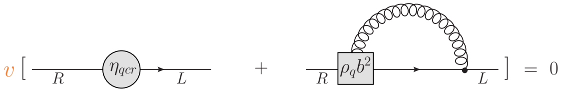


- UV divergencies are exactly compensated by the IR behaviour

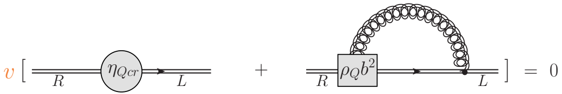
Critical tuning in the NG phase $\langle|\Phi|^2\rangle = v^2$ at 1-loop

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

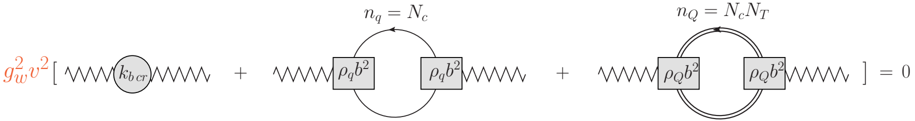
- The cancellation mechanism of the "Higgs-like" quark mass term $v\,\bar{q}q$



- 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 $g_w^2 v^2 \mathrm{Tr}\,[W_\mu W_\mu]$

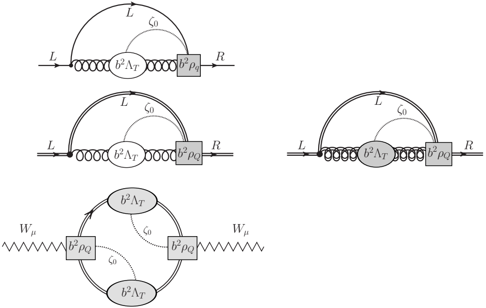


NP elementary particle masses: fermions & W-bosons

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

- $O^T_{6,\bar{Q}Q} = b^2 \alpha_T \rho_Q \Lambda_T |\Phi| \left[\bar{Q}_L \not{\mathcal{D}}^{AGW} Q_L + \bar{Q}_R \not{\mathcal{D}}^{AG} Q_R \right]$
- $O^s_{6,\bar{Q}Q} = b^2 \alpha_s \rho_Q \Lambda_T |\Phi| \left[\bar{Q}_L \not{\mathcal{D}}^{AGW} Q_L + \bar{Q}_R \not{\mathcal{D}}^{AG} Q_R \right]$
- $O_{6,GG} = b^2 \alpha_T \rho_Q \Lambda_T |\Phi| F^G \cdot F^G$ • $O_{6,AA} = b^2 \alpha_s \rho_Q \Lambda_T |\Phi| F^A \cdot F^A$

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



quark

Tera-quark

W

Finite terms, 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

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

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

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

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

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

implying

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

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

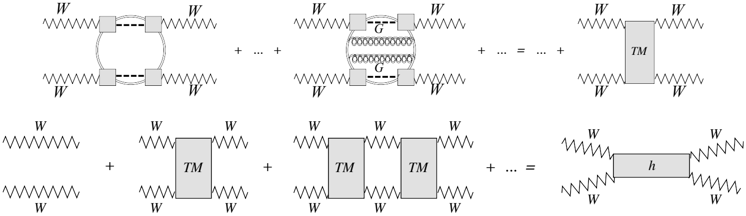
$$M_W^{NP} = C_w \Lambda_T \,, \qquad C_w = g_w c_w \,, \; c_w = k_w \mathrm{O}(\alpha_T, \ldots)$$

The 125 GeV resonance & comparison with the SM

125 GeV resonance & comparison with the SM

No need for a Higgs $\rightarrow$ 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 QEL
- If we do so, perhaps not surprisingly, one finds that, up to small corrections, $\mathrm{QEL}_{d=4}$ resembles very much the SM with $v_H \sim \Lambda_T$

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

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

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

- $\mathcal{L}^{\mathcal{NG}}_{\triangle\rfloor\triangledown}$ 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

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

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

i.e. a unitary & renormalizable theory

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 $\alpha_y \ll \alpha_s \ll \alpha_T \rightarrow m_\ell \ll m_q \ll m_{Q_T}$
  - mass hierarchy problem as there is no fundamental Higgs
- NP masses are "naturally" light ['t Hooft]
  - symmetry enhancement ($\sim$ recovery of $\tilde{\chi}$) of the massless theory
- 125 GeV resonance is a WW/ZZ state bound by Tera-exchanges
- LEEL of the model very similar to the SM Lagrangian
- One gets gauge coupling unification in SM+Tera-sector (no SUSY)
- Phenomenology largely unexplored

Thanks for your attention