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. Milestones of a (yet unfinished) road towards a bSMm with no Higgs
   - the simplest model yielding NP "naturally" light quark masses
     $$m_q^{NP} \sim c_q(\alpha_s)\Lambda_{\mathrm{RGI}}, \quad c_q(\alpha_s) = \mathrm{O}(\alpha_s^2)$$
   - extension to incorporate weak interactions, leading to
     $$M_W \sim g_w c_w(\alpha)\Lambda_{\mathrm{RGI}}, \quad c_w(\alpha) = \mathrm{O}(\alpha),$$
   - (extension to include hypercharge and leptons)
   - top and W mass formulae require $\Lambda_{\mathrm{RGI}} \gg \Lambda_{\mathrm{QCD}}$, hence $\rightarrow$
   - $\exists$ super-strongly interacting (Tera) particles yielding $\Lambda_{\mathrm{RGI}} = \mathrm{O}(\#\mathrm{TeV})$
3. A few implications
   - Mass "hierarchy" problem bypassed - no fundamental Higgs!
   - Dependence of NP masses on gauge couplings is such that coupling ranking $\alpha_y \ll \alpha_s \ll \alpha_T \rightarrow$ fermion mass ranking $m_\ell \ll m_q \ll m_{Q_T}$
   - A bonus: SM+Tera-particles $\rightarrow$ gauge coupling unification (no 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

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

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

- $\mathcal{L}_{kin}(q, A, \Phi) = \dfrac{1}{4}(F^A \cdot F^A) + \bar{q}_L \slashed{\mathcal{D}}^A q_L + \bar{q}_R \slashed{\mathcal{D}}^A q_R + \dfrac{1}{2}\text{Tr}\left[\partial_\mu \Phi^\dagger \partial_\mu \Phi\right]$

- $\mathcal{V}(\Phi) = \dfrac{\mu_0^2}{2}\text{Tr}\left[\Phi^\dagger \Phi\right] + \dfrac{\lambda_0}{4}\left(\text{Tr}\left[\Phi^\dagger \Phi\right]\right)^2$

- $\mathcal{L}_{Yuk}(q, \Phi) = \eta\left(\bar{q}_L \Phi q_R + \bar{q}_R \Phi^\dagger q_L\right)$

- $\mathcal{L}_{Wil}(q, A, \Phi) = \dfrac{b^2}{2}\rho\left(\bar{q}_L \overleftarrow{\mathcal{D}}^A_\mu \Phi \mathcal{D}^A_\mu q_R + \bar{q}_R \overleftarrow{\mathcal{D}}^A_\mu \Phi^\dagger \mathcal{D}^A_\mu q_L\right)$

- $\mathcal{L}_{\text{toy}}$ key features
  - presence of the "irrelevant" chiral breaking $d = 6$ Wilson-like term
  - Φ, despite appearances, not the Higgs, but UV completion of $\mathcal{L}_{\text{toy}}$
- $\mathcal{L}_{\text{toy}}$ notations
  - $b^{-1} \sim \Lambda_{UV} =$ UV cutoff, $\eta =$ Yukawa coupling, ρ to keep track of $\mathcal{L}_{Wil}$

Theoretical background

1. $\mathcal{L}_{toy}$ is formally power-counting renormalizable (like Wilson LQCD)

2. and exactly invariant under the (global) transformations

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

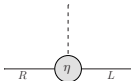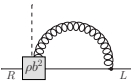$$\tilde{\chi}_{L/R} : \begin{cases} q_{L/R} \to \Omega_{L/R} q_{L/R} \\[2mm] \bar{q}_{L/R} \to \bar{q}_{L/R} \Omega_{L/R}^\dagger \end{cases} \qquad \Omega_{L/R} \in \mathsf{SU}(2)$$

- $\chi_L \times \chi_R$ exact, can be realized
  - *á la* Wigner
  - *á la* Nambu–Goldstone

- $\tilde{\chi}_L \times \tilde{\chi}_R$ (chiral transformations) broken for generic η and ρ

3. 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

4. No (perturbative) linear mass divergencies (unlike Wilson LQCD)

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 $\eta = \eta_{cr}(\rho)$ 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 $\langle |\Phi|^2 \rangle = 0 \rightarrow$ effective $\bar{q}_R \Phi q_L$ + hc vertex absent

  $= 0$ [box is the Wilson-like vertex]

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

- Observations
  - b^2 factor from the Wilson-like vertex is compensated by the quadratic loop divergency b^{-2}, yielding finite 1-loop diagrams
  - we get symmetry enhancement and Φ-fermion decoupling
- Q: after Higgs-like mass cancellation, any fermion mass term left?
  A: YES, a non-perturbative one!

The road to NP mass generation - II

The origin of NP masses

1. Like in QCD, chiral $\tilde{\chi}_L \times \tilde{\chi}_R$ Symmetry is Spontaneously Broken
2. At $O(b^2)$, besides PT terms, in NG phase also NP terms occur
3. Cutoff effects of regularized theory are analyzed *á la* Symanzik
   - One finds that $O(b^2)$ operators necessary to describe the peculiar NP cutoff features ensuing from the $S\tilde{\chi}SB$ phenomenon are

     $$O_{6,\bar{q}q} \propto b^2 \Lambda_s \alpha_s |\Phi| \left[\bar{q} \overleftrightarrow{\mathcal{D}}^A q \right] \qquad O_{6,FF} \propto b^2 \Lambda_s \alpha_s |\Phi| \left[F^A \cdot F^A \right]$$

   - $O_{6,\bar{q}q}$ & $O_{6,FF}$ 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 by UV power divergencies in loops to finite contributions

4. Bookkeeping of NP effects can be standardly described including new diagrams derived from the extended Symanzik Lagrangian

   $$\mathcal{L}_{\text{toy}} \to \mathcal{L}_{\text{toy}} + \Delta\mathcal{L}_{NP}^{Sym}$$
   $$\Delta\mathcal{L}_{NP}^{Sym} = b^2 \Lambda_s \alpha_s |\Phi| \left[c_{FF} F^A \cdot F^A + c_{\bar{q}q} \bar{q} \overleftrightarrow{\mathcal{D}}^A q \right] + O(b^4)$$

A diagrammatic understanding of NP masses - III

- New NP self-energy diagrams emerge yielding masses

- 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 $\mathcal{L}_{toy}$

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

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

- 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

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

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

1. QEL describing physics of the critical model in NG phase, Γ^{NG}
   - No chiral breaking Yukawa term
   - Include in Γ^{NG} all $\chi_L \times \chi_R$ invariant operators functions of $q, \bar{q}, A, U$

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

2. New operators can be formed [U transforms like Φ] and one finds

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

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

3. From $U = \mathbb{1} + i\vec{\tau}\vec{\zeta}/v + \dots$ 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 $\Lambda_s = \Lambda_{\mathrm{RGI}}$ is the RGI scale of the theory
- Let us focus on the top quark. Can we make the NP formula

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

  compatible with the phenomenological value of the top mass?

- As an order of magnitude, we clearly need to have for Λ_{RGI}

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

  so as to get a top mass in the 10^2 GeV range $\rightarrow$

- Super-strongly interacting particles must exist yielding a full theory with

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

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

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

- We extend the Lagrangian to include weak and Tera-interactions
  - Tera-particles $\rightarrow$ we duplicate what we did for quarks
  - Weak bosons $\rightarrow$ 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) = \dfrac{1}{4}\Big(F^A \cdot F^A + F^G \cdot F^G + F^W \cdot F^W \Big) + $

$+ \Big[\bar{q}_L \slashed{\mathcal{D}}^{AW} q_L + \bar{q}_R \slashed{\mathcal{D}}^A q_R \Big] + \Big[\bar{Q}_L \slashed{\mathcal{D}}^{AGW} Q_L + \bar{Q}_R \slashed{\mathcal{D}}^{AG} Q_R \Big] + \dfrac{k_b}{2} \text{Tr} \left[(\mathcal{D}_{\mu}^{\,W} \Phi)^{\dagger} \mathcal{D}_{\mu}^{\,W} \Phi \right]$

- $\mathcal{V}(\Phi) = \dfrac{\mu_0^2}{2} k_b \text{Tr} \left[\Phi^{\dagger} \Phi \right] + \dfrac{\lambda_0}{4} \left(k_b \text{Tr} \left[\Phi^{\dagger} \Phi \right] \right)^2$

- $\mathcal{L}_{Yuk}(q, Q; \Phi) = \eta_q \left(\bar{q}_L \Phi q_R + \bar{q}_R \Phi^{\dagger} q_L \right) + \eta_Q \left(\bar{Q}_L \Phi Q_R + \bar{Q}_R \Phi^{\dagger} Q_L \right)$

- $\mathcal{L}_{Wil}(q, Q; \Phi; A, G, W) = \dfrac{b^2}{2} \rho_q \left(\bar{q}_L \overleftarrow{\mathcal{D}}_{\mu}^{\,AW} \Phi \mathcal{D}_{\mu}^{A} q_R + \bar{q}_R \overleftarrow{\mathcal{D}}_{\mu}^{\,A} \Phi^{\dagger} \mathcal{D}_{\mu}^{AW} q_L \right) + $

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

Symmetries and criticality

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

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

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

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

As before, we fix the Lagrangian parameters so as to force invariance under $\tilde{\chi}_L \times \tilde{\chi}_R$

Again, in NG phase criticality implies Higgs-like masses cancellation

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

$$\bullet\, O_{6,\bar{Q}Q}^{T} = b^2 \alpha_T \rho_Q \Lambda_T |\Phi| \left[\bar{Q}_L \mathcal{D}^{AGW} Q_L + \bar{Q}_R \mathcal{D}^{AG} Q_R \right]$$

$$\bullet\, O_{6,\bar{Q}Q}^{s} = b^2 \alpha_s \rho_Q \Lambda_T |\Phi| \left[\bar{Q}_L \mathcal{D}^{AGW} Q_L + \bar{Q}_R \mathcal{D}^{AG} Q_R \right]$$

$$\bullet\, O_{6,GG} = b^2 \alpha_T \rho_Q \Lambda_T |\Phi| F^G \cdot F^G \qquad \bullet\, O_{6,AA} = b^2 \alpha_s \rho_Q \Lambda_T |\Phi| F^A \cdot F^A$$

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

quark

Tera-quark

W
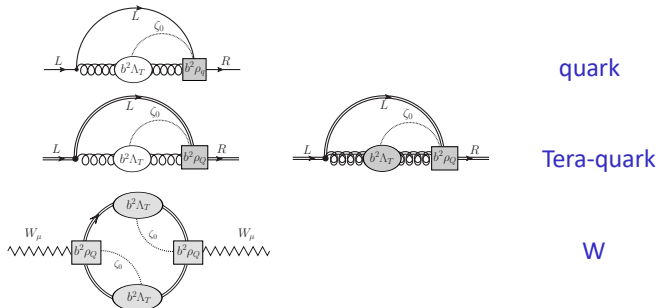
Finite terms, owing to UV-IR compensation, yielding $O(\Lambda_T)$ masses

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

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

$$+ \left[\bar{q}_L \, \slashed{\mathcal{D}}^{WA} q_L + \bar{q}_R \, \slashed{\mathcal{D}}^A q_R\right] + C_q \Lambda_T \left(\bar{q}_L U q_R + \bar{q}_R U^\dagger q_L\right) +$$

$$+ \left[\bar{Q}_L \, \slashed{\mathcal{D}}^{WAG} Q_L + \bar{Q}_R \, \slashed{\mathcal{D}}^{AG} Q_R\right] + C_Q \Lambda_T \left(\bar{Q}_L U Q_R + \bar{Q}_R U^\dagger Q_L\right) +$$

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

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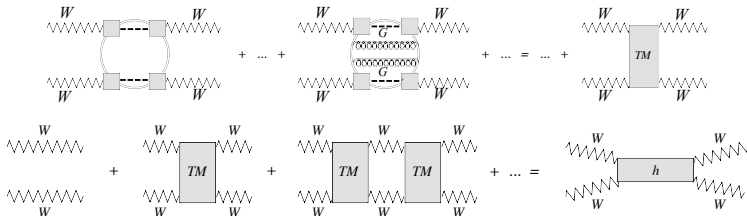
incorporating the mass formulae

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

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

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

The 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, $\text{QEL}_{d=4}$ resembles very much the SM with $v_H \sim \Lambda_T$
- possibly with the exception of tri- and four-linear h couplings

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

$$\Gamma_{4\,cr}^{NG}(q; A, W; U, h) = \frac{1}{4} F^A \cdot F^A + \frac{1}{4} F^W \cdot F^W + \left[\bar{q}_L \, \mathcal{P}^{AW} q_L + \bar{q}_R^u \, \mathcal{P}^A q_R^u + \bar{q}_R^d \, \mathcal{P}^A q_R^d \right] +$$

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

$$+ (y_q h + k_q k_v) \left(\bar{q}_L U q_R + \bar{q}_R U^\dagger q_L \right)$$

- $\Gamma_{4\,cr}^{NG}$ 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 $\Gamma_{4\,cr}^{NG}$ 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

$$\Gamma_{4\,cr}^{NG}(q; A, W; \Phi) \rightarrow \frac{1}{4} F^A \cdot F^A + \frac{1}{4} F^W \cdot F^W + \left[\bar{q}_L \, \mathcal{P}^{AW} q_L + \bar{q}_R^u \, \mathcal{P}^A q_R^u + \bar{q}_R^d \, \mathcal{P}^A q_R^d \right] +$$

$$+ \frac{1}{2} \text{Tr} \left[(\mathcal{D}_\mu^W \Phi)^\dagger \mathcal{D}_\mu^W \Phi \right] + \widetilde{\mathcal{V}}(h) + y_q \left(\bar{q}_L \Phi q_R + \bar{q}_R \Phi^\dagger q_L \right) \sim \Gamma^{SM}$$

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

i.e. a unitary & renormalizable theory

Conclusions

Conclusions

- We have identified a NP mechanism for elementary particle mass generation successfully confirmed by lattice simulations
- yielding $m_f^{NP} \propto \alpha_f^2 \Lambda_{\mathrm{RGI}}$ & $M_W \propto g_w \alpha \Lambda_{\mathrm{RGI}}$ (to lowest loop order)
  - $m_{top}, M_W \sim 10^2$ GeV call for a Tera-strong interaction
  - necessary to get a whole 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 ($\alpha_y \ll \alpha_s \ll \alpha_T \to m_\ell \ll m_q \ll m_{Q_T}$)
  - mass hierarchy 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
- We get gauge coupling unification in SM+Tera-sector (no SUSY)
- Phenomenology largely to be still worked out
- To move towards a realistic model
  - need to introduce families
  - need to split quarks & leptons within $SU(2)_L$ doublets
  - need to give mass to neutrinos that are (naturally) massless

Thanks for your attention

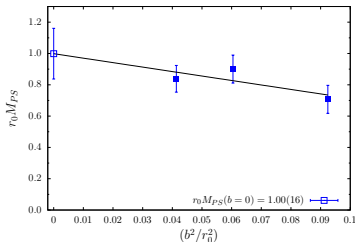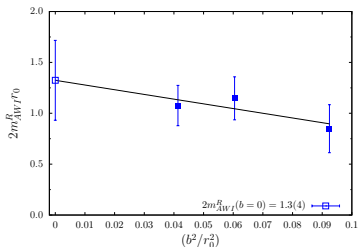# Back-up Slides

- 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"

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

- 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

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