The Great Beyond at the Exascale: Dynamical Simulations of the Frezzotti-Rossi Model

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The mechanism and its consequences

- novel, universal, intrinsically non-perturbative feature of QFT
  - **"non-perturbative anomaly"** – interplay of IR and UV
  - dynamical elementary particle mass generation

- for BSM physics: requires additional super-strong dynamics at high energy "Tera-fermions + Tera-gluons"

[R. Frezzotti, G.C. Rossi, Phys.Rev.D 92 (2015) 5, 054505 (hep-lat:1402.0389)]

- unifying NP mechanism
  - masses for fermions, Tera-fermions and weak gauge bosons, all $\propto \Lambda_{\mathrm{RGI}}$
  - $\Lambda_{\mathrm{RGI}} \sim$ few TeV
  - mass hierarchy due to different gauge coupling constants g_s^2, g_T^2, g_w^2 in the different sectors

- "Higgs" boson as a $|2W^+W^- + ZZ\rangle$ bound state due to Tera-strong force

- **low energy quantum effective Lagrangian (LEQEL) SM-like**

- extension to fully realistic models possible (leptons, weak hypercharge assignments etc.)

[R. Frezzotti, G.C. Rossi, PoS LATTICE2018 (2018) 190 (hep-lat:1811.10326)]

Basic UV-regulated Lagrangian

details: [R. Frezzotti, G.C. Rossi, PoS LATTICE2018 (2018) 190 (hep-lat:1811.10326)]

- quarks q, Tera-quarks Q
- gluons $\mathbf{A}_\mu$, Tera-gluons $\mathbf{G}_\mu$, weak boson triplet $\mathbf{W}_\mu$
- **auxiliary** complex scalar $SU(2)$-doublet ϕ (matrix notation Φ)

$$\frac{1}{2}F^{\mathbf{A},\mathbf{G},\mathbf{W}} \cdot F^{\mathbf{A},\mathbf{G},\mathbf{W}} + \frac{k_b}{2}\,\mathrm{tr}\left[\mathcal{D}_\mu^{\mathbf{W}}\Phi^\dagger \mathcal{D}_\mu^{\mathbf{W}}\Phi\right] + \mathcal{V}(\Phi^\dagger\Phi)$$

$$+ \left(\bar{q}_L \not{\mathcal{D}}^{\mathbf{AW}} q_L + \bar{q}_R \not{\mathcal{D}}^{\mathbf{A}} q_R\right) + \left(\bar{Q}_L \not{\mathcal{D}}^{\mathbf{AGW}} Q_L + \bar{Q}_R \not{\mathcal{D}}^{\mathbf{AG}} Q_R\right)$$

$$+ \eta_q \left(\bar{q}_L \Phi q_R + \bar{q}_R \Phi^\dagger q_L\right) + \eta_Q \left(\bar{Q}_L \Phi Q_R + \bar{Q}_R \Phi^\dagger Q_L\right)$$

So far so normal, but in addition, the naïvely irrelevant, $d = 6$ **pseudo-Wilson terms**:

$$+ \frac{1}{2\Lambda_{\mathrm{UV}}^2}\rho_q \left(\bar{q}_L \overleftarrow{\mathcal{D}}_\mu^{\mathbf{AW}} \Phi \mathcal{D}_\mu^{\mathbf{A}} q_R + \bar{q}_R \overleftarrow{\mathcal{D}}_\mu^{\mathbf{A}} \Phi^\dagger \mathcal{D}_\mu^{\mathbf{AW}} q_L\right)$$

$$+ \frac{1}{2\Lambda_{\mathrm{UV}}^2}\rho_Q \left(\bar{Q}_L \overleftarrow{\mathcal{D}}_\mu^{\mathbf{AGW}} \Phi \mathcal{D}_\mu^{\mathbf{AG}} Q_R + \bar{Q}_R \overleftarrow{\mathcal{D}}_\mu^{\mathbf{AG}} \Phi^\dagger D_\mu^{\mathbf{AGW}} Q_L\right)$$

Power divergent mass terms forbidden by exact global chiral symmetry acting on fermions, scalars and W.

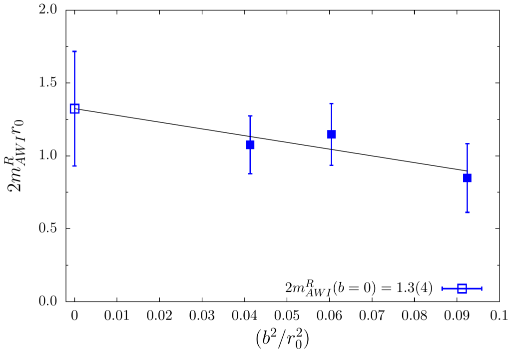
The critical model in the absence of weak interactions

[Phys.Rev.Lett. 123 (2019) 6, 061802 (hep-th:1901-09872)]

Toy model

Scalars, "Tera-quarks" and "Tera-gluons" $\rightarrow$ fermion mass generation mechanism demonstrated in quenched approximation on the lattice

- tune Yukawa coupling: $\eta_Q \rightarrow \eta_Q^{\mathrm{cr}}$
  - Yukawa and pseudo-Wilson terms compensate at critical value
  - fermionic chiral symmetry maximally enhanced
  - **no Yukawa terms in LEQEL**
  - up to discretisation artefacts, Tera-quarks **should be massless**
  - **they are not!**
- $m_Q \sim c_Q(g_G)\Lambda_{\mathrm{RGI}}$
  - **indep. of scalar v.e.v.!**
  - **not at all like the Higgs mechanism**



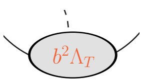
renormalised current Tera-quark mass in the critical model in the continuum limit
lattice spacing: $b = 1/\Lambda_{\mathrm{UV}}$
[Phys.Rev.Lett. 123 (2019) 6, 061802]

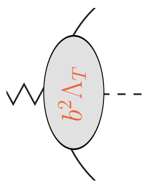
What about the electroweak mass scale?

[R. Frezzotti, G.C. Rossi, PoS LATTICE2018 (2018) 190 (hep-lat:1811.10326) & upcoming publication]

In multilimit $\eta_Q \to \eta_Q^{\mathrm{cr}}$, $\eta_q \to \eta_q^{\mathrm{cr}}$, $k_b \to k_b^{\mathrm{cr}}$

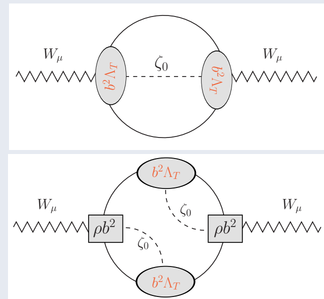
- maximal symmetry enhancement
- (natural fine-tuning in the 't Hooft sense)
- scalar decouples
  - **no Yukawa terms**
  - **no weak gauge boson mass terms**
- everything should be massless
- conjecture: **it won't be**
- Tera-quark loops essential!
  - NP vertices in LEQEL





  - (powers of the cut-off scale cancel in masses)

W mass



Pseudo-diagrams to reason about "lowest order" NP-contributions in LEQEL.

Similar diagrams for quark and Tera-quark mass contributions.

W mass: Need dynamical simulations!

Physics Goals and Computational Setup

Target observables

- ratio **W** mass / "Tera-meson" mass: $M_W/M_T \Rightarrow$ estimate of scale of new physics
- bound-state in WW-channel $\Rightarrow$ composite Higgs state, SM-like LEQEL

Toy model including weak interactions

- Tera-quark & scalar doublets, Tera-gluons (no SM quarks and gluons necessary at this stage)
- fermion discretisation suitable for **dynamical simulations**
  - Wilson clover + heavy gauge smearing
    - no doublers
    - small discretisation errors
- RM123 method for weak sector [G.M. de Divitiis et al., Phys. Rev. D 87, 114505], [D. Giusti et al., Phys.Rev.D 95 (2017) 11]

Challenges and Complications

- First of its kind
  - how will the solvers behave?
  - slowing down due to scalar field $\Rightarrow$ probably need improved sampling algorithms
- Large parameter space, many limits to be taken $\rightarrow$ numerous simulation points.
- Scalar correlators need very high statistics $\rightarrow$ required to follow line of constant physics in scalar sector.
- Fermion-disconnected contributions in dynamical theory $\rightarrow$ hierarchichal probing? distillation?
- Job for Exascale-level hardware!

Milestones and Outlook

1. Study new fermion discretisation in quenched approximation
   - investigate parameter tuning $\eta_Q \to \eta_Q^{\mathrm{cr}}$ (and Wilson clover $m_0 \to m_{\mathrm{cr}}$)
   - reproduce (some) results of [Phys.Rev.Lett. 123 (2019) 6, 061802]
2. Implement efficient dynamical simulation code for (pre-)Exascale hardware.
3. First simulations $\to$ study possible / necessary algorithmic improvements.
4. Tuning to critical parameters $\eta_Q \to \eta_Q^{\mathrm{cr}}, k_b \to k_b^{\mathrm{cr}}$ in dynamical simulations.
5. Full set of ensembles at one, later multiple lattice spacings.
6. Confirm or falsify W mass generation $\to$ mass ratio $\to$ estimate of new physics scale
7. Confirm or falsify WW-channel bound state. $\to M_{\mathrm{Higgs}}/M_W$

Outlook

Construction of candidates for BSM theory requires **much further theoretical and phenomenological study**. Simulation of full model with minimal realistic particle content will be a **Computational Grand Challenge**!

Thanks for your attention!