Studying how the particle spectra of GUTs emerge

Pascal Törek

with Axel Maas and René Sondenheimer

University of Graz

Granada, 22nd of June, 2017

Motivation - Physical states

- Physics is gauge invariant:
  Non-Abelian gauge theories $\Rightarrow$ bound states

- Electroweak physics:
  - Elementary fields (Higgs, W/Z) treated as if they were observable in perturbation theory
  - But they are gauge dependent
    $\Rightarrow$ non-observable objects

- Why does perturbation theory work at all?

FMS mechanism in the SM

[Fröhlich, Morcchio and Strocchi, PLB**97** (1980) and NPB**190** (1981)]

- Construct gauge-invariant operator:

$$O(x) = (\phi^\dagger \phi)(x)$$

- Expand correlator in fluctuations around vev and in conventional perturbation theory: $\phi(x) = v + h(x)$

$$\langle O(x)\bar{O}(y)\rangle = 4v^2\langle h(x)h(y)\rangle_0 + \langle h(x)h(y)\rangle_0^2 + \ldots$$

- Compare poles on both sides: Same mass
- Confirmed on the lattice (also for 1^- channel)

  [Maas, MPL **A28** (2013) / Maas and Mufti, JHEP (2014)]

- Works also for the rest of the SM
- Does it work for BSM theories?

GUT-like theory

- Same logic as in SM leads to a **conflict**
- GUT inspired theories:
  Gauge group is larger than global symmetry group
- Consider $SU(N)$ gauge theory ($N > 2$) with one fundamental scalar ϕ
  - Global symmetry: $U(1)$ custodial symmetry
- Perturbative construction: $SU(N) \xrightarrow{\langle\phi\rangle} SU(N-1)$
  - $2(N-1)+1$ massive and $N(N-2)$ massless gauge bosons
  - 1 massive real scalar field h

Physical spectrum of the GUT-like theory

- 0^+ $U(1)$-singlet channel: $O(x) = (\phi^\dagger \phi)(x)$

$$\langle O(x)\bar{O}(y)\rangle = 4v^2\langle h(x)h(y)\rangle + \ldots$$

  - 1 massive state
  - Mass of perturbative Higgs

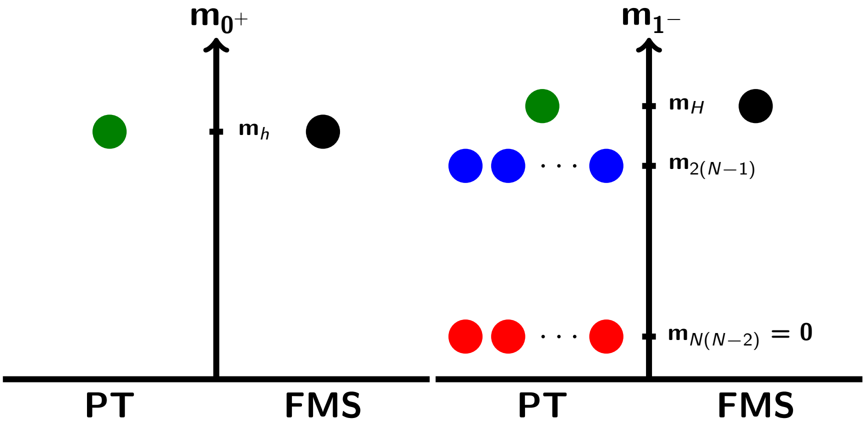
- 1^- $U(1)$-singlet channel: $O_\mu(x) = i(\phi^\dagger D_\mu \phi)(x)$

$$\langle O_\mu(x)\bar{O}^\mu(y)\rangle = v^4\langle W^H_\mu(x)W^{H\ \mu}(y)\rangle + \ldots$$

  - 1 massive state
  - Mass of heaviest gauge boson W^H

Comparison between PT and FMS

- Contradiction in the singlet vector channel between physical and perturbative spectrum
- No contradiction in the singlet scalar channel



$SU(3)$ with a fundamental scalar - Lattice

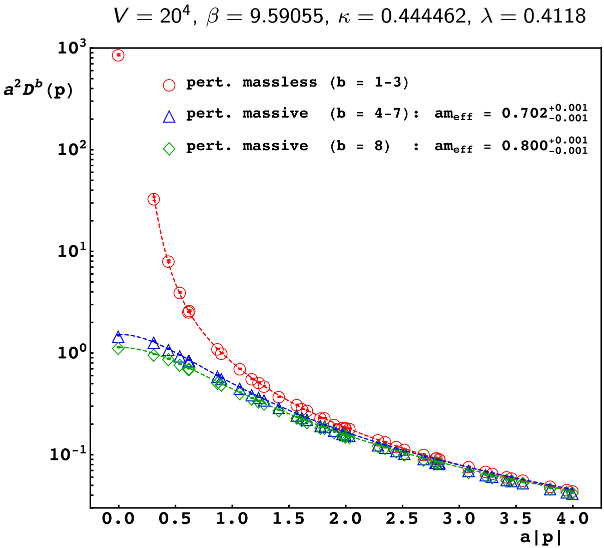
[Maas and Törek, PRD**95** (2017), 1607.05860]

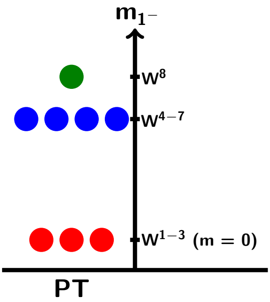
- Lattice action: $U_{x,\mu} = e^{iW_{x,\mu}} \in SU(3)$

$$S[U,\phi] = \frac{\beta}{3}\sum_{\Box} \mathrm{Re}\,\mathrm{tr}[U_{\Box}] + \sum_{x}\Big[\phi_x^\dagger\phi_x + \lambda(\phi_x^\dagger\phi_x - 1)^2 - \\ - \kappa\sum_{\mu}(\phi_x^\dagger\, U_{x,\mu}\, \phi_{x+\hat{\mu}} + c.c.)\Big]$$

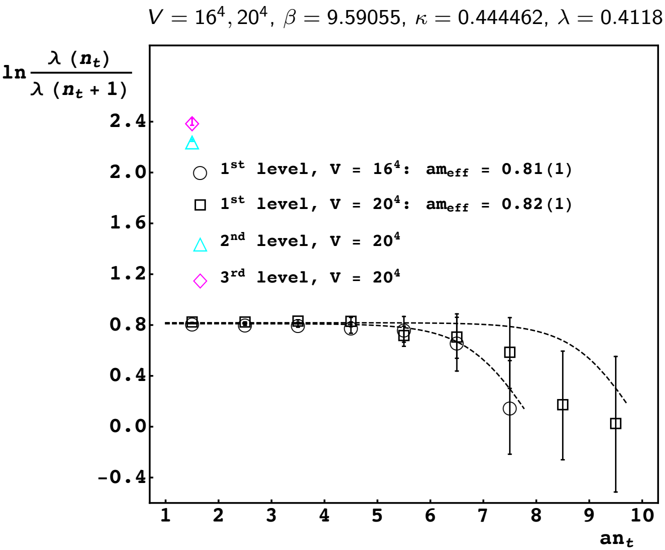
- Generating configurations: Multi-hit Metropolis
- To study elementary fields: Gauge fixing required
  - Local gauge fixing: Minimal Landau gauge $\partial_\mu W_\mu(x) = 0$
  - Global gauge fixing: Rotate Higgs field into $\phi \propto (0,0,1)$

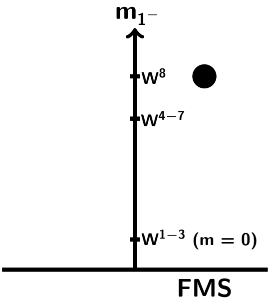
Masses from gauge-variant d.o.f.



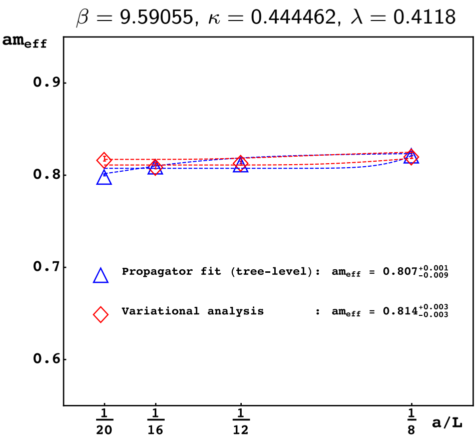


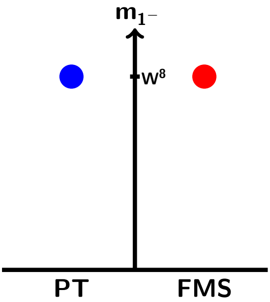
Masses from gauge-invariant d.o.f.





Volume dependency





- Single massive ground state with mass of W^8
- Exactly like FMS mechanism predicts
- Also confirmed for 0^+ channel

Open $U(1)$ states in the $SU(3)$ case

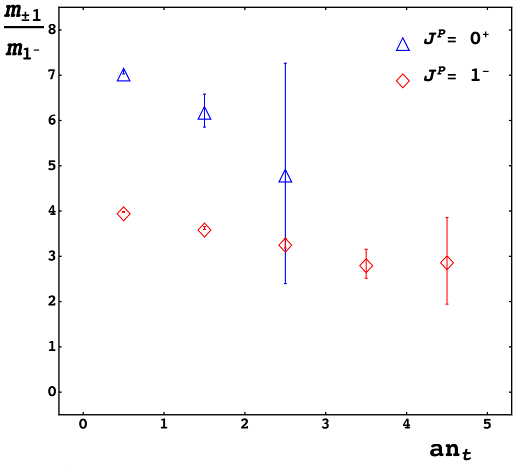
- There should be states with open $U(1)$ q-number:

$$\mathcal{O}^{0^+,1}(x) = \Big[\epsilon_{ijk}\ \phi_i\ (D_\mu\phi)_j\ (D_\mu D_\nu D_\nu\phi)_k\Big](x)$$
$$\mathcal{O}^{0^+,-1}(x) = \mathcal{O}^{0^+,1}(x)^\dagger$$
$$\mathcal{O}_\mu^{1^-,1}(x) = \Big[\epsilon_{ijk}\ \phi_i\ (D_\mu\phi)_j\ (D_\nu D_\nu\phi)_k\Big](x)$$
$$\mathcal{O}_\mu^{1^-,-1}(x) = \mathcal{O}_\mu^{1^-,1}(x)^\dagger$$

- Should be stable (conserved q-number)
- Not predicted by perturbation theory
- Application of FMS leads to complicated pole structure: Under investigation

Effective masses of open $U(1)$ states

$V = 16^4, \beta = 6.85535,\ \kappa = 0.456074,\ \lambda = 2.3416,\ n_{\text{smear}} = 10$



- Signals are very noisy
- Masses are of the order of the cut-off

Summary and conclusions

- FMS applied to SM reproduces correct spectrum and it is based on gauge invariance

  [Egger *et al.*, 1701.02881 / Török and Maas, 1610.04188 /

  Maas and Mufti, 1312.5579 / Maas, 1205.6625 /

  Fröhlich *et al.*, PLB**97** (1980) and NPB**190** (1981)]

- $SU(N)$ gauge theory with one fundamental scalar

  [Maas, Sondenheimer and Török, to be published]

  - FMS is supported by lattice results for $SU(3)$

    [Maas and Török, PRD**95** (2017), 1607.05860

    and PoS LATTICE2016, 1610.04188]

  - Open $U(1)$ states need further investigations

Outlook

[Maas, Sondenheimer and Törek, to be published]

- Toy models on the market where further **conflicts** are expected:
  - $SU(N)$ with adjoint scalar field
  - $SU(N)$ with adjoint and fundamental scalars
- FMS predicts entirely different spectrum than perturbation theory
- Classes of **conflicts** are testable on the lattice
- Conventional GUTs seem to fail to reproduce low energy spectrum

Running coupling