Physical spectrum of a partially Higgsed gauge theory

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Motivation

- Summarizing situation in SM: [Talk by A. Maas]

  - FMS mechanism: [Fröhlich et al., PL B97 (1980) and NP B190 (1981)]
    Spectrum of physical states (bound states) and elementary states ($W/Z$, Higgs, etc.) coincide

  - Multiplet structure of gauge sector traded for multiplet structure of custodial symmetry

  - Gauge group = custodial group

    $\Rightarrow$ Same degeneration pattern

- Applicability of FMS mechanism relies on:

  - Special structure of SM: Local = global multiplet
  - Smallness of Higgs fluctuations

- Does it also work in BSM scenarios?

  [Maas, 1502.02421 / Törek and Maas, 1509.06497]
Partially Higgsed gauge theory

- Aim is to construct a counter-example:
  - **GUT inspired theories:**
    - Gauge group larger than global symmetry group
  - **Local $\neq$ global multiplet

- Toy model: $SU(3)$ gauge group with fundamental Higgs $\phi$

\[
\mathcal{L} = (D_\mu \phi) ^\dagger (D_\mu \phi) + \mu^2 \phi^\dagger \phi - \frac{\mu^2}{2v^2} (\phi^\dagger \phi)^2 + \frac{1}{2} tr [W^2_{\mu\nu}]
\]

- Perturbative construction: $SU(3) \xrightarrow{\langle \phi \rangle} SU(2)$

- Perturbative spectrum:
  - **4 + 1** massive and 3 massless gauge bosons
  - **1** massive Higgs boson
$J^P = 1^-$ singlet channel

- Conflict expected in vector channel [Törek and Maas, 1509.06497]

- FMS mechanism: [Fröhlich et al., PL B97 (1980) and NP B190 (1981)]

  - Composite gauge-invariant operator:
    \[ O_\mu(x) = i(\phi^\dagger D_\mu \phi)(x) \]

  - Fix to gauge with non-vanishing vev (minimal ’t Hooft-Landau gauge)

  - Expand Higgs around vev: $\phi_i(x) = v\delta_{i,3} + \eta_i(x)$

  \[
  \langle O_\mu(x)O_\mu^\dagger(y) \rangle = v^4 \langle W_\mu^8(x)W_\mu^8(y) \rangle + O(\eta W/v)
  \]

- Correlators have same mass poles $\Rightarrow$ same mass

- Only a single massive particle is predicted $\Rightarrow$ Contradiction to perturbative spectrum
Lattice studies: Basic setup

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

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

- Generating configurations: Multi-hit Metropolis algorithm

- 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 \( \phi \propto (0, 0, 1) \)
Phase diagram: QLR vs. HLR

- Depending on $\beta$, $\kappa$ and $\lambda$ different expectations:
  - ★ Non-Abelian gauge theory: QCD-like region (QLR)
  - ★ Higgs sector: Higgs-like region (HLR)

- Quantity to measure polarization: $\bar{\phi} = \frac{1}{V} \sum_x \phi_x$
  

- Quantity to distinguish the regions:
  
  $$\langle \bar{\phi}^2 \rangle = \left\langle \left| \frac{1}{V} \sum_x \phi_x \right|^2 \right\rangle \approx \frac{\xi}{V}$$

- QLR: $\langle \bar{\phi}^2 \rangle \xrightarrow{V \to \infty} 0$ for $\xi$ finite

- HLR: $\langle \bar{\phi}^2 \rangle \xrightarrow{V \to \infty} \text{const.} > 0$ for $\xi$ infinite
Phase diagram: QLR vs. HLR

\[ \langle \bar{\phi}^2 \rangle \]

\[ \Delta \text{QLR: } \beta = 5.7936, \kappa = 0.153236, \lambda = 4.1639 \]

\[ \Diamond \text{HLR: } \beta = 8.1138, \kappa = 0.698703, \lambda = 9.9043 \]

- Large values of \( \kappa \) \(\iff\) large negative tree-level masses
  \(\Rightarrow\) BEH effect in this gauge (depends also on \( \beta, \lambda \))

- Small values of \( \kappa \) \(\Rightarrow\) No BEH effect
Phase diagram
Propagators

- Good agreement with tree-level perturbation theory

\[ V = 20^4, \beta = 9.59055, \kappa = 0.444462, \lambda = 0.4118 \]

- Dashed lines: Fits to \( Z/p^2 \) and \( Z/(p^2 + (a m_{\text{eff}})^2) \)
Spectroscopy in $1^-$ channel - Setup

- Variational analysis with operator set:
  (larger operator basis is work in progress)

$$O_\mu = \text{Re}\left(i \ tr \left[ \phi_i^\dagger U_{ij}^{\mu} \phi_j \right] \right) \text{ and } O_\nu O_\nu O_\mu$$

- Links stout-smeared and Higgs APE-smeared

- Total operator set consists of 3-times and 4-times smeared $O$
  \[ \Rightarrow \text{Crosscorrelation matrix } C(n_t) \]

- Generalized eigenvalue problem: $C(n_t) \vec{v} = \lambda(n_t) C(n_0) \vec{v}$
  \[ \Rightarrow \lambda^{(k)}(n_t) \propto e^{-n_t E_k} \left( 1 + O(e^{-n_t \Delta E_k}) \right) \]

- Energy levels: $E_k$ from $\ln \frac{\lambda^{(k)}(n_t)}{\lambda^{(k)}(n_{t+1})} \Rightarrow E_0 \equiv m_{\text{eff}}$
Spectroscopy in \(1^-\) channel - Results

\[ V = 16^4, 20^4, \beta = 9.59055, \kappa = 0.444462, \lambda = 0.4118 \]

\[ \ln \left( \frac{\lambda(n_t)}{\lambda(n_t + 1)} \right) \]

- **1\textsuperscript{st} level, \(V = 16^4\):** \(a_{\text{eff}} = 0.810^{+0.003}_{-0.003}\)
- **1\textsuperscript{st} level, \(V = 20^4\):** \(a_{\text{eff}} = 0.818^{+0.003}_{-0.003}\)
- **2\textsuperscript{nd} level, \(V = 20^4\)
- **3\textsuperscript{rd} level, \(V = 20^4\)

\[ \text{Dashed/dotted lines: Results of fit } \lambda(n_t) = A \cosh \left( a_{\text{eff}} (n_t - L/2) \right) \]
Volume dependency of $m_{\text{eff}}$

- Single massive ground state with mass of $W^8$
- Exactly like FMS mechanism predicts

\[ \beta = 9.59055, \kappa = 0.444462, \lambda = 0.4118 \]

\[ \text{Propagator fit (tree-level)}: \quad am_{\text{eff}} = 0.801 \pm 0.007 \]

\[ \text{Variational analysis:} \quad am_{\text{eff}} = 0.816 \pm 0.003 \]

- Dashed/dotted lines: Fits of $am_{\text{eff}}$ to $A + B \ e^{-cV}$
Conclusions

- $SU(3)$ gauge theory with fundamental Higgs

- Perturbative framework: 4+1 massive and 3 massless gauge bosons

- Perturbative description works well for propagators

- FMS mechanism: Single massive state in $1^-$ channel

- Lattice results support FMS prediction