How to describe the physics of a GUT in a gauge invariant way

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Outline

Motivation

Higgs mechanism

Grand unified theories (GUTs)

FMS mechanism

Model GUT and FMS mechanism

Conclusions and outlook
Motivation

Why grand unified theories (GUTs)?

- Successful description of SM: $SU(3)_C \times SU(2)_W \times U(1)_Y$
- Still many open issues:
  - Number of parameters
  - Fractional charges
  - ...

Aim of this project?

- Calculation of physical spectrum of a model GUT
- Test a certain mechanism for this model GUT

Needs several ingredients:

- Higgs mechanism
- FMS mechanism
- Lattice methods
Higgs mechanism - A short reminder I

- Consider the linear sigma model:

  \[ N \text{ real scalar fields } \phi_i \text{ and } V(\phi) = \frac{\lambda}{4} \left( \phi_i \phi_i - \frac{\mu^2}{\lambda} \right)^2 \]
Consider the linear sigma model:

\[ N \text{ real scalar fields } \phi_i \text{ and } V(\phi) = \frac{\lambda}{4} \left( \phi_i \phi_i - \frac{\mu^2}{\lambda} \right)^2 \]

**SO\(N\)** symmetric model

- **Configuration with lowest energy:** \( \bar{n}_i = n_i \sqrt{\frac{\mu^2}{\lambda}} = n_i v \),
  \( n = (0, \ldots, 0, 1) \)
- Set \( \phi(x) = (\pi(x), \eta(x) + v) \): **SO\((N - 1)\)** symmetry
- **\((N - 1)\)** massless fields \(\pi\) and one massive field \(\eta\)
The Higgs mechanism - A short reminder II

- Goldstone theorem:
  - Massless fields $\Rightarrow$ Goldstone fields
    # of broken generators
  - Massive fields $\Rightarrow$ Higgs fields
    # of unbroken generators

$\Delta L = g^2 v^2 \frac{1}{4} \{ T^a, T^b \}_a \overline{A}^a \overline{A}^b \equiv \frac{1}{2} M^2_{ab} \overline{A}^a \overline{A}^b$
The Higgs mechanism - A short reminder II

- Goldstone theorem:
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- Choice of $n$ arbitrary: include explicit symmetry breaking in $\mathcal{L}$ and study $v \to 0$

- Gauge theory: Goldstone’s *eaten* by gauge fields
  # of broken generators $\Leftrightarrow$ # of massive gauge bosons

\[
\Delta \mathcal{L} = \frac{g^2 v^2}{4} n \{ T^a, T^b \} n A^a_\mu A^b_\mu \equiv \frac{1}{2} M^2_{ab} A^a_\mu A^b_\mu
\]
The Higgs mechanism - A short reminder II

- Goldstone theorem:
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    $\#$ of broken generators
  - Massive fields $\Rightarrow$ Higgs fields
    $\#$ of unbroken generators

- Choice of $n$ arbitrary: include explicit symmetry breaking in $\mathcal{L}$ and study $\nu \to 0$

- Gauge theory: Goldstone’s *eaten* by gauge fields
  $\#$ of broken generators $\Leftrightarrow$ $\#$ of massive gauge bosons

$$\Delta \mathcal{L} = \frac{g^2 \nu^2}{4} n^\dagger \{ T^a, T^b \} n A^a_\mu A^b_\mu \equiv \frac{1}{2} M_{ab}^2 A^a_\mu A^b_\mu$$

- Choice of $n \Leftrightarrow$ *gauge fixing* ('t Hooft gauge, unitary gauge)

  ≠ spontaneous breaking of gauge symmetry [Elitzur (1975)]

Hidden gauge symmetry
Grand unified theories (GUTs) - Why we study GUTs?

- SM has 19 parameters ⇒ reduction possible?
- Coupling unification: $g_U = g_S = g_W = \sqrt{\frac{8}{3}} e$ (for $SU(5)$)

![Graph showing $1/\alpha_i$ vs $\log Q$ for SM and MSSM](image)

[PDG, Phys. Rev. D86, 010001 (2012)]

- Quantization of $e$ ($Y$ arbitrary in SM) and why $Q_e = 3Q_d = -3Q_u/2$?
- Chiral anomalies cancel of quarks and leptons ⇒ relation?
- ...
Grand unified theories (GUTs) - What is a GUT?

- Based on concept of gauge theories

- Describe elementary interactions by a gauge theory with a single gauge group $G \Rightarrow \exists$ only one gauge coupling $g$

- Restrictions on $G$:
  
  - $G_{SM} = SU(3)_C \times SU(2)_W \times U(1)_Y \subset G$
  
  - Fermion representations must be anomaly free

- $G \xrightarrow{SSB} \ldots \xrightarrow{SSB} G_{SM}$
  
  Higgs mechanisms necessary

- …
Grand unified theories (GUTs) - What is a GUT?

- \( \dim G > \dim G_{SM} \Rightarrow \) additional gauge bosons
  - Leptoquarks: transition between leptons and quarks
  - Baryon-number violation: not observed yet
  - Proton decay: not observed yet

- Very small effect

- Experimental status: grand unification only at very high energies \( \Rightarrow \) symmetry must be "spontaneously broken"

- Examples: \( E_6, E_7, E_8, SO(10), SU(5) \)
SU(5) GUT as a model - Gauge sector I

- Decompose $SU(5)$ in terms of $(SU(3)_C, SU(2)_W)_Y$
- Gauge bosons in adjoint representation of $SU(5)$:

$$A_\mu = A_\mu^a \frac{\lambda^a_{(5)}}{2} = \frac{1}{\sqrt{2}} \begin{pmatrix}
\frac{1}{\sqrt{2}} G^a_\mu \lambda^a_{(3)} \\
X_{r,\mu} & X_{g,\mu} & X_{b,\mu} \\
Y_{r,\mu} & Y_{g,\mu} & Y_{b,\mu}
\end{pmatrix}
\begin{pmatrix}
X^\dagger_{r,\mu} & Y^\dagger_{r,\mu} \\
X^\dagger_{g,\mu} & Y^\dagger_{g,\mu} \\
X^\dagger_{b,\mu} & Y^\dagger_{b,\mu}
\end{pmatrix}
- \frac{1}{2} \sqrt{\frac{3}{5}} Y W B_\mu$$

- Assignments:
  - $SU(3)$ octet of gluons $G^a, a = 1, 2, \ldots, 8$
  - Isovector of bosons $W^i, i = 1, 2, 3$
  - Isoscalar boson $B_\mu$
  - 12 more gauge bosons (leptoquarks)
    $X_c, Y_c, X^{\dagger}_c, Y^{\dagger}_c, c = r, g, b$
SU(5) GUT as a model - Gauge sector II

- $SU(5)$ must be strongly broken: $\not R$ quark $\leftrightarrow$ lepton $\Rightarrow$
  Leptoquarks must have huge masses
- Symmetry breaking pattern:

\[
\begin{array}{c}
SU(5) \\
\downarrow 24
\end{array} \xrightarrow{1st \text{ Higgs}} \begin{array}{c}
SU(3)_C \times SU(2)_W \times U(1)_Y \\
\downarrow 8 \quad \downarrow 3 \quad \downarrow 1
\end{array} \xrightarrow{2nd \text{ Higgs}} \begin{array}{c}
SU(3)_C \times U(1)_{em} \\
\downarrow 8 \quad \downarrow 1
\end{array}
\]

- 12 massive gauge bosons
- 3 massive gauge bosons $Z, W^\pm$

Questions answered by $SU(5)$:

- Coupling unification
- Quantization of $e$ and fractional charges
- (Wrong) prediction of weak mixing angle

Critique of $SU(5)$:

- # of parameters is increased
- Proton lifetime ($\tau_{SU(5)}^{p \rightarrow e + \pi^0} = 2 \times 10^{31}$ a, $\tau_{exp}^{p \rightarrow e + \pi^0} > 1.6 \times 10^{33}$ a)
SU(5) GUT as a model - Gauge sector II

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\[
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SU(5) & \rightarrow SU(3)_C \times SU(2)_W \times U(1)_Y \\
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&SU(5) \quad \xrightarrow{1^{st} \text{ Higgs}} \quad SU(3)_C \times SU(2)_W \times U(1)_Y \\
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\end{align*}
\]

- 12 massive gauge bosons
- Leptoquarks

- 3 massive gauge bosons
- $Z, W^\pm$

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FMS mechanism


*Higgs phenomenon without symmetry breaking order parameter*
FMS mechanism


*Higgs phenomenon without symmetry breaking order parameter*

Consists of three main parts:

- Proof that $\langle \phi \rangle$ has to vanish (in temporal gauge) and exponential decay of gauge invariant $0^+$ 2-point function
- Existence and completeness of gauge invariant fields
- Perturbative expansion in Higgs fluctuations for gauge invariant correlation functions
FMS mechanism


*Higgs phenomenon without symmetry breaking order parameter*

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Assumptions for the proofs:

- Lattice regularization
- Fluctuation of Higgs field is small
- Construction special for SM
Weak and Higgs sector of the SM I

- Lagrangian of this sector:

\[ \mathcal{L} = -\frac{1}{4} W^a_{\mu\nu} W^a{}^{\mu\nu} + (D_\mu \phi)^(\dagger) (D^\mu \phi) + \mu^2 \phi^(\dagger) \phi - \lambda (\phi^(\dagger) \phi)^2 \]

- Invariant under $SU(2)_{\text{local}} \times SU(2)_{\text{global}}$ transformations:
  - $SU(2)$ pseudo-real: 2 Higgs d.o.f. $\Rightarrow$ 2 $W$-bosons
  - Need 3-$W$ bosons $\Rightarrow$ use 2 multipletts
  - Redundance $\Rightarrow$ $SU(2)_{\text{local}} \times SU(2)_{\text{global}}$ invariance
  - $SU(2)_{\text{global}}$: custodial symmetry
    $\Leftrightarrow$ flavor symmetry in Higgs sector
Weak and Higgs sector of the SM II

- Higgs mechanism: Expand $\mathcal{L}$ at minimum $\bar{\phi}_i = n_i \nu$ of $V(\phi)$
  
  \[ \phi_i(x) = \eta_i(x) + n_i \nu \]

  - Without gauge fixing: $\langle \phi_i(x) \rangle = 0$
  - With gauge fixing: $\langle \phi_i(x) \rangle = n_i \nu$ (unitary, 't Hooft gauge)

- Remaining symmetry of $\mathcal{L}$: $SU(2)_{\text{global}}$
  custodial symmetry

- Note: Gauge symmetry is hidden (gauge fixed $\mathcal{L}$)

- Propagators are gauge dependent:
  
  \[ \langle \eta(x) \dagger \eta(y) \rangle_{\text{fixed}} \neq 0 \quad (\text{Higgs, } J^P = 0^+) \]
  \[ \langle W^a_\mu(x) W^b \mu(y) \rangle_{\text{fixed}} \neq 0 \quad (\text{W-Bosons, } J^P = 1^-) \]
Weak and Higgs sector of the SM II

\[ \bar{\phi}_i = n_i v \]

\[ \phi_i(x) = \eta_i(x) + n_i v \]

Without gauge fixing:
\[ \langle \phi_i(x) \rangle = 0 \]

With gauge fixing:
\[ \langle \phi_i(x) \rangle = n_i v \] (unitary, 't Hooft gauge)

Remaining symmetry of \( L \):
\( SU(2)_c \) global custodial symmetry

Note: Gauge symmetry is hidden (gauge fixed \( L \))

Propagators are gauge dependent:
\[ \langle \eta(x) \eta(y) \rangle \neq 0 \] (Higgs, \( J^P = 0^+ \))
\[ \langle W_a(x) W_b(y) \rangle \neq 0 \] (W-Bosons, \( J^P = 1^- \))

Physics is gauge invariant:

Why does description with gauge dependent objects in perturbation theory work so well?
Weak and Higgs sector of the SM III

- Contradiction can be resolved: FMS mechanism
  - Gauge invariant states $\Rightarrow$ composite operators
  - Choose gauge with $\langle \phi \rangle \neq 0$
  - Expand operator around Higgs expectation value $n_i v$

Examples:

- $0 +$ custodial singlet channel
  $$\langle \phi^\dagger_i (x) \phi_j (y) \rangle = v^4 + 4 v^2 (c + n_i n^\dagger_j \langle \eta^\dagger_i (x) \eta_j (y) \rangle) + O(\eta^3/v^3)$$

- $1 -$ custodial triplet channel
  $$\langle (\text{tr} \tau^a \phi^\dagger D^\mu \phi)(x)(\text{tr} \tau^a \phi^\dagger D^\mu \phi)(y) \rangle = \bar{c} \langle W^a \mu (x) W^a \mu (y) \rangle + O(\eta W/v)$$

Same poles and multiplicities on left- and right-hand sides

Explains that gauge dependent and gauge invariant spectrum coincides and why the description of Higgs sector in the SM is so successful
Weak and Higgs sector of the SM III

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- Examples:

0$^+$ custodial singlet channel

$$\langle \phi_i^*(x) \phi_i(x) \phi_j^*(y) \phi_j(y) \rangle = v^4 + 4v^2(c + n_i n_j^* \langle \eta_i^*(x) \eta_j(y) \rangle) + O(\eta^3/v^3)$$

1$^-$ custodial triplet channel

$$\langle (\text{tr} \tau^a \phi^\dagger D^\mu \phi)(x) (\text{tr} \tau^a \phi^\dagger D_\mu \phi)(y) \rangle = \bar{c} \langle W^a_\mu(x) W^a_{\mu}(y) \rangle + O(\eta W/v)$$
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  - $1^-$ custodial triplet channel
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$H + H = H + H + H + H + \ldots$

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Weak and Higgs sector of the SM III

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$$\begin{align*}
\langle \phi \rangle &
\langle \phi \rangle = v + 4v^2 (c + n_i n_j \langle \eta \eta \rangle) + O(\eta^3/v^3) \\
\end{align*}$$

- Same poles and multiplicities on left- and right-hand sides

Explains that gauge dependent and gauge invariant spectrum coincides and why the description of Higgs sector in the SM is so successful
Model GUT I

Idea

- Take a (simple) gauge group as GUT group: $SU(3)$
- Take fundamental Higgs fields $\phi, \psi$
- Break GUT group twice:

$$SU(3) \xrightarrow{\langle \phi \rangle} SU(2) \xrightarrow{\langle \psi \rangle} 1$$

- Mimic weak/Higgs sector of SM:
  3 $W$'s ($m_W \approx 80\text{GeV}$) and 1 Higgs ($m_H \approx 126\text{GeV}$)
  additional 5 heavy gauge bosons and 3 heavy Higgs
- Test FMS mechanism
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Lagrangian

$$\mathcal{L} = -\frac{1}{4} W^a_{\mu \nu} W^a{^{\mu \nu}} + (D_\mu \phi)^\dagger (D^\mu \phi) + (D_\mu \psi)^\dagger (D^\mu \psi) - V(\phi, \psi) + \mathcal{L}_{\text{fix}} + \mathcal{L}_{\text{ghost}}$$

$$V(\phi, \psi) = -\mu^2 (\phi^\dagger \phi) + \frac{\mu^2}{2v^2} (\phi^\dagger \phi)^2 - \omega^2 (\psi^\dagger \psi) + \frac{\omega^2}{2w^2} (\psi^\dagger \psi)^2 + \alpha (\phi^\dagger \psi)(\psi^\dagger \phi)$$
Model GUT II

- Higgs field expectation values: $\langle \phi_i \rangle = n_i v$, $\langle \psi_i \rangle = m_i w$

- $SU(3) \rightarrow SU(2)$: $\langle \phi_i \rangle = n_i v$, $n = (0, 0, 1)$
  - 5 broken generators $\Leftrightarrow$ 5 massive gauge, 1 Higgs boson
  - 3 invariant generators ($SU(2)$ subgroup) $\Leftrightarrow$ 3 massless W’s

- $SU(2) \rightarrow 1$: $\langle \psi_i \rangle = m_i w$, $m = (1, 0, 0)$
  - 3 broken generators $\Leftrightarrow$ 3 massive W’s, 3 Higgs bosons
  - No invariant generators

- In total: $5 + 3$ massive gauge bosons, $1 + 3$ Higgs bosons

- Choice of $n, m$: gauge fixing required
Model GUT III

Two scales: $v, w$

$v \rightarrow \infty$: Heavy and light sector decouple

Correct phenomenology
FMS mechanism in the model I

FMS mechanism for $1^-$ channel

- Gauge invariant correlator with $1^-$: $\chi_\alpha = \phi, \psi, \alpha = 1, 2$

$$O^\mu_{\mu}(\chi_1, \chi_2)(x) = (\chi_1^\dagger D_\mu \chi_2)(x)$$

- Expand $\chi_\alpha = \eta_\alpha + n_\alpha v_\alpha$

$$\langle O^\mu_{\mu}(\chi_1, \chi_2)(x) O^\mu_{\mu}(\chi_1, \chi_2)(y)^\dagger \rangle = c^{ab} \langle W^a_\mu(x) W^b_\mu(y) \rangle + \mathcal{O}(\eta W / v)$$

- $c^{ab}$ depends on $v, w, n, m$

- Same poles $\Rightarrow$ equivalence of mass spectrum

- Different predictions for different # of Higgs fields
FMS mechanism in the model II

SU(3) + 1 Higgs field

- Expand: \( \phi = \eta + n \nu \)

\[
\langle O^{(\phi,\phi)}_{\mu}(x) O^{(\phi,\phi)}_{\mu}(y)^\dagger \rangle = c^{ab} \langle W^a_{\mu}(x) W^b_{\mu}(y) \rangle + \mathcal{O}(\eta W / \nu)
\]

- \( c^{ab} = 0 \) for \( a, b = 1, 2, 3 \) and \( c^{ab} \neq 0 \) for \( a, b = 4, \ldots, 8 \)

- FMS mechanism: 5 massive states

- Perturbation theory: 5 massive and 3 massless states

- Different possibilities:

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- What is correct? We don’t know yet ⇒ lattice
FMS mechanism in the model III

$SU(3) + 2$ Higgs fields

- Expand: $\phi = \eta + n \nu, \psi = \chi + m w$

\[ \langle O_{\mu}^{(\phi,\psi)}(x) O_{\mu}^{(\phi,\psi)}(y) \rangle = c^{ab} \langle W^a_{\mu}(x) W^b_{\mu}(y) \rangle + \mathcal{O}(\{\eta, \chi \} W / [\nu, w]) \]

- $c^{ab} \neq 0$ for $a, b = 1, \ldots, 8$

- FMS mechanism: $5 + 3$ massive states

- Perturbation theory: $5 + 3$ massive states

- FMS mechanism vs. perturbation theory: same predictions

- FMS mechanism should work $\Rightarrow$ lattice
Conclusions and outlook

Conclusions

- Reminder on Higgs mechanism
- Introduction to GUTs
- FMS mechanism in SM and in our model

Outlook

- Put it on the lattice
- Test FMS mechanism in $SU(3) + 1$ and $SU(3) + 2$ Higgs
- Include fermions (maybe)

Thank you!
Conclusions and outlook

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Thank you!