Observables in Higgsed Theories

Axel Maas

4th of July 2014
#ichep2014
Valencia, Spain
Field theory & Experiment

- Qualitative questions
Field theory & Experiment

- Qualitative questions
- What kind of bumps can be expected in an experiment?
  - Non-trivial question even in weakly interacting theories
    - E.g. hydrogen atom in QED
    - Why does perturbation theory work so well?
- Could there be more around at the Higgs?
  - Still big field theory questions
Field theory & Experiment

- Qualitative questions
- What kind of bumps can be expected in an experiment?
  - Non-trivial question even in weakly interacting theories
    - E.g. hydrogen atom in QED
    - Why does perturbation theory work so well?
  - Could there be more around at the Higgs?
    - Still big field theory questions
- Are there insights for BSM scenarios?
  - Not only in strongly interacting theories
Field theory & Experiment

- Qualitative questions
- What kind of bumps can be expected in an experiment?
  - Non-trivial question even in weakly interacting theories
    - E.g. hydrogen atom in QED
    - Why does perturbation theory work so well?
  - Could there be more around at the Higgs?
    - Still big field theory questions
- Are there insights for BSM scenarios?
  - Not only in strongly interacting theories
- The lattice can answer these questions
The Higgs sector as a gauge theory

- The Higgs sector is a gauge theory

\[ L = -\frac{1}{4} W^a_{\mu \nu} W^a_{\mu \nu} + (D^j_\mu h^j) + D^\mu_{ik} h_k + \lambda (h^a h^+_a - \nu^2)^2 \]

\[ W^a_{\mu \nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + gf^a_{bc} W^{b}_\mu W^{c}_\nu \]

\[ D^{ij}_\mu = \delta^{ij}_\mu \partial_\mu - ig W^a_\mu t^{ij}_a \]

- Ws \( W^a_\mu \) (80 GeV)

- Higgs \( h_i \) (120 GeV)

- Couplings \( g, \nu, \lambda \) and some numbers \( f^{abc} \) and \( t^{ij}_a \)

- No QED: Ws and Zs are degenerate
Symmetries

\[ L = -\frac{1}{4} W^a_{\mu \nu} W^a_{\nu} + (D^i_{\mu} h^j)^* D^i_{\mu} h_k + \lambda (h^a h^+_a - \nu^2)^2 \]

\[ W^a_{\mu \nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + gf^a_{bc} W^b_\mu W^c_\nu \]

\[ D^{ij}_\mu = \delta^{ij} \partial_\mu - ig W^a_\mu t^{ij}_a \]

- Local SU(2) gauge symmetry
  - Invariant under arbitrary gauge transformations \( \phi^a(x) \)

\[ W^a_\mu \rightarrow W^a_\mu + (\delta^a_b \partial_\mu - gf^a_{bc} W^c_\mu) \phi^b \]

\[ h_i \rightarrow h_i + g t^{ij}_a \phi^a h_j \]

- Global SU(2) Higgs custodial symmetry
  - Acts as right-transformation on the Higgs field only

\[ W^a_\mu \rightarrow W^a_\mu \]

\[ h_i \rightarrow h_i + a^{ij} h_j + b^{ij} h^*_j \]
Physical states

- Weak charge is not gauge-invariant
  - Carriers are 'unphysical'
- Experiments measure peaks in cross-sections
  - Physical objects – what are they?
Physical states

- Weak charge is not gauge-invariant
  - Carriers are 'unphysical'
- Experiments measure peaks in cross-sections
  - Physical objects – what are they?
- Field theory: Observables are composite objects
  - Higgs-Higgs, W-W, Higgs-Higgs-W etc.

- Not asymptotic states in perturbation theory
  - Non-perturbative approach required: Lattice

[Fröhlich et al. PLB 80, 't Hooft ASIB 80, Bank et al. NPB 79]
- Simpelst $0^+$ bound state \( h^+ (x) h(x) \)
  - Same quantum numbers as the Higgs
  - No weak or custodial charge
Simpelst $0^+$ bound state $h^+(x)h(x)$

- Same quantum numbers as the Higgs
- No weak or custodial charge
- Mass is about 120 GeV
Mass relation - Higgs

- $0^+$ bound state at 120 GeV
- Higgs at tree-level: 120 GeV
- Coincidence? No.
Mass relation - Higgs

- $0^+$ bound state at 120 GeV
- Higgs at tree-level: 120 GeV
- Coincidence? No.
  - Duality between elementary states and bound states
    \[
    h = v + \eta
    \]
    \[
    \langle (h^+ h)(x)(h^+ h)(y) \rangle \approx \text{const} + \langle \eta^+ (x) \eta(y) \rangle + O(\eta^3)
    \]
  - Same poles to leading order

[Fröhlich et al. PLB 80, Maas MPLA'13, Maas et al. JHEP'14]
Mass relation - Higgs

- 0\(^+\) bound state at 120 GeV
- Higgs at tree-level: 120 GeV
- Coincidence? No.
  - Duality between elementary states and bound states
    \[ h = \nu + \eta \]
    \[ \langle (h^+ h)(x)(h^+ h)(y) \rangle \approx \text{const.} + \langle \eta^+ (x) \eta(y) \rangle + O(\eta^3) \]
  - Same poles to leading order
- Deeply-bound relativistic state
  - Mass defect~constituent mass
  - Cannot describe with quantum mechanics
  - Very different from QCD and QED bound states
State spectrum

[Maas et al. Unpublished, PoS’12]

~ Higgs

\(0_1^+\)
State spectrum

- Vector state $1^-$ with operator $\text{tr} t^a \frac{h^+}{\sqrt{h^+ h}} D_\mu \frac{h}{\sqrt{h^+ h}}$
  - Only in a Higgs phase close to a simple particle
  - Custodial triplet, instead of gauge triplet
Vector state $1^-$ with operator $\text{tr} \, t^a \frac{h^+}{\sqrt{h^+ h}} D_\mu \frac{h}{\sqrt{h^+ h}}$

- Only in a Higgs phase close to a simple particle
- Custodial triplet, instead of gauge triplet
- 80 GeV mass...
Mass relation - $W$

- Vector state: 80 GeV
- $W$ at tree-level: 80 GeV
- Same mechanism

$$\langle (h^+ D_\mu h)(x)(h^+ D_\mu h)(y) \rangle$$

$h = v + \eta \\ \simeq const. + \langle W_\mu(x)W_\mu(y) \rangle + O(\eta^3)$

$\partial v = 0$

- Same poles at leading order

[Fröhlich et al. PLB 80, Maas MPLA'13, Maas et al. JHEP'14]
• Duality generates 'physical' Higgs and W/Z states
• Duality generates 'physical' Higgs and W/Z states
• Other channels: Suppressed, but mimic new physics
  • Depend strongly on details [Maas et al. Unpublished, Wurtz et al.'13]
- Duality generates 'physical' Higgs and W/Z states
- Other channels: Suppressed, but mimic new physics
  - Depend strongly on details [Maas et al. Unpublished, Wurtz et al.'13]
- Always true? SM: Likely. BSM/other parameters?
Generic physics

Spectrum development in the $0^+$ singlet channel

Arbitrary units, since no well-defined mass any more

[Maas et al. unpublished]
Generic physics

Spectrum development in the $0^+$ singlet channel

Threshold to two (far separated) particles

Arbitrary units, since no well-defined mass any more
“Large” couplings: Landau pole at electroweak scale

[Maas et al. unpublished]
**Generic physics**

- **“Large” couplings:** Landau pole at electroweak scale
- **But not non-perturbatively** [Langguth et al. PLB’85, Evertz et al. PLB’86]
  - 'Higgs' lighter than 'W': QCD-like behavior
    - Lattice artifact because of triviality?

---

**Spectrum development in the 0+ singlet channel**

- **Lowest state energy/1. trivial state energy**

---

[Maas et al. unpublished]
“Large” couplings: Landau pole at electroweak scale

But not non-perturbatively [Langguth et al. PLB’85, Evertz et al. PLB’86]

• 'Higgs' lighter than 'W': QCD-like behavior
  • Lattice artifact because of triviality?
Generic physics

- "Large" couplings: Landau pole at electroweak scale
- But not non-perturbatively [Langguth et al. PLB'85, Evertz et al. PLB'86]
  - 'Higgs' lighter than 'W': QCD-like behavior
    - Lattice artifact because of triviality?
Generic physics

• "Large" couplings: Landau pole at electroweak scale

• But not non-perturbatively [Langguth et al. PLB’85, Evertz et al. PLB’86]
  • 'Higgs' lighter than 'W': QCD-like behavior
    • Lattice artifact because of triviality?

PRELIMINARY
“Large” couplings: Landau pole at electroweak scale

But not non-perturbatively [Langguth et al. PLB’85, Evertz et al. PLB’86]

- 'Higgs' lighter than 'W': QCD-like behavior
  - Lattice artifact because of triviality?
- Above threshold: Almost 'heavy 'photons'
Implications for Higgsed theories

- Higgsed theories appear a lot in BSM
  - GUTs, 2HDM, (some) SUSY models, ...
- Structure observed here is not generic
  - Mass relation of elementary states and observable states only possible for light but not too light Higgs
  - Global symmetries determines observable state spectrum
    - SM Higgs sector is special because custodial and gauge group are the same
- Each case may be different
Higgs sector with light Higgs successfully described by perturbation theory around classical physics

- Possible by 'accident'
- Higgs not too light
  - Higgs effect operational
- Higgs not too heavy
  - Distinguishable Higgs state remains
- Gauge and custodial symmetry group identical
- Subject to lattice artifacts
- Non-perturbative statement
- Still many open field theoretical questions – full SM?
- Implications for observables in BSM scenarios?