Higgs Theory I

Scale and Symmetry in Particle Theory

Wolfgang Kilian

University of Siegen

Symmetries and Phase Transitions
Dresden, September 2016

Outline

Part I: Scale and Symmetry in Particle Theory

Part II: The Higgs Mechanism in Weak Interactions

Part III: Symmetries Beyond the Higgs?

Why Particle Physics is Simple

Condensed Matter, Early Universe, Quark-Gluon Plasma, ...

- finite density and temperature
- various degrees of space/time symmetry
- complicated states and processes
- model Hamiltonians, symmetries, effective quantum field theory

Why Particle Physics is Simple

Condensed Matter, Early Universe, Quark-Gluon Plasma, ...

- finite density and temperature
- various degrees of space/time symmetry
- complicated states and processes
- model Hamiltonians, symmetries, effective quantum field theory

Particle Physics

- model Lagrangian, symmetries, effective quantum field theory

Why Particle Physics is Simple

Condensed Matter, Early Universe, Quark-Gluon Plasma, ...

- finite density and temperature
- various degrees of space/time symmetry
- complicated states and processes
- model Hamiltonians, symmetries, effective quantum field theory

Particle Physics

- model Lagrangian, symmetries, effective quantum field theory
- simple states, undefined/zero density and temperature

Why Particle Physics is Simple

Condensed Matter, Early Universe, Quark-Gluon Plasma, ...

- finite density and temperature
- various degrees of space/time symmetry
- complicated states and processes
- model Hamiltonians, symmetries, effective quantum field theory

Particle Physics

- model Lagrangian, symmetries, effective quantum field theory
- simple states, undefined/zero density and temperature
- exact Poincaré symmetry

Why Particle Physics is Simple

Condensed Matter, Early Universe, Quark-Gluon Plasma, . . .

- finite density and temperature
- various degrees of space/time symmetry
- complicated states and processes
- model Hamiltonians, symmetries, effective quantum field theory

Particle Physics

- model Lagrangian, symmetries, effective quantum field theory
- simple states, undefined/zero density and temperature
- exact Poincaré symmetry

Why Particle Physics is Simple

Condensed Matter, Early Universe, Quark-Gluon Plasma, ...

- finite density and temperature
- various degrees of space/time symmetry
- complicated states and processes
- model Hamiltonians, symmetries, effective quantum field theory

Particle Physics

- model Lagrangian, symmetries, effective quantum field theory
- simple states, undefined/zero density and temperature
- exact Poincaré symmetry
- fundamental interactions and degrees of freedom unknown

S Matrix

In phenomenological particle physics, there is only one observable:

$$S_{io} = \langle \text{out} | \text{in} \rangle$$

The connection between theory and experiment is

$$p(\text{in} \to \text{out}) \propto |S_{io}|^2$$

S Matrix and Quantum Field Theory

A relativistic quantum field theory ( ) is a quantum theory where the basic degrees of freedom are operators ( ) which map the invariant ground state ( ) to irreducible representation states of the Poincaré group ( ), and where all states can be constructed by repeated application of those operators.

S Matrix and Quantum Field Theory

A relativistic quantum field theory (QFT) is a quantum theory where the basic degrees of freedom are operators (fields) which map the invariant ground state (vacuum) to irreducible representation states of the Poincaré group (particles with mass and spin), and where all states can be constructed by repeated application of those operators.

S Matrix and Quantum Field Theory

A relativistic quantum field theory (QFT) is a quantum theory where the basic degrees of freedom are operators (fields) which map the invariant ground state (vacuum) to irreducible representation states of the Poincaré group (particles with mass and spin), and where all states can be constructed by repeated application of those operators.

The *existence* of nontrivial, realistic QFTs is a conjecture, which is however extremely useful for phenomenological particle physics.

S Matrix and Quantum Field Theory

A relativistic quantum field theory (QFT) is a quantum theory where the basic degrees of freedom are operators (fields) which map the invariant ground state (vacuum) to irreducible representation states of the Poincaré group (particles with mass and spin), and where all states can be constructed by repeated application of those operators.

The *existence* of nontrivial, realistic QFTs is a conjecture, which is however extremely useful for phenomenological particle physics.

S-matrix elements are defined and computed as ratios of pole residues of Green functions (= field operator expectation values).

A relativistic QFT contains infinitely more information than the associated S matrix, but this information is unphysical and arbitrary.

S Matrix and Quantum Field Theory

A relativistic quantum field theory (QFT) is a quantum theory where the basic degrees of freedom are operators (fields) which map the invariant ground state (vacuum) to irreducible representation states of the Poincaré group (particles with mass and spin), and where all states can be constructed by repeated application of those operators.

The *existence* of nontrivial, realistic QFTs is a conjecture, which is however extremely useful for phenomenological particle physics.

S-matrix elements are defined and computed as ratios of pole residues of Green functions (= field operator expectation values).

A relativistic QFT contains infinitely more information than the associated S matrix, but this information is unphysical and arbitrary.

S Matrix and Quantum Field Theory

There may be an infinite set of different QFTs, or other theories, which generate the same observed S-matrix.

S Matrix and Quantum Field Theory

There may be an infinite set of different QFTs, or other theories, which generate the same observed S-matrix.

All such theories must be considered as equivalent.

S Matrix and Quantum Field Theory

There may be an infinite set of different QFTs, or other theories, which generate the same observed S-matrix.

All such theories must be considered as equivalent.

Particle Physics is searching for particularly simple representatives.

Scaling in Particle Physics

Nontrivial symmetry transformation:

scaling in particle physics

- No temperature or density variables
- Exact Lorentz invariance $\Rightarrow$ set $c = 1$
- Quantum theory $\Rightarrow$ set $\hbar = 1$

$$\text{mass} = \text{momentum} = \text{energy} = \frac{1}{\text{length}} = \frac{1}{\text{time}}$$

Scales in Particle Physics

Today's standard unit: GeV

1 GeV	proton mass	nuclear physics (1960s)
10 GeV	jets	subnuclear physics (1970s)
100 GeV	W, Z, t	electroweak physics (1980/90s)
$1,000$ GeV	LHC	Higgs physics (2010s)
$10,000$ GeV	unexplored	???
$\vdots$		
$10^{\sim 12}$ GeV		neutrino physics?
$\vdots$		
10^{19} GeV		gravitation

Scaling in QFT

Simple quantum field theories are those which realize simple scaling properties of the S matrix

$$E_i, \mathbf{p}_i \to \lambda E_i, \lambda \mathbf{p}_i$$

$\Rightarrow$ unique whenever particle masses become negligible.

In the QFT, scaling is represented but not uniquely defined.

Good Theories

Particle Physics understanding of a good QFT:

- finite (small) set of degrees of freedom = fields
- finite (small) set of free parameters = masses, coupling strengths
- local
- predictive
- form-invariant under scale transformations
- renormalizable
- can be defined by a polynomial Lagrangian
- weakly interacting over most of the scaling range
- unitary calculated S-matrix in perturbative expansion

Good Theories

Particle Physics understanding of a good QFT:

- finite (small) set of degrees of freedom = fields
- finite (small) set of free parameters = masses, coupling strengths
- local
- predictive
- form-invariant under scale transformations
- renormalizable
- can be defined by a polynomial Lagrangian
- weakly interacting over most of the scaling range
- unitary calculated S-matrix in perturbative expansion

These conditions are all equivalent to each other

Effective and Fundamental Theories

- Classification of interactions in Lagrangian field theory:
  1. relevant: $D < 4$ (masses) $=$ break scaling for low energy (IR) ($=$ correlation lengths)
  2. marginal: $D = 4$
  3. irrelevant: $D < 4$ $=$ break scaling for high energy (UV cutoff)

Effective and Fundamental Theories

- Classification of interactions in Lagrangian field theory:
  1. relevant: $D < 4$ (masses) = break scaling for low energy (IR) (= correlation lengths)
  2. marginal: $D = 4$
  3. irrelevant: $D < 4$ = break scaling for high energy (UV cutoff)

$\Rightarrow$ a Good QFT consists only of marginal interactions: critical

A Theory of (massless) Quarks and Gluons

Quarks have spin $\frac{1}{2}$.

A Theory of (massless) Quarks and Gluons

Quarks have spin $\frac{1}{2}$.

Gluons have spin 1.

A Theory of (massless) Quarks and Gluons

Quarks have spin $\frac{1}{2}$.

Gluons have spin 1.

There are qqg and ggg interactions.

A Theory of (massless) Quarks and Gluons

Quarks have spin $\frac{1}{2}$.

Gluons have spin 1.

There are qqg and ggg interactions.

The interactions are form-invariant under scaling transformations.

A Theory of (massless) Quarks and Gluons

Quarks have spin $\frac{1}{2}$.

Gluons have spin 1.

There are qqg and ggg interactions.

The interactions are form-invariant under scaling transformations.

A critical relativistic QFT containing such interacting spin-$\frac{1}{2}$ and spin-1 fields is severely constrained. It must be a non-abelian gauge theory.

QCD Gauge Theory

1. The spin-1 particles can be combined in the adjoint representation of some Lie algebra.

   The self-interactions are determined by the structure constants of that algebra f^{abc}.

2. The spin-$\frac{1}{2}$ particles can be combined in any representation(s) of the same Lie algebra

   The mutual interactions are determined by the generator (matrix) elements of that algebra T^a_{ij}.

A Lagrangian generating this will show classical gauge invariance (local continuous symmetry). The would-be external states should appear in symmetry multiplets.

For quarks and gluons: $SU(3)$

The S Matrix of QCD

A relativistic QFT that contains spin-1 states suffers from a fundamental problem:

$$||G^\mu||^2 = \langle G^\mu | G^\mu \rangle \propto g^{\mu\mu}$$

$\Rightarrow$ There are states with negative norm.

Kugo, Ojima

The S Matrix of QCD

A relativistic QFT that contains spin-1 states suffers from a fundamental problem:

$$||G^\mu||^2 = \langle G^\mu | G^\mu \rangle \propto g^{\mu\mu}$$

$\Rightarrow$ There are states with negative norm.

Resolution:

The S matrix elements for longitudinal and scalar polarization precisely match the S matrix elements for scalar ghost fields, that we have to add to the quantized theory.

Kugo, Ojima

The S Matrix of QCD

A relativistic QFT that contains spin-1 states suffers from a fundamental problem:

$$||G^\mu||^2 = \langle G^\mu | G^\mu \rangle \propto g^{\mu\mu}$$

$\Rightarrow$ There are states with negative norm.

Resolution:

The S matrix elements for longitudinal and scalar polarization precisely match the S matrix elements for scalar ghost fields, that we have to add to the quantized theory.

We need a unitary projection where we evaluate the S matrix only for transversal polarizations. The matching property guarantees that probability is conserved for this subset of external states.

KUGO, OJIMA

The S Matrix of QCD

A relativistic QFT that contains spin-1 states suffers from a fundamental problem:

$$||G^\mu||^2 = \langle G^\mu | G^\mu \rangle \propto g^{\mu\mu}$$

$\Rightarrow$ There are states with negative norm.

Resolution:

The S matrix elements for longitudinal and scalar polarization precisely match the S matrix elements for scalar ghost fields, that we have to add to the quantized theory.

We need a unitary projection where we evaluate the S matrix only for transversal polarizations. The matching property guarantees that probability is conserved for this subset of external states.

Proof: gauge symmetry $\rightarrow$ BRST symmetry
Only BRST singlets are retained in the S matrix.

Kugo, Ojima

The QCD Singularity

For any initial value, the dimensionless (marginal) QCD interaction strength develops a singularity in the infrared.

This phenomenon is known as dimensional transmutation.

There is a definite mass scale associated with the singularity where the interaction becomes strong, such that

- asymptotic quarks/gluons can't be isolated anymore
- only symmetry singlets (hadrons) become free particles
- their masses are related to the singularity, roughly all ~ 1 GeV.

This is the origin of most of the mass in the Universe.

Beyond QCD

QCD dimensional transmutation just doesn't explain the masses of

1. leptons (and neutrinos), especially the electron
2. pions, kaons, . . . (lightest meson states)
3. . . . and the observed transitions between quarks or leptons.

Weak Interactions

The transitions between quarks and leptons are mediated by new particles (resonances) with spin 1 and masses

$$W^+, W^- : \quad M = 80 \text{ GeV}, \qquad Z^0 : \quad M = 92 \text{ GeV}$$

The masses are similar but not equal: symmetry?

Weak Interactions

The transitions between quarks and leptons are mediated by new particles (resonances) with spin 1 and masses

$$W^+, W^- : \quad M = 80 \text{ GeV}, \qquad Z^0 : \quad M = 92 \text{ GeV}$$

The masses are similar but not equal: symmetry?

Antique but natural explanation: W, Z are strongly interacting composite "mesons" of some new unknown interaction ...

but:

Symmetry of the Weak Interactions

Direct Observation (LEP, Tevatron, 1980s–90s):

1. The (self)-interactions of the new resonances are determined by the tensor ϵ^{abc}, the structure constants of $SU(2)$.
2. The interactions of quarks and leptons with W, Z are determined by the Pauli matrices σ^a_{ij}, the generators of $SU(2)$.

   [. . . and the photon is also involved: $U(1)$]

$\Rightarrow$ Weak and electromagnetic interactions are (asymptotically) uniquely described by a

$$SU(2) \times U(1) \text{ gauge theory,}$$

except for the fact that there are quark, lepton and W/Z masses.

Is the Symmetry Real?

In the asymptotic regime, the symmetry properties of the interactions are not just a property of Green functions, they are evident in observables.

Examples:

- Jet emission and jet scaling in LHC data
- W-Z-photon universality in deep-inelastic scattering at HERA
- Four-fermion production (via W^+W^-) at LEP 2

Is the Symmetry Real?

In the asymptotic regime, the symmetry properties of the interactions are not just a property of Green functions, they are evident in observables.

Examples:

- Jet emission and jet scaling in LHC data
- W-Z-photon universality in deep-inelastic scattering at HERA
- Four-fermion production (via W^+W^-) at LEP 2

In asymptotia, the symmetries and scaling properties of the QFT are real.

Is the Symmetry Real?

In the asymptotic regime, the symmetry properties of the interactions are not just a property of Green functions, they are evident in observables.

Examples:

- Jet emission and jet scaling in LHC data
- W-Z-photon universality in deep-inelastic scattering at HERA
- Four-fermion production (via W^+W^-) at LEP 2

In asymptotia, the symmetries and scaling properties of the QFT are real.

In the IR, the S matrix does not show any symmetry.

Summary, Part I

- All known interactions of particle physics apparently reduce asymptotically to a critical effective QFT with symmetry

$$SU(3) \times SU(2) \times U(1)$$

- Such a symmetry is mandatory if there is scaling behavior.
- There are relevant operators that disturb this picture: quark and lepton mass terms. There is also the QCD singularity, so the S matrix has no local symmetry except QED.
- We have no idea whether there is an UV cutoff or what are the symmetries of the fundamental interactions, if any. The symmetry in the QFT may be fundamental or emergent.