The discovery of the Higgs boson: a major achievement and a problem

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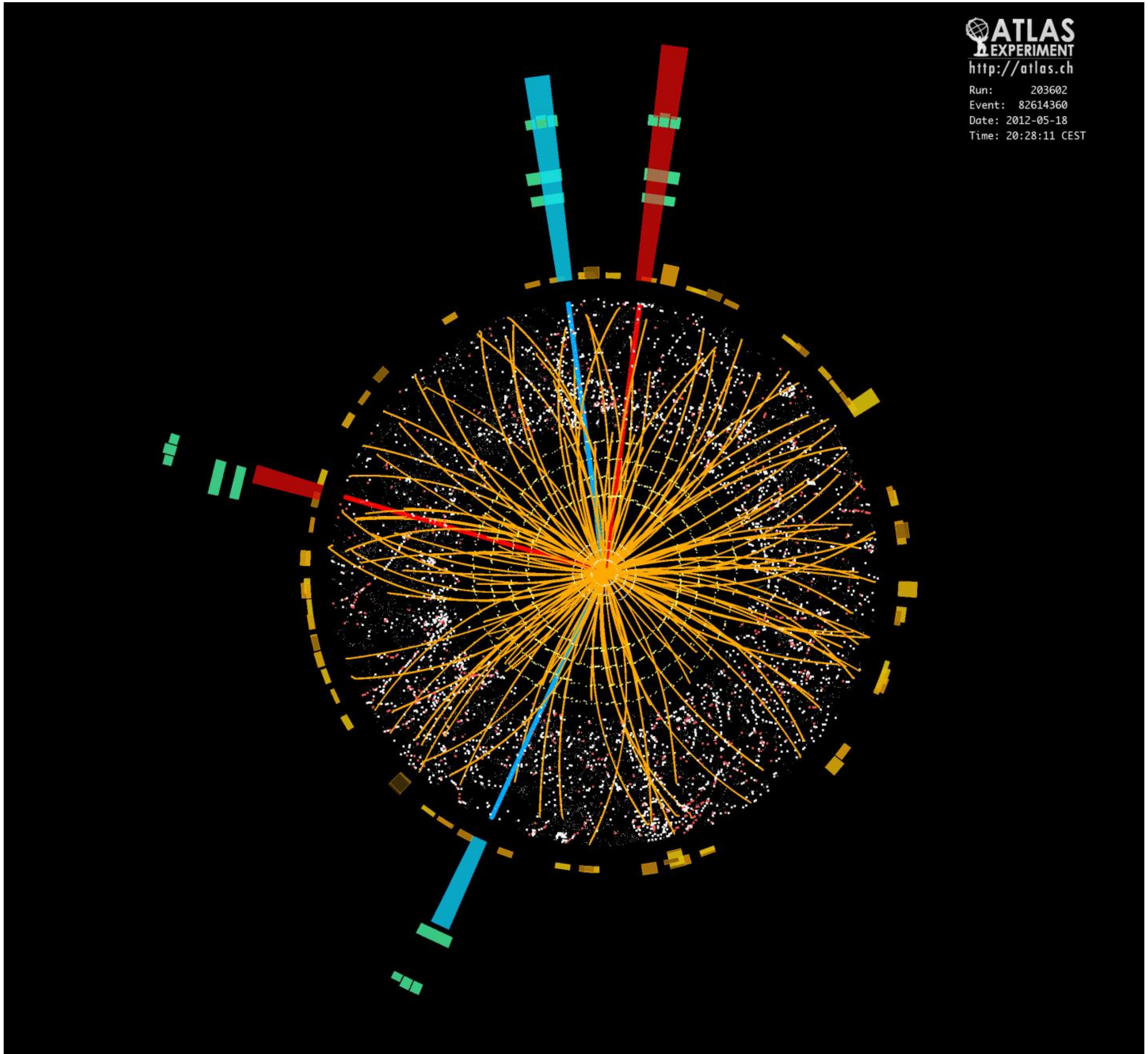
The Higgs boson discovery

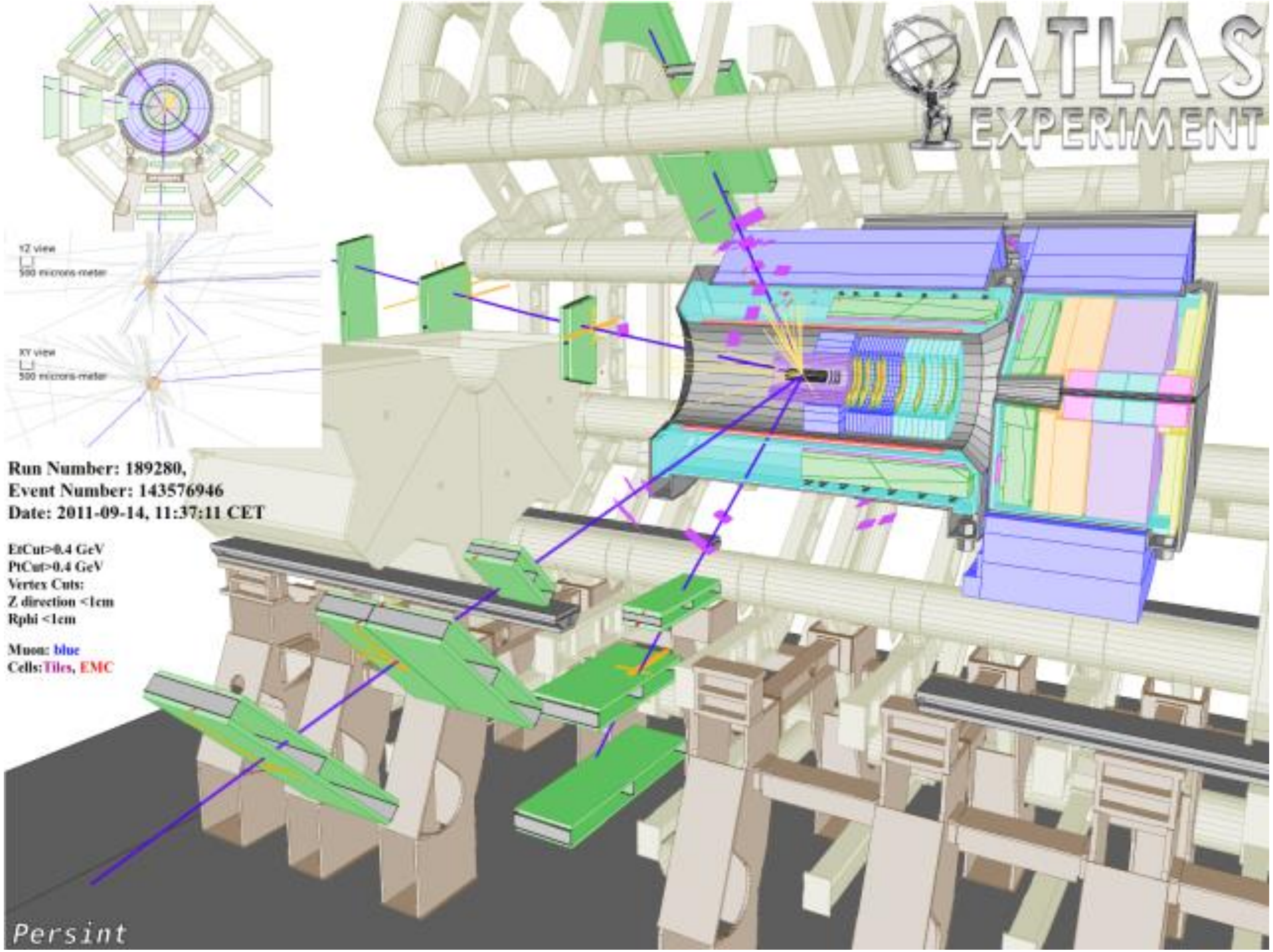
After about 40 years of experimental efforts that involved several colliders, most notably the LEP (Large Electron-Positron collider at CERN), the Tevatron (proton-antiproton collider at Fermilab) and, finally, the specifically designed LHC proton-proton collider, the discovery by the Atlas and CMS detectors of a new particle with a mass of about 125 GeV was announced in July 2012 at CERN. It had, and still has (2022), all the required properties to be the predicted Higgs scalar boson.

The prediction was based on a theoretical model, the Standard Model, whose construction itself also required four decades of theoretical effort.

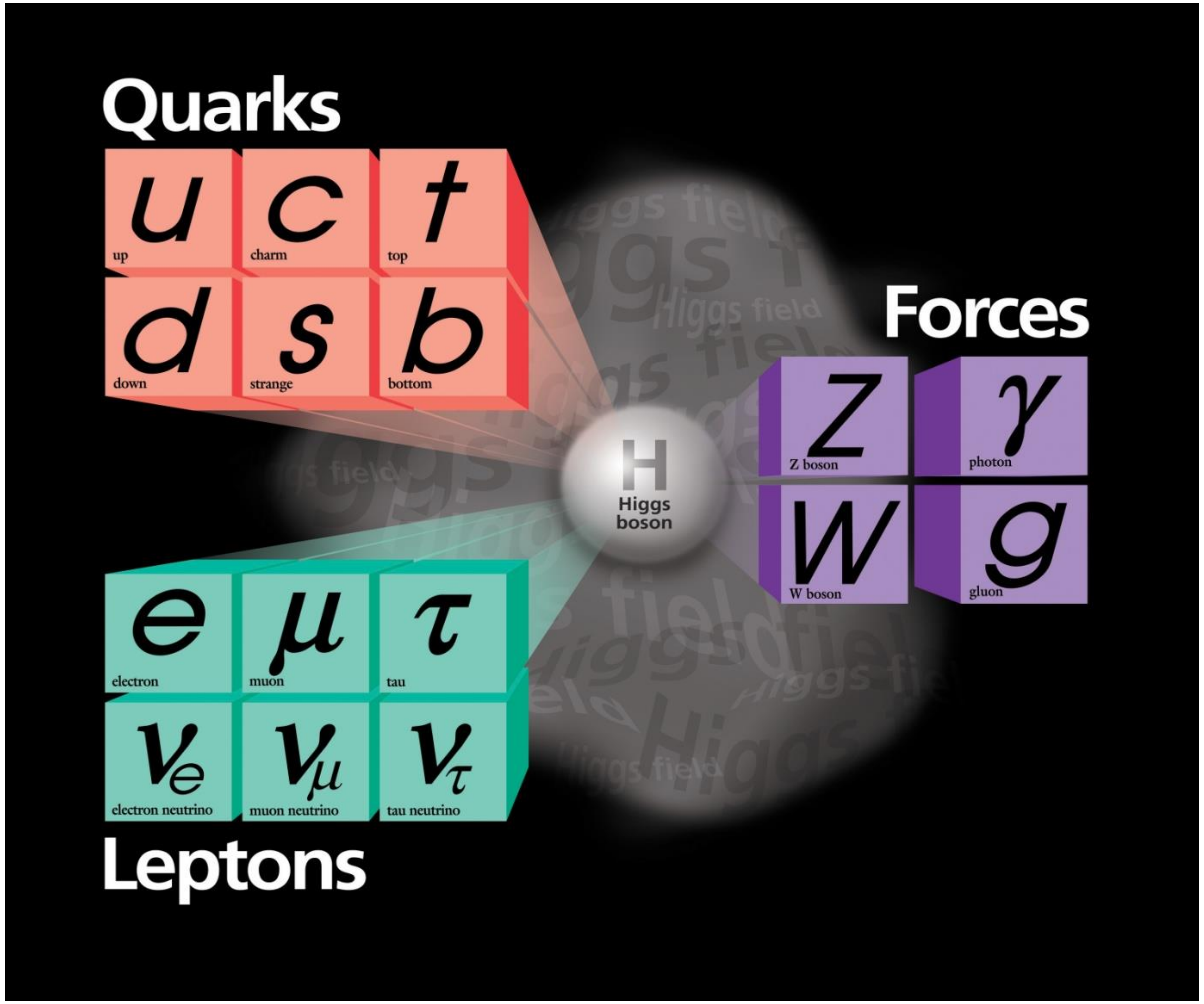
Higgs particle in the 4 e channel



Higgs particle in the 4 muon channel (Atlas)



The fundamental particles after 2012



The Higgs boson, the unique fundamental scalar particle

The theoretical framework: a Quantum Field Theory

Following the birth of Quantum Mechanics (1925-1926) and Dirac's equation (1928), construction of a first local relativistic quantum theory, Quantum Electrodynamics (QED) (1928-1949)

QED is a quantum field theory (QFT): *A* unified quantum relativistic description of the interactions between charged particles (QED), requires including a quantized version of Maxwell's theory, a classical field theory that describes the evolution of the electric and magnetic fields.

A non-relativistic theory of individual point-like particles is very different from a field theory: Fields , unlike particles, propagate an infinite number of degrees of freedom: the value of the field at each point in space.

Therefore, QFT's have some unusual new properties.

QED, the original sin: the problem of infinities

Formal construction of a QFT (Heisenberg-Pauli 1930). Then, 4 years for a first correct calculation of a quantum correction (Weisskopf 1934) because

(i) QED is an Abelian gauge theory: since one dynamical field is the vector potential, this necessitates gauge fixing, a non-trivial issue.

(ii) A non-relativistic perturbation theory was used.

(iii) At first, the role of the negative energy states in Dirac equation was unclear (later interpreted as positrons, discovered by Anderson (1932)).

Finally, a clear outcome: The result was divergent (short distance (UV) singularities or, equivalently, large momentum divergences).

All proposed solutions to the problem involved sacrificing locality (point-like particles and contact interactions) difficult for a relativistic theory or some basic law of physics like unitary (conservation of probabilities).

QED: the miracle of renormalization

1947 Shelter Island conference: Measurements of the Lambshift (Lamb and Retherford) and of the anomalous moment of the electron (Rabi group) reported.

Approximate calculation by Bethe, based on subtracting infinities, gives a result close to the Lambshift experimental value.

In two years, Feynman, Schwinger, Tomanaga, Dyson develop the rules of relativistic perturbation theory and renormalization theory:

(1) Artificial and non-physical modification (regularization) of the theory at short distance or at a large energy-momentum scale Λ (called cut-off).

(2) Perturbative calculation of physical quantities.

(3) Renormalization of fields and elimination of the parameters of the initial Lagrangian in favour of direct relations between physical observables.

QED: a renormalizable QFT

Remarkably enough, in QED, in the relations between physical observables the infinities of perturbation theory cancel, the infinite Λ limit is finite and universal or short distance insensitive (i.e., independent of the specific modification at scale Λ).

A QFT sharing this property is called renormalizable.

Only a limited class of QFTs are renormalizable: this focused the search for new QFTs to describe also weak and strong interactions.

Two remarks:

(1) The cancellation of infinities is perturbative: it occurs within the expansion in powers of the fine structure constant α.

(2) Renormalization requires tuning all parameters of the Lagrangian as functions of the cut-off Λ, which is extremely strange.

After QED, construction of a renormalizable QFT unifying, to some extent, weak and electromagnetic interactions (1950-1974)

Towards a combined model for weak and electromagnetic interactions

Quantum Electrodynamics (QED) is characterized by an Abelian gauge symmetry: Invariance under local (in space-time) phase transformations.

Gauge symmetry seems to imply the existence of massless vector particles (the photon in QED) associated with the gauge field.

Weak interactions (generating the weak nuclear force) can be described, at low energy, by charged current-current contact (i.e., local) non-renormalizable interactions.

Such interactions could be explained by the exchange of two very massive vector fields.

A gauge theory with at least two additional vector fields implies a generalization of QED to non-Abelian gauge symmetries.

However, a major problem: find a gauge symmetric mechanism to give masses to gauge bosons.

Spontaneous symmetry breaking (SSB)

The mechanism to give masses to gauge fields is based on SSB, an idea coming from statistical physics and the theory of phase transitions. A general framework was provided by Landau (1937).

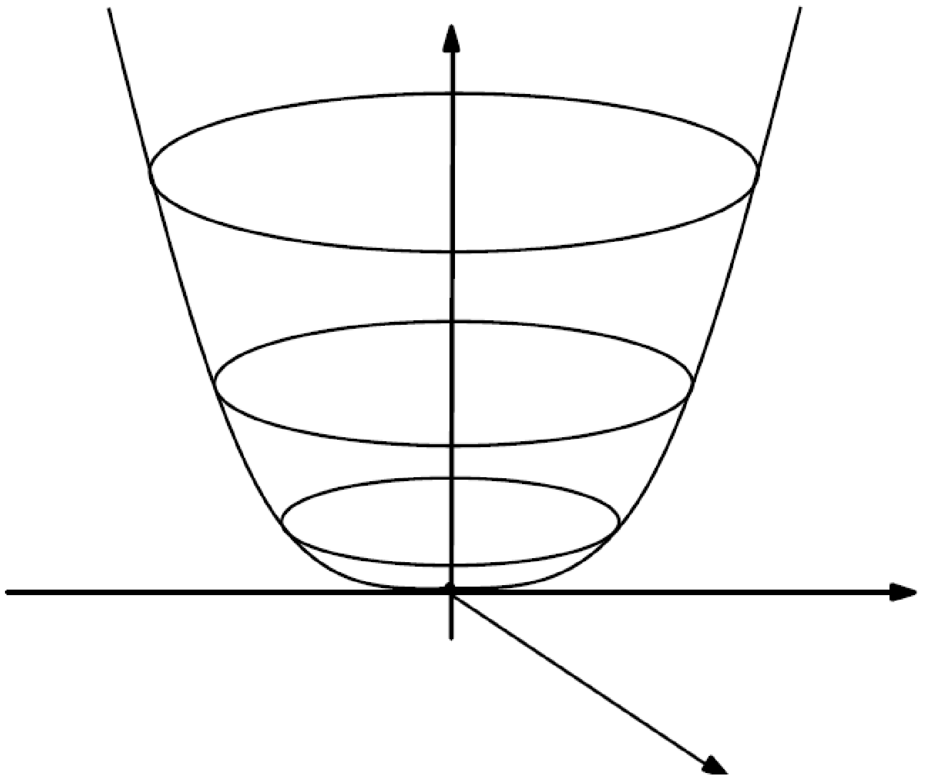
In the case of continuous symmetries, in non-gauge theories, SSB implies the presence of massless scalar particles (Nambu-Goldstone bosons).

In the context of low energy hadron physics, the notion of SSB was initially introduced in the form of an approximate SU(2)XSU(2) chiral symmetry (1960-1962):

pions, due to their relative small mass, can be considered as almost massless Goldstone bosons

Phase transition and SSB: disordered phase

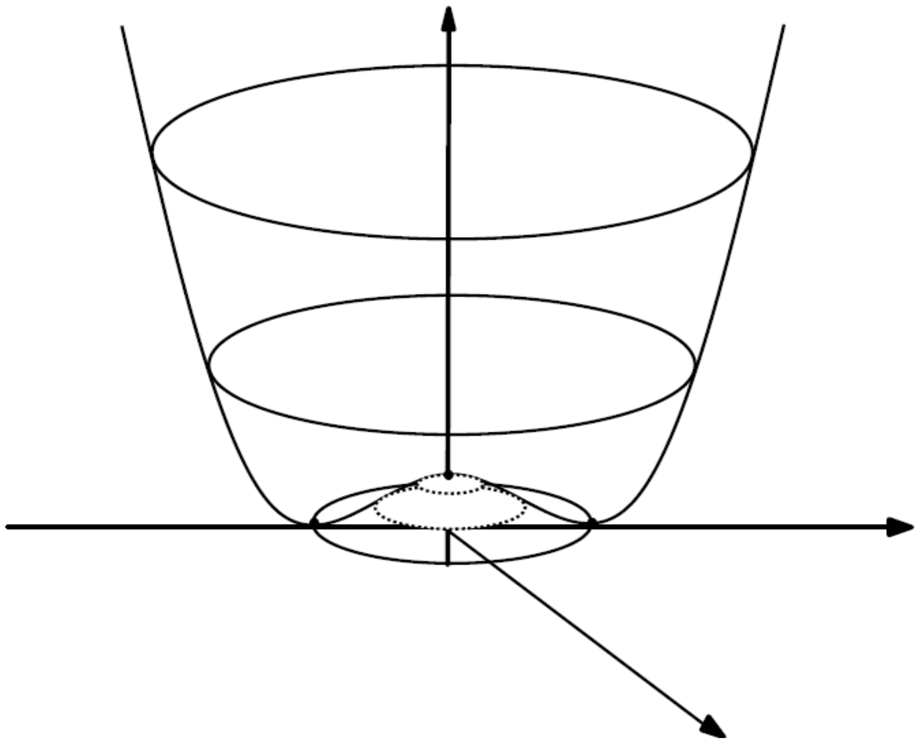
Energy surface:
symmetric minimum,
the example of O(2)
symmetry



Invariance under rotations around the vertical axis implies that, the minimum of the energy surface, when it is unique, is located here at the origin because it is an invariant point.

Phase transition and SSB: ordered phase

Energy surface: degenerate minima, the example of O(2) symmetry



Invariance under rotations around the vertical axis implies that the energy surface has a circle of minima. Goldstone modes correspond to the flat direction in the circle of minima.

Renormalization with SSB

The straightforward perturbative expansion contains infinities that have to be removed by renormalization.

The renormalization constants in the symmetric phase and the broken phase are the same: the proof of the property is not so simple because in the spontaneously broken phase the perturbative expansion is no longer explicitly symmetric.

The proof involves proving generalized Ward-Takahashi identities and was reported, for non-gauge theories, in

B.W. Lee, Renormalization of the sigma-model, Nuclear Physics B9 (1969) 649-672;

K. Symanzik, Renormalizable Models with Simple Symmetry Breaking, Commun. Math. Phys. 16 (1970) 48-80.

Non-Abelian gauge theories

The classical non-Abelian, extension of Maxwell's electrodynamics, was formulated in

C.N. Yang and R.L. Mills, *Conservation of Isotopic Spin and Isotopic Gauge Invariance*, Phys. Rev. 96 (1954) 191-195.

Gauge symmetry is implemented by demanding invariance under non-Abelian (non-commutative), space-time dependent group transformations.

Massless vector bosons, associated to all group generators, are predicted.

But the quantization of such a theory is not a simple extension of the quantization of QED, as pointed out by

R.P. Feynman, *Quantum theory of gravitation*, Acta Phys. Polon. 24 (1963) 697.

Gauge symmetry and SSB: the Higgs mechanism

A combination of SSB and gauge symmetry makes it possible, for a suitable choice of a scalar field representation, to give masses to gauge fields and eliminate the unwanted massless Goldstone bosons.

This is now called the **Higgs mechanism**.

A model for the combined weak and electromagnetic interactions can then be constructed: the gauge group is G=SU(2)XU(1), spontaneously broken down to H=U(1) by the non-vanishing expectation value of a 4-component scalar field.

Three massless Goldstone bosons are generally expected. Here, they decouple while three corresponding gauge fields (W+-, Z) become massive as can be shown by a gauge transformation. A massive scalar survives, the Higgs boson, and a massless photon.

The classical Higgs mechanism

The possibility of a classical `Higgs mechanism' is stressed in

P.W. Higgs, Broken symmetries, massless particles and gauge fields, Phys. Lett. 12 (1964) 132-133; Broken symmetries and the masses of gauge bosons, Phys. Rev. Lett. 13 (1964) 508-509

F. Englert and R. Brout, Broken symmetry and the mass of vector bosons, Phys. Rev. Lett. 13 (1964) 321-323,

G.S. Guralnik, C.R. Hagen and T.W.B. Kibble, Conservation laws and massless particles, Phys. Rev. Lett. 13 (1964) 585-587.

The general framework is linearized classical field equations for coupled gauge and scalar fields.

Classical Abelian (Ginzburg-Landau)-Higgs mechanism and superconductivity

To describe a superconductor in a magnetic field,

Ginzburg, V. L. and Landau, L. D., *On the Theory of Superconductivity*, J.E.T.P. 20, 1064 (1950),

had already introduced the classical Abelian Higgs mechanism. They showed that SSB can give a mass to an Abelian gauge field (here the vector potential associated to the magnetic field) without generating a massless scalar.

In P.W. Anderson, *Plasmons, Gauge Invariance and Mass*, Phys. Rev. 130 (1963) 439-442,

the example of superconductivity is again stressed but the classical proof is incomplete..

The relativistic Higgs mechanism

P.W. Higgs, *Spontaneous Symmetry Breakdown without Massless Bosons*, Phys. Rev. 145 (1966) 1156-1163.

It is shown, in the classical approximation, that after SSB in an Abelian QED-like theory with a charged scalar field, a gauge transformation can transform the initial Lagrangian into a Lagrangian with only physical degrees of freedom, i.e., a massive `Higgs' field and a massive vector field.

This more physical representation is often called `unitary gauge' but leads to non-renormalizable field theories.

In the article, it is also shown that the results still hold for the leading quantum corrections, in a specific gauge.

The argument is generalized to a non-Abelian classical gauge theory in

T.W.B. Kibble, *Symmetry Breaking in Non-Abelian Gauge Theories*, Phys. Rev. 155 (1967) 1554-1561.

Non-Abelian gauge theories: quantization

The solution of the very difficult quantization problem was finally reported in 1967 in

L.D. Faddeev and V.N. Popov, *Feynman diagrams for the Yang-Mills field*, Phys. Lett. 25B (1967) 29-30; Perturbation theory for gauge-invariant fields, Kiev report No. ITP 67-36.

See also

B. DeWitt, *Quantum theory of gravity II, III*, Phys. Rev. 162 (1967) 1195-1239; ibidem, 1239-1256.

The construction relies on field integral and functional techniques.

Towards renormalization and unitarity

Two articles immediately triggered a large theoretical activity

G. 't Hooft, *Renormalization of massless Yang-Mills fields*, Nucl. Phys. B35 (1971) 173-199.

G. 't Hooft, *Renormalizable Lagrangians for massive Yang-Mills*, Nucl. Phys. B35 (1971) 167-188,

where it is argued that some models based on non-Abelian gauge theories, both in the symmetric phase and in the case of spontaneous symmetry breaking, could be renormalizable.

Abelian Higgs model: Full quantum theory and renormalization

Motivated by 't Hooft's work, Lee proves rigorously to all orders in perturbation theory that the Abelian Higgs model is renormalizable, that it contains no massless scalar boson but instead a massive scalar field and a massive vector field and satisfies unitarity :

B.W. Lee, *Renormalizable Massive Vector-Meson Theory-Perturbation Theory of the Higgs Phenomenon*, Phys. Rev. D5 (1972) 823-835.

This article also seems to be at the origin of the denominations "Higgs mechanism" and "Higgs boson".

Toward a combined model for weak and electromagnetic interactions

The Higgs mechanism contains two ingredients: masses given to vector (gauge) fields and absence (or decoupling) of massless scalar (Nambu-Goldstone) bosons.

In gauge theories, due to the necessity of gauge fixing, an additional step is required, the **proof of unitarity** (and thus **conservation of probabilities**).

The non-Abelian case is especially involved because quantization generates additional non-physical spinless fermions (`Faddeev–Popov ghosts').

One has to prove that, even after renormalization, the contributions of both Goldstone bosons and spinless fermions cancel in physical observables.

Only when this program is completed, can perturbative calculations safely be performed.

Non-Abelian gauge theories: Renormalization and Unitarity

The first complete proofs of renormalizability rely on a set of generalized Ward-Takahashi identities derived in

A.A. Slavnov, *Ward identities in gauge theories*, Theor. Math. Phys. 10 (1972) 99-107; J.C. Taylor, *Ward identities*, Nucl. Phys. B33 (1971) 436-444.

They are used to prove renormalizability and unitarity of non-Abelian gauge theories in the broken phase in

B.W. Lee and J. Zinn-Justin, *Spontaneously broken gauge symmetries, I,II, III*, Phys. Rev. D5 (1972) 3121-3137, 3137-3155, 3155-3160; *ibidem*, *Spontaneously broken gauge symmetries, IV General gauge formulation*, Phys. Rev. D7 (1973) 1049-1056.

Non-Abelian gauge theories: Renormalization and Unitarity

The complexity of these initial proofs is a consequence of gauge fixing and spontaneous symmetry breaking, which completely destroy the beautiful geometric simplicity of the initial Lagrangian, leading to the appearance of a non-local contribution (from the Faddeev-Popov determinant) and non-physical particles, the would-be Goldstone bosons .

Also relevant are articles by Fradkin and Tyutin, 't Hooft and Veltman, Fujukawa, Lee and Sanda, Ross and Taylor…

BRST symmetry

After introduction of non-physical spinless fermions `(Faddeev-Popov ghosts') to represent the Faddeev-Popov determinant, the quantized gauge action becomes local and has an unexpected fermion-like symmetry now called BRST symmetry:

C. Becchi, A. Rouet and R. Stora, *The Abelian Higgs-Kibble Model. Unitarity of the S Operator*, Phys. Lett 52B (1974) 344; ibidem, *Renormalization of the Abelian Higgs-Kibble Model*, Comm. Math. Phys. 42 (1975) 127; ibidem, *Renormalization of gauge theories*, Ann. Phys. (NY) 98 (1976) 287-321.}

I. Tyutin, Preprint of Lebedev Physical Institute, 39 (1975).

General proof and ZJ equation

This symmetry has been used to give a completely general, much more transparent, proof of renormalizability, gauge independence and unitarity covering all semi-simple groups, renormalizable gauges..., based on a general master equation (called Zinn-Justin equation by Weinberg):

J. Zinn-Justin (1975), Renormalization of gauge theories, Bonn lectures 1974, Trends in Elementary Particle Physics, Lecture Notes in Physics 37 pages 1-39, H. Rollnik and K. Dietz eds., Springer Verlag, Berlin;

Functional and probabilistic methods in quantum field theory, Acta Universitatis Wratislaviensis 368 (1976) 435-453, Saclay preprint T 76/048.

The effective field theory (EFT) viewpoint: Emergence of renormalizable field theories **and RG**

The EFT viewpoint is inspired by the theory of critical Phenomena in statistical physics:

An initial finite, non-local theory exists at very high energy (or momentum) equivalent at lower energies to an infinite sum of local interactions with parameters generically of order 1.

Due to a perturbative RG flow, at even lower energies, non-renormalizable interactions decay like powers of the scale ratio and become negligible, renormalizable interactions vary logarithmically and survive, super-renormalizable interactions and mass terms increase like powers and eventually become problems.

The EFT viewpoint: triviality issue and fine tuning problem

Some consequences are:

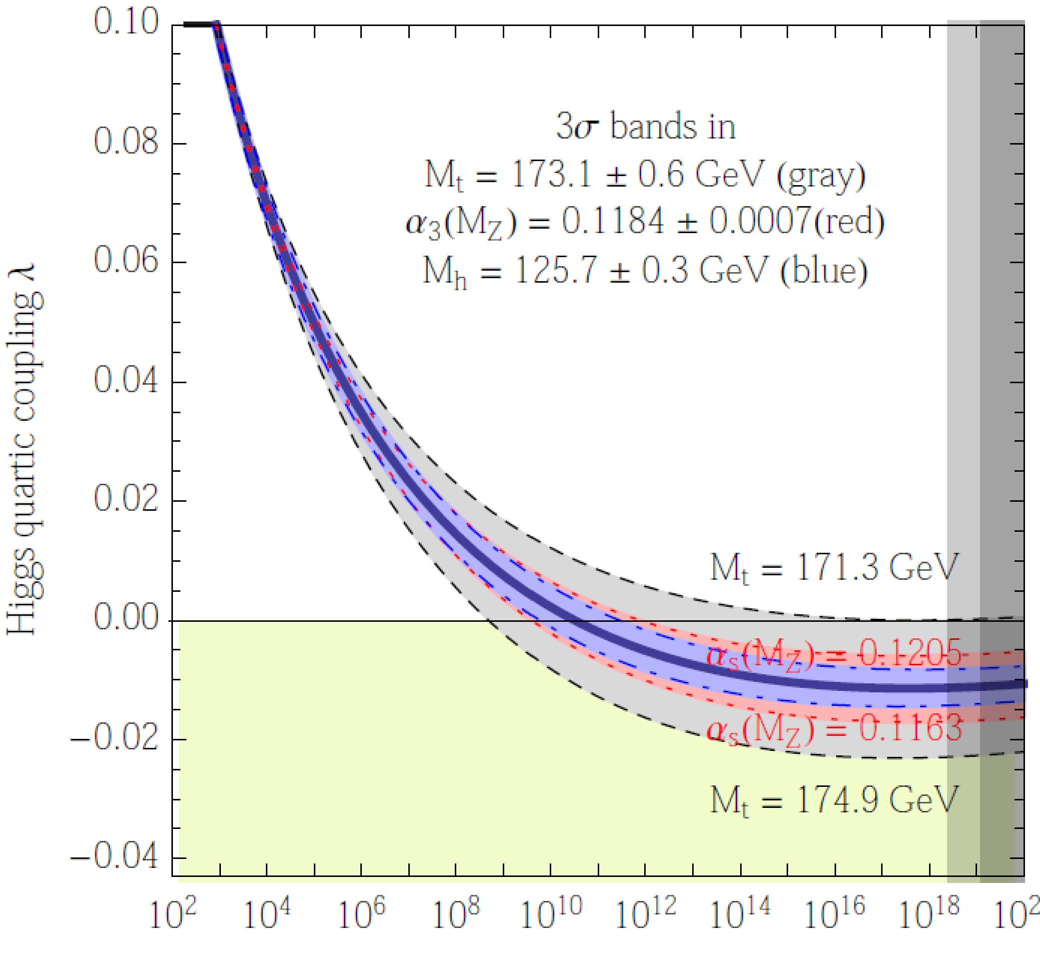
In IR free theories like QED, interactions vanish if one insists taking the infinite cut-off limit (the triviality issue). In the EFT viewpoint, this is no longer a problem because the cut-off is large but remains finite and QED is valid only much below this large cut-off scale.

The effective interaction become small logarithmically at low energy, which is consistent with the small value of α.

However, in the Standard Model of particle physics, the fine-tuning of the coefficient of the Higgs mass term becomes a real concern.

EFT, RG flow fixed line and consistency limit

Depending, on the physical value of the Higgs top mass ratio, if it is too far from the fixed line, one may either be in a situation where the initial (large momentum) value of the fermion-boson coupling is unnaturally small, or one finds a scale at which the model becomes inconsistent since the Higgs self-coupling vanishes. In both cases new physics is required. Calculations (e.g. Degrassi et al 2012) seem to indicate that the second scenario is more plausible. However, the Higgs mass is such that the energy scale is at least 10^{10} GeV !



The EFT viewpoint: Fine tuning problem

RG arguments, based on the desert hypothesis, suggest that the Higgs and top masses are such that the Standard Model could be consistent up to 10^{10} GeV. However, this leads to a fantastic fine-tuning problem:

$$f = 3(\Lambda/m_{Higgs}\, c^2)^2/8\pi^2 \cong 10^{15}$$

Since until now no new particles has been found at the LHC below about 1 TeV in many channels and 2 TeV in some, for a Higgs mass of 125 GeV/c^2, the amount of fine-tuning is probably still acceptable.

$$f = (\Lambda/m_{Higgs}\, c^2)^2 \cong O(100)$$

For a possible Future Circular hadron Collider with energy up to 100 TeV, without new physics, the fine-tuning factor would reach up to at least f=O(10^4), which would be much harder to accept.

Higgs boson mass, the fine-tuning problem and supersymmetry

Before LHC, a proposal for solving the fine-tuning problem was based on supersymmetry: the super-partners of known particles cancel (to a large extent because SUSY is broken) the contributions of known particles.

Unfortunately, no super-particles has been discovered yet up to masses between 500 Gev and more than 2 TeV, depending on channels.

For example, due to the strong coupling of Higgs and top, tops give a large contribution, which was supposed to be cancelled by their superparners, the stops (scalars). However, $m_{stop} > 500$ GeV (assuming the simplest SUSY models) while $m_{top} = 173$ GeV, which yields a factor 8 in contribution.