My Higgs story

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NIKHEF

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Higgs particle…. What does it mean ?

What does it do ? It is claimed to give mass to all other particles. What does that mean ?

Can we now predict the masses of all particles ?

**No, it predicts nothing except its own existence.
But it does not even predict its own mass.**

In this talk it will be attempted to explain why the Higgs particle is important to the theory of the Standard Model.

But other facts are very important as well. For example, there must be a build-in symmetry. Of course, in the end, the real reason for the importance of a theory is that one can calculate processes, and check if they agree with experiment.

The self-energy of the electron.

1904: theory of Abraham and Lorentz.

In that theory the electron is assumed to be a small sphere with radius *r*. The charge is smeared out over this sphere. The self-energy is the energy of this sphere assuming that it is zero if r is infinite:

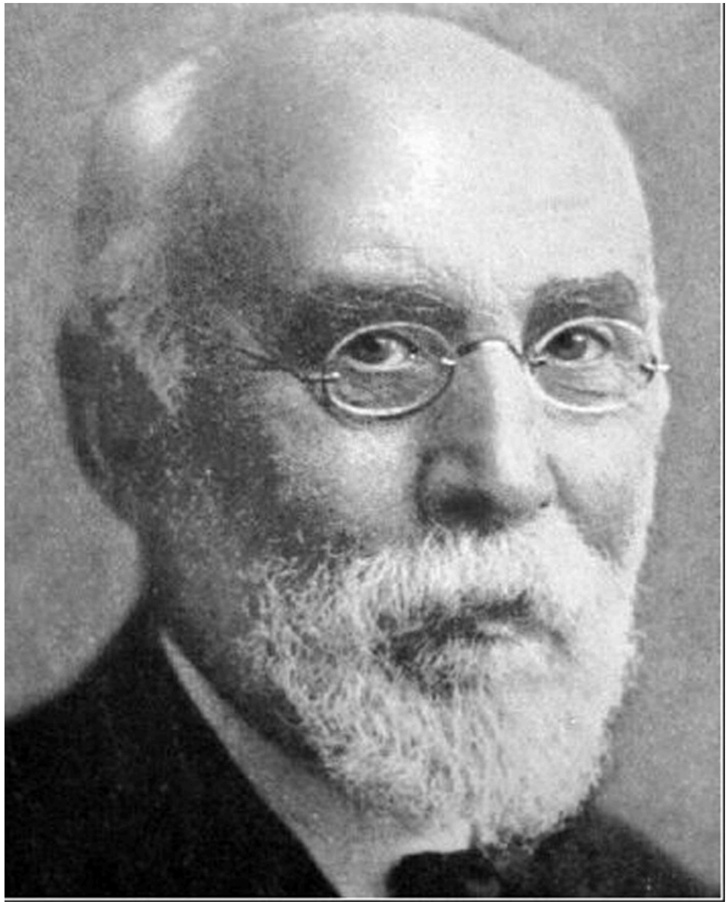
$$E \propto \frac{1}{r}$$

It is inversely proportional to the radius *r*.

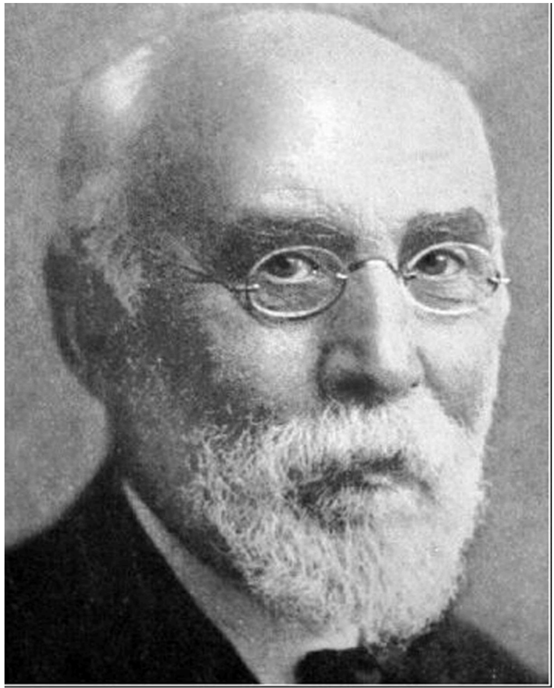
The smearing out of the charge is called a regulator mechanism. The radius *r* is the regulator parameter. If *r* goes to zero the energy *E* becomes infinite inversely proportional to this radius. One speaks of a linear divergence.

This description remained part of the theory for some 35 years.

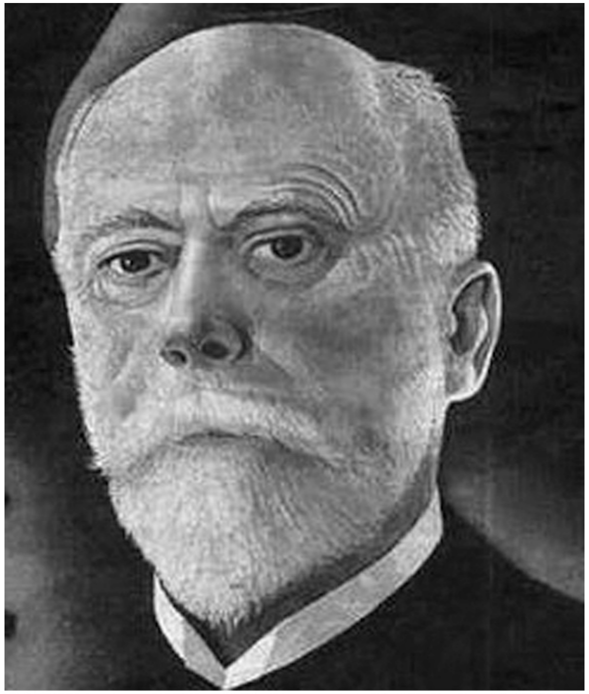
Max Abraham 1875-1922



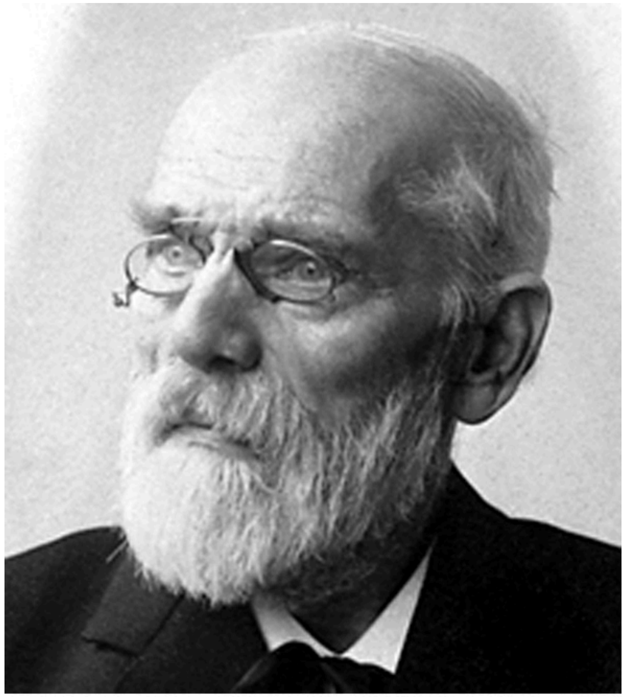
Hendrik Lorentz 1853-1928



Hendrik Lorentz 1853-1928



Willem Einthoven 1866-1927



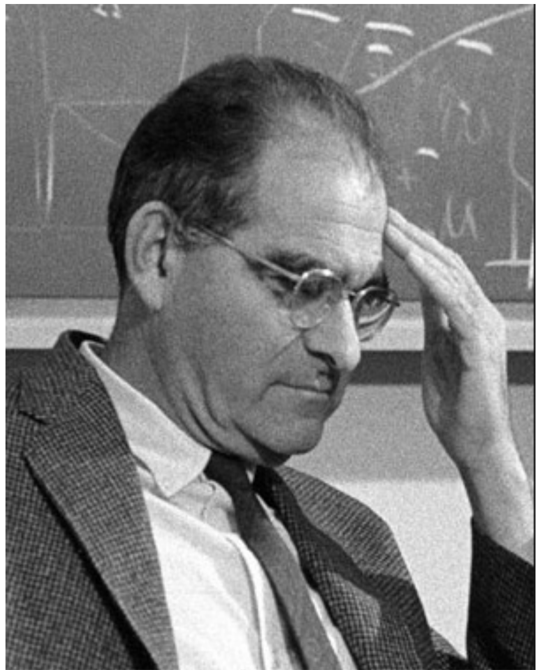
J van der Waals 1837-1923

Standard quantummechanics cannot describe processes involving the creation of new particles. To treat the latter type of processes one needs quantum field theory.

Quantum field theory was created in 1929 by Heisenberg and Pauli. The calculation of the electron self-energy was done by Weisskopf in 1939.

W. Heisenberg 1901-1976

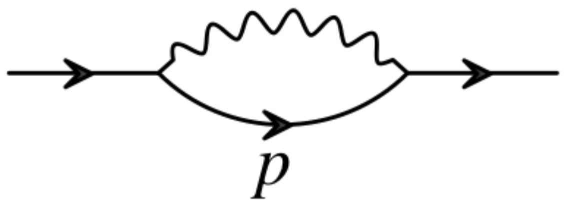
Wolfgang Pauli 1900-1958



Victor Weisskopf 1906-2002

The result was still infinite, except that now the degree of divergence was logarithmic. Here is how that goes in simplified form:

Self-energy Feynman diagram



Corresponding expression:

$$\int d_4 p \quad \frac{1}{p} \; \frac{1}{p^2}$$

That expression is linearly divergent. However that becomes logarithmic if we use symmetric integration:

$$\int_{-\Lambda}^{+\Lambda} dx = x|_{-\Lambda}^{+\Lambda} = 0$$

We see here the following. If you want to deal with infinite objects you have to invent a way to make them finite, that is to invent a regulator mechanism. And then, given a regulator parameter, take the limit to reality.

A new complication arises: the regulator mechanism may violate important properties. For example, in the above case Lorentz invariance is violated. A sphere will not remain a sphere when subjected to a Lorentz transformation. This may result in unwanted effects.

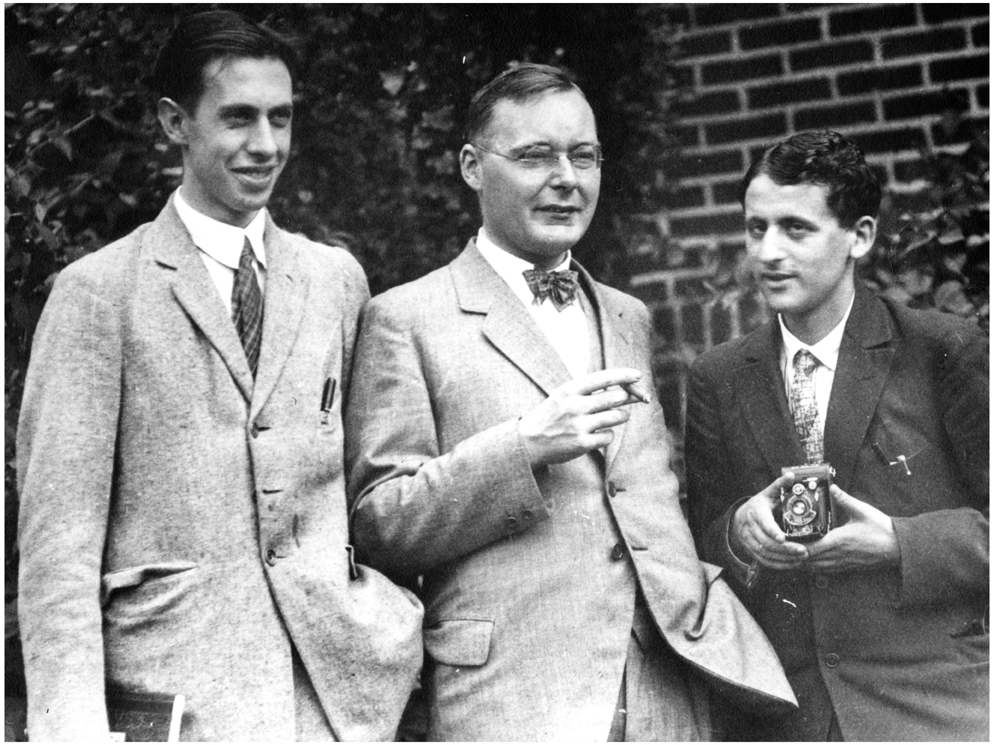
There is another important property, which is the conservation of electric charge. That is a consequence of gauge invariance of the theory. The regulator method should respect that property.

Pauli and Villars understood this. They developed a regulator method for quantum electrodynamics that respected gauge invariance and Lorentz invariance.

Then there was the great revolution of 1948.

There were two experiments that gave results that could not be explained by ordinary quantum mechanics: the Lamb shift and the anomalous magnetic moment of the electron. Everyone felt that quantum field theory was needed here, but there was really no way of doing that and every calculation got stuck in infinities.

Then Kramers (Leiden) came with his idea of renormalization.



G. Uhlenbeck, H. Kramers, S. Goudsmit

Consider the electron self-energy. There is, in addition to the 'bare mass', the energy due to the electric field of the electron itself (which is infinite). De sum of the two is the observed mass of the electron.

$$m_{exp} = m_{bare} + m_{self}$$

But, argued Kramers, no one knows the mass of un uncharged electron, so why not absorb the (infinite) self-energy in this (unknown) bare mass.

A theory where all infinities can be absorbed in the available free parameters is called a renormalizable theory. After absorbing the infinities observable quantities can be computed.

The idea of Kramers made all the difference. Calculations were done by Bethe, Feynman, Schwinger and Tomonaga, giving results that agreed with experiment. The resulting theory is the renormalizable theory of quantumelectrodynamics.

However, the most important result was that of Feynman. He developed a simple method to do the actual calculations.
For any given calculation make a few drawings (called Feynman diagrams), and subsequently using simple rules (the Feynman rules) one can write down the expressions to be calculated.

In other words: given the Feynman rules for a given theory you can compute every experimental prediction of that theory.

Dyson developed the formal theory, deriving these results within the canonical formalism, thus guaranteeing unitarity.

After receiving the Nobel prize in 1965 Feynman gave a lecture at CERN and he asked the rhetorical question: what did I really do ? I just constructed a bookkeeping scheme.

But in a complicated theory (such as field theory) simplification is very necessary and the key to further progress.

Feynman’s car.

1959. Scottish summer school.

Some participants: Cabibbo, Robinson, Glashow, Veltman.
Higgs had the key of the wine cellar. He described de group above as the gang of four, as we kept pestering him about the wine.


Geoffrey Chew 1924

At this school Chew preached the end of quantum field theory.

Instead he proposed S-matrix theory, based on ideas involving analytical properties of scattering amplitudes.

We did not believe anything from that.

Personally I thought that unstable particles made for a counterexample.

In the end, looking back, all of these statements are wrong.

Unstable particles

So I started working on unstable particles. The funny thing was that the Feynman rules were more or less generally known, but nobody had developed a consistent theory. There existed no clear derivation of these rules, although the result seemed correct. What to do ?

Like with many 'problems' that I have encountered, the answer is that there is no problem. Just think about it clearly.

For any given theory the procedure is simply. Start deriving the Feynman rules. The derivation goes in some standard way (Dyson) That guarantees that a number of fundamental properties hold. But it happens that for unstable particles that approach breaks down. We know the result but do not know how to derive it.

Well, it is simple. Check if these fundamental properties hold. Then there is no need to worry where these rules came from.

What are these fundamental properties ? **They are unitarity (conservation of probability) and causality.**

So I started working on the problem of showing that a given set of Feynman rules is correct, and in about 1 year I found a way to solve that problem.

Veltman, M. Physica 29
1963 186-207

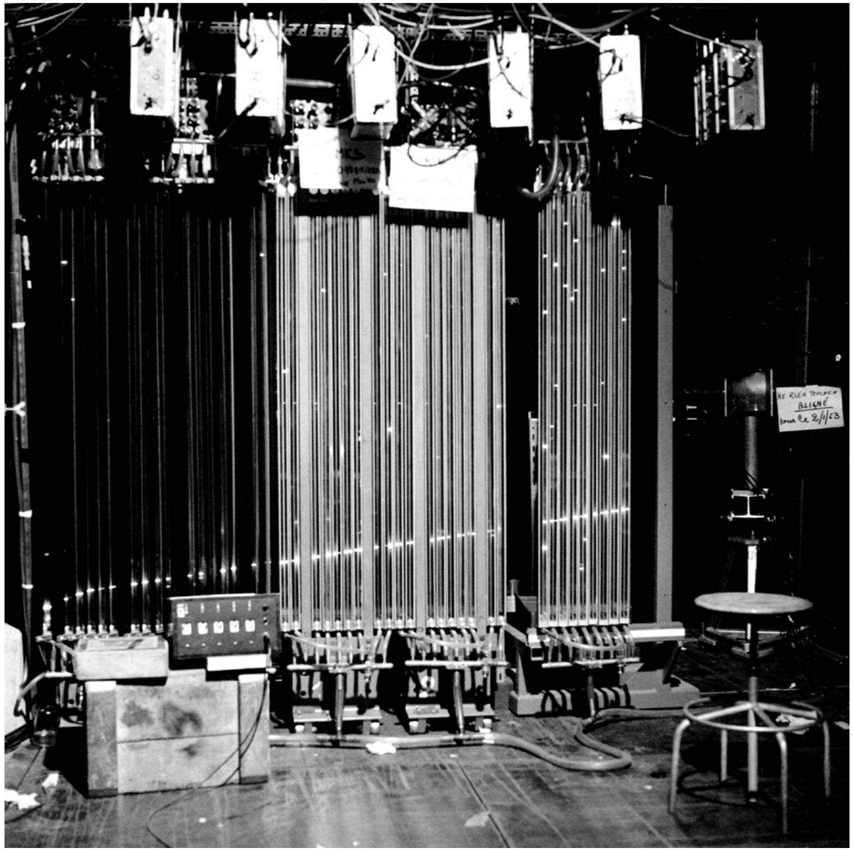
UNITARITY AND CAUSALITY IN A RENORMALIZABLE FIELD THEORY WITH UNSTABLE PARTICLES

M. VELTMAN *)

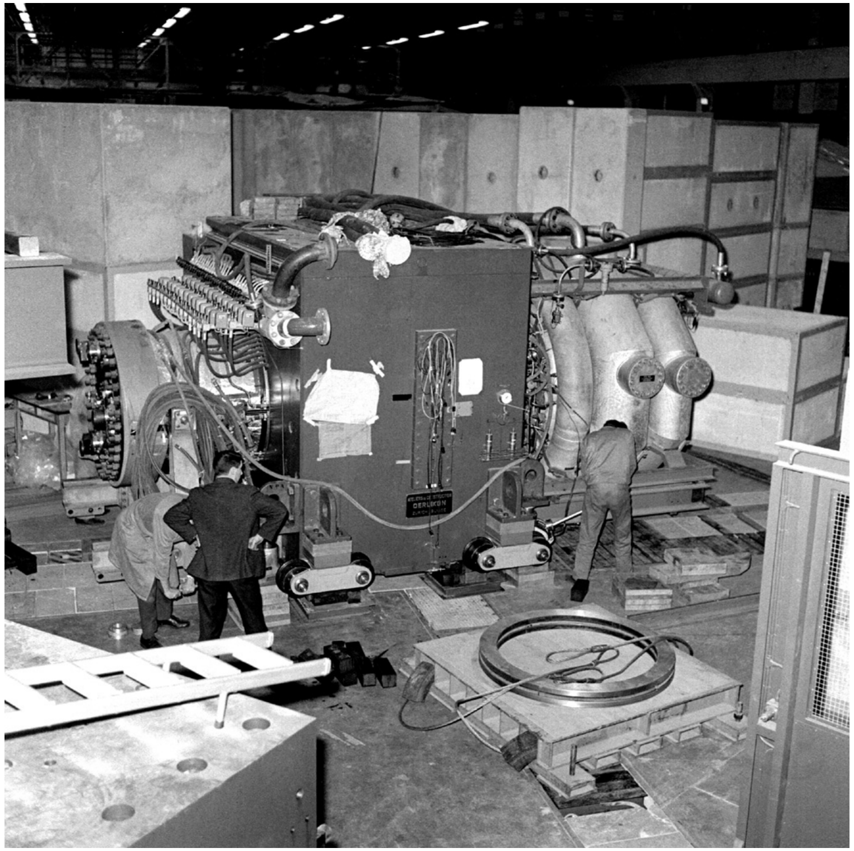
As you can see the publication date was three years later for no good reason. Also, Physica was mainly used for publications on statistical mechanics, not particle physics. For all I know the article was for at least 5 years read by only one person, Symanzik.

In any case, after this I worked with Feynman rules of which I could see if they were correct, and did not care where they did come from.

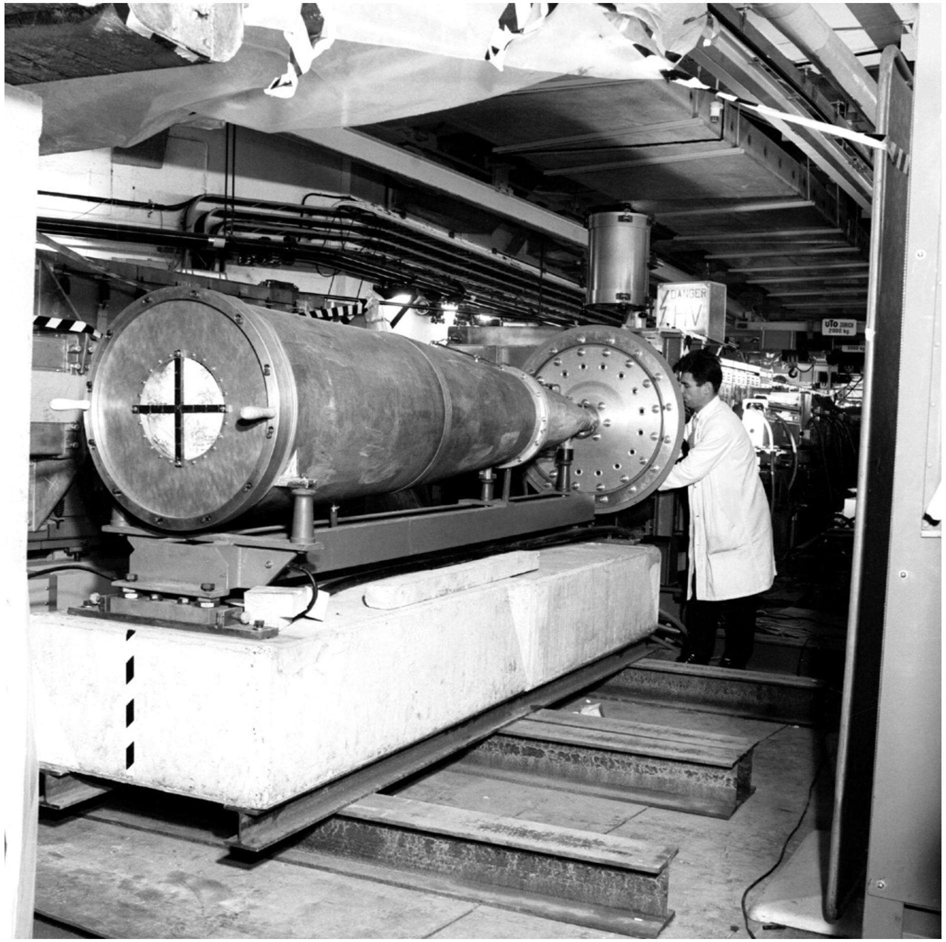
In 1961 I moved to CERN, following my thesis advisor Leon van Hove, staying there till 1966, learning a lot about particle physics experiments. I more or less joined the big (for that time) CERN neutrino experiment and in fact I was their spokesman at the Brookhaven conference in 1963 (140 participants, of which 15 had or would get the Nobelprize).



Spark chamber



Bubble chamber



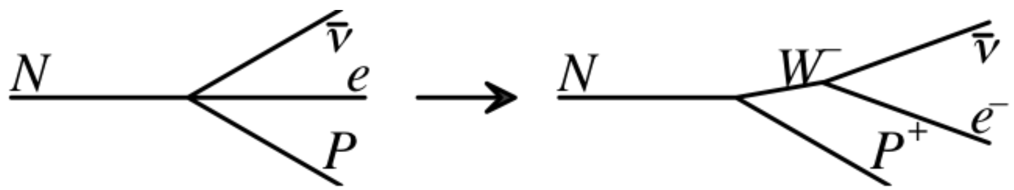
van der Meer’s magnetic horn

Simon van der Meer

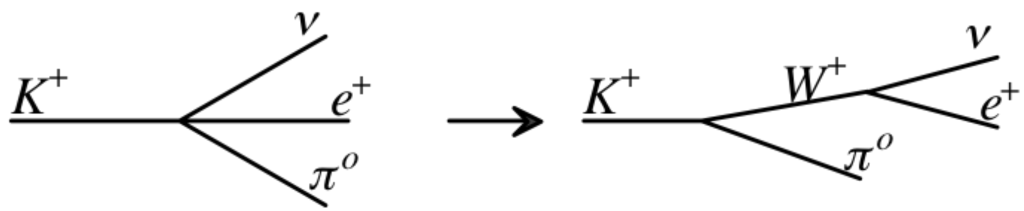
To make a long story short, I returned to Utrecht in 1966; in 1968 I had convinced myself that the **weak interactions** were some form of a **Yang-Mills theory**. **I could not have done that without the knowledge of experimental physics that I had acquired at CERN.**

Weak interactions. A collective for a large number of phenomena observed experimentally and characterized by their relative weakness. Examples: neutron decay, muon decay, neutrino events. The interactions had a well-known structure, at least in lowest order. This structure strongly suggested the existence of spin 1 particles, called vector bosons. Examples:

Neutron decay.

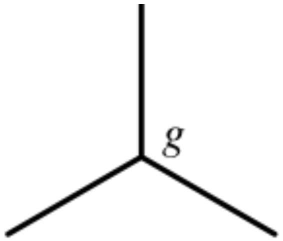


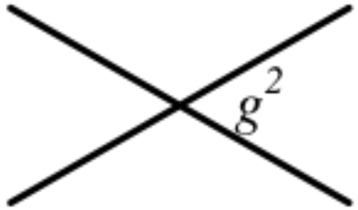
K-meson decay:



No one knew how to attack these interactions beyond the lowest order. It was the main problem of those days.

A Yang-Mills theory is a theory about vector particles interacting with each other in precisely described manner (there is a symmetry). There is a three-point and a four-point interaction:





So I started to investigate this theory of mutually interacting vector bosons, with the hope that it would be a renormalizable theory. The starting point was terrible: the Feynman rules for this theory let to very, very bad divergencies. For example I looked at WW scattering and found divergencies of the form infinity to the eight power at the one loop level.

Salam claimed to have proven non-renormalizability.

Abdus Salam 1926-1996

Nucl. Phys. 21(1960)624

RENORMALIZATION PROBLEM FOR VECTOR MESON THEORIES

A. KOMAR † and ABDUS SALAM

Received 22 August 1960

Abstract: The renormalizability problem of the Yang-Mills theory of vector mesons with mass is considered. It is shown, that the divergences of such a theory are those of the electrodynamics of charged vector mesons. This general feature is illustrated by direct calculation of the lowest order divergent diagrams. It is concluded that renormalizability of this theory seems rather unlikely.

Phys. Rev. 127(1962)331

Renormalizability of Gauge Theories*

ABDUS SALAM
Imperial College, London, England

(Received November 27, 1961)

By generalization of methods developed by Kamefuchi, O'Raifeartaigh, and Salam, conditions for renormalizability of general gauge theories of massive vector mesons are derived. These conditions are stated explicitly in Eqs. (39) and (40) of the text. It is shown that all theories based on simple Lie groups (with the one exception of the neutral vector meson theory in interaction with a conserved current) are unrenormalizable.

This was the state of affairs in 1968.

Then I discovered an important thing. First of all, there were many more diagrams than in the usual renormalizable theories, and secondly, there were many cancellations between the diagrams, due to the symmetry of the theory.

The question was how to attack this situation. It was quite hopeless to work out the diagrams and check that the infinities cancel. There were just too many of them, all these divergencies led to unclear and murky situations. Even with a computer (actually, in the period 1966-1972 no suitable computer was at my disposal in Utrecht) it was quite impossible to do things. Besides, computers have no ideas. It was a total mess.

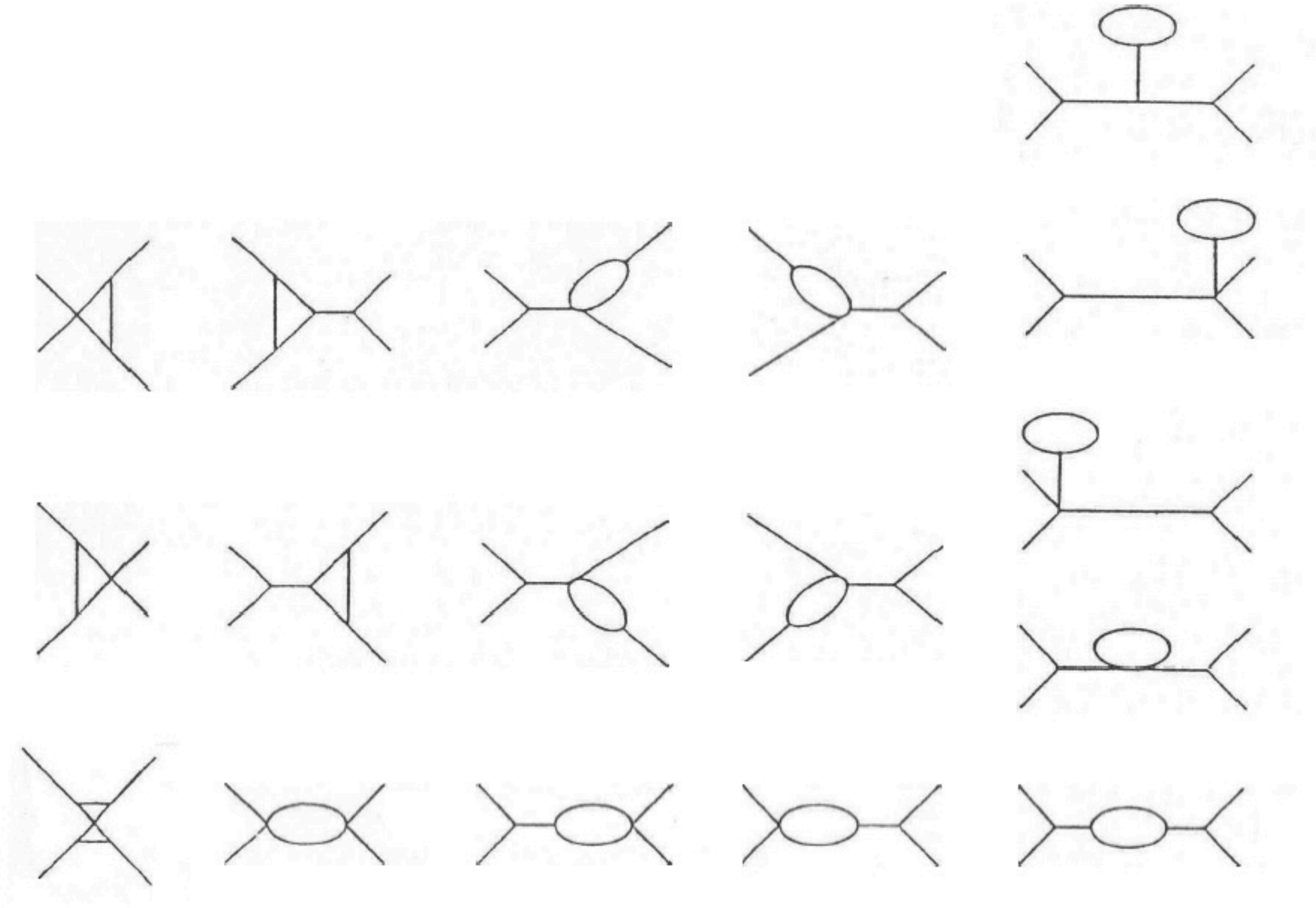
There was only one thing that I could think of. I must try to invent alternative Feynman rules such that:

- physics would be unchanged;

- all cancellations were somehow already part of the new rules.

I found a way to derive such new rules, involving ghost particles, and miraculously almost all infinities disappeared. This was 1968.

To get an idea: here some contributing diagrams to WW scattering.



De way the theory looked like at that time was pretty terrible. But gradually I cleaned up piece by piece. After a while it became clear that not all was fine. The theory was not quite renormalizable. The trouble was with the masses of the vector bosons. The massless case seemed renormalizable.

In a pure Yang-Mills theory the masses of the vector bosons are zero. On the other hand, from the experiment, it was clear that the vector bosons of weak interactions were quite massive.

I did not know how to attack this situation. Enter the sigma model (of Schwinger) in the form of Hugo Strubbe. Strubbe was a Belgian who wanted to come to the Institute. He had worked on the sigma model of Schwinger, and wanted to continue his work in Utrecht.

Hugo Strubbe, in Utrecht
Oct. 1970 – Dec. 1971

The sigma model (Schwinger 1957) was a theory of a system of three pions and one further spinless particle called the sigma. This sigma particle had interactions with the pions and also self-interactions such that there was a state with everywhere a sigma field present but with an energy less than zero, that is less than the vacuum.

Therefore the vacuum decays into the sigma vacuum which then becomes the standard vacuum.

Thus in this model the sigma vacuum replaces the usual one. If now some particle has an interaction with that sigma field in the vacuum it will get some potential energy, manifest as a mass. In other words, here is a way to give particles a mass. Choosing the strength of the coupling to the sigma field one can get any mass.

Schwinger used this method to give a mass to the muon.

Hugo Strubbe gave a lecture about that when arriving at the Institute, and ‘t Hooft attending that seminar got the idea to apply this to generate a mass for the vector bosons.

And here was again a miracle: the last difficulties in the Yang-Mills theory disappeared and the theory became fully renormalizable, that is all occurring infinities could be absorbed in the available free parameters. Theories with a Yang-Mills structure were now renormalizable theories.

‘t Hooft presented this result at the 1971 conference in Amsterdam which created a revolution.

The next issue was to find the precise model for the weak interactions. Such a model existed already although it had received virtually no attention. It was proposed by Weinberg in 1967 but actually never mentioned by him before 1972.

Now what about Higgs ? In connection with ‘t Hooft’s paper it was discovered that giving vector bosons a mass using a sigma vacuum was already treated by Higgs and others. They had introduced a model in connection with superconductivity.

What happened is this. It was discovered that within a superconductor electromagnetic fields have a finite range. In particle physics that is what you get if the particle has a mass. So Higgs (and Englert and Brout) started to work on the problem of how to give a photon a mass. **More specifically, they wanted the photon to have a mass inside a superconductor but not outside.** The solution was to assume some field inside the superconductor that would, like in the sigma model, give a mass to a particle moving in that field.

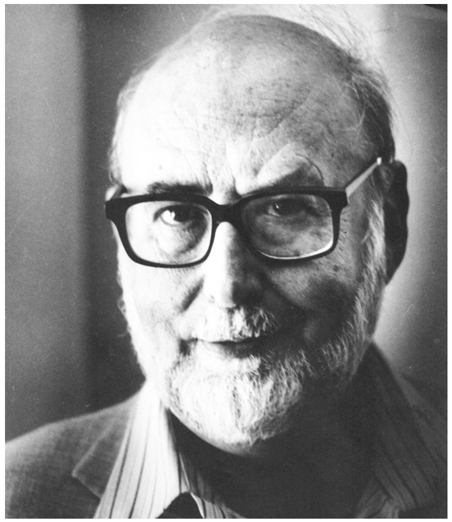
Higgs discovered that unavoidably such a construction would give rise to another particle, what we now call the Higgs particle.

Also in the cases that ‘t Hooft discussed there was such a Higgs particle, except he did not call it that. Later that was corrected

Peter Higgs, 12 Nov. 1965, Chapel Hill, NC.

Higgs: 1929

Robert Brout 1928 - 2011



Francois Englert 1932

Conclusion

The importance of the Higgs construction is that it made the theory of Yang-Mills fields renormalizable. **Observable results can be calculated and compared with experiment,** and that has happened in a multitude of ways in the last 40 years, up to and including the recent discovery of the Higgs particle.

At this point one may ask:
- why does nature at low energies use only renormalizable theories ?
- what about gravitation ?

There are other questions:
- why three generations of quarks and leptons ?
- why masses ranging from eV to 180 GeV ?
- etc.

Have fun…