The Standard Model and Carlo's Contributions

Gerard 't Hooft

Institute for Theoretical Physics
Utrecht University
the Netherlands

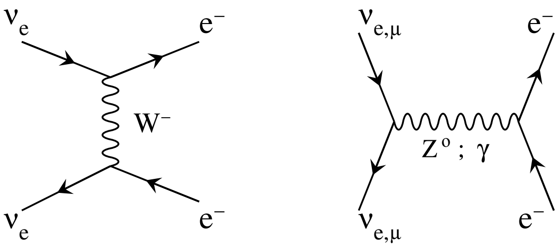
Presented at the Symposium to celebrate
Carlo Rubbia's 90th birthday,
October 18, 2024.

The role of *vector particles* in the fundamental interactions among elementary particles became clear from theoretical studies (Yang and Mills) as well as experimental observations, which showed that vector and axial vector interactions dominated over scalar or tensor terms.

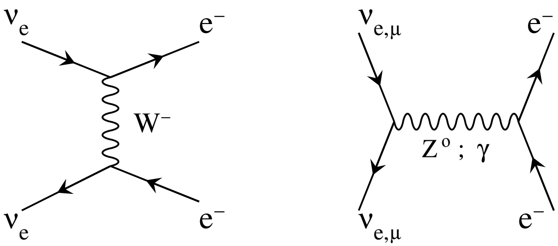
But the algebras did not close.

St. Weinberg showed in his *model of leptons* that you *can* have a closed algebra if you assumed the existence of yet another vector particle, the Z^0.

It would cause new *neutral current effects*.



Fierz transformation: connect neutrinos to neutrinos instead of electrons: exchange neutrino with electron. This yields a



Fierz transformation: connect neutrinos to neutrinos instead of electrons: exchange neutrino with electron. This yields a

minus sign.

The two contributions to neutrino electron scattering interfere negatively.

The intermediate vector bosons $W^{\pm}$ were well understood in the 1960s. St. Weinberg earned his Nobel Prize by realizing you have to close the algebra: Z^0.

In his "Model of Leptons", he also mentioned the scalar particle generated by this mechanism: the *Higgs*.

In the quark sector, the algebra also had to be completed: the GIM mechanism, postulating the charm quark.

To account for CP violation, two more quarks would be needed (the 3×3 CKM matrix), matching the three accompanying leptons.

In 1974 R. Gatto summarised the situation then encountered:

In 1974 R. Gatto summarised the situation then encountered:

scenario zero: there is nothing more than the particles that we now have in our models.

This is what we now call the Standard Model.

In 1974 R. Gatto summarised the situation then encountered:

scenario zero: there is nothing more than the particles that we now have in our models.

This is what we now call the Standard Model.

As for those new particles in our models:

What was needed most urgently was a direct observation of the $W^{\pm}$ and Z^0 vector particles.

In 1974 R. Gatto summarised the situation then encountered:

scenario zero: there is nothing more than the particles that we now have in our models.

This is what we now call the Standard Model.

As for those new particles in our models:

What was needed most urgently was a direct observation of the $W^{\pm}$ and Z^0 vector particles.

Some theorists warned that the predicted particles would be too heavy to ever be observed . . .

In 1974 R. Gatto summarised the situation then encountered:

scenario zero: there is nothing more than the particles that we now have in our models.

This is what we now call the Standard Model.

As for those new particles in our models:

What was needed most urgently was a direct observation of the $W^{\pm}$ and Z^{0} vector particles.

Some theorists warned that the predicted particles would be too heavy to ever be observed . . .

"Theorists should not worry", Carlo emphasised,

"If these particles exist, we experimentalists will find them!"

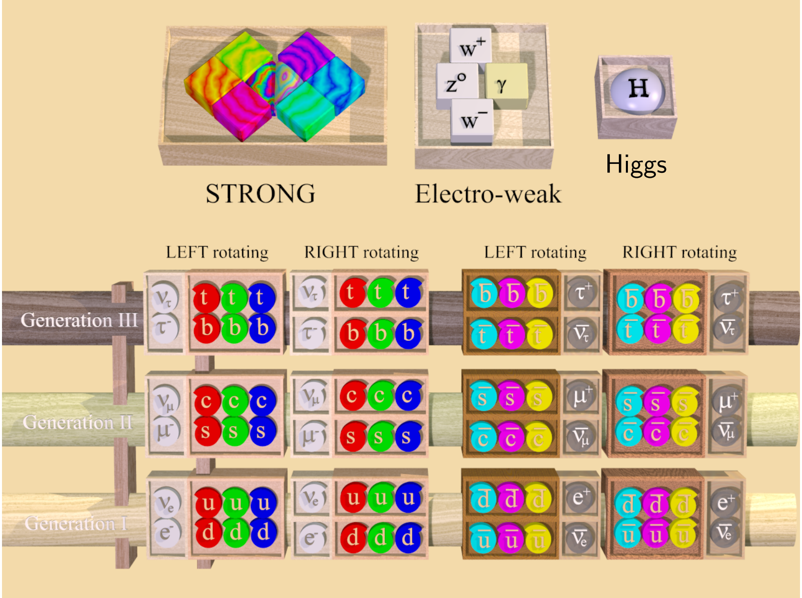
This was exactly what Rubbia and colleagues, 1982, 1983, at CERN did, using $\bar{p}p$ collisions.

NP 1984 was for Carlo Rubbia and Simon van der Meer

This left only one thing that still had to be detected:

the Higgs particle.

The Standard Model (scenario 0)



These were marvellous enjoyable events. Theoreticians eagerly made predictions, experimentalists checked them – and often experimentalists came with big surprises (J/Ψ), and sometimes the theorists triumphed

(such as the confirmation, long overdue, of the Higgs particle),

while finally the surprising agreement was reached that all this fits perfectly in the simplest of these models: the Standard Model.

Gatto's scenario 0 was realised head-on.

Most of these happy events came 1960 - 1990 (roughly). After that, making real progress became harder, that is, in particle physics.

I wish theoreticians could say:

Most of these happy events came 1960 - 1990 (roughly). After that, making real progress became harder, that is, in particle physics.

I wish theoreticians could say:

Experimentalists should not worry, we'll make a theory that explains what you are finding
(over 20 'freely adjustable' Standard Model variables . . .)

Most of these happy events came 1960 - 1990 (roughly). After that, making real progress became harder, that is, in particle physics.

I wish theoreticians could say:

Experimentalists should not worry, we'll make a theory that explains what you are finding
(over 20 'freely adjustable' Standard Model variables . . .)

But here we are not very successful.

Astronomy is doing better (gravitational waves, exoplanets), and they are having more fun now, just as paleontologists (giant centipedes)

Nevertheless I have good hopes that there will be new surprises also in particle physics. Such as new algebraic relations between interaction strengths, and mass relationships that will bring us closer to complete understanding. For instance, we should learn how to derive constraints on the allowed parameter values of the Standard Model, from imposing physical constraints on the behaviour of black holes.

Nevertheless I have good hopes that there will be new surprises also in particle physics. Such as new algebraic relations between interaction strengths, and mass relationships that will bring us closer to complete understanding. For instance, we should learn how to derive constraints on the allowed parameter values of the Standard Model, from imposing physical constraints on the behaviour of black holes.

All I know right now is that such derivations, which will put the gravitational force in the picture, can still be much improved.

(Belated) Happy birthday, Carlo !