Status of the theory (Langacker notation)

Perturbative field theory is characterized by weak coupling (finite higher order corrections)

- Lagrangian of a field theory contains interaction vertices

$$L(\phi,\partial_\mu\phi)=\frac{1}{2}[(\partial_\mu\phi)^2-m^2\phi^2]-V(\phi)$$

kinetic energy mass interactions

- Propagators describe exchanges of virtual or unstable particles
- Feynman diagrams combine Lagrangian with propagators to calculate scattering and decay amplitudes
- Transition amplitude from state *i* to state *f* is M_{fi} (from Feynman rules)

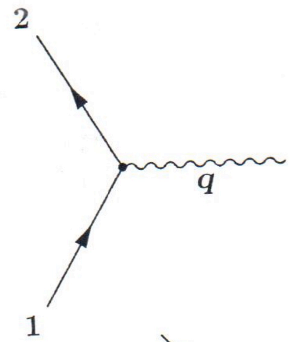
$$|U_{fi}|^2=|(2\pi)^4\delta^4(\sum_k p_{f_k}-p_1-p_2)M_{fi}|^2$$

- Differential cross section for 2 -> 2 scattering

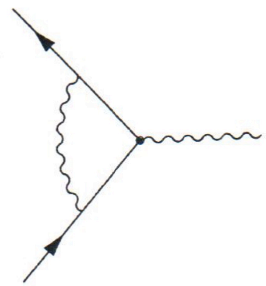
$$d\sigma=\frac{(2\pi)^4\delta^4(p_3+p_4-p_1-p_2)}{4E_1E_2|\beta_1-\beta_2|}\frac{d^3p_3}{(2\pi)^3 2E_3}\frac{d^3p_4}{(2\pi)^3 2E_4}|M_{fi}|$$

Higher order effects in QCD are analogous to those in QED with the substitution of gluon for a photon and quark for electron. (W,Z for weak processes). $\alpha_s \sim 1$
Examples of e-p vertex and loop corrections

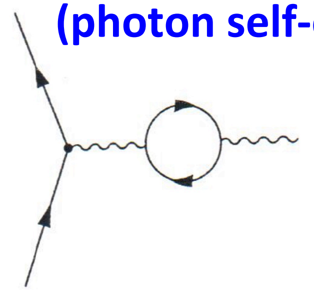
e-p vertex



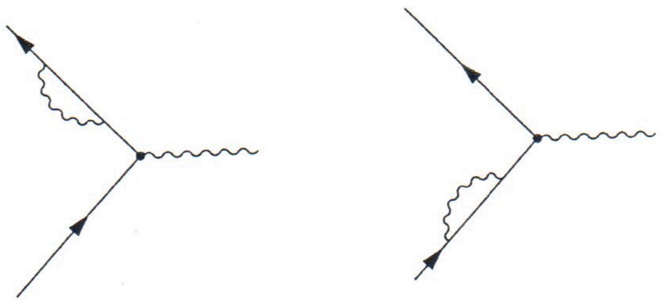
vertex correction



vacuum polarization (photon self-energy)



electron self-energy



Vacuum polarization leads to a running coupling constant.
In QED, the coupling constant $\alpha = 1/137$ at the energy equal to the mass of the muon, but is ~1/128 at the energy of Z boson.

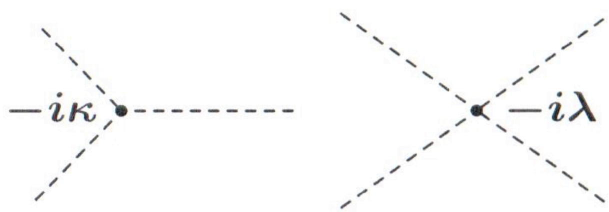
$$\frac{1}{\alpha(Q^2)} = \frac{1}{\alpha(Q_0^2)} - \frac{1}{3\pi}\ln\frac{Q^2}{Q_0^2}$$

QCD analogy

Feynman diagrams

Transition amplitude M_{fi} between initial $|i>$ and final $|f>$ state .

1. Draw connected and topologically distinct diagram in momentum space. Internal lines correspond to virtual (exchanged) particles. The internal and external lines meet at vertices corresponding to interactions.
2. There is a factor $-i\kappa$ at every three-point vertex and a factor $-i\lambda$ at each four point vertex

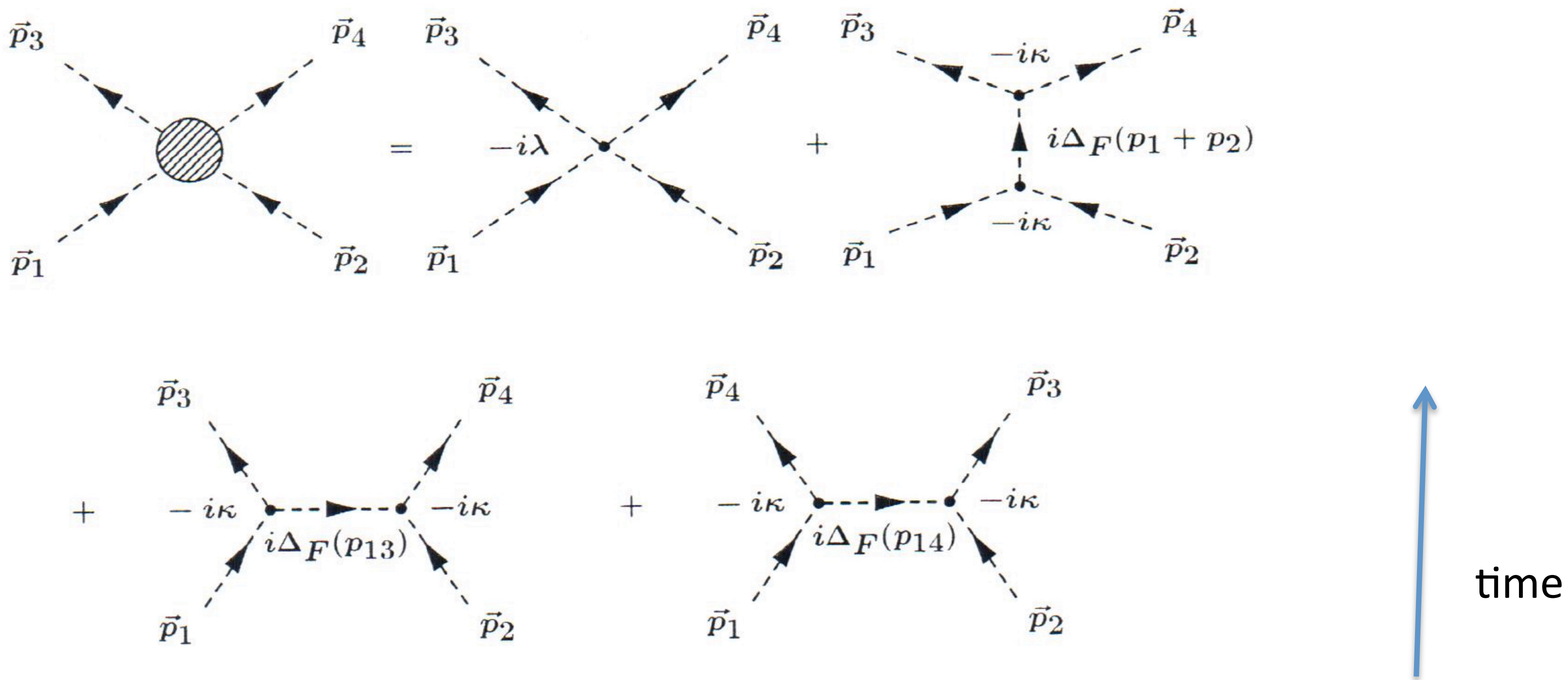


3. For each internal line there is a factor

$$i\Delta_F(k) = \frac{i}{k^2 - m^2 + i\varepsilon}$$

4. Four-momentum is conserved at each vertex
Integrate over each internal momentum with a factor $\int \frac{d^4k}{(2\pi)^4}$

Tree level diagrams for a Hermitian scalar field



$$M_{fi} = \langle p_3 p_4 | M | p_1 p_2 \rangle$$

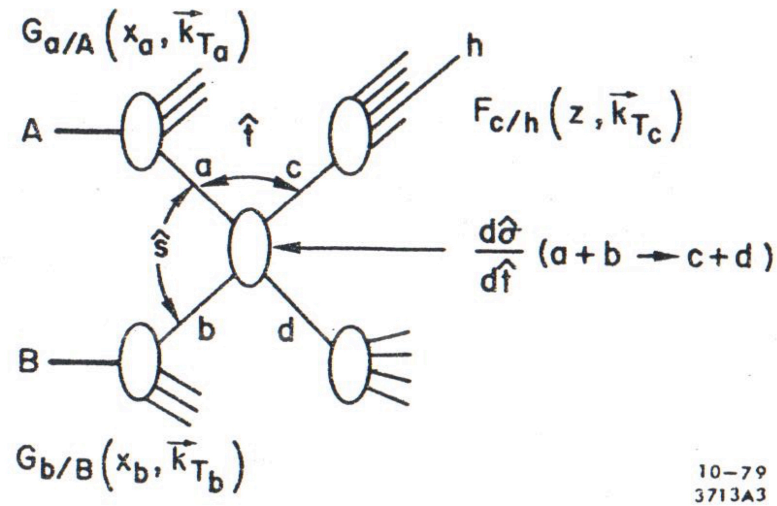
- **Homework** - read about Feynman diagrams.

  any textbook is OK

- Calculate cross section for $e^+e^- \to \mu^+\mu^-$

  2 weeks ?

1980 picture of hard scattering process resulting in large p_T particles



2016 today we have Standard Model and we can calculate the cross section for a+b -> c+d with the complete precision of theoretical approach.

We still rely on phenomenology for G (pdf) and F (fragmentation)

In absence of complete mathematical theory we build phenomenological "models" to describe, e. g, how partons ("real" and "virtual" share proton momentum or how a colored parton fragments into colorless observable particles.

We have a very elaborate models for parton distribution functions (pdf) for a proton but these always must be adjusted to fit data at new energies. We do not have any knowledge of a pdf's for π or K mesons.

The fragmentation functions are based not on any fundamental theoretical principle but on a picture of colored strings between the partons that break at a certain tension (Lund model). The color strings are somehow confined in the formation of the observable hadrons. The picture is adjusted to fit the data from e+e- annihilations into pairs of quarks and has been verified only up to the ½ of the LEP energy of ~60 GeV. Most of the "tuning" of this picture is due to tension between the ability of theory to calculate effects of radiation from first principles and the fragmentation picture that also includes radiation. It is easy to generate double counting when merging QCD with fragmentation picture

Problems

For the past several years you have heard triumphant statements about successes of the Standard Model. It true that Higgs boson was a necessary component of the model and so far it looks that what we have found matches its expected properties. The elegance of the SM relies on the fact that a general symmetry group of the Theory of Everything can be broken into pieces and SM can be nicely identified with one of those. Unfortunately there is an infinite number of ways that TOE can be broken.

There are, however, many problems that have not been resolved, were swept under the rug or are treated with silence as a mésalliance in royal family. The two most obvious are:

The mass of the neutrino

The strong CP problem

Both invoke solutions that generate problems for the Standard Model and indicate that Standard Model is incomplete.

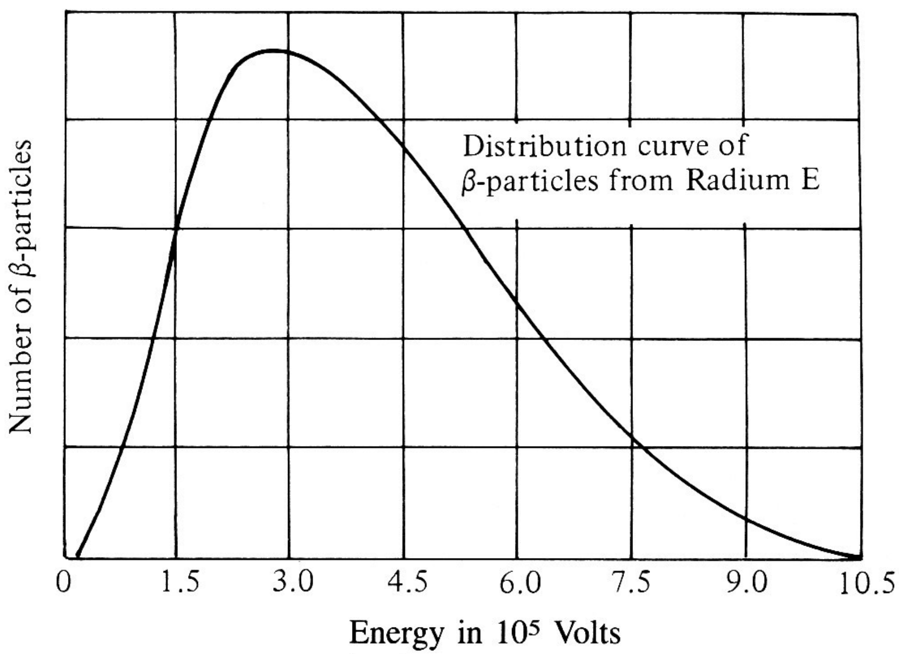
In addition there is a long-standing problem that is much more general that just for our field:

The theory of general relativity (100 years old this year) has not been made consistent with quantum mechanics and so far quantum theory of gravity has not been yet achieved. Fortunately the cosmology is not yet the stage that detailed quantitative tests can be possible.

Neutrinos

A puzzle in β – decay: the continuous electron energy spectrum

First measurement by Chadwick (1914)



Radium E: $^{210}Bi_{83}$
(a radioactive isotope produced in the decay chain of ^{238}U)

If b – decay is $(A, Z) \rightarrow (A, Z+1) + e^-$, then the emitted electron is mono-energetic:

electron total energy $E = [M(A, Z) - M(A, Z+1)]c^2$

(neglecting the kinetic energy of the recoil nucleus $\frac{1}{2}p^2/M(A,Z+1) << E$)

Several solutions to the puzzle proposed before the 1930's (all wrong), including violation of energy conservation in b – decay

December 1930: public letter sent by W. Pauli to a physics meeting in Tübingen

Zürich, Dec. 4, 1930

Dear Radioactive Ladies and Gentlemen,

...because of the "wrong" statistics of the N and ^{6}Li nuclei and the continuous b-spectrum, I have hit upon a desperate remedy to save the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin ½ and obey the exclusion principle ..... The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous b-spectrum would then become understandable by the assumption that in b-decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and electron is constant.

.... For the moment, however, I do not dare to publish anything on this idea ......

So, dear Radioactives, examine and judge it. Unfortunately I cannot appear in Tübingen personally, since I am indispensable here in Zürich because of a ball on the night of 6/7 December. ....

W. Pauli

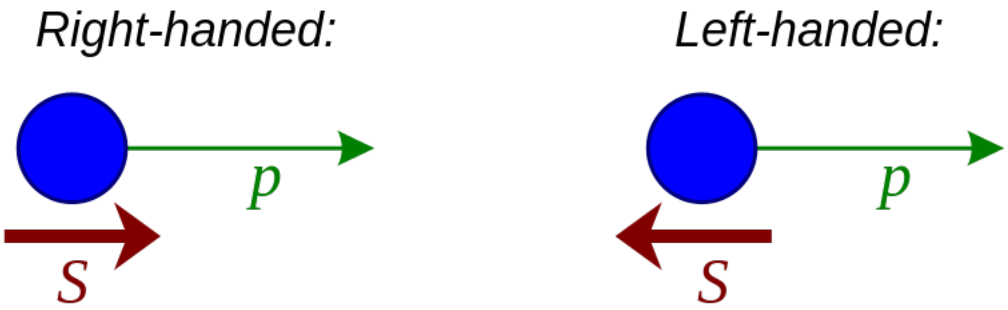
NOTES

- Pauli's neutron is a light particle -> not the neutron that will be discovered by Chadwick one year later
- As everybody else at that time, Pauli believed that if radioactive nuclei emit particles, these particles must exist in the nuclei before emission

Chirality in physics

In mathematics, chiral phenomenon is one that is not identical to its mirror image.
In particle physics spin of a particle is used to define handedness (**helicity**).
For massless particle handedness is the same as chirality.
The symmetry transformation between the two is called **parity**.

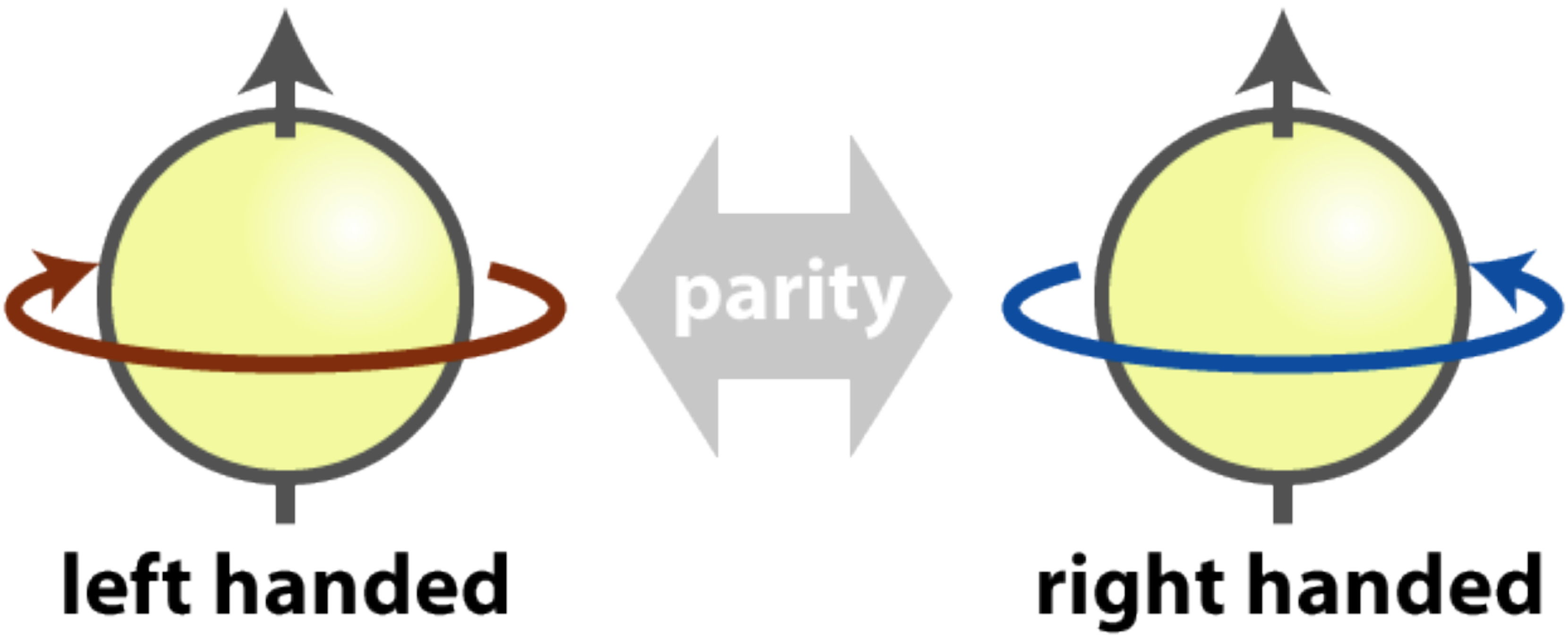
Helicity of a particle is right-handed if the direction of its spin is the same as the direction of its motion.
Mathematically, helicity is the sign of the projection of the spin vector onto the momentum vector.



DISCRETE SYMMETRIES

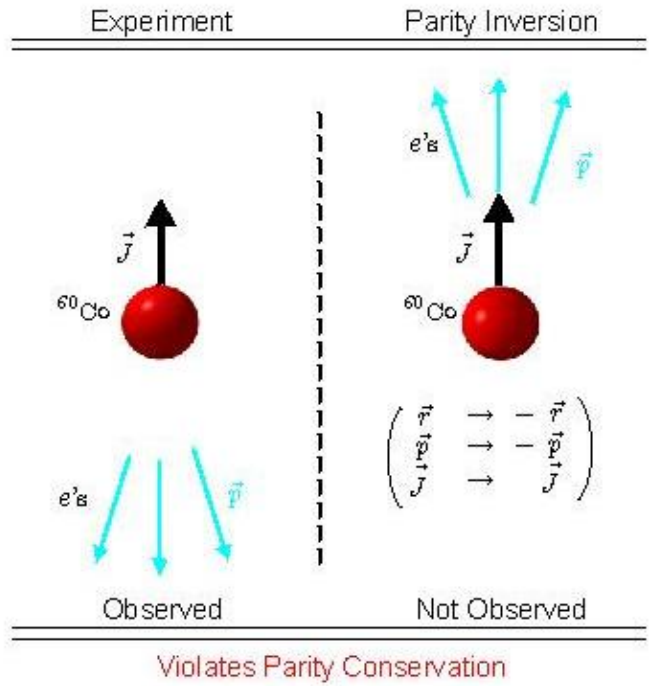
Mirror reflection

Mirror reverses forward-backward direction while maintaining the two other axes. It reverses left and right but not up and down



1956 C.S. Wu experiment - decay of polarized Co(60)

Beta decay of Cobalt(60) – electron emitted in the direction of the nuclear spin



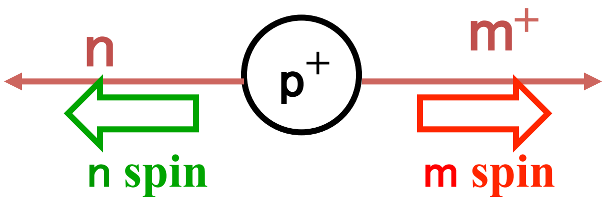
In the mirror image of the process –spin points downwards but electrons are still emitted upwards –in the direction opposite to spin

Radioactive decays (weak interactions) maximally violate parity P

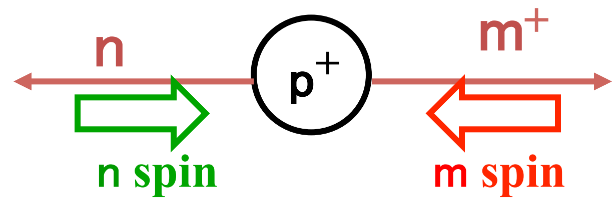
1956: Suggestion (by T.D. Lee and C.N. Yang)
Weak interactions are NOT INVARIANT under Parity

p^+ -> m^+ + n decay

Parity invariance requires that the two states



A



B

must be produced with equal probabilities -> the emitted m^+ is not polarized

Experiments find that the m^+ has full polarization opposite to the momentum direction -> STATE A DOES NOT EXIST
→ MAXIMAL VIOLATION OF PARITY INVARIANCE

Neutrino mass

Since the series of measurements starting with polarized Co60 decays observed by Wu showed that neutrinos are always left handed it was assumed until few years ago that neutrinos are massless.

Goldhaber, Grodins and Sunyar (1958) measured the handedness by studying europium-152 nucleus capturing an atomic electron.

The europium 152 underwent inverse beta decay to produce unstable samarium 152 and a neutrino/ Samarium then decayed by emitting a gamma ray. With a nucleus at rest and the emission of gamma ray and a neutrino back-to-back their handedness must be the same to conserve angular momentum.

The neutrinos were always left-handed.

For massive object moving with velocity less than c and observer could overtake the object and would see it moving in opposite direction, i.e. the left-handed spin would appear right-handed. The right-handed neutrino has never been observed.

The absence of observation of right-handed neutrino led to assumption that the neutrinos have zero mass and that the right-handed neutrinos do not exist.

Neutrino mass

The problem of neutrino mass arose with several observations:

- In 1987 there was an optical observation of a supernova explosion some 150000 light-years away in Large Magellanic Cloud (nearest neighbor to our galaxy). Two large volume water Cerenkov detectors - Kamiokande in Japan and IMB in Ohio observed a group o ~20 neutrino events that seemed correlated in direction with that supernova, but came full three hour later than the light from the explosion. That indicated a very small but non-zero mass of the neutrino.
- Most of the energy of a star (including our Sun) is carried out by the electron neutrinos. Several experiments starting with Davis' 20 years' search showed that the flux of these neutrinos arriving on Earth is about half of that expected from the Solar Model. That can be explained by the neutrino oscillation – a transformation of the electron neutrino into a muon neutrino. The energy of the neutrino produced in the Sun is smaller than that needed to produce muon so the muon neutrino does not interact with a detector. Only electron neutrino interact producing detectable electron. Such oscillations require neutrino to have non-ero mass.

Neutrino mass

In general, the Standard Model provides a mechanism for particles to acquire mass through interactions with Higgs boson. Higgs boson has spin zero thus is neither left-handed nor right-handed. Quantum Field Theory plus Lorenz invariance shows that a particle interaction with Higgs boson results in a left-handed particle becoming right-handed and then left-handed after the second interaction with Higgs and so on. The frequency of such interactions is proportional to particle mass.

Extensions od the Standard Model with Dirac right handed neutrinos
- right-handed W is heavy and has weak coupling, 10^{26} weaker then with ordinary neutrino
-Arkani-Hamed, Dimopoulos,Dvali – superstring theory – right-handed neutrinos may move in extra dimensions while all other particles do not

Majorana neutrinos – are their own antiparticles. The left-handed neutrino interacting with Higgs produces a very heavy right-handed allowed by Heisenberg uncertainty principle. That one interacts right away with Higgs producing another left-handed state.