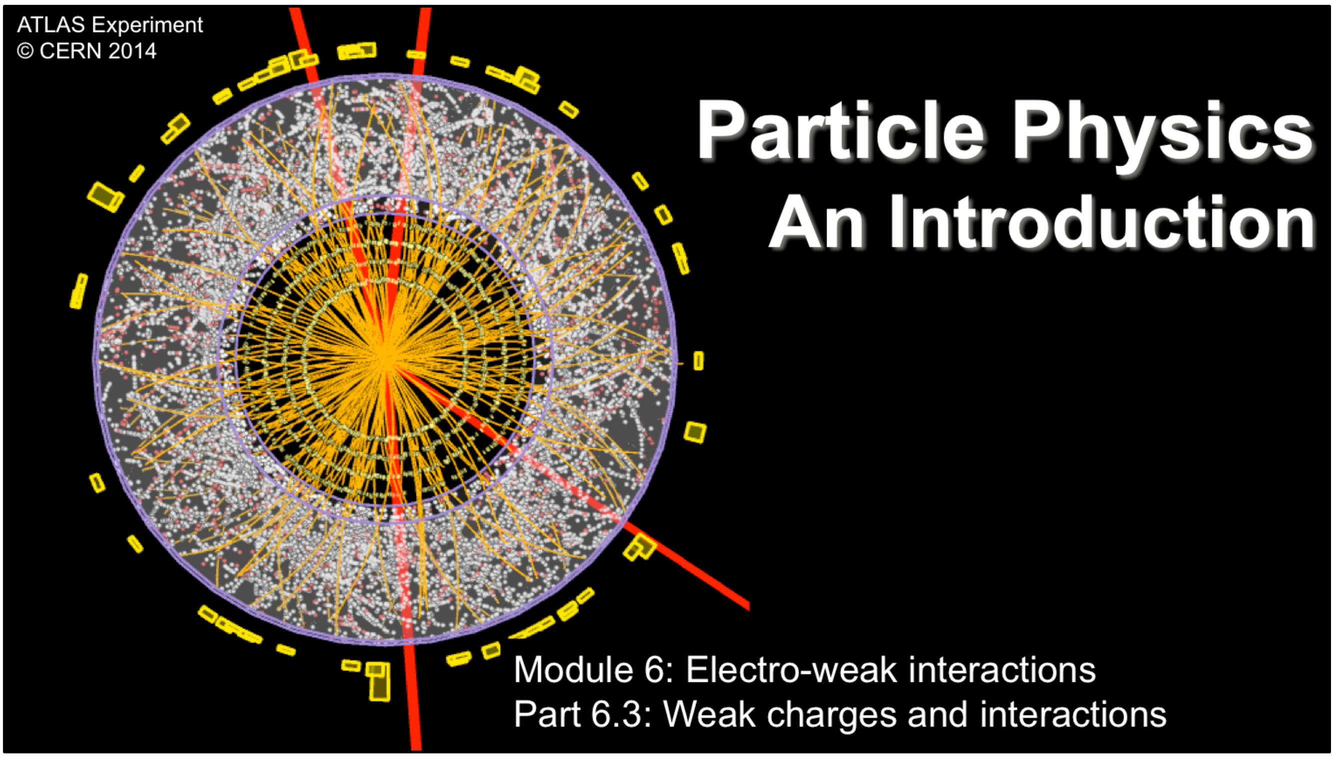
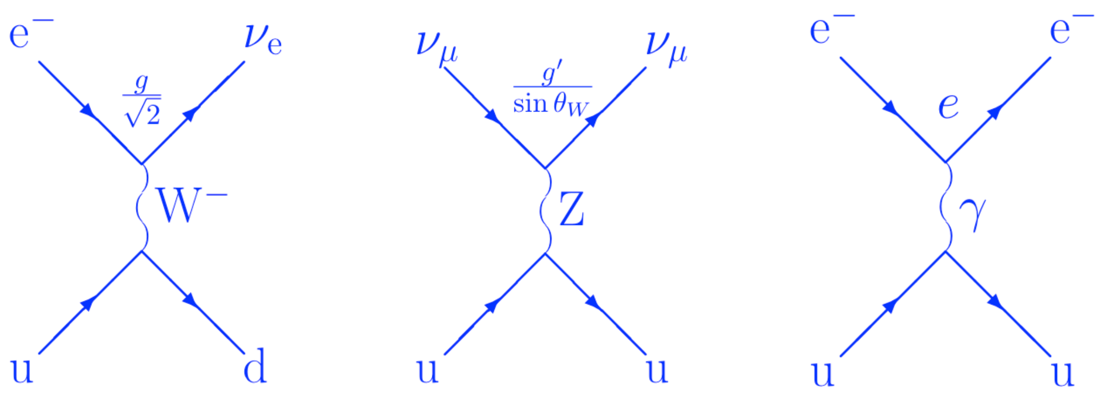


In this 6th module, we are discussing weak interactions.

In this 3rd video we will go through the general properties of these interactions, which are not quite like the others.

After following this video you will know:

- The non-conservation of parity by weak interactions;
- The main vertices and the charges of weak interactions.



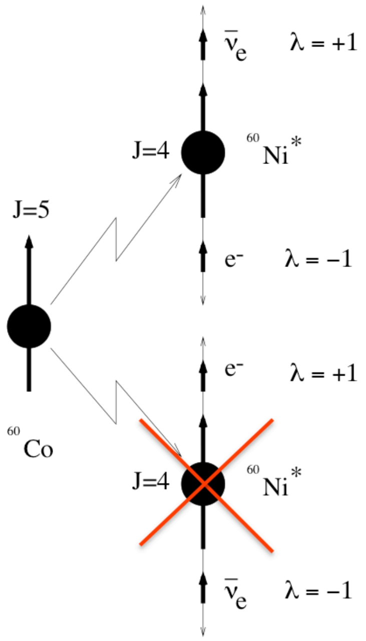
$$g' \cos\theta_W = g \sin\theta_W = e \quad ; \quad \cos\theta_W = M_W/M_Z$$

- Weak interactions do not deserve their name. Their **apparent weakness** at low energy is due to the fact that they are transmitted by **heavy particles**, the neutral Z and the charged $W^\pm$ bosons. Their propagator weakens the amplitude at low momentum transfer.
- Their **coupling constants**, g and g', on the other hand, are of comparable magnitude as the electric charge, e. Indeed, they are connected by the condition of **electro-weak unification** which involves the Weinberg angle ϑ_W. Its value is close to 30°. Instead of 3 coupling constants there is thus only one plus an angle.
- The tangent of this angle is the ratio of g' and g. At the same time, it links the **masses of the weak bosons** by $\cos\vartheta_W = M_W/M_Z$.
- Feynman diagrams for **typical charged and neutral weak interactions** are shown in the two left graphs.
- Comparison with the corresponding photon exchange diagram shows that the structure of the weak amplitude is quite similar to that of electromagnetism. The neutral component of weak interactions can even **interfere** with electromagnetic interactions, when it acts between charged particles.
- The charged weak interaction is the only force that can **change the flavor** of matter particles. It can even mediate between members of different generations at the same vertex.

	Spin	# bar.	# lept.	Q elec.	T, T_3 weak[1]	C strong
Leptons:						
ν_L, ν_M, ν_H	$1/2$	0	$+1$	0	$1/2, +1/2$	0
e^-, μ^-, τ^-	$1/2$	0	$+1$	-1	$1/2, -1/2$	0
Quarks:						
u, c, t	$1/2$	$+1/3$	0	$+2/3$	$1/2, +1/2$	R, G, B
d, s, b	$1/2$	$+1/3$	0	$-1/3$	$1/2, -1/2$	R, G, B
Gauge Bosons:						
γ	1	0	0	0	0	0
Z, $W^\pm$	1	0	0	$0, \pm 1$	$1, (0, \pm 1)$	0
Gluons	1	0	0	0	0	$C\bar{C}$
Vacuum:						
Higgs	0	0	0	0	0	0

[1] Mind helicities and mixtures!

- There are, however, **major differences** between electromagnetic and weak interactions:
    - The **weak charge** is a quantity with two components, in contrast with a single component for the electromagnetic charge and three components for color. The weak charge is called **weak Isospin** by analogy to spin. One characterizes particles by their total weak isospin, *T,* and its third component, T_3. They determine the coupling constants *g* and *g'*, together with the electromagnetic coupling *e*.
    - The weak force is transmitted by **vector bosons** similar to the photon and the gluon, but very heavy. The $W^\pm$ mass is of the order of 80 GeV, that of the Z of the order of 90 GeV. The two **bosons carry themselves weak isospin** and can thus interact among themselves. In addition, charged bosons can obviously interact with the photon.
    - **Weak interactions do not conserve parity.** Thus they produce polarization phenomena, even from non-polarized initial states. This explains the small print remark at the bottom.
- This non-conservation of parity is the most visible example of symmetries respected by other interactions, but not by weak interactions. Weak interactions do not even respect the **combined *CP* symmetry** and are therefore the only known interaction, which distinguishes between matter and antimatter. We will discuss this in video 6.8.
- At the same time – and probably for the same reason – they are the only interactions, which **connect particles from different generations** at a single vertex. They thus do not conserve flavor. This fact is well established for quarks, and has also been observed for leptons, as we will see in video 6.7 and 6.10.

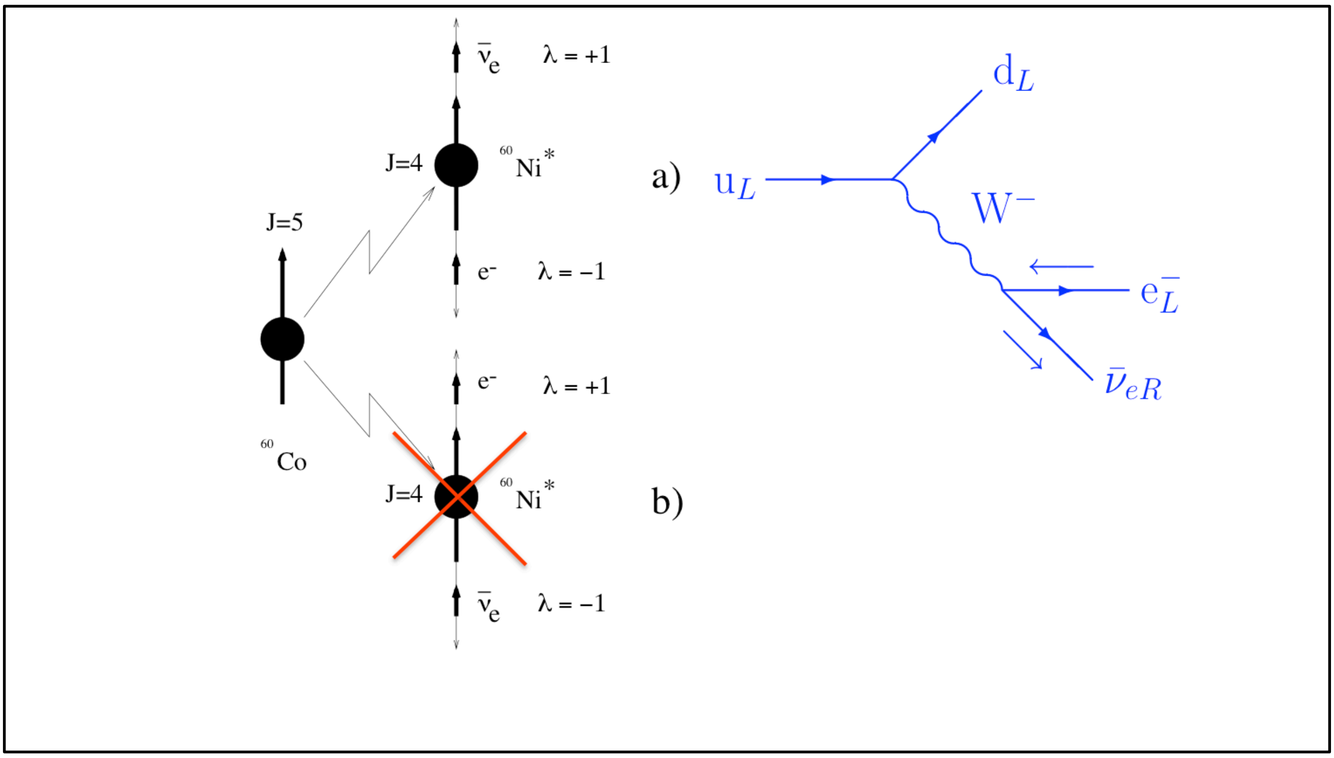


a) $$\frac{d\Gamma}{d\Omega} = \Gamma_0\left(1 - \frac{\vec{\sigma}\vec{p}}{E}\right)$$

b) $$\frac{d\Gamma}{d\Omega} = \Gamma_0\left(1 + \frac{\vec{\sigma}\vec{p}}{E}\right)$$

Wu, C. S.; Ambler, E.; Hayward, R. W.; Hoppes, D. D.; Hudson, R. P.; Phys.Rev.**105** (1957) 1413

- Let us first discuss the discovery of **parity non-conservation** in charged weak interactions.
- In 1956, based on a study of **experimental data obtained by C.S. Wu**, Lee and Yang concluded that weak interactions are not invariant under the operation of parity, $P\varphi(t,r) = \varphi(t,-r)$.
- In order to investigate their behavior under this transformation, C.S. Wu and colleagues have designed an experiment that remains a classic of our discipline. It uses **beta decay** of neutrons, n ➔ p e$^-$ ν_e-bar, bound in ^{60}Co nuclei. At low temperature, of the order of 0.01 K, and in the presence of a magnetic field, the spin vectors of these nuclei with $J = 5$ are strongly aligned with the magnetic field direction.
- Their decay ^{60}Co(J=5) ➔ ^{60}Ni*(J=4) e$^-$ ν_e-bar, can lead to two **spin configurations**. *p* and *E* denote momentum and energy of the emitted electron, and σ denotes a unit vector in the direction of the spin of the nucleus.
    - In case a), the electron is emitted in a direction **opposite** to the ^{60} Co spin.
    - In case b), it is emitted **in** the direction of the initial spin.
    - Any combination of the two cases is allowed by conservation of angular momentum.
- The experiment showed the angular distribution of **case a) only,** and does not admit a contribution − however small – of configuration b). This corresponds to a **maximum violation of parity** symmetry. Indeed, conservation of parity would require the probabilities of the two configurations a) and b) to be the same.



- This also means that **charged weak interactions only admit a certain spin direction** of participating fermions. In our example, the two spins of electron and neutrino must be aligned with that of the nucleus to conserve angular momentum. In case a), **the electron spin is anti-parallel to its direction of motion**, the **anti-neutrino spin is parallel.** So we find that the **lepton** has **negative helicity**, it is **left-handed**. The **anti-lepton** has a **positive helicity**, it is **right-handed**.
- This property of charged weak interactions can be generalized. As far as we know, the **W only interacts with fermions of negative helicity and anti-fermions of positive helicity**. Charged weak interactions violate parity to a maximum extent.

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \; T = 1/2\,;\; T_3 = \begin{cases} +1/2 \\ -1/2 \end{cases} \qquad e_R, \nu_{eR} \;\; T = 0\,;\; T_3 = 0$$

$$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \; T = 1/2\,;\; T_3 = \begin{cases} +1/2 \\ -1/2 \end{cases} \qquad \mu_R, \nu_{\mu R} \;\; T = 0\,;\; T_3 = 0$$

$$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \; T = 1/2\,;\; T_3 = \begin{cases} +1/2 \\ -1/2 \end{cases} \qquad \tau_R, \nu_{\tau R} \;\; T = 0\,;\; T_3 = 0$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \; T = 1/2\,;\; T_3 = \begin{cases} +1/2 \\ -1/2 \end{cases} \qquad u_R, d_R \;\; T = 0\,;\; T_3 = 0$$

$$\begin{pmatrix} c \\ s \end{pmatrix}_L \; T = 1/2\,;\; T_3 = \begin{cases} +1/2 \\ -1/2 \end{cases} \qquad c_R, s_R \;\; T = 0\,;\; T_3 = 0$$

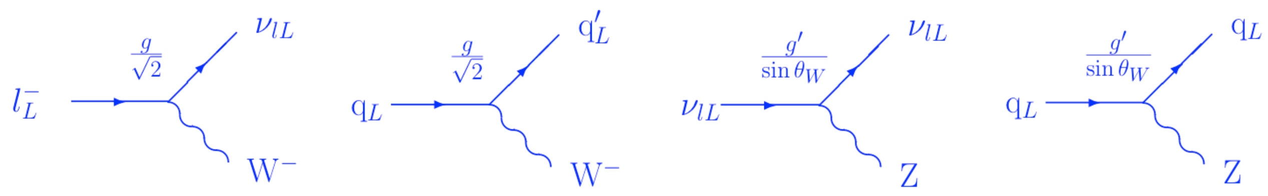
$$\begin{pmatrix} t \\ b \end{pmatrix}_L \; T = 1/2\,;\; T_3 = \begin{cases} +1/2 \\ -1/2 \end{cases} \qquad t_R, b_R \;\; T = 0\,;\; T_3 = 0$$

- Consequently, we assign **left-handed leptons** to **doublets** of weak isospin, **right-handed leptons** to **singlets**. In this way, left handed matter fields carry a weak charge and are coupled to W and Z, right-handed matter fields do not.
- In the same manner, **quarks** are assigned to doublets and singlets according to their helicity.

- For antimatter fields, the opposite is true. Right-handed antilepton and antiquark fields carry weak isospin, left-handed ones do not.

$$\begin{pmatrix} W^+ \\ Z \\ W^- \end{pmatrix} \; T = 1 \; ; \; T_3 = \begin{cases} +1 \\ \;\;0 \\ -1 \end{cases}$$

- The $W^\pm$ and Z belong to a **triplet of weak isospin** with *T=1.* They can therefore interact among themselves. In addition, the $W^\pm$ obviously carry an electromagnetic charge and can interact with the photon.



- Weak interactions **conserve weak isospin**, such that the fundamental weak interaction vertices with matter are as shown.
- Here *l* denotes a generic **charged lepton** and ν_l a **neutrino** of the same flavor; *q* is an **up-type quark**, *q'* a down-type quark. The exact definitions will be given later.
- **W interactions** change T_3 by one unit, so a charged lepton is transformed into a neutrino, an up-type quark into a down-type quark, or vice versa. Attention: the emitted neutrinos and quarks do not necessary belong to the same generation.
- The **interaction of the Z boson** keep T_3 the same and conserve flavor.

In the next video we will present a prototype of W interactions, namely muon and tau lepton decay.