

# High Energy Physics

## Lecture 2: Properties of Elementary Particles

# The fundamental particles of the Standard Model

Generations:	1	2	3	Charge
Neutrinos	$L_e=1$ $\nu_e$ $<7 \text{ eV}$	$L_\mu=1$ $\nu_\mu$ $<170 \text{ keV}$	$L_\tau=1$ $\nu_\tau$ $<30 \text{ MeV}$	<b>0</b>
Ch Leptons	$e^-$ $L_e=1$ $0.511 \text{ MeV}$	$\mu^-$ $L_\mu=1$ $106 \text{ MeV}$	$\tau^-$ $L_\tau=1$ $1.78 \text{ GeV}$	<b>-1</b>
Up-type quarks	$u$ $C=1$ $5 \text{ MeV}$	$c$ $C=1$ $1.5 \text{ GeV}$	$t$ $T=1$ $170 \text{ GeV}$	<b>2/3</b>
Down-type quarks	$d$ $S=-1$ $10 \text{ MeV}$	$s$ $S=-1$ $200 \text{ MeV}$	$b$ $B=-1$ $4.7 \text{ GeV}$	<b>-1/3</b>

## Explanations to the table of fundamental particles:

$L_e, L_\mu, L_\tau$  are *lepton numbers*: they must be conserved in all particle reactions.

Lepton numbers are a particular case of **quantum numbers**.

Other quantum numbers are

C (**charm**), S (**strangeness**), T (**truth** or **topness**)

and B (**beauty** or **bottomness**): these are conserved in some reactions but not in others!

Our most urgent task is now to get to know how the various reactions are understood.

# Fundamental Interactions

Four types of interactions are known:

Gravitational

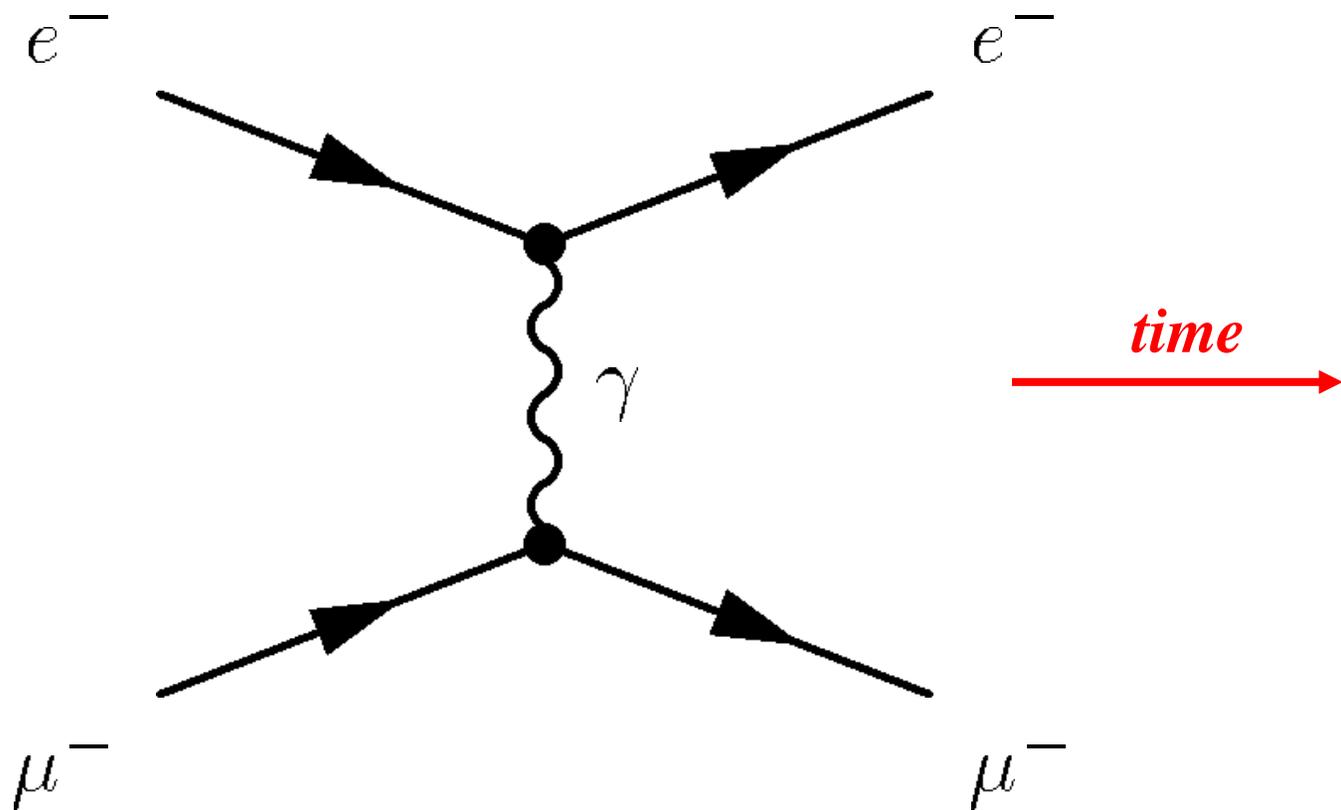
Weak

Electromagnetic

Strong

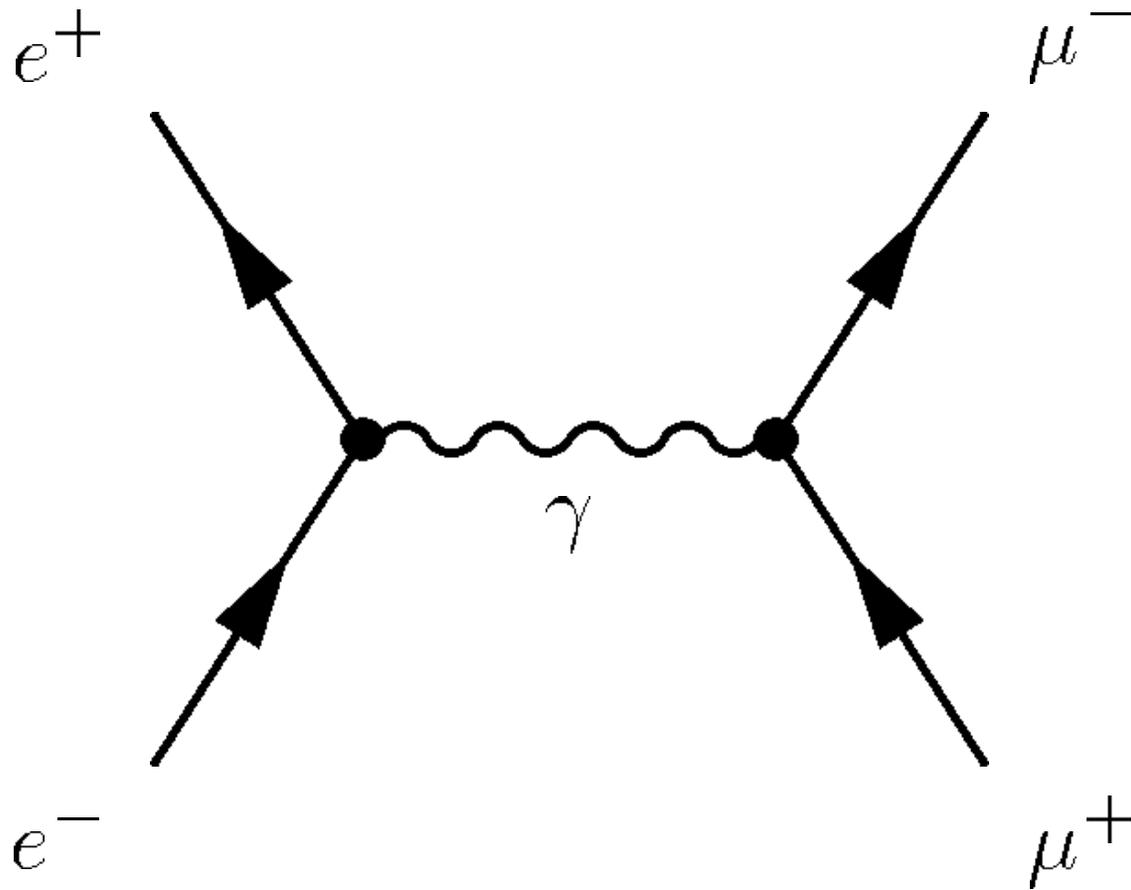
*The gravitational interaction plays no role in particle interactions.*

**The e.m. interaction** takes place between charged particles by exchange of a photon; example: electron-muon scattering



*Neutrinos do not interact electromagnetically!*

Another example: electron-positron annihilation into a muon pair:



**The weak interaction** is mediated by the  
Intermediate **V**ector **B**oson

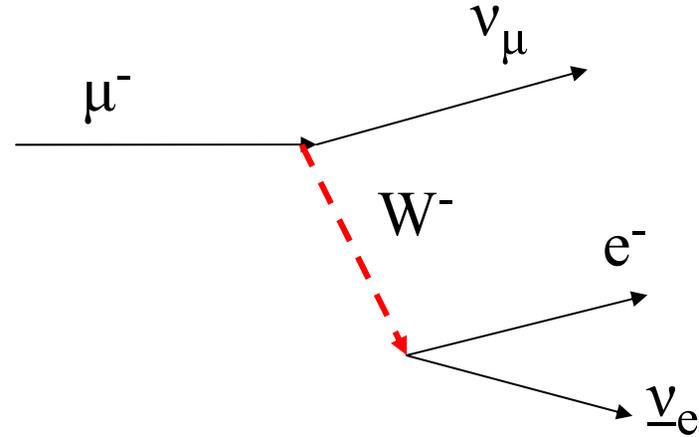
The **IVB** was predicted theoretically in the 1960s by  
Sheldon Glashow, Abdus Salam and Stephen Weinberg  
(NPP 1979)

There was much indirect evidence for its existence  
but it was discovered only in 1983.

The IVB comes in three charge states: positive,  
negative and neutral. The charged IVB is called  
**W boson**, and the neutral one is the **Z boson**.

*All fundamental particles take part in the weak interactions.*

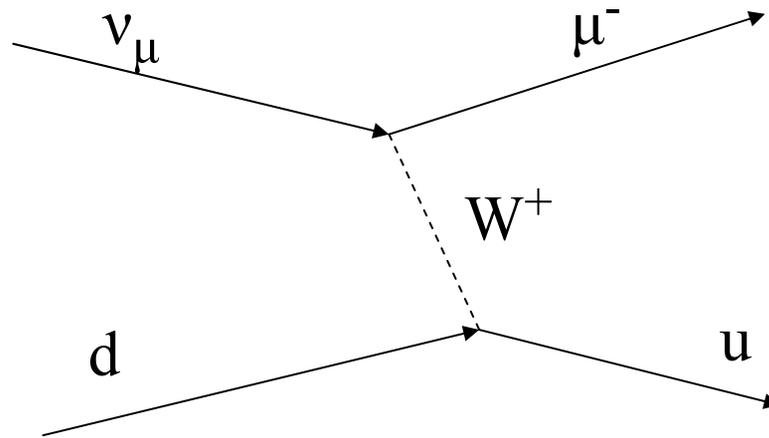
Example of a weak interaction process: Muon decay



The muon emits a  $W^-$  boson and converts into a muon-neutrino; the  $W$  boson decays into an electron and an electron-antineutrino.

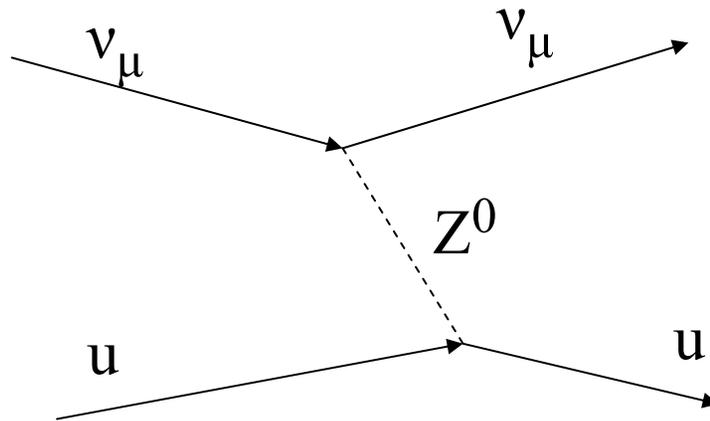
*Note the conservation of charge and of lepton numbers!*

Neutrino – quark scattering: CC process:



Neutrino - quark collisions can take place only via IVB exchange; if a  $W$  boson is exchanged, the reaction is called a **charged current (CC)** process.

Neutrino – quark scattering: NC process:



Neutrino - quark scattering can go via Z boson exchange; this is called **neutral current (NC)** process

Such reactions are observed when a large volume of a dense medium is exposed to a high-intensity beam of high-energy neutrinos: the proton or neutron that is hit by the neutrino breaks up leaving a characteristic trace, and the outgoing neutrino is “identified” by the absence of an outgoing muon (cf. the previous example of a CC reaction that has an outgoing muon!)

**Strong interactions** are mediated by *gluons*. Only quarks take part in strong interactions: they carry a special kind of “charge” that comes in three varieties. This charge is called *colour* (American: color).

The three colour charges are usually (but not universally!) called: *Red*, *Yellow* and *Blue*; antiquarks carry the corresponding *anticolour*.

In this way a quark-antiquark system can be colourless: this is a *meson*.

The three quarks in a baryon are put together such that the baryon is colourless.

Gluons also carry colour; this enables them to mediate the strong interaction.

The colour force can be repulsive or attractive. An attractive colour force can give rise to the binding of quarks.

Consider a bound state of a quark-antiquark system, *i.e.* a meson. The gluon (or gluons) binding them form a *colour string* (or *colour tube*).

If the quark and antiquark are pulled apart, then the colour string gets more and more stretched while the binding force remains constant. This means that more and more energy is put into the colour string.

Eventually the string breaks and a quark-antiquark pair is created at the free ends of the string.

*This is much like the appearance of a magnetic North pole and a South pole on the opposite surfaces of a magnet that is broken into two pieces.*

The theories which describe the electromagnetic, weak and strong interactions are called *Quantum Electrodynamics*, *weak interaction theory* and *Quantum Chromodynamics*.

The weak interaction theory has been unified with QED into a single *Electroweak theory*.

This was the achievement of Glashow, Salam and Weinberg.

They could predict with reasonable accuracy what the masses of the  $W$  and  $Z$  boson should be.

The experiments to discover the IVBs were guided by this prediction.

The actual masses were found to be close to the predicted ones.

The photon, IVB and the gluons are called *gauge bosons*. This has to do with a physical property of the field theories – the electroweak theory and QCD – that they are invariant under a transformation known as *gauge transformation*.

### Properties of the gauge bosons:

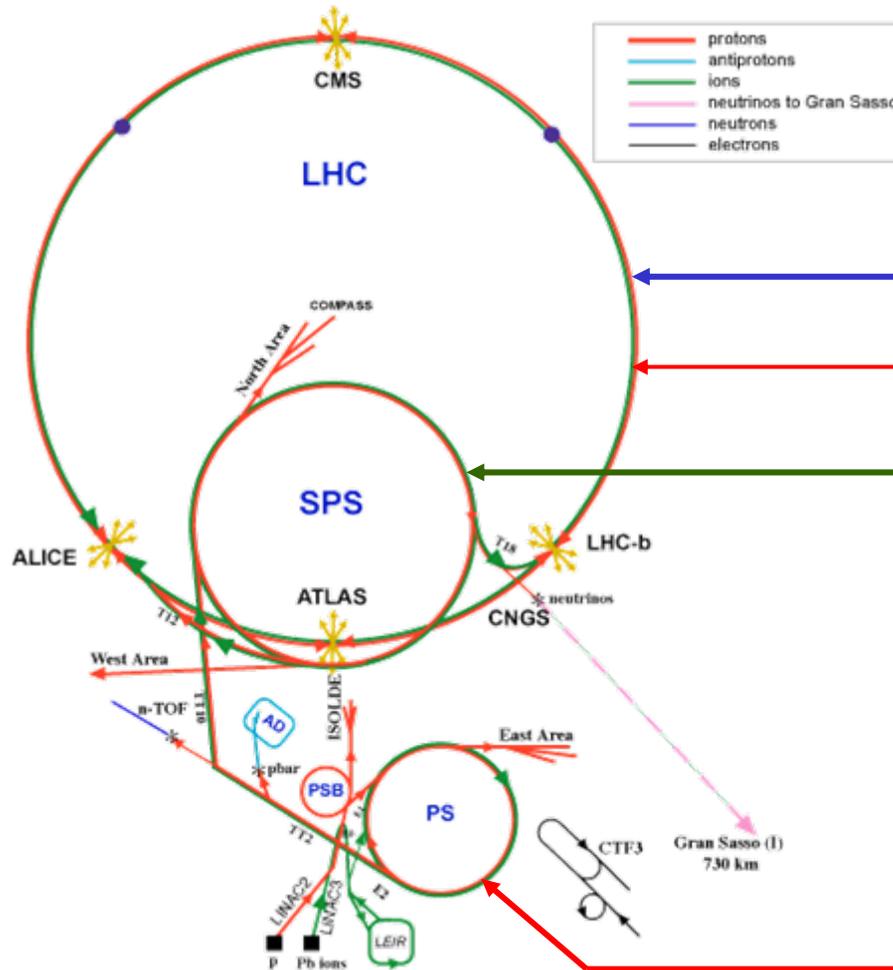
Name	Symbol	el. charge	Mass/GeV
Photon	$\gamma$	0	0
W boson	$W^+$	+1	80.425 +/- 0.038
	$W^-$	-1	
Z boson	$Z^0$	0	91.1876 +/- 0.0021
Gluon	G	0	0 <i>colour</i>

The high accuracy of the Z boson mass,

$$91.1876 \pm 0.0021 \text{ MeV}/c^2$$

(2 parts in  $10^{-5}$ ) is mainly the result of nearly 10 years of work of the Large Electron-Positron collider (LEP) at CERN.

# The CERN Accelerator Complex



LEP: 1989 - 2000  
 LHC: planned 2007 -

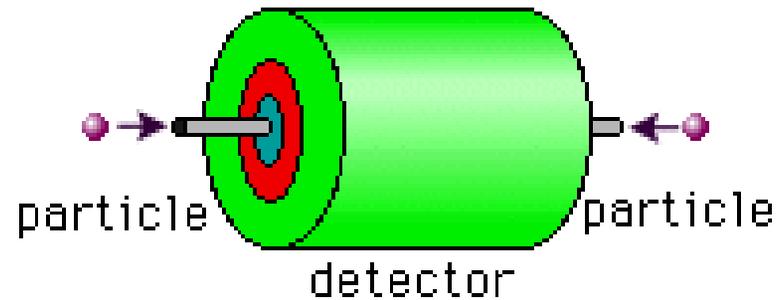
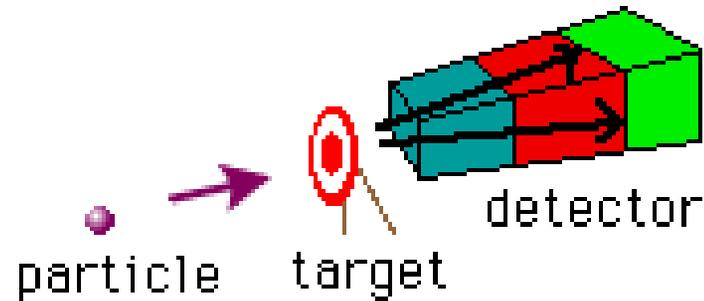
SPS: 1976 –  
 (SppS: 1981 – 1990)

PS: 1959 -

**Exercise:** how much hydrogen has been used up by the CERN accelerators since the commissioning of the PS in 1959?

**Hint:** the typical number of protons in the PS beam is of the order of  $10^{13}$  per second.

# Fixed target & collider experiments



### **Advantage of fixed target experiments:**

a great variety of beam particles and of target material.

Beam particles can be stable or unstable particles:  
protons, pions, muons, ... hyperons

Target material can be anything from liquid hydrogen to iron, lead, solid and liquid compounds.

*The high density of targets can be used to observe rare reactions, such as neutrino induced reactions.*

### **Disadvantage of fixed target experiments:**

limited energy available for the reaction, much energy goes into the overall kinetic energy of the system of final state particles.

## **Advantage of collider experiments:**

the highest possible energy is available for the reaction, no energy is lost into the overall K.E. of the final state particles.

At a later stage we shall look at an exercise to quantify this statement.

## **Disadvantage of collider experiments:**

only stable particles can be used as beam particles: protons and antiprotons, electrons and positrons.

There are plans to build photon colliders and plans to build muon colliders. But it has been very quiet on the muon collider front for several years now.