Tales of the particle world

Ilaria Brivio

21-23 November 2017
Part I

What are Elementary particles?
Giant Earthworm

Human

Meter (m)
10^0 meters

1 m

Rafflesia

Dodo Bird

Beach ball
Elementary particles in ordinary matter

- **Electrons**
- **Protons and neutrons**
- **Quarks**
  - u
  - d

**Electric charge**

\[
\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1 \\
\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0
\]

**Masses**

\[E = mc^2\]

1 eV = 1.782662 \times 10^{-33} \text{ g}

1 MeV = 1000000 eV

2.2 MeV

4.7 MeV

0.51 MeV
pion: $\overline{RR}$

proton: RGB
for each particle there is an antiparticle

opposite charge and color

same mass
Why are we made of atoms and not anti-atoms?
What keeps the quarks together in a proton?
Particle interactions
Fundamental forces

- Electromagnetism
- Gravity
- Strong force
- Weak force
interactions are mediated by force carriers
interactions are mediated by force carriers

Electromagnetism

particles with \textit{electric charge} exchange photons

a long range force
interactions are mediated by force carriers

Electromagnetism

- particles with electric charge exchange photons
  - a long range force

Strong force

- particles with color exchange gluons
  - so strong that its range is only the size of an atomic nucleus

- gluons themselves have color
interactions are mediated by force carriers

<table>
<thead>
<tr>
<th>Force</th>
<th>Particles with electric charge exchange photons</th>
<th>Particles with color exchange gluons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetism</td>
<td>photon</td>
<td></td>
</tr>
<tr>
<td>Strong force</td>
<td>particles with color exchange gluons</td>
<td>so strong that its range is only the size of an atomic nucleus</td>
</tr>
<tr>
<td>Weak force</td>
<td>W boson</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z boson</td>
<td></td>
</tr>
</tbody>
</table>
The Weak Interaction
Beta-decays of nuclei

\[ ^{14}_{6}C \rightarrow ^{14}_{7}N + e^{-} + \bar{\nu}_{e} \]

\[ ^{3}_{1}T \rightarrow ^{3}_{2}He + e^{-} + \bar{\nu}_{e} \]
Conservation laws

The total energy is also conserved

\[ m_n > m_p + m_e + m_\nu \]

The W mass is 80 times bigger than that of the neutron!

The electric charge is the same before and after the decay

The number of particles is the same

\[ m_n = 940 \text{ MeV} \]
\[ m_p = 938 \text{ MeV} \]
\[ m_e = 0.51 \text{ MeV} \]
\[ m_\nu \approx 0 \]
Virtual particles

In the quantum world we can create virtual particles, with energy different from their ordinary mass. But they must live for a very short time. A virtual W can live only up to $10^{-27}$ s. In this time it travels about $10^{-7}$ nm.

Weak interactions have a very short range!
Neutrinos

neutrinos are neutral and colorless

they feel only the weak force → very elusive

they have very tiny masses, that have not been precisely measured yet and were not predicted by theory!

they could be their own antiparticles, but we do not know for sure yet
Summarizing

**QUARKS**
- u (up) with charges 2.2 MeV and 2/3
- d (down) with charges 4.7 MeV and -1/3

**LEPTONS**
- $\nu_e$ (e-neutrino) with charges < 2 eV and 0
- e (electron) with charges 0.51 MeV and -1

**MEDIATORS**
- $\gamma$ (photon) with charges 0 and 0
- g (gluon) with charges 0 and 0
- W (W boson) with charges 80 GeV and +1
- Z (Z boson) with charges 91.2 GeV and 0
W’s transform a particle into another

\[ n \xrightarrow{W^-} p^+ \]

\[ \bar{\nu}_e \]

\[ d \rightarrow u \]

\[ e^- \]

\[ < 2 \text{ eV} \]

\[ \nu_e \]

4.7 MeV

80 GeV

W boson

2.2 MeV

+2/3

down

80 GeV

W boson

0.51 MeV

-1
electron

< 2 eV

e-neutrino
... and their flavor

In Nature there are 3 copies of the same matter constituents.

Each copy is called GENERATION or FLAVOR.

Each generation is HEAVIER than the previous one.
... and their flavor

in Nature there are 3 copies of the same matter constituents

each copy is called GENERATION or FLAVOR

not all the transformations happen with the same probability!
... and their flavor

in Nature there are **3 copies** of the same matter constituents each copy is called **GENERATION** or **FLAVOR**

Why are there **3** generations?

Why do they have such different **masses**?

Why do they transform into each other with these probabilities?

And why are the lepton transitions so homogeneous compared to the quarks ones?
particles of the second and third generation do not constitute ordinary matter because they are not stable
particles of the second and third generation do not constitute ordinary matter because they are **not stable**
to ”see” heavy particles we need enough energy to produce them

more in the second part!

also... didn’t we forget someone?
Part II

How do we explore the Particle World?
The Large Hadron Collider

a ring 27 km long

Geneva, Switzerland
protons are accelerated to 99.9999991% of the speed of light

they complete 11,245 laps every second
The Large Hadron Collider

right now they collide with an energy of 13 TeV
The Large Hadron Collider right now they collide with an energy of 13 TeV.
Two big detectors: ATLAS and CMS
Two big detectors: ATLAS and CMS
Reconstructing what happened

1 billion collisions per second

that produce 50,000 TB of data every year

Image credit: Andre Holzner, CERN
Reconstructing what happened
Finding the Higgs boson
Theory

the importance of
the Higgs
Fundamental interactions

**Quarks**
- u (up) quark: 2.2 MeV, +2/3
- d (down) quark: 4.7 MeV, -1/3

**Leptons**
- $\nu_e$ (e-neutrino): < 2 eV, 0
- e (electron): 0.51 MeV, -1

**Mediators**
- $\gamma$ (photon): 0 eV, 0
- g (gluon): 0 eV, 0
- W (W boson): 80 GeV, +1
- Z (Z boson): 91.2 GeV, 0
Symmetries explain the rationale of the interactions

The coordinate combination \( a_x b_x + a_y b_y \) gives always the same number if we turn the vectors around.

It's an invariant of the rotation symmetry.
Symmetries explain the rationale of the interactions

\[ a_x b_x + a_y b_y \text{ is an invariant of the symmetry.} \]

To combine A and B in a way that respects the rotation symmetry we must pair

- \( a_x \) with \( b_x \)
- \( a_y \) with \( b_y \)

and take the sum.

Other combinations are not allowed.
Symmetries explain the rationale of the interactions

For each force, a symmetry tells us which interactions must exist and which are forbidden.

Particles ↔ Components of some vectors (depending on the charge, color etc)
The importance of the Higgs boson

The symmetry of the weak interactions is a weird one: it forbids all the masses!

masses are allowed only if there is one extra particle: the Higgs boson
the stronger a particle interacts with the Higgs field, the larger its mass
## The Standard Model

### Quarks
- **Up** (u) charge +2/3, mass 2.2 MeV
- **Down** (d) charge -1/3, mass 4.7 MeV
- **Charm** (c) charge +2/3, mass 1.28 GeV
- **Strange** (s) charge -1/3, mass 96 MeV
- **Top** (t) charge +2/3, mass 173.2 GeV
- **Bottom** (b) charge -1/3, mass 4.18 GeV

### Leptons
- **Electron** (e) mass < 2 eV
- **Muon** (μ) mass < 0.19 MeV
- **Tau** (τ) mass < 18 MeV
- **Electron neutrino** (νₑ) mass < 0 eV
- **Muon neutrino** (ν₁) mass < 0 eV
- **Tau neutrino** (ν₂) mass < 0 eV

### Mediators
- **Gluon** (g) mass 0 GeV
- **Photon** (γ) mass 0 GeV
- **W boson** (W) mass 80 GeV
- **Z boson** (Z) mass 91.2 GeV

**Higgs boson** (h) mass 125.1 GeV
Experiment

Hunting the Higgs
What does the Higgs look like?

The Higgs lives for a very short time:

about $10^{-22}$ s

after that it decays into other lighter particles.

The easiest to detect are

2 photons or 4 leptons (electrons or muons)
Looking for the Higgs in LHC data

collect information about what comes out of the p p collisions

look for collisions that produced 2 photons or 4 leptons

there are so many ways this can happen!!
Looking for the Higgs in LHC data

2. Look for collisions that produced 2 photons or 4 leptons.
   - There are so many ways this can happen!!
3. For each collision event: can we explain this with some other process?
   - Yes: This is background: not what we were looking for.
   - No: It can be the Higgs!
4. Is the effect compatible with the theoretical expectation of the Higgs?
   - No: Nothing significant then. Just random events.
   - Yes: We have discovered it!
We have discovered it!

YES

Nothing significant then. Just random events.

NO

this is background: not what we were looking for

there are so many ways this can happen!!

for each collision event: can we explain this with some other process?

YES

important tools have been developed by theorists, that allow to simulate precisely what happens in the LHC

NO

it can be the Higgs!

NO

is the effect compatible with the theoretical expectation of the Higgs?

NO

having very accurate theoretical predictions is crucial!

YES

We have discovered it!
$\sqrt{s} = 7$ TeV \; \int L dt = 4.83 \text{ fb}^{-1} \quad \text{Nov 3, 2011}

$\sqrt{s} = 8$ TeV \; \int L dt = 20.65 \text{ fb}^{-1} \quad \text{Dec 9, 2012}

\textbf{ATLAS Preliminary}

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel

- Signal ($m_h = 125$ GeV)
- Background $ZZ^{(*)}$
- Background $Z + \text{jets, } t\bar{t}$
- Data

Image credit: ATLAS Collaboration, CERN
Open questions

Are there other particles that can be discovered at the LHC?

Why is the Higgs mass 125 GeV?

Why is the neutrinos’ mass not zero? And are they their own antiparticle or not?

Why are there 3 generations of quarks and leptons? Is there an explanation for their masses and mixing probabilities?

Why are we made of atoms and not antiatoms?
The End