Past, present future: LHC and future possibilities

Part 1:
Open problems in particle physics after the Higgs discovery

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The questions addressed by Particle physics are the same that guided the development of Natural Philosophy in the course of History.

- How does the Universe work?
- Where does it come from?
- Where is it going?

- What are the ultimate components of matter?
- How do they “move”?
- What “moves them”?

The most ambitious among all sciences!
Even the approach followed by ancient philosophers is similar to the one used by the modern physicist:

to indentify few fundamental principles, from which to derive the properties of all natural phenomena, both in the macrocosm (the sky, the Universe) and at the human scale

In common, the identification of two categories:

(a) The components of matter
(b) The forces that govern their behaviours
Example

Components: air, water, fire, earth

Forces:
- air and fire pushed upwards
- earth and water pulled downwards

Judgement of correctness:
how come a tree falls in the water, but then gets pushed up and floats?

Reevaluation of the theory (Archimedes)
- all matter is pulled downwards, but with intensity proportional to its weight:
  A body immersed in water receives a push upwards equal to the weight of the displaced water

=> the first historical example of "unification of forces"?

This theory is simpler, and better than the previous one, as it suddenly also explains new phenomena, like the wind: warm air is lighter than cold air, it goes up, and forces cold air to move in => the wind
Example: Unifying physics at the human and cosmic scales

I. Newton

\[ F = -G_N \frac{M \, m}{R^2} \]
Example: Unifying physics at the cosmic and microscopic scales

I. Newton

\[ F = - G_N \frac{M m}{R^2} \]

E. Rutherford

\[ F = - \alpha \frac{Q q}{R^2} \]

C-A de Coulomb
.... and from atomic to subnuclear ....

Structure within the Atom

Quark
Size < $10^{-19}$ m

Electron
Size < $10^{-18}$ m

Nucleus
Size = $10^{-14}$ m

Neutron and Proton
Size = $10^{-15}$ m

Atom
Size = $10^{-10}$ m

If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

History of the Universe

Key:
- W, Z bosons
- Quark
- Gluon
- Electron
- Muon
- Neutrino

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dark matter
23%

dark energy
73%

non-luminous atoms (e.g. planets, dead stars, dust, etc), ~4%

stars, neutrinos, photons ~0.5%
The main task of CERN is to continue exploring the smallest scales, to unveil the phenomena that took place at the beginning of the history of the Universe, and which shaped its evolution until today.
“Watching” the very small

- To resolve details at a scale $L$, we must use waves with a wavelength $\lambda$ smaller than $L$

  E.g.: the radar at an airport operates with a wavelength $\lambda \sim 30\text{cm}$. It cannot resolve the presence of a single flying bird!

  The smaller $L$, the smaller the wavelength $\lambda$

  Since $E \sim$ frequency and frequency $\sim 1/\lambda \Rightarrow$
  
  - the smaller the object size $L$, the bigger the energy required to “see” it!
This large energy, however, must be concentrated in a small volume, of a size comparable to $\lambda$.

A hammer hit carries much more energy than the light beam of a microscope, but we cannot see a microbe with it!

$\Rightarrow$ to study physics at the shortest distances, we need small probes, of the highest energies.
\[ E = \sqrt{\frac{M c^2}{1 - \frac{v^2}{c^2}}} \]
Large energies not only allow to probe short distances, but give the possibility to create new, heavier particles!!
Enters the LHC

booster, 157m (1972)

proton synchrotron
628m (1959)

super-proton synchrotron,
7km (1976)

linac

PROTON SYNCHROTRON
628m (1959)

LINAC

BOOSTER, 157m (1972)
LHC, 27 km
(1989 as LEP, 2008 as LHC)

Super-proton synchrotron,
7 km (1976)

Proton synchrotron
628 m (1959)

Linac

Booster, 157 m (1972)
The LHC accelerator

- $E_{\text{beam}} = 7000 \text{ GeV} \sim 7500 \ m_{\text{proton}} \ c^2$
  - $E=mc^2 / \sqrt{1-v^2/c^2} \Rightarrow v = 0.99999999 \ c$

- $E_{\text{beam}} = 7000 \text{ GeV} \sim 7 \times 10^{12} \text{ eV} \sim 5 \text{ trillions} \ 1.5V \text{ batteries}$
  - $\sim 100 \text{ M km of batteries, about } d[\text{Earth-Sun}]$

- $N_{\text{proton}} \sim 10^{11}/\text{bunch} \times 2800 \text{ bunches/beam} \times 2 \text{ beams} \sim 10^{14}$

- Energy stored $\sim 350 \text{ MJ} \sim 80 \text{ kg of TNT} \sim \text{TGV running full speed}$
2808 proton bunches
10,000 turns/sec
40 million bunch crossings per sec
The Standard Model
# LEPTONS

<table>
<thead>
<tr>
<th>Particle</th>
<th>Electric Charge</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>-1</td>
<td>Electric charge -1. Responsible for electricity and chemical reactions. Rarely interacts with other matter.</td>
</tr>
<tr>
<td>electron neutrino</td>
<td>0</td>
<td>Created with muons when some particles decay.</td>
</tr>
</tbody>
</table>

# QUARKS

<table>
<thead>
<tr>
<th>Quark</th>
<th>Electric Charge</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>up</td>
<td>+2/3</td>
<td>Protons have 2 up quarks. Neutrons have 1 up quark.</td>
</tr>
<tr>
<td>down</td>
<td>-1/3</td>
<td>... and one down quark. ... and two down quarks.</td>
</tr>
<tr>
<td>charm</td>
<td></td>
<td>A heavier relative of the up.</td>
</tr>
<tr>
<td>strange</td>
<td></td>
<td>A heavier relative of the down.</td>
</tr>
<tr>
<td>top</td>
<td></td>
<td>Heavier still, recently observed.</td>
</tr>
<tr>
<td>bottom</td>
<td></td>
<td>Heavier still.</td>
</tr>
</tbody>
</table>

ANTIMATTER

Each particle also has an antimatter counterpart ... sort of a mirror image.
## The forces in Nature

<table>
<thead>
<tr>
<th>TYPE</th>
<th>INTENSITY OF FORCES (DECREASING ORDER)</th>
<th>BINDING PARTICLE (FIELD QUANTUM)</th>
<th>OCCURS IN:</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRONG NUCLEAR FORCE</td>
<td>$\sim 1$</td>
<td>GLUONS (NO MASS)</td>
<td>ATOMIC NUCLEUS</td>
</tr>
<tr>
<td>ELECTRO-MAGNETIC FORCE</td>
<td>$\sim 10^{-3}$</td>
<td>PHOTONS (NO MASS)</td>
<td>ATOMIC SHELL ELECTROTECHNIQUE</td>
</tr>
<tr>
<td>WEAK NUCLEAR FORCE</td>
<td>$\sim 10^{-5}$</td>
<td>BOSONS $Z^0, W^+, W^-$ (HEAVY)</td>
<td>RADIOACTIVE BETA DESINTEGRATION</td>
</tr>
<tr>
<td>GRAVITATION</td>
<td>$\sim 10^{-38}$</td>
<td>GRAVITONS (?)</td>
<td>HEAVENLY BODIES</td>
</tr>
</tbody>
</table>

**THE EXCHANGE OF PARTICLES IS RESPONSIBLE FOR THE FORCE**
Lepton Interactions \((l=e,\mu,\tau)\)

- \(\alpha\) \(-e\) = electric charge

- \(\alpha\) \(g_W\) = weak charge
Quark Interactions

$\alpha \frac{2}{3} e$

Photon

$\alpha \frac{-1}{3} e$

Photon

$q' \ W \ \propto g_W$

$q \ Z \ \propto g_S = \text{strong coupling}$
From these fundamental building blocks (elementary particles and interactions), one gets all matter that we are made of, that surrounds us, and that forms all structures observed in the universe: planets, stars, galaxies
Example

Proton

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

Neutron

\[ Q = \frac{2}{3}e - \frac{1}{3}e - \frac{1}{3}e = 0 \]
Example: neutron decay

\[ n \rightarrow p \text{ electron neutrino} \]
Example: radioactivity

\[ N_Z \rightarrow N_{Z+1} e^{-} \nu \]

Diagram showing the process of radioactivity with particles and quarks.
Transformations like the previous one, in which protons and neutrons turn into each other with emission of electrons and neutrinos, gave rise at the beginning of the Universe to the generation of all light elements (hydrogen, deuterium, helium, lithium, etc).

\[
4 \text{p} \rightarrow \text{He} + 2 \text{e}^+ + 2 \nu + 1.6 \times 10^{-13} \text{J} \\
4 \times 10^{-17} \text{Kcalories}
\]

They are the driving mechanism for energy creation in the stars, transforming the lighter elements into heavier ones. In the biggest stars, this leads to the creation of heavy nuclei like oxygen, silicon, ..., iron. At the end of their lives, the gravitational pressure leads to a gigantic final collapse, followed by an explosion that scatters all these elements through space where, meeting gas nebulae ready to form new stars, they give rise to planetary systems like ours.
The Higgs boson
The vacuum, and the Higgs field

We call vacuum the state of any volume of the Universe if we were to take away from it all matter and interactions from nearby matter.

The Standard Model predicts that the vacuum is occupied by a constant density field of the Higgs boson, which we cannot “take away”.

This permeates the Universe like an ether, everywhere and permanently, since about $10^{-10}$ seconds after the Big Bang.

Interacting with this field, particles acquire their mass.
The Higgs and particles’ masses

Light propagating in a medium is slowed down by its continuous interaction with the medium itself

\[ c_{\text{medium}} < c_{\text{vacuum}} \]

The time it takes to move across the medium is longer than if light were propagating in the vacuum,

Think of the Higgs field as being a continuum medium embedding the whole Universe. Particles interacting with it will undergo a similar “slow-down” phenomenon. Rather than “slowing down”, however, the interaction with the Higgs medium gives them “inertia” \( \Rightarrow \text{mass} \)
Detecting the Higgs boson

Like any other medium, the Higgs continuum background can be perturbed. Similarly to what happens if we bang on a table, creating sound waves, if we “bang” on the Higgs background (something achieved by concentrating a lot of energy in a small volume) we can stimulate “Higgs waves”. These waves manifest themselves as particles, the so-called Higgs bosons.

What is required is that the energy available be larger than the Higgs mass ⇒ LHC !!!
Higgs production at the LHC
\( H \rightarrow 2 \ \text{photons} \)

\( H \rightarrow ZZ^* \rightarrow 4 \ \text{leptons} \)
To firmly establish the “what”:
- discover the crucial missing element of the Standard Model, namely the **Higgs boson** => done!
- Are there new fundamental interactions, too weak to have been observed so far?
- Are there new generations of quarks or leptons?
- Are quarks & leptons elementary or do they have a substructure?
- What is the particle responsible for the **Dark Matter** in the Universe?
Searching for new forces ....

\[ \int L \, dt = 5.0 \, \text{fb}^{-1} \]

\[ \sqrt{s} = 7 \, \text{TeV} \]
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- discover the crucial missing element of the Standard Model, namely the Higgs boson => done!
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To firmly establish the “how”:
- “how” particles acquire a mass: is the Higgs mechanism of the Standard Model correct? => continue study of Higgs properties
- “how” does the strong force work
- “how” matter behaves under the Big Bang conditions of high density and temperature => continue study of heavy ion collisions
Probing Higgs properties...
Studying propagation through the quark-gluon plasma ...
So far, no deviation from the predictions of the SM has been found!

- Good news!
  - The Standard Model is confirmed!!

- Bad news!
  - If we don’t see deviations from the SM, how do we move forward, towards answering other big questions?
Big questions still open after the first 3 yrs of LHC

- What is the real source of the Higgs field that permeates the Universe?

- What are the particles forming dark matter?

- How was the matter-antimatter asymmetry of the Universe generated?

- Why are there 3 families of quarks and leptons, so similar but also so different from each other? Why are neutrinos so different from everything else?
Run 2: 13 to 14 TeV c.m. with peak luminosity of $\sim1.7\times10^{34}$ cm\(^{-2}\) s\(^{-1}\)

Run 3: 14 TeV c.m. with peak luminosity of $\sim2\times10^{34}$ cm\(^{-2}\) s\(^{-1}\)

LS2: 18 months
Connection of LINAC4
LHC Injectors Upgrade

LS3: 30 months
High Luminosity LHC

to be followed by 10 more years, 2025-2035, to collect $>100$ times more data than currently available!!