Particle Physics and its History

Cognitive Festival
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Ancient building blocks of the Universe
What is the world made out of?

What are we made out of?

**Ogg** (many years BC)
What is inside?

**Aristotele** (384–322 BC)
Space and all matter is continuously filled

**Democritus** (460–371 BC)
Matter consists of indivisible elementary particles
atomos (αΤΟΜΟΣ) = indivisible

**Plato** (ca 428–348 BC)
Elementary symmetries

- Fire
- Earth
- Air
- Water
- Ether
What is the world made out of?

What are we made out of?

WHO IS RIGHT?

THINKING ALONE DOES NOT GIVE THE ANSWER!

HOW TO PROCEED?

DO EXPERIMENTS AND GET THE ANSWERS!

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Matter consists of indivisible elementary particles, atomos (ατομος) = indivisible

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Space and all matter is continuously filled

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Elementary symmetries

Ogg (many years BC)
What is inside?
Scattering experiments

The path to an understanding
of the fabric of space and time
Scattering Particles – what is in the Black Box?
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Scattering Particles – an every day experience

Too ‘see’ an apple, you need to scatter particles off it.

- Photons are the particles that make up light
- The eye measures scattered photons off an apple from a light source
  - Your eyes are particle detectors, transforming the properties of photons into electric signals transported via the visual nerve to a vast processing and reconstruction engine – your brain.
  - Momentum & Energy - i.e. direction of flight and colour
  - Intensity - i.e. number of such photons per second
- The brain reconstructs out of this in a masterful online-reconstruction of the data in real time the
  → Shape, Size, Distance, Colour, Texture of the Apple
Resolving small scale objects

All particles have an associated wavelength → quantum mechanics

Particle wavelength: \( \lambda = \frac{h}{p} = \frac{\text{Planck's constant}}{\text{momentum}} \)

One needs huge momenta to resolve small scale structures

→ One needs big accelerators to go deep into the heart of matter

The wavelength of the photons determines the resolution power to see small scale structures.

Even the strongest microscope operating with light is incapable of resolving structures of the size of an atom.

\[ \lambda = 1 \text{ nm} \]

E.g. accelerating an electron with a standard 1.5 V battery
Unknown object in a cave

Wavelength ~ diameter of a basket ball

After many basket balls thrown
Unknown object in a cave

Wavelength ~ diameter of a tennis ball

After many tennis balls thrown
Unknown object in a cave

Wavelength ~ diameter of a marble

After many marbles thrown

better dash off !!
A brief historic overview

using particle accelerators at ever increasing energies
120 years of accelerating particles

1897 Accelerating electrons
Cathode ray tube
J.J. Thomson

1931 First circular accelerator
Ernest O. Lawrence & M. Stanley Livingston

1940

Today: LHC
1894-1897 discovery of the electron

J.J. Thomson discovered the electron and also determined its mass through scattering of cathode rays at gas molecules in the rest gas of the cathode ray tube.

“Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen?” (J.J. Thomson)

Cathode Rays Philosophical Magazine, 44, 293 (1897)

\[ m_e \approx \frac{m_H}{1836} \]

Atoms are not elementary particles

Thomson’s model of the inner structure of the atom

- atoms consist out of a positively charged sphere
- negatively charged electrons are evenly distributed
- the radius \( r \) of an atom is \( r \sim 10^{-10} \) m.

Sir Joseph John Thomson
*18 December 1856, Manchester
†30 August 1940, Cambridge

Nobel Prize 1906
“in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases.”
Atoms have a positively charged, massive nuclei. Negatively charged electrons surround the nuclei. The radius of the nuclei is $10^{-15} \text{ m} \approx 10^{-5} \times$ atomic radius. The mass of the nuclei is approximately equal to the mass of the atom.

The scattering of alpha and beta particles by matter and the structure of the atom
By E. Rutherford, Phil.Mag.Ser. 6 21, p. 669-688, (April, 1911)
The inside of protons....

The **wavelength** of the photon corresponds to the diameter of the projectile used

- basketball
- tennis ball
- marble

The higher the collision energy, the smaller the wavelength of the penetrating photon and thus higher resolving power.

➢ **Protons** and **neutrons** consist out of **quarks** and **gluons**.

➢ Three quarks (valence-quarks) determine the quantum numbers of the proton (or neutron).

➢ Valence-quarks are immersed in a sea of virtual quark–anti-quark pairs and gluons.
The Innermost of Matter Revealed

using Accelerators

If an atom’s radius would be as large as from Tbilisi to CERN (3000 km),
the LHC could still resolve 3 millimetre scale objects.
Accelerators and discovered particles

A “Livingston plot” showing the evolution of accelerator laboratory energy from 1930 until 2005. Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.

Energy equivalent to a fix-target experiment

\[ E_{FT}^{obs} = \frac{E_{cm}^2}{2m_p} \]

- Fix-target experiment, beam energy measured in laboratory system
- \( E_{cm} \) Collision energy measured in centre of momentum system

1 MeV, 10 MeV, 100 MeV, 1 GeV, 10 GeV, 100 GeV, 1 TeV, 10 TeV, 100 TeV, 1 PeV, 10 PeV, 100 PeV, 1 EeV

LHC

LEP

HERA

ISR

SppS

Tevatron

The Quark Idea (up, down, strange)
(top)

\( \nu \)
\( \tau \)

\( \Lambda_b \)

\( B_s \)

1910
1920
1930
1940
1950
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010

\( \phi \)
\( \omega \)
\( \rho \)
\( \rho^0 \)
\( \omega^0 \)
\( \phi^0 \)
\( \pi^+ \)
\( \pi^- \)
\( \mu^+ \)
\( \mu^- \)
\( \pi^0 \)
\( \eta \)
\( \eta' \)
\( \Omega^- \)
\( \kappa^0 \)
\( \Lambda \)
\( \Sigma^- \)
\( \Xi^- \)
\( \Psi^- \)
\( \Sigma^0 \)
\( \Xi^0 \)
\( \Omega^- \)
\( \Psi^- \)
\( \Psi^0 \)

...and many more!

...and many more!

Energy level
Matter and Forces
Matter, Space and Forces

Matter is composed out of building blocks → the elementary particles.

The variety of all complex systems and everything in nature and the whole Universe is composed out of these elementary particles.

These elementary particles have no inner structure, they show no spatial dimension.

Space is probably completely empty

But why does matter – e.g. a table – appear massive?

The particles interact with each other → fundamental forces!

What are these forces, that bind nature together?
Natures four fundamental Forces

Gravity

electro-magnetic force

strong force

weak force
Forces

Forces between particles are mediated by particles!
Photons, gluons and vector-bosons are well known and well established.

The graviton lacks experimental evidence...
A Universe full of Particles

Every cow, all the trees, the stones, humans, the planets, the sun, the stars and everything else consist of:

- At least 99.999...999% empty space
- Small particles (<10^{-19} m – point like?)
  - electrons
  - up-quarks
  - down-quarks

they are hold together by

- photons
- gluons
- vector-bosons
- gravity

Furthermore, vector-bosons (weak force) transmute **electrons** into **neutrinos**

- Every human radiates of 340 million neutrinos – daily!
  (20 mg $^{40}$Ka)

(20 mg $^{40}$Ka)
The Standard Model
of Particle Physics
The Standard Model fits on a T-shirt

An exact description of all experimental results ever made (except gravity...)

**Basic symmetries, quantum mechanics** and **special relativity** are enough to understand the dynamics of elementary particles – that are the building blocks of the Universe.

**I would say, quite an achievement...**

1st line: the **boson fields** of the basic forces (electromagnetic, weak, strong)

2nd line: interactions involving **quarks** and **leptons**.

3rd line: **mass generation** of quarks and leptons through their interaction with the Higgs-field $\phi$.

4th line: **mass generation** of bosons and the Higgs vacuum.

well, some questions remain... the work hasn’t finished!
The Standard Model fits on a T-shirt

is a short notation of...

1st line: the boson fields of the basic forces (electromagnetic, weak, strong)

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4th line: mass generation of bosons and the Higgs vacuum.
Higgs
$p\cdot p$ collision $\rightarrow$ 2 electrons & 2 muons
Higgs production in $p-p$ collisions
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".
Particles and Cosmology

Let’s draw the Universe
Particle collisions resemble the Big Bang
Understanding the very first moments of our Universe after the Big Bang

380,000 years
Constructing the Universe

- Knowing the elementary particles, their properties and interactions, i.e. the Standard Model, we now know how to construct the universe.
- It consists out of elementary particles.
- It all started with a Big Bang some 13.7 billion years ago.
- We can try drawing the picture of evolution of all and everything – from the Big Bang onward.

LHC 14 TeV ≈ 10^{-14} s
Particle Physics meets Cosmology

The Ouroboros "tail-devouring snake"
Particle Physics meets Cosmology

The Ouroboros "tail-devouring snake"
A journey to continue
Unifying Theories

Magnetism
- Faraday, Ampère, Biot, Savart, ...
- Electro-dynamics
  - QED
  - Feynman
- Electricity
  - Maxwell
  - long-range
- Weak force
  - Weak theory
    - Fermi
    - long-range
    - short-range
- Strong force
  - short-range
- Celestial mechanics
  - Kepler
  - long-range
- Terrestrial dynamics
  - Galilei
  - Gravity
  - General relativity
    - Einstein
  - Newton
- Electro-weak theory
  - Glashow, Salam, Weinberg
  - Veltmann, ’t Hooft, ...
- Standard Model
  - SUSY
  - Grand Unification
- Quantum gravity
- Theory of Everything

Classical Physics
Relativity & Quantum fields
Strings?
The end

or maybe the beginning for you...