School of Computational Techniques for Physics Students in Kenya

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Introduction to particle physics

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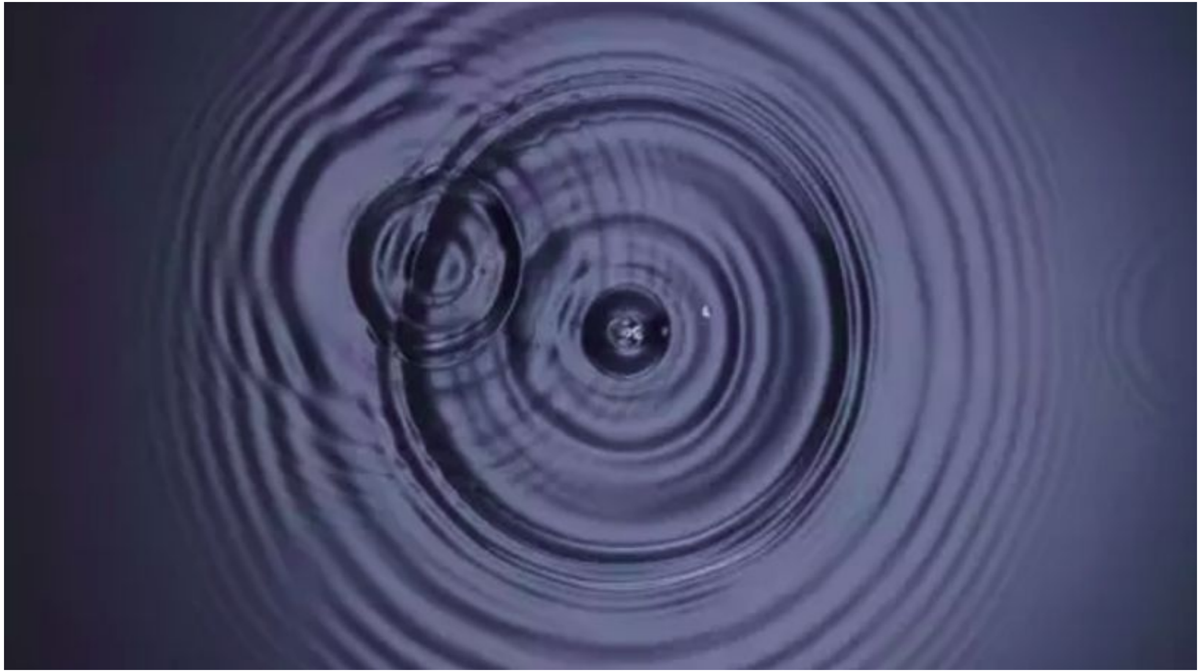
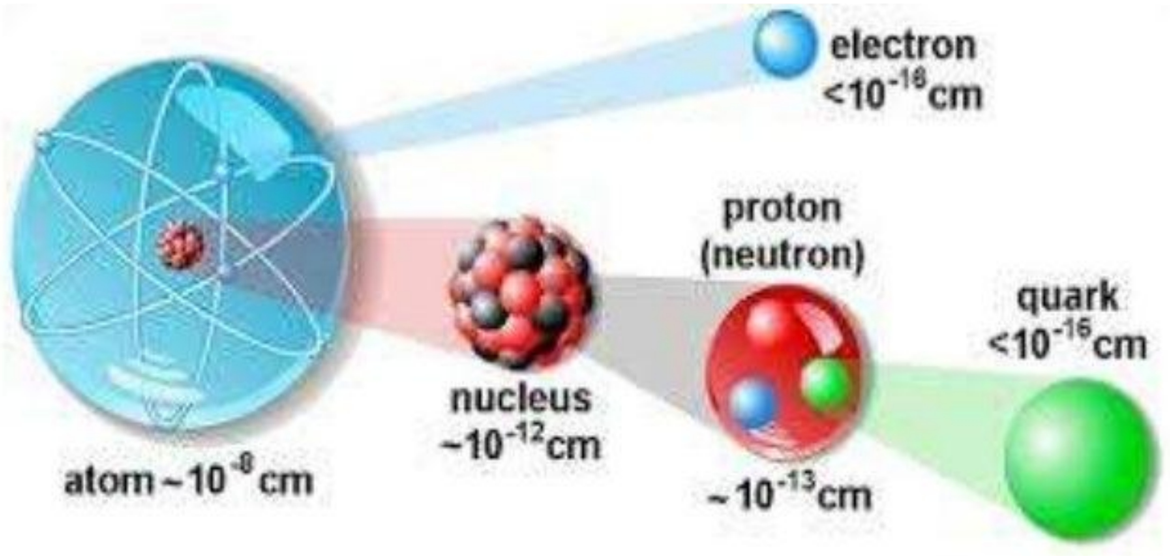
What is a particle?

The perturbation of a **classical field** propagates in space like a **wave**
The perturbation of a **quantum field** propagates in space like a **particle**



A **particle** is a complex, quantum object with **wave-like** and **particle-like** properties

Elementary and composite particles



An **elementary particle** is a particle with no internal structure (as far as we know)
A **composite particle** is instead composed by two or more elementary particles

The fundamental forces of nature

An interaction between particles is modelled through exchange of vector bosons
These are responsible for three of the four fundamental forces of nature

The fundamental forces of nature

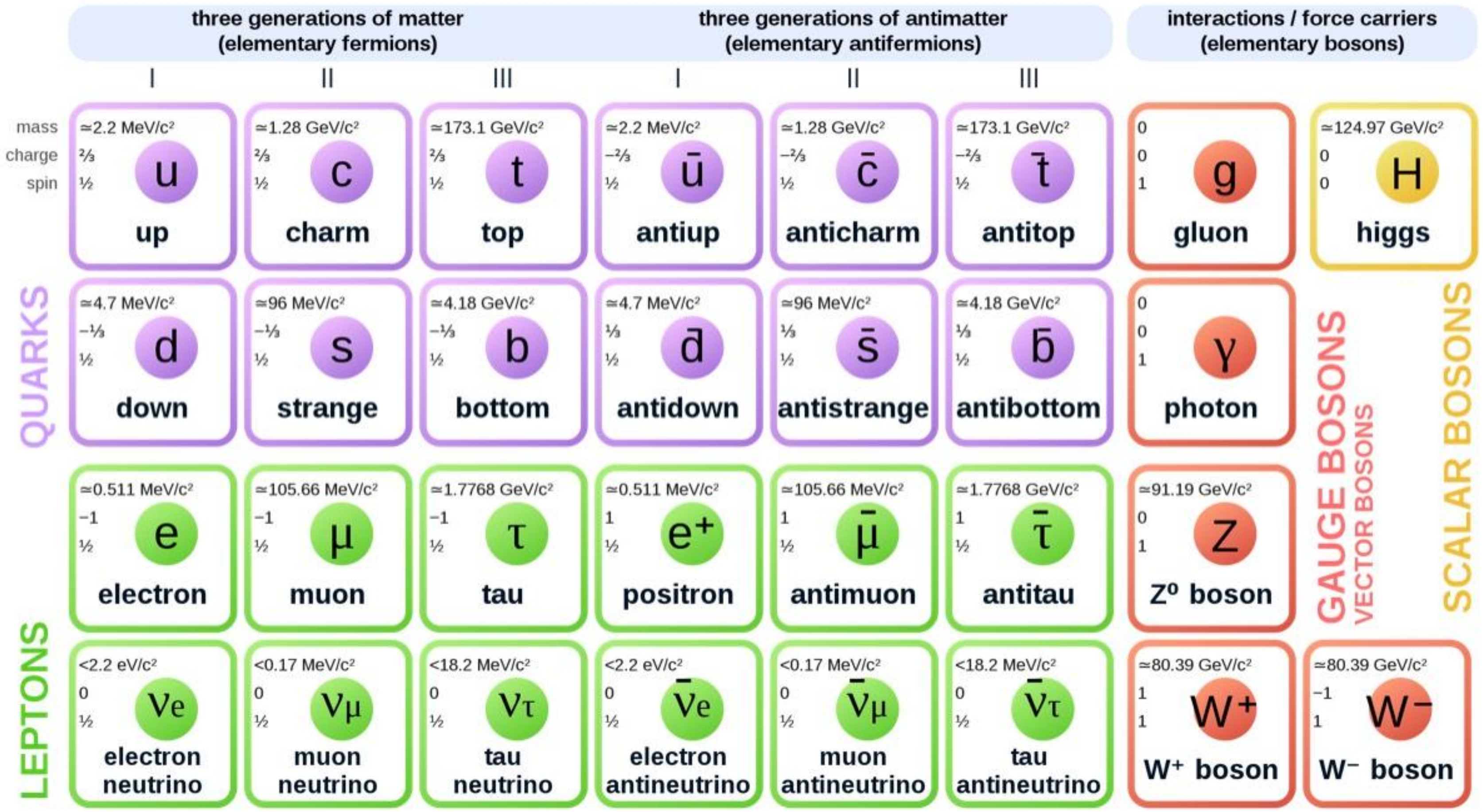
Electromagnetic interactions: responsible for electrical and magnetic phenomena, atomic binding and stability, molecular binding…

Strong nuclear interactions: responsible for the binding and stability of the atomic nuclei, for the binding of quarks into composite particles…

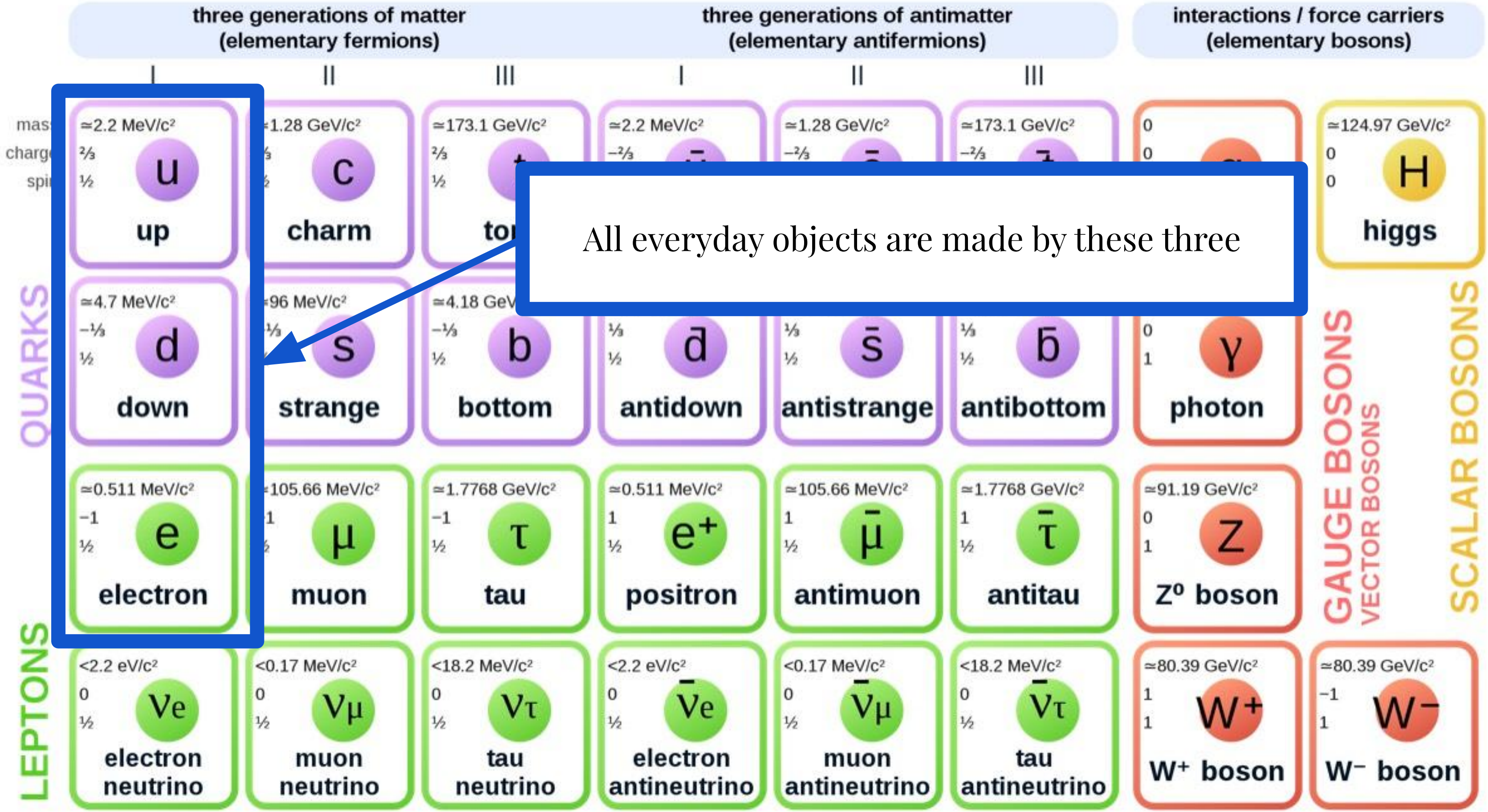
Weak nuclear interactions: responsible for radioactivity, β decays, matter-antimatter asymmetry…

Gravity is in principle the fourth fundamental force, but its description is based on geometrical properties of space-time and there is no way to include it in the Standard Model of particles.

The Standard Model of elementary particles

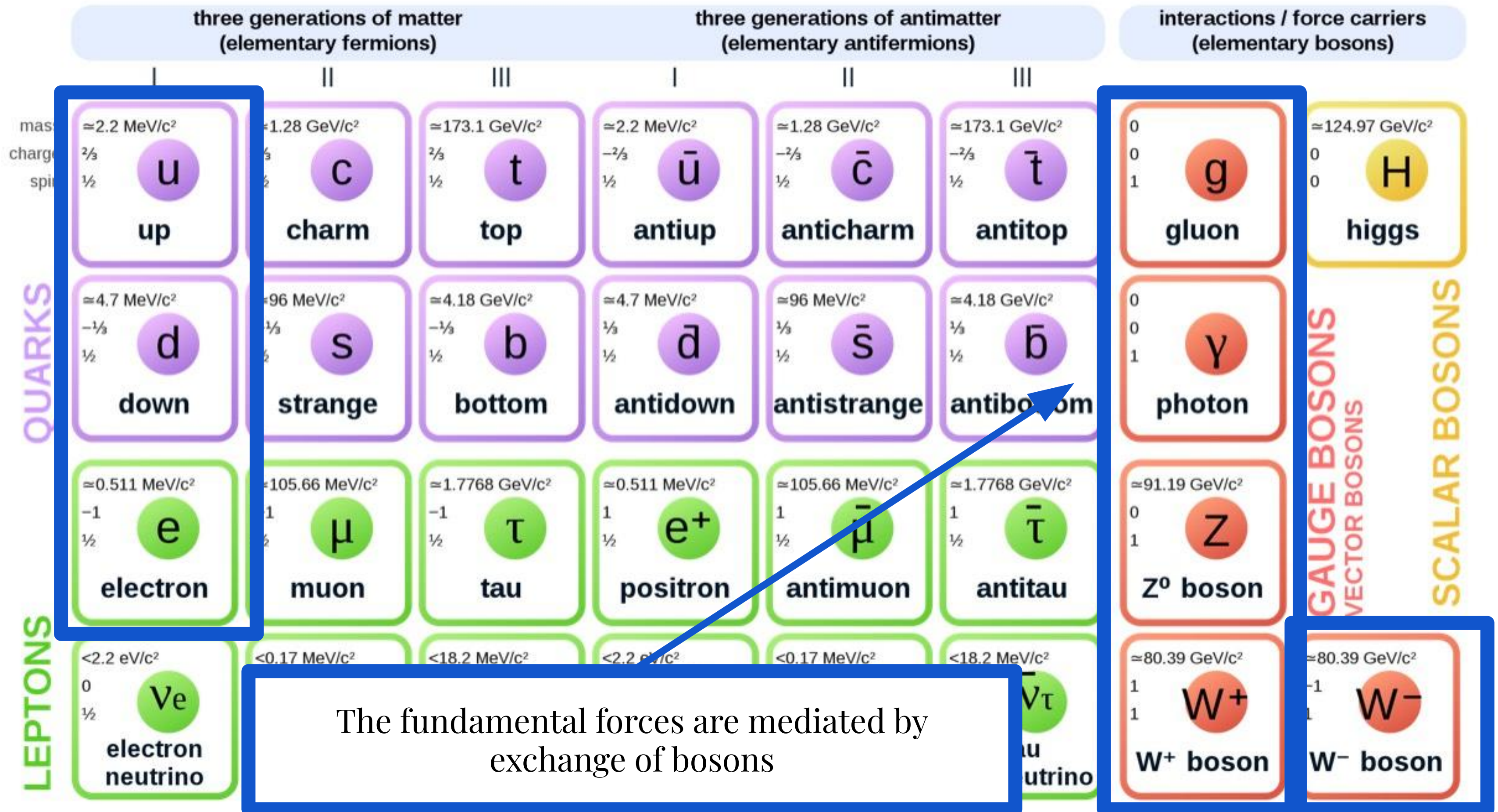


The Standard Model of elementary particles



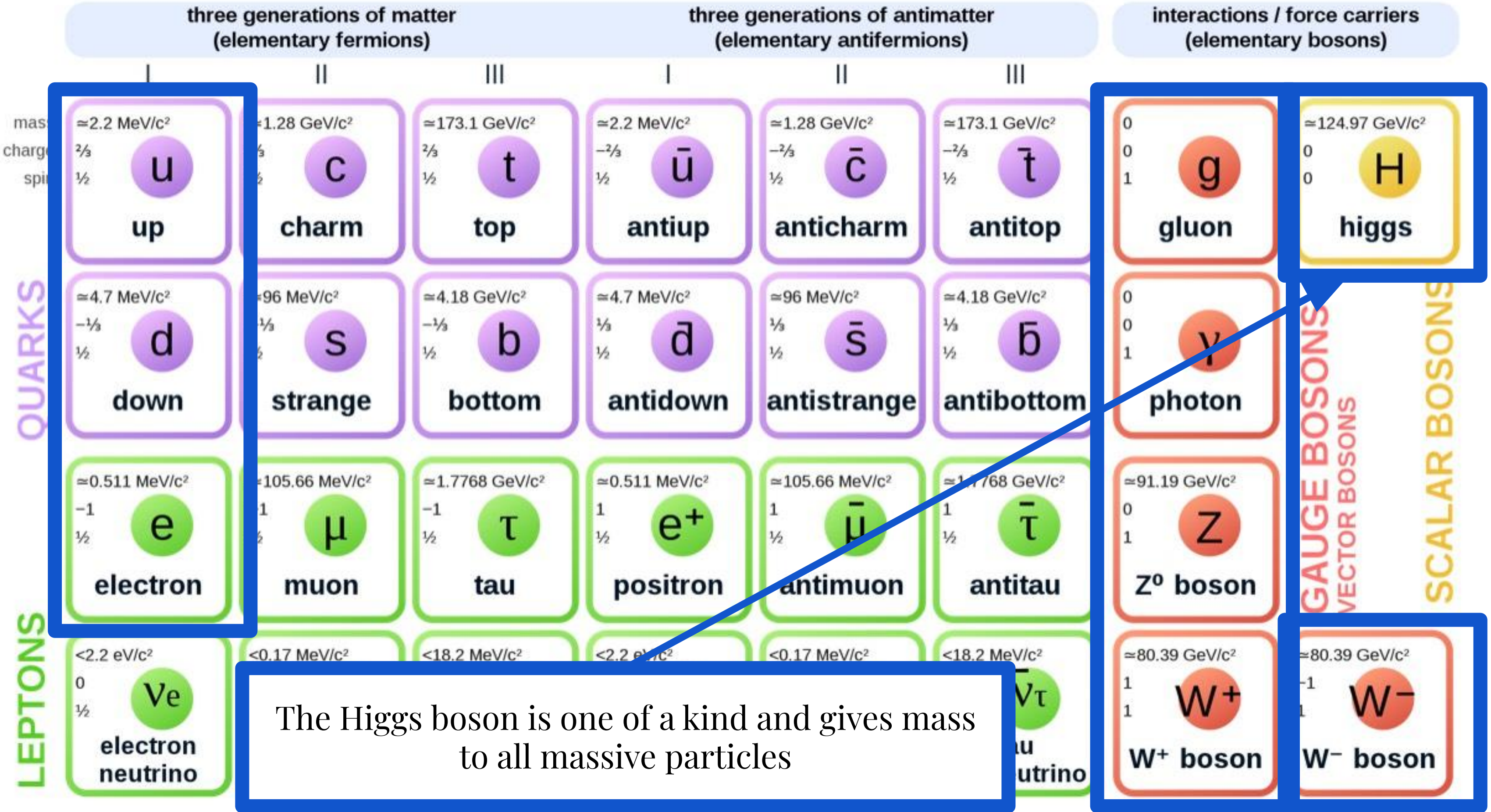
All everyday objects are made by these three

The Standard Model of elementary particles



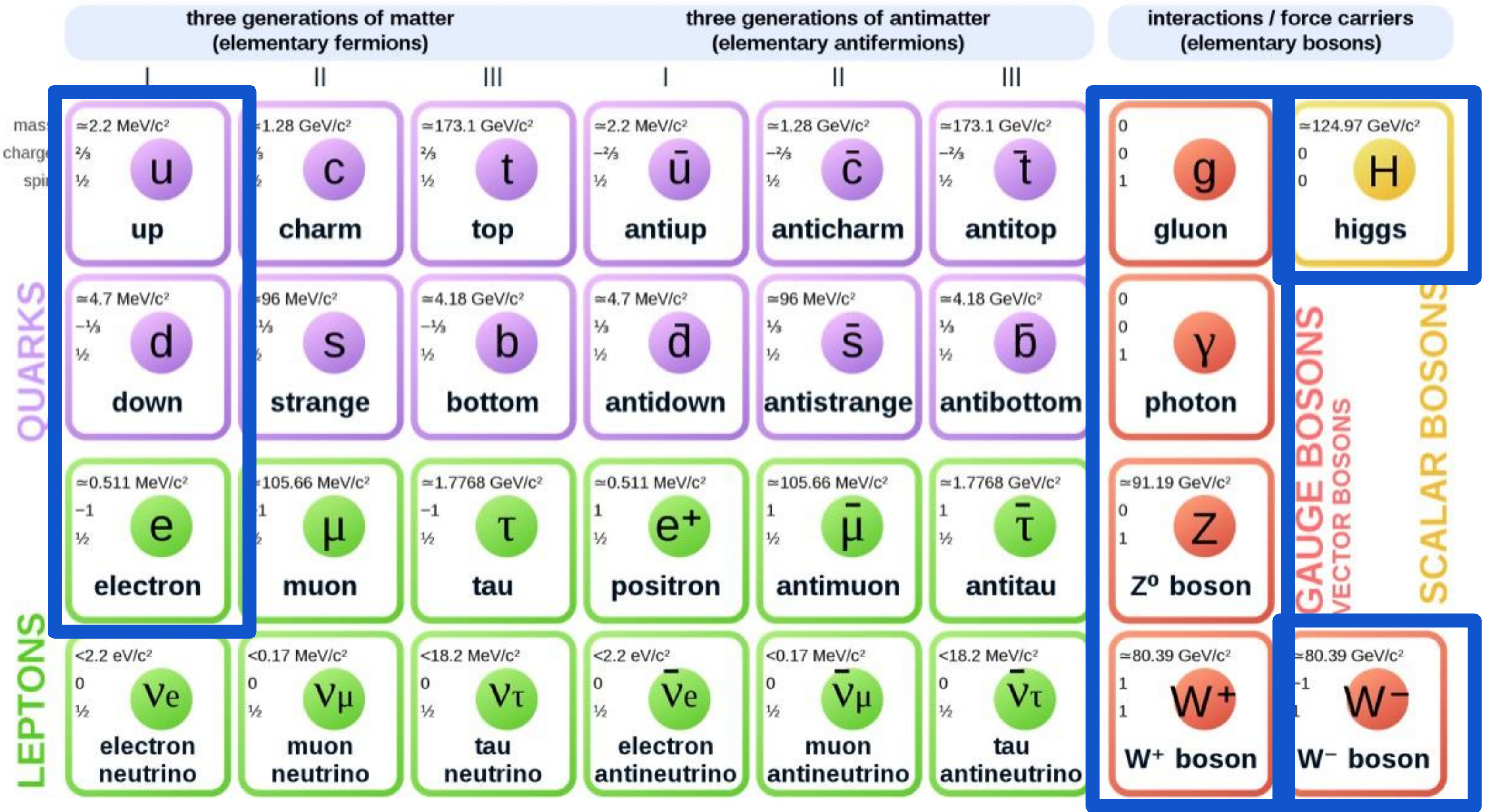
The fundamental forces are mediated by exchange of bosons

The Standard Model of elementary particles



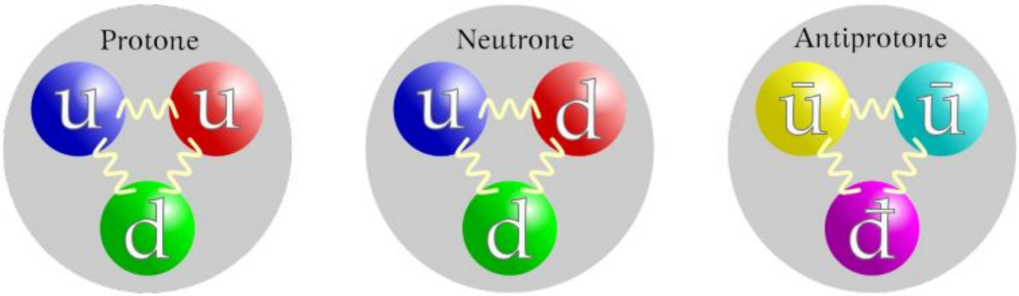
The Higgs boson is one of a kind and gives mass to all massive particles

The Standard Model of elementary particles

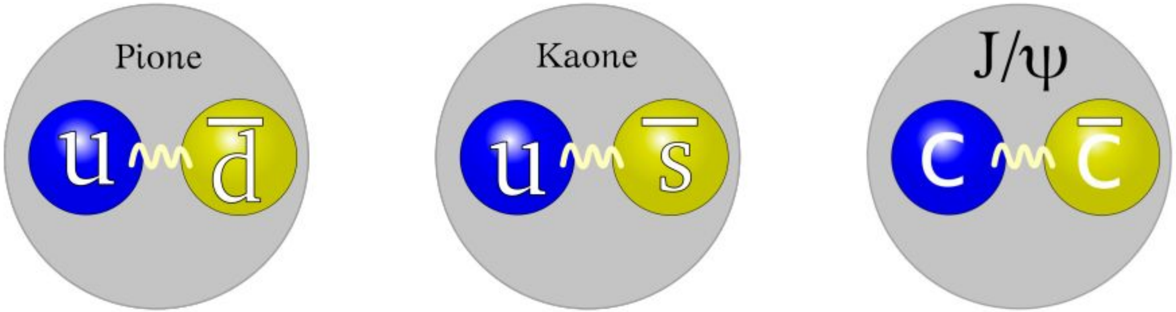


Composite particles

Fundamental particles can aggregate to form more complex, **composite** particles
Three quarks form a **baryon**, three antiquarks form an **antibaryon**



A quark and an antiquark form a **meson**



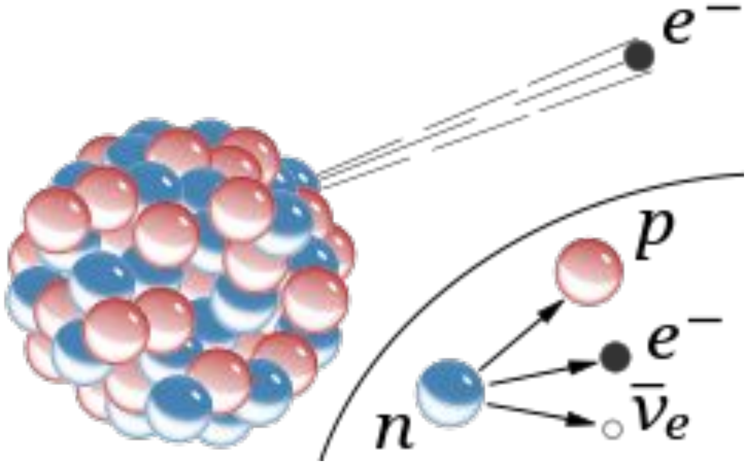
Radioactive decays

We know today that unstable atomic nuclei can rearrange their internal structure to achieve a more stable equilibrium, losing some energy in the process.

There are several types of radioactive decays, some of which are regulated by the strong or electromagnetic forces.

A kind of “special” radioactive decay is the so-called **beta decay**

This decay is regulated by the weak force



Radioactive decays

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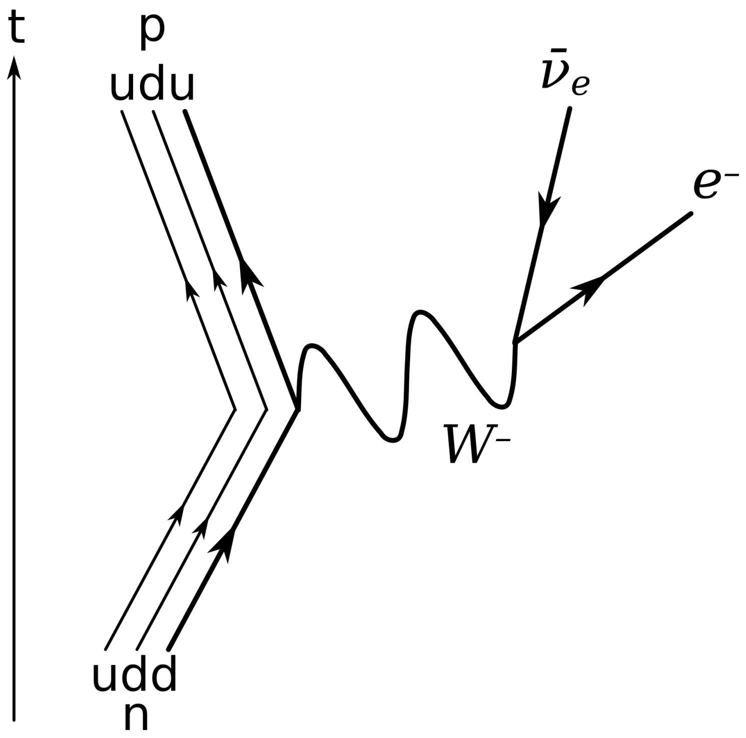
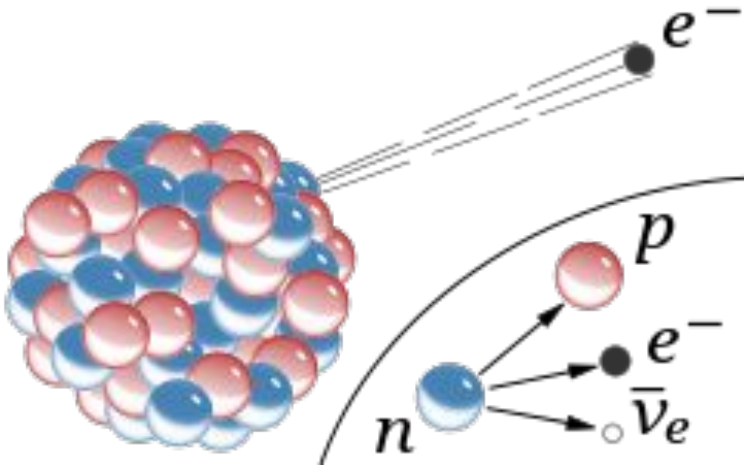
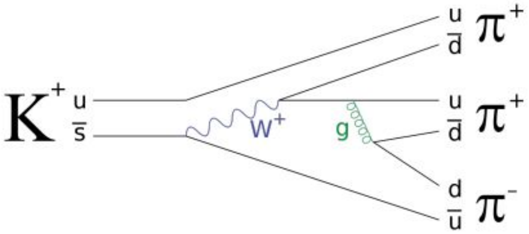
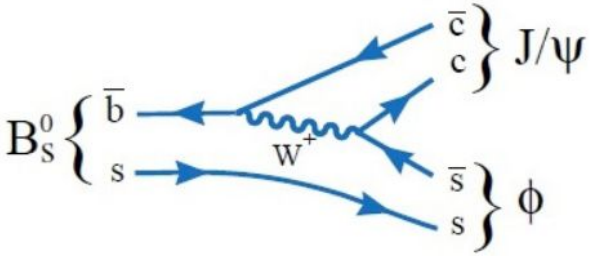




Particle decays

Almost all composite particles are unstable and they tend to disaggregate, or **decay** into smaller, lighter particles conserving energy and momentum





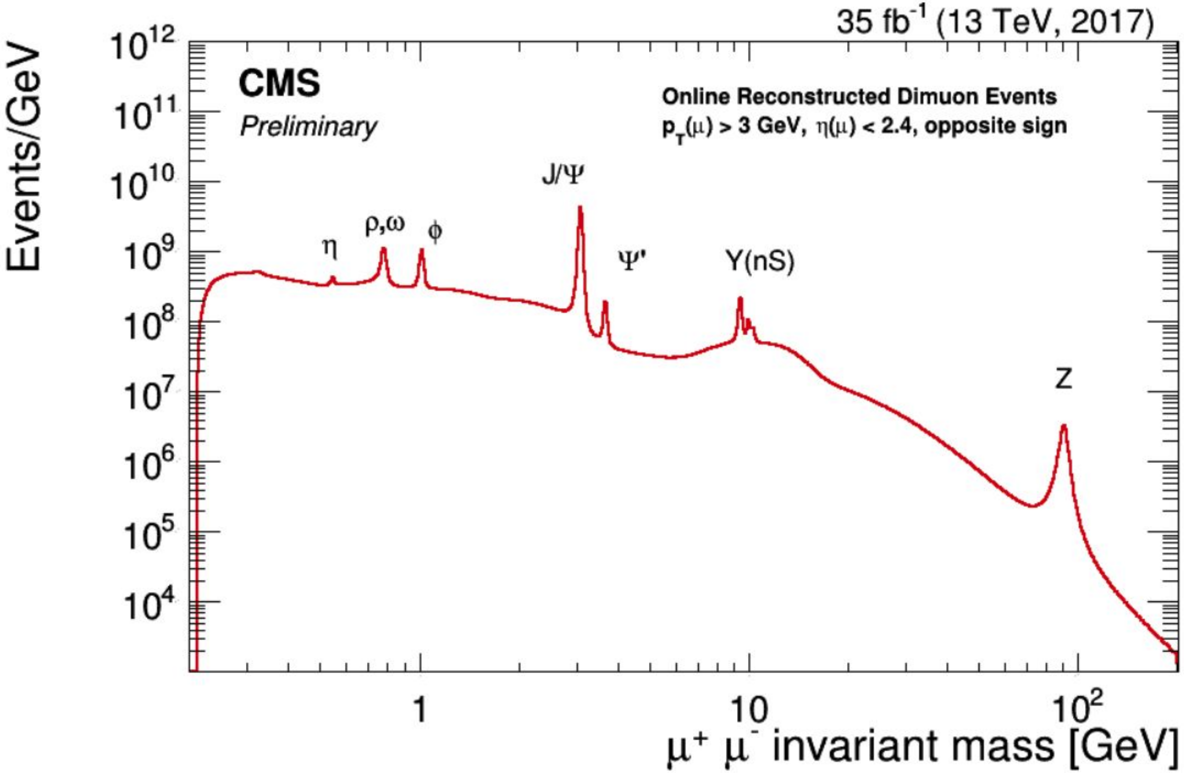
The typical decay times range from 10^{-10} to 10^{-25} seconds. So **we are only able to observe a small subclass of particles** with our instruments!

Luckily, we can use the conservation of momentum and energy along with Einstein's equation to calculate the mass of the original particle!

$$E = \sqrt{m^2c^4 + pc^2} \implies mc^2 = \sqrt{(E_1 + E_2 + E_3 + ...)^2 - (p_1 + p_2 + p_3 + ...)^2 c^4}$$

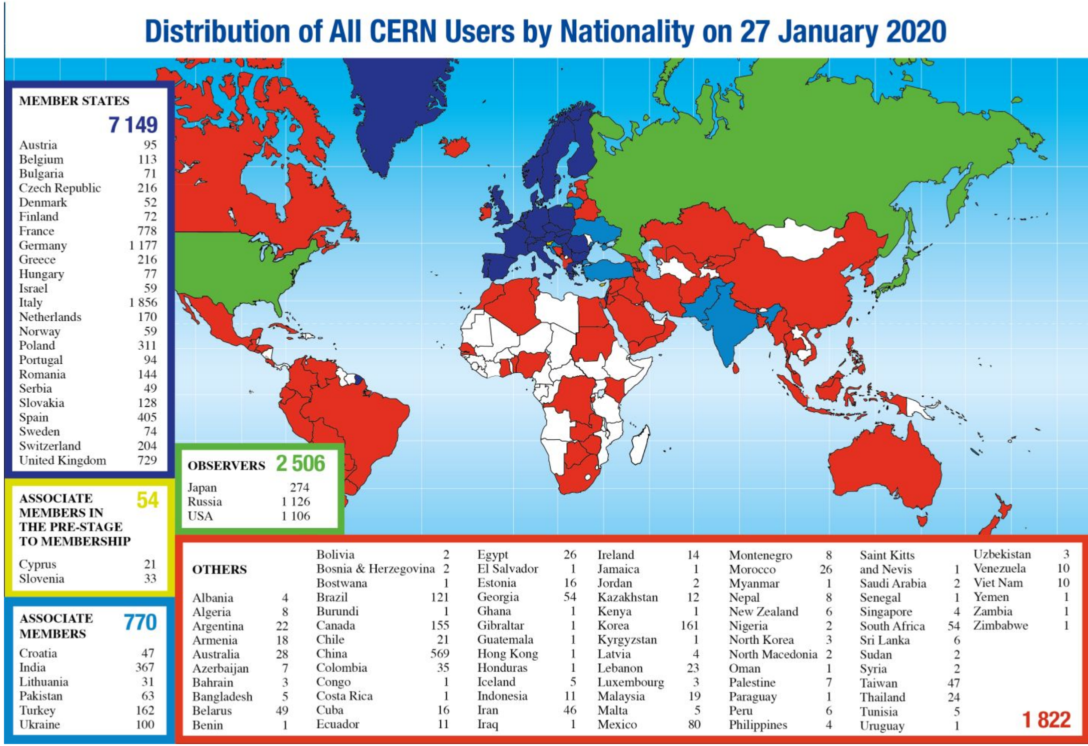
Particle decays

We can observe particles decaying "immediately" by looking at the mass of the combination of their (more stable) decay products!



CERN

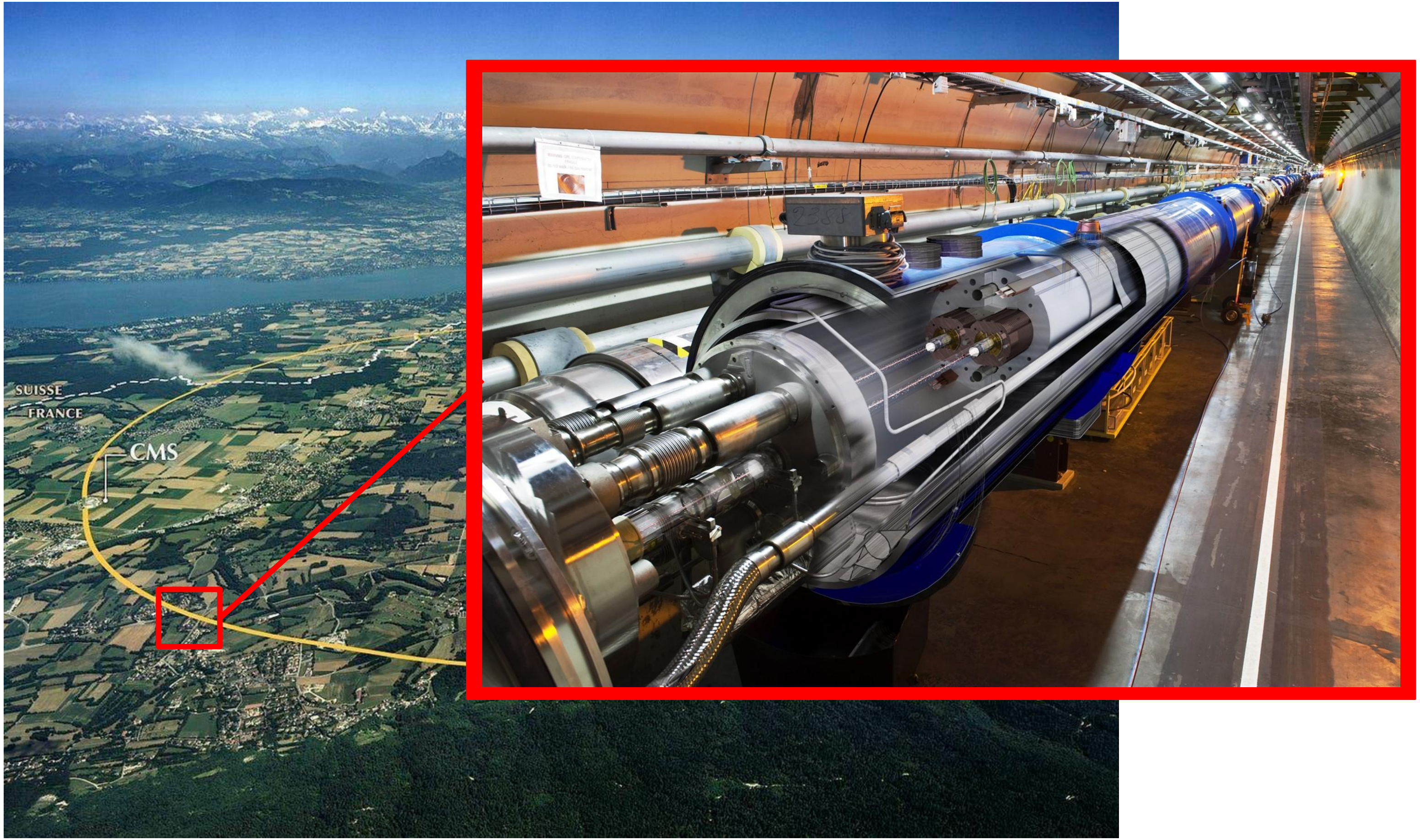
- Conseil Européen pour la Recherche Nucléaire
- Funded in 1954 by 12 countries
- Scientific organisation promoting international collaboration and peace through fundamental and applied research
- CERN is one of the largest research centres in the world
- Today: more than 12000 scientists from more than 600 institutes in 115 countries worldwide



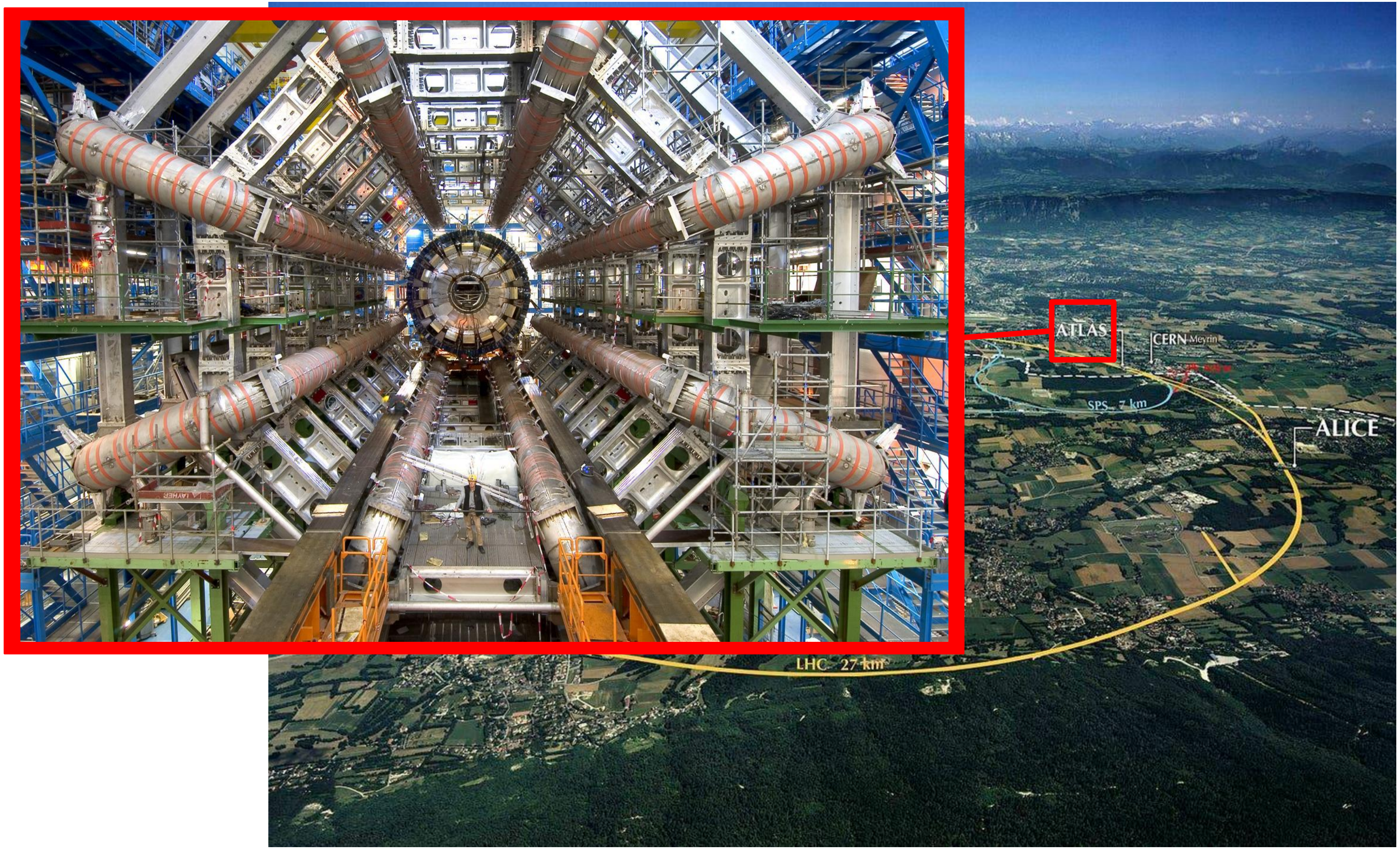

CERN
World Wide Web Initiative
EIZO

The Large Hadron Collider at CERN

The Large Hadron Collider at CERN



The Large Hadron Collider at CERN



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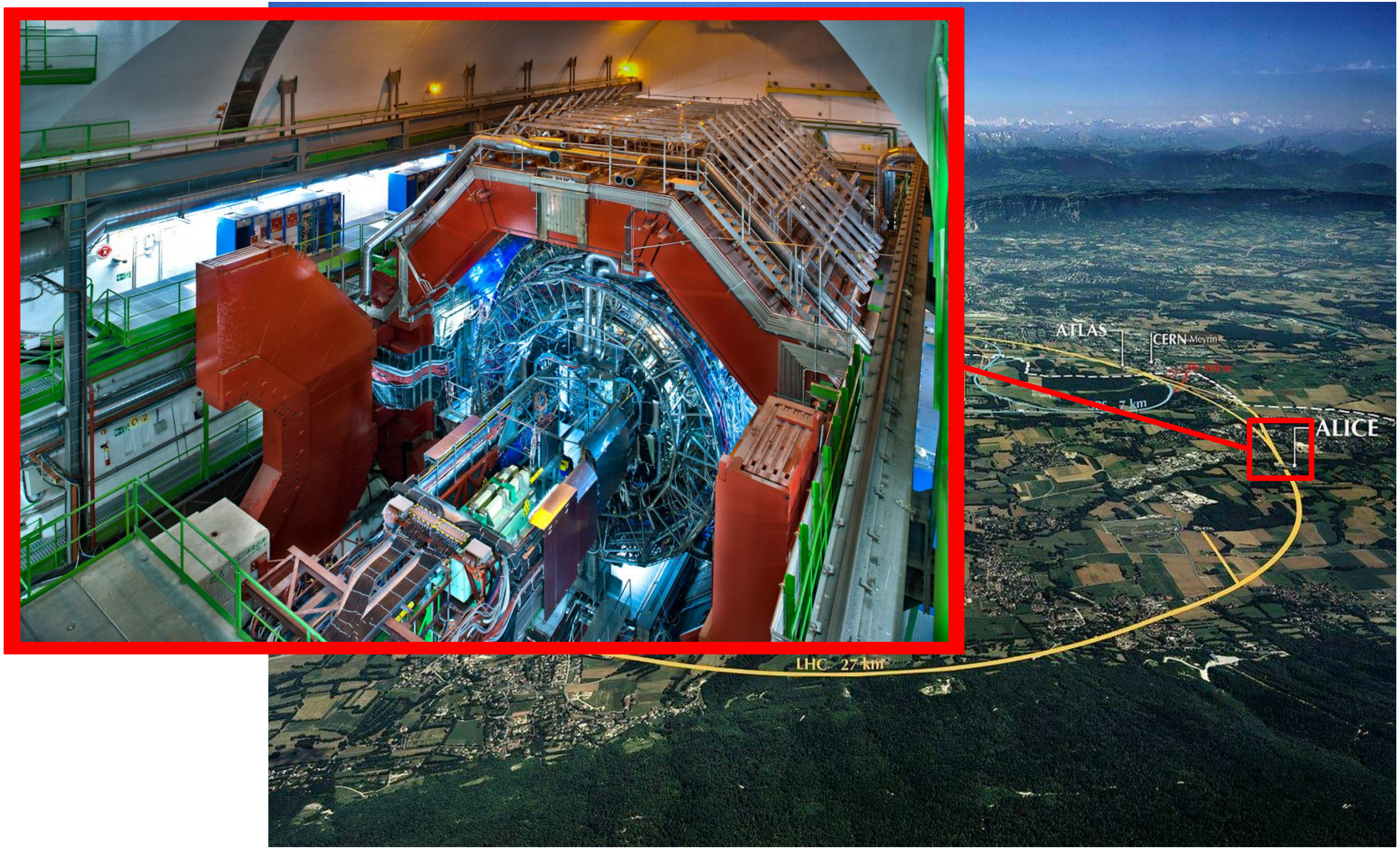

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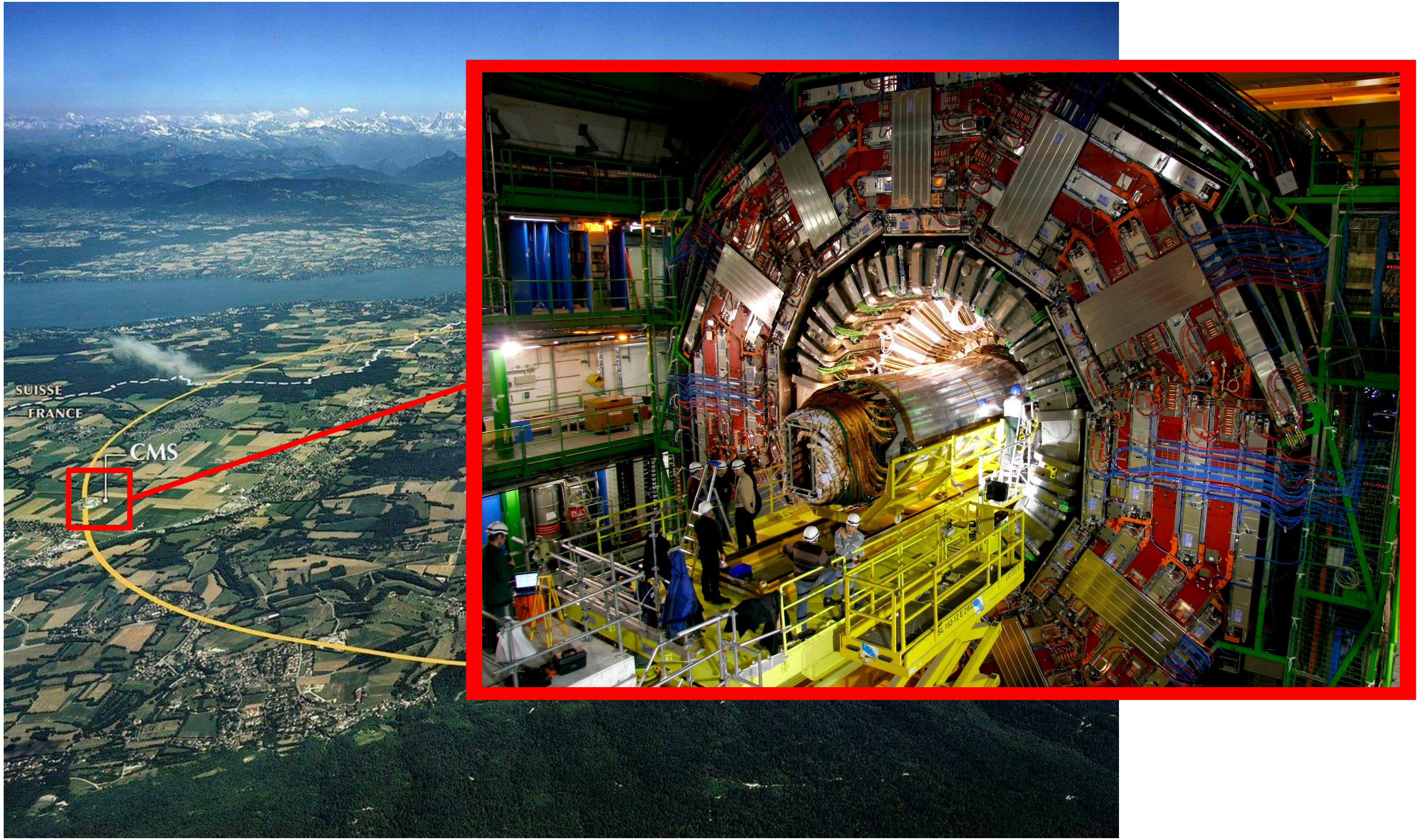

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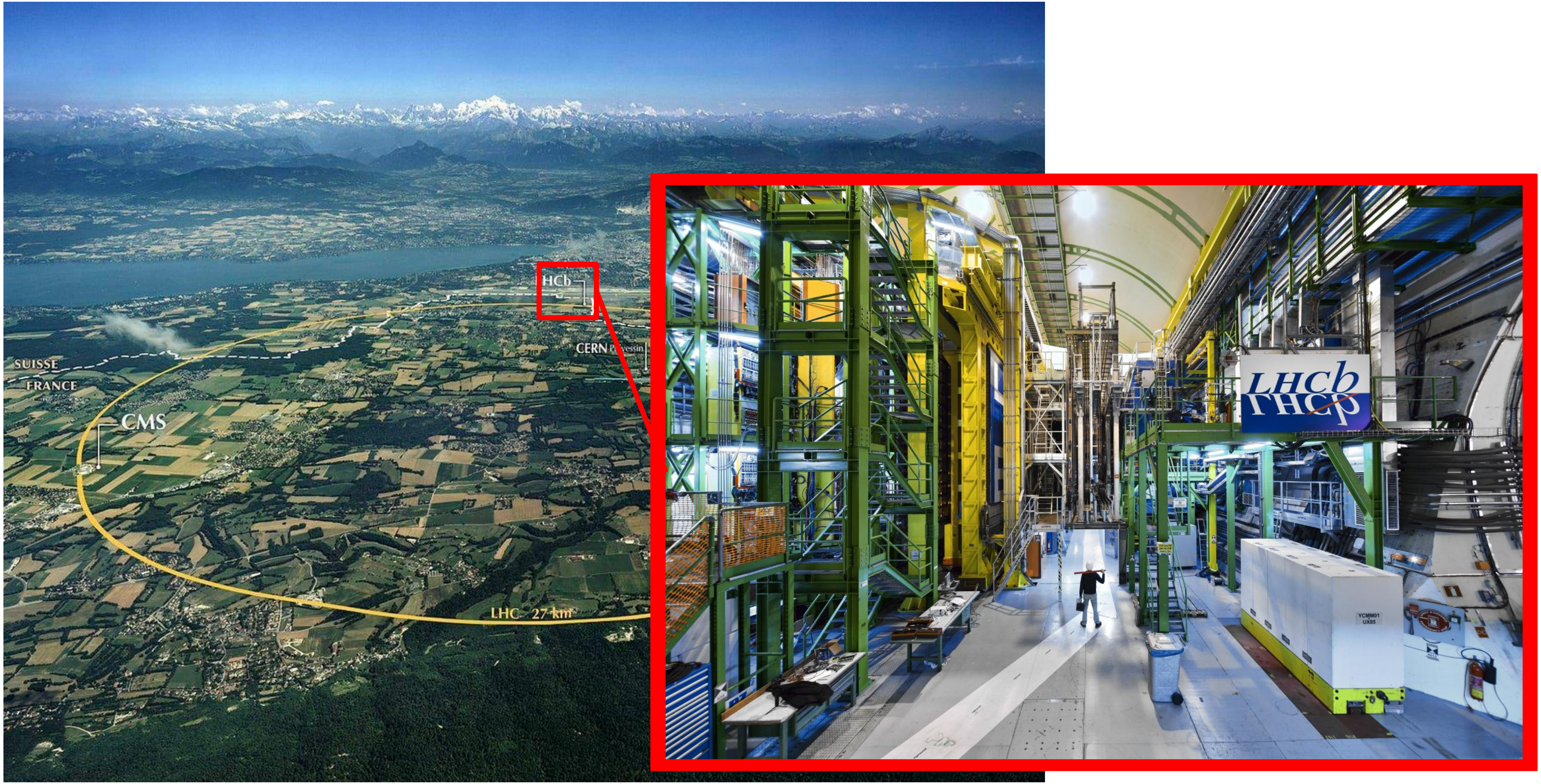
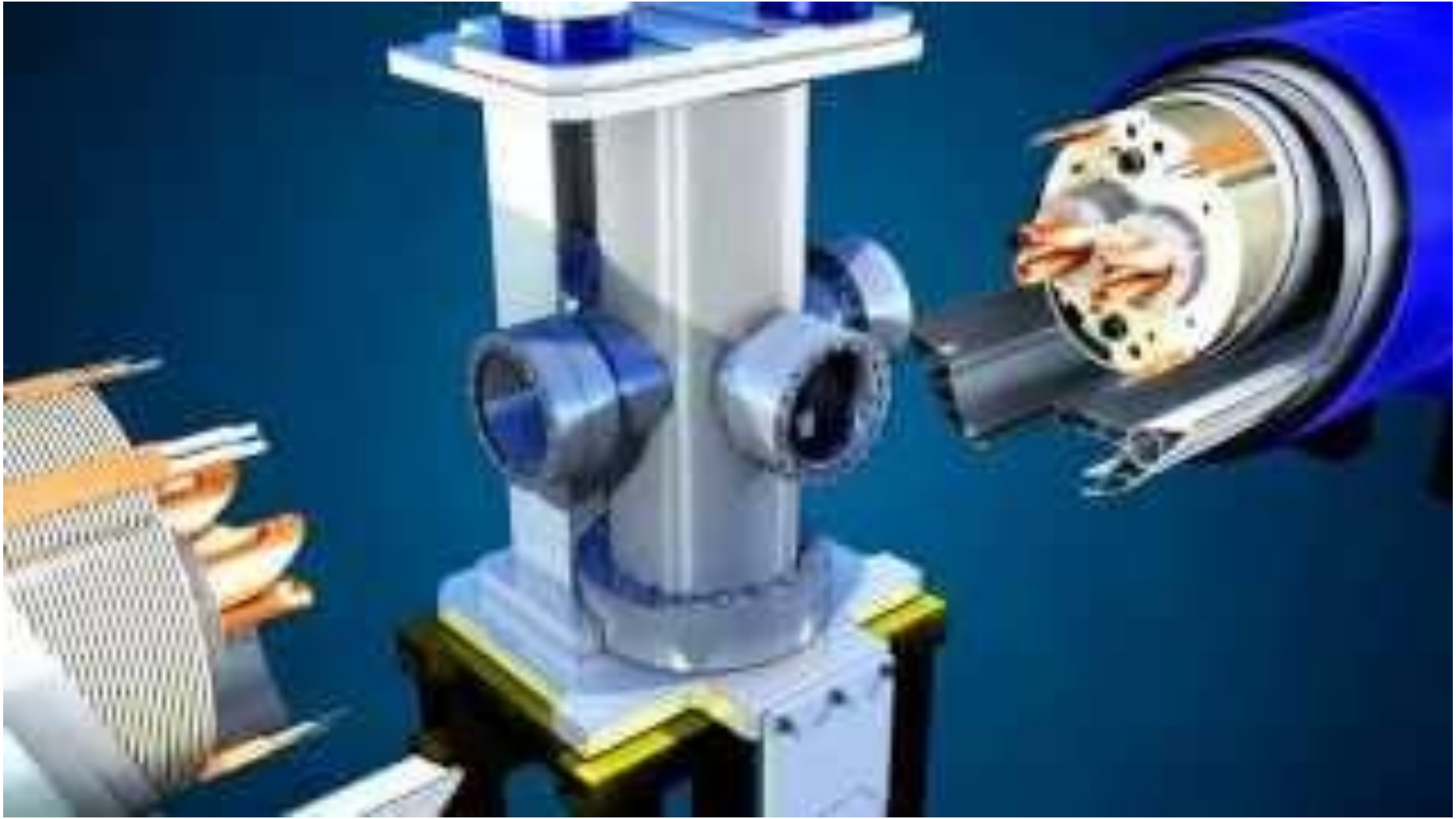
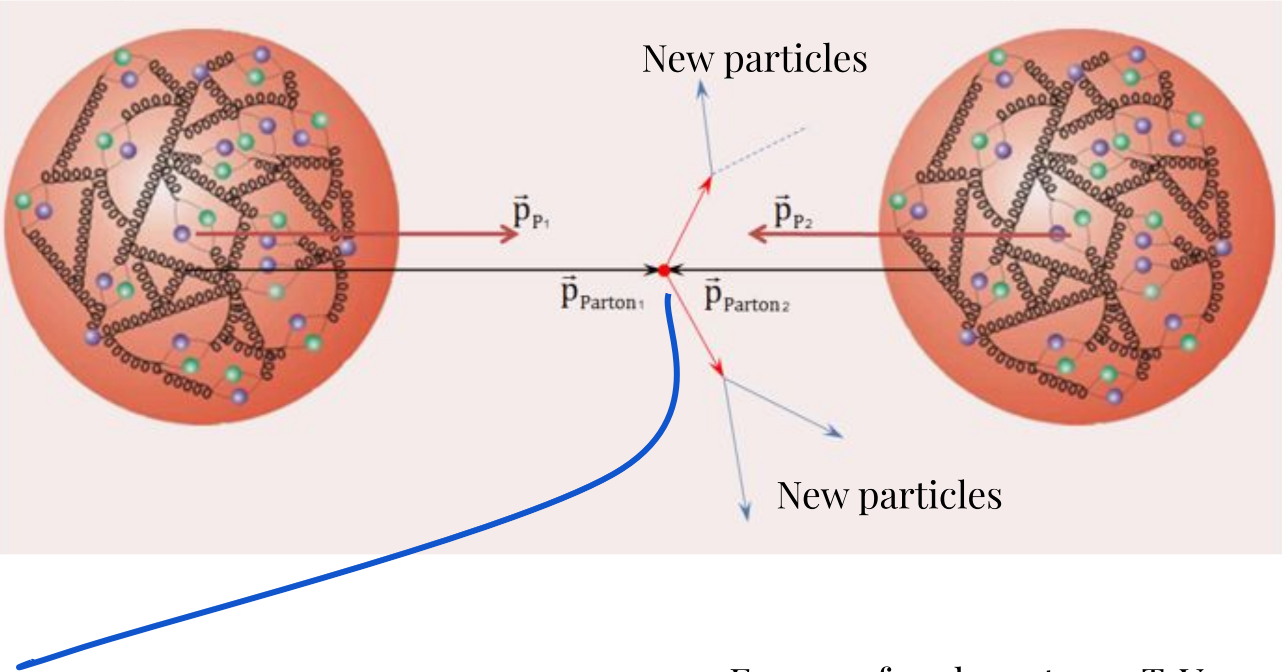




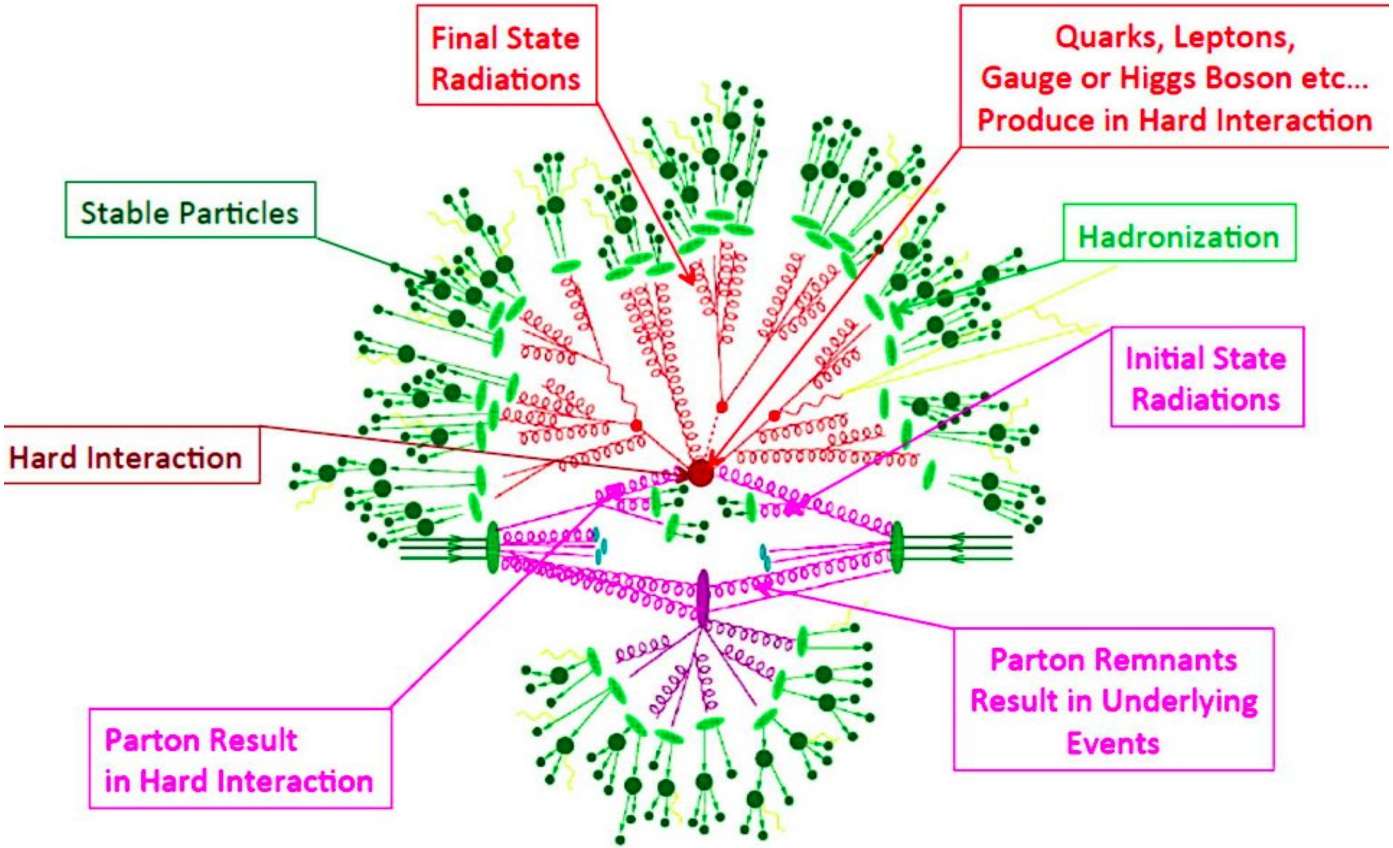
Proton-proton collisions at the LHC



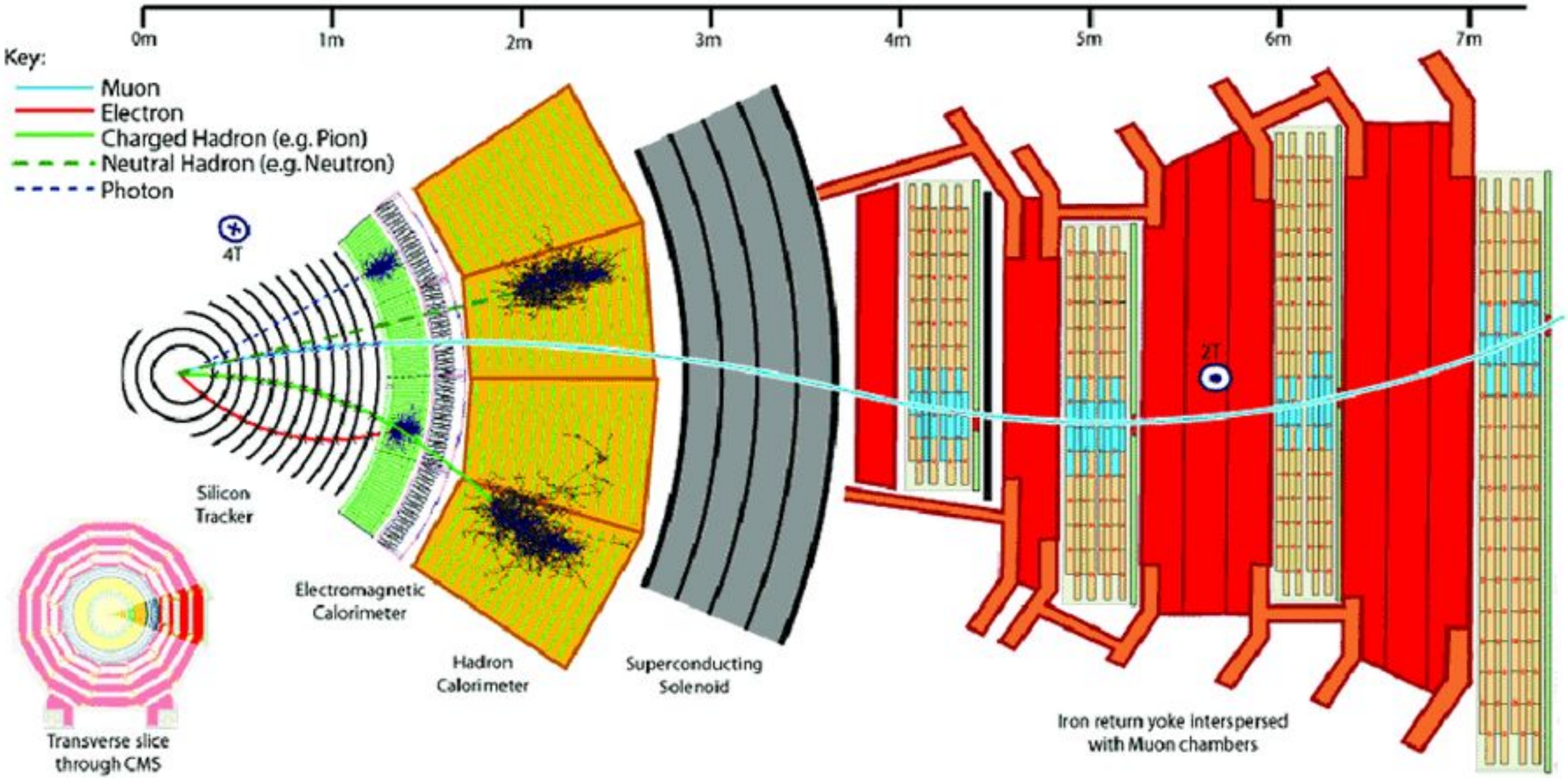
Primary interaction vertex (PV)

Energy of each proton: 7 TeV
Energy of centre of mass: 14 TeV
Each parton carries a fraction of it according to specific probability distributions

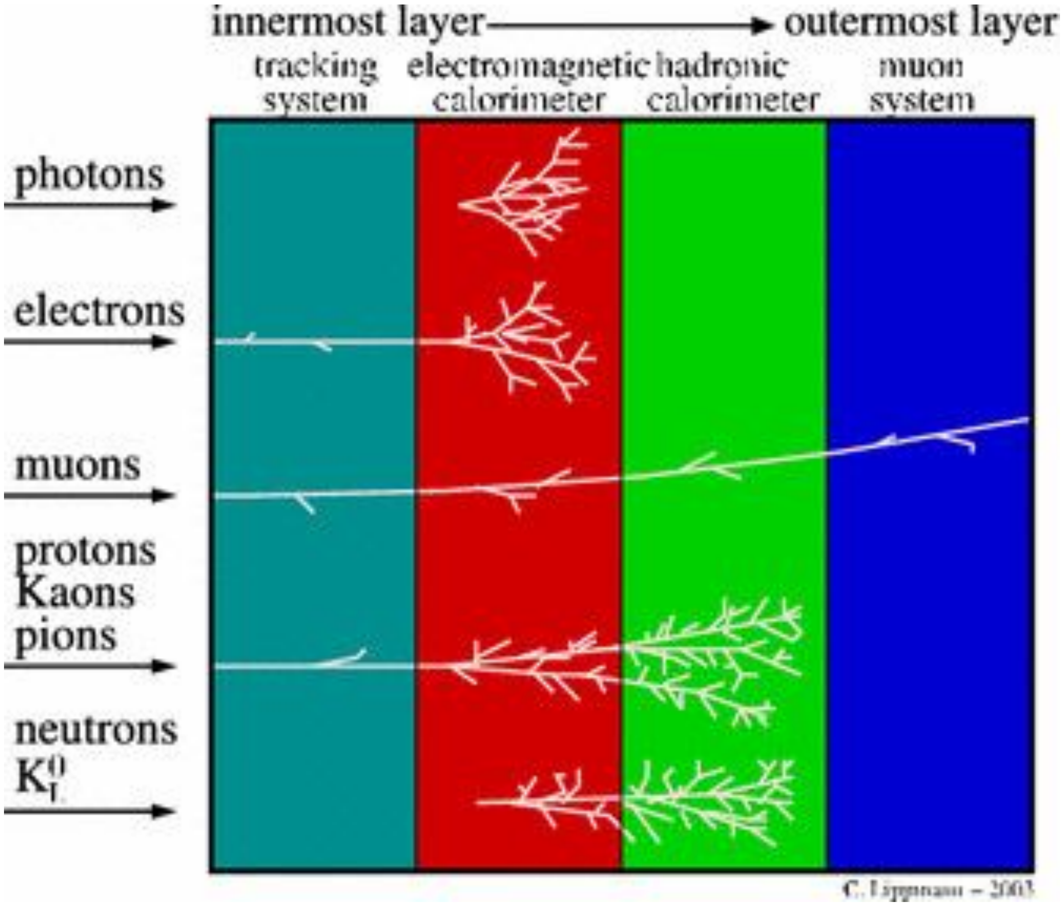
Proton-proton collisions at the LHC



Particle detectors



Particle detectors



General overview of a HEP detector

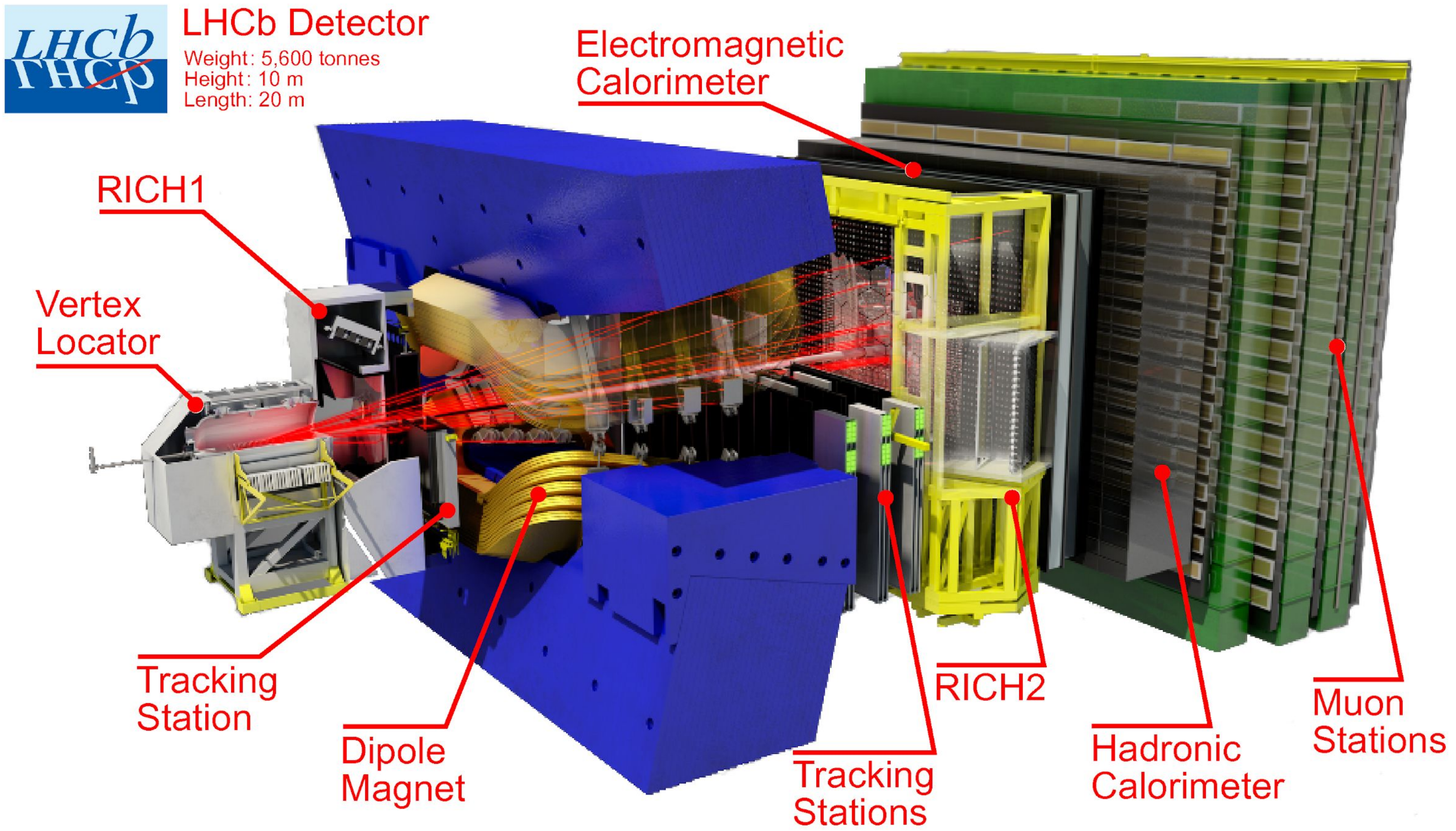
Several layers made with different materials, electronics, readout

Each of them with a different goal

Different particle species interact with the materials differently

They all leave **hits** in the detector

The LHCb detector at CERN



Topological structure of an event

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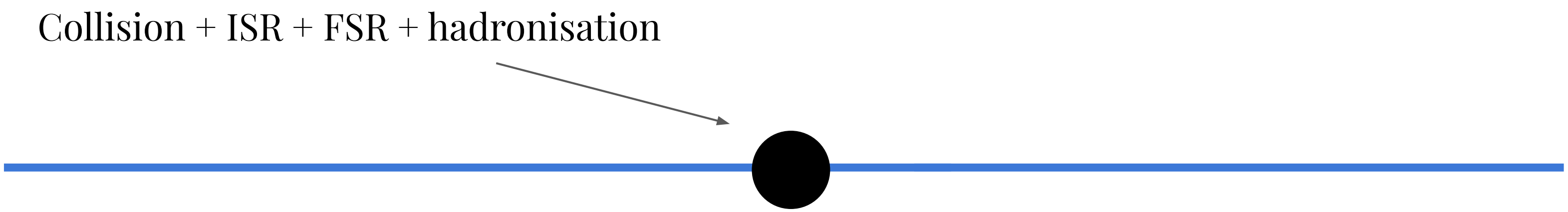

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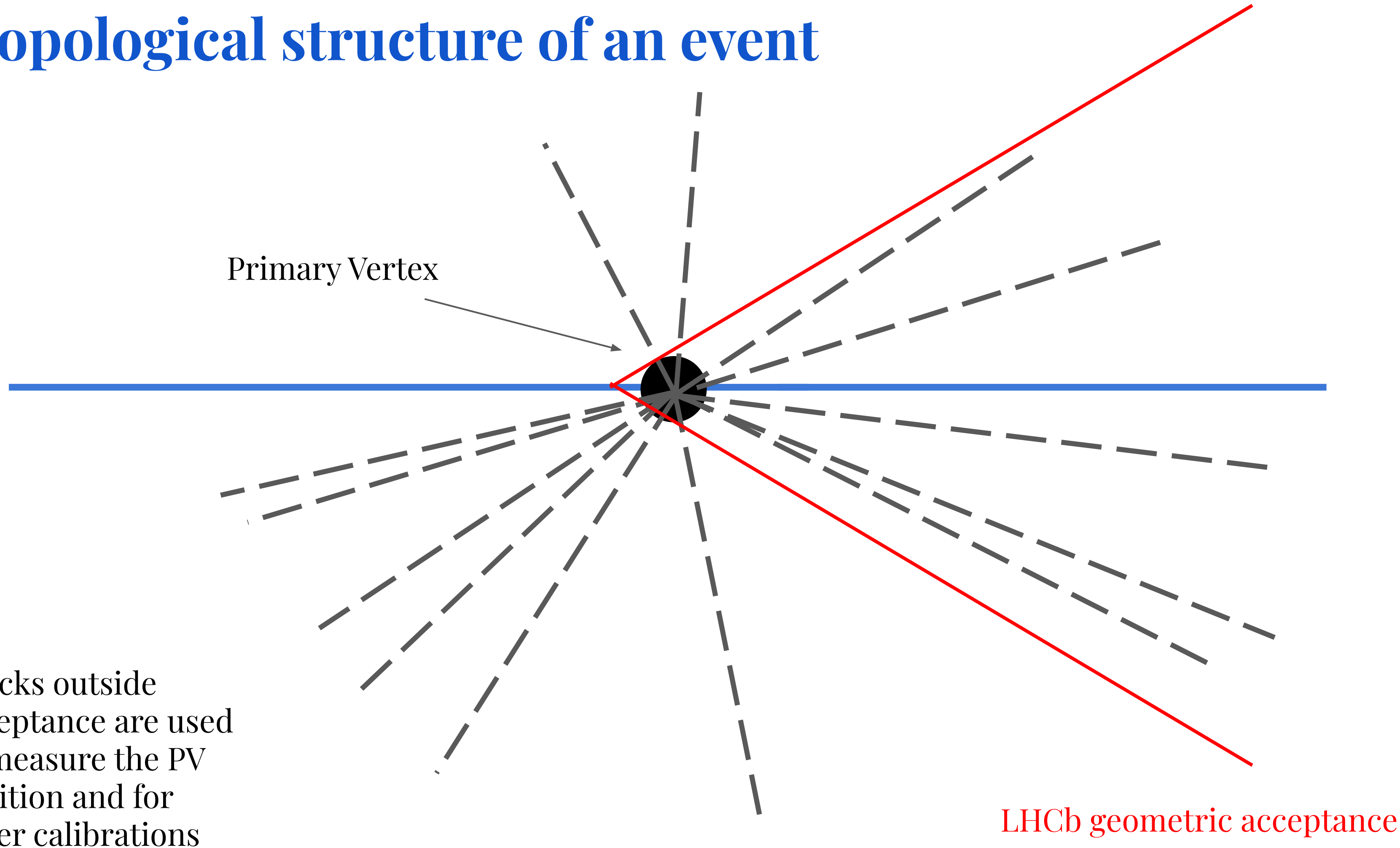
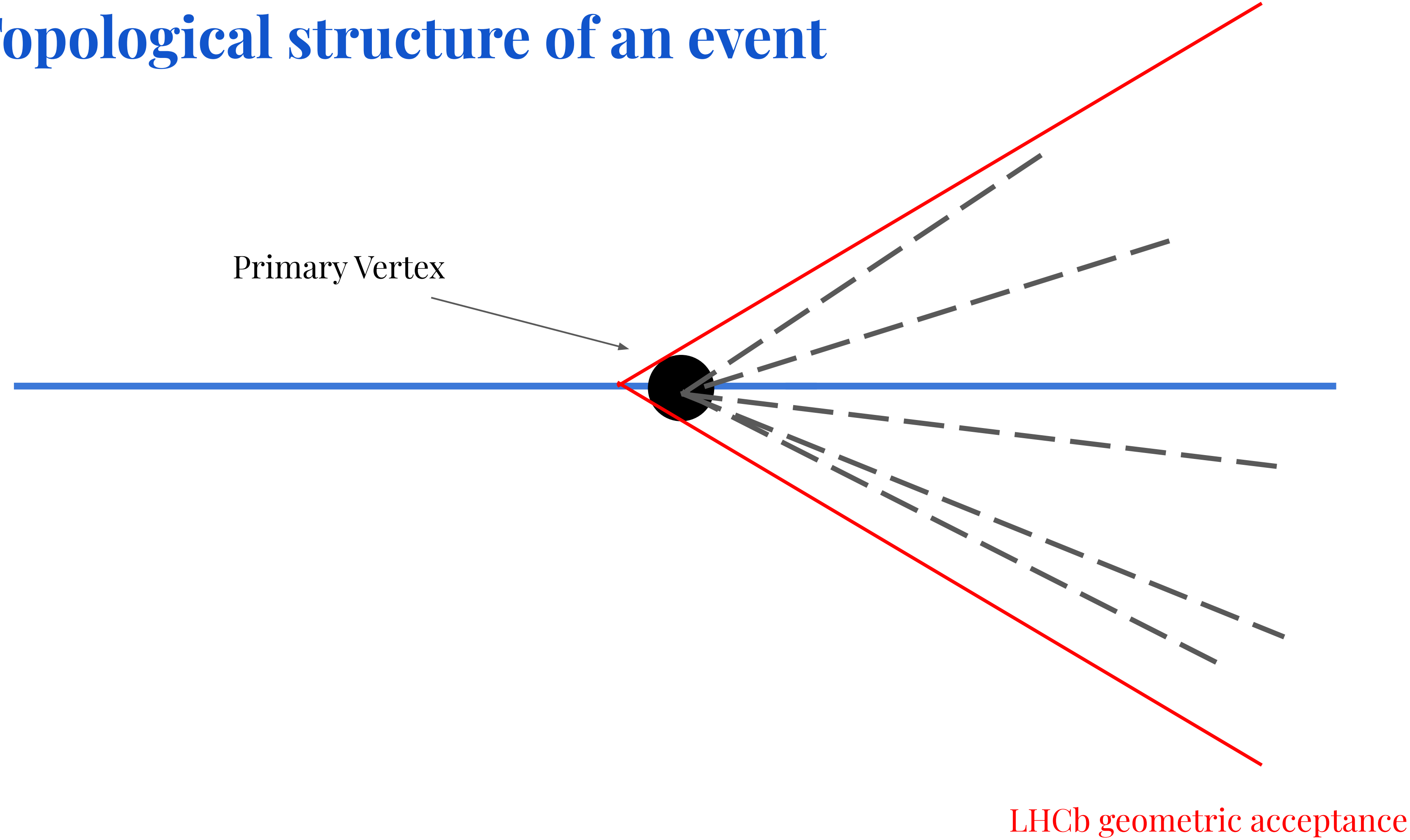


Tracks outside acceptance are used to measure the PV position and for other calibrations

Topological structure of an event



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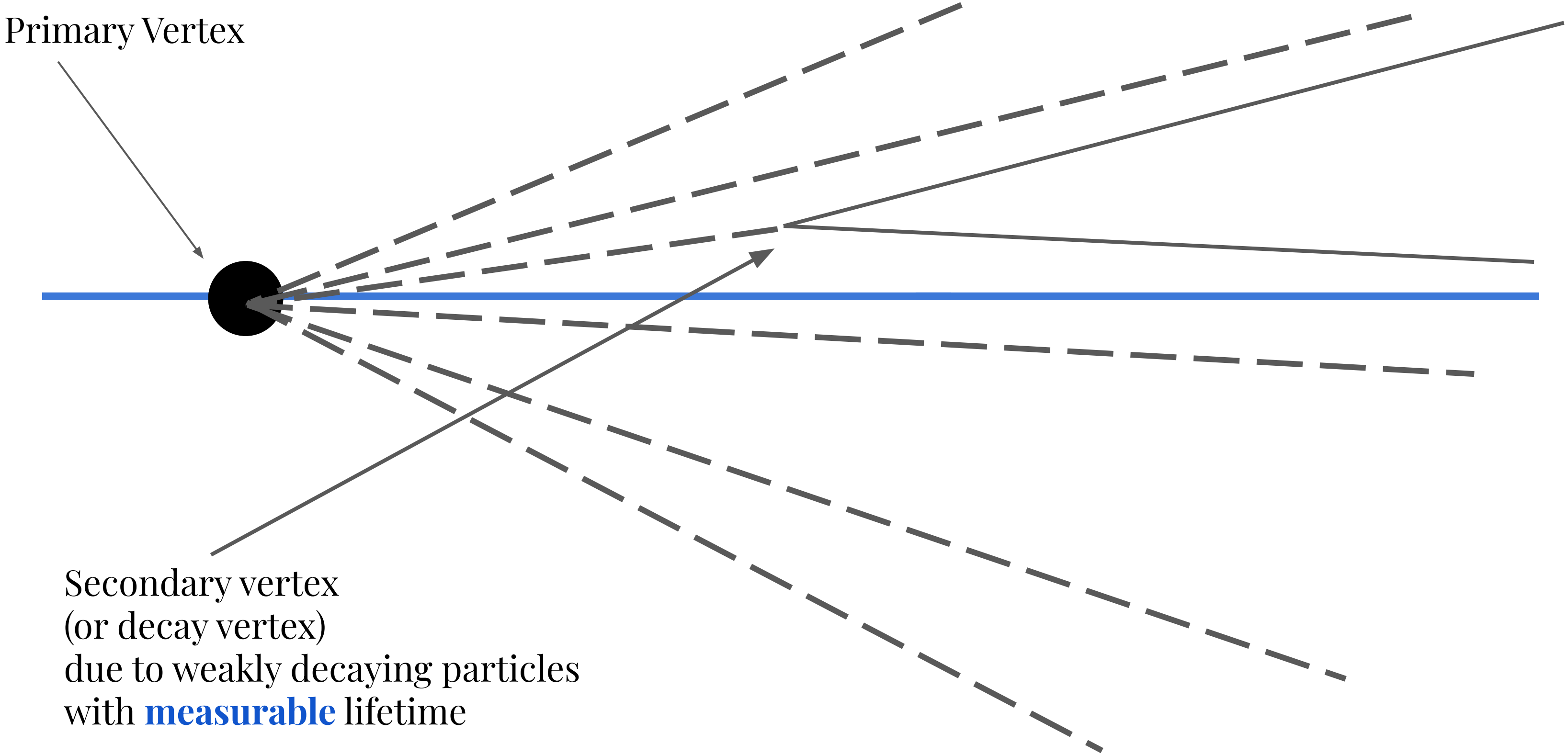

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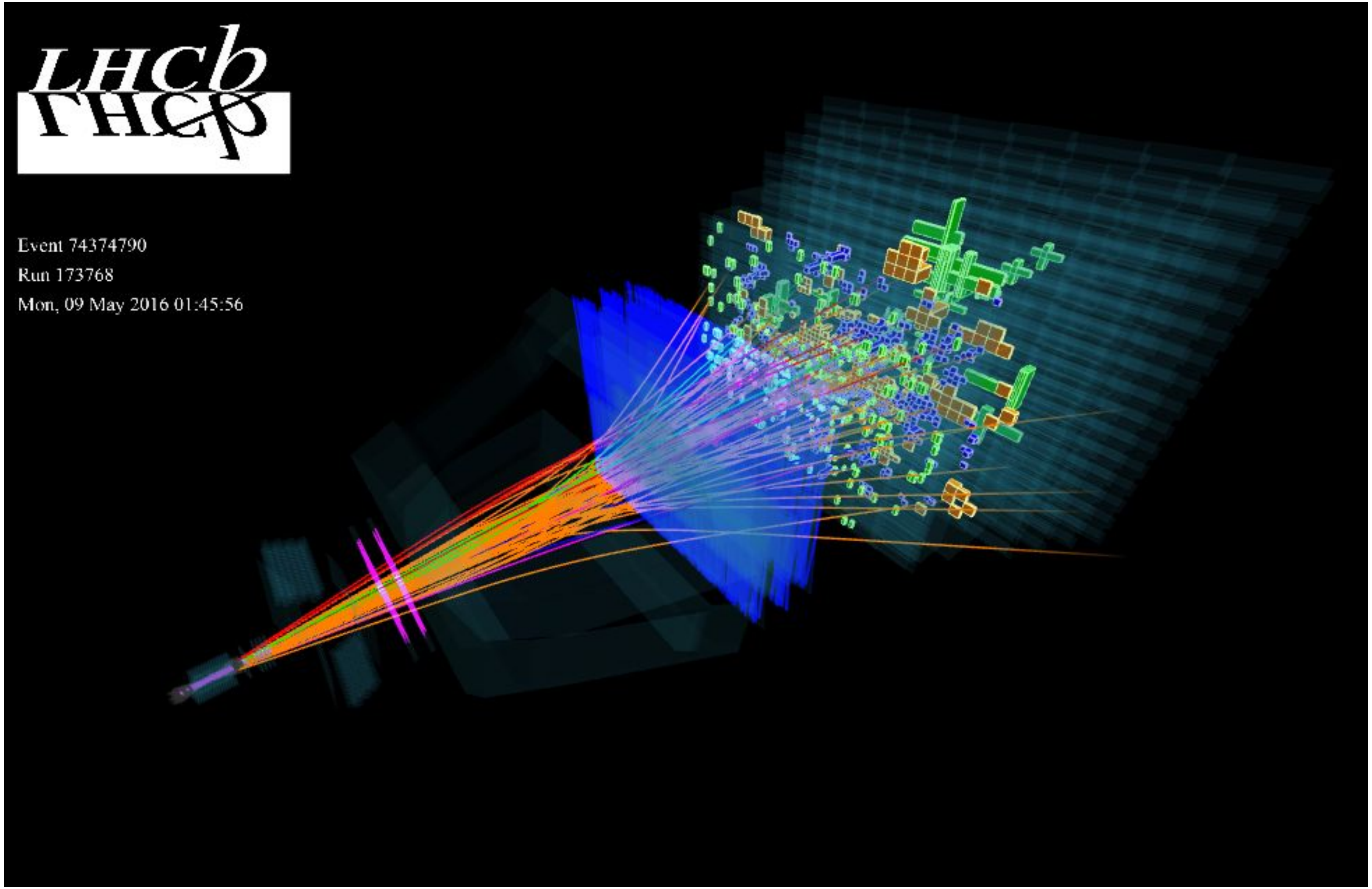

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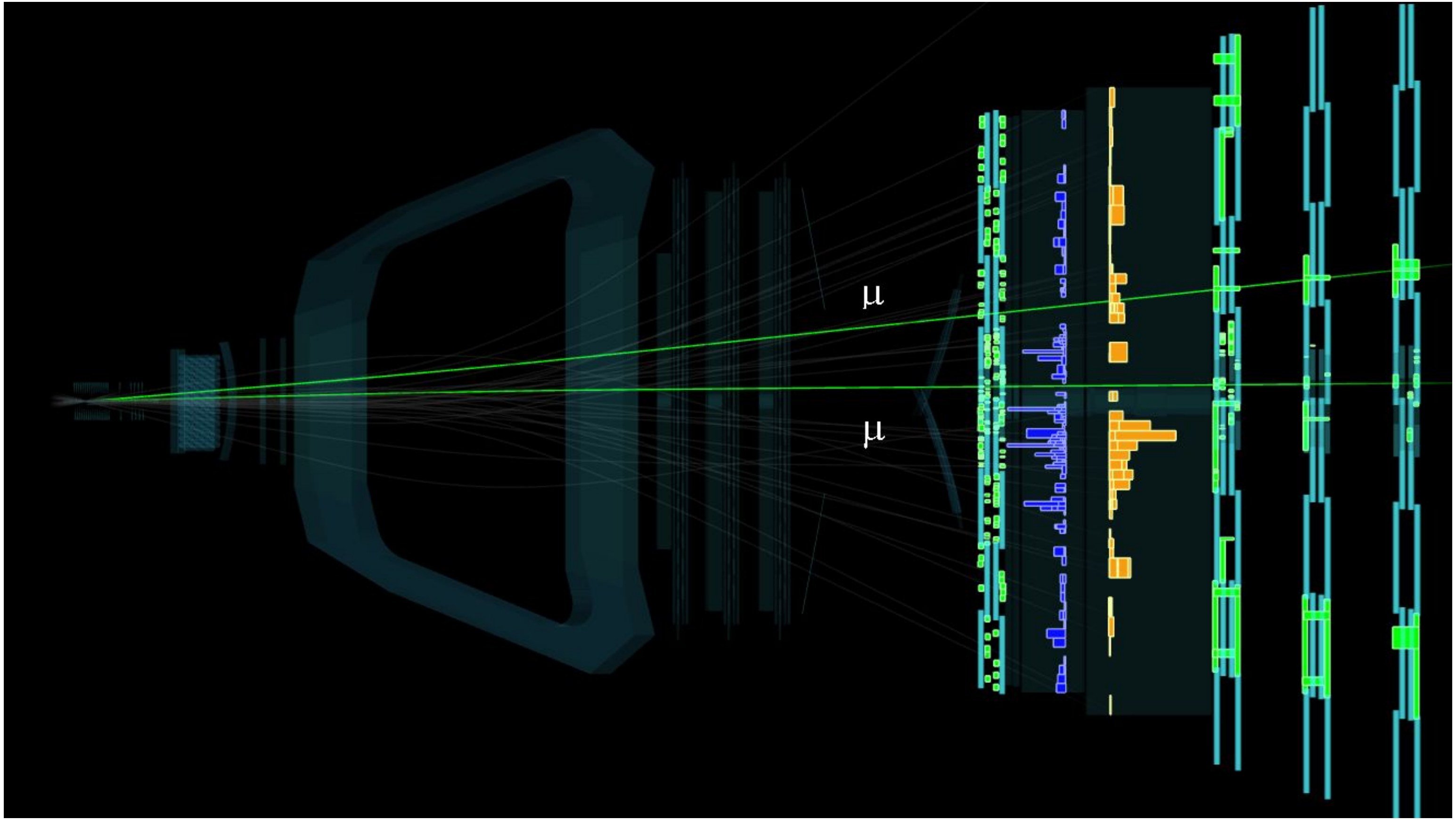

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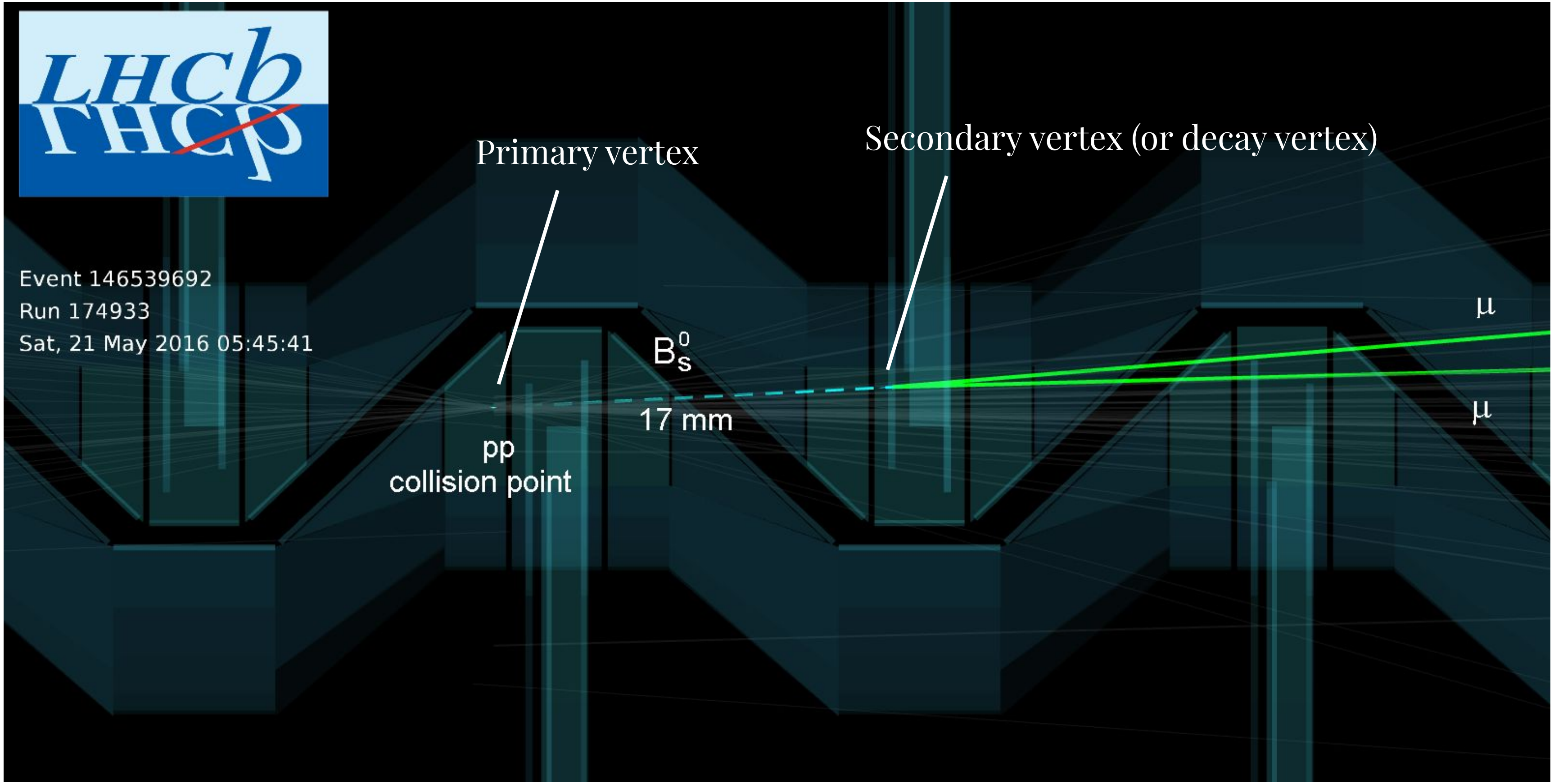
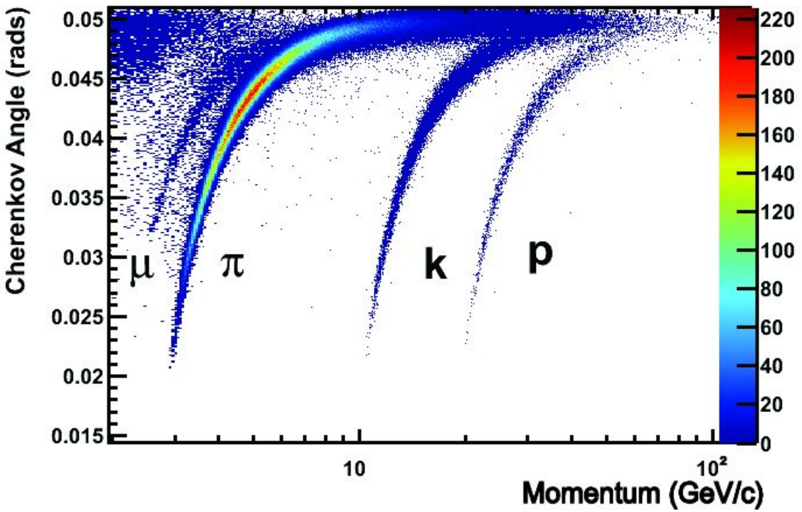


Particle identification (PID) at LHCb

LHCb has two RICH detectors for PID (Ring-Imaging Cherenkov detectors)

They make use of the Cherenkov effect to discriminate between the various particle species

It is not important to understand exactly how do they work right now, but this allows LHCb to be very precise with PID and to have specific PID variables to use in data analysis



Backtracking from hits to observables

Hits in the tracking system
or in the muon stations

↓

TRACKS

↓

Direction of flight
Momentum
Distance from PV
Distance from other tracks
Impact Parameter (IP)
….

Hits in the calorimeters

↓

CALO CLUSTERS

↓

Energy deposits
Bremsstrahlung recovery
Direction of flight (neutral)
…

Hits in the RICH

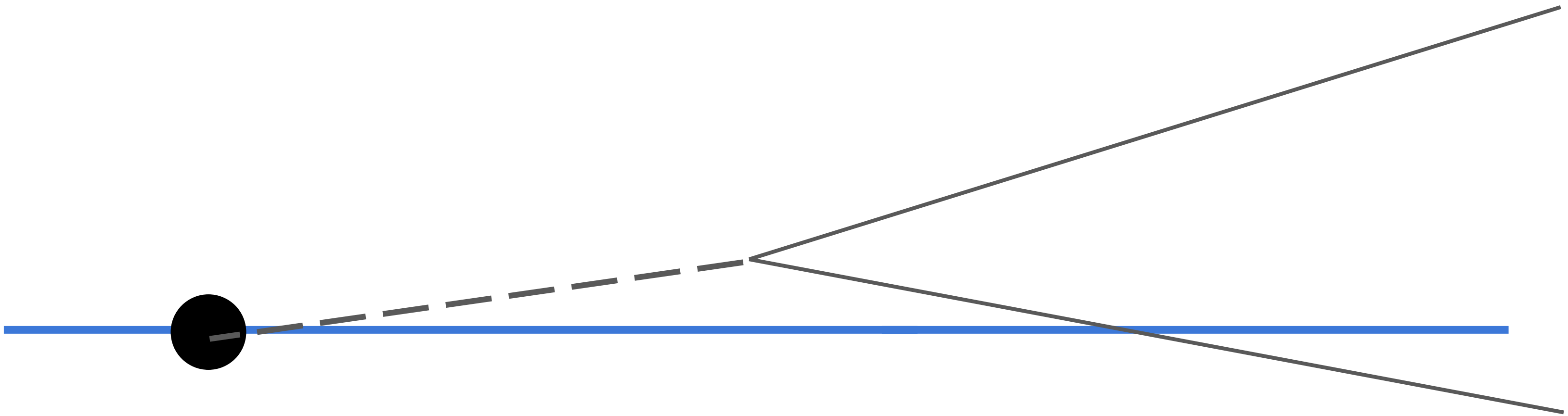
↓

CHERENKOV RINGS

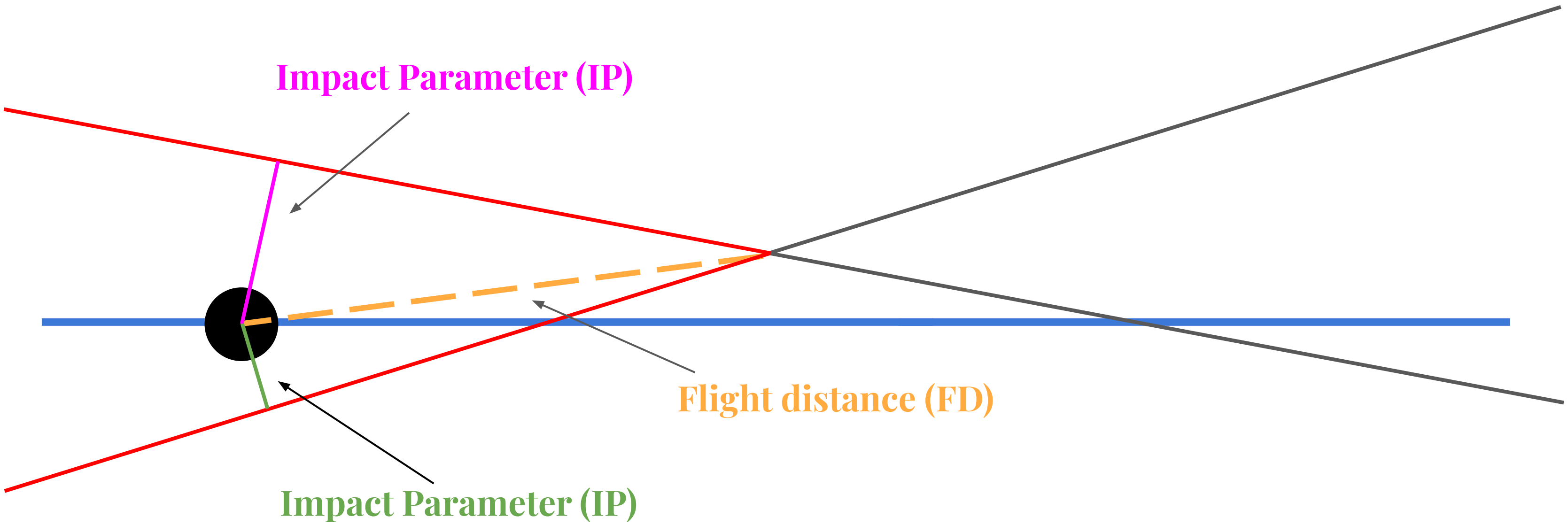
↓

Velocity
Mass
Particle identification
….

Impact parameter and flight distance



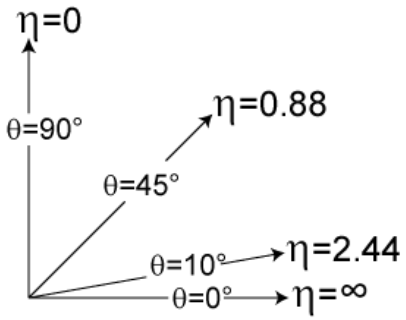
Impact parameter and flight distance



Tracks coming from secondary vertices can be identified by having an IP incompatible with zero.
Tracks coming from the primary vertex instead will have zero or very small IP.
Flight distance (FD) is the distance between the decay vertex and the PV.

Some useful definitions

- **Cartesian coordinates**: as a convention, the z-axis is horizontal and parallel to the proton beam line, the y-axis is vertical and the x-axis is horizontal and perpendicular to the beam line
- **Transverse plane**: the x-y plane (at z=0)
- **Momentum**: the momentum of a particle, calculated from the curvature radius of its track
- **Transverse momentum**: the projection of the momentum onto the transverse plane
- **Energy**: for neutral particles is measured from the calorimeters, while for charged particles is calculated by setting a mass hypothesis to a track with given momentum
- **Impact parameter**: the smallest distance between a track and the PV
- **Flight distance**: distance between the decay vertex and the PV
- **Impact parameter χ^2**: smallest distance between a track and PV divided by PV position uncertainty
- **Flight distance χ^2**: distance between decay vertex and PV divided by PV position uncertainty
- **DLLx or ProbNNx**: the probability that a given track is due to a specific particle species x
- **Invariant mass**: for a track, the known mass of the particle; for a combination of tracks, the norm of the sum of the 4-momenta of the single tracks
- **Pseudorapidity η**: angular variable, calculated from the azimuthal angle as $\eta=-\log[\tan(\theta/2)]$, useful in HEP: LHCb acceptance is in range $2<\eta<5$
- There are many other variables commonly used in data analysis, relative to the single tracks or particles and relative to the global event



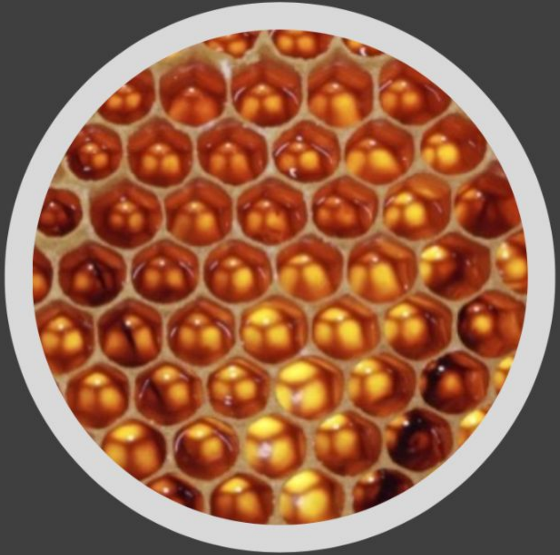
Structure of a dataset

The experimental or simulated data are collected in an object called an **ntuple**
You may think of it as a very large table where each row represents an event and each column an observable

Event 0	K_PX	K_PY	K_PZ	pi_ETA	B_MASS	B_IP	...
Event 1	K_PX	K_PY	K_PZ	pi_ETA	B_MASS	B_IP	...
Event 2	K_PX	K_PY	K_PZ	pi_ETA	B_MASS	B_IP	...
Event 3	K_PX	K_PY	K_PZ	pi_ETA	B_MASS	B_IP	...
Event 4	K_PX	K_PY	K_PZ	pi_ETA	B_MASS	B_IP	...
Event 5	K_PX	K_PY	K_PZ	pi_ETA	B_MASS	B_IP	...
Event 6	K_PX	K_PY	K_PZ	pi_ETA	B_MASS	B_IP	...
....	....	...	...	...	...	...	...

Symmetries in Nature

Nature is full of interesting and beautiful symmetries!



From Nature to Physics

Why are we so interested in symmetries in physics?

- **Emmy Noether** in 1915 enunciated a theorem that links symmetries in physics to quantities that are conserved, that is, they remain unchanged between the beginning and the end of a process

- The theorem states that
**"If a system has continuous symmetry,
then there exist corresponding quantities conserved over time."**

- The conservation of energy, momentum and angular momentum are just some examples of quantities conserved thanks to continuous symmetries

- These conservation laws are of fundamental importance in physics!

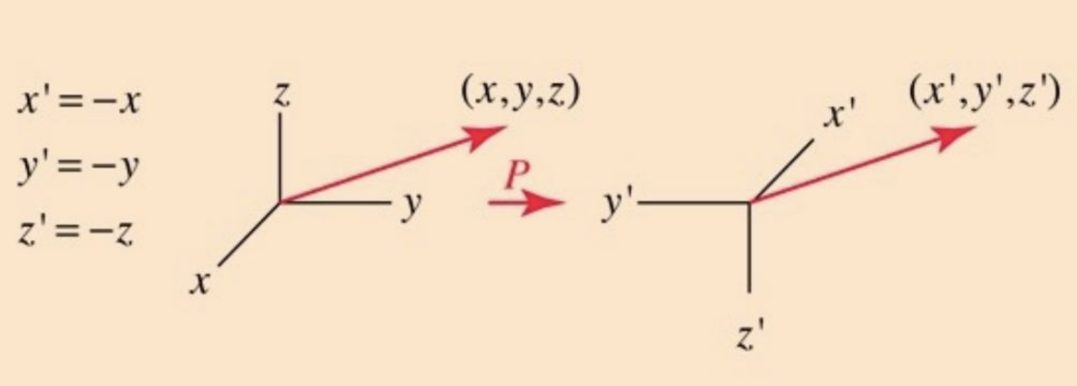
A discrete symmetry: parity (P)

There are also some discrete symmetries that have always been thought to be conserved, such as the parity transformation (P)

- In the illustration the x-y-z reference system has undergone a parity transformation (i.e. a mirror-like reflection followed by a 180 degree rotation around the z axis)

- Experiments showed that gravity and electromagnetism respected parity symmetry

- What about particle decays?



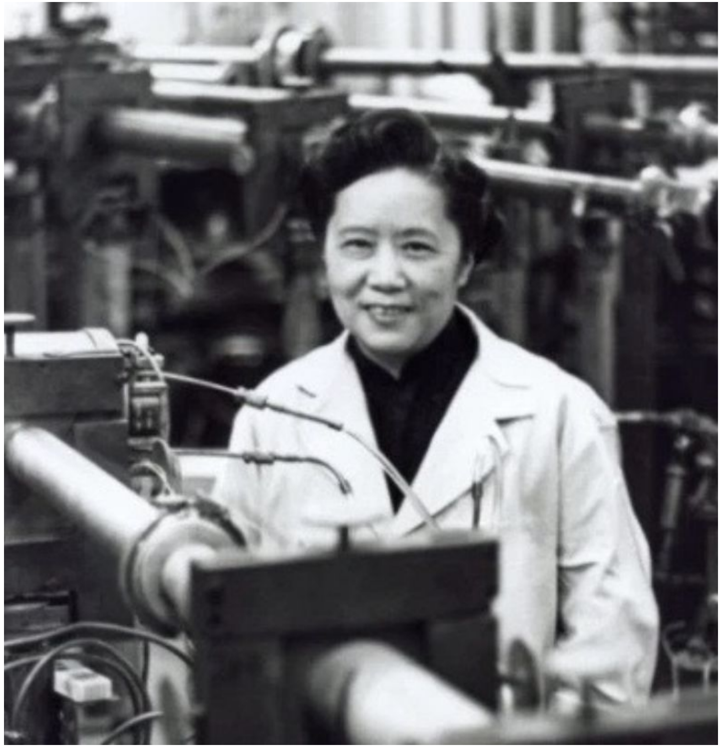
The Wu experiment

Chien-Shiung Wu tried to understand whether in particle physics the parity transformation was really a conserved quantity

• To do this, he obtained radioactive Cobalt-60 which should have decayed according to the reaction

• To carry out the experiment, the Cobalt-60 had to be cooled to almost absolute zero (-274 degrees) and "oriented" via a magnetic field

• If parity had been a preserved symmetry in the decay, Wu would have had to count the same number of electrons emitted in the direction of the magnetic field and in the direction opposite to the magnetic field



The Wu experiment

Wu measured an asymmetry between the electrons emitted in the two directions!

This important milestone is the first observation of parity symmetry violation

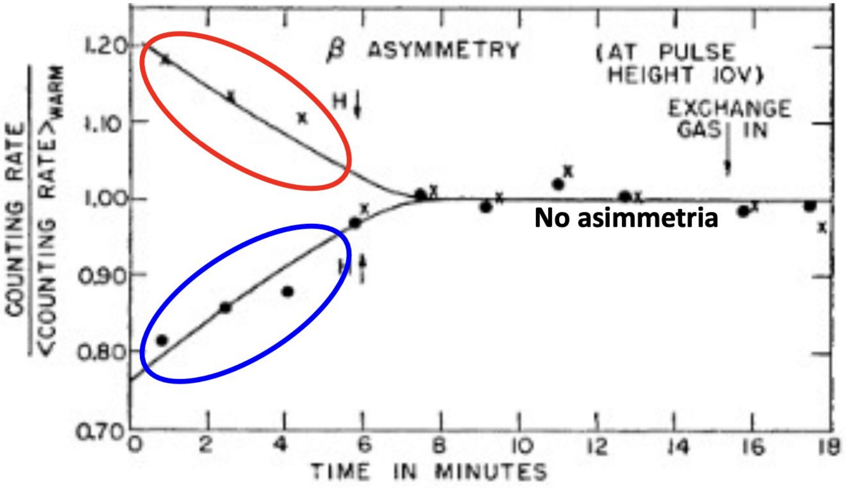


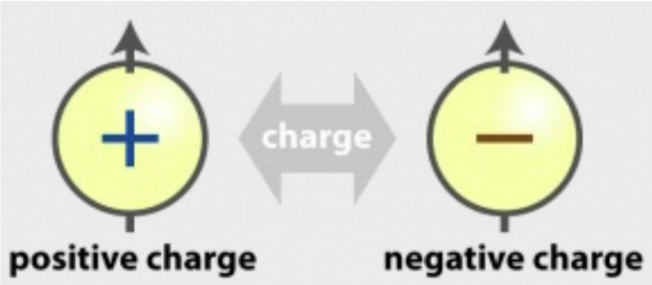
FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

Sadly parity was violated also in real life:

Tsung-Dao Lee and Chen Ning Yang, two (male) theoretical physicists who gave the idea won the Nobel prize, while Wu did not win anything :(

Another discrete symmetry: charge conjugation (C)

As with parity symmetry, it was thought that another discrete symmetry, called charge conjugation (C) was conserved not only in gravitational and electromagnetic interactions, but also in nuclear interactions.



But this symmetry was found to be violated as well in an experiment in 1957!

Moreover, a third experiment in 1964 also measured the violation of the CP symmetry - that is both P and C combined!

Violation of CP

Ok but…why do we care?

We are interested because it could be the answer to **one of the most fascinating open questions in physics**:

What is the origin of our Universe?

- If you think about it for a moment, you will realize that in our universe matter has totally taken over and there are only very small traces of anti-matter

- In fact, we live on a planet made up of matter, in a solar system made up of matter, in a galaxy made up of matter,…

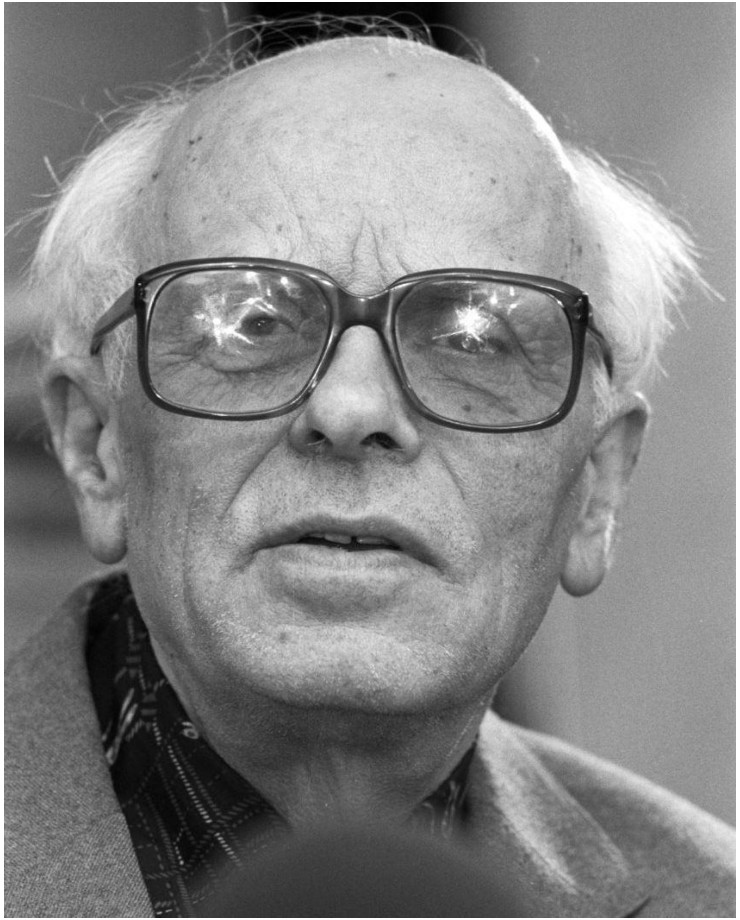
- So, where did the antimatter go and what does this do with CP violation?

The three Sakharov's conditions

In order for much more matter than antimatter ùto be generated a few moments after the Big Bang, according to physicist Andrei Dmitrievič Sakharov, three fundamental conditions were necessary

1. Violation of the baryon number
2. Violation of CP symmetry
3. Interactions outside thermal equilibrium

- Sakharov's theory is still one of the most accredited and has the violation of CP as its fundamental ingredient
- For this reason, it is of fundamental importance to continue searching for particle decays that can be used to measure the parameters regulating CP violation



Your dataset for this school

One of the decays where the CP violation has been observed most clearly is that of the B meson decaying into $K\pi$ mesons

• You will analyse a dataset collected by the LHCb experiment at CERN in 2011 to search for CP violation and measure its properties

• To look for CP violation in these decays you need to compare the number of decays into $K^+\pi^-$ and those into $K^-\pi^+$ corresponding to decays of B mesons and their antiparticle

• If we observe that one decay occurs more frequently than another, we have found the violation of CP!