Tales of the particle world

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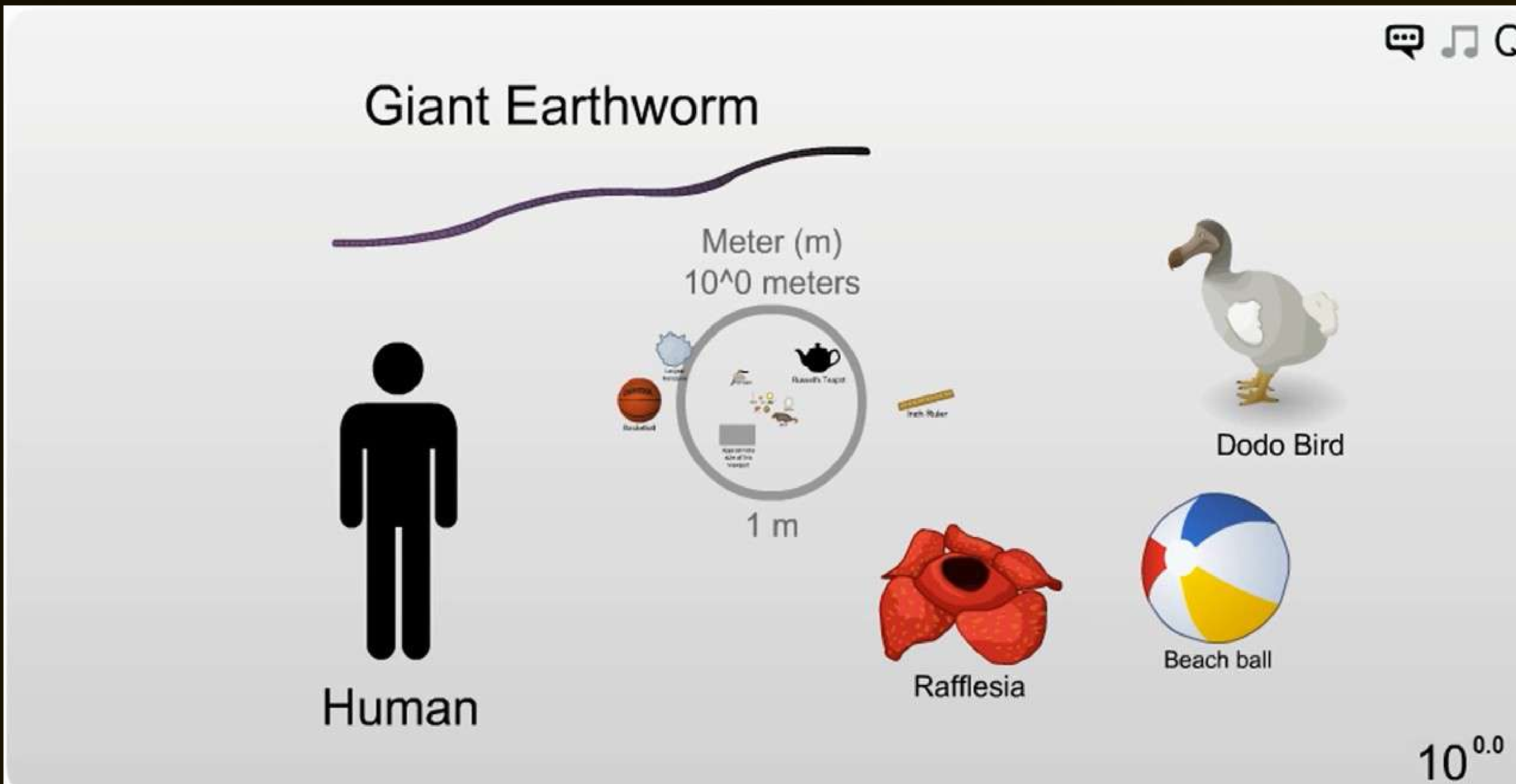
21-23 November 2017

The Niels Bohr International Academy

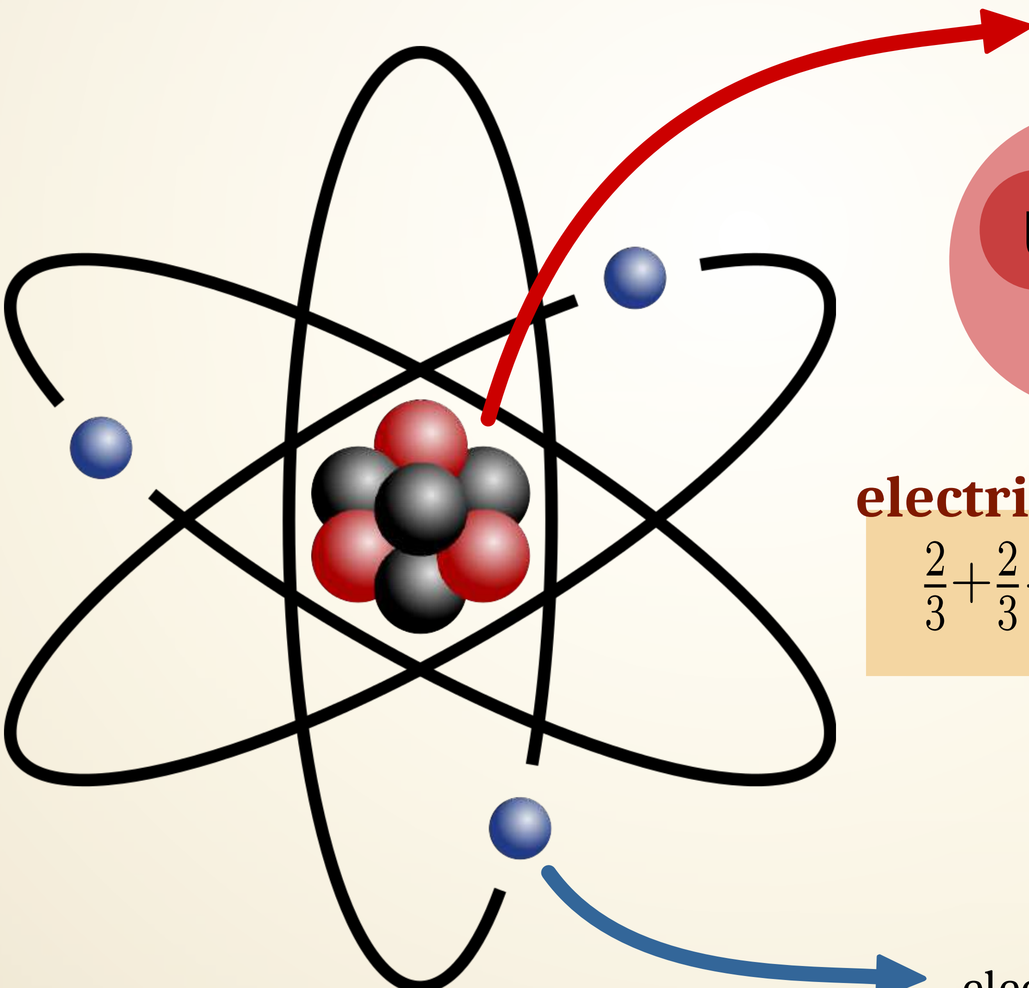
Part I

What are Elementary particles?


DRINK ME

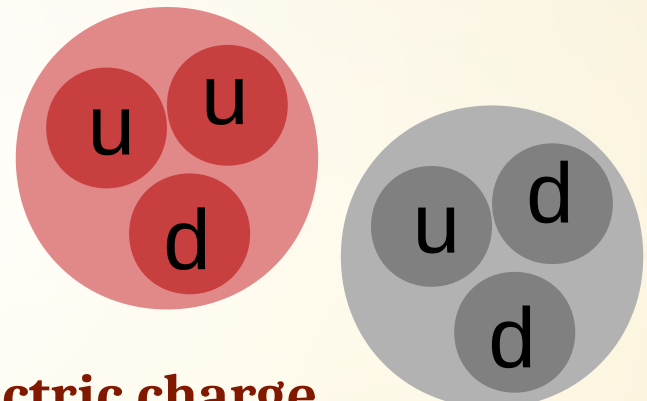

Giant Earthworm
Meter (m)
10^0 meters
1 m
Dodo Bird
Beach ball
Rafflesia
Human
10^0.0

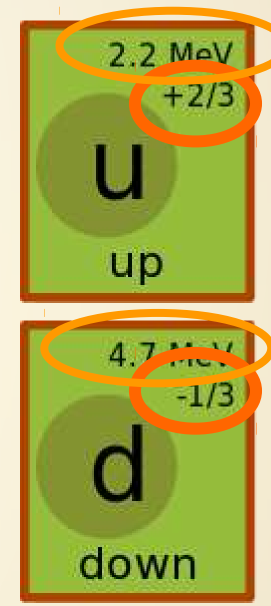
Elementary particles in ordinary matter



quarks

~~protons and neutrons~~



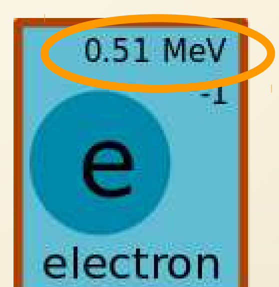


electric charge

$$\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=+1 \qquad \frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0$$

masses

electron

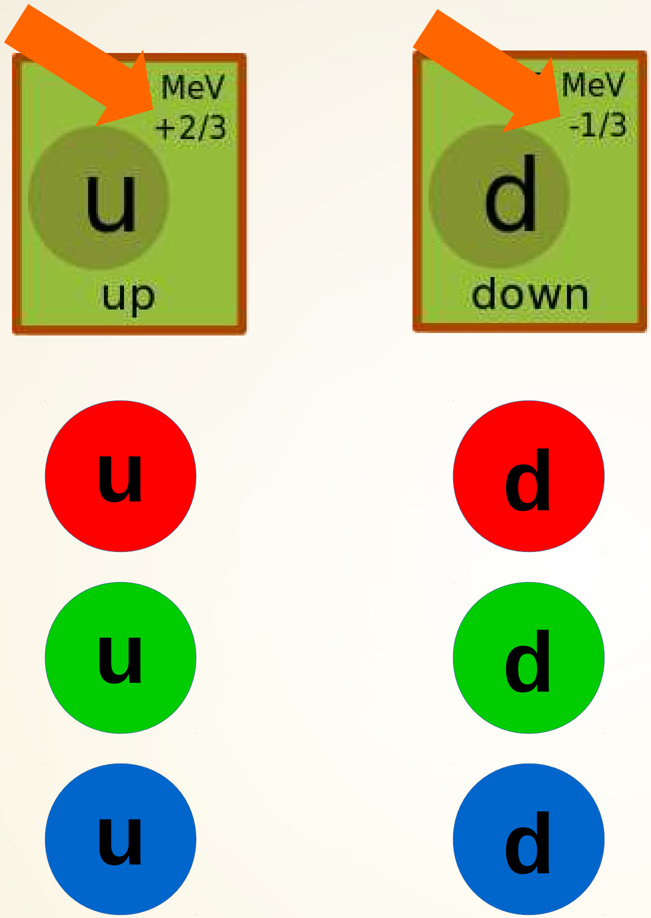


$E = mc^2$

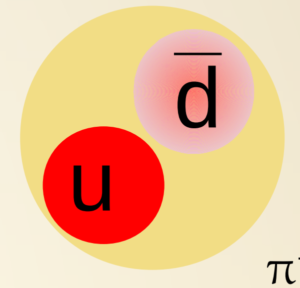
1 eV = 1.782662 10^{-33} g

1 MeV = 1000000 eV

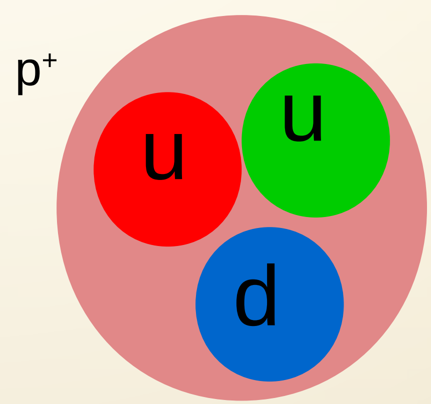
Quarks



pion: R$\bar{R}$

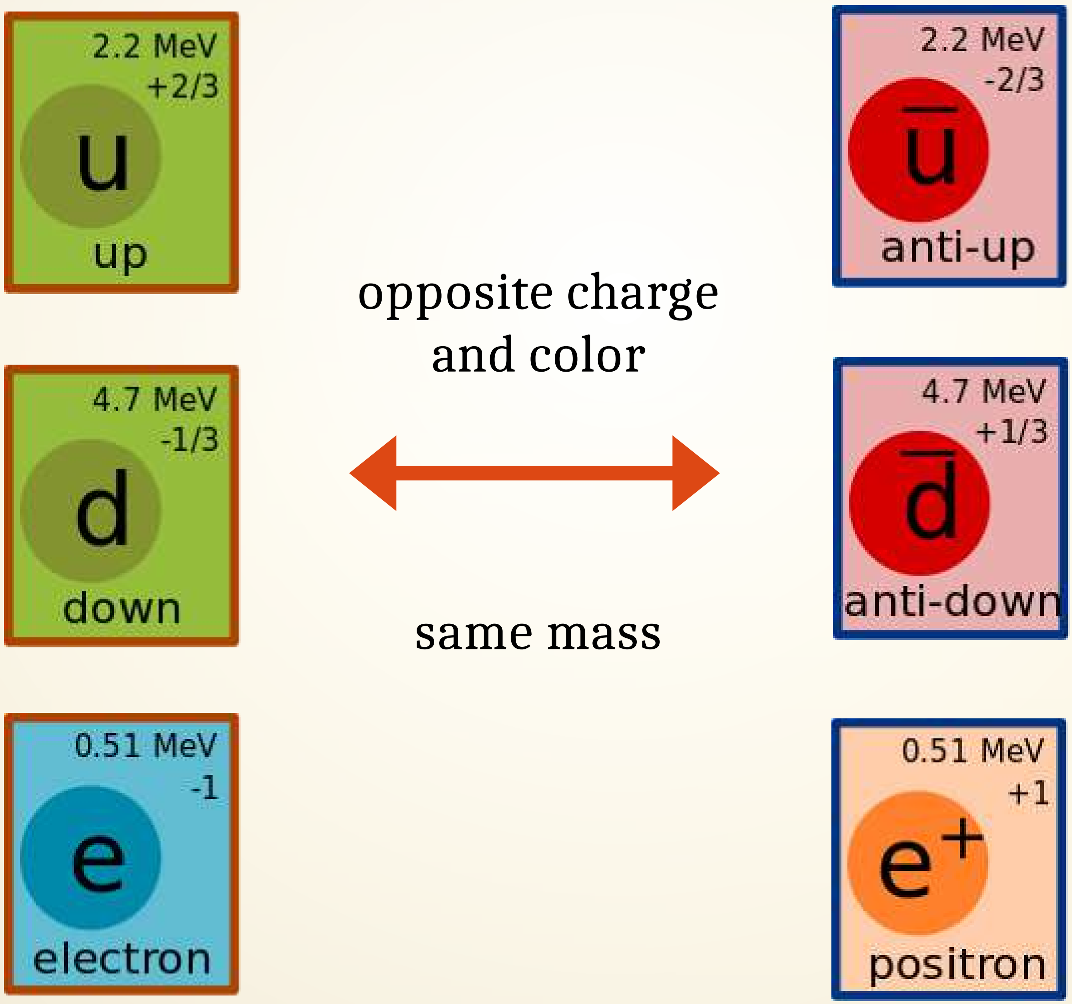


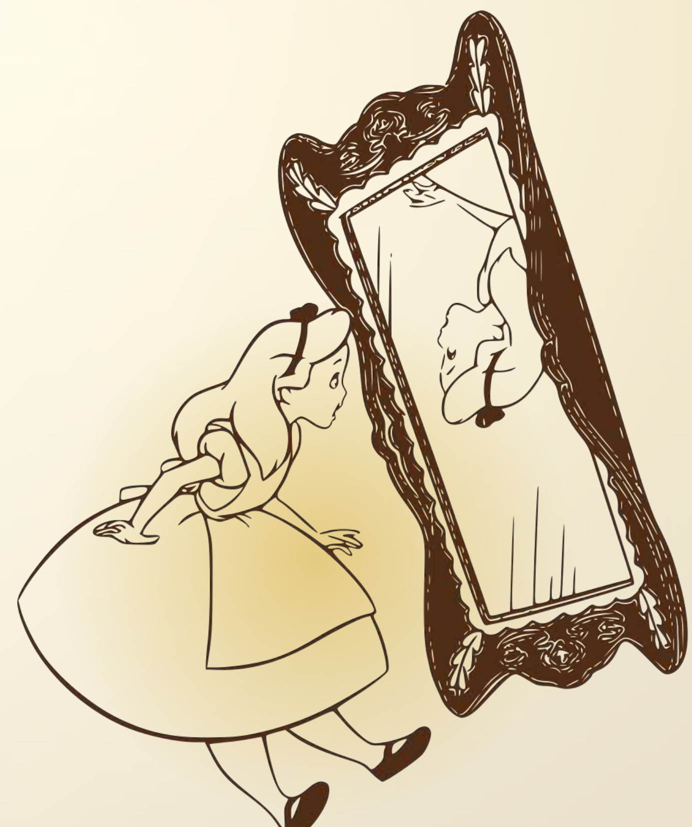
proton: RGB



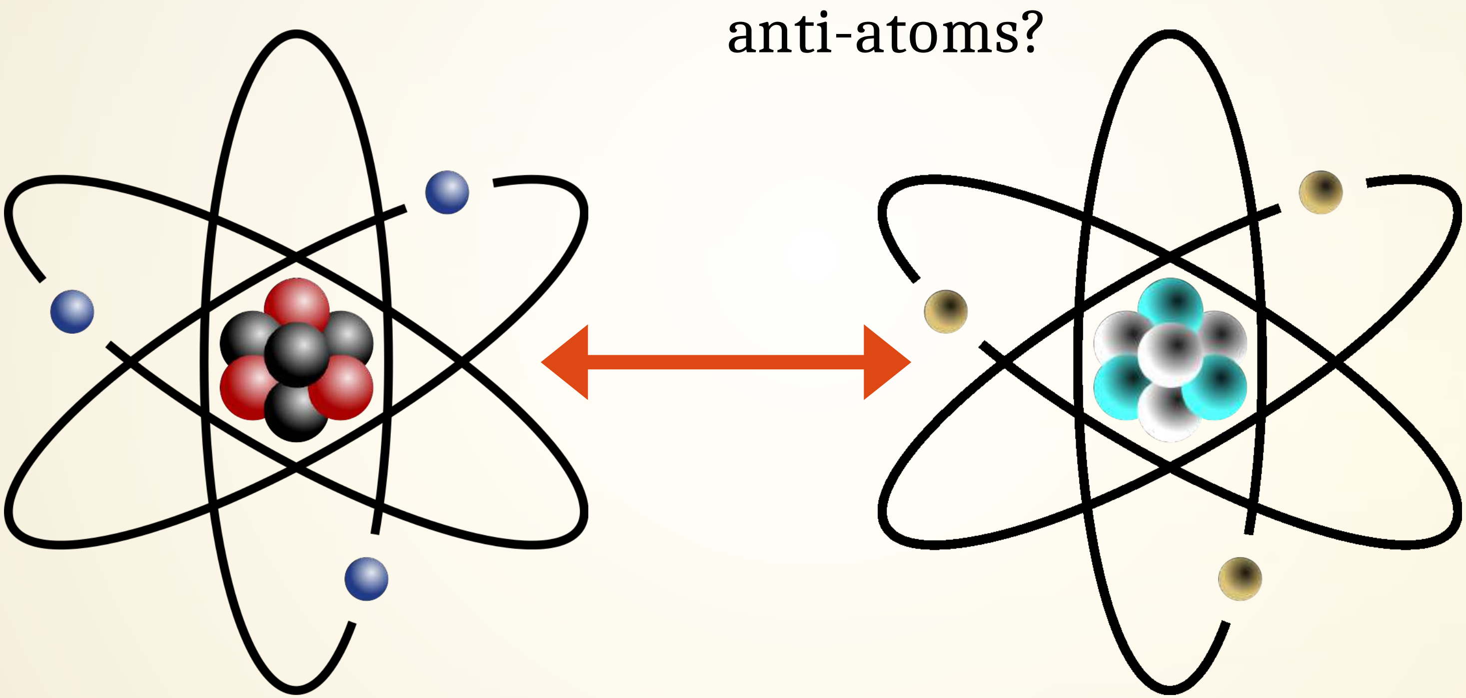
Antimatter

for each particle there is an antiparticle

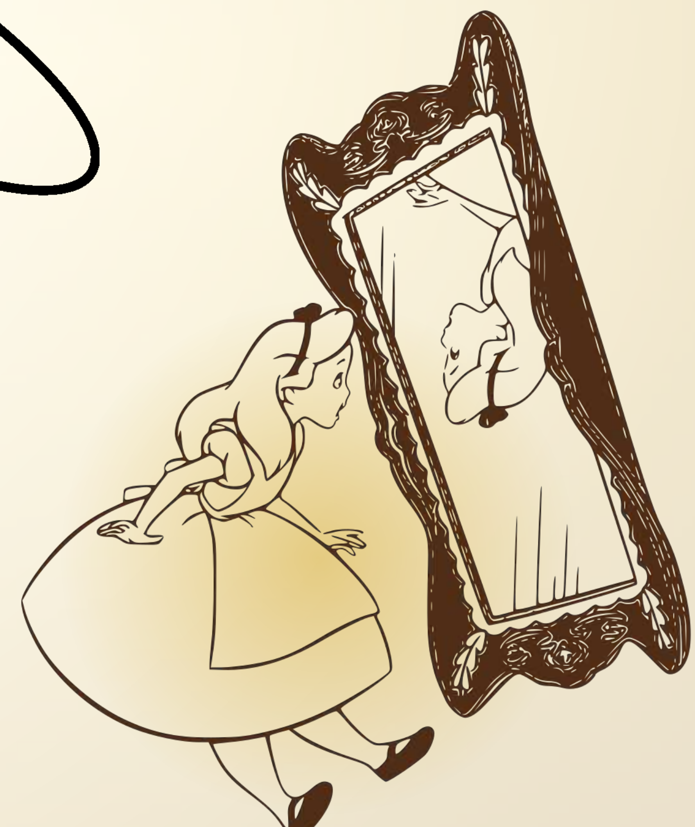


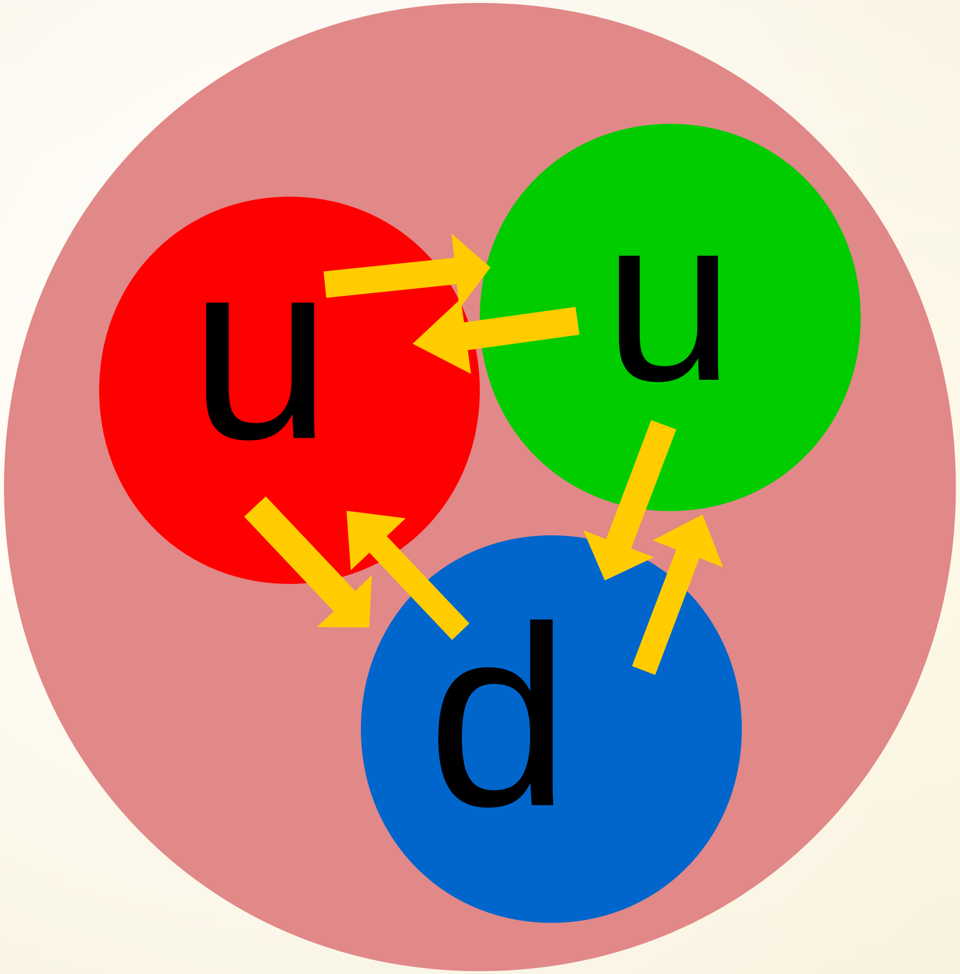


Antimatter



Why are we made of atoms and not antiatoms?

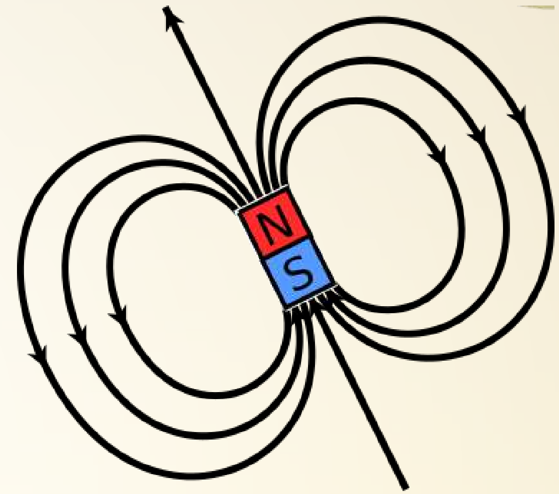




What keeps the quarks together in a proton?

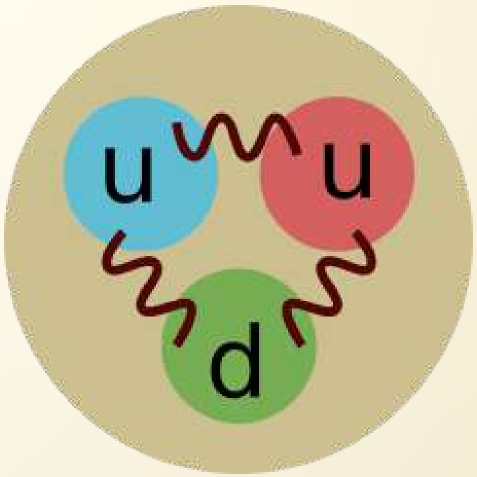
Particle interactions

Fundamental forces



Electromagnetism

Gravity



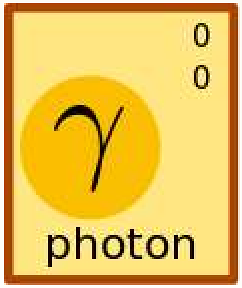
Strong force

Weak force

interactions are mediated by force carriers

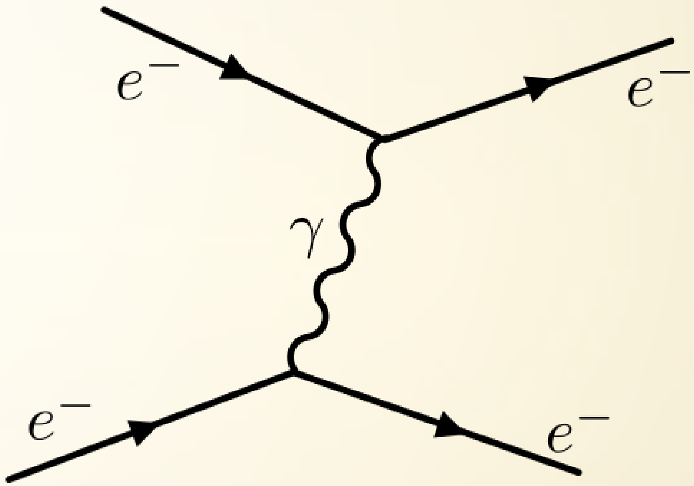
interactions are mediated by force carriers

Electromagnetism



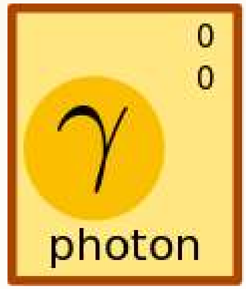
particles with <u>electric charge</u> exchange photons

a long range force



interactions are mediated by force carriers

Electromagnetism



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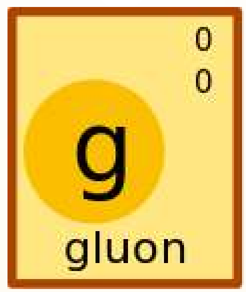
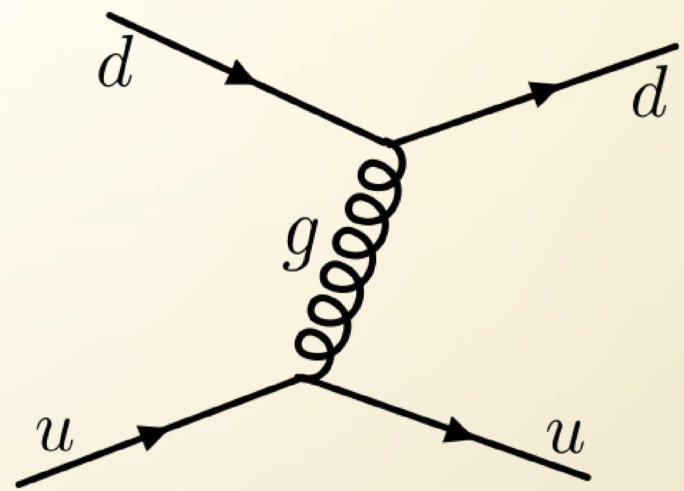
a long range force

Strong force

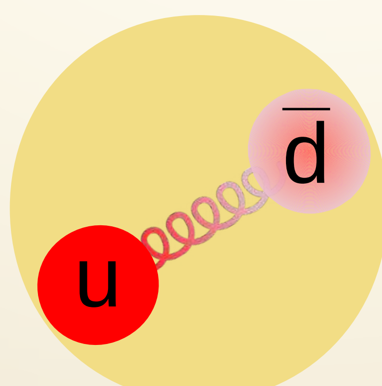


particles with color exchange gluons

so strong that its range is only the size of an atomic nucleus

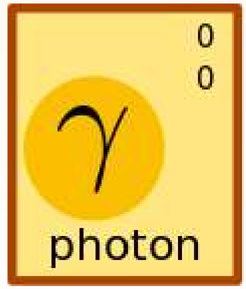


gluons themselves have color



interactions are mediated by force carriers

Electromagnetism



particles with electric charge exchange photons

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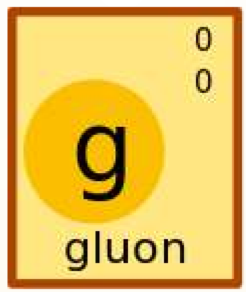

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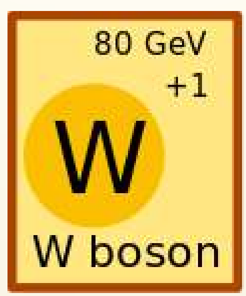
Weak force

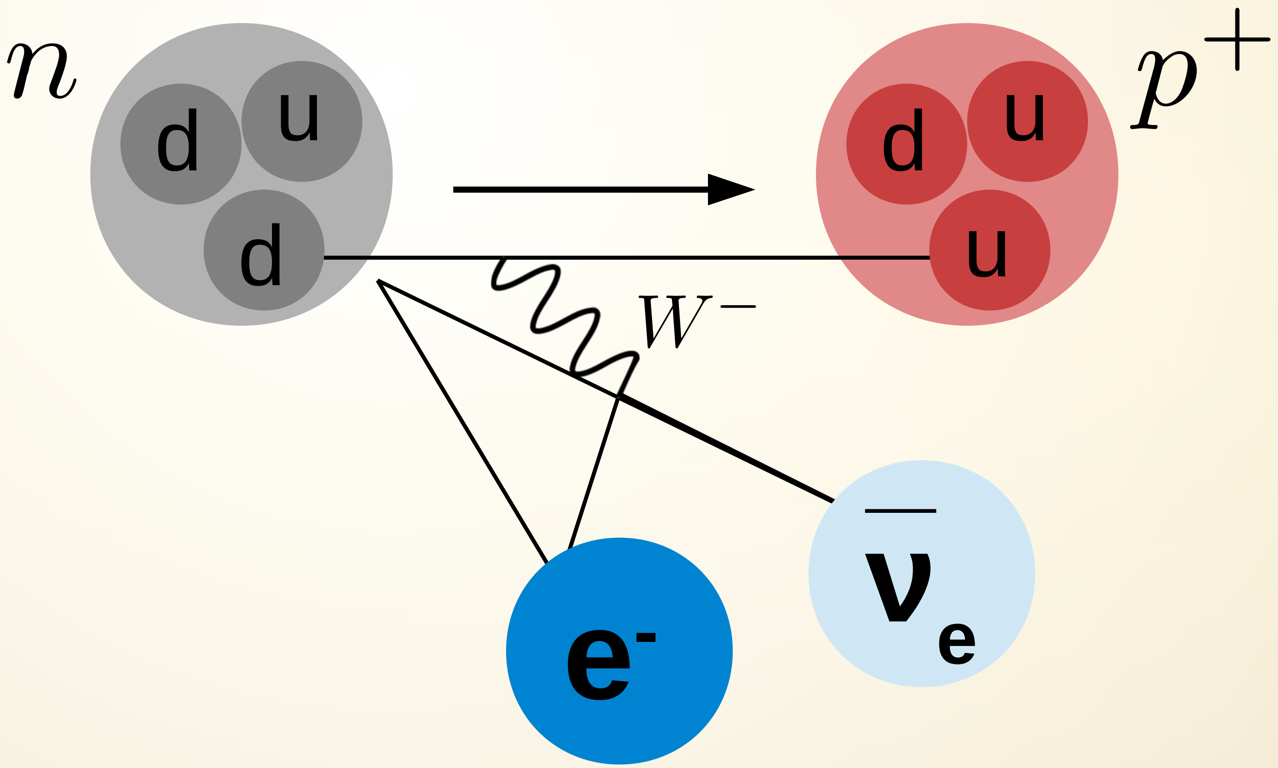


The Weak Interaction

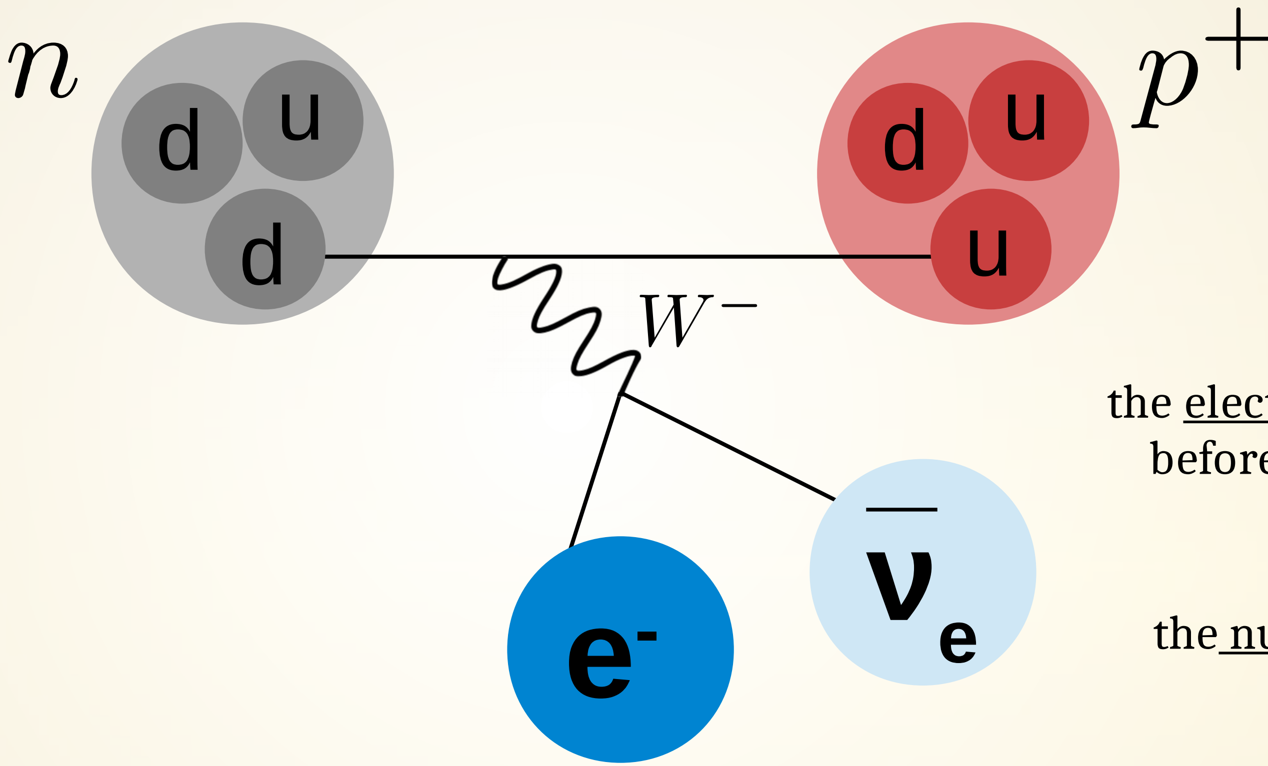
Beta-decays of nuclei

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

$$^{3}_{1}T \rightarrow ^{3}_{2}He + e^{-} + \bar{\nu}_e$$



Conservation laws



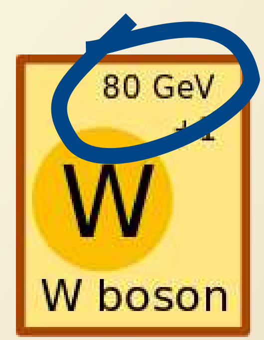
the electric charge is the same before and after the decay

the number of particles is the same

The total energy is also conserved

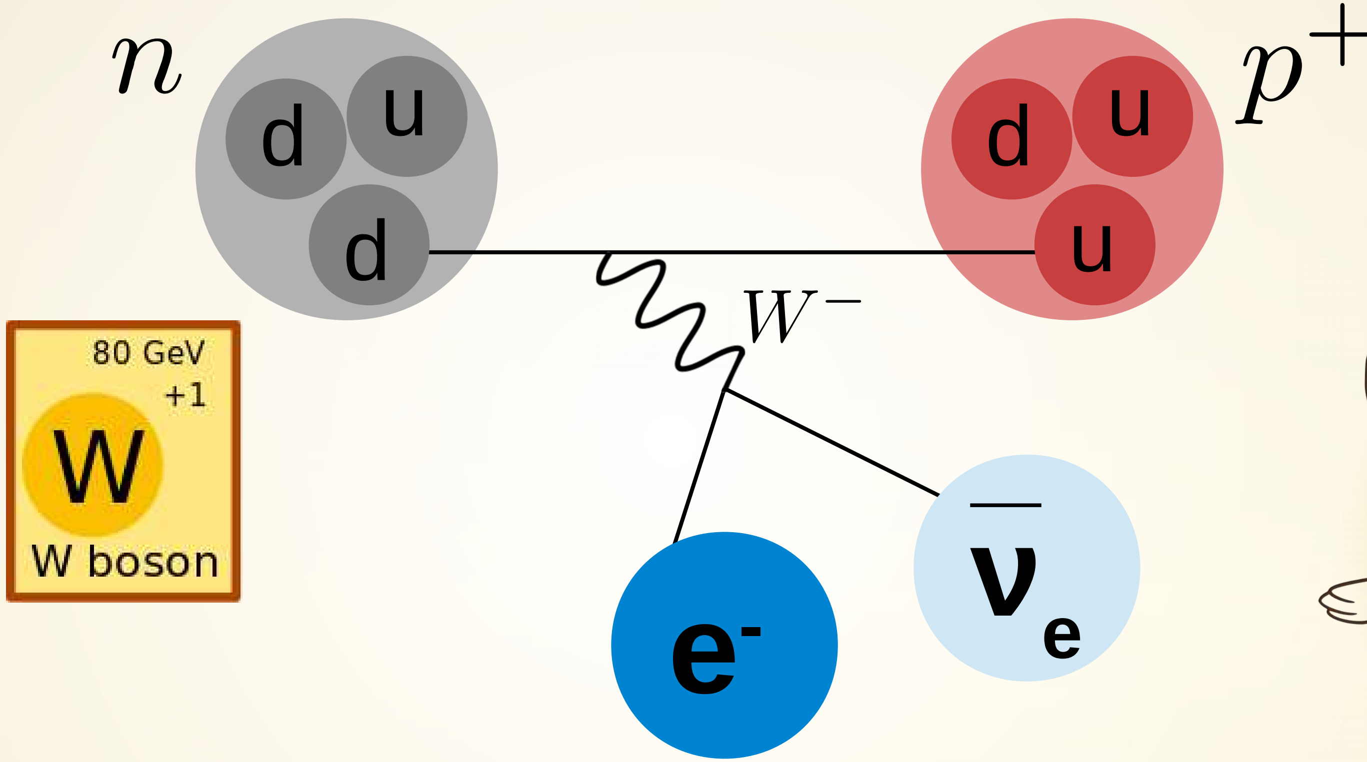
$$m_n > m_p + m_e + m_\nu$$

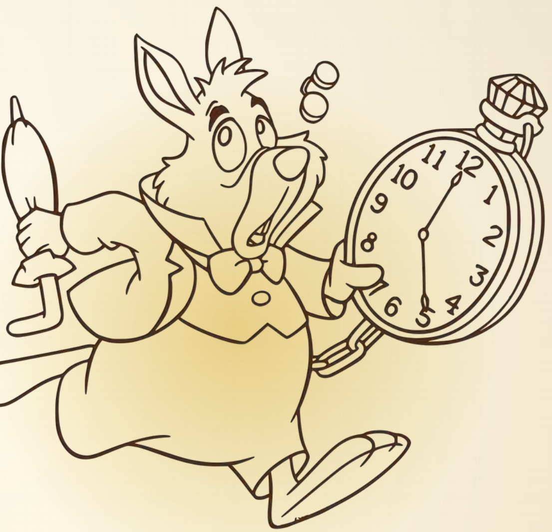
$$\begin{aligned} m_n &= 940 \text{ MeV} \\ m_p &= 938 \text{ MeV} \\ m_e &= 0.51 \text{ MeV} \\ m_\nu &\simeq 0 \end{aligned}$$



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

Virtual particles





Uncertainty principle

*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.*

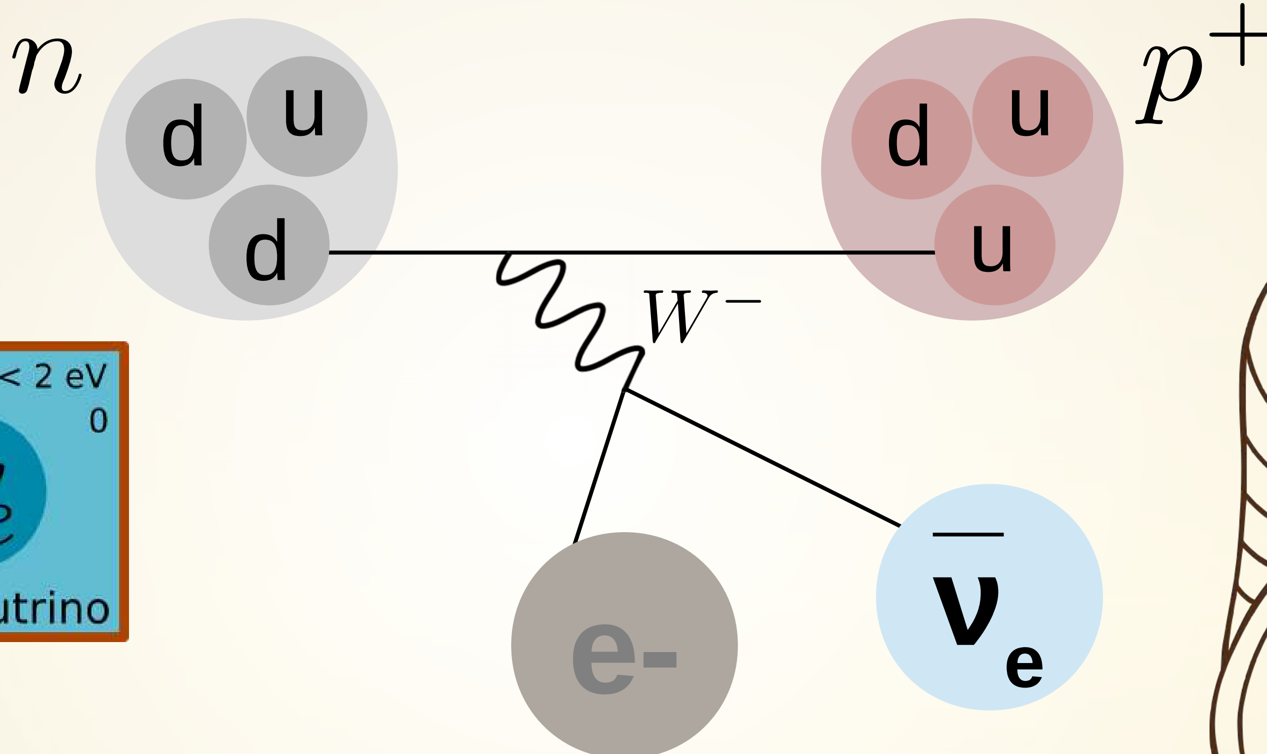
$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

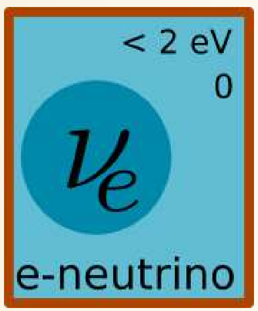
A virtual W can live only up to 10^{-27} s.

In this time it travels about 10^{-7} nm.

Weak interactions have a very short range!

Neutrinos





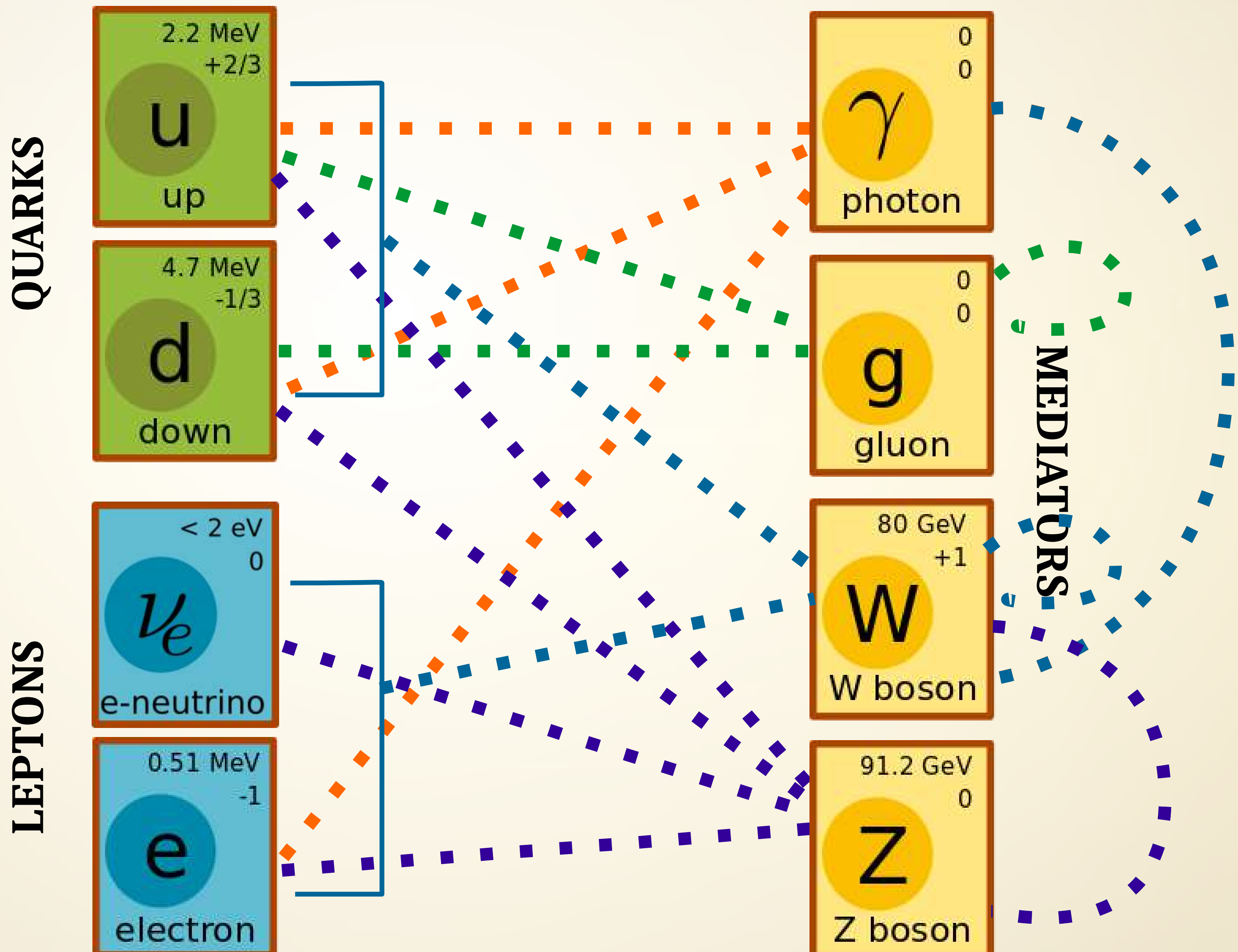
neutrinos are <u>neutral</u> and <u>colorless</u>

they feel only the weak force → **very elusive**

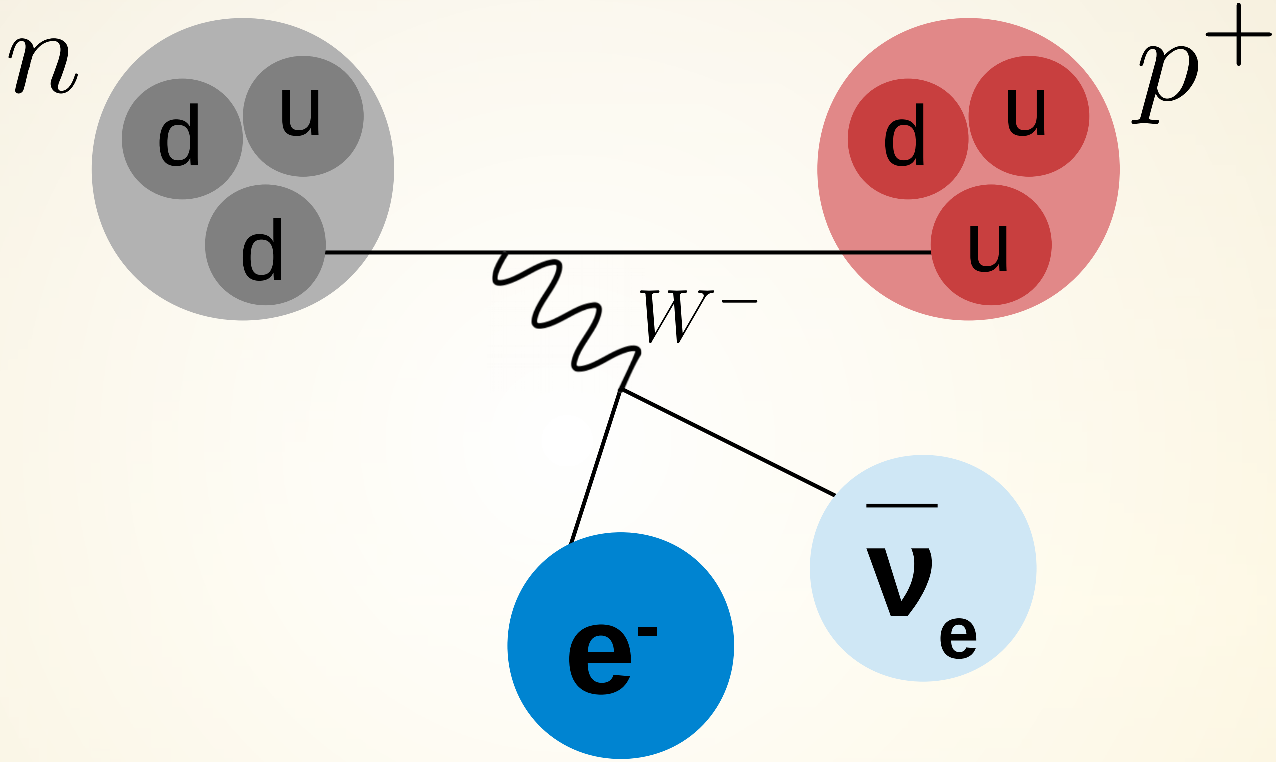
they have **very tiny masses**, that have not been precisely measured yet and were <u>not predicted</u> by theory!

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

Summarizing



W's transform a particle into another

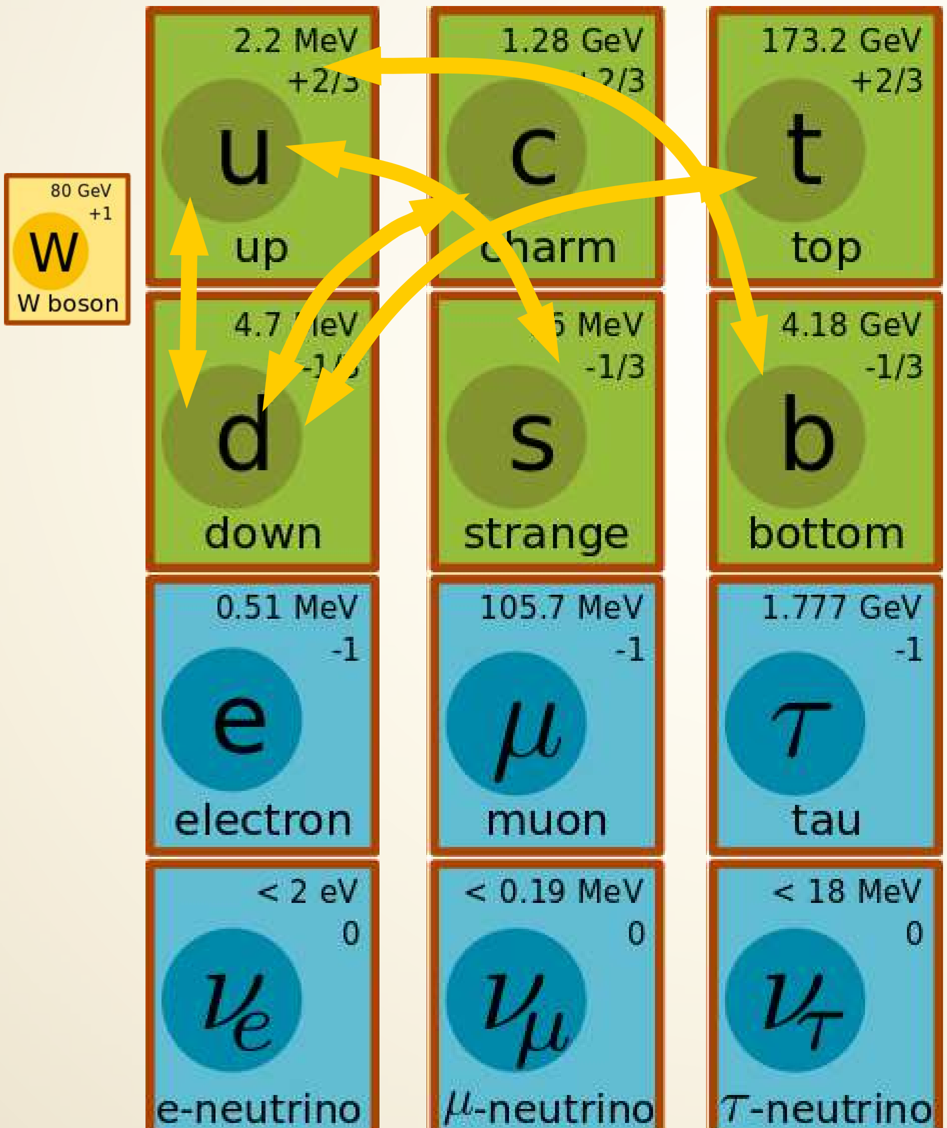


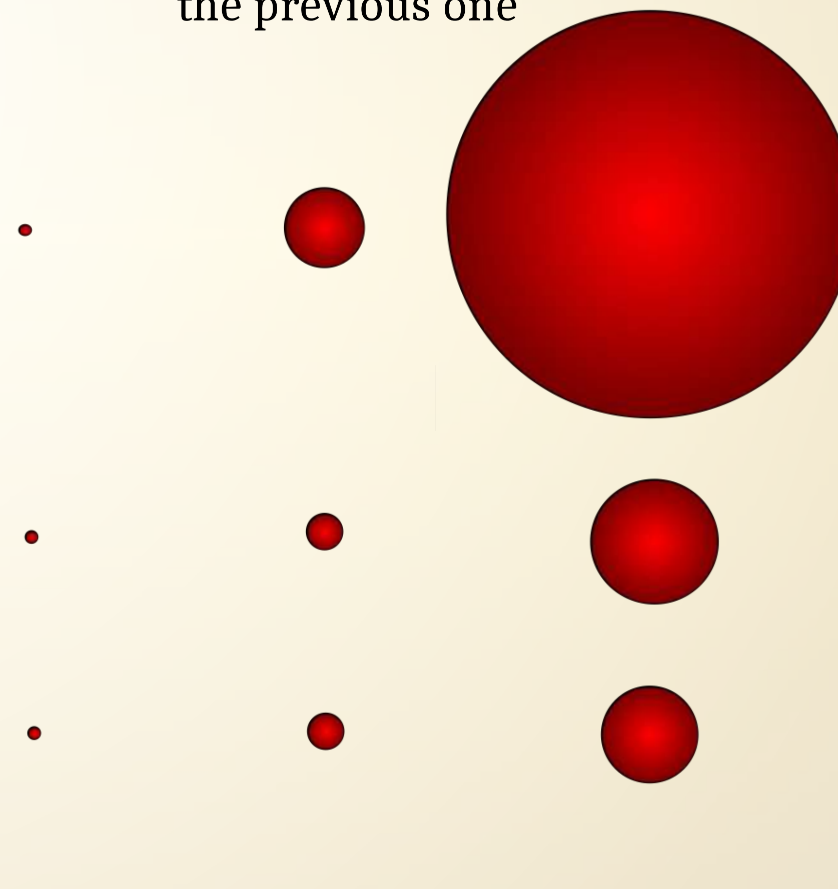
... and their flavor

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





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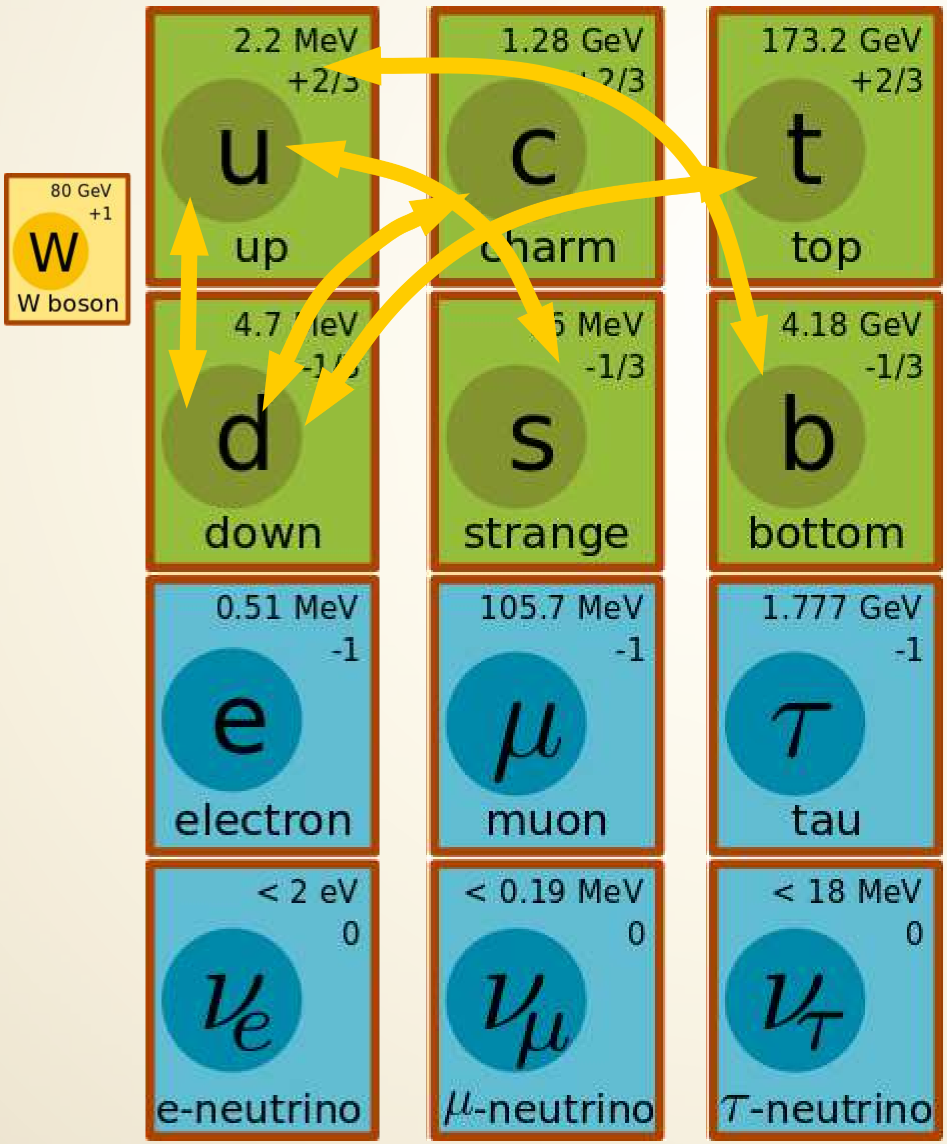
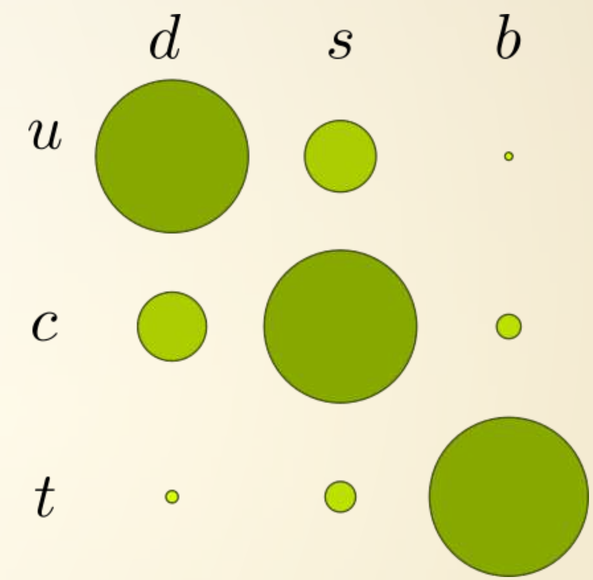
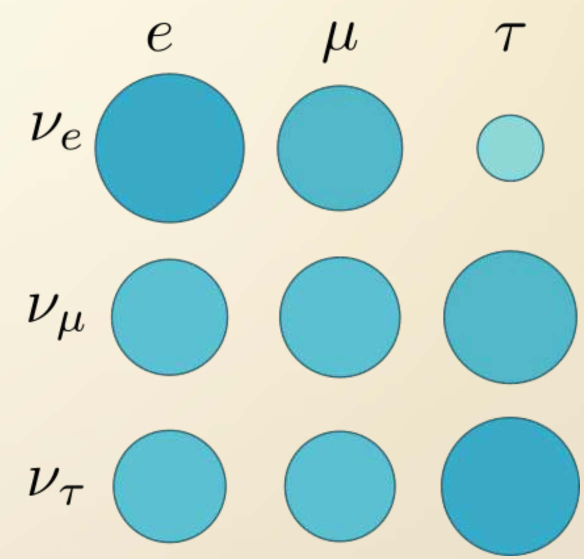




not all the transformations happen with the same <u>probability</u>!



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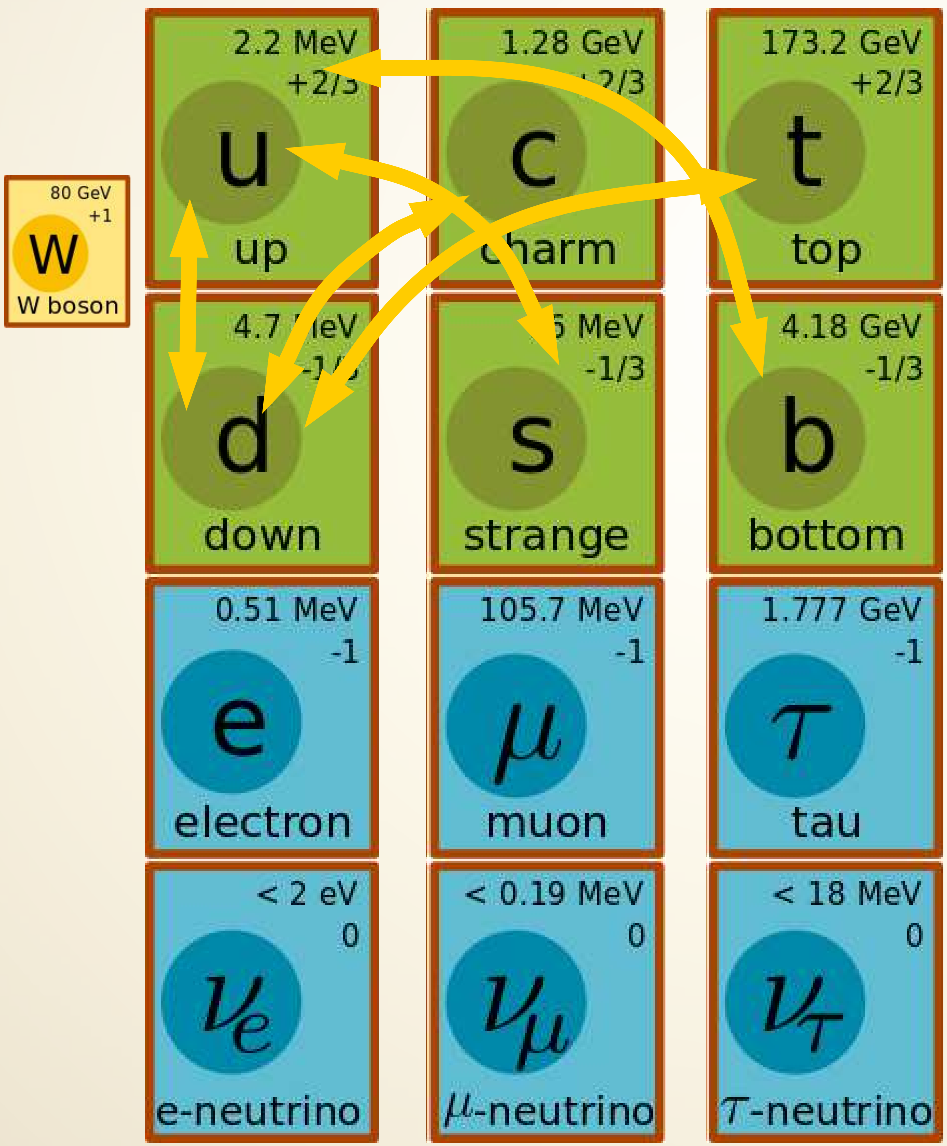


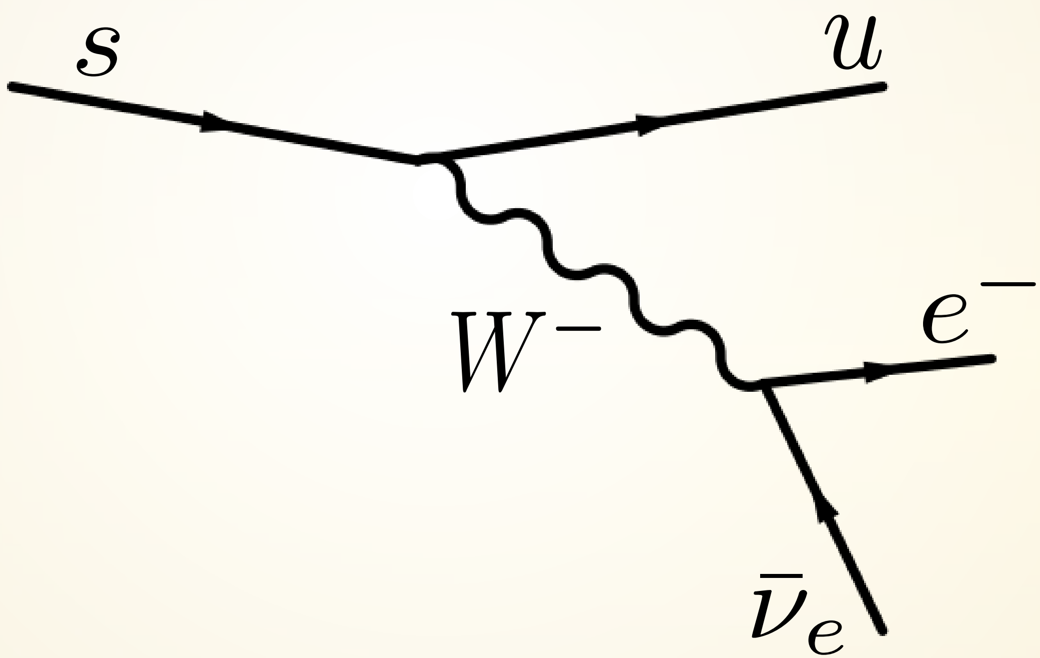
Why are there **3** generations?

Why do they have such different <u>masses</u>?

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**



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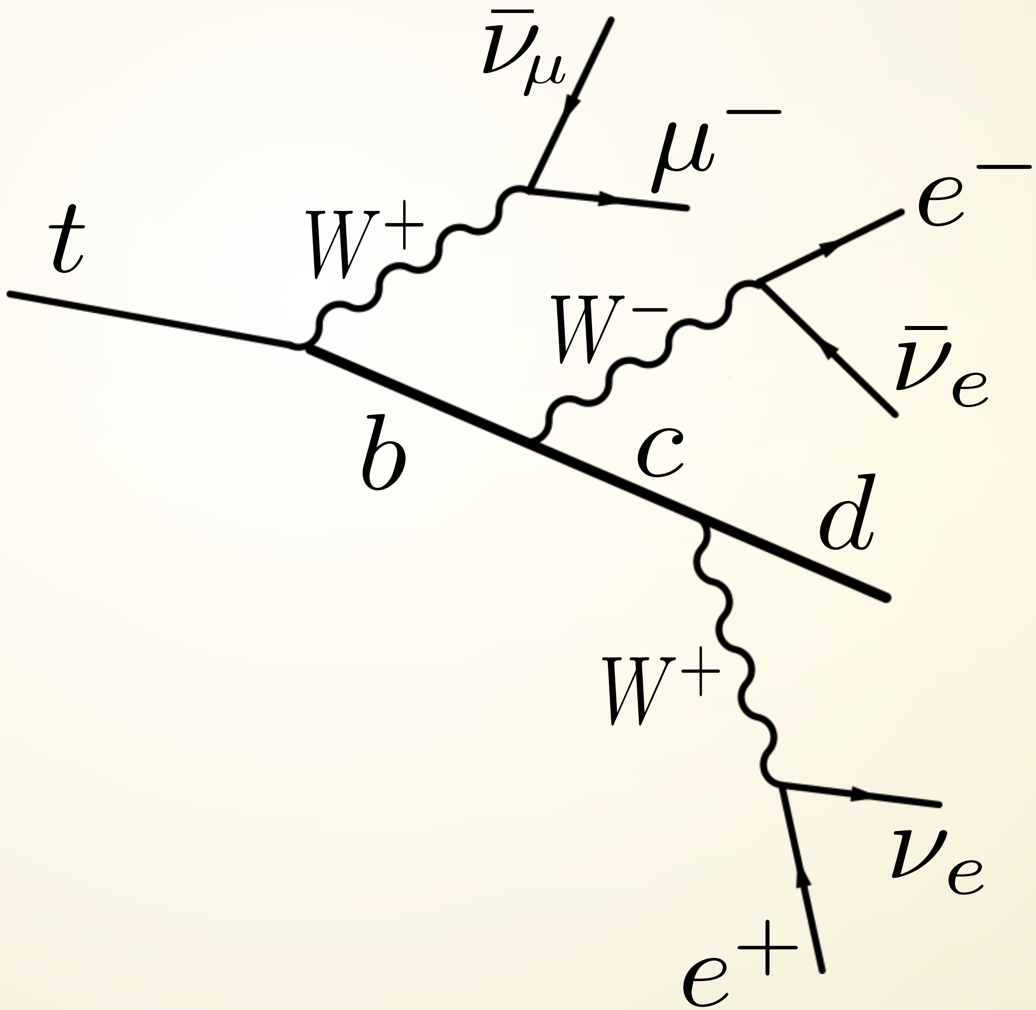
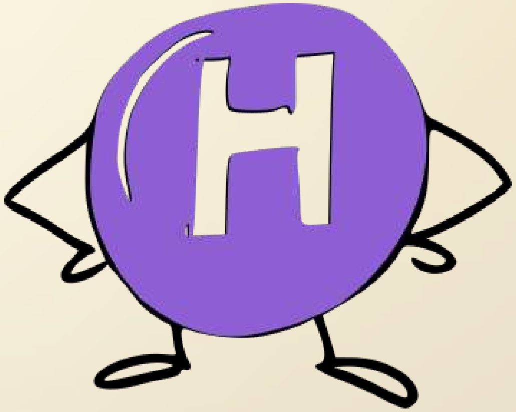


to ”see” heavy particles we need enough energy to produce them

more in the second part!

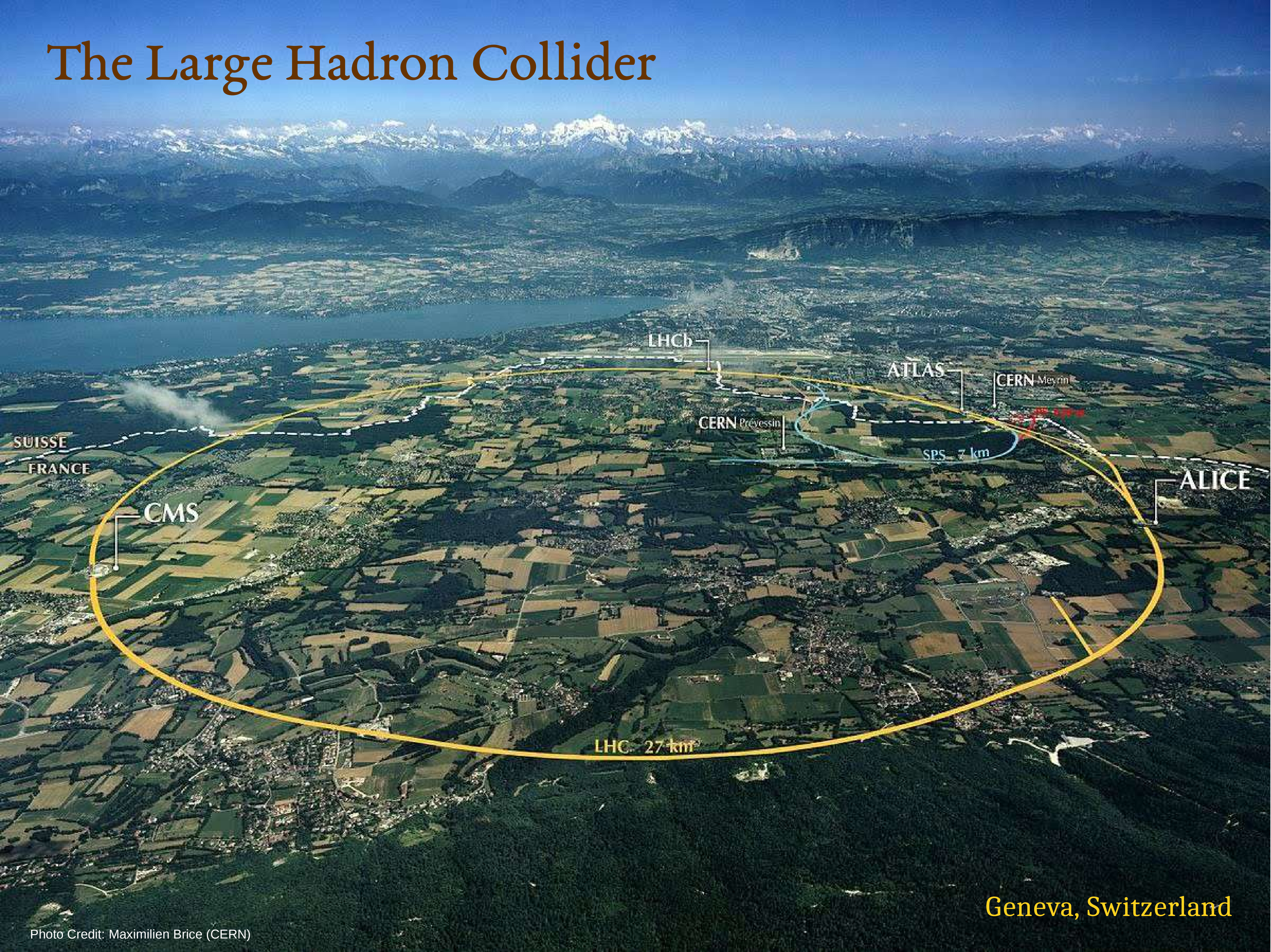
also... didn’t we forget someone?



Part II

How do we explore the Particle World?

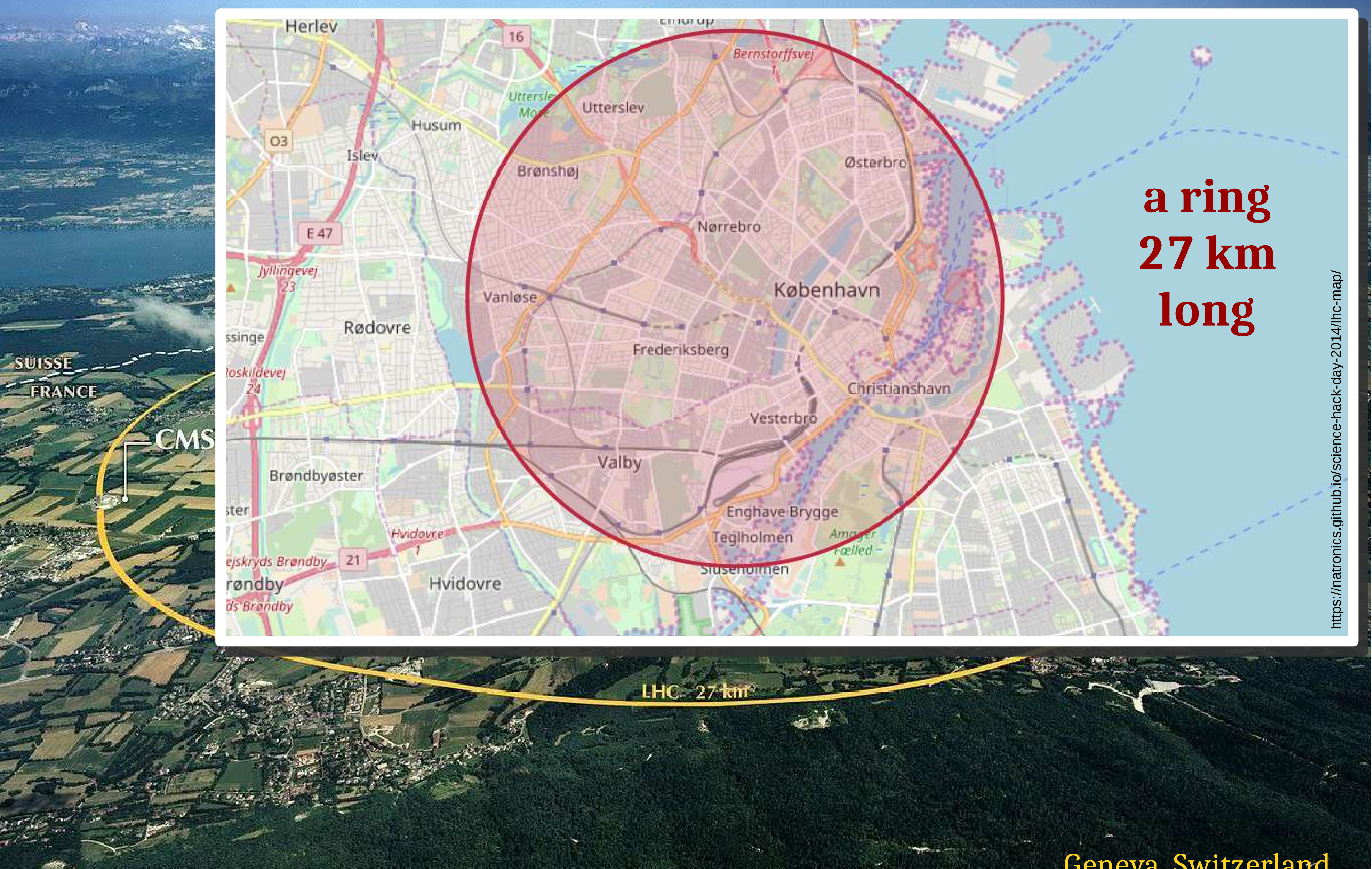
The Large Hadron Collider



Geneva, Switzerland

Photo Credit: Maximilien Brice (CERN)

The Large Hadron Collider



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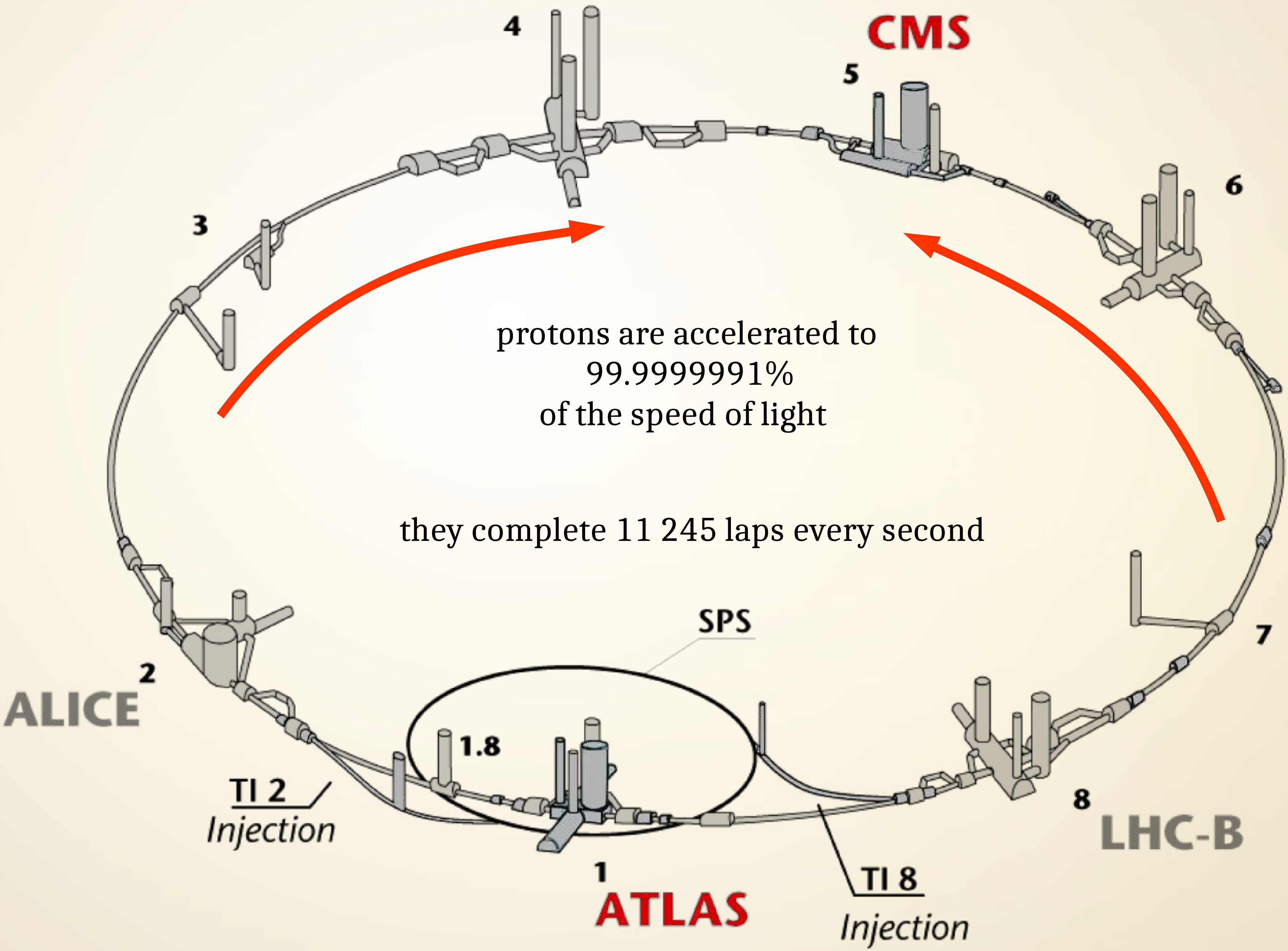
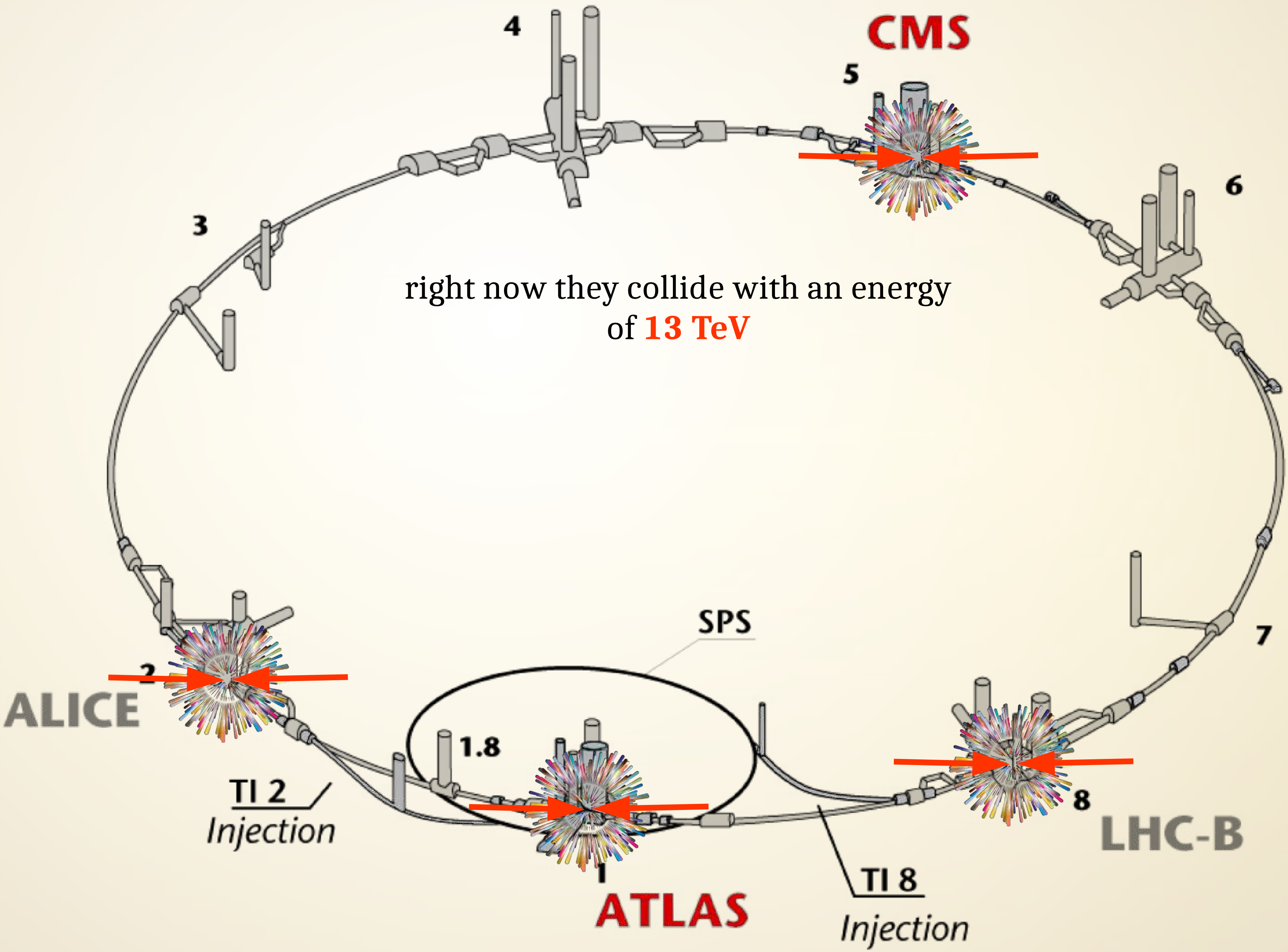
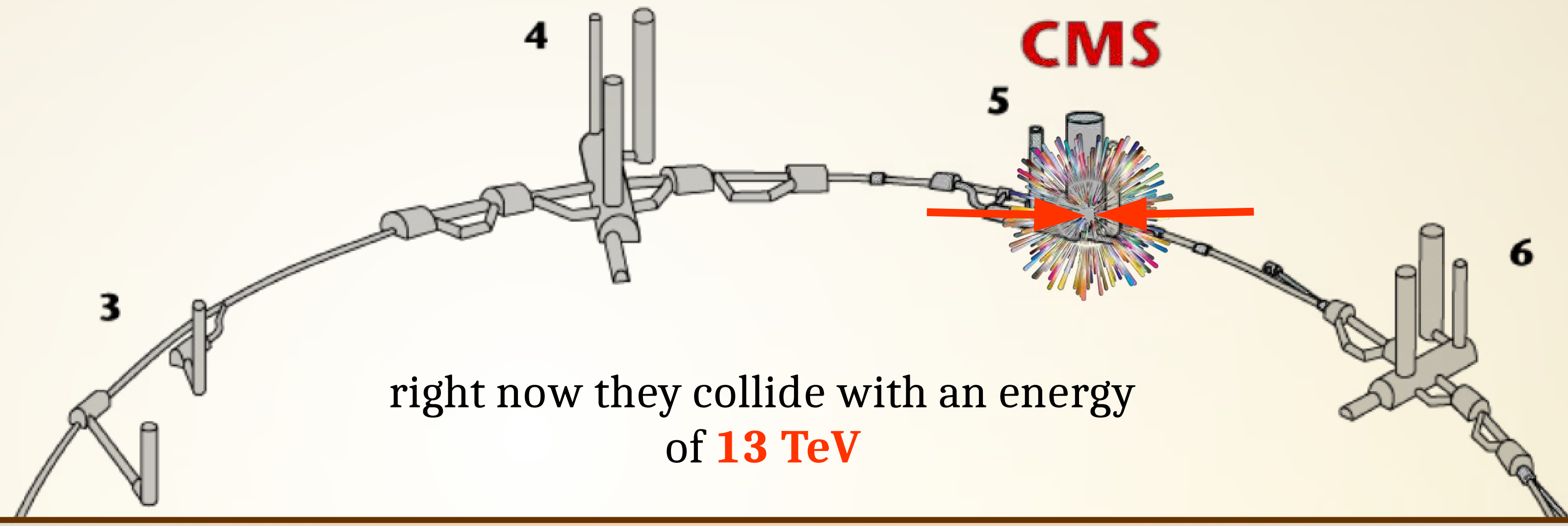


Image from: CERN AC – HF267

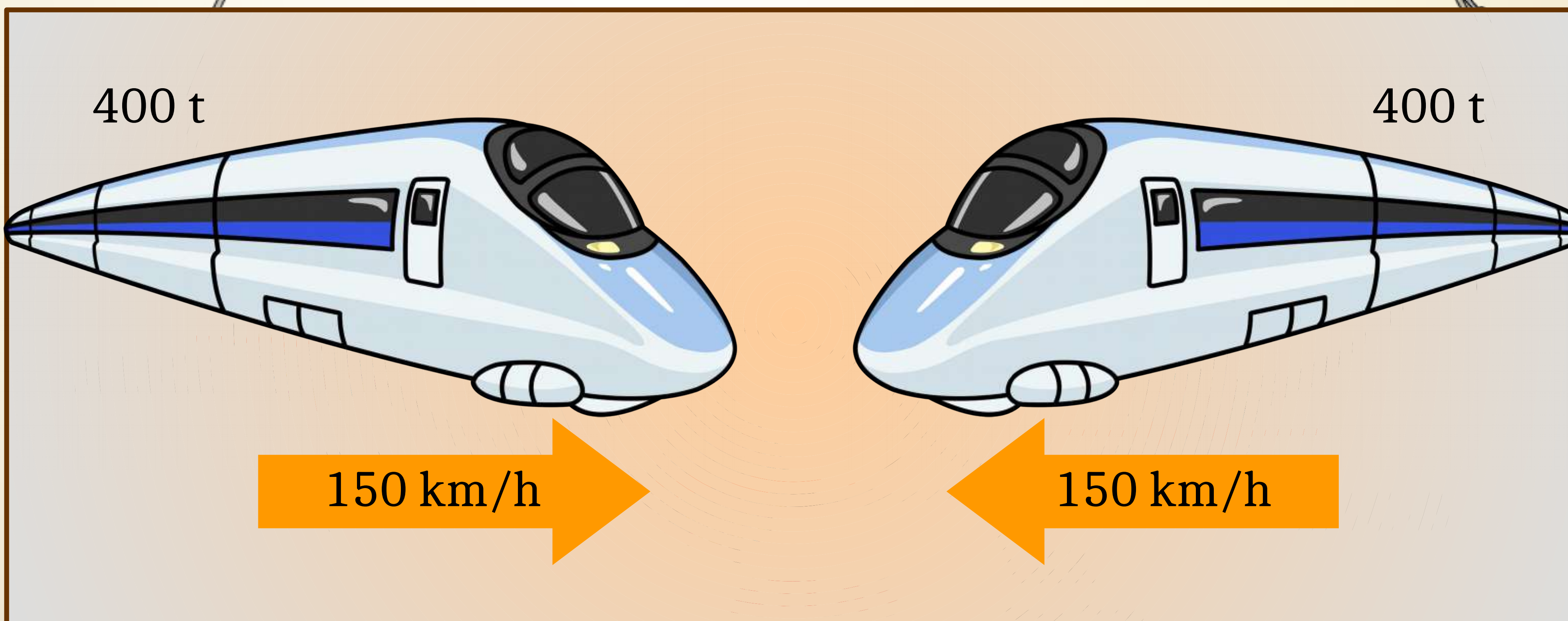
The Large Hadron Collider



The Large Hadron Collider



right now they collide with an energy of **13 TeV**



Two big detectors: ATLAS and CMS

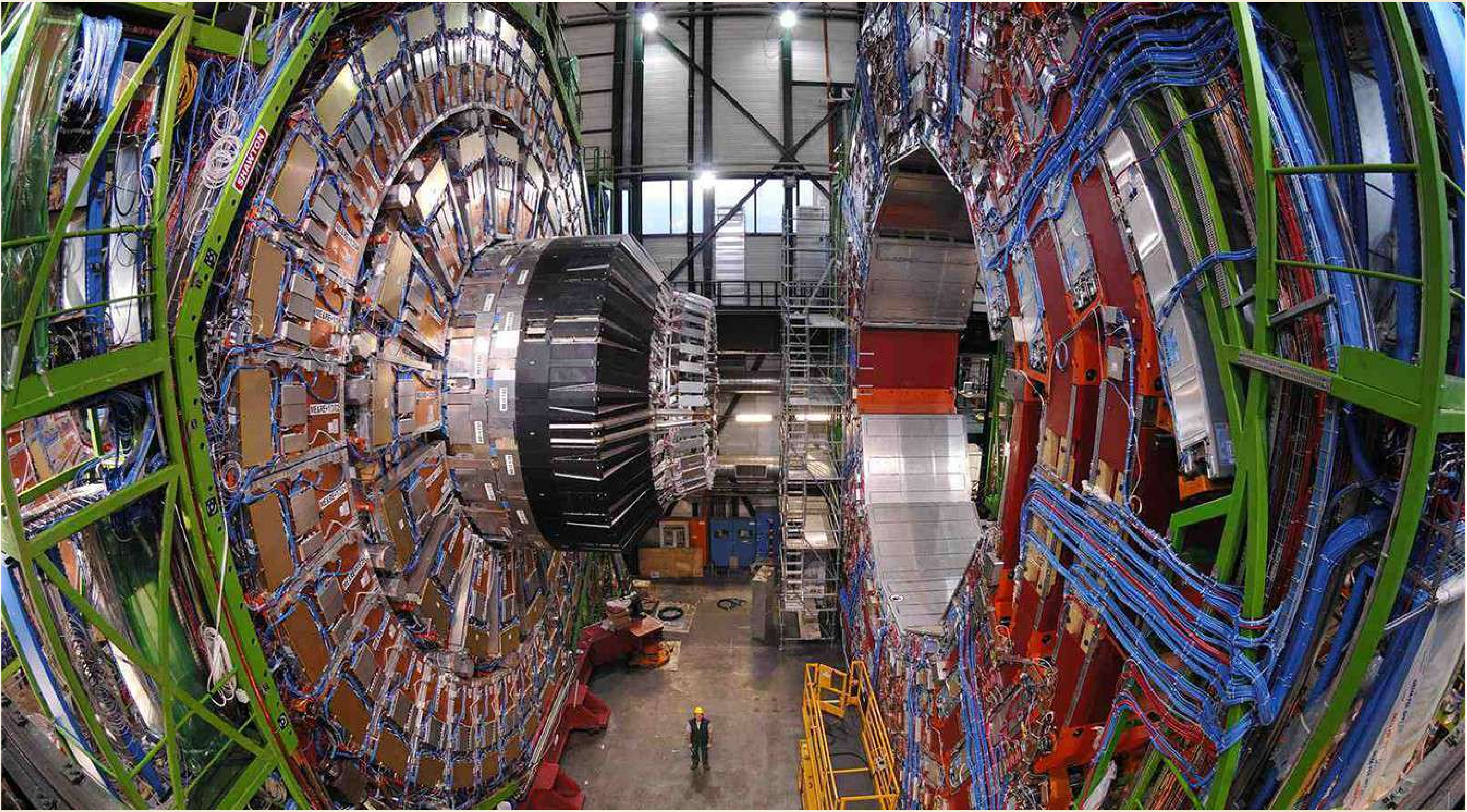


Photo Credit: (CERN)

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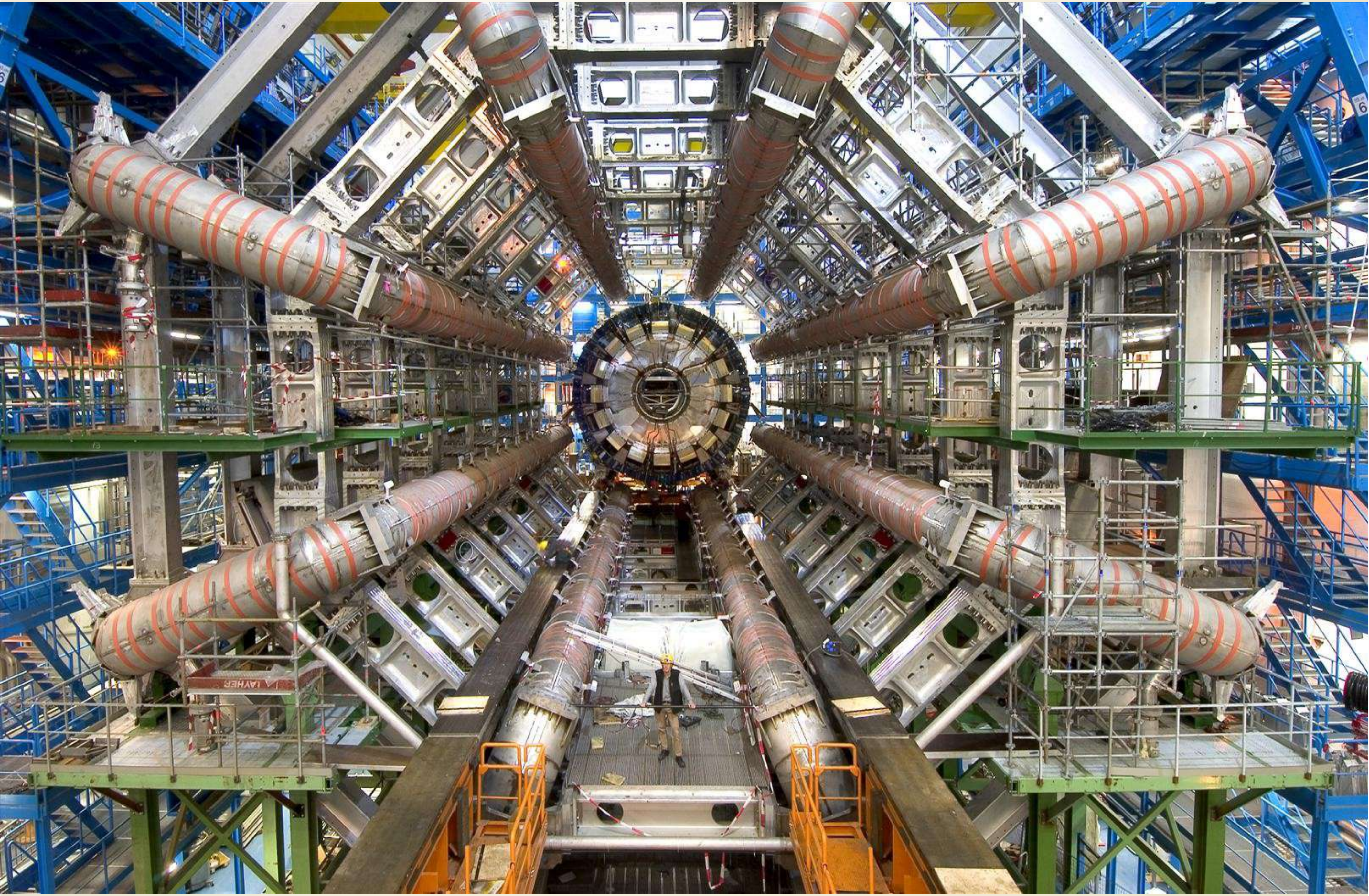
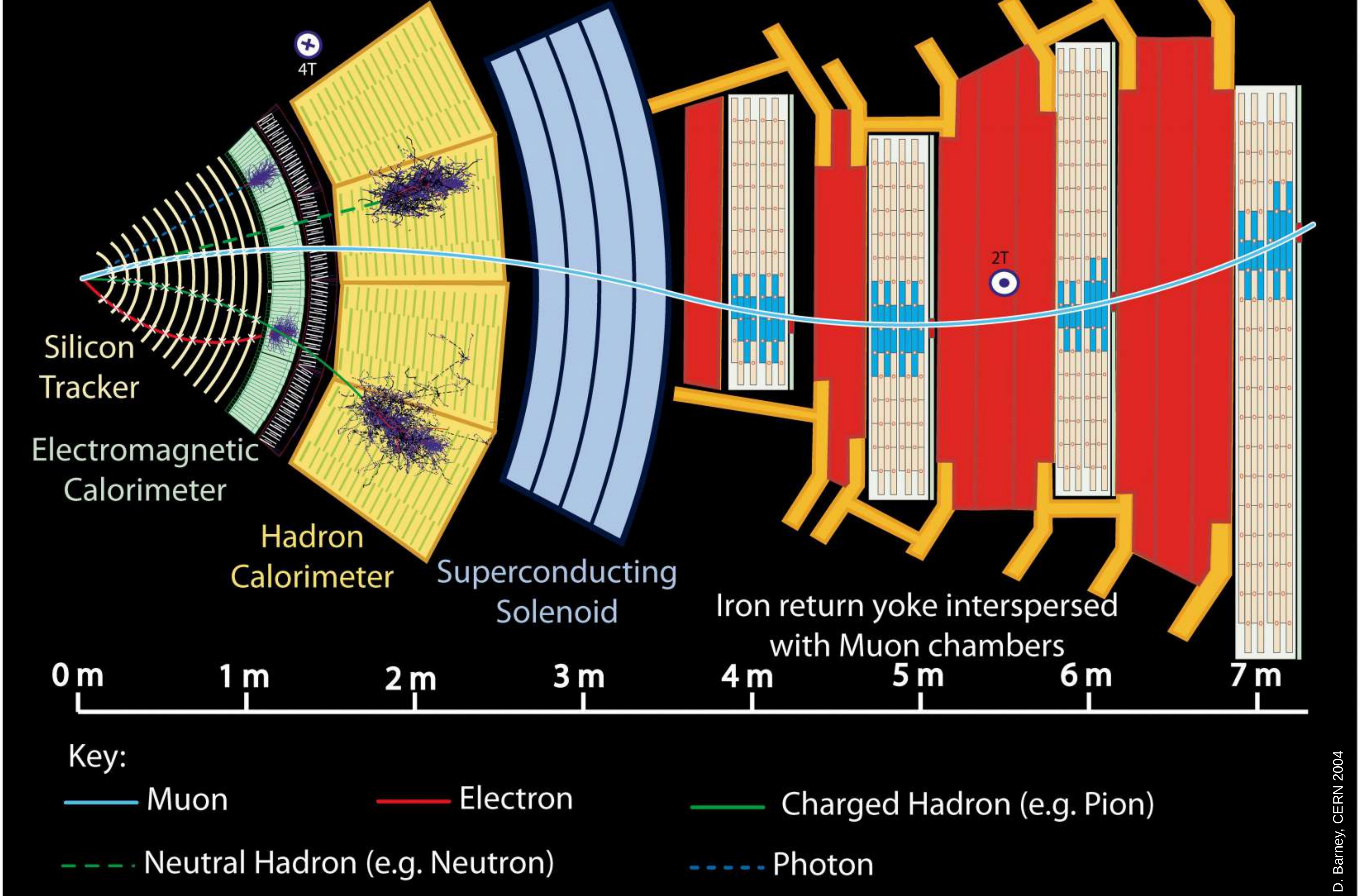


Photo Credit: Maximilien Brice (CERN)

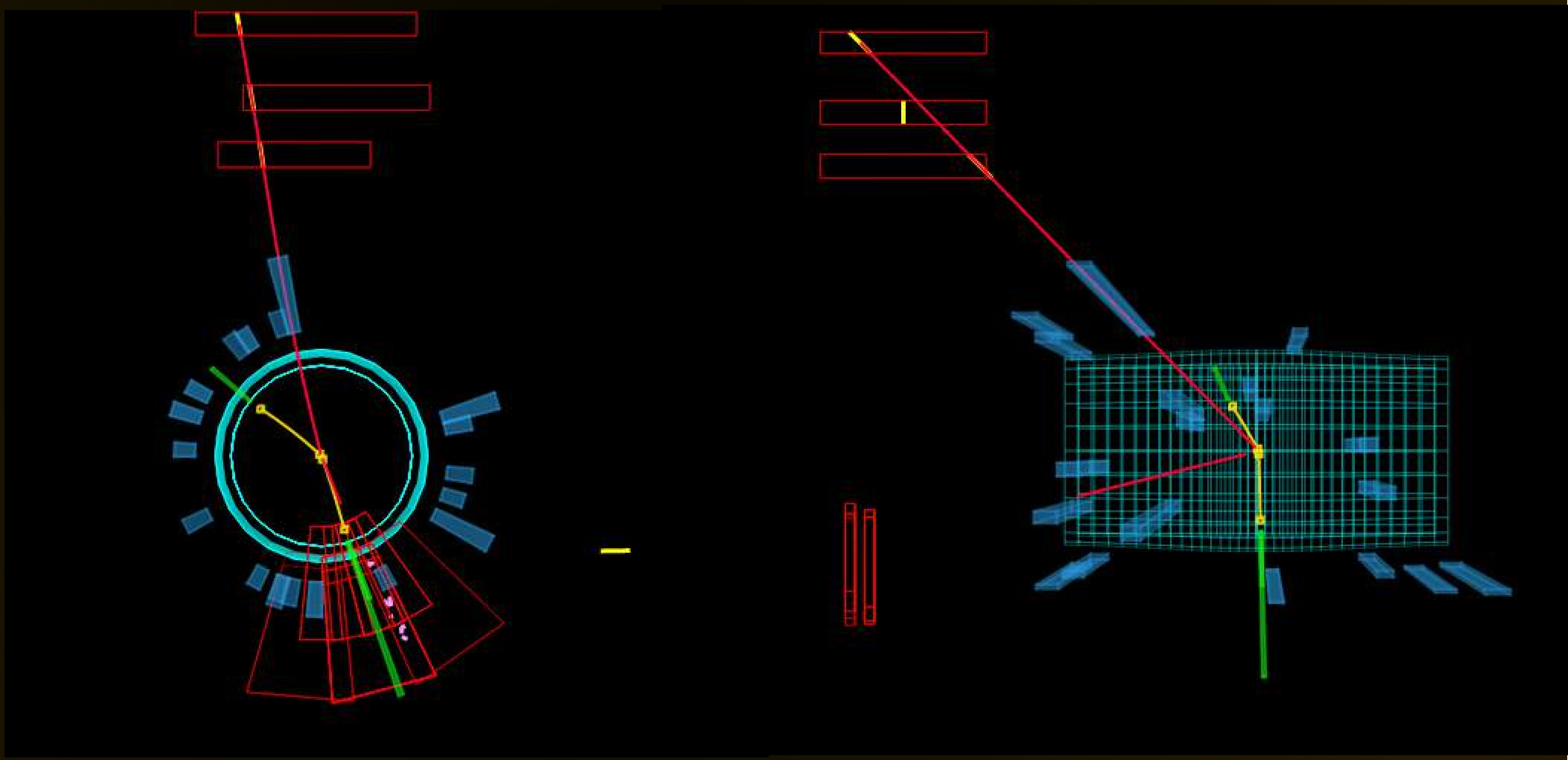
A slice of CMS



Reconstructing what happened

Image credit: Andre Holzner, CERN

Reconstructing what happened



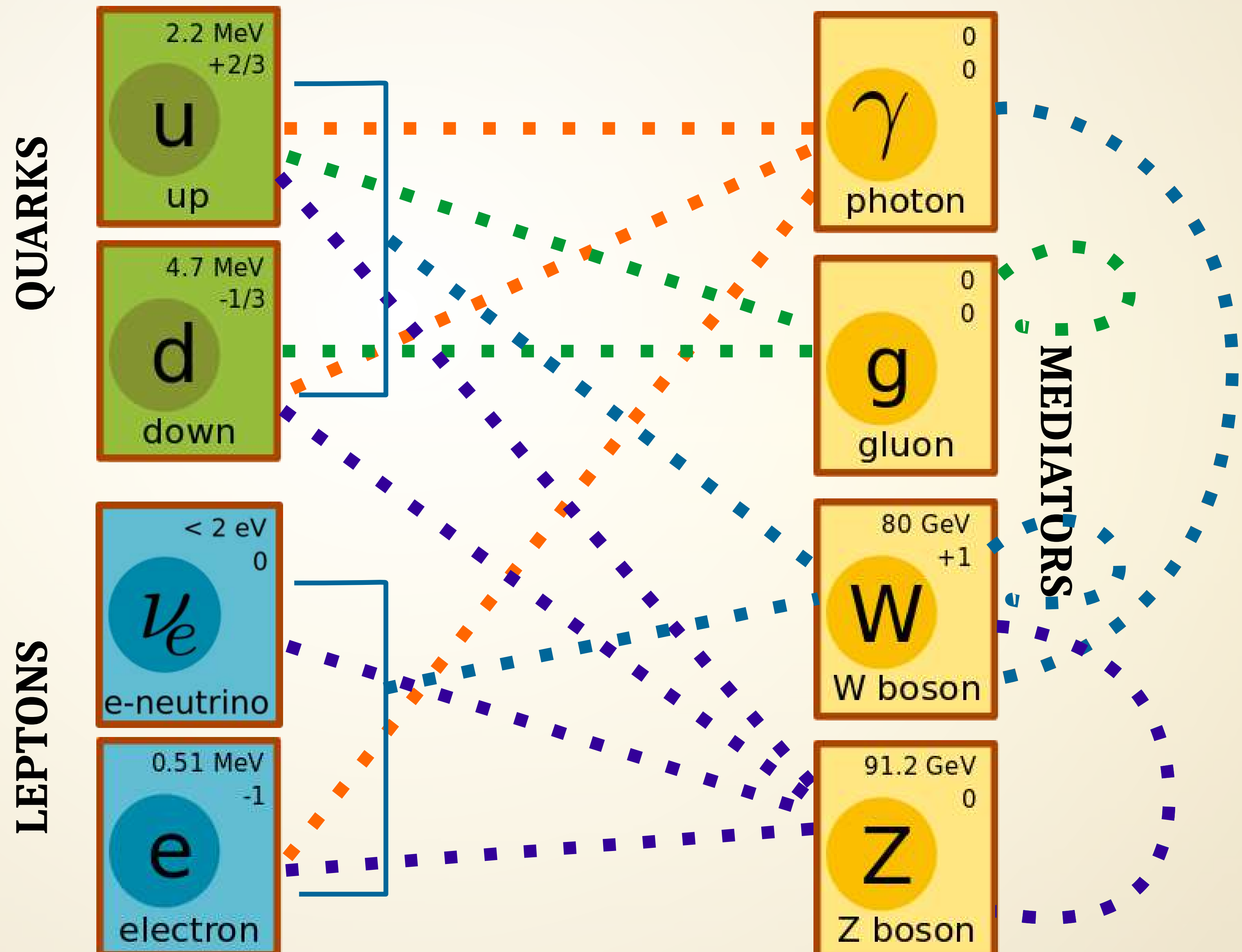
Real events from: https://www.i2u2.org/elab/cms/event-display/

Finding the Higgs boson

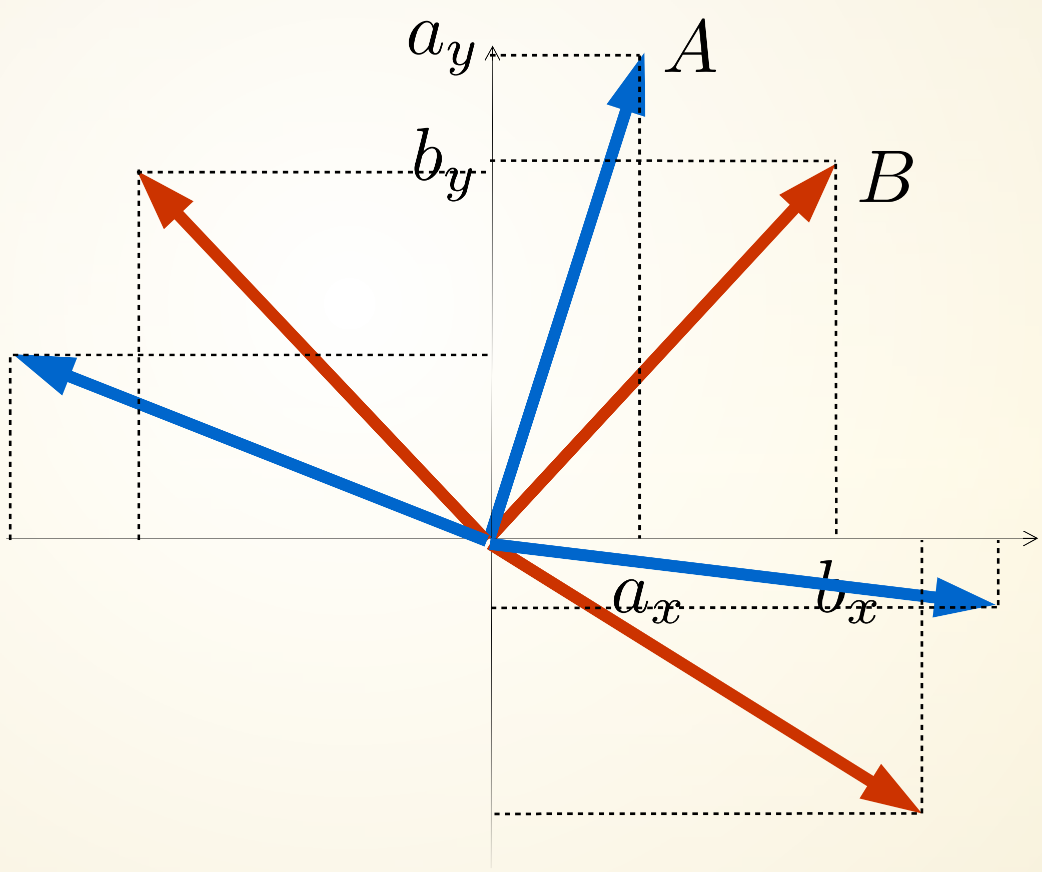
Theory

the importance of the Higgs

Fundamental interactions



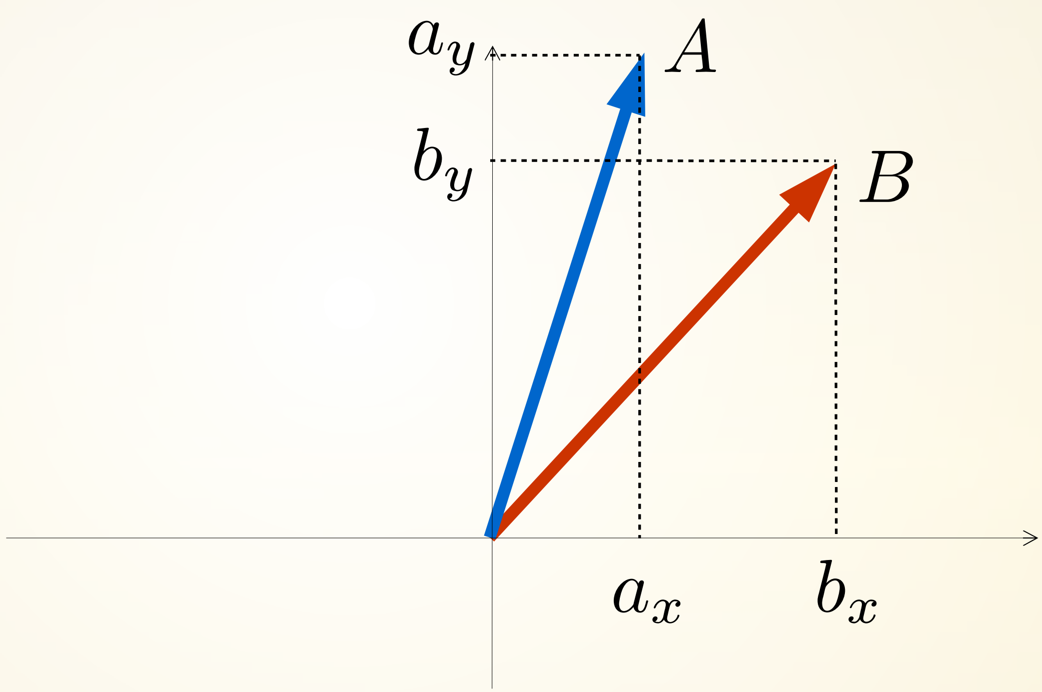
Symmetries explain the rationale of the interactions



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 <u>invariant</u> of the rotation symmetry

Symmetries explain the rationale of the interactions



$a_x b_x + a_y b_y$ is an invariant of the symmetry.

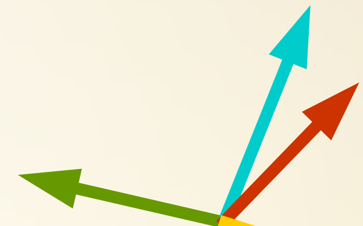
To combine A and B in a way that respects the rotation symmetry we <u>must</u> pair

a_x with b_x and a_y with b_y and take the sum.

Other combinations are <u>not allowed</u>.

Symmetries explain the rationale of the interactions

particles ⟷ **components of some vectors**



(depending on the charge, color etc)

for each force, a symmetry tells us

which interactions must exist and

which are forbidden

The importance of the Higgs boson

The symmetry of the weak interactions

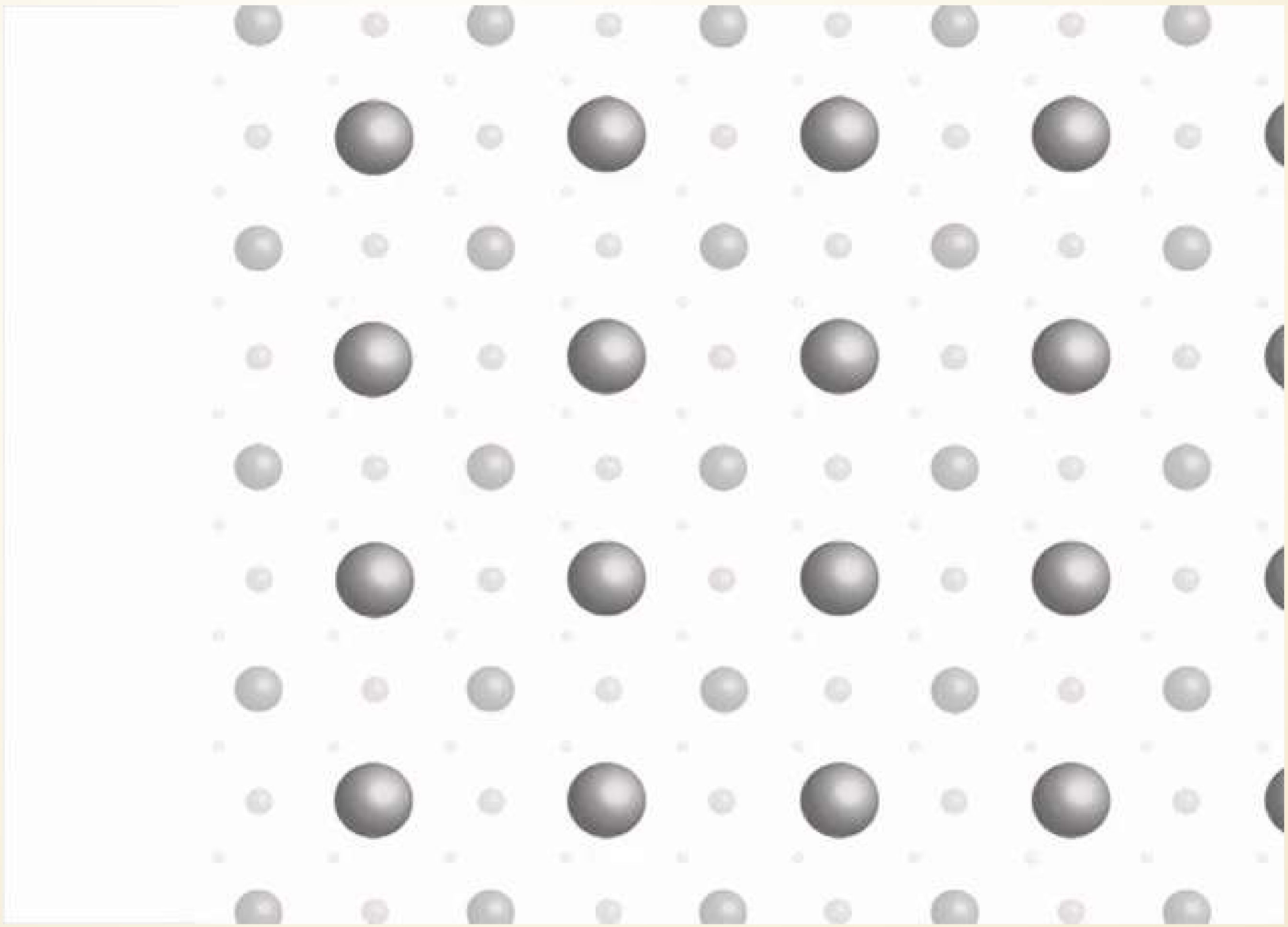
is a weird one:

it forbids all the masses!

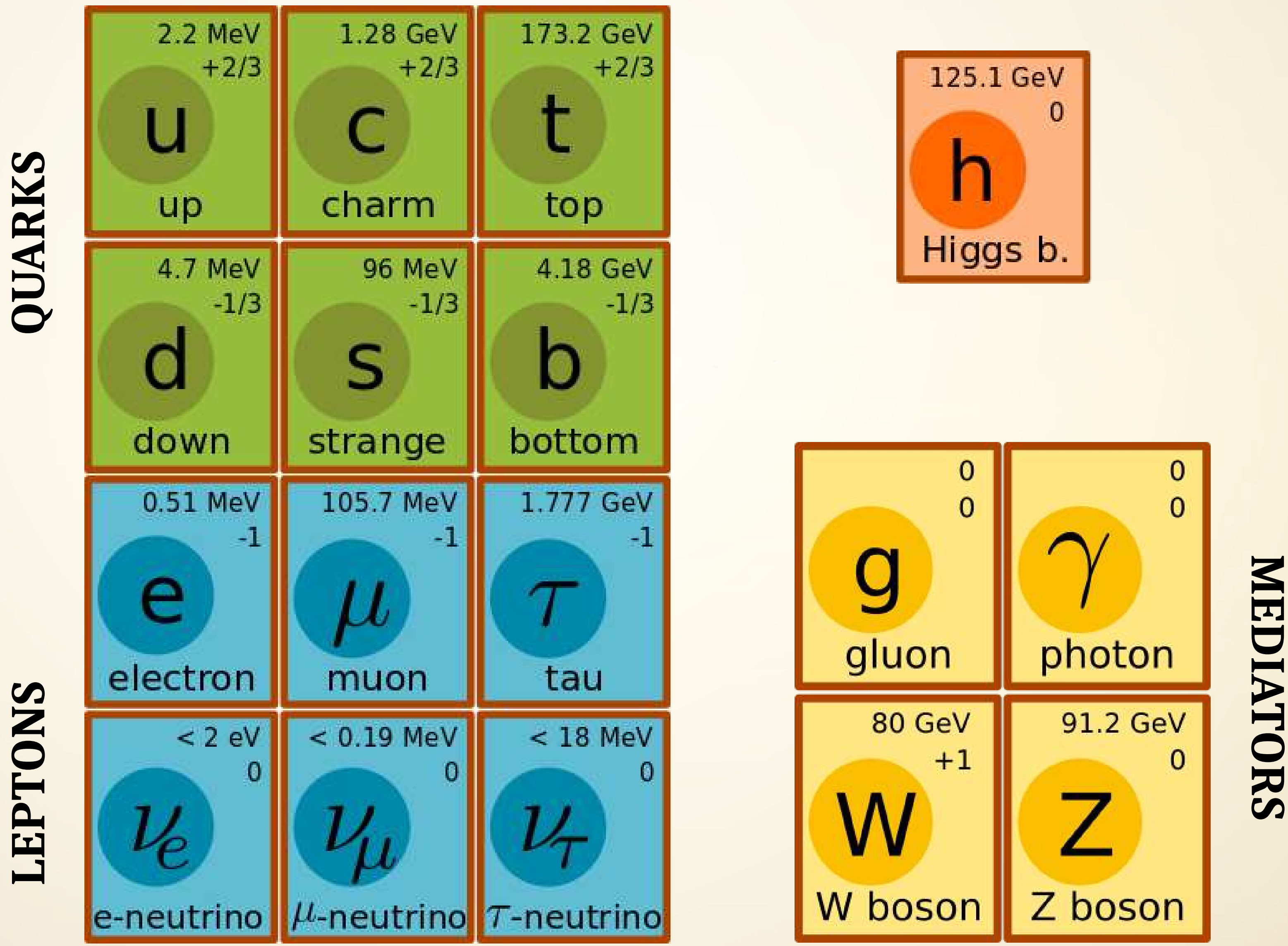
masses are allowed only if there is one extra particle:

the Higgs boson

the stronger a particle interacts with the Higgs field,
the larger its mass



The Standard Model



Experiment

Hunting the Higgs

What does the Higgs look like?

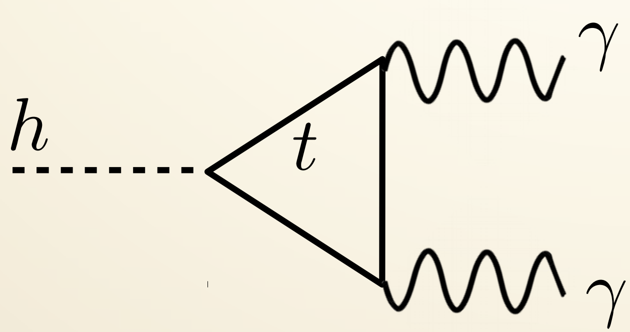
The Higgs lives for a very short time:

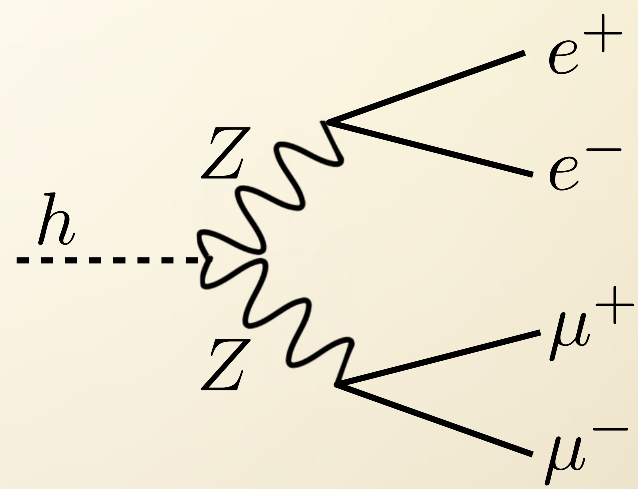
about 10^{-22} s

after that it decays into other lighter particles.

The easiest to detect are

2 photons or 4 leptons (electrons or muons)



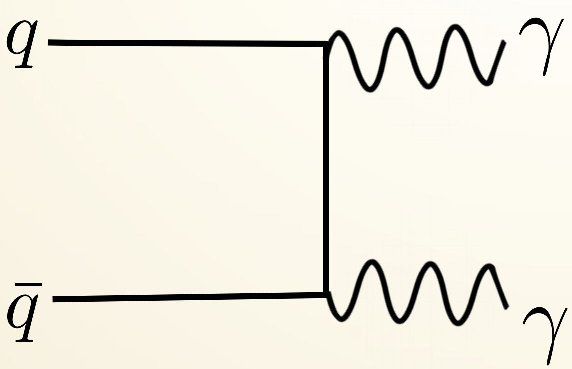


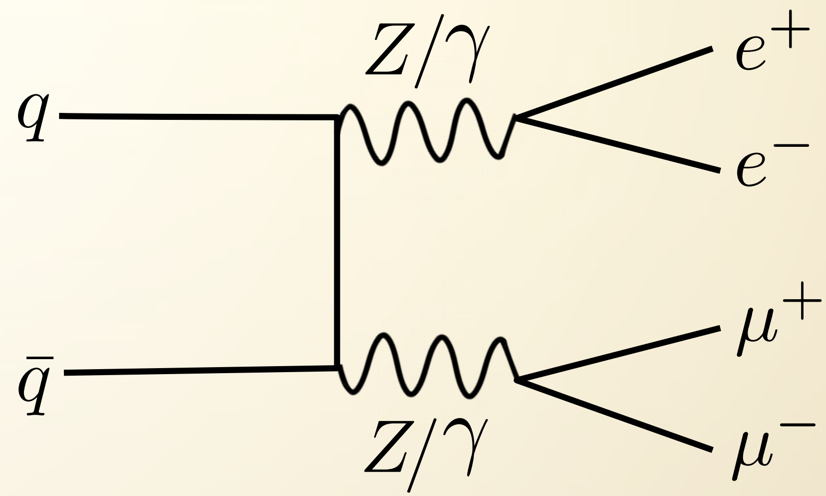
Looking for the Higgs in LHC data

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

collect information about what comes out of the p p collisions

look for collisions that produced 2 photons or 4 leptons

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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!

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

NO

Nothing significant then. Just random events.

YES

We have discovered it!

Looking for the Higgs in LHC data

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having very accurate theoretical predictions is crucial!

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

YES

We have discovered it!

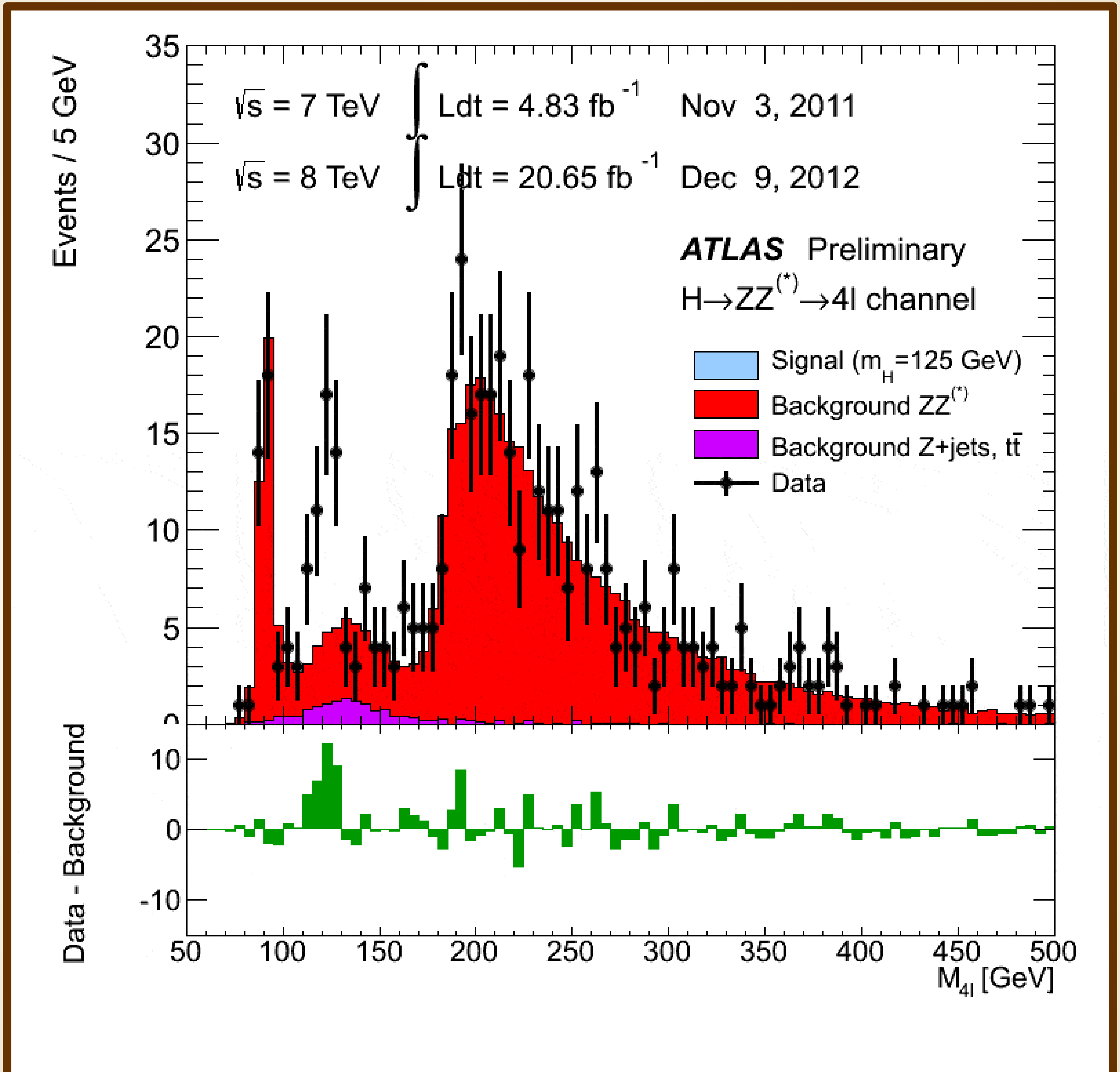
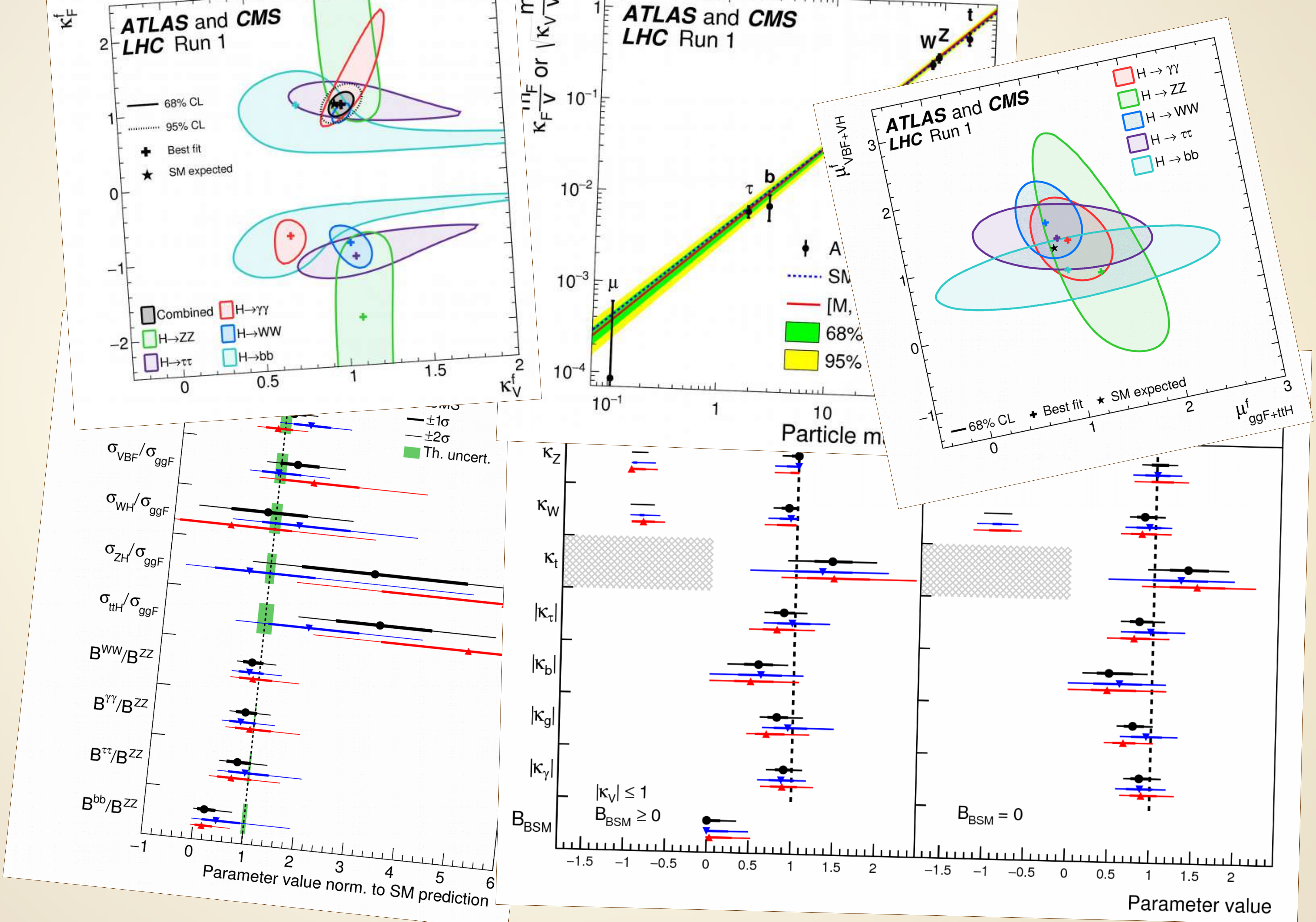


Image credit: ATLAS Collaboration, CERN

ATLAS+CMS combination
JHEP 08 (2016) 045



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