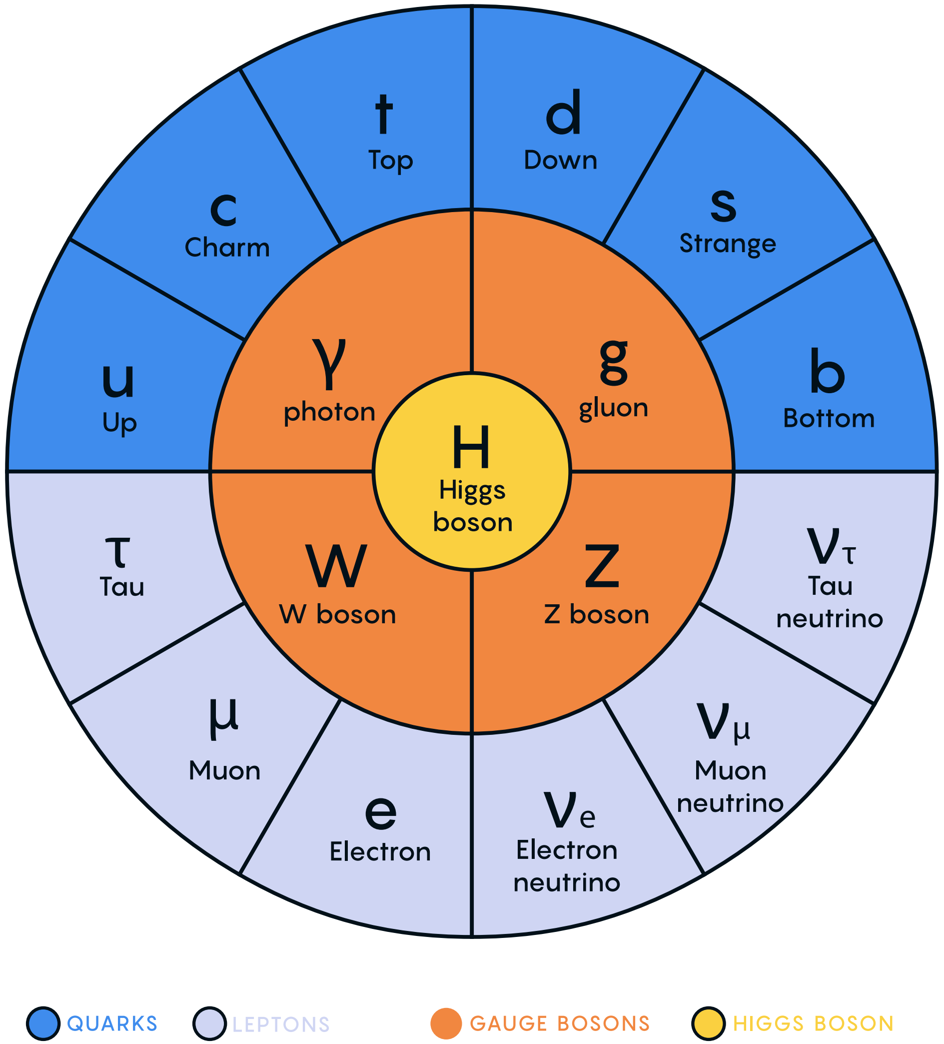
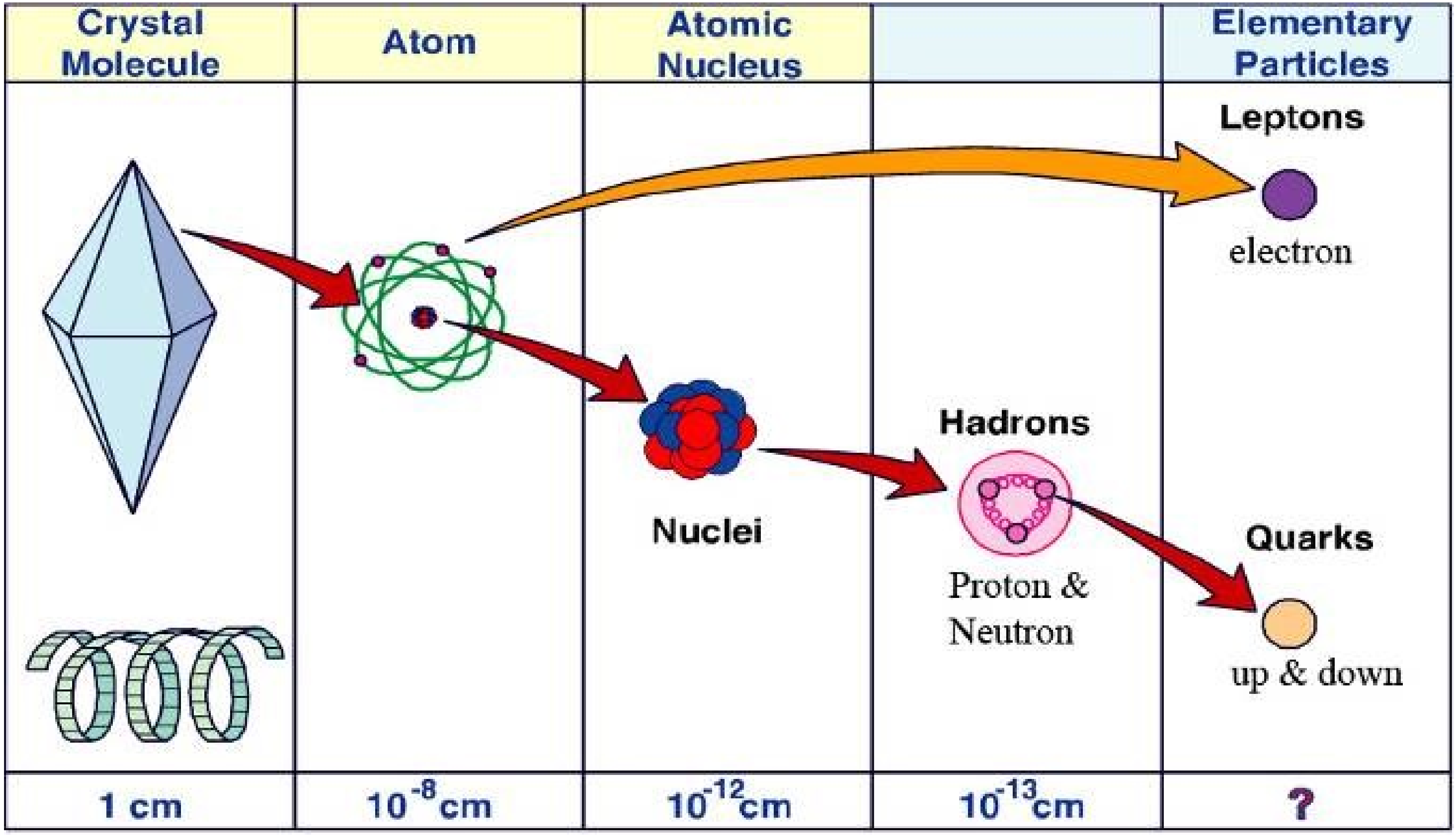
Brussels III

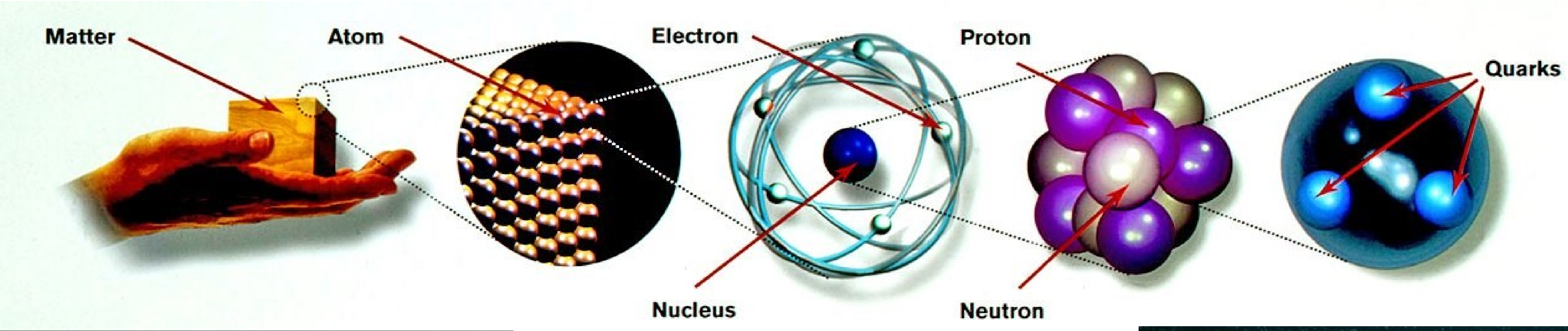
The Standard Model and its open questions

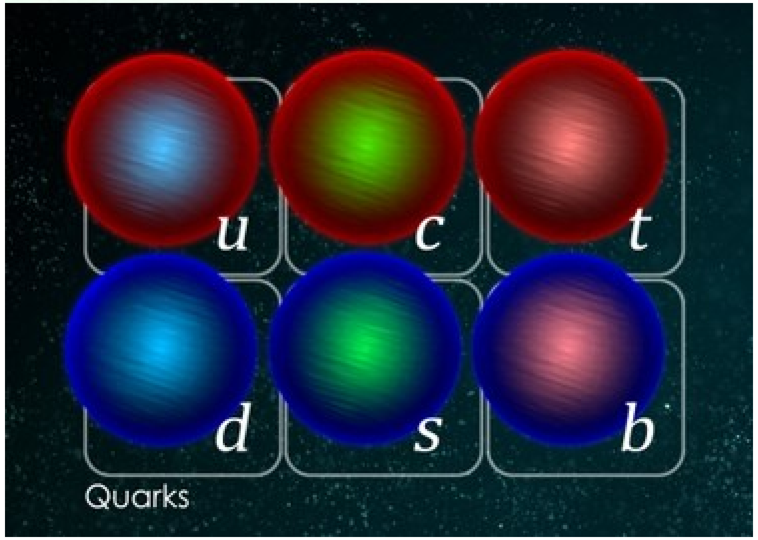


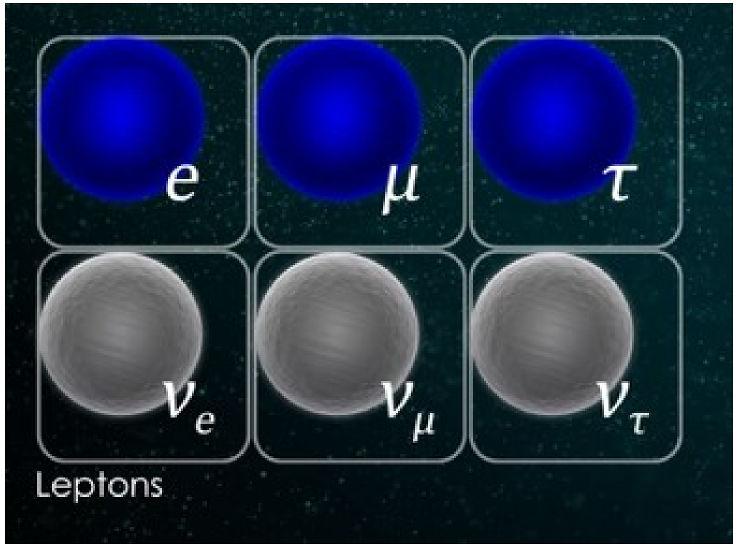
Our current understanding



What is the Universe made of ?







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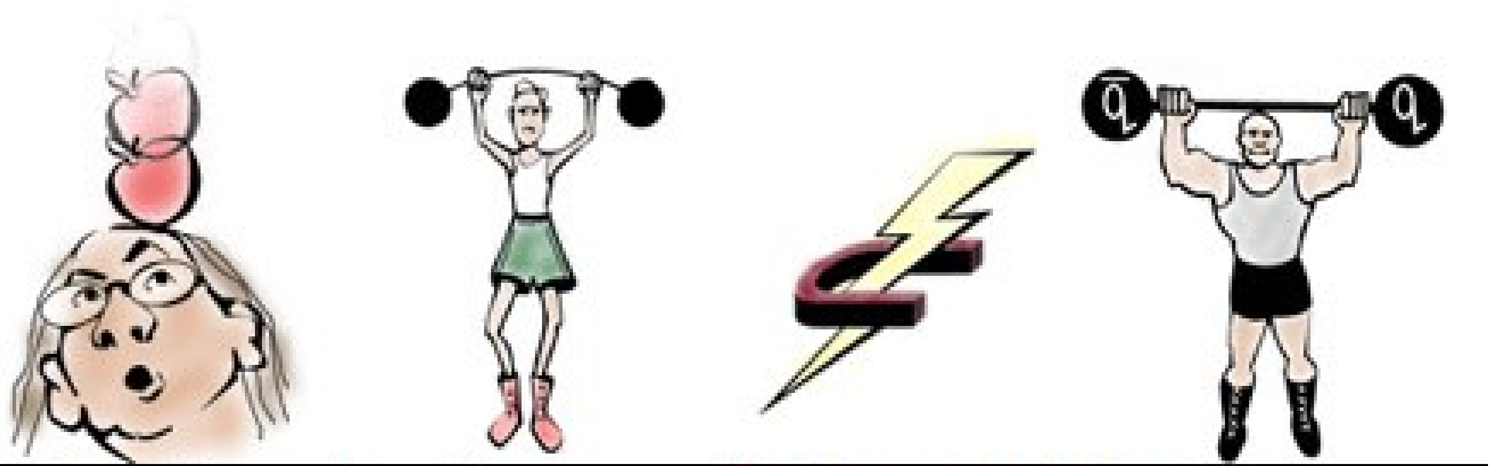
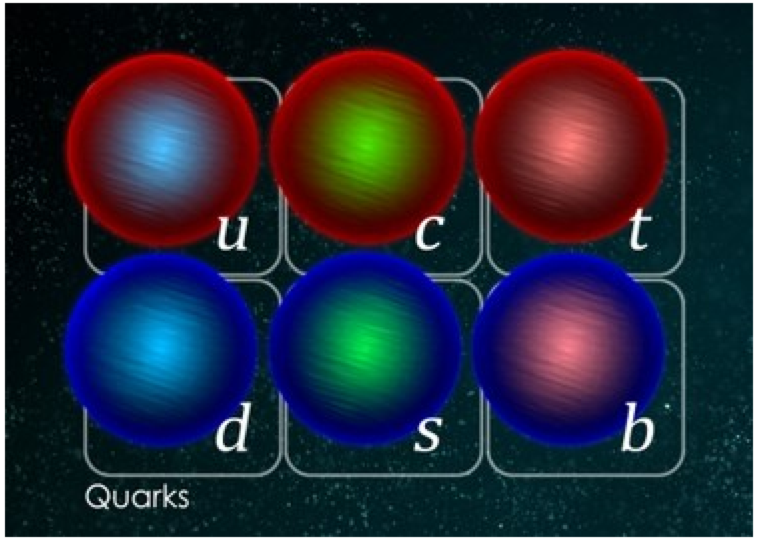
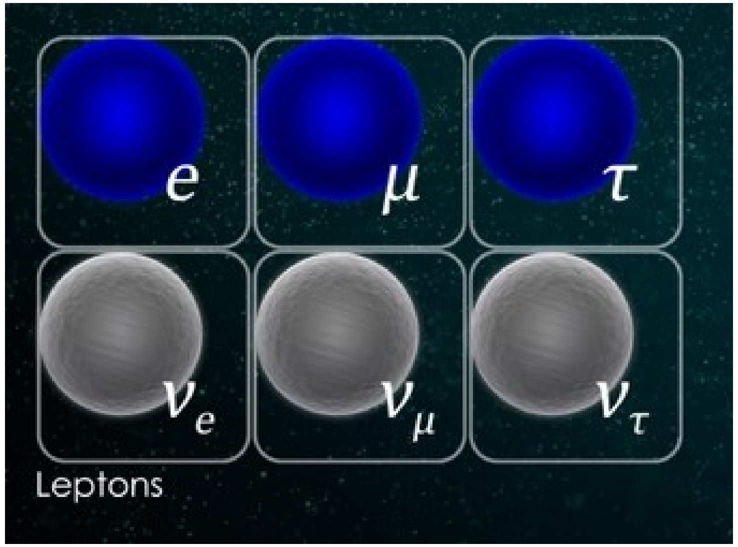
… and what keeps it together ?



	Gravity	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

… and what keeps it together ?





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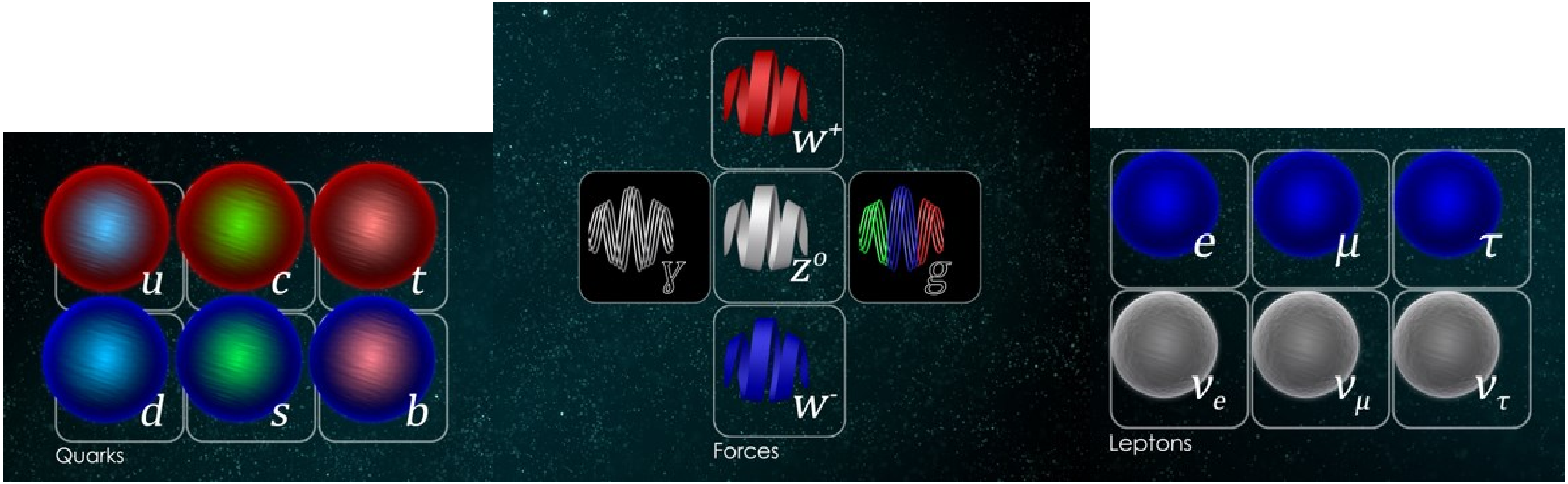

At the very beginning : matter...

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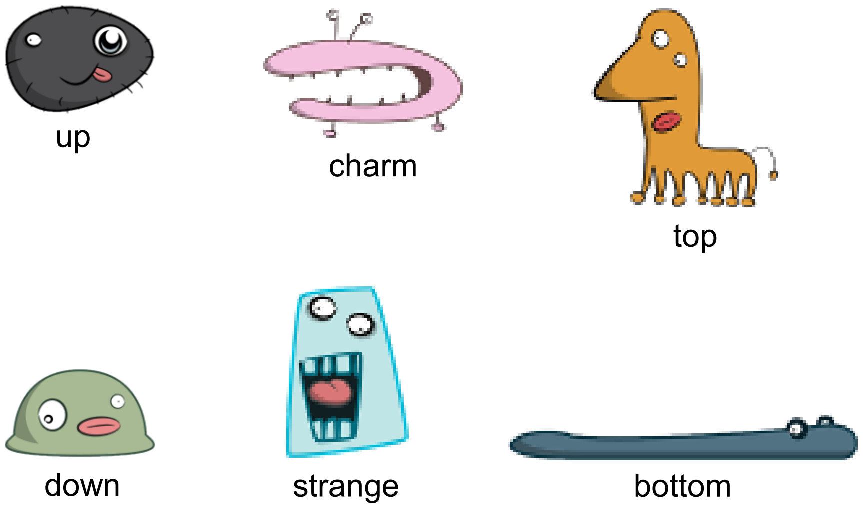
13.7 billion years ago, there were other things in the Universe…

Quarks



Leptons

...and antimatter !

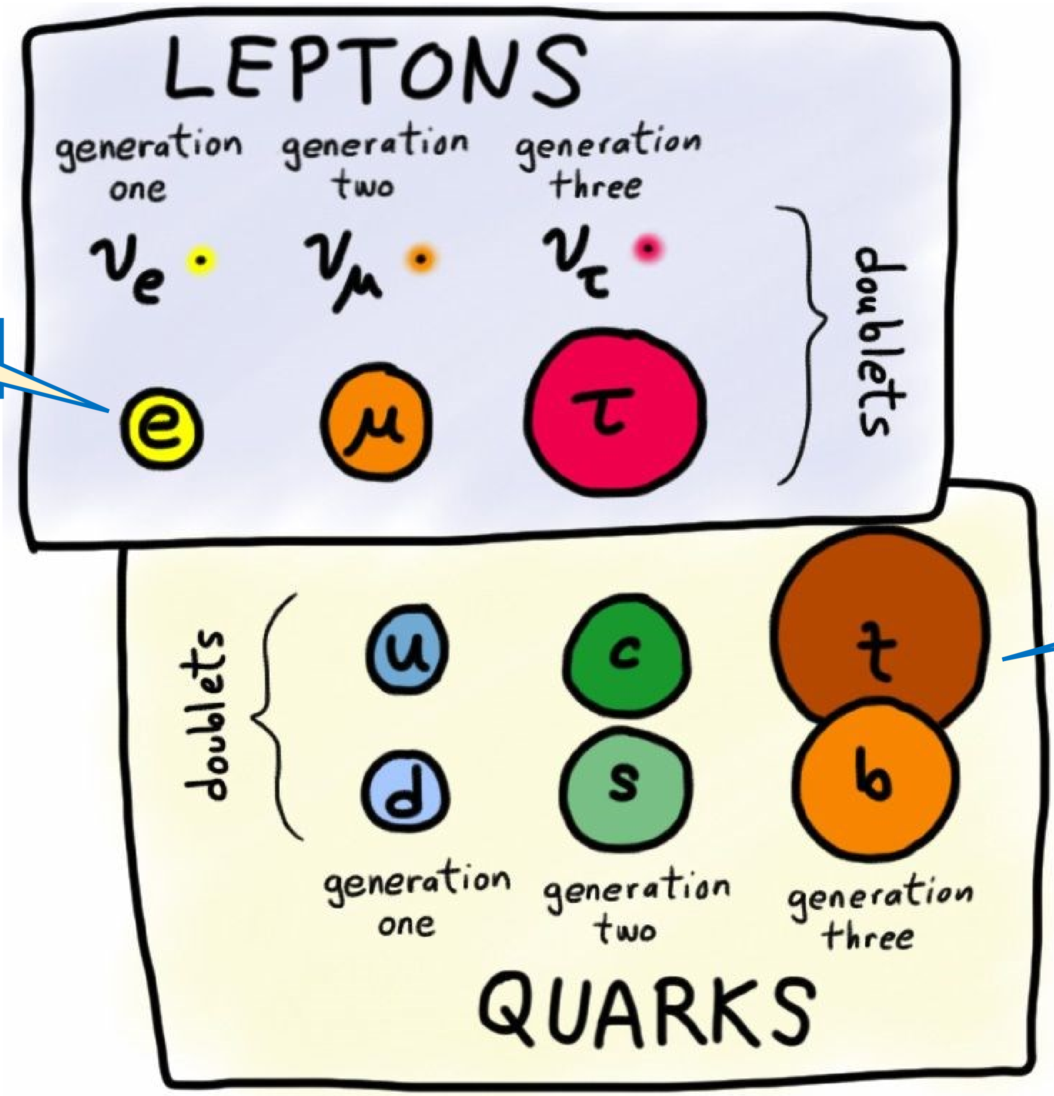
For every type of particle → There is an antiparticle

But, as far as we can tell, there is virtually no anti-matter naturally existing in our Universe…..

Particles and antiparticles have identical mass (and spin) but <u>opposite electric charge</u>

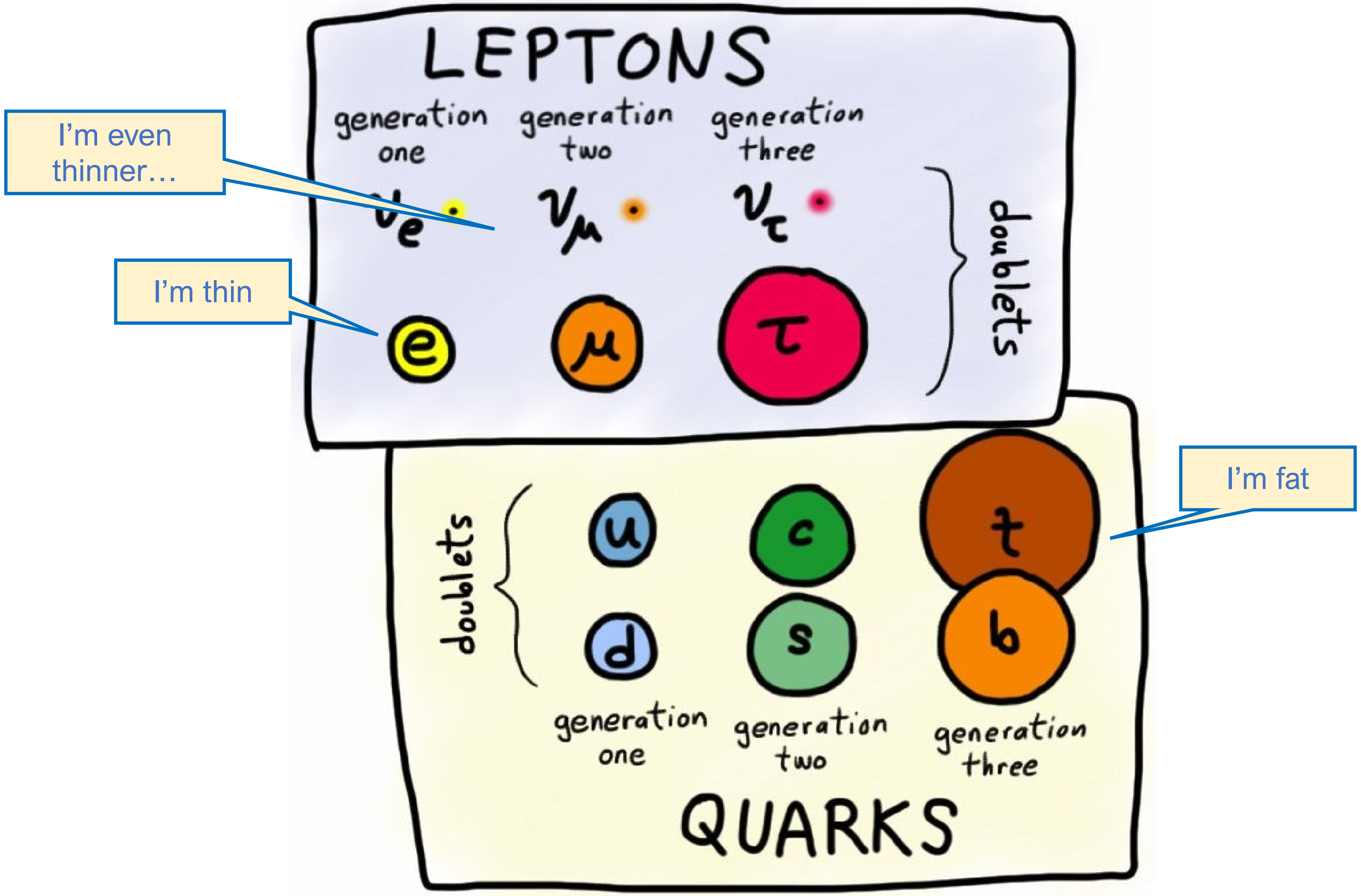
Why different masses ?

I'm thin



I'm fat

Why different masses ?



Why different masses ?

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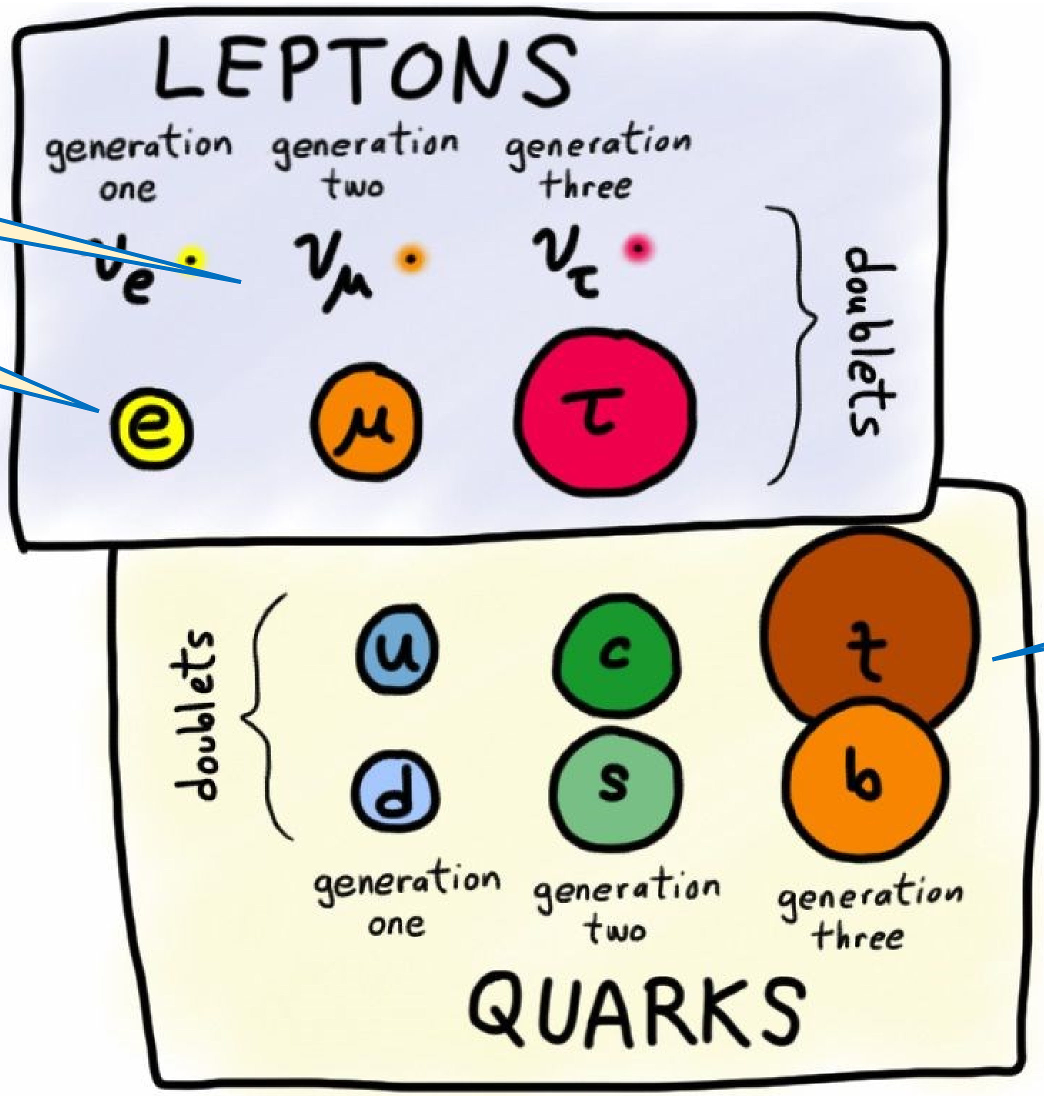
I’m even thinner…

I’m thin

I’m fat




Prof. Englert


Prof. Higgs

Brussels III

Why different masses ?

You can imagine a flat, untouched snowfield…

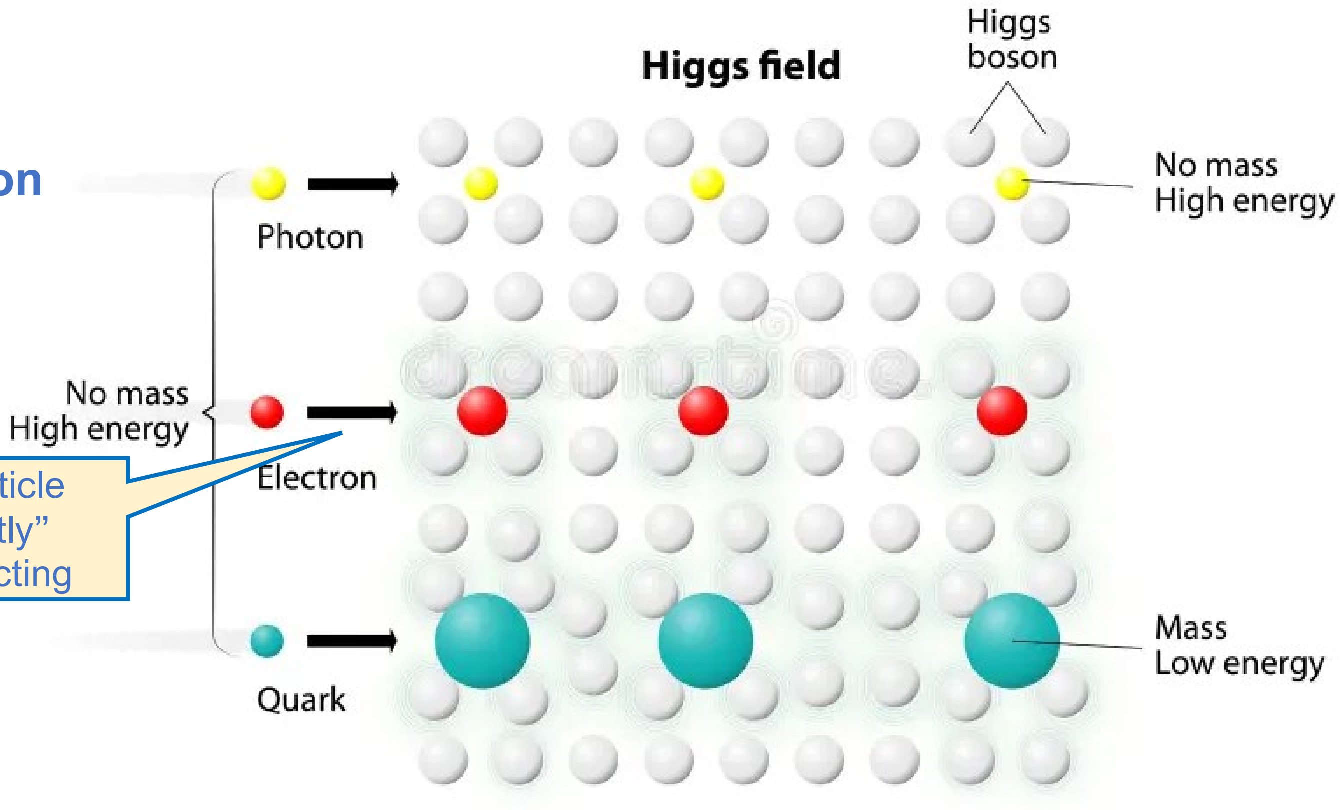
…then a **light** particle may come…

…or a **heavy** particle!

The Higgs mechanism

You can imagine a flat, untouched snowfield…
→ The **Higgs field** → mediated by the **Higgs boson**

…then a **light** particle may come…



A particle "lightly" interacting

…or a **heavy** particle!

The Higgs mechanism

You can imagine a flat, untouched snowfield…
→ The **Higgs field** → mediated by the **Higgs boson**

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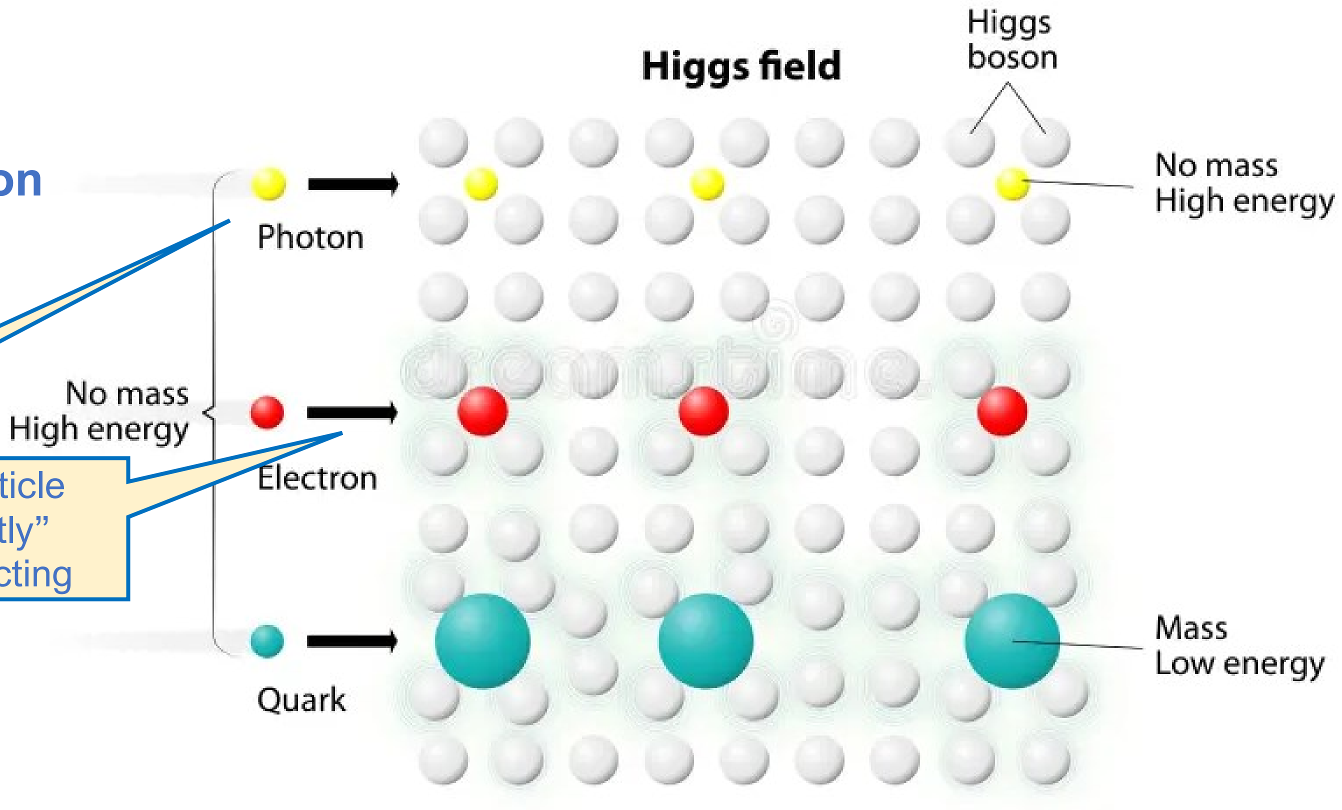
A particle not interacting at all

A particle "lightly" interacting



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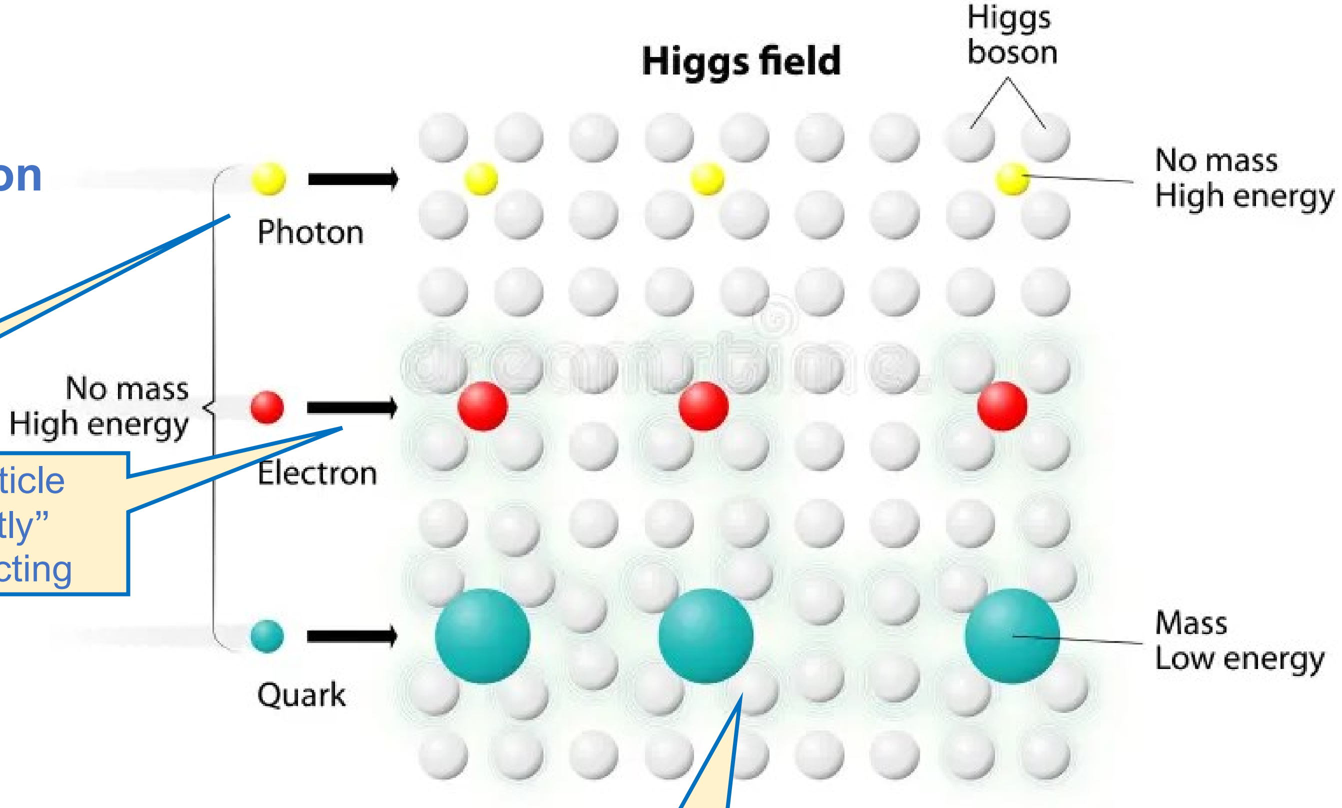


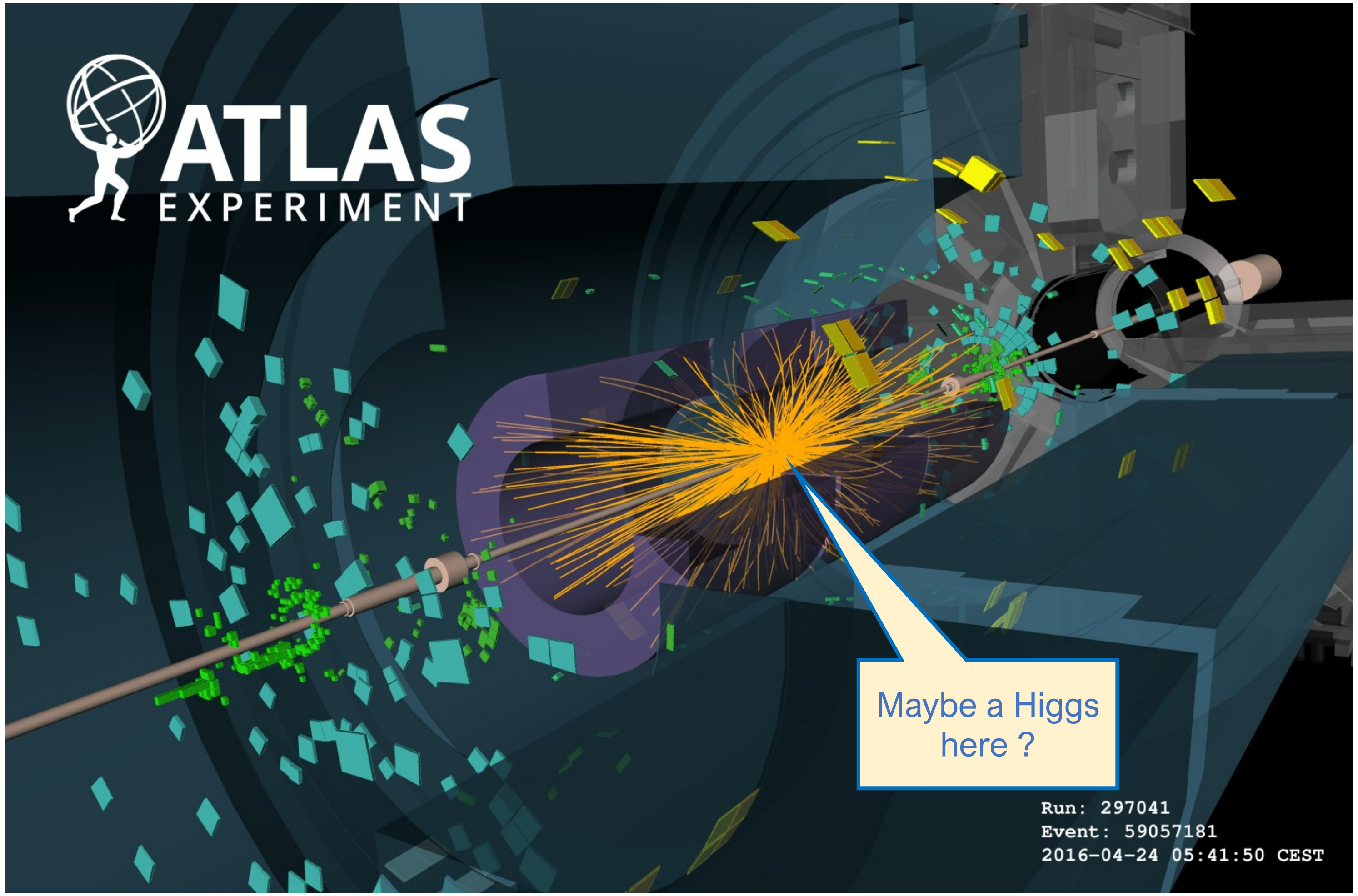
A particle not interacting at all

A particle "lightly" interacting

…or a **heavy** particle!

A particle "strongly" interacting

How does the Higgs look like?



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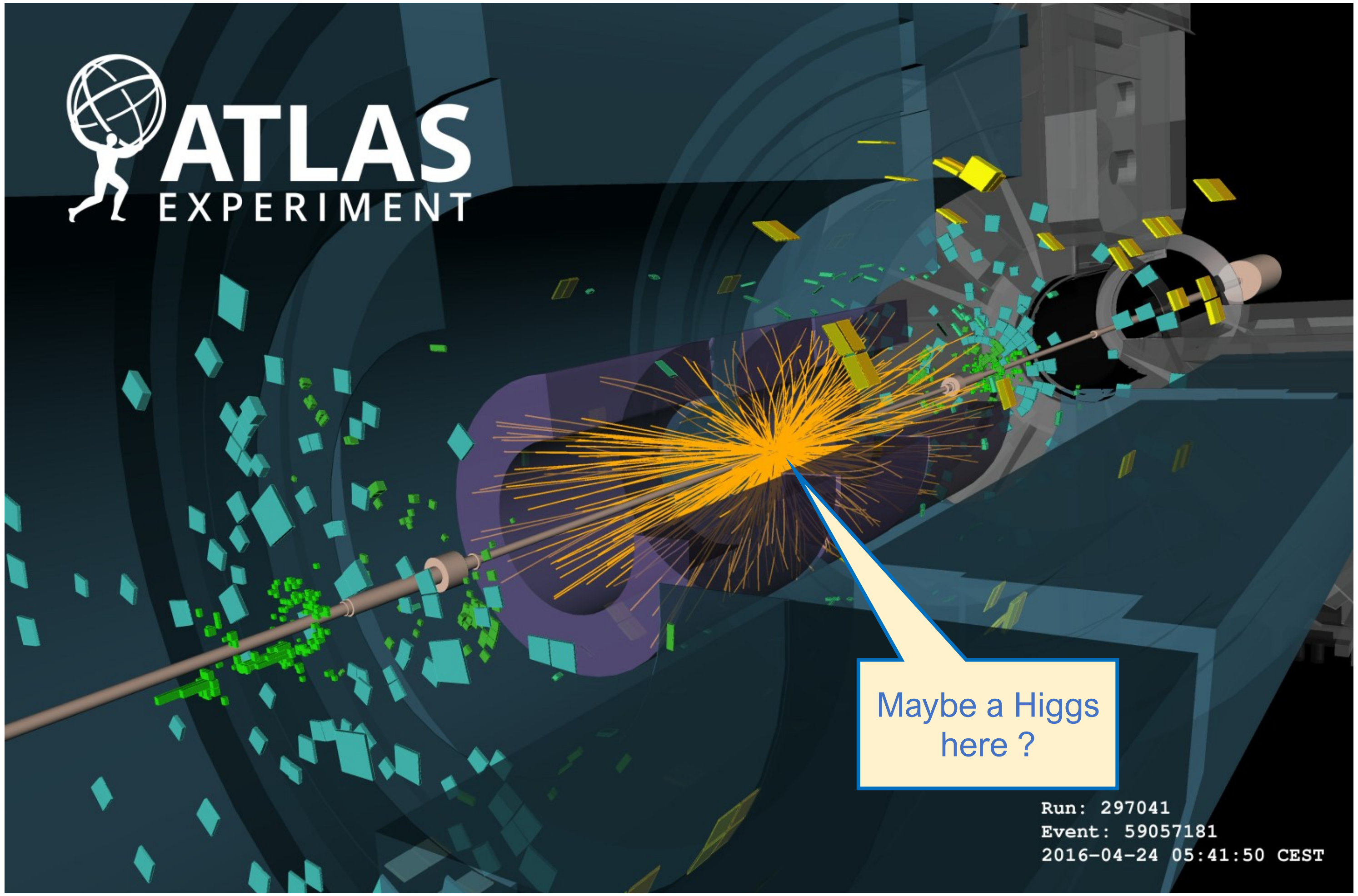
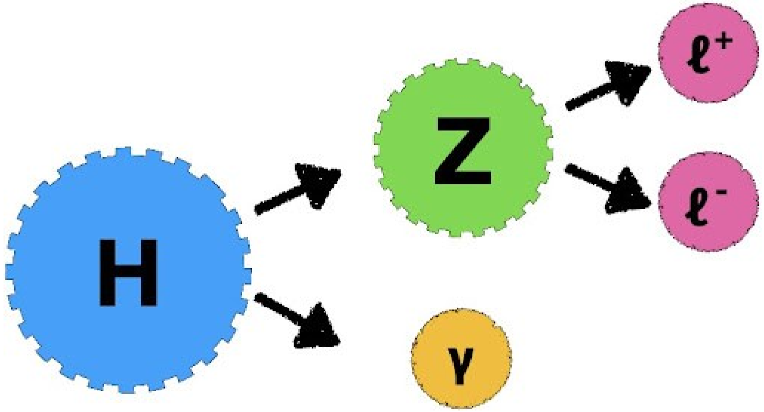


It decays in other particles after a time around 10^{-22} sec



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Summary of the Standard Model

The Standard Model is a (quantum!) theory that summarizes our current knowledge of the physics of **Fundamental Particles**…

The intrinsic **angular momentum** of particles, in units of $h/2\pi = 1.05 \cdot 10^{-34}$ J·s

The “type” of particle

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times 10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-2)\times 10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.05-2)\times 10^{-9}$	0
τ tau	1.777	–1

In units of electron charge ($1.6 \cdot 10^{-19}$ C)

Masses are given in term of GeV/c^2 (remember $E = mc^2$)
1 GeV/c^2 = $1.778 \cdot 10^{-27}$ kg

The energy unit in particle physics is the electronvolt (**eV**), the energy gained by one electron when crossing the potential difference of 1 Volt
1 GeV = 10^9 eV = $1.6 \cdot 10^{-10}$ J

Summary of the Standard Model

Brussels III

The Standard Model is a (quantum!) theory that summarizes our current knowledge of the physics of **Fundamental Particles**…

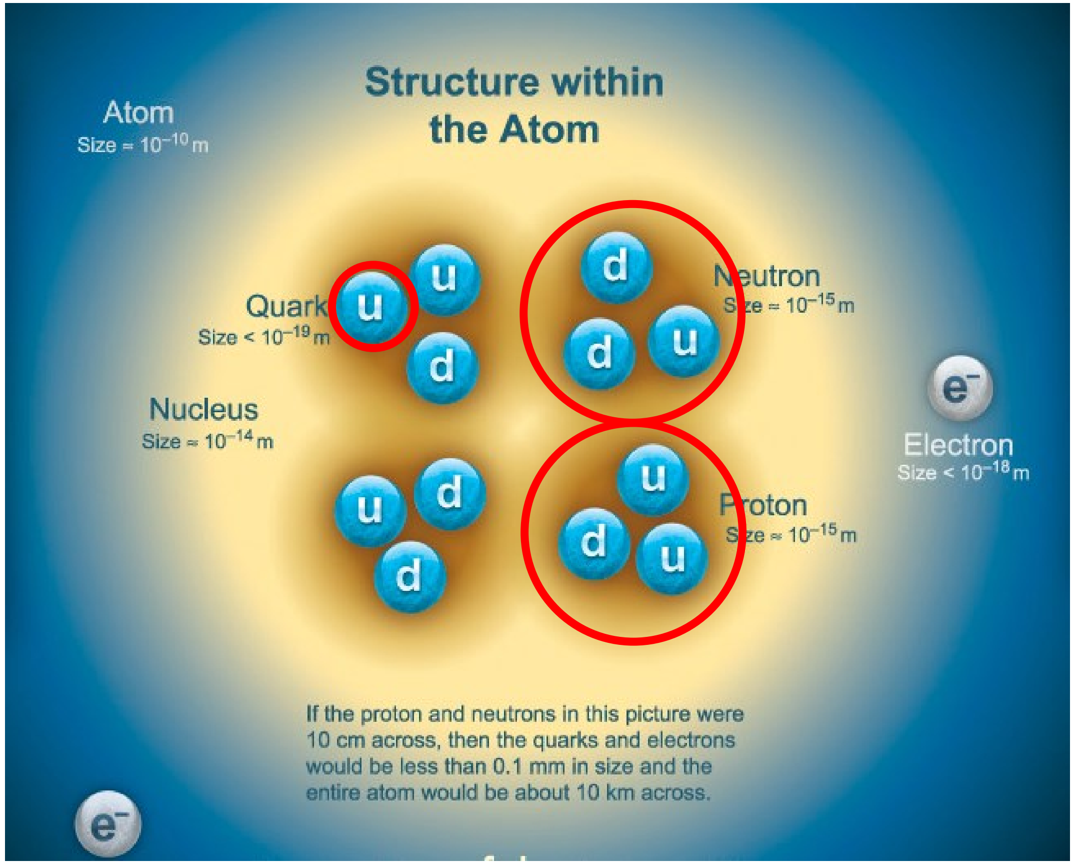
Spin is always multiple of 1/2

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2			Quarks spin =1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0	**u** up	0.002	2/3
e electron	0.000511	–1	**d** down	0.005	–1/3
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0	**c** charm	1.3	2/3
μ muon	0.106	–1	**s** strange	0.1	–1/3
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0	**t** top	173	2/3
τ tau	1.777	–1	**b** bottom	4.2	–1/3

Summary of the Standard Model

The Standard Model is a (quantum!) theory that summarizes our current knowledge of the physics of **Fundamental Particles**…



Summary of the Standard Model

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…and of **Fundamental Interaction** (force between particles or decay of unstable particle)

BOSONS force carriers
spin = 0, 1, 2, …

Spin is always integer

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W$^-$	80.39	–1
W$^+$ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Higgs Boson spin = 0		
Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

Properties of the interactions

Each quark carries 3 types of **"color" charge**.
Just as electrical charge interact by exchanging photons, color-charged particles interact by exchanging gluons

In (relativistic) quantum mechanic, all forces are mediated by a particle

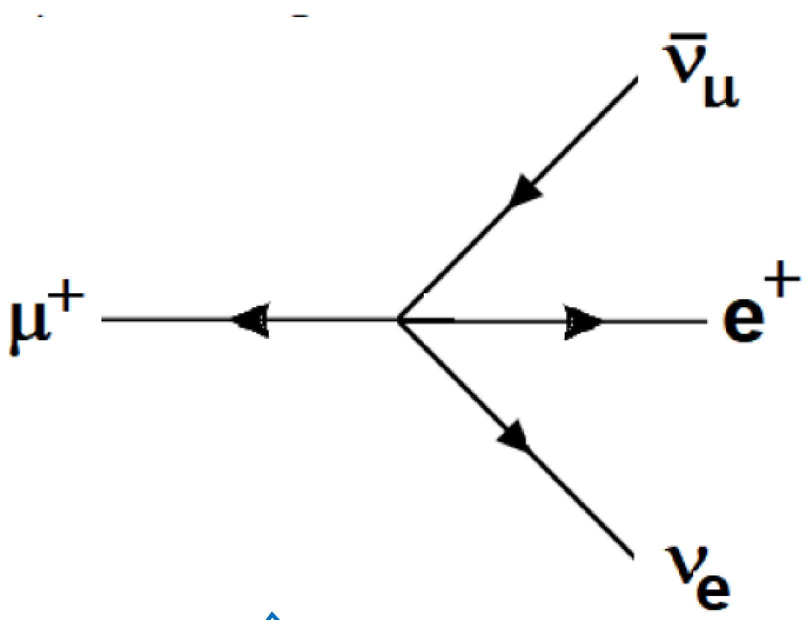
Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Intensity compared to electromagnetic force between two quarks

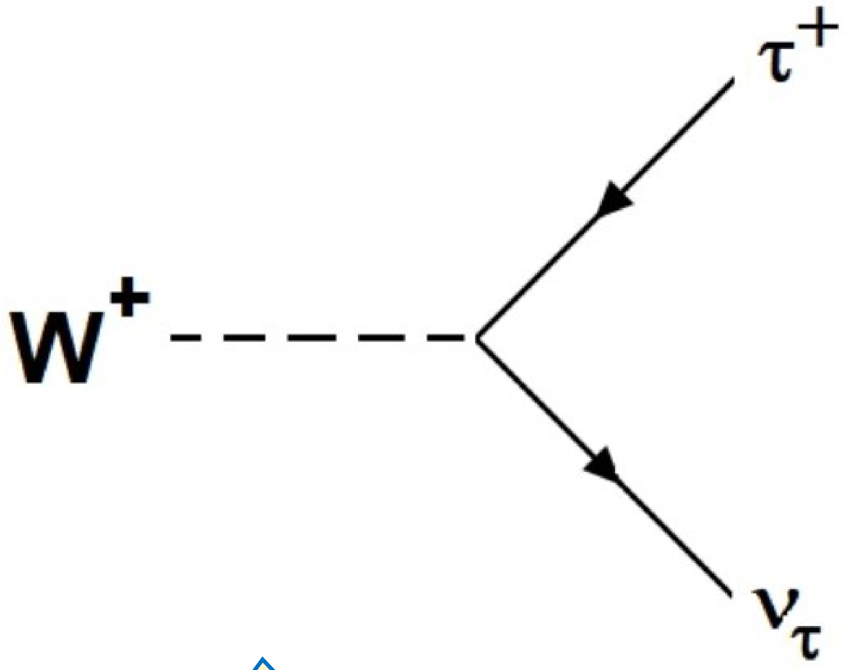
Weak Interaction: for closer distances, the strength is stronger

Strong Interaction: for closer distance, the strength is weaker!

Examples of interactions



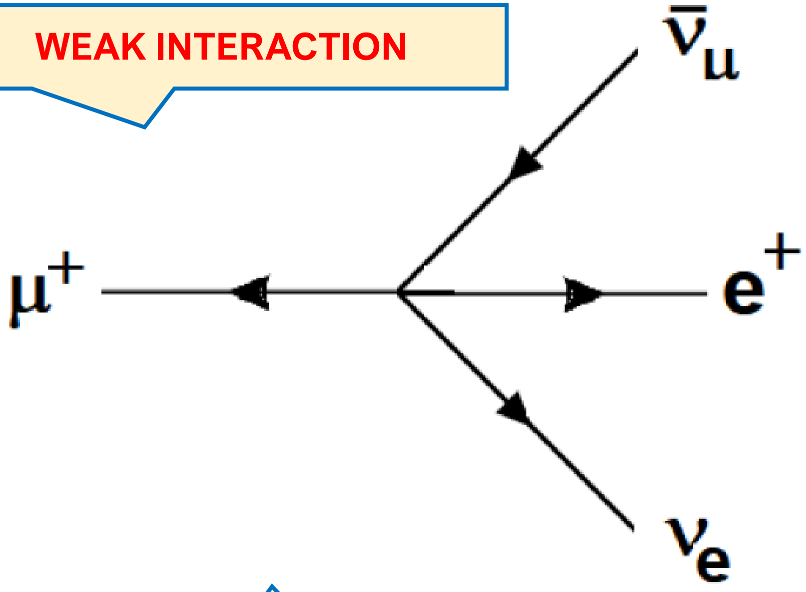
An **antimuon** transforms into an antimuon neutrino, a positron, and an electron neutrino.



A **W⁺ boson** transforms into a tau lepton and a tauonic neutrino

Examples of interactions

WEAK INTERACTION



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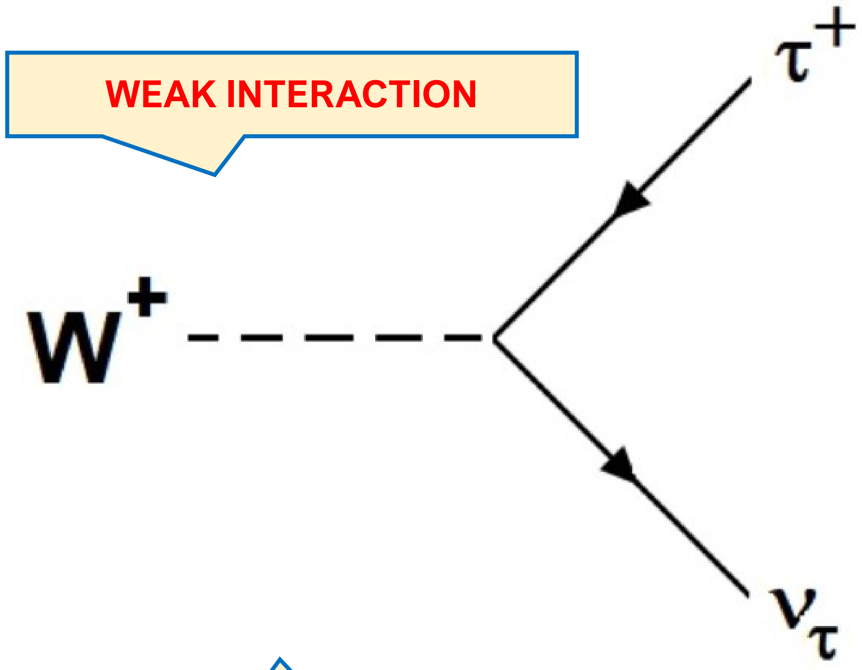

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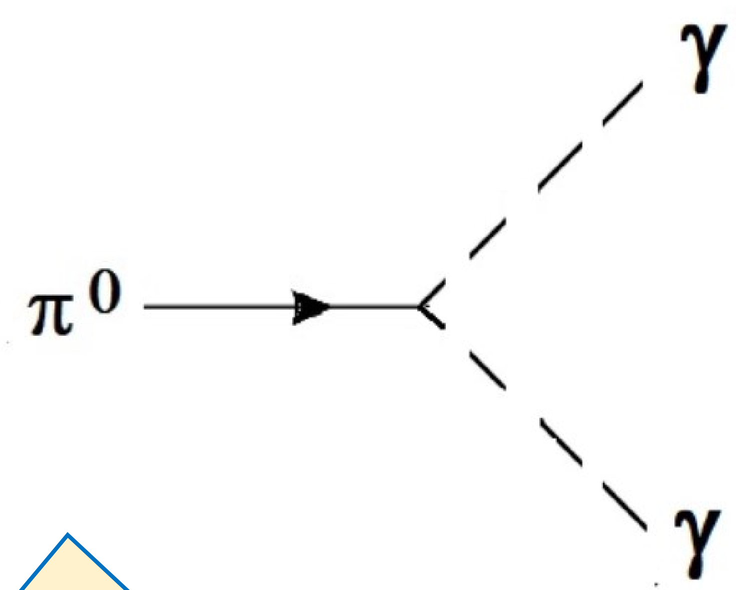
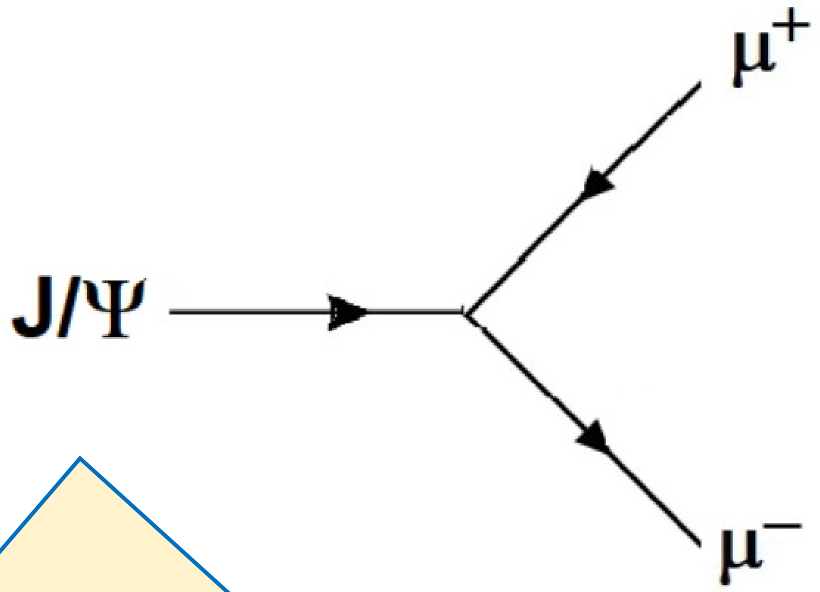


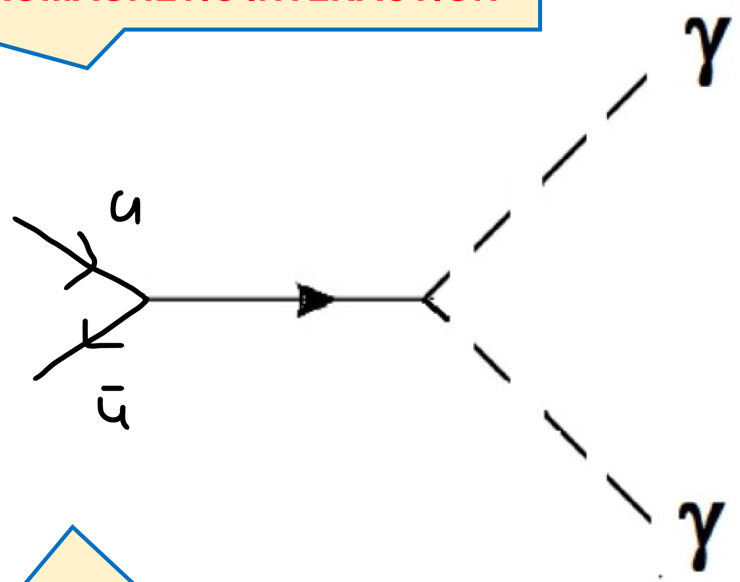
A **neutral Pion** decays in a couple of photons.
The neutral Pion is a **meson** composed of $u\bar{u}$ and $d\bar{d}$ quarks.



A **J/Psi** meson transforms into a positive muon and negative muon.
The J/Psi meson is composed by $\bar{c}c$ quarks

Examples of interactions

ELECTROMAGNETIC INTERACTION



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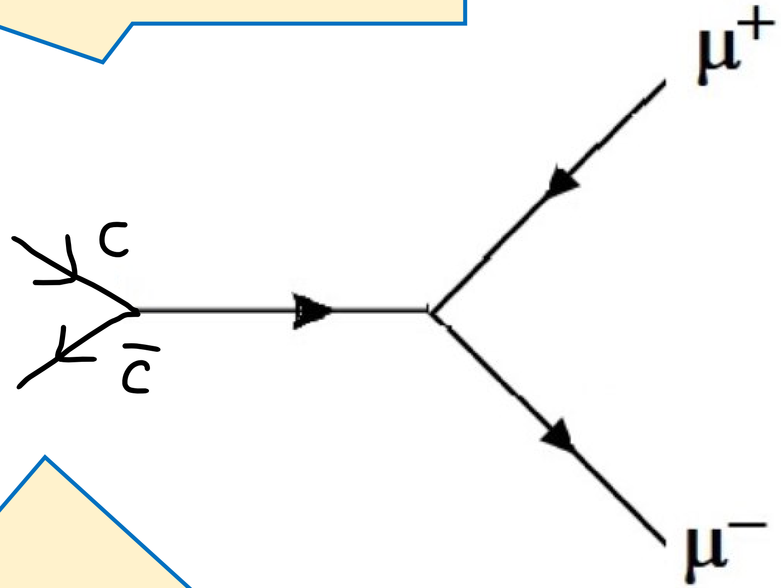
WEAK INTERACTION



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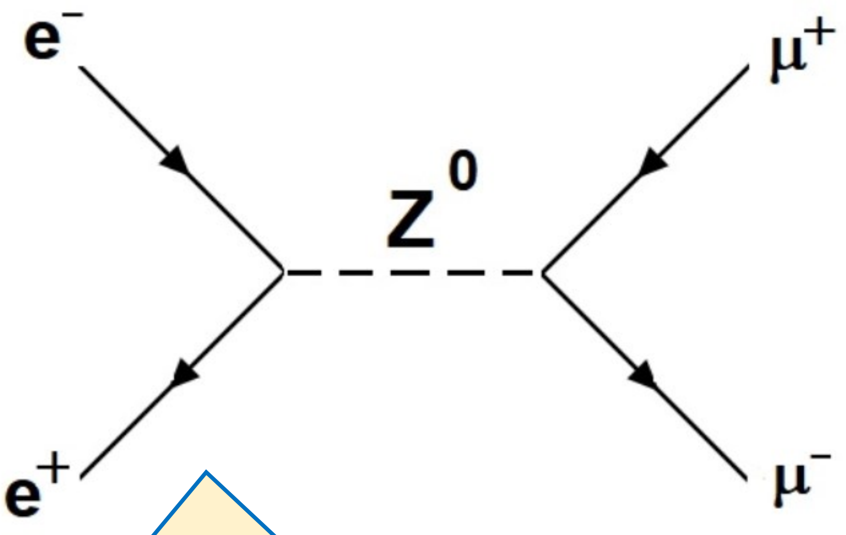
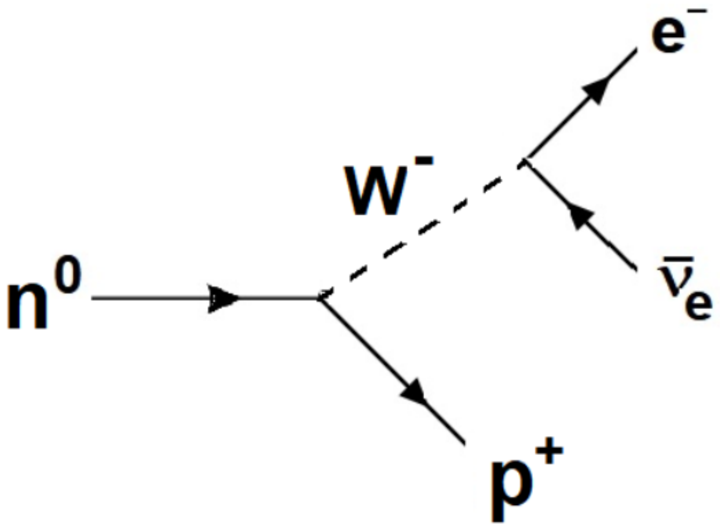


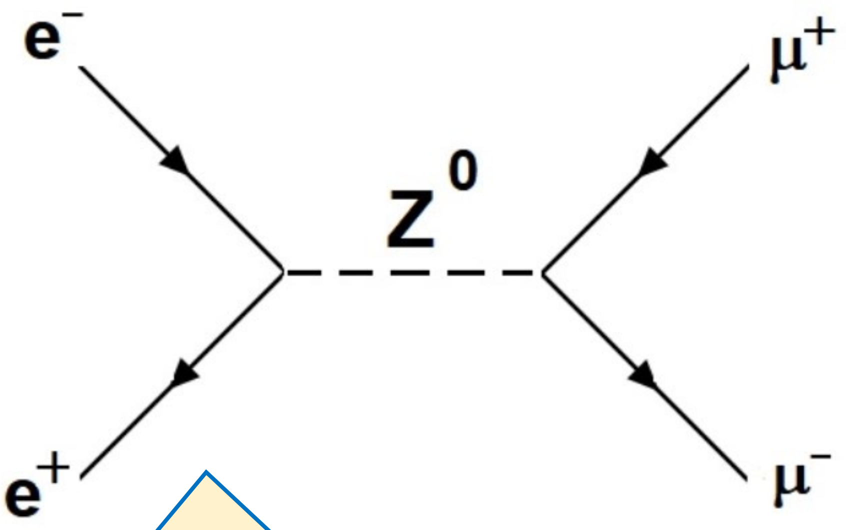
A collision between an electron and an antielectron (positron), producing a muon-antimuon pair



A neutron transforming in a proton (**Beta decay**)

Examples of interactions

WEAK INTERACTION



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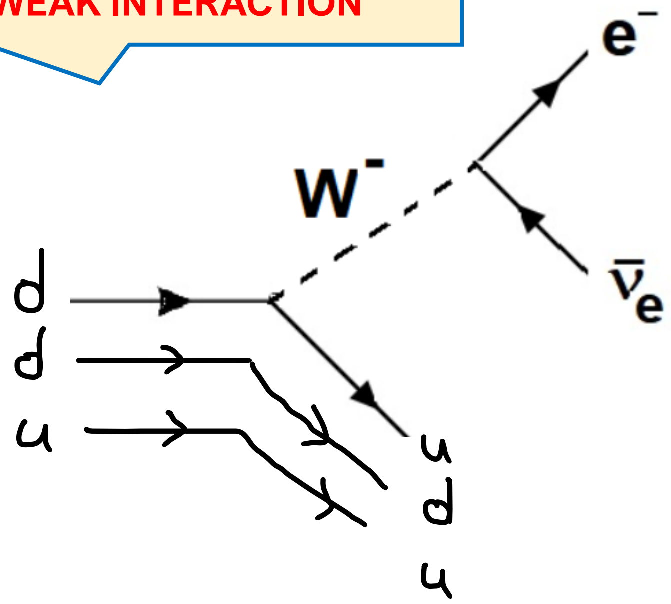

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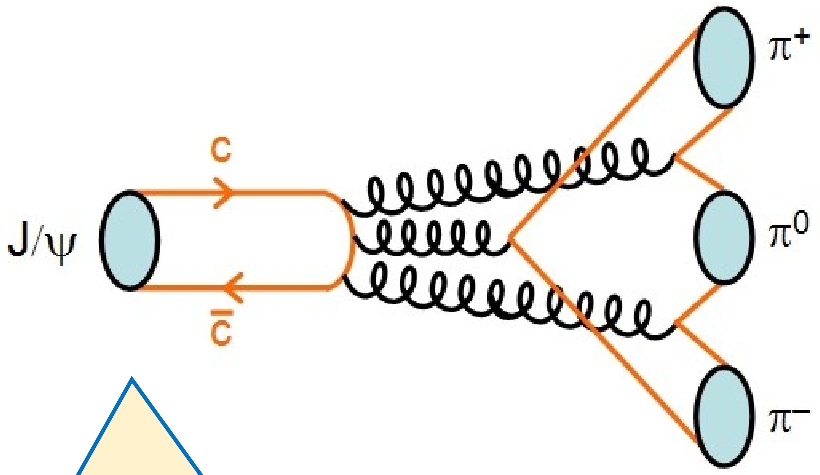
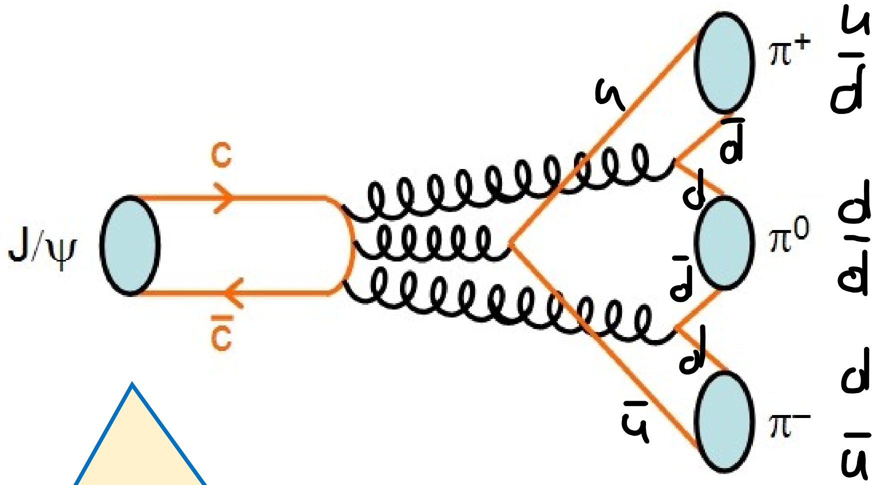


A **J/Psi** meson transforms into a positive, negative and neutral pion.
The J/Psi meson is composed by $\bar{c}c$ quarks.
The Pions are composed by u and d quarks and antiquarks

A proton-proton collision…

Examples of interactions

STRONG INTERACTION



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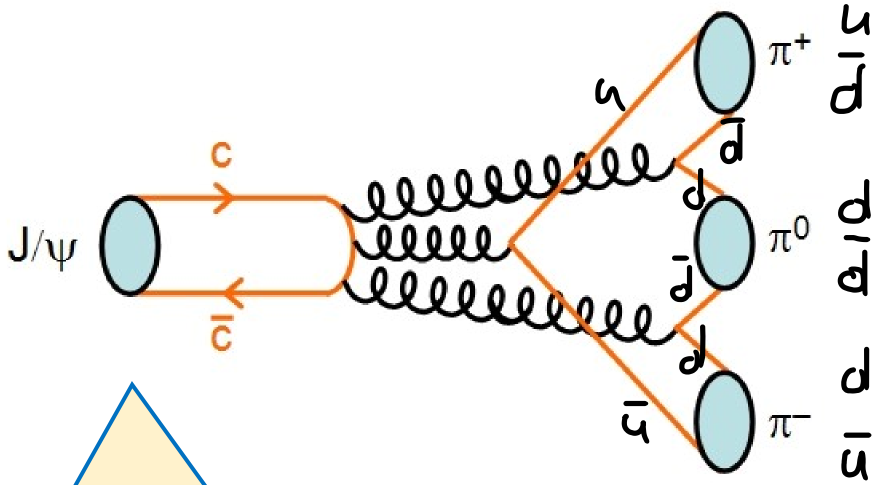

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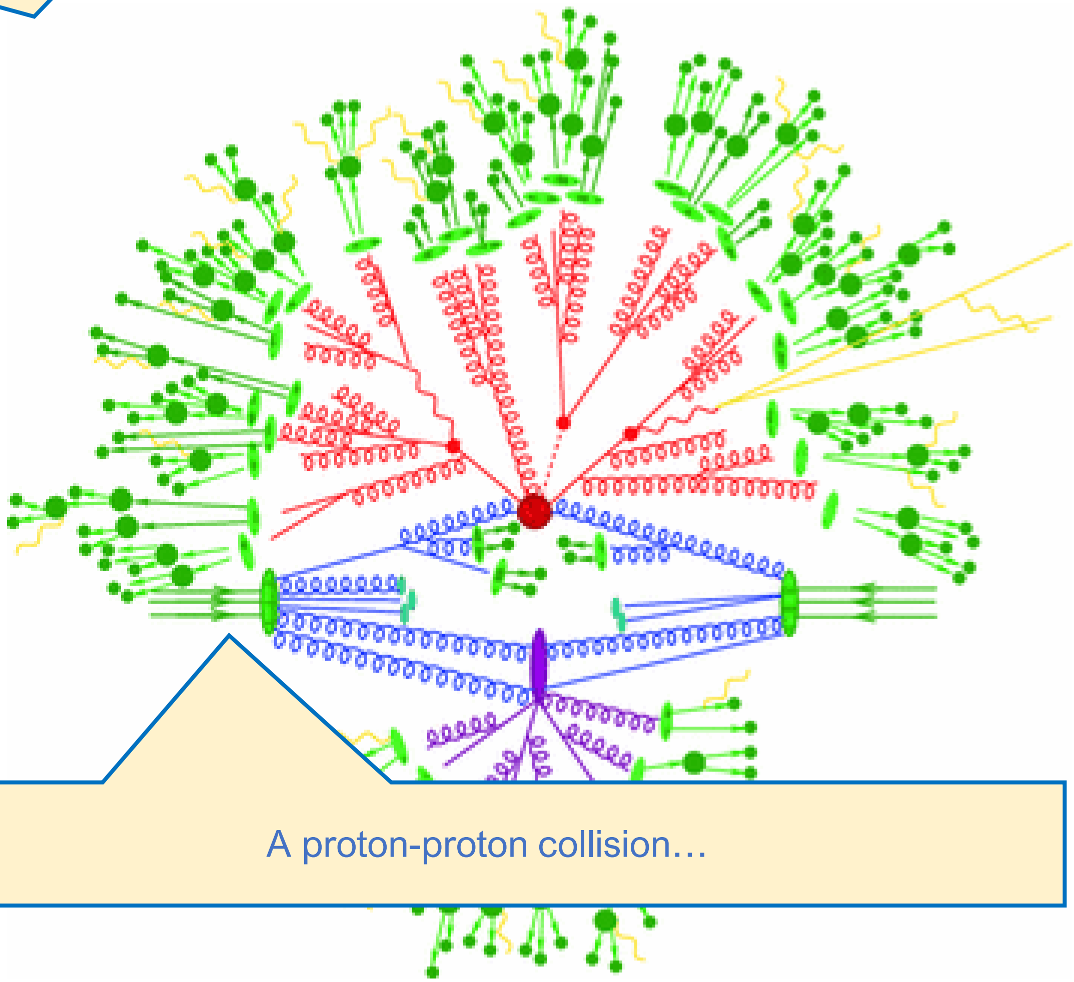


A proton-proton collision…

Unsolved misteries

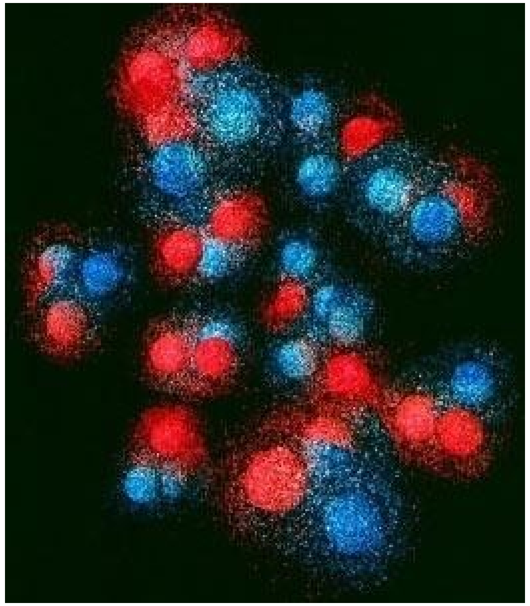
- For **all the particles** we observe and we created, the Standard Model can explain their properties, decay, interaction strength etc.

- In all the measurements performed in particle physics, **the agreement with the Standard Model has proved excellent**

→ ***Is the Standard Model our final model of everything ?***

Unsolved misteries

- There are many questions the Standard Model cannot (yet) answer to:
  - Are **quarks and leptons actually fundamental**, or are they made up of even more fundamental particles?



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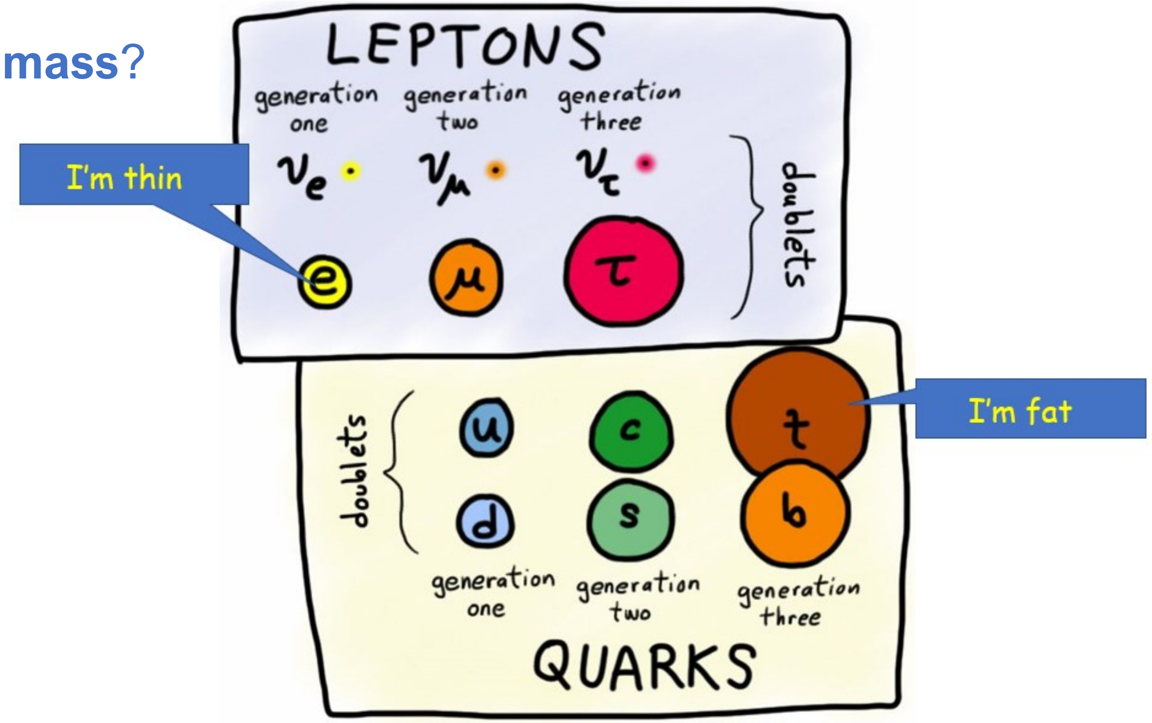

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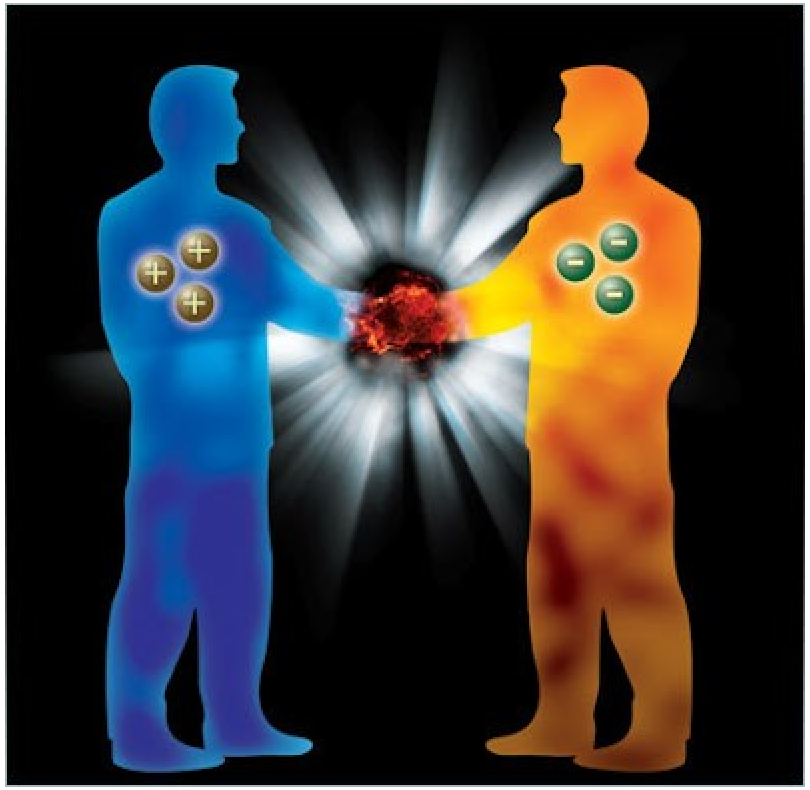

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  - What is this the **“dark matter”?**

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  - Why the **Universe expansion is accelerating ?**

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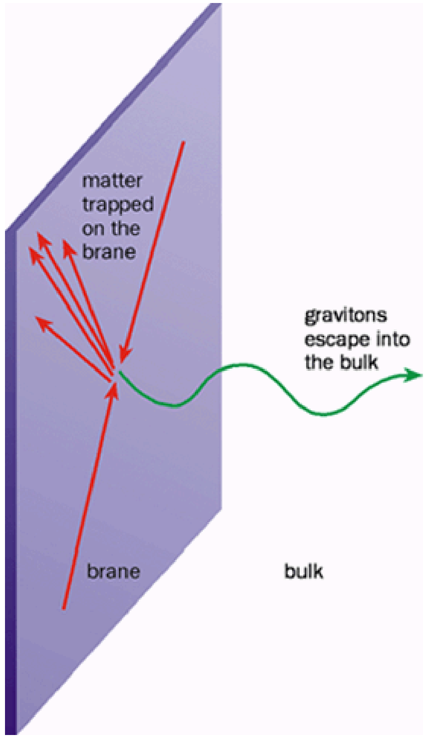
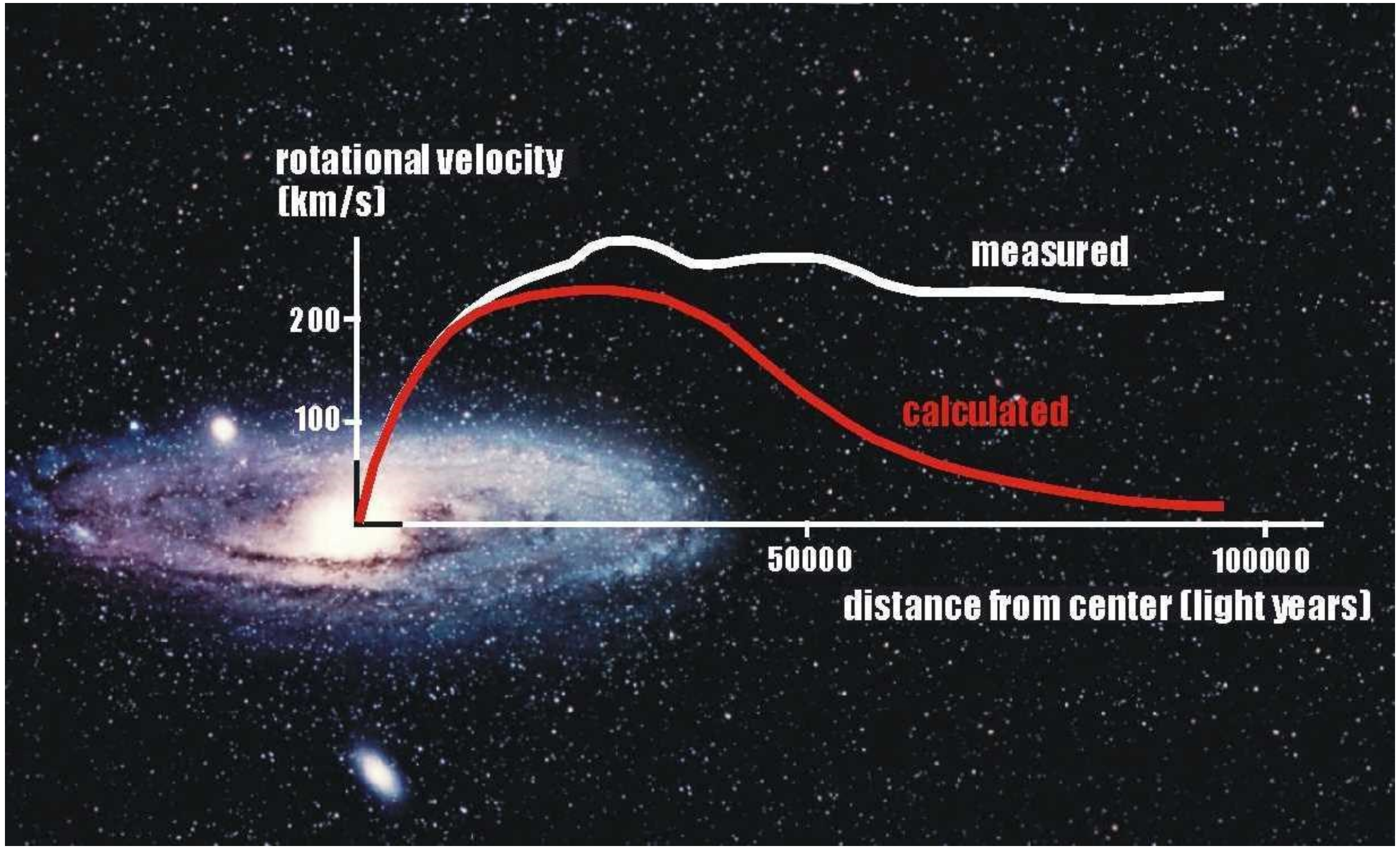
  - Why is there **more matter than antimatter in the universe** ?
  - What is this the **“dark matter”?**
  - Why the **Universe expansion is accelerating ?**
  - Why **gravity force** does not fit in this model ?



Dark Matter: why we need it?

- Astronomers have measured the speed of stars as a function of distance of the galaxy center (and of galaxies in a cluster, as a function of distance from the cluster center)



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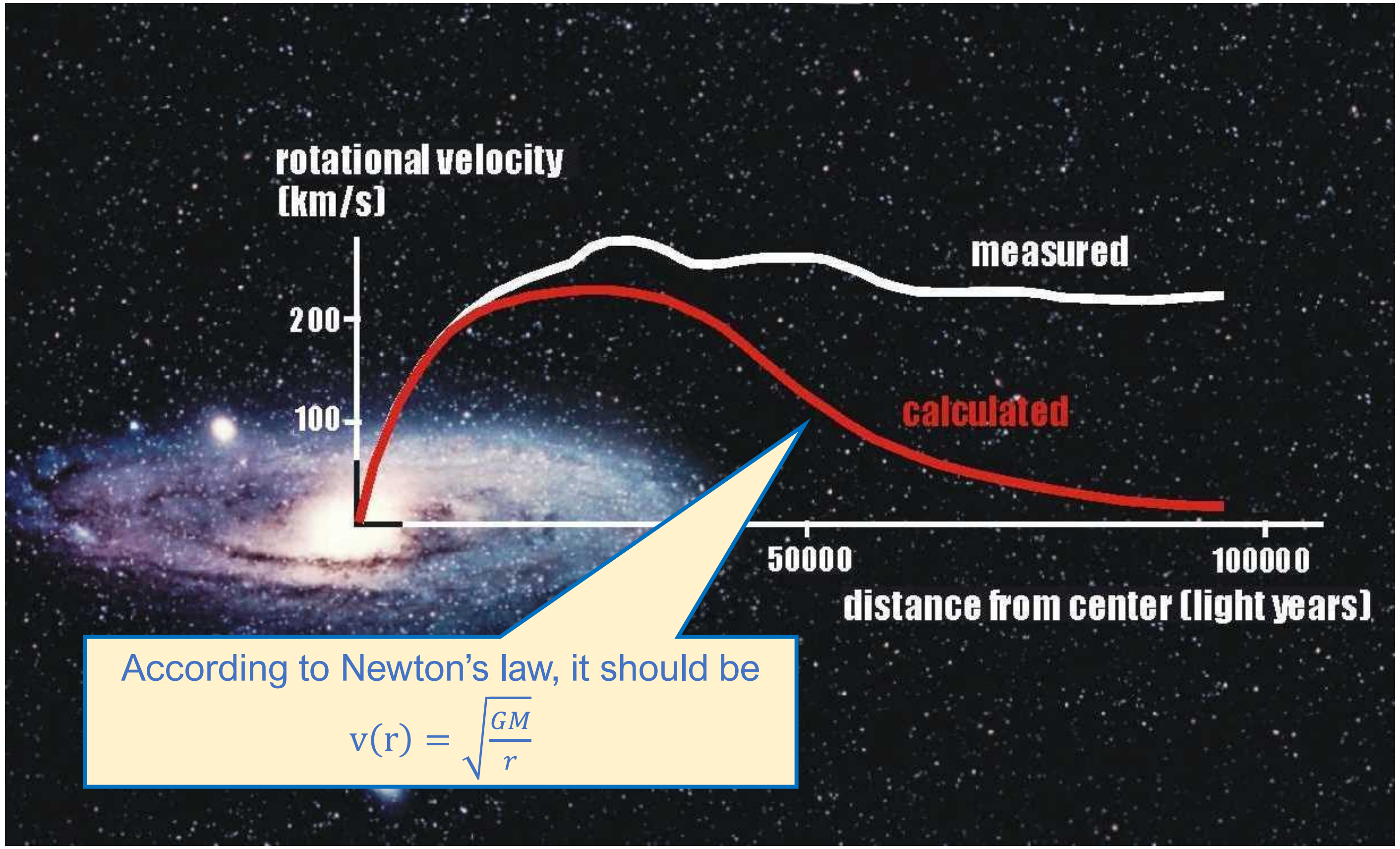

According to Newton's law, it should be

$$v(r) = \sqrt{\frac{GM}{r}}$$

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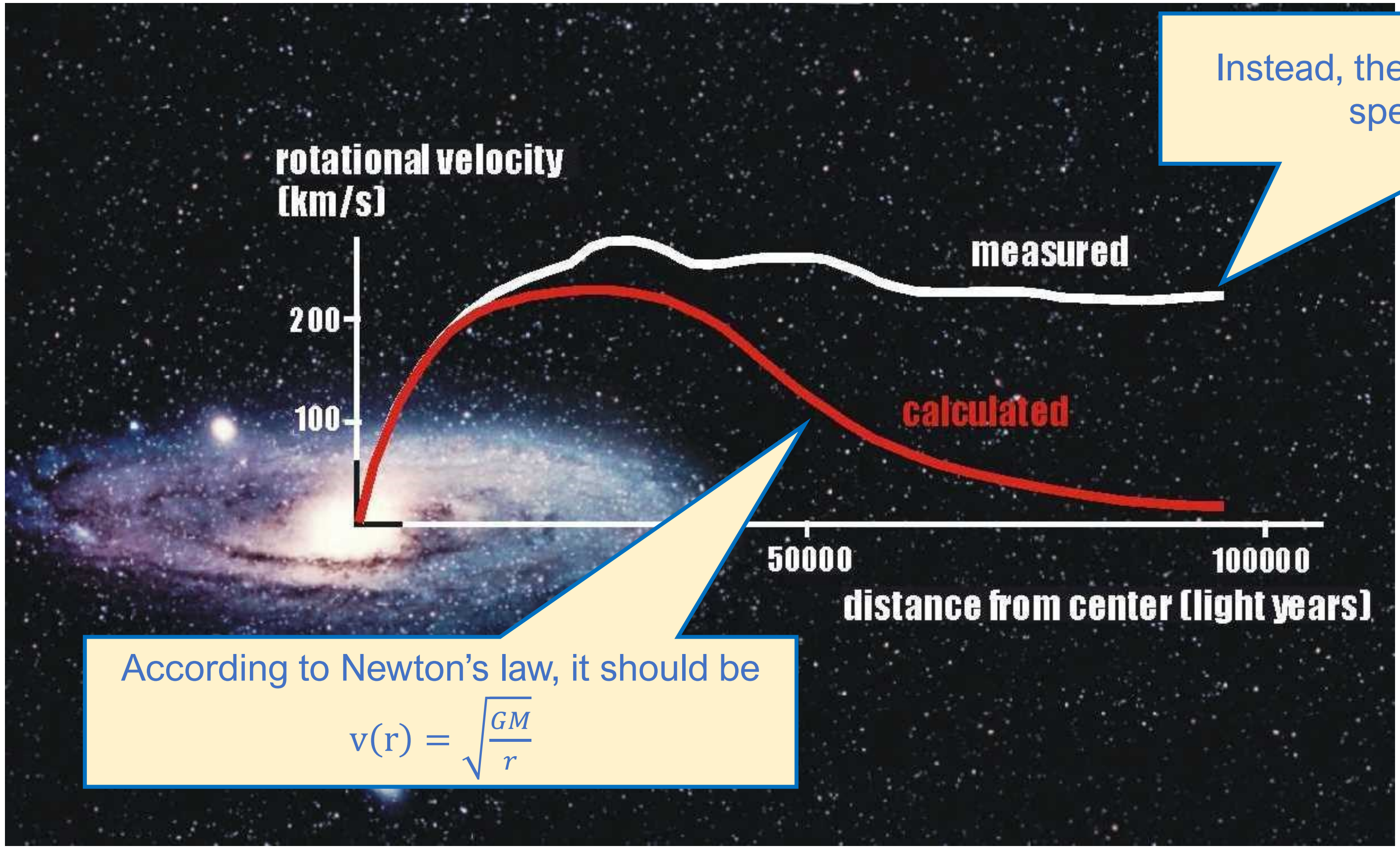


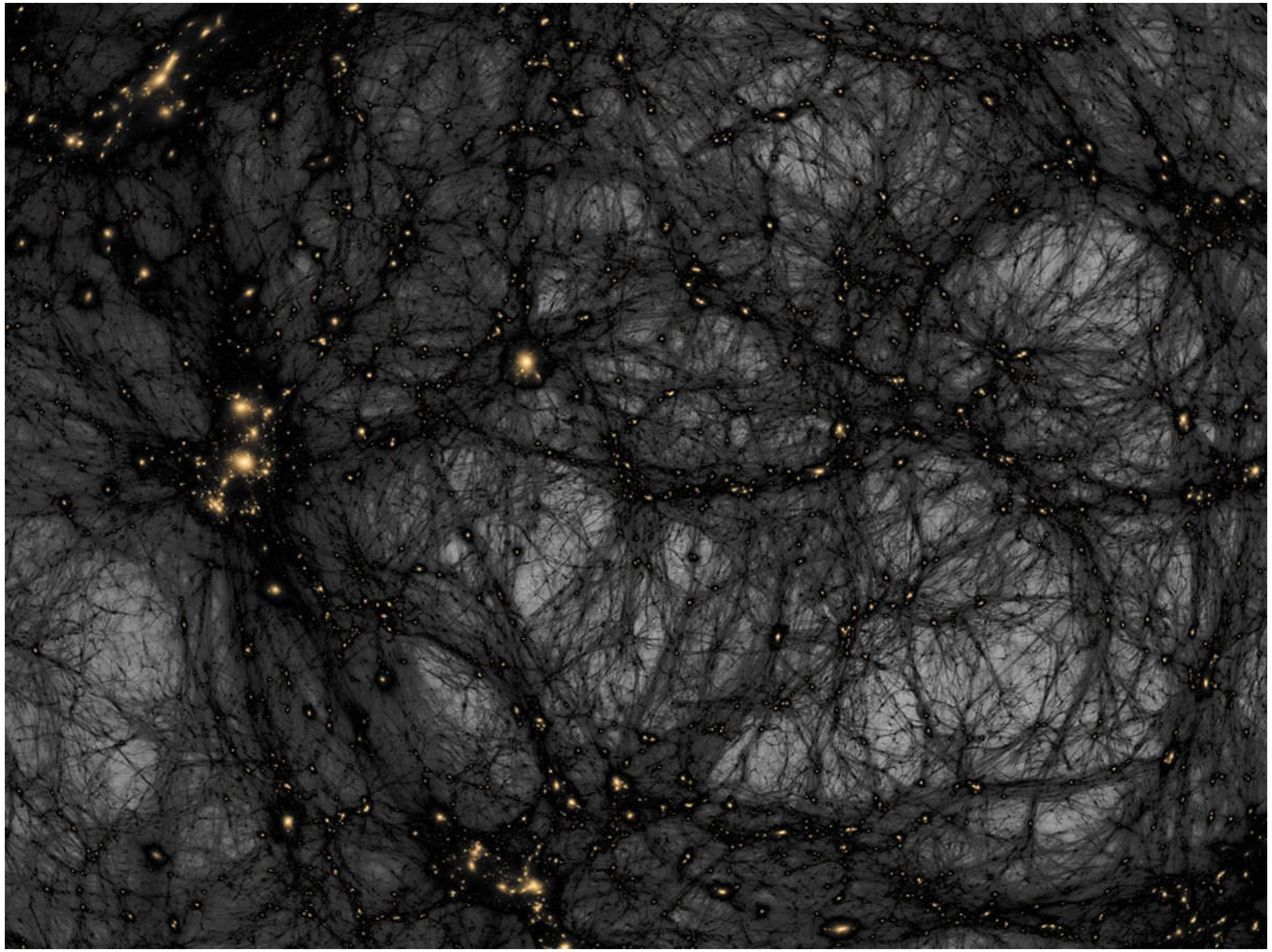
Instead, the measures suggested the speed is flattening…

According to Newton's law, it should be

$$v(r) = \sqrt{\frac{GM}{r}}$$

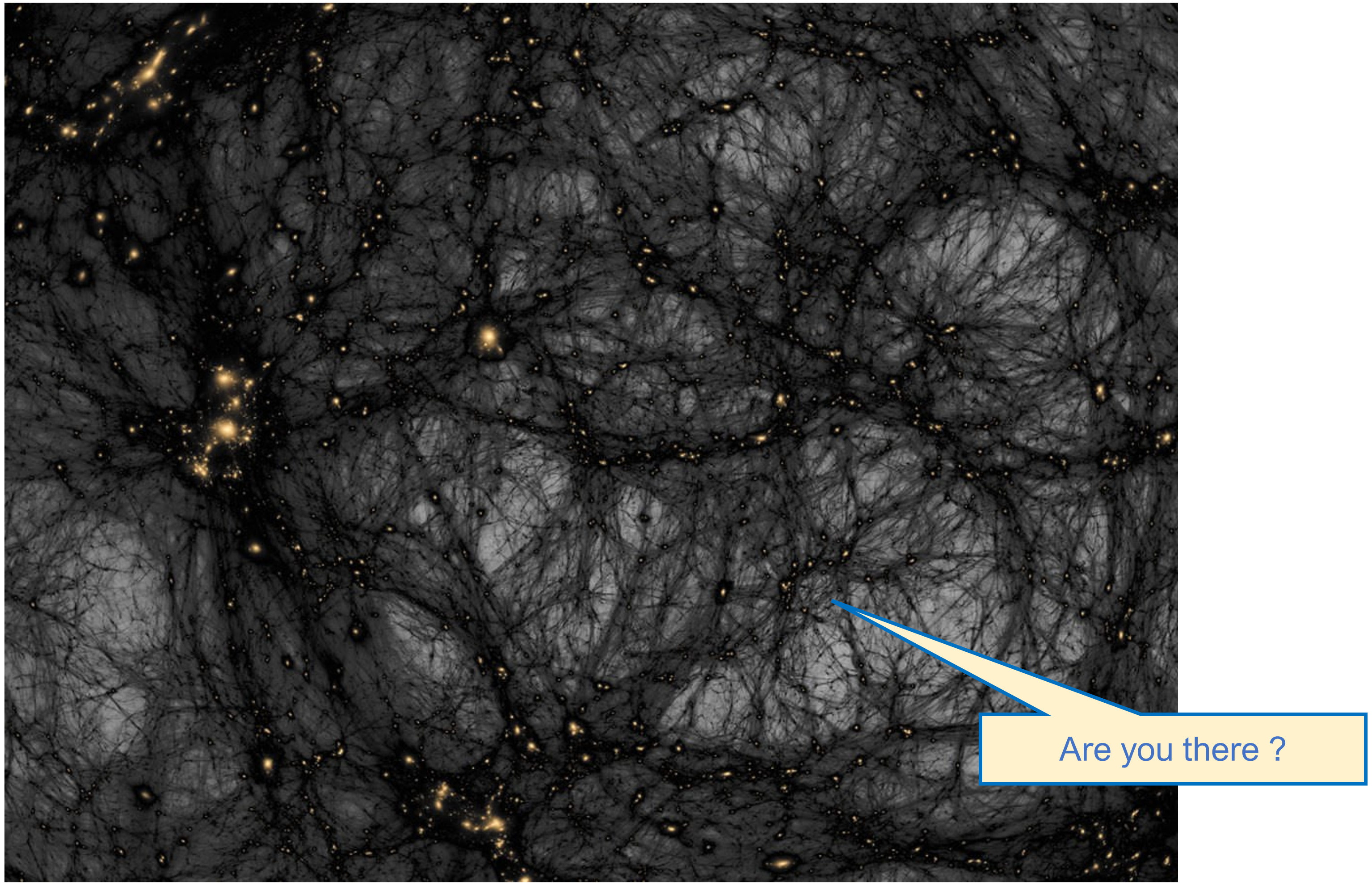
Dark Matter exists!

Nowadays, we can compute where dark matter is and how much it is…



Dark Matter exists!

We understood that Dark Matter is around five times more abundant that «luminous» matter …



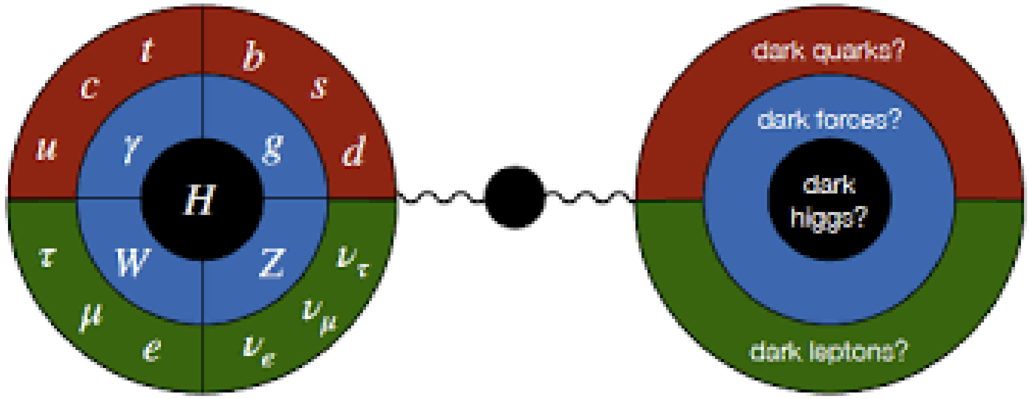
Dark Matter: what is made of?

…but we don't know what it is!

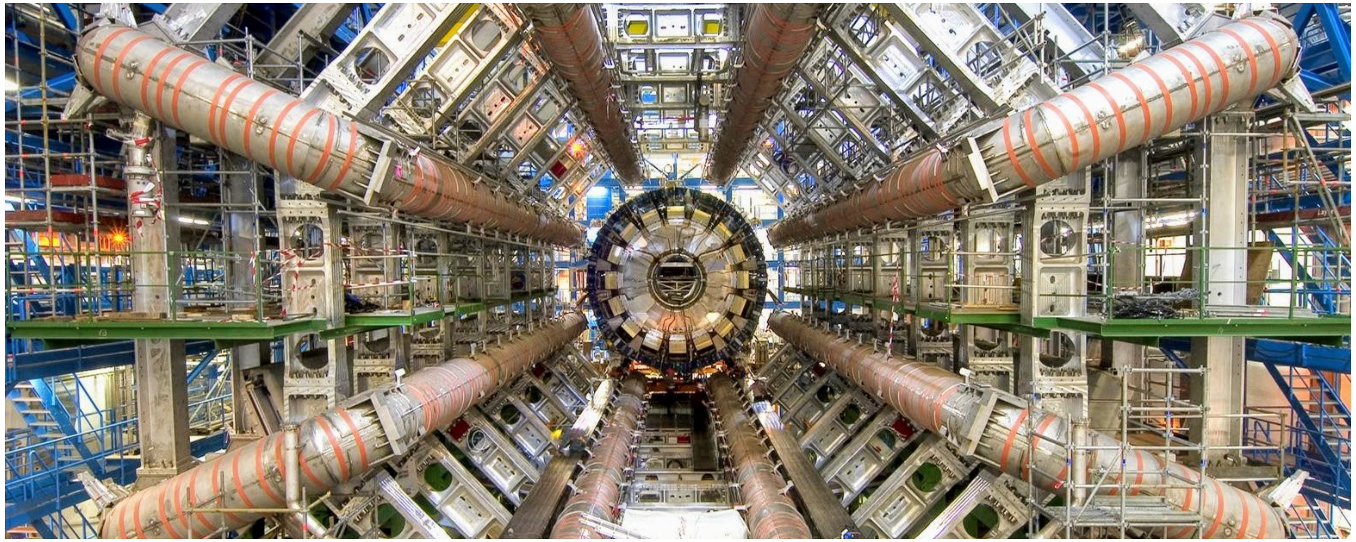
- It should be affected by the **Gravitational Interaction** only

- Should be **different from all the matter** we know up to know:
  - New kind of particle ? (or many type of particles?)
  - Compact objects as black holes?
  - Or is it a kind of wave-like disturbance ?

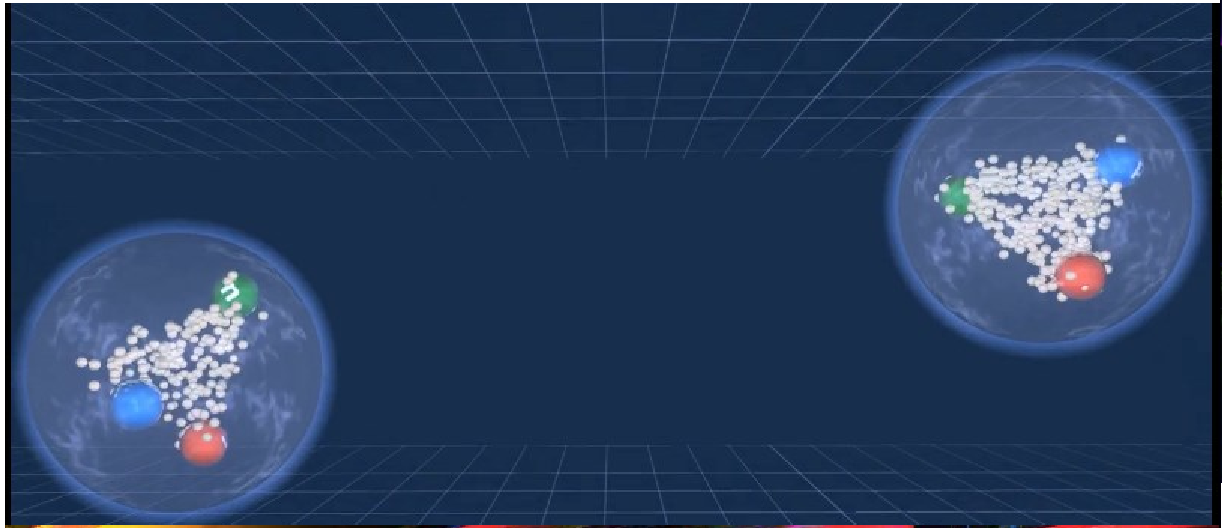
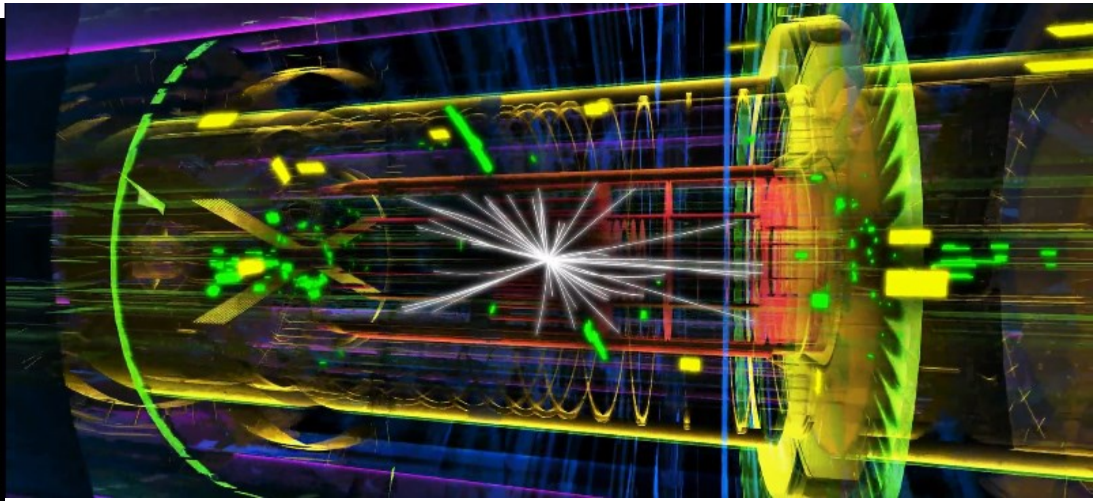
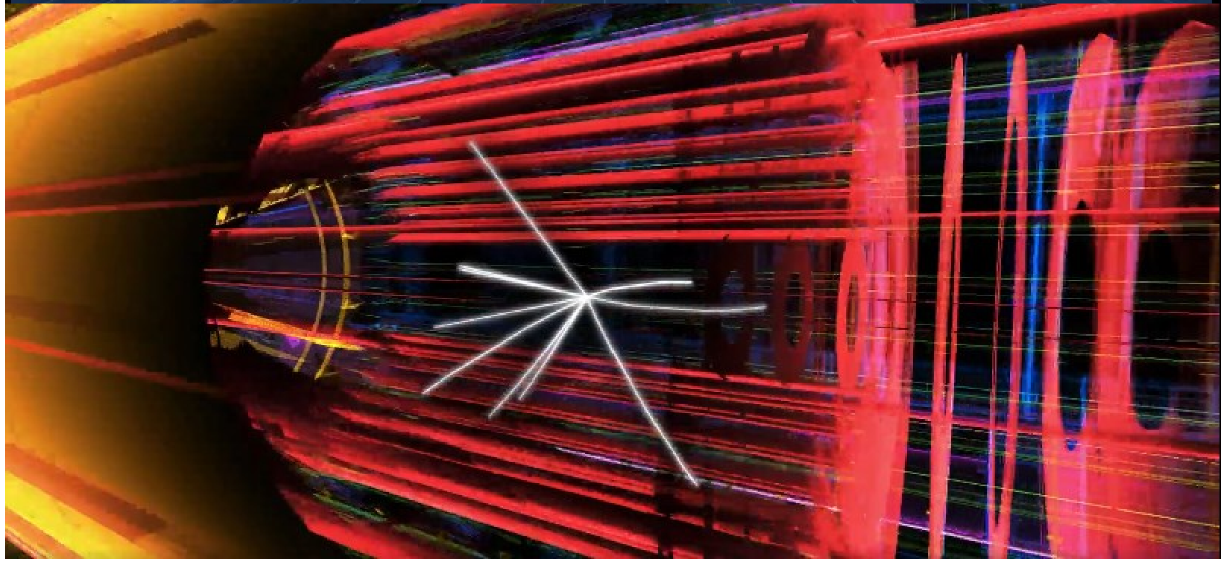
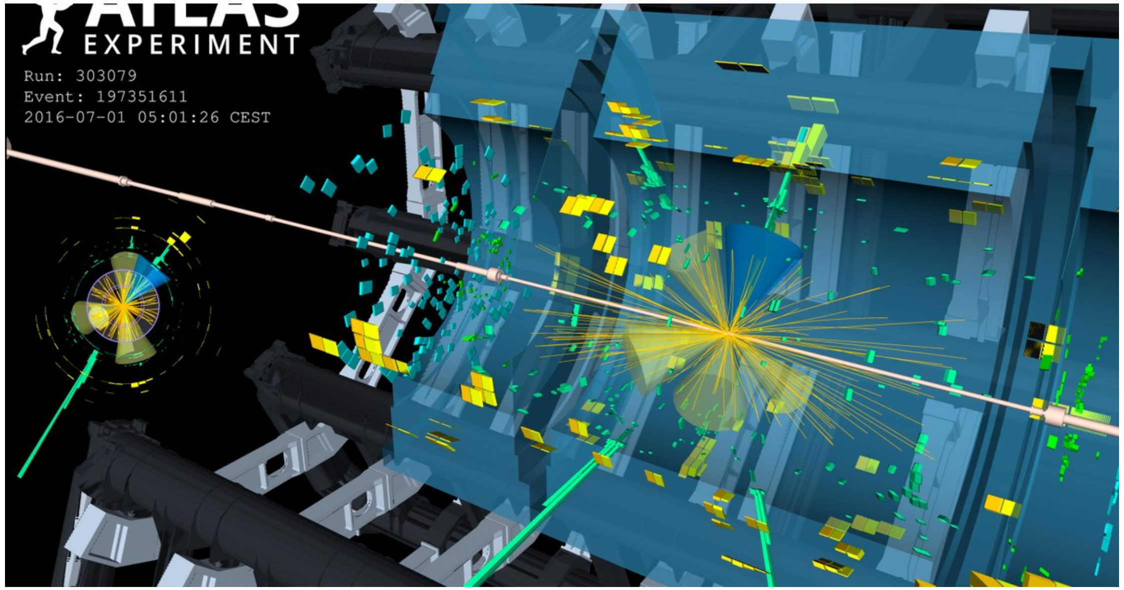
- Does it live in a «hidden Universe» (Dark Sector), connected to our universe by new forces?



The ATLAS detector (and how to use it)

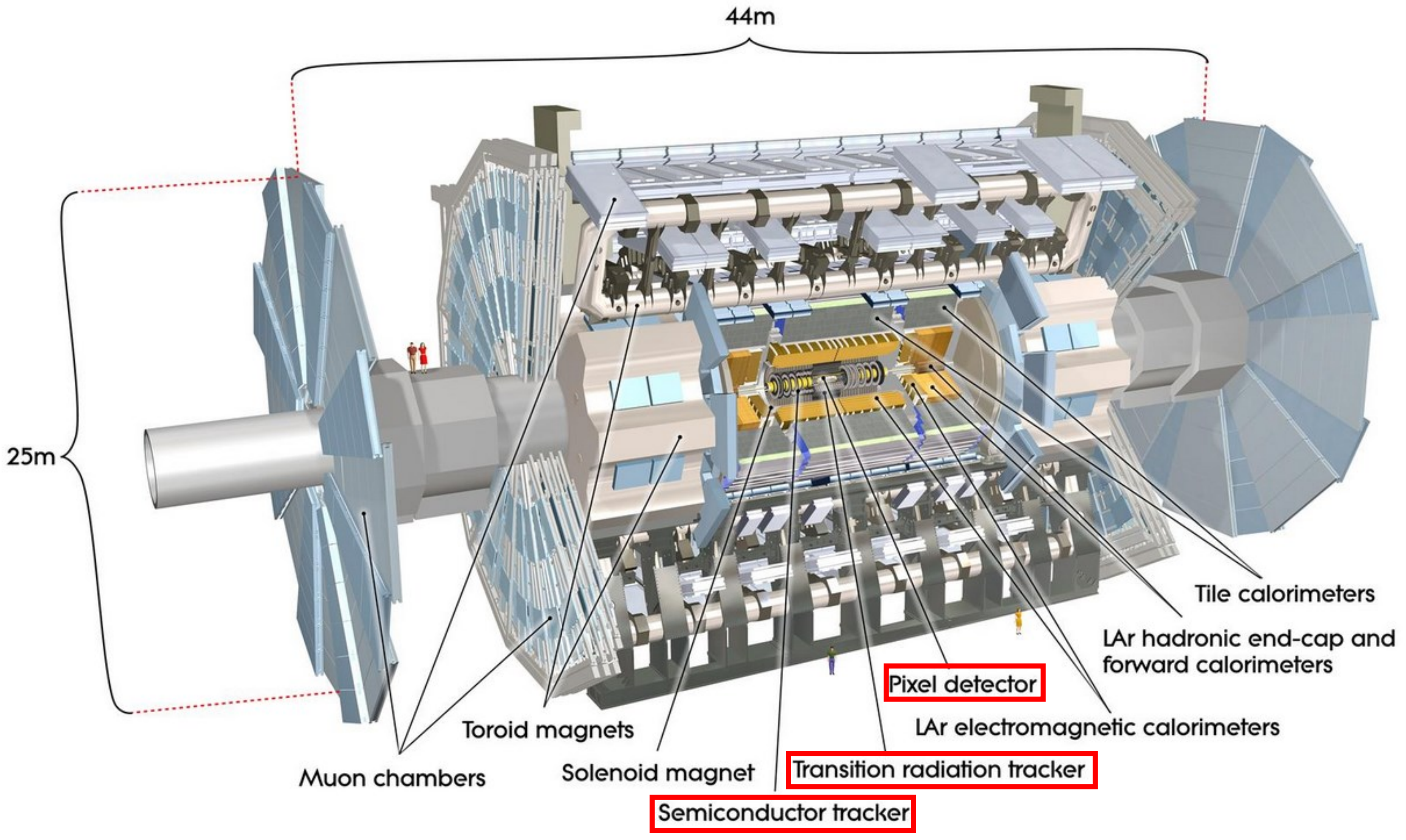


When a proton meets another proton…

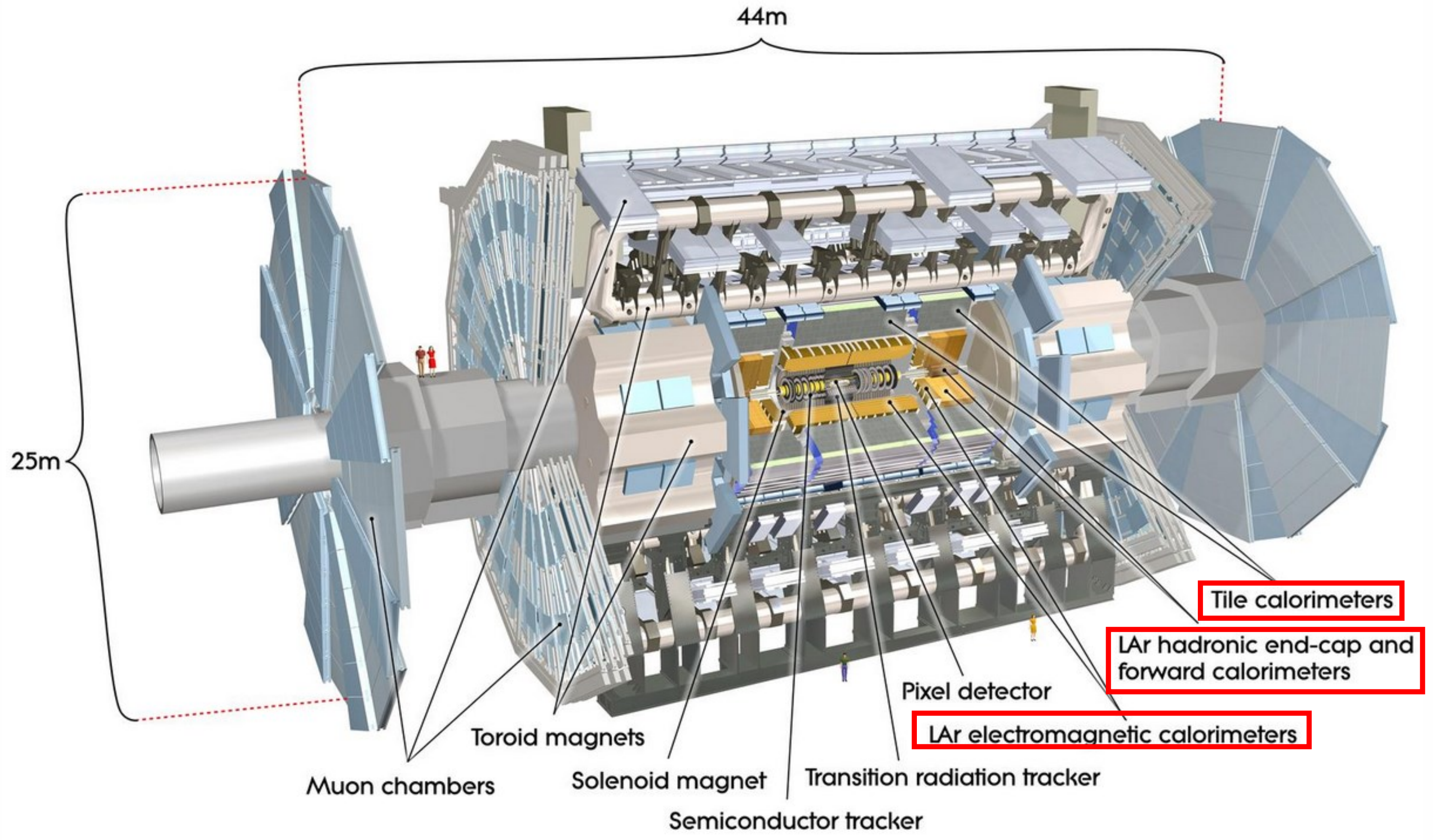
The ATLAS detector

- the **Inner Detector** is installed around the center of the ATLAS, right after the LHC beam pipe. It consists of **three different sub-detector technologies**, all designed to accurately record **tracks of charged particles** produced at the collision point and moving outwards. Neutral particles (e.g. photons) pass through the Inner Detector unnoticed



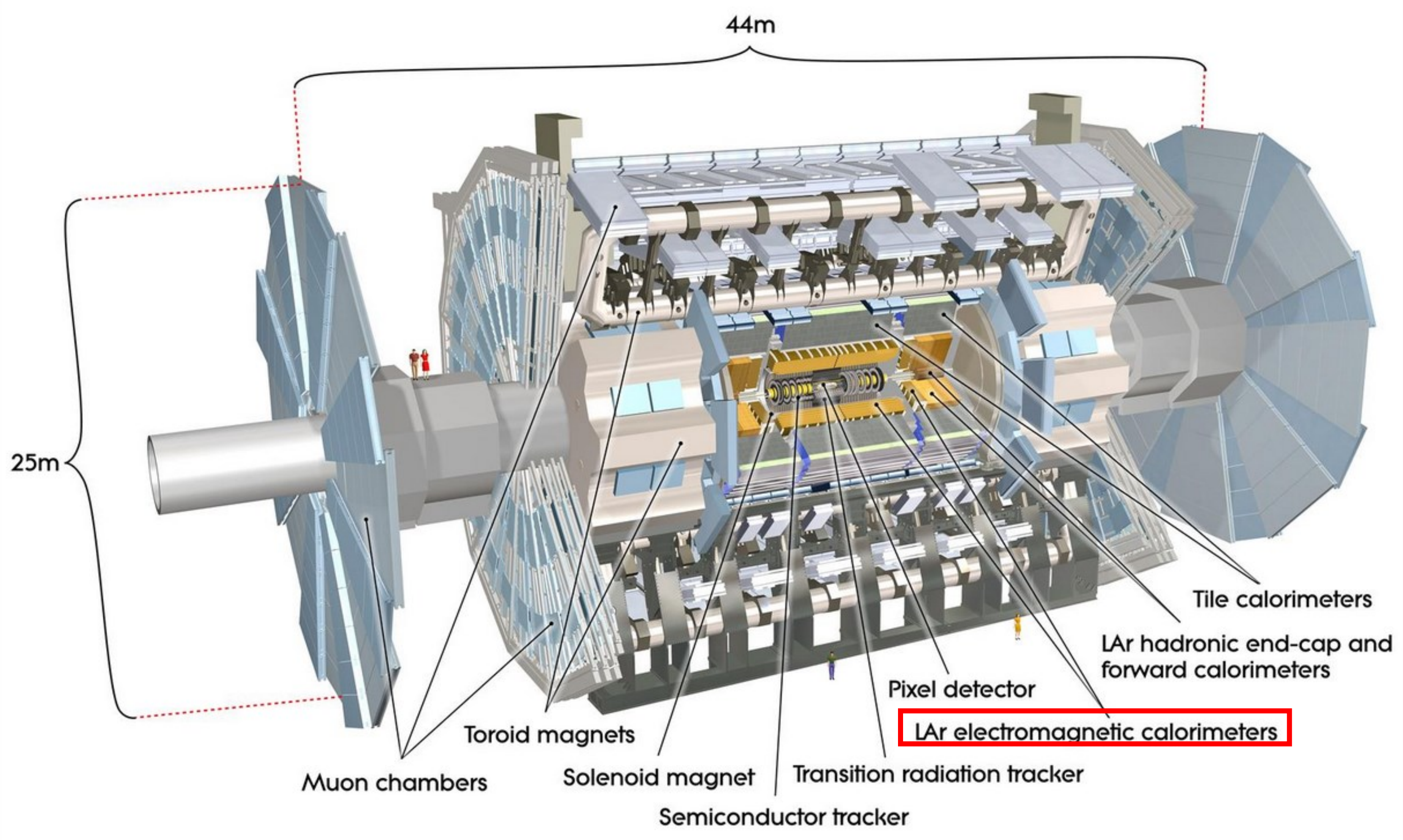
The ATLAS detector

- the **Calorimeters** contain heavier materials (e.g. steel, lead), which cause both charged and neutral incoming particles to interact and **deposit all of their energy**, allowing us to measure it. In particular, the energy of an incoming particle is distributed among a bunch of lighter particles, which appear as a localized **particle-shower in the detector**



The ATLAS detector

- There are two calorimeter systems in ATLAS:
  - **the electromagnetic calorimeters** absorb and measure the energy of **electrons, positrons and photons**. Energetic hadrons penetrate this calorimeter leaving only a fraction of their energy



The ATLAS detector

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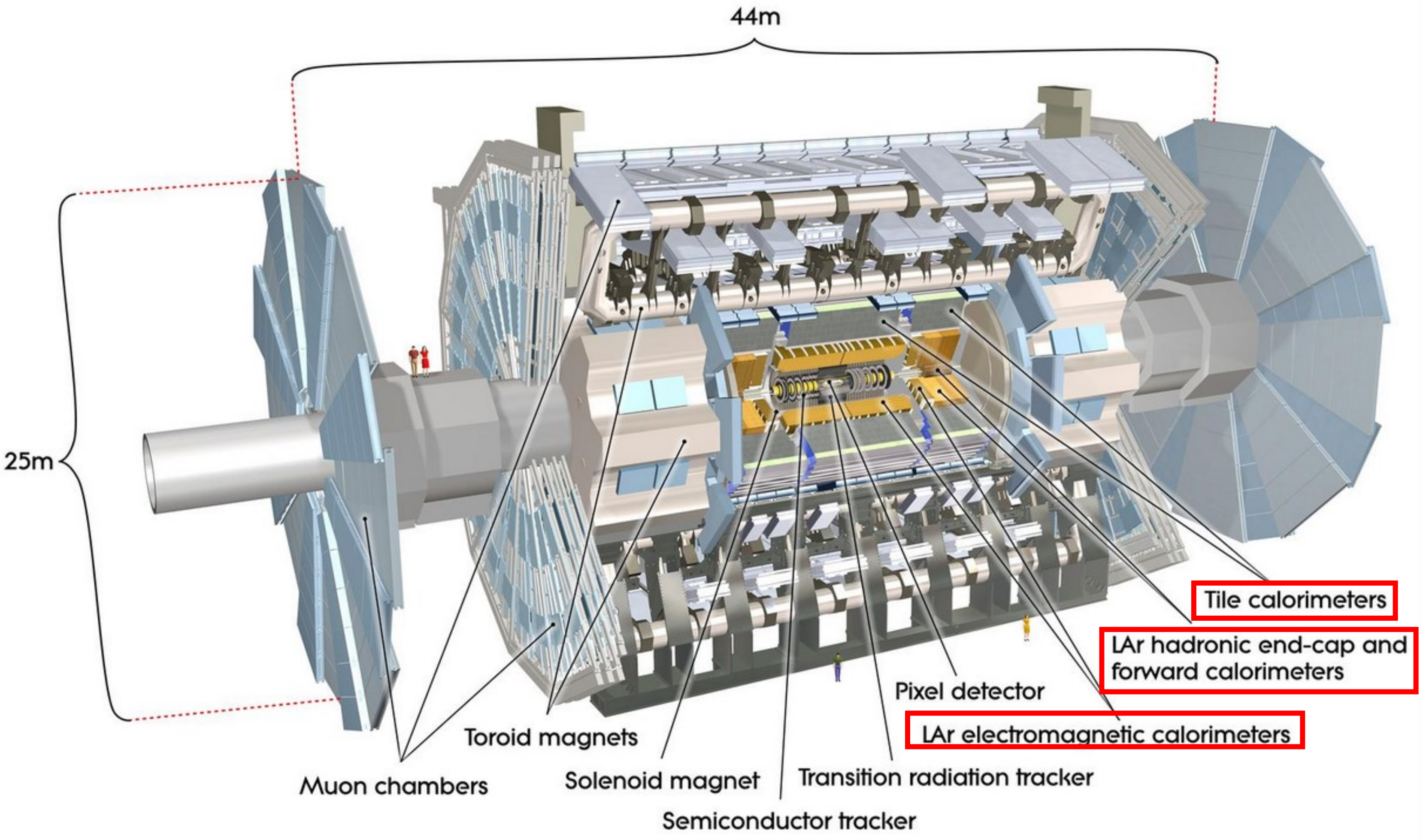
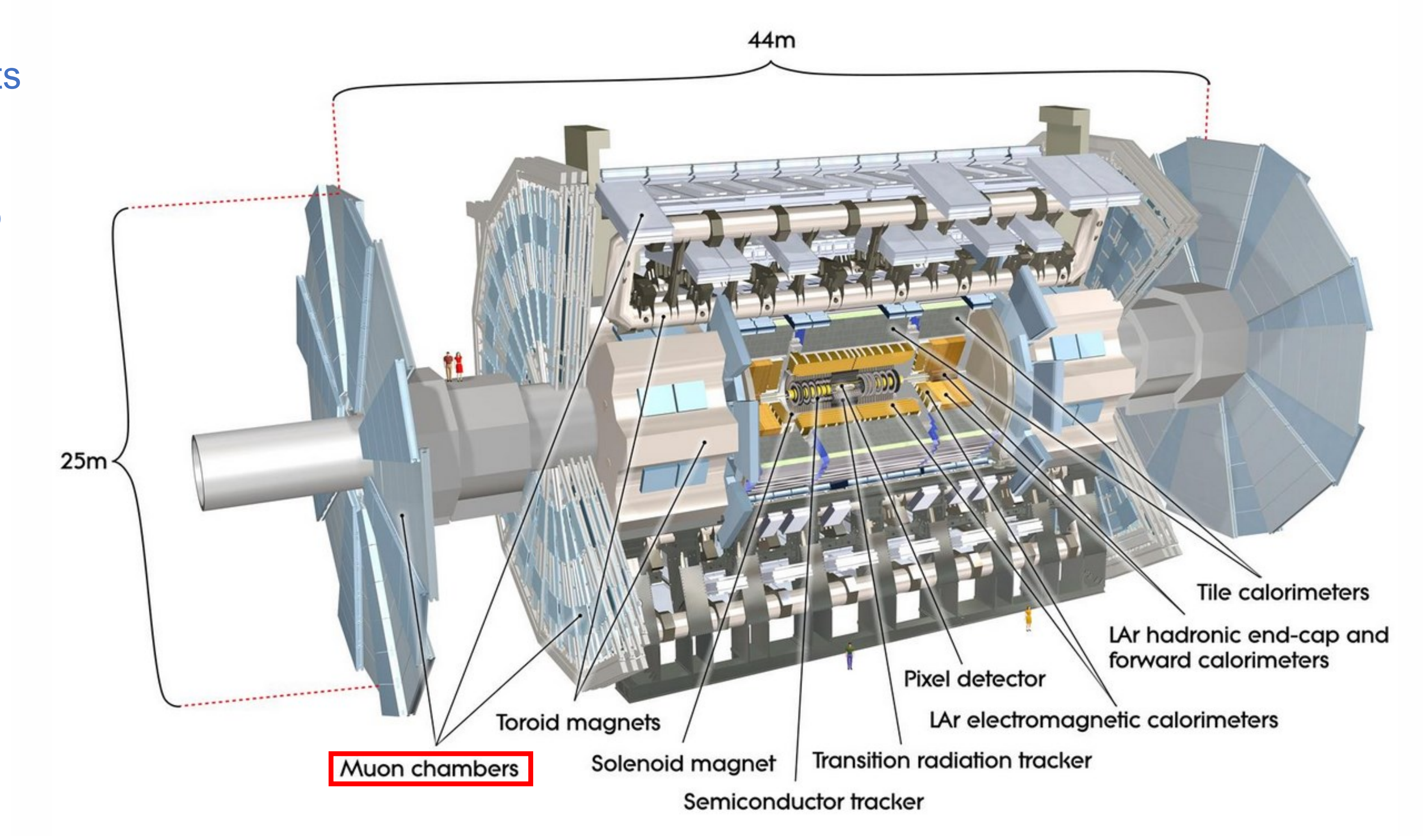
  - **the electromagnetic calorimeters** absorb and measure the energy of **electrons, positrons and photons**. Energetic hadrons penetrate this calorimeter leaving only a fraction of their energy
  - the **hadronic calorimeters** measure the total energy of **hadrons, such as protons and neutrons**. They stop almost all particles allowing us to measure their energy



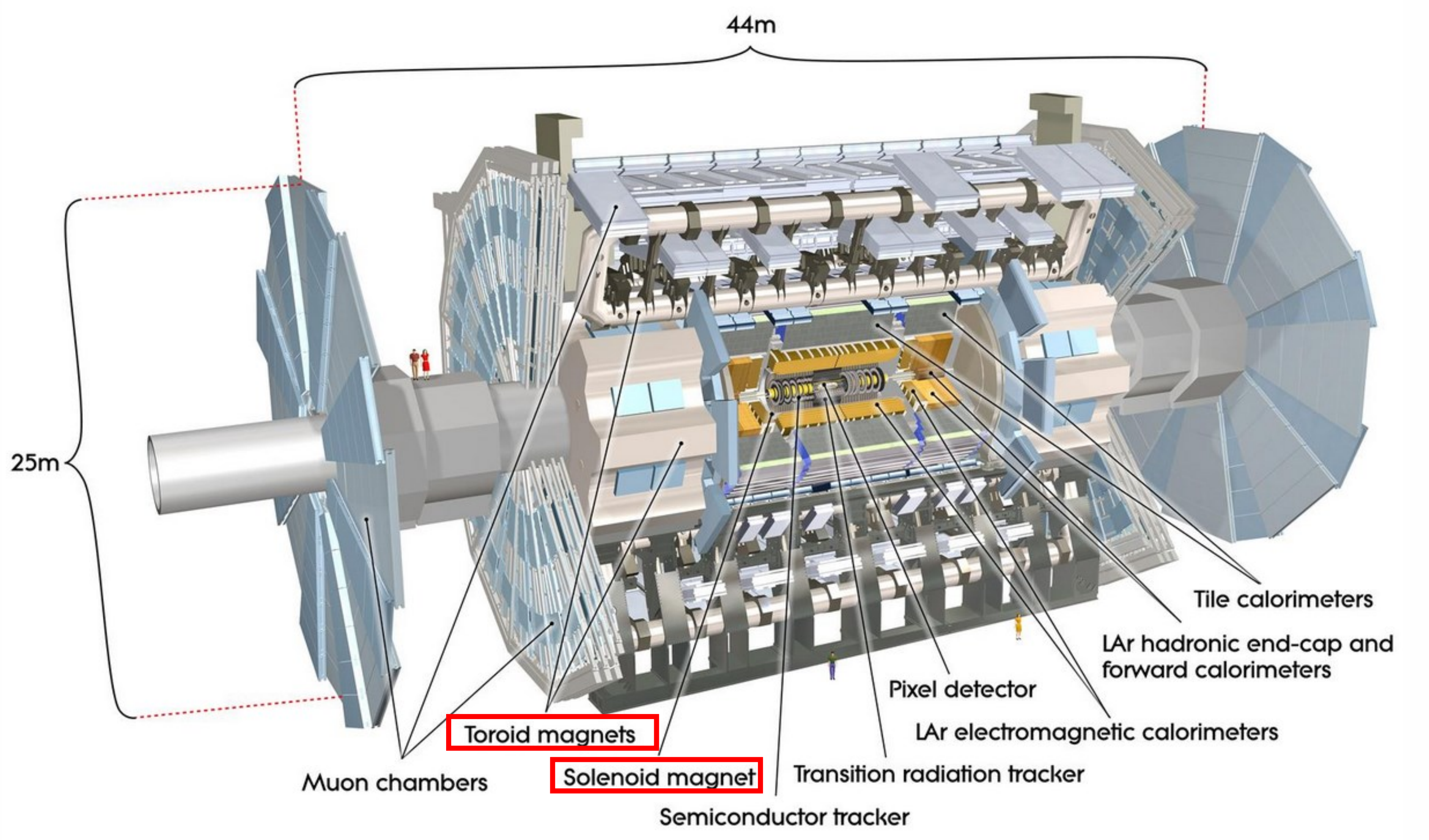
The ATLAS detector

- the **Muon Spectrometer** detects the **energetic muons** which leave little energy in the other detectors and have the ability to penetrate the entire detector



The ATLAS detector

- the **Magnet Systems** bend charged particles in the Inner Detector and the Muon Spectrometer, allowing for their momenta to be measured accurately from their track curvature



The ATLAS detector

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In total :

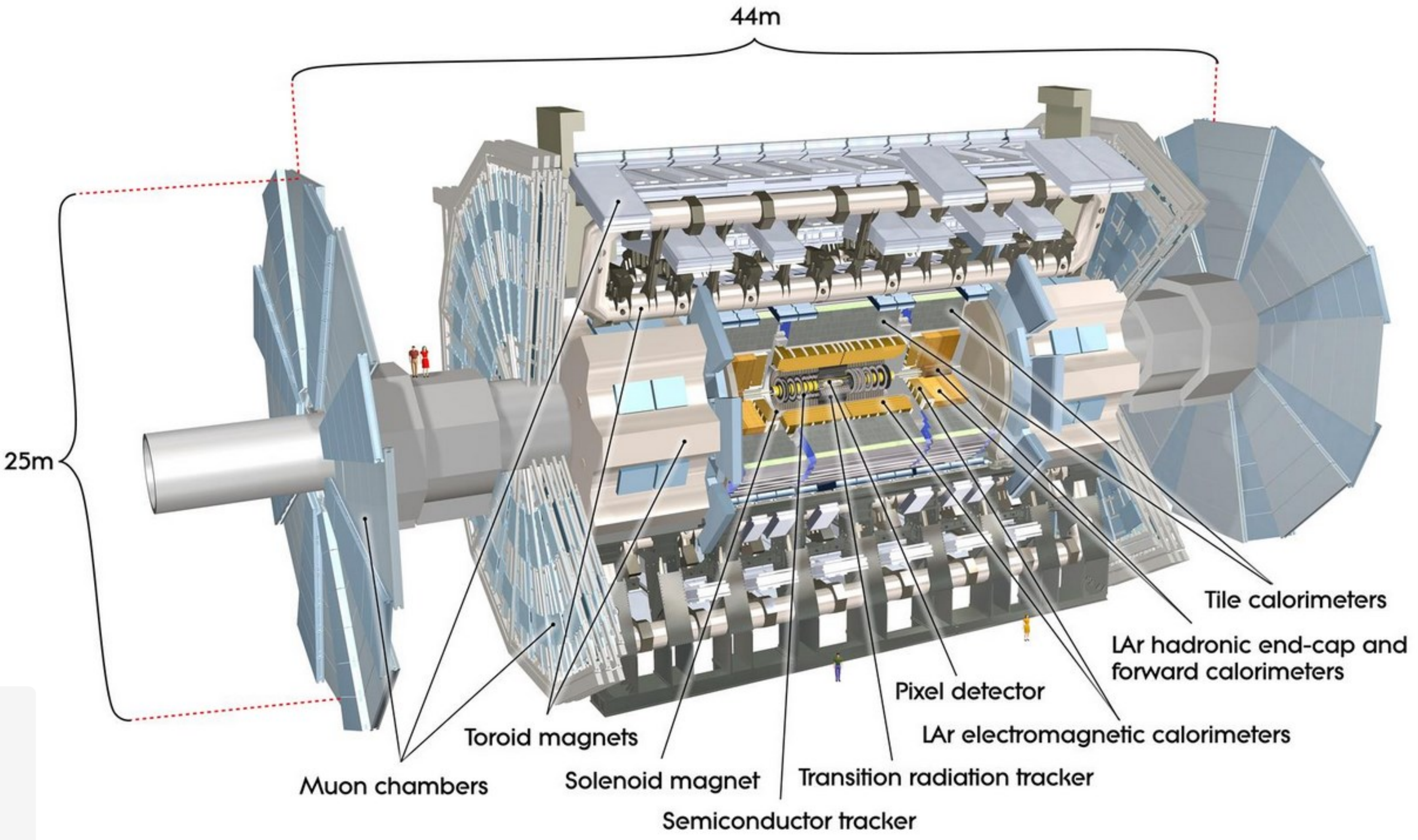
- 44 meters in length
- 25 meters in diameter (about the height of a 6 storeys building)
- Overall weight 7 000 tons
- Around 100 million electronic channels
- Around 3 000 km of cables

3000 Scientific authors

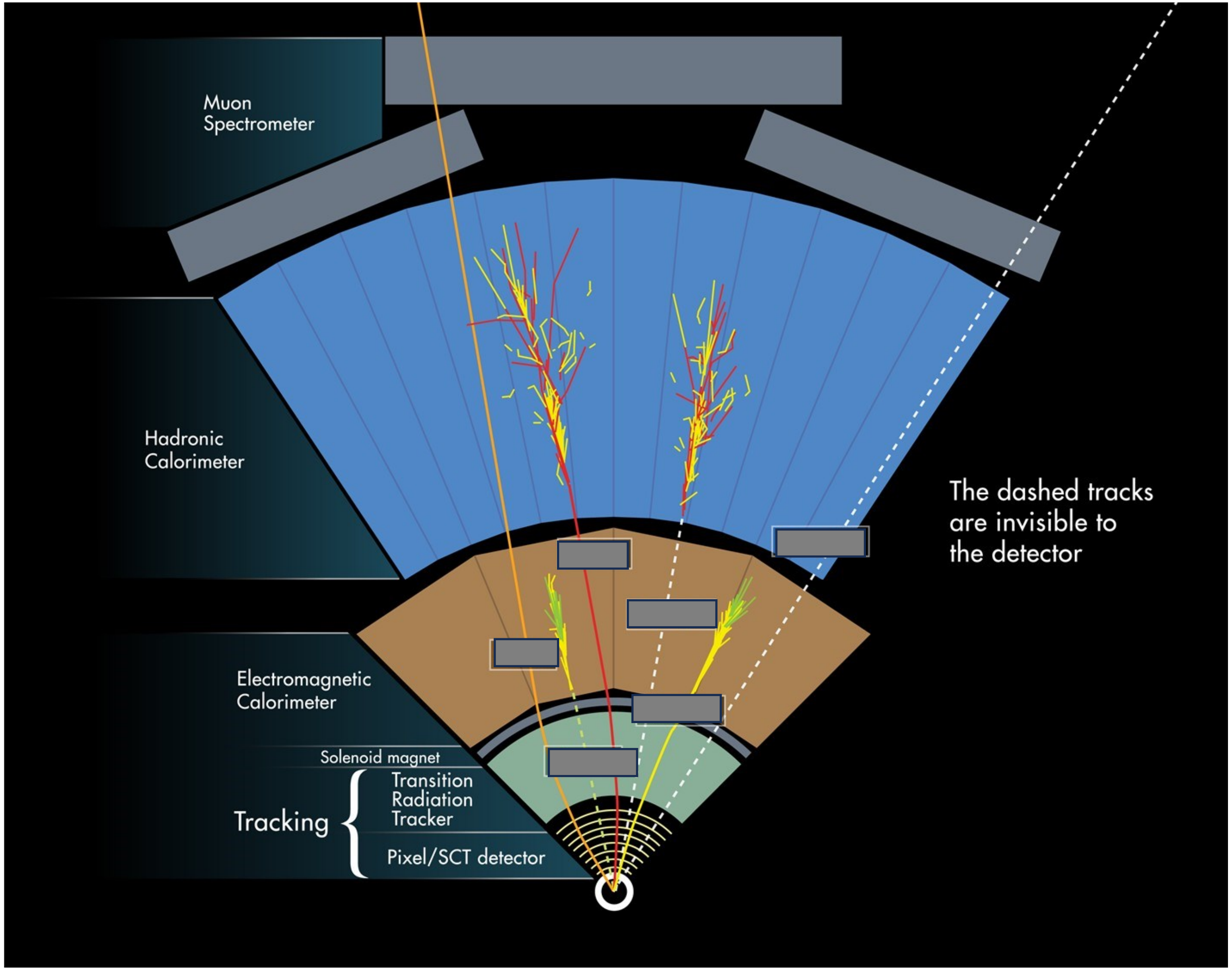
182 Institutions

42 Countries

1200 Doctoral students



The ATLAS subdetectors



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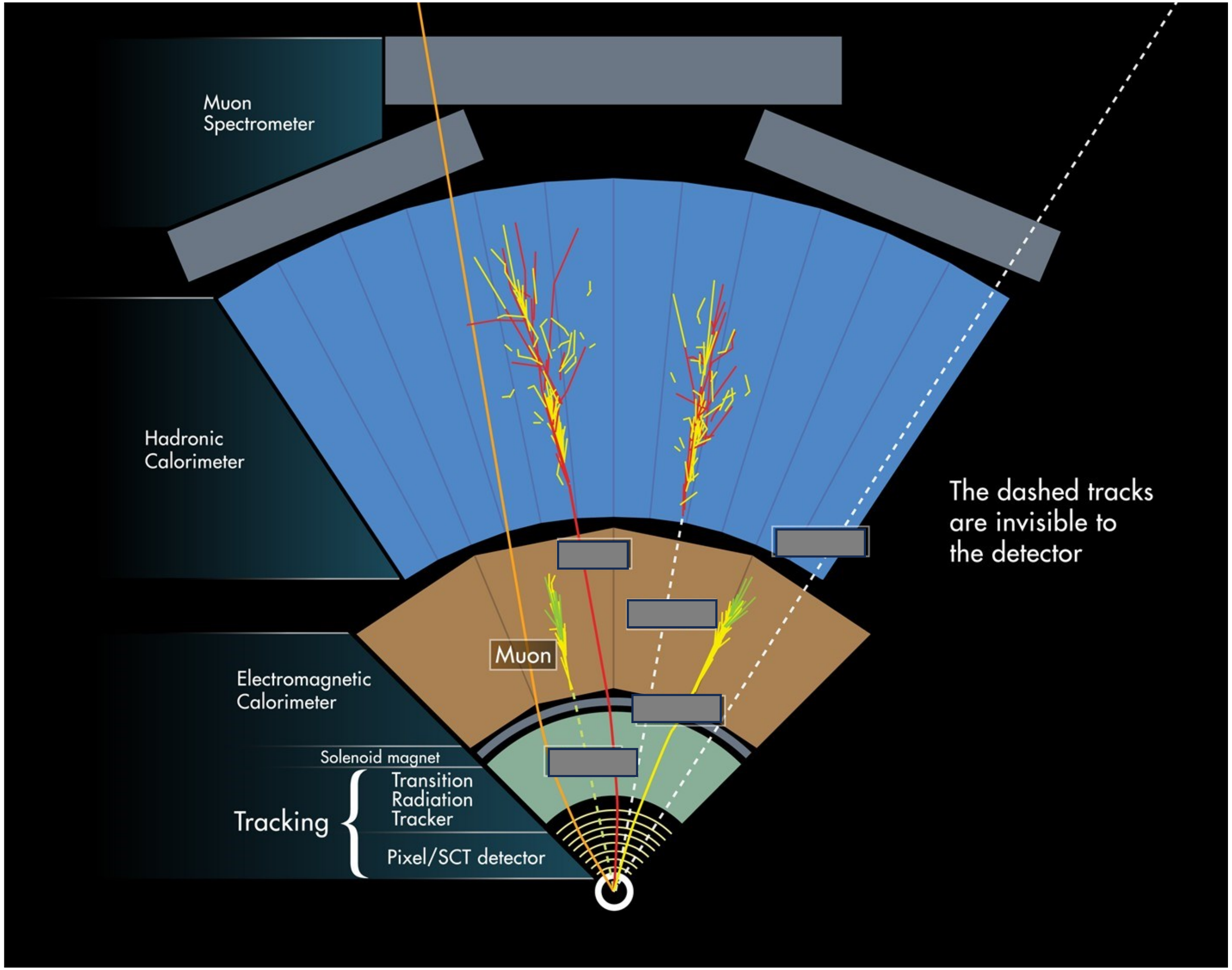

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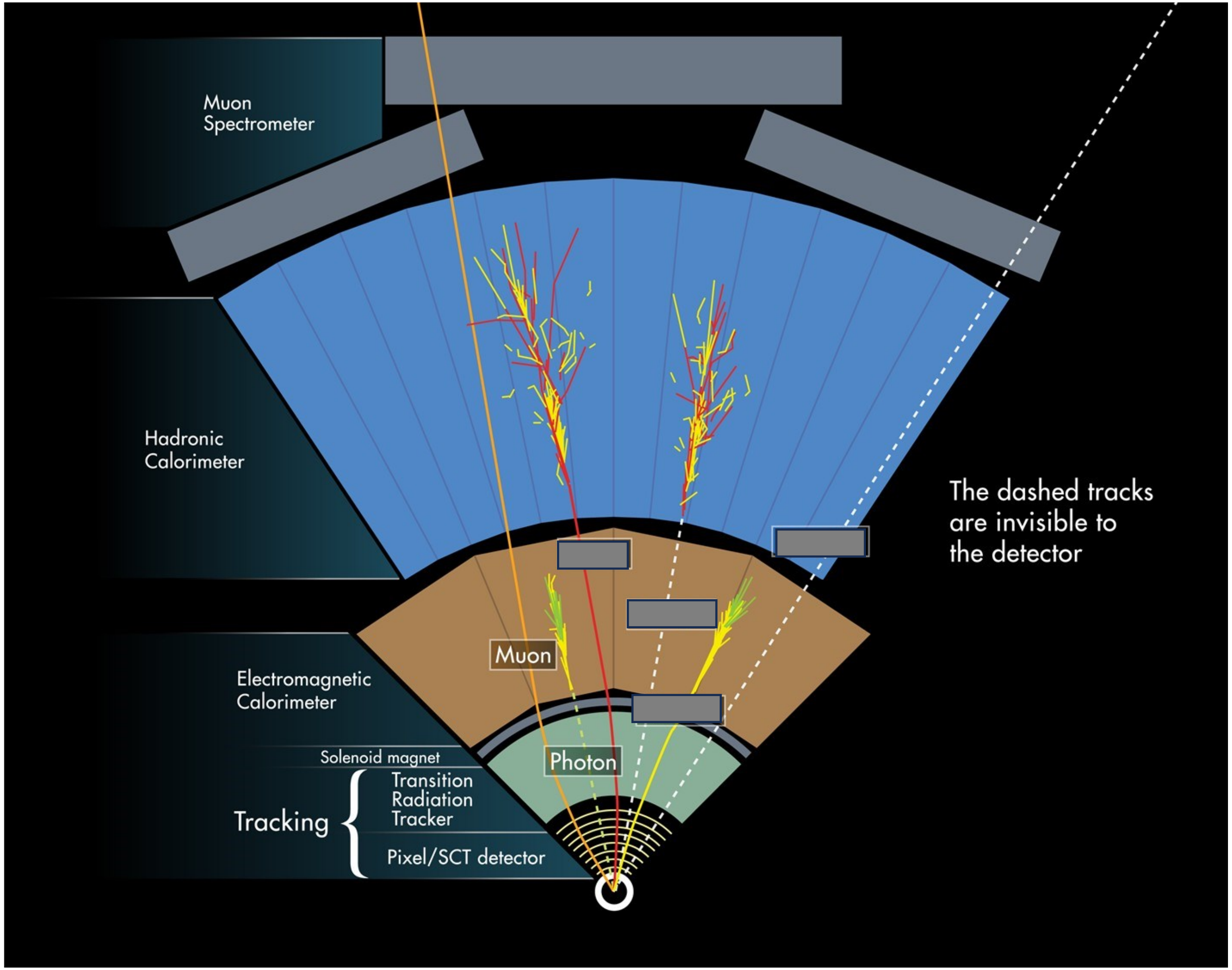
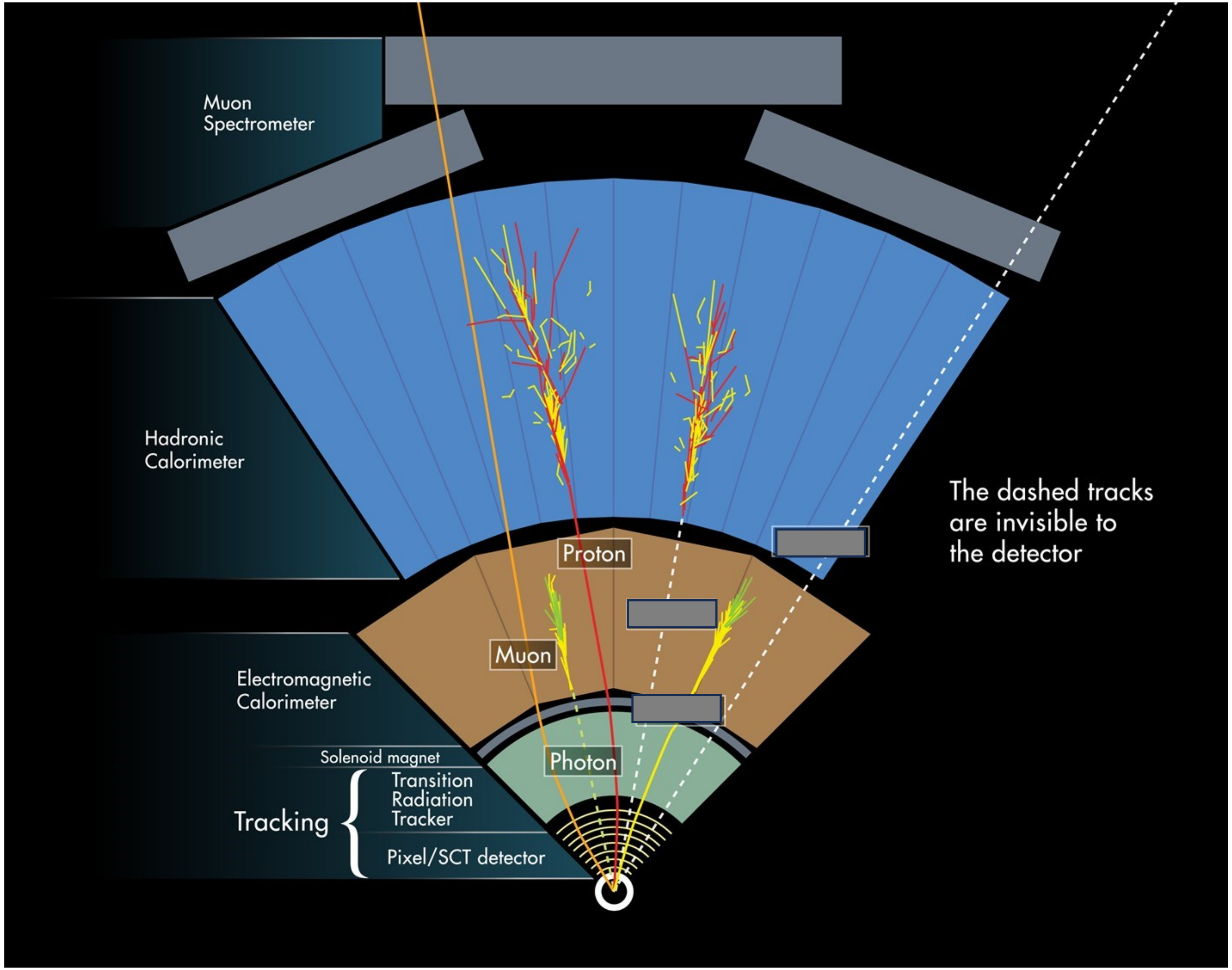


The ATLAS subdetectors

Brussels III



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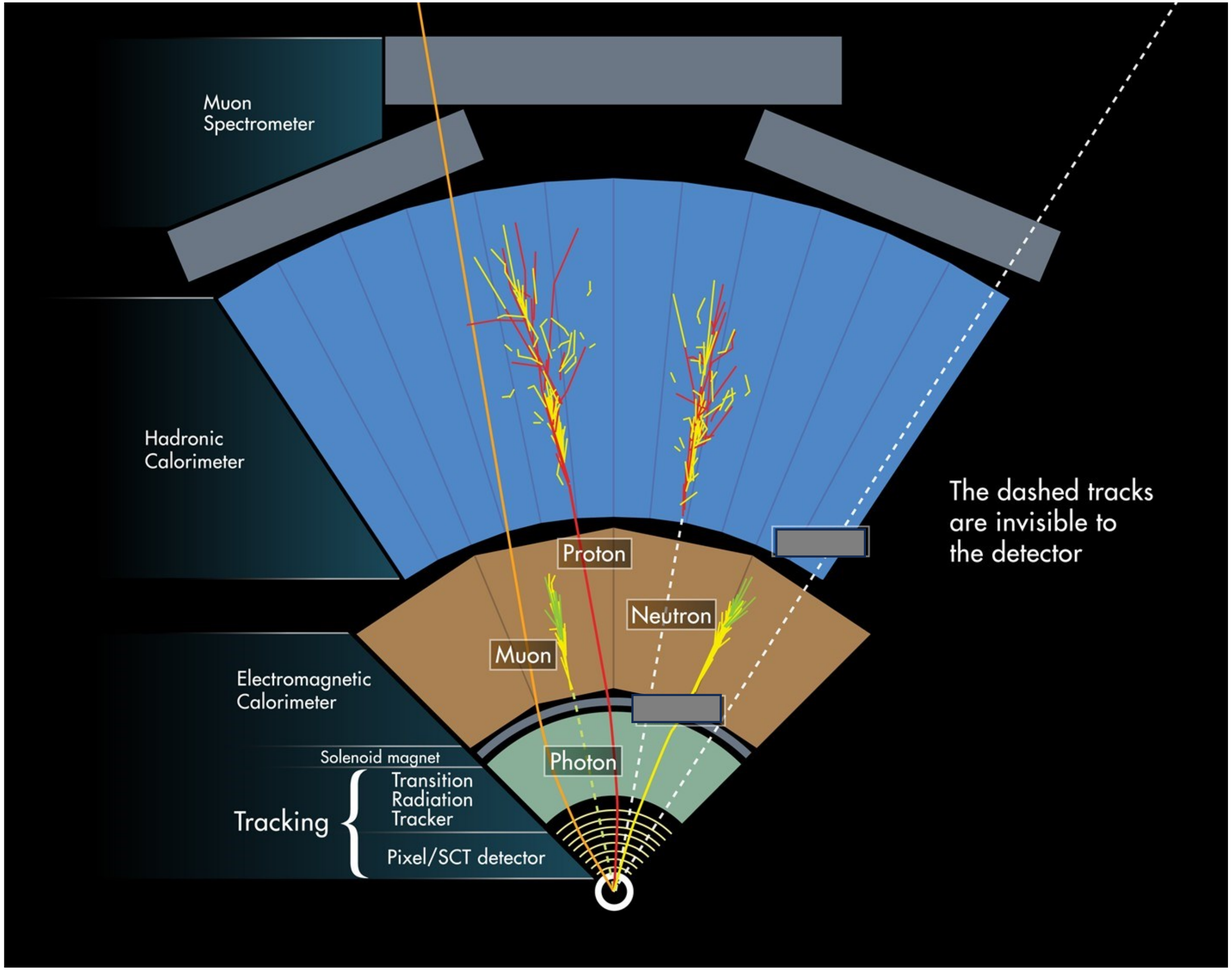

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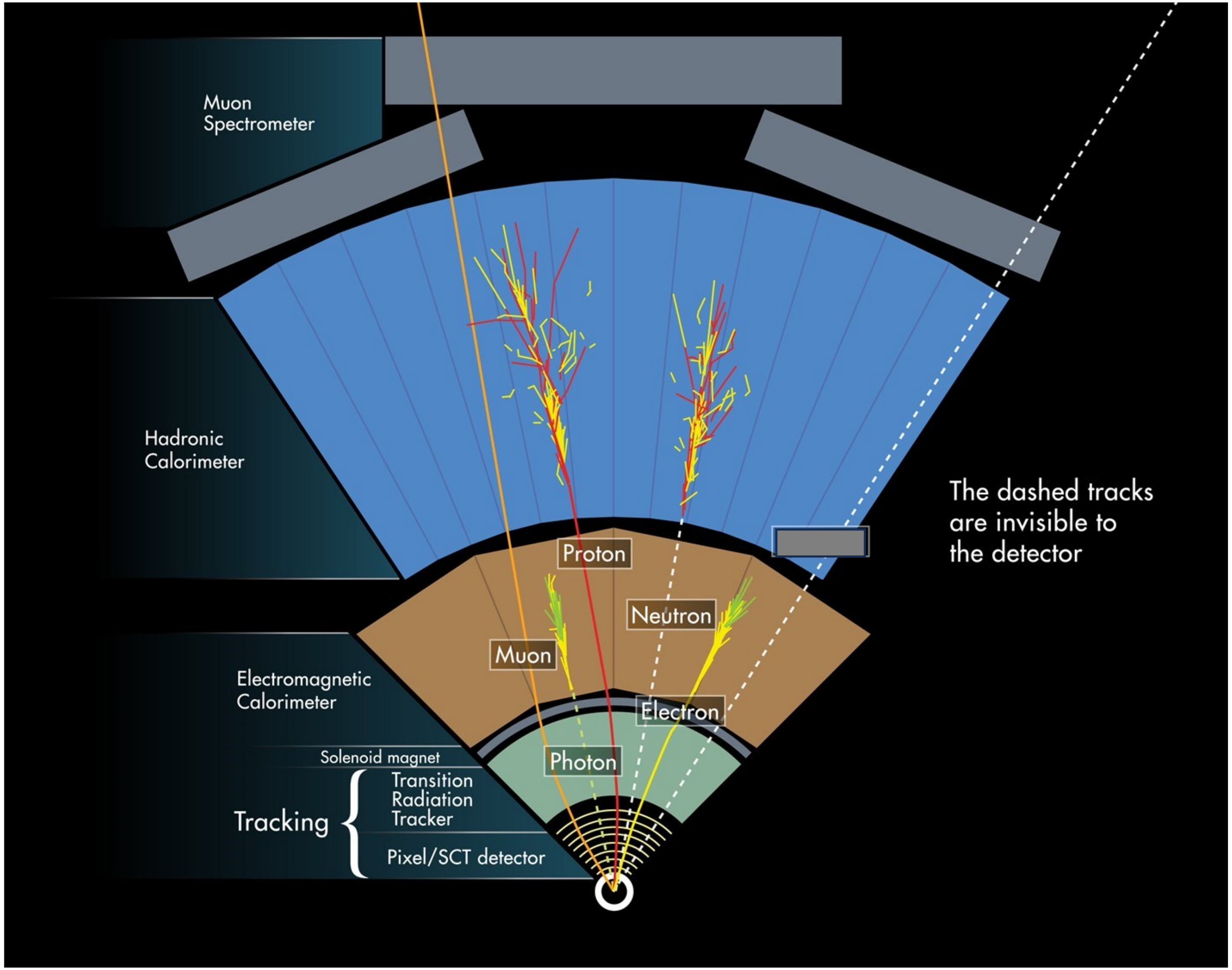

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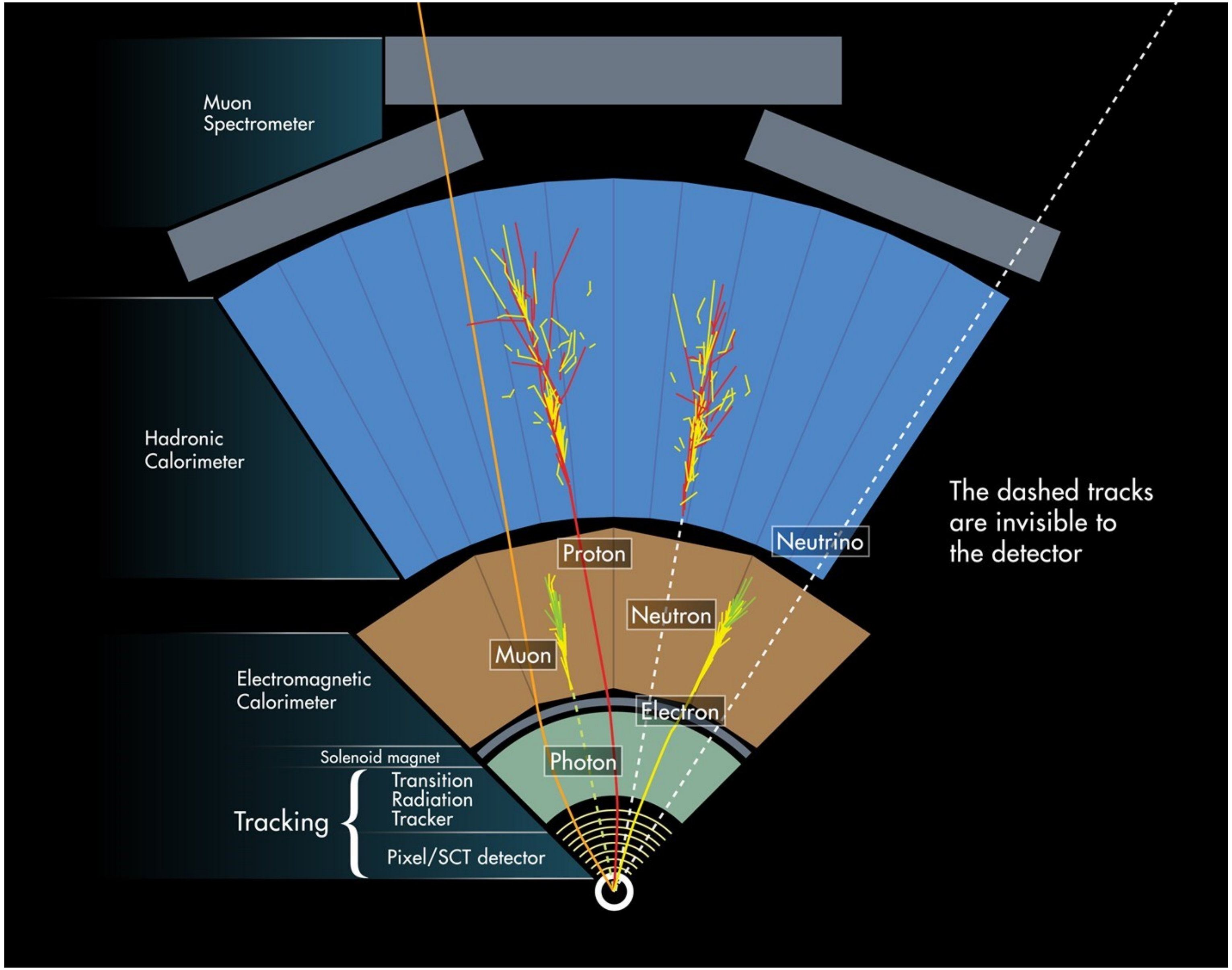
The ATLAS subdetectors



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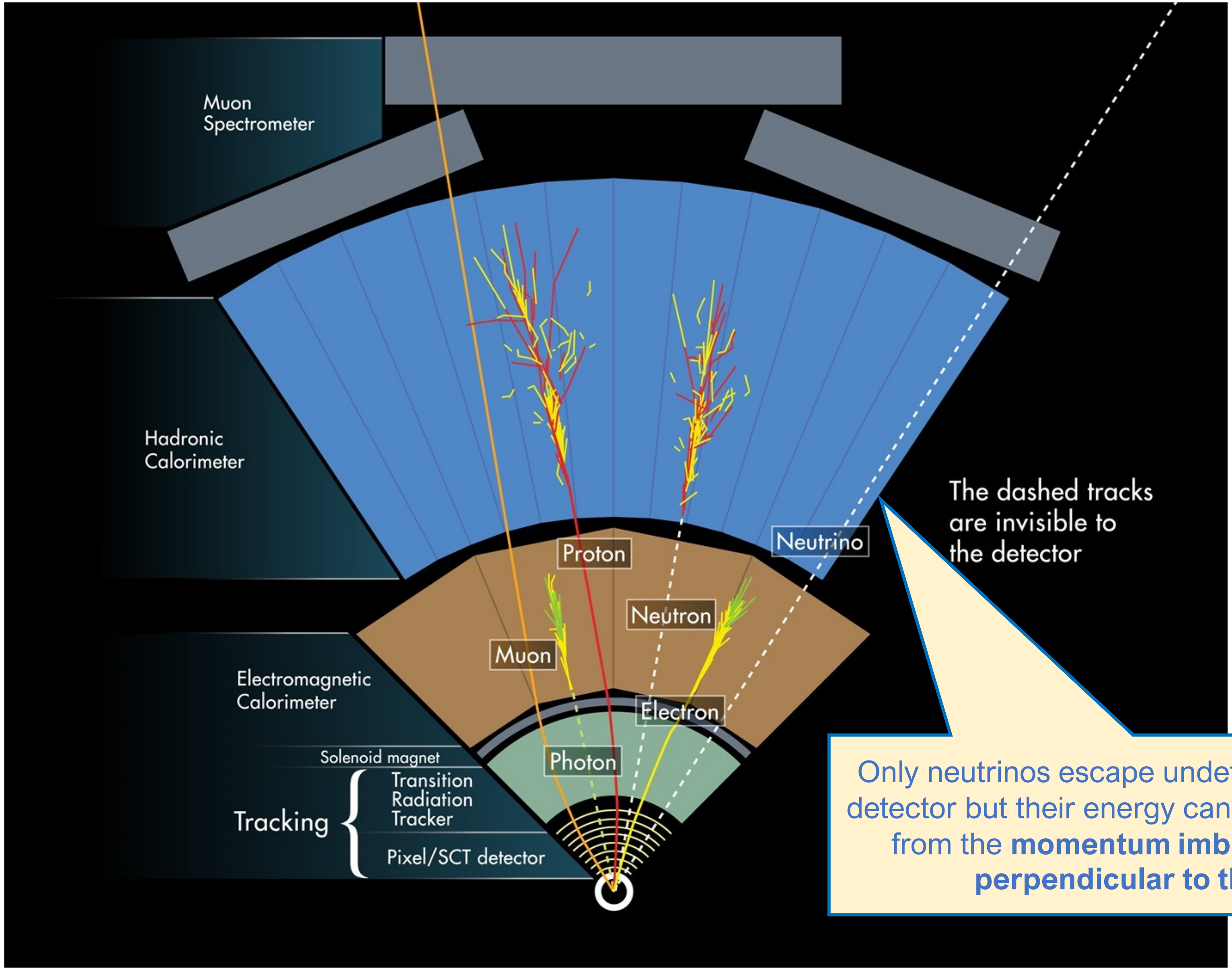
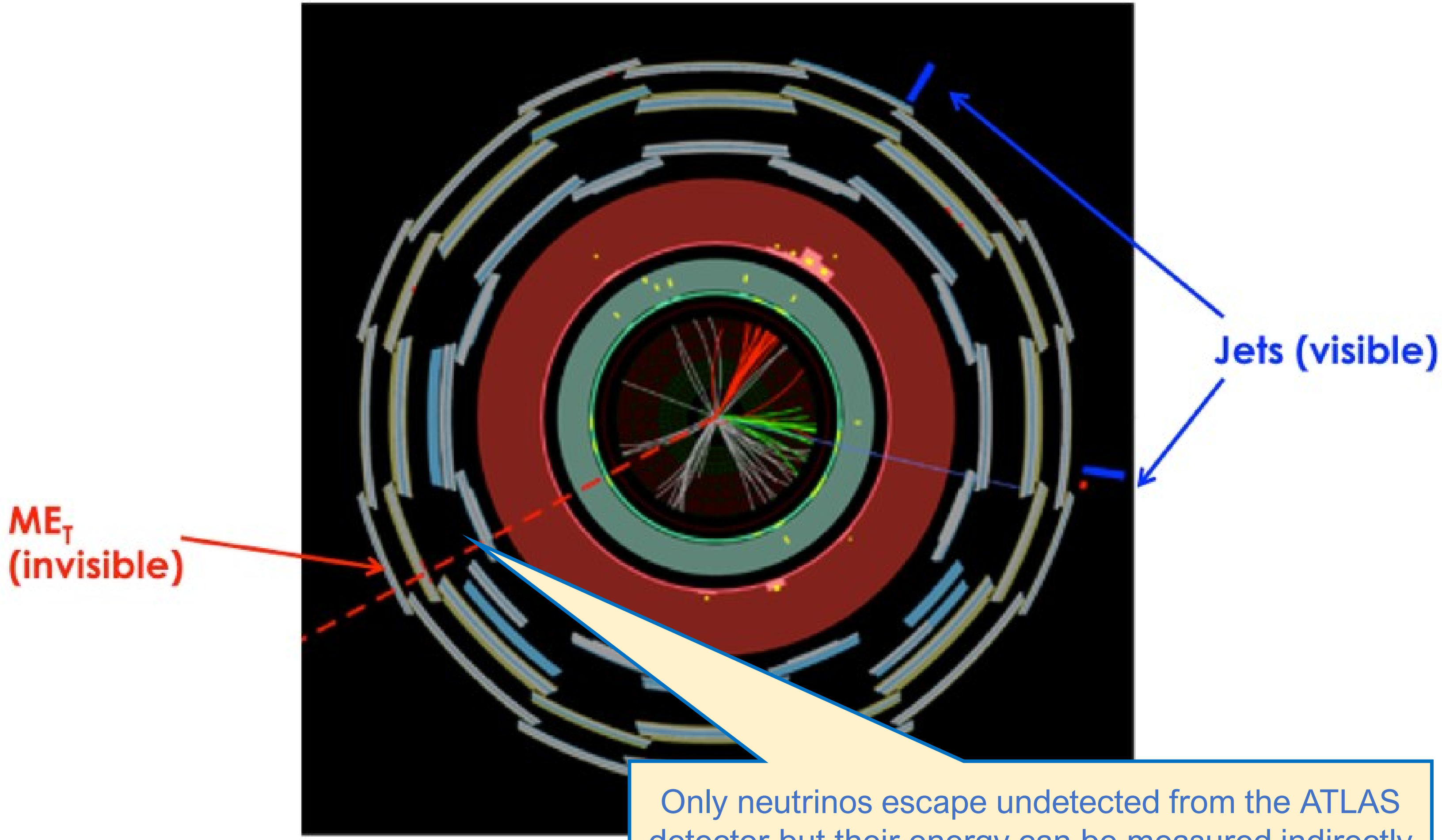


Only neutrinos escape undetected from the ATLAS detector but their energy can be measured indirectly from the **momentum imbalance in the plane perpendicular to the beam axis**

The ATLAS subdetectors



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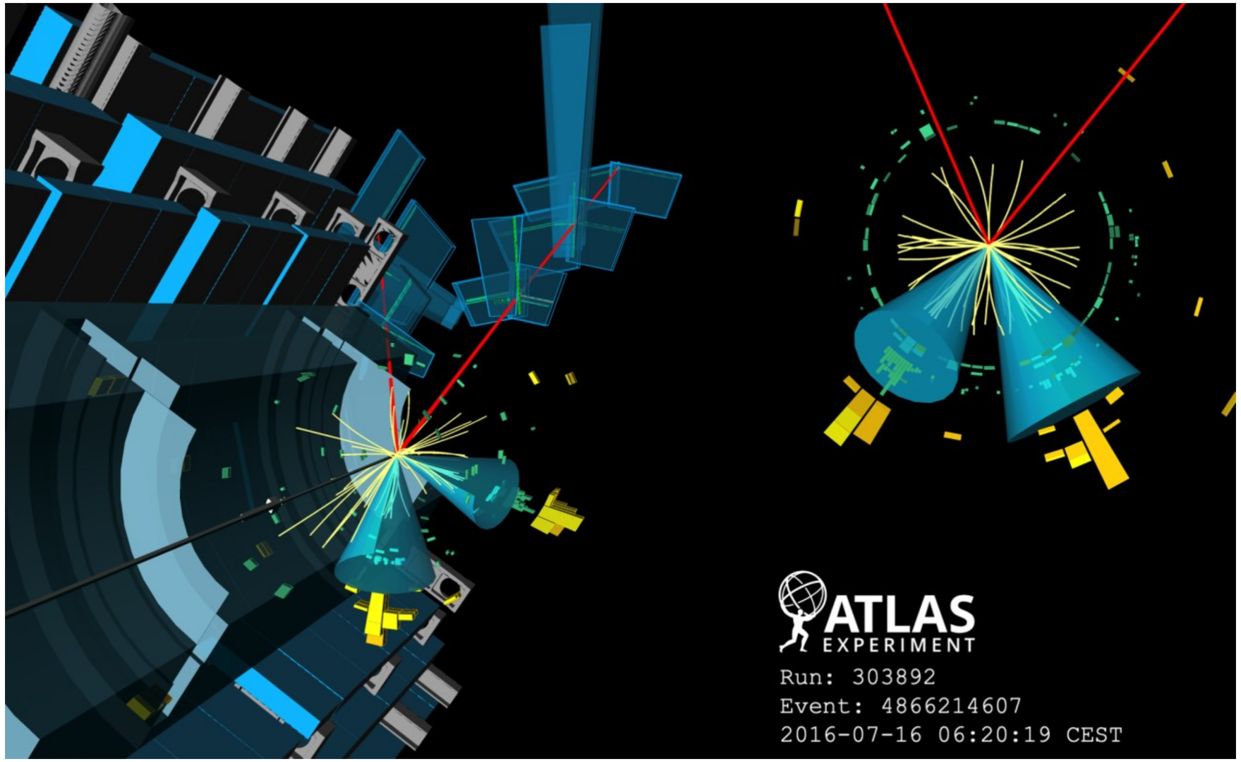
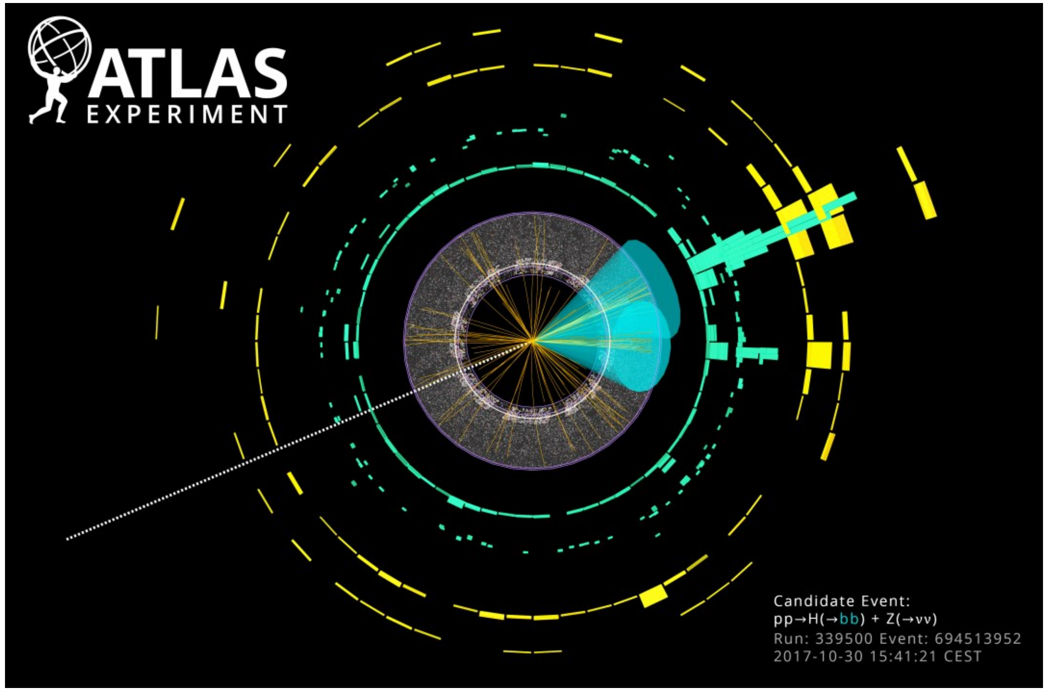
Detecting heavy, short-lived particles

The design we saw is optimized to reconstruct particles that:

- are **produced at the collision point**
- are **unstable**, decaying almost immediately in particles we can reconstruct
- are **massive**, so they can produce secondary particles that are energetic enough





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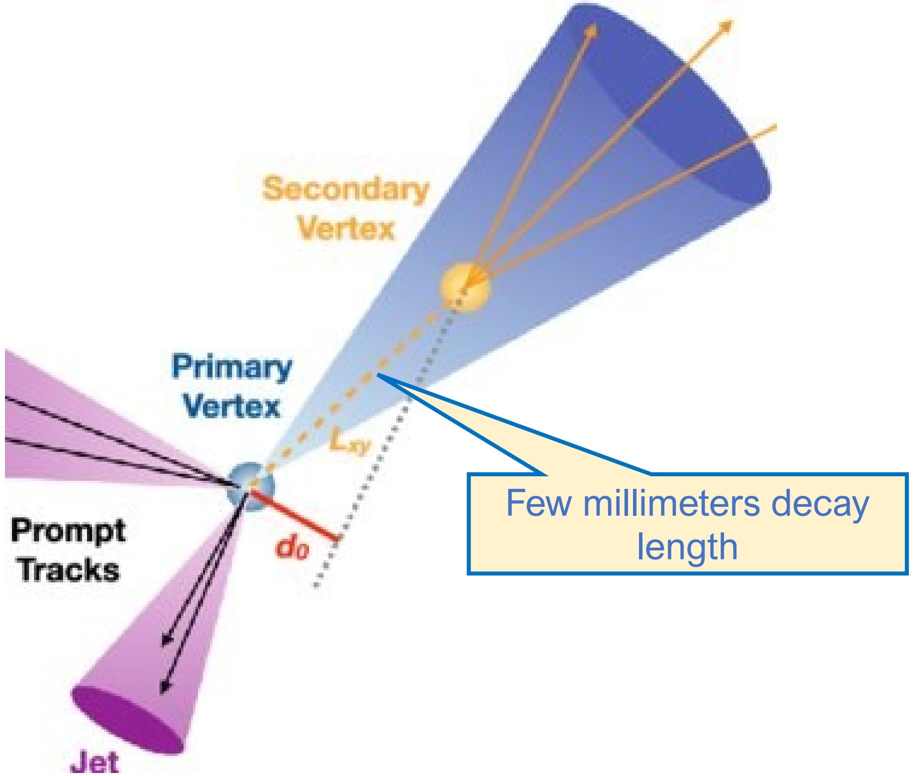
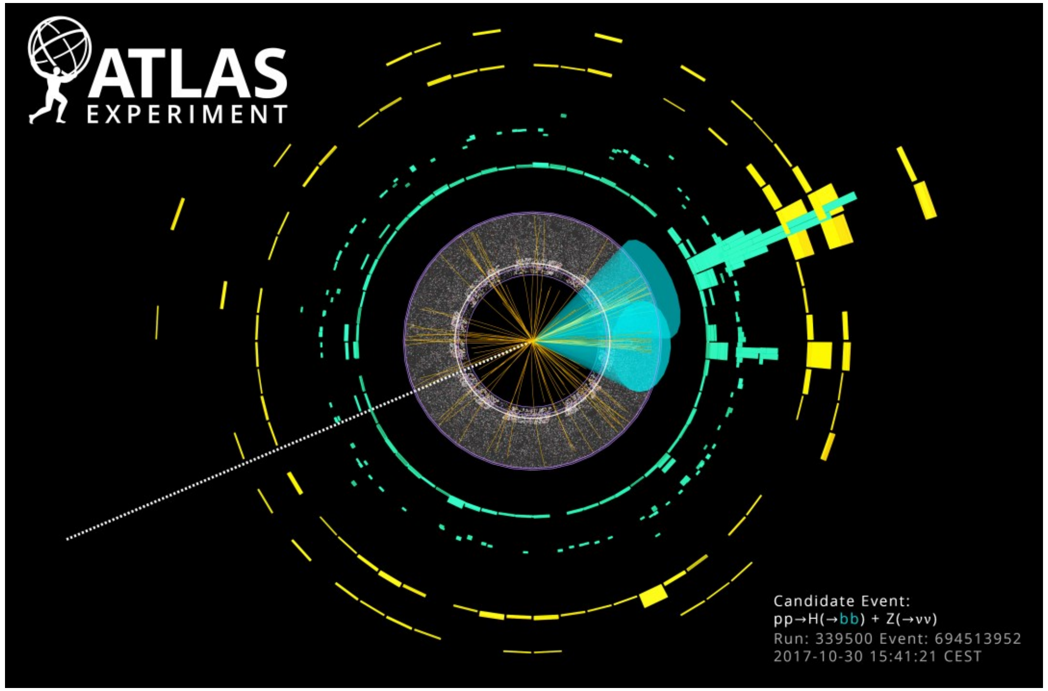
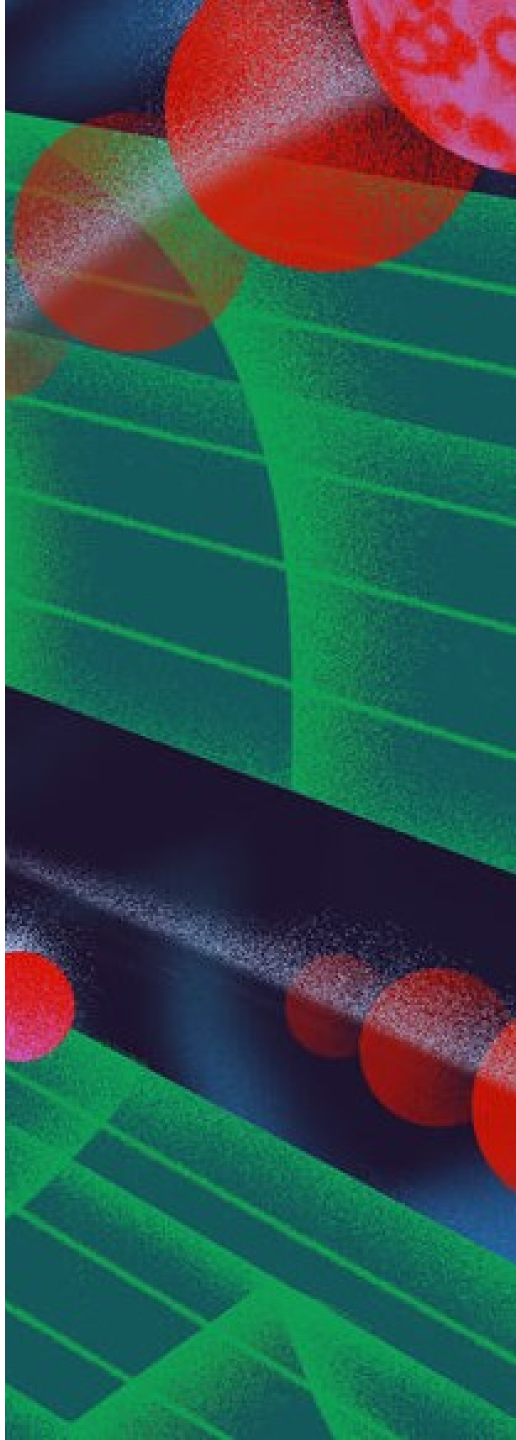




Brussels III

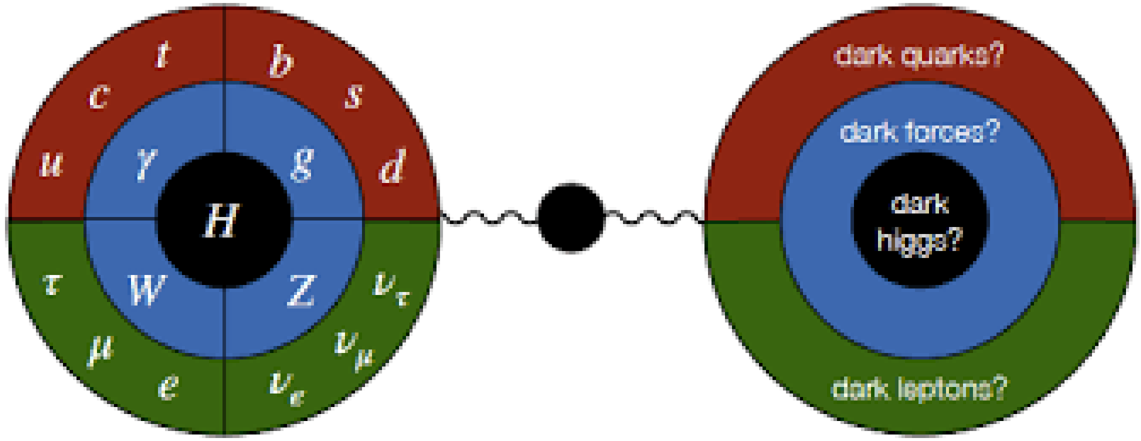
Introduction to long-lived particle



What if long-lived particles exist ?

Strong theoretical motivations underpin searches for Long Lived particles (**LLPs**)

- **Dark matter** could be part of a **larger dark sector**, parallel to the Standard Model (SM), with new particles and interactions
- If **dark quarks** could be produced at the LHC, they would undergo fragmentation and hadronisation in the dark sector resulting in characteristic "dark showers"



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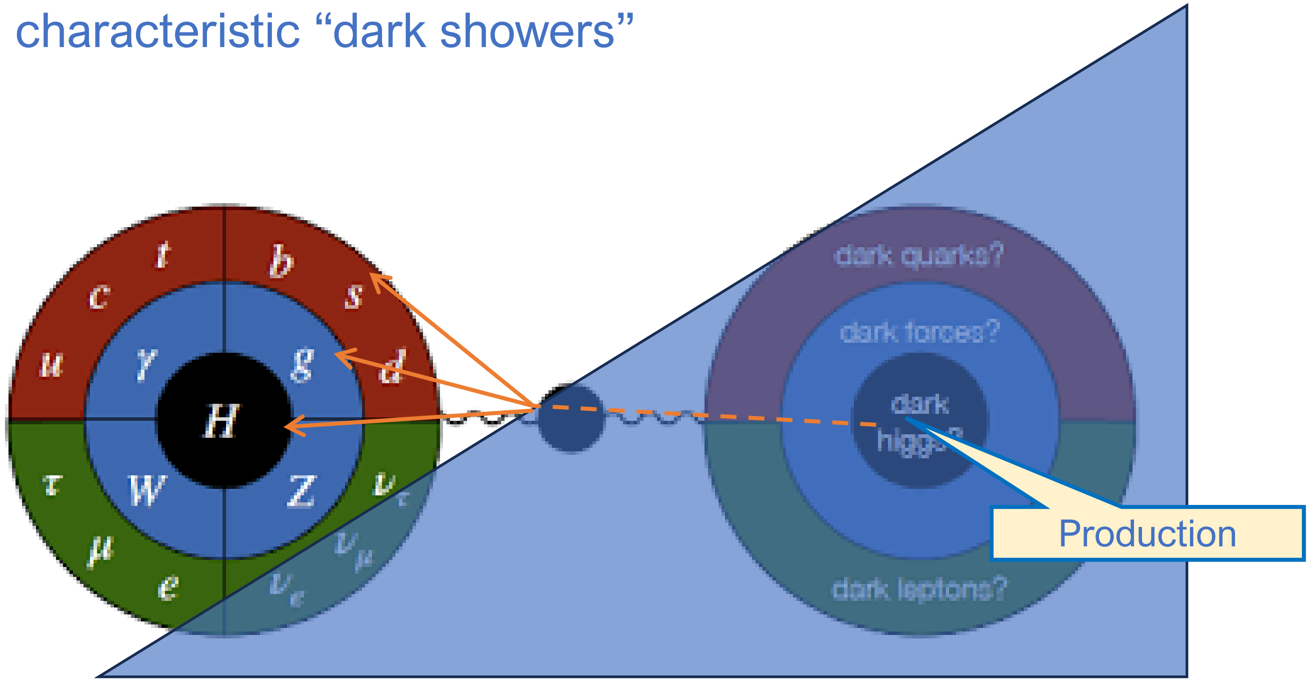
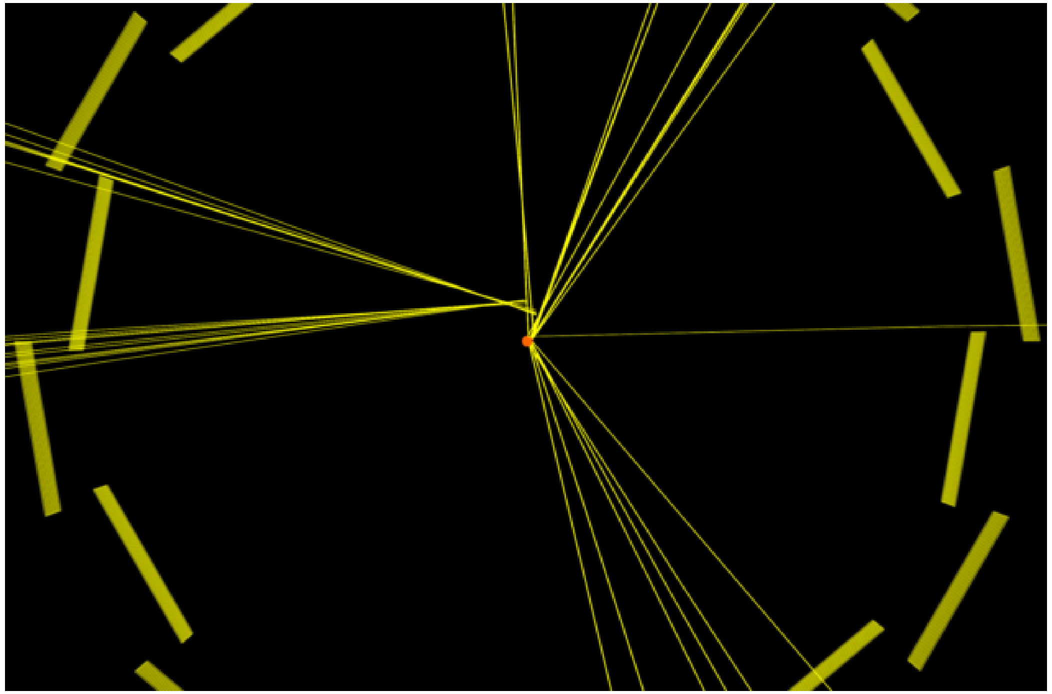


Displaced vertex

- When particles decay to quarks, they undergo a process called **hadronisation**, which leads to **sprays of collimated particles** in the ATLAS detector called jets
- If a new, neutral LLP were to decay to quarks in the outer layer of the calorimeter, it would leave behind **“displaced” jets**

- These would leave to a very unusual signature in the experiment:
  - the jets would have **no associated particle trajectories in the tracking detector**
  - would be very narrow compared to their Standard Model counterparts, since the spray of particles wouldn’t have time to become spatially separated
  - would leave a high fraction of their total energy in the hadronic part of the calorimeter



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Brussels III

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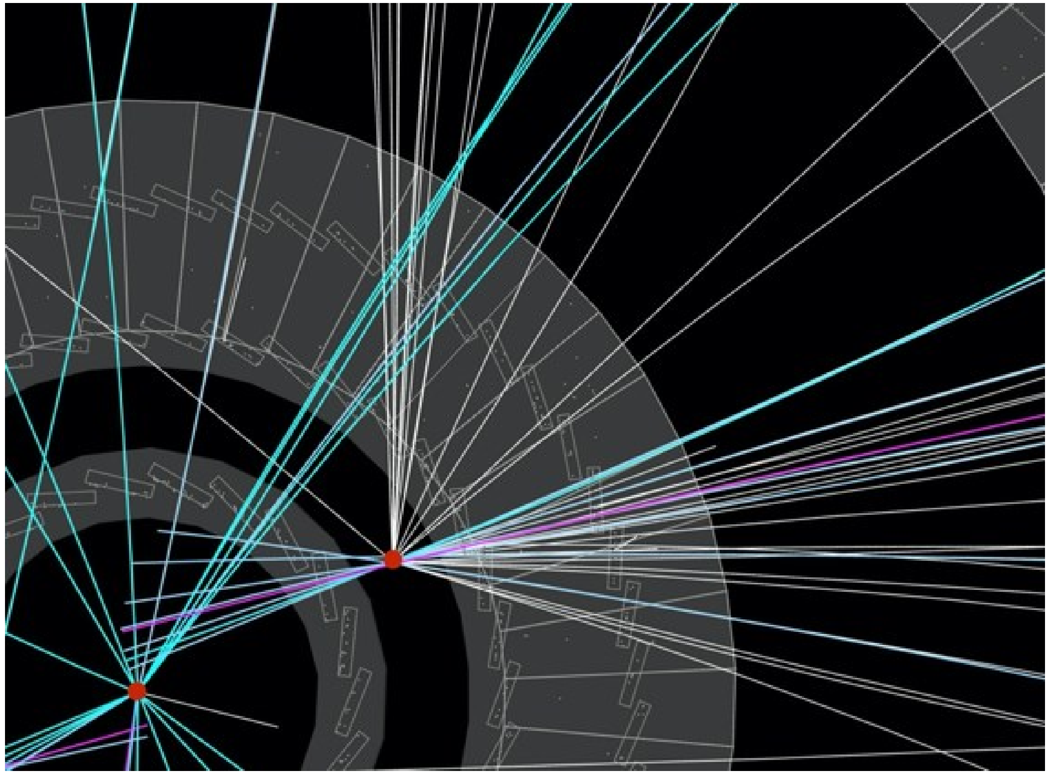

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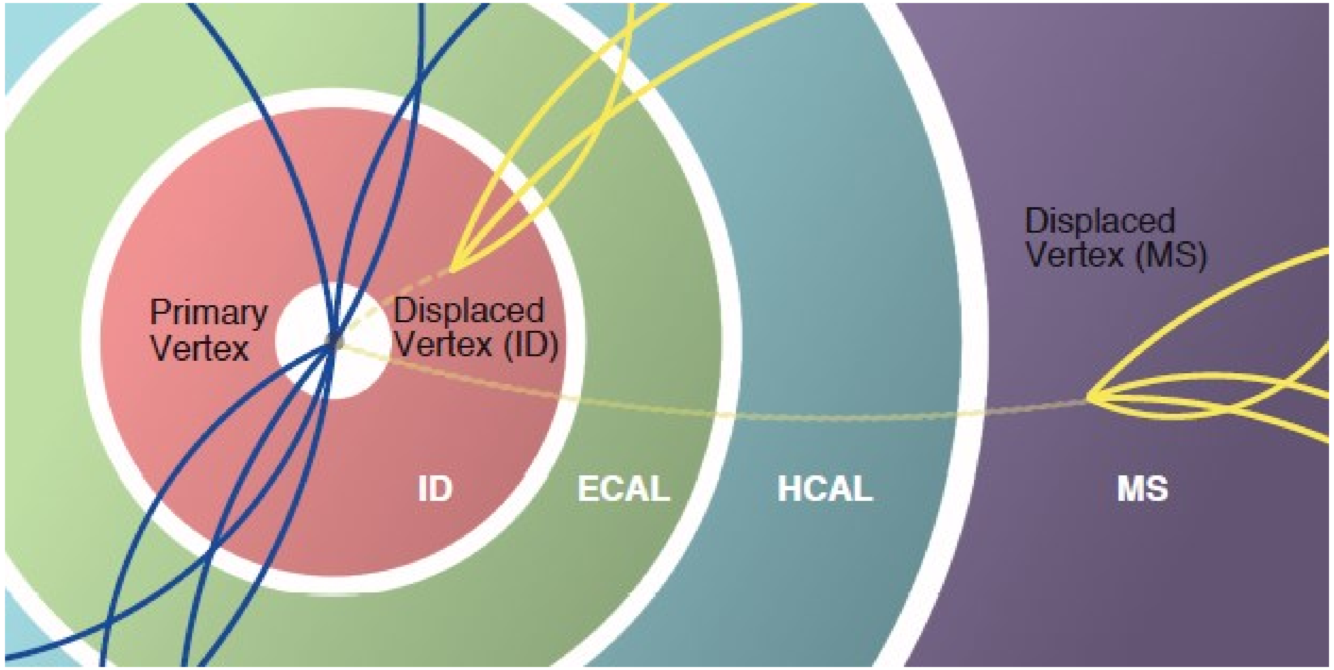
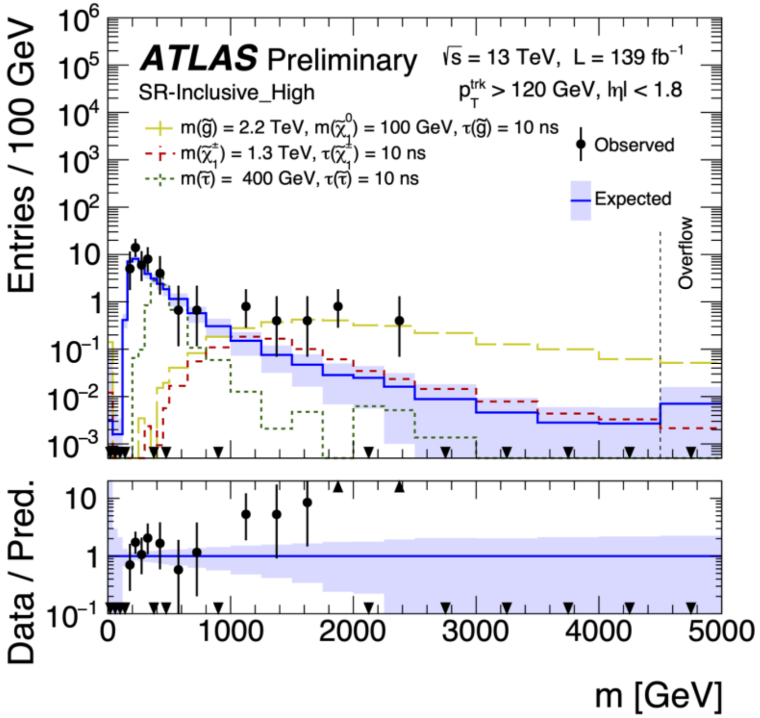
How to look for a LLP ?

Detecting LLPs at the LHC experiments requires a **paradigm shift** with respect to the usual data-analysis and trigger strategies.

- they could decay anywhere in the detector
- as the layers of the ATLAS experiment are instrumented differently, evidence of LLPs would look different depending on which layer the particle decays in (**displaced leptons**, **displaced jets**…)



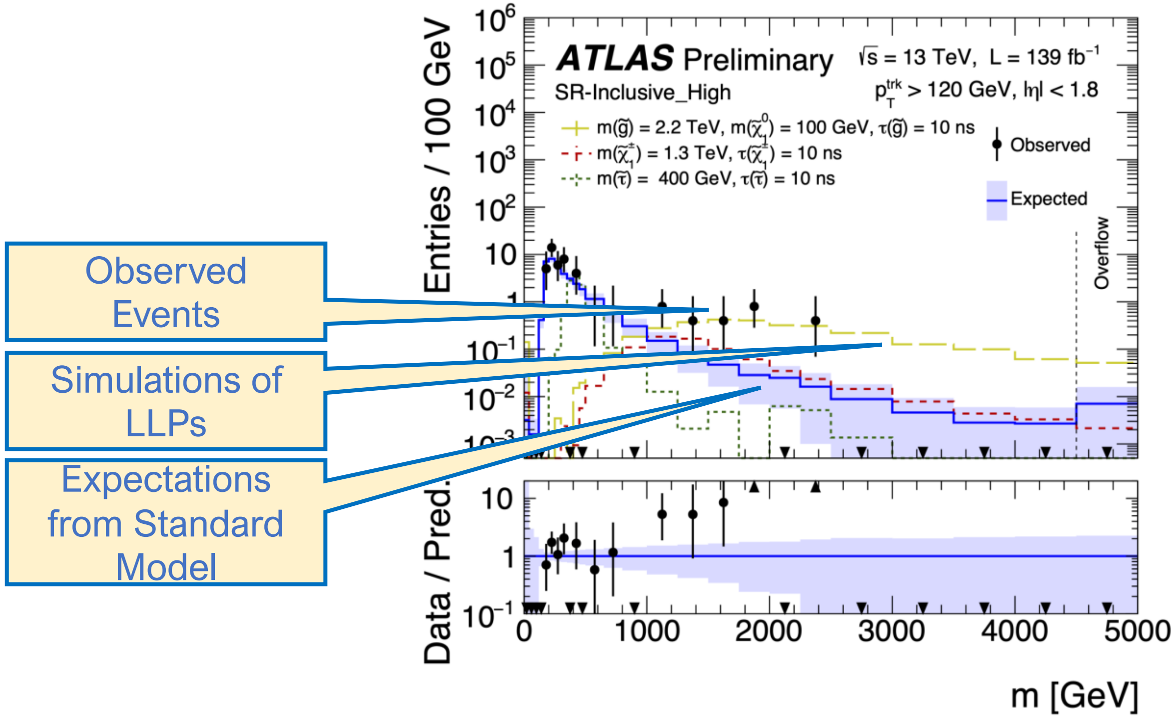


How to look for a LLP ?

Tasks such as the identification of displaced vertices and converted photons are non-trivial, and therefore, complex algorithms (including **machine learning** and **neural networks**) are usually employed.

Background processes can mimic displaced vertexes:

- **Standard Model processes** where some particle is not properly reconstructed
- interactions of the **LHC beam with material** from the accelerator itself, or with residual gas
- **Cosmic rays** interacting with detectors



How can YOU look for an LLP ?

In some cases, distinguish an **LLP signature from the background** may be easy for a human eye:

- You will try to perform this classification on a set of **Event Displays**
- This classification can be useful to **fine-tune the machine-learning algorithms**

The project today consists of three stages:

- **Stage 1:** you will identify Displaced Vertices, as the signatures of long-lived particles
- **Stage 2:** you will identify the signatures of known particles (electrons, muons, photons) in the ATLAS detector
- **Stage 3a:** you will look for a Higgs boson decaying in a pair of photons
- **Stage 3b:** you will look for long-lived particles decaying far from the beam collision point

How can YOU look for an LLP ?

- **Stage 0:** have a break first…