INTERNATIONAL
MASTERCLASSES

hands on particle physics

Particle detection, event displays and analysis

March 2024 - Halil Saka, Fotios Ptochos

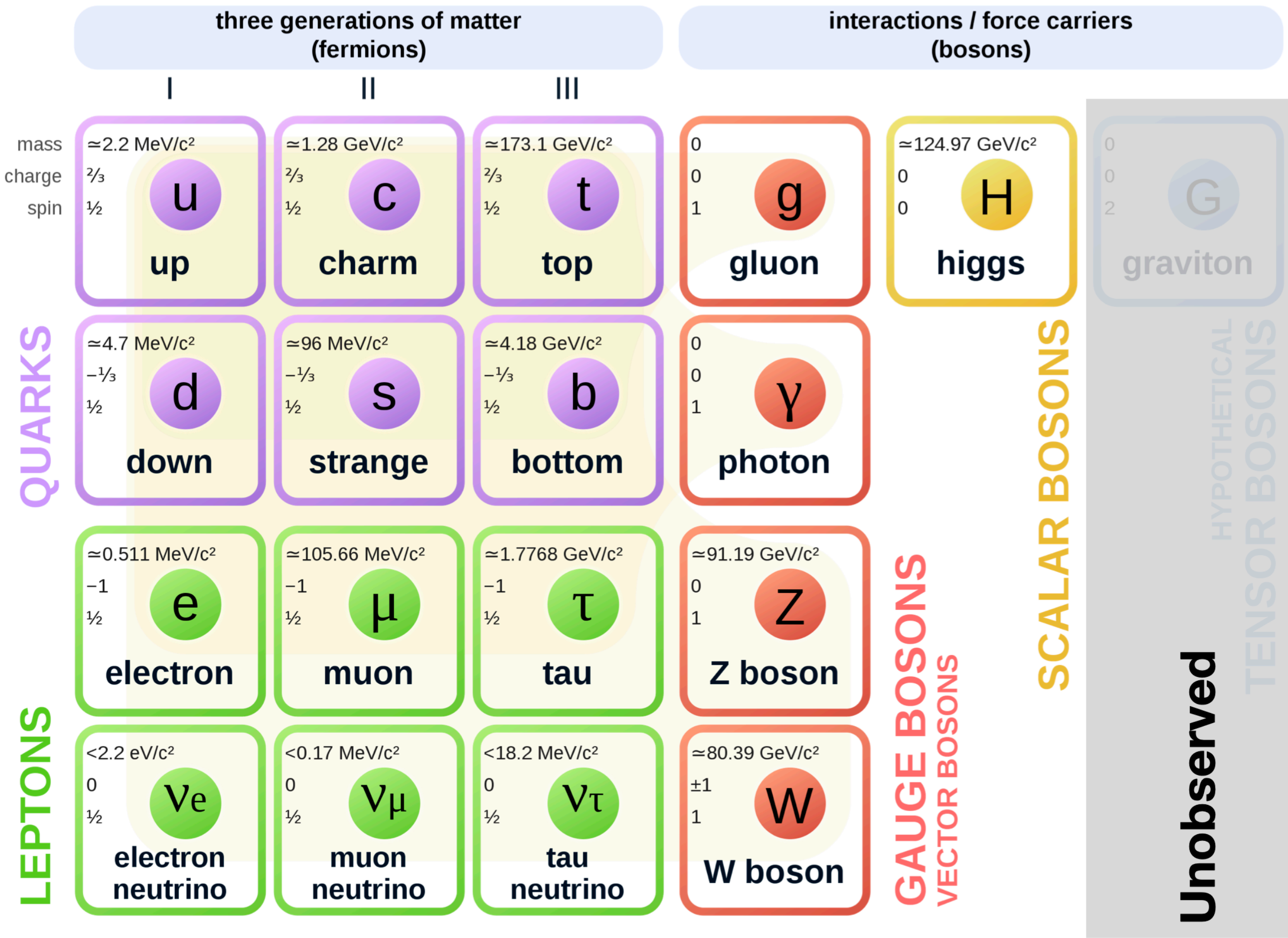
CERN

International Particle Physics Outreach Group

University of Cyprus

The periodic table of particles

Hadrons
Baryons (3q)
Mesons (2q)



- Hadronically (strong force) interacting particles: all quarks (via gluons)
- Electromagnetically interacting particles: all particles with electric charge (via photons)
- How many of these particles are stable? Observable?

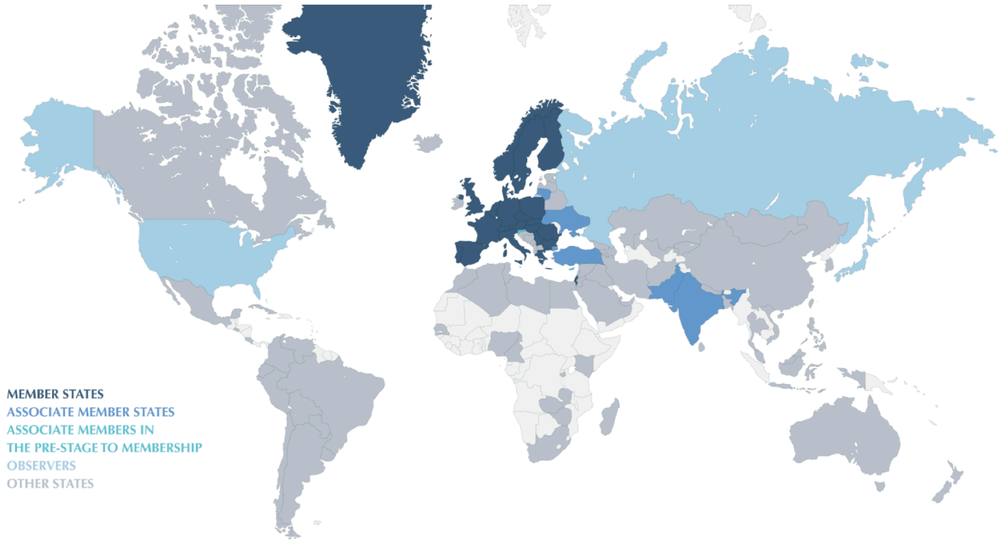
https://en.wikipedia.org/wiki/Physics_beyond_the_Standard_Model

What is CERN?

- European Council for Nuclear Research (*Conseil Européen pour la Recherche Nucléaire)* **CERN** has been founded in 1952.

- Today, our understanding of matter goes much deeper than the nucleus, and CERN's main area of **research is particle physics**. Because of this, the laboratory operated by CERN is often referred to as the **European Laboratory for Particle Physics**.

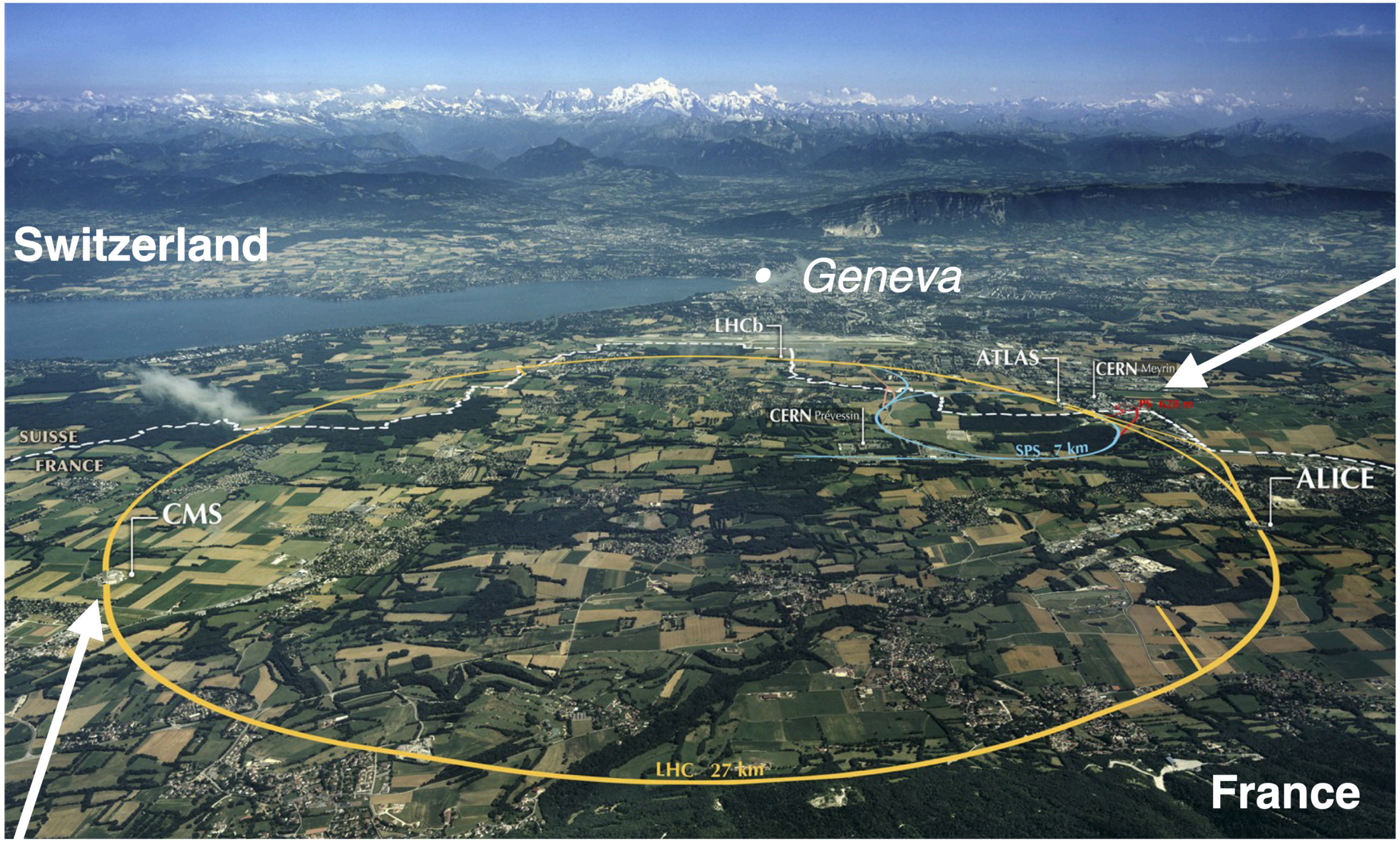
- Today (since 2008) CERN is the **host laboratory** of the **Large Hadron Collider** (LHC) and the **experiments** (**detectors**) on it, including the **CMS** detector.



- We will discuss the LHC later on.

What is the LHC?

- The **Large Hadron Collider** is a particle **accelerator and collider** that pushes protons (or ions) to near the speed of light.
- It sits about **100m underground** and consists of a **27-km ring of superconducting magnets**.
- It holds **two beams of protons traveling in opposite directions**



https://www.washington.edu/news/2019/03/05/faser-detector-lhc/

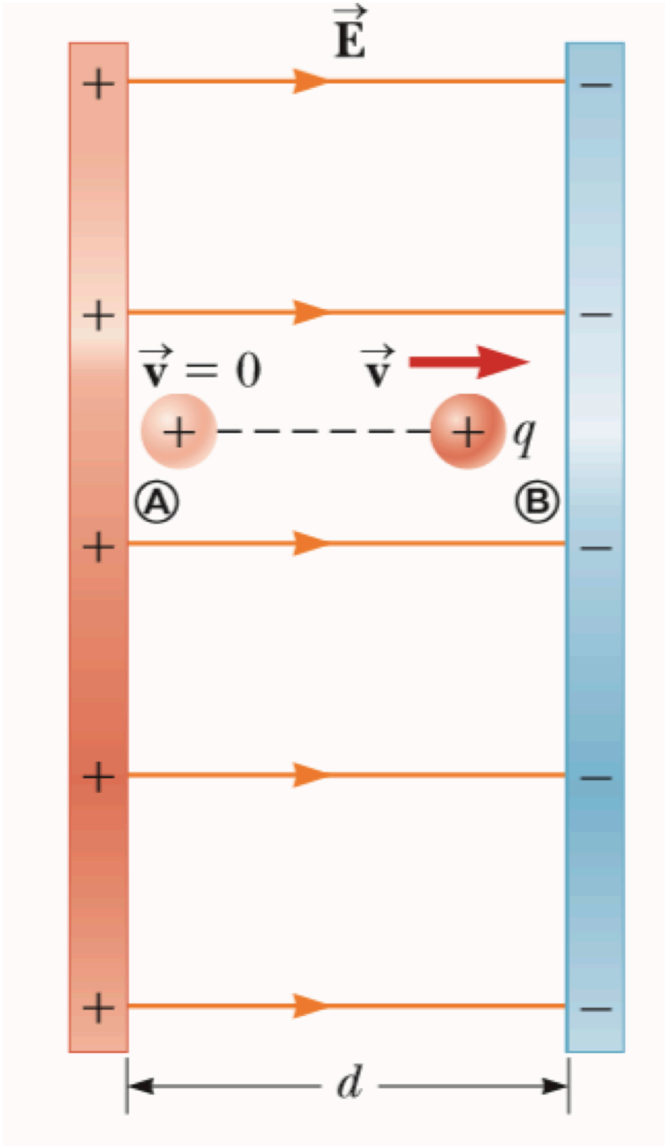
Quick reminder of the Lorentz Force

$$F_{Lorentz} = q\overrightarrow{E} + q\vec{v} \times \overrightarrow{B}$$

$$F = qE = ma$$

$$U = q\Delta V$$

$$K = \frac{1}{2}mv^2$$



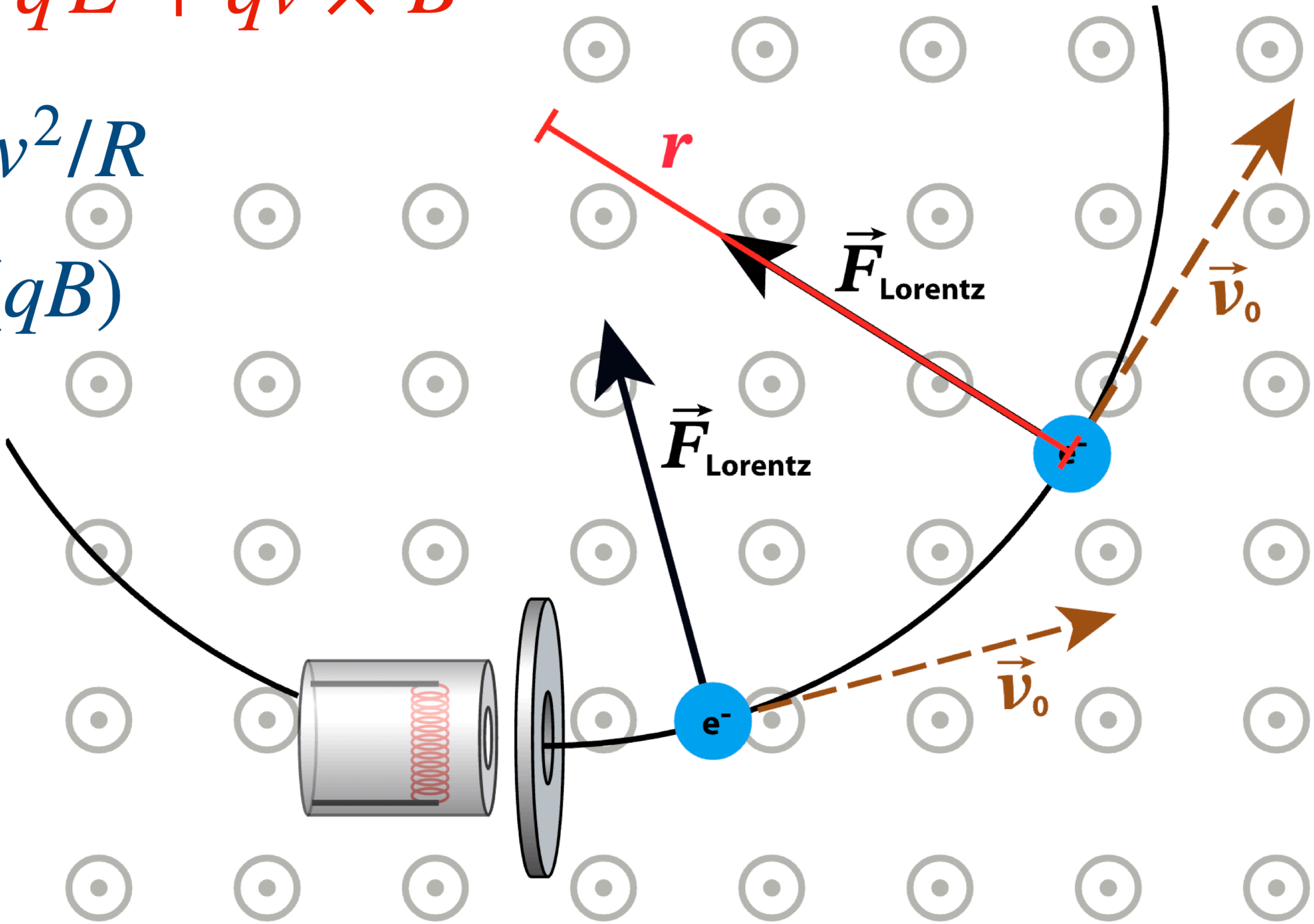
ΔV

Quick reminder of the Lorentz Force

$$F_{Lorentz} = q\vec{E} + q\vec{v} \times \vec{B}$$

$$qvB = mv^2/R$$

$$R = mv/(qB)$$

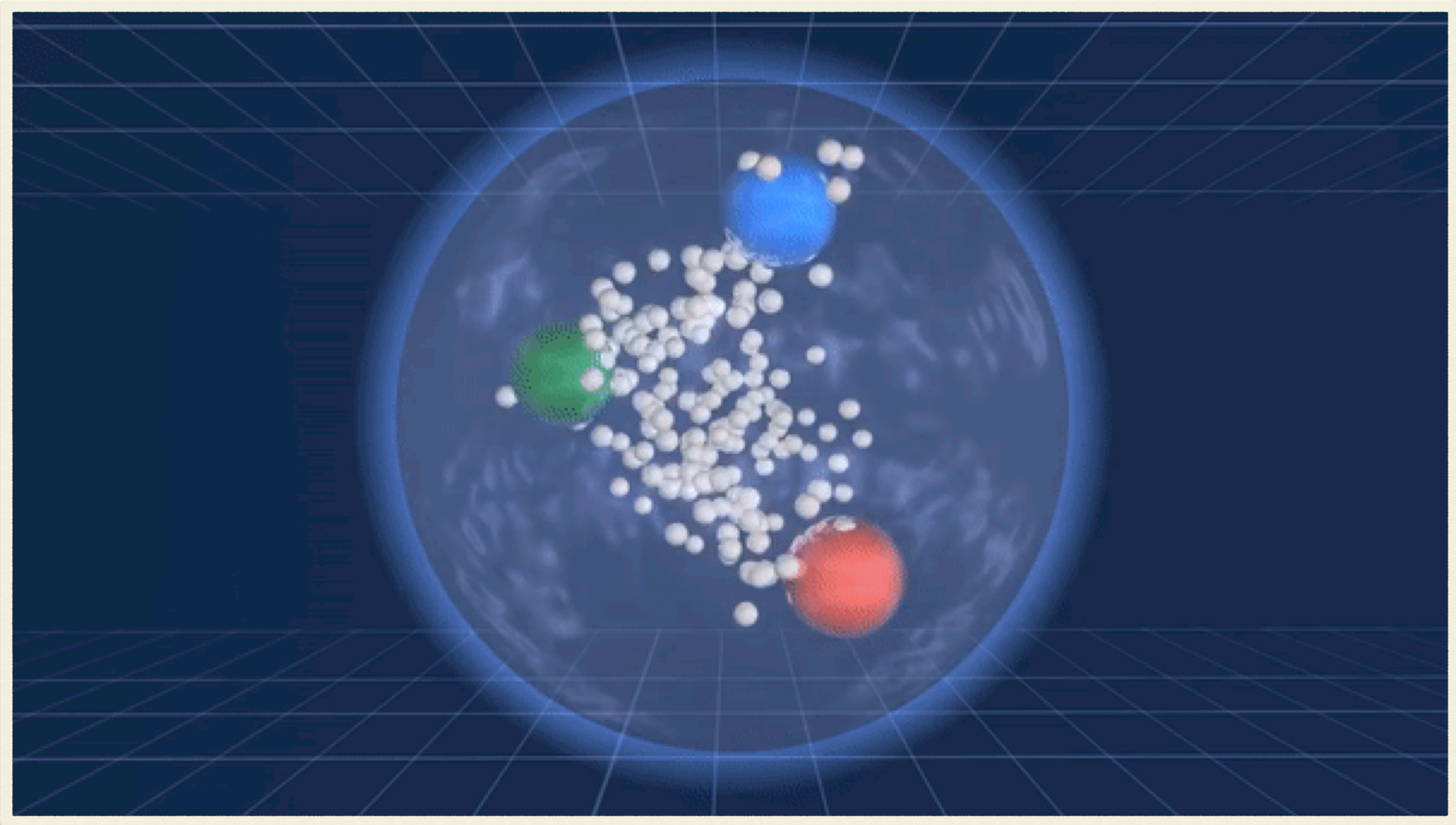


https://virtuelle-experimente.de/en/b-feld/b-feld/kraefte.php

What does the LHC do?

https://youtu.be/pQhbhpU9Wrg

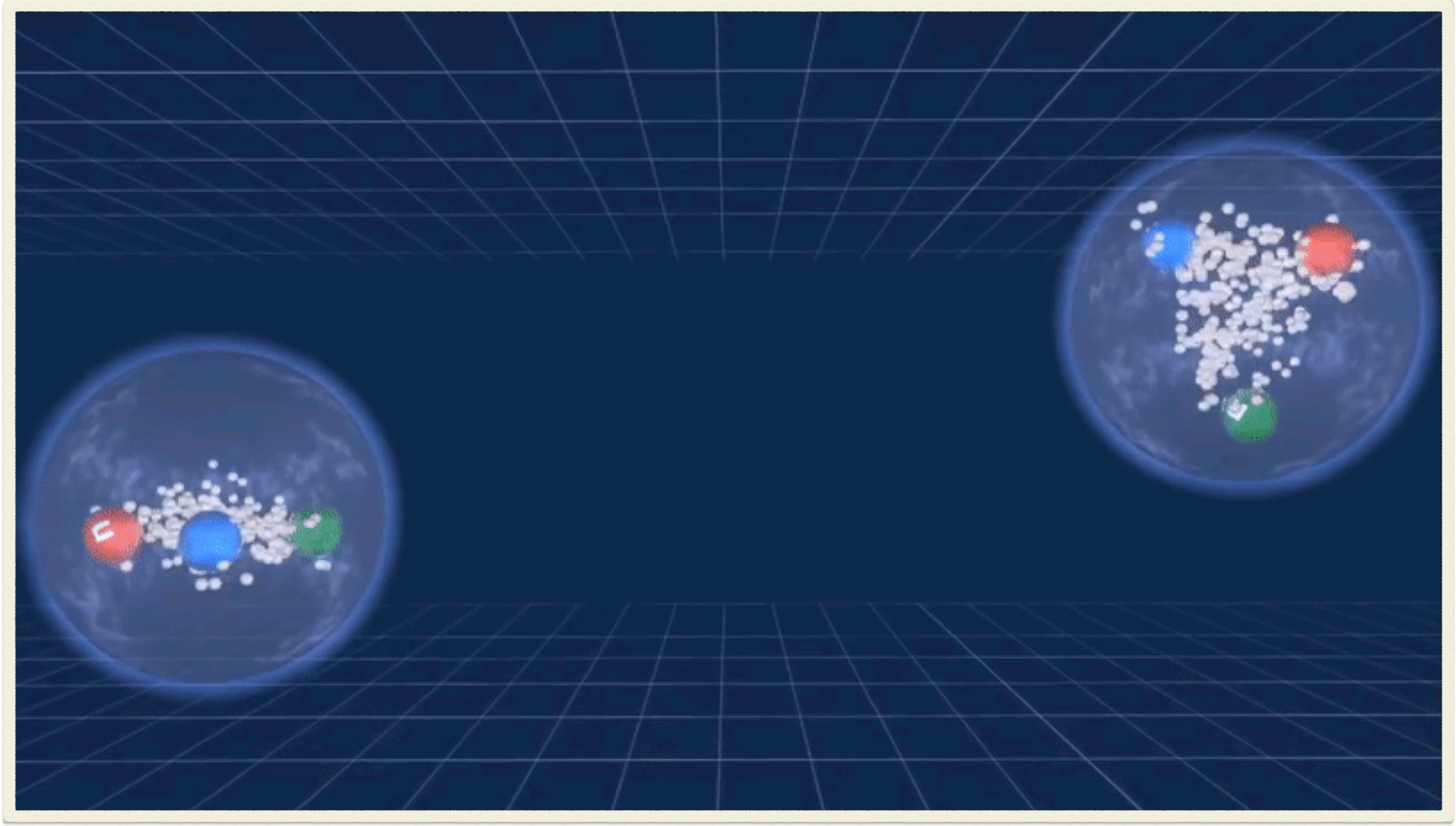
Colliding protons to produce a Z boson



$E = mc^2$ *and quantum mechanics at work!*

https://youtu.be/7HpQGR1gjXk

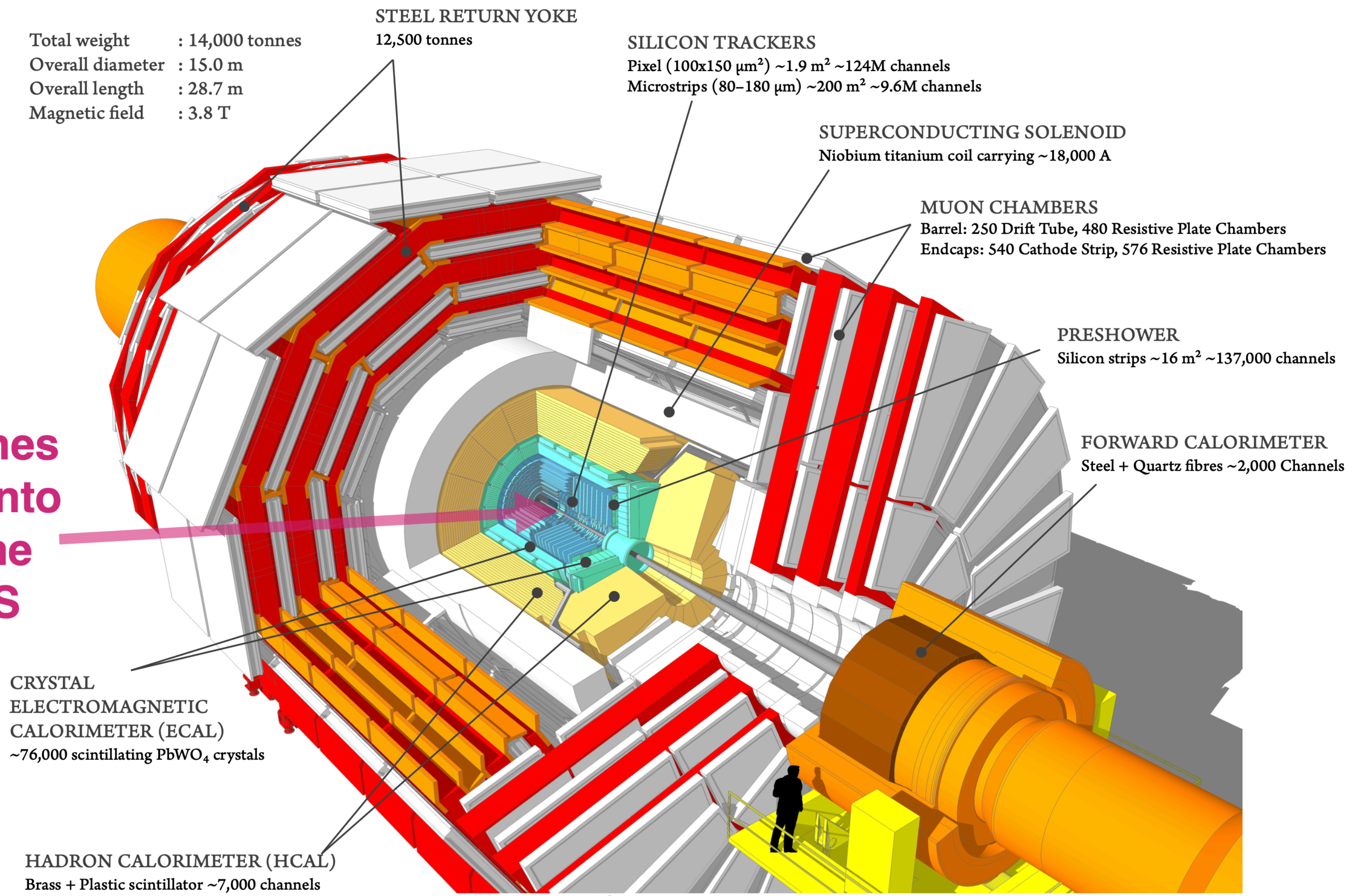
Colliding protons to produce an H boson



https://youtu.be/wZpfHzlhuzg

What is CMS?

- **Compact Muon Solenoid** is a multi-purpose **particle detector** at the Large Hadron Collider (LHC) at CERN.
- It is the name of the collaboration (group), and the experiment (apparatus).

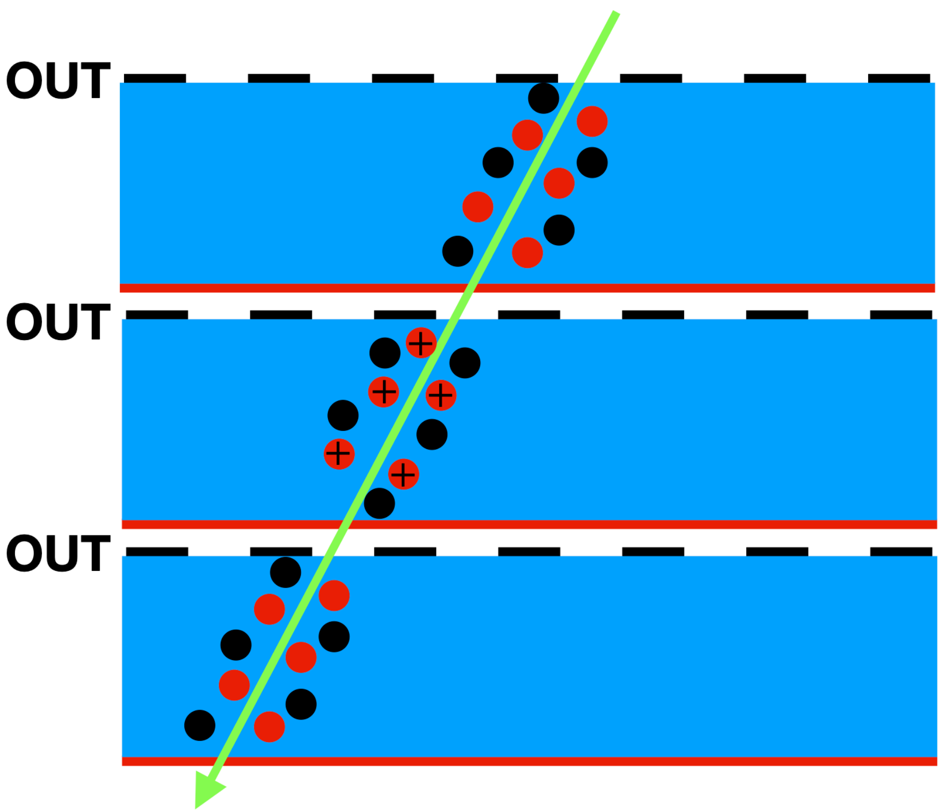


Proton bunches are brought into collision at the center of CMS

http://cds.cern.ch/record/2665537

Particle detectors: Tracking vs Calorimetry

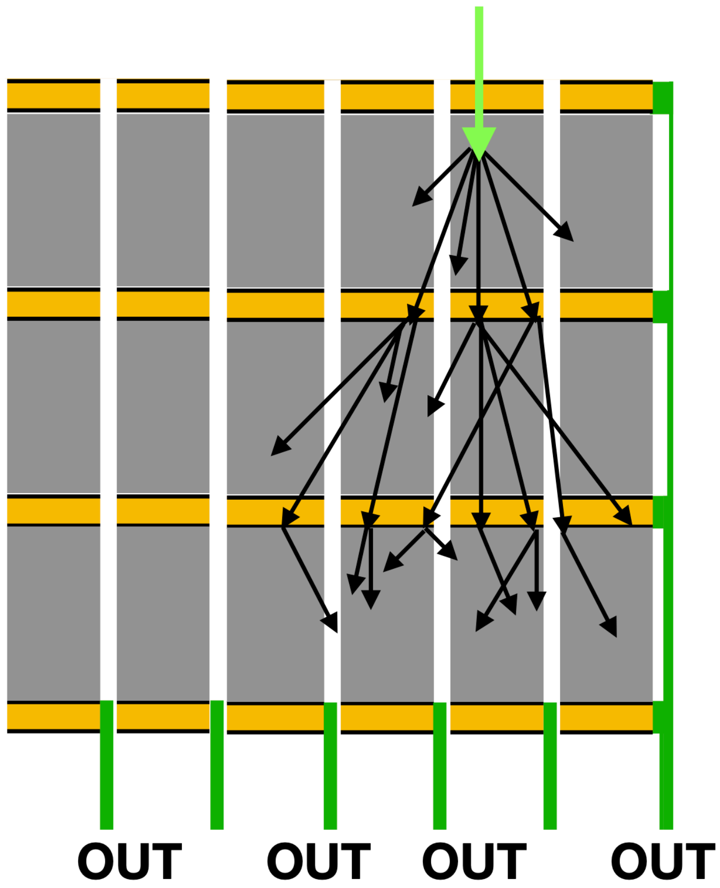
A typical tracker



Green: Incoming particle

Particle produces small signals to indicate its path

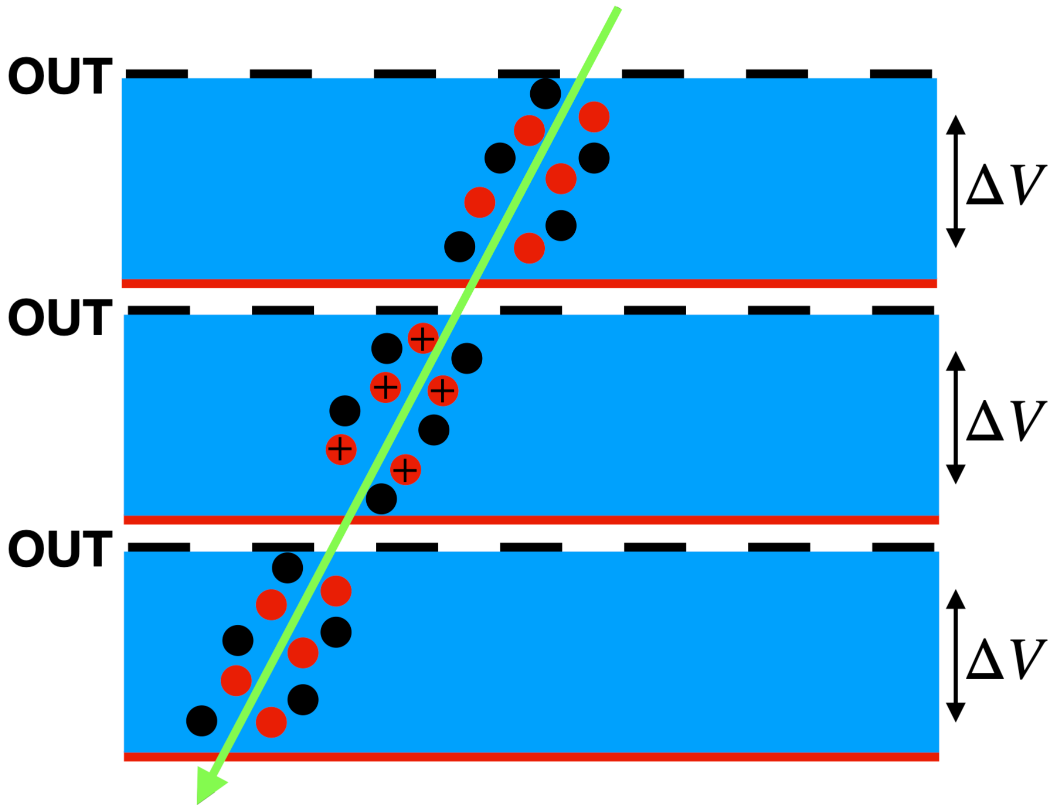
A typical calorimeter



Green: Incoming particle

Particle is fully absorbed to measure its energy

Particle detectors: A typical tracker

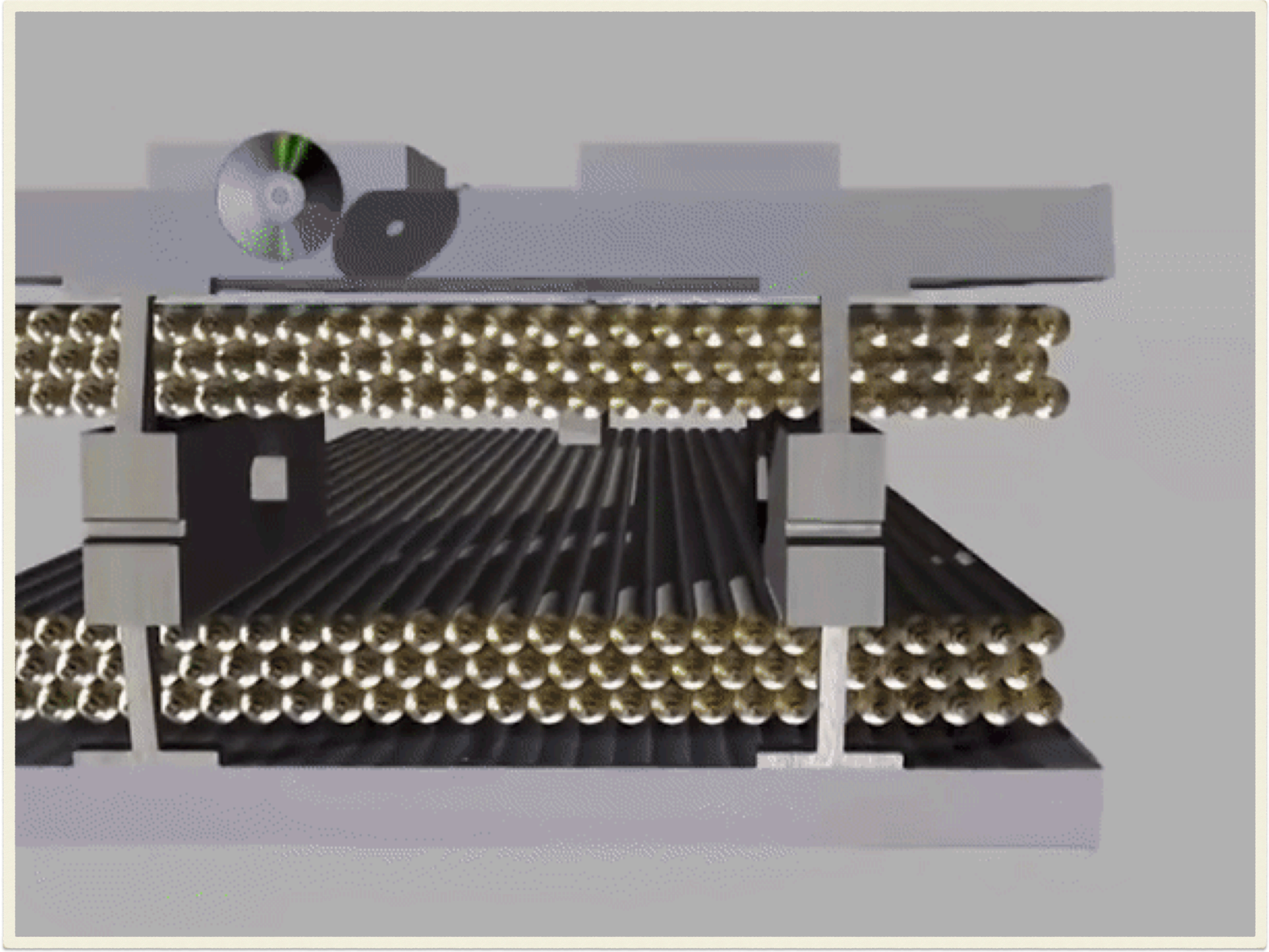


A typical tracker

- **Particle in, particle out**
- Typical "spacing" is $\sim 100\mu$m - 1mm
- Typical materials: silicon, noble gasses, etc.
- **Charged** particles only, needs to **ionize** the active material.
- Output: electrical

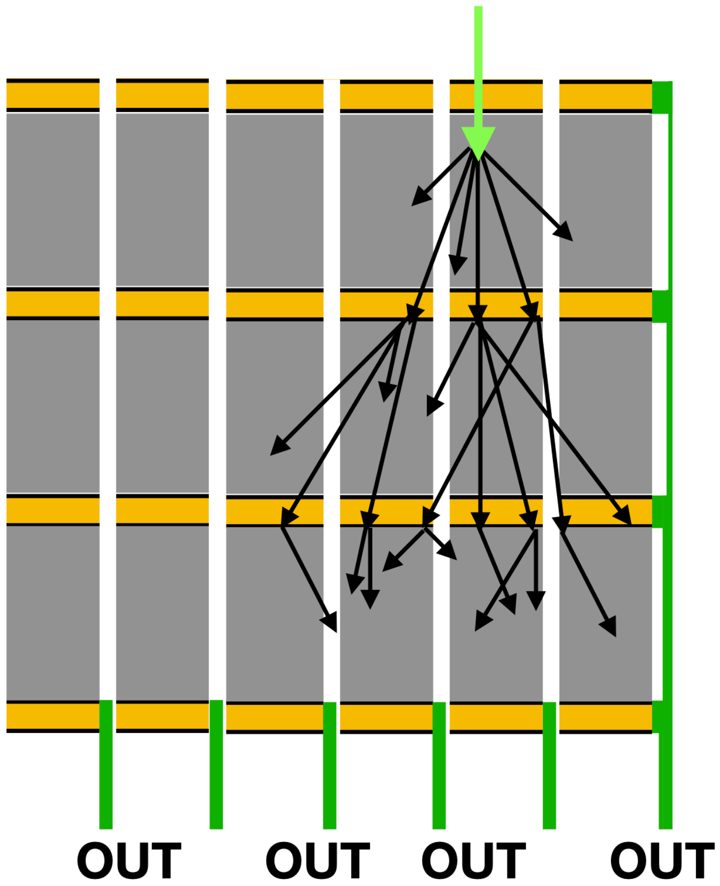
ionize: split electrons from nucleus.

Particle detectors: A typical tracker



https://youtu.be/A8L2RtvEKok

Particle detectors: A typical calorimeter



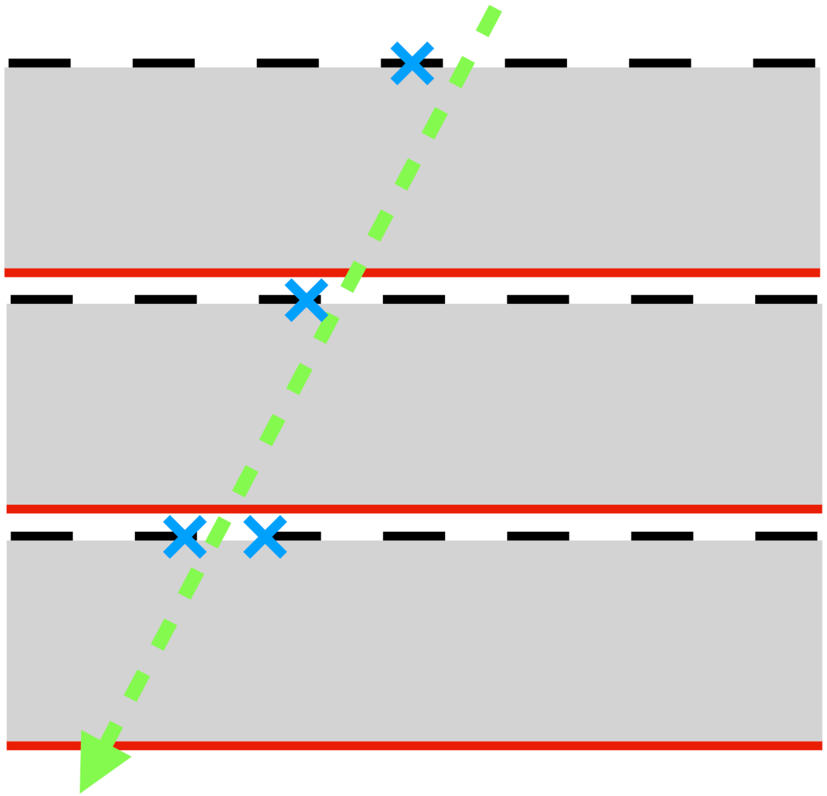
A typical calorimeter

- Particle is **absorbed**.
- Typical "spacing" is $\sim$ 2cm - 20cm
- Typical material: Scintillator, high density material
- **Charged or neutral** particles (but must **interact** with the **high density** material)
- Output: light $\rightarrow$ electrical.

Scintillate: emit light at a characteristic frequency upon de-excitation of valence electrons.

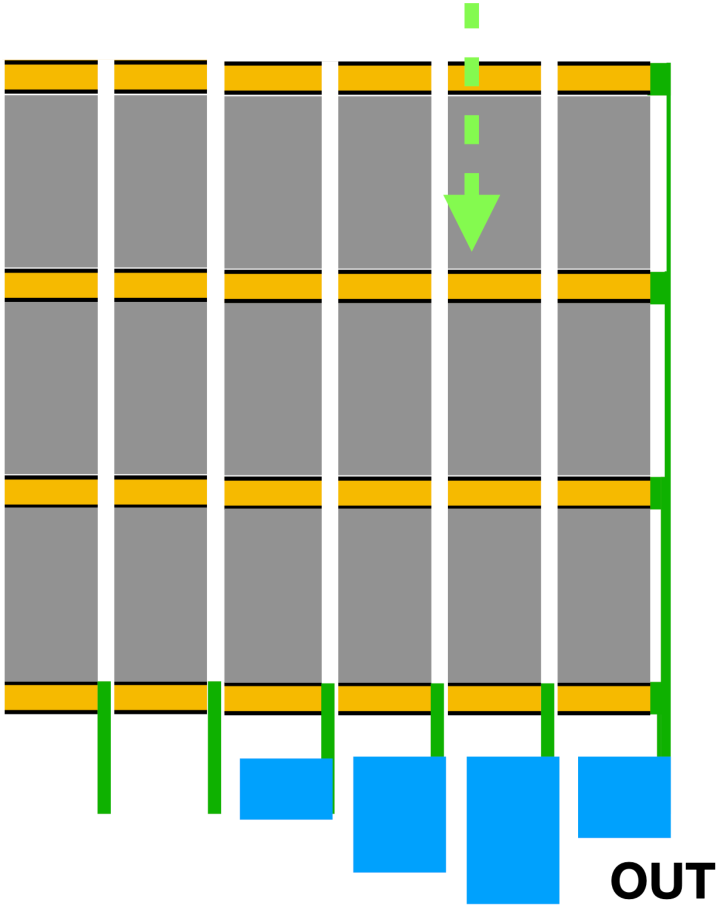
Particle detectors: Tracking vs Calorimetry

A typical tracker



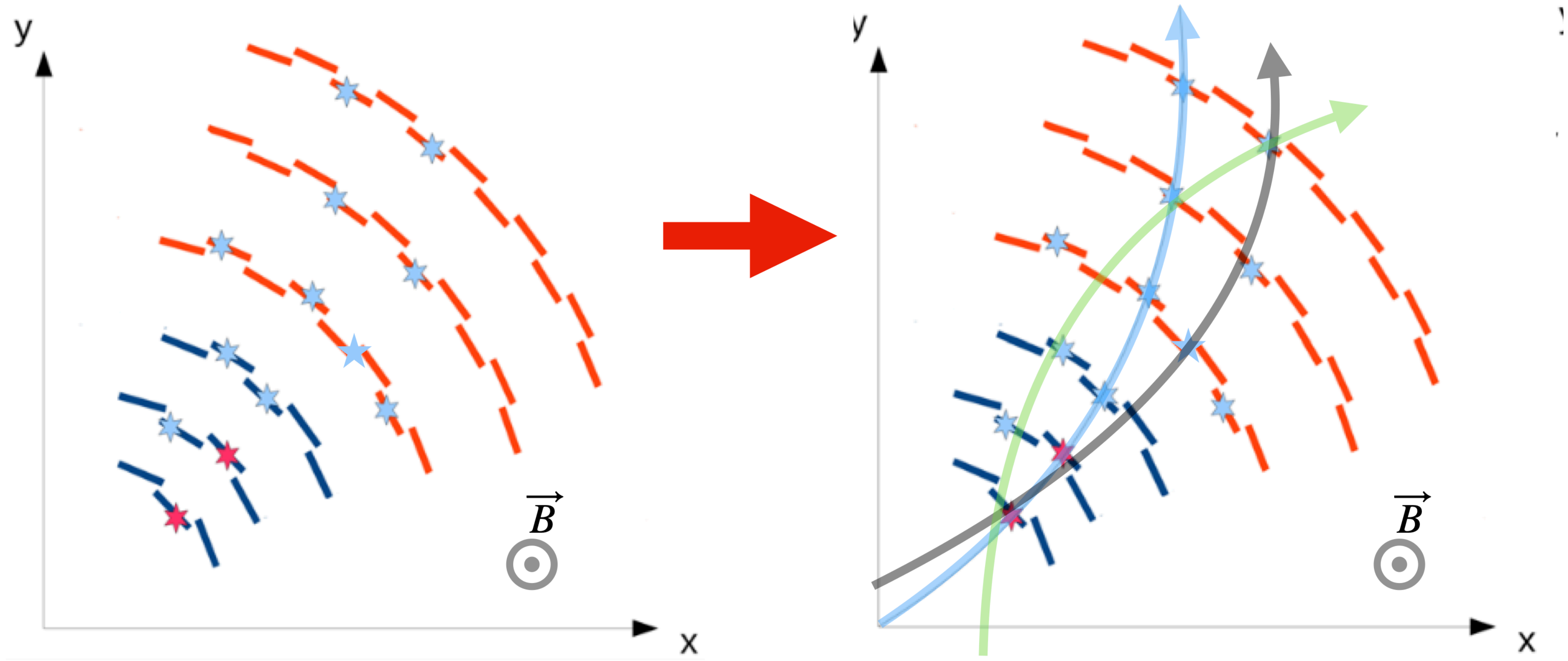
Blue: Information readout from detector
Next task: Connecting the “dots”

A typical calorimeter



Blue: Information readout from detector
Next task: Clustering (grouping) the dots

Particle detectors: Connecting the dots

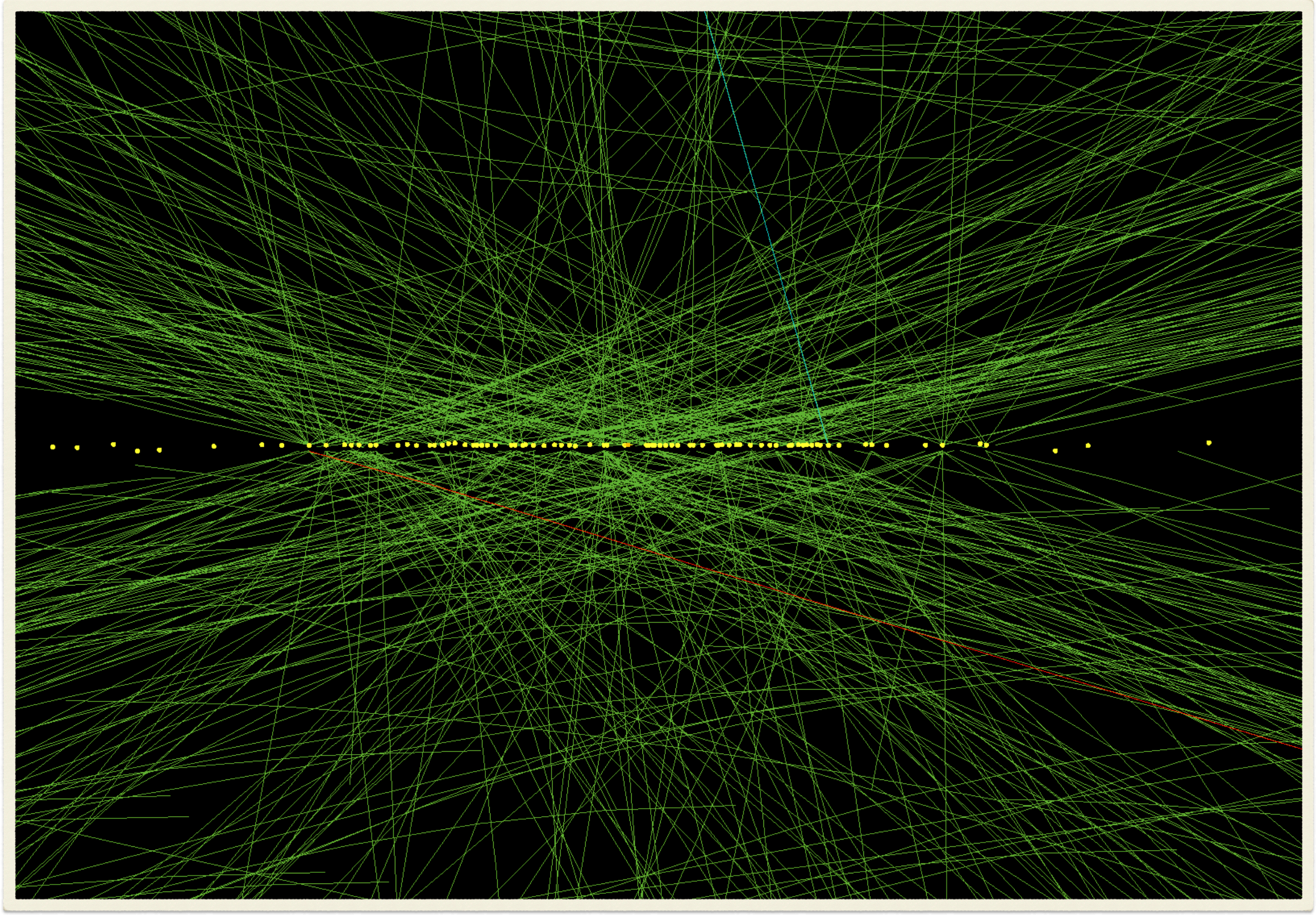


Each star indicates a "hit" in the tracker layer

Which curve is correct?

https://iopscience.iop.org/article/10.1088/1126-6708/2008/04/063
https://www.epj-conferences.org/articles/epjconf/pdf/2017/19/epjconf_ctdw2017_00016.pdf
https://www.quantumdiaries.org/2011/06/01/anatomy-of-a-jet-in-cms/

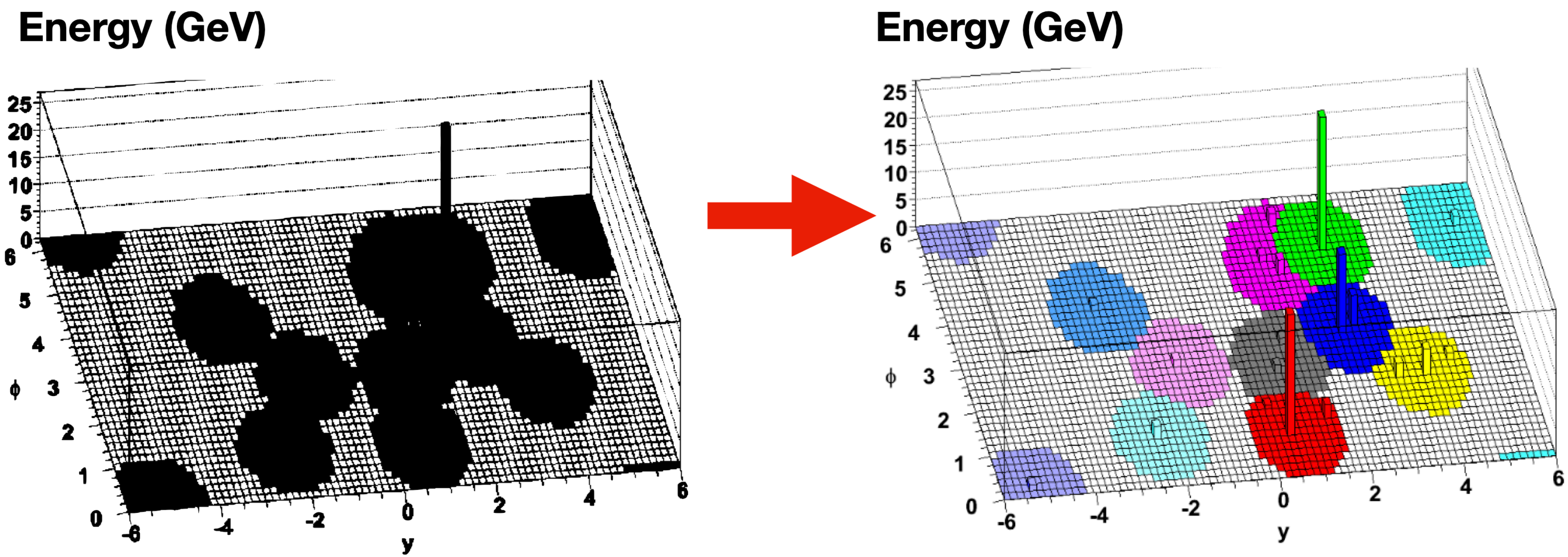
Tracking in real life



http://cms.web.cern.ch/news/reconstructing-multitude-particle-tracks-within-cms

Particle detectors: Clustering the dots

- It is a lot of effort to correctly disentangle and identify observed signal in a detector. The process is known as **reconstruction.**

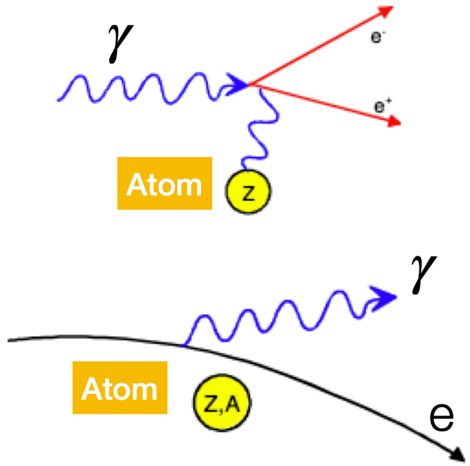


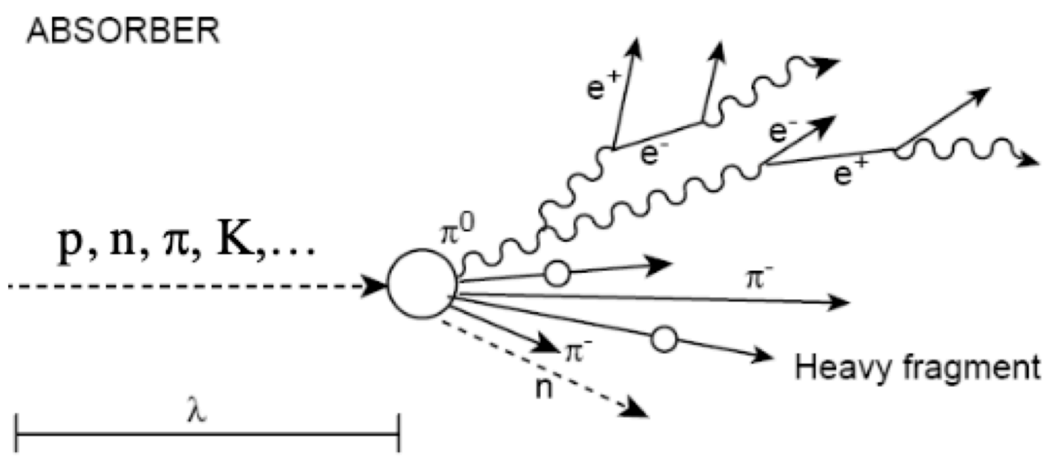
Is the cluster correct?

https://iopscience.iop.org/article/10.1088/1126-6708/2008/04/063
https://www.epj-conferences.org/articles/epjconf/pdf/2017/19/epjconf_ctdw2017_00016.pdf
https://www.quantumdiaries.org/2011/06/01/anatomy-of-a-jet-in-cms/

Electromagnetic vs Hadronic interactions

Pair production



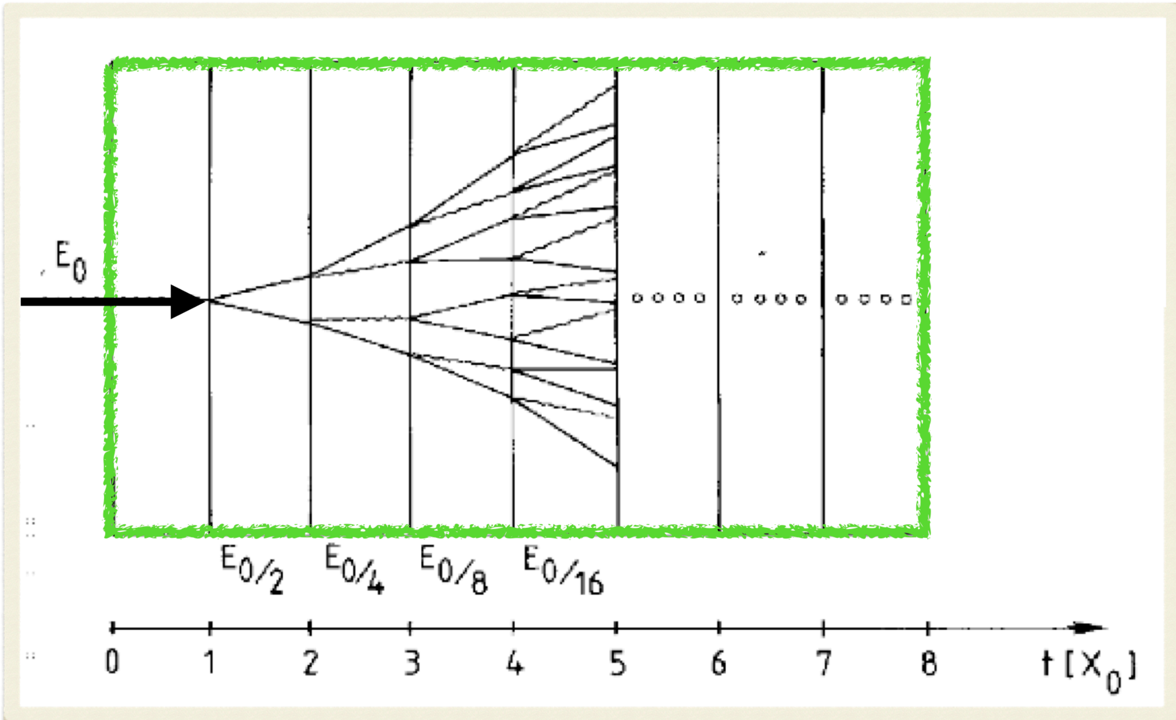


EM

Bremsstrahlung radiation length

$$-\frac{dE}{dx} \sim \frac{AZ^2E}{m^2}$$

Less depth is sufficient



HAD

nuclear interaction length

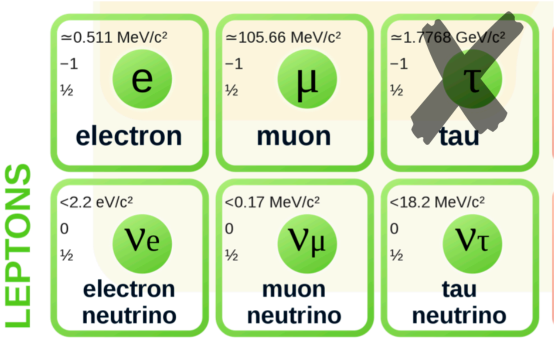
$$-\frac{dE}{dx} \sim A^{1/3}E$$

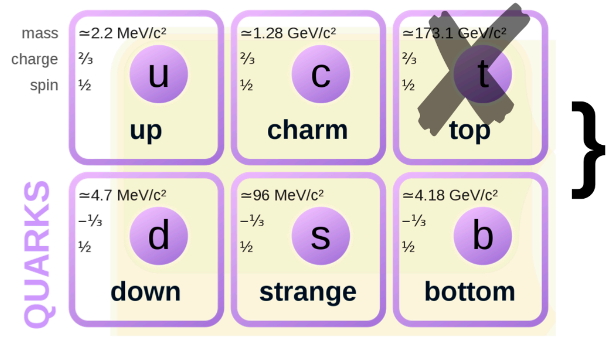
More depth is needed

https://indico.cern.ch/event/518474/contributions/1198681/attachments/1267581/1877122/Calorimetry-lecture-to-Southampton-students-4May2016-Cockerill-compressed.pdf

Identifying particles in CMS

Electromagnetic interactions





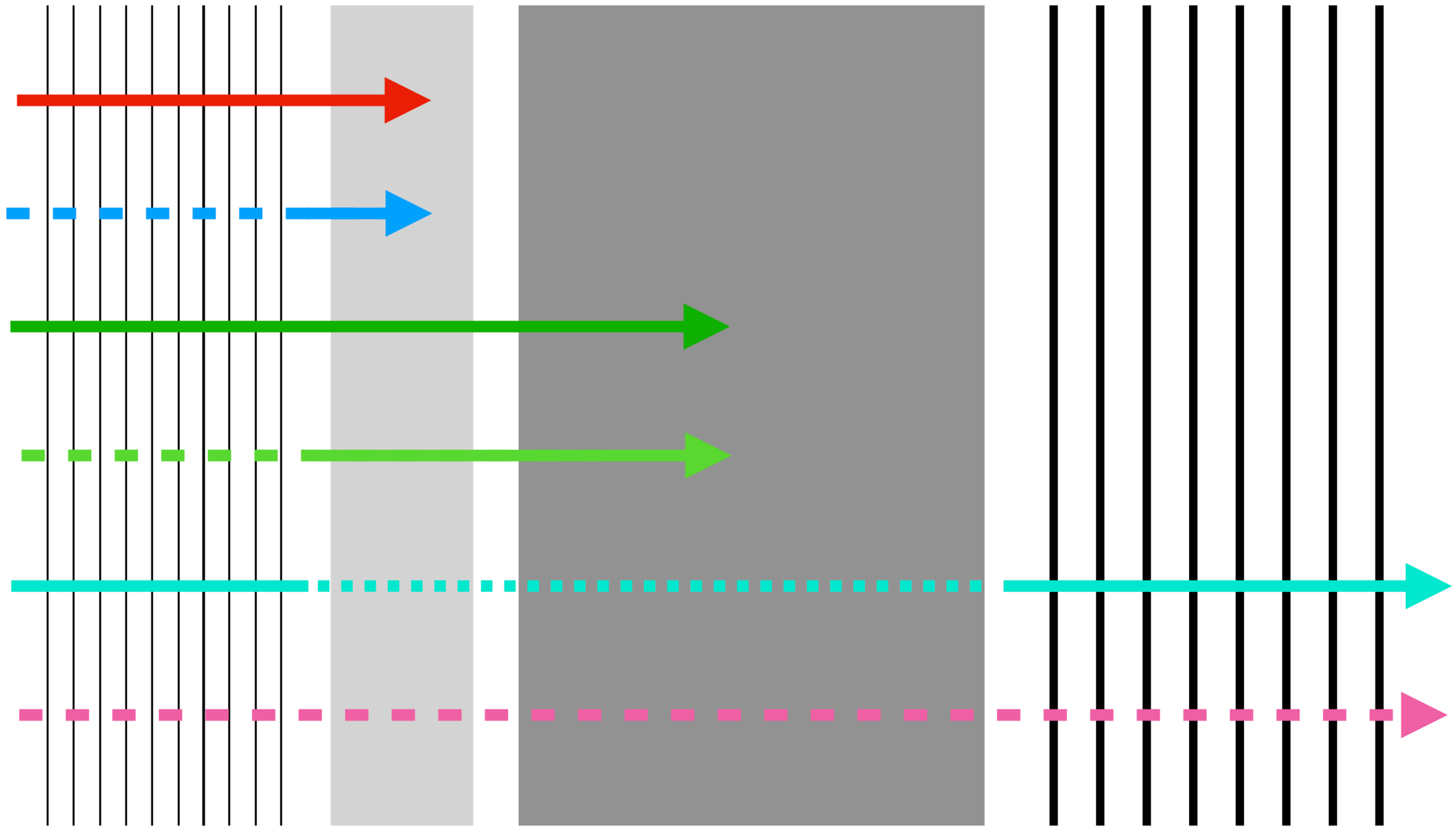
$\pi, p, n, K, ..$

Strong force (Hadronic) Interactions

Tracker

Calorimeters

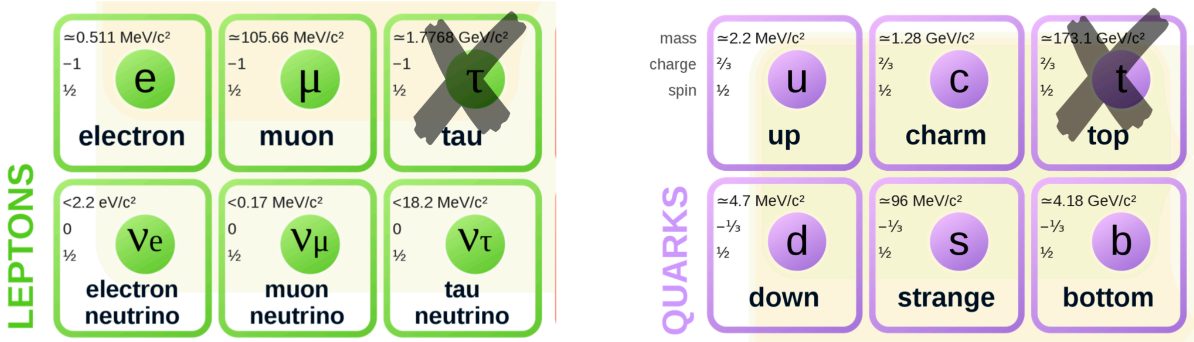
Tracker



?

Where you stop is what you are!

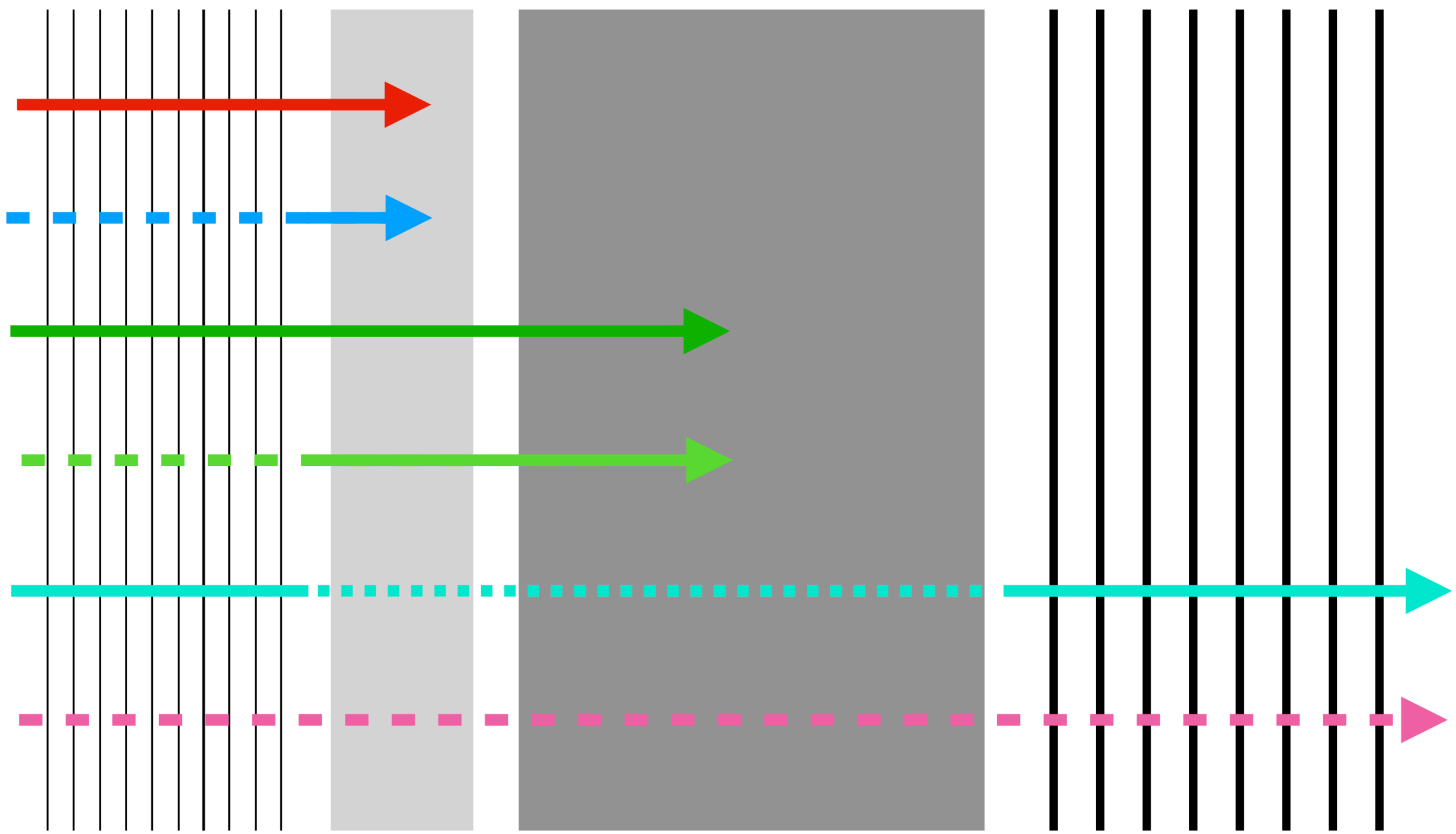
Electromagnetic interactions



} $\pi, p, n, K, ..$

Strong force (Hadronic) Interactions

Tracker | Calorimeters | Tracker



Electron

Photon

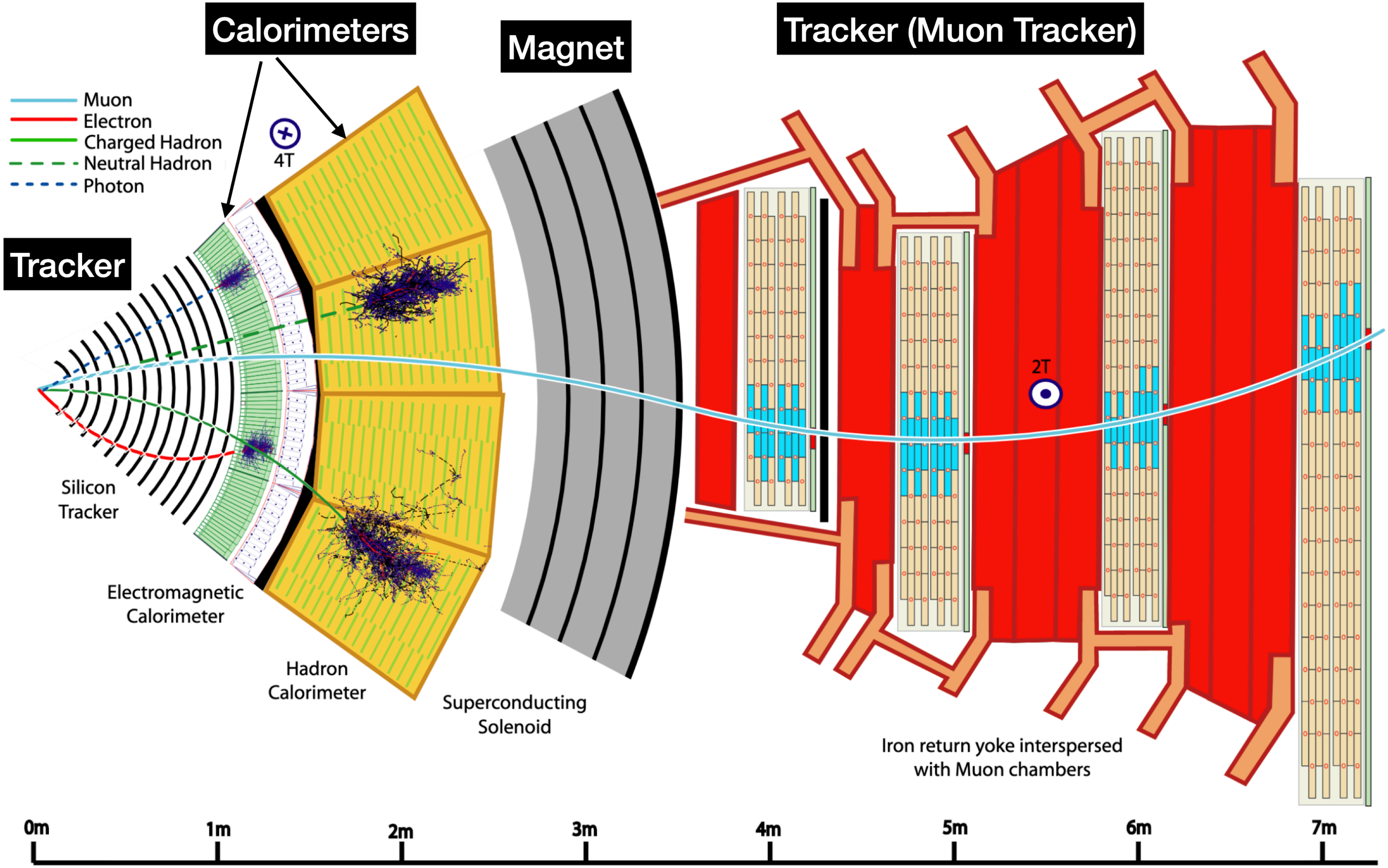
Pions (charged hadrons)

Neutrons (neutral hadrons)

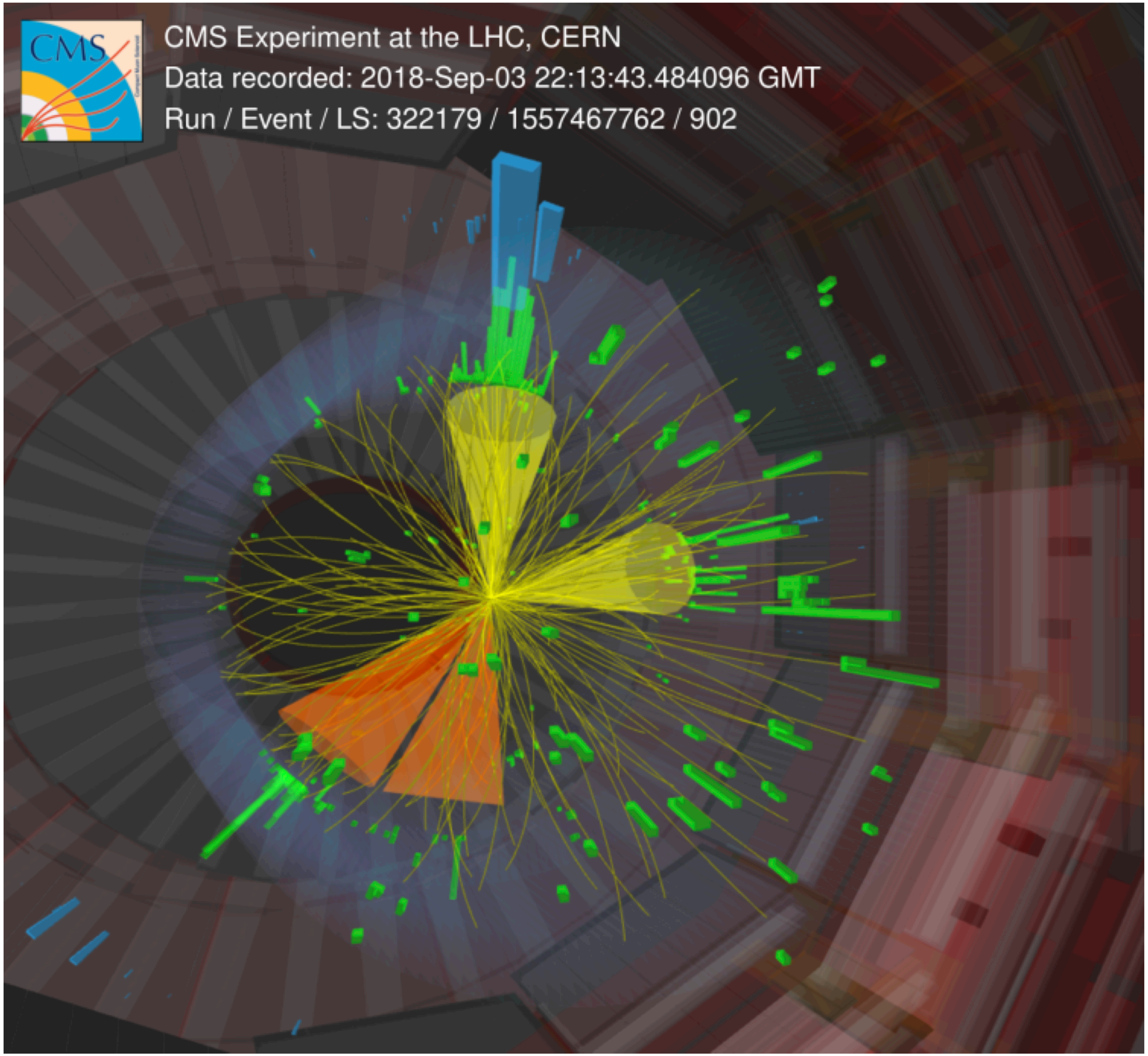
Muons

Neutrinos

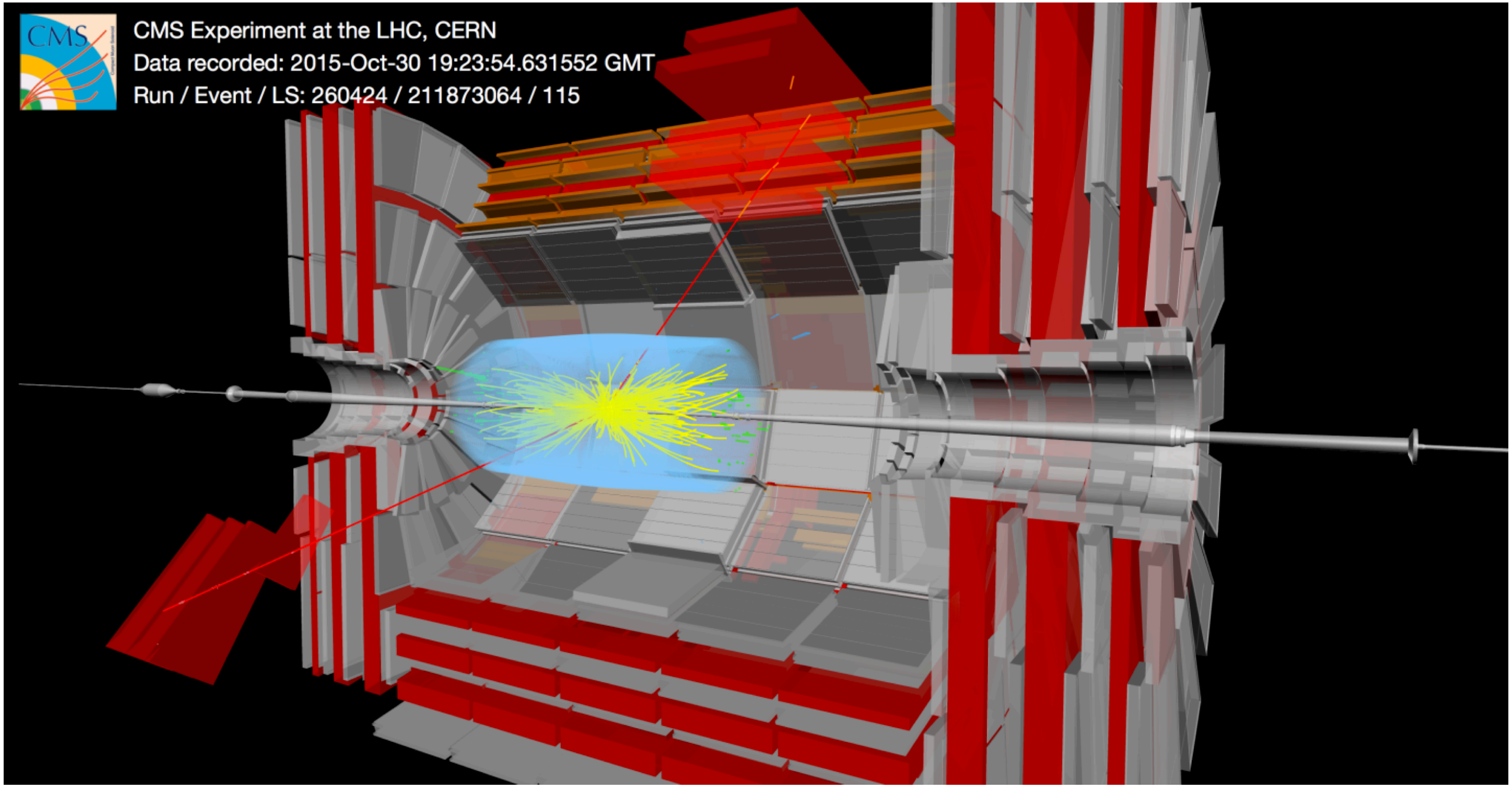
Identifying particles in CMS



A real event display



How does a Z boson look like in real life?



https://cds.cern.ch/record/2114775

Special relativity crash course

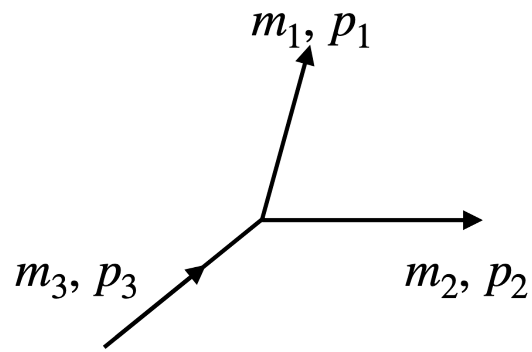
$$E = mc^2 \quad \rightarrow \quad E = \sqrt{(mc^2)^2 + (\ \vec{p}\ \ c)^2}$$

Mass-energy equivalence

$$m^2 = E^2 - \ \vec{p}\ ^2$$

This looks like length of four-momentum vector $m^2 = \ (E_1, p_x, p_y, p_z)\ ^2$**.**
This is the "invariant mass"

$$m_3^2 = (E_1 + E_2)^2 - \ \vec{p_1} + \vec{p_2}\ ^2$$



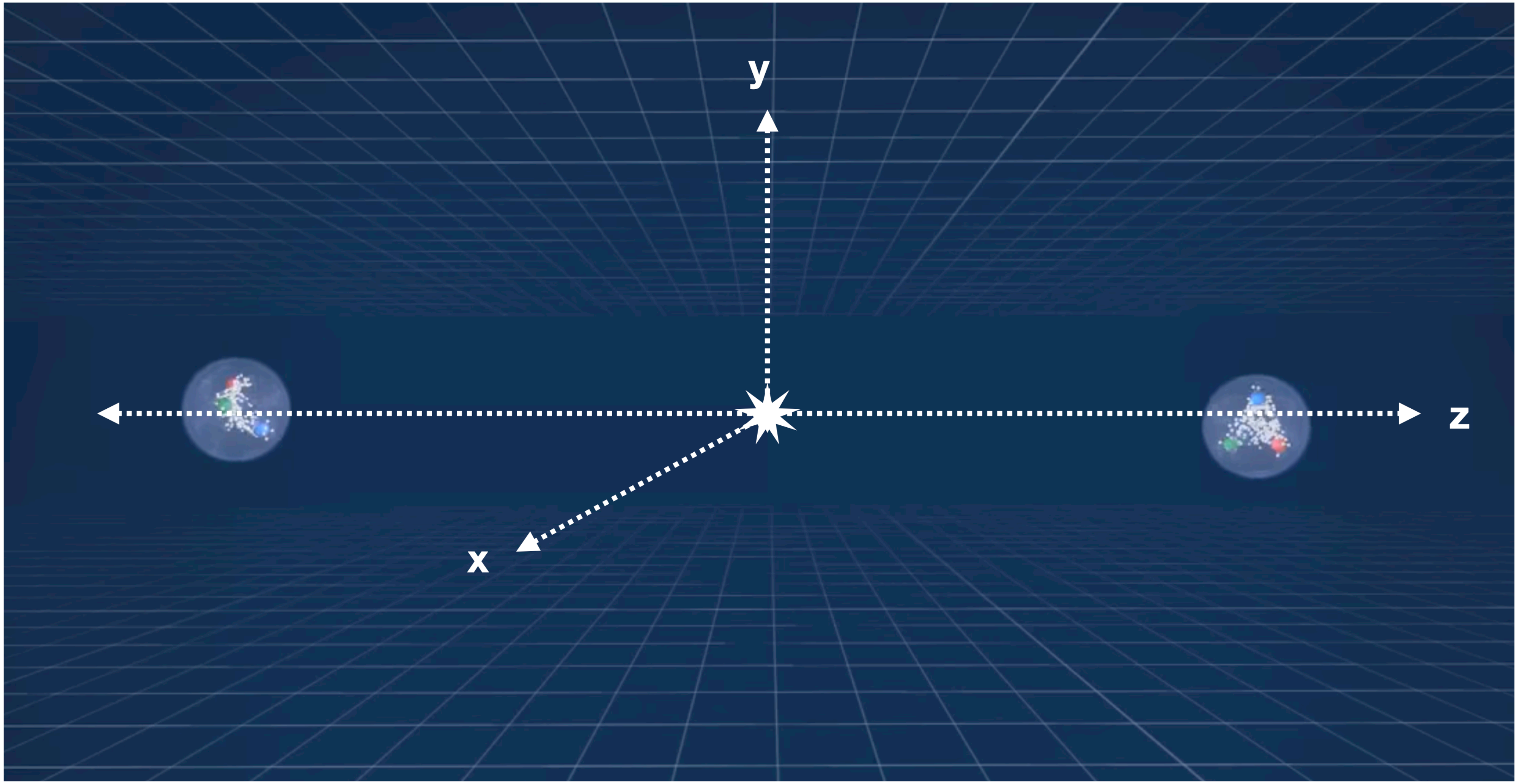
Sum of 2 four-momenta follow conservation of energy and momentum.

$$p_1 = (E_1, p_{x1}, p_{y_1}, p_{z_1}) \qquad \vec{p_1} = (p_{x1}, p_{y_1}, p_{z_1})$$

$$p_2 = (E_2, p_{x2}, p_{y_2}, p_{z_2}) \qquad \vec{p_2} = (p_{x2}, p_{y_2}, p_{z_2})$$

Four-momentum vs (3D) momentum

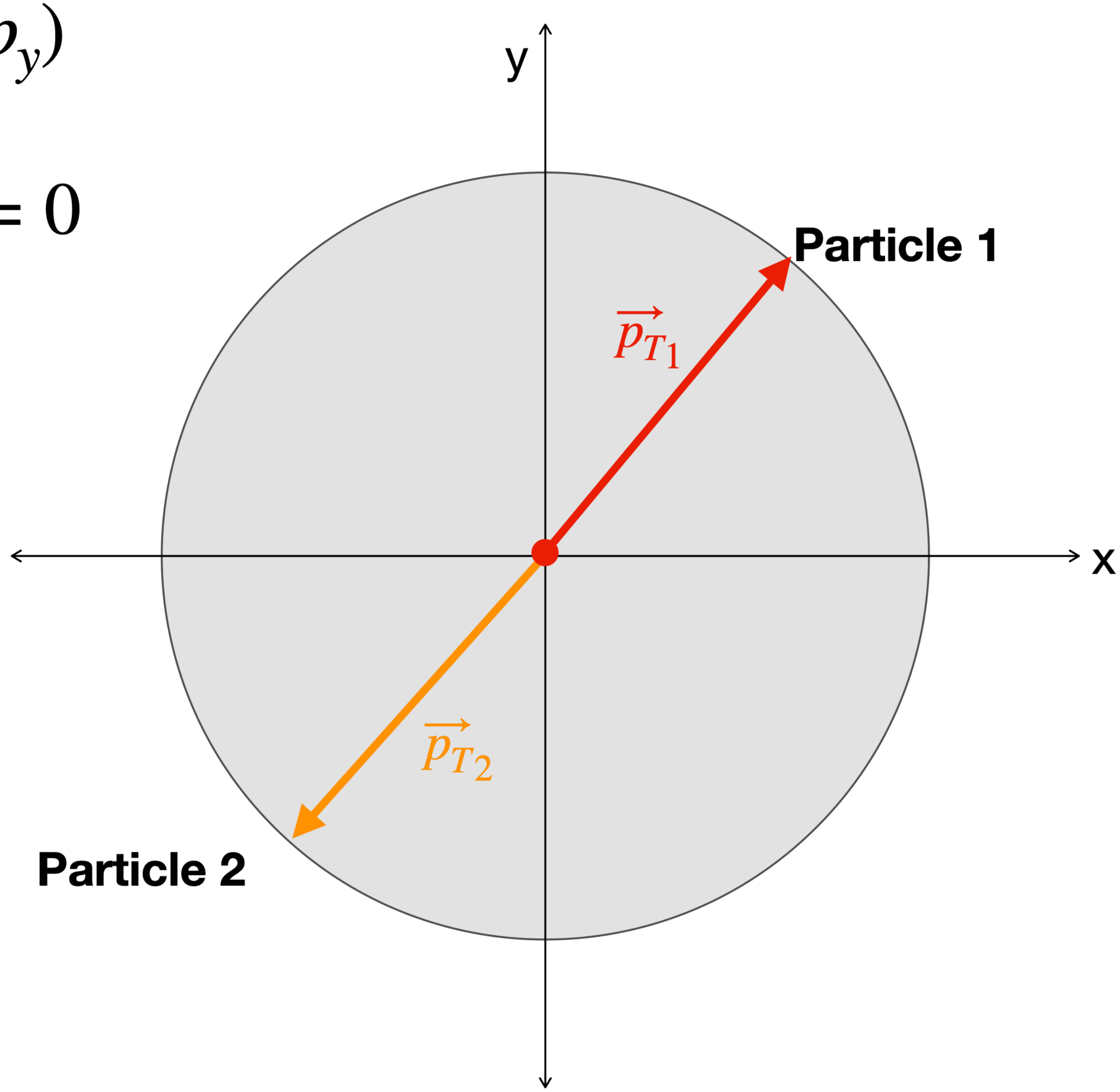
Momentum conservation



Momentum balance in the xy plane

$$\overrightarrow{p_T} = (p_x, p_y)$$

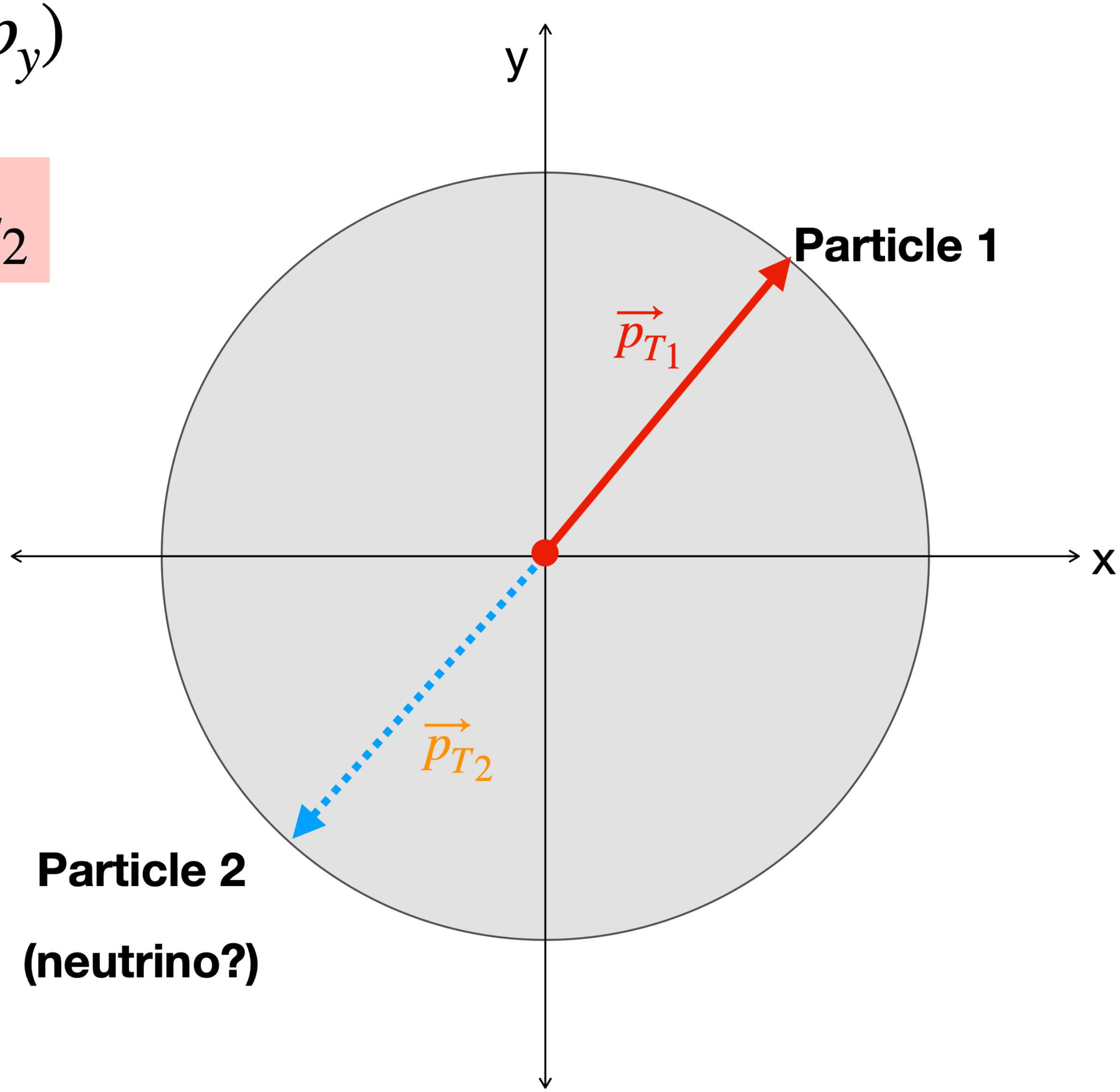
$$\overrightarrow{p_{T_1}} + \overrightarrow{p_{T_2}} = 0$$



Momentum balance in the xy plane

$$\overrightarrow{p_T} = (p_x, p_y)$$

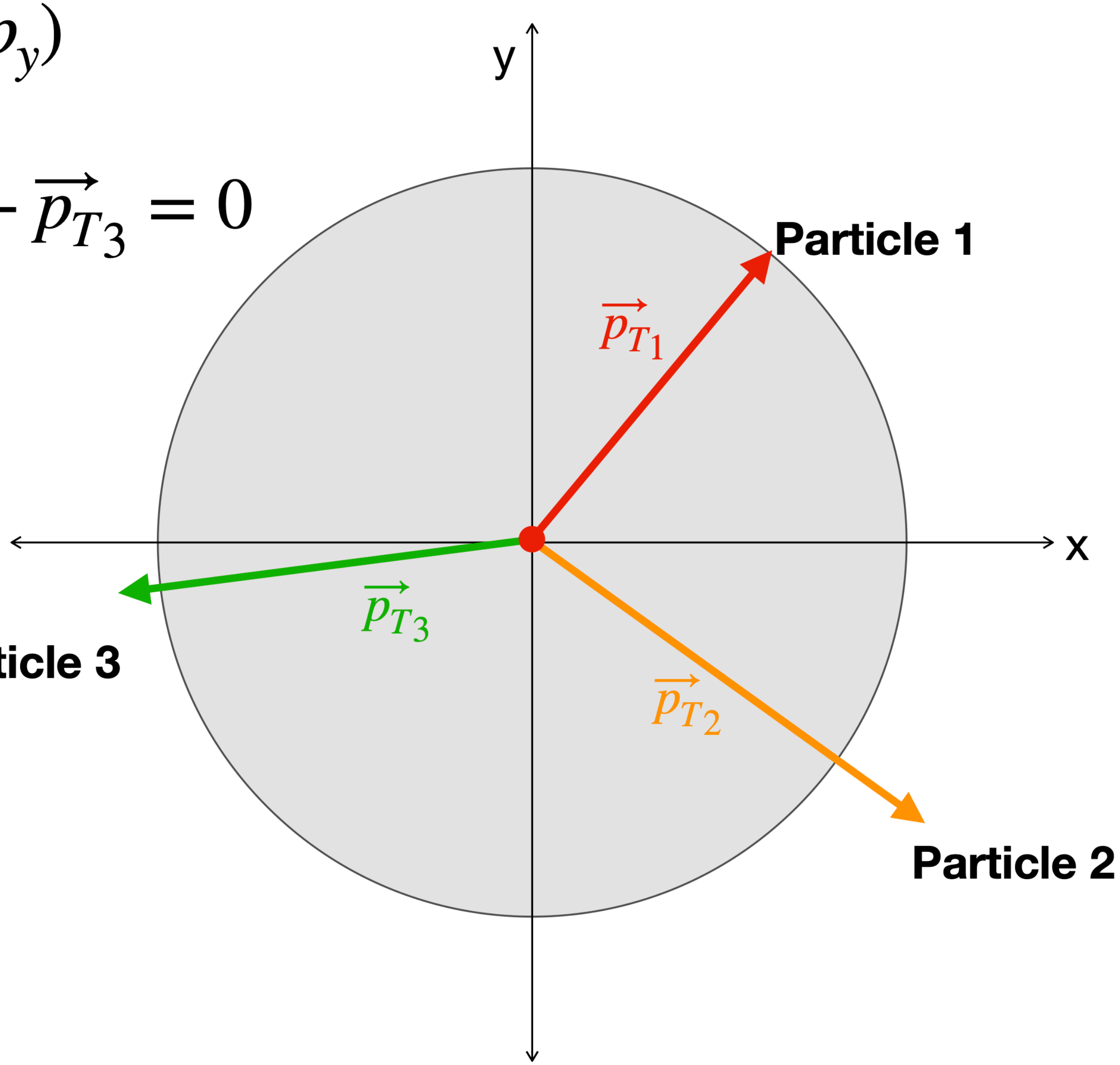
$$\overrightarrow{p_{T_1}} = -\overrightarrow{p_{T_2}}$$



Momentum balance in the xy plane

$$\overrightarrow{p_T} = (p_x, p_y)$$

$$\overrightarrow{p_{T_1}} + \overrightarrow{p_{T_2}} + \overrightarrow{p_{T_3}} = 0$$



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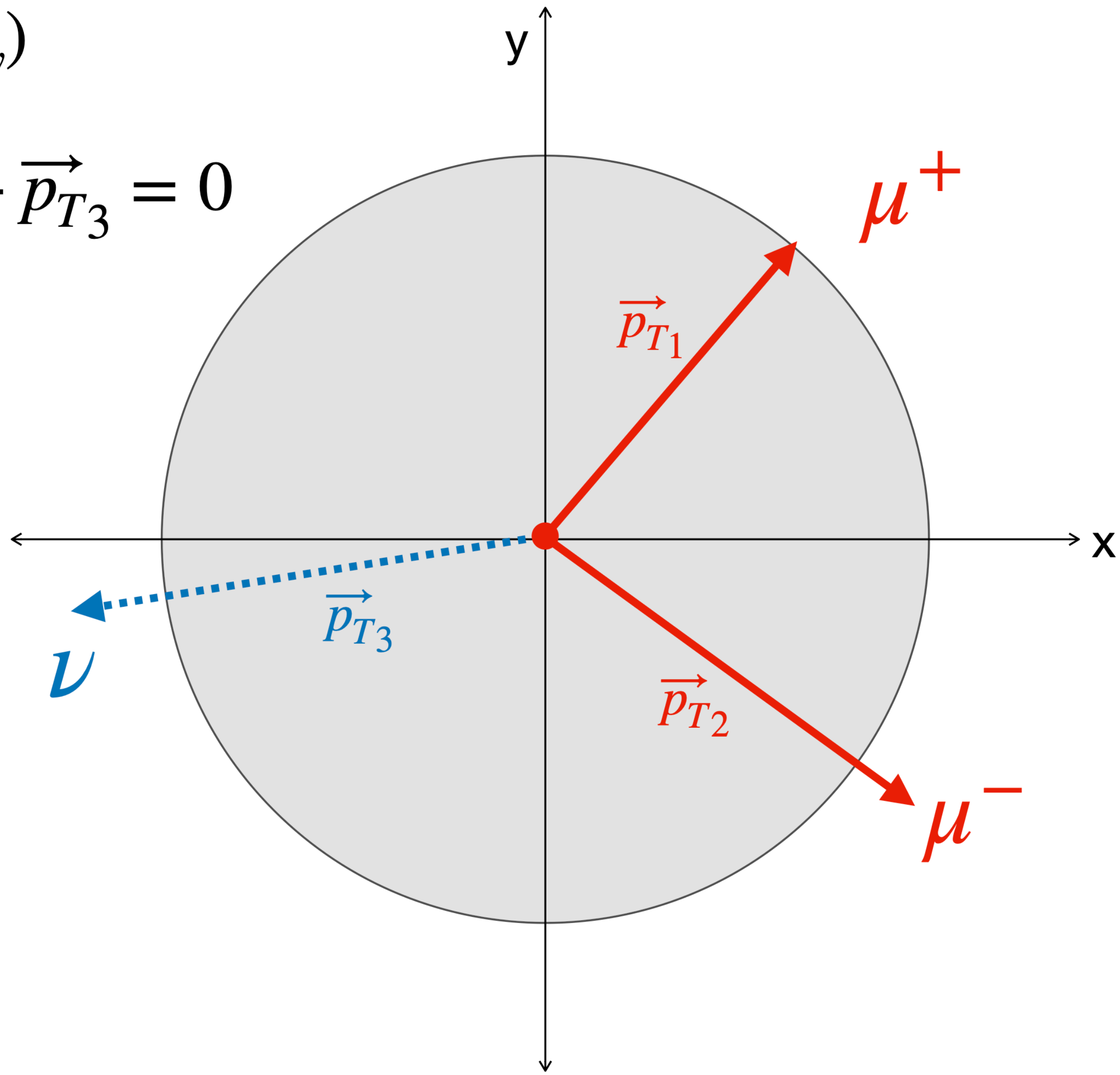

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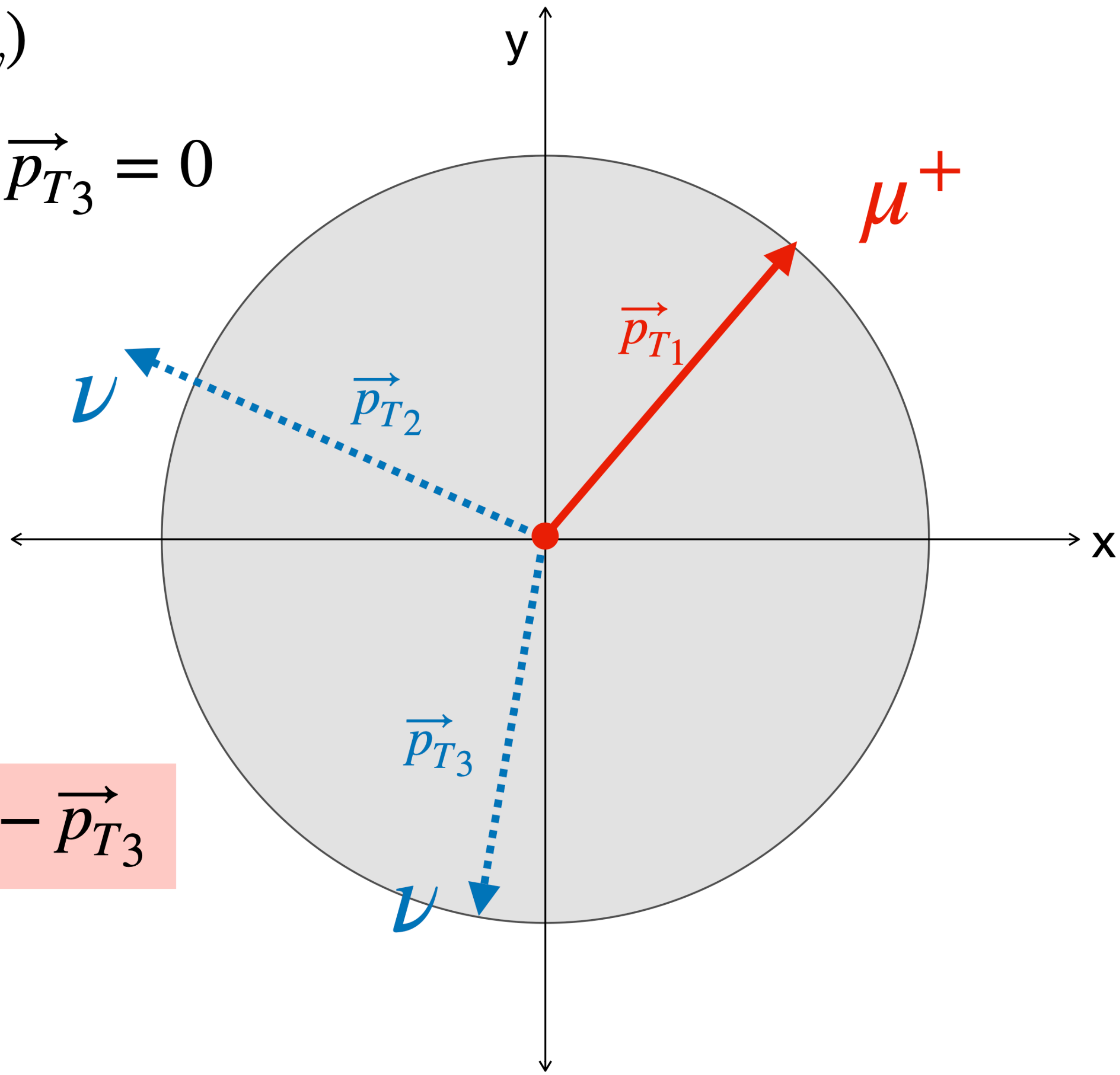
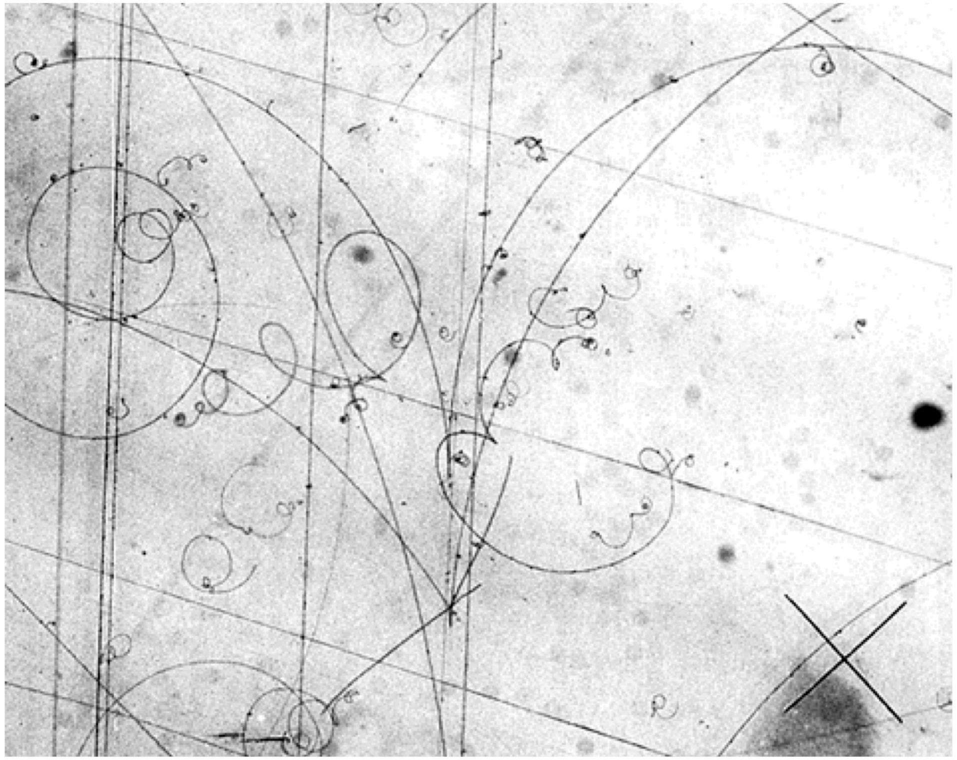


$$\overrightarrow{p_{T_1}} + \overrightarrow{p_{T_2}} = -\overrightarrow{p_{T_3}}$$

Early trackers

- In the pre-digital era, many different techniques were used, most of which dependent on ionization.
- **Bubble chamber:** vapor tracks (→gas) formed along the ionization path of charged particles in a superheated liquid, typically hydrogen.
- **Cloud chamber:** condensation tracks (→liquid) formed along the ionization path of charged particles in a supersaturated gas, typically ethanol.



https://hst-archive.web.cern.ch/archiv/HST2005/bubble_chambers/BCwebsite/index.htm

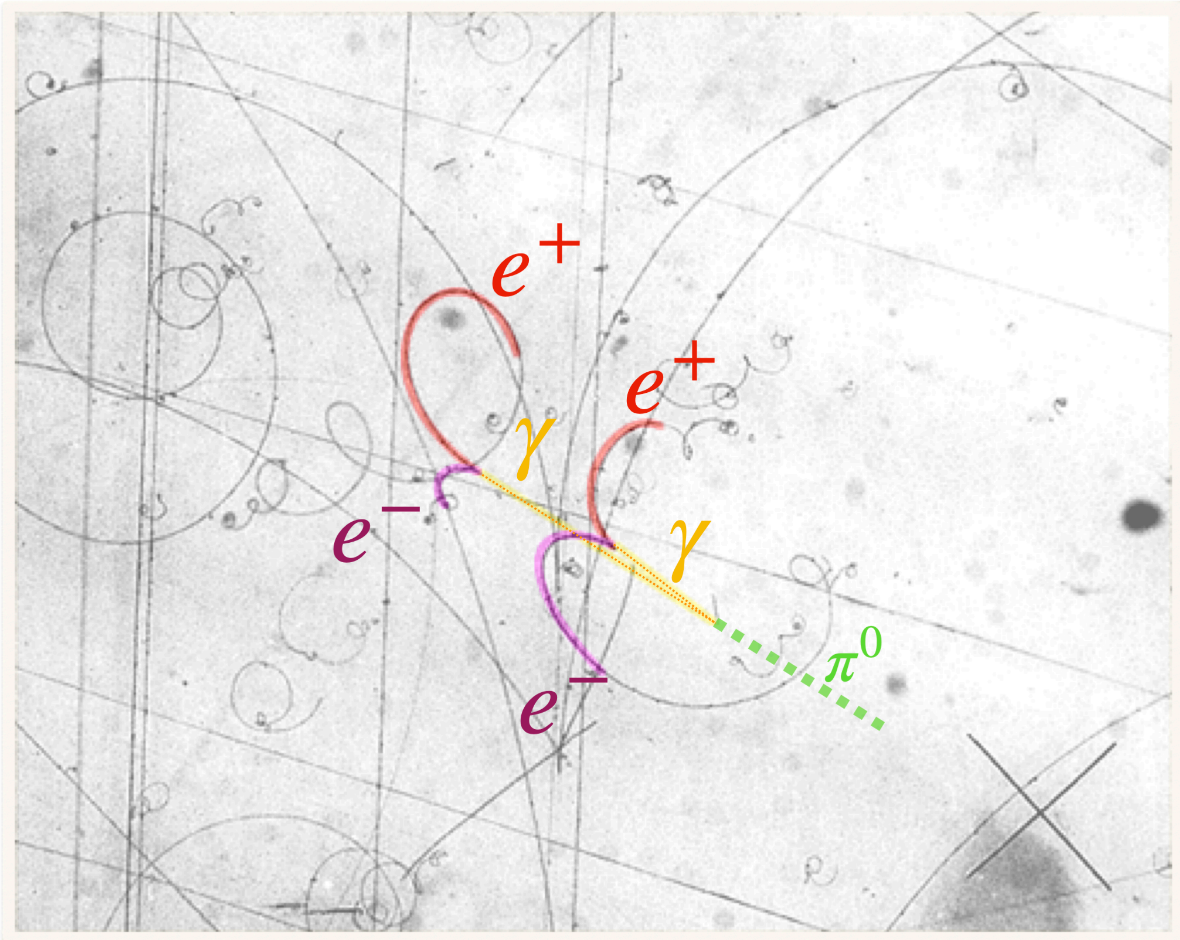
Early trackers

- Identifying individual particles is a challenge even with a few tracks!
- Why does the “coils” appear? (Assume this is in constant magnetic field)

https://hst-archive.web.cern.ch/archiv/HST2005/bubble_chambers/BCwebsite/index.htm

Early trackers

- In order to “see” that the two photons come from the same pion, we need to calculate the **momentum of each photon** (how?), and the invariant mass of the two-photon system.



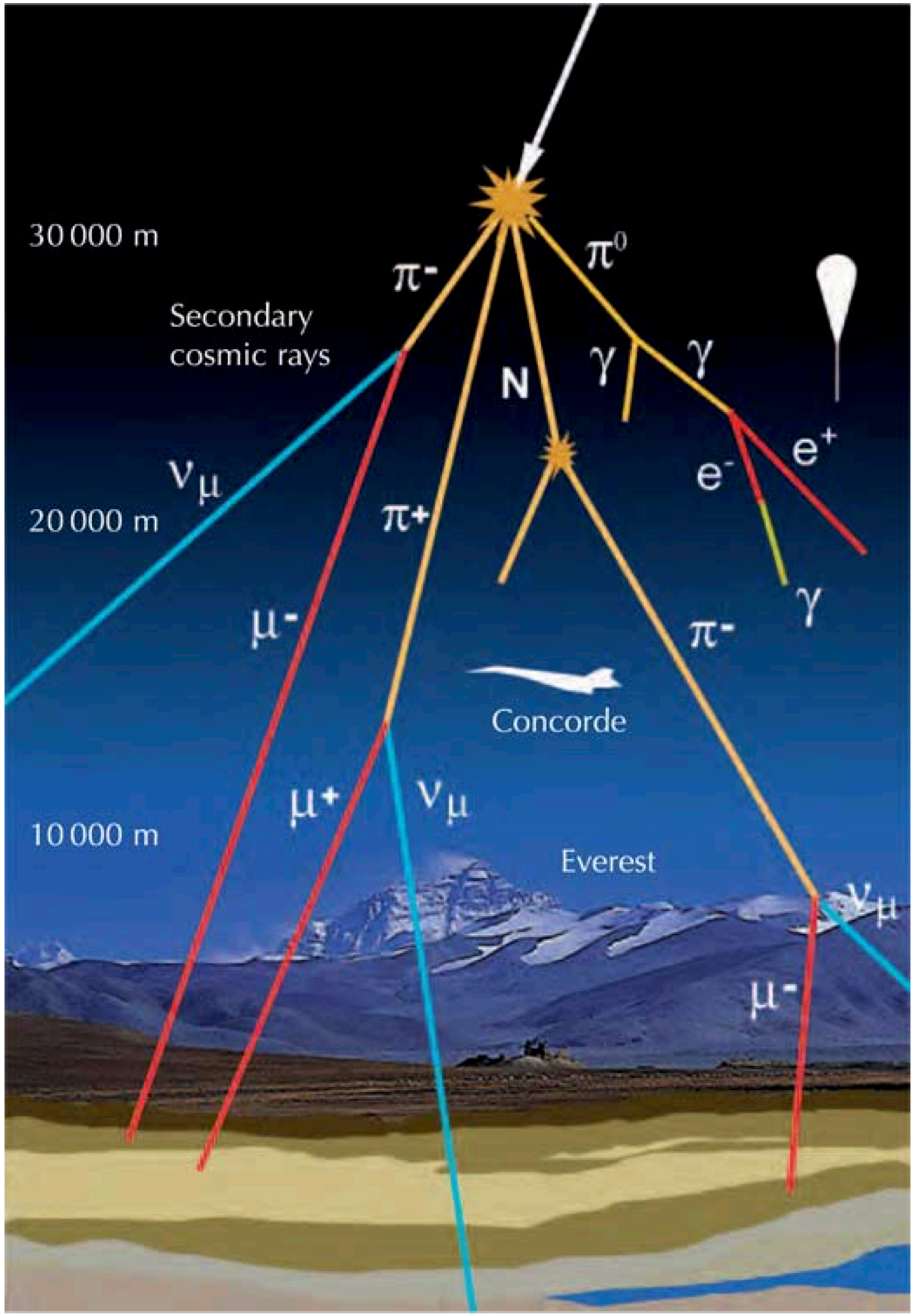
$\pi^0 \rightarrow \gamma\gamma \rightarrow e^+e^-e^+e^-$

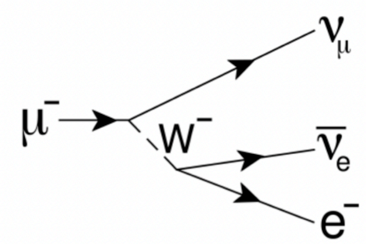
↑

liquid nuclei

https://hst-archive.web.cern.ch/archiv/HST2005/bubble_chambers/BCwebsite/index.htm

Cosmic muons





Scheme of muon decay in electron and two neutrino

Mean lifetime is: 2.2 μs

Time dilation:

$$\Delta t_{obs} = \frac{\Delta t}{1 - v^2/c^2}$$

~20km

https://physicsopenlab.org/2016/01/10/cosmic-muons-decay/

Coincidence counters

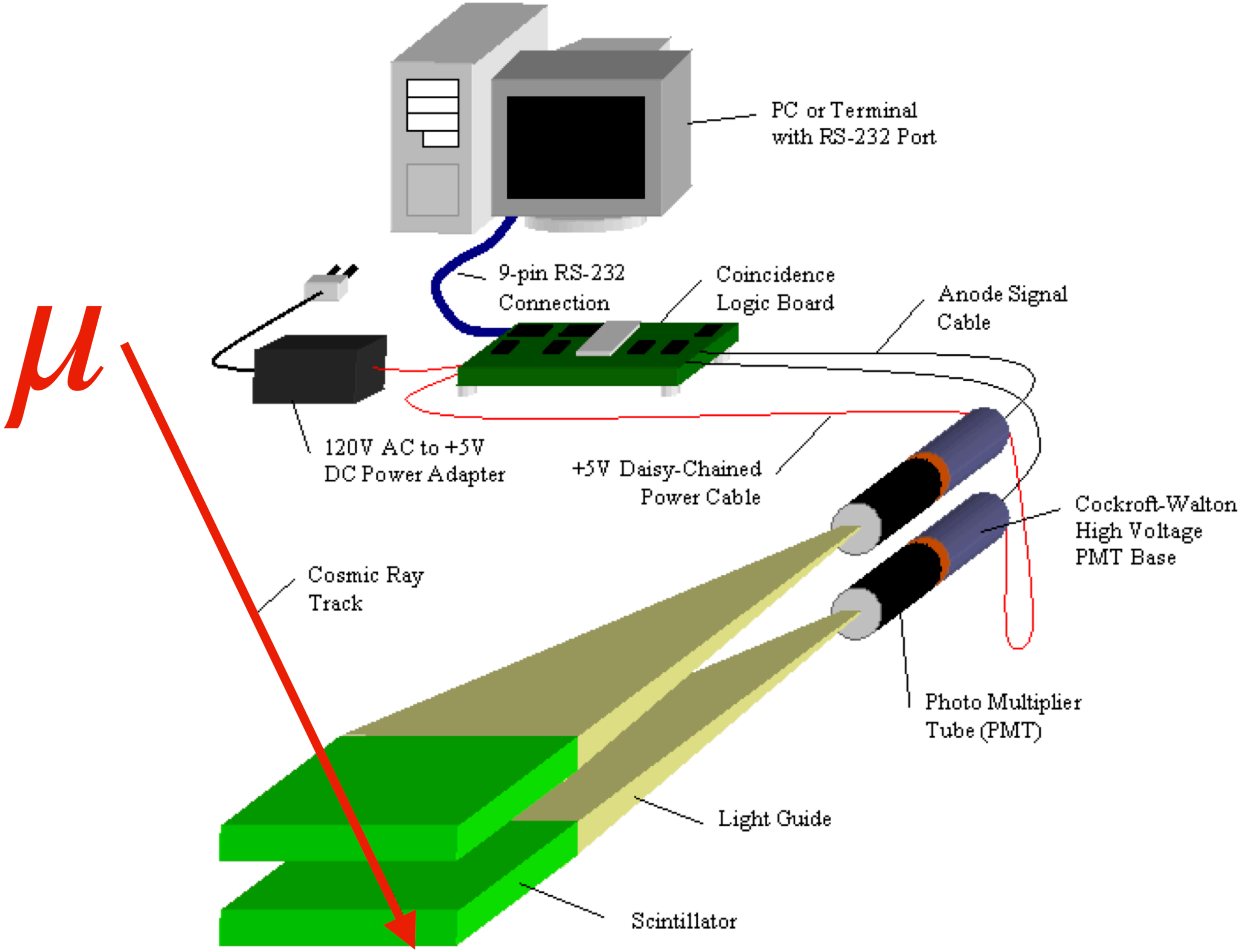
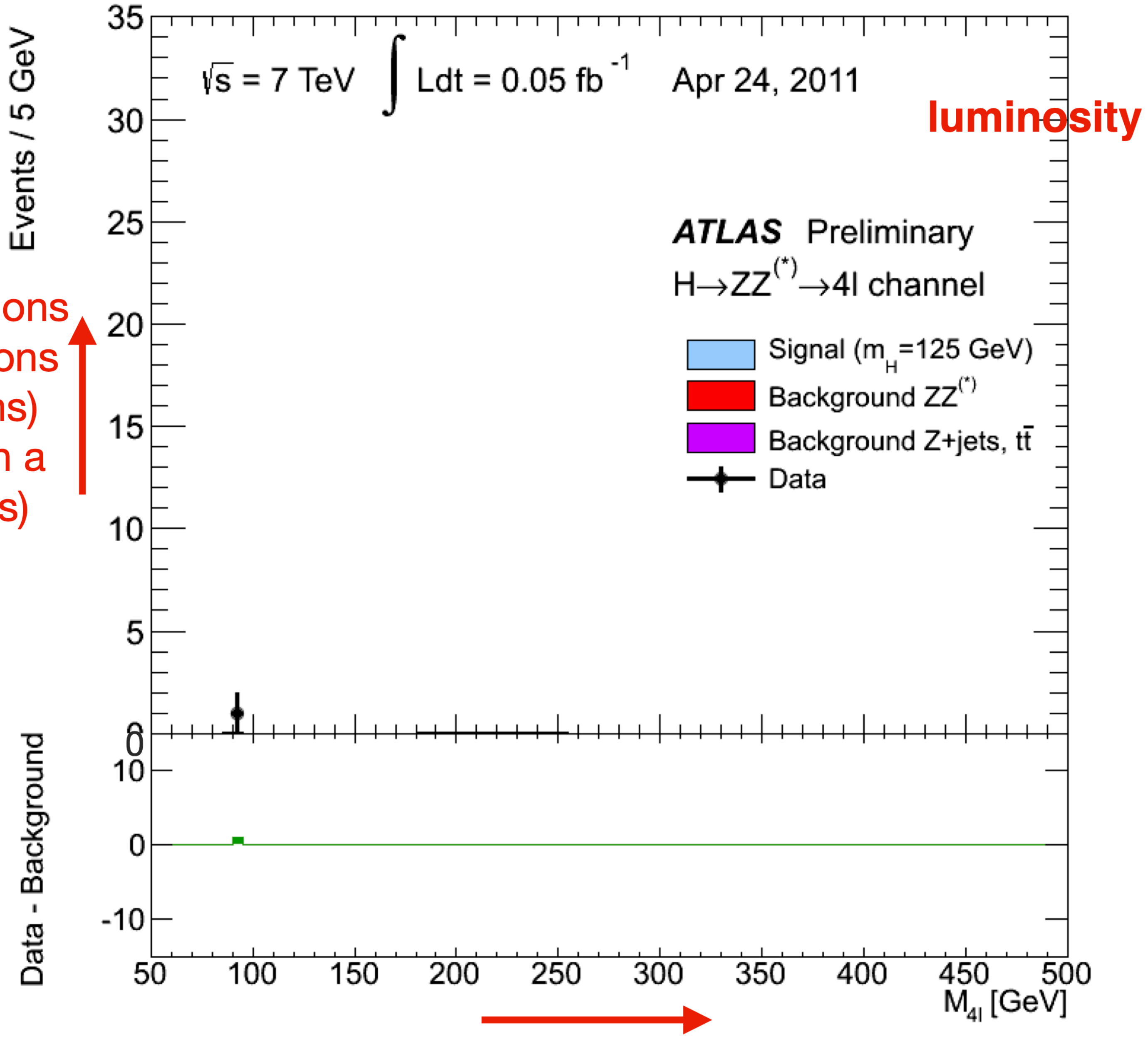


Figure 1. QuarkNet Cosmic Ray Detector System

https://physicsopenlab.org/2016/01/10/cosmic-muons-decay/

Let’s put everything all together

Number of pp collisions that produce 4 leptons (electrons or muons) that have a mass in a given range (x-axis)



Mass of 4 leptons (electrons or muons)

https://cds.cern.ch/record/2230893/files/Higgs4l.gif