

The Particle Adventure

International Masterclass - hands on particle physics

Particle detection

March 2023 - Halil Saka, Fotios Ptochos



University of Cyprus

The periodic table of particles

Hadrons
Baryons (3q)
Mesons (2q)

	three generations of matter (fermions)			interactions / force carriers (bosons)		
	I	II	III			
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$	0
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0	2
	u up	c charm	t top	g gluon	H higgs	G graviton
	d down	s strange	b bottom	γ photon		
	e electron	μ muon	τ tau	Z Z boson		
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson		

QUARKS (vertical label on the left of the quark section)

LEPTONS (vertical label on the left of the lepton section)

GAUGE BOSONS VECTOR BOSONS (vertical label on the right of the gauge boson section)

SCALAR BOSONS (vertical label on the right of the scalar boson section)

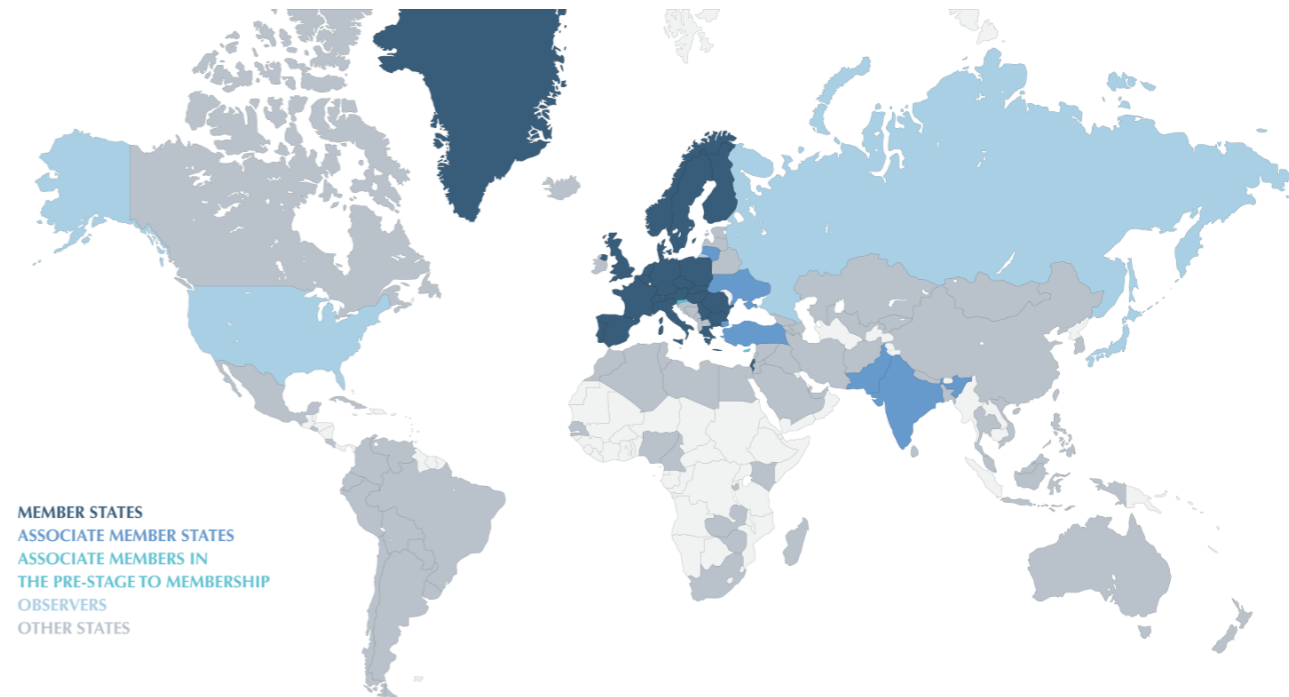
Unobserved (vertical label on the right of the graviton cell)

HYPOTHETICAL TENSOR BOSONS (vertical label on the right of the graviton cell)

- 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?

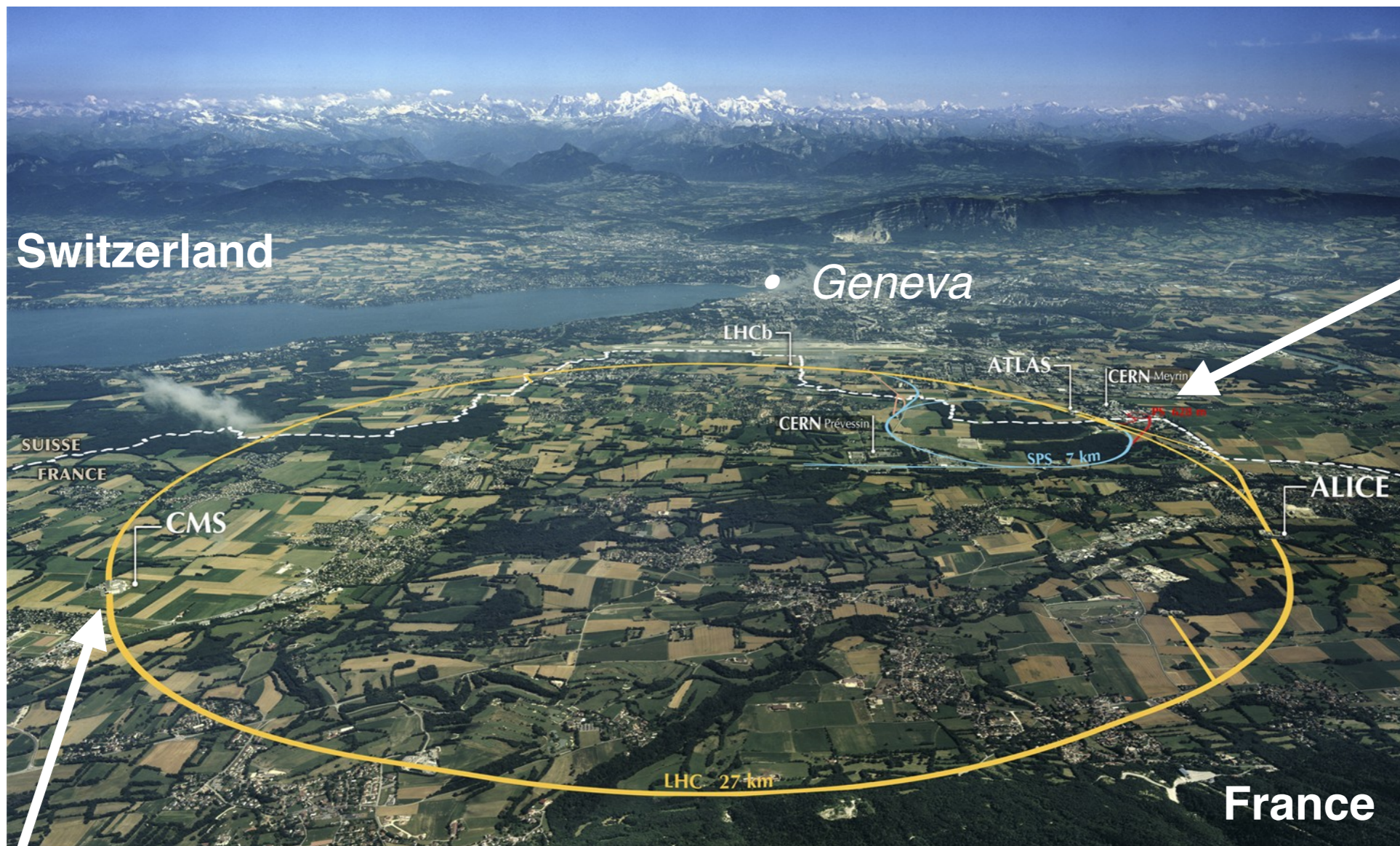
What is CERN?

- 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?

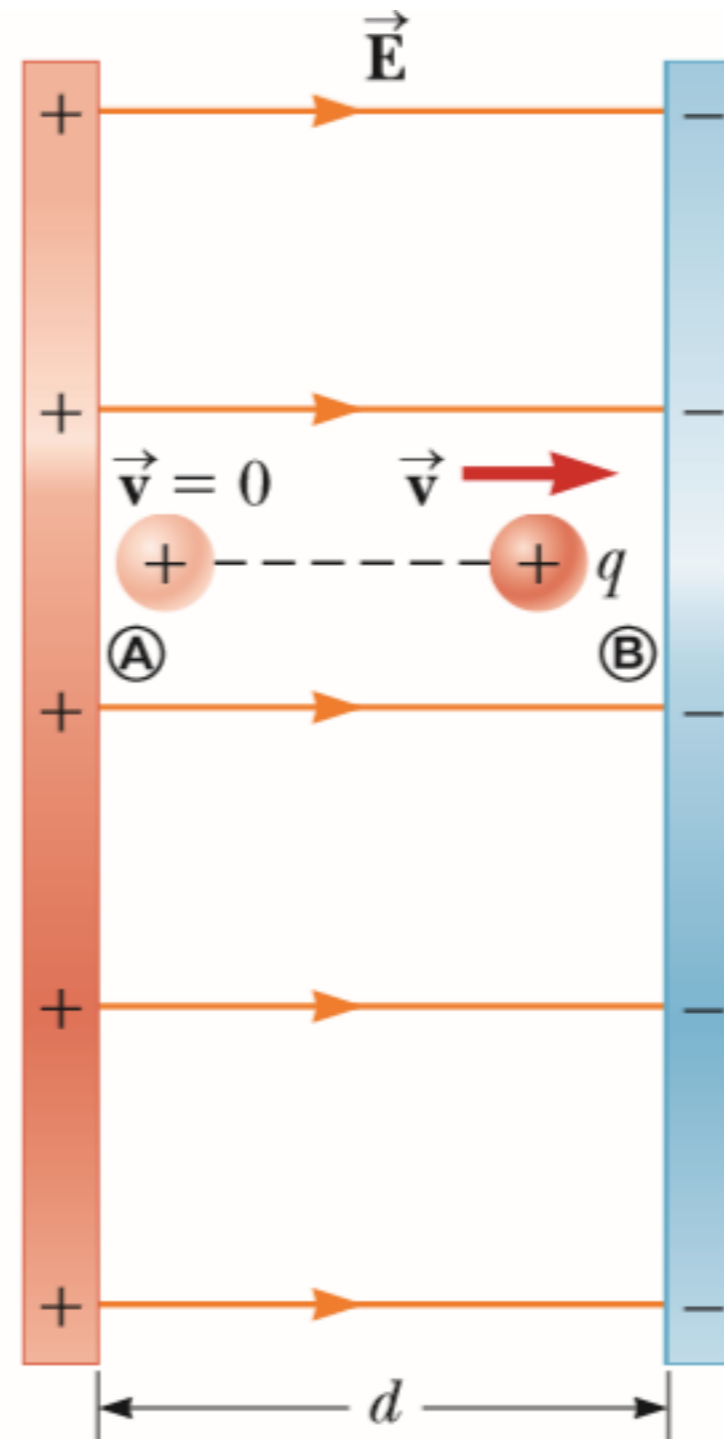
- The **Large Hadron Collider** is a particle **accelerator and collider** that pushes protons (or ions) to near the speed of light.
- It sits about **100m underground** and consists of a **27-km ring of superconducting magnets**.
- It holds **two beams of protons traveling in opposite directions**



CMS detector

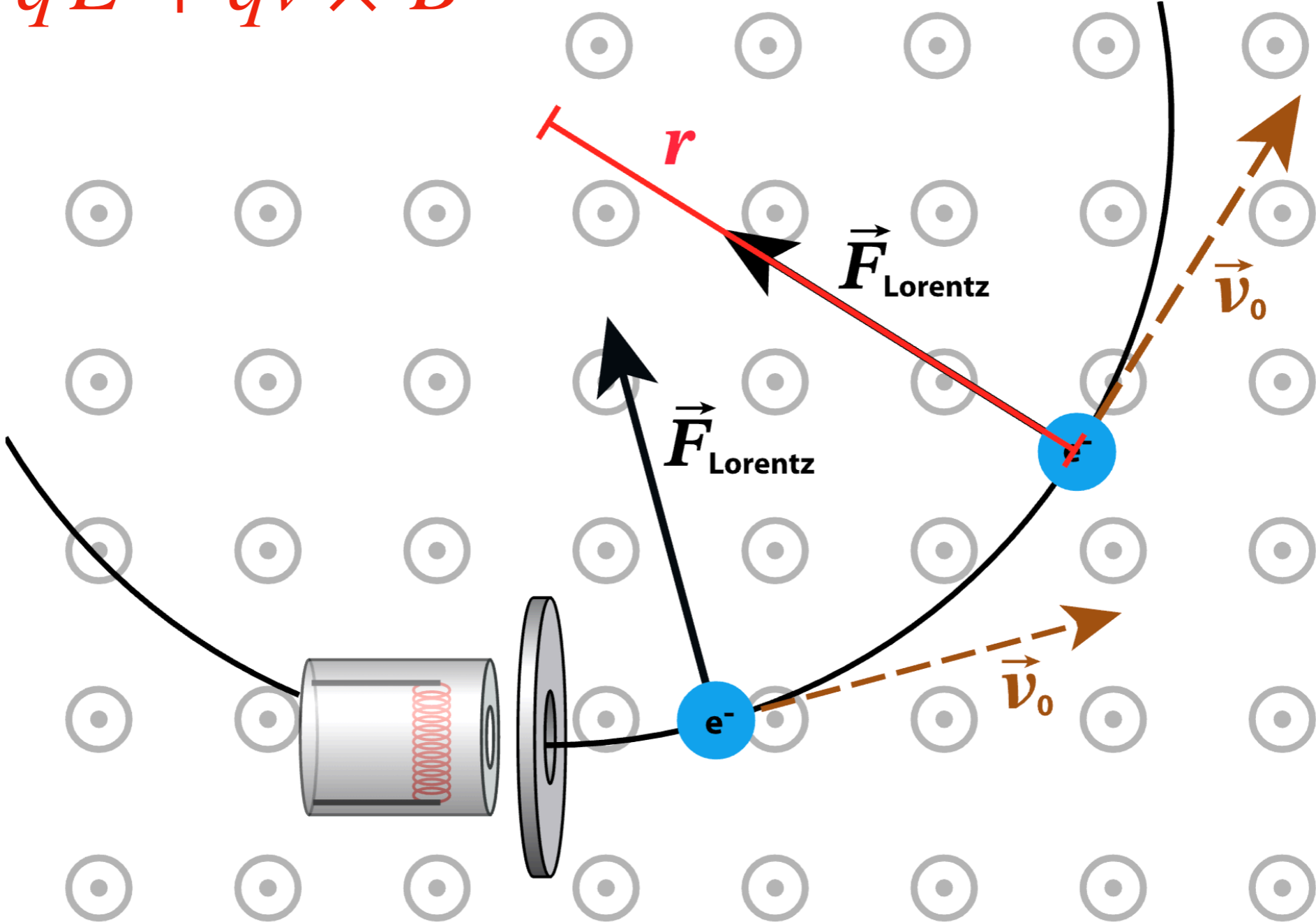
Quick reminder of the Lorentz Force

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



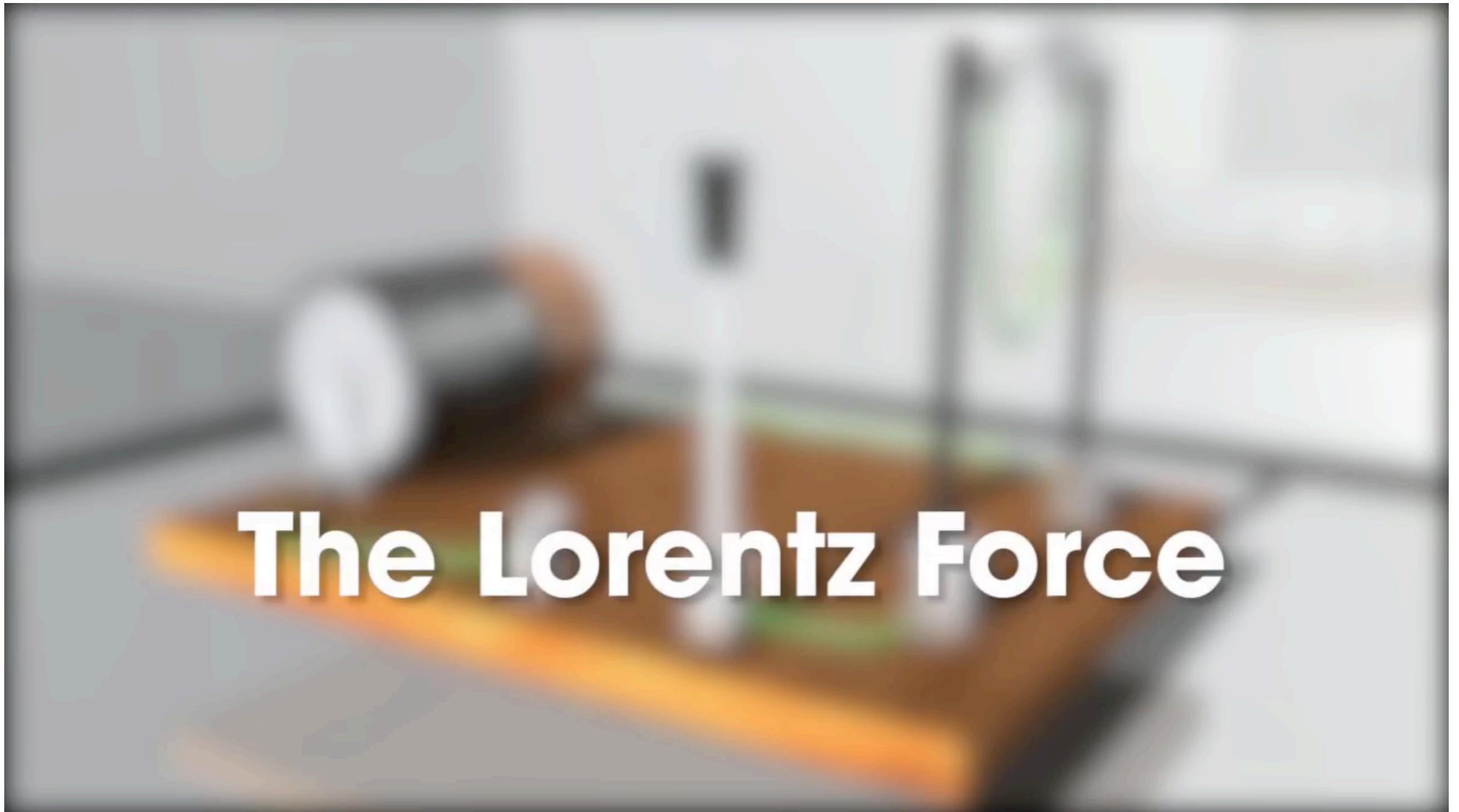
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Quick reminder of the Lorentz Force

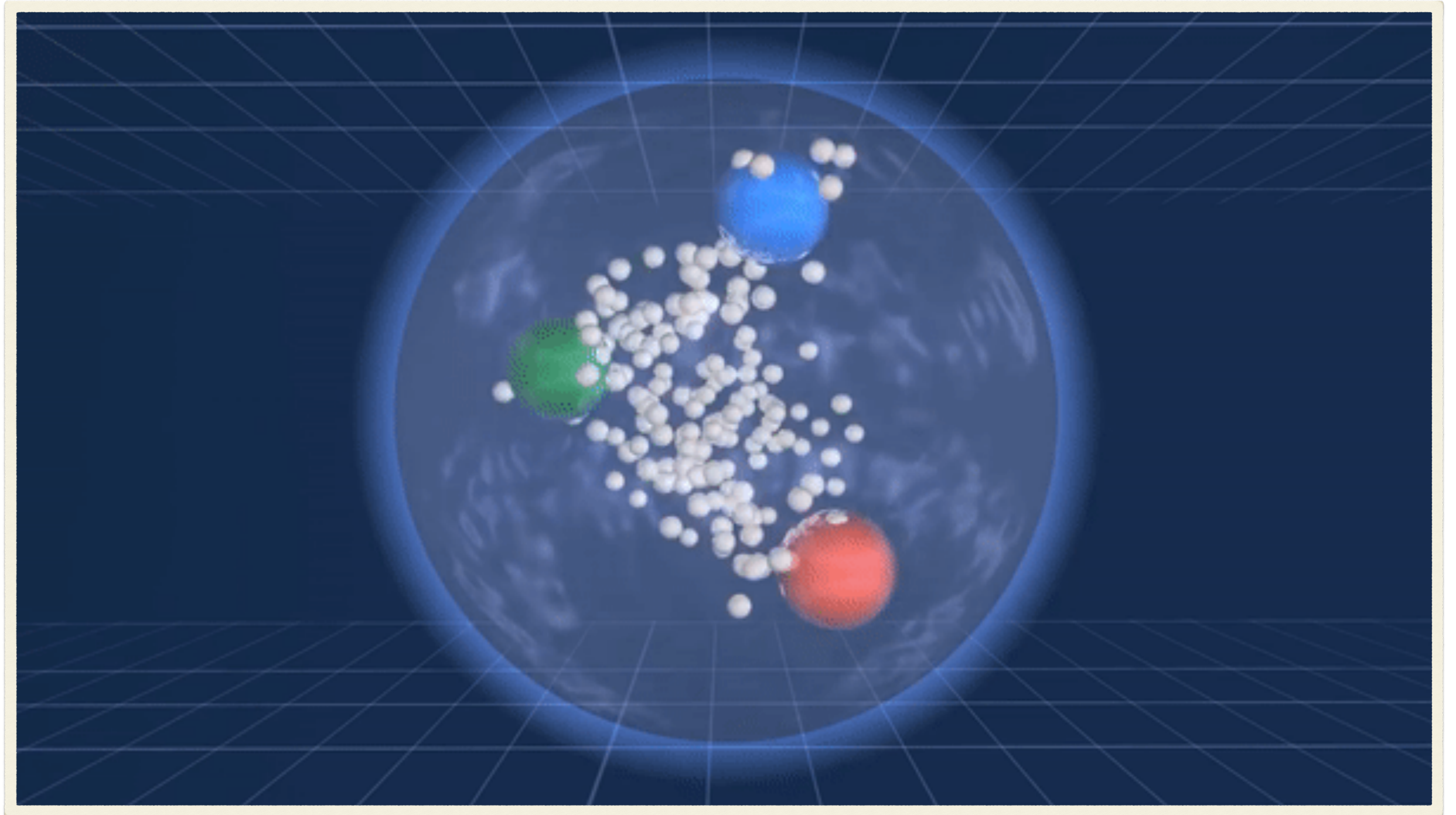
$$F_{Lorentz} = q\vec{E} + q\vec{v} \times \vec{B}$$



What does the LHC do?



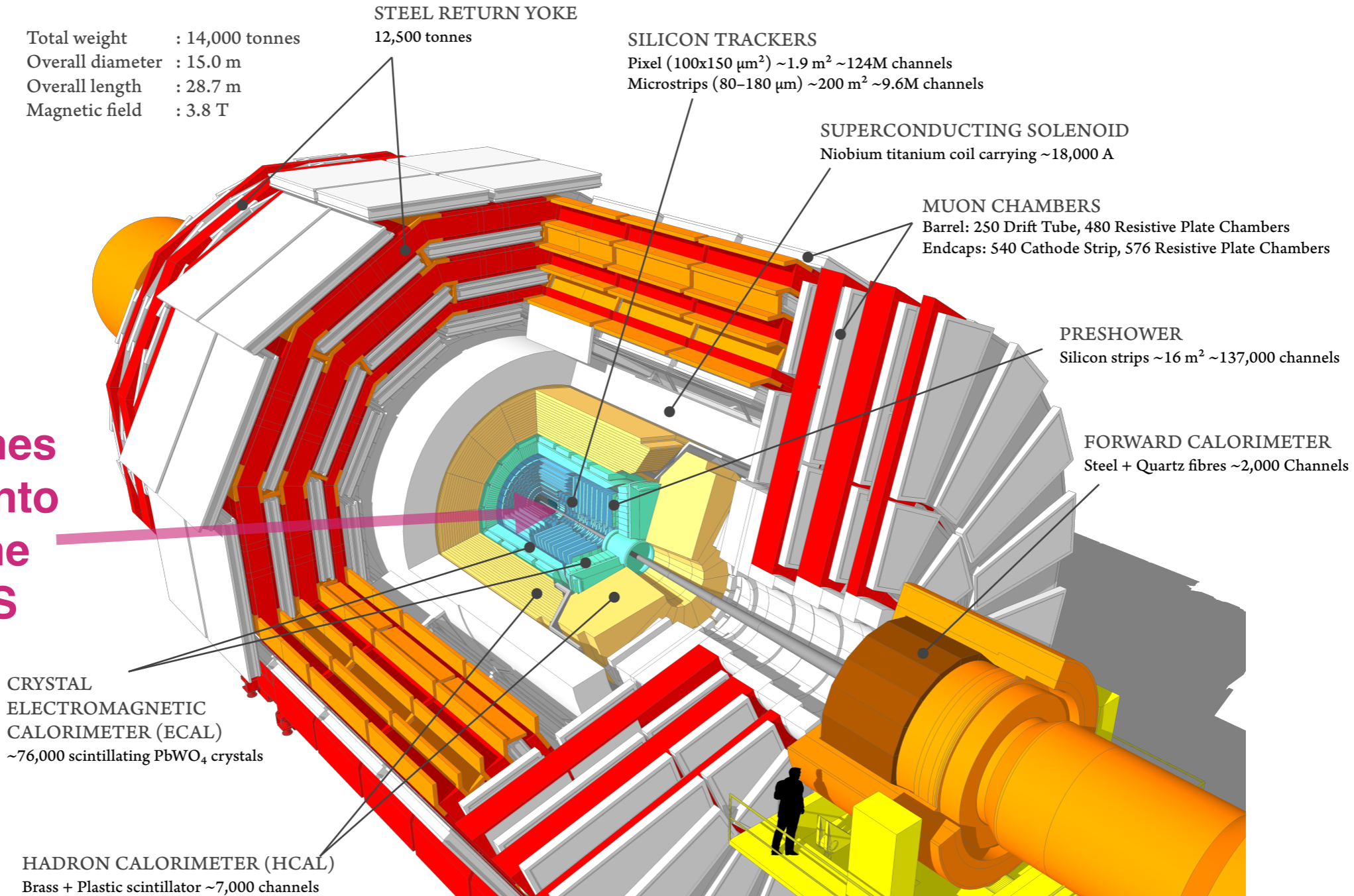
Colliding protons to produce a Z boson



What is CMS?

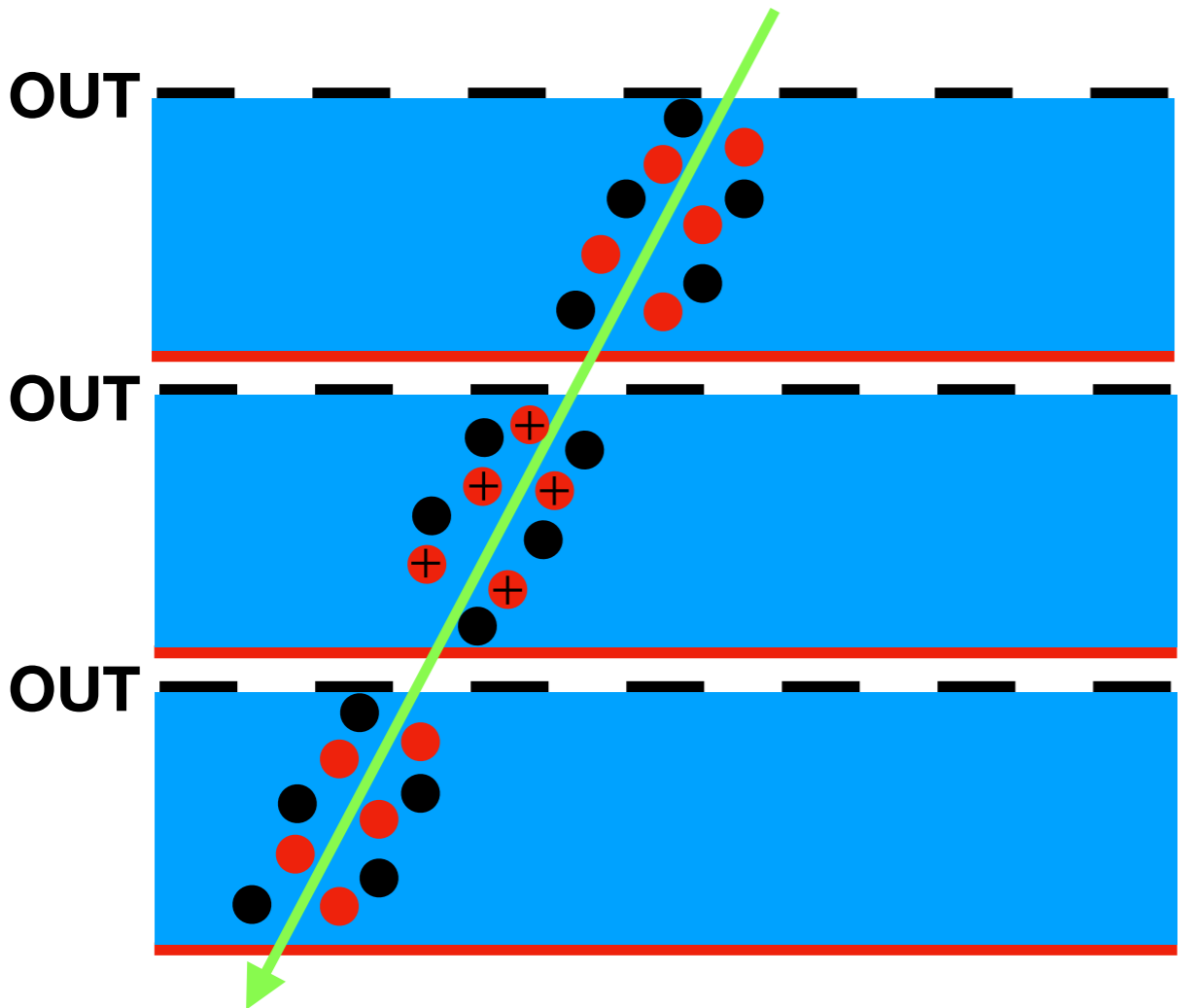
- **Compact Muon Solenoid** is a multi-purpose **particle detector** at the Large Hadron Collider (LHC) at CERN.
- It is the name of the collaboration (group), and the experiment (apparatus).

Proton bunches are brought into collision at the center of CMS



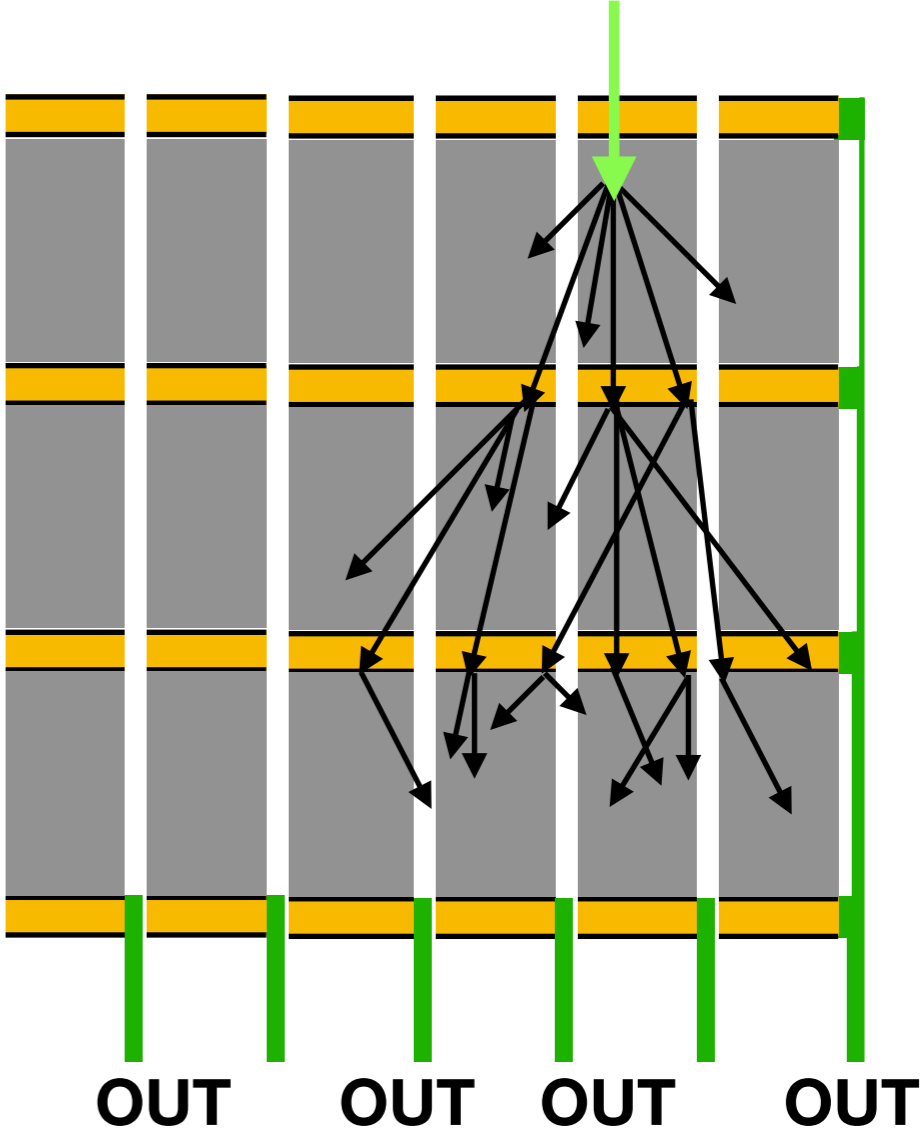
Particle detectors: Tracking vs Calorimetry

A typical tracker



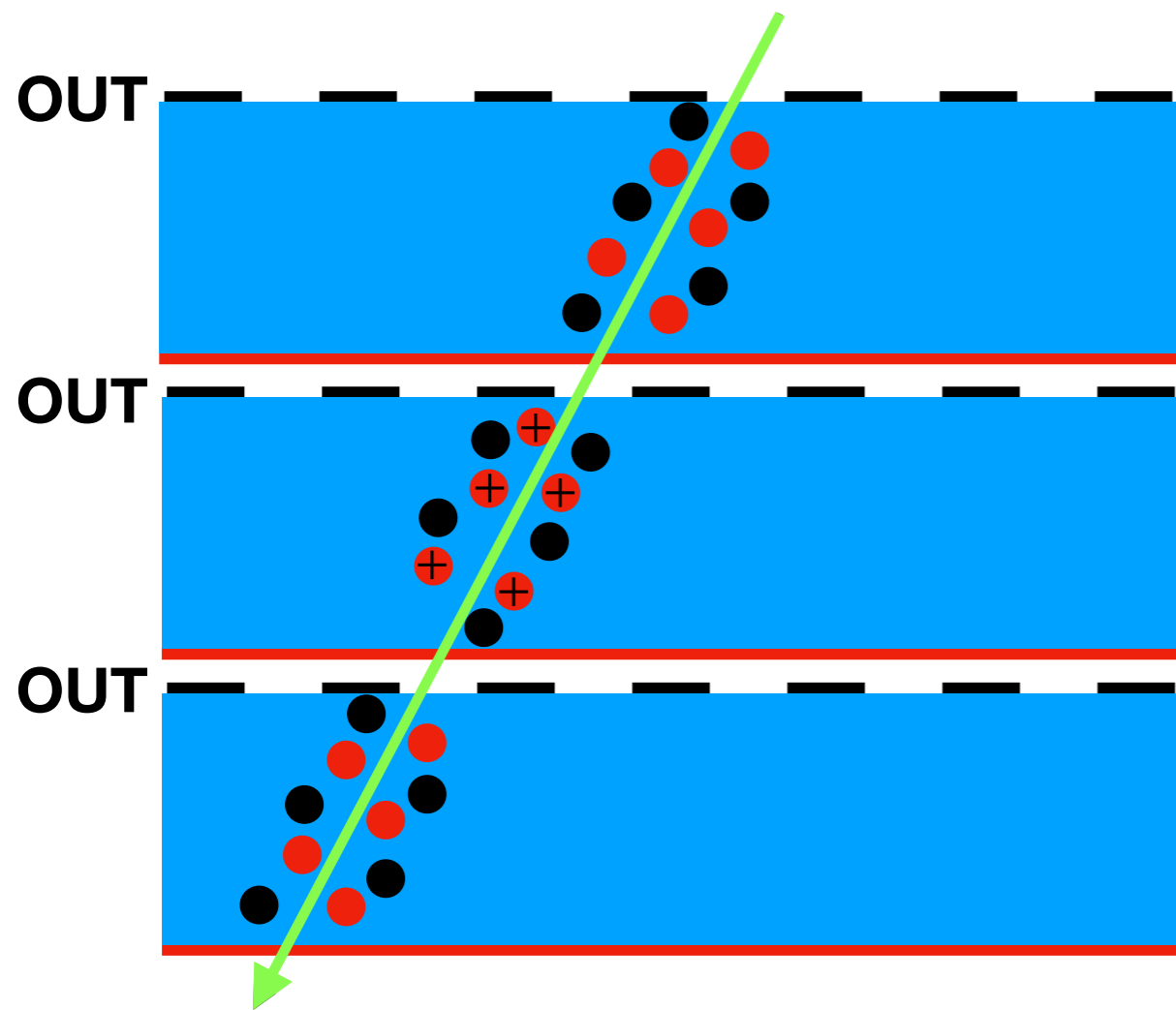
Green: Incoming particle

A typical calorimeter



Green: Incoming particle

Particle detectors: A typical tracker

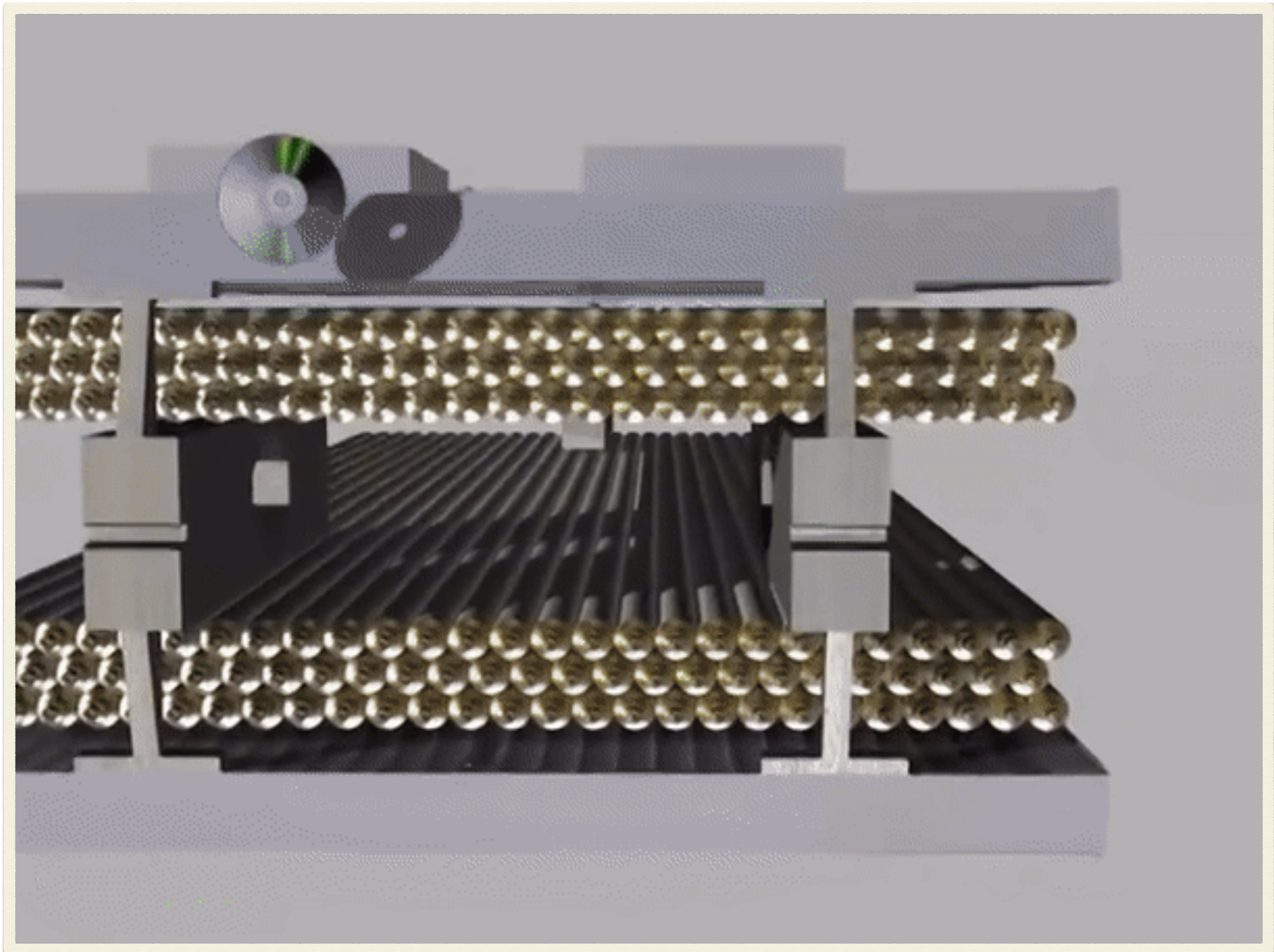


A typical tracker

ionize: split electrons from nucleus.

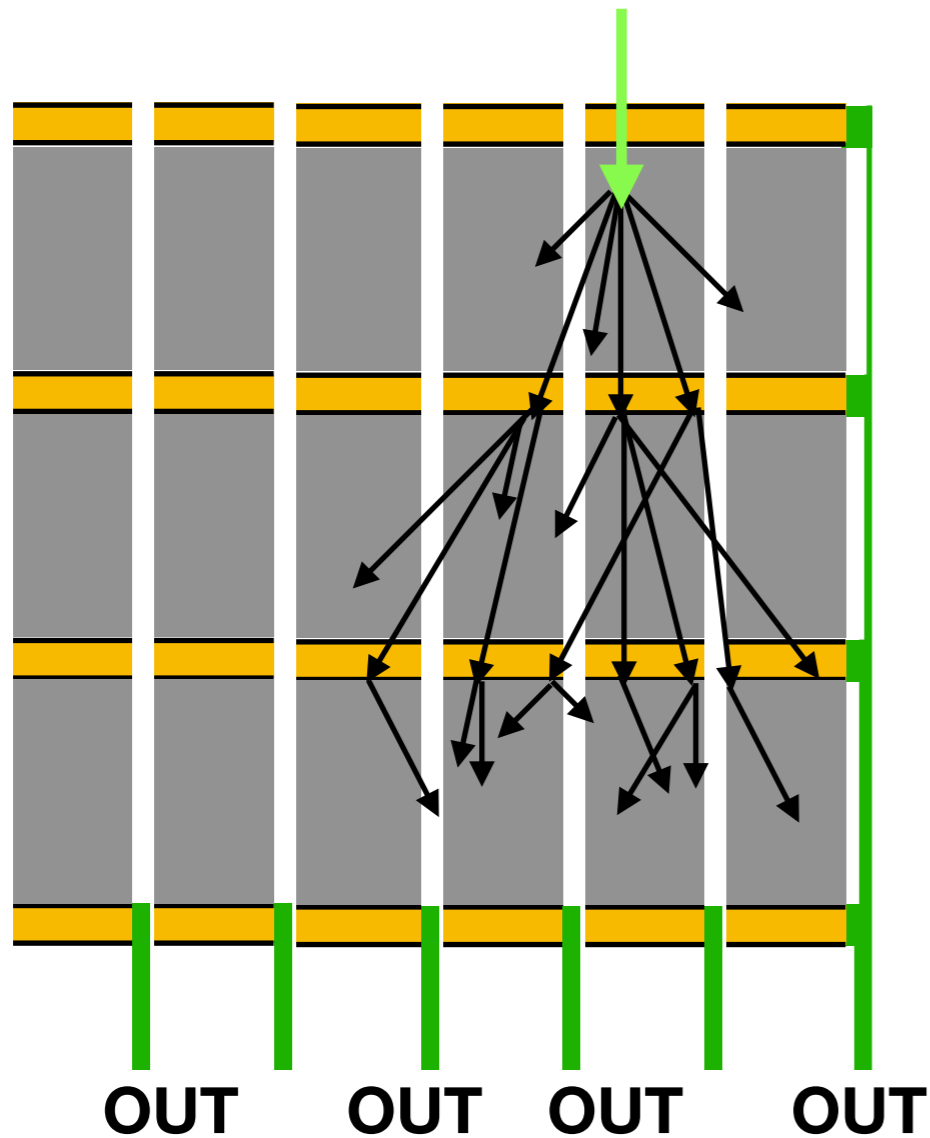
- Particle in, particle out
- Typical “spacing” is
 $\sim 100\mu\text{m} - 1\text{mm}$
- Typical materials: silicon, noble gasses, etc.
- **Charged** particles only, needs to **ionize** the active material.
- Output: electrical

Particle detectors: A typical tracker



<https://youtu.be/A8L2RtvEKok>

Particle detectors: A typical calorimeter

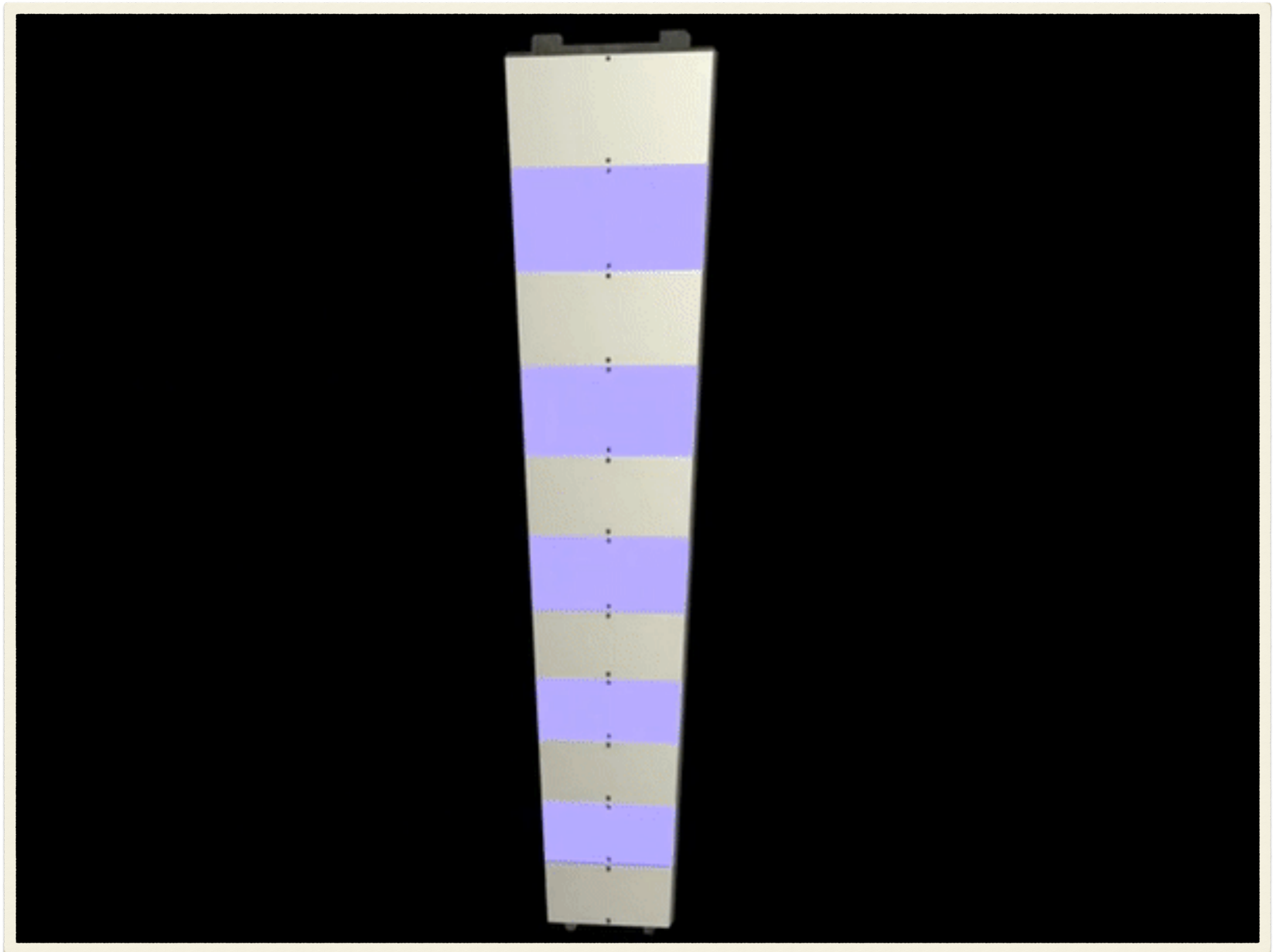


A typical calorimeter

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

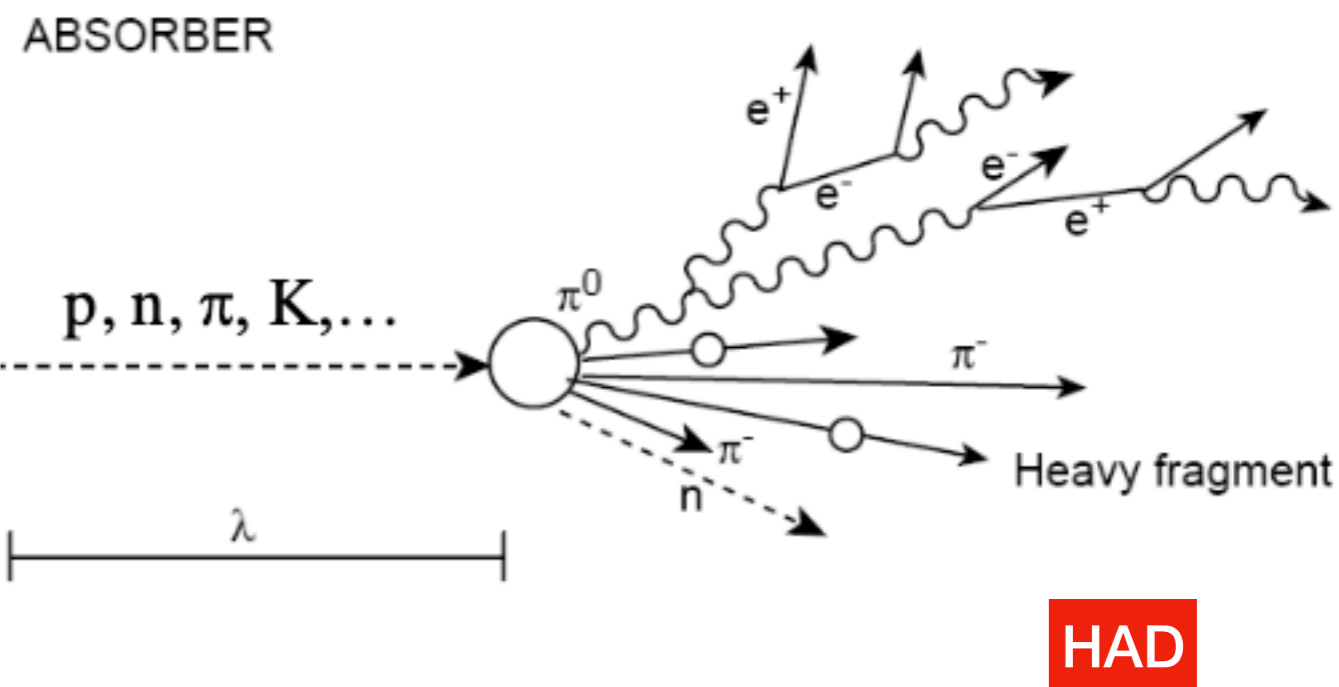
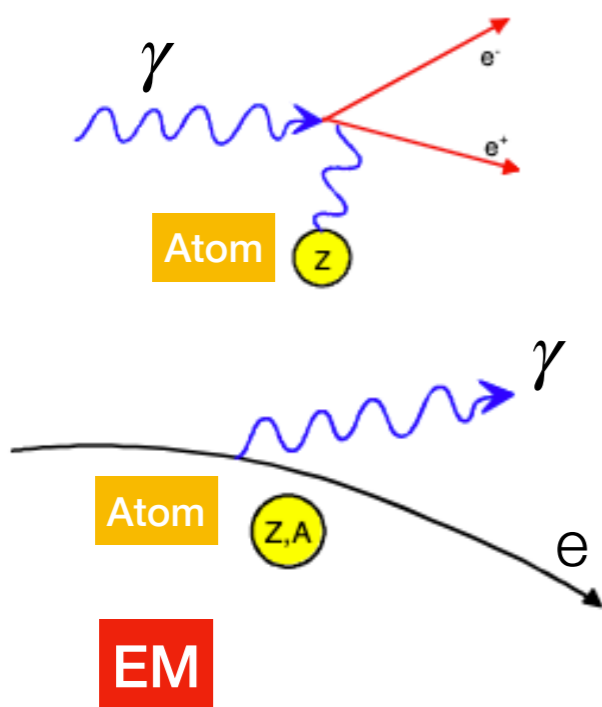
Scintillate: emit light at a characteristic frequency upon de-excitation of valence electrons.

Particle detectors: A typical calorimeter

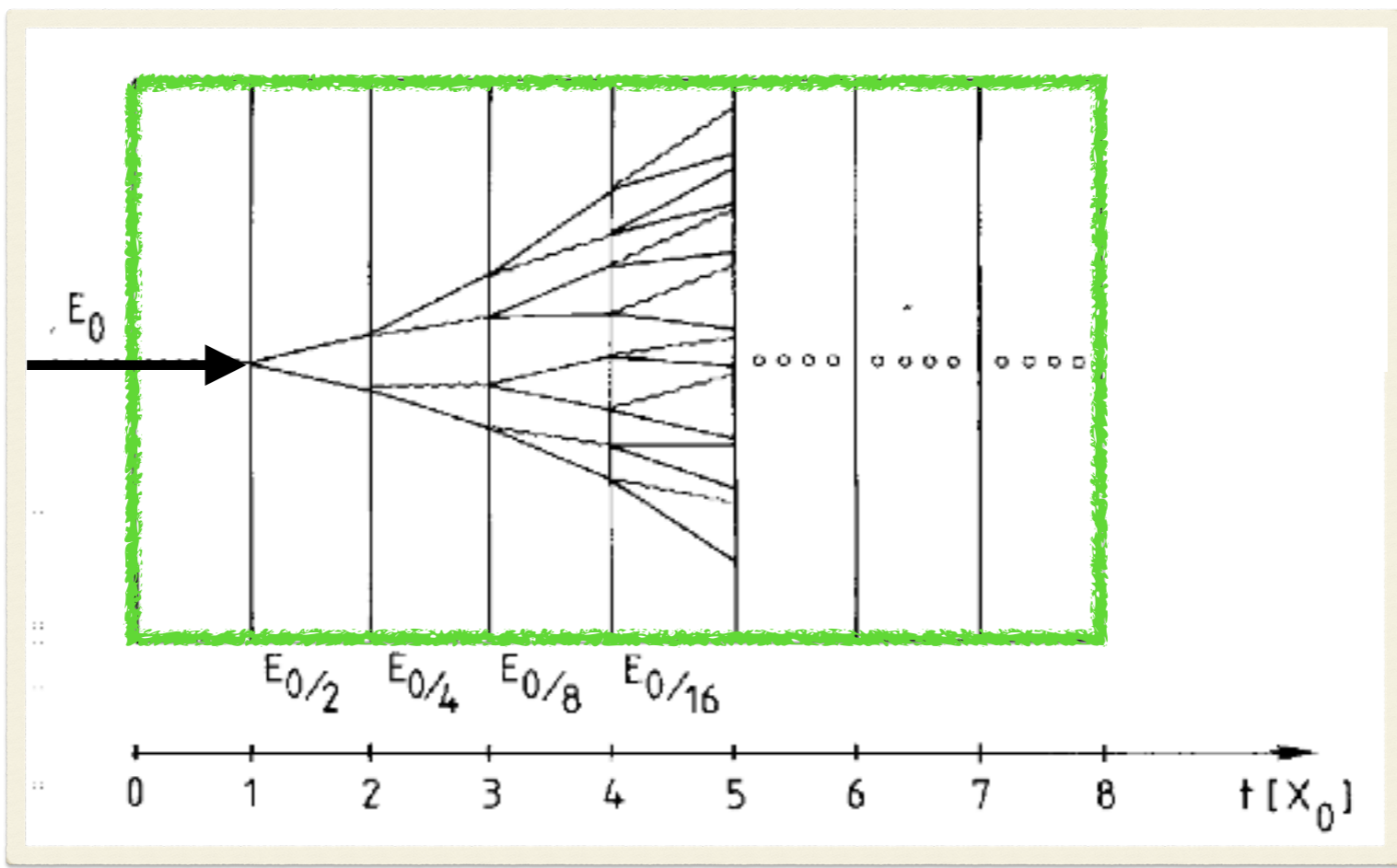


https://youtu.be/6KEB21_ngCE

Electromagnetic vs Hadronic interactions

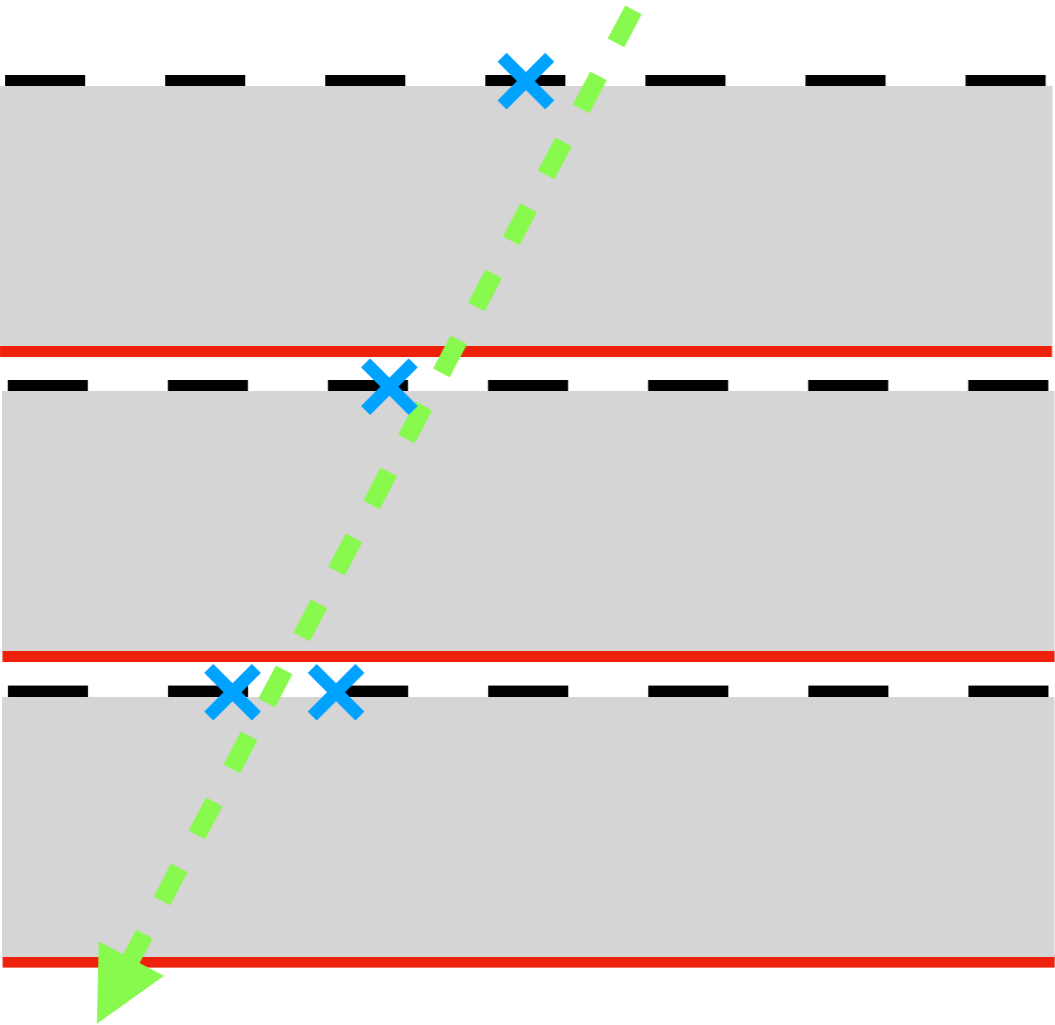


Bremsstrahlung radiation $\sim Z^2 E/m^2$



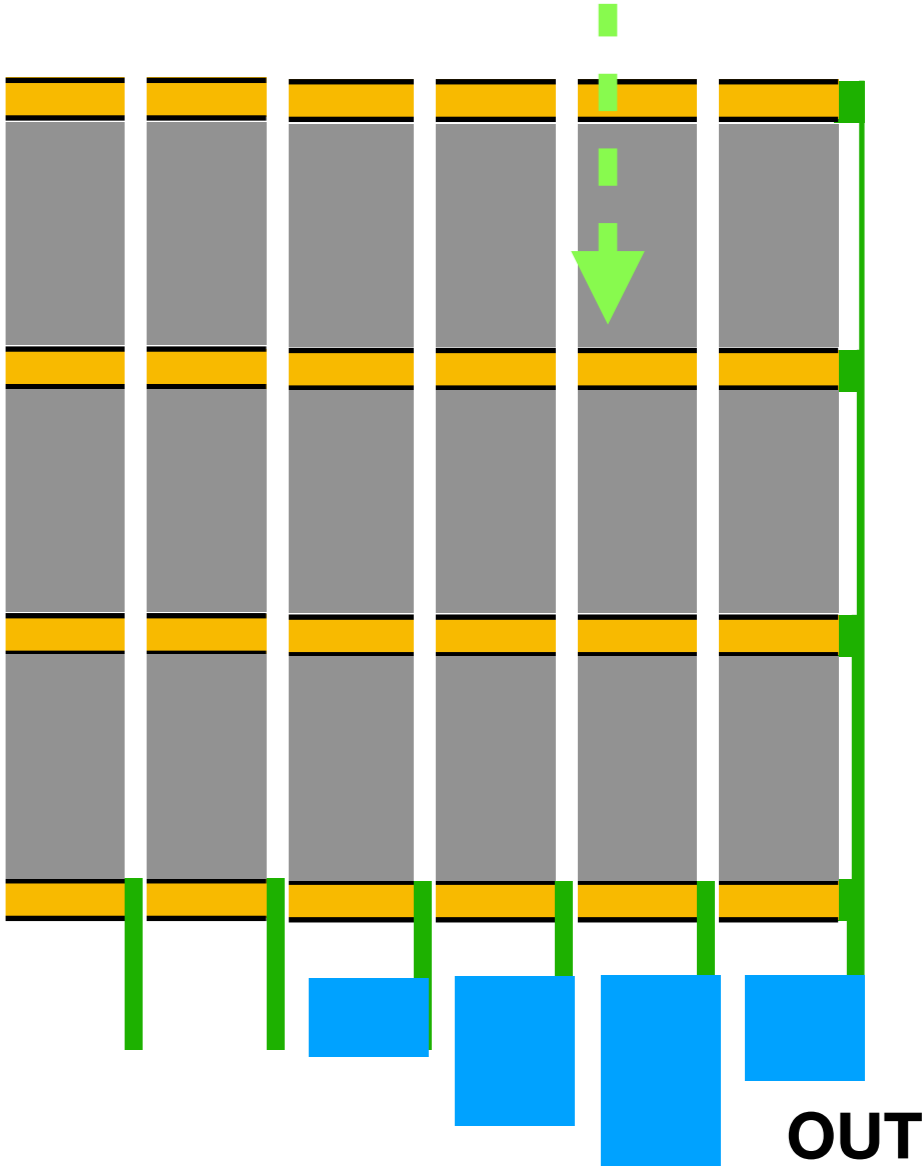
Particle detectors: Tracking vs Calorimetry

A typical tracker



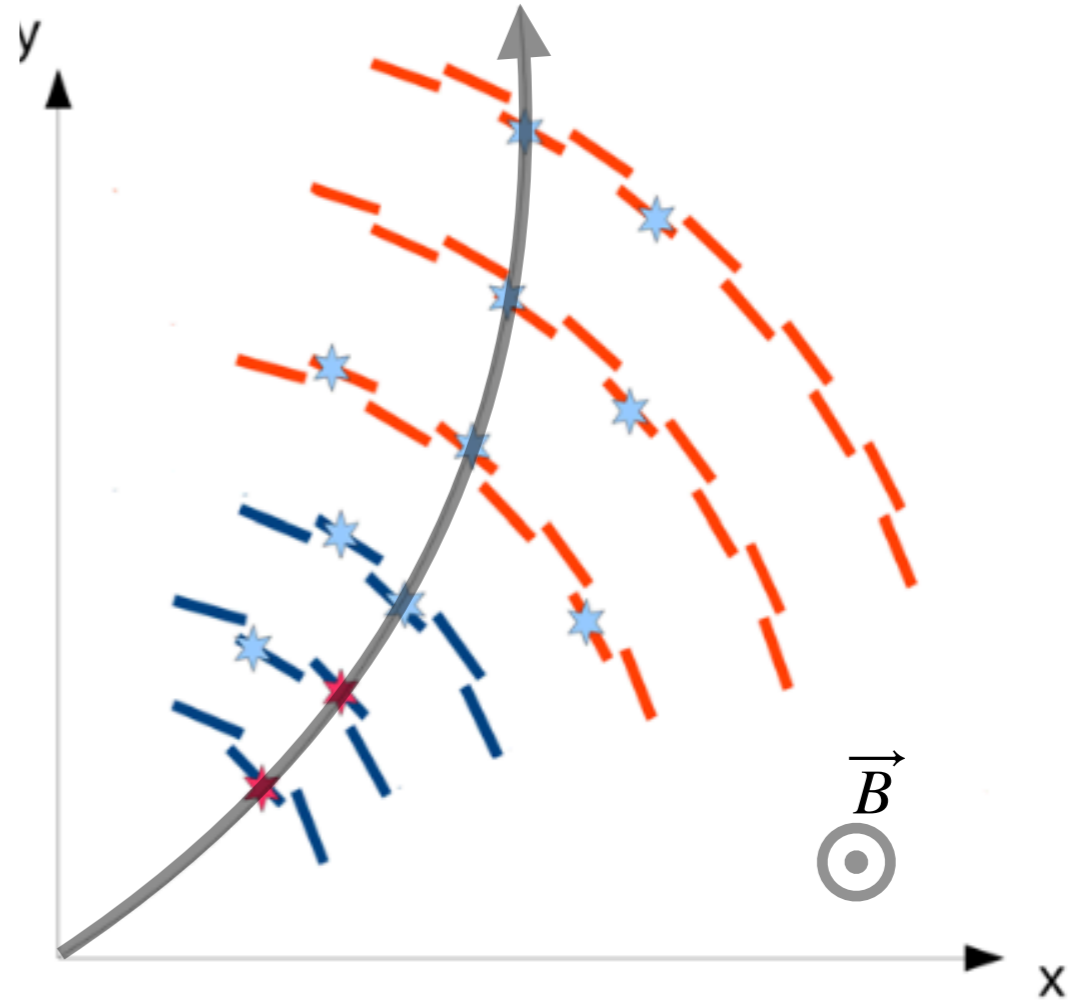
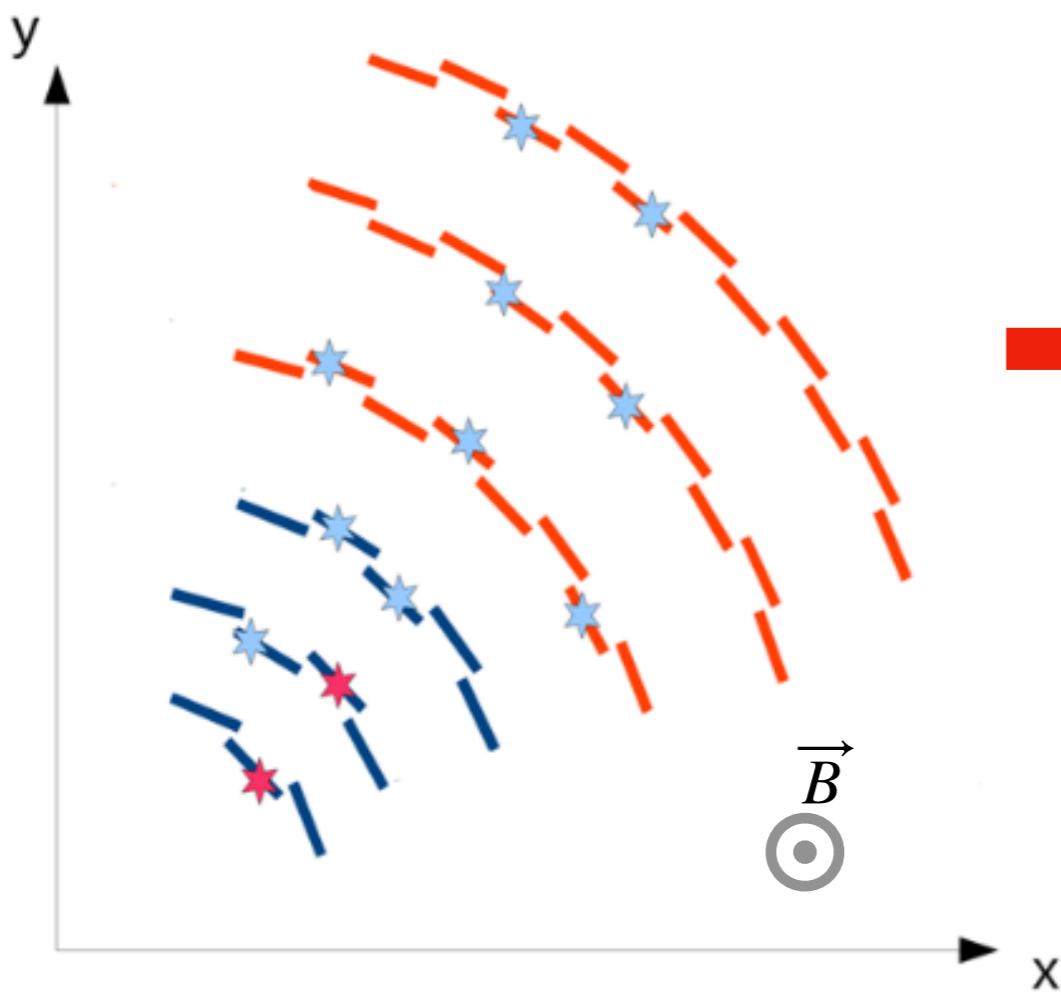
Blue: Information readout from detector
Next task: Connecting the “dots”

A typical calorimeter



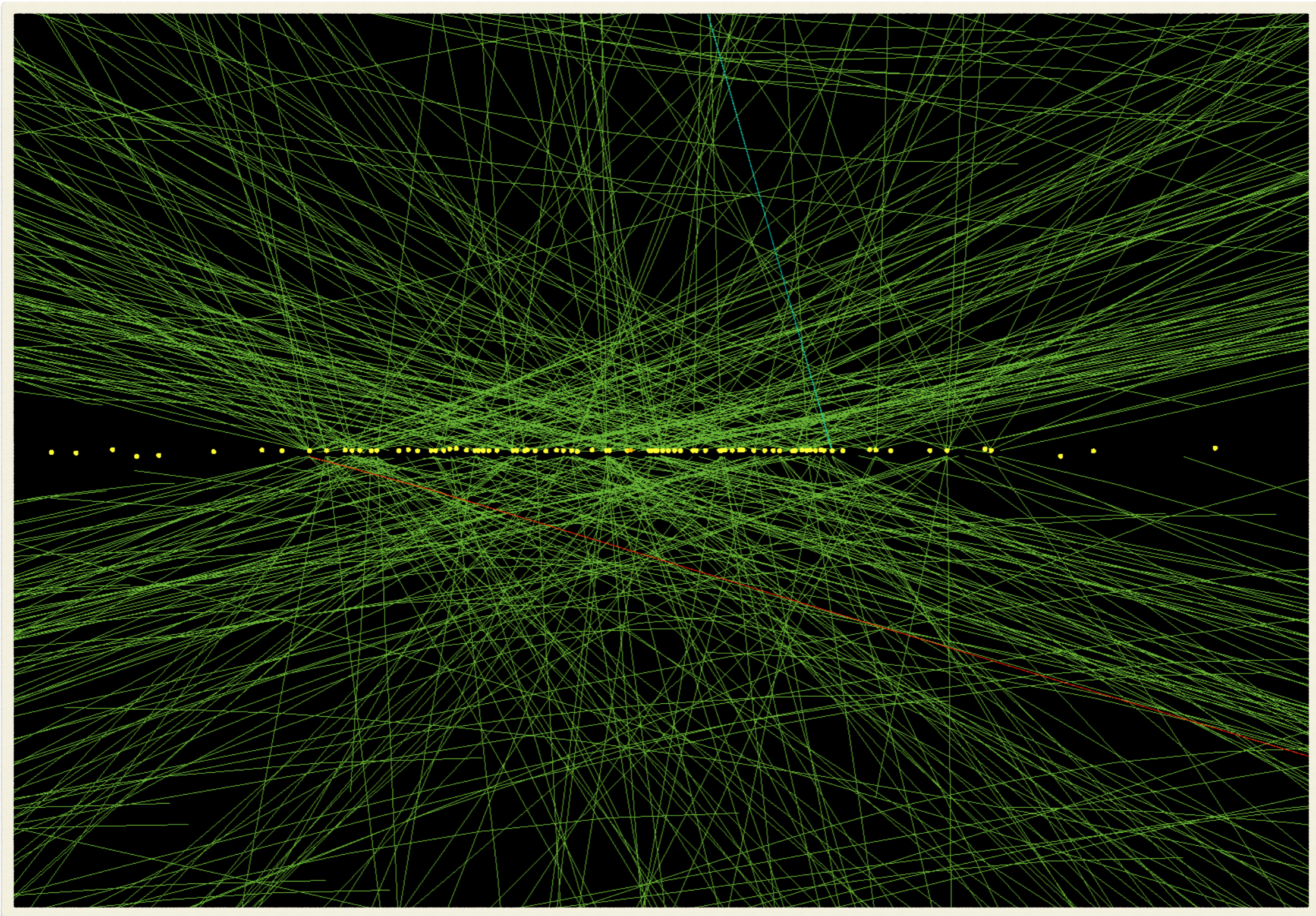
Blue: Information readout from detector
Next task: Clustering (grouping) the dots

Particle detectors: Connecting the dots



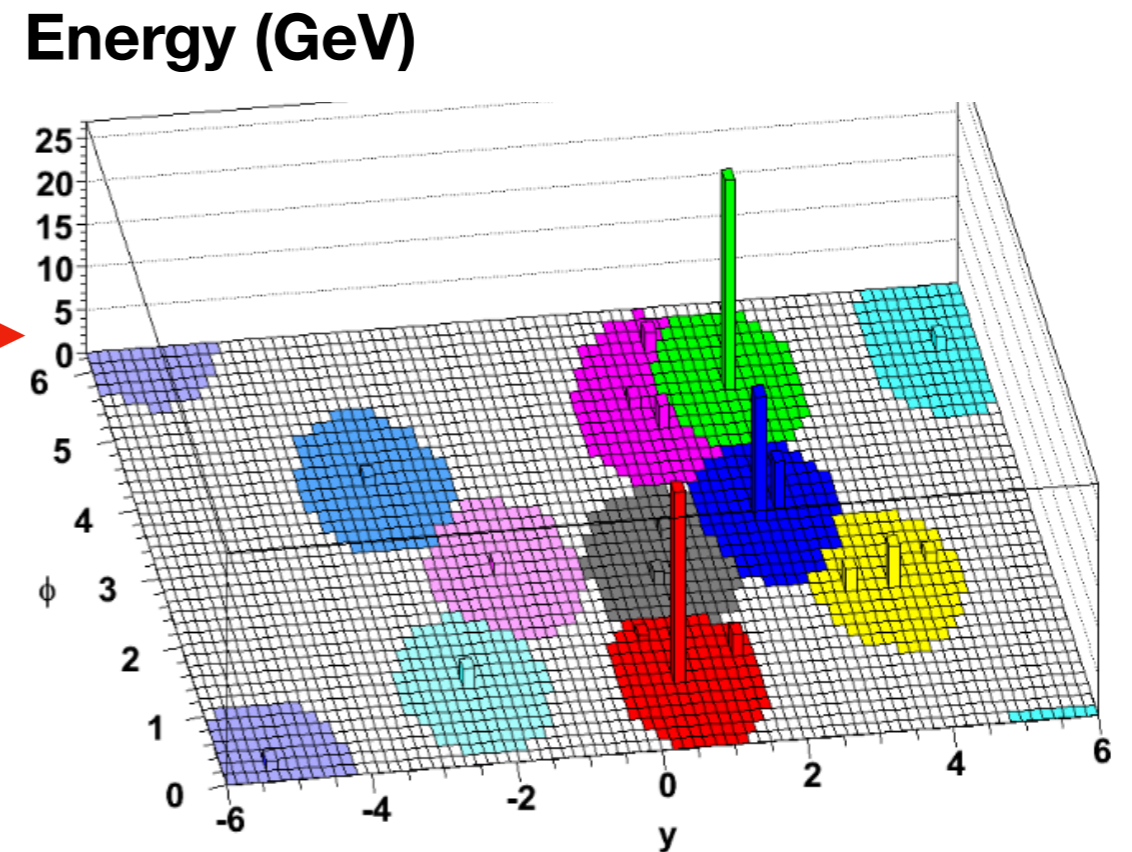
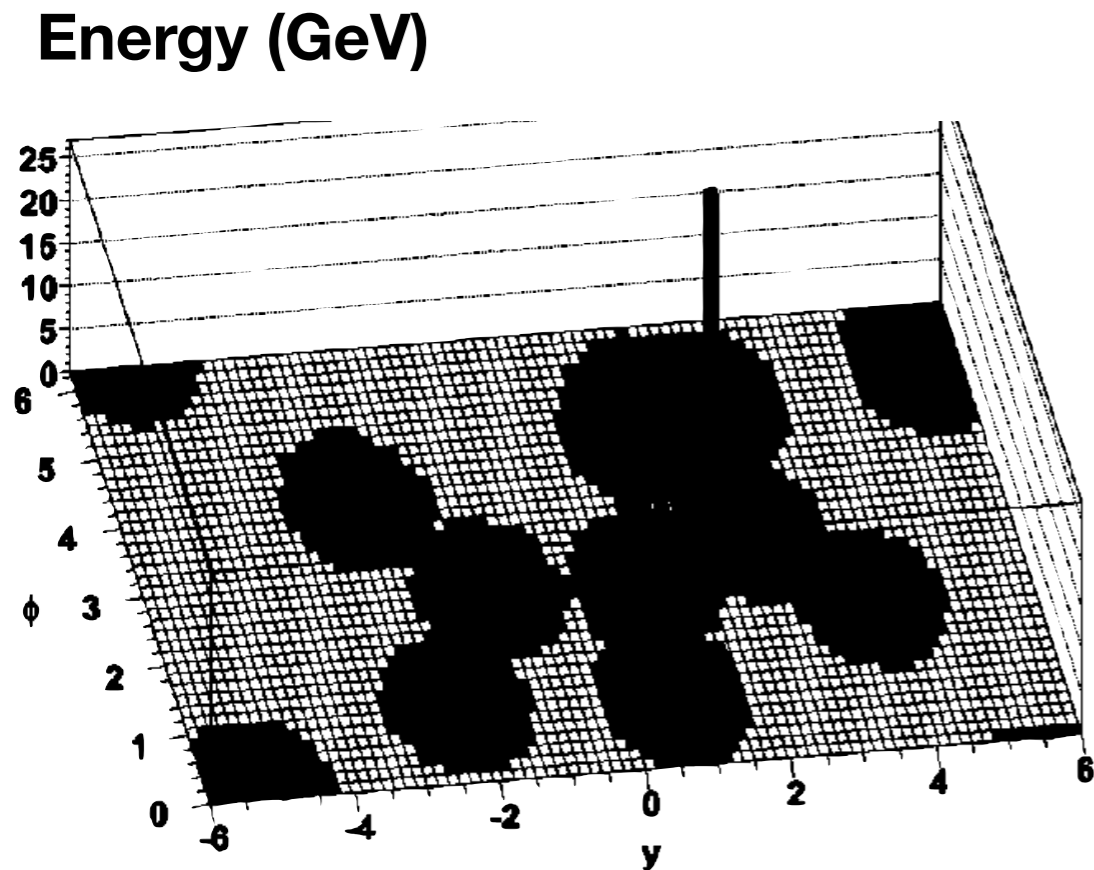
Is the curve correct?

Tracking in real life



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?

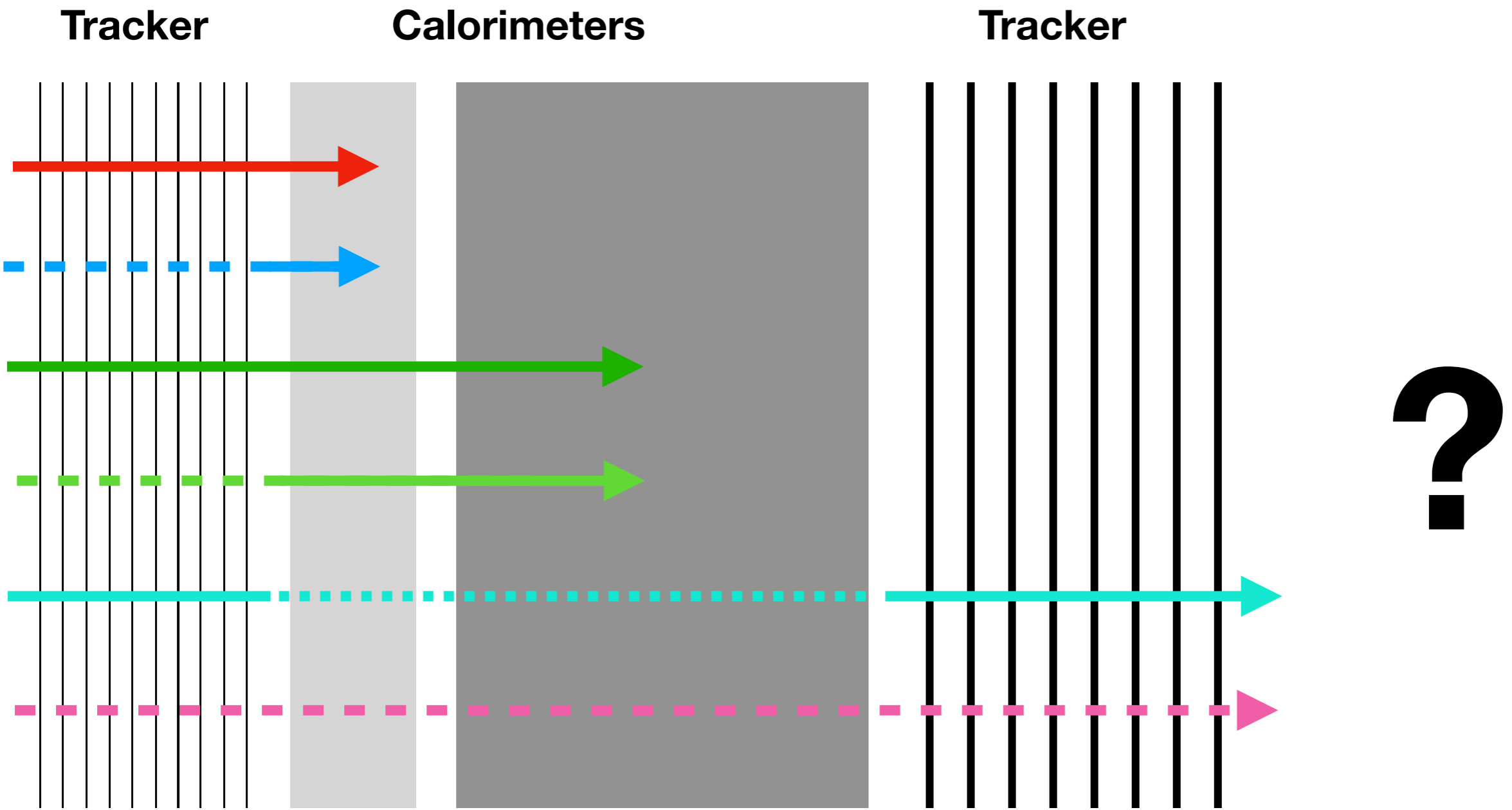
Identifying particles in CMS

QUARKS

mass charge spin	$\approx 2.2 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ u up	$\approx 1.28 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ c charm	$\approx 173.1 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ t top
	$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ d down	$\approx 96 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ s strange	$\approx 4.18 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ b bottom

LEPTONS

	$\approx 0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ e electron	$\approx 105.66 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ μ muon	$\approx 1.7768 \text{ GeV}/c^2$ -1 $\frac{1}{2}$ τ tau
	$< 2.2 \text{ eV}/c^2$ 0 $\frac{1}{2}$ ν_e electron neutrino	$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_μ muon neutrino	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_τ tau neutrino



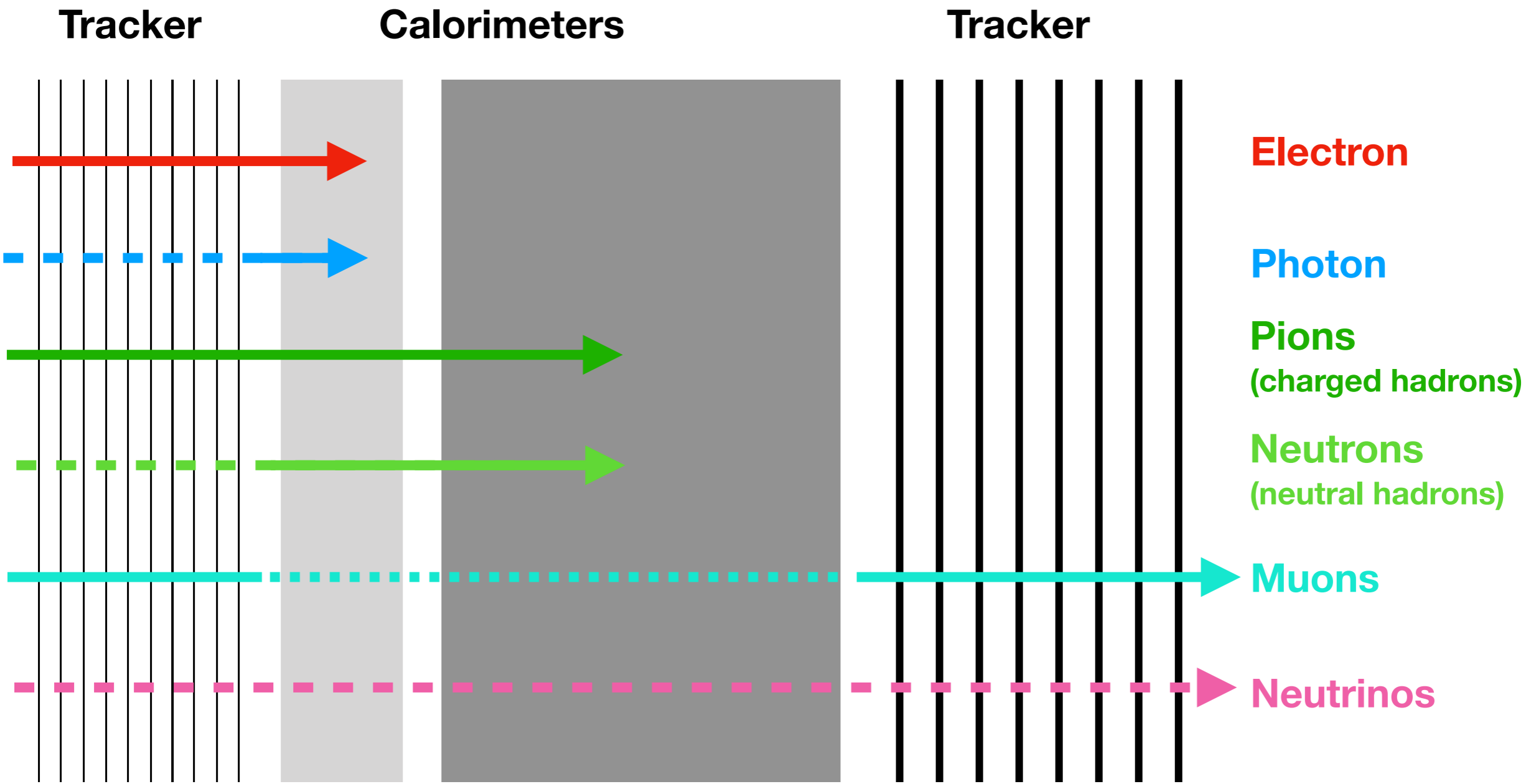
Identifying particles in CMS

QUARKS

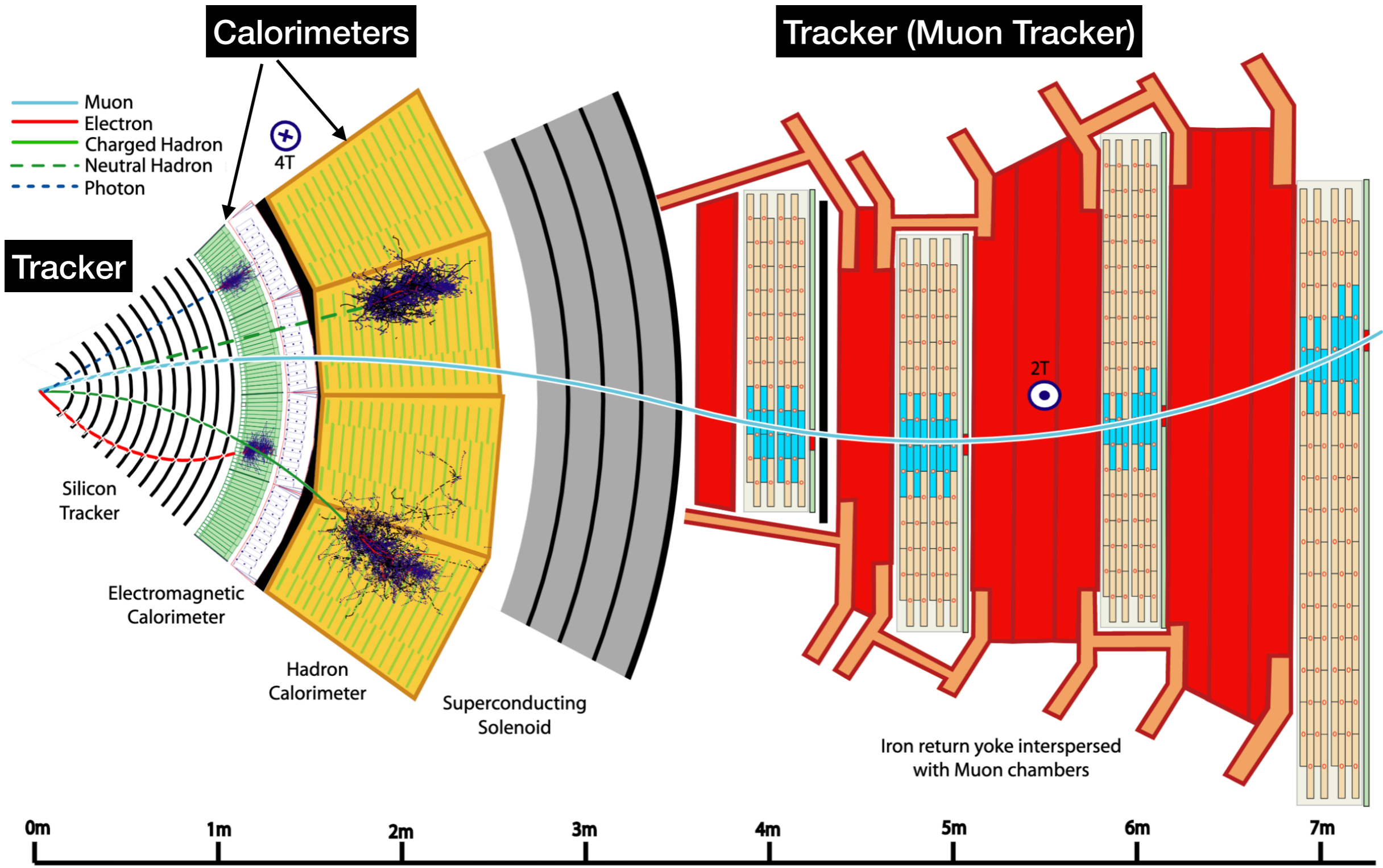
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Identifying particles in CMS





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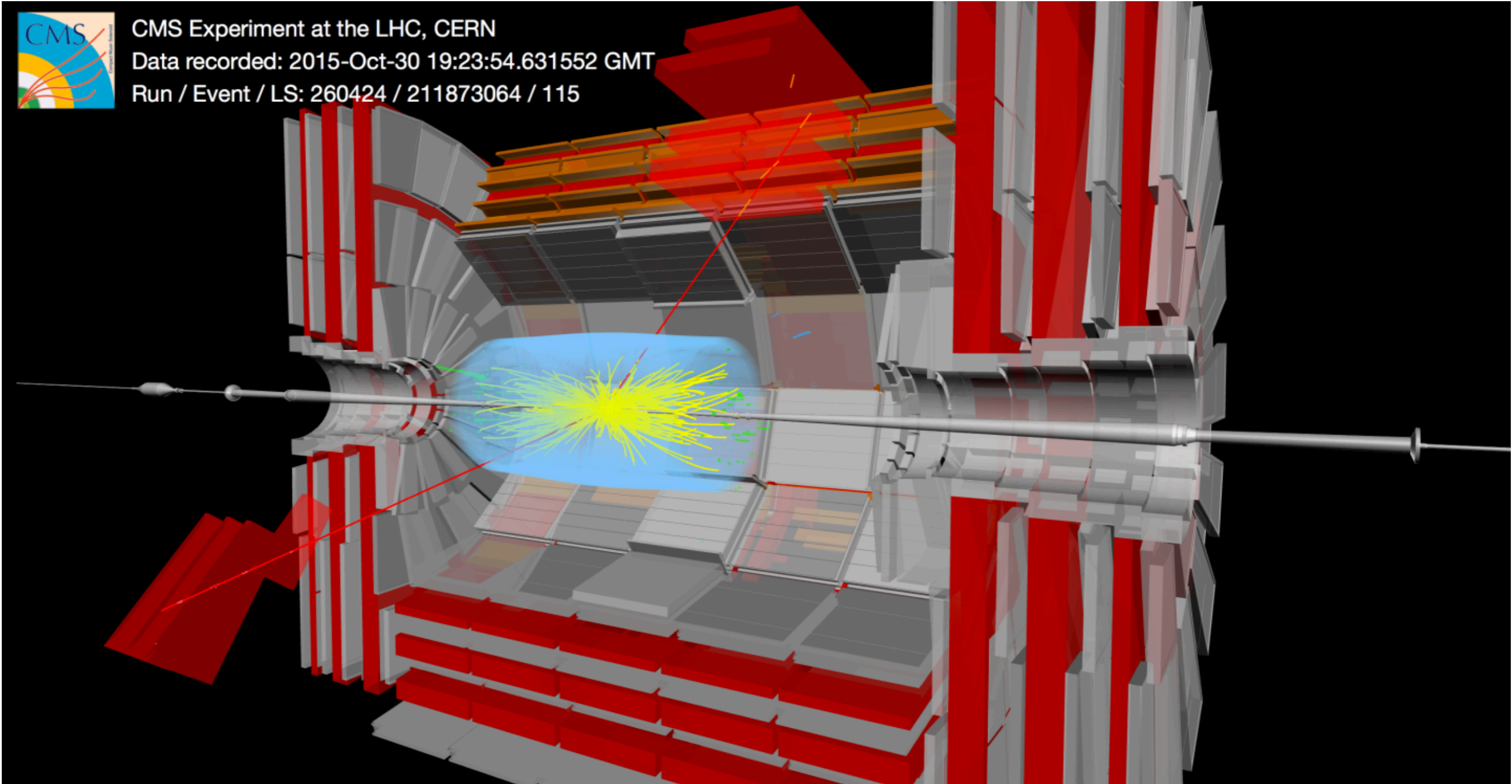
Particle collisions and data analysis

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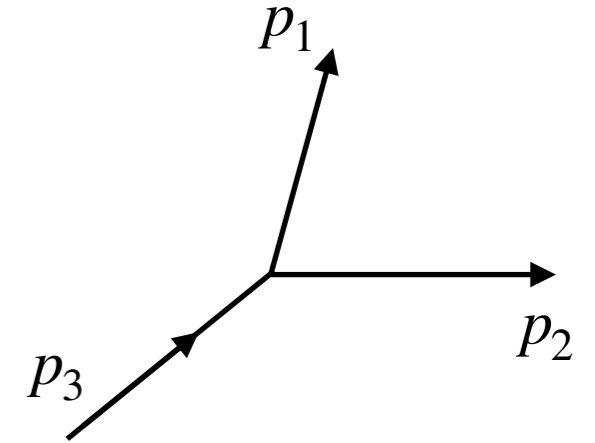
How does a Z boson look like in real life?



Special relativity crash course

$$E^2 = m^2 c^4 + |\vec{p}|^2 c^2 \quad \longrightarrow \quad E^2 = m^2 + |\vec{p}|^2$$

**Mass-energy
equivalence**



$$p_1 = (E_1, p_{x1}, p_{y1}, p_{z1}) \quad \vec{p}_1 = (p_{x1}, p_{y1}, p_{z1})$$

$$p_2 = (E_2, p_{x2}, p_{y2}, p_{z2}) \quad \vec{p}_2 = (p_{x2}, p_{y2}, p_{z2})$$

Four-momentum vs (3D) momentum

$$|p_1|^2 = E_1^2 - |\vec{p}_1|^2 = m_1^2$$

$$|p_2|^2 = E_2^2 - |\vec{p}_2|^2 = m_2^2$$

Length of four-momentum is invariant under Lorentz Transformations. This is the "invariant mass"

$$p_3 = p_1 + p_2 = (E_1 + E_2, p_{x1} + p_{x2}, p_{y1} + p_{y2}, p_{z1} + p_{z2})$$

$$m_3^2 = |p_3|^2 = (E_1 + E_2)^2 - |\vec{p}_1 + \vec{p}_2|^2$$

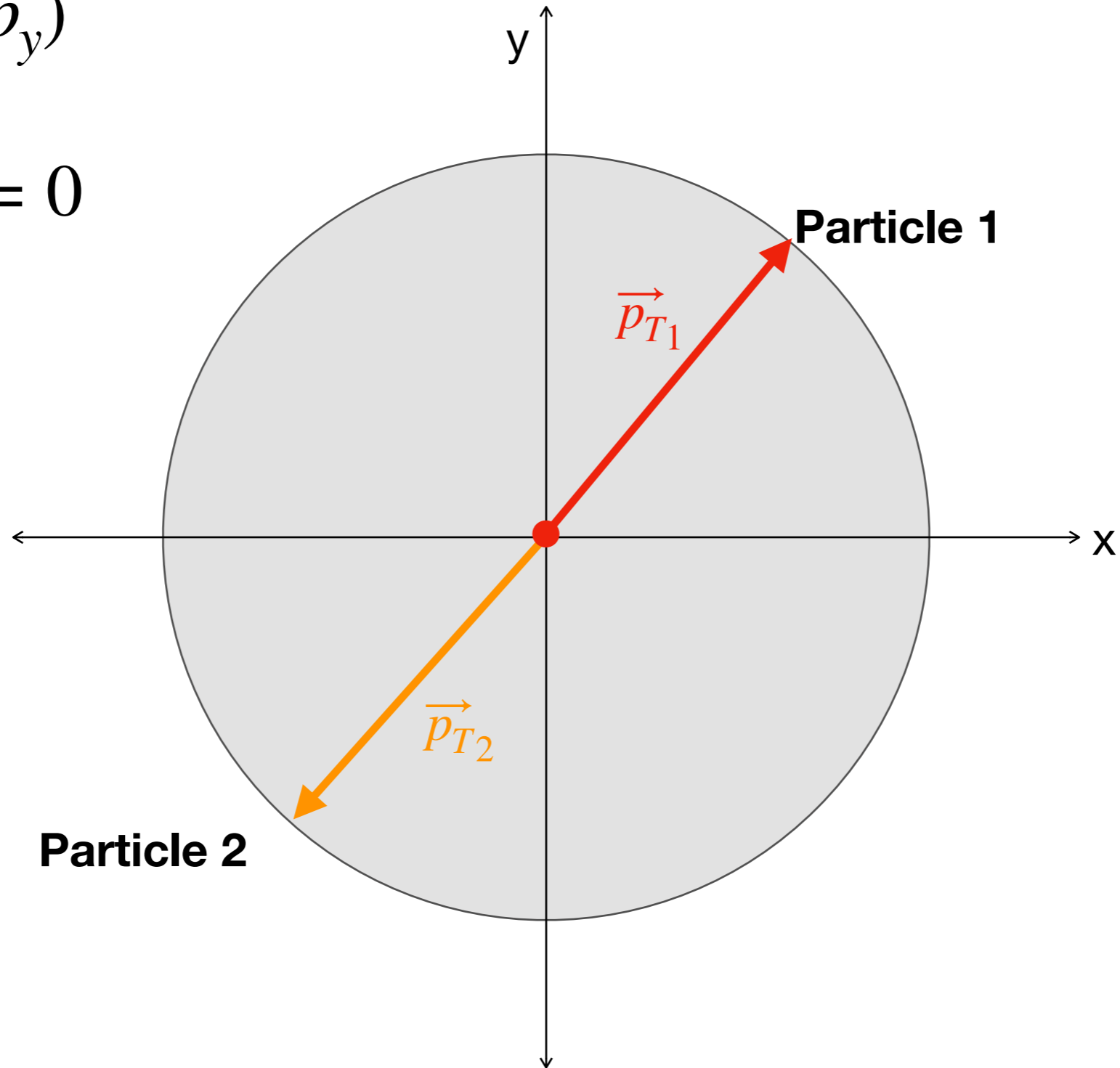
Sum of 2 four-momenta follow conservation of energy and momentum.

Invariant mass of particles #1 and #2

Momentum balance in the xy plane

$$\vec{p}_T = (p_x, p_y)$$

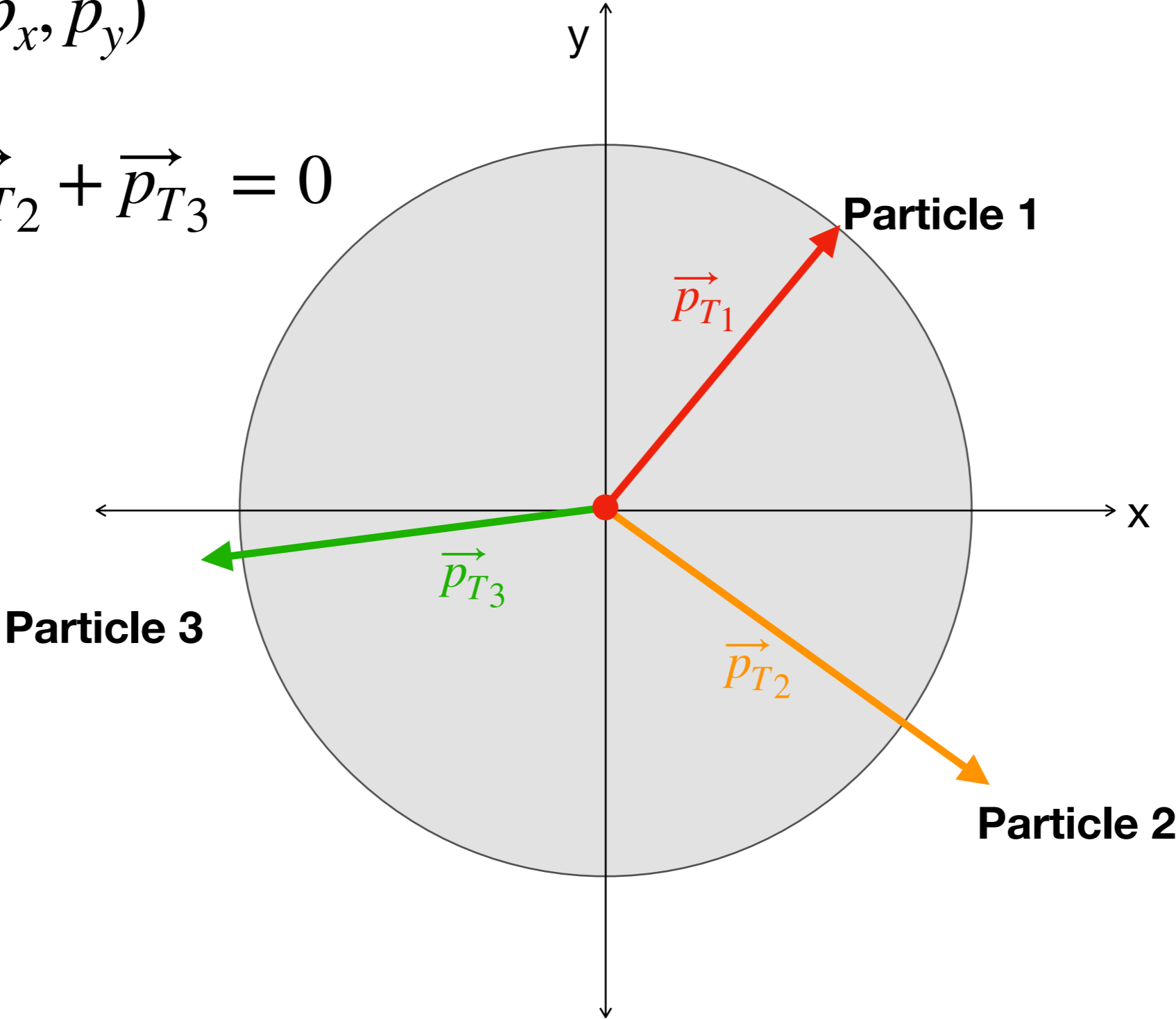
$$\vec{p}_{T1} + \vec{p}_{T2} = 0$$



Momentum balance in the xy plane

$$\vec{p}_T = (p_x, p_y)$$

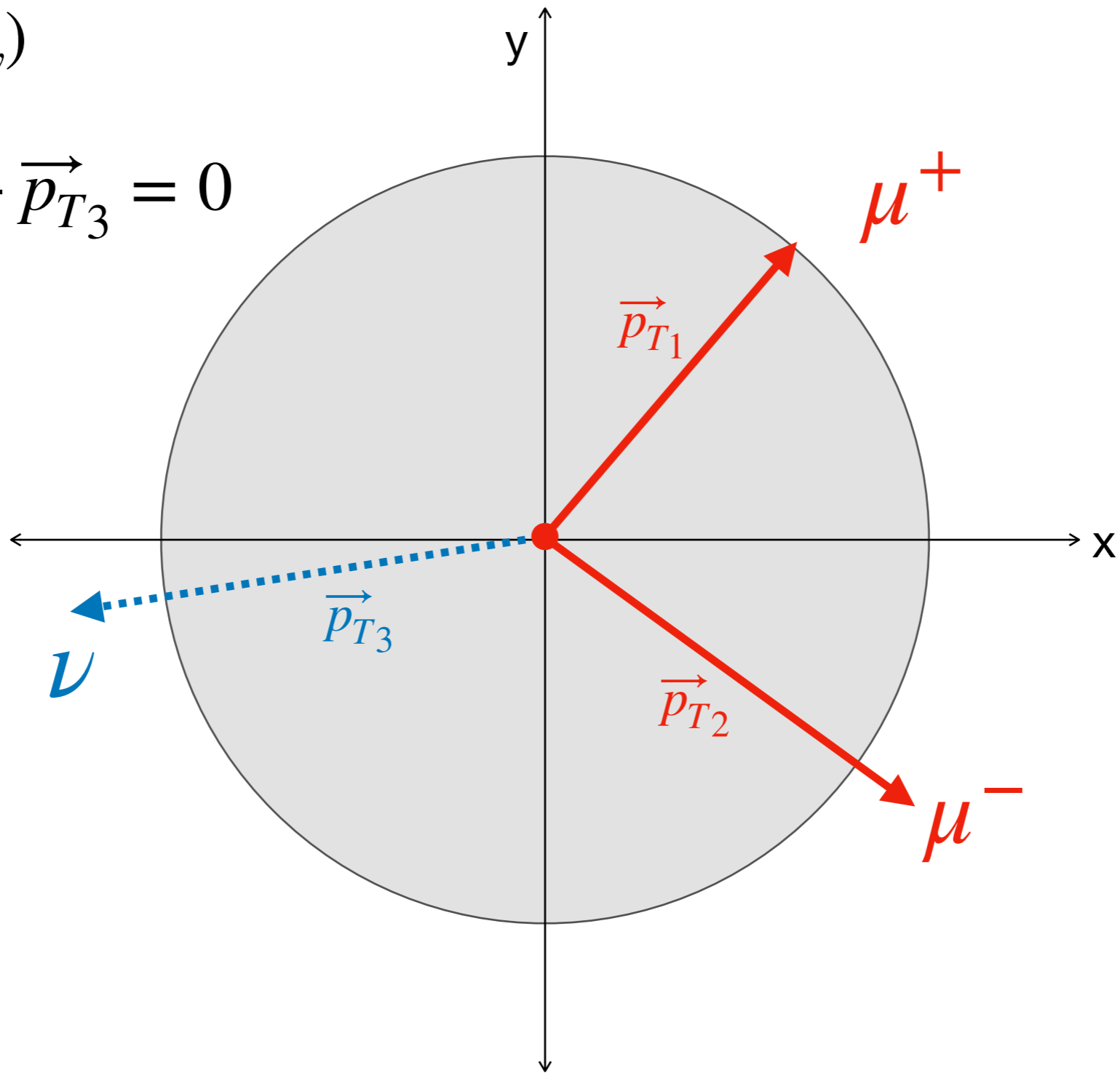
$$\vec{p}_{T1} + \vec{p}_{T2} + \vec{p}_{T3} = 0$$



What about neutrinos?

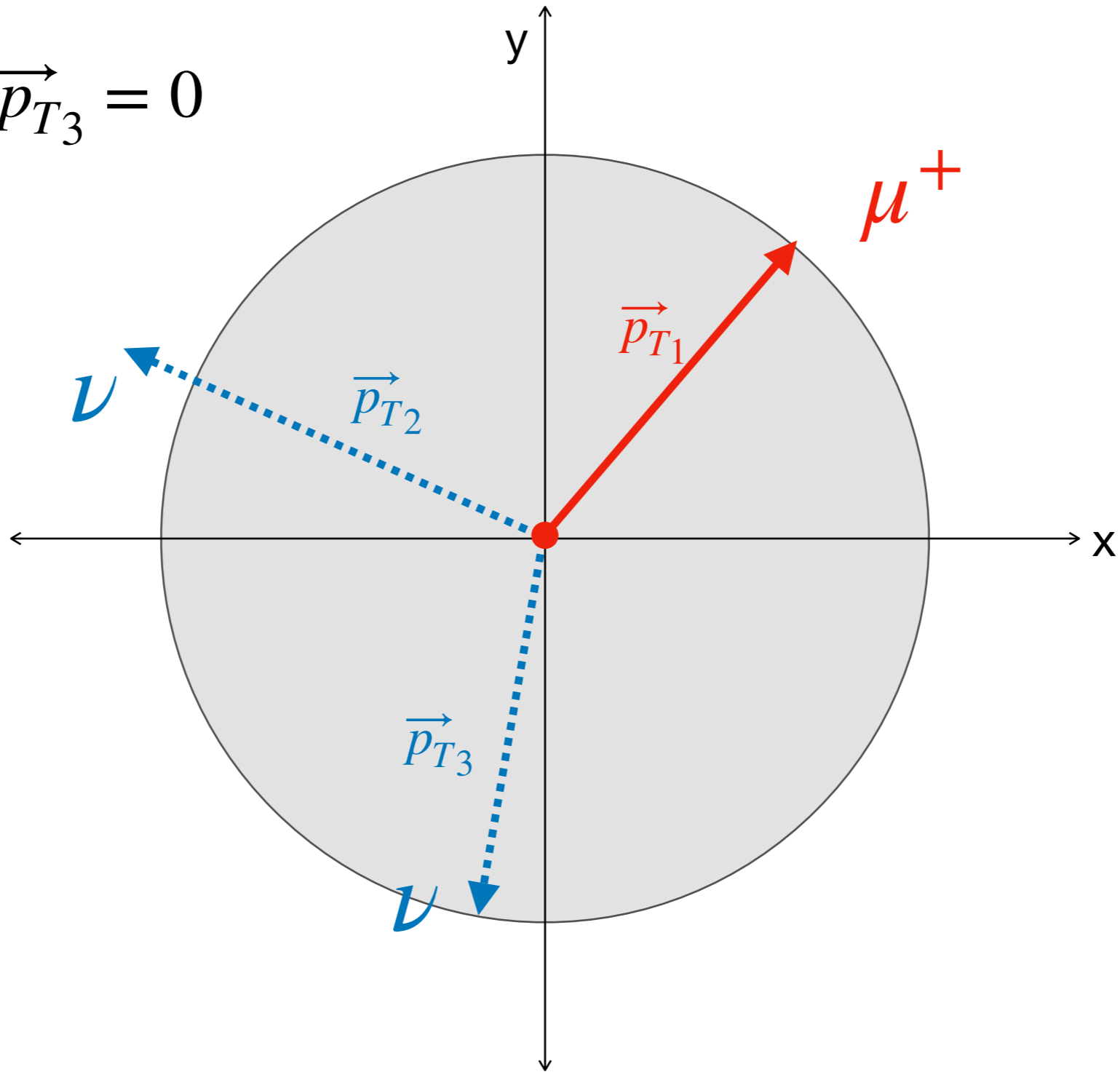
$$\vec{p}_T = (p_x, p_y)$$

$$\vec{p}_{T1} + \vec{p}_{T2} + \vec{p}_{T3} = 0$$



What about neutrinos?

$$\vec{p}_{T1} + \vec{p}_{T2} + \vec{p}_{T3} = 0$$

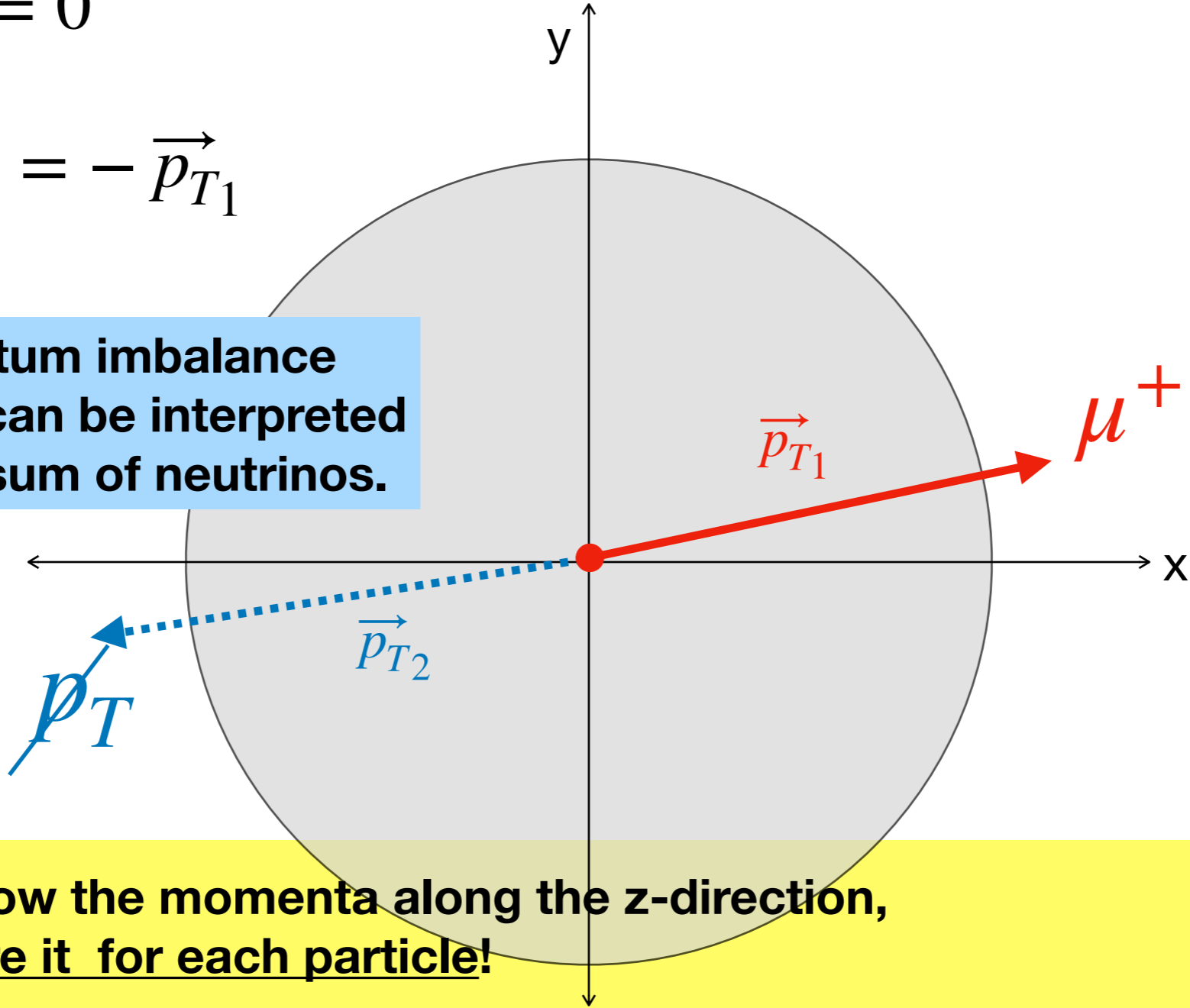


Restoring the order: missing momentum

$$\vec{p}_{T1} + \vec{p}_{T2} = 0$$

$$\cancel{\vec{p}_T} \equiv \vec{p}_{T2} = -\vec{p}_{T1}$$

The momentum imbalance measurement can be interpreted as the vector sum of neutrinos.



If we don't know the momenta along the z-direction, let's just ignore it for each particle!

$$\vec{p}_T = (p_x, p_y) \quad E_T^2 = m^2 + |\vec{p}_T|^2$$

$$m_{T3}^2 = (E_{T1} + E_{T2})^2 - |\vec{p}_{T1} + \vec{p}_{T2}|^2$$

Transverse mass (M_T) is useful when there is missing momentum in the event!



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Backup

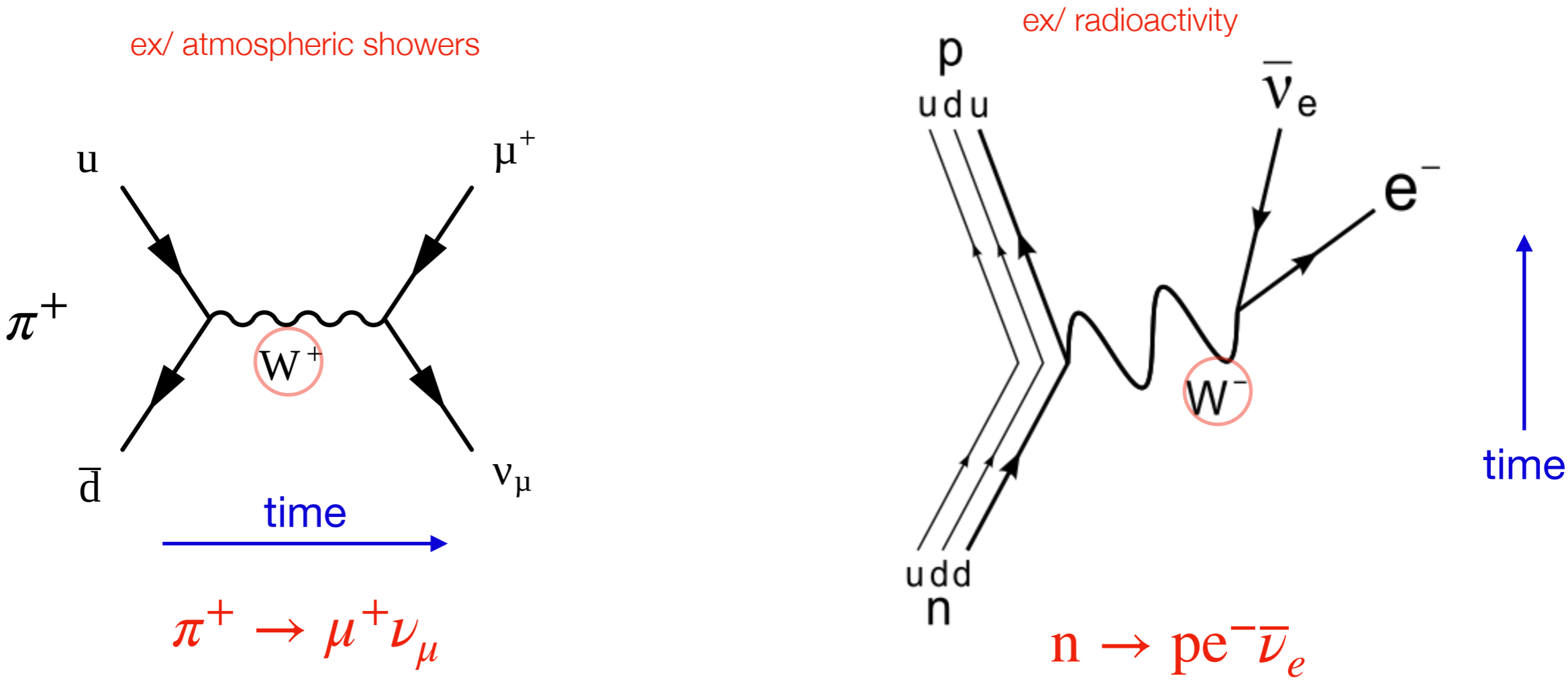
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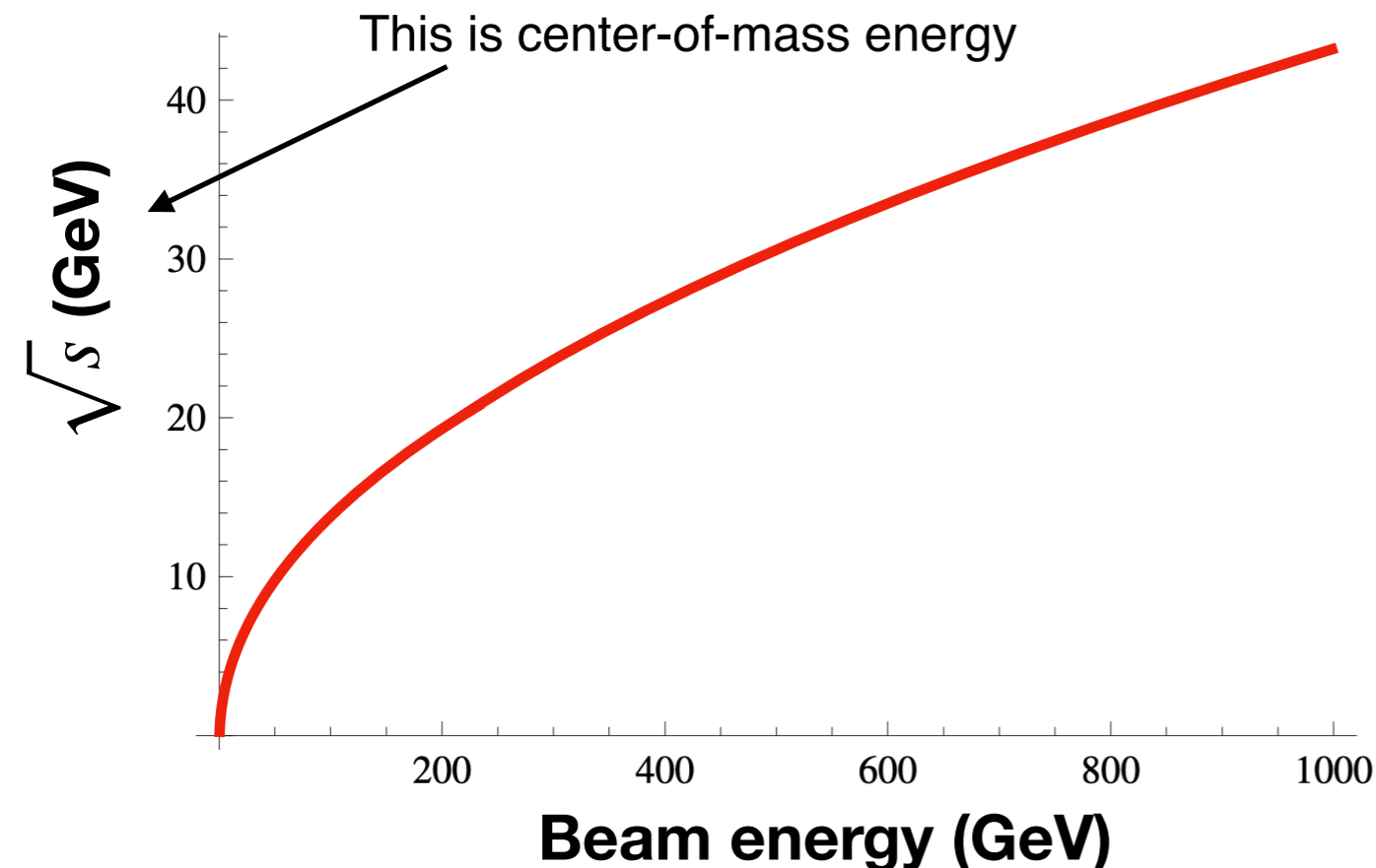
Particle decays in Feynman diagrams

- We can use these “ingredients” for an **economical description** of processes (interactions) we observe in our universe.
- These can be represented by **Feynman diagrams**.



Why do we collide protons?

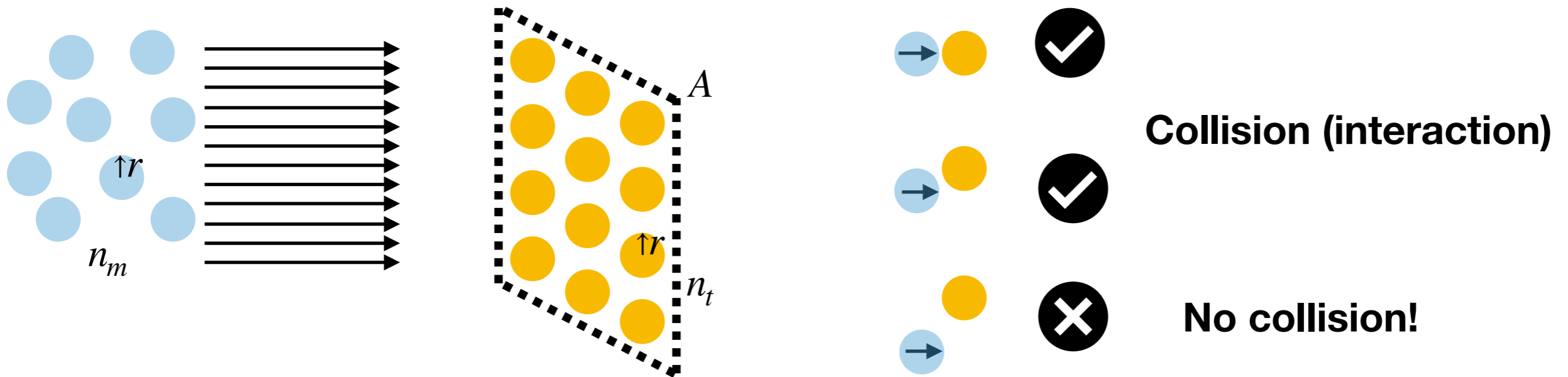
- Just shooting one proton to another fixed proton is easier (experimentally).
- Center of mass energy \sqrt{s} is a measure of the energy available for the production of new particles after the collision, remember $E = mc^2$. This is important if we aim to produce new, unknown, potentially heavy particles.
- Colliding protons is more efficient in this sense!



Colliding	$\sqrt{s} \sim E_{\text{Beam}}$
Fixed target	$\sqrt{s} \sim \sqrt{E_{\text{Beam}}}$

To achieve $\sqrt{s} = 100$ GeV with protons:
Colliding beam energy ~ 50 GeV
Fixed target beam energy ~ 5000 GeV

How to quantify amount of data and interactions?



Probability of interaction?

$$P_{int} = \frac{1}{A} \int p(x, y) dA \longrightarrow p(x, y) = \begin{cases} 1 & \text{if } x^2 + y^2 < 2r \\ 0 & \text{else} \end{cases}$$

$$\begin{aligned} N_{int} &= n_m P_{int} = n_m \frac{n_t \pi (2r)^2}{A} \\ &= \frac{n_m n_t}{A} \pi (2r)^2 \\ &= L \sigma \end{aligned}$$

L (Luminosity) is a property of how many particles we collide and how closely we pack them (in units of inverse area).

σ (cross-section) is a property of the interaction (in units of area). In elementary particle interactions $p \sim |\langle \psi_i | S | \psi_f \rangle|^2$

The units of area

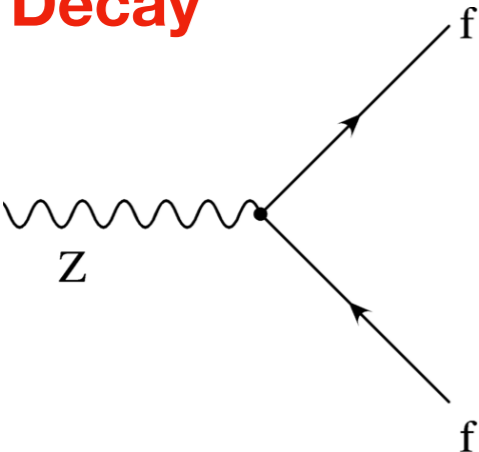


- The **relevant cross-section (i.e. area) unit** at the LHC is typically **femtobarns**, or **picobarns**, ..
- Why is the unit **barn** and not m^2 or cm^2 ?
- In 1940s, physicists working at Purdue University in Indiana (USA) wanted a catchy name for **the size of an atomic nucleus of uranium (this happens to be large compared to other atomic nuclei)**. They chose the “barn” as the unit! → **“broad as a barn door”**
- **A femtobarn (fb), then, is $10^{-39} cm^2$** ($1 b = 10^{-24} cm^2 = 100 fm^2$).
- **The amount of data collected by a detector is reported in units of inverse area..**
- Note that the **smaller the units of (integrated) luminosity, the larger the actual amount of data** in that dataset!

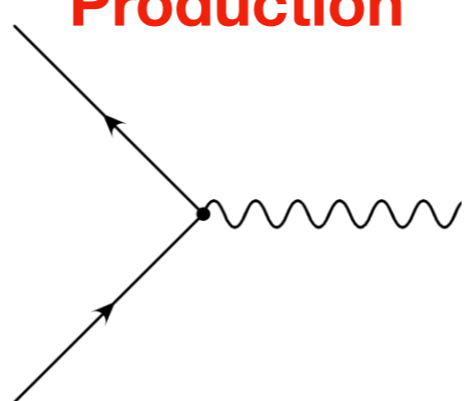


Particle Production, Decay, Lifetime, Width

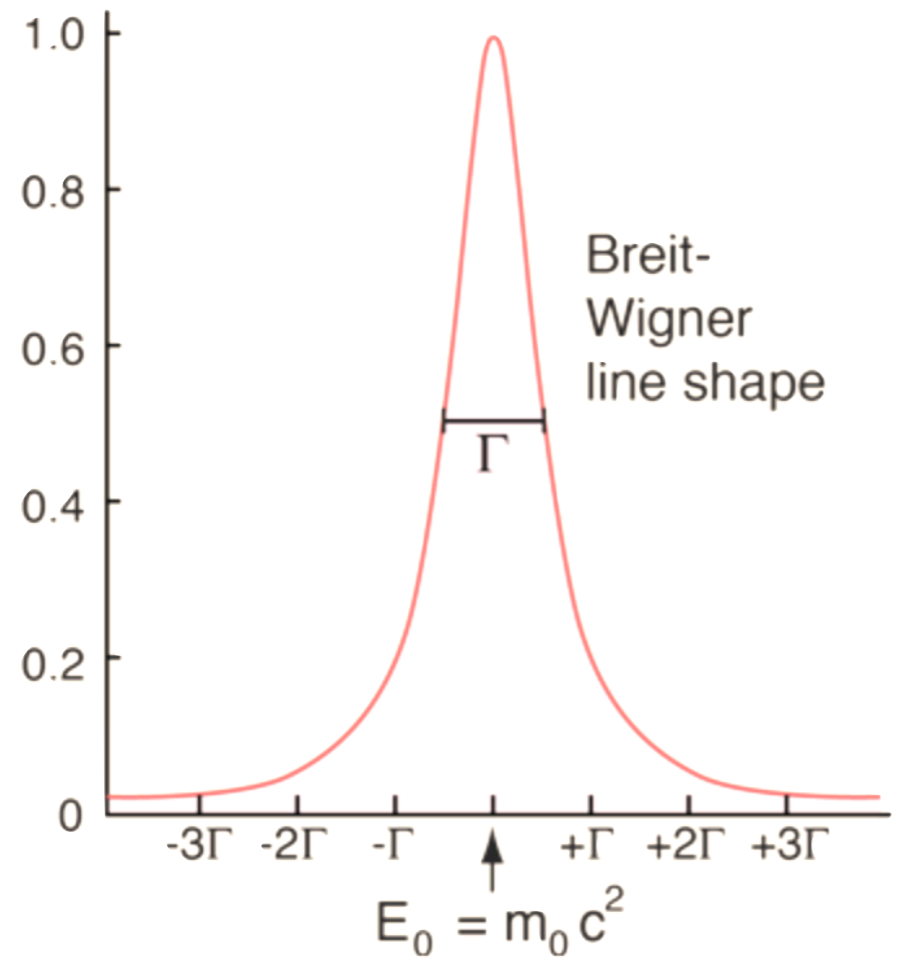
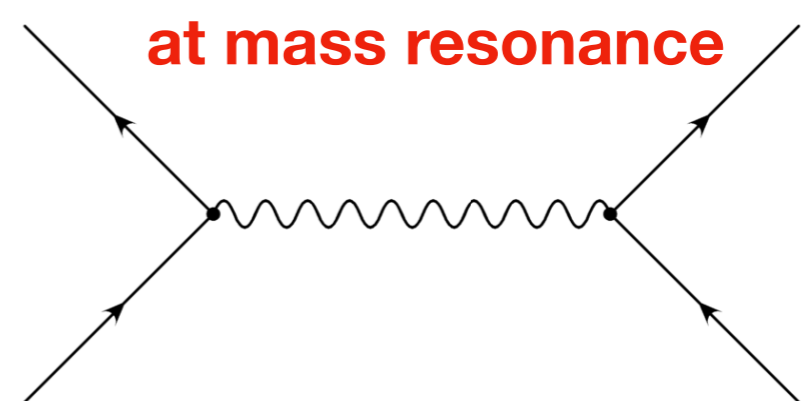
Decay



Production



Production+Decay at mass resonance

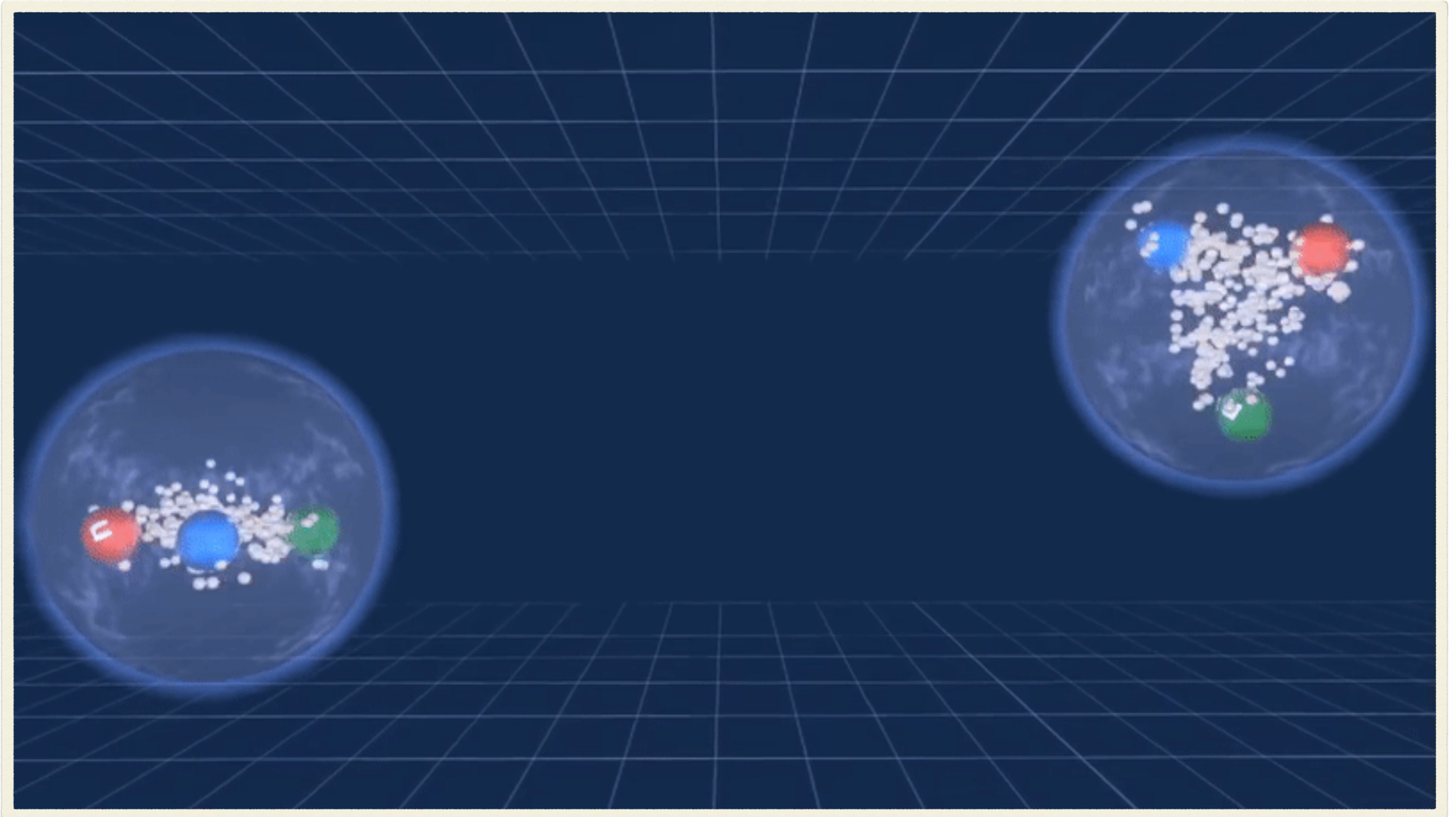


Heisenberg uncertainty principle states that : $\Delta E \Delta t > \frac{\hbar}{2}$

This means for particles with **short lifetimes**, there will be a **significant uncertainty** in the “energy”.

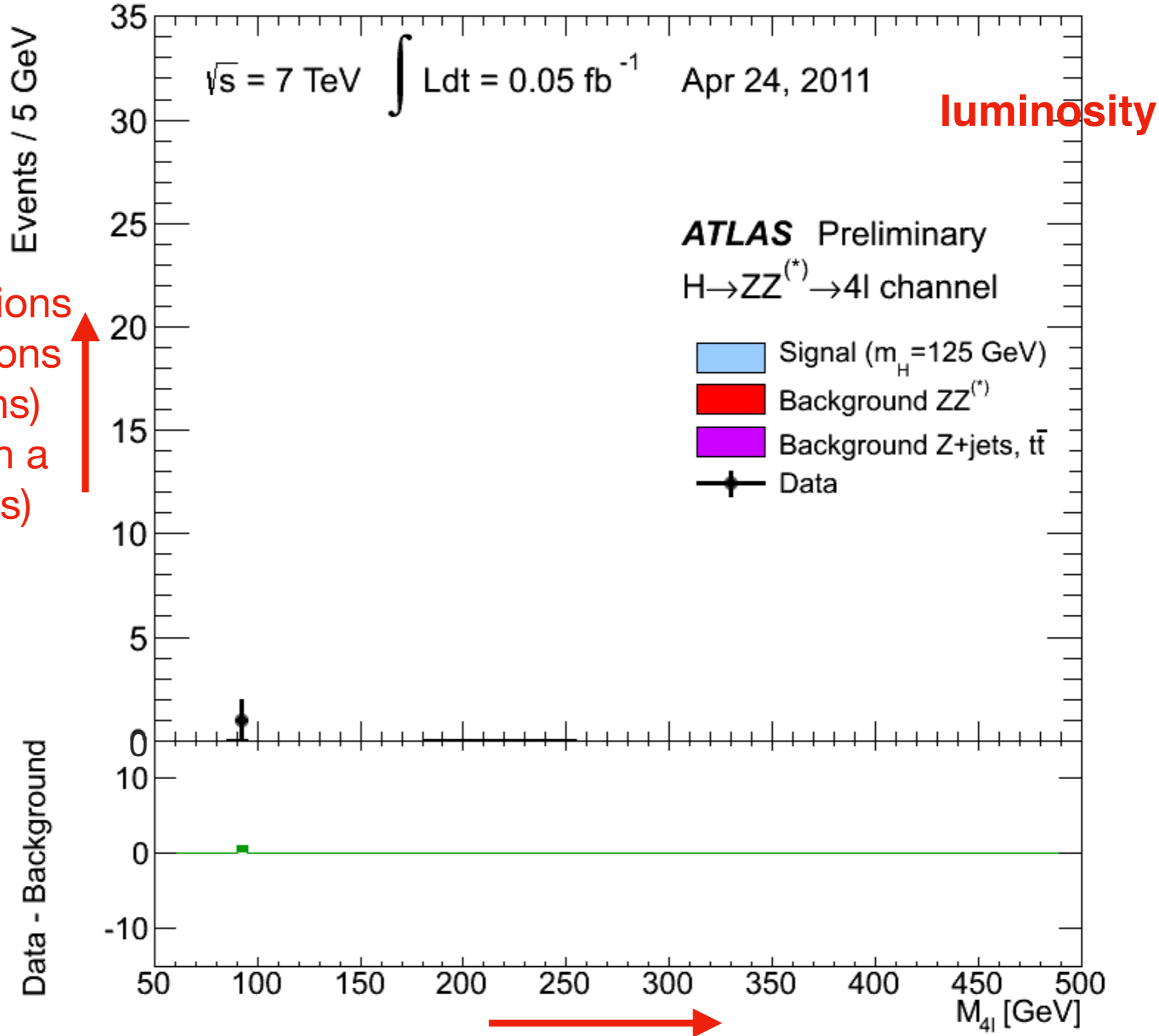
Repeated measurement of the energy (mass) of an unstable particle will give a distribution of energies called a Breit-Wigner distribution.

Colliding protons to produce a H boson



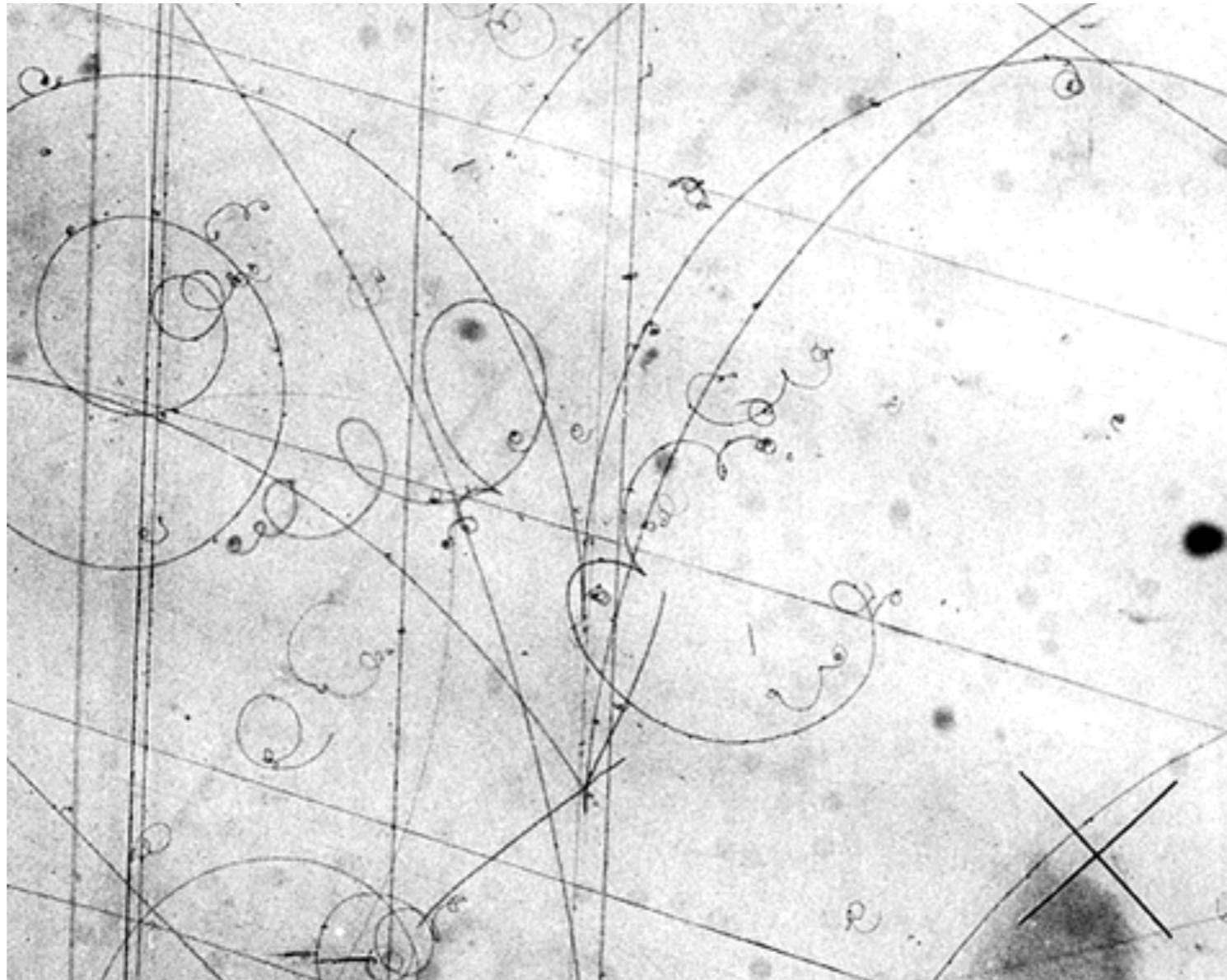
What is the benefit of more data?

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



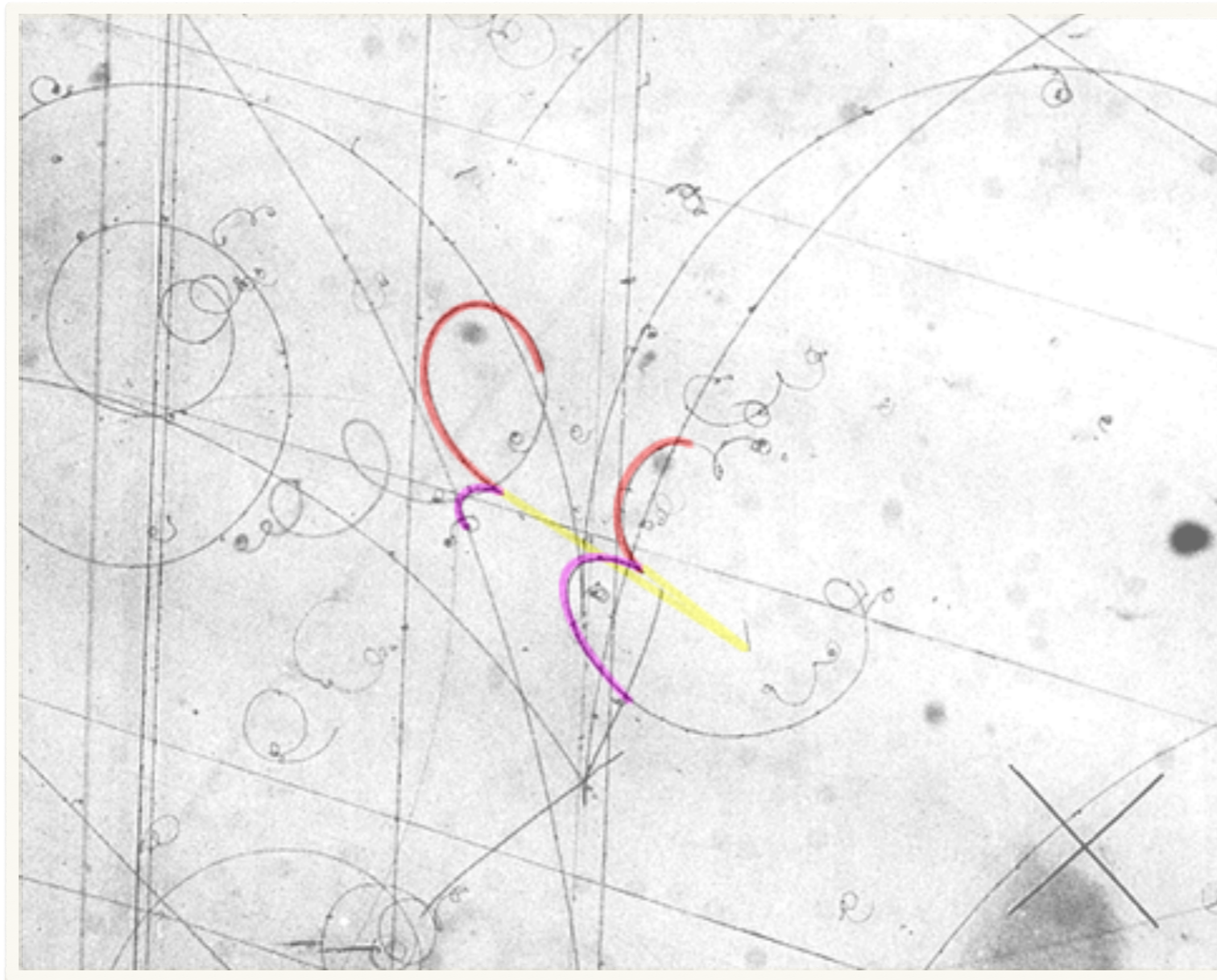
Early trackers

- In the pre-digital era, many different techniques were used, most of which dependent on ionization.
- A bubble chamber works by the vapor tracks formed along the ionization path of charged particles in a superheated liquid (hydrogen).



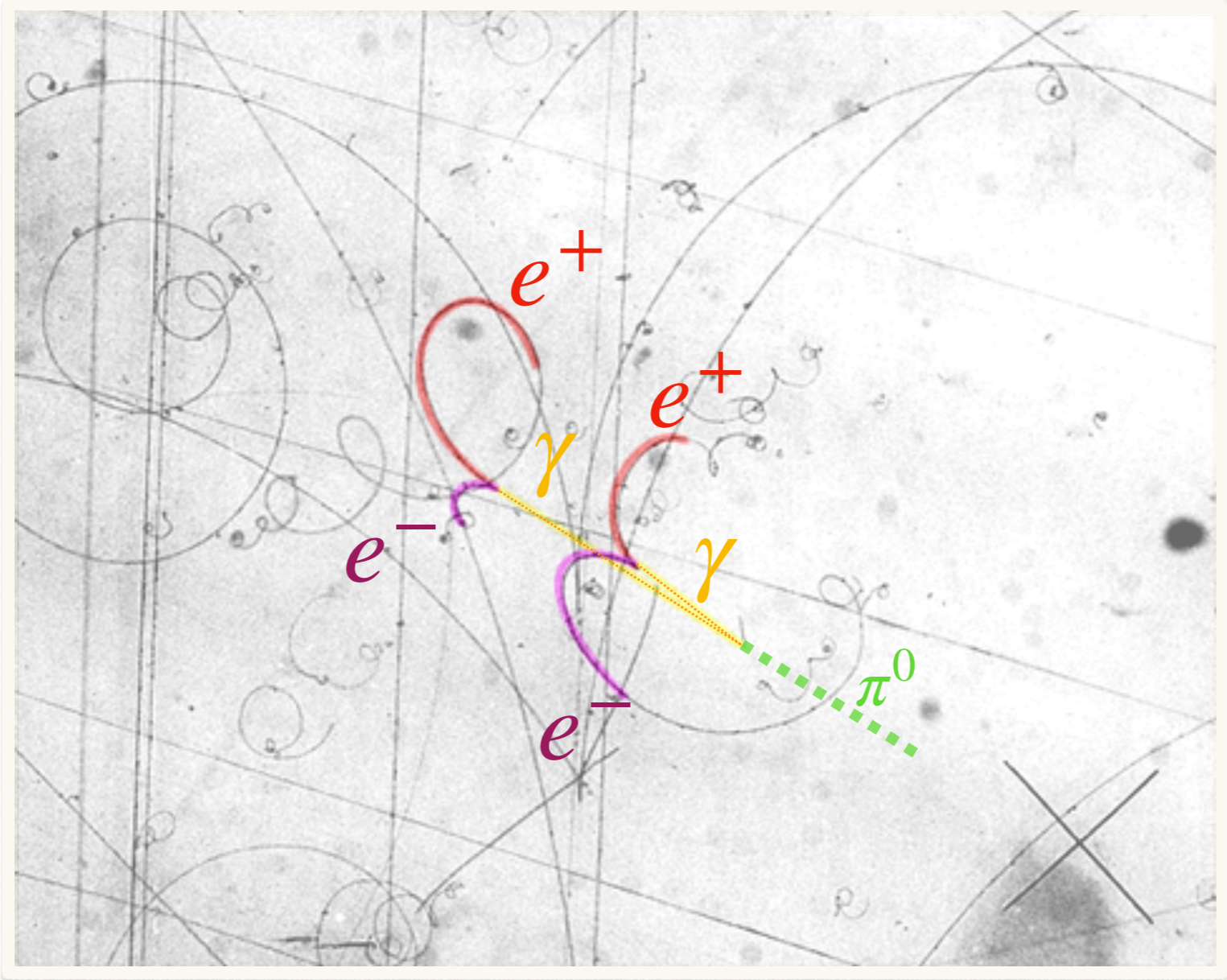
Early trackers

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

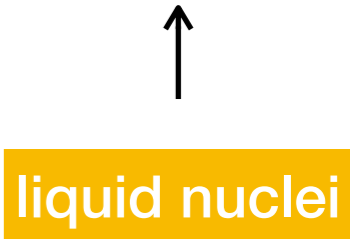


Early trackers

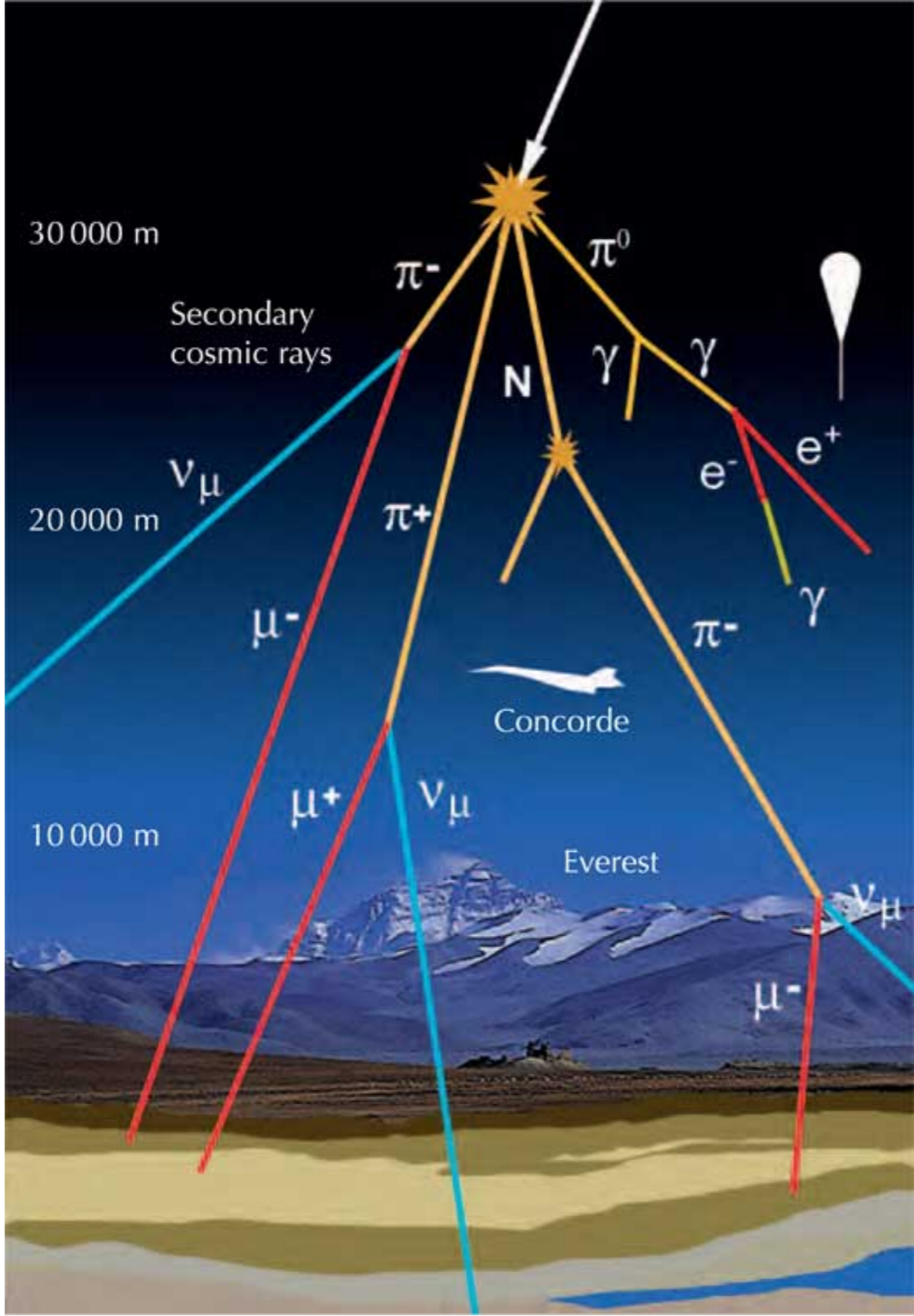
- In order to “see” that the two photons come from the same pion, we need to calculate the **momentum of each photon** (how?), and the invariant mass of the two-photon system.



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

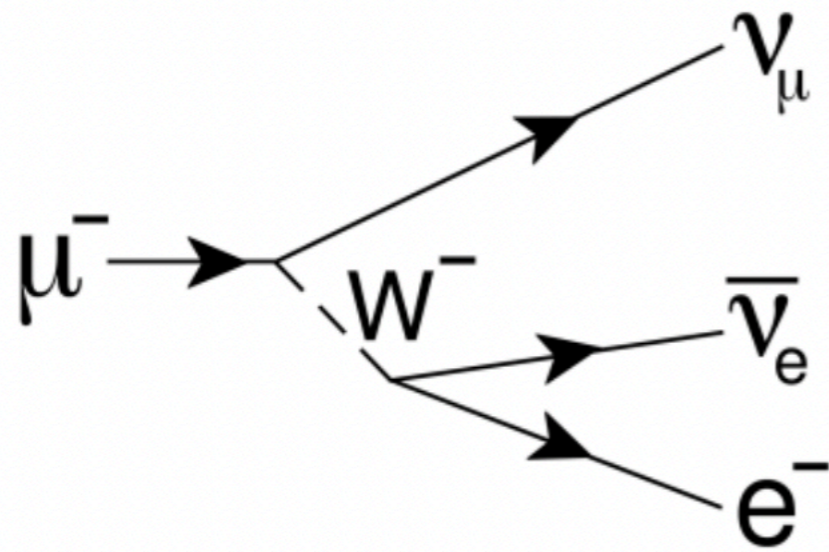


Cosmic muons



~20km

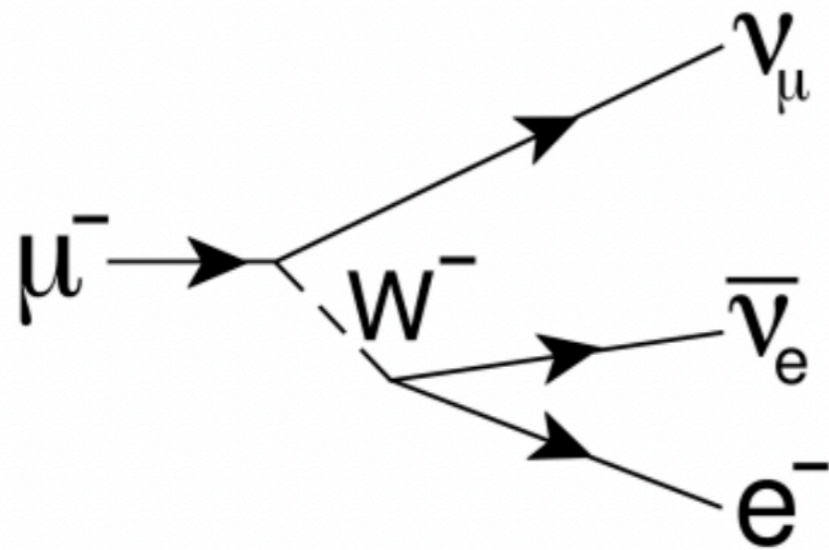
Muon decay



Mean lifetime is: $2.2 \mu s$

Scheme of muon decay in electron and two neutrino

Muon decay



Scheme of muon decay in electron and two neutrino

Mean lifetime is: $2.2 \mu s$

Time dilation: $\Delta t' = \frac{\Delta t}{1 - v^2/c^2}$

Observer: $\Delta t'$

Muon: Δt

Coincidence counters

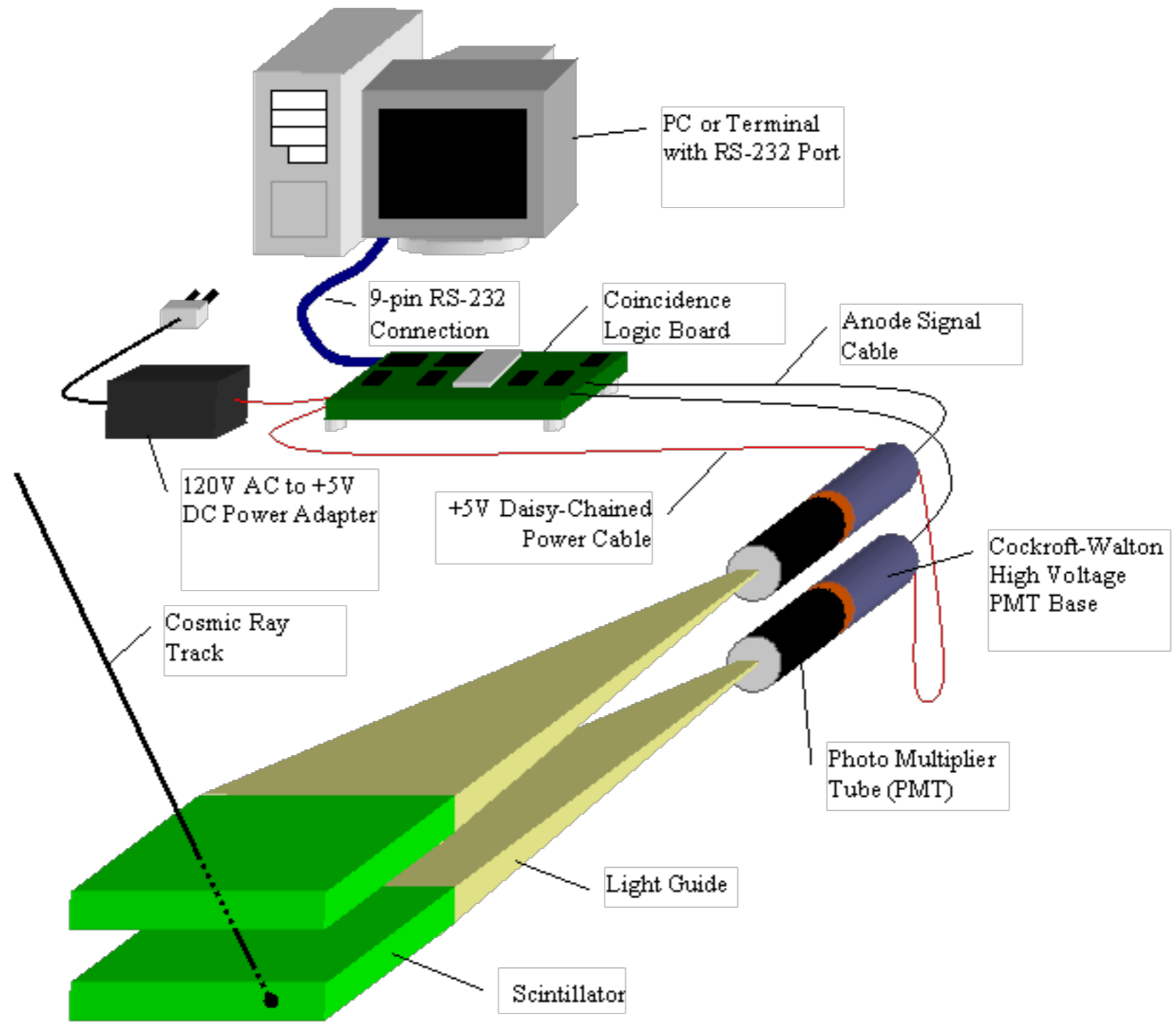


Figure 1. QuarkNet Cosmic Ray Detector System

