WHO PASSED BY HERE?

WHICH DIRECTION WERE THEY GOING?

WERE THEY GOING FAST OR SLOW?

WERE THEY BIG OR SMALL?

@Claire_Lee

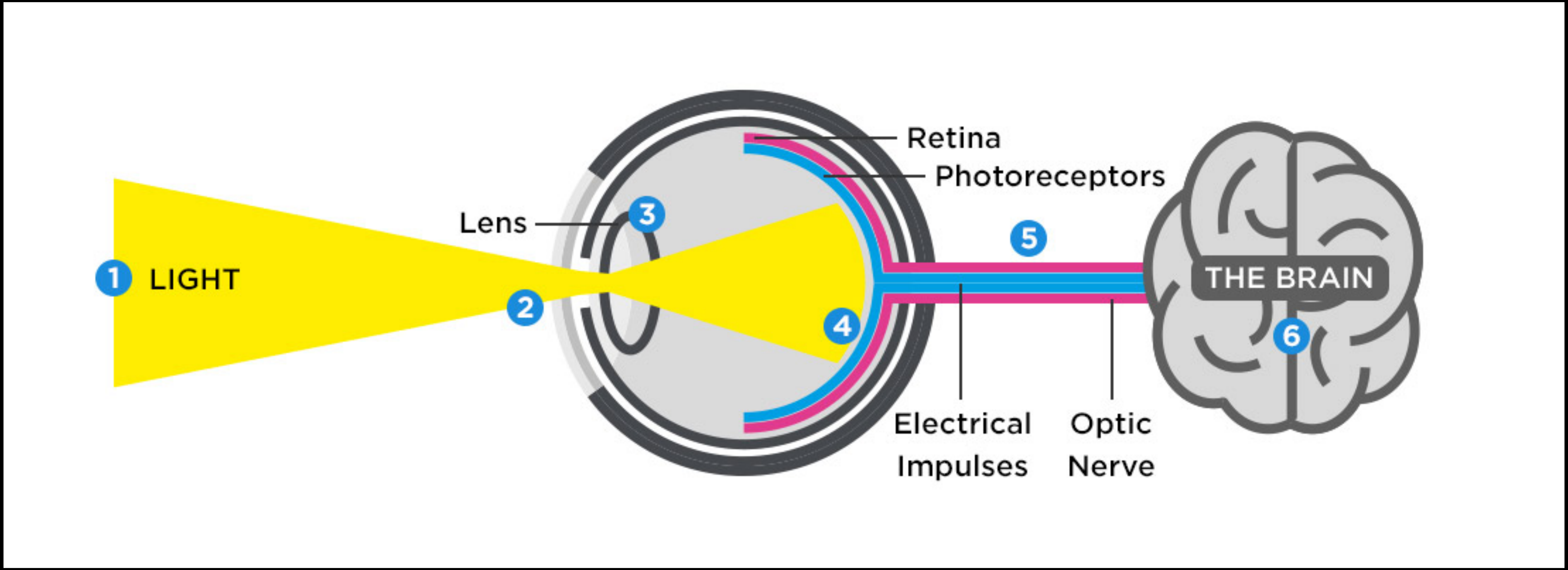
PARTICLE DETECTORS:

HOW WE SEE THE THINGS WE CANNOT SEE

DR. CLAIRE LEE (SHE/HER)
APPLICATION PHYSICIST AT FERMILAB

- To be able to study the universe & develop theories about the way it works we need to be able to measure it!
- Our theories are only as good as how well they match to the data
- But the process of measuring tiny particles changes their properties
- This is the challenge for the experimental physicist

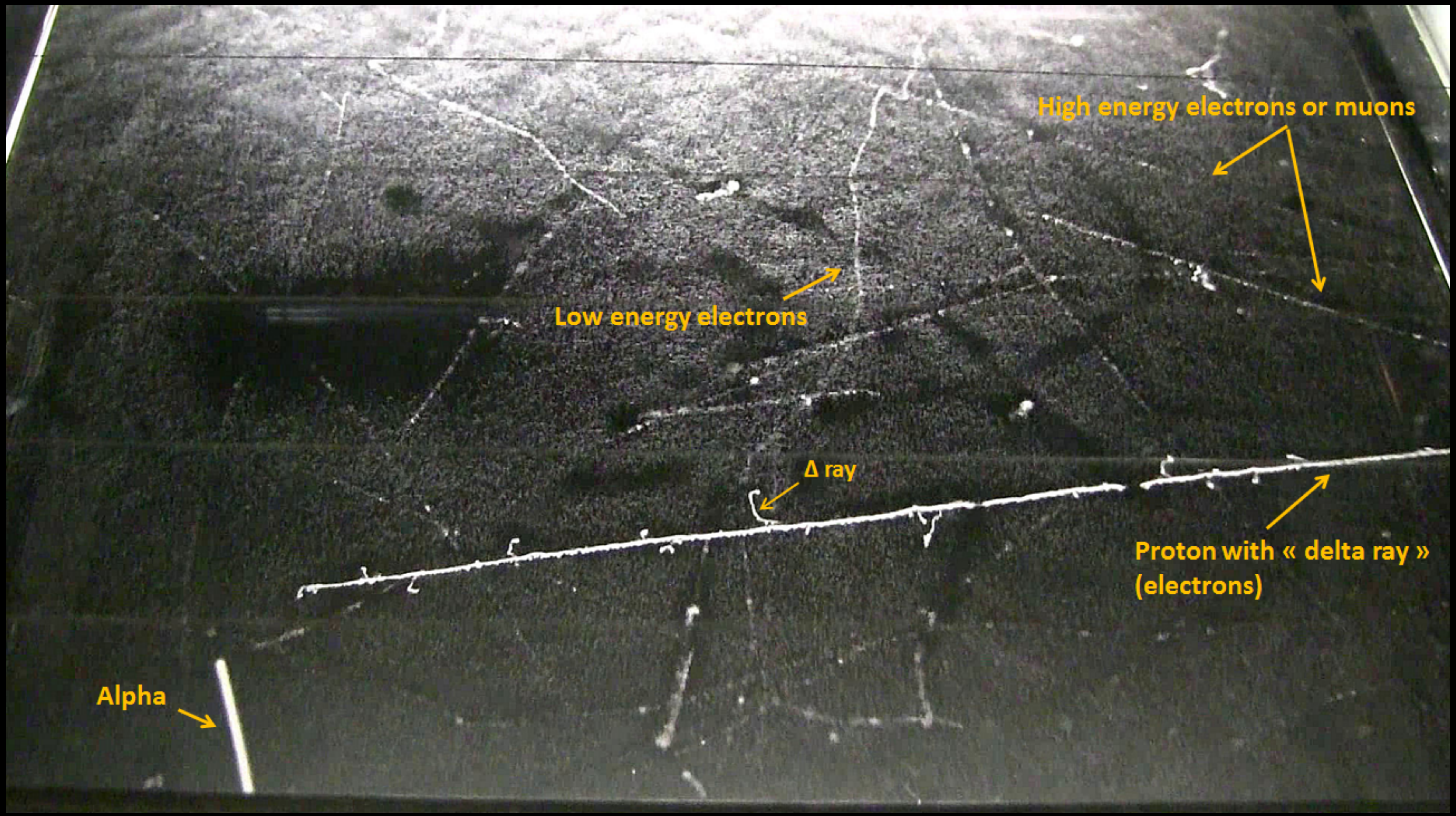
MOST WELL-KNOWN PARTICLE DETECTOR



SO... WE SEE BECAUSE OF THE INTERACTIONS BETWEEN LIGHT AND THE MATTER OF OUR EYES.

ALL PARTICLE DETECTORS

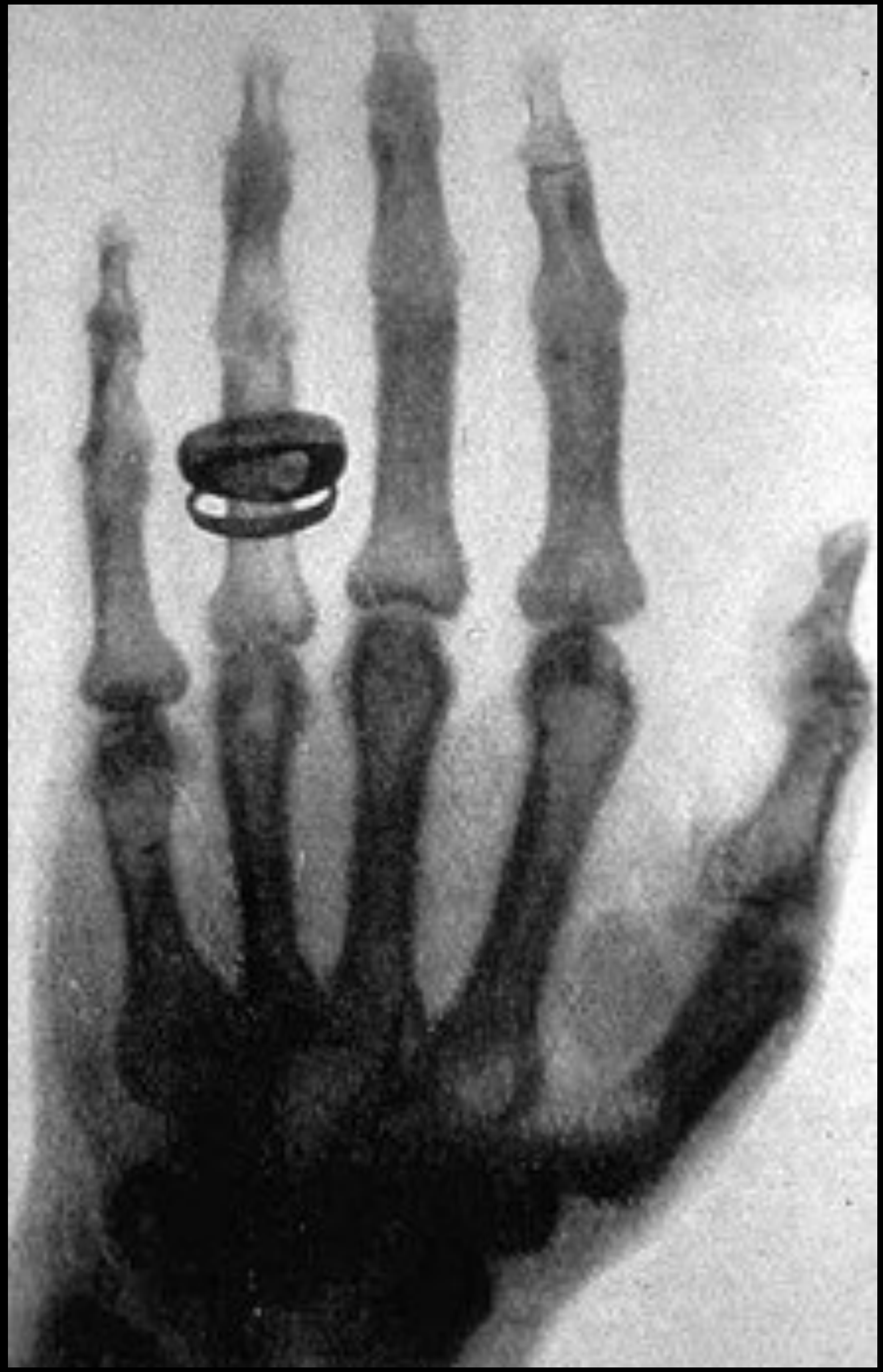
- And it turns out that that's exactly how particle detectors work, too!



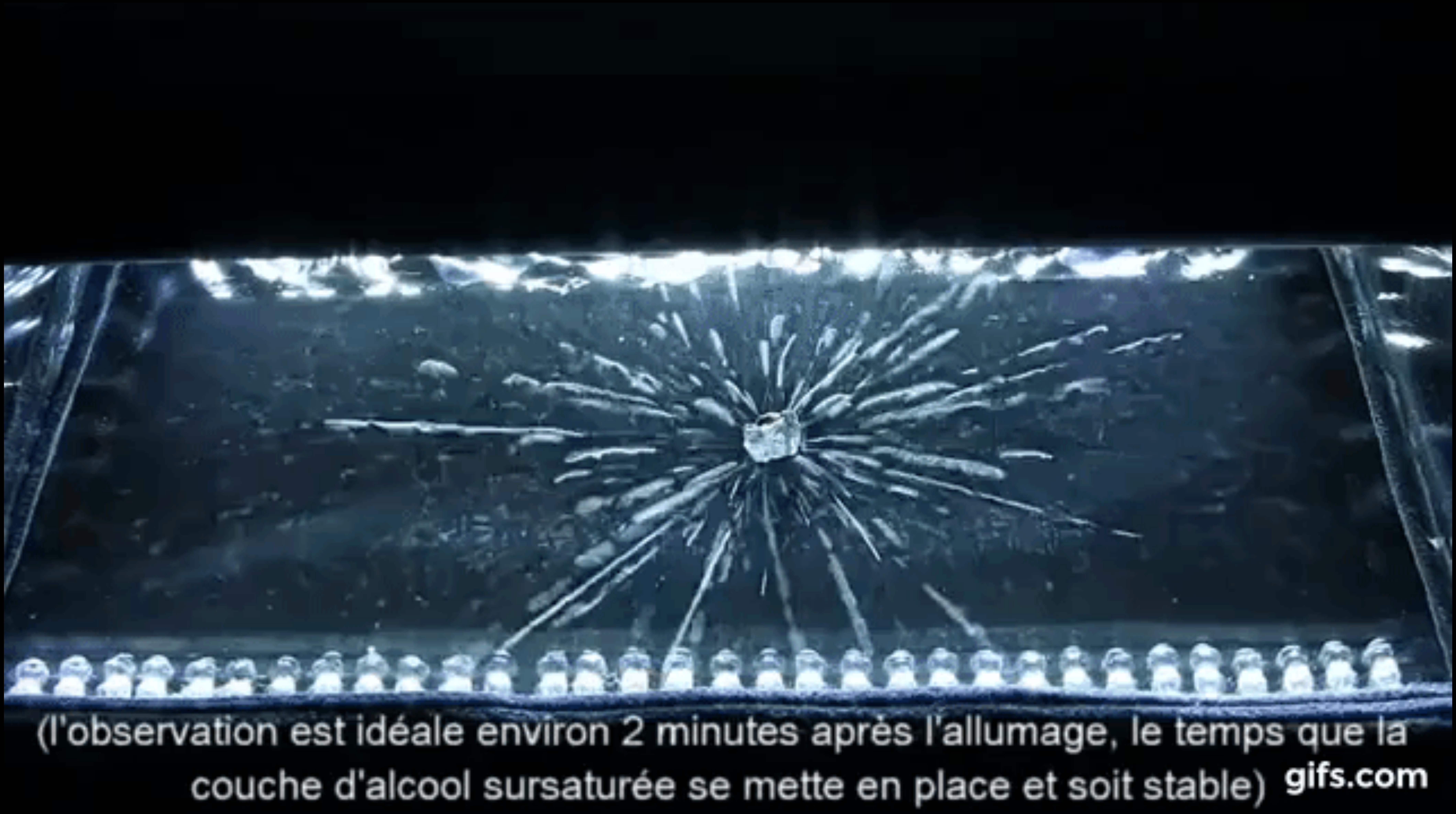
WE DETECT PARTICLES BECAUSE OF THE INTERACTIONS BETWEEN PARTICLES AND THE MATTER OF OUR DETECTORS.

X-RAYS

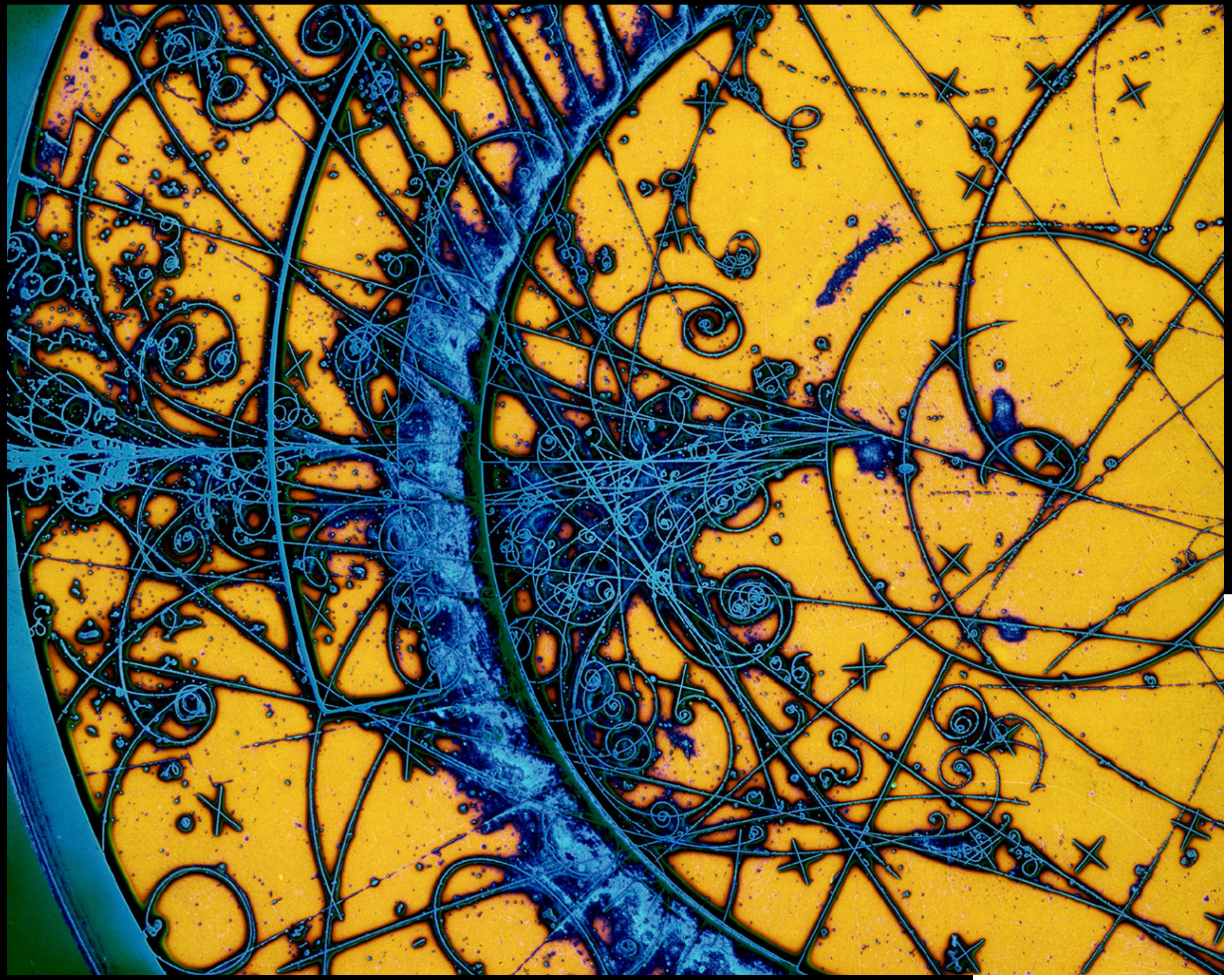
- 1896: An x-ray picture taken by Wilhelm Röntgen of Albert von Kölliker's hand at a public lecture on 23 January

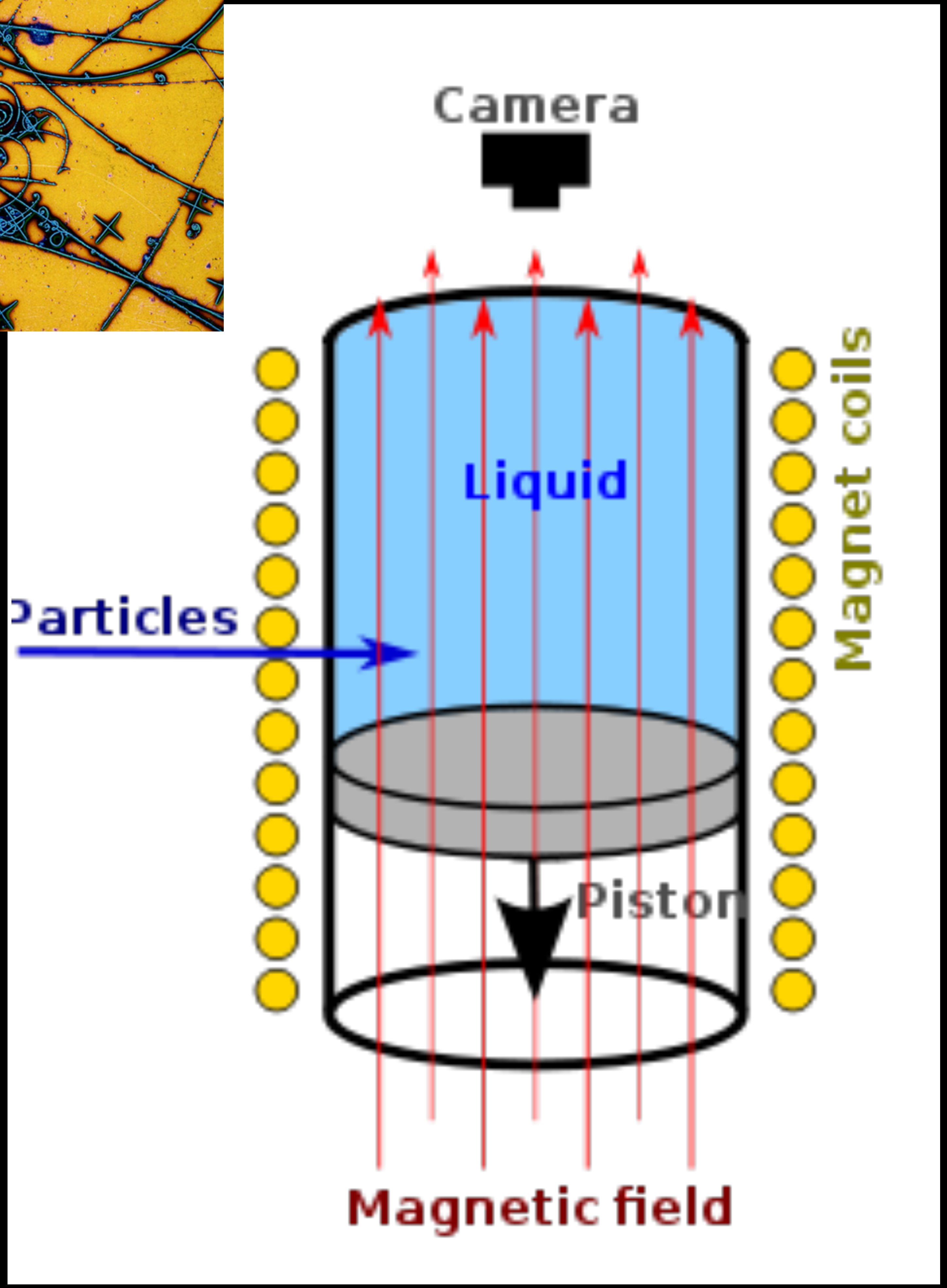


CLOUD CHAMBERS

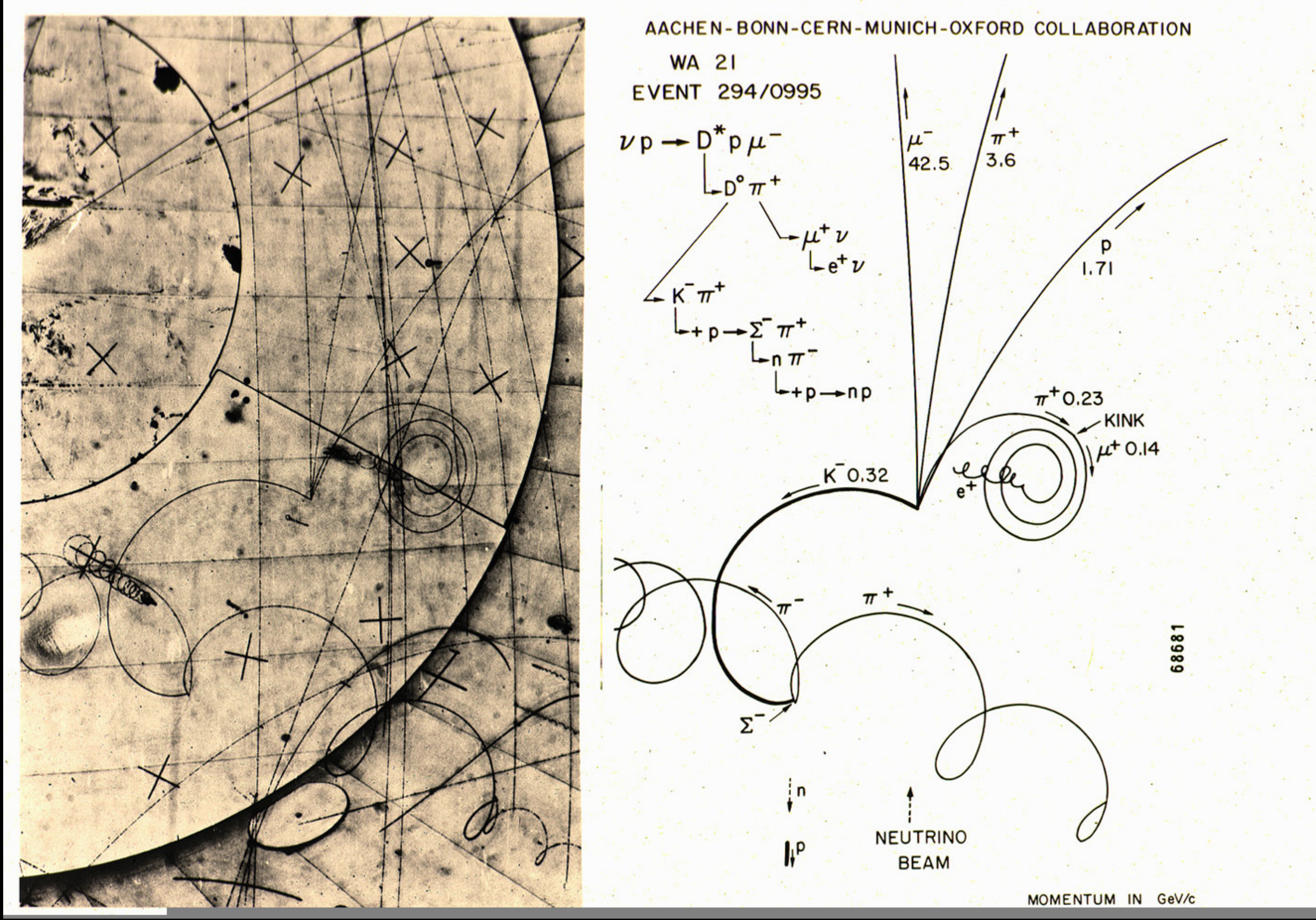


BUBBLE CHAMBERS





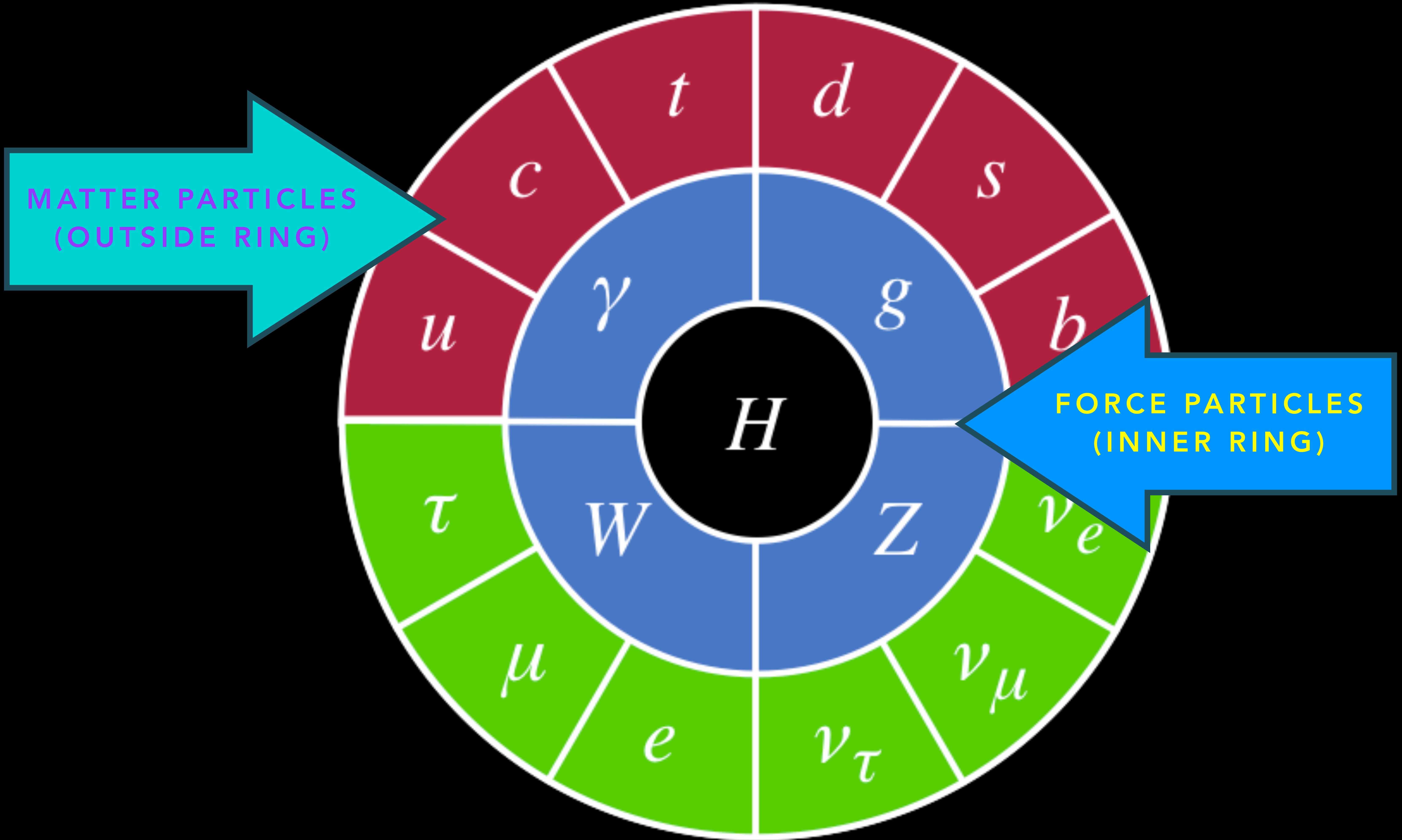
- This event shows real particle tracks from the Big European Bubble Chamber (BEBC), which observed neutrino and hadron beams between 1973 and 1984 from the PS and SPS.
- In this event a neutrino interacts with a proton producing an excited D meson.




SUBATOMIC PARTICLES
BOSON | FERMIUM | HADRON | LEPTON | MESON | BARYON
ATOM
Most of an atom
is empty space.
NUCLEUS
PROTON
u
u
d
Quark
d
d̄
s
Quarks
Proton
Neutron
Electron
(Lepton)

THE STANDARD MODEL OF PARTICLE PHYSICS

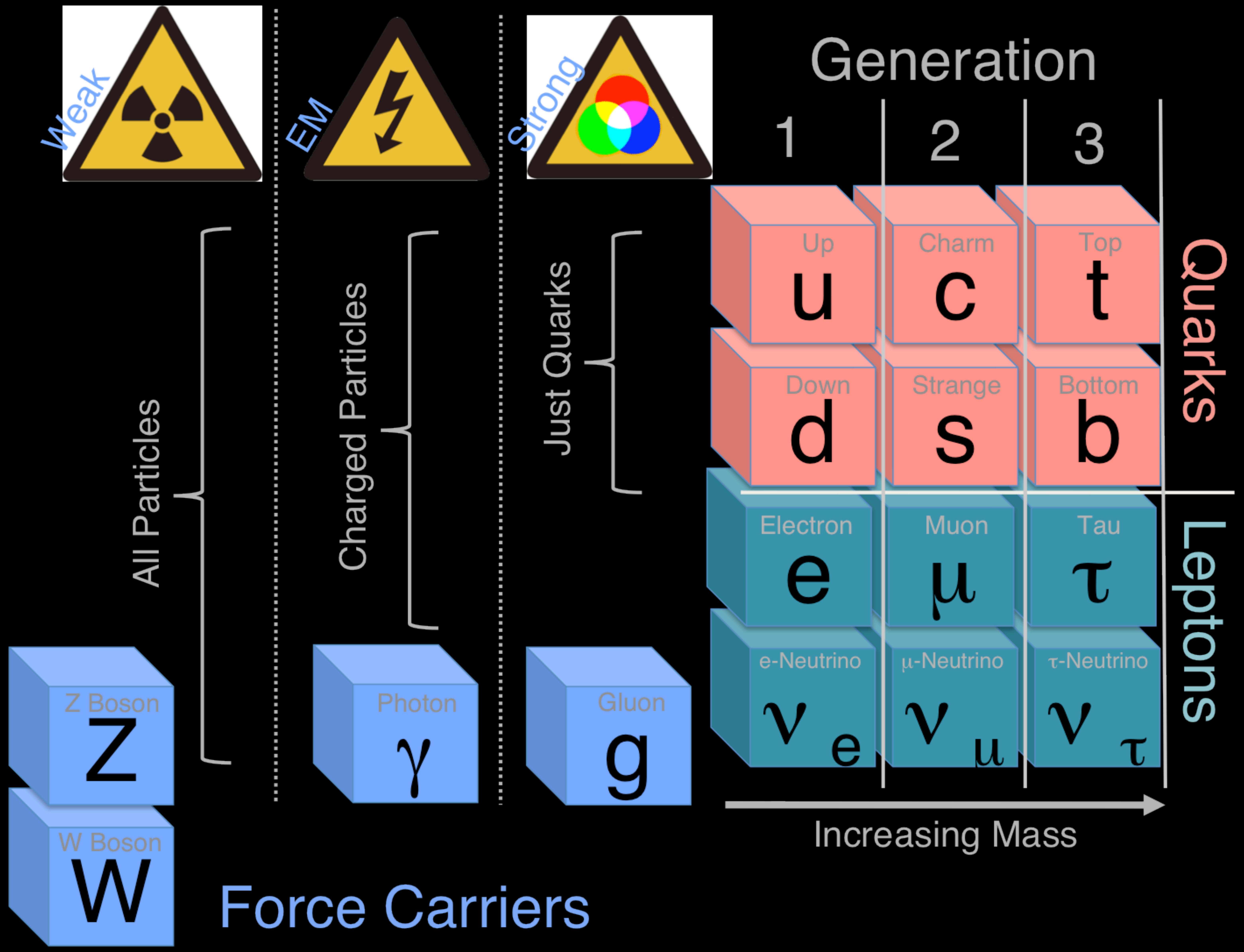
IT'S LIKE THE "PERIODIC TABLE" OF PHYSICS

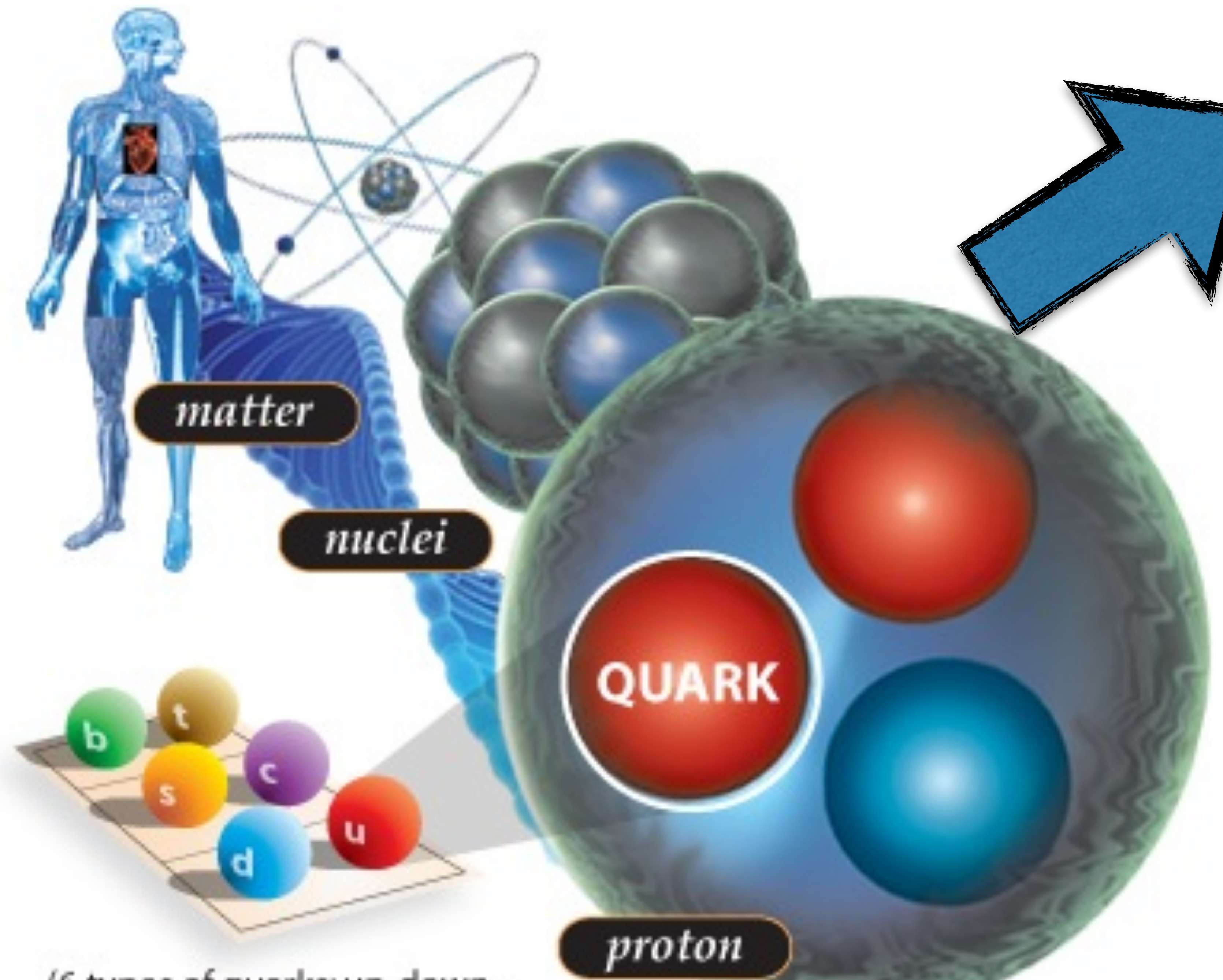


(IMAGE CREDIT: PARTICLE FEVER)

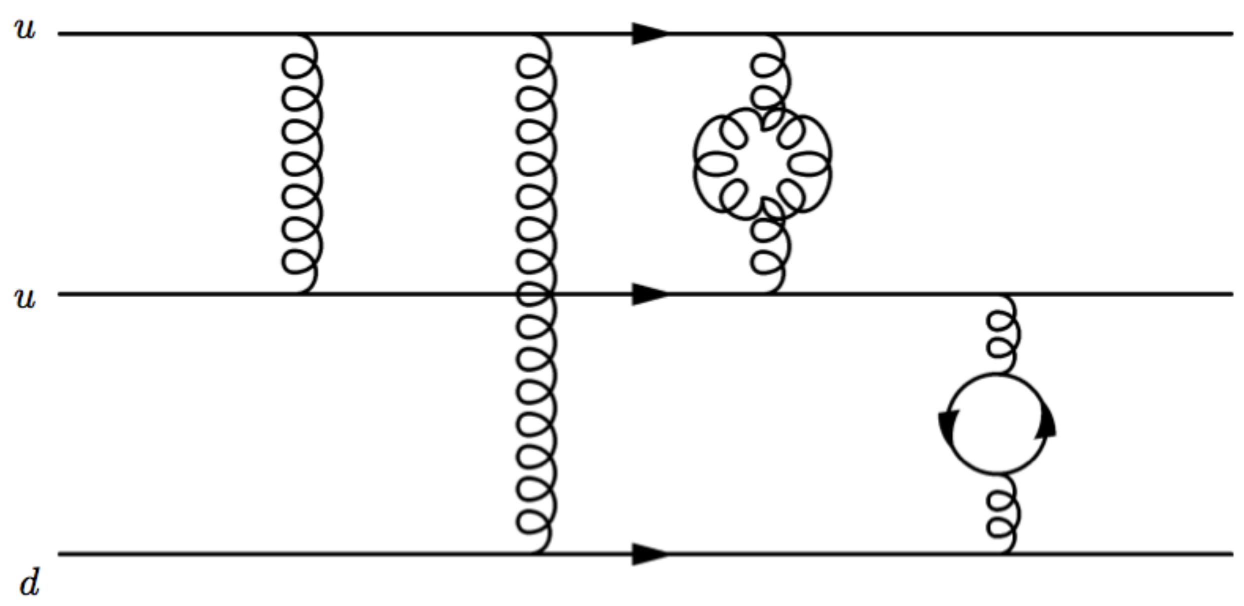
FORCES AND PARTICLES

- A force is another way of saying “an interaction”
- The range of a force depends on the mass of the particle that carries that force
- Most interactions we experience in daily life are based on the electromagnetic force

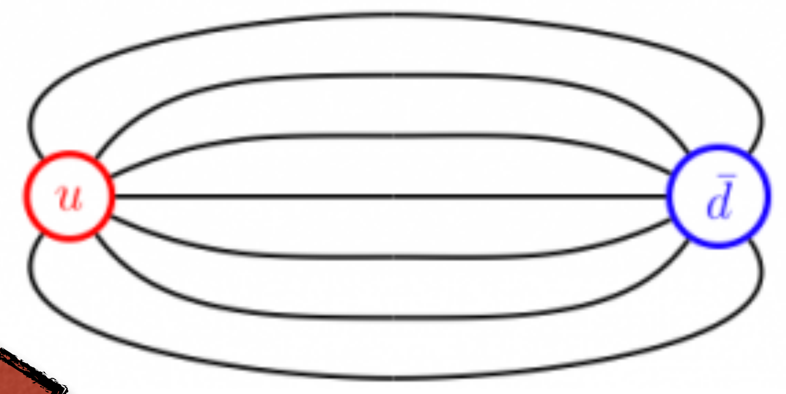




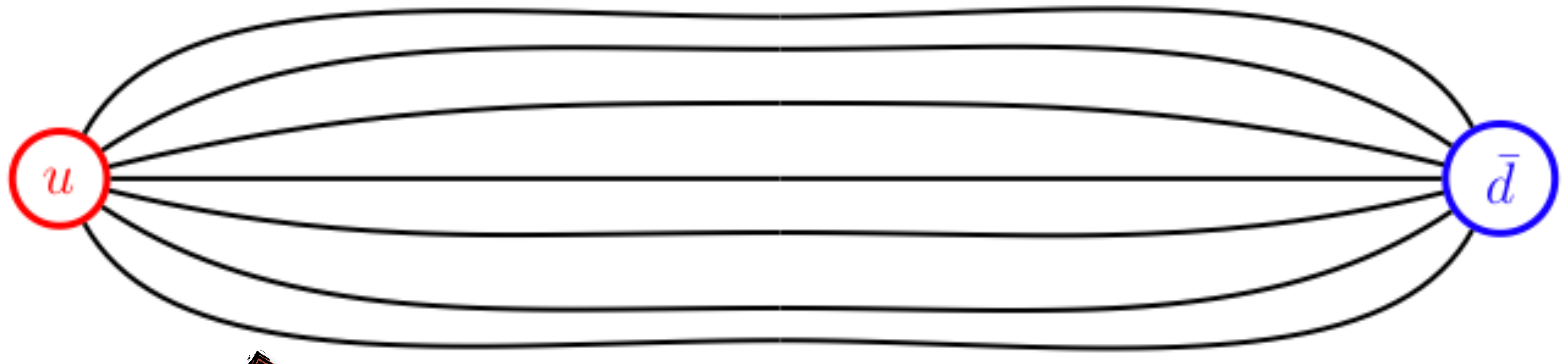
(6 types of quarks: up, down, charm, strange, top and bottom)

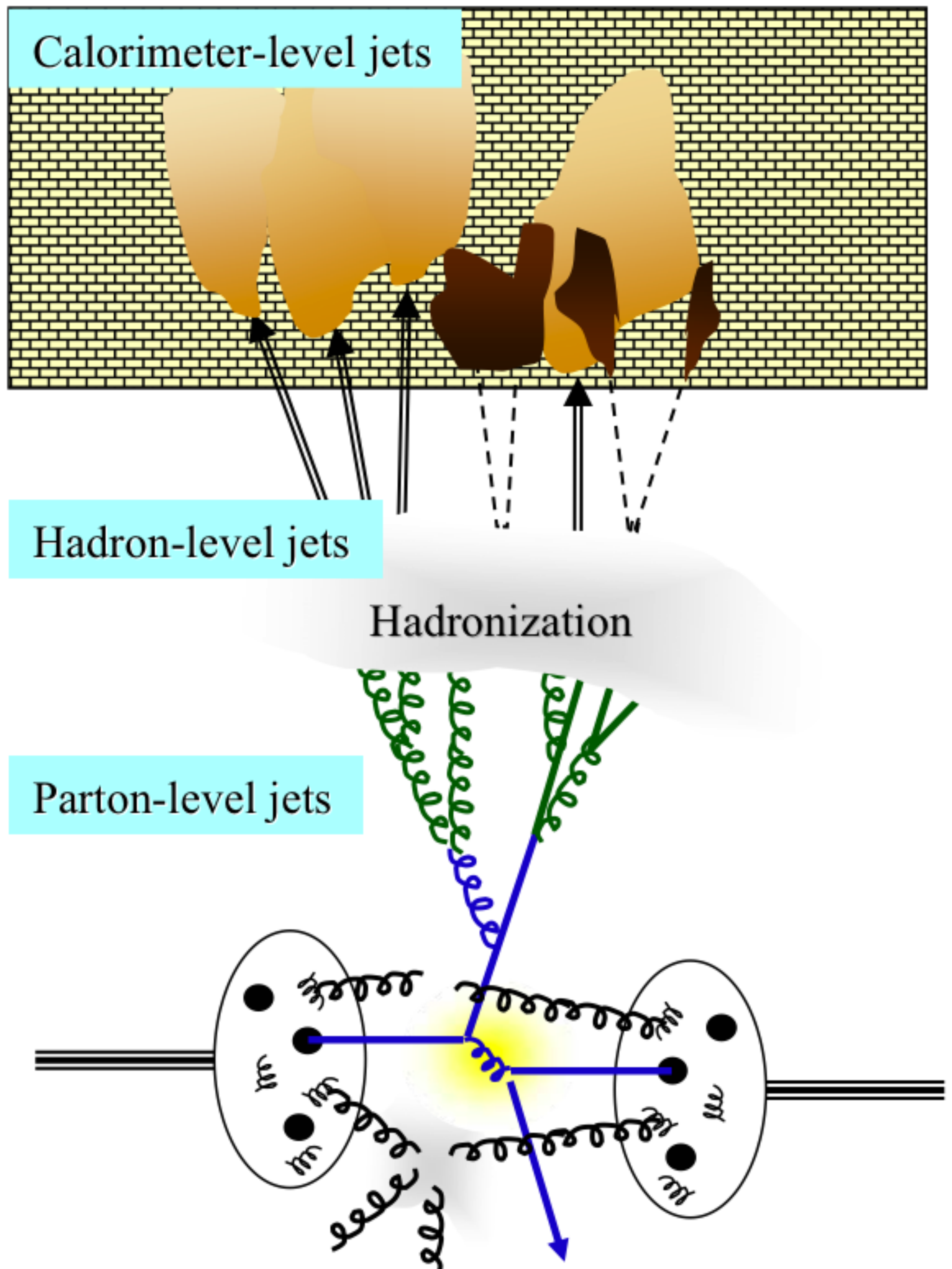


Confinement:
Quarks cannot
exist on their own!

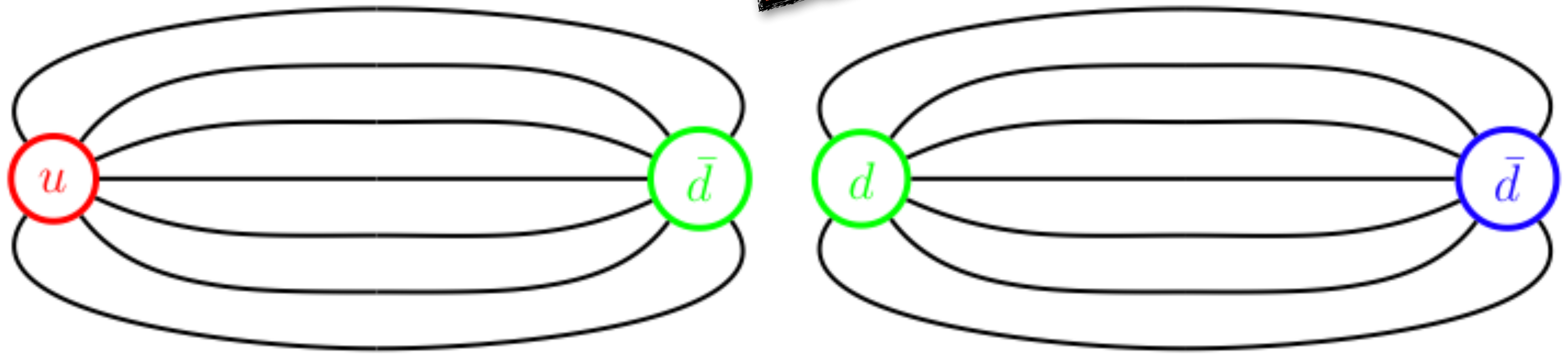


Pull apart!





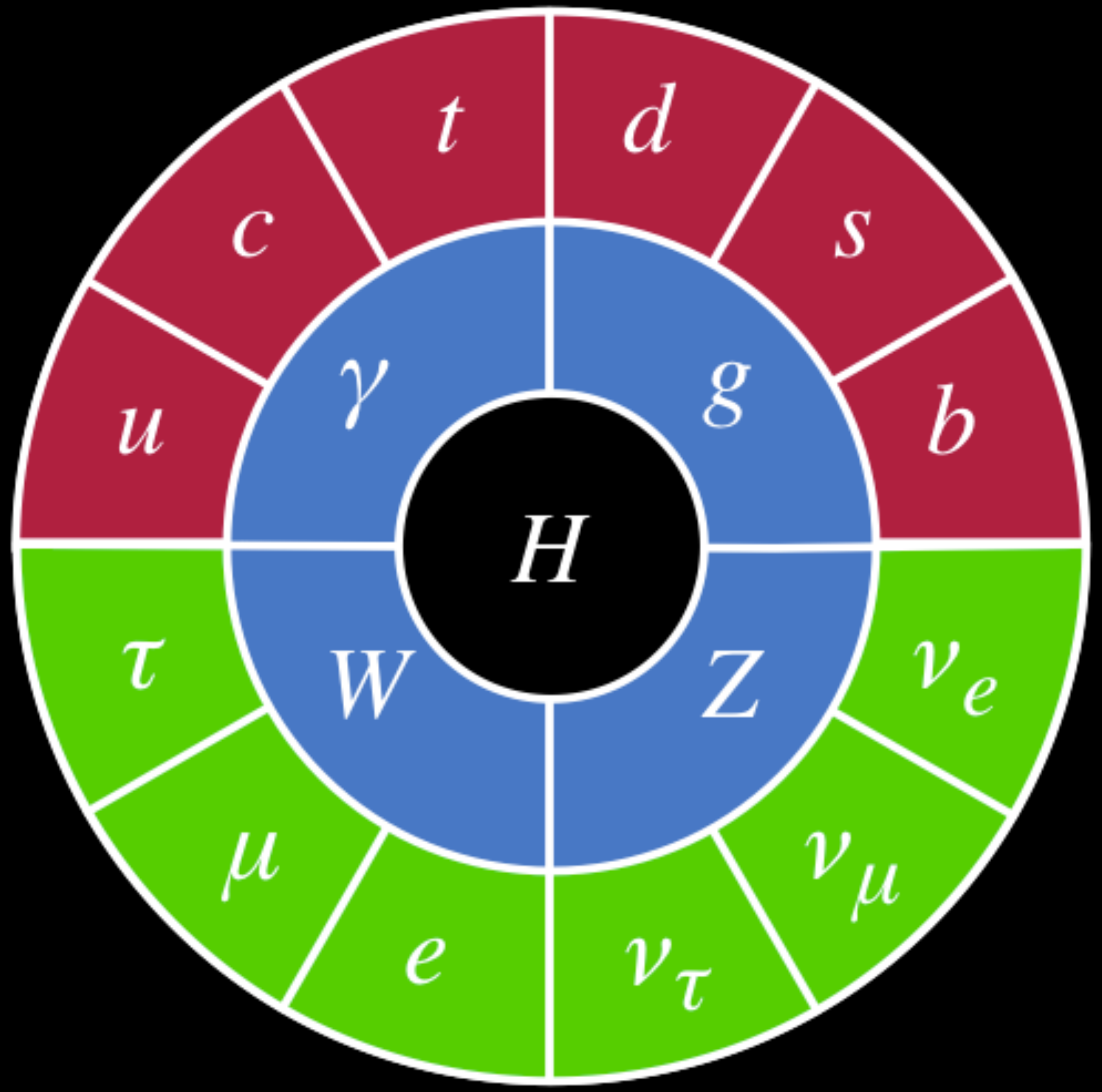
Pull more!



POP! more particles!

WHAT PARTICLES CAN WE DETECT?

- We don't observe all of the Standard Model particles in our daily life
  - Heavier particles decay into lighter particles
  - Quarks&gluons combine due to confinement

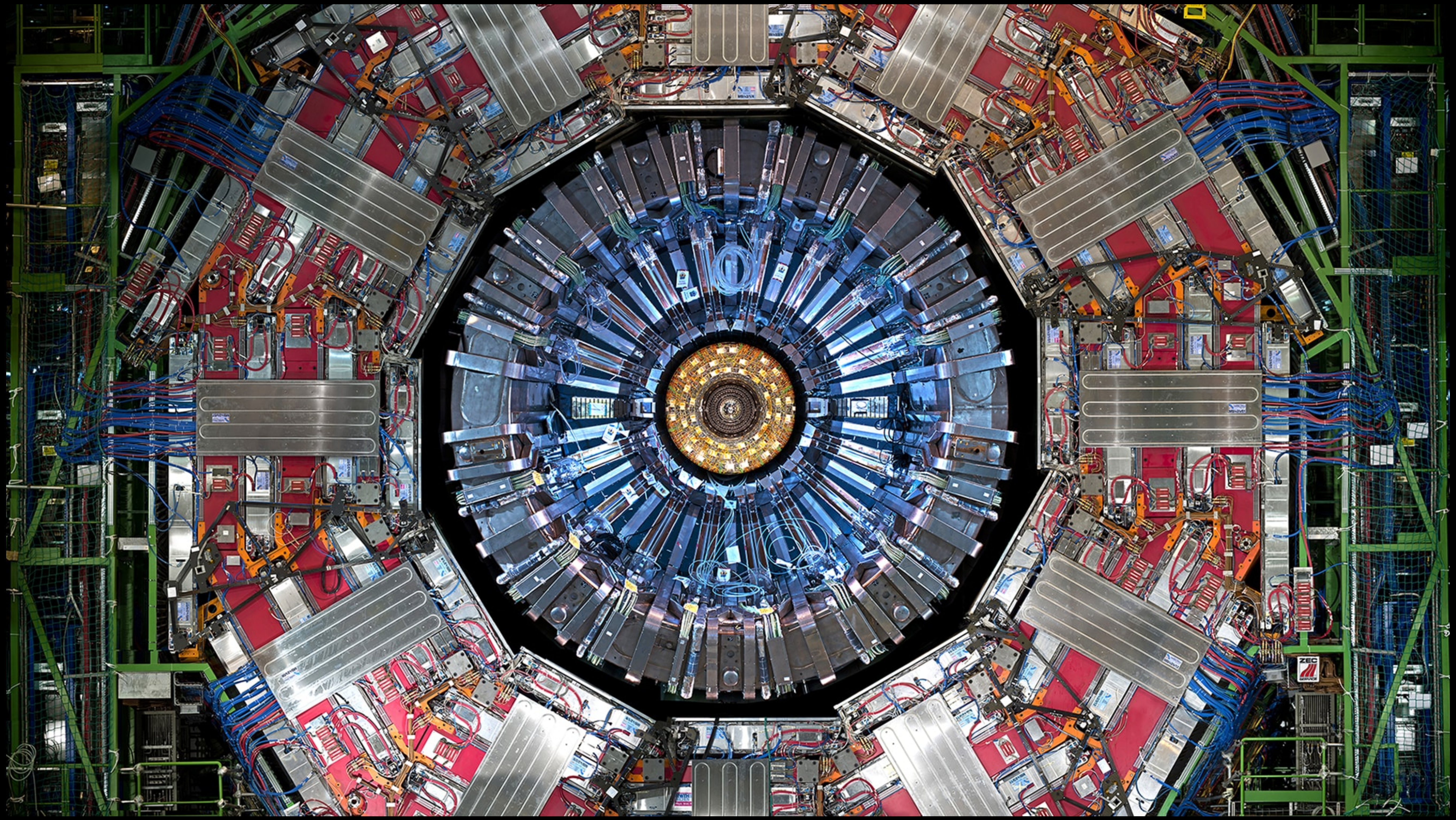


- Final state particles: electrons, photons, (muons), hadrons & their antiparticles

- electrons (and positrons)
- photons
- muons (and antimuons)
- charged hadrons (eg protons)
- neutral hadrons (eg neutrons)

IDENTIFYING PARTICLES

- What are the things we need to measure to be able to distinguish between the different types of particles?



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IDENTIFYING PARTICLES

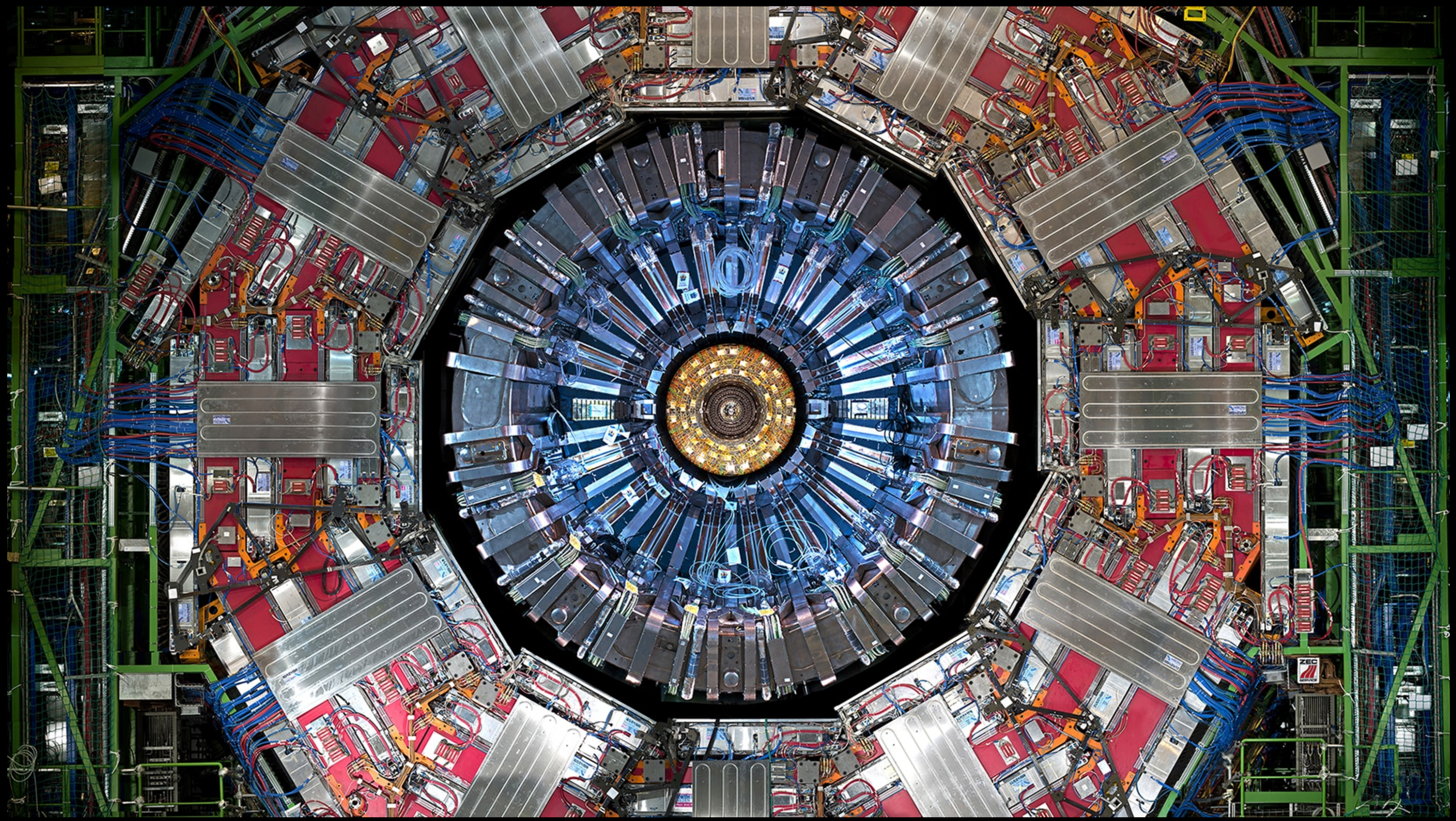
- What are the things we need to measure to be able to distinguish between the different types of particles?

ENERGY

MASS

MOMENTUM

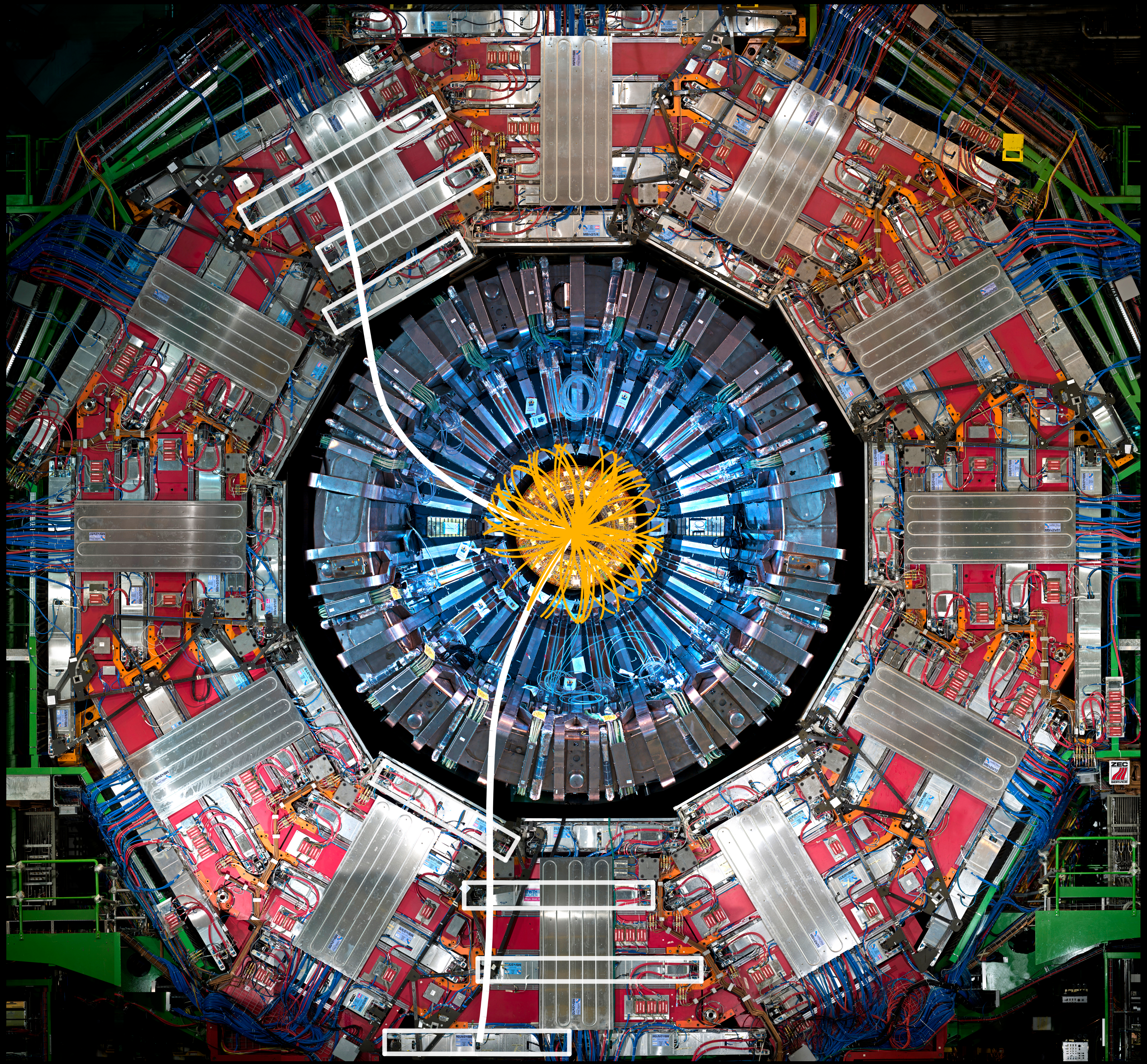
CHARGE



- electrons (and positrons)
- photons
- muons (and antimuons)
- charged hadrons (eg protons)
- neutral hadrons (eg neutrons)

SO, HOW DO WE MAKE THESE MEASUREMENTS?

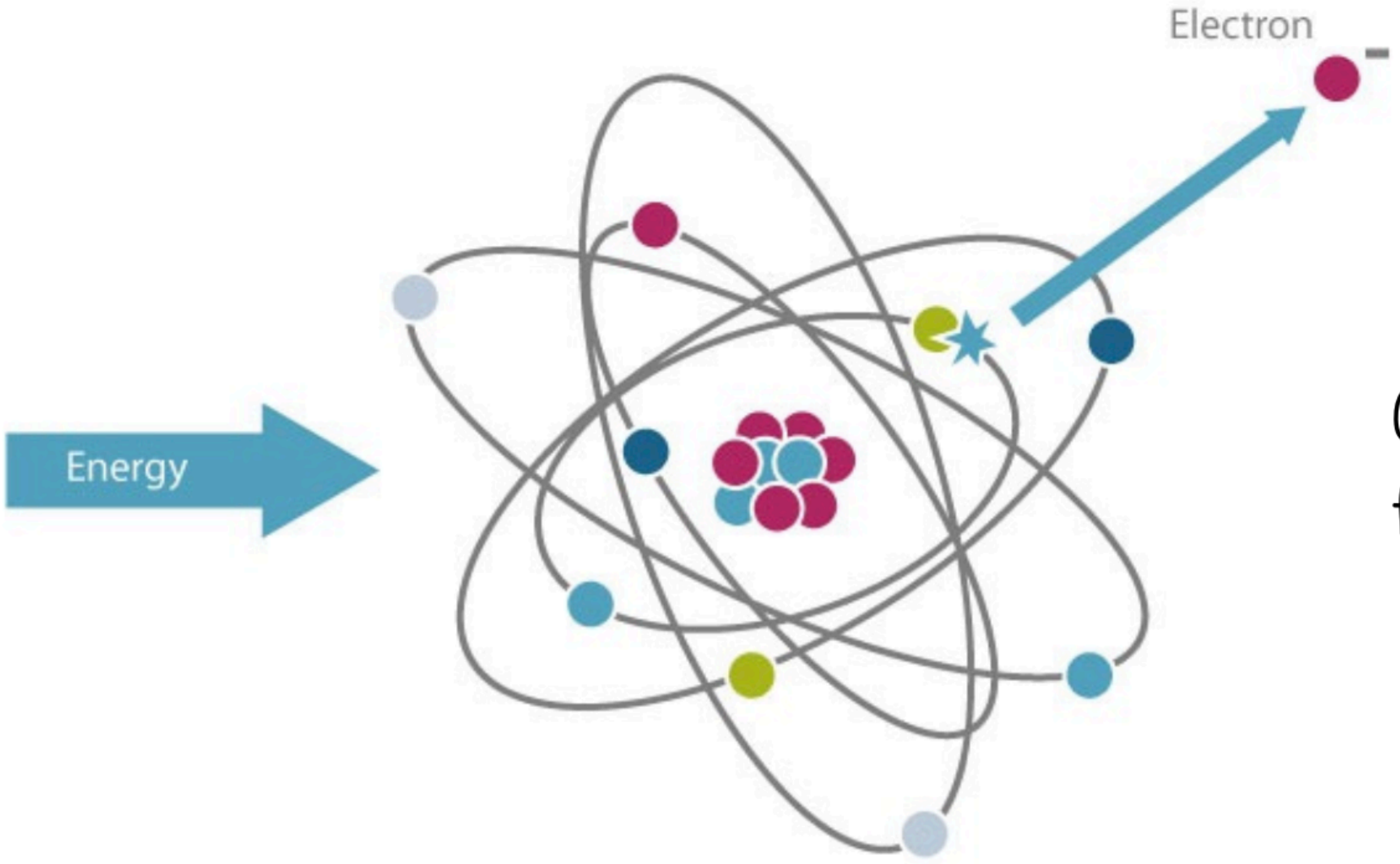
- In order to detect a particle it must interact with the material of the detector.
- Some examples of the ways particles interact:
  - Ionisation
  - Photoemission
  - Cherenkov radiation
  - Transition radiation
  - Compton scattering
  - Pair production
  - Bremsstrahlung



EXAMPLE 1: IONISATION

- Ionization

Gives off charge!

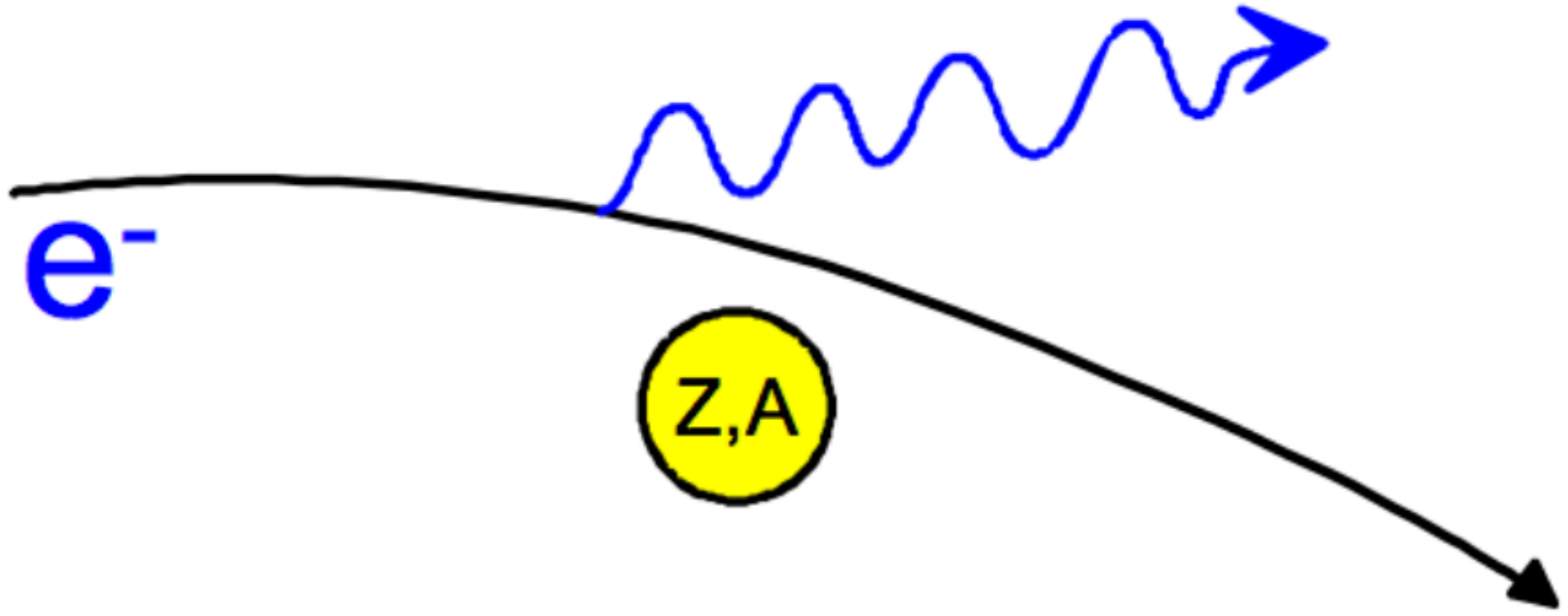


Charged particle "knocks" an electron free, leaving the atom ionised

EXAMPLE 2: BREMSSTRAHLUNG

- Bremsstrahlung

Gives off light!

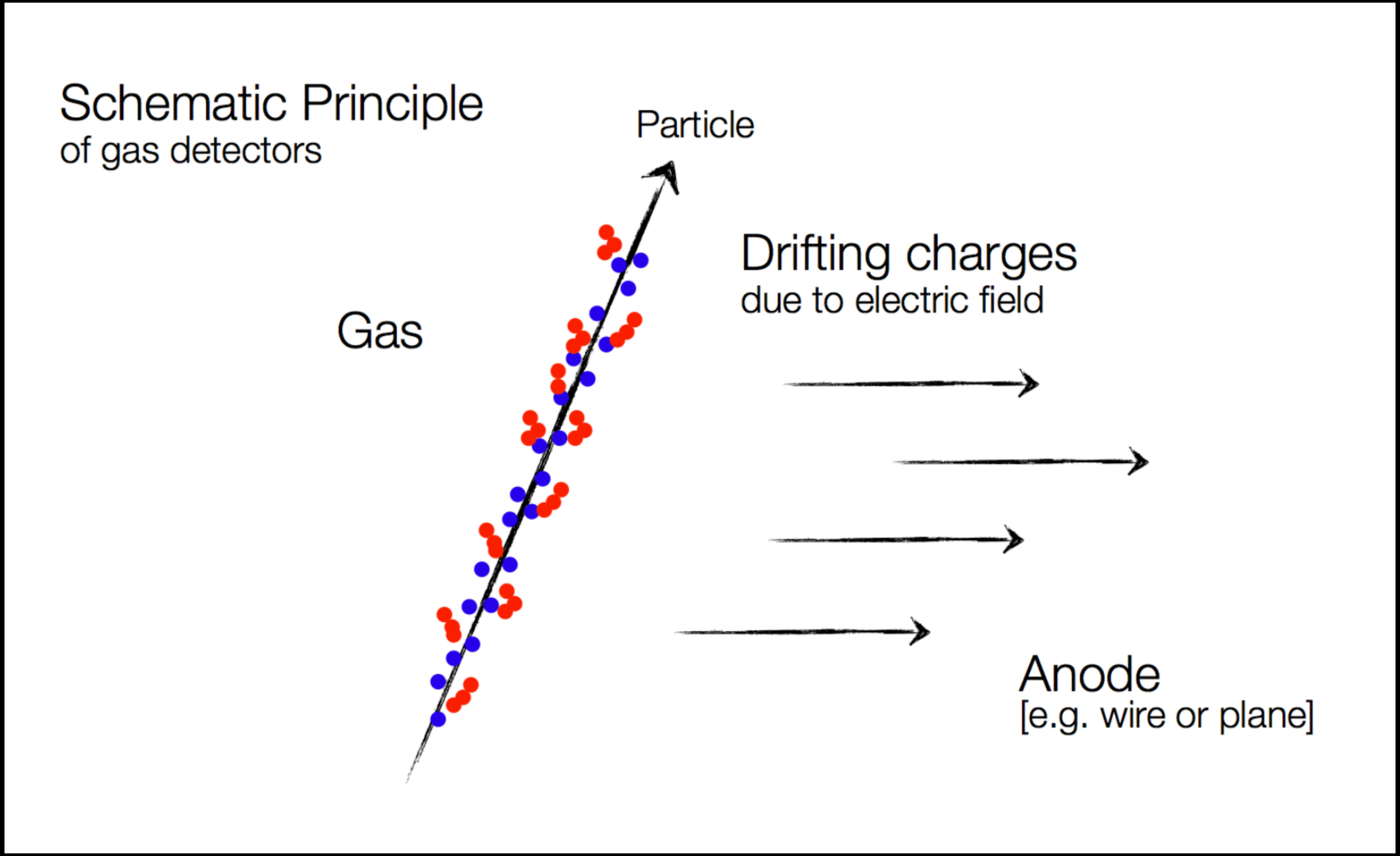


As an electron gets bent around a nucleus it emits a photon.

HOW DETECTORS WORK

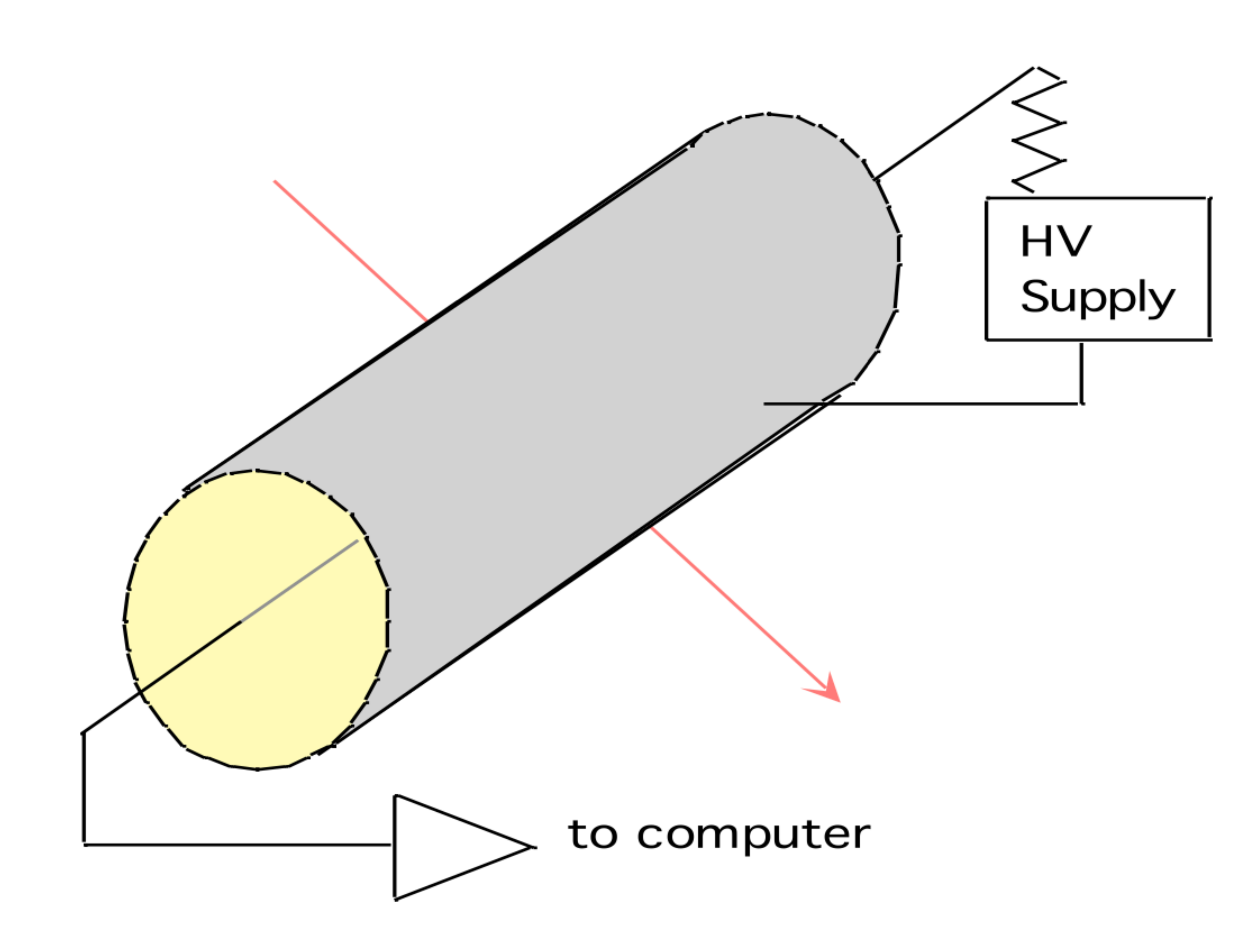
- In order to detect a particle it must interact with the material of the detector
  - Most particle detectors actually detect the light or electric charge the particle leaves behind
- BUT: The properties of the particle may be different after we have detected it:
  - Lower Energy
  - Different Momentum
  - Completely Stopped
- We can tell what kind of particle it is by how it changes as it goes through the detector, and what it leaves behind (eg. light, electric charge).
  - We can also build our detectors in a particular way, “tuning” them to detect a particular type of particle while ignoring another

LET'S USE IONIZATION TO BUILD A PARTICLE DETECTOR!



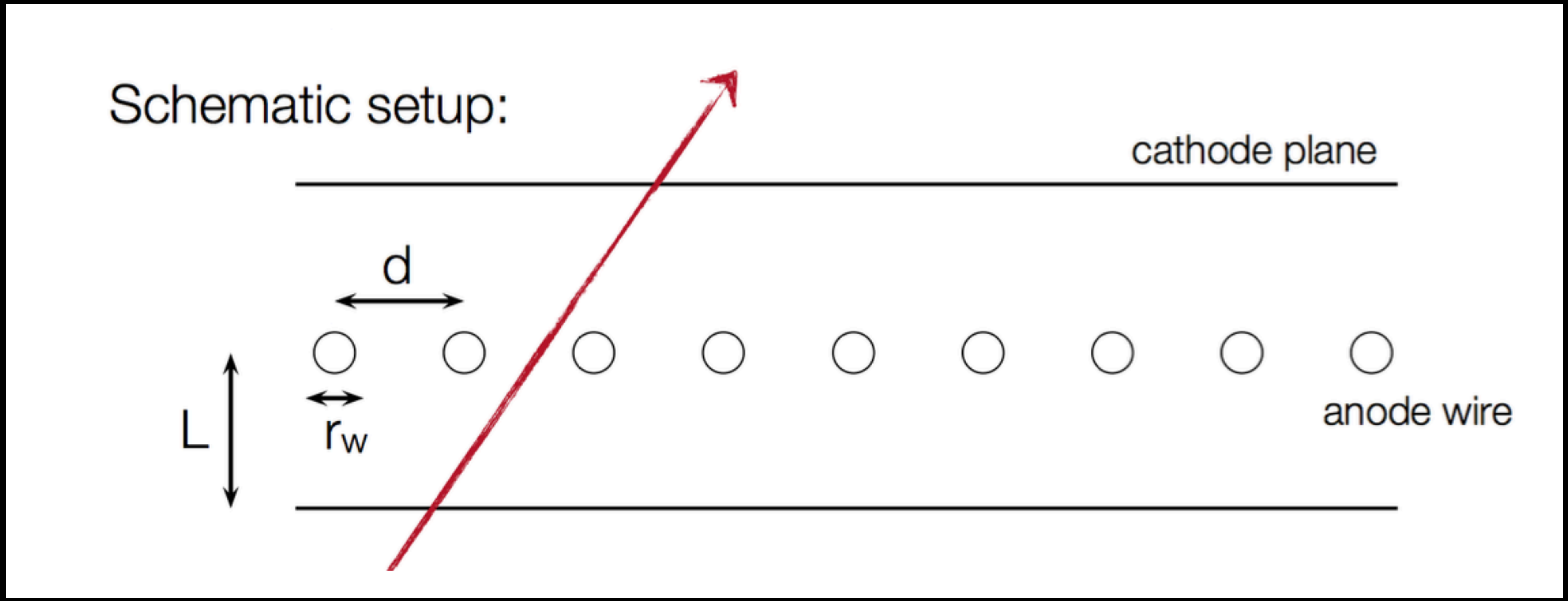
LET'S USE IONIZATION TO BUILD A PARTICLE DETECTOR!

- Take a tube
- Fill it with a gas: (noble gases are more likely to ionize than others. Let's use Argon)
- Insert a conducting surface to make an intense electric field: The field at the surface of a small wire gets extremely high, so use tiny wires
- Attach electronics and apply high voltage
- And we're done!

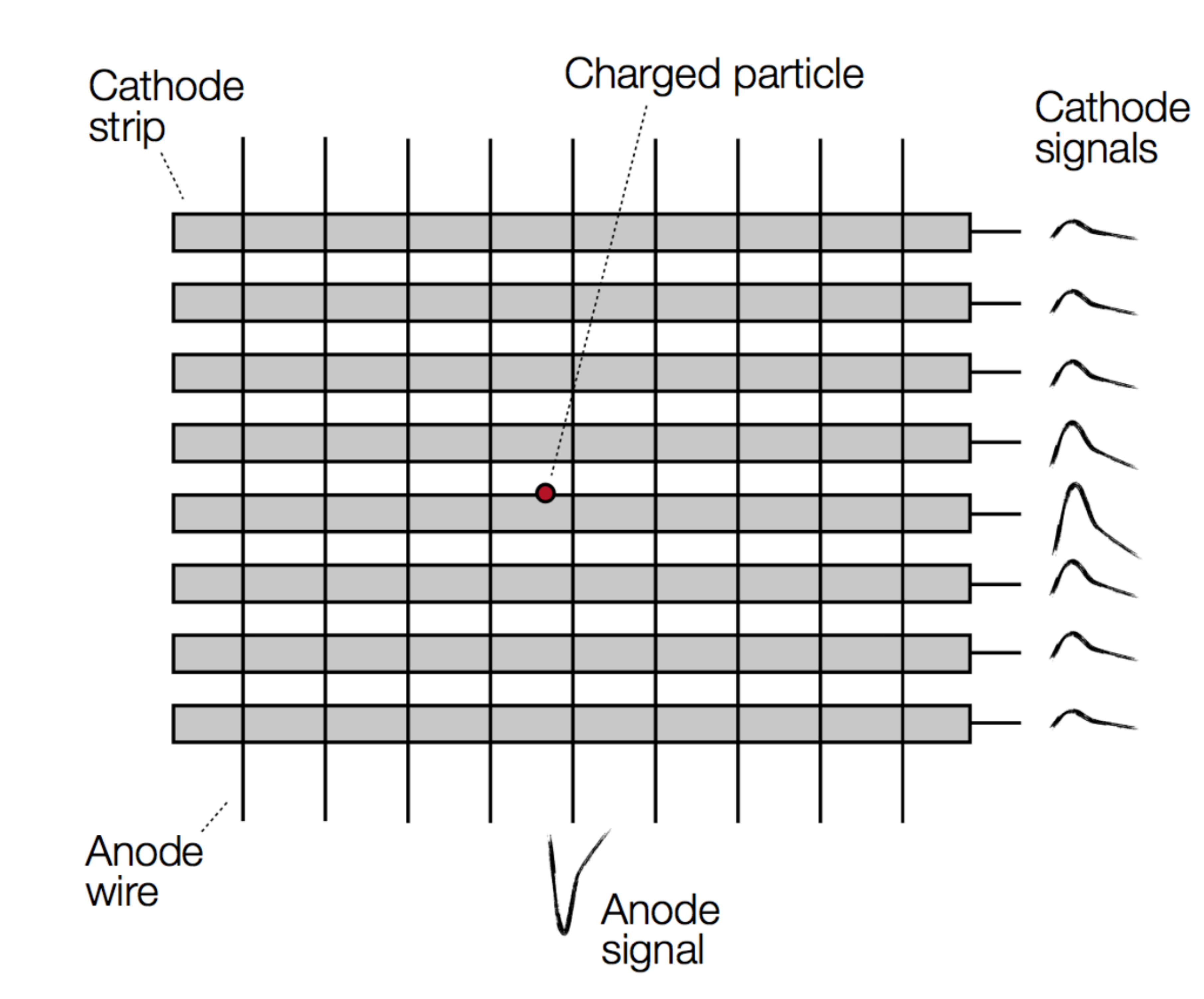


HOW CAN WE MAKE THIS MORE ACCURATE OVER A LARGE AREA?

MULTI WIRE CHAMBER

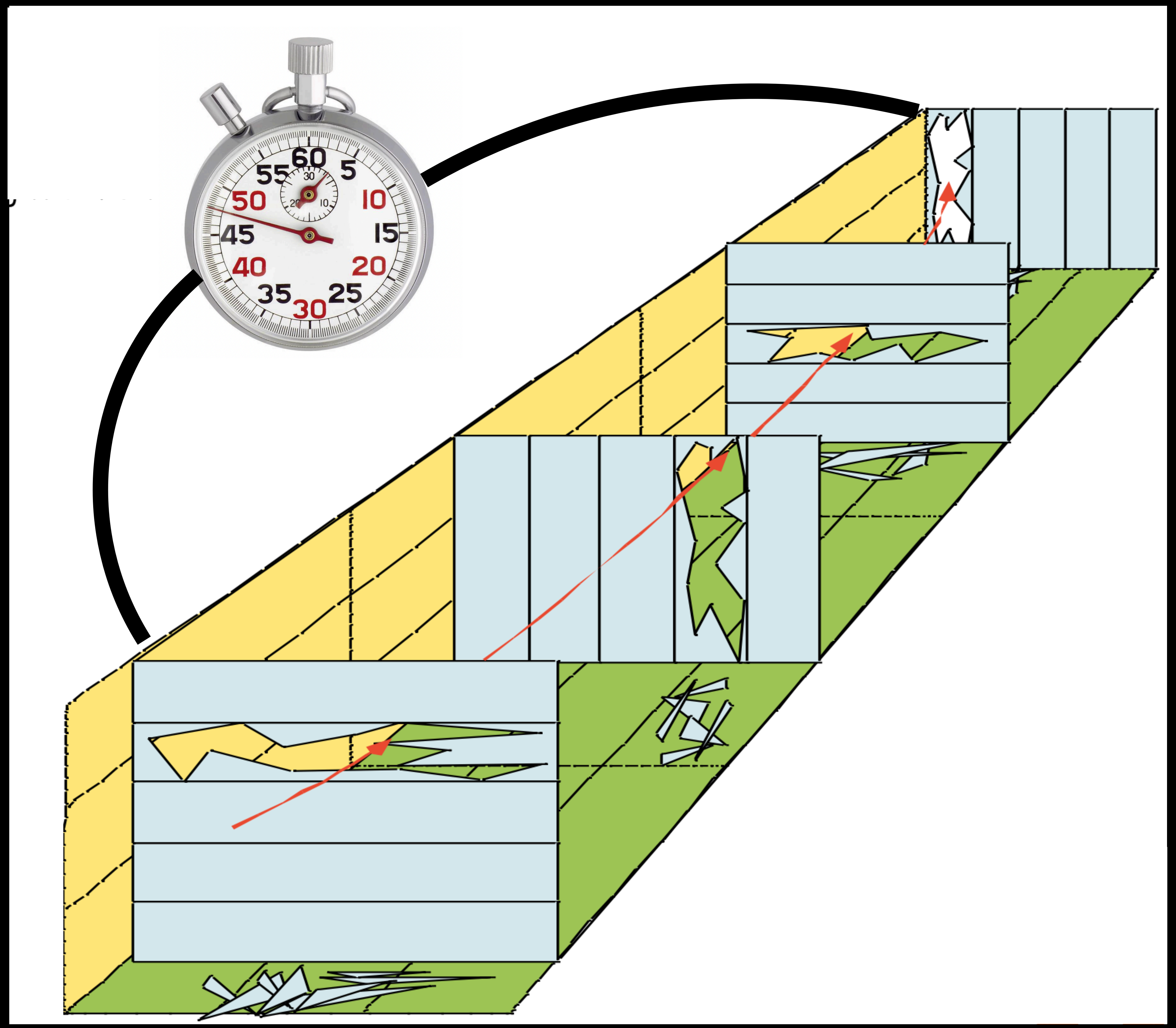


- We can use many wires to get a more accurate position measurement



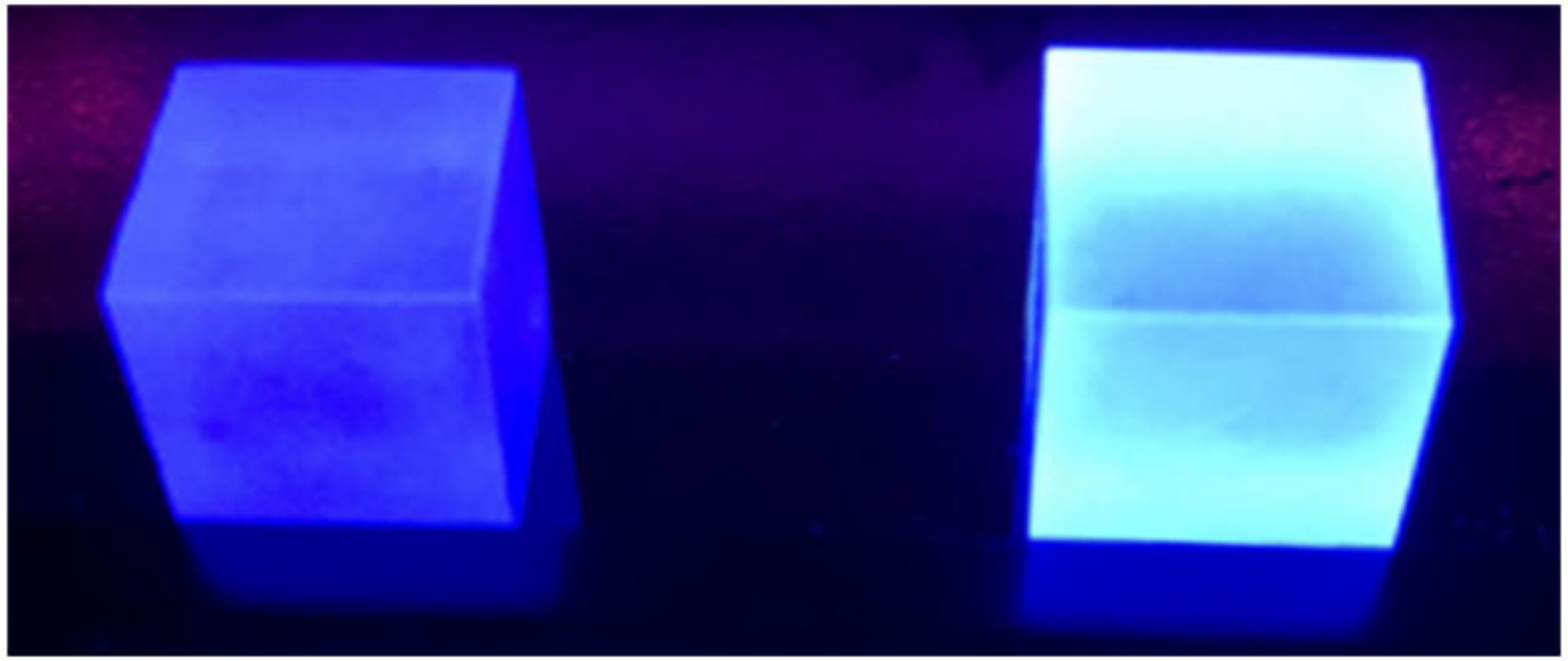
TRACKING PLANES

- We can also layer the chambers longitudinally along the particle direction
- If we make several measurements of track position along the length of the track, we can figure out the whole trajectory.
- We can also time the signals coming from each of the layers to get the momentum



WHAT ABOUT USING THE PRODUCED LIGHT?

- Many materials radiate light, but most also absorb that light again so that it never gets out.
- However, a type of material called a scintillator produces light that does not get reabsorbed

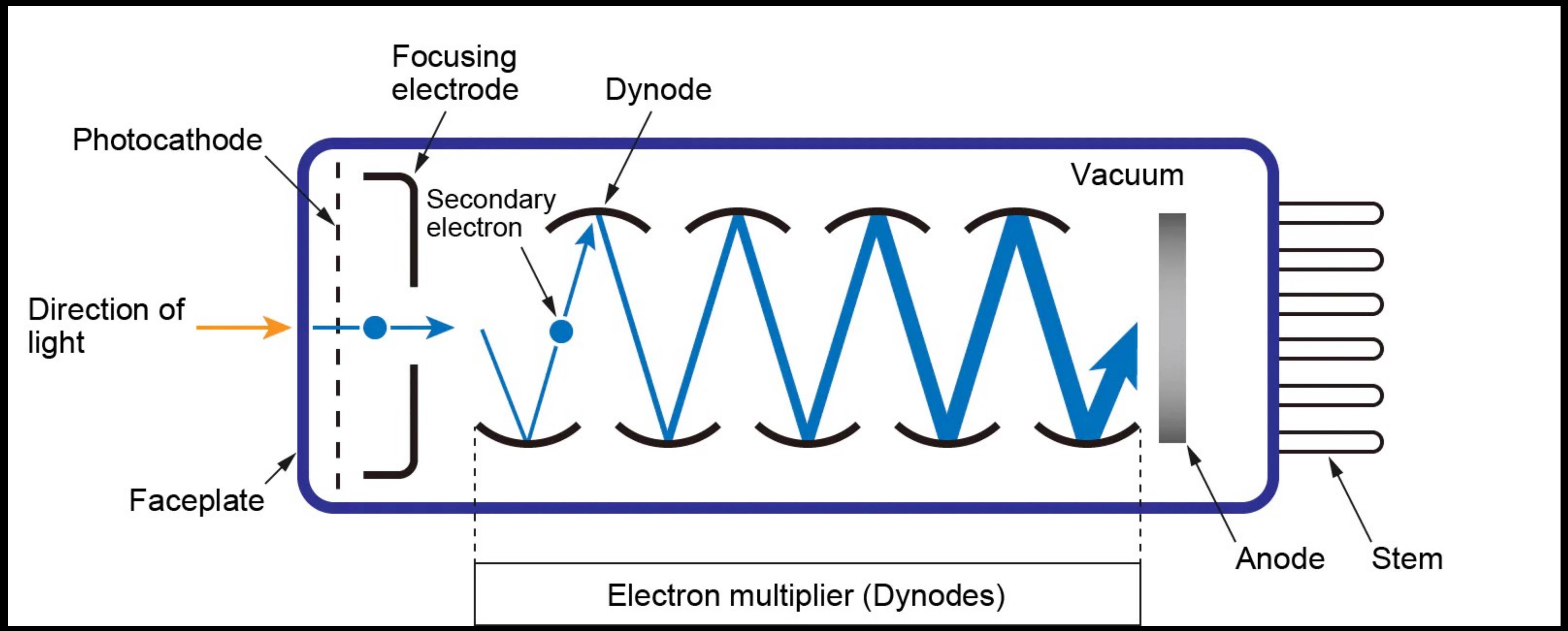


NaI scintillation crystal (left), NaI:Tl scintillation crystal(right) excited by a 254 nm wavelength (UV) LED lamp

PHOTOMULTIPLIER TUBES

- Photomultipliers convert light into a detectable electronic signal
  – Uses photo-electric effect to convert photons to photo-electrons

- Typical PMT Gain: > 1 million
  - A PMT can "see" single photons!



CALORIMETRY

- If we completely stop a particle (eg in a scintillator) then all of its energy will be transferred into signal – This is called a calorimeter
- Basically:
  - Incoming particle creates a particle shower
  - Energy deposited in form of: heat, ionization, excitation of atoms, Cherenkov light, etc
- Calorimeters can measure the energy of both charged and neutral particles
- You would have a different EM or hadronic calorimeter depending on whether you stop the particle using the EM or strong force

THE CMS ELECTROMAGNETIC CALORIMETER IS MADE UP OF 78'000 LEAD TUNGSTATE CRYSTALS. EACH ONE TOOK AROUND 2 DAYS TO GROW

CALORIMETRY

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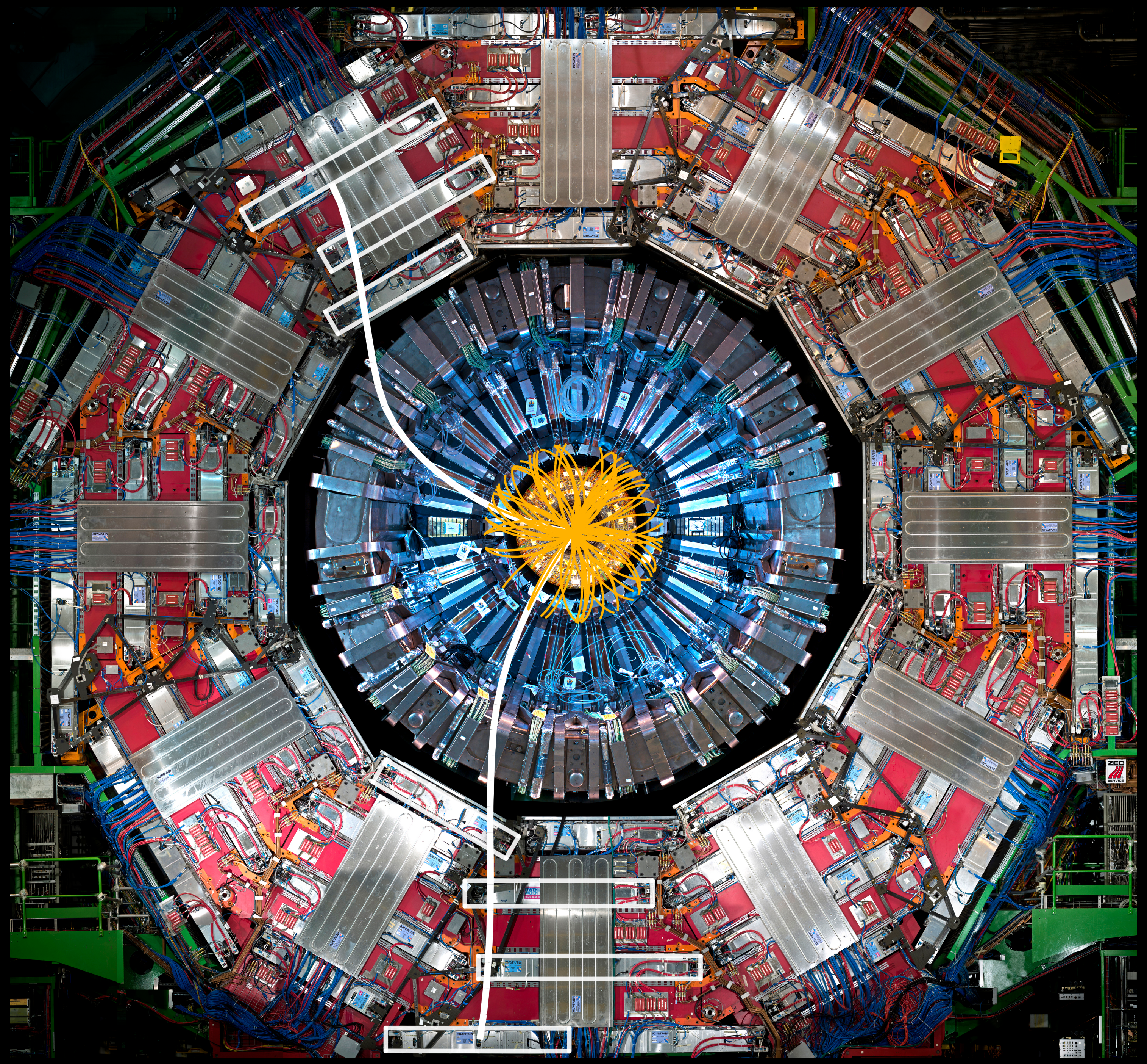
THE CMS HADRONIC CALORIMETER USED OVER A MILLION WORLD WAR II BRASS SHELL CASINGS, AS WELL AS OPTICAL DECODER UNITS MADE BY HIGH SCHOOL STUDENTS

MINI SUMMARY

- We detect particles from their interactions with matter !
- Most interactions either give off light or electric charge – we build our detectors to exploit these in different ways
- As time has gone on, the detectors have become more and more complex
- Instead of using just one type of detector, people started putting different types together to get more information



HOW WOULD YOU TELL THE DIFFERENCE BETWEEN:

- proton and neutron
- electron and muon
- positron and proton
- electron and positron

HOW WOULD YOU TELL THE DIFFERENCE BETWEEN:

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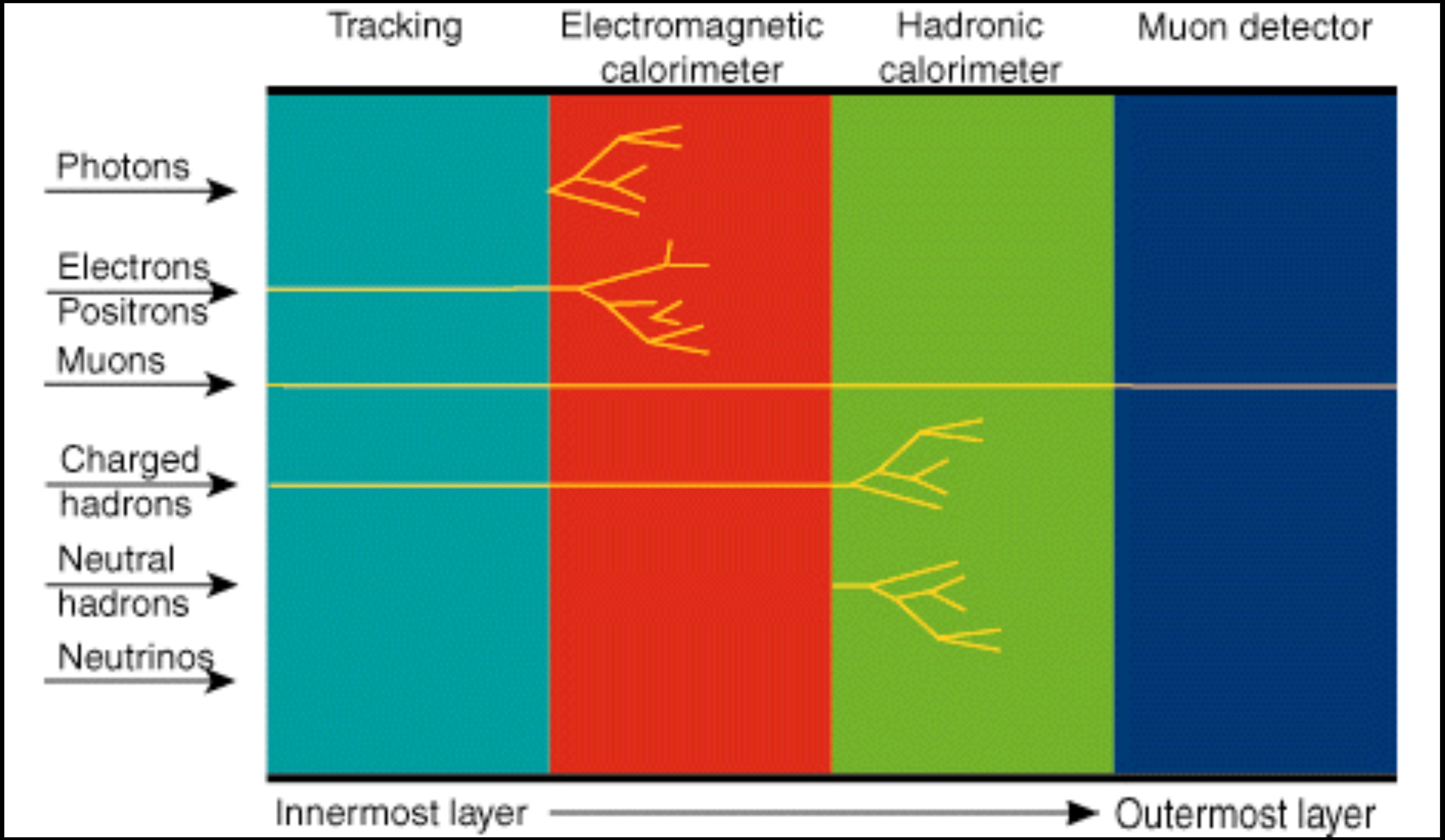
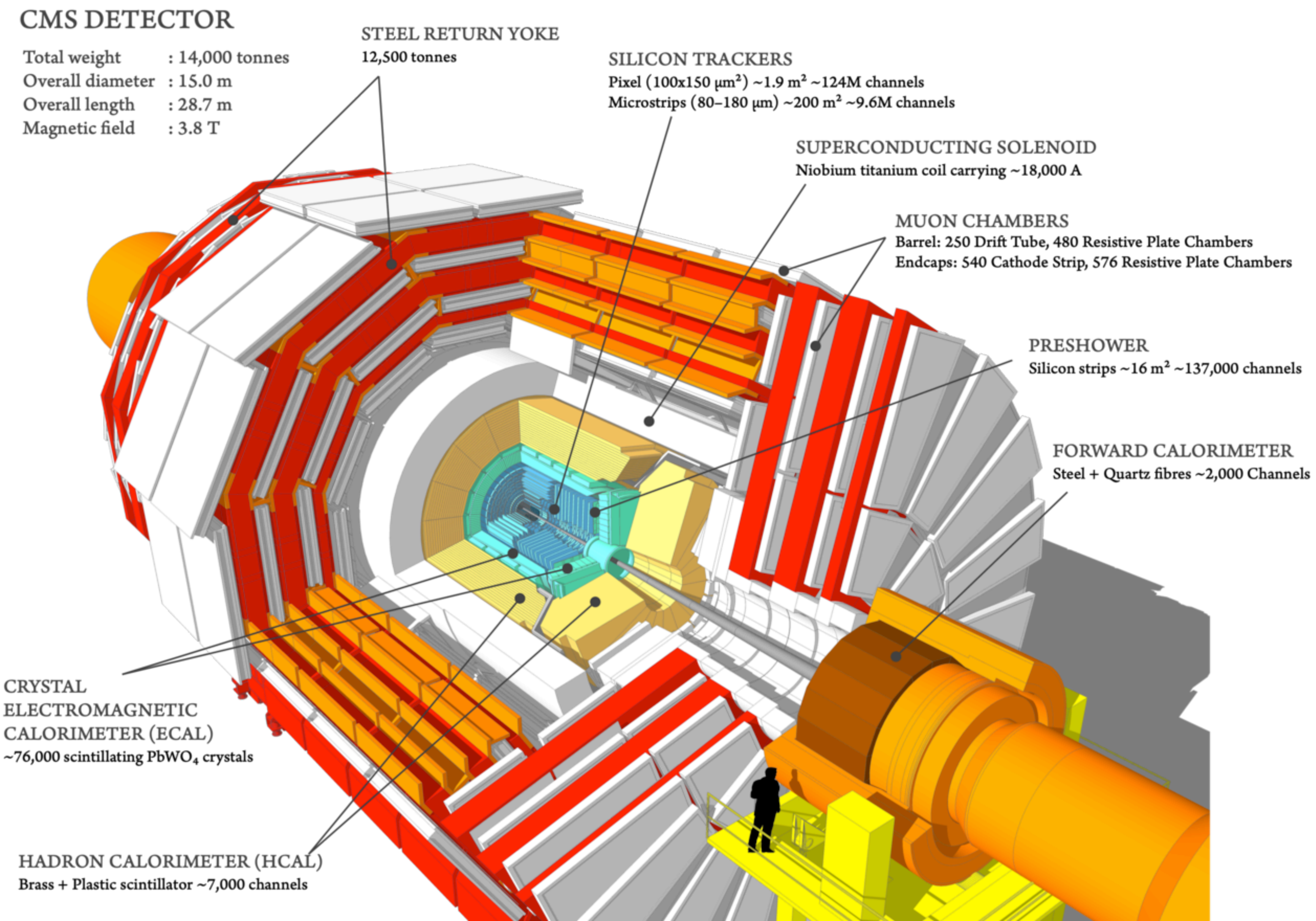
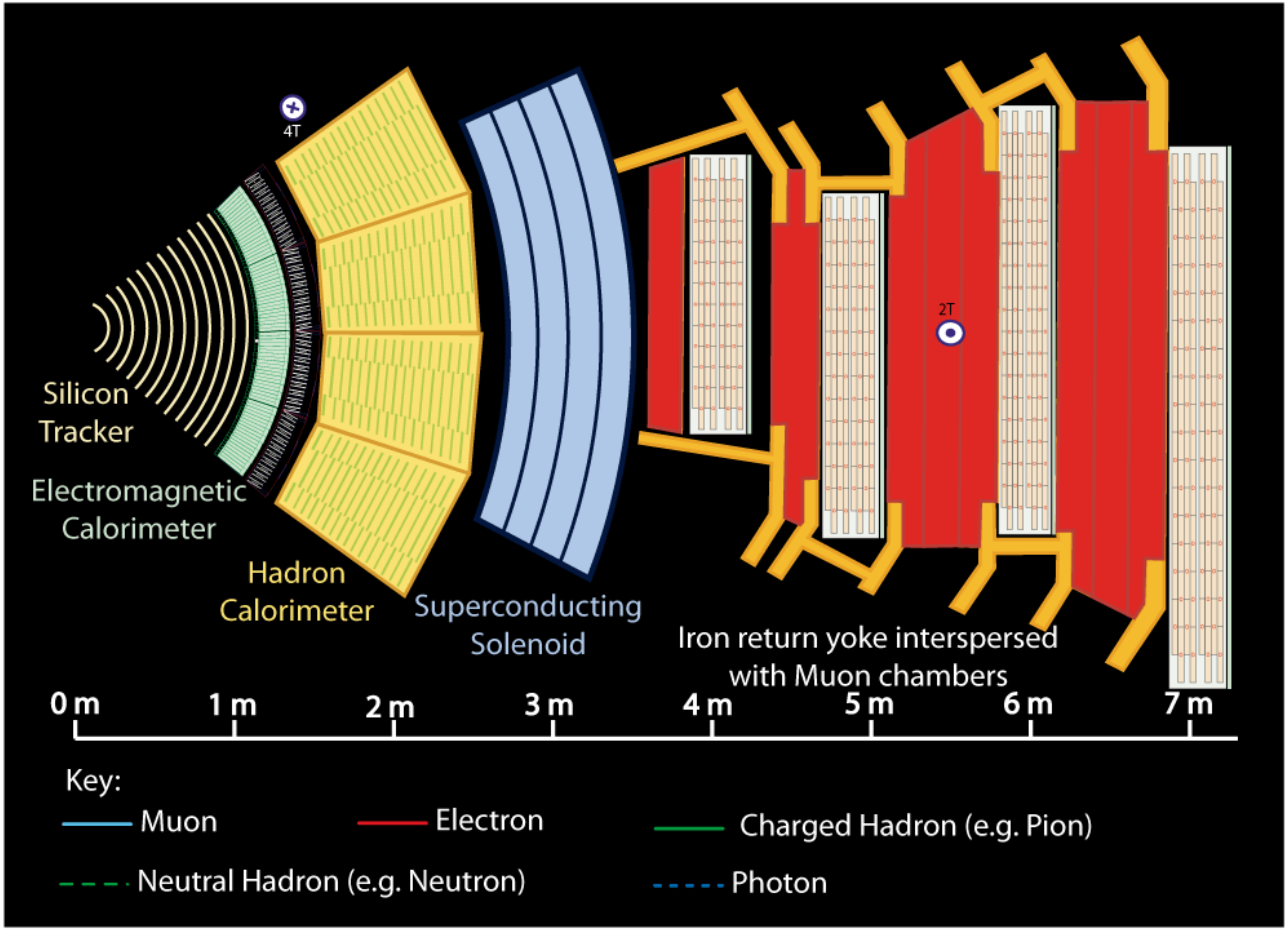
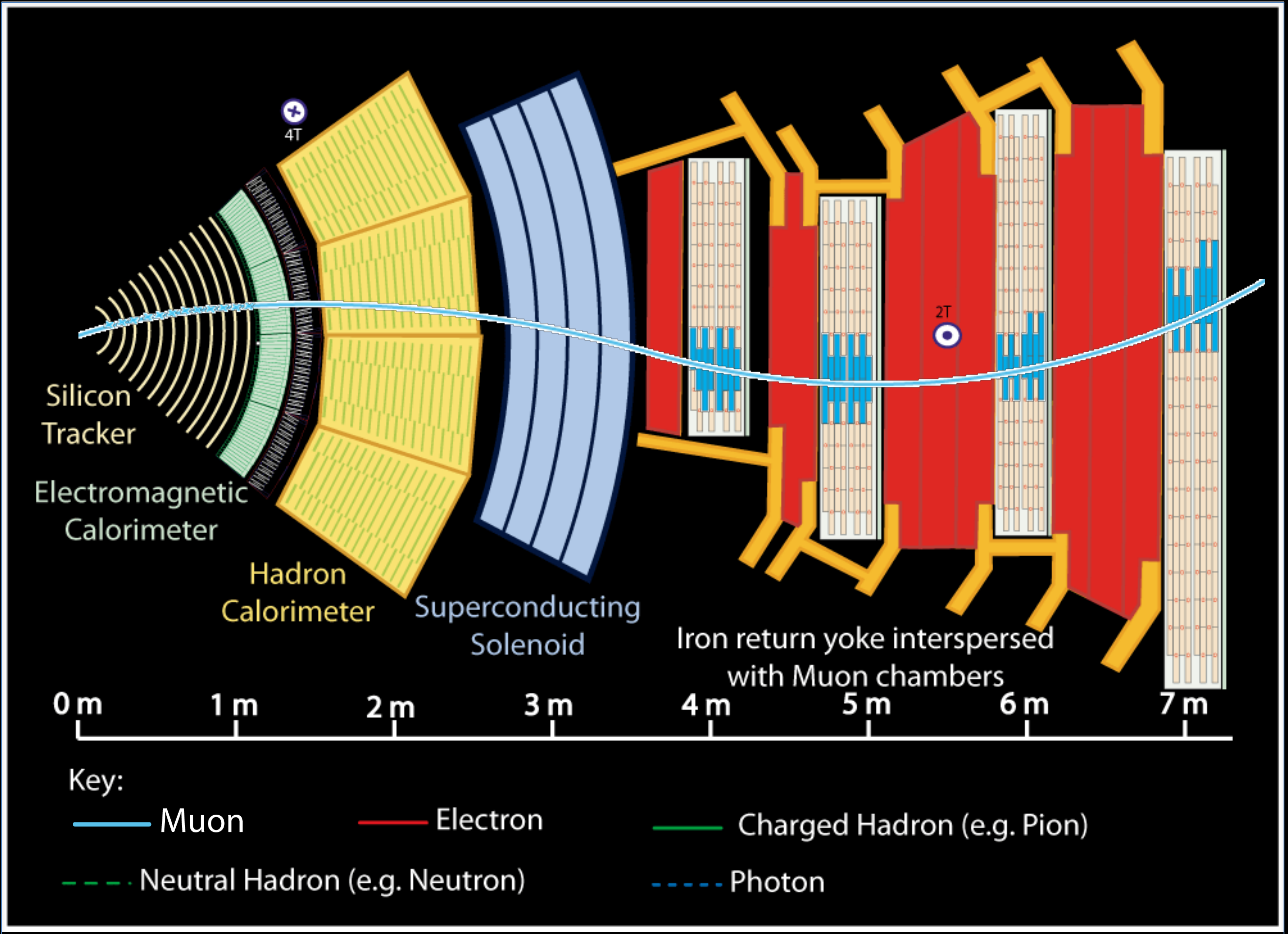
- electron and positron





CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm²) ~1.9 m² ~124M channels
Microstrips (80–180 μm) ~200 m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000 A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16 m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels


4T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon



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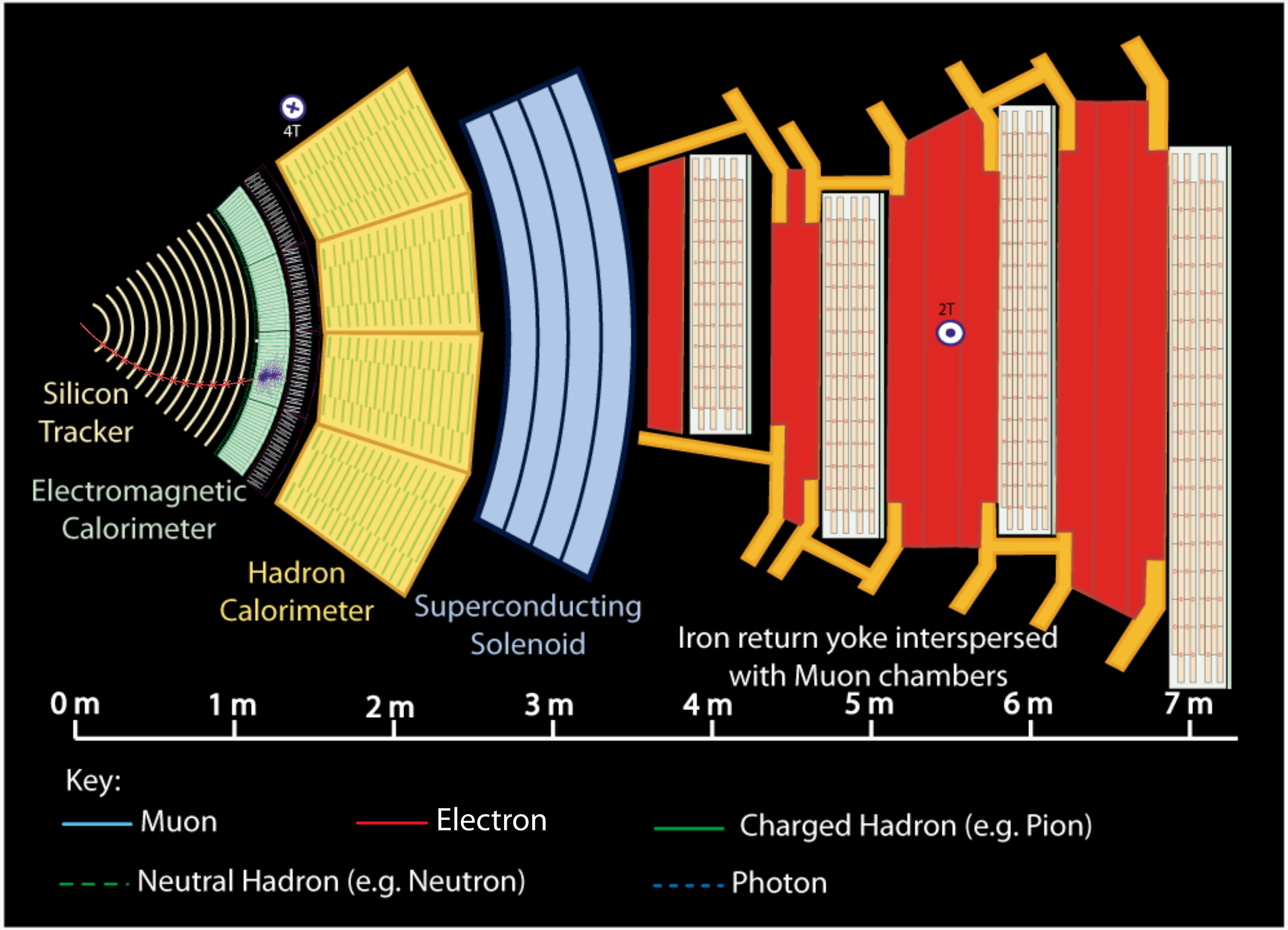
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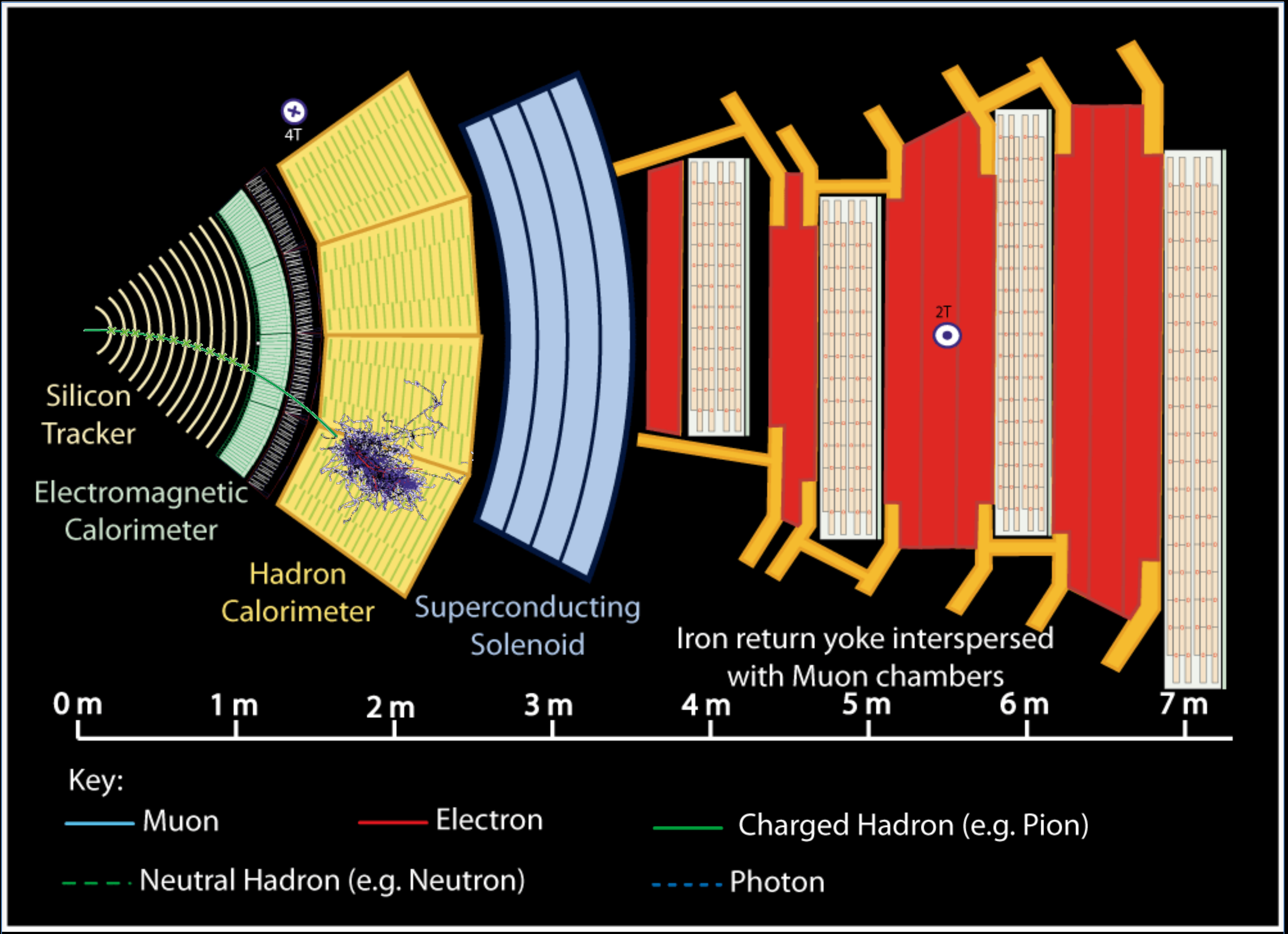
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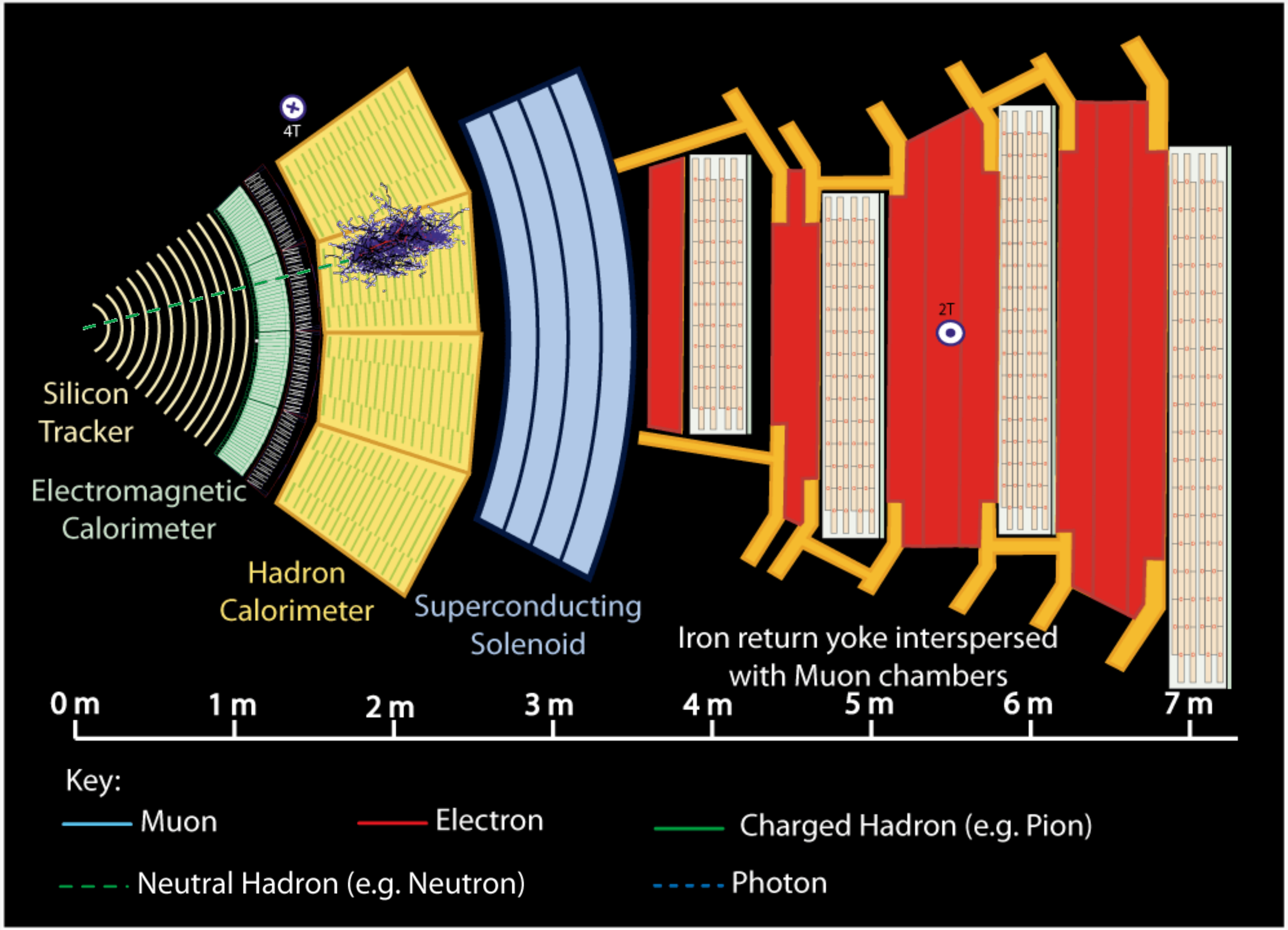

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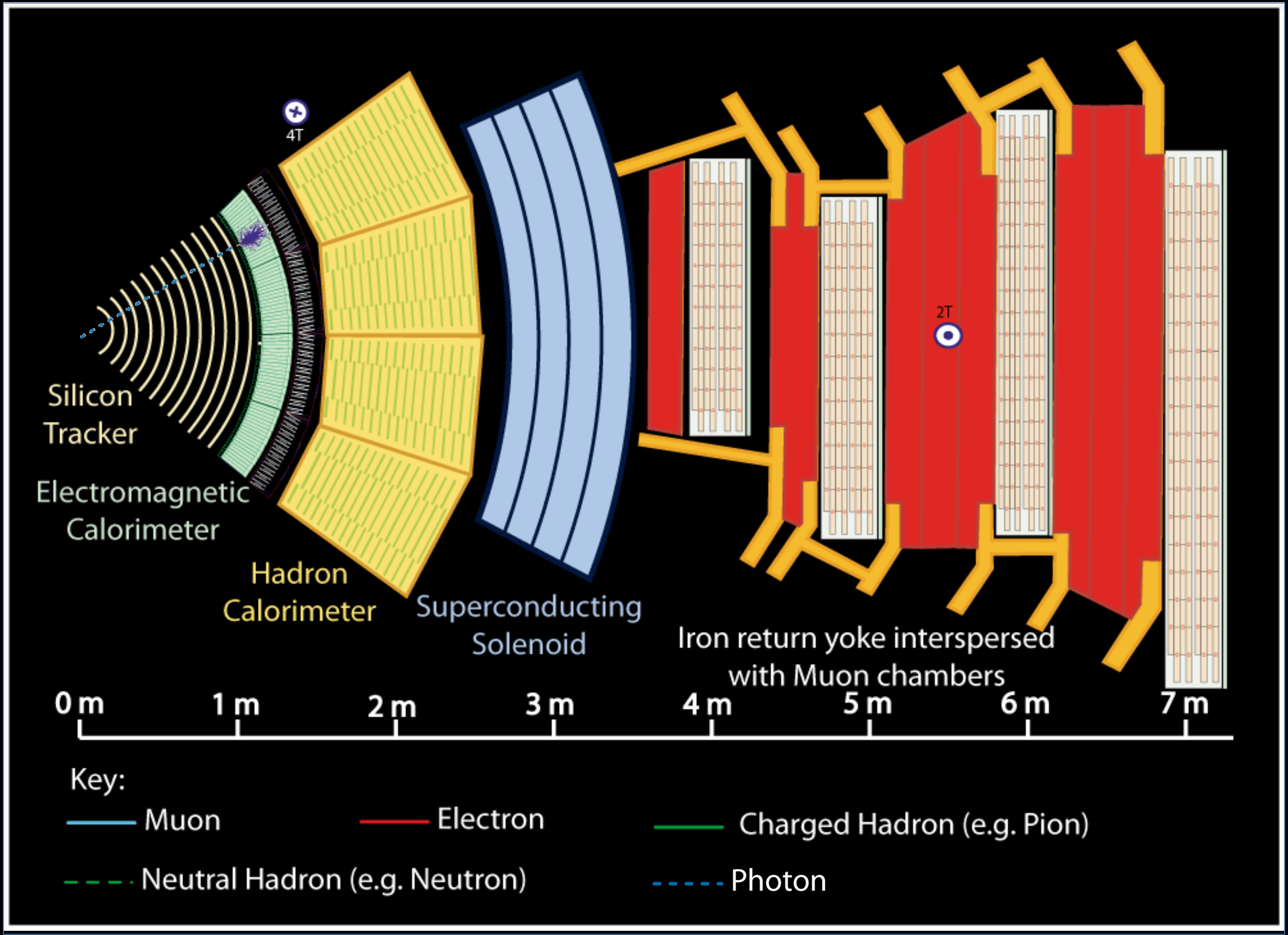
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Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

A PARTICLE FACTORY

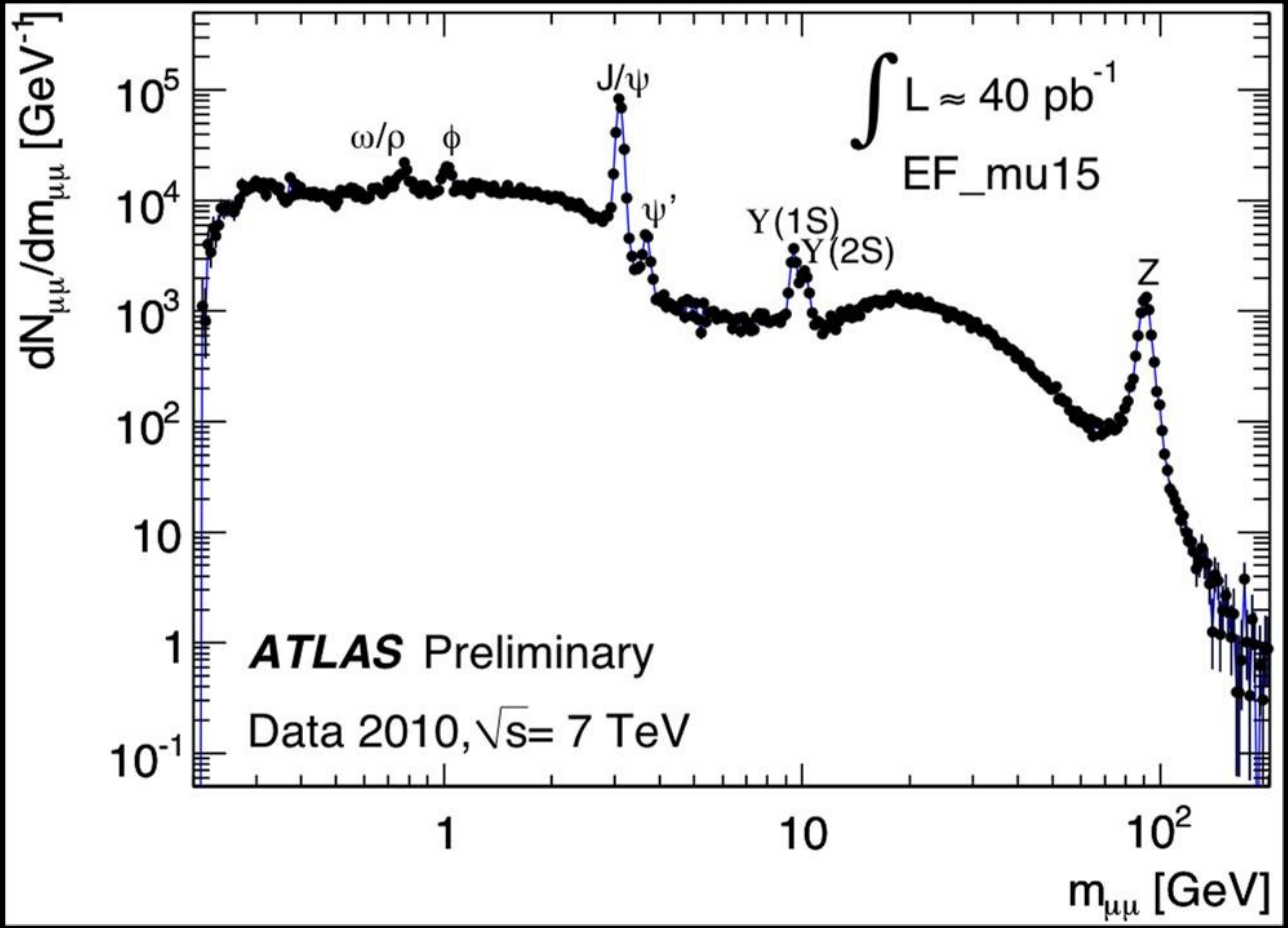
- Bunches of protons collide 40 million times per second at 4 points around the LHC ring

- At each of these points is a huge detector specially designed to "catch" all the outgoing particles

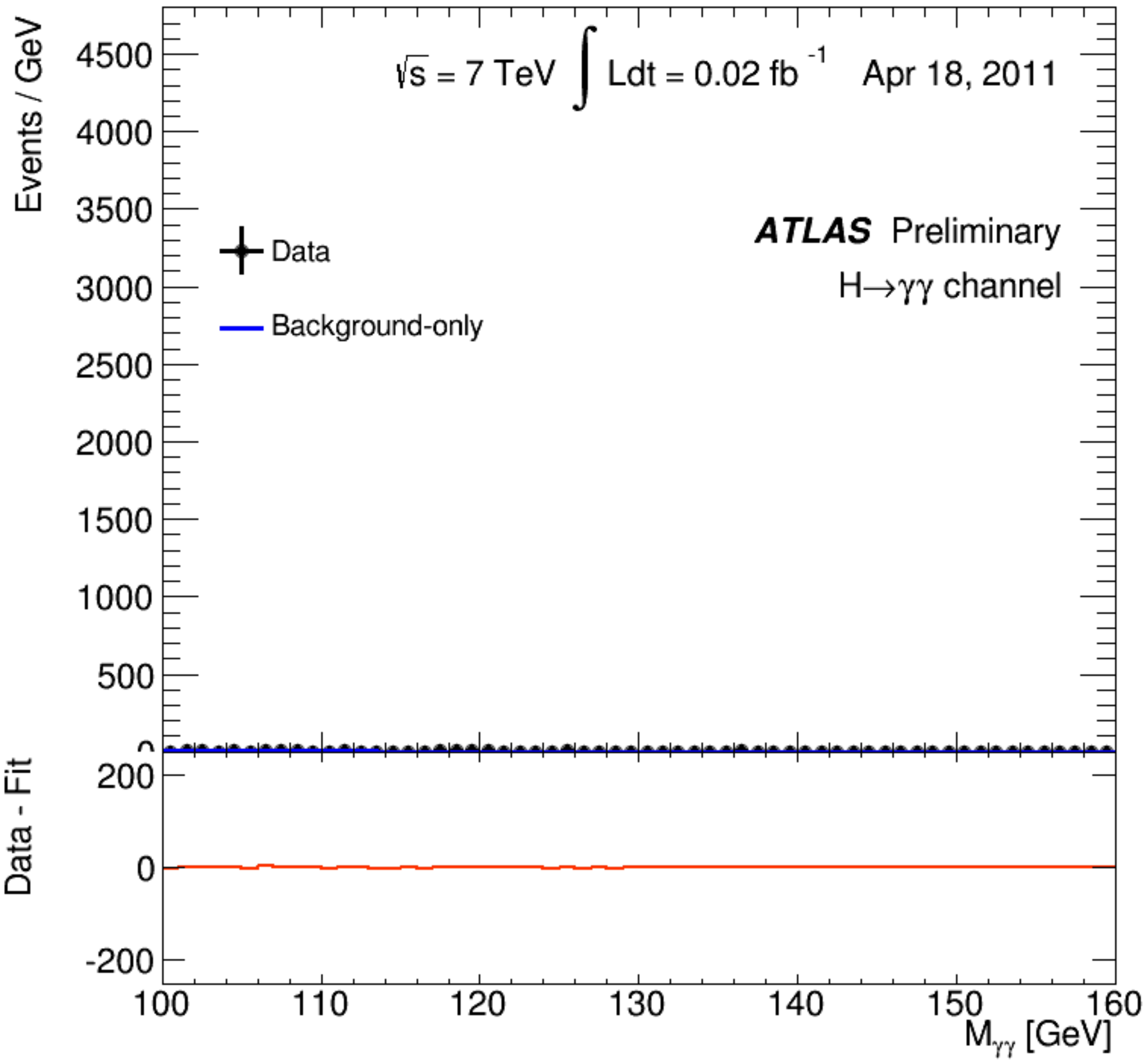
FIRST THINGS FIRST

MAKING SURE THE DETECTOR WORKS WELL

- Basically every particle physics data plot ever:
  - x-axis: range of something we're measuring (like mass)
  - y-axis: how many times the something has happened
  - Smooth curve shows the background (random stuff)
  - Bumpss indicate a particle!



SO HOW DO WE FIND A HIGGS?



COMBINED MASS OF 2 PHOTONS

THE END

- We detect particles from their interactions with matter
- Most interactions either give off light or electric charge, so we build our detectors to exploit these in different ways
- The detectors at the LHC are gigantic feats of engineering and physics, that use many different technologies layered together to give an almost complete picture of everything that comes out of the LHC collisions

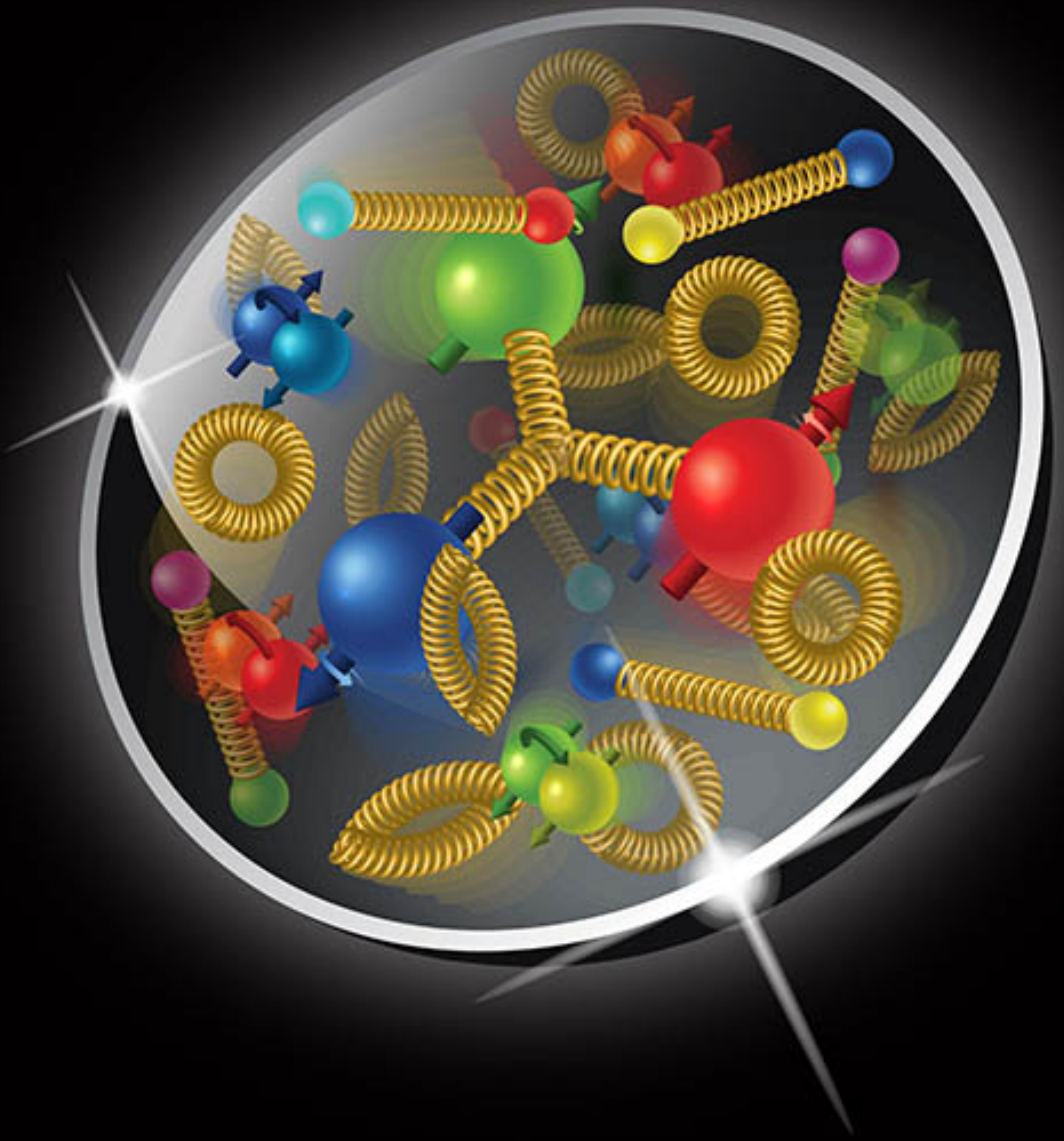

THANK YOU!
CMS.CERN
@CLAIRE_LEE

INSIDE A PROTON

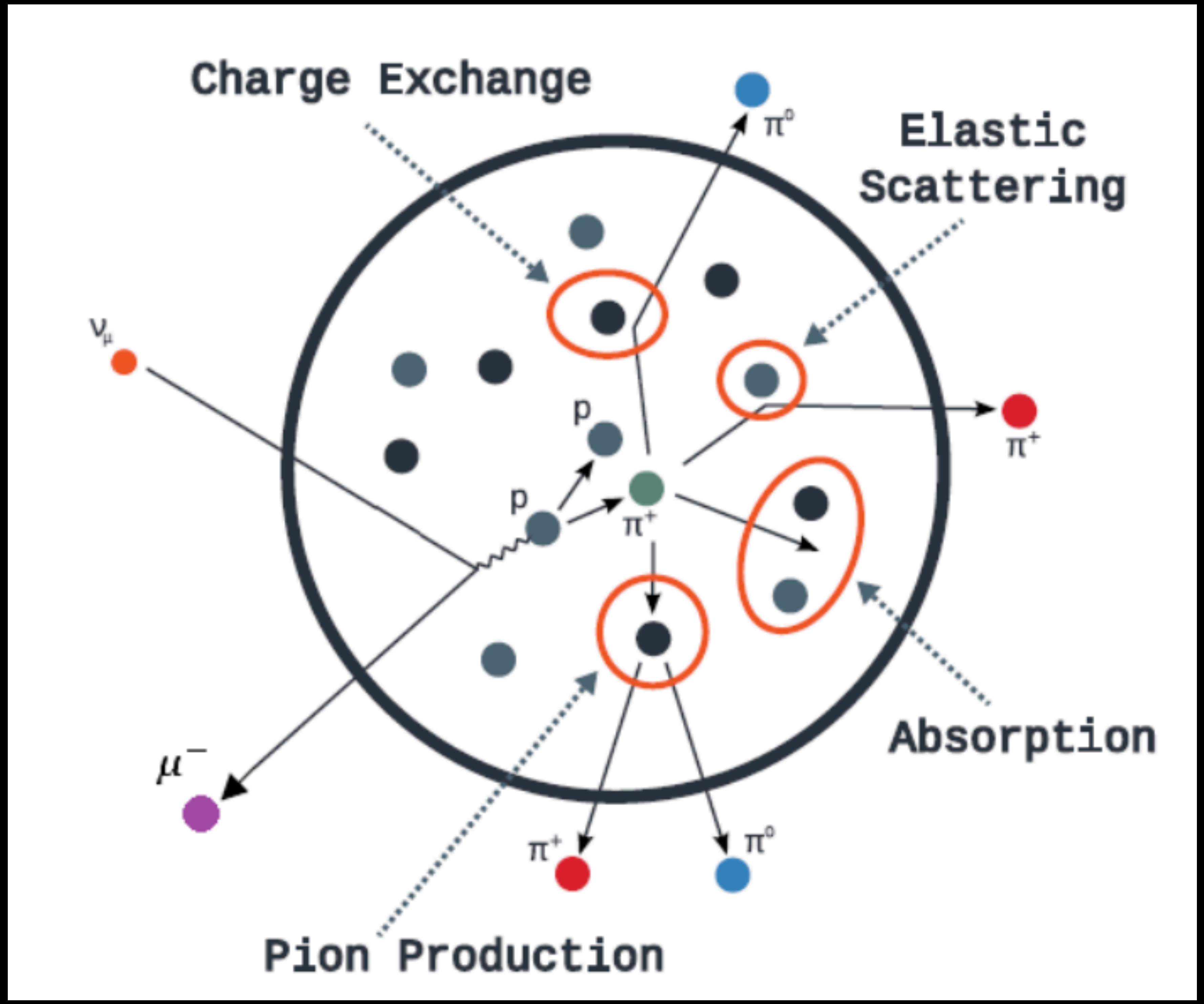
(AT LHC ENERGIES)

- The three "valence" quarks
- "Sea" quarks: quark-antiquark pairs popping in and out of existence
- Gluons holding them all together

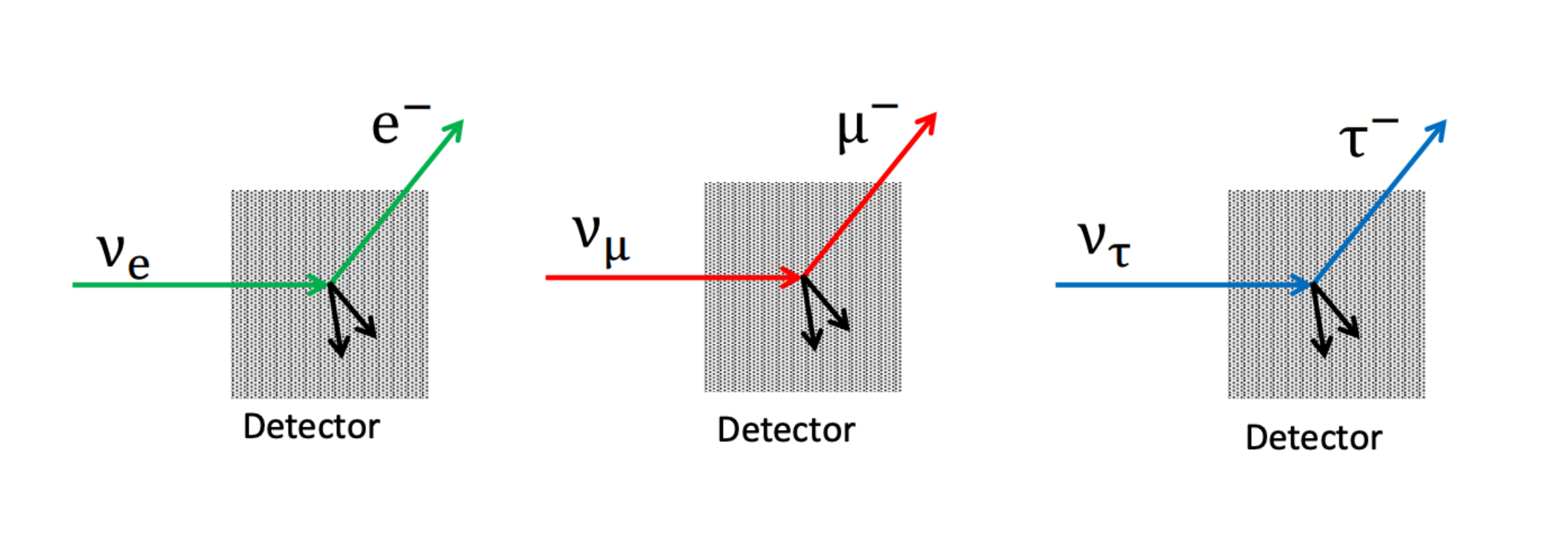
- Ideal discovery machine!

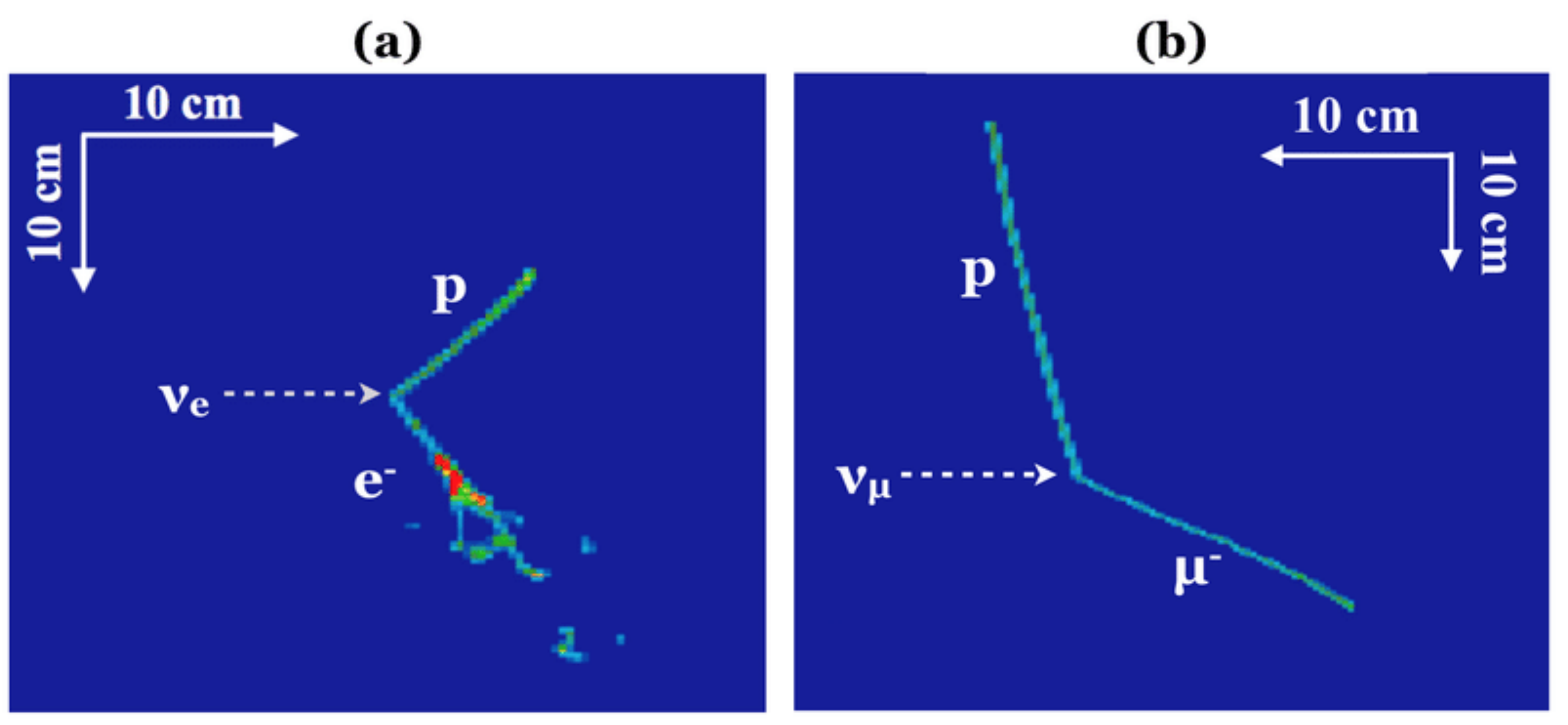


DETECTING NEUTRINOS



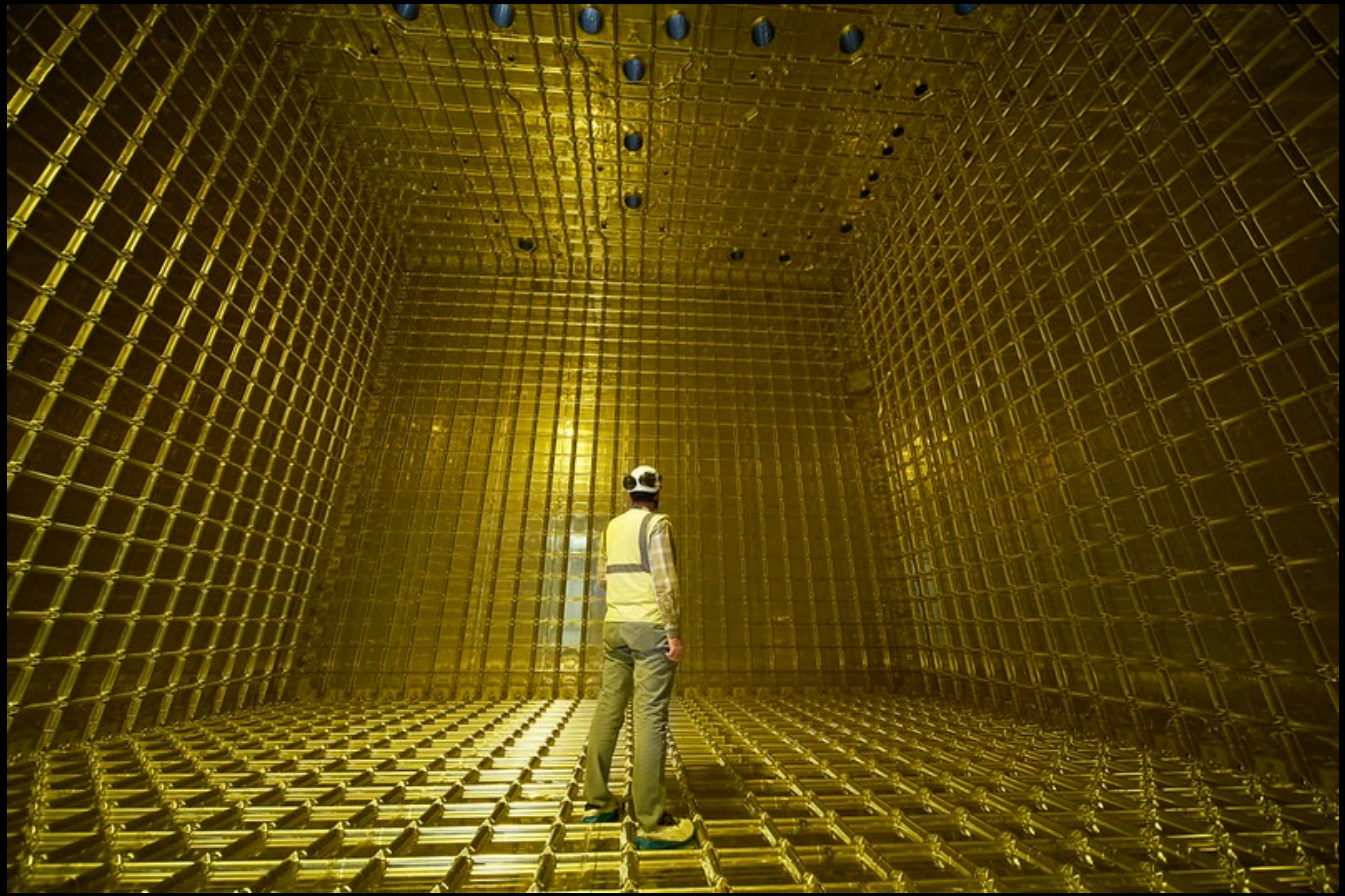
- If a neutrino interacts with matter, it produces a lepton of the same flavour as the neutrino:

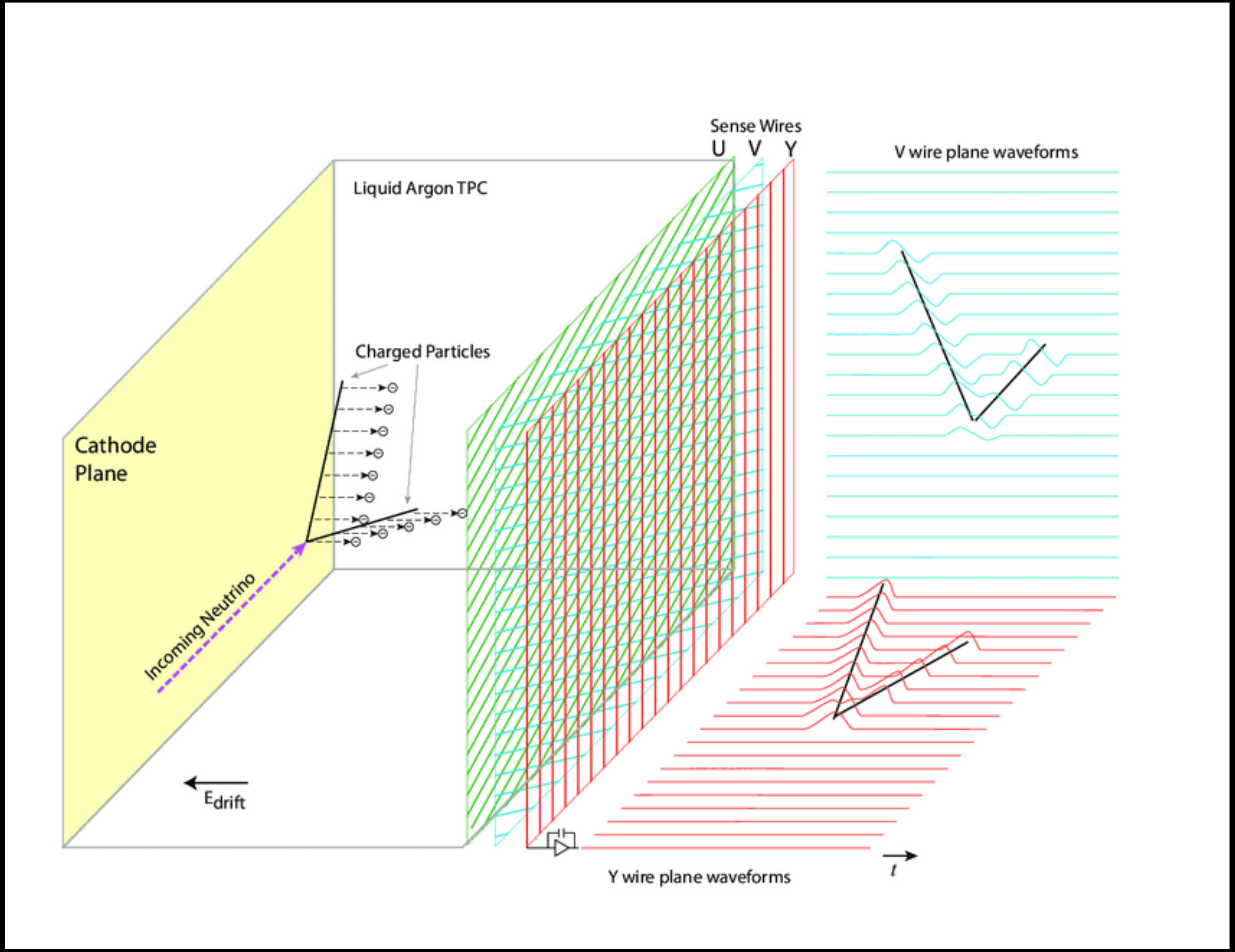


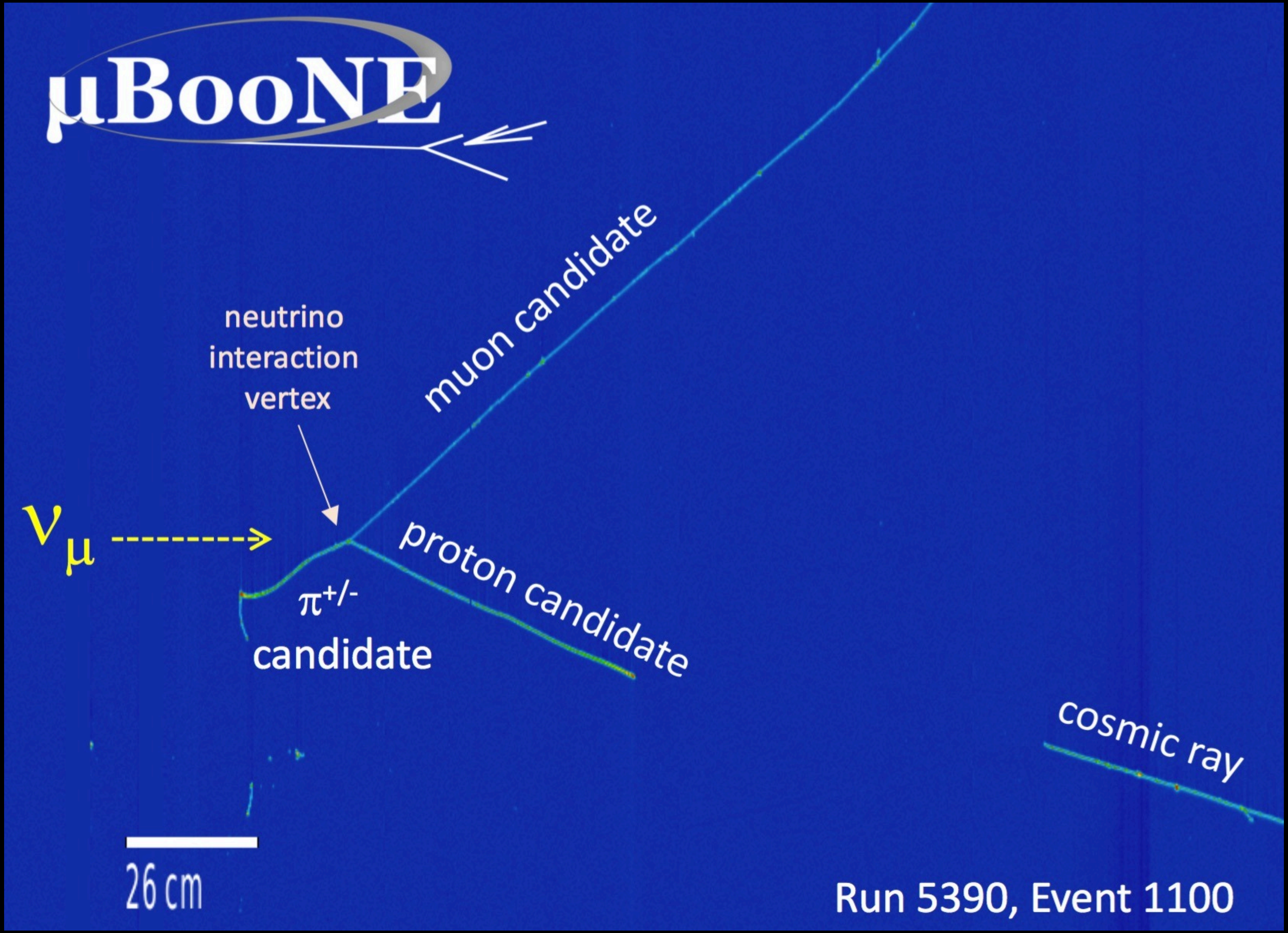


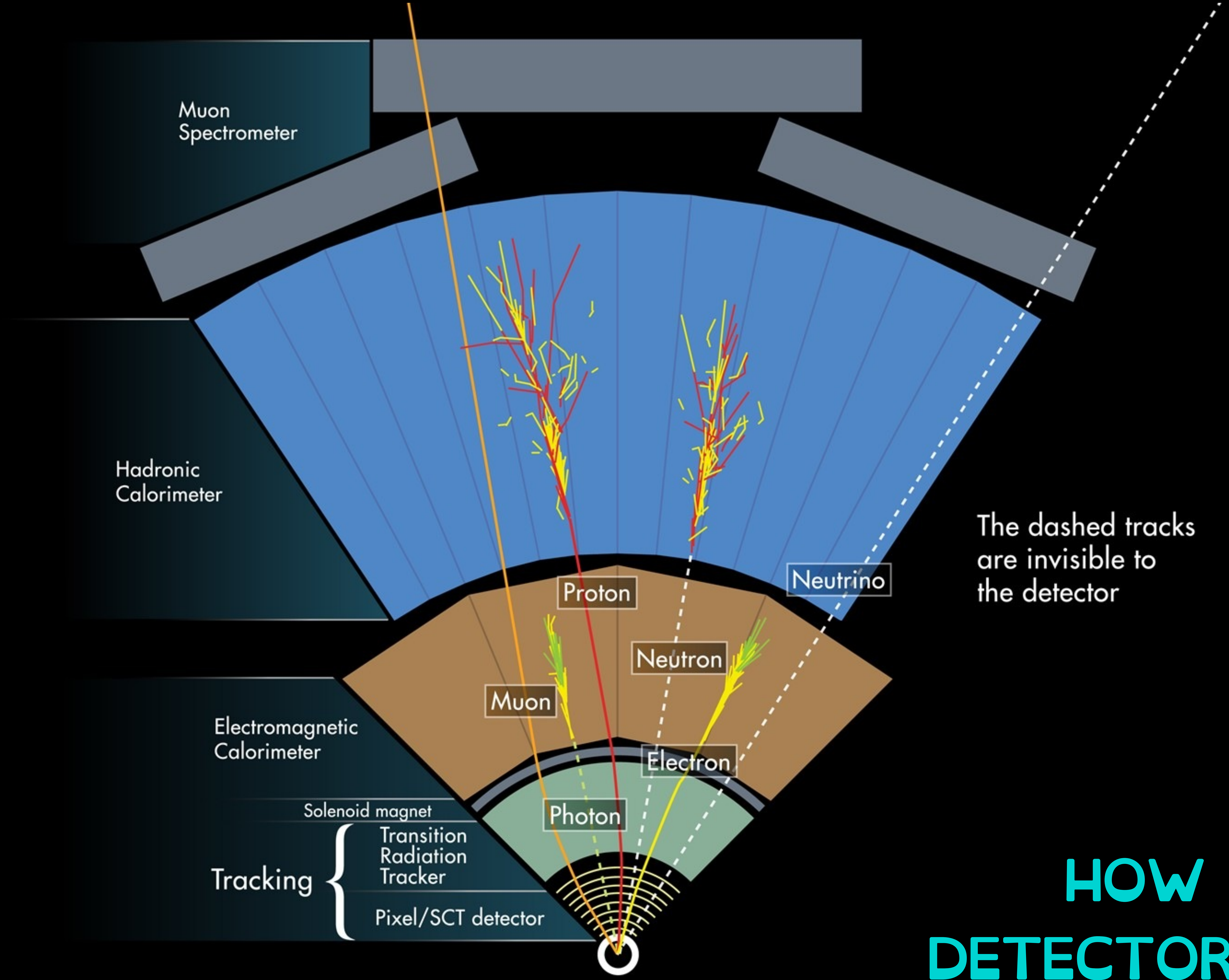
- The thing is, you really need A LOT of neutrinos if you're hoping to detect even one!

A DUNE PROTOTYPE






μBooNE
muon candidate
neutrino interaction vertex
ν_μ
proton candidate
$\pi^{+/-}$ candidate
cosmic ray
26 cm
Run 5390, Event 1100



HOW THE DETECTOR WORKS

THE FORCES OF PARTICLE PHYSICS