

PHYS 7363 - Experimental Particle Detection and Detectors I

Condensed Slides for Week 1
Saptaparna Bhattacharya

Key dates

- Weeks 1-4: Particle interaction with matter
 - Interaction of charged and neutral particles
 - Particle showers
- Weeks 5-9: Detector technologies:
 - Tracking detectors (gaseous detectors, semiconductor detectors)
 - Particle detection with photons (scintillators, Cherenkov detectors)
 - Calorimetry (electromagnetic and hadronic calorimeters)
- Weeks 10-12: Large and small scale experiments:
 - Triggering and data acquisition
 - Tracking
 - Full reconstruction (particle flow)
- Week 13-15: Preparation for final project:
 - FCC-ee: https://indico.fnal.gov/event/67484/contributions/314057/attachments/187076/257915/US%20FCC%20Tutorial_FullSim.pdf
 - Muon collider: <https://mcd-wiki.web.cern.ch/software/tutorials/fermilab2024/>

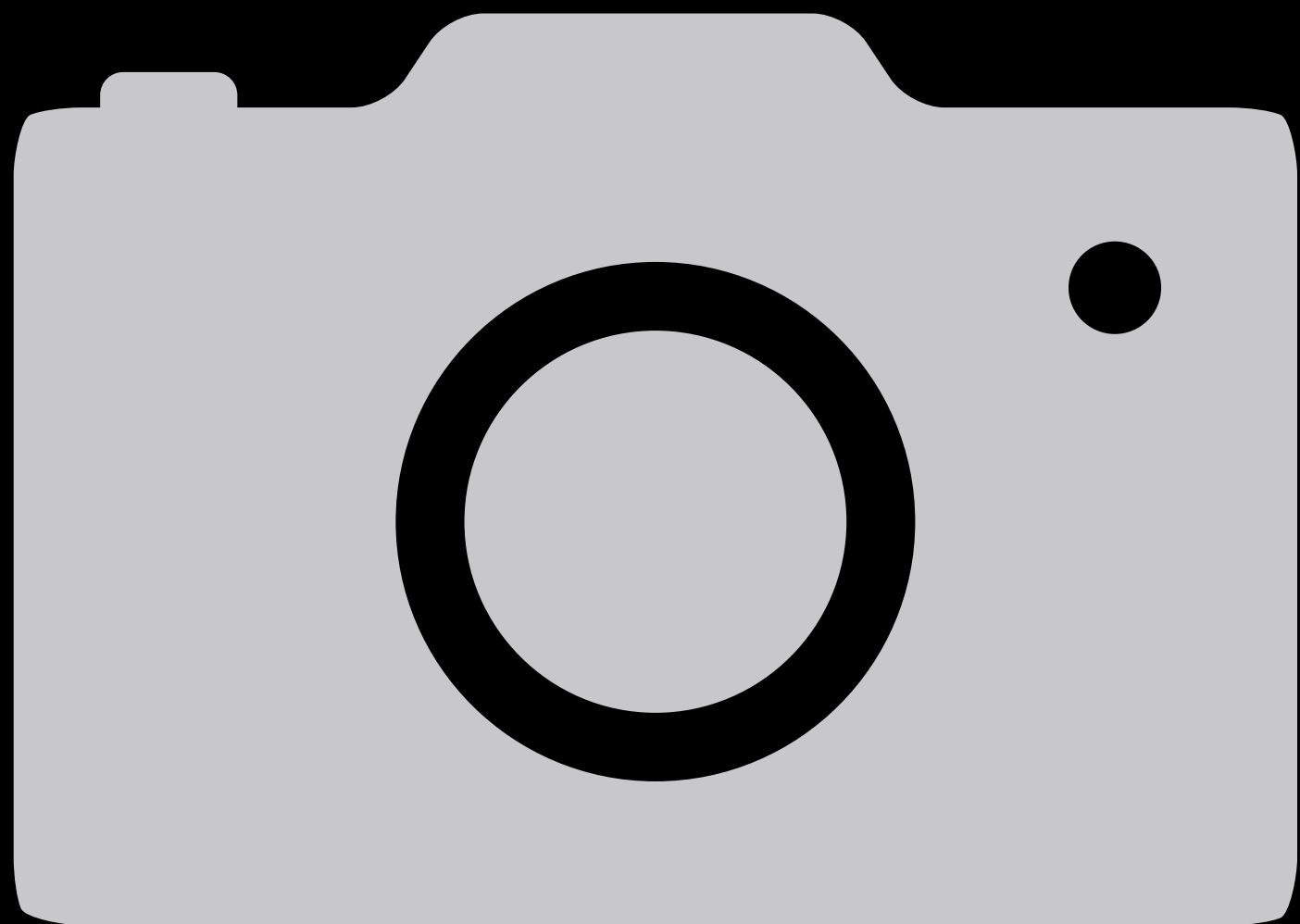
Resources

- PDG review: Passage of particles through matter
 - <https://pdg.lbl.gov/2020/reviews/rpp2020-rev-passage-particles-matter.pdf>
- N. Wermes / H. Kolanoski, “Particle Detectors”, Oxford University Press, 2020
- C. Grupen / B. Schwartz, “Particle Detectors”, Cambridge University Press, 2011
- F. Hartmann, “Evolution of Silicon Sensor Technology in Particle Physics”
- A. Strandlie, R. Frühwirth, Pattern Recognition, Tracking and Vertex Reconstruction in Particle Detectors

- What do you know about detectors?
- Which sub detector are you working on?

What are the requirements of a particle physics detector?

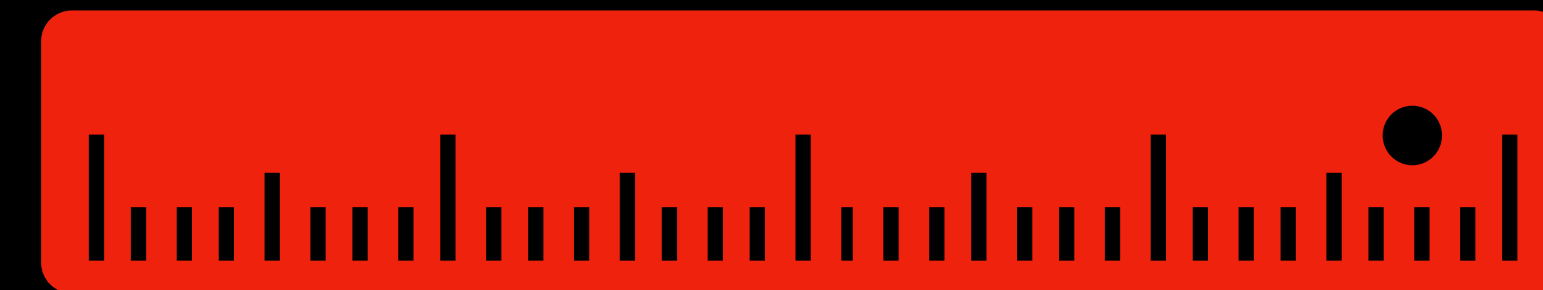
Detect



Identify



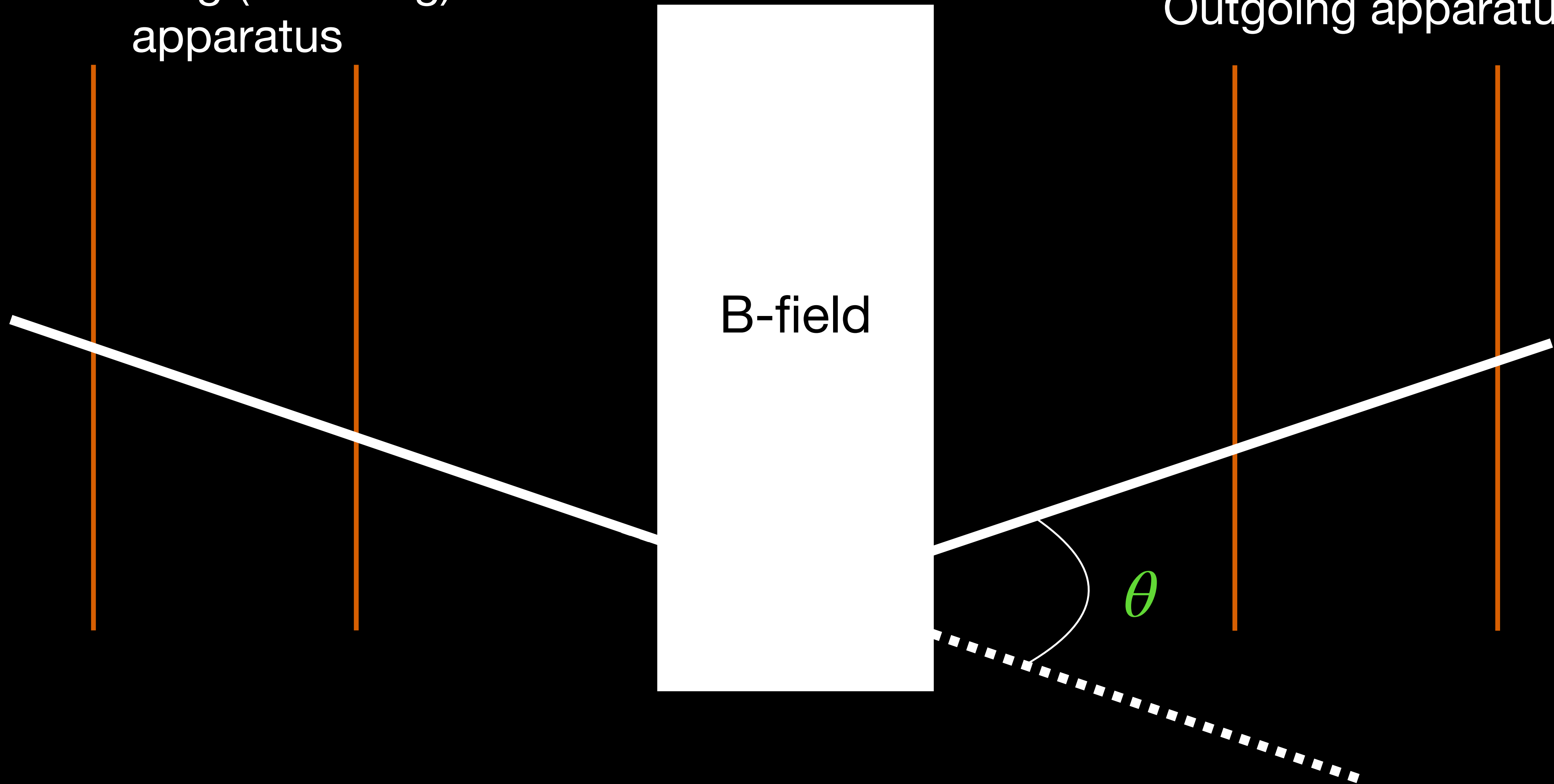
Measure



A simple detector

Detecting (incoming)
apparatus

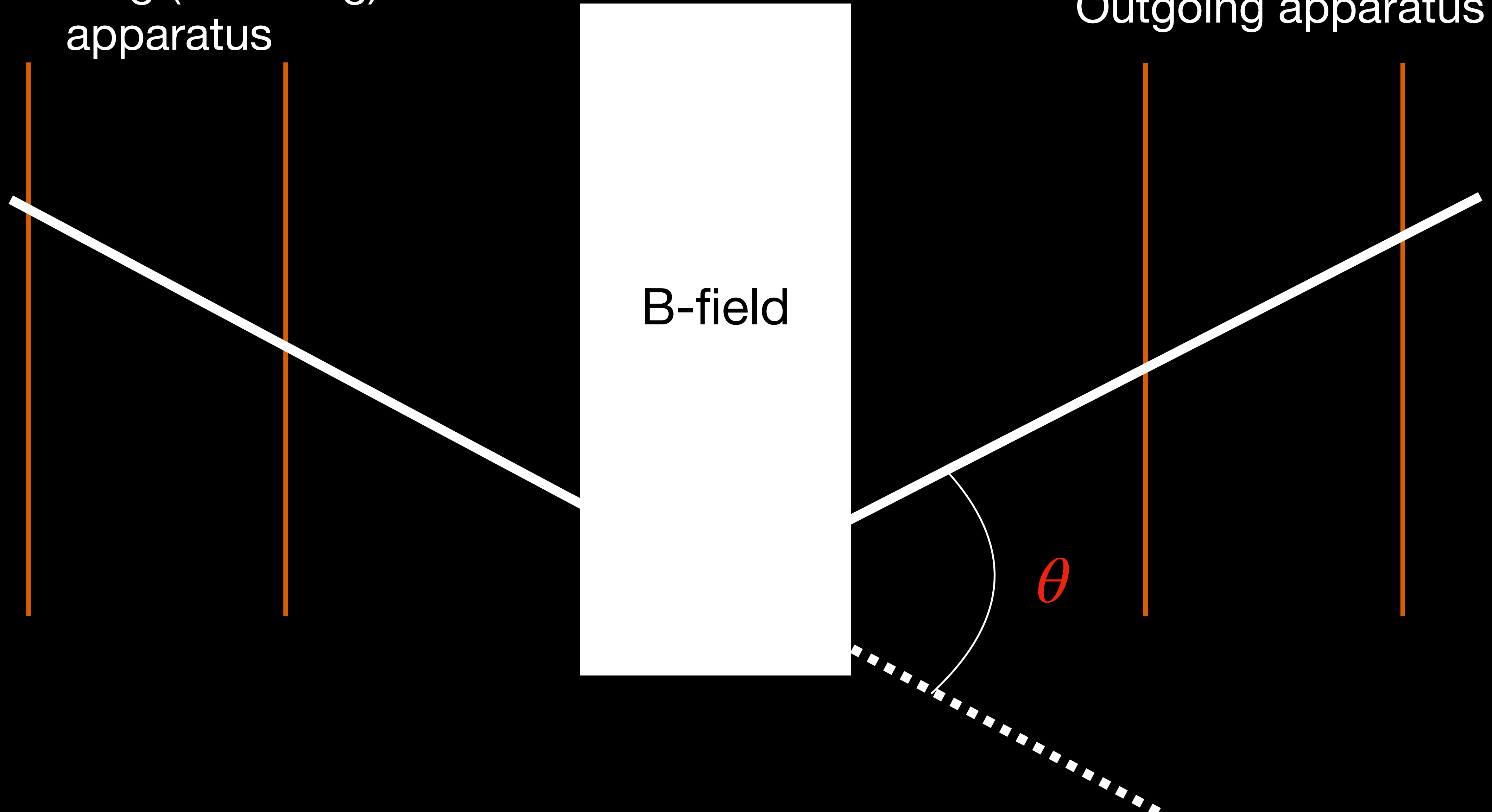
Outgoing apparatus



A simple detector

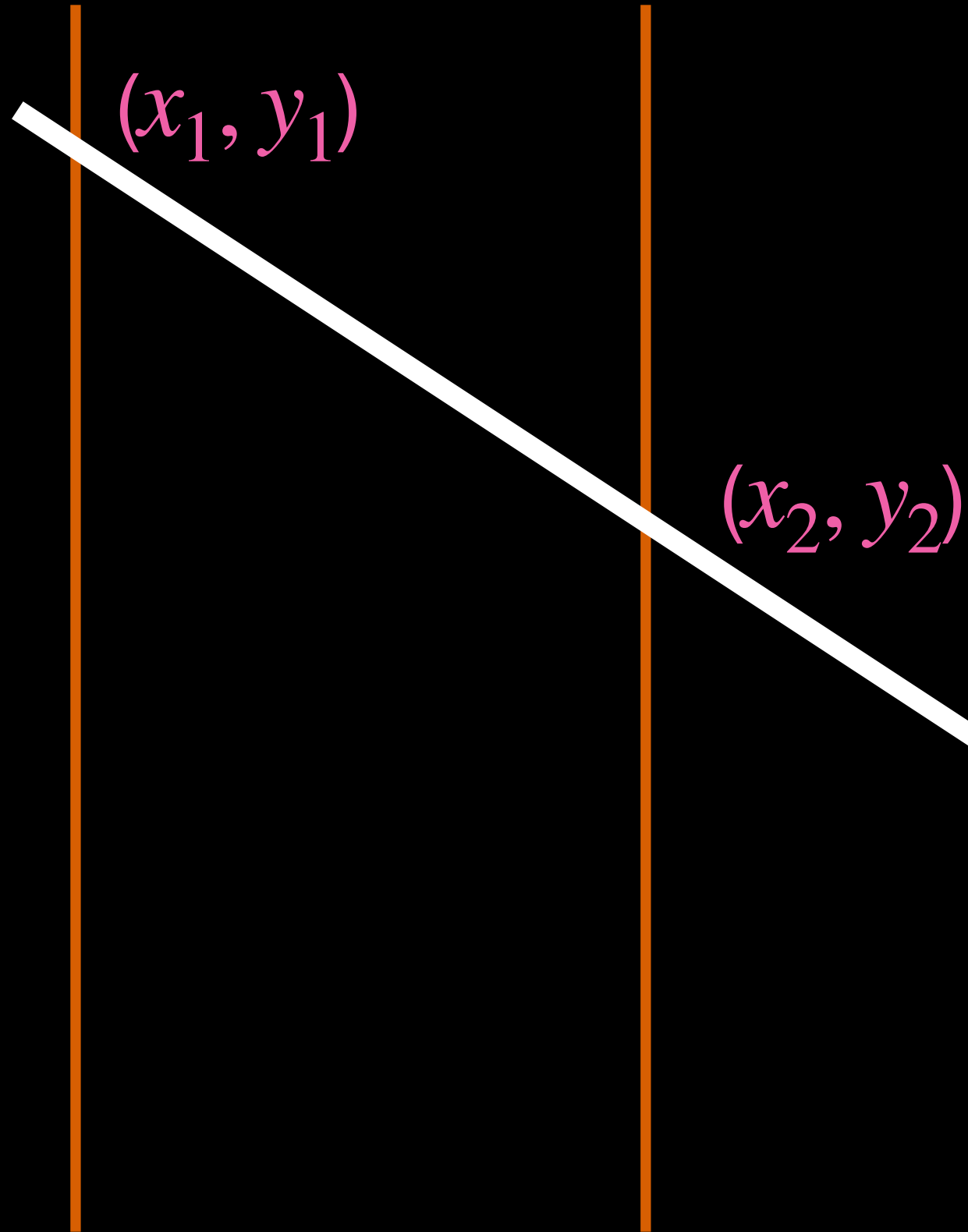
Detecting (incoming)
apparatus

Outgoing apparatus

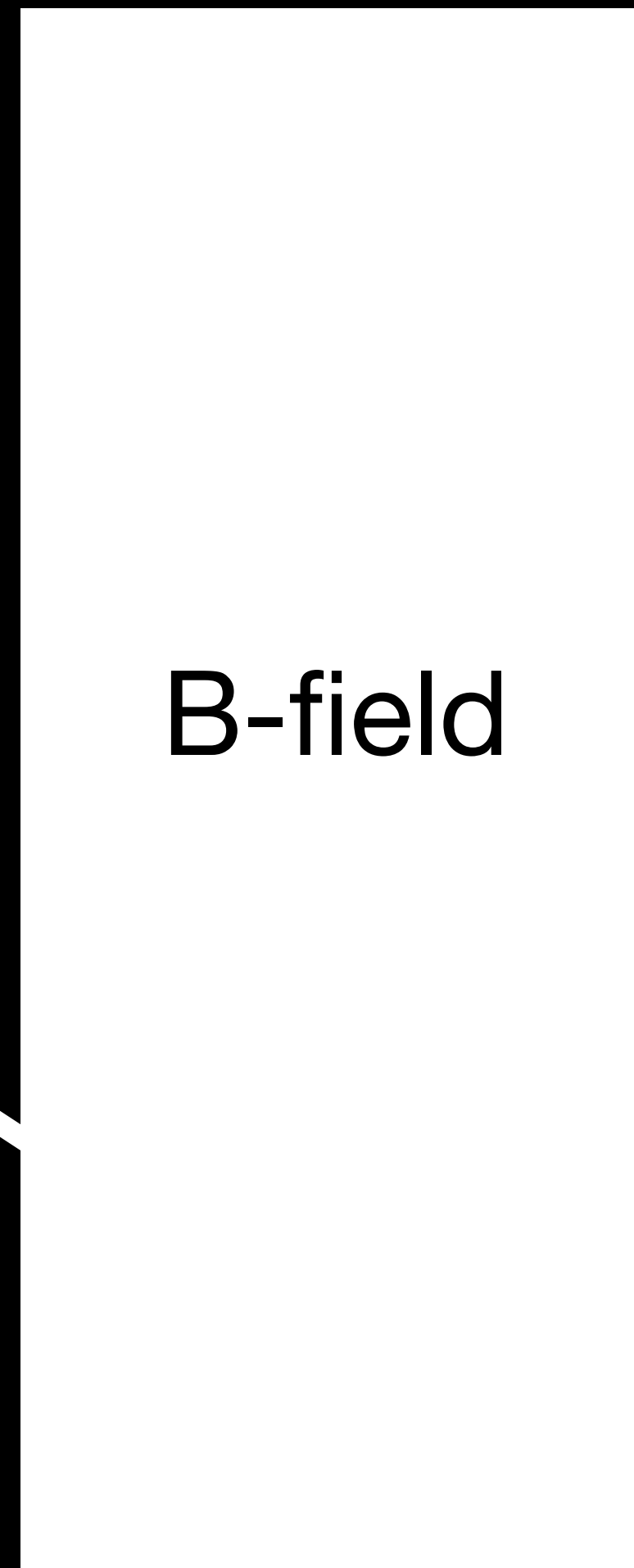


A simple detector

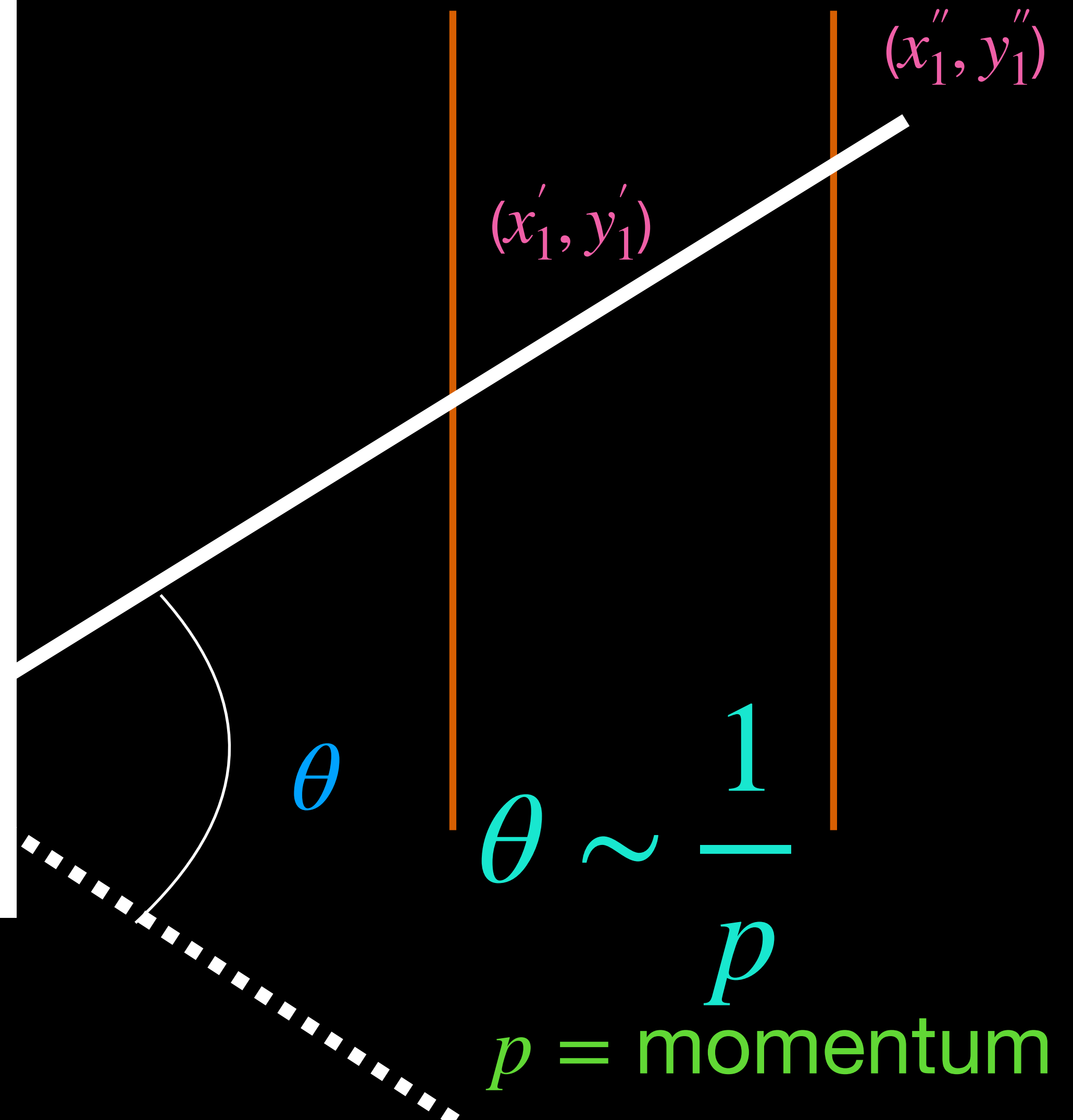
Detecting (incoming)
apparatus



Use coordinates to construct
straight line trajectory \rightarrow track



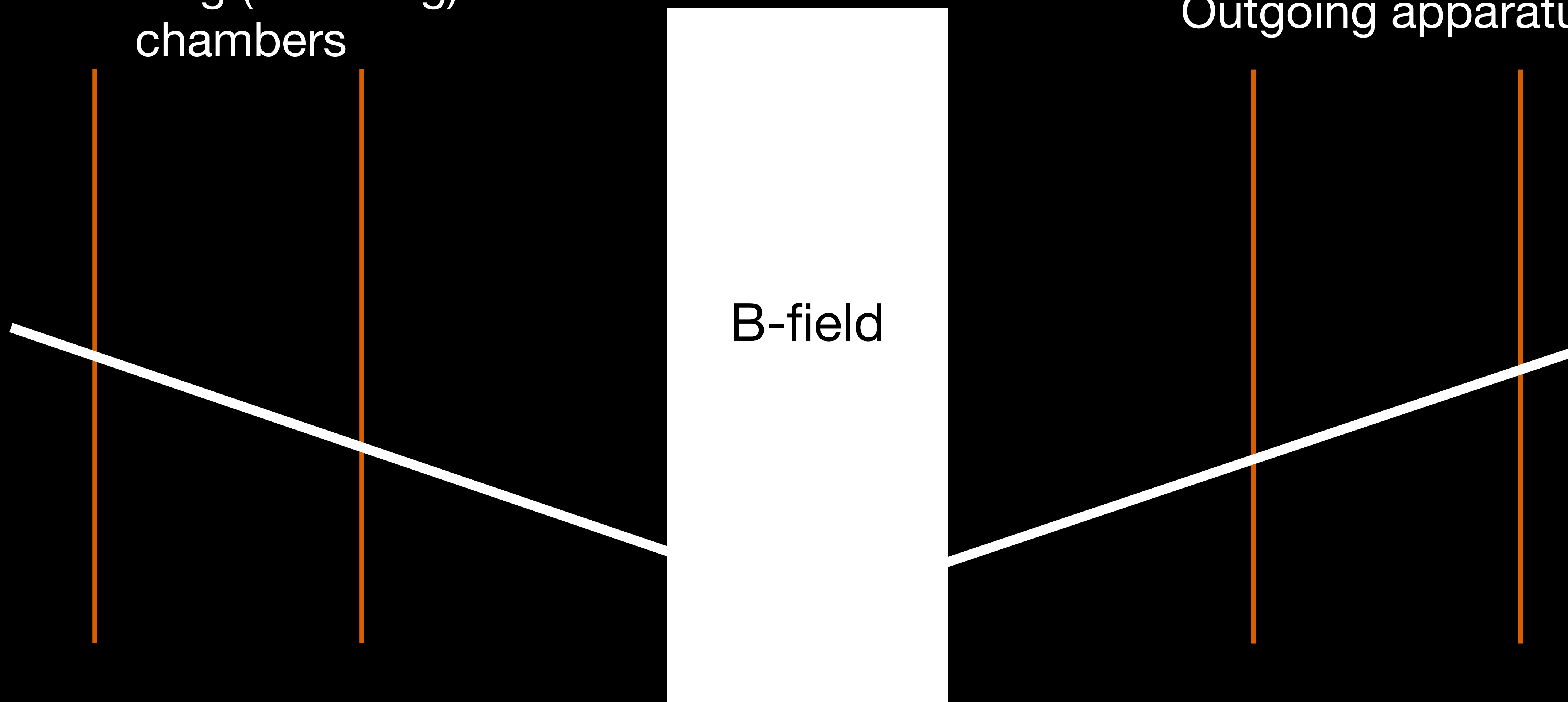
Outgoing chambers



A simple detector

Detecting (incoming)
chambers

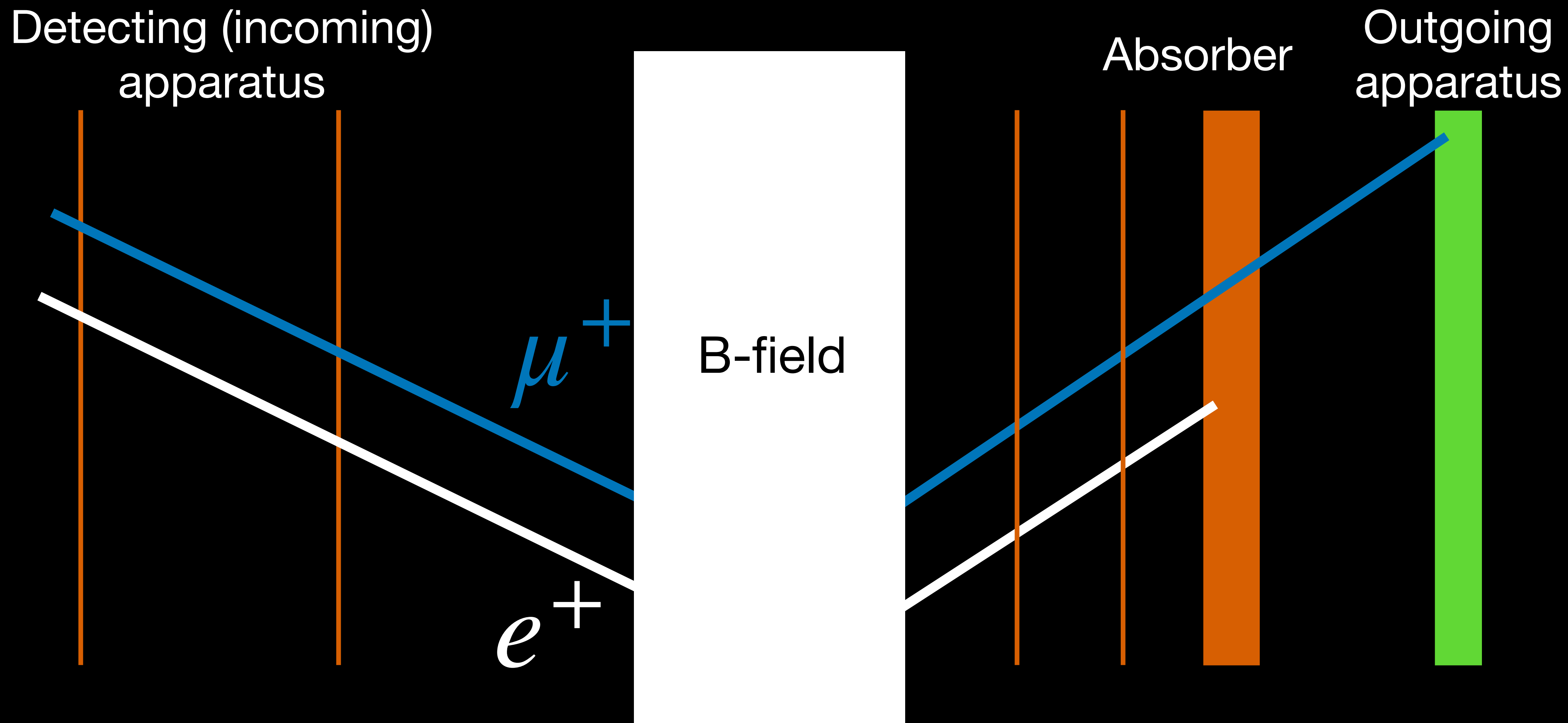
Outgoing apparatus



Same principle applies to e and μ

At LHC energies, $p \sim E$

A simple detector — for different types of particles

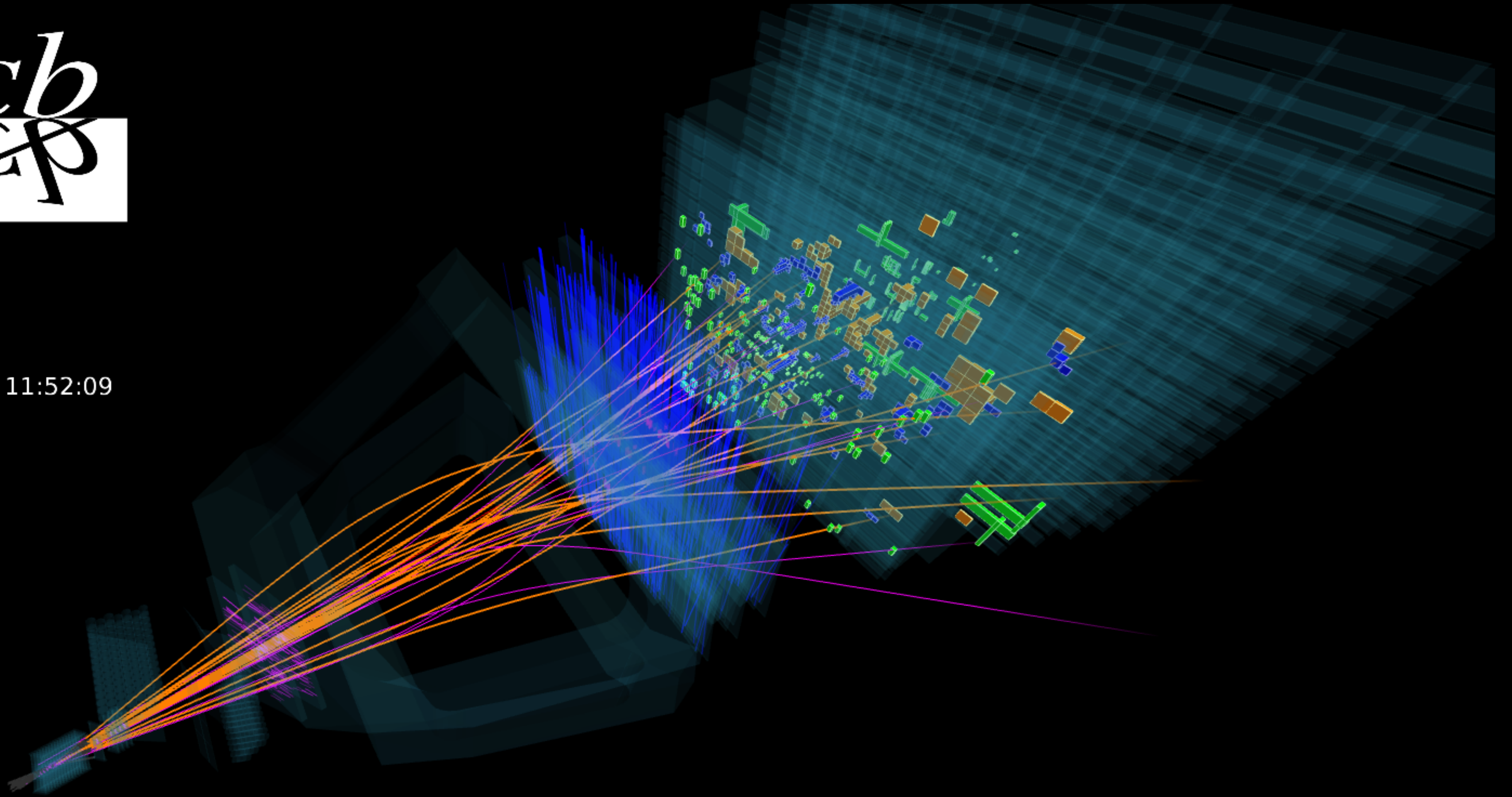




Event 41383468

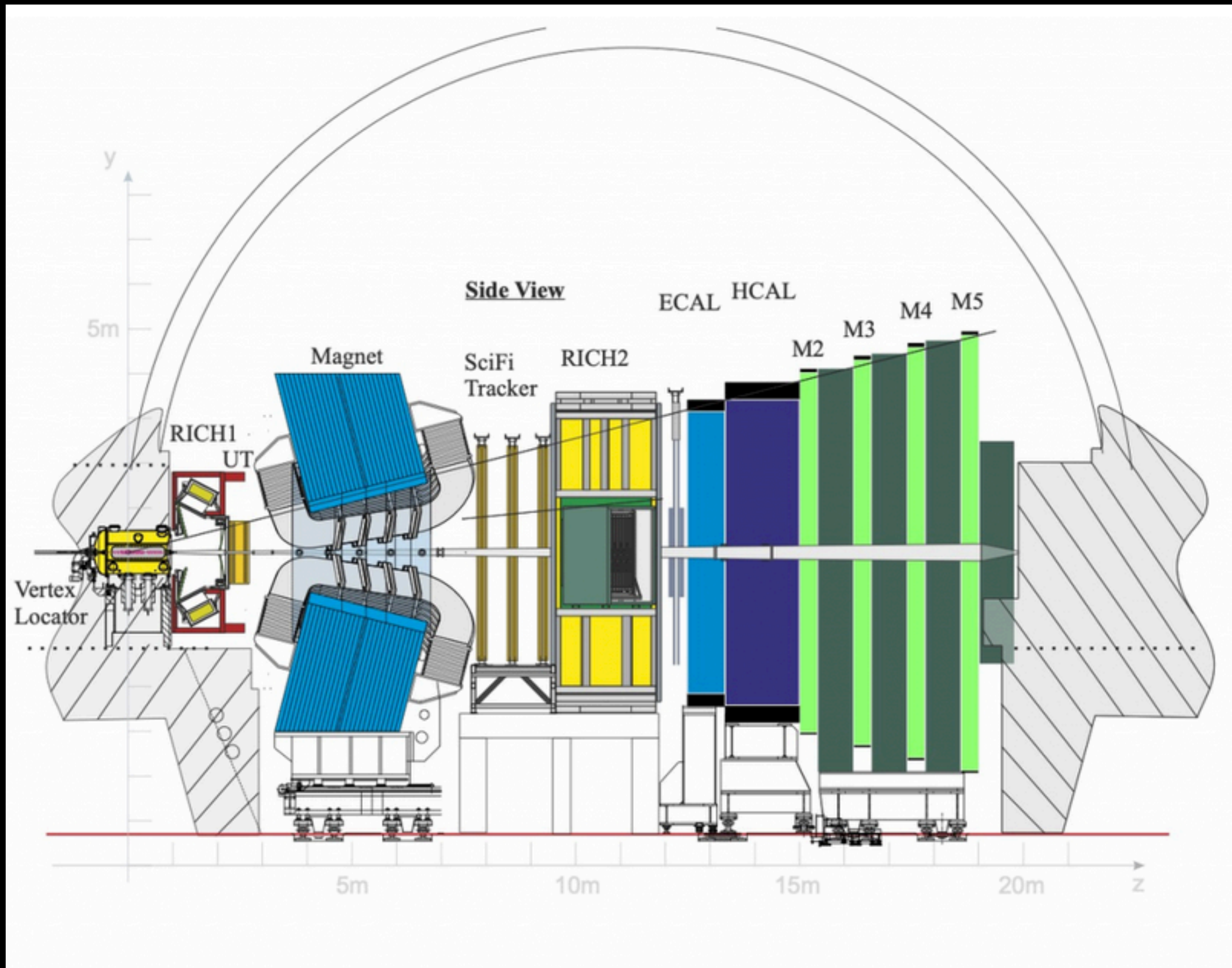
Run 153460

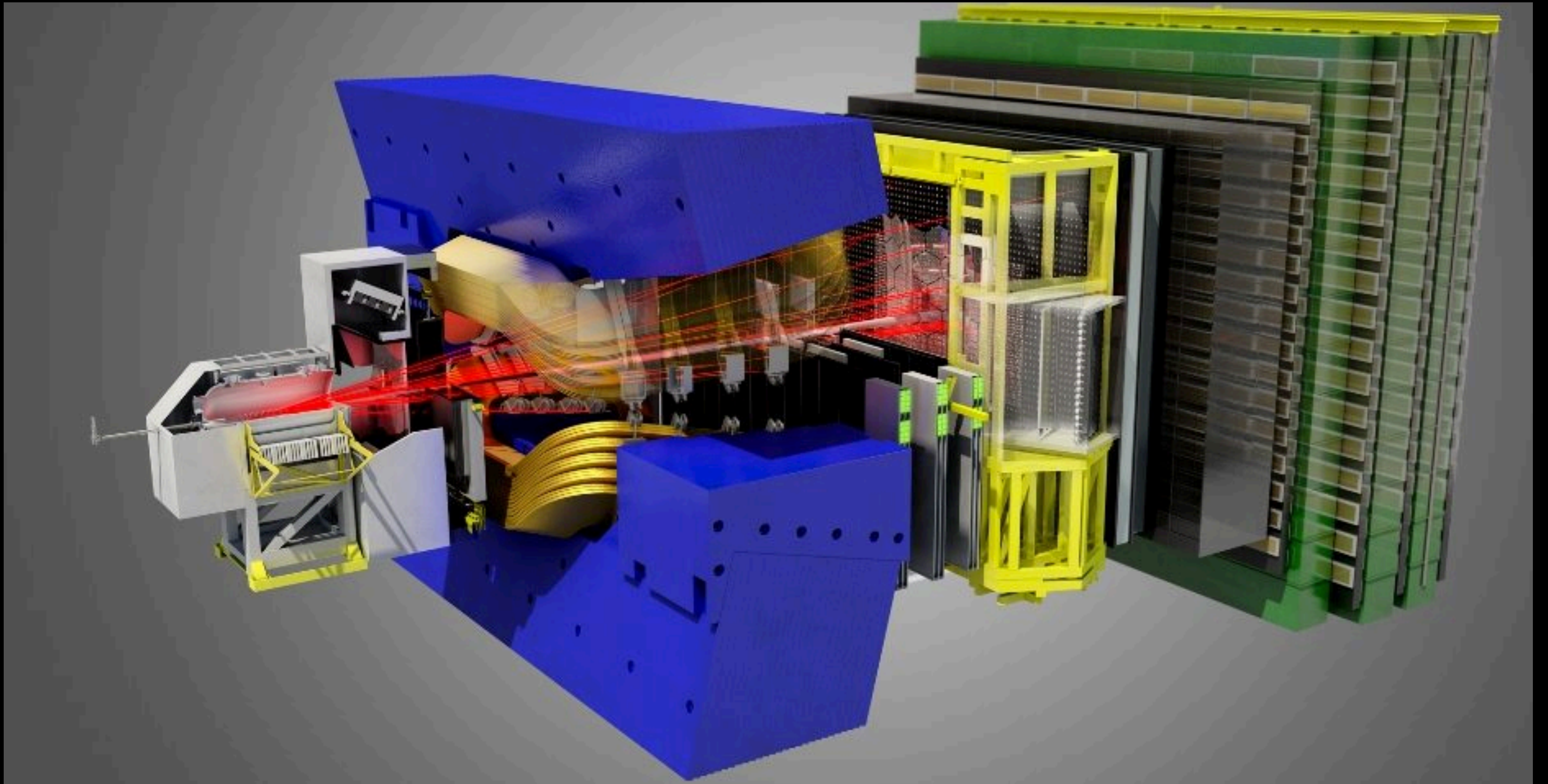
Wed, 03 Jun 2015 11:52:09



An LHC experiment — based on elements of a simple detector

Technical design of the LHCb detector





Design of the LHCb detector

What have we learned so far

- Charged particles can be detected through interaction with a detector
- Momenta can be measured from their trajectories → tracking

Other means of measurement

Energy can be measured through interaction with matter → calorimetry

What equation do we use most often in our analyses?

$$E = \sqrt{p^2 + m^2}$$

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

Reading material: Follow chapter 1 and 2 of
N. Wermes / H. Kolanoski

Two types of interactions

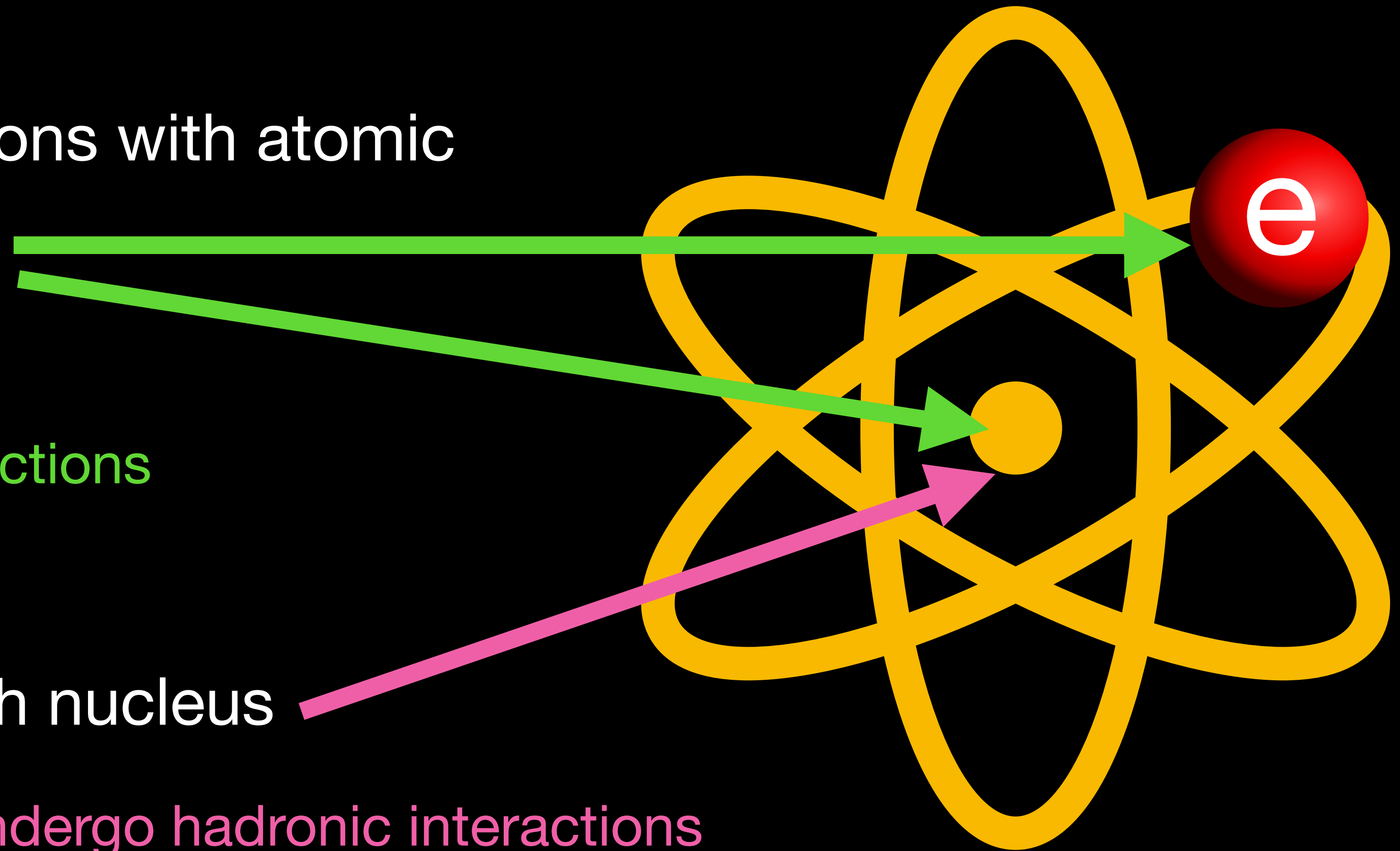
- Electromagnetic interactions with atomic electrons and nucleus

Photons, electrons and muons undergo electromagnetic interactions

- Hadronic interactions with nucleus

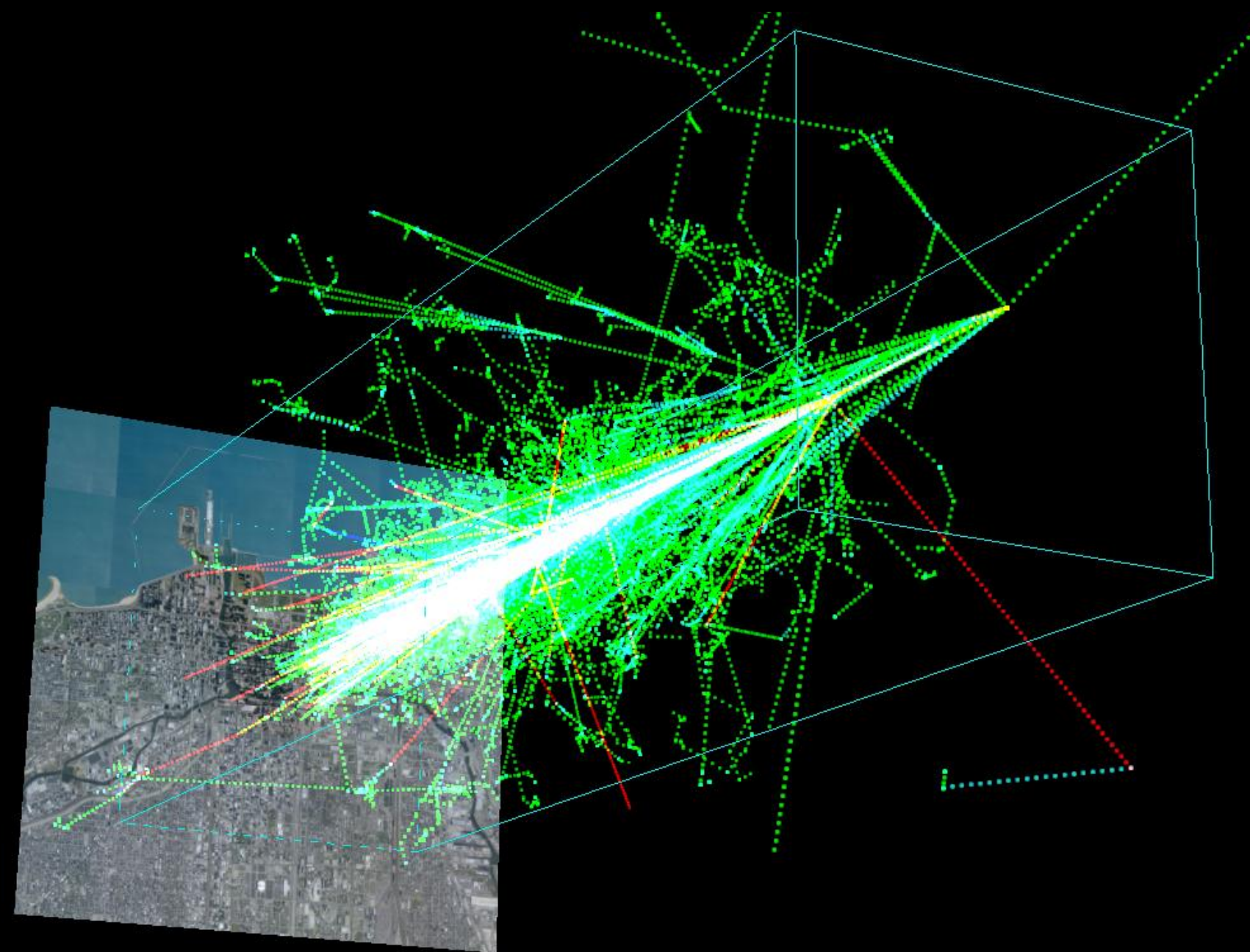
Protons, neutrons and pions undergo hadronic interactions

Hadronic interactions involve quarks and gluons and the strong force

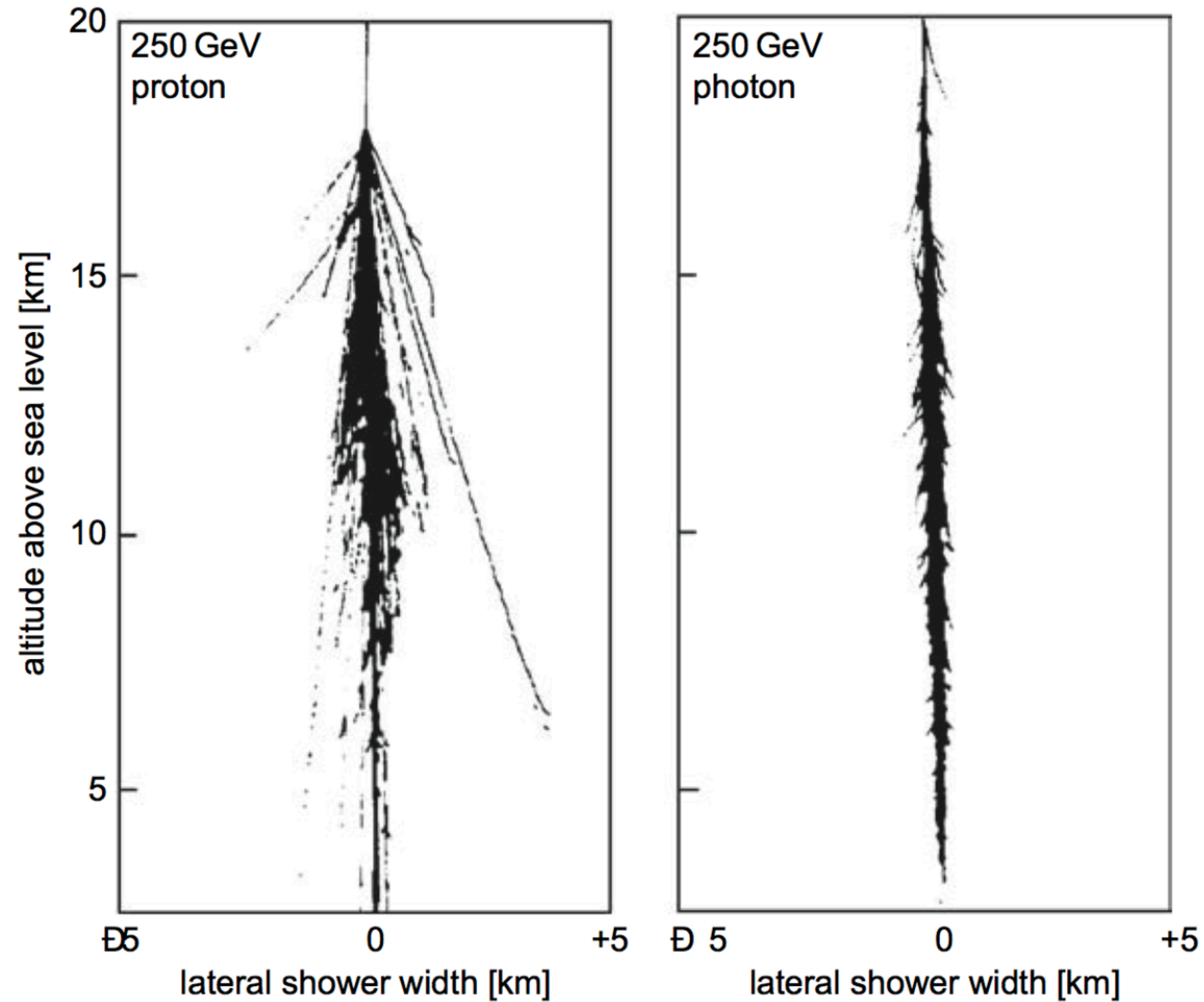


Two types of showers

- Electromagnetic showers are short and dense and initiated immediately
- Hadronic showers are larger and diffused and initiated with some delay

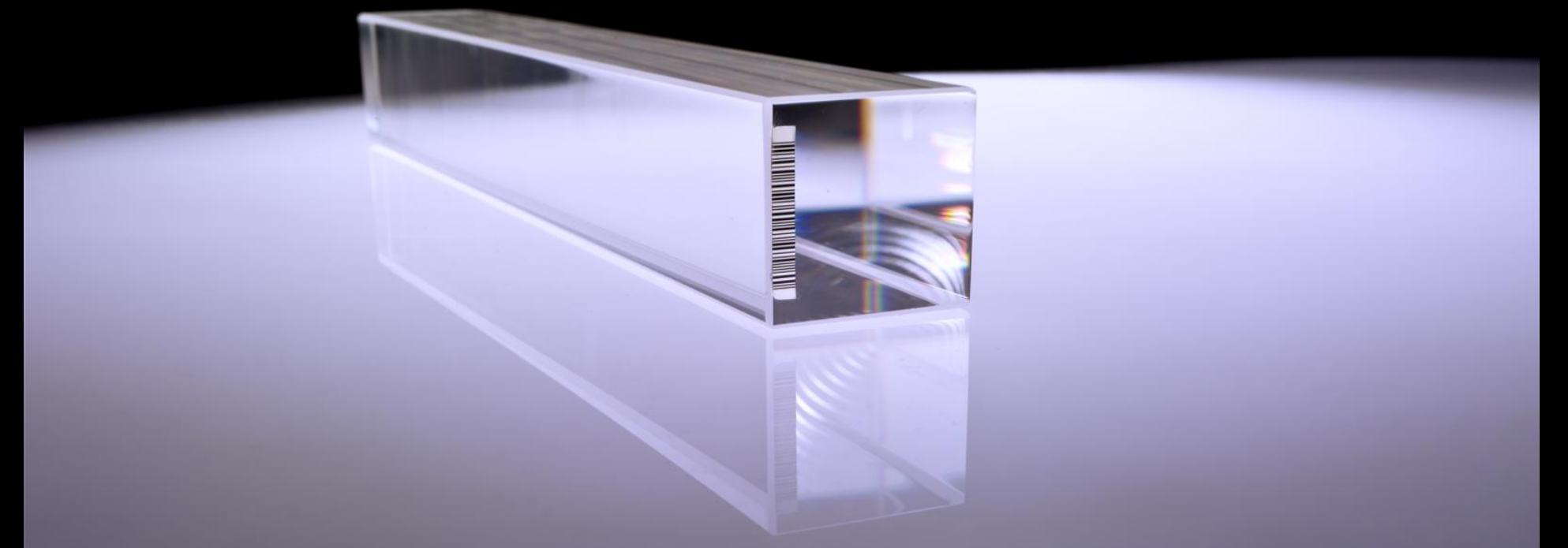


Two types of showers



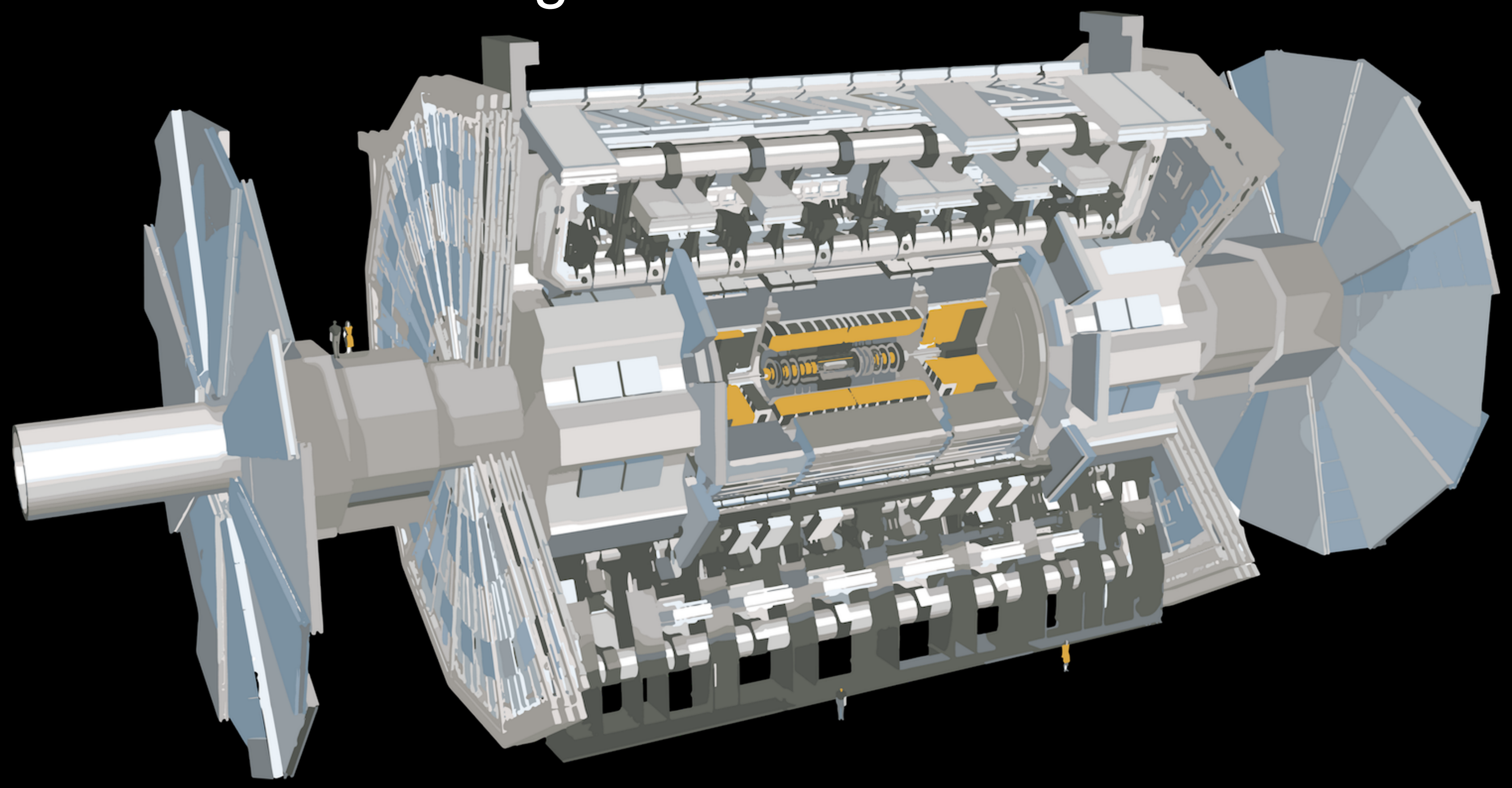
Calorimeters

- The energy absorbed is proportional to the energy of incoming particle
- We can use this fact to build a detector that measures shower energies
- CMS uses special crystals to measure the energy of electromagnetic showers like those induced by a photon
- CMS also has a hadronic calorimeter, built using traditional techniques

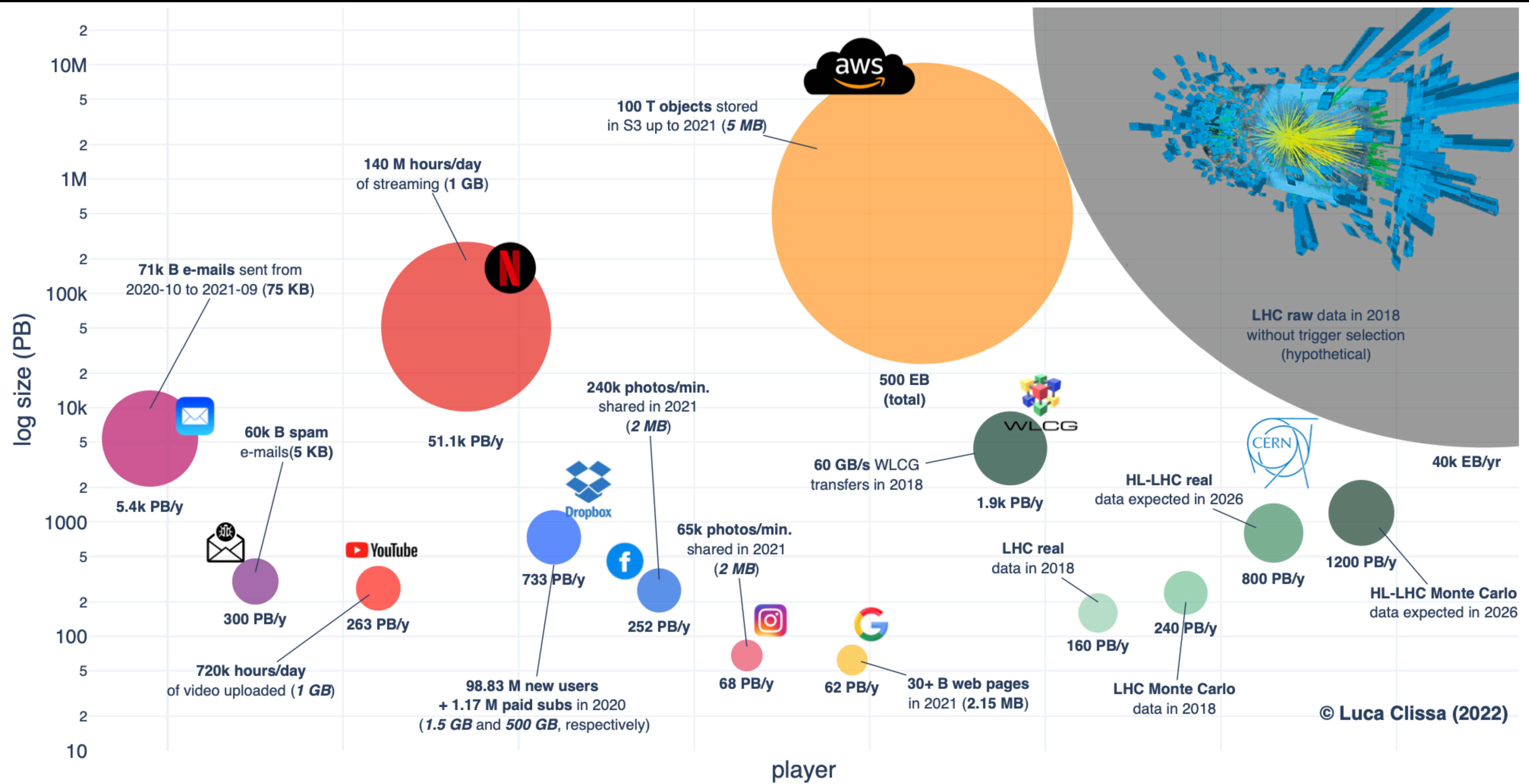


Electromagnetic calorimeter
made with lead tungstate
crystals

Focusing on the ATLAS detector



Data Collection



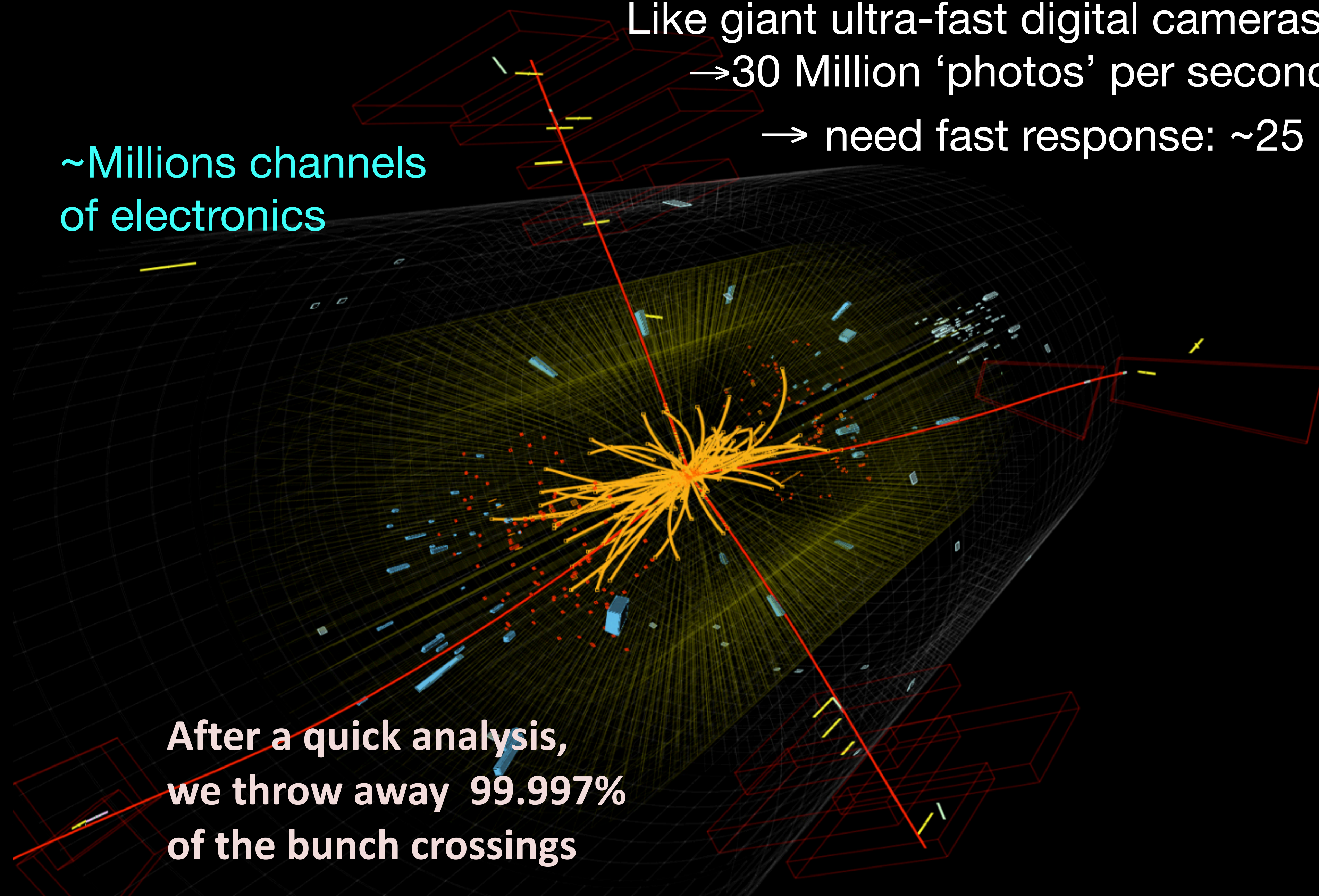
~Millions channels
of electronics

Like giant ultra-fast digital cameras

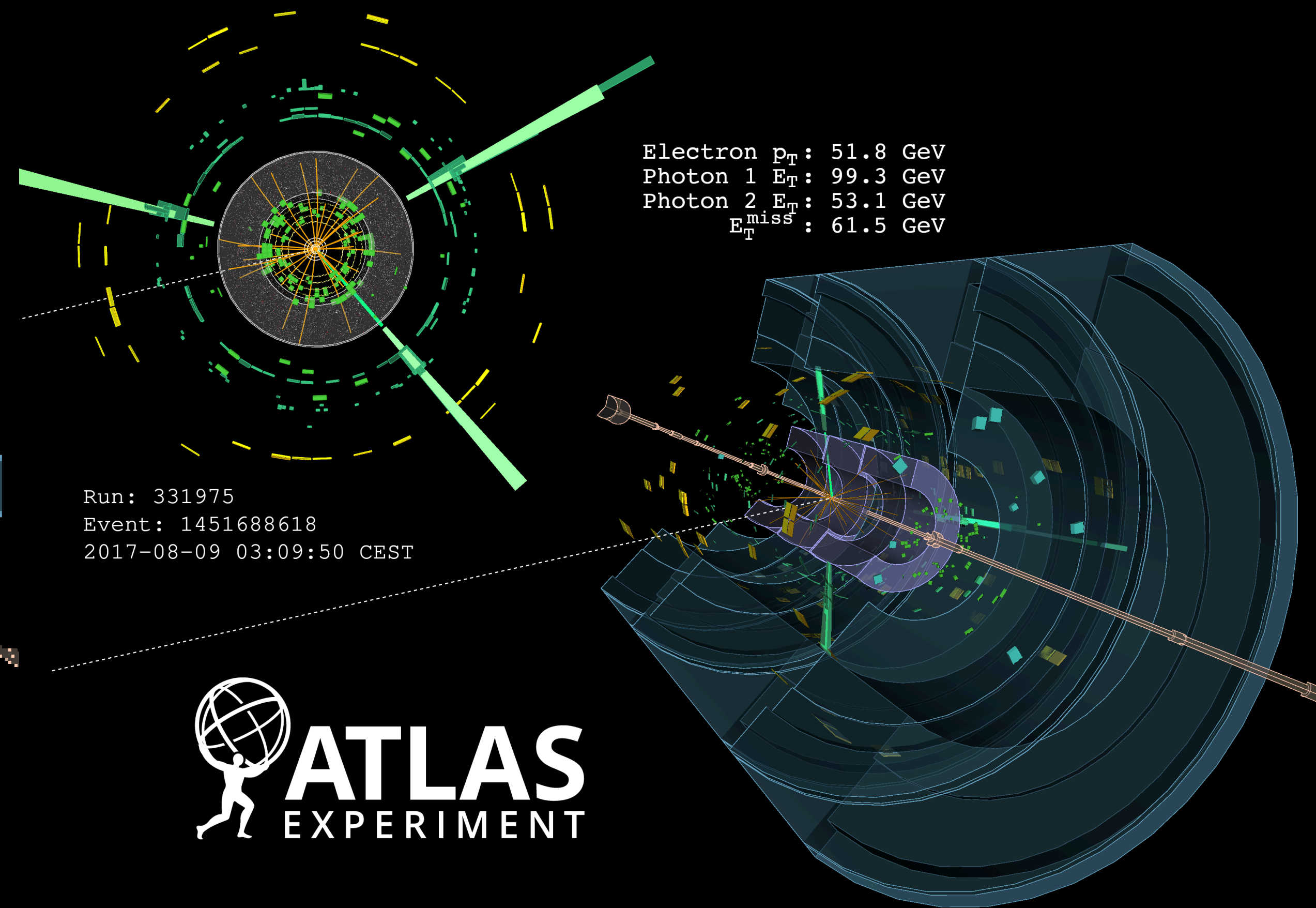
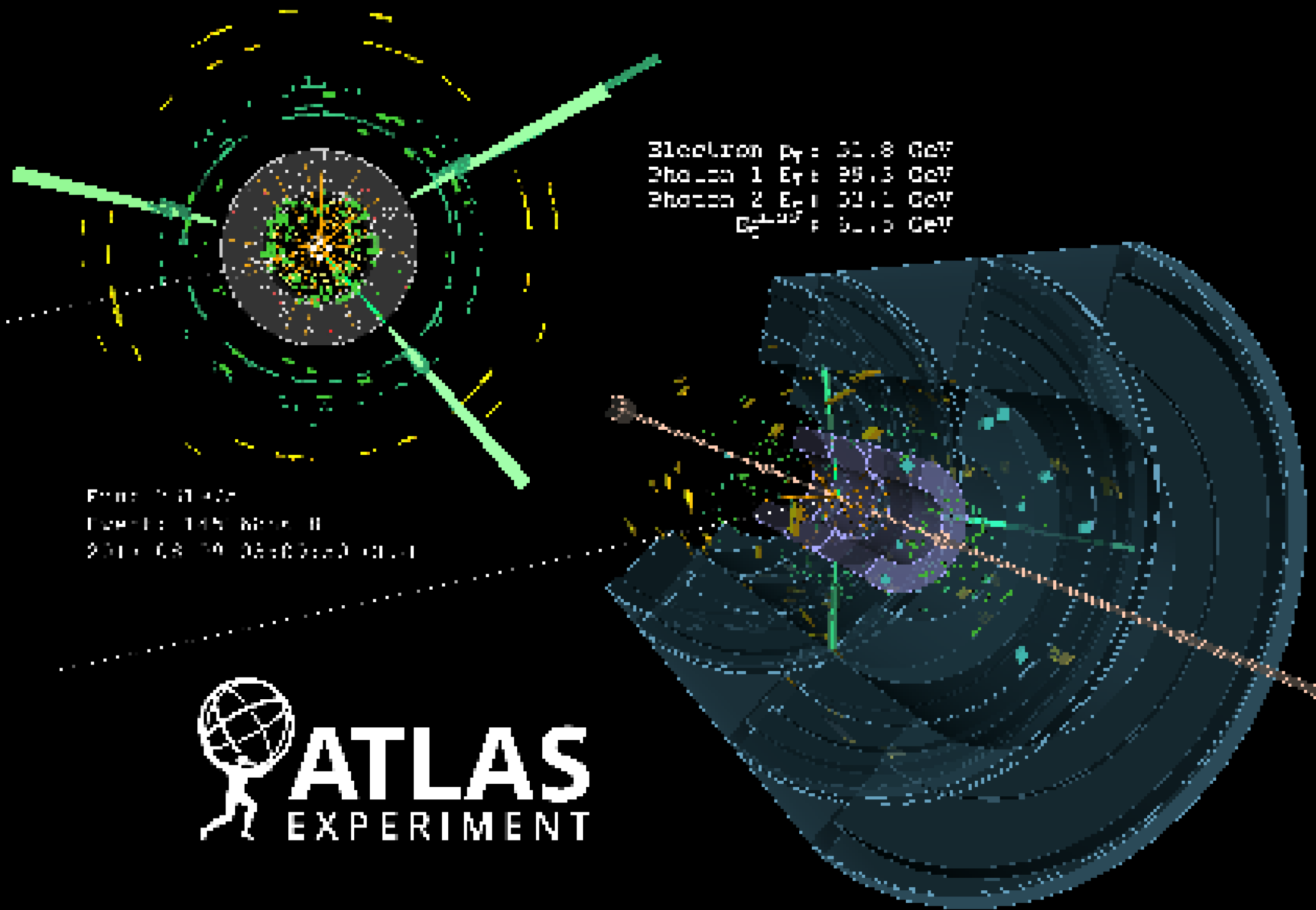
→ 30 Million 'photos' per second

→ need fast response: ~25 ns

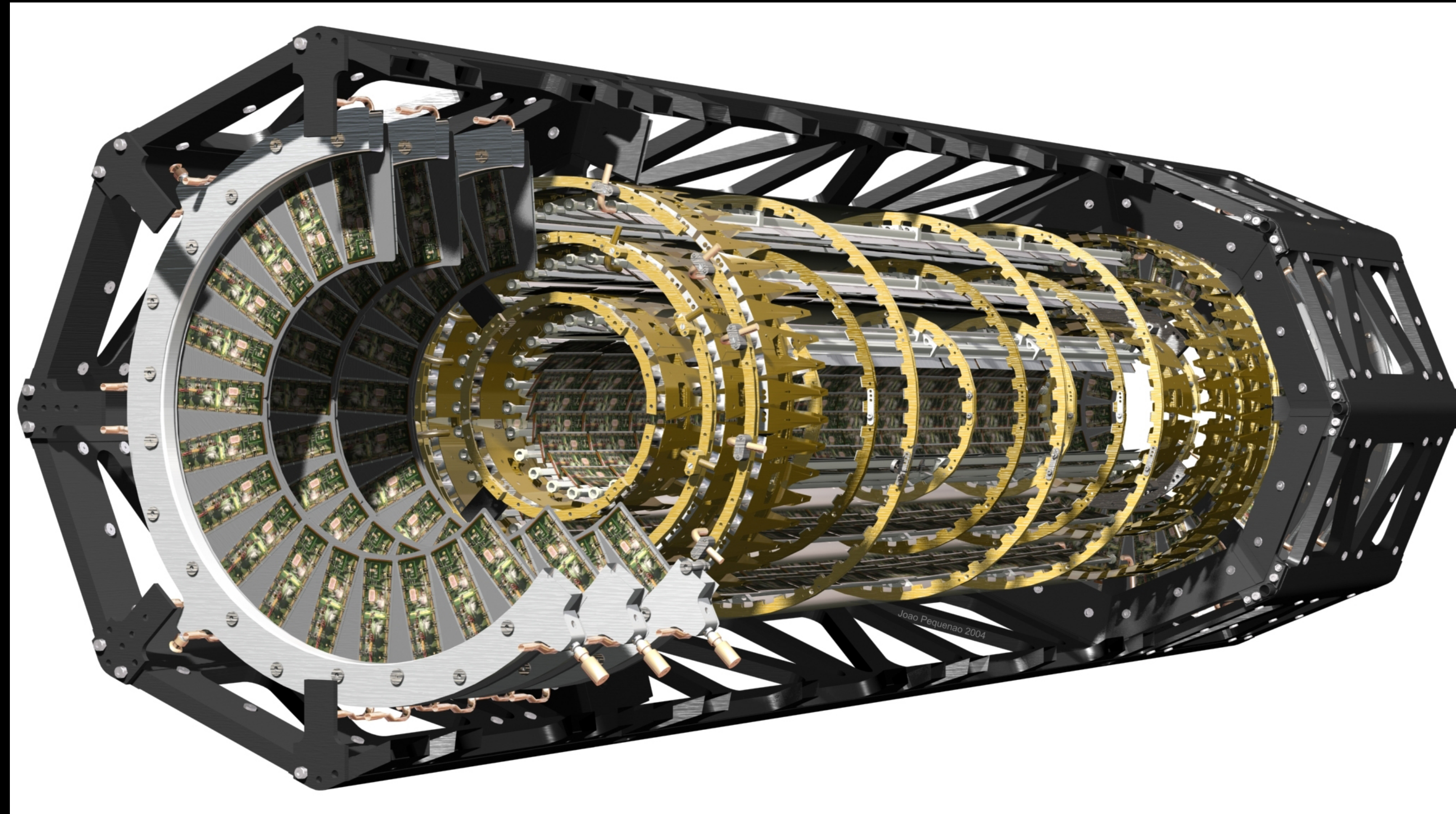
After a quick analysis,
we throw away 99.997%
of the bunch crossings

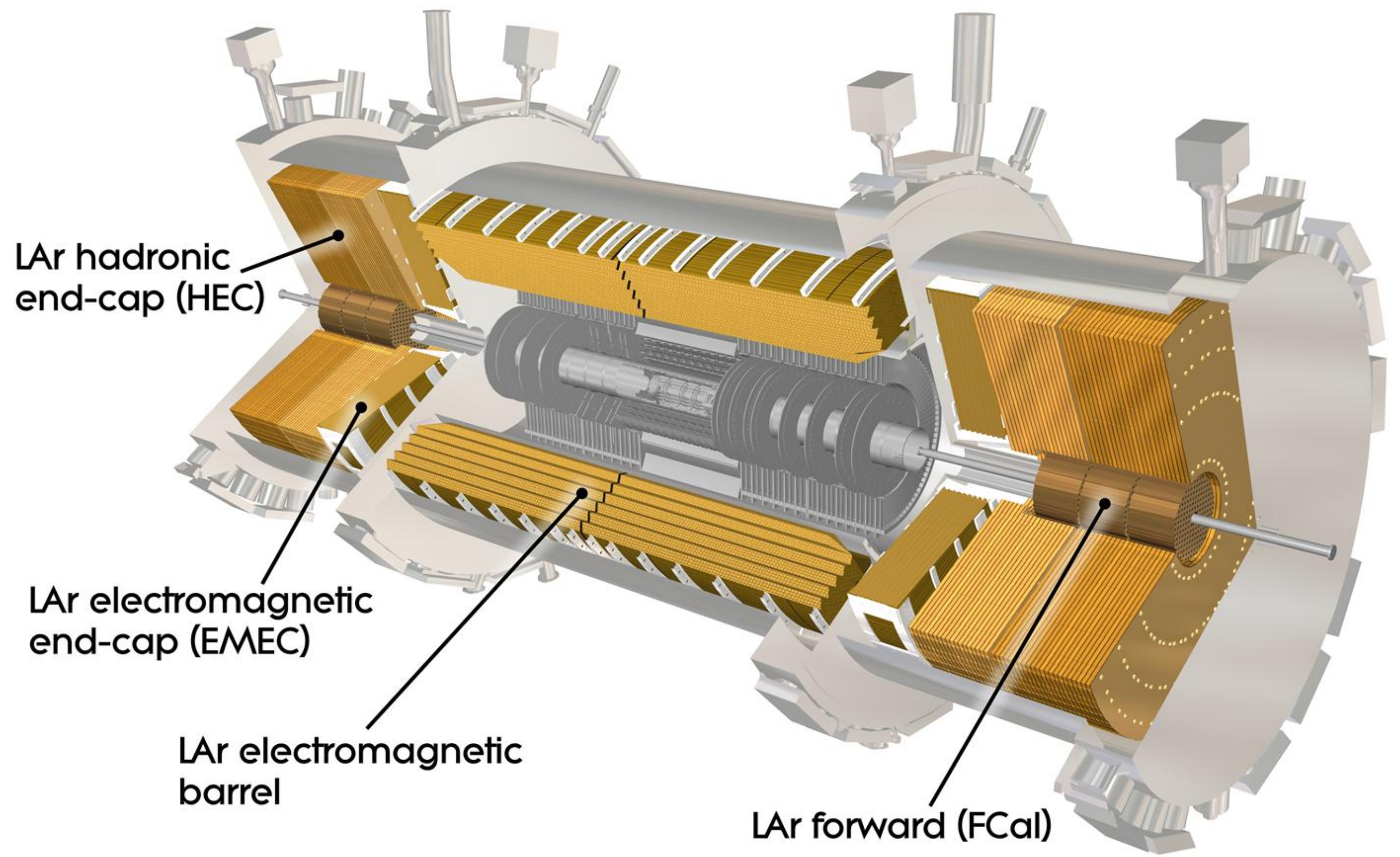


Trigger



Inner detector — the tracker



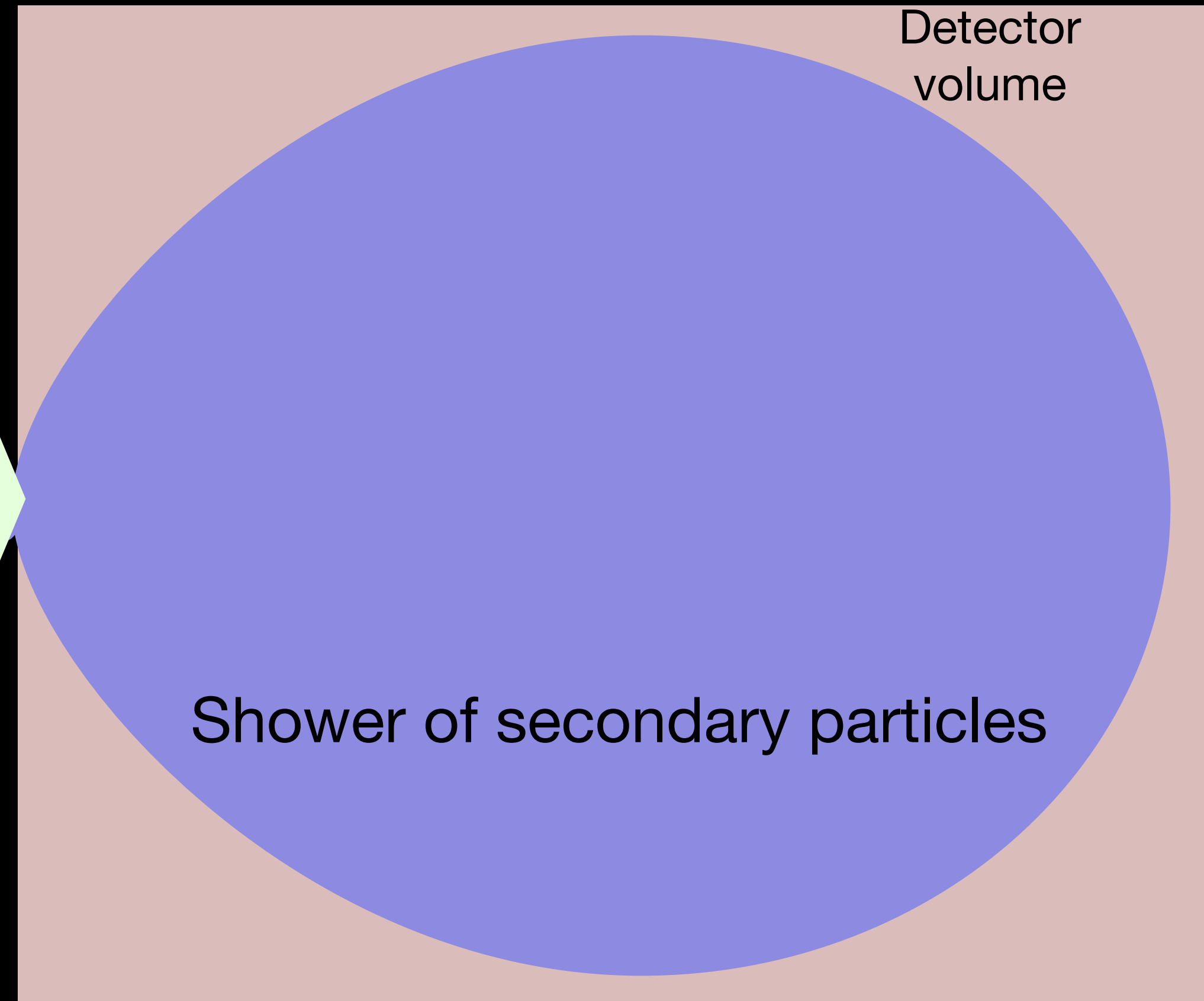


Homogeneous calorimeter

Convert energy E of incident particles to detector response

$$S \propto E$$

Incoming particle

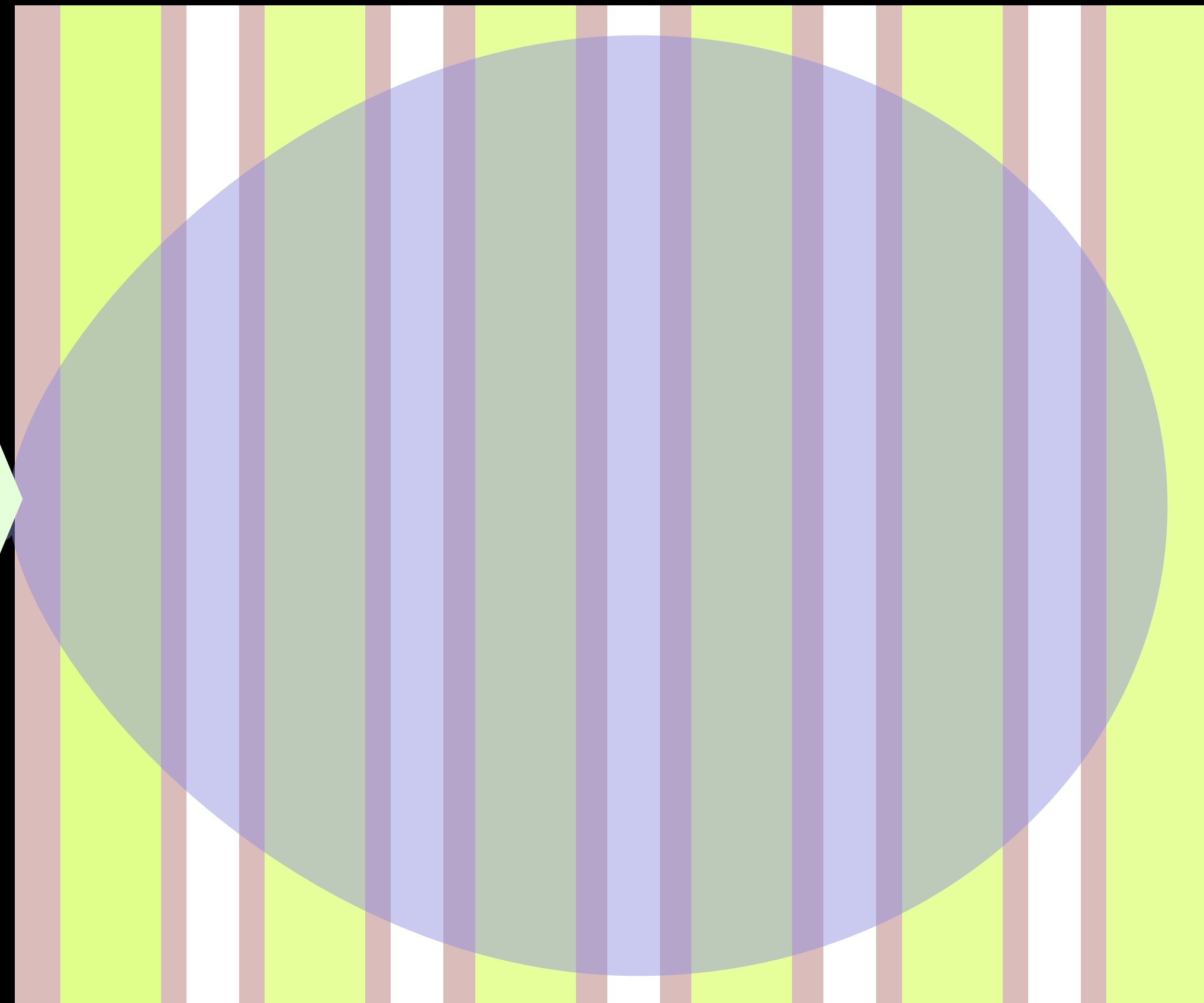
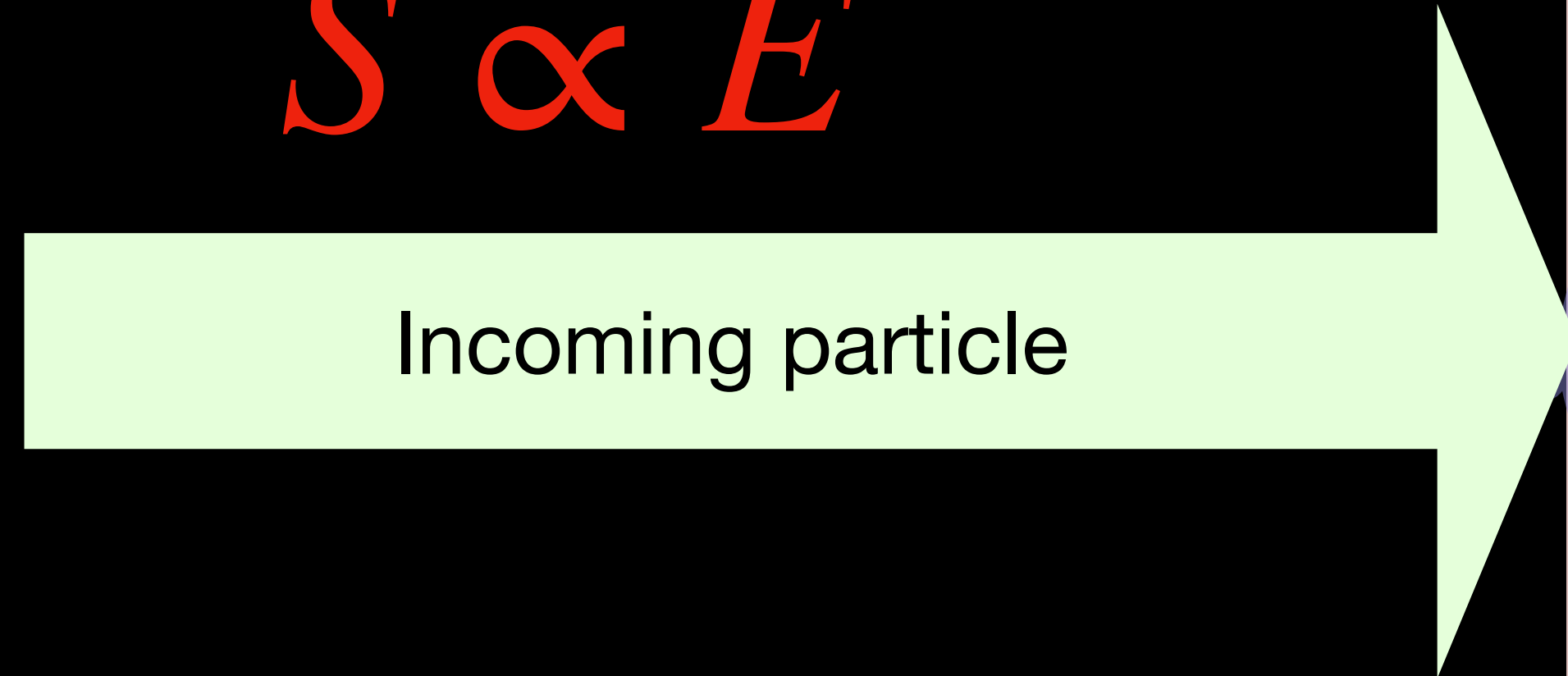


This is a homogenous calorimeter — think of lead tungstate ECAL in CMS

Sampling calorimeter

Convert energy E of incident particles to detector response

$$S \propto E$$

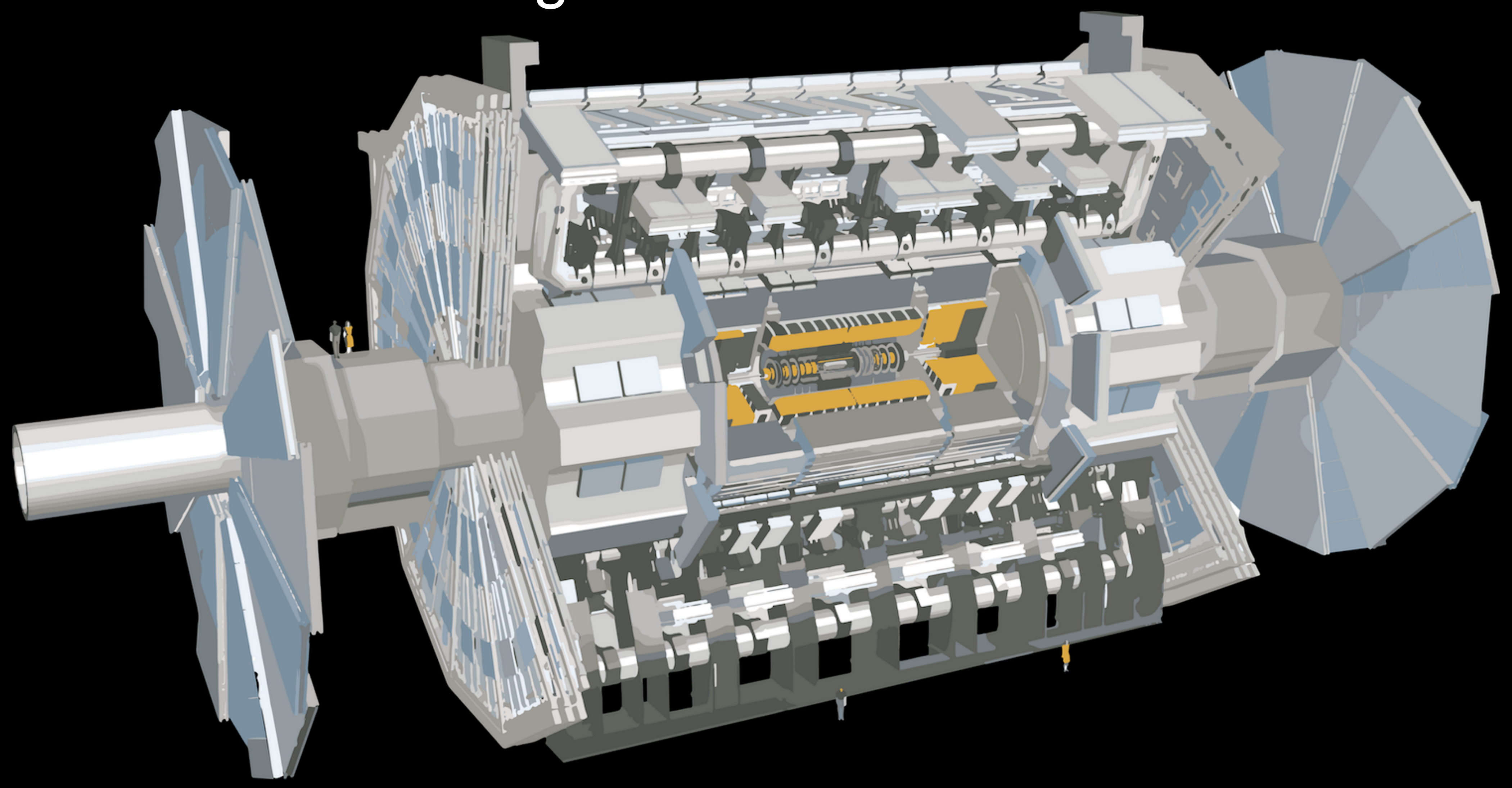


Detector volume

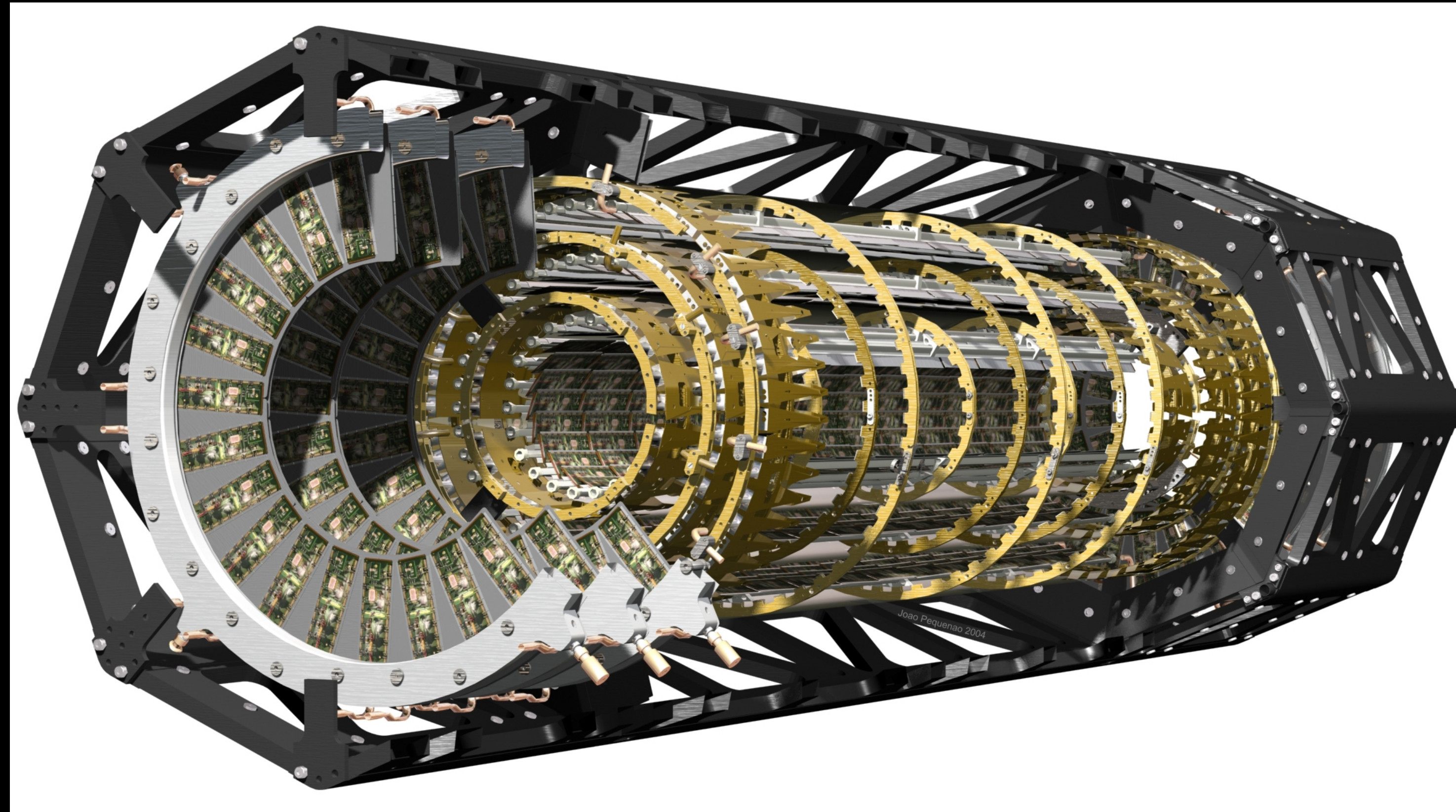
Interleaved with passive absorber material and active detectors

This is a sampling calorimeter — think Shower of secondary particles of HighGranularity Calorimeter in CMS

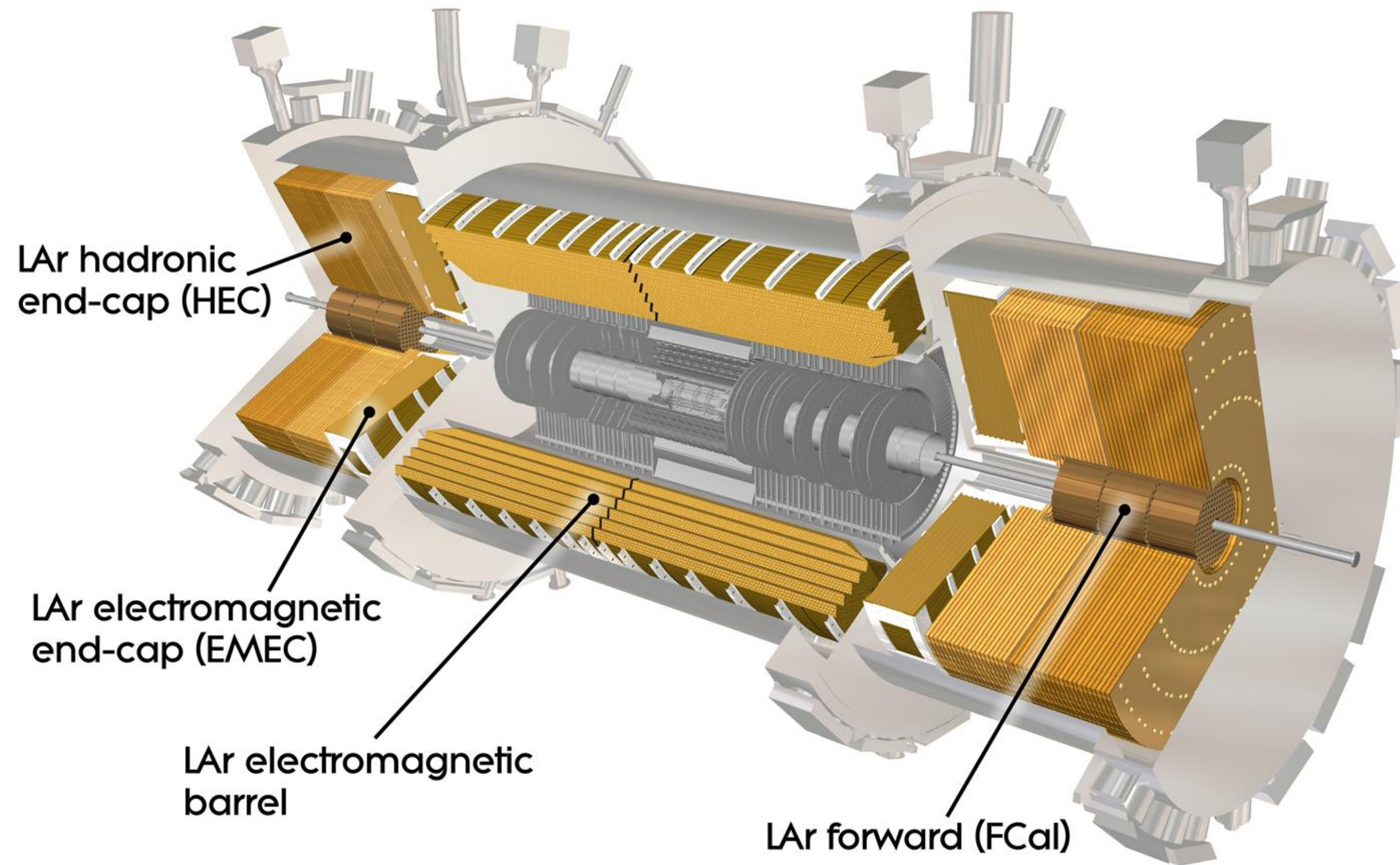
Focusing on the ATLAS detector



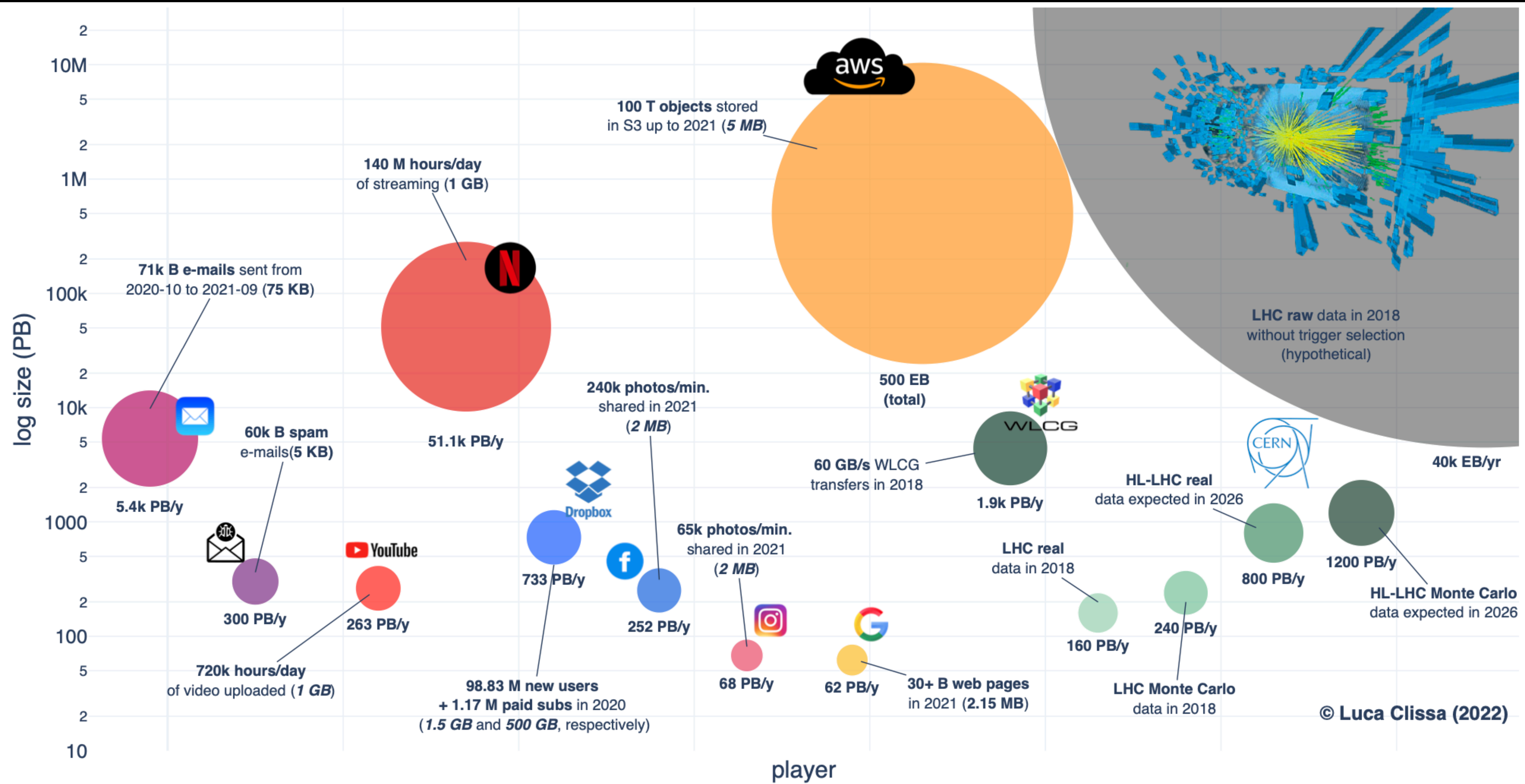
Inner detector — the tracker



Calorimeters



Data Collection



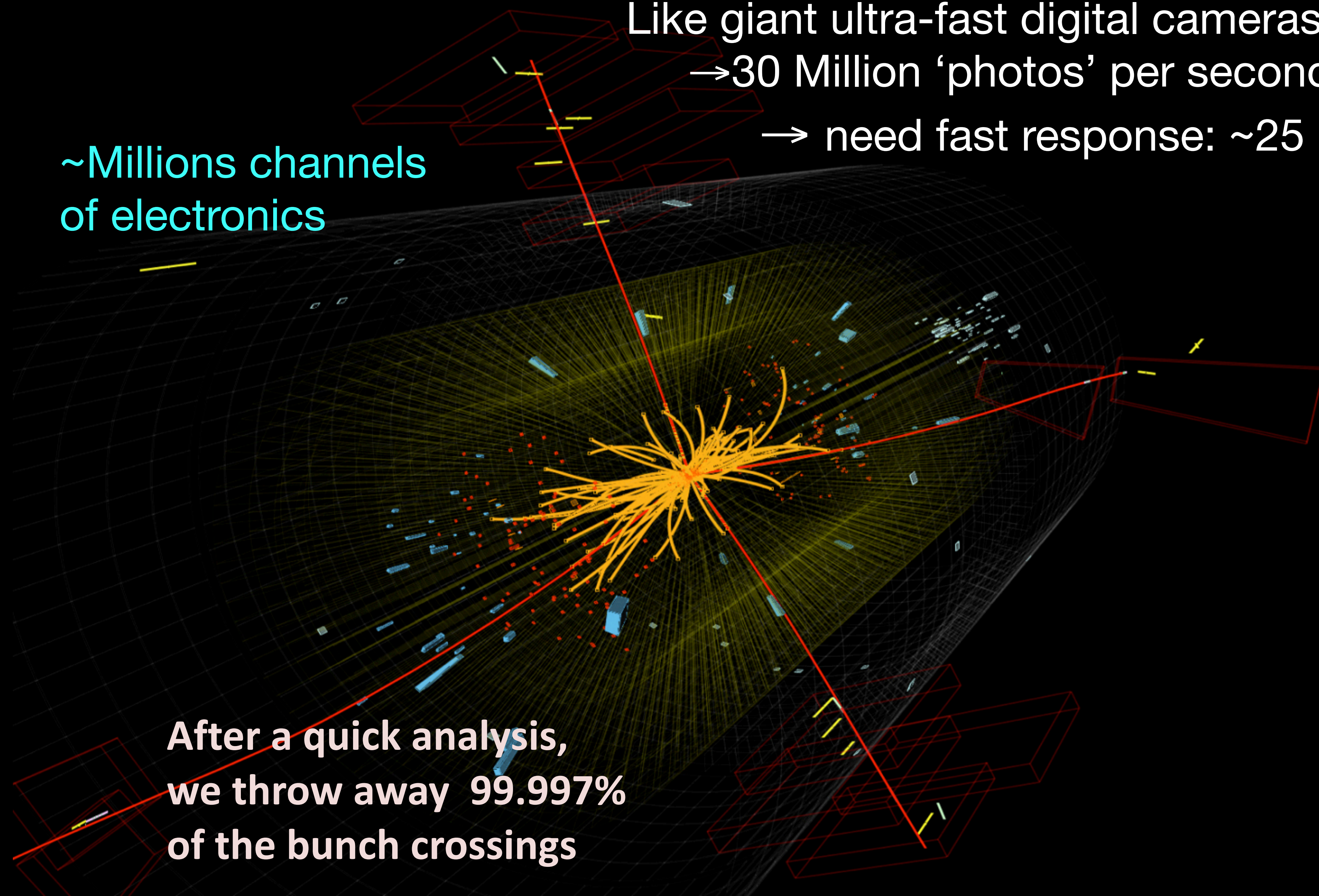
~Millions channels
of electronics

Like giant ultra-fast digital cameras

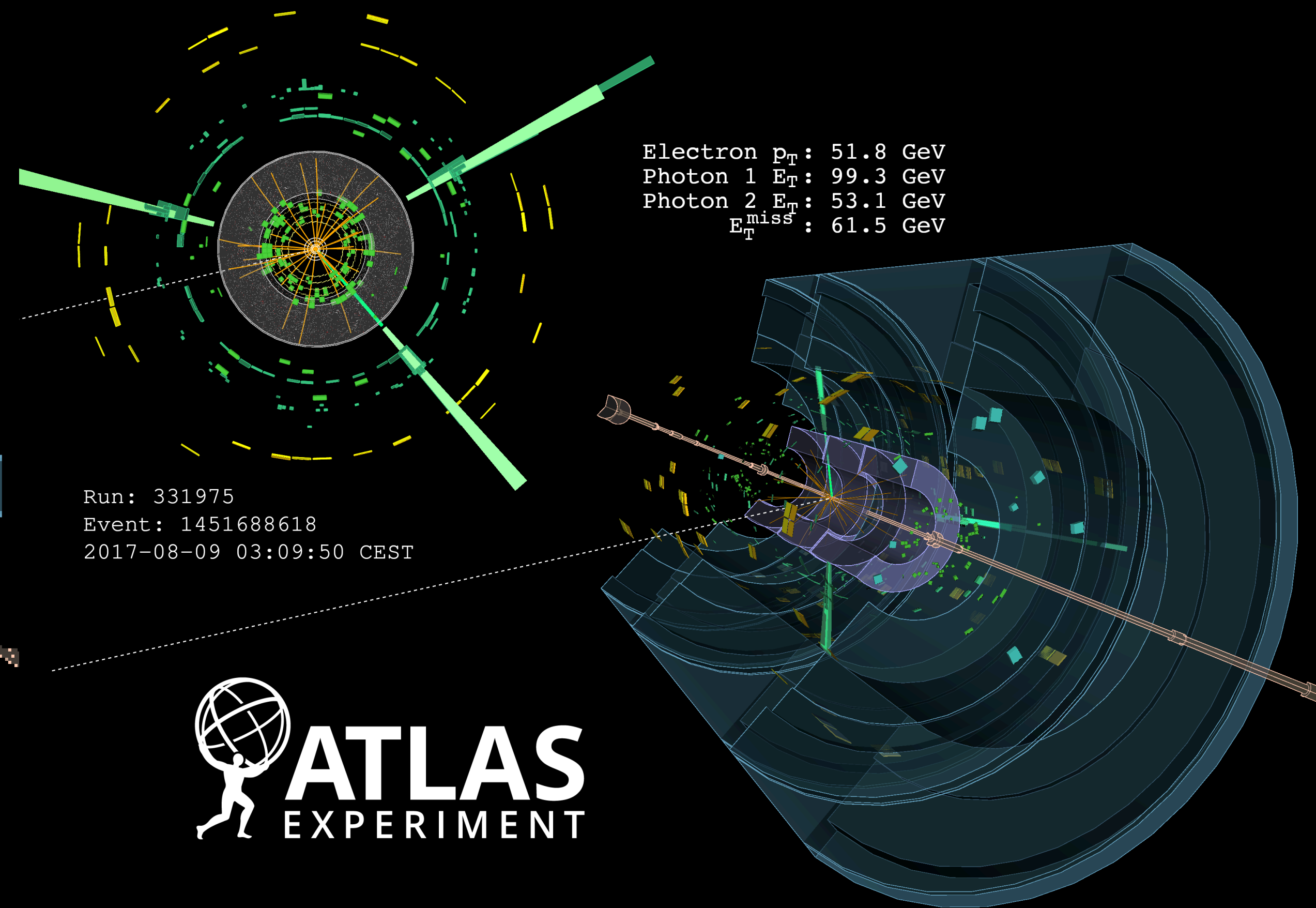
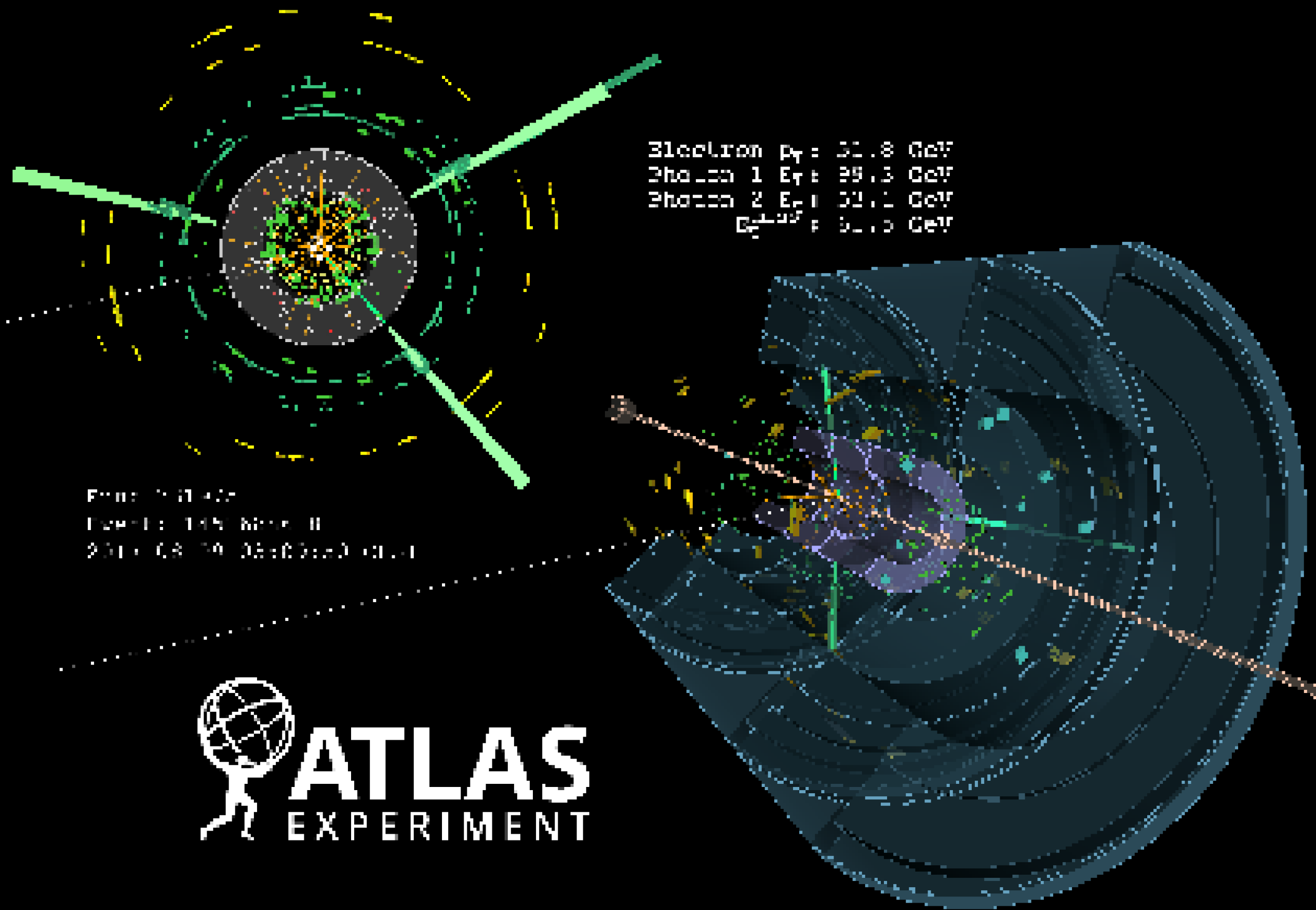
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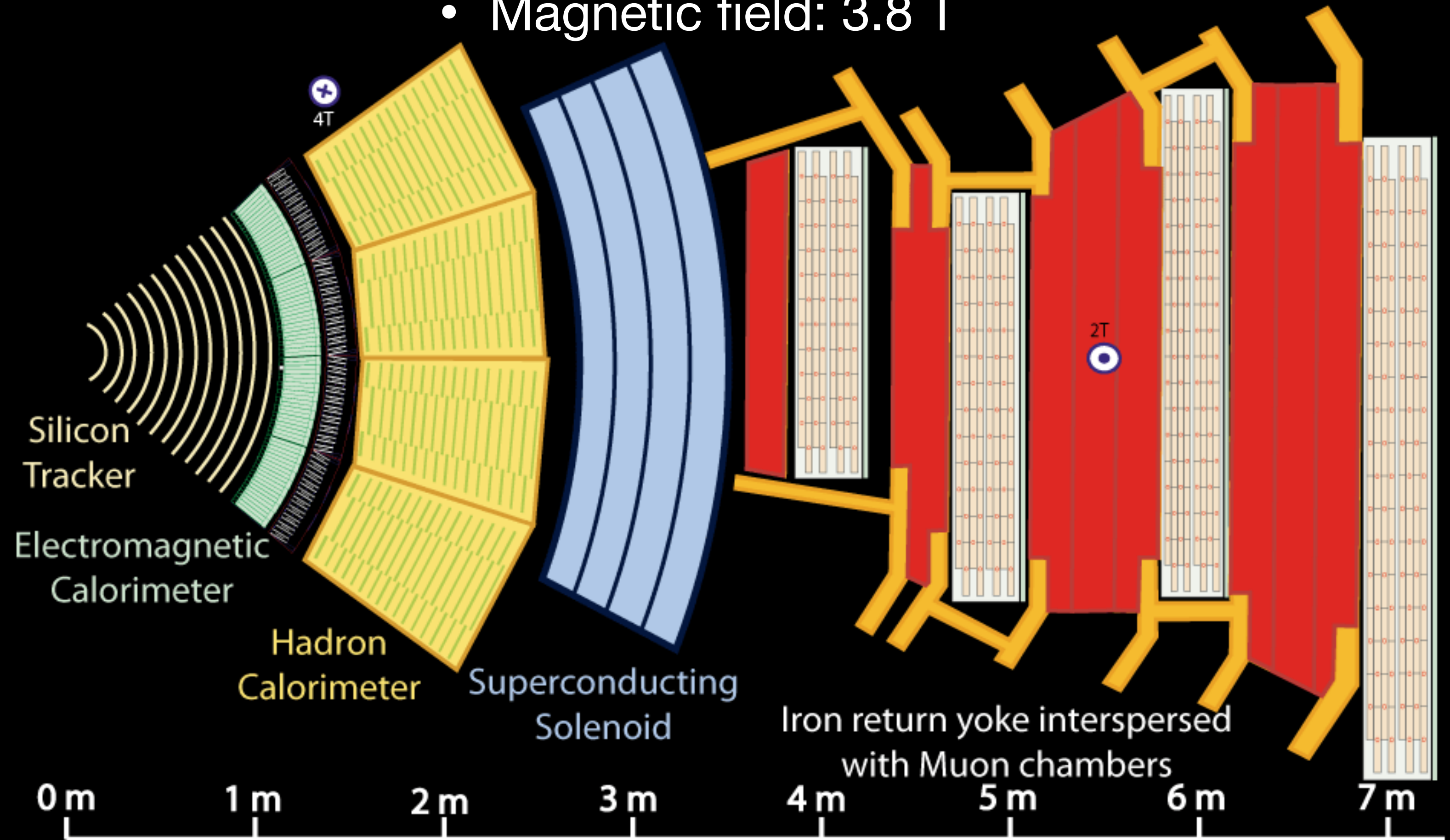
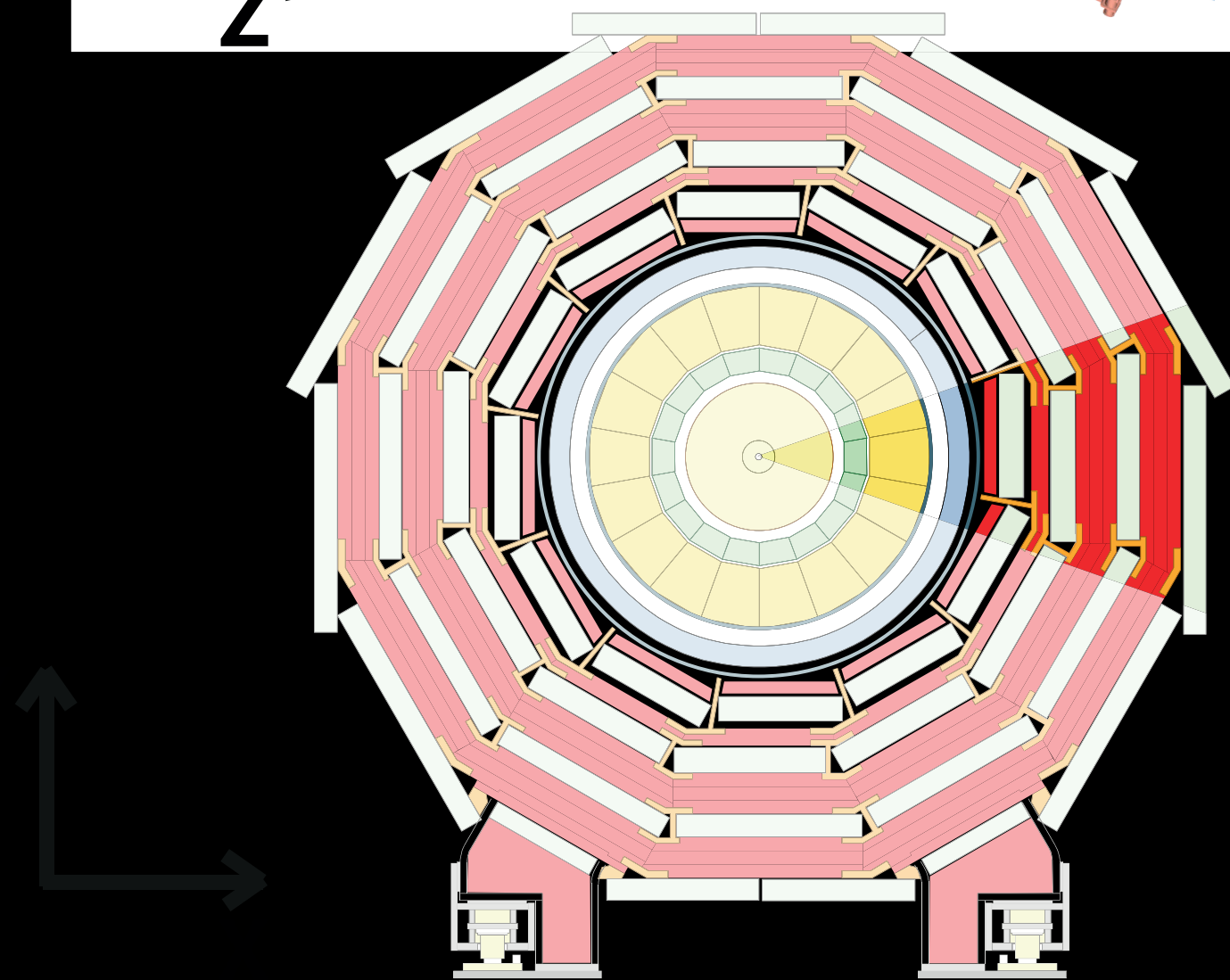
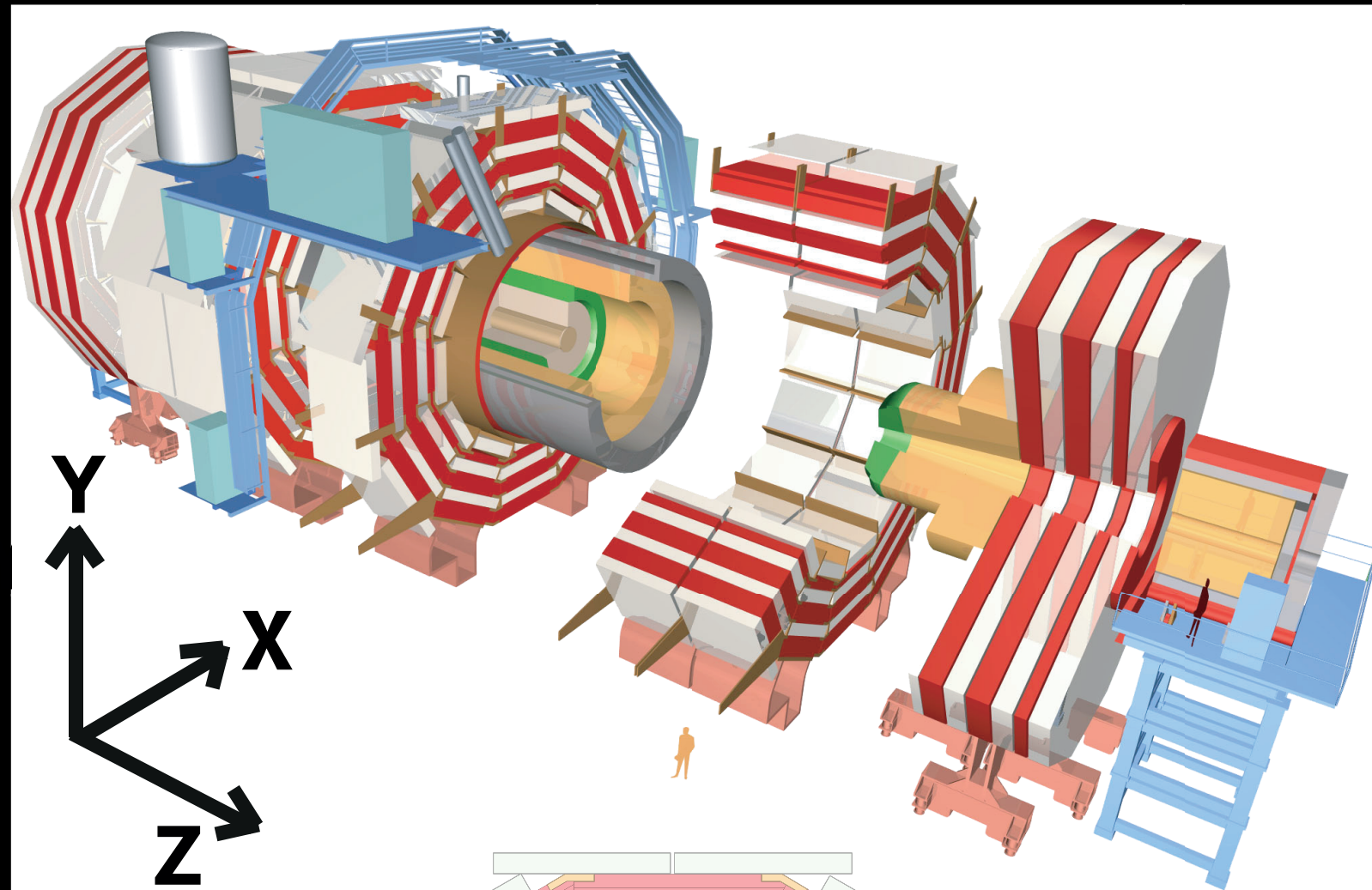
After a quick analysis,
we throw away 99.997%
of the bunch crossings



Trigger



- Weight: 14,000 Tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T



Key:

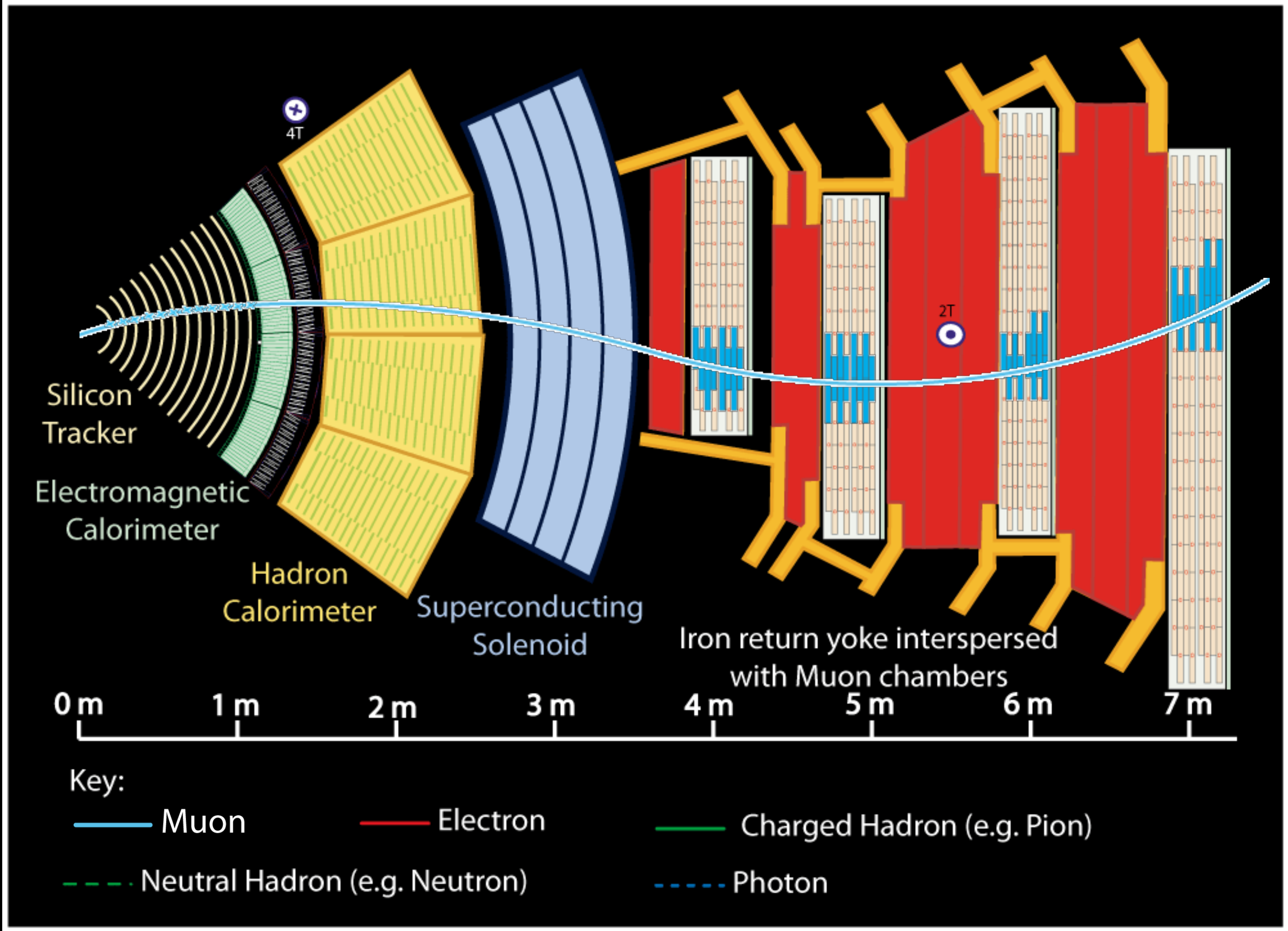
— Muon

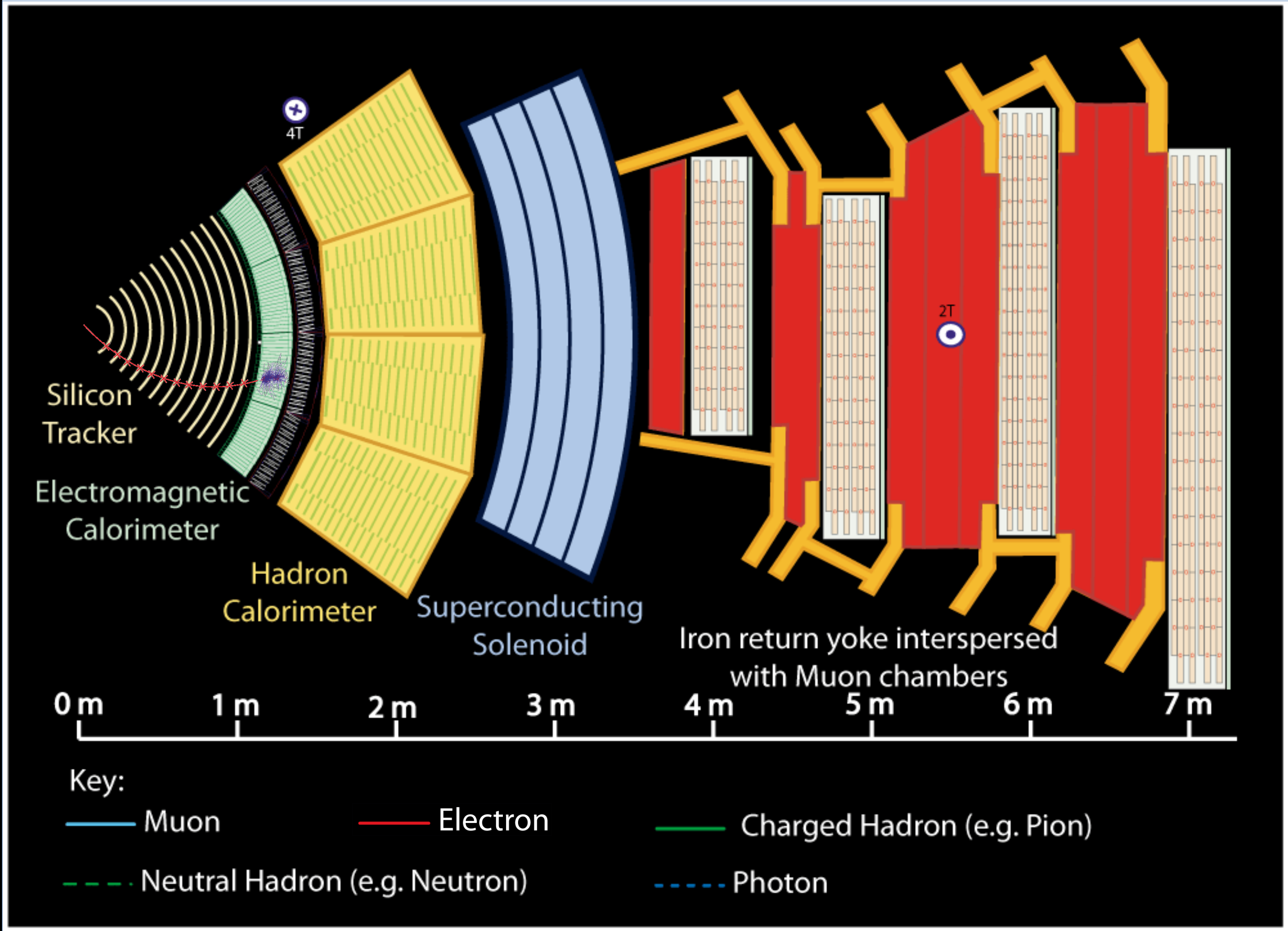
— Electron

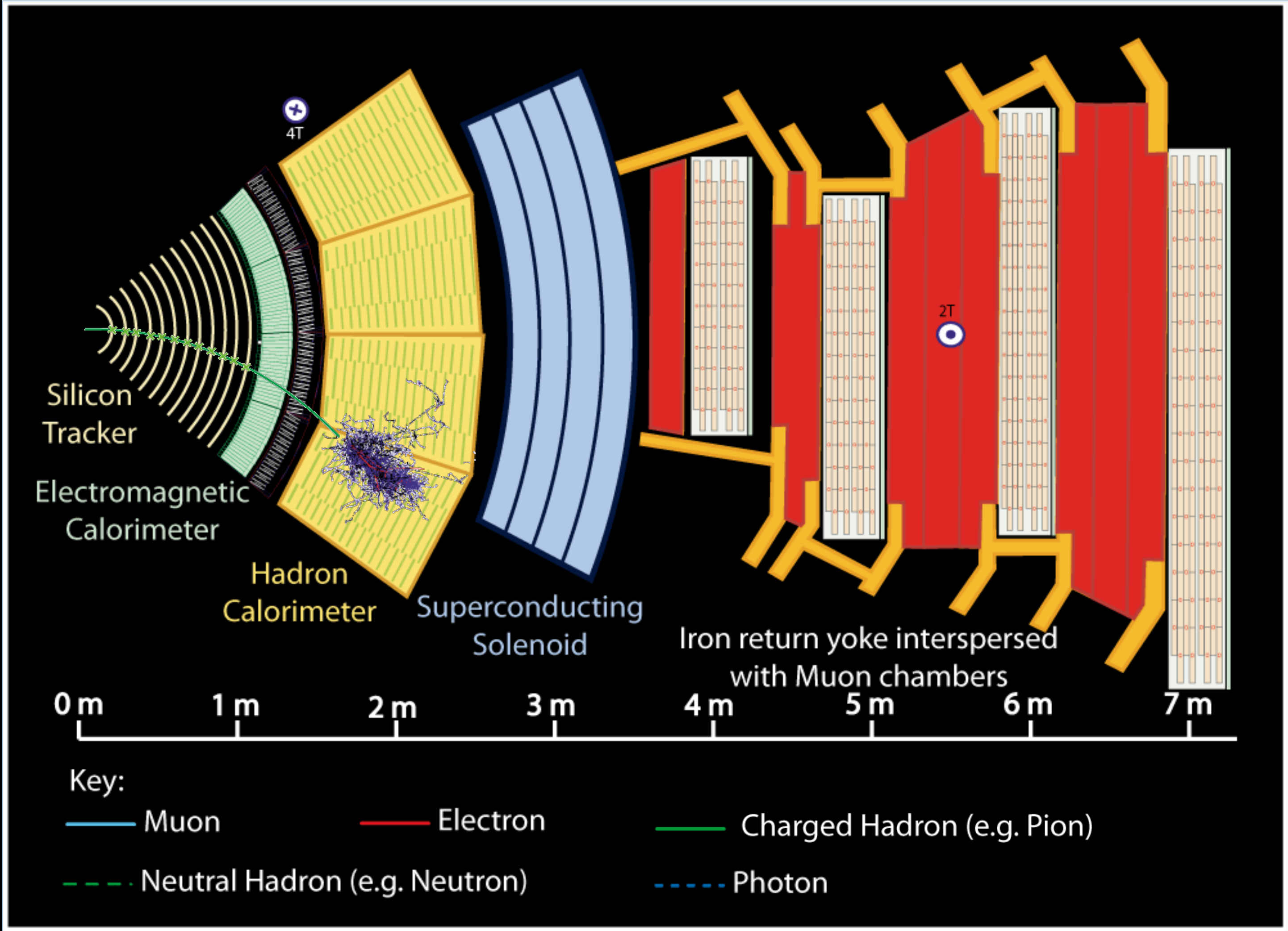
— Charged Hadron (e.g. Pion)

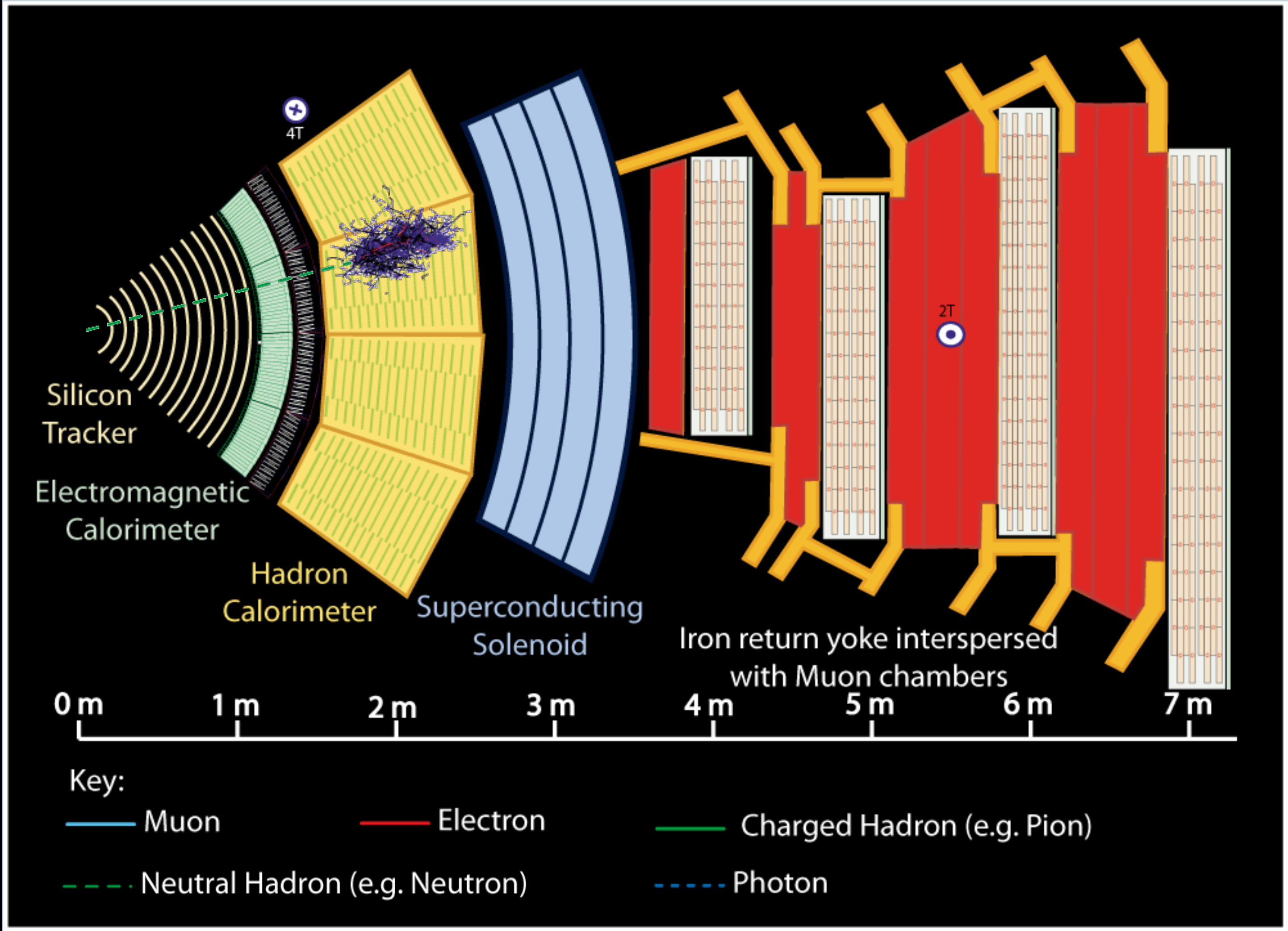
- - - Neutral Hadron (e.g. Neutron)

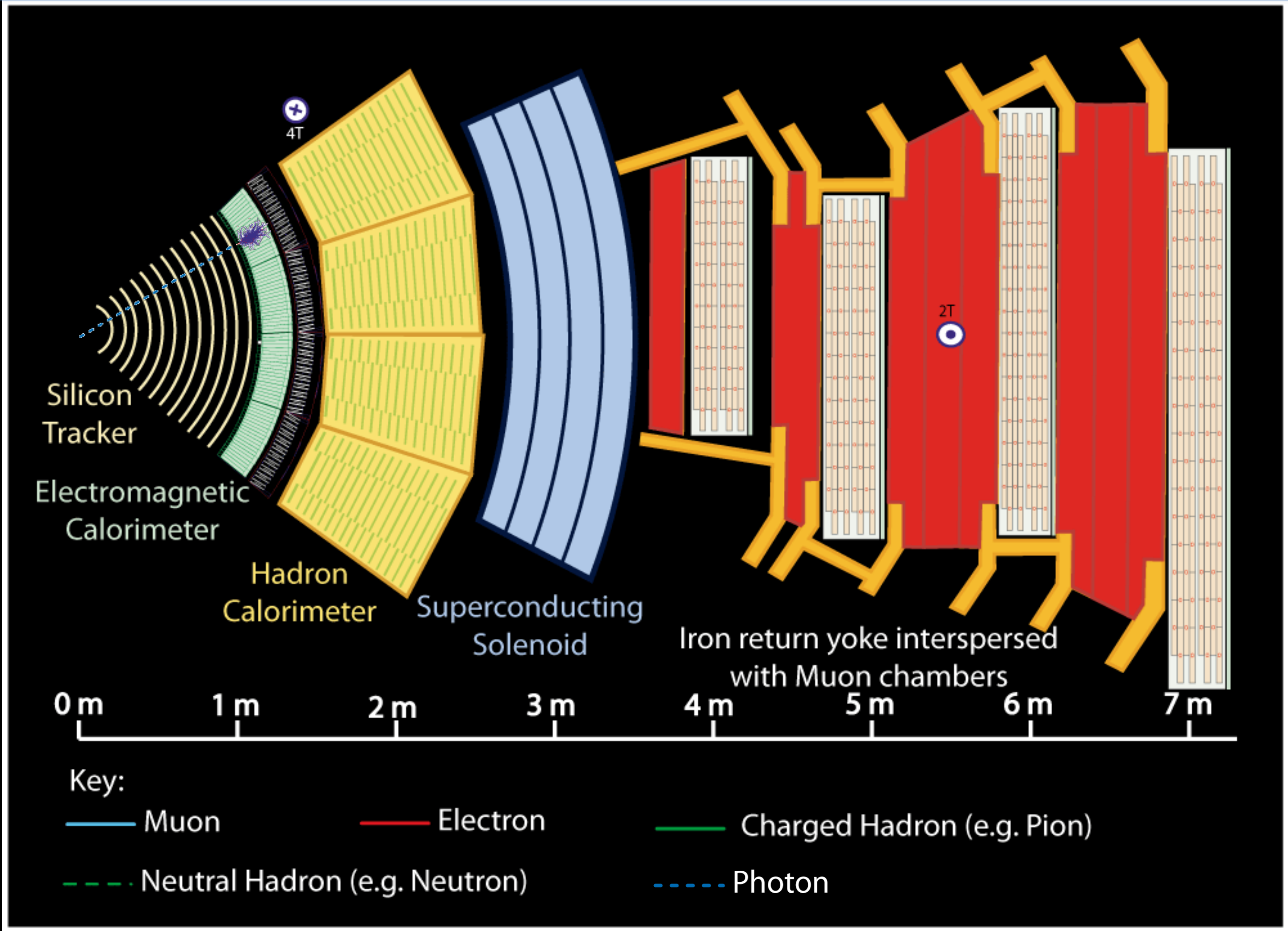
- - - Photon











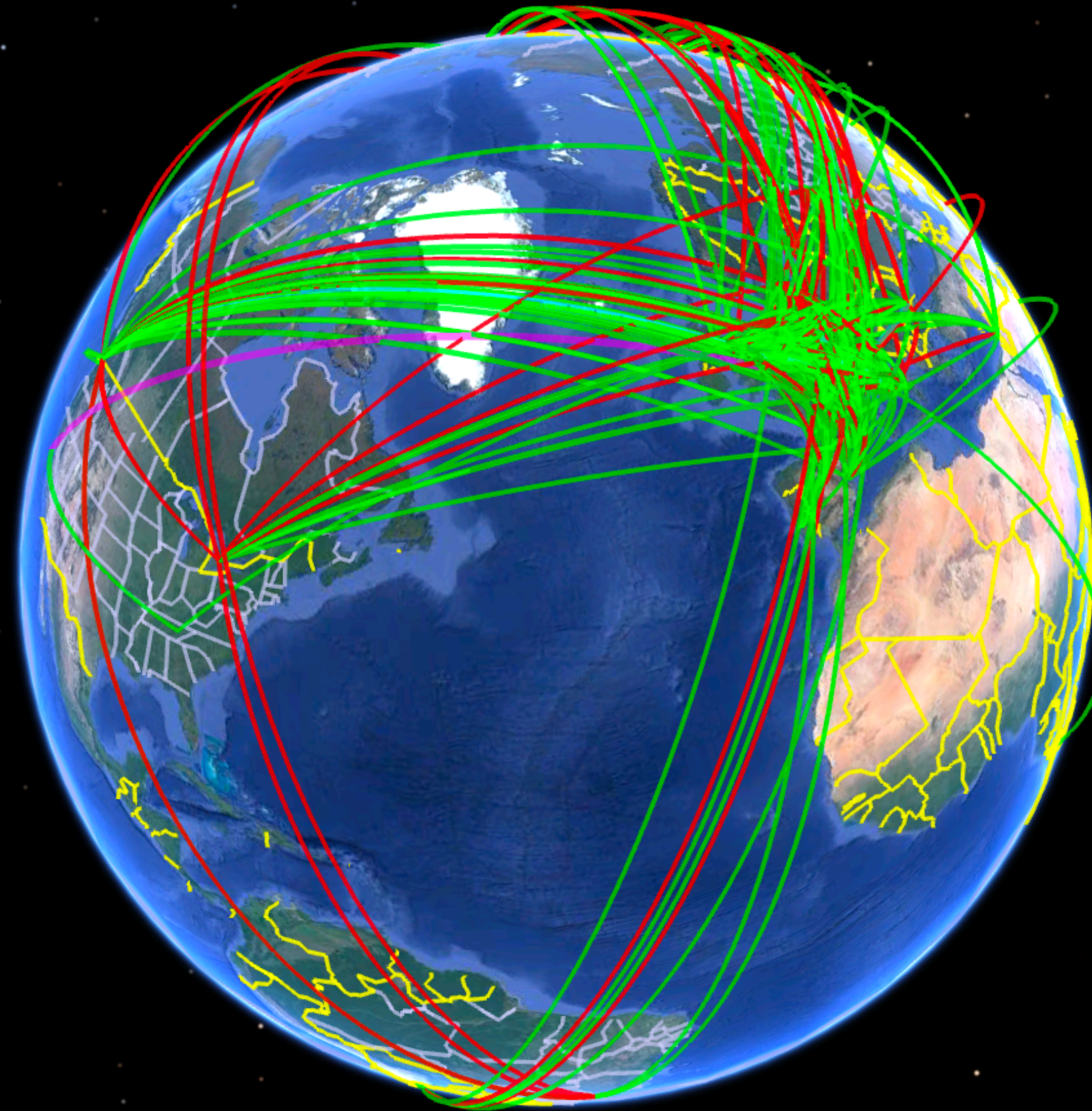
Data storage

- Archiving the vast quantities of data is an essential function at CERN
- Magnetic tapes are used as the main long-term storage medium
- Custom CERN storage system created for the extreme LHC computing requirements
- Seven billion files (as of June 2022) stored → matching the exceptional performances of the LHC machine and experiments

8/26/2021 9:01:35 am
8:52 am 9:02 am

Running jobs: 425936
Active CPU cores: 1098036
Transfer rate: 49.51 GiB/sec

Computing infrastructure.



Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image IBCAO
Image Landsat / Copernicus

Google Earth

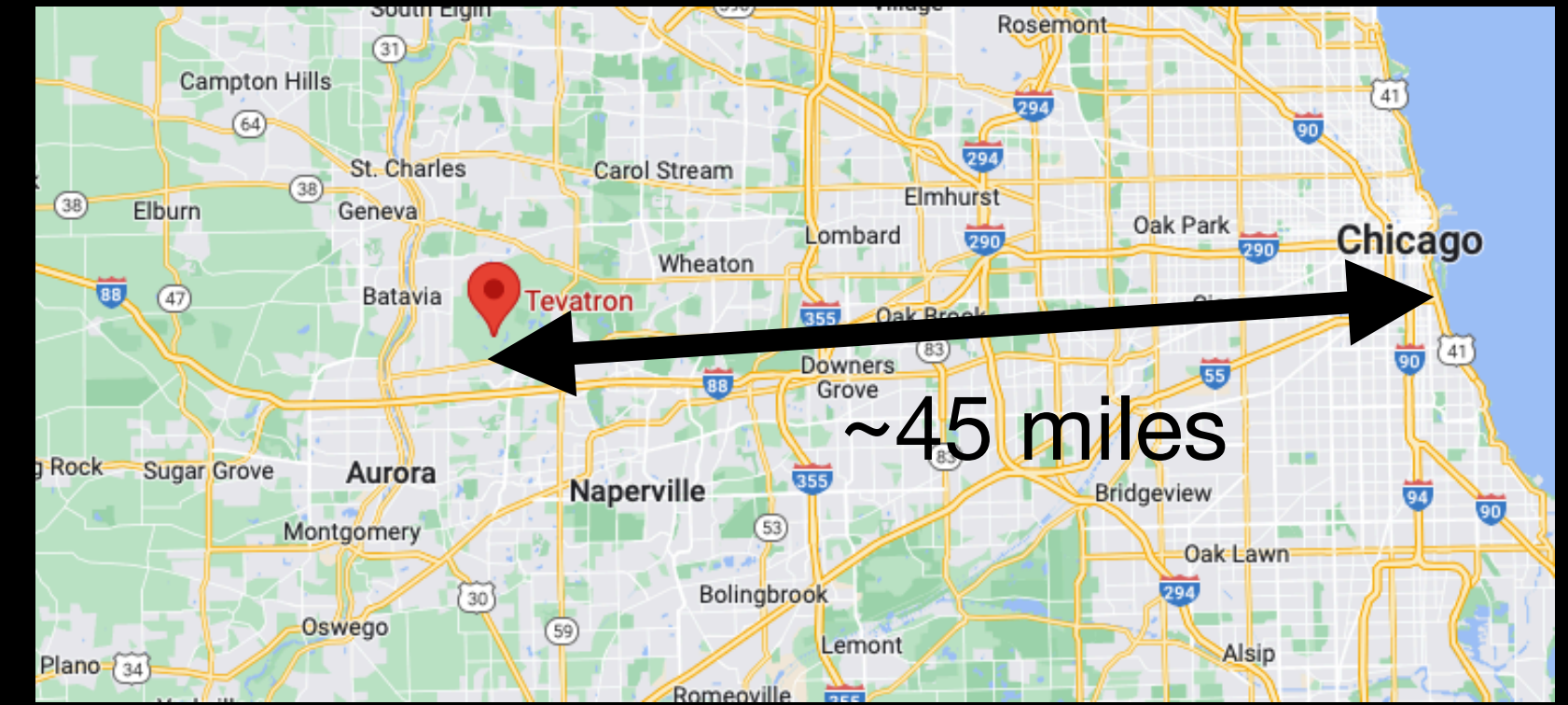
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Taking a step back: designing the accelerator

Designing an experiment to find the Higgs boson

The Higgs is massive — what did we learn from previous experiments

- What would guide our intuition as to how massive is the Higgs?
- We have not observed the Higgs in previous experiments → not light
- We know from the Tevatron that the mass of the Higgs boson lies between 115 and 135 GeV
 - $115 < m_H < 135$ GeV
- For comparison, the mass of the proton is ~ 1 GeV

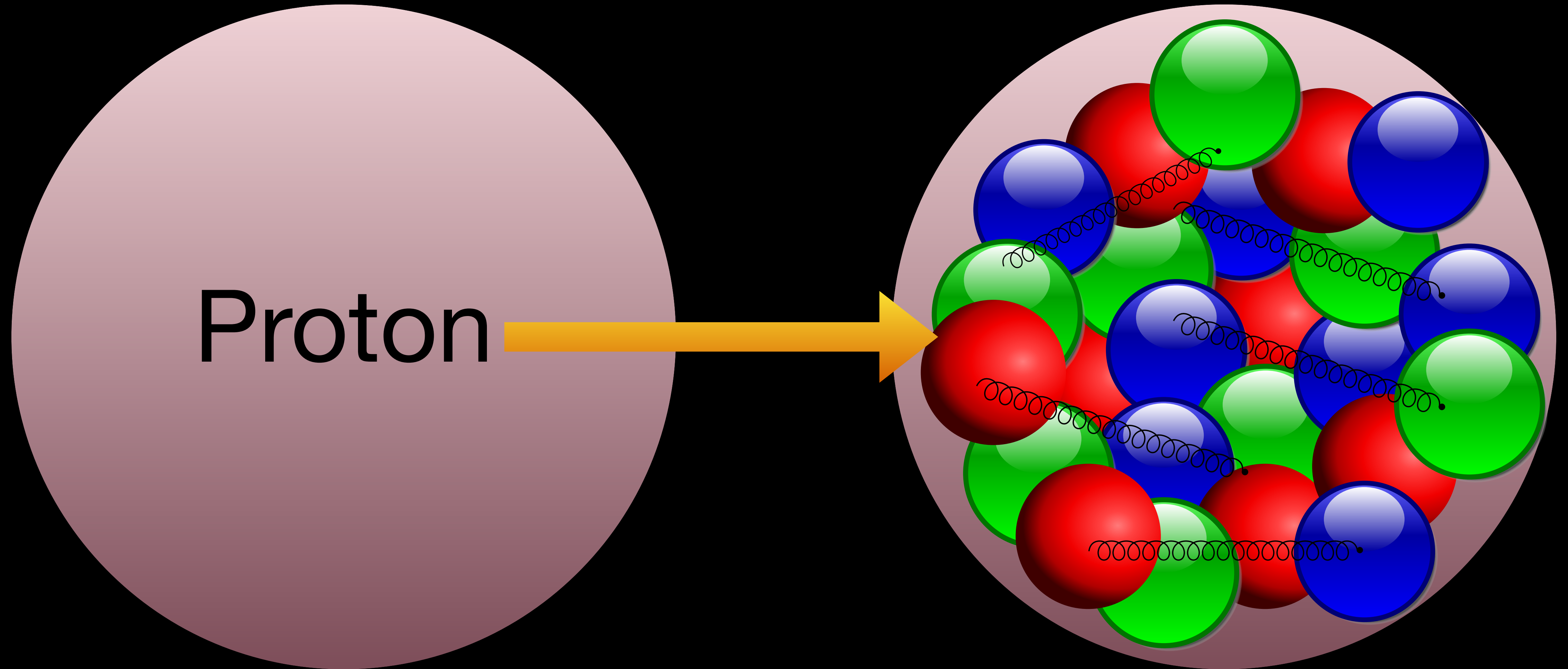


How to produce particles through annihilation?



Enough energy to produce the Higgs

Colliding protons is like colliding a bag of marbles



What else can we collide to produce a particle?

Standard Model of Elementary Particles

		three generations of matter (elementary fermions)			three generations of antimatter (elementary antifermions)			interactions / force carriers (elementary)	
		I	II	III	I	II	III		
Fundamental	QUARKS	mass $\approx 2.2 \text{ MeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ u up	mass $\approx 1.28 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ c charm	mass $\approx 173.1 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ t top	mass $\approx 2.2 \text{ MeV}/c^2$ charge $-\frac{2}{3}$ spin $\frac{1}{2}$ \bar{u} antiup	mass $\approx 1.28 \text{ GeV}/c^2$ charge $-\frac{2}{3}$ spin $\frac{1}{2}$ \bar{c} anticharm	mass $\approx 173.1 \text{ GeV}/c^2$ charge $-\frac{2}{3}$ spin $\frac{1}{2}$ \bar{t} antitop	0 0 1 g gluon	mass $\approx 124.97 \text{ GeV}/c^2$ 0 0 0 H higgs
		mass $\approx 4.7 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ d down	mass $\approx 96 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ s strange	mass $\approx 4.18 \text{ GeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ b bottom	mass $\approx 4.7 \text{ MeV}/c^2$ charge $\frac{1}{3}$ spin $\frac{1}{2}$ \bar{d} antidown	mass $\approx 96 \text{ MeV}/c^2$ charge $\frac{1}{3}$ spin $\frac{1}{2}$ \bar{s} antistrange	mass $\approx 4.18 \text{ GeV}/c^2$ charge $\frac{1}{3}$ spin $\frac{1}{2}$ \bar{b} antibottom	0 0 1 γ photon	GAUGE BOSONS VECTOR BOSONS
mass $\approx 0.511 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ e electron	mass $\approx 105.66 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ μ muon	mass $\approx 1.7768 \text{ GeV}/c^2$ charge -1 spin $\frac{1}{2}$ τ tau	mass $\approx 0.511 \text{ MeV}/c^2$ charge 1 spin $\frac{1}{2}$ e^+ positron	mass $\approx 105.66 \text{ MeV}/c^2$ charge 1 spin $\frac{1}{2}$ $\bar{\mu}$ antimuon	mass $\approx 1.7768 \text{ GeV}/c^2$ charge 1 spin $\frac{1}{2}$ $\bar{\tau}$ antitau	mass $\approx 91.19 \text{ GeV}/c^2$ 0 0 1 Z Z ⁰ boson			
Stable	LEPTONS	mass $< 2.2 \text{ eV}/c^2$ 0 $\frac{1}{2}$ ν_e electron neutrino	mass $< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_μ muon neutrino	mass $< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_τ tau neutrino	mass $< 2.2 \text{ eV}/c^2$ 0 $\frac{1}{2}$ $\bar{\nu}_e$ electron antineutrino	mass $< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ $\bar{\nu}_\mu$ muon antineutrino	mass $< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ $\bar{\nu}_\tau$ tau antineutrino	mass $\approx 80.39 \text{ GeV}/c^2$ 1 1 W^+ W ⁺ boson	mass $\approx 80.39 \text{ GeV}/c^2$ -1 1 W^- W ⁻ boson

Let's do some back-of-the-envelope calculations

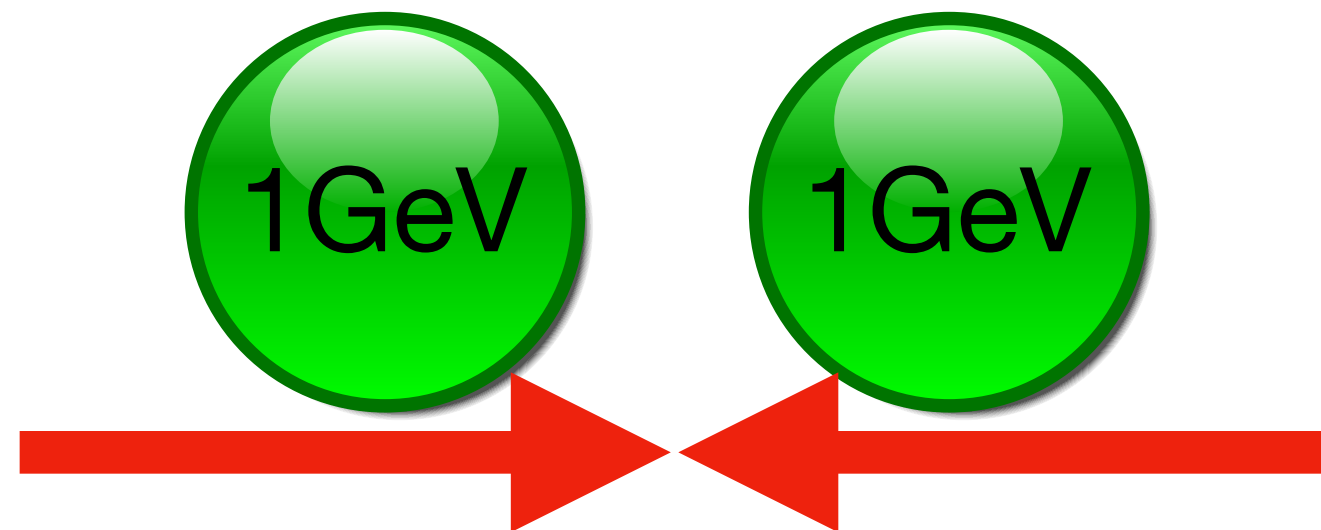
$$E = mc^2$$

Let's set $c=1$
(convention)

Mass of a proton is ~ 1 GeV

Colliding two protons at rest
is a no go

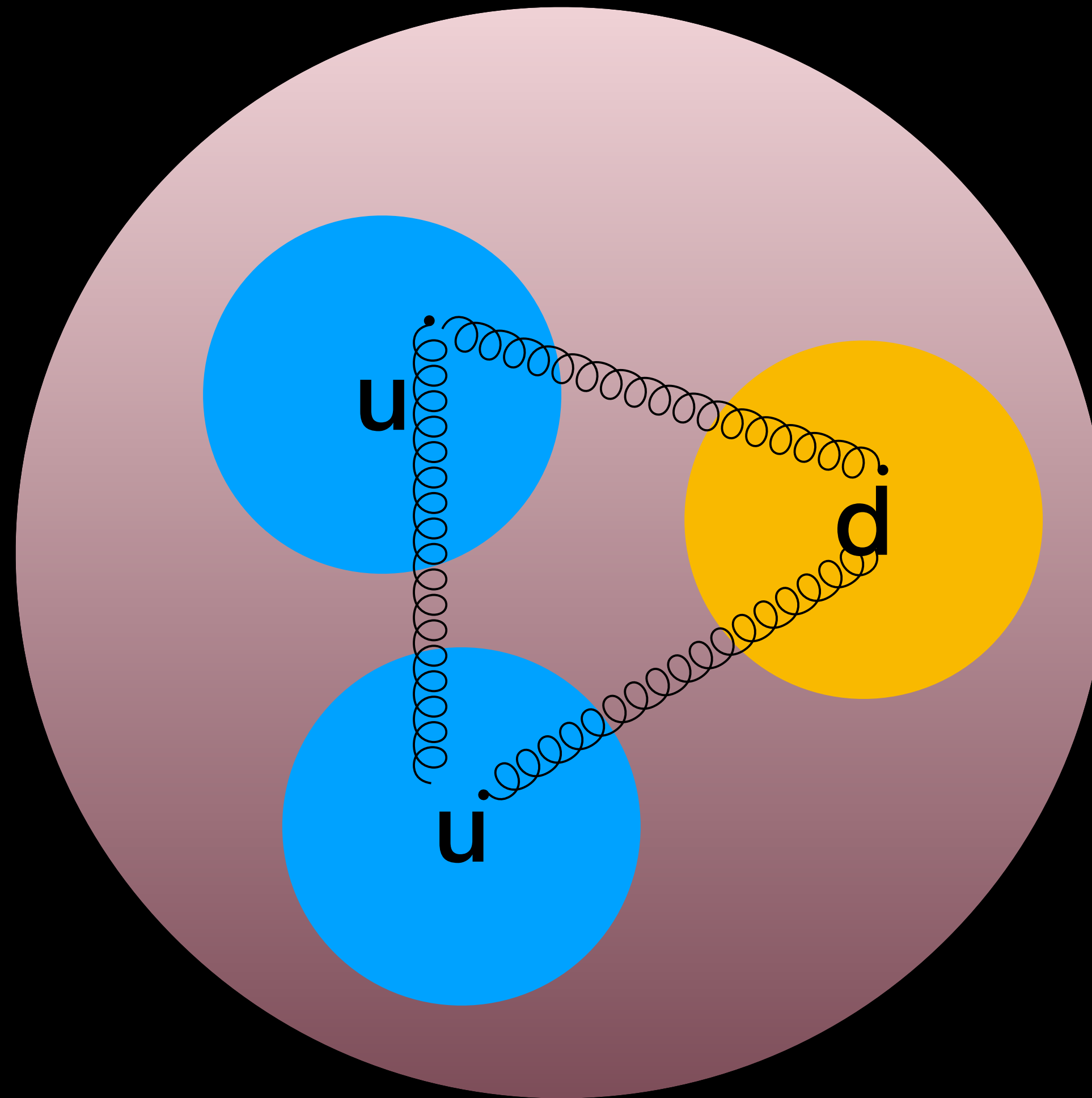
Total energy = $1 + 1$ GeV = 2 GeV



Total energy =
Kinetic energy + rest mass

Pump the protons with energy,
so that the collision can result
in the creation of a particle that
is 125 times heavier

Structure of the proton in a parton model



Protons have to be accelerated to very high energies

Each quark carries only a small fraction of the proton's energy

Need protons at 4 TeV to make quark-antiquark annihilation to produce Higgs at 125 GeV

The proton contains 2 “up”-type quarks and 1 “down”-type quark connected by gluon lines

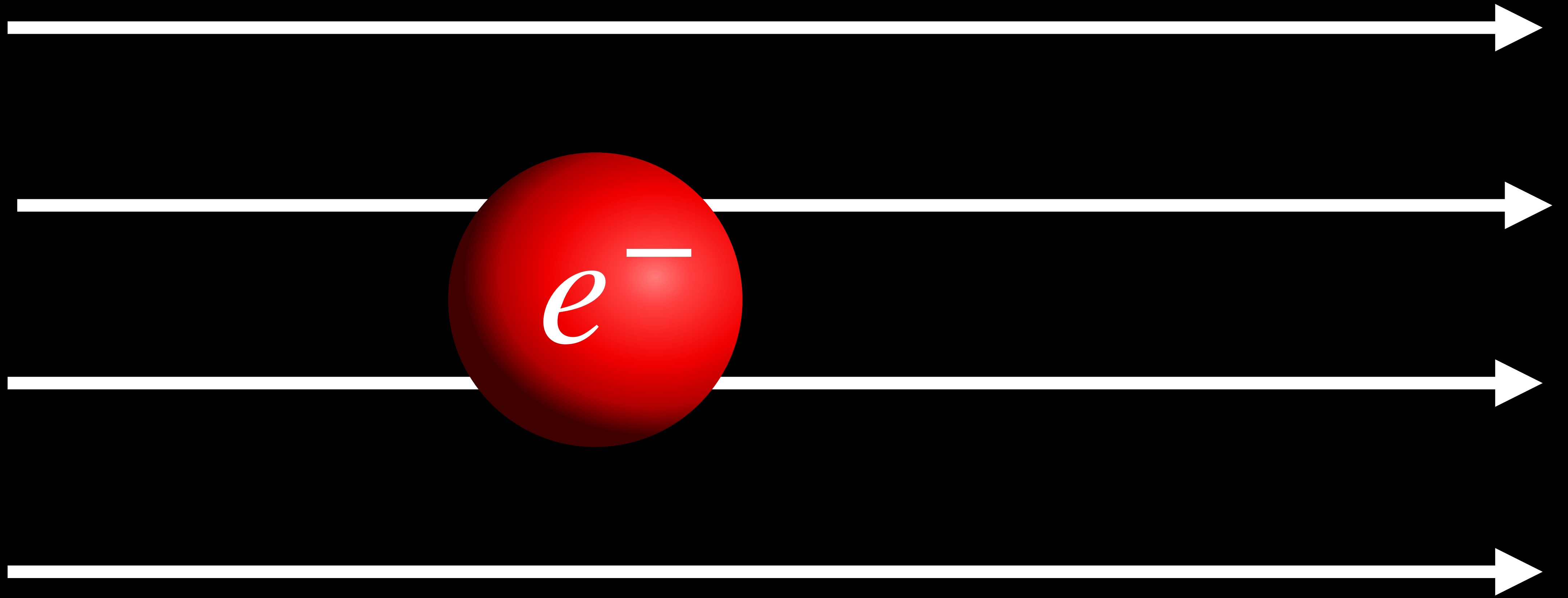
How to accelerate particles to high energy?

Electric field →



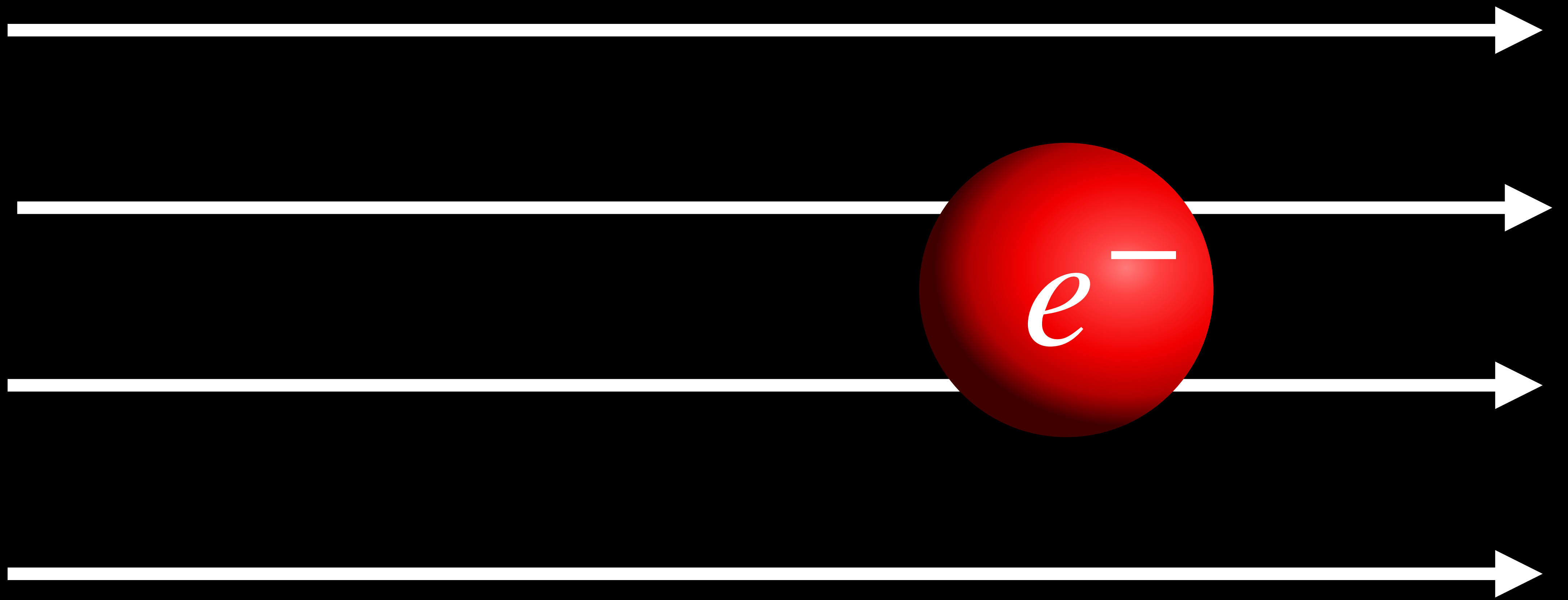
How to accelerate particles to high energy?

Electric field →



How to accelerate particles to high energy?

The force acting on the particle $\vec{F} = q\vec{E} = m\vec{a}$



Cyclotron

Proposed by Ernest Lawrence and patented in 1932

① Ion source (negative charges here)

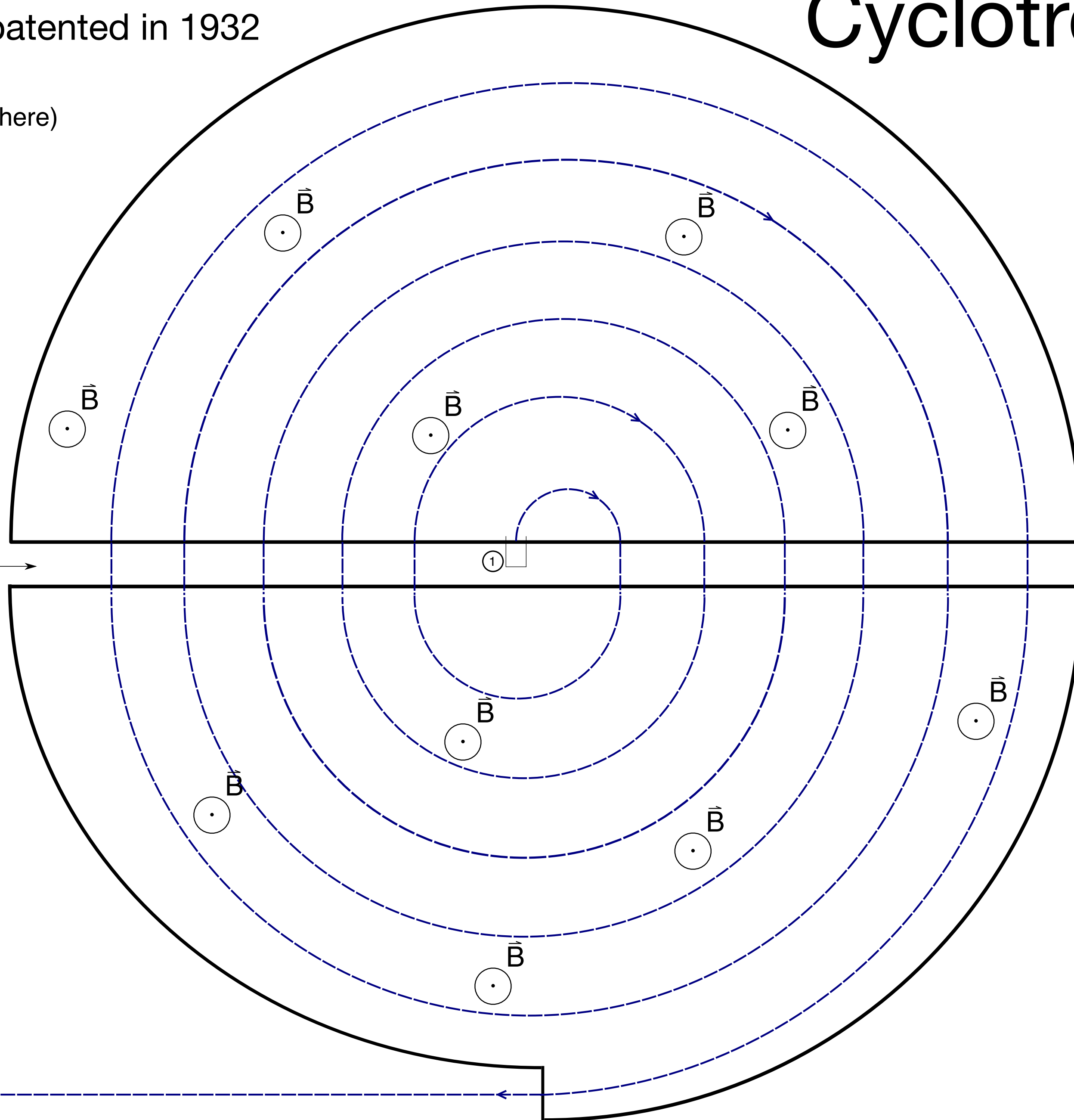
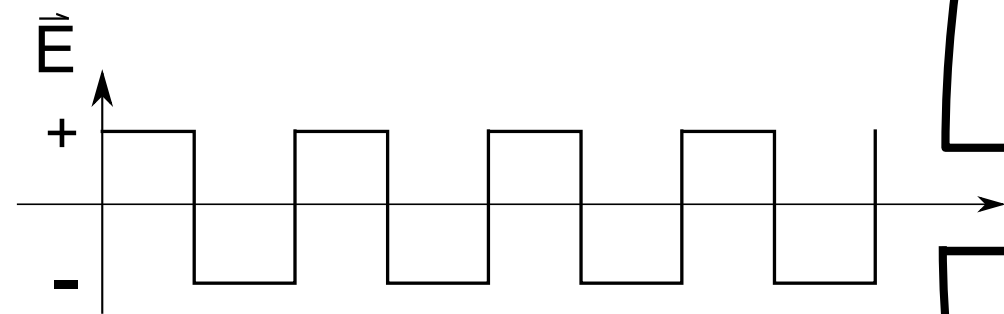
② Accelerated ions

\vec{B} Magnetic field

\vec{E} Electric field

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

B field acts perpendicular to the direction of motion

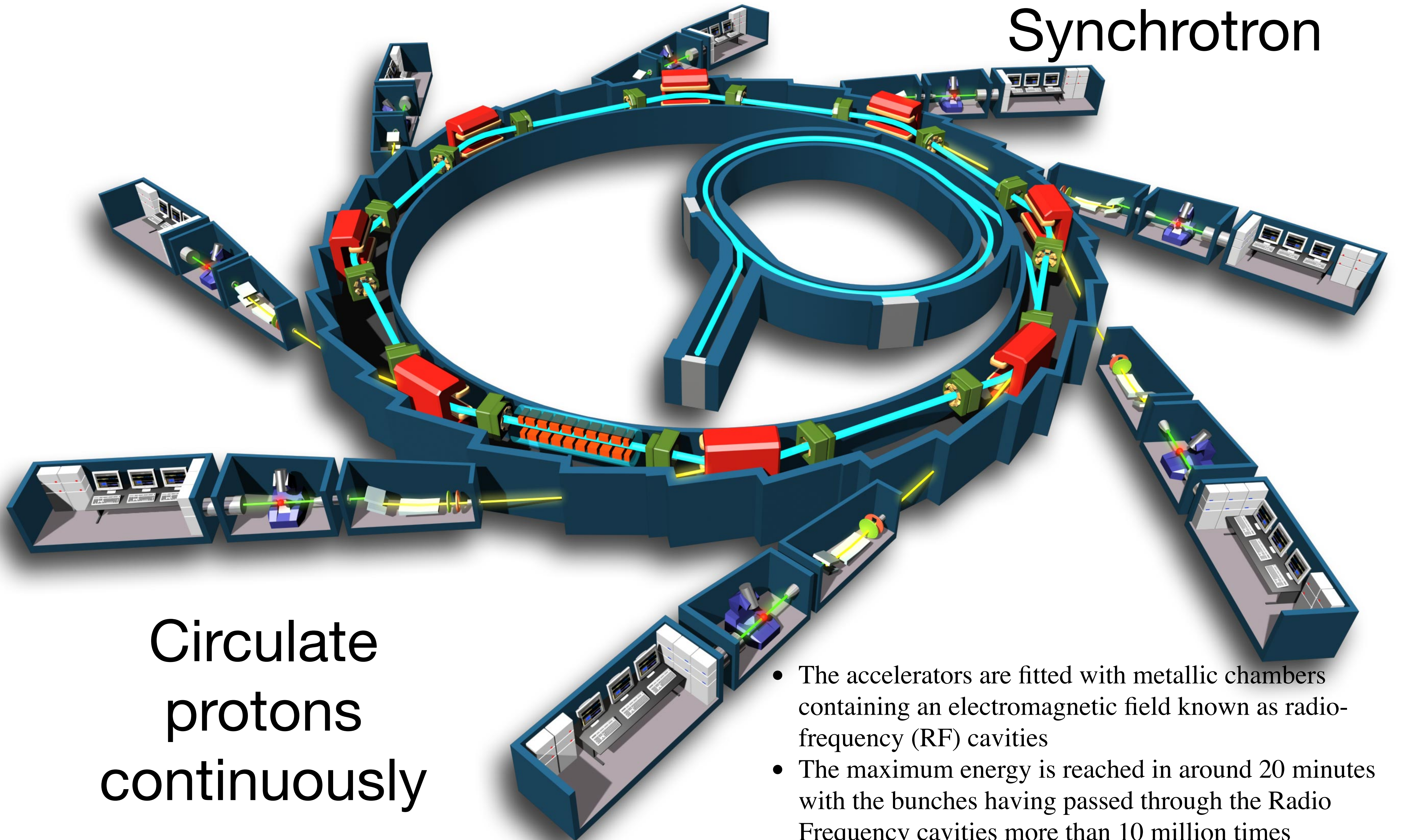


$$\text{Kinetic } E = \frac{1}{2}mv^2 = \frac{q^2B^2R^2}{2m}$$

R = radius at which the energy is determined



Synchrotron

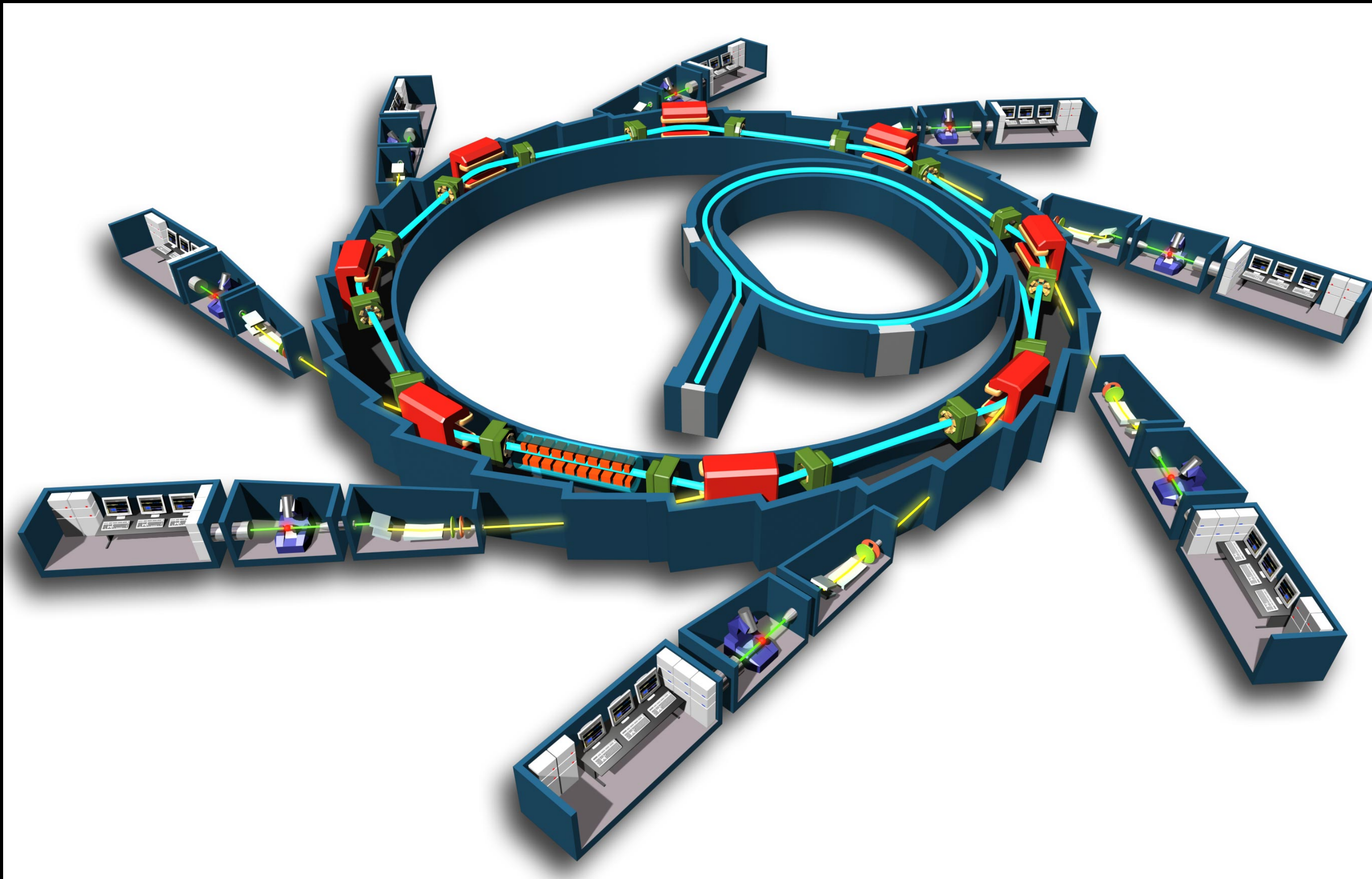


Circulate
protons
continuously

- The accelerators are fitted with metallic chambers containing an electromagnetic field known as radio-frequency (RF) cavities
- The maximum energy is reached in around 20 minutes with the bunches having passed through the Radio Frequency cavities more than 10 million times

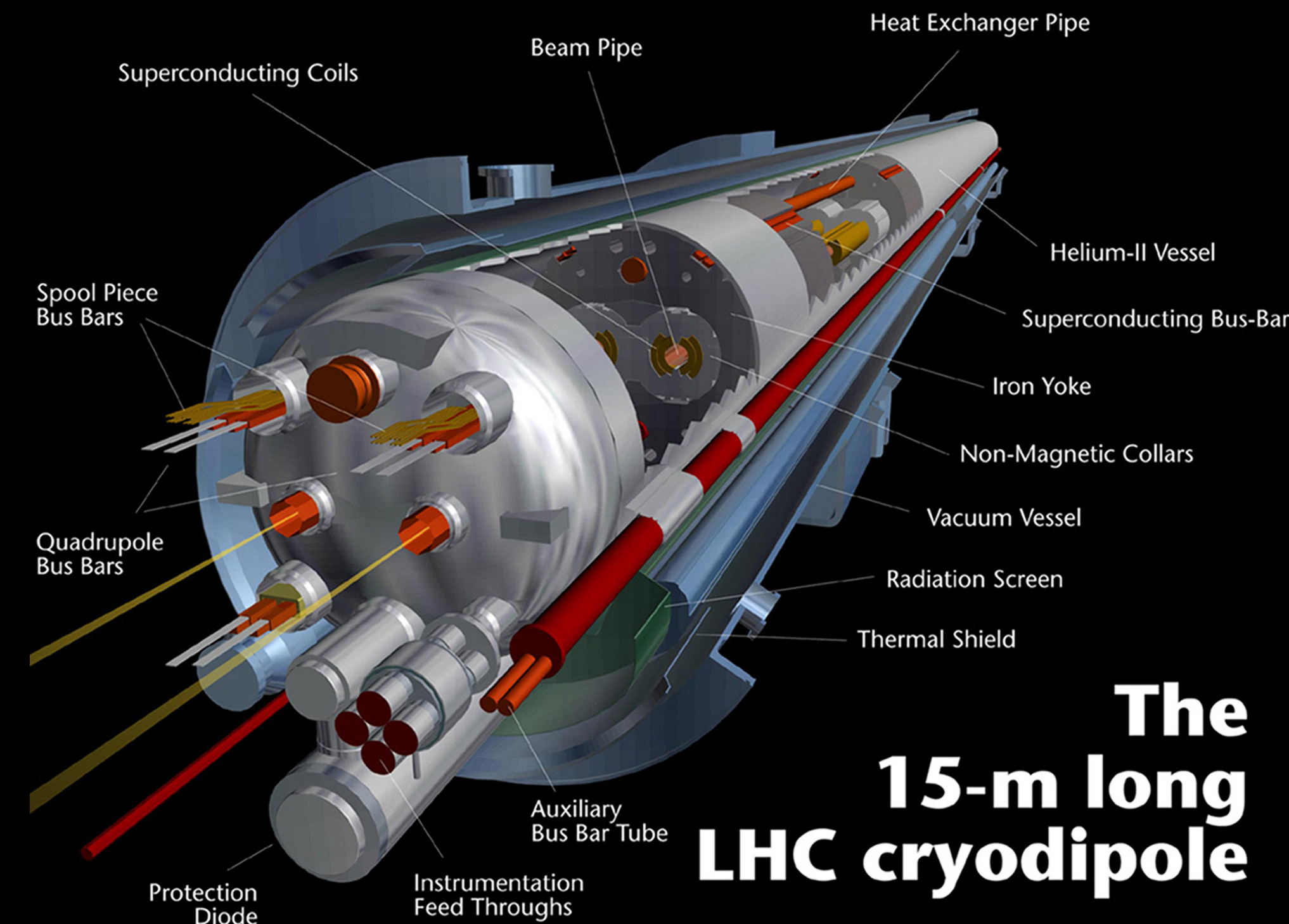
Synchrotron

- Protons receive a kick from the radio-frequency cavity
- Energy increased from 450 GeV to 6500 TeV
- The electric field is made to oscillate → timing important
- Slow (or fast protons) will be given a kick in the right direction to achieve desired beam energy
- Naturally sorts itself into bunches

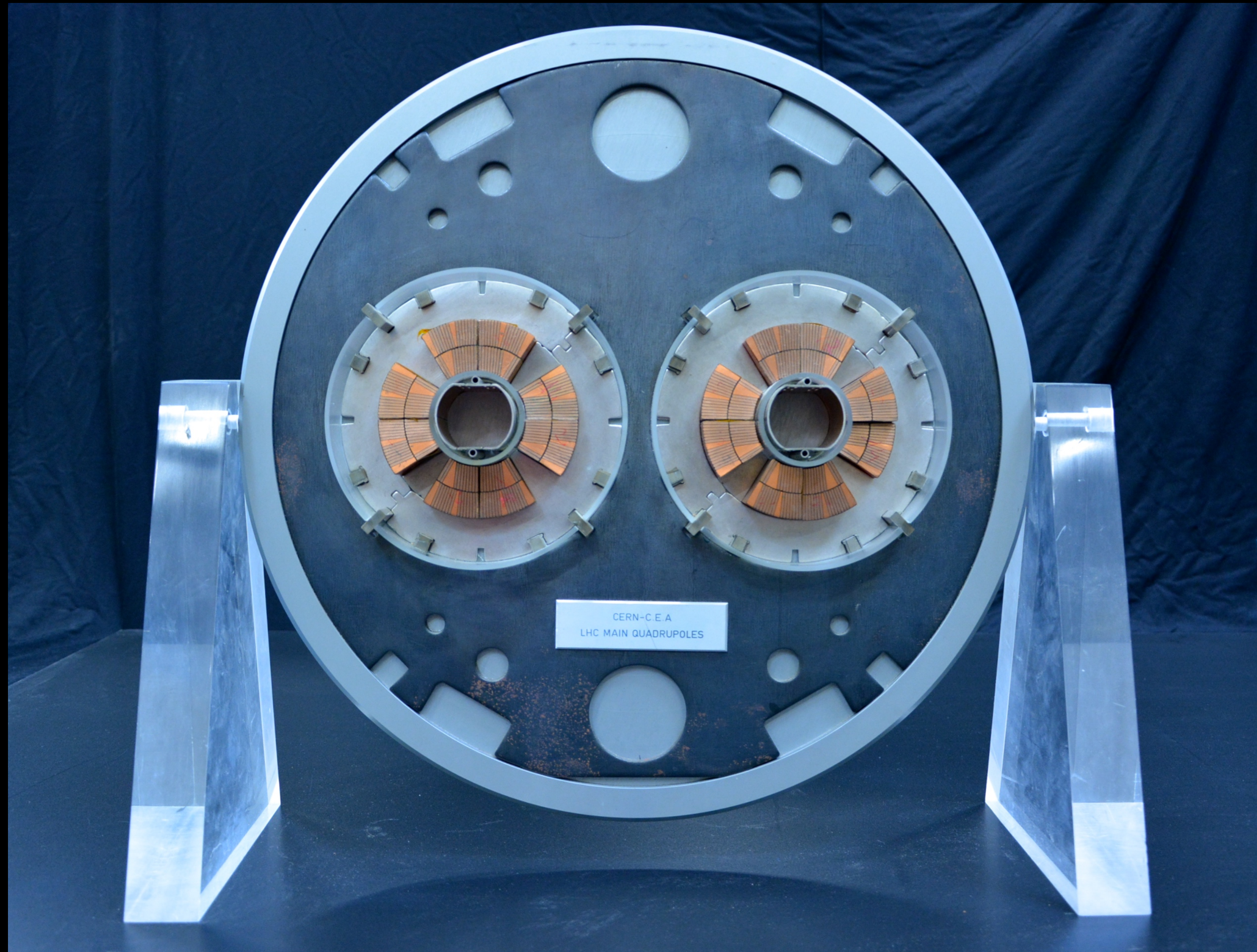


How to use magnets to bend beams and collide?

- Dipole magnets are used to bend the paths of the protons around the 27 km ring
- Squeezed for collision into a space narrower than human hair
- Require huge forces to control them
- Computer-generated image of an LHC dipole magnet
- Magnets must be cooled to 1.9 K (less than -270.3°C) → superconducting coils can produce the required 8 T magnetic field strength



LHC magnets



A quadrupole focusing magnet

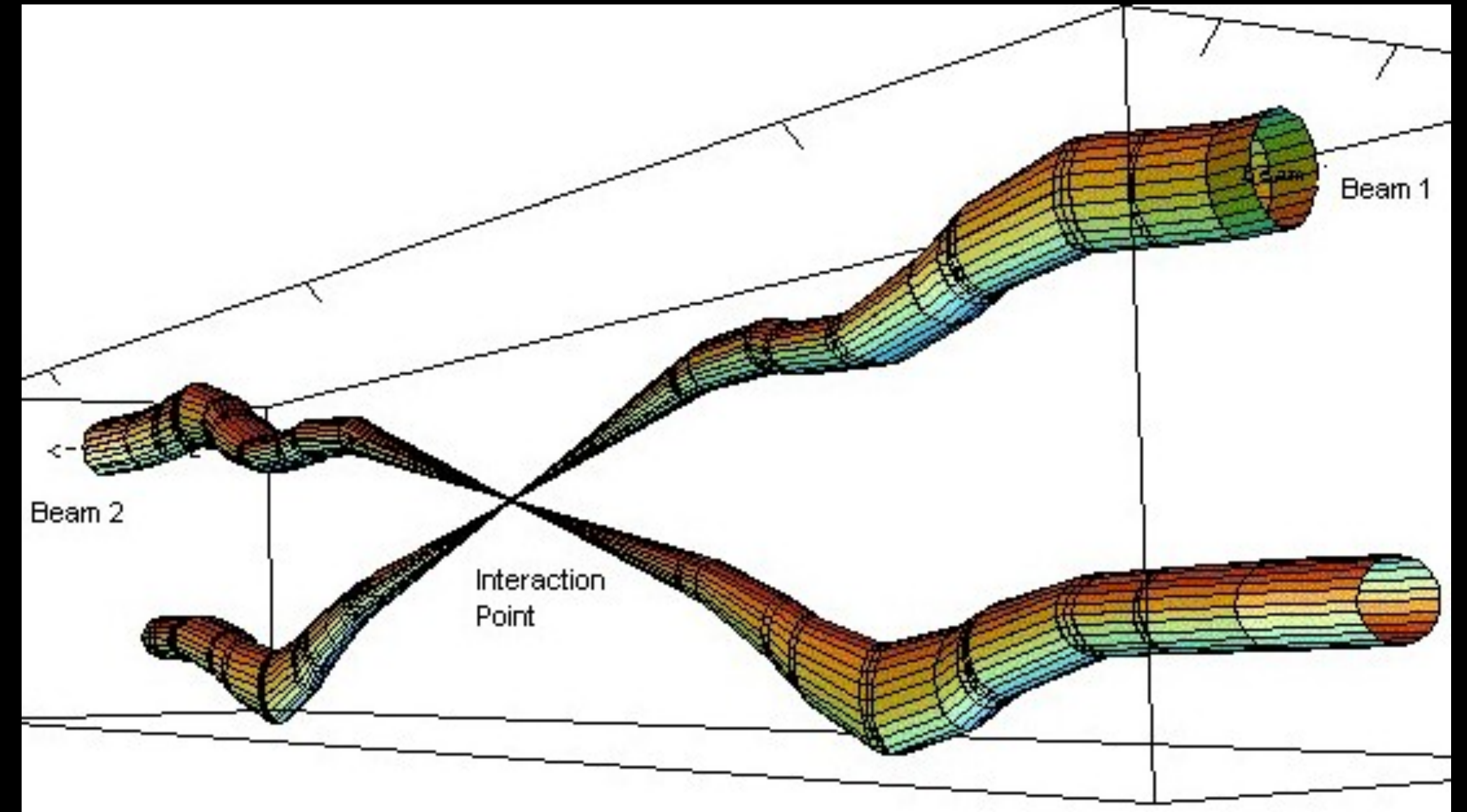
- Use a quadrupole magnet to focus beams
- Quadrupole magnets focus the proton beams
- Squeeze them so that more particles collide when the beams cross paths
- Precision needed analogous to colliding two knitting needles launched from either side of the Atlantic Ocean

To recapitulate...

○ Two kinds of magnets needed



1. Dipole magnets to bend the beams of protons
2. Quadrupole magnets to focus the proton beams at the detectors



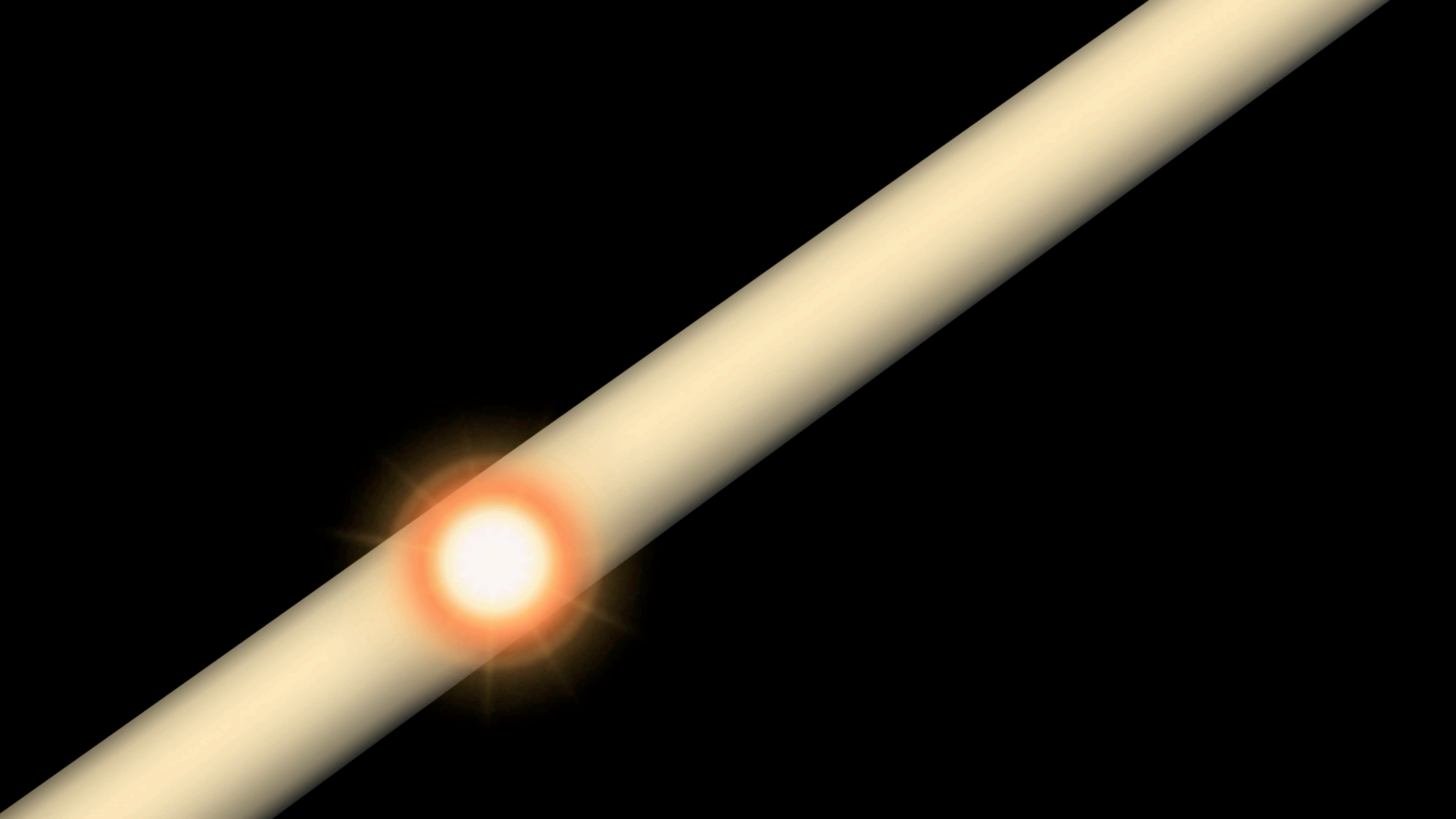
Magnets are key

- LHC uses the tunnel built for a previous generation of experiment
- Often referred to as a “poisoned gift” as obvious way to increase energy = construct a bigger tunnel
- Build stronger magnets!
- Not so easy! Increasing magnetic field by factors of two is highly non-trivial
- Need magnetic fields stronger six times stronger than an MRI machine



Magnets are key

- In 1986, when R&D on the LHC started, three key issues needed to be addressed:
 - High field
 - Superfluid He
 - Two-in-one design
- Revolutionary two-in-one design used → perfect for usage in small tunnels
- Two magnetic channels are hosted in the iron yoke → can be housed with a small cryogenic module
- Originally developed at Brookhaven National Lab but deemed unnecessary at the time → we will build a big tunnel for the Superconducting Super Collider
- Huge win for the LHC when a field of 9 T at 1.8 K was reached in 1987 → most critical milestone



Astroparticle physics

Detectors in Astroparticle physics

- Research field encompasses huge energy scales (100 keV to 10^{21} eV)
- Wide array of detectors:
 - Balloon and satellite experiments: light and compact detectors
 - Air shower detector: calorimeters which measure cosmic ray initiated showers only in one plane
 - Neutrino detectors for low energies
 - Detectors for high energy neutrinos of cosmic origin

Large Hadron Collider (LHC) timeline

Key Date	Event
March 1984	Should we build a Large Hadron Collider (LHC) in the preexisting tunnel?
January 1987	President Reagan announces support for the Superconducting Super Collider - a circular accelerator with an 87 km circumference — smash particles at 40 TeV. Still need the LHC?
October 1992	The two multipurpose experiments at the LHC publish letters of intent. Specialized experiment (ALICE) follows suit.
October 1993	Superconducting Super Collider project canceled
April 1994	Magnet prototype built and achieves 8.73 T
December 1994	LHC construction is approved by the CERN Council

Large Hadron Collider (LHC) timeline

Key Date	Event
October 1995	LHC conceptual design report published
January 1997	CMS and ATLAS experiments approved. Other specialized experiments approved.
December 1997	United States admitted as CERN observer state
July 1998	Gallo-Roman ruins discovered at the CMS site — 6 month delay
May 2002-February 2005	ATLAS and CMS caverns excavated, reinforced and inaugurated
April 2007	The last LHC dipole magnet goes underground
September 10 2008	The LHC starts up

Homework

- Do some literature survey
 - Find the “detector papers” for each of these experiments (ATLAS, CMS, LHCb, Alice)
- Read the foundational choices made in detector design: why are we building this detector
- What is the physics motivation
- Let’s have a 5 min/person discussion on the physics motivation next week
- For astro-particle, pick one experiment

Next week (1-2): overview

- Particle interaction with matter:
 - ionisation and excitation of atoms in media by charged particles
 - bremsstrahlung: photon radiation emitted by charged particles in the fields of atomic nuclei
 - photon scattering and photon absorption
 - Cherenkov and transition radiation
 - Nuclear reactions
 - Weak interactions

Synchrotron

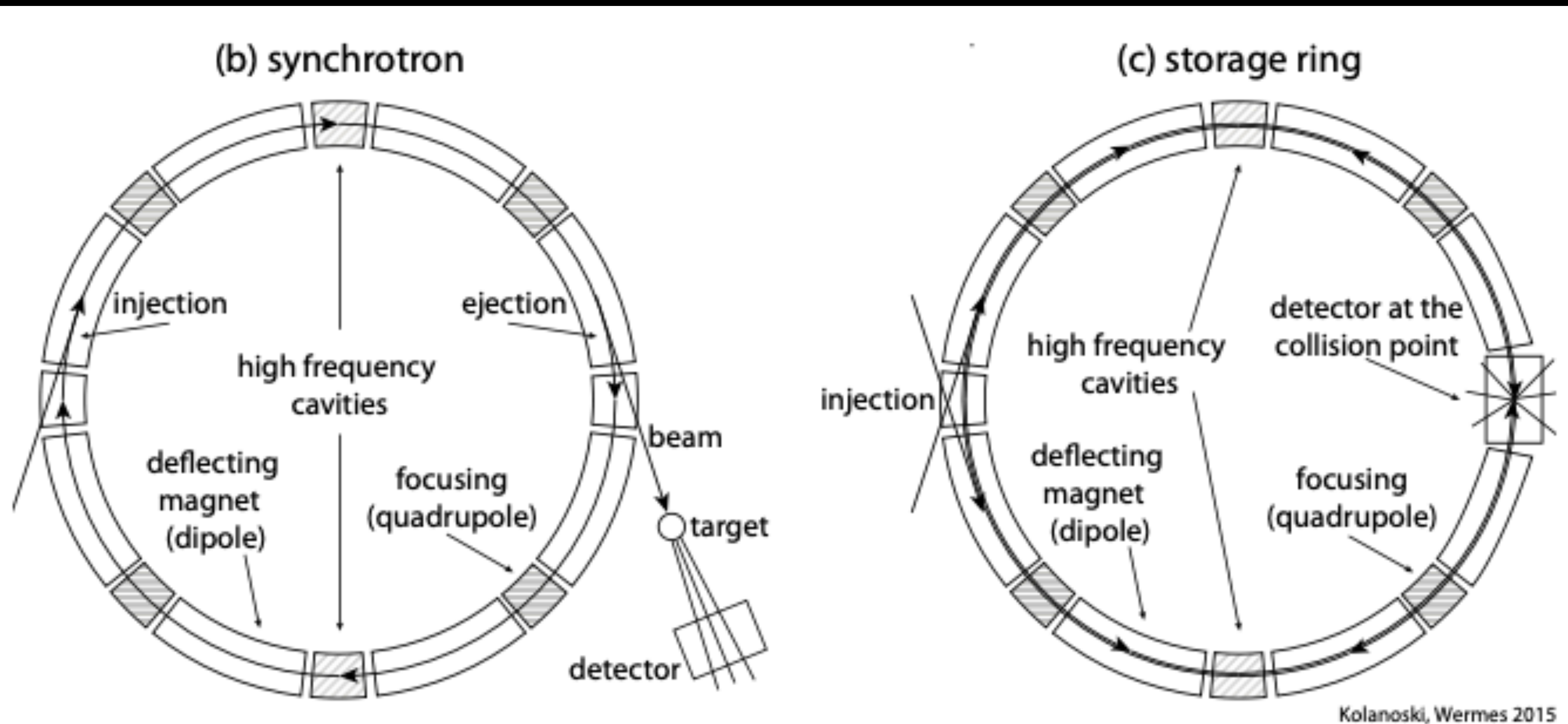


Fig. 2.8 Schematic sketches of three important accelerator types. The first classification separates into linear accelerators (a) and circular accelerators (b, c). Under the circular accelerators one distinguishes the scheme of a synchrotron (b) with a beam in the machine and an ejected external beam and the scheme of a storage ring (c) with two oppositely circulating particle beams which are collided at a crossing point.

A storage ring is a special type of synchrotron in which the kinetic energy of the particles is kept constant

- Electron-volt (eV) is a unit of energy equal to the amount of kinetic energy gained by a single electron when it's accelerated through an electric potential difference of one volt
- In traditional units = 1.602×10^{-19} Joules