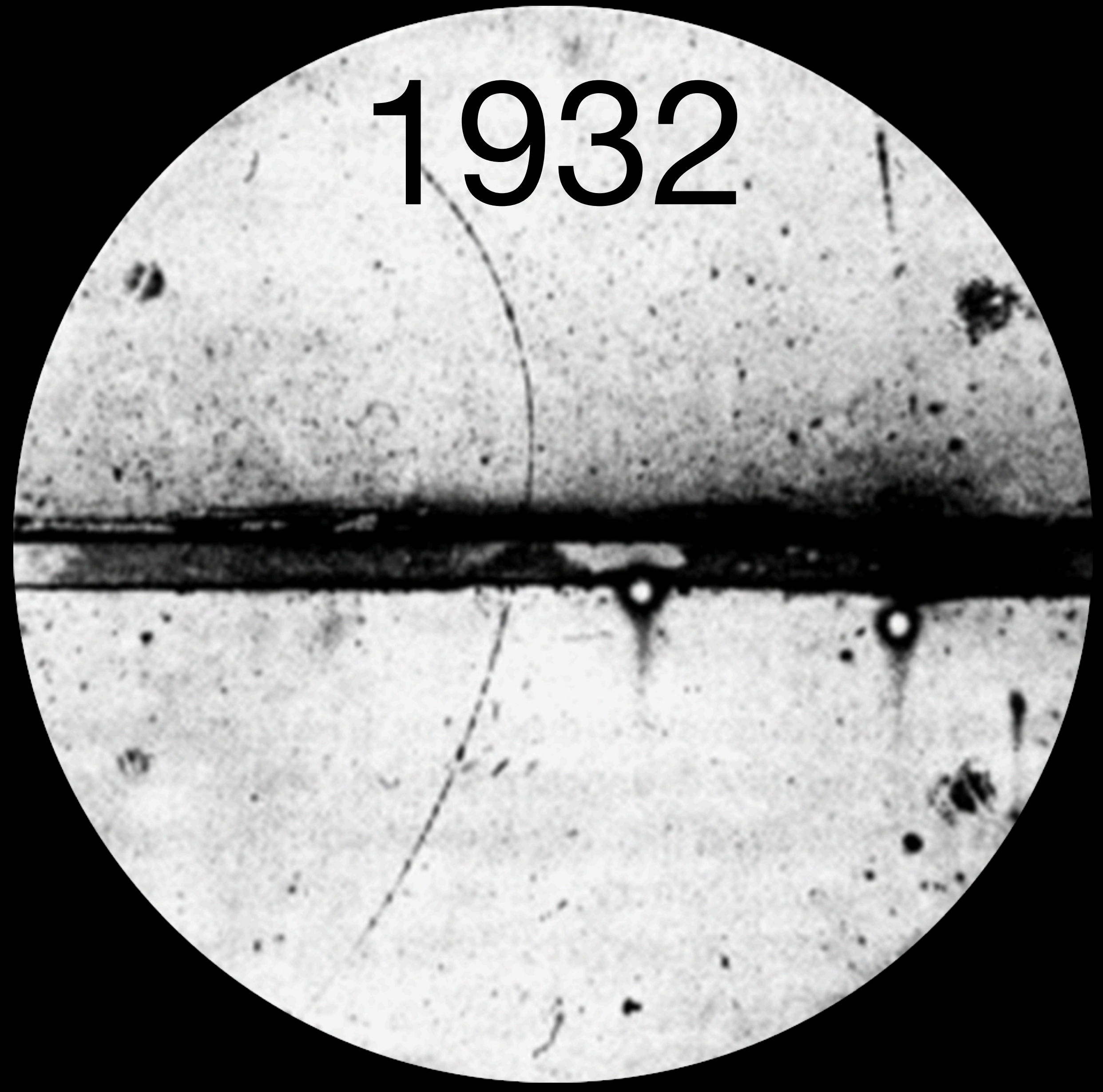
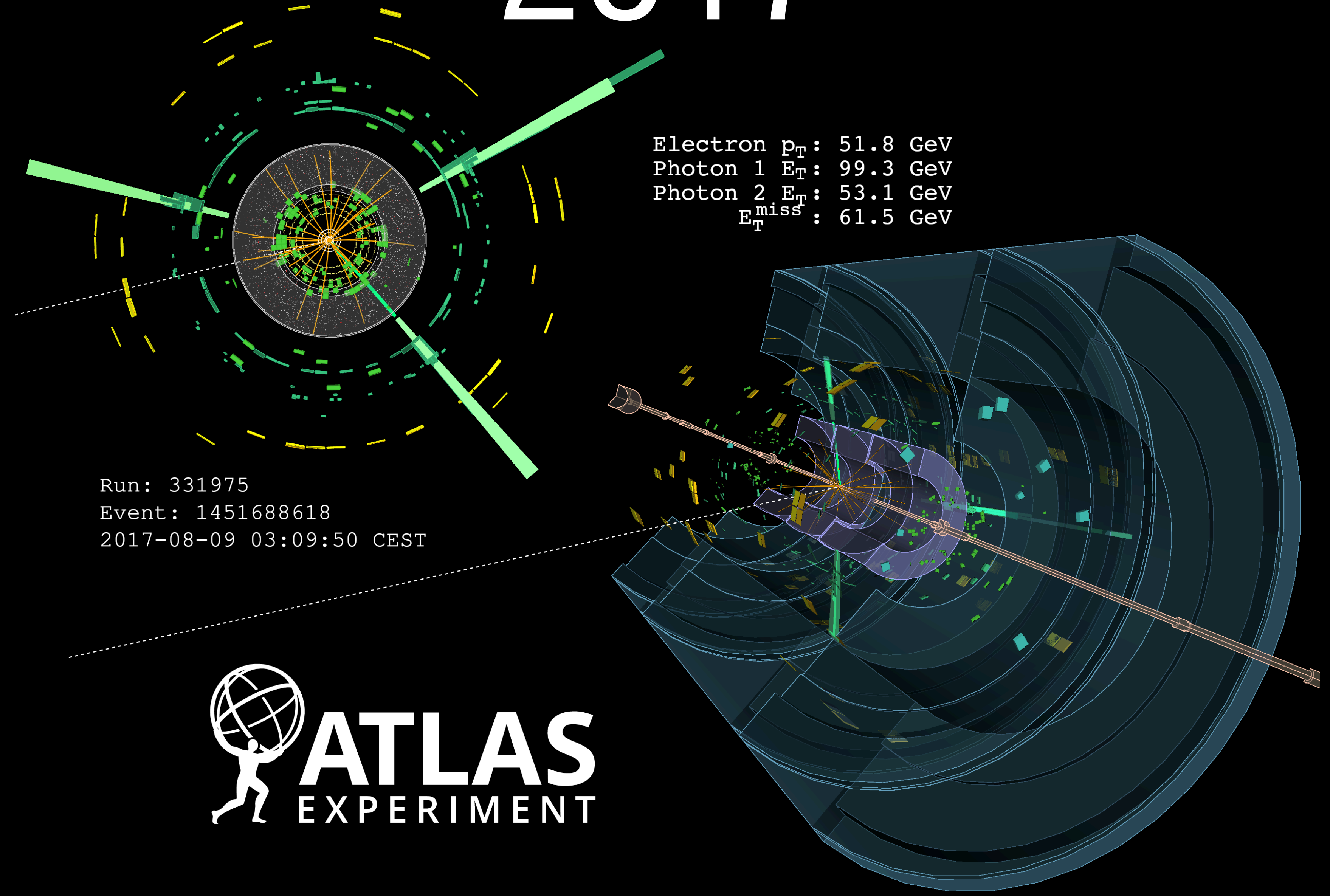
PHYS 7363 - Experimental Particle Detection and Detectors I



2017



Particle detectors are the workhorses of experimental physics. In this course, we'll dive deep into their physics, exploring the incredible evolution of our experimental techniques over the past nine decades. You'll gain a solid understanding of *particle detection* and *identification*, examine the intricate designs of modern detectors, and learn how machine learning is being harnessed to push the boundaries of detector design. If you're intrigued by how we "see" subatomic particles, this course is for you!

Detect Identify Measure

To discuss prerequisites (and any questions on the content of the course), please contact me: saptaparnab@smu.edu

Multiboson group at SMU

- I joined Southern Methodist University as an Assistant Professor in the fall of 2024
- My research interests lie in multiboson physics, polarization measurements and effective field theories
- I am interested in studying event generators on GPUs and contributing to ATLAS upgrades

Schedule

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
August	18	19	20	21	22	23	24
	25	26	27	28	29	30	31
September	1	2	3	4	5	6	7
	8	9	10	11	12	13	14
	15	16	17	18	19	20	21
	22	23	24	25	26	27	28
October	29	30	1	2	3	4	5

Schedule

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
October	6	7	8	9	10	11	12
	13	14	15	16	17	18	19
	20	21	22	23	24	25	26
	27	28	29	30	31	1	2
November	3	4	5	6	7	8	9
	10	11	12	13	14	15	16
	17	18	19	20	21	22	23
	24	25	26	27	28	29	30
December	1	2	3	4	5	6	7
	8	9	10	11	12	13	14

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/

Career Development

THE HERTZ FELLOWSHIP

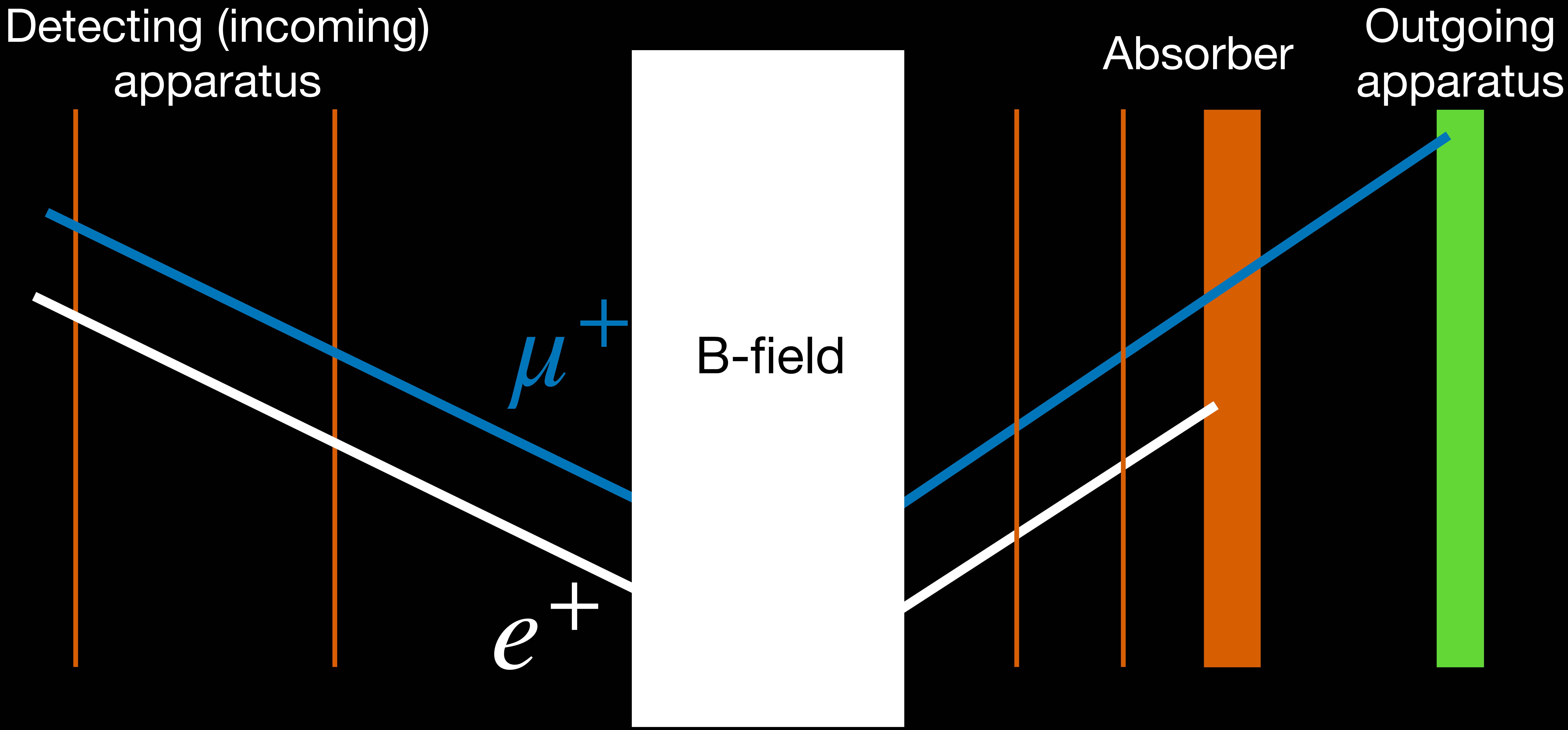
APPLY FOR THE HERTZ FELLOWSHIP

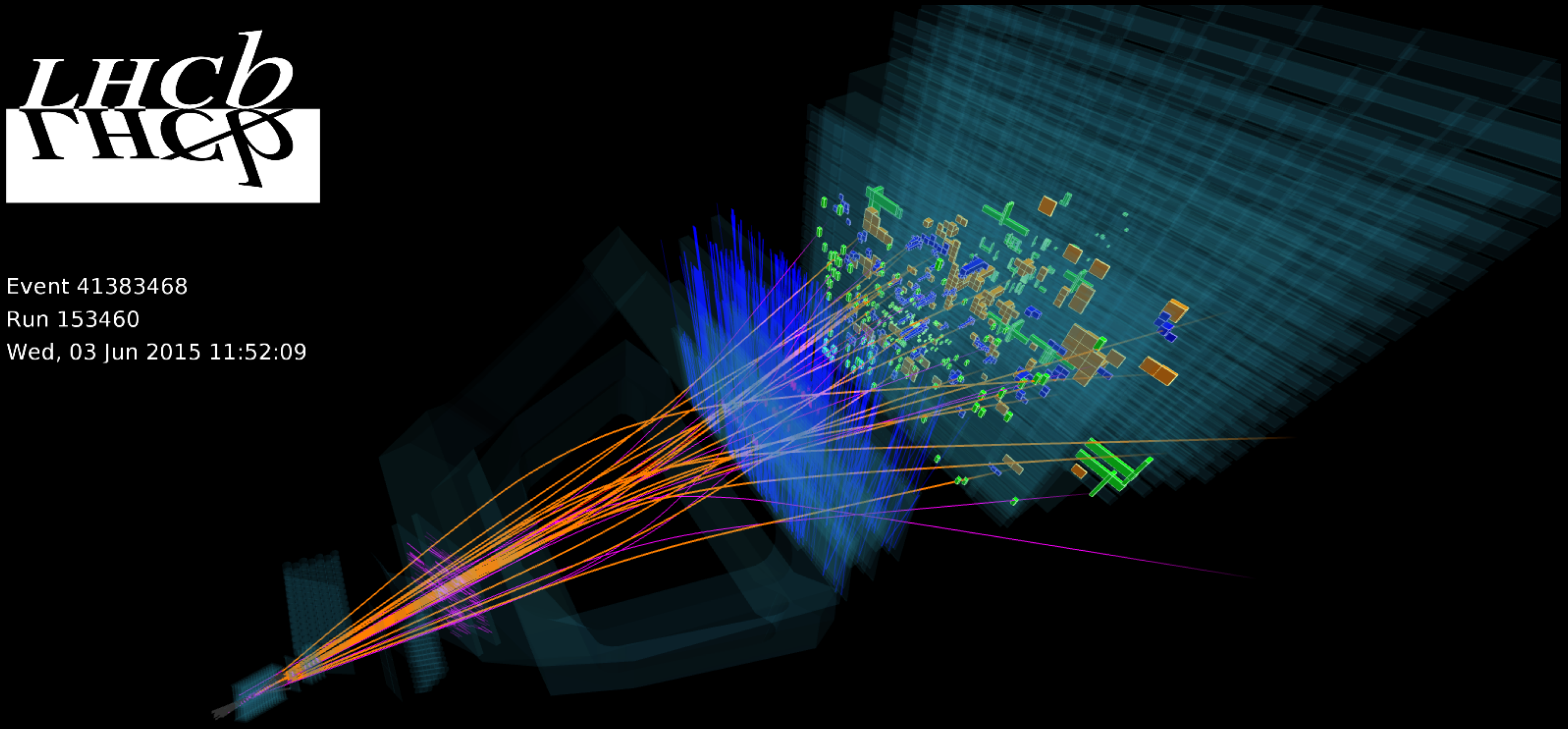
The 2026 Hertz Fellowship application is now open through October 31, 2025.

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
- Georg Viehhauser/Tony Weinberg, “Detectors in Particle Physics: A Modern Introduction”, CRC Press, Taylor and Francis Group
- 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
- LHC experiment design: https://www.nature.com/articles/nature06078

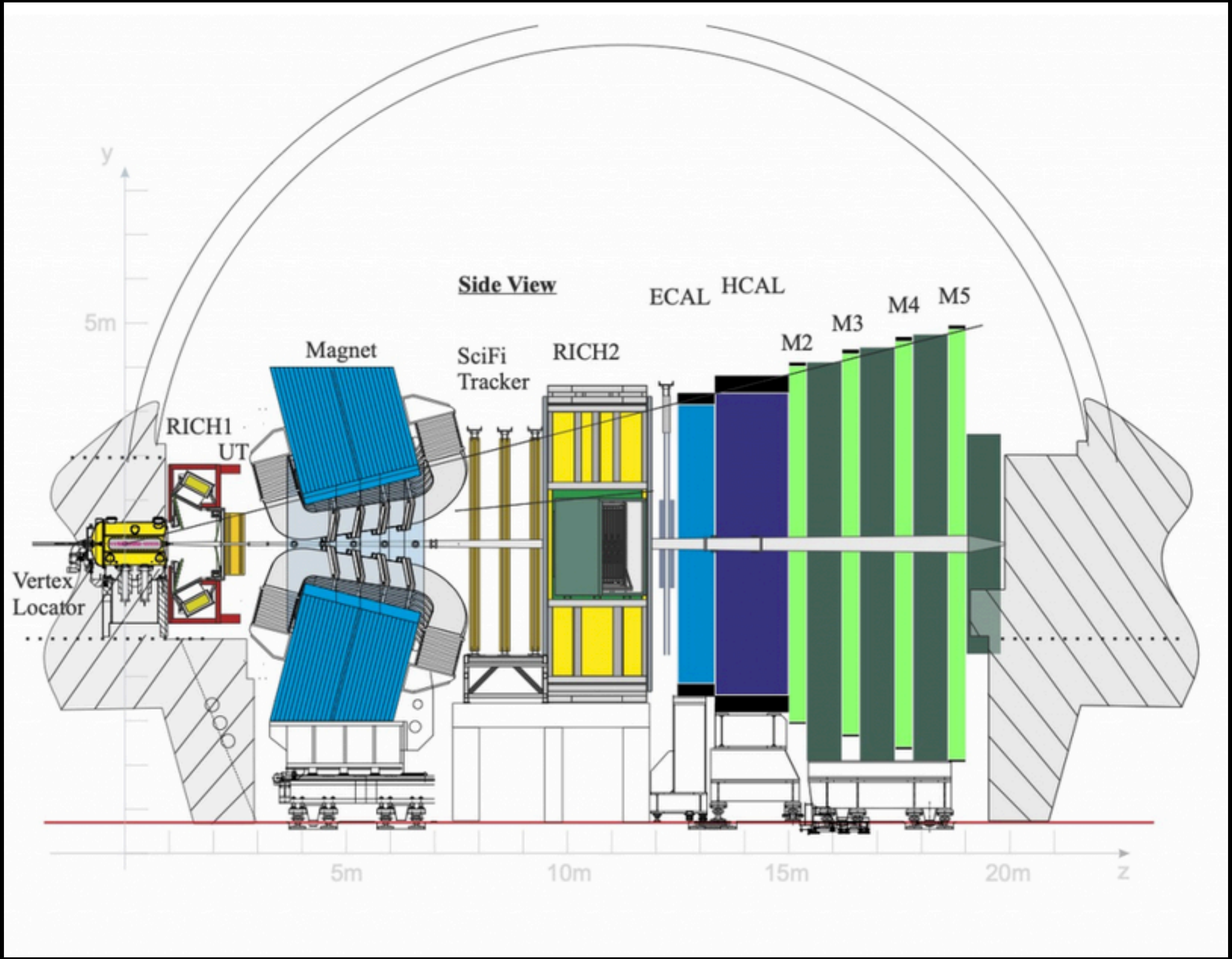
A simple detector — for different types of particles

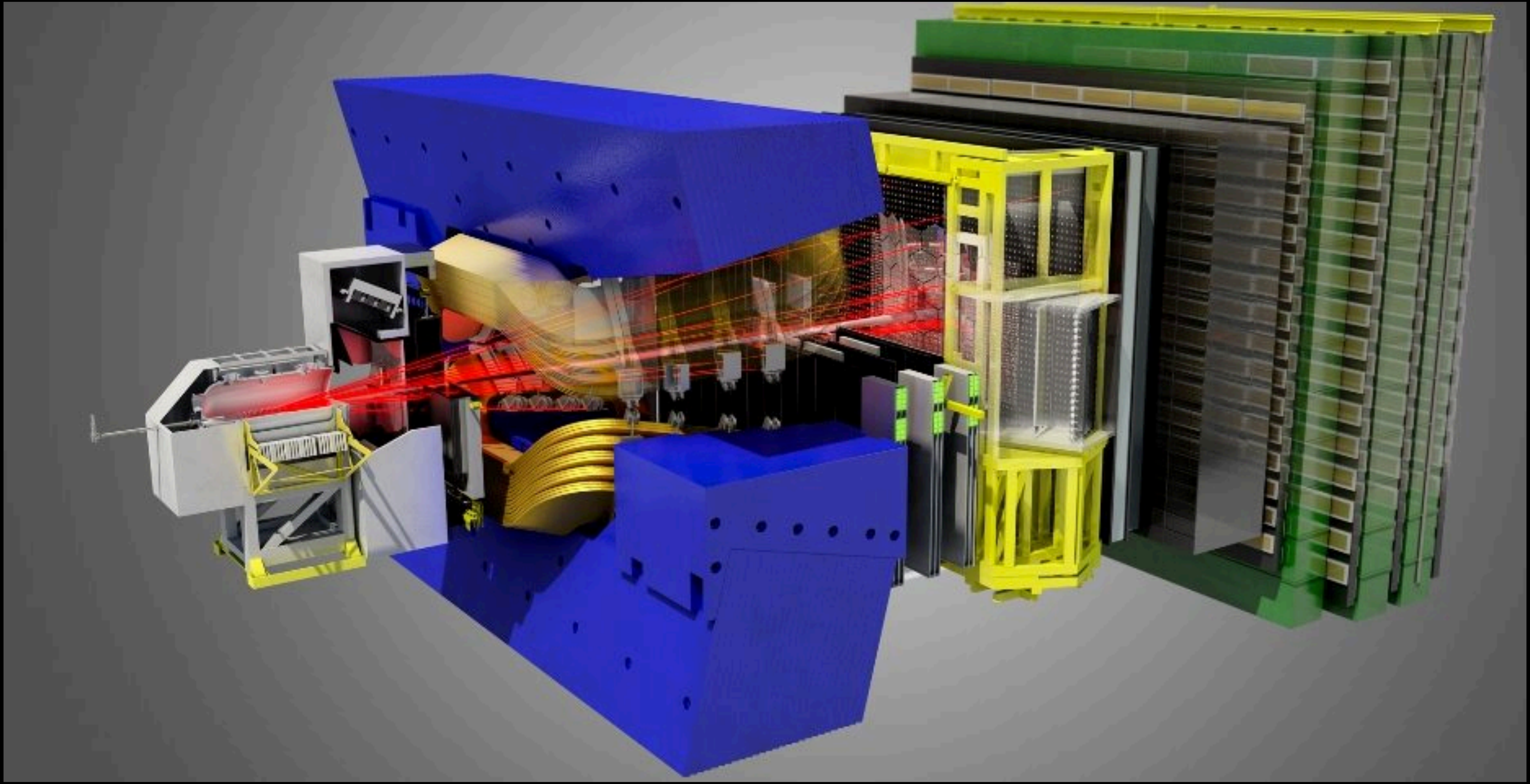




An LHC experiment — based on elements of a simple detector

Technical design of the LHCb detector





Design of the LHCb detector

What equation do we use most often in our analyses?

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

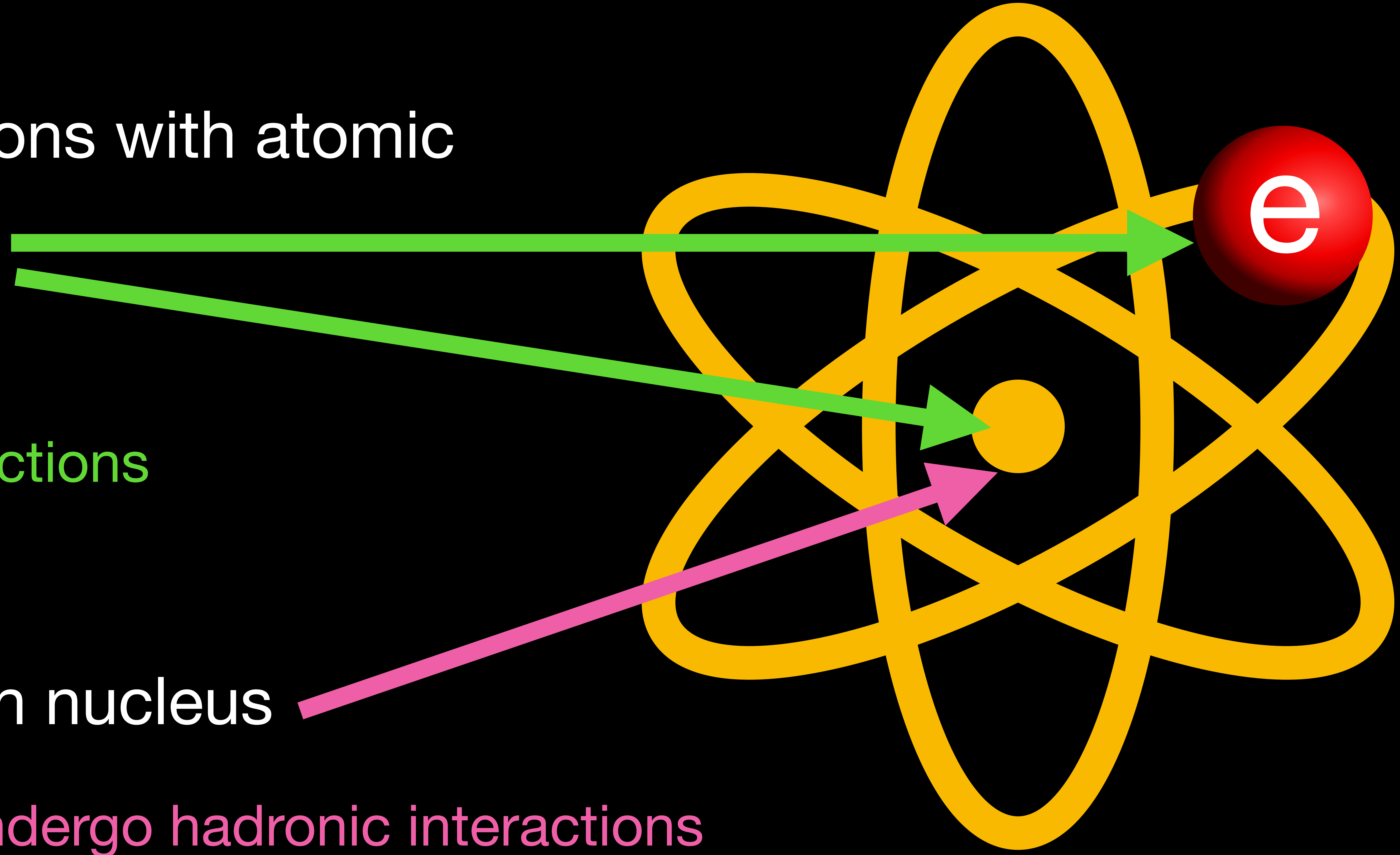
What have we learned so far

- Charged particles can be detected though 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

Two types of interaction



- Electromagnetic interactions with atomic electrons and nucleus

Photons, electrons and muons undergo electromagnetic interactions

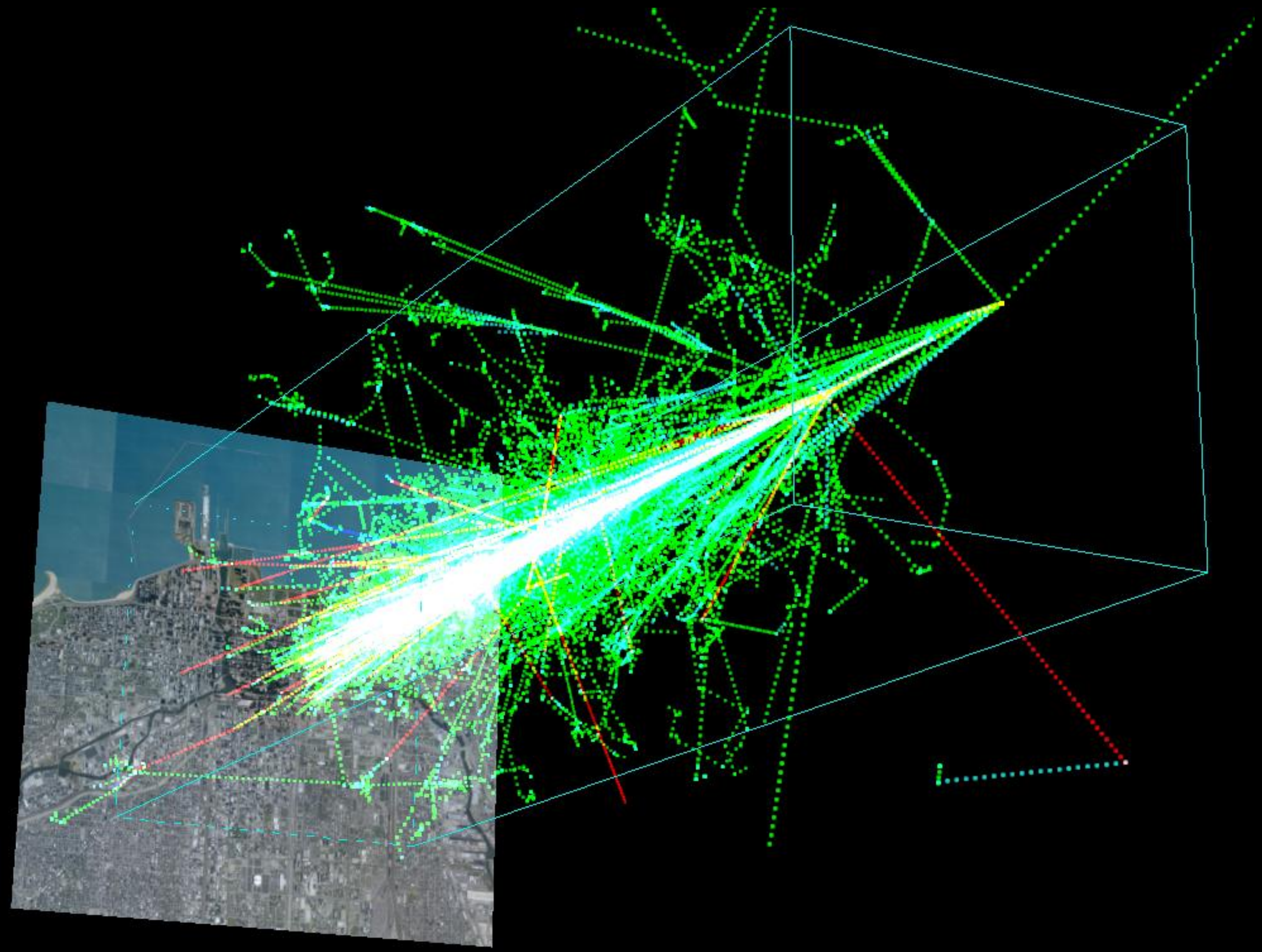
- Hadronic interactions with nucleus

Protons, neutrons and pions undergo hadronic interactions

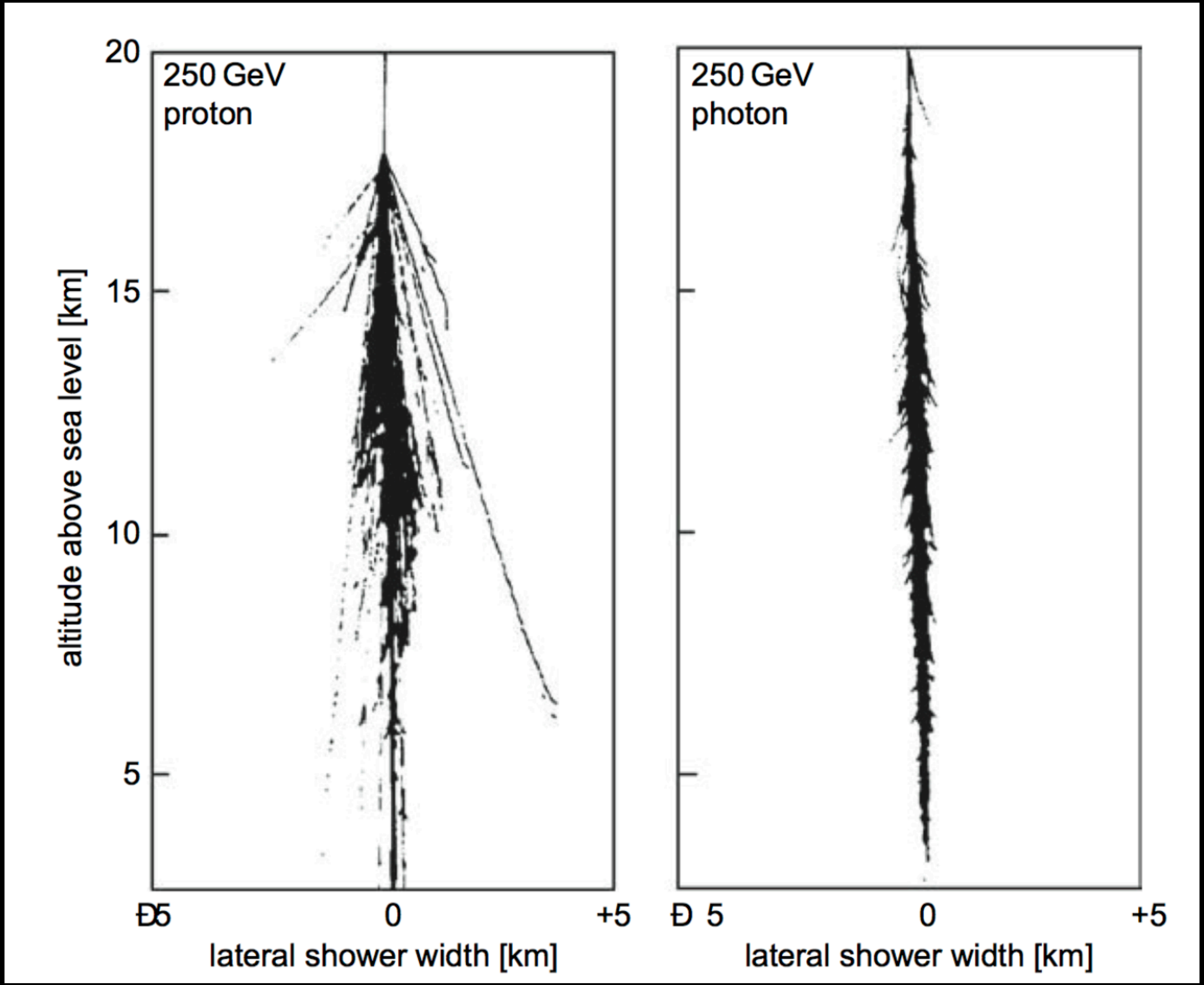
Hadronic interactions involve quarks and gluons and the strong force

Two types of showers

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

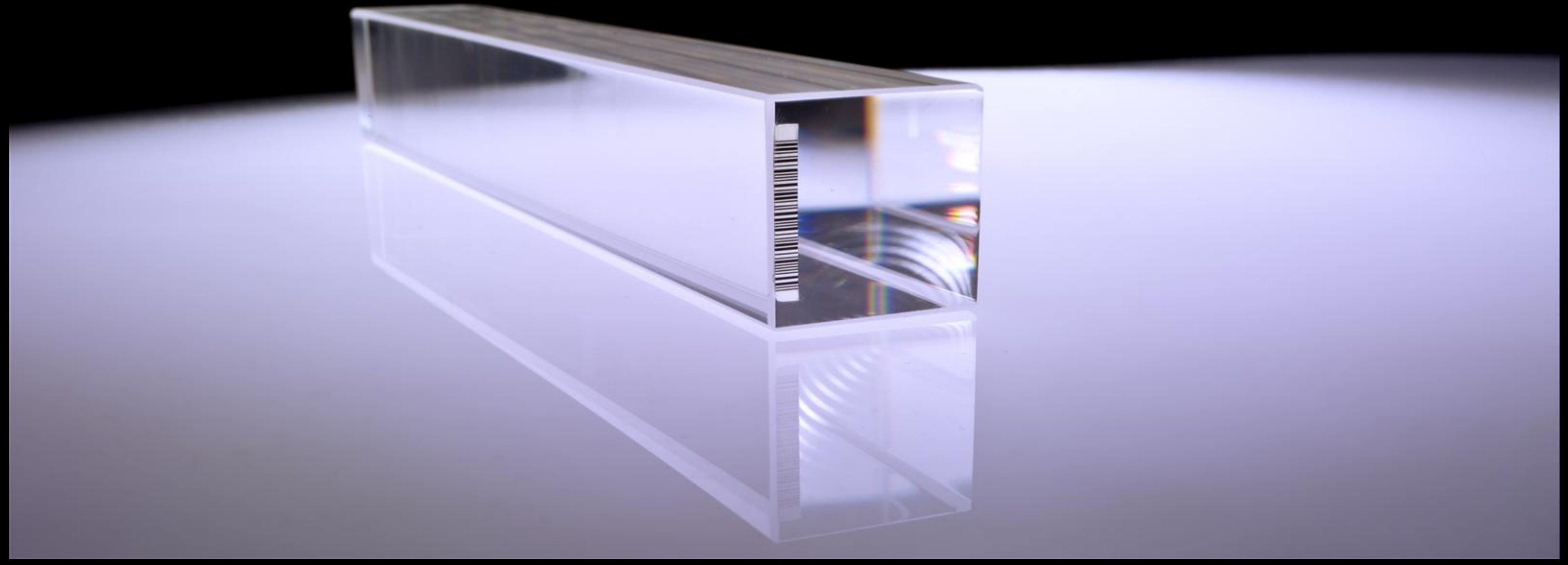


Two types of showers



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

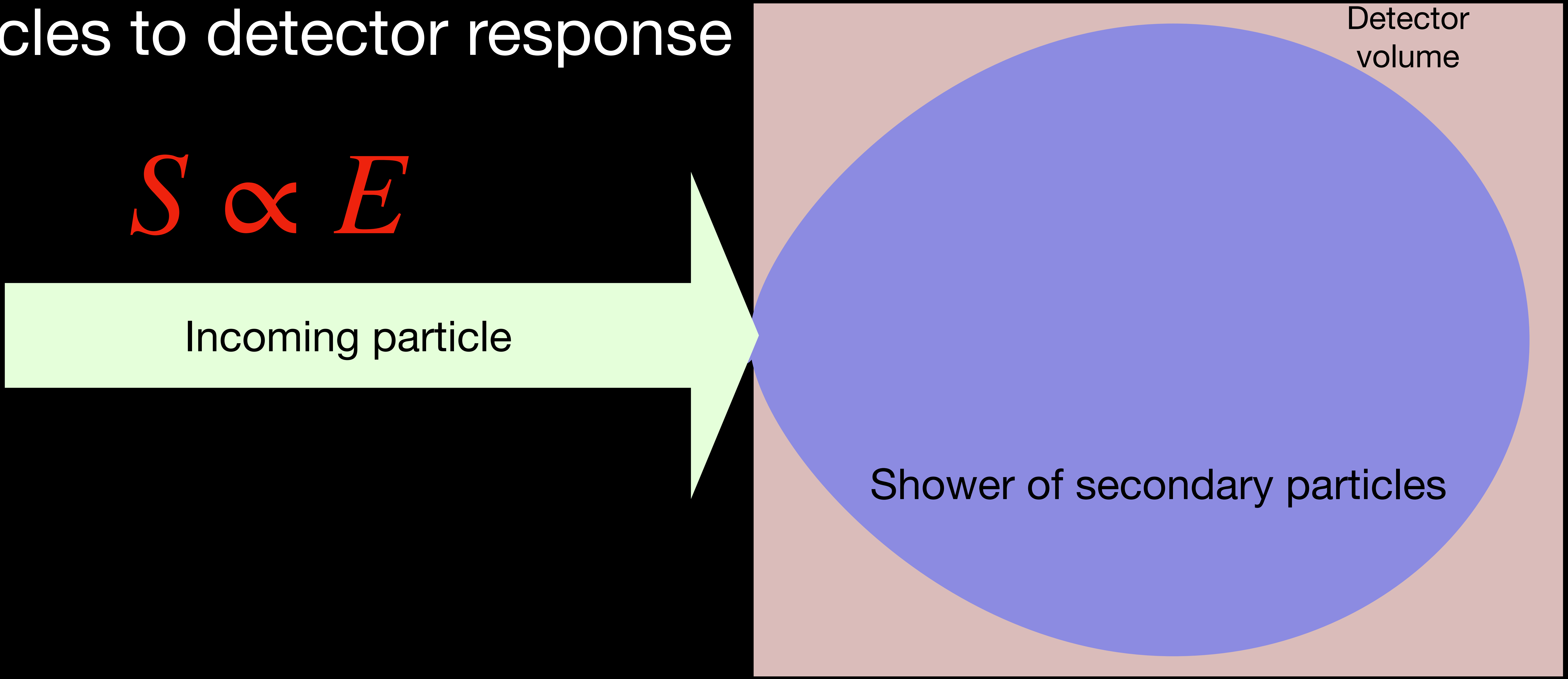


Electromagnetic calorimeter made with lead tungstate crystals

Homogeneous calorimeter

Convert energy E of incident particles to detector response

$$S \propto E$$

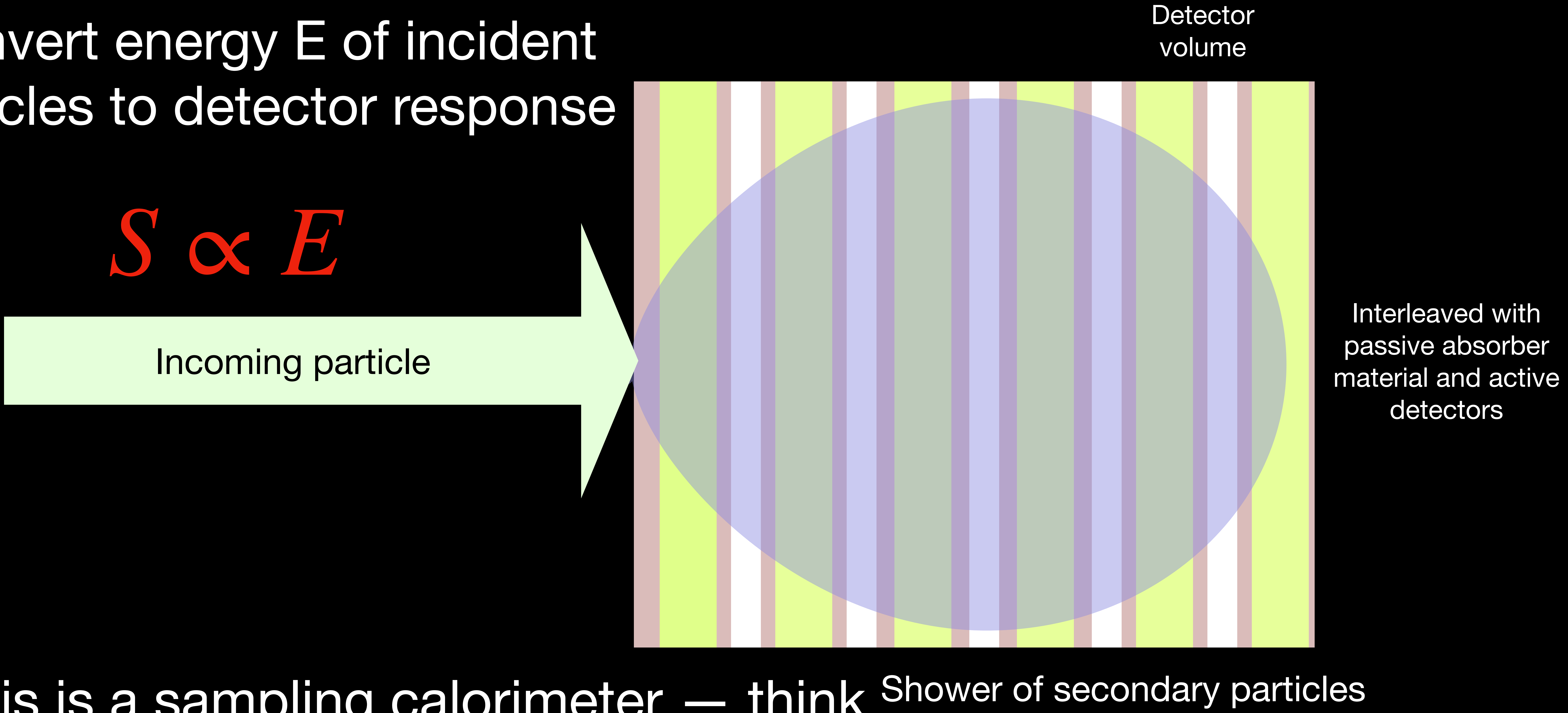


This is a homogenous calorimeter — think of lead tungstate ECAL in CMS

Sampling calorimeter

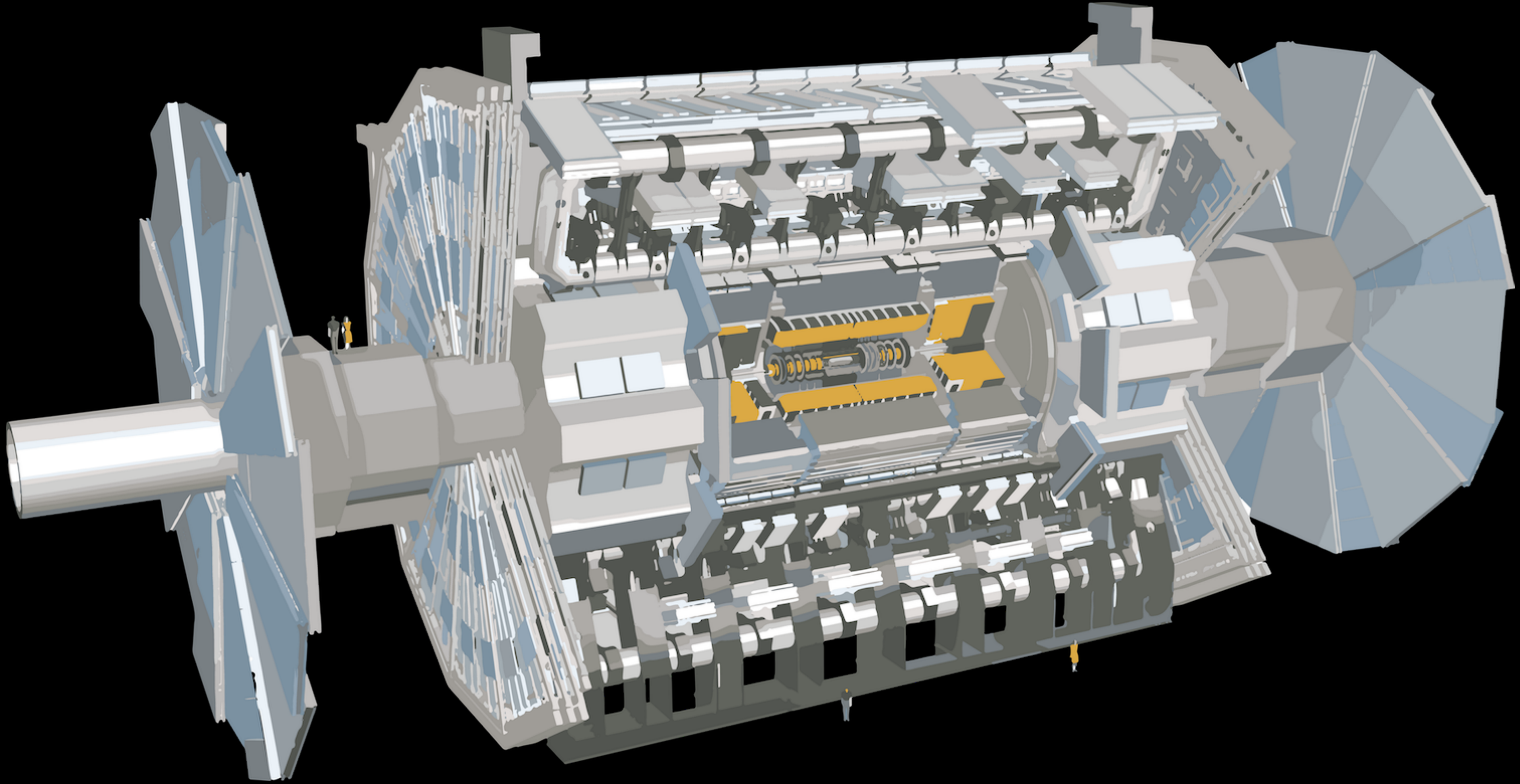
Convert energy E of incident particles to detector response

$$S \propto E$$

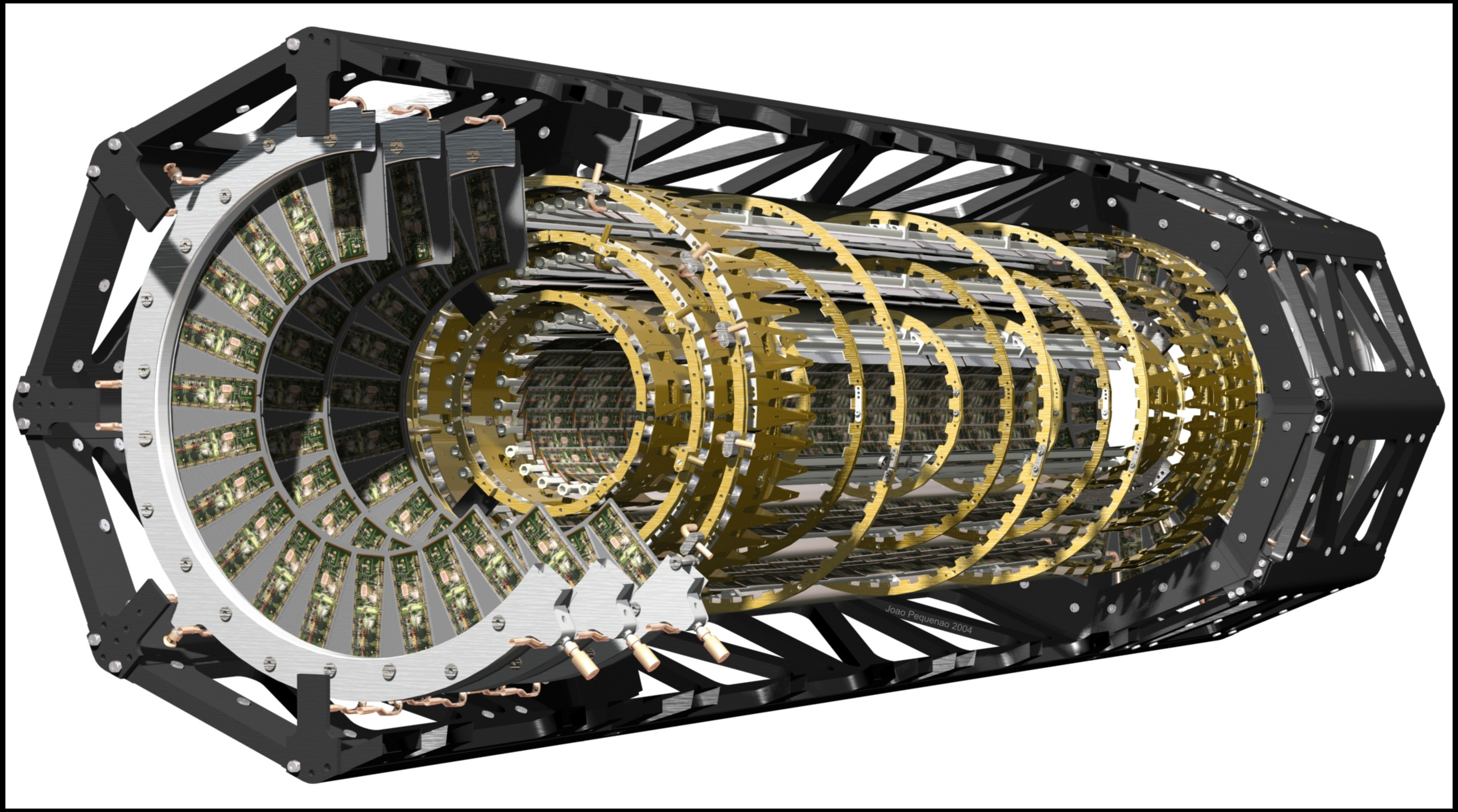


This is a sampling calorimeter — think of HighGranularity Calorimeter in CMS

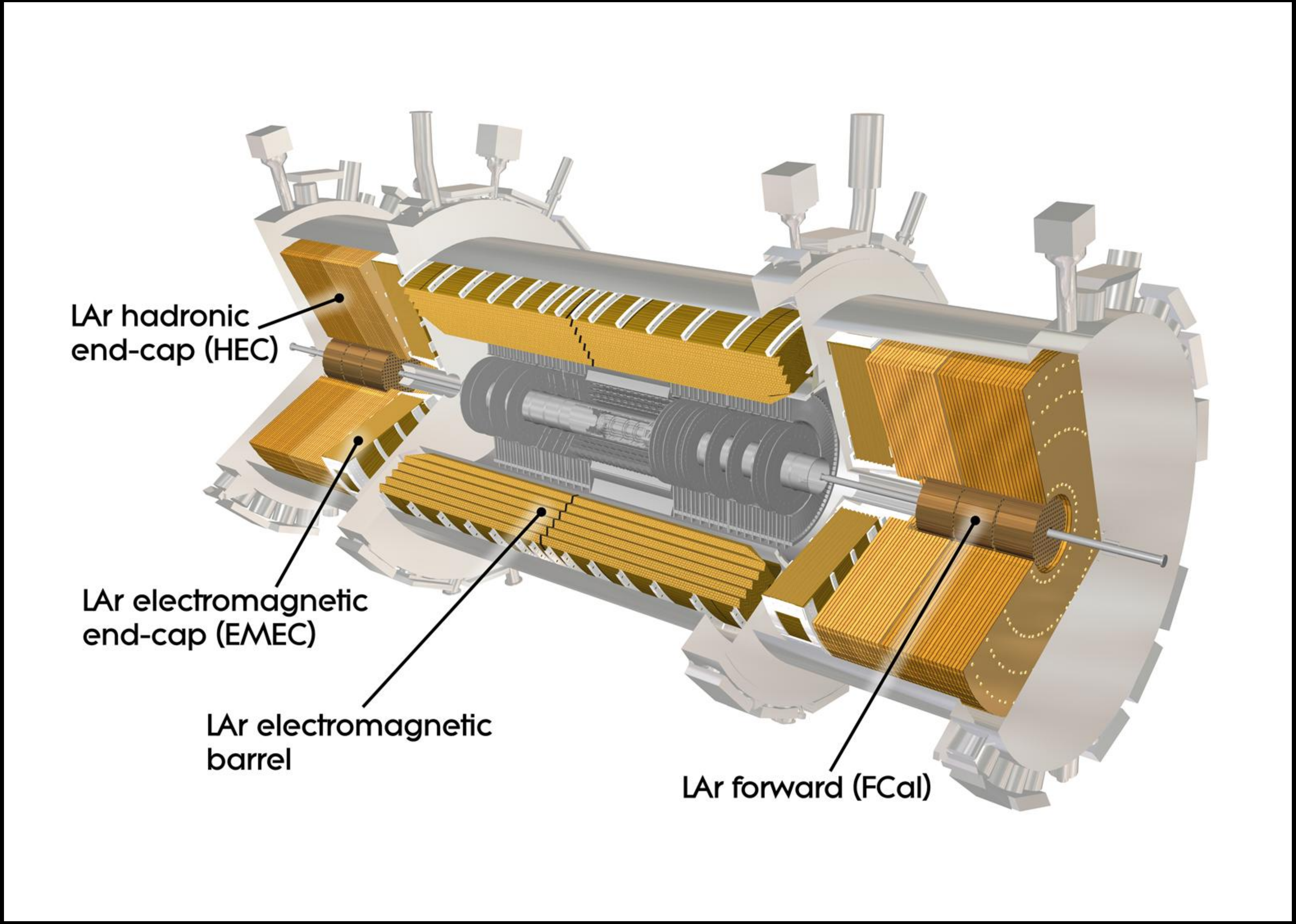
Focusing on the ATLAS detector



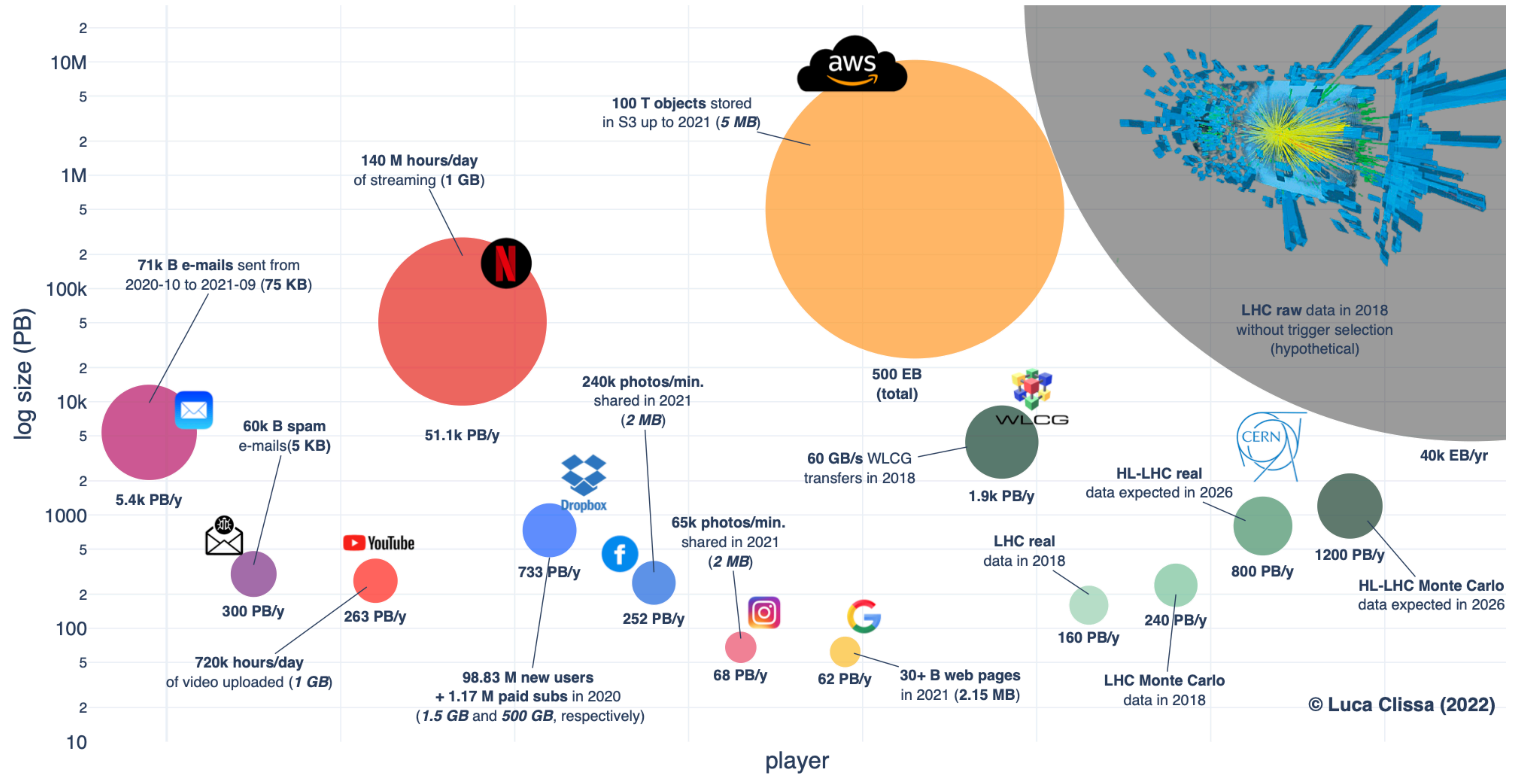
Inner detector — the tracker

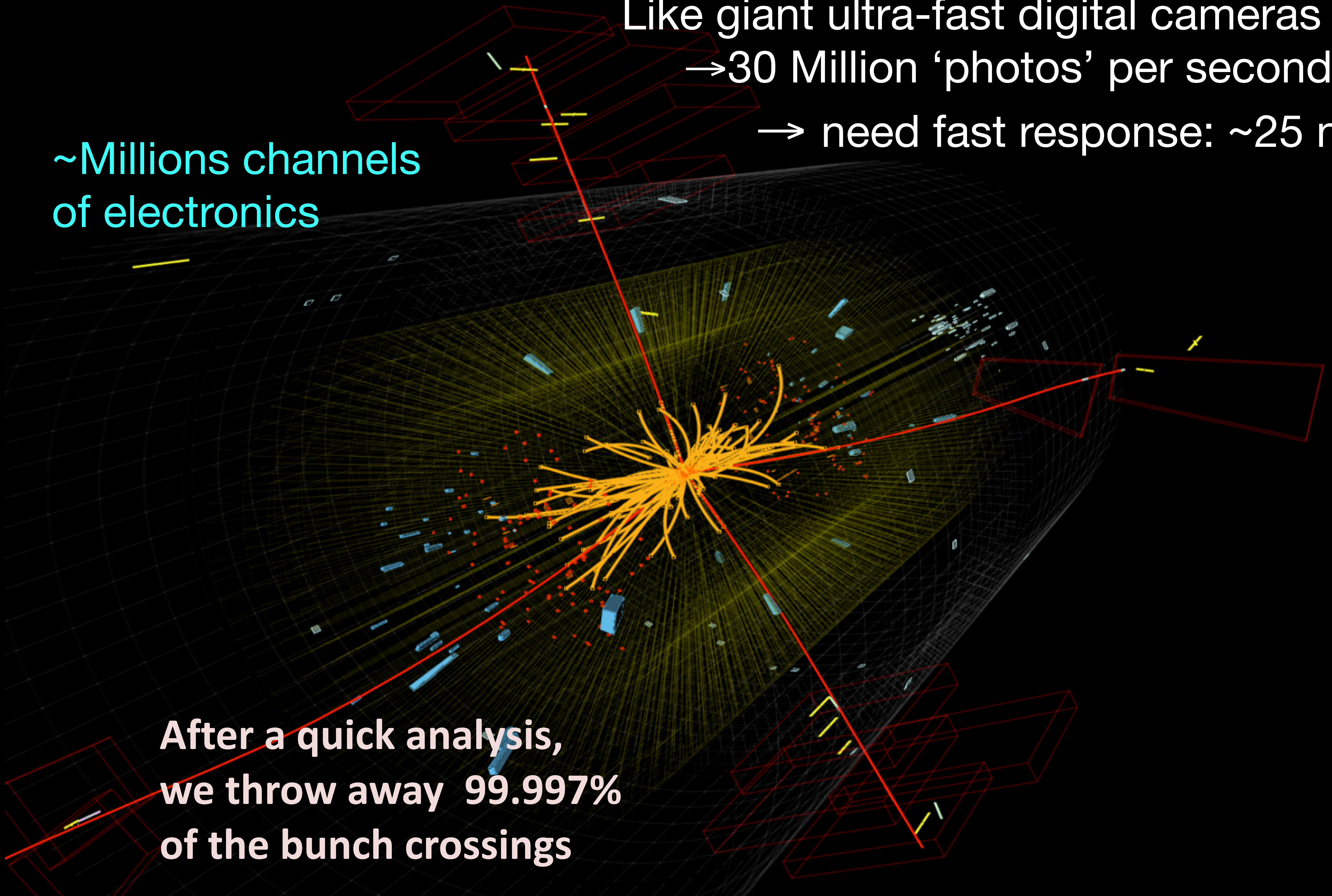


Calorimeters



Data Collection





Like giant ultra-fast digital cameras

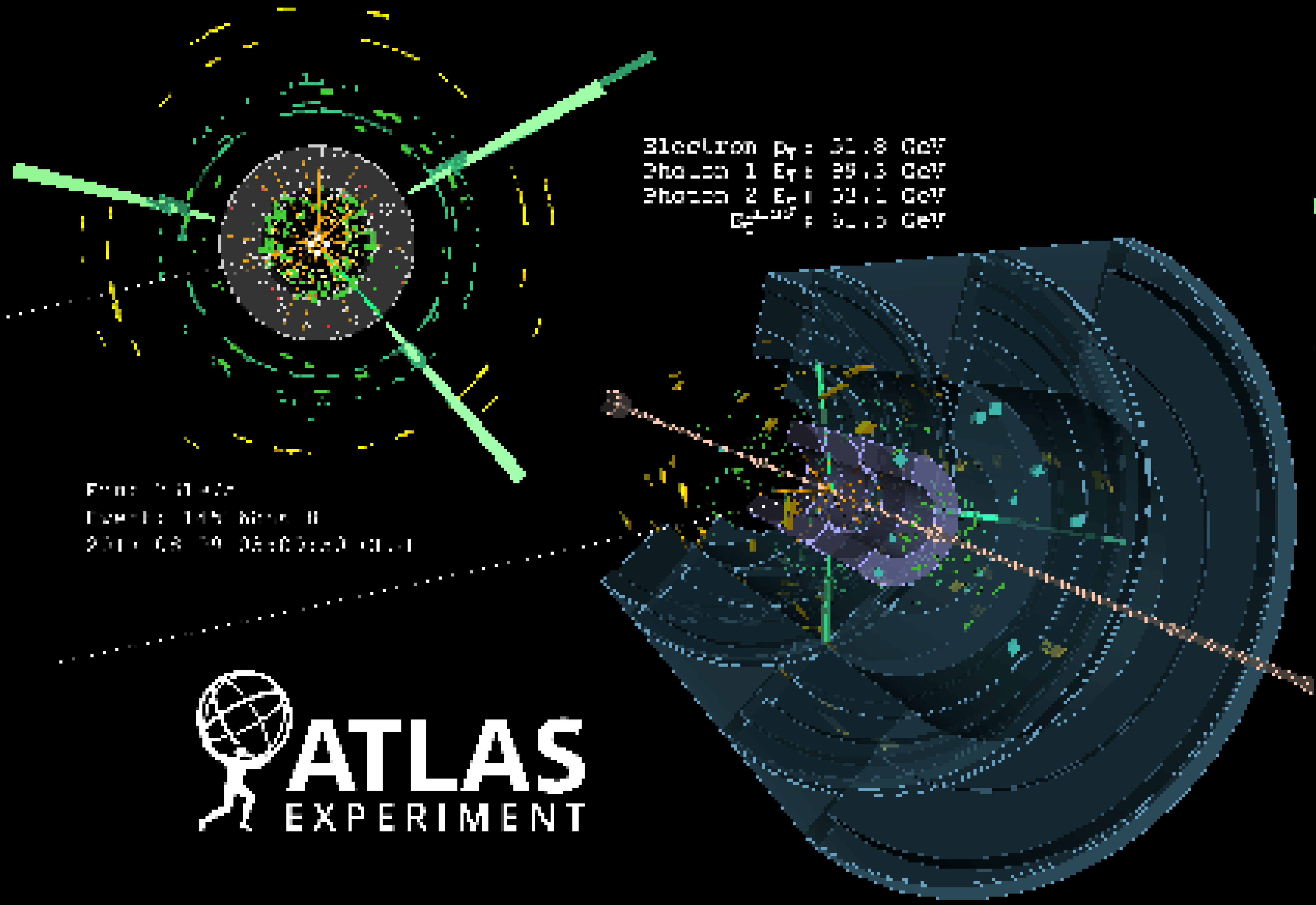
→30 Million ‘photos’ per second

→ need fast response: ~25 ns

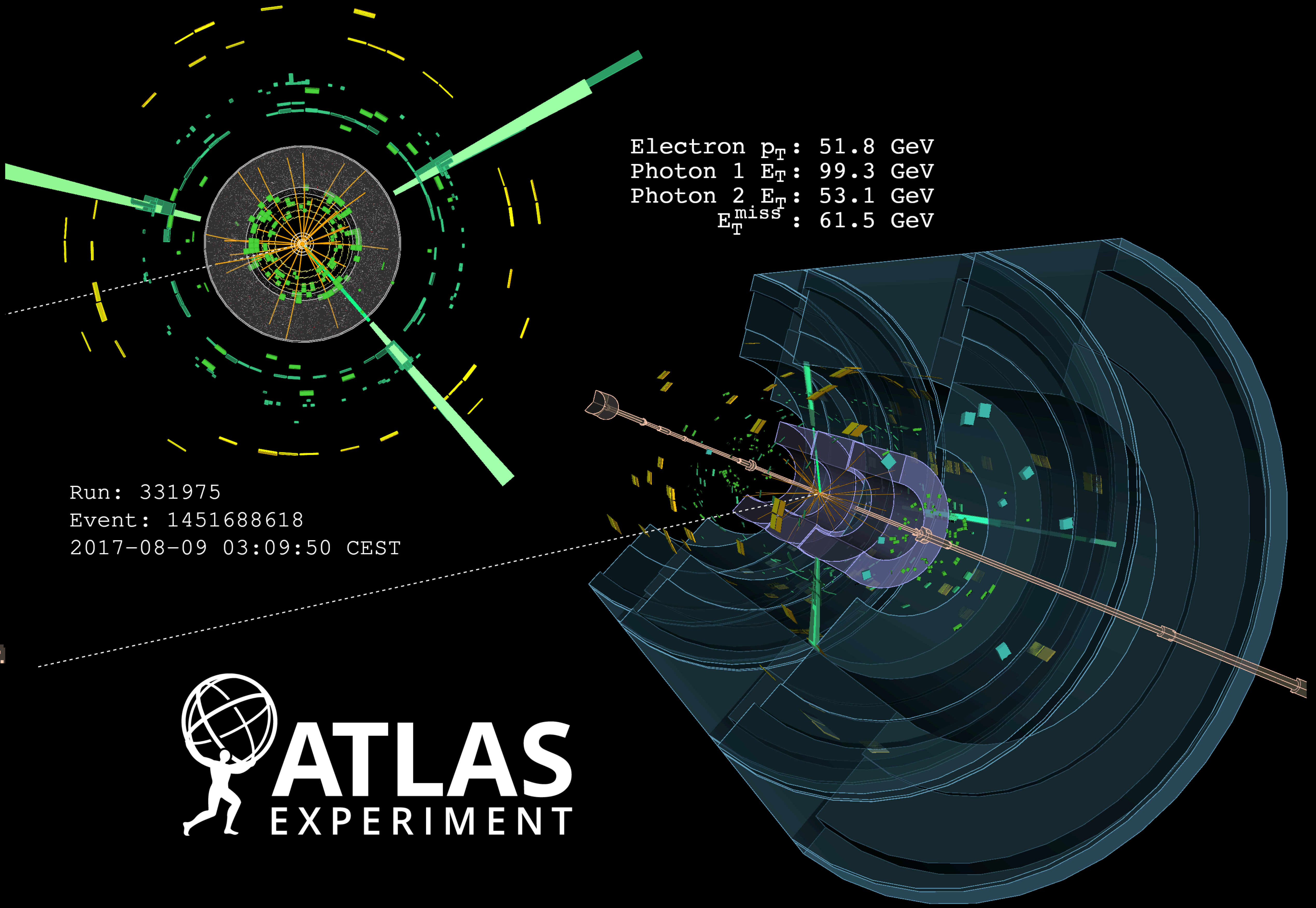
~Millions channels
of electronics

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

Trigger



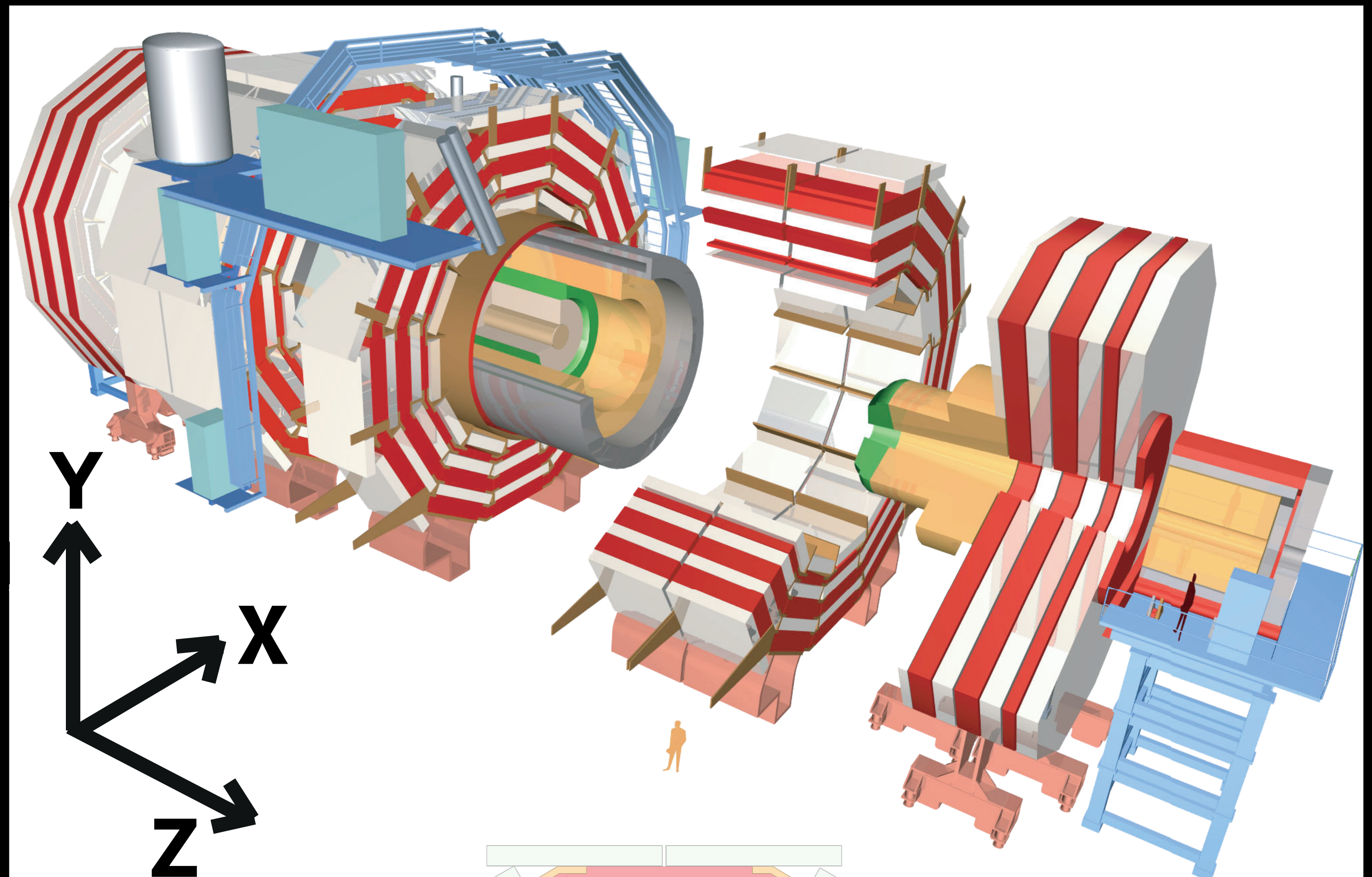
ATLAS
EXPERIMENT

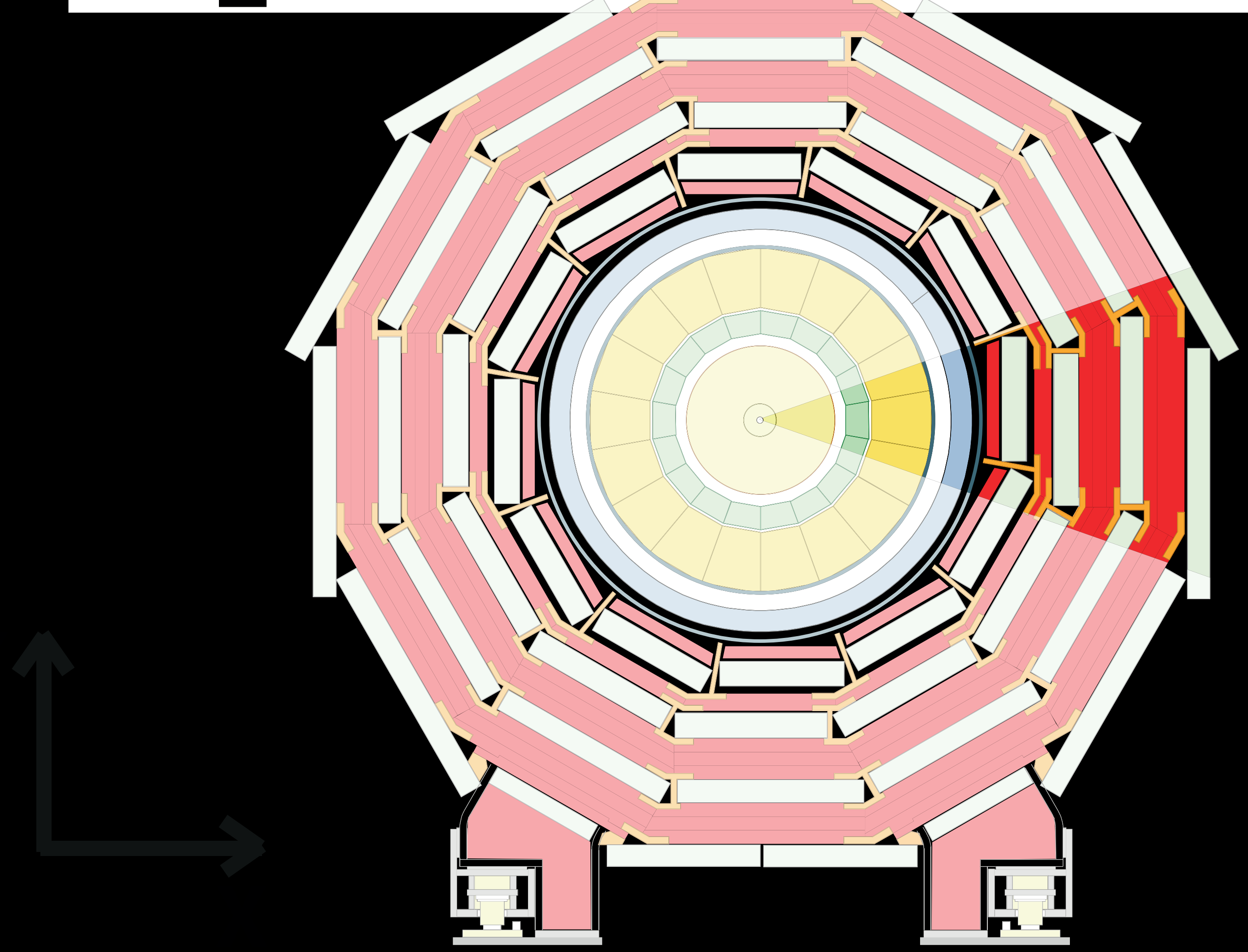


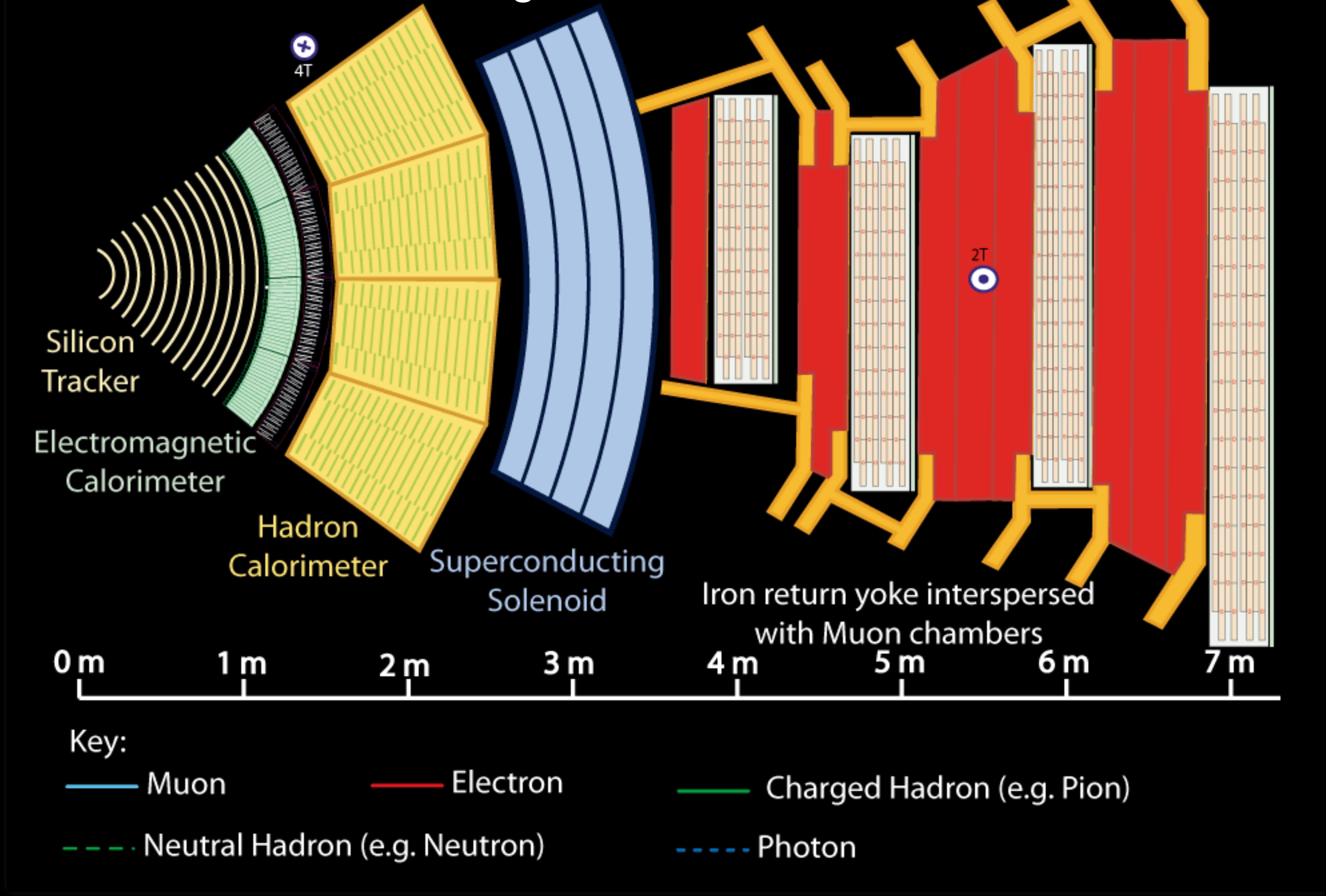
Electron p_T: 51.8 GeV
Photon 1 E_T: 99.3 GeV
Photon 2 E_T: 53.1 GeV
E_T^{miss}: 61.5 GeV
Run: 331975
Event: 1451688618
2017-08-09 03:09:50 CEST
ATLAS
EXPERIMENT

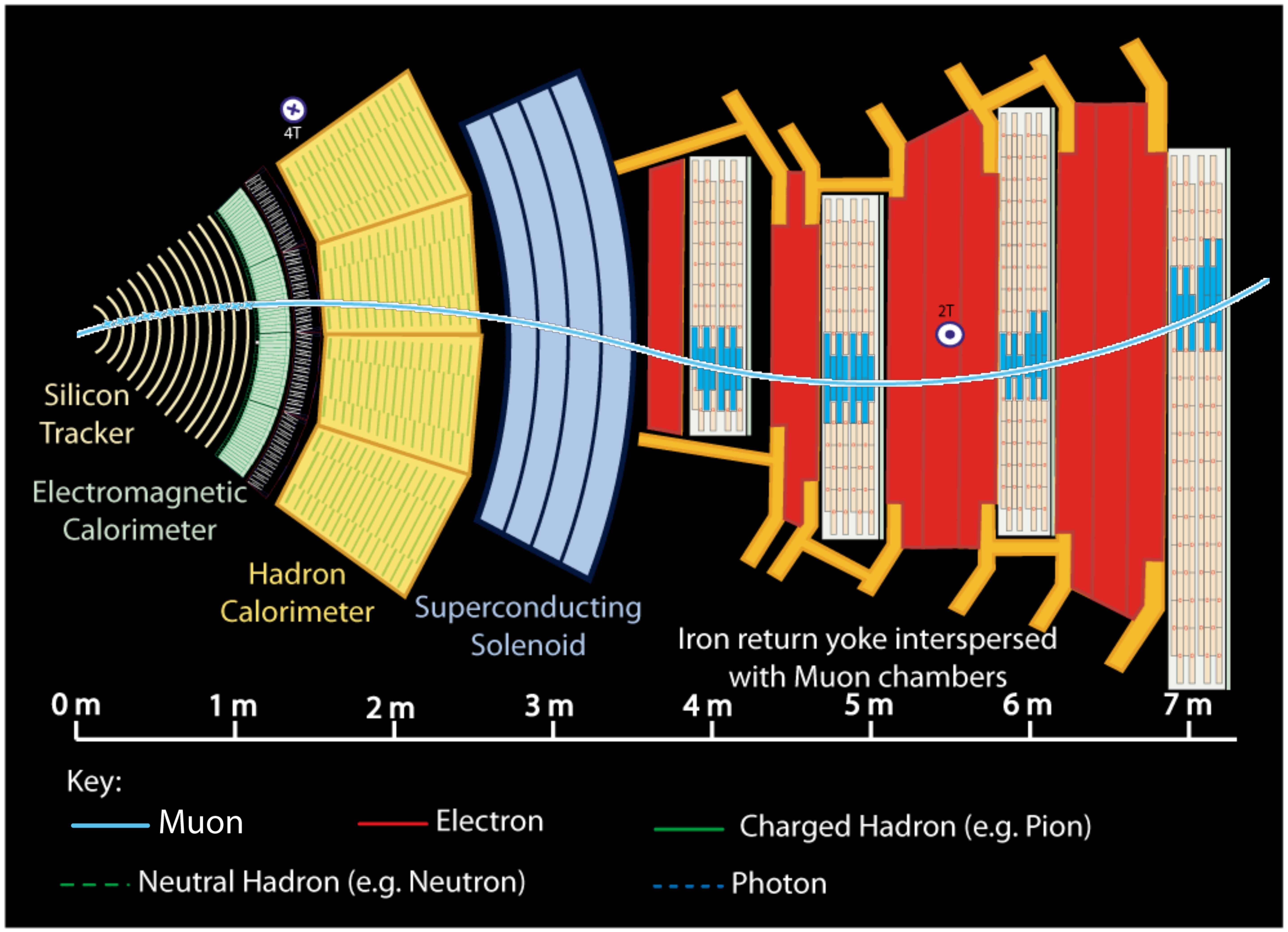

Muon Spectrometer
Hadronic Calorimeter (TileCal)
Electromagnetic Calorimeter (Liquid Argon)
Solenoid Magnet
Tracking
Transition Radiation Tracker
Pixel & Silicon-Strip Detectors
Beampipe

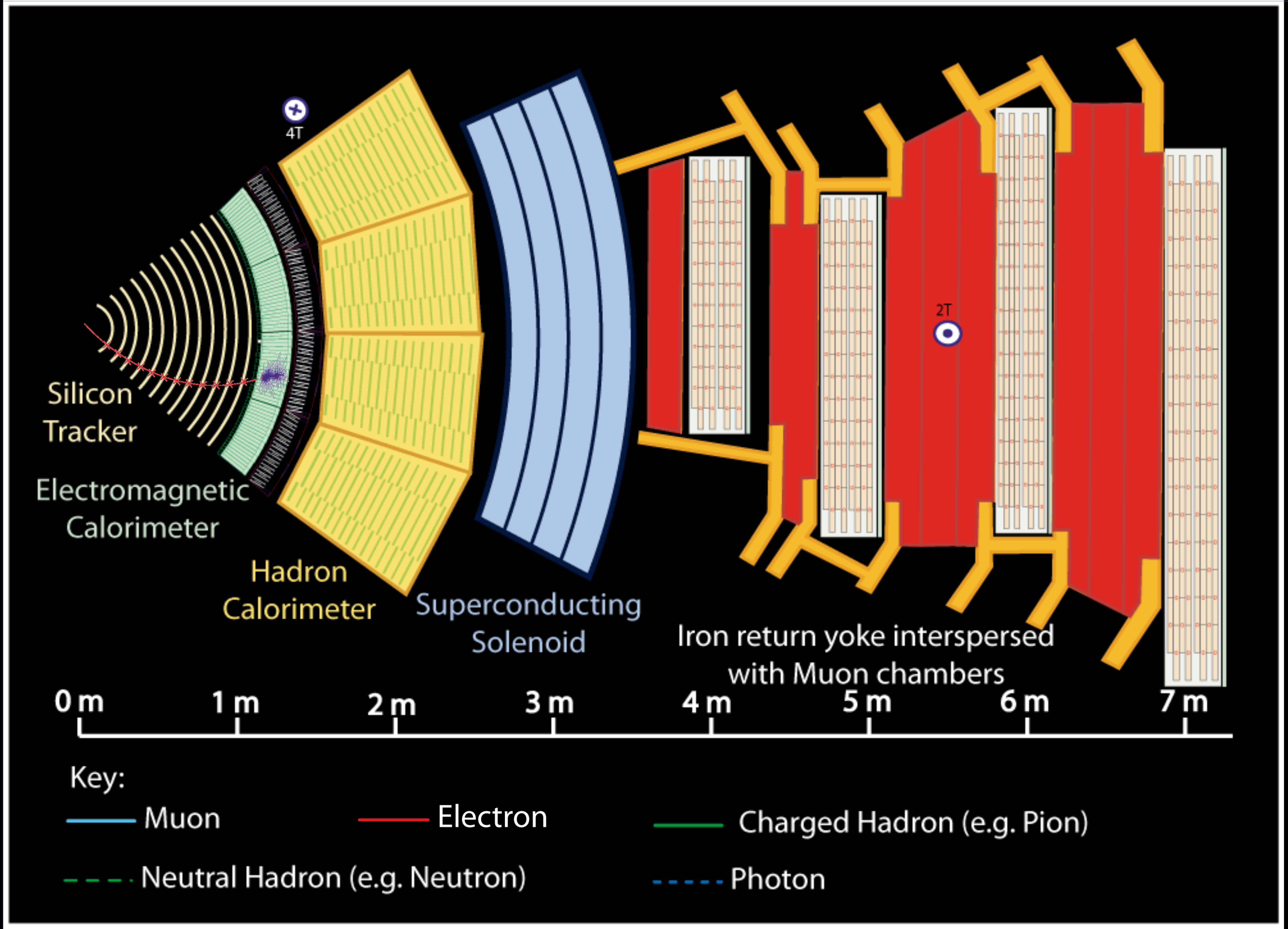
- Weight: 14,000 Tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T








4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
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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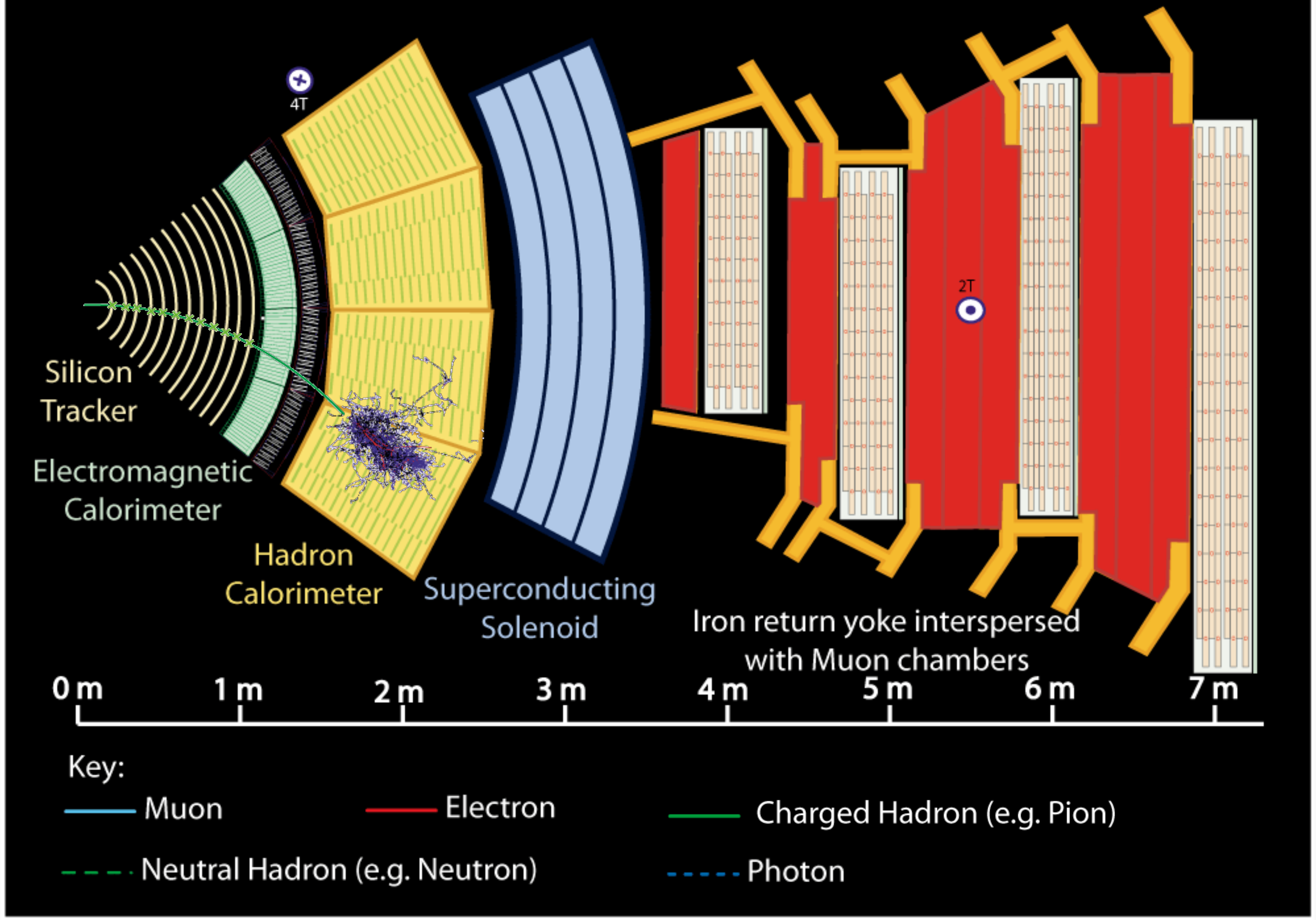
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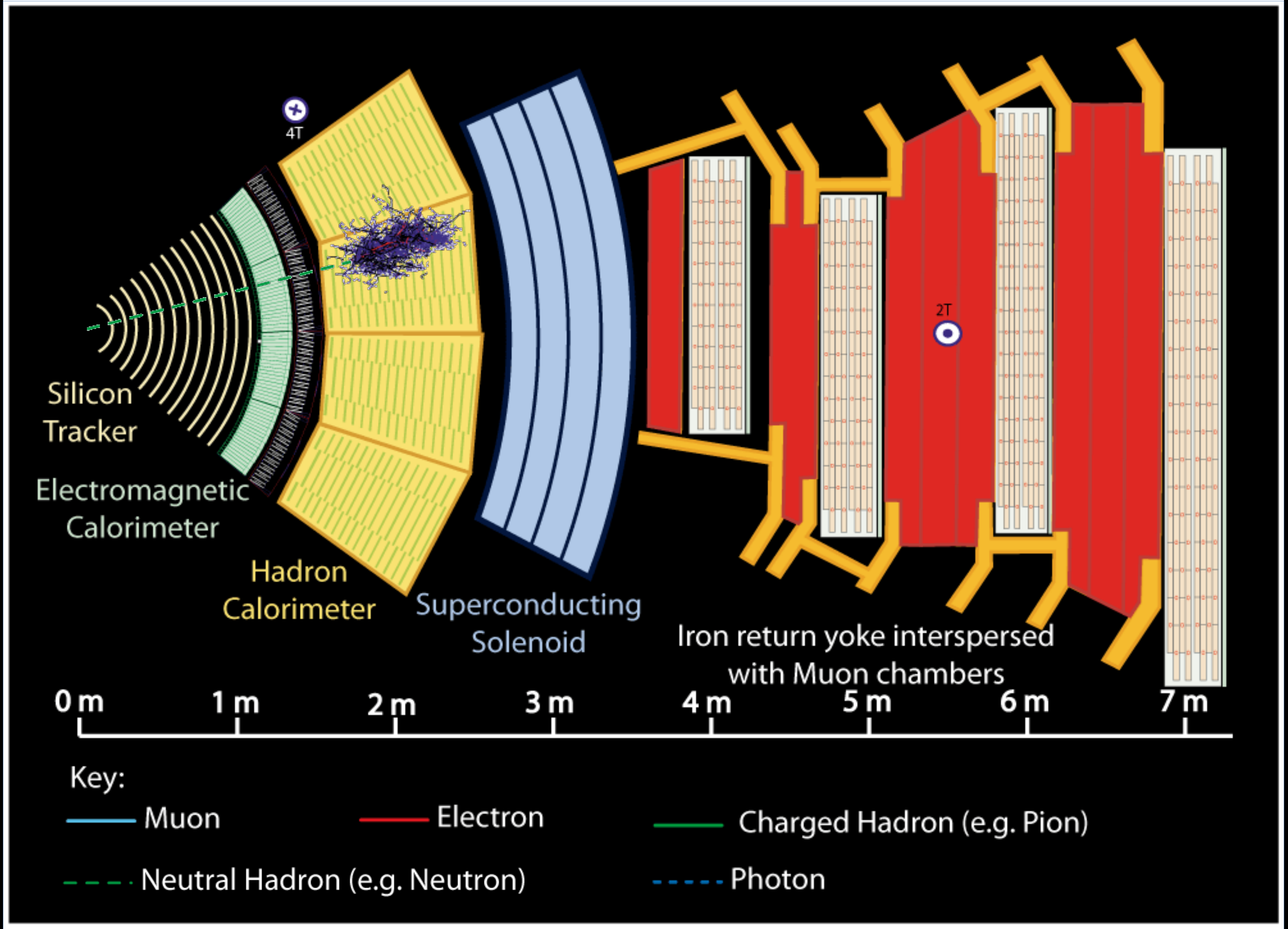
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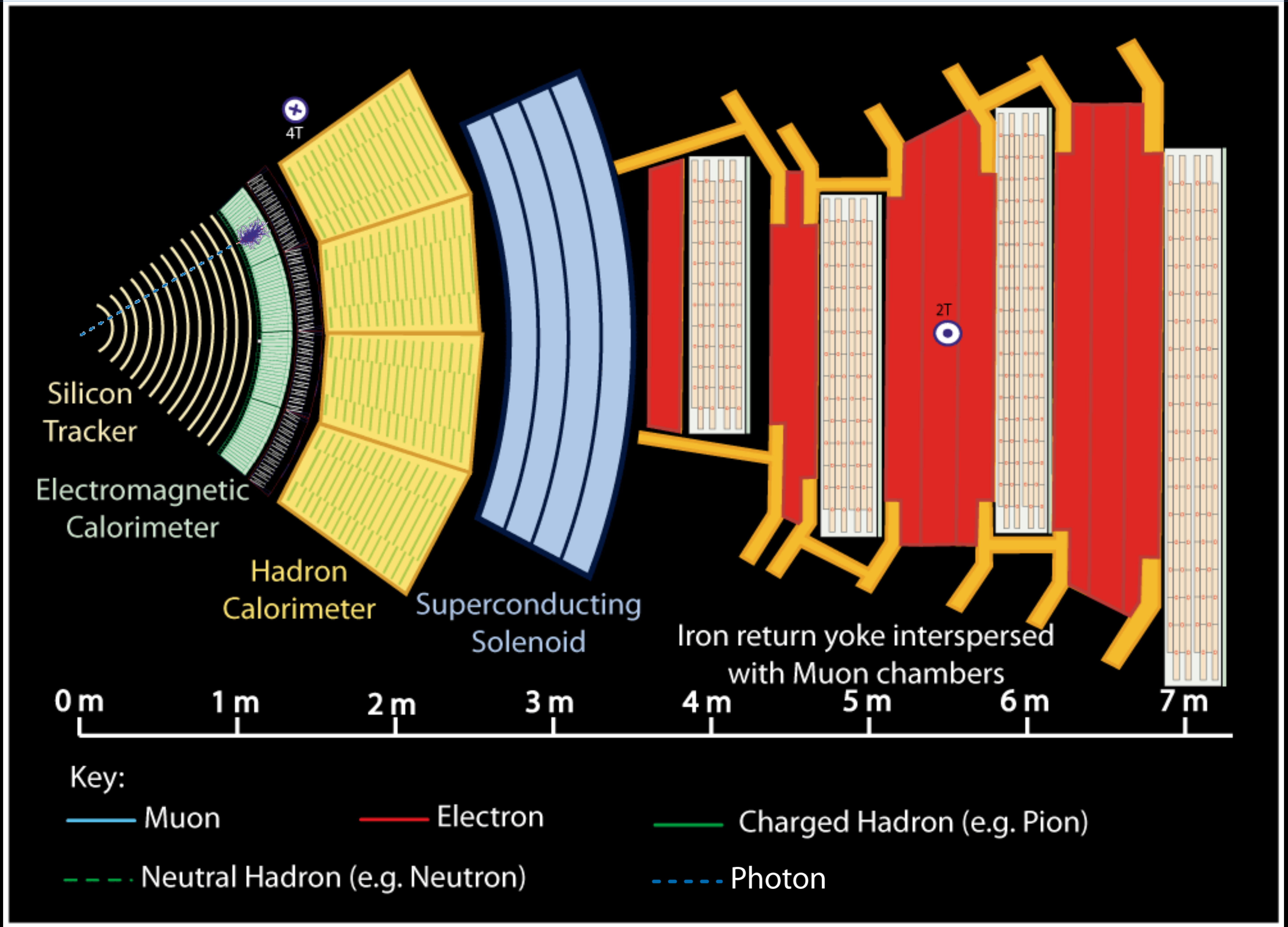
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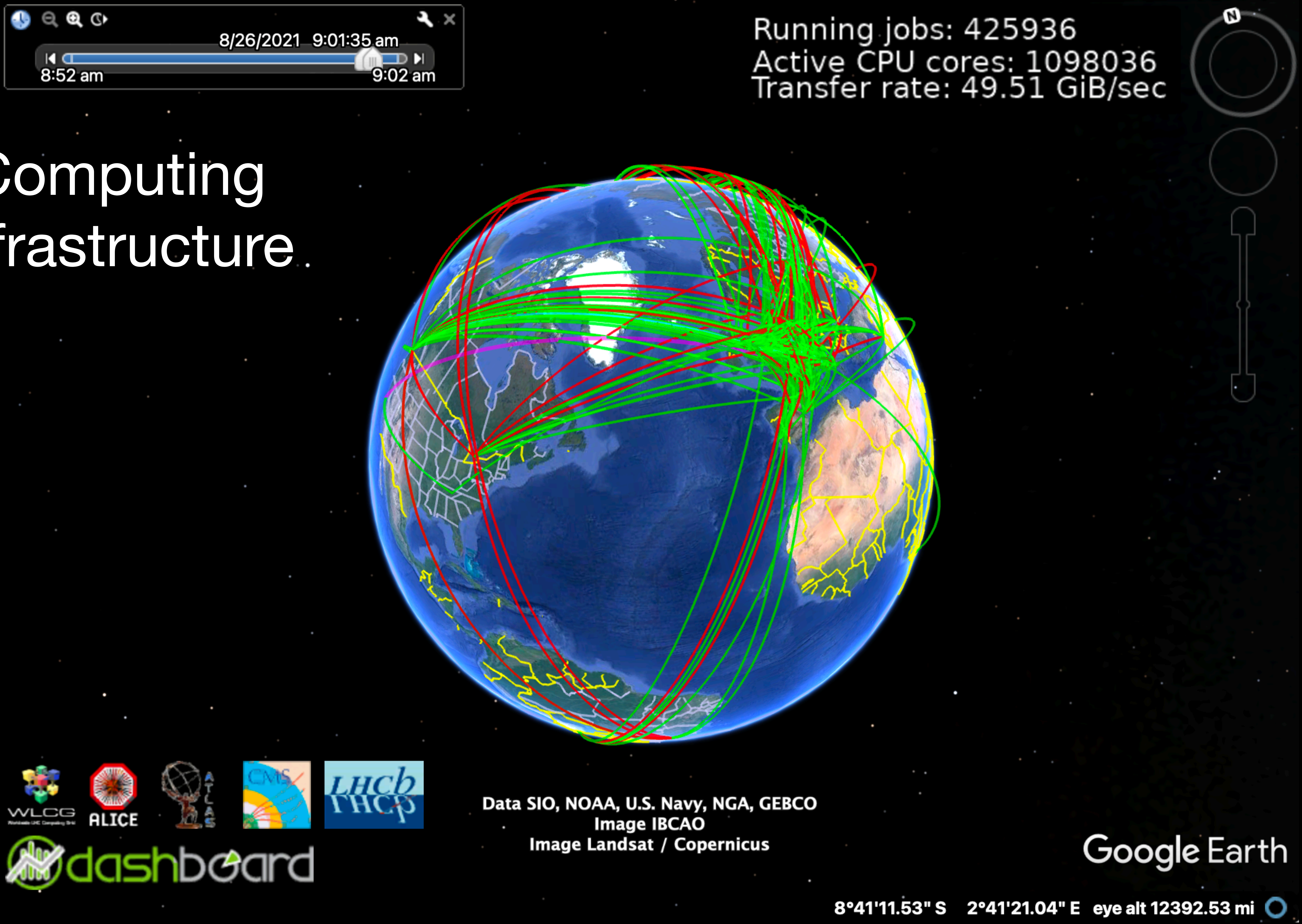
Neutral Hadron (e.g. Neutron)
Photon

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

Computing infrastructure

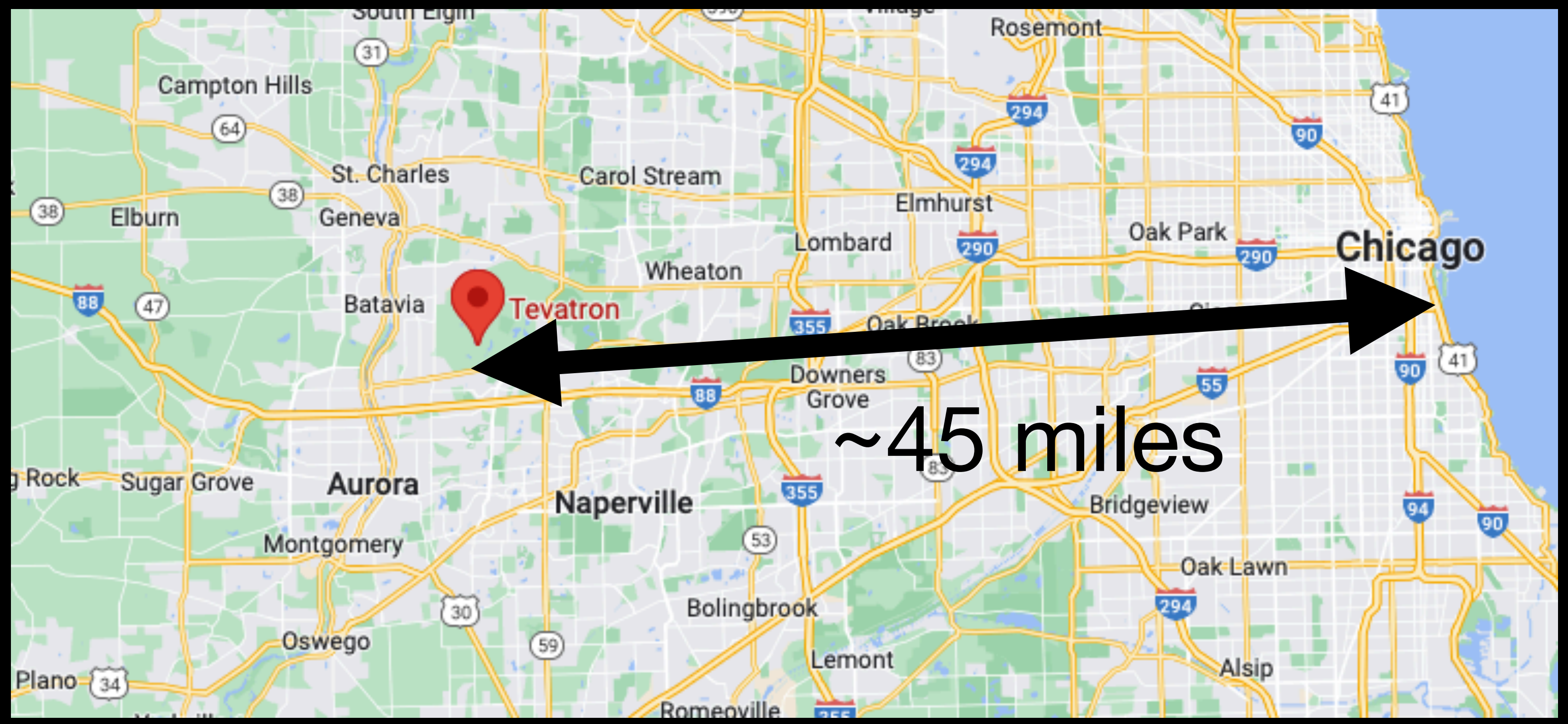


Running jobs: 425936
Active CPU cores: 1098036
Transfer rate: 49.51 GiB/sec

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

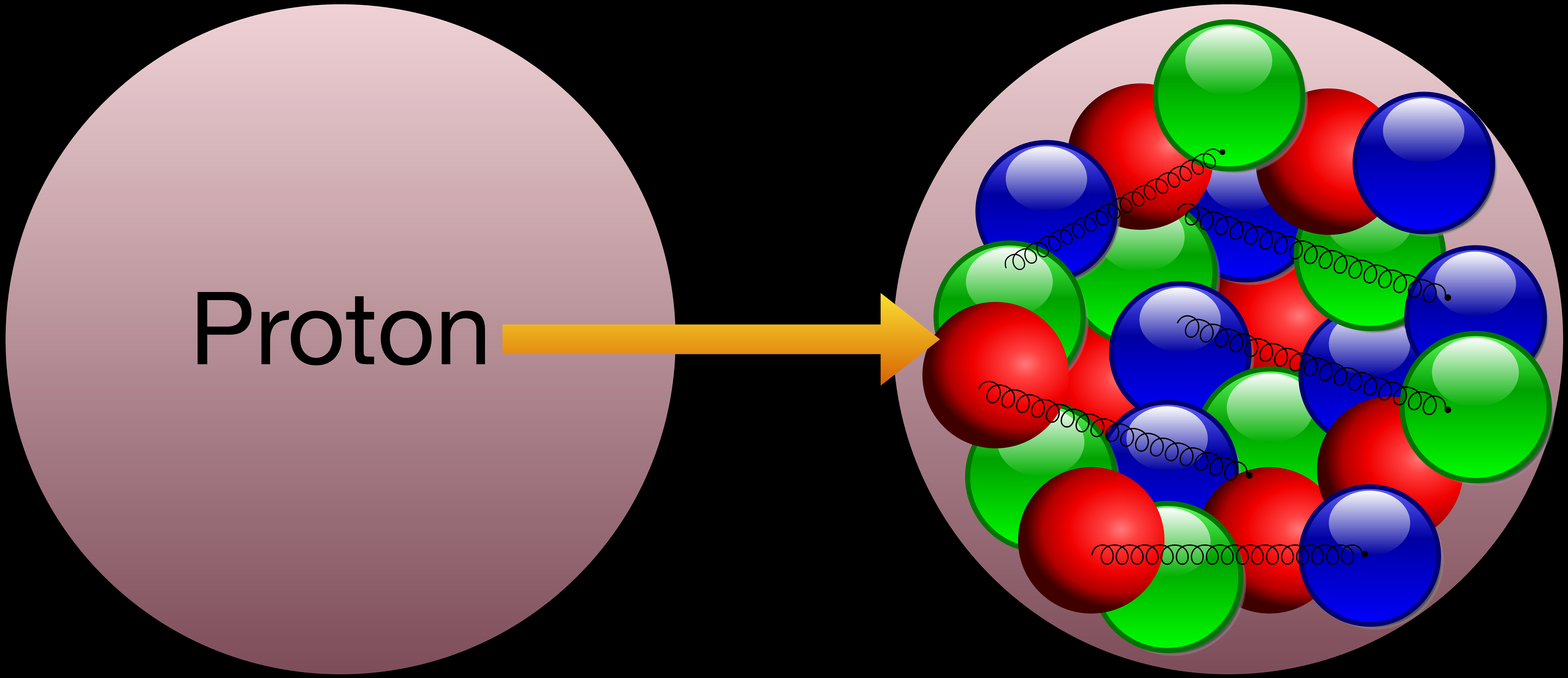
- What would guide our intuition as to how massive is the Higgs?
  - We have not observed the Higgs in previous experiments → not light
  - We know from the Tevatron that the mass of the Higgs boson lies between 115 and 135 GeV
    - $115 < m_H < 135$ GeV
  - For comparison, the mass of the proton is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



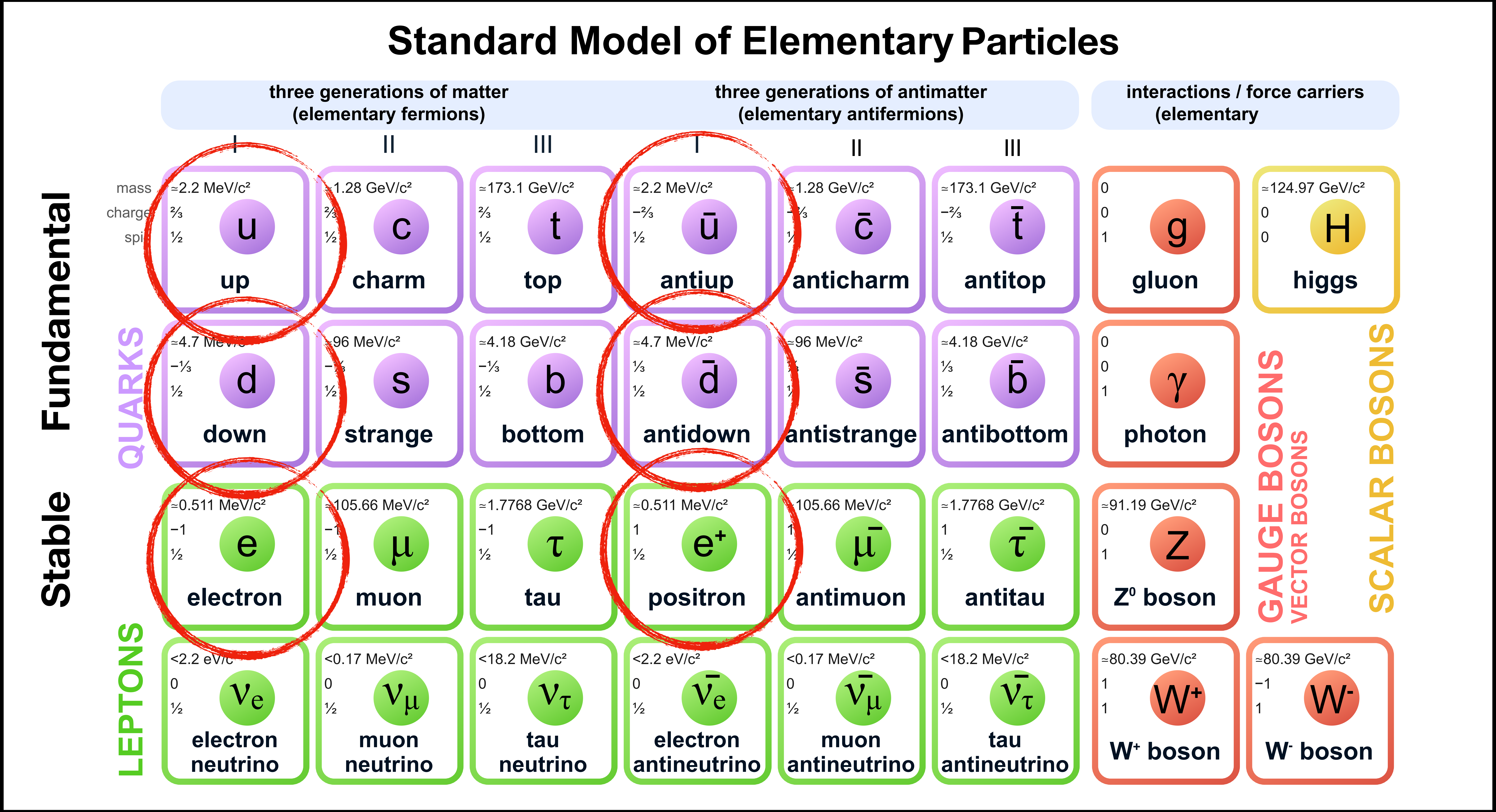
How to produce particles through annihilation?

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 charge spin	≈2.2 MeV/c² ⅔ ½ u up	≈1.28 GeV/c² ⅔ ½ c charm	≈173.1 GeV/c² ⅔ ½ t top	≈2.2 MeV/c² −⅔ ½ $\bar{u}$ antiup	≈1.28 GeV/c² −⅔ ½ $\bar{c}$ anticharm	≈173.1 GeV/c² −⅔ ½ $\bar{t}$ antitop	0 0 1 g gluon	≈124.97 GeV/c² 0 0 H higgs
		≈4.7 MeV/c² −⅓ ½ d down	≈96 MeV/c² −⅓ ½ s strange	≈4.18 GeV/c² −⅓ ½ b bottom	≈4.7 MeV/c² ⅓ ½ $\bar{d}$ antidown	≈96 MeV/c² ⅓ ½ $\bar{s}$ antistrange	≈4.18 GeV/c² ⅓ ½ $\bar{b}$ antibottom	0 0 1 γ photon	
Stable	LEPTONS	≈0.511 MeV/c² −1 ½ e electron	≈105.66 MeV/c² −1 ½ μ muon	≈1.7768 GeV/c² −1 ½ τ tau	≈0.511 MeV/c² 1 ½ e^+ positron	≈105.66 MeV/c² 1 ½ $\bar{\mu}$ antimuon	≈1.7768 GeV/c² 1 ½ $\bar{\tau}$ antitau	≈91.19 GeV/c² 0 1 Z Z^0 boson	
		<2.2 eV/c² 0 ½ ν_e electron neutrino	<0.17 MeV/c² 0 ½ ν_μ muon neutrino	<18.2 MeV/c² 0 ½ ν_τ tau neutrino	<2.2 eV/c² 0 ½ $\bar{\nu}_e$ electron antineutrino	<0.17 MeV/c² 0 ½ $\bar{\nu}_\mu$ muon antineutrino	<18.2 MeV/c² 0 ½ $\bar{\nu}_\tau$ tau antineutrino	≈80.39 GeV/c² 1 1 W^+ W^+ boson	≈80.39 GeV/c² −1 1 W^- W^- boson

GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS

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

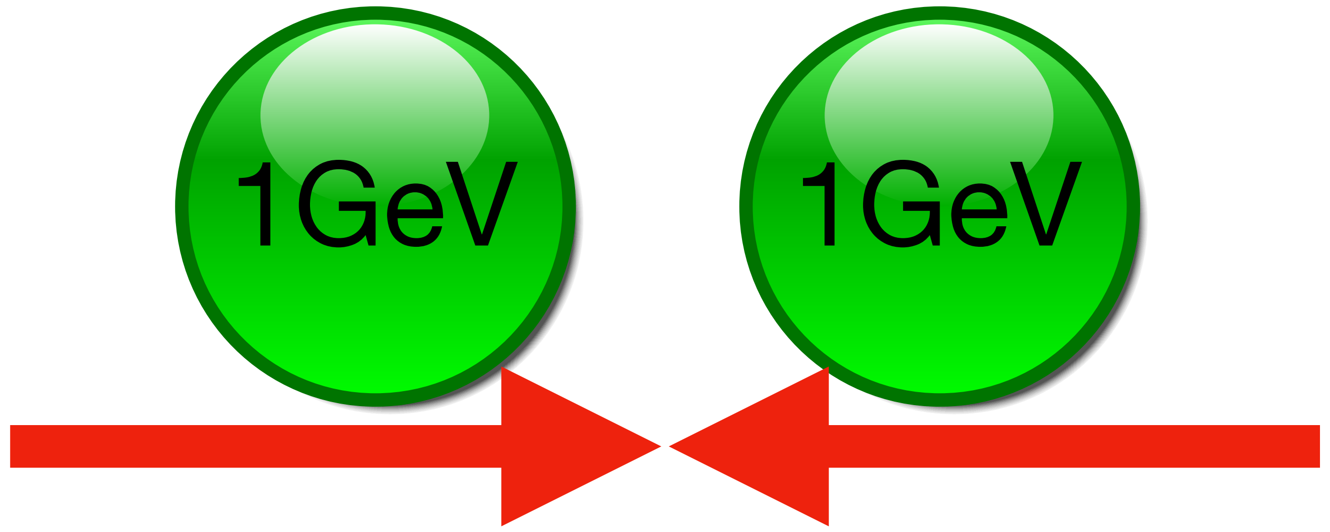
$$E = mc^2$$

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

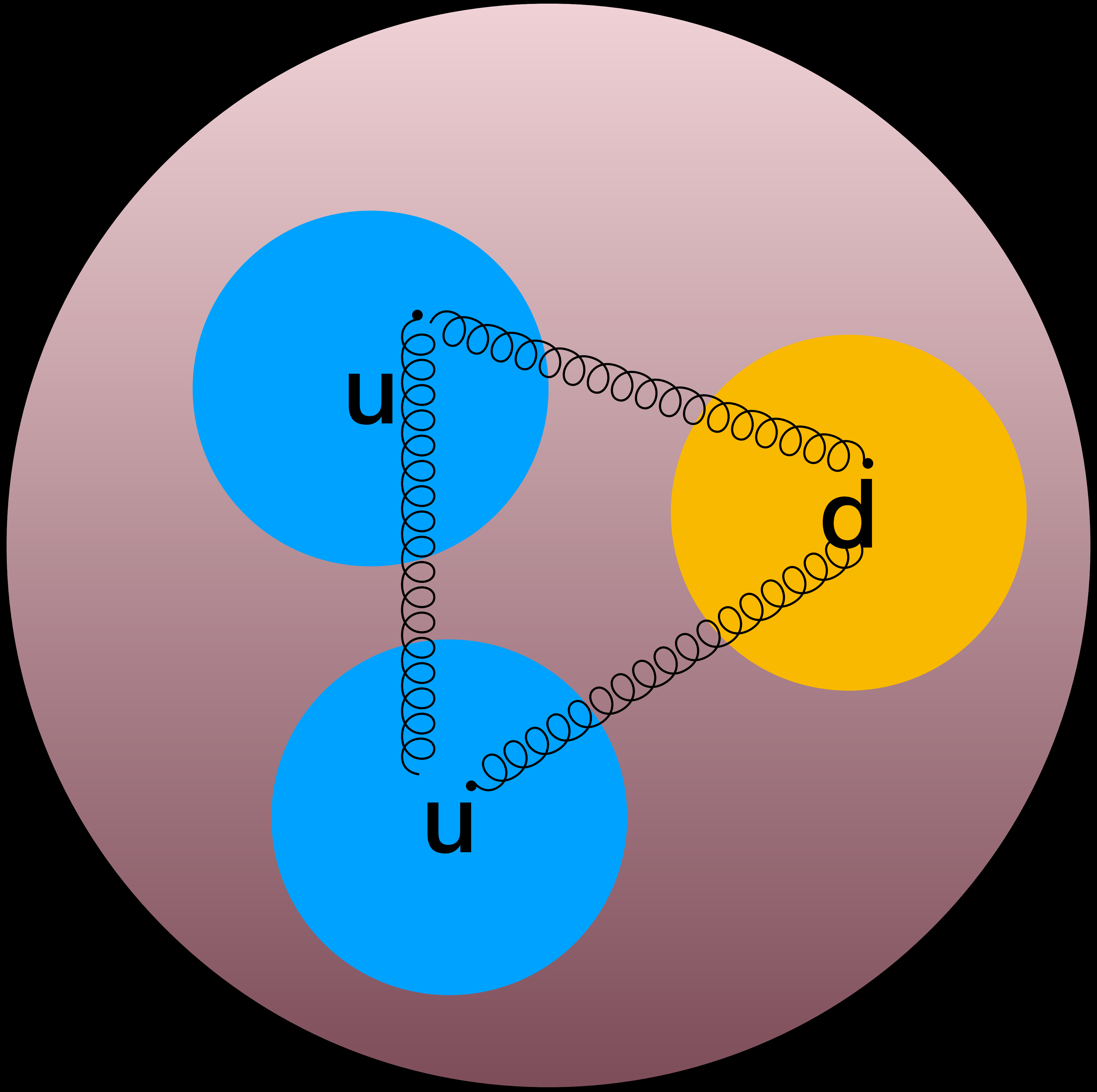


Total energy =
Kinetic energy + rest mass

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

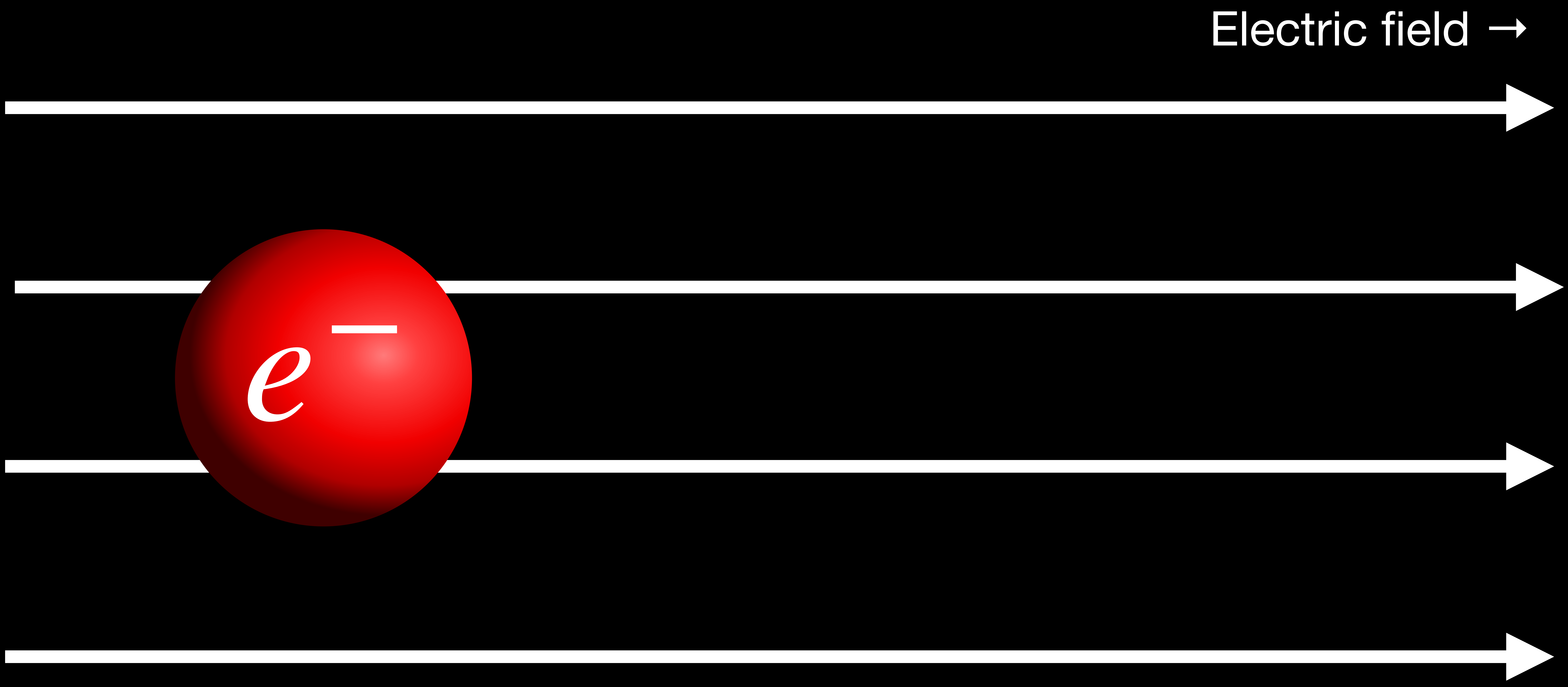


Each quark carries only a small fraction of the proton’s energy

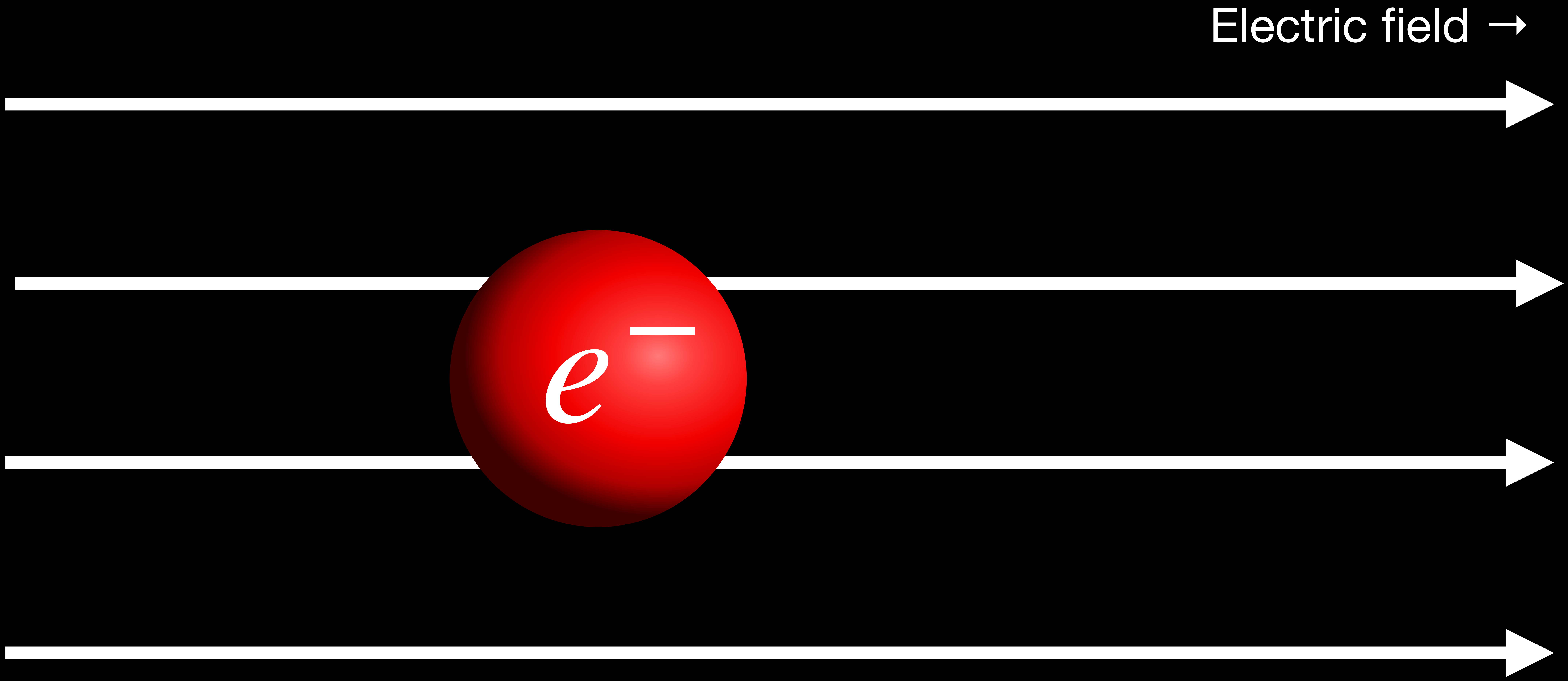
Need protons at 4 TeV to make quark-antiquark annihilation to produce Higgs at 125 GeV

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

How to accelerate particles to high energy?

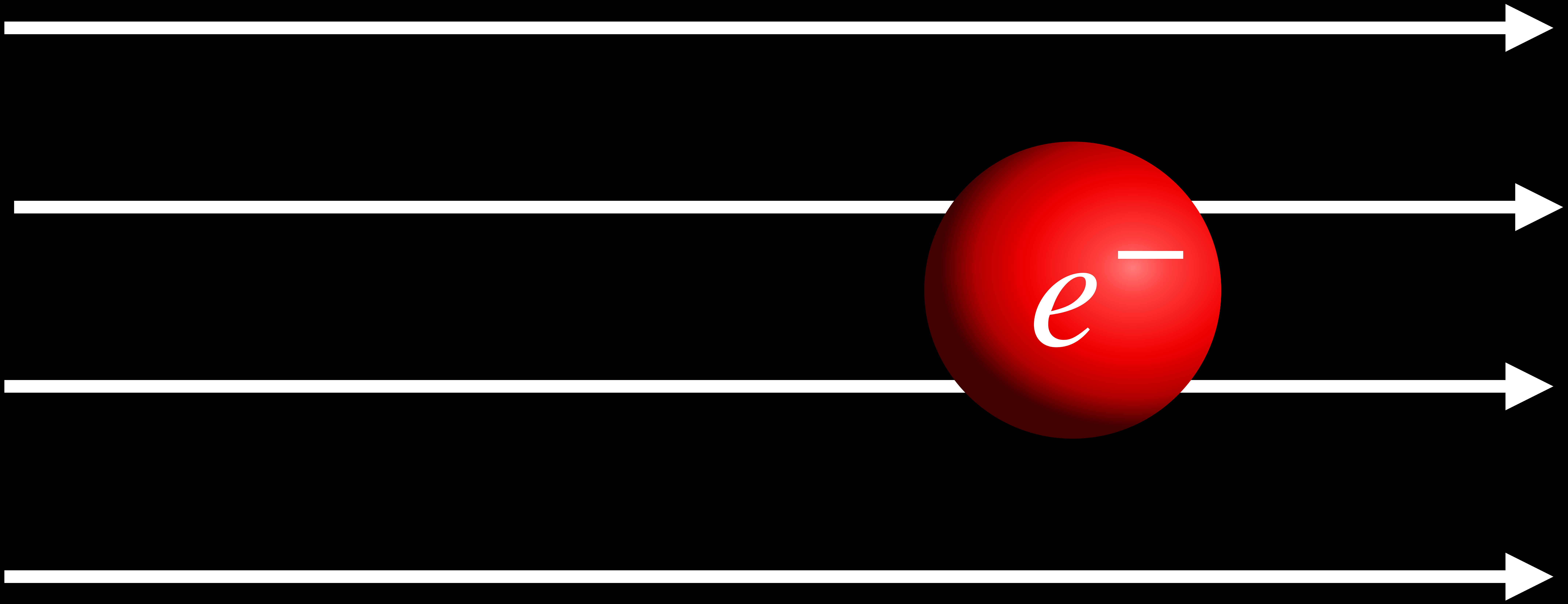


How to accelerate particles to high energy?



How to accelerate particles to high energy?

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



Cyclotron

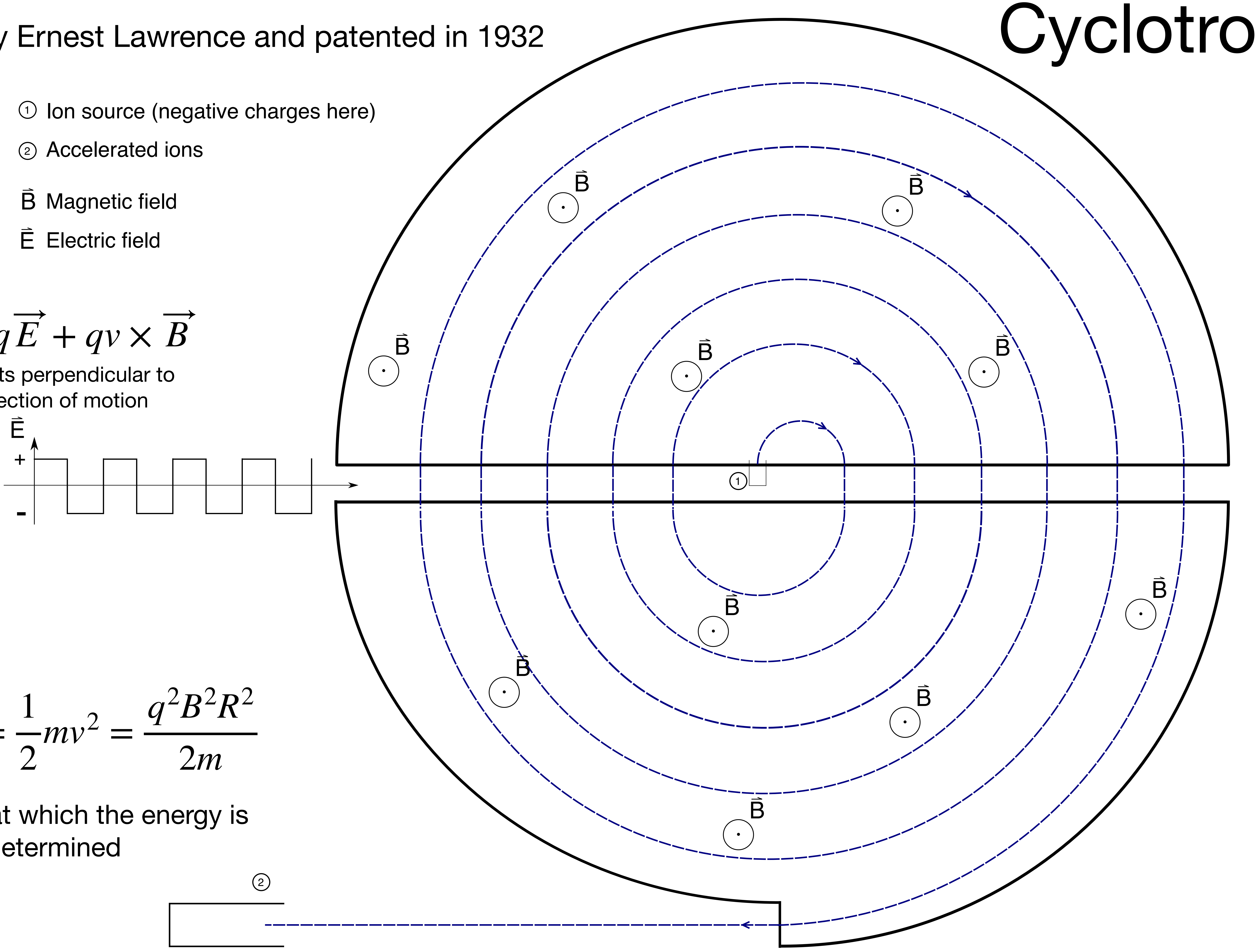
Proposed by Ernest Lawrence and patented in 1932

① Ion source (negative charges here)

② Accelerated ions

$\vec{B}$ Magnetic field

$\vec{E}$ Electric field



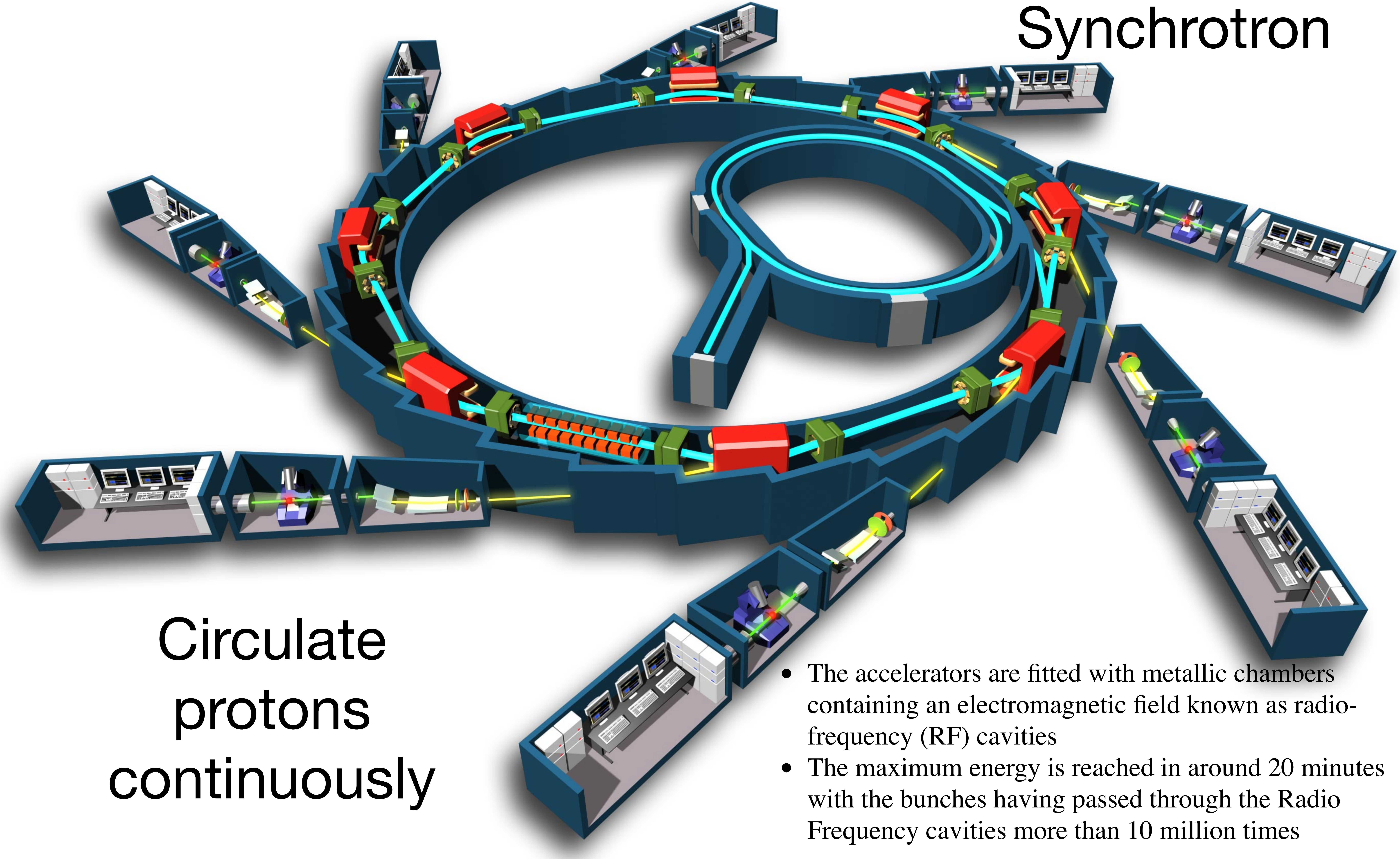
$$\overrightarrow{F} = q\overrightarrow{E} + qv \times \overrightarrow{B}$$

B field acts perpendicular to the direction of motion

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

R = radius at which the energy is determined

Synchrotron

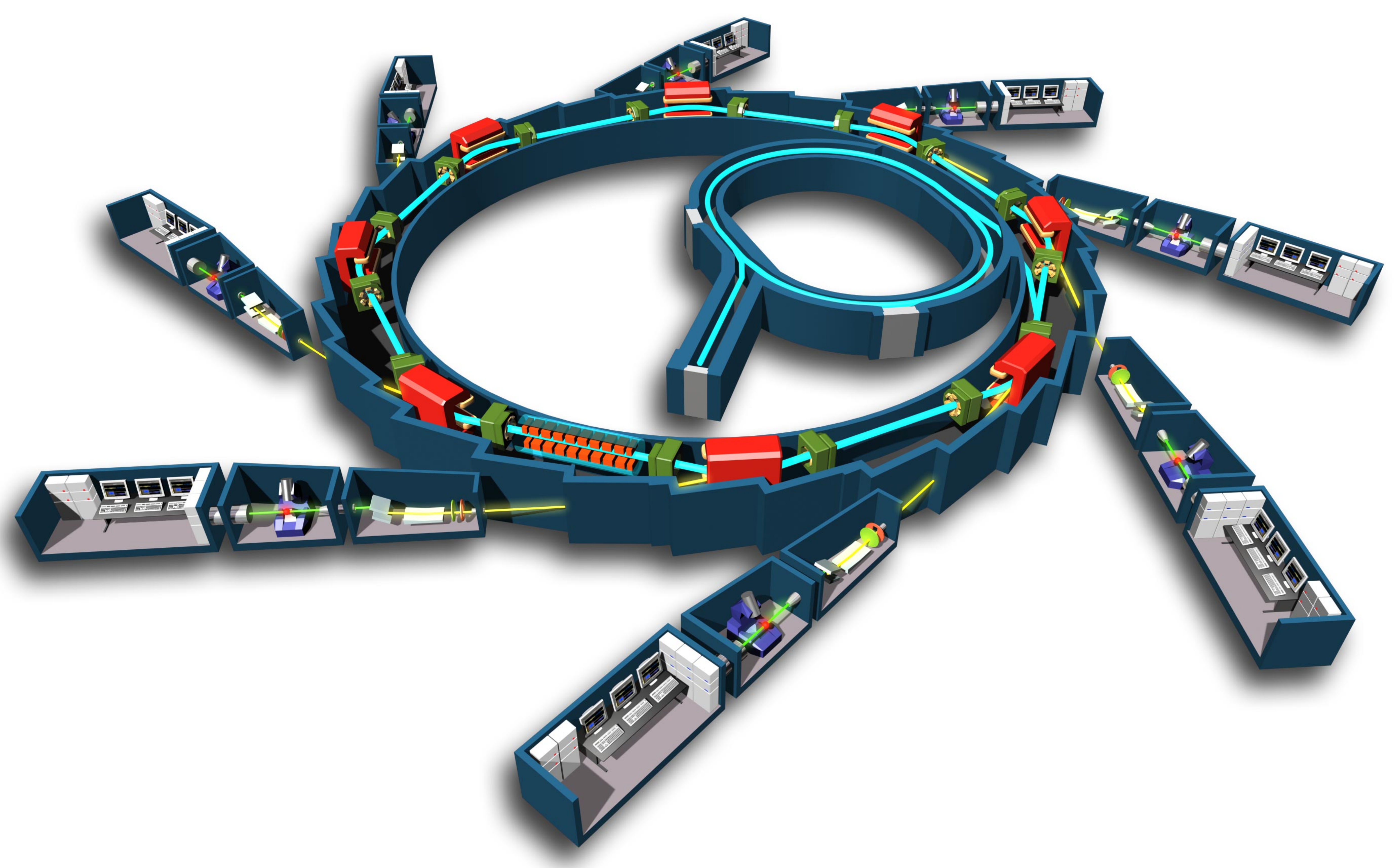


Circulate protons continuously

- 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?

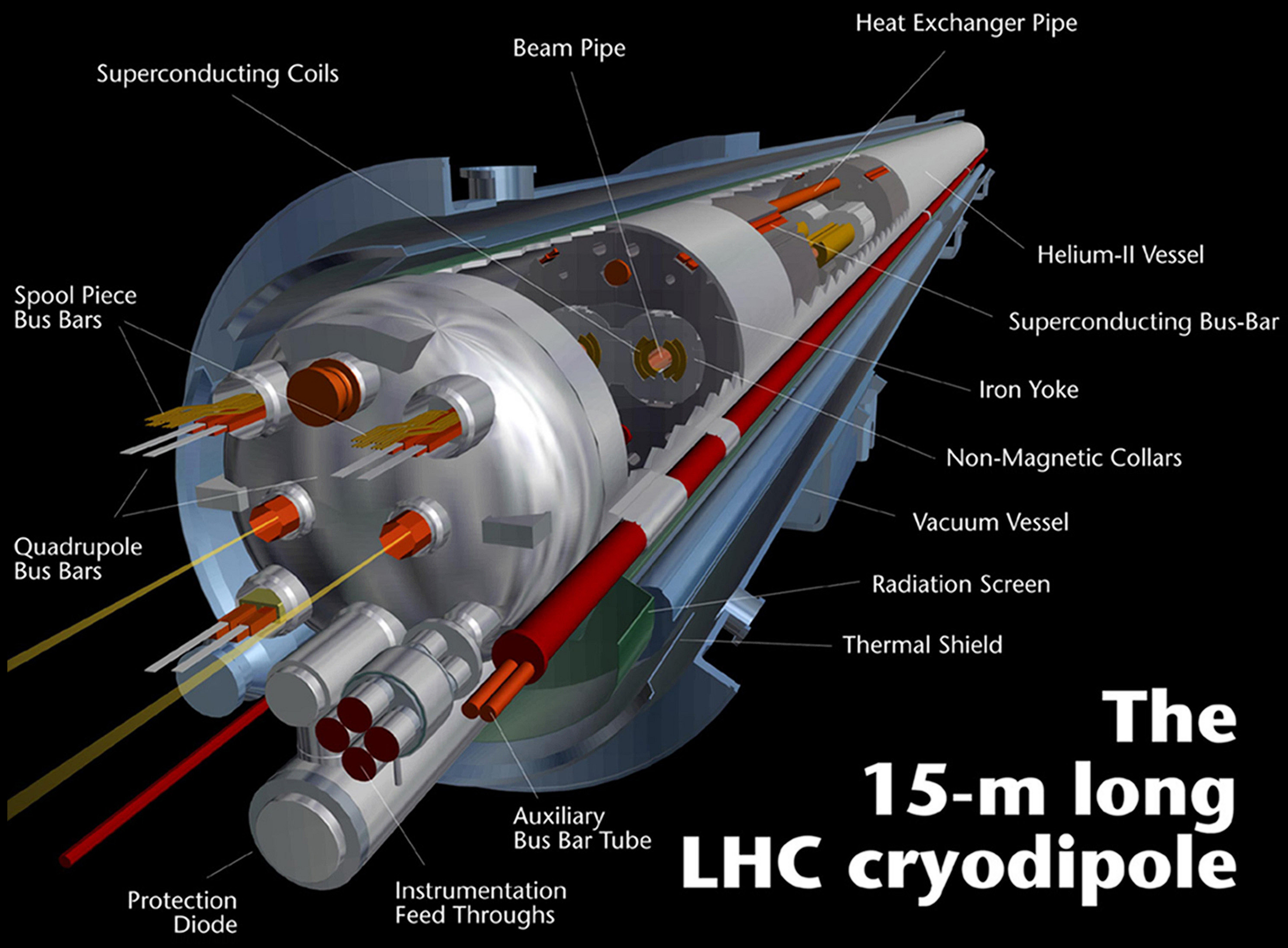
- Dipole magnets are used to bend the paths of the protons around the 27 km ring

- Squeezed for collision into a space narrower than human hair

- Require huge forces to control them

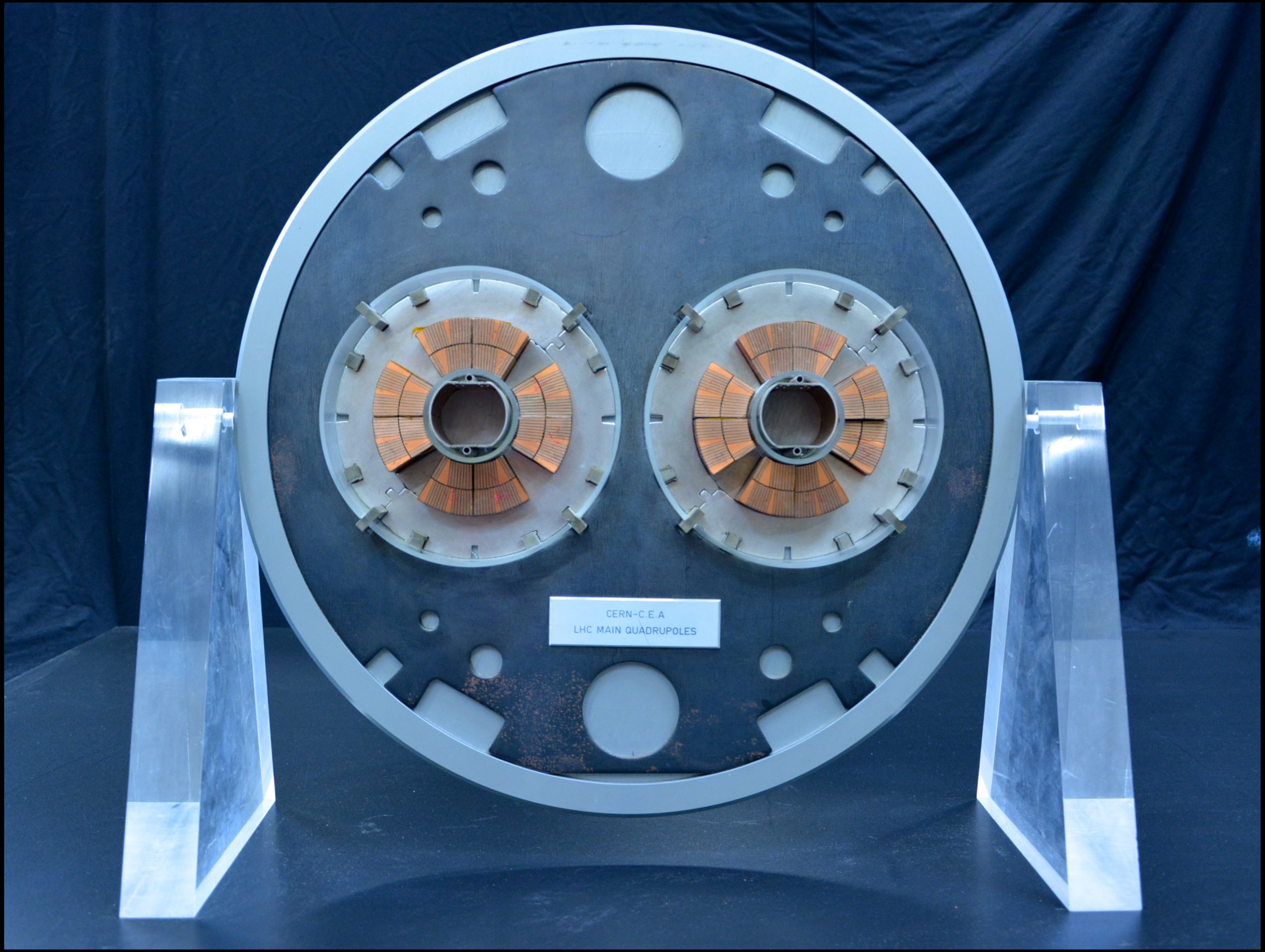
  - Computer-generated image of an LHC dipole magnet

  - Magnets must be cooled to 1.9 K (less than –270.3°C) → superconducting coils can produce the required 8 T magnetic field strength



The 15-m long LHC cryodipole

LHC magnets



A quadrupole focusing magnet

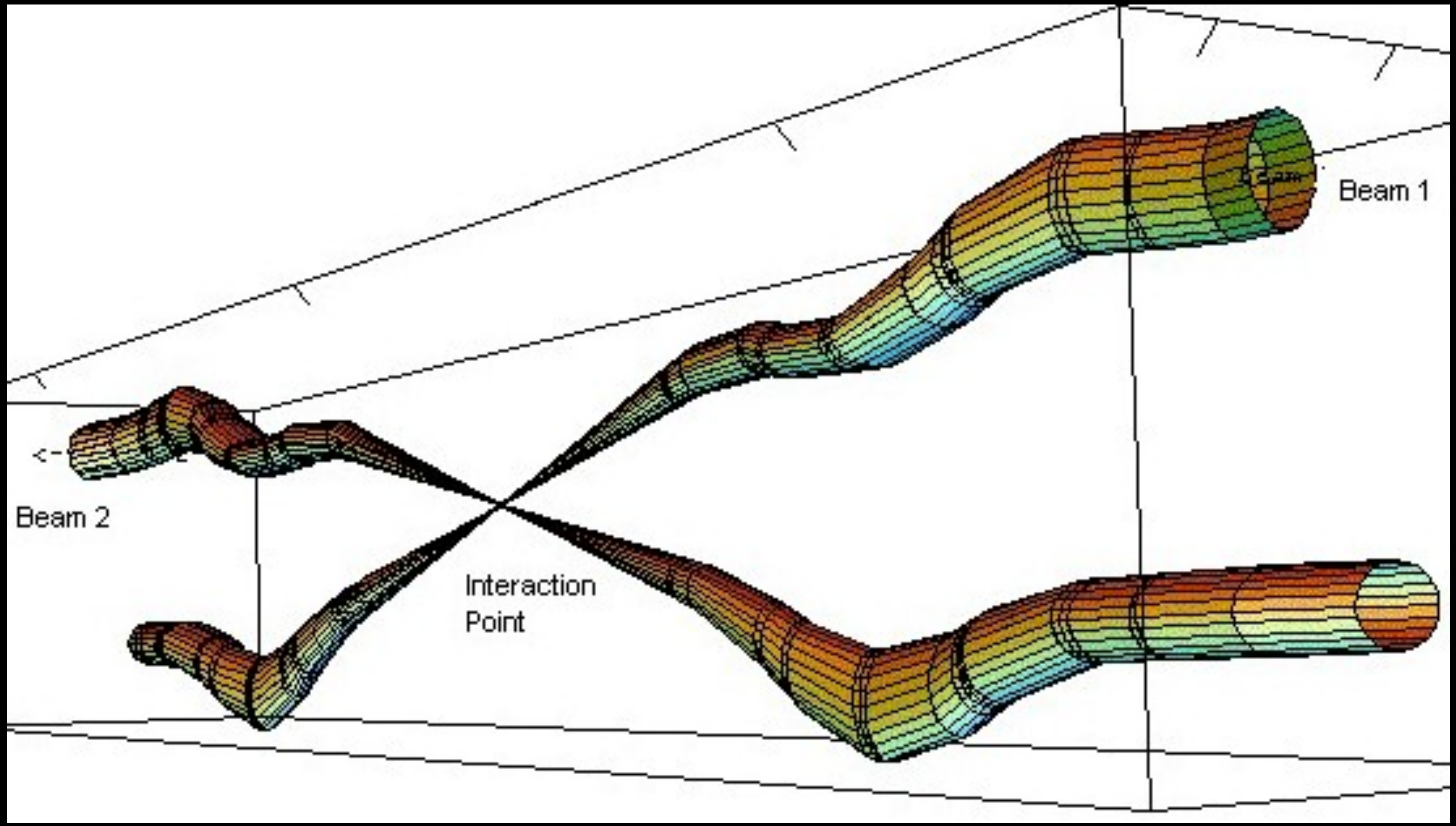
- Use a quadrupole magnet to focus beams
- Quadrupole magnets focus the proton beams
  - Squeeze them so that more particles collide when the beams cross paths
- Precision needed analogous to colliding two knitting needles launched from either side of the Atlantic Ocean

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

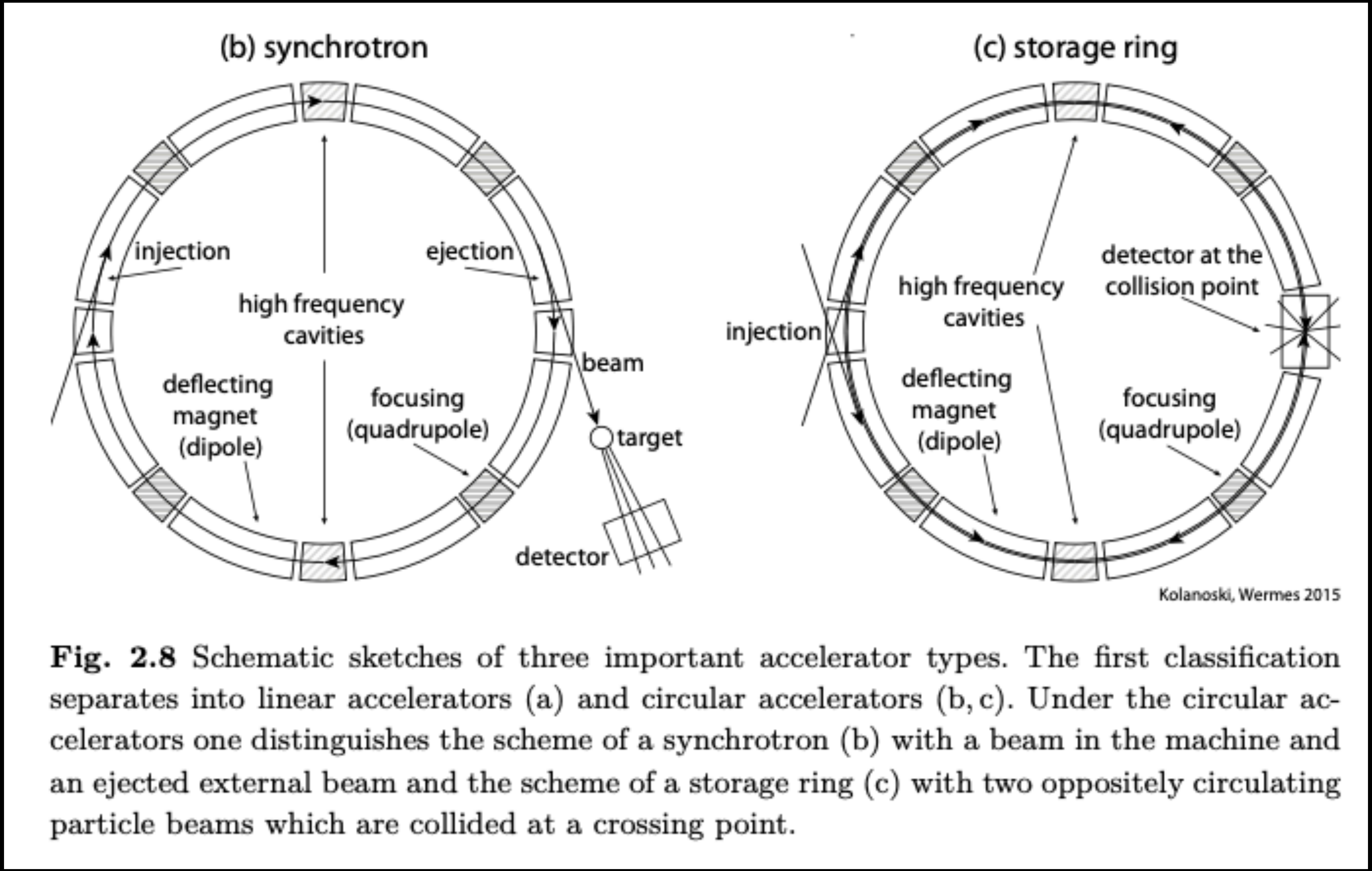


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Fig. 2.8 Schematic sketches of three important accelerator types. The first classification separates into linear accelerators (a) and circular accelerators (b, c). Under the circular accelerators one distinguishes the scheme of a synchrotron (b) with 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 potenti difference of one volt

- In traditional units = 1.602 X 10^{-19} Joules