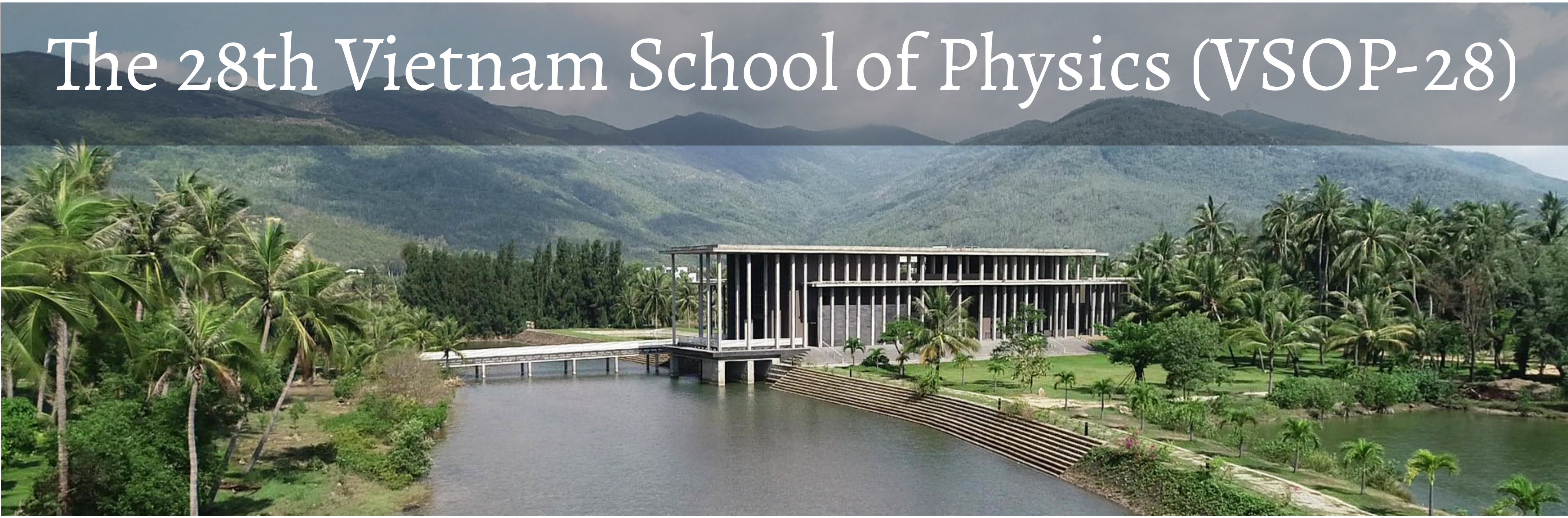


Experimental methods for physics at the LHC

Sourabh Dube

IISER PUNE

July 24, 2022 to
August 5, 2022

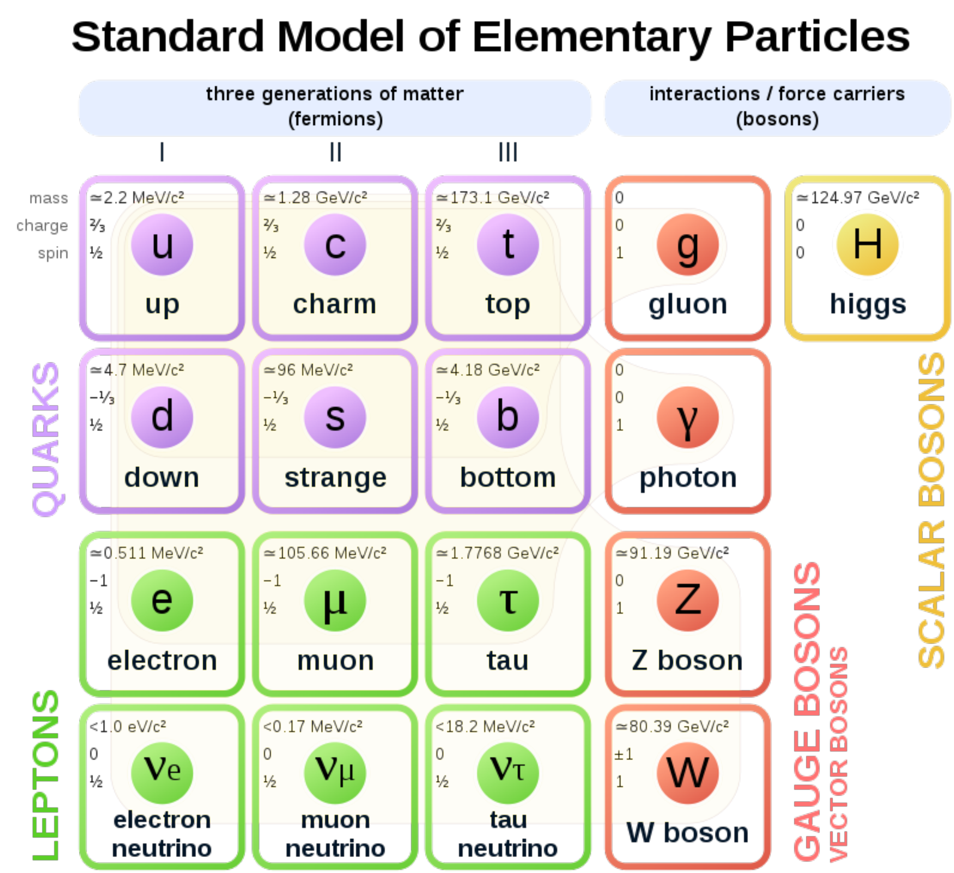
Lecture 2: Detectors

Particle detection

Particles can only be detected, if they interact with something.

Conversely, the primary interactions of particles can be used to detect them.
(eg. photons through EM interactions, hadrons through strong and EM interactions)

Which particles can we detect?



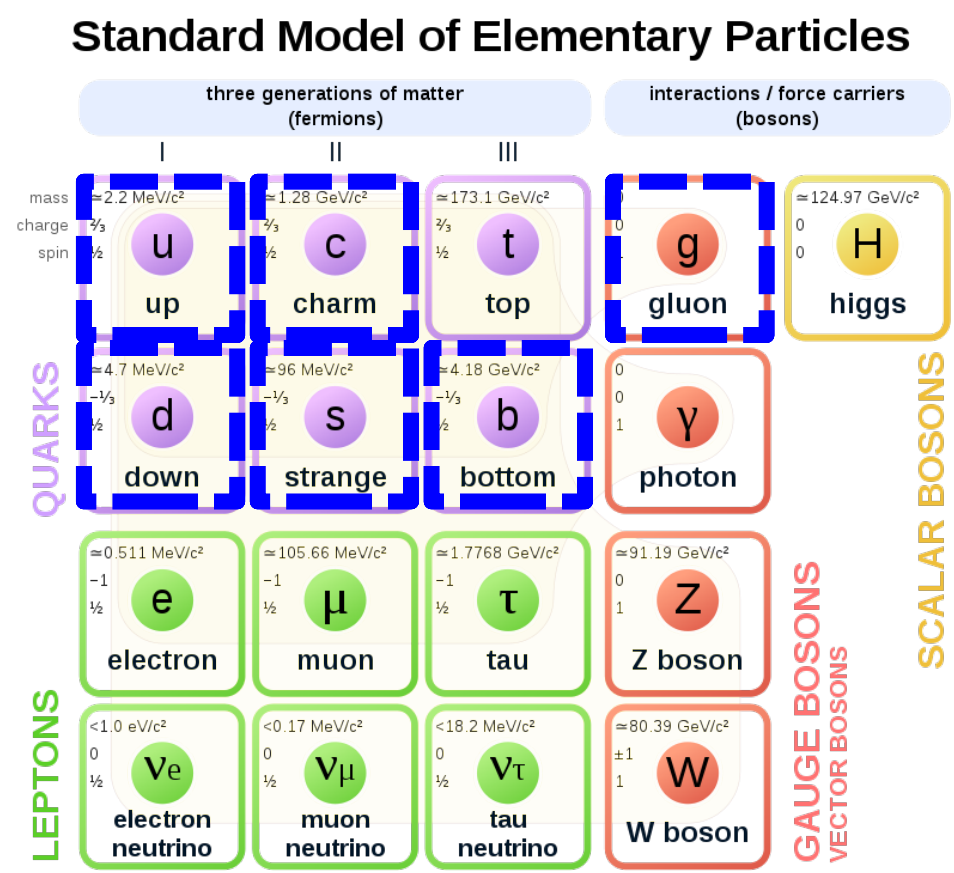
Particle detection

Particles can only be detected, if they interact with something.

Conversely, the primary interactions of particles can be used to detect them.
(eg. photons through EM interactions, hadrons through strong and EM interactions)

Which particles can we detect?

These hadronize, producing hadrons such as pions, kaons, neutrons etc.



Some relevant properties

Name	Mass	Approx. Travel distance
e	0.51 MeV	stable
γ	0	stable
μ	105 MeV	6250 m
τ	1.8 GeV	50 μm
$\pi^{\pm}$	140 MeV	56 m
n	939 MeV	10^{11} m
W	80.4 GeV	10^{-19} m
Z	91.2 GeV	10^{-19} m

Some particles can be detected directly, some will decay – so we must infer their presence.

Energy Loss in material

LINK

Particle interacting with bulk material

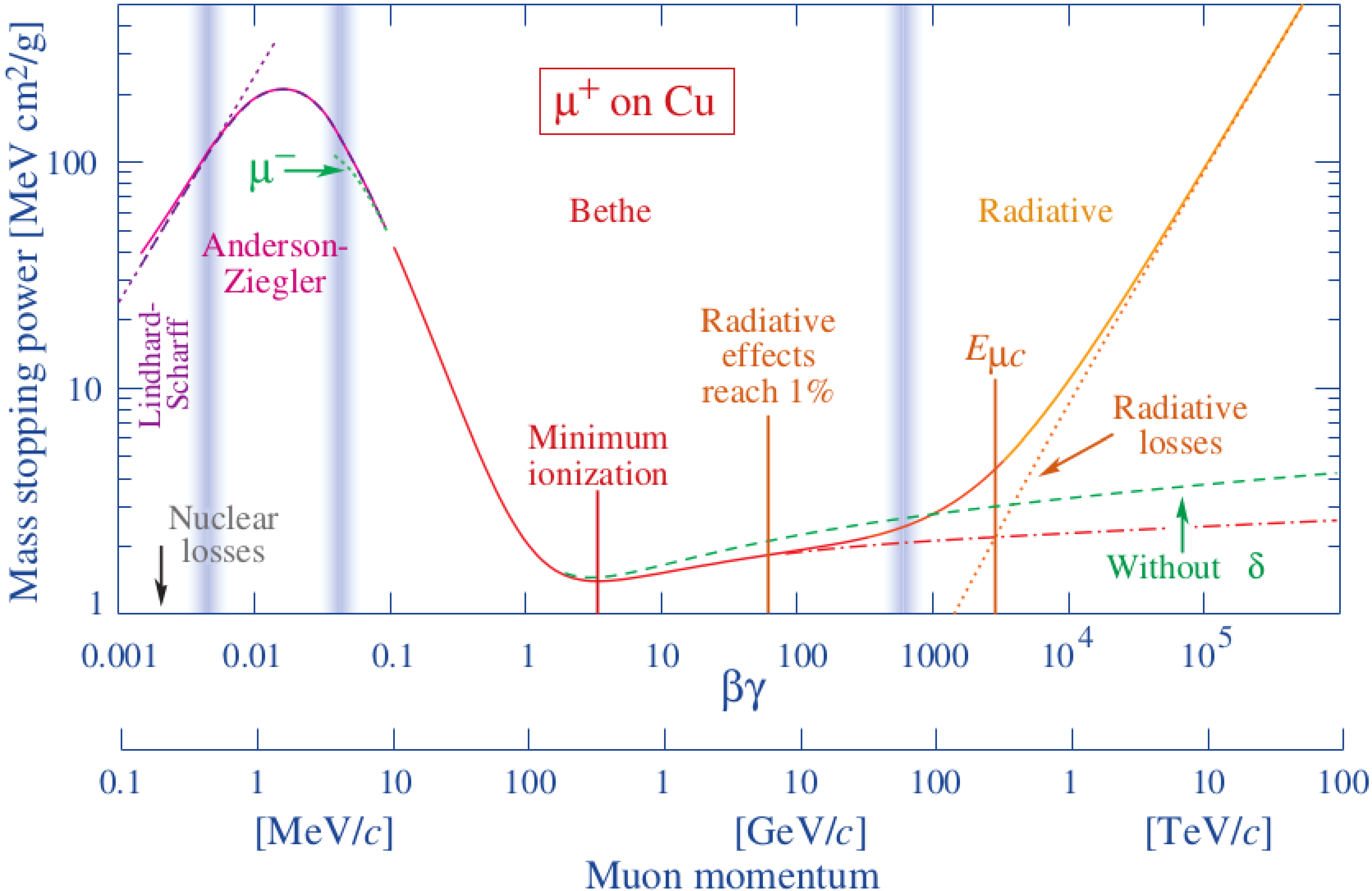
A beam of particles passes through a slab of material –
(a) many small interactions (b) All-or-nothing

(a) Add up the energy losses and deflections statistically.
(b) Either particle is eliminated, or it moves through undeflected.

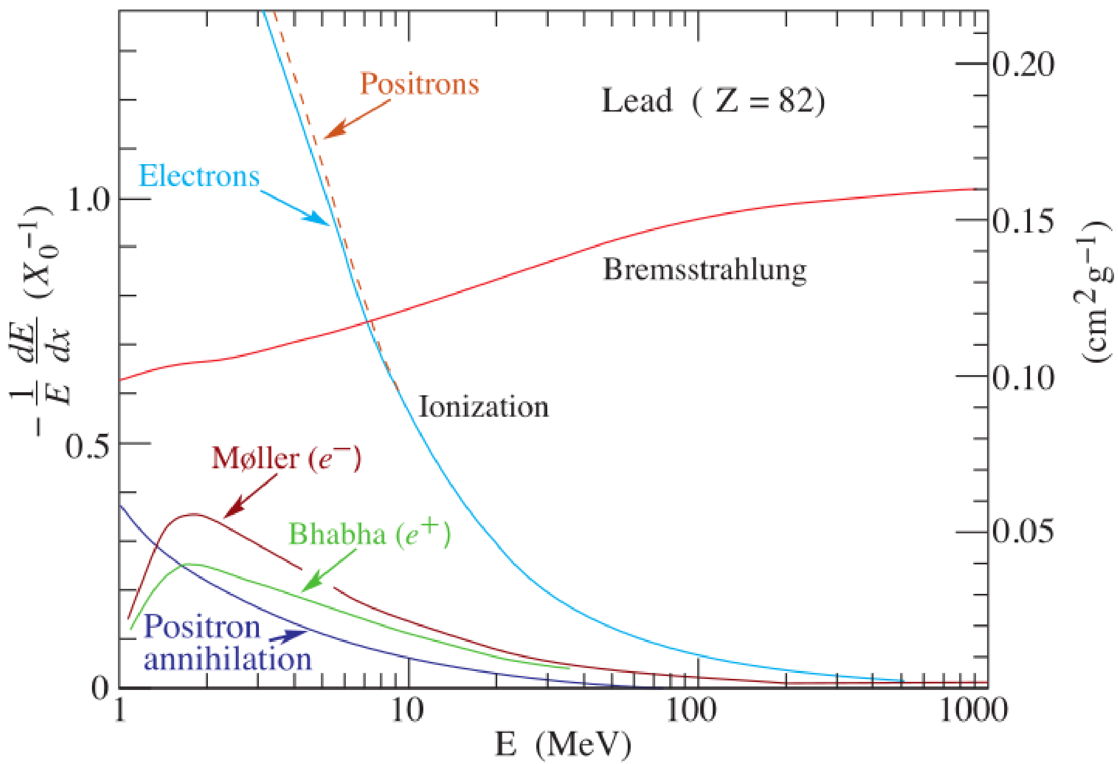
Heavy charged particles lose energy through ionization or excitation of atoms of material, with the energy loss dE/dx given by the Bethe-Bloch equation
dE/dx is proportional to Z^2 of absorber, q^2 of the particle, and inversely proportional to speed of incoming particle.

At high energies, radiative losses and pair production dominate energy loss.
In addition we have Cerenkov radiation (particle velocity > phase velocity of light in that medium) and Transition Radiation (when particle traverses materials of different optical properties)

Interactions with matter



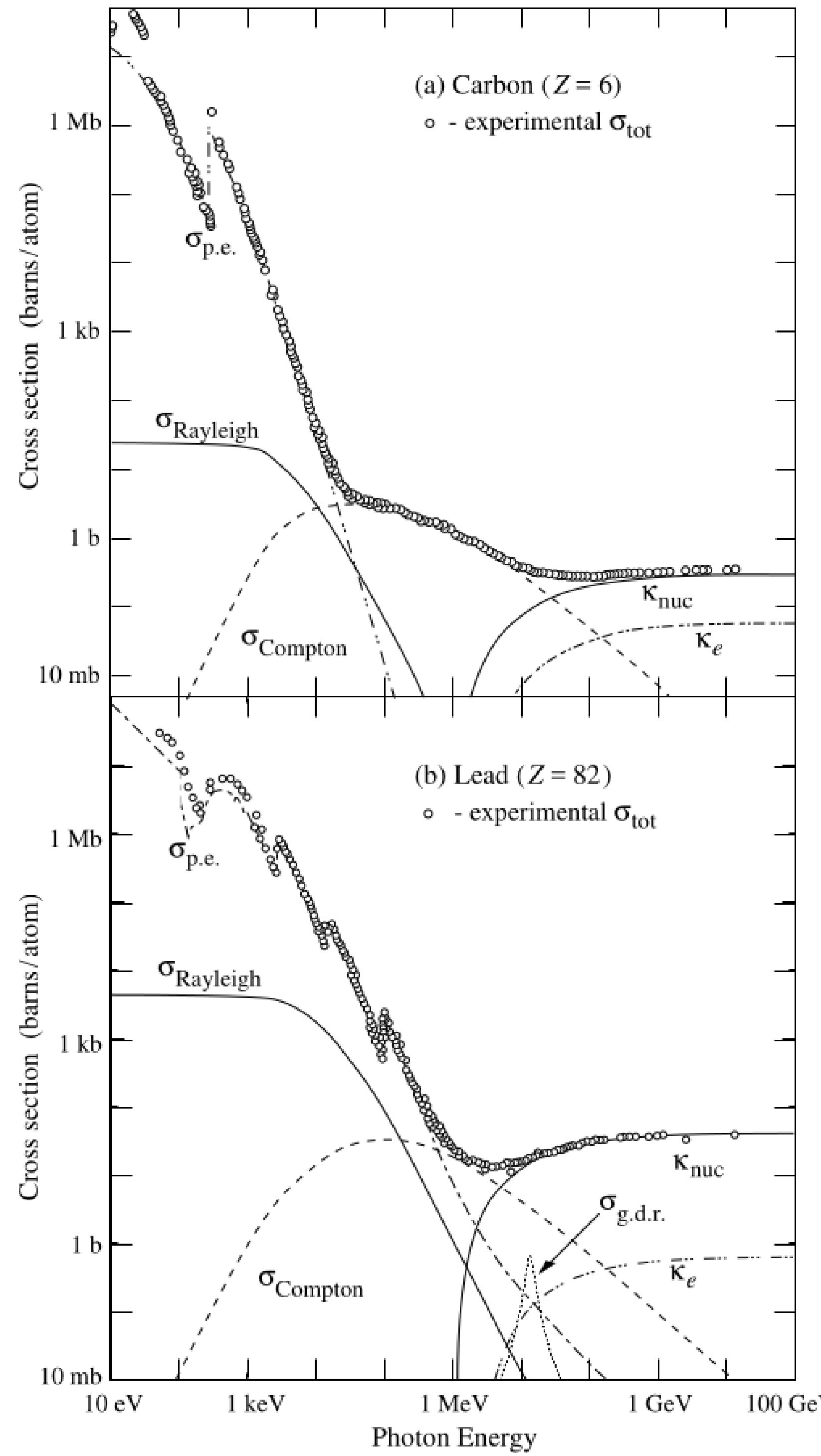
Electrons and photons



X_0 = radiation length

The mean distance over which energy will decrease to 1/e of its value.

The bremsstrahlung loss goes as ~ E/X0



What would we like to measure?

1. The 4-vector of the particle, i.e. the momentum $\bar{p}$ and the energy E.
   The momentum is a vector, so we will also get direction of the particle's travel.

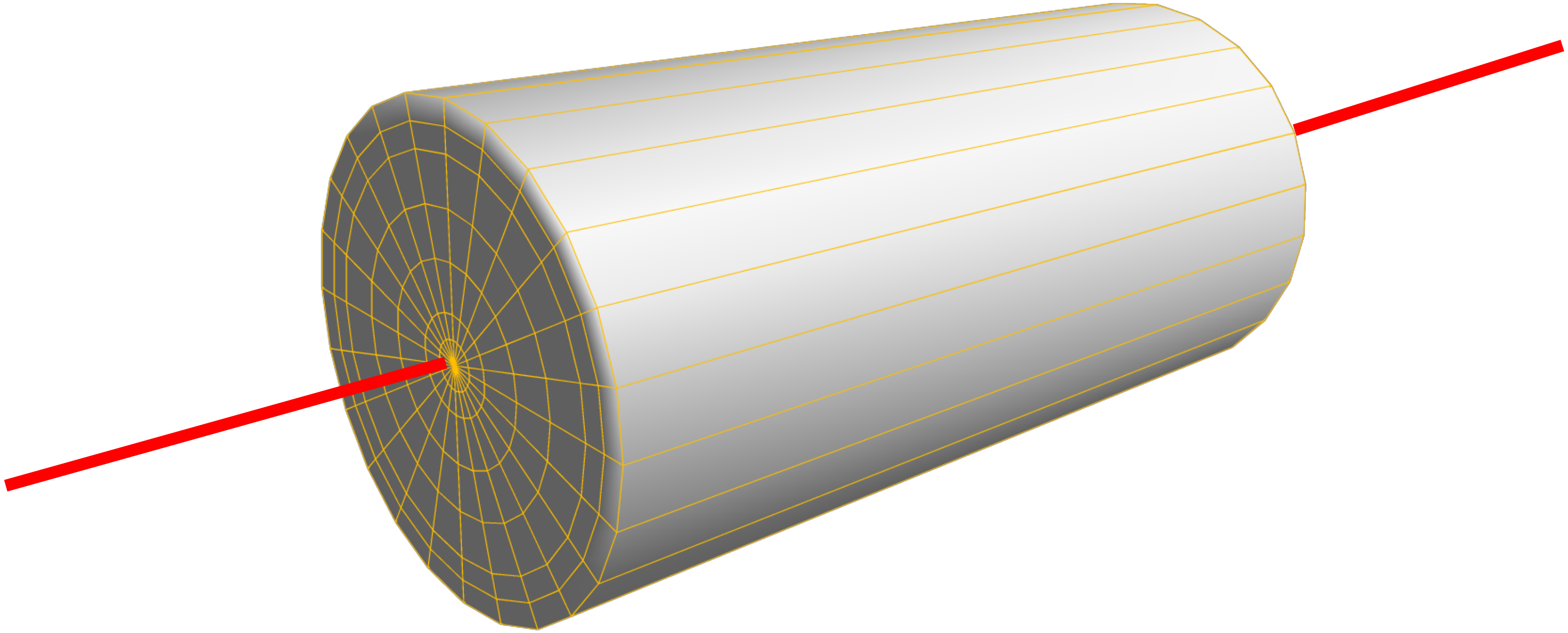
2. Charge

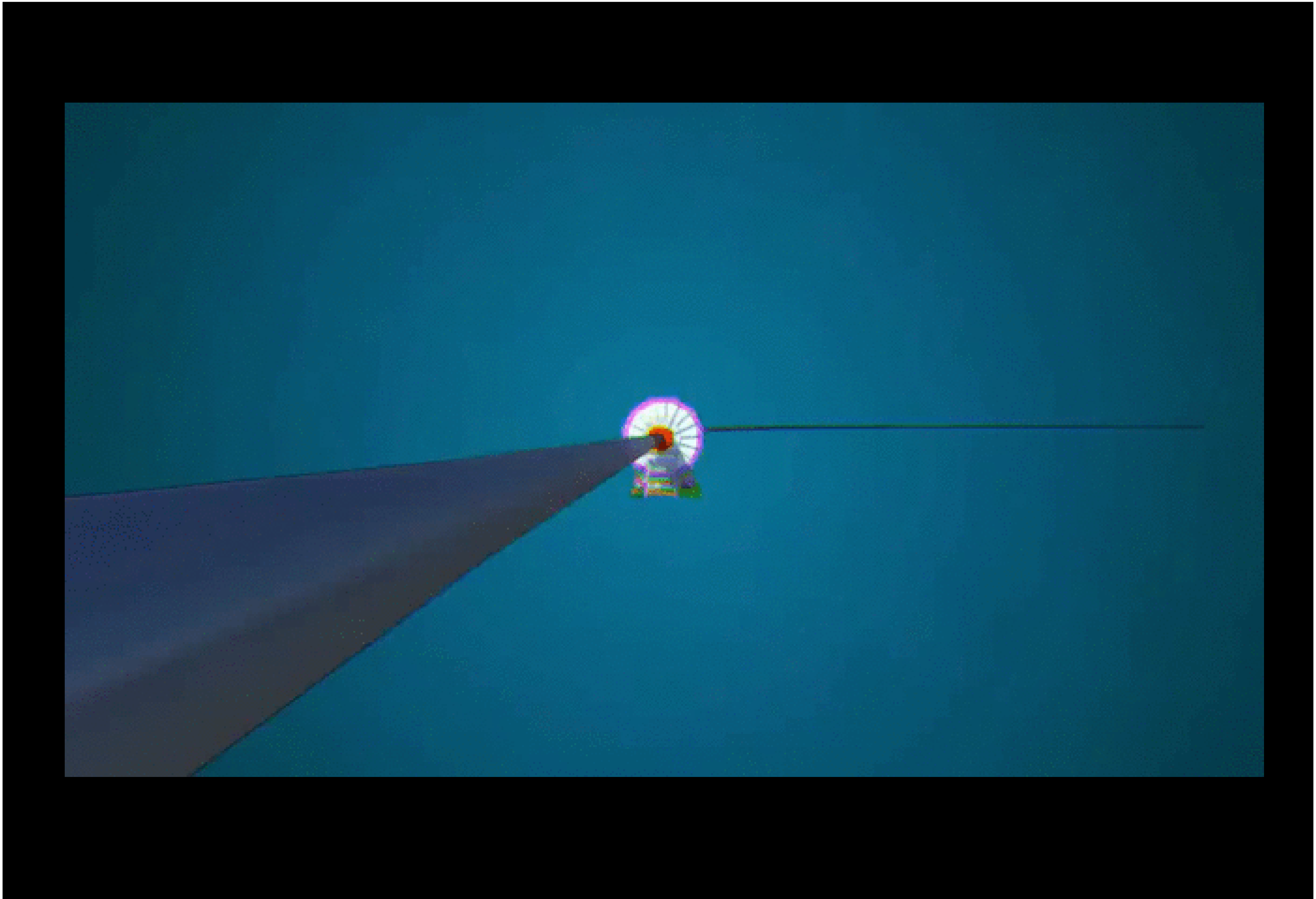
3. If it decays, then where? Its lifetime?

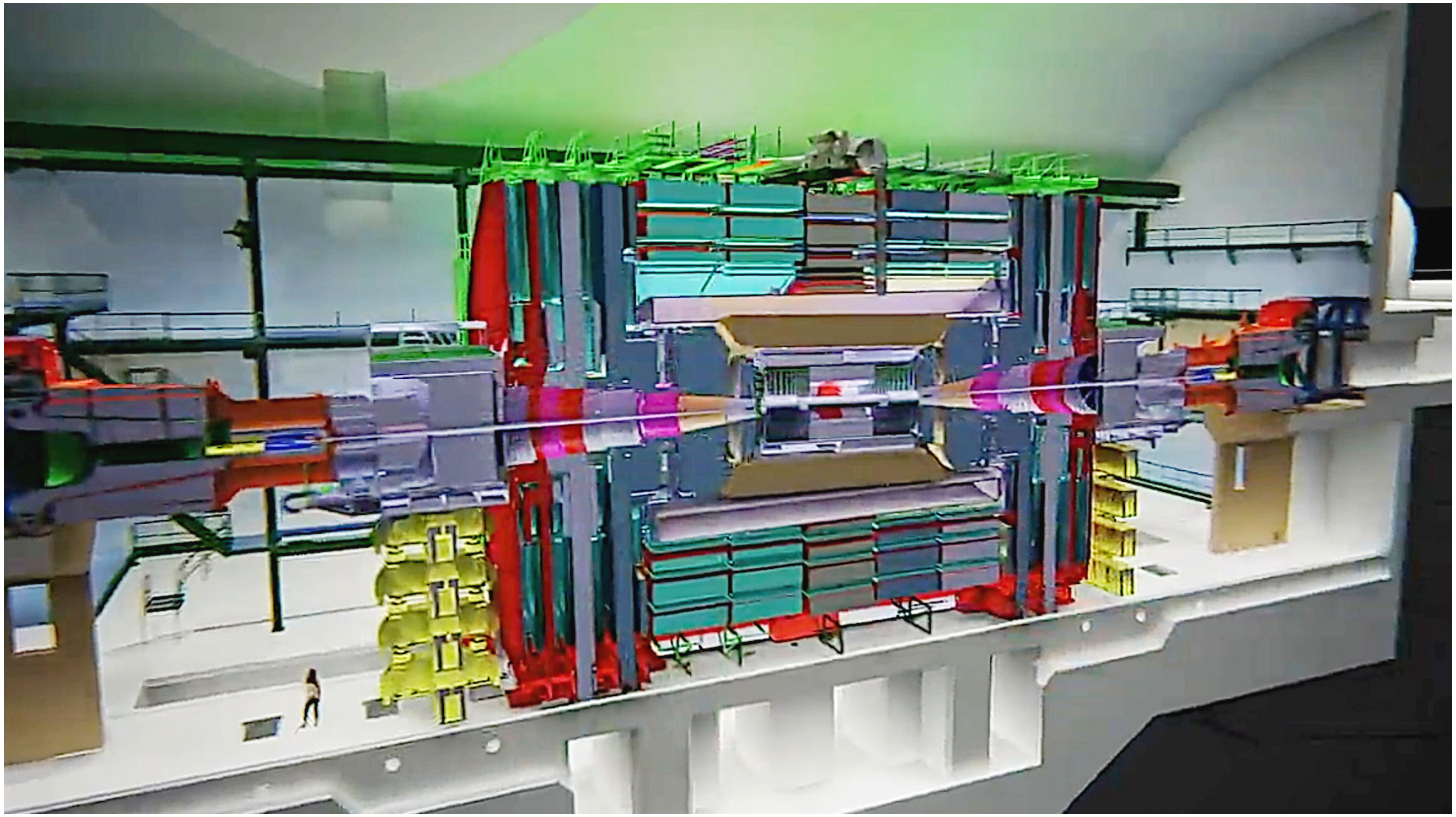
4. How many particles of each kind

5. Anything special? Did the particle interact unusually with our detector?

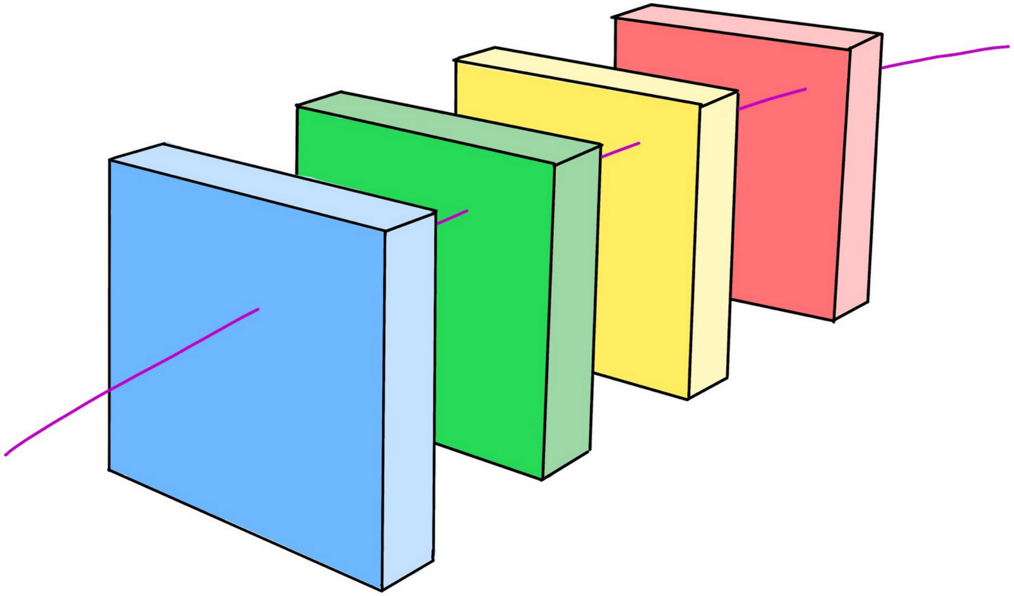
Typical detector design

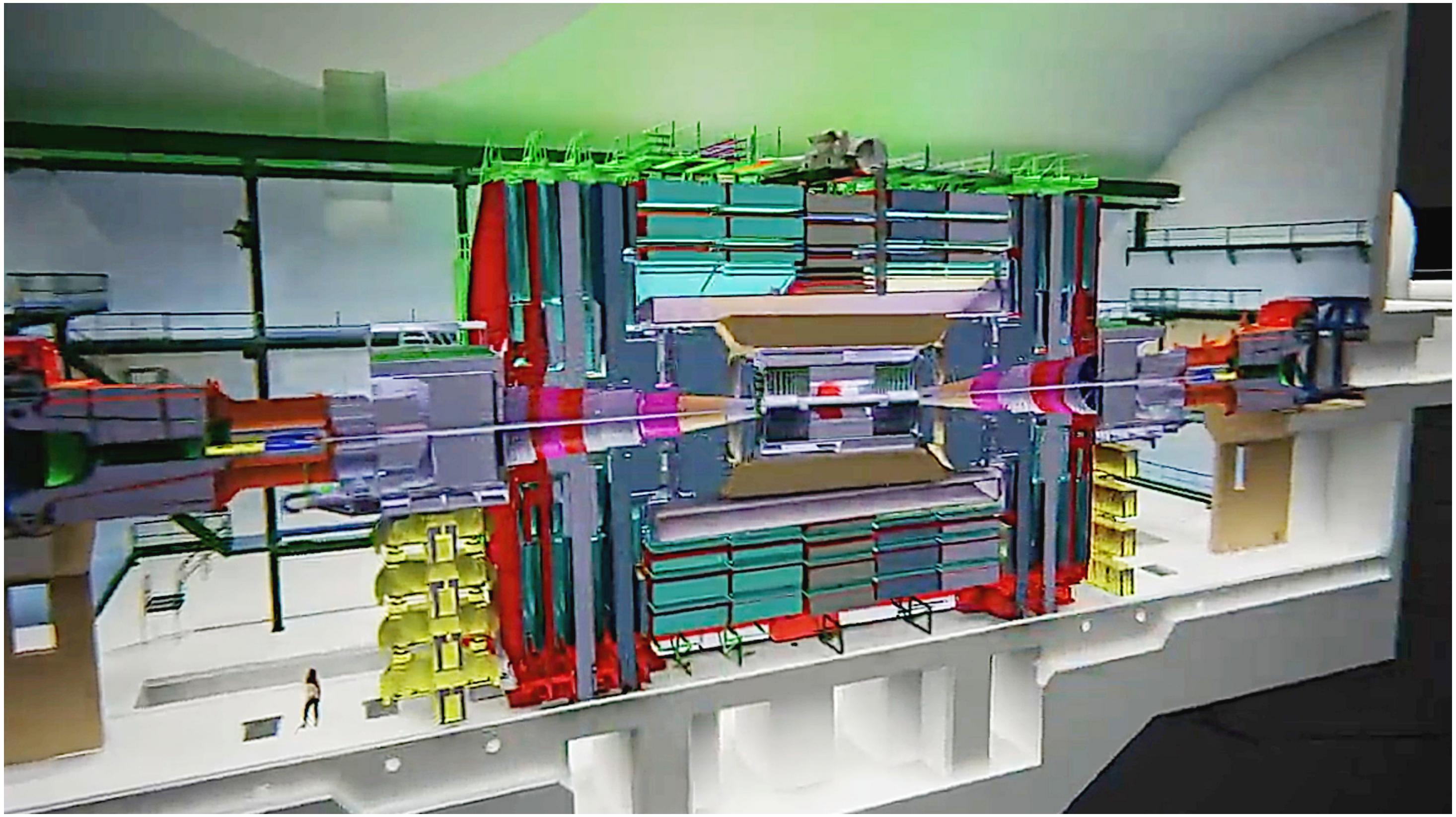




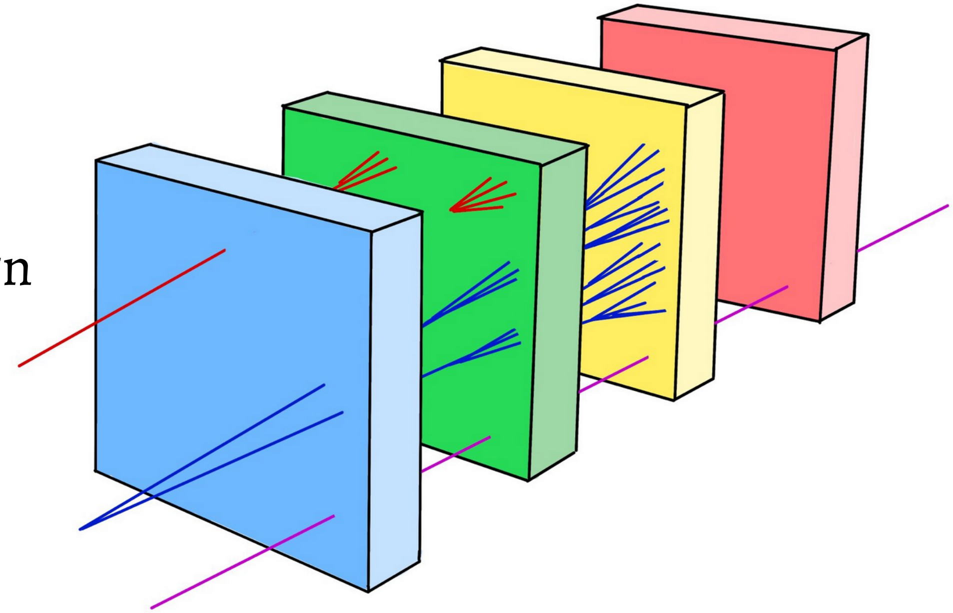


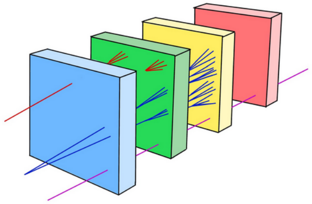
A particle produced in a collision will traverse the different sub detectors where it will interact.





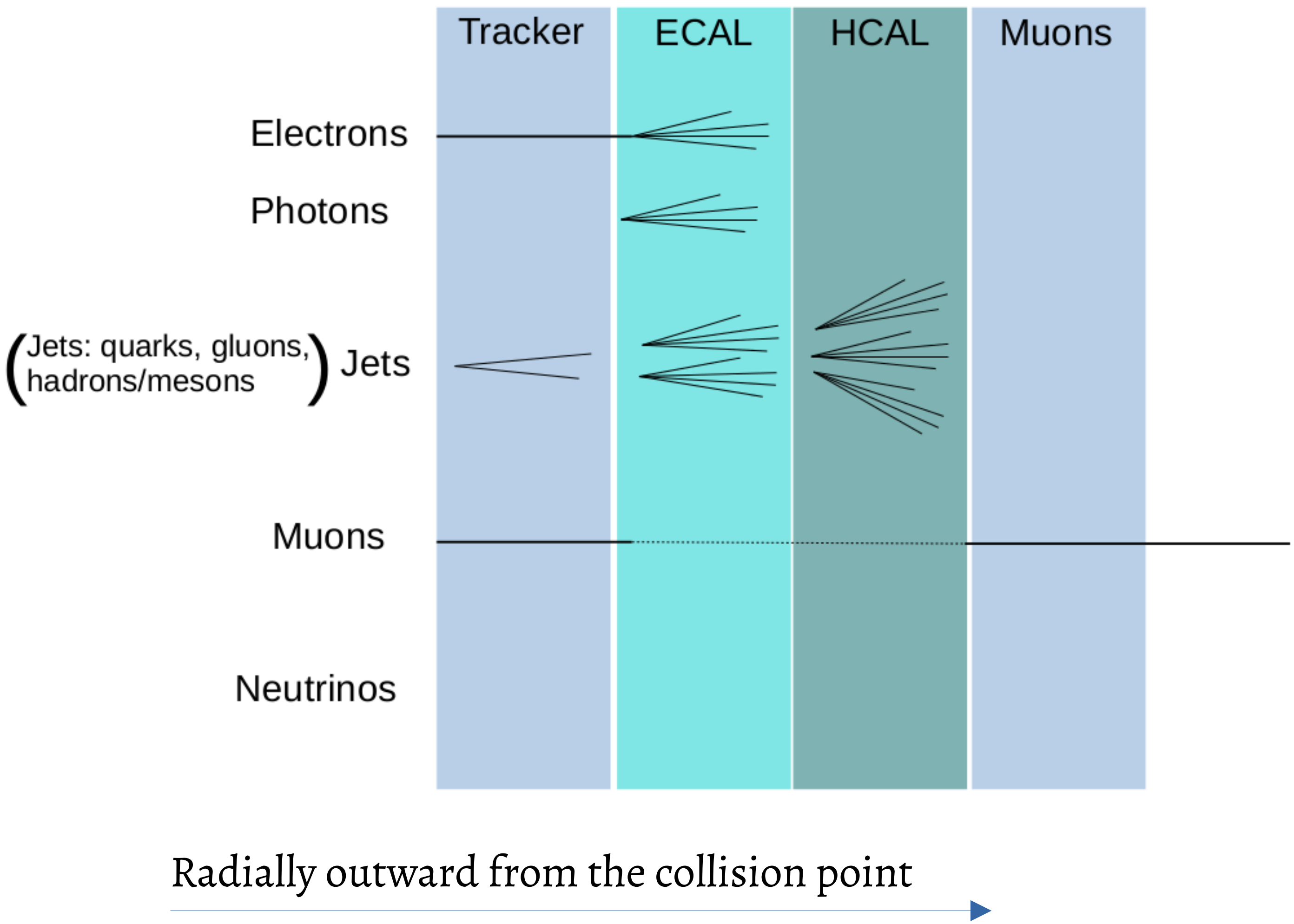
Different particles will interact differently (!!) since that is how we design the detector





Building a detector

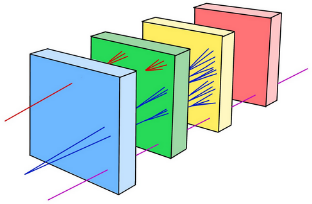
Aim: measure the 4-vectors of the particles produced in a collision
Use various subdetectors in a careful design to identify particles.



Tracker: measures trajectory of charged particles, and sign of charge.

Calorimeters:
Measures energy of the particle (needs to stop particle completely)

Muon detector: just another tracker.



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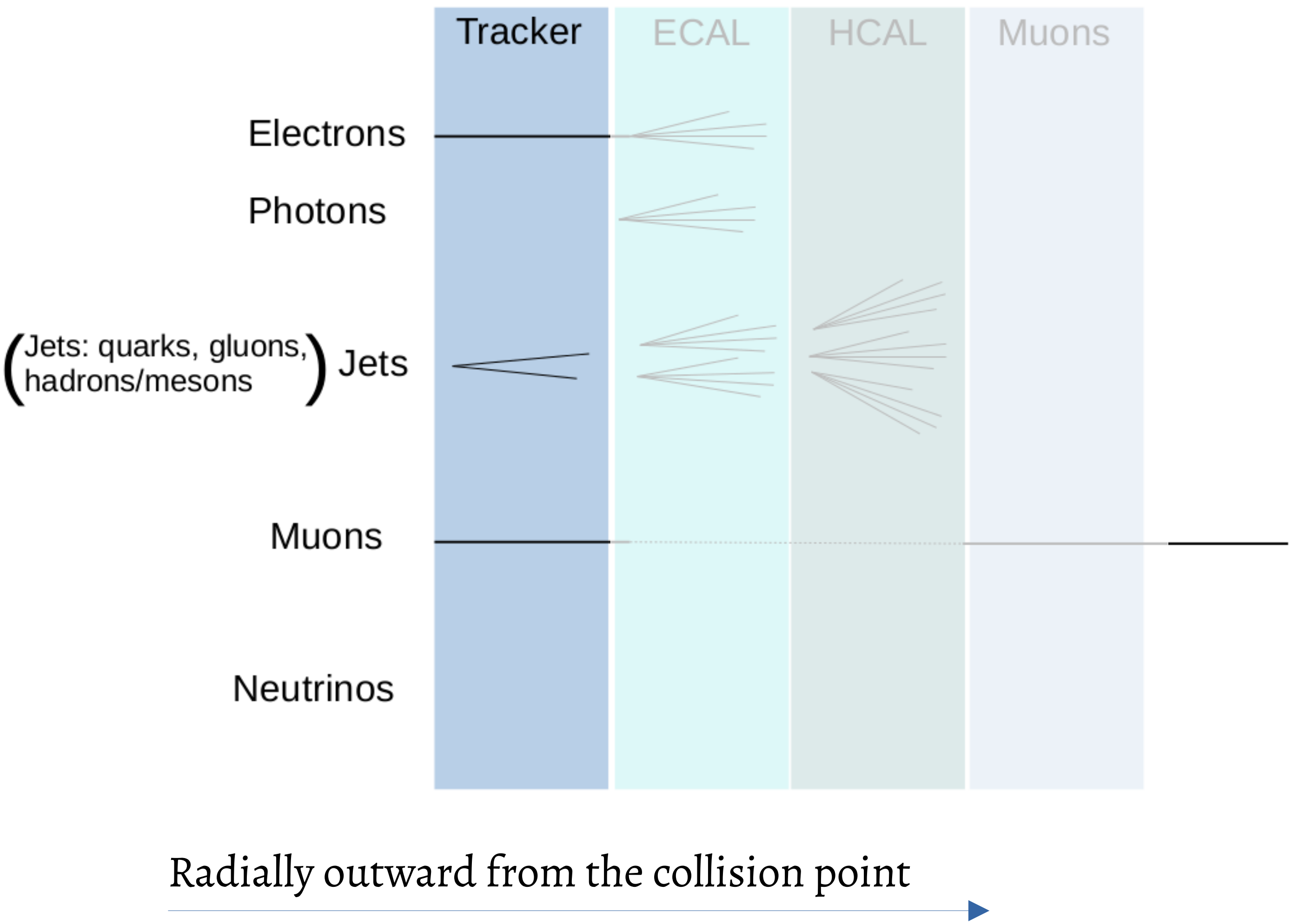
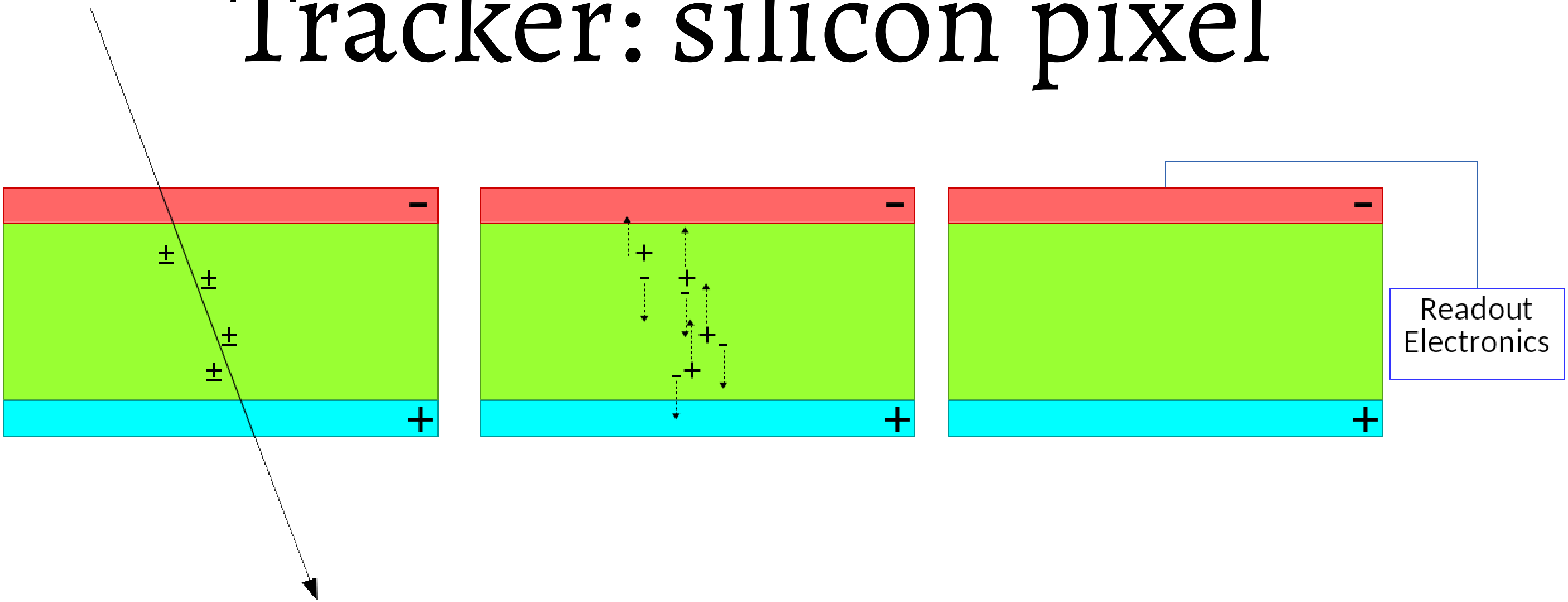


Tracker: measures trajectory of charged particles, and sign of charge. (q and momentum vector p).
Does not stop particle.

Tracker: silicon pixel



Consider a silicon diode, with reverse bias applied.

A passing charged particle created electron-hole pairs.

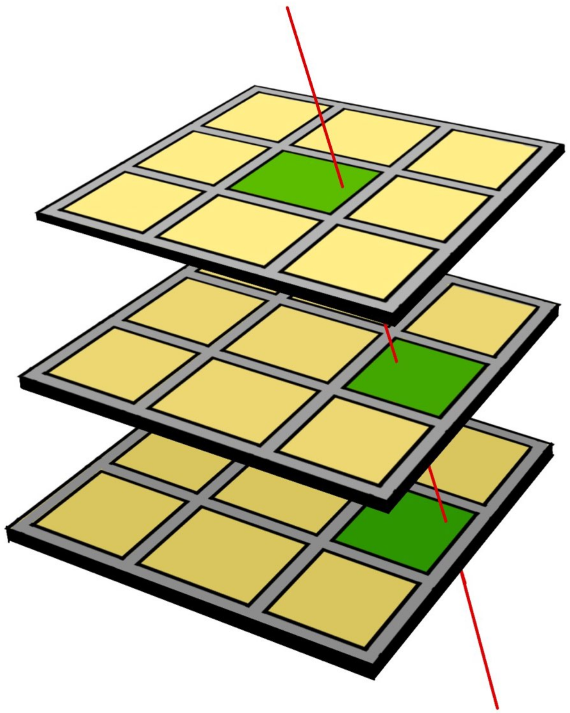
These electrons drift to the end where the total charge is read out.

The typical size of a pixel is 150×150 μm[2] with a thickness of 300 microns, and a charged particle will lose some keV of energy passing through it.

Tracker: silicon pixels

Imagine a stack of pixel layers.

As a particle goes through, we can trace its path based on which pixels are lit up.



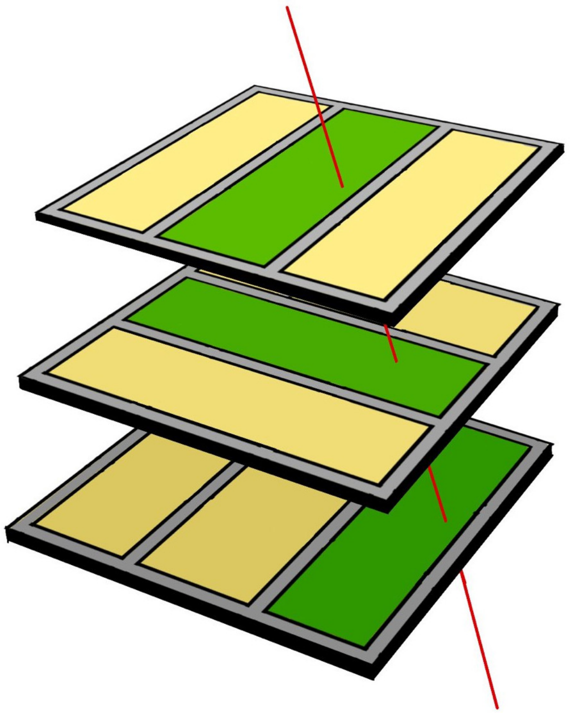
Tracker: silicon strip

Imagine a stack of pixel layers.

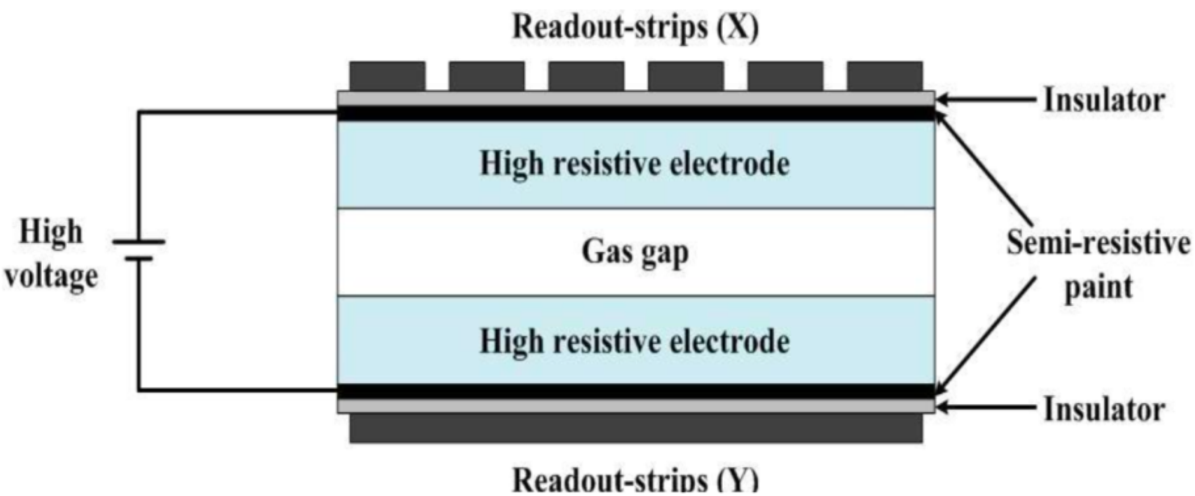
As a particle goes through, we can trace its path based on which pixels are lit up.

But pixels are expensive to make, and there will be too many readout channels.

We can make silicon strip detectors to cover a larger area with less readout channels.

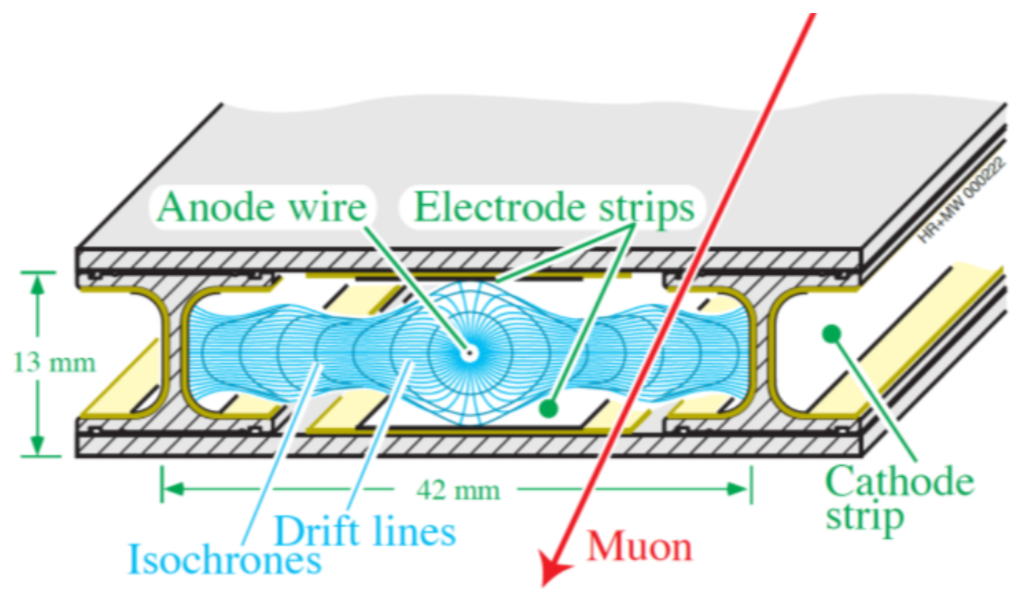


Tracker: for muons



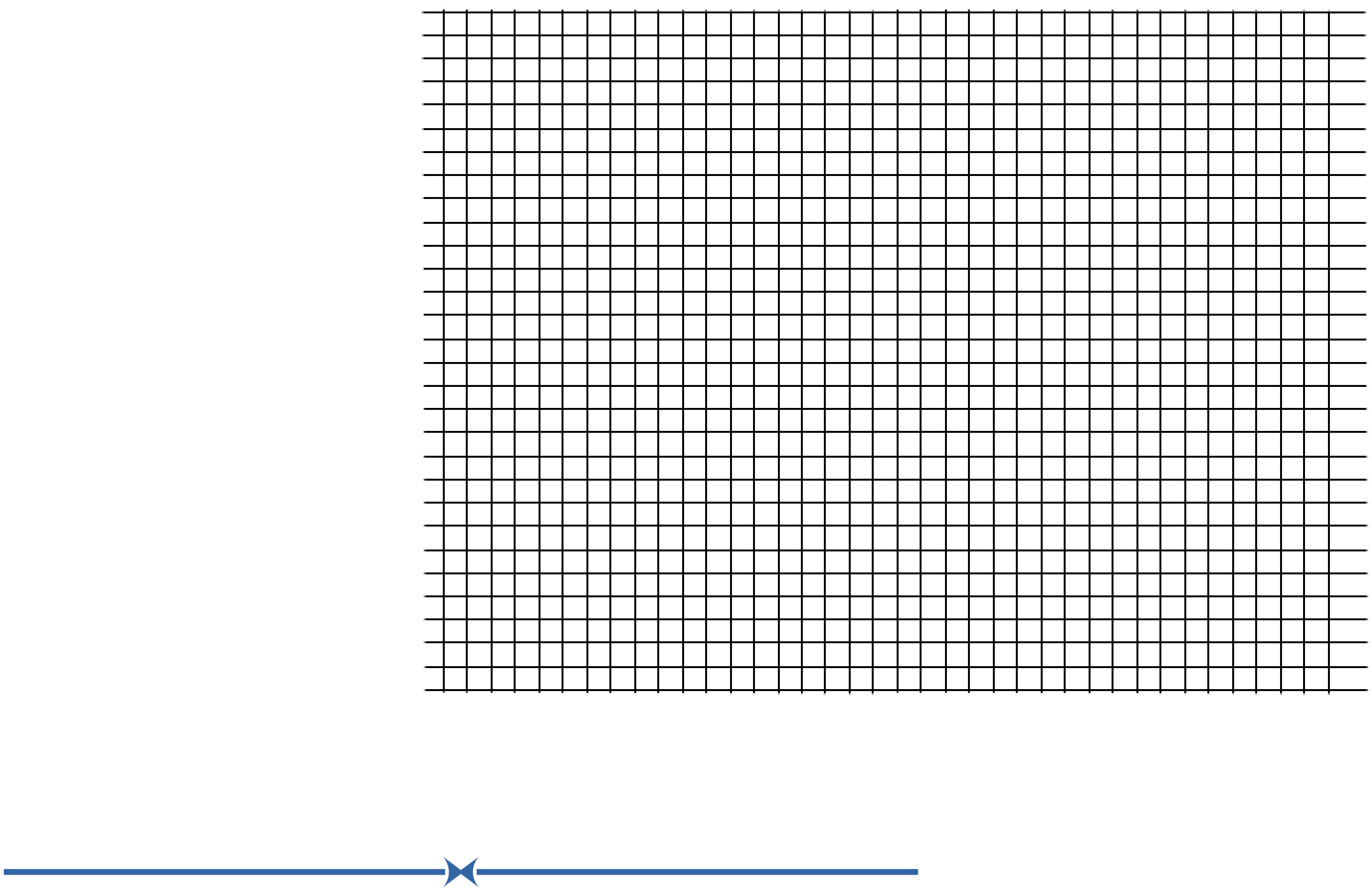
RPCs: Resistive plate chambers

DTs: Drift tubes



General idea of tracking

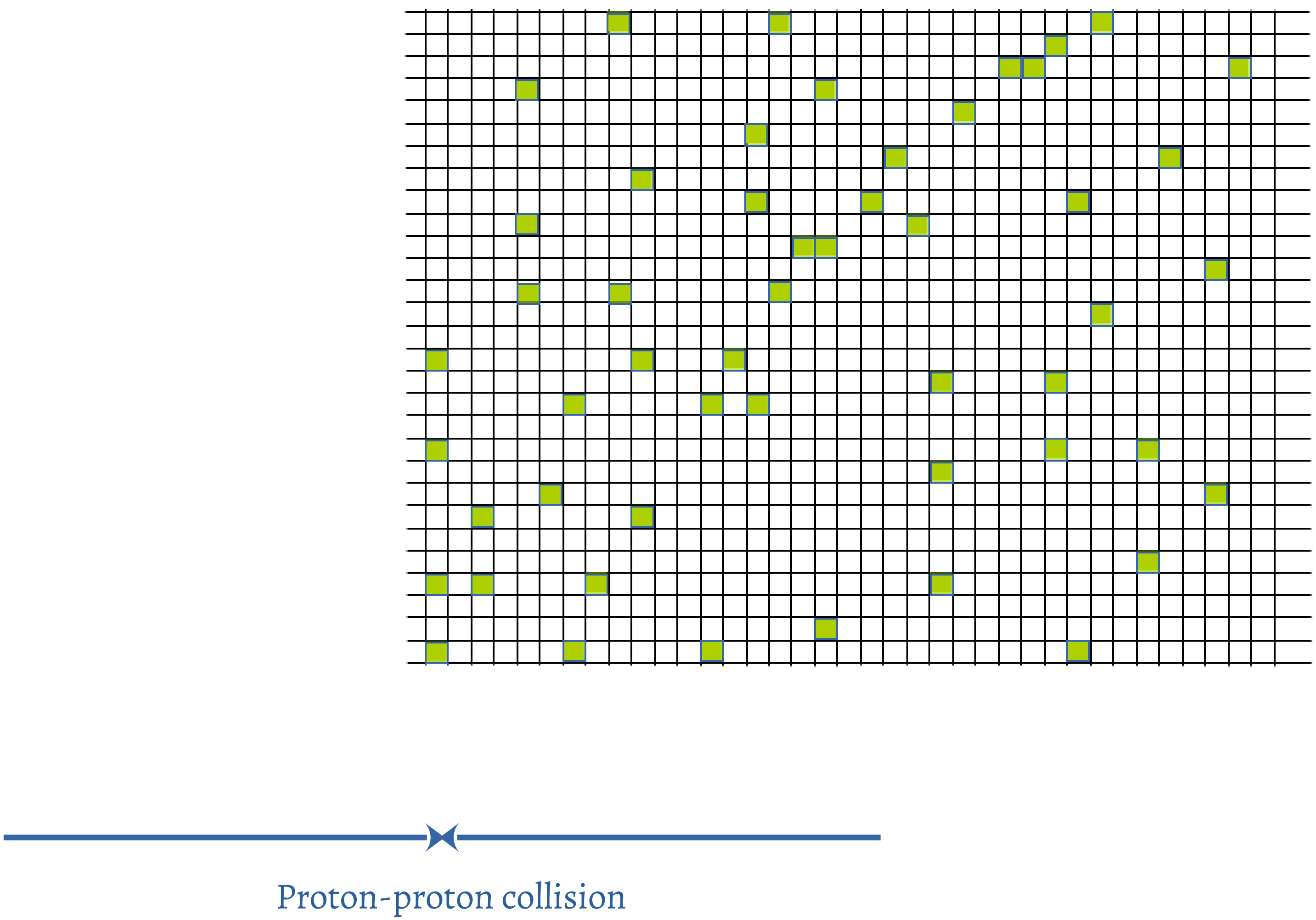
⊗ B-field



Proton-proton collision

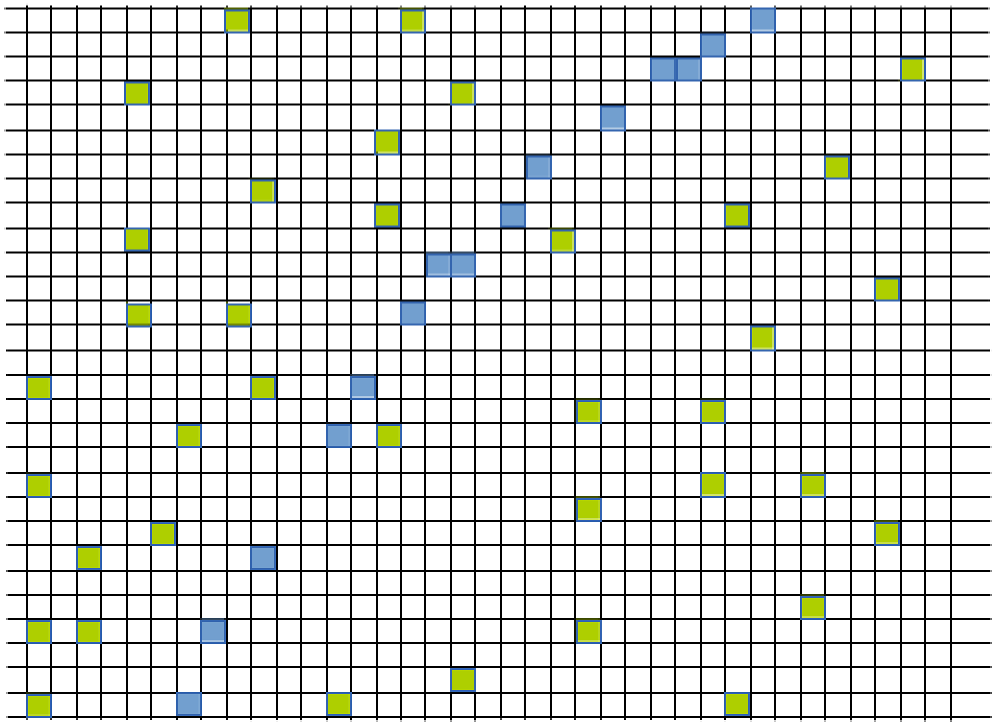
General idea of tracking

⊗ B-field



General idea of tracking

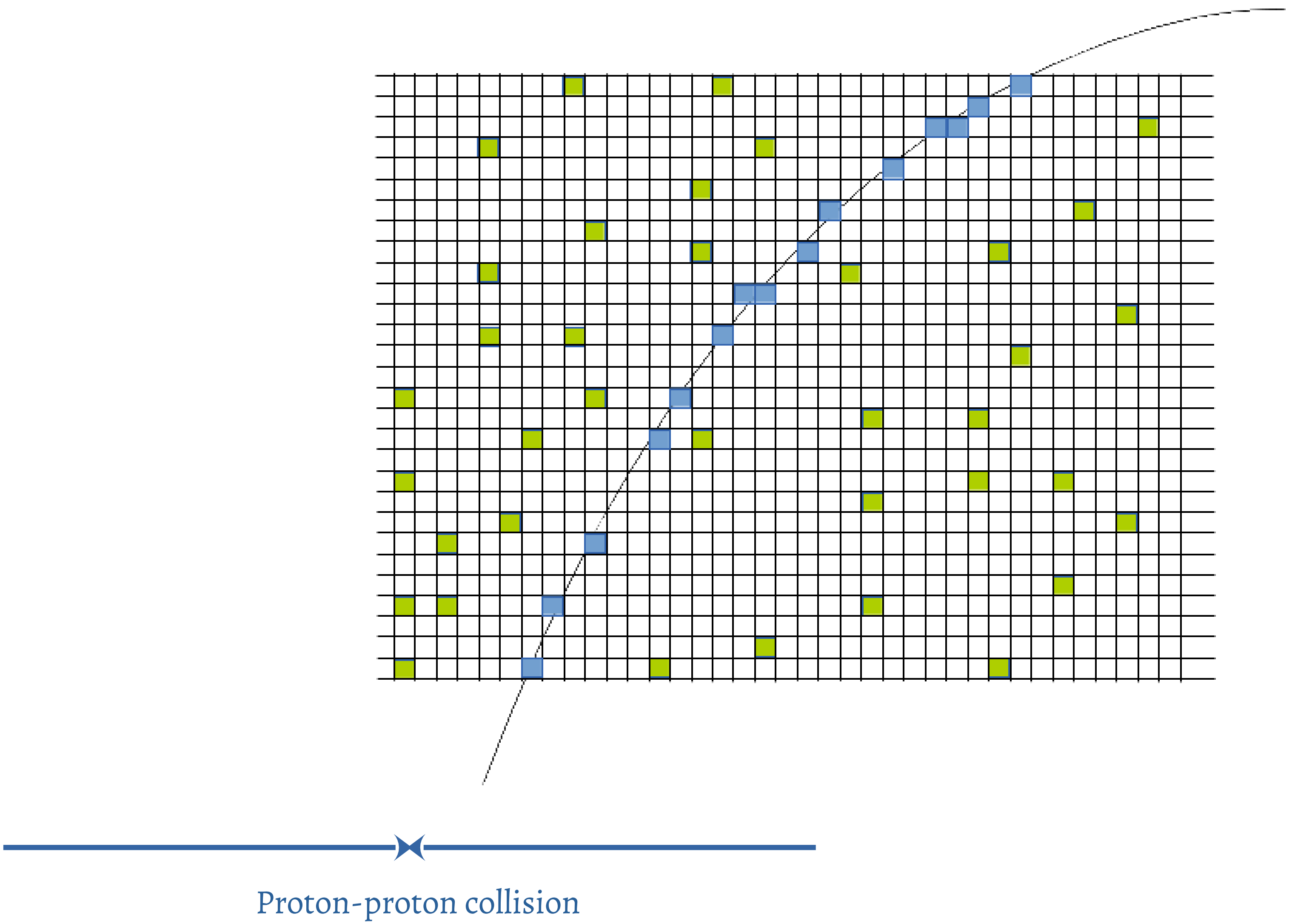
⊗ B-field



Proton-proton collision

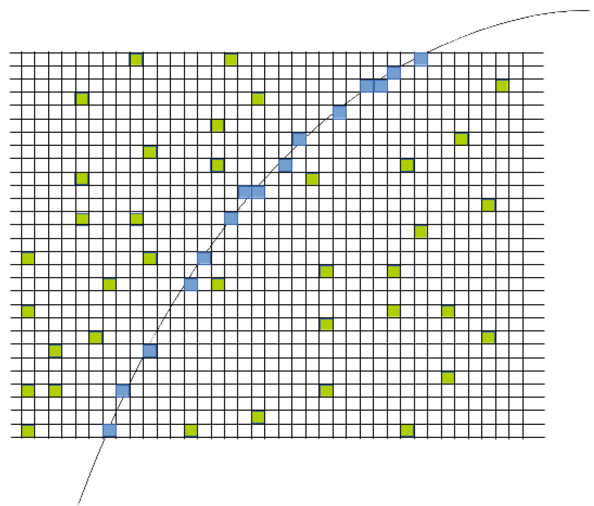
General idea of tracking

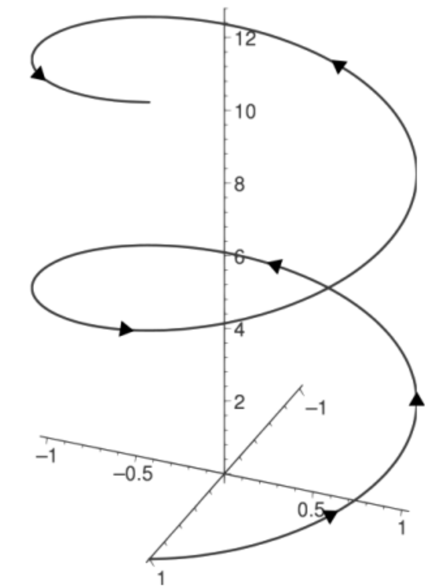
⊗ B-field



General idea of tracking

⊗ B-field





Measure charge (direction of bending), fit the trajectory as a helix. This allows us to determine

Radius of curvature – thus the momentum (p_T)

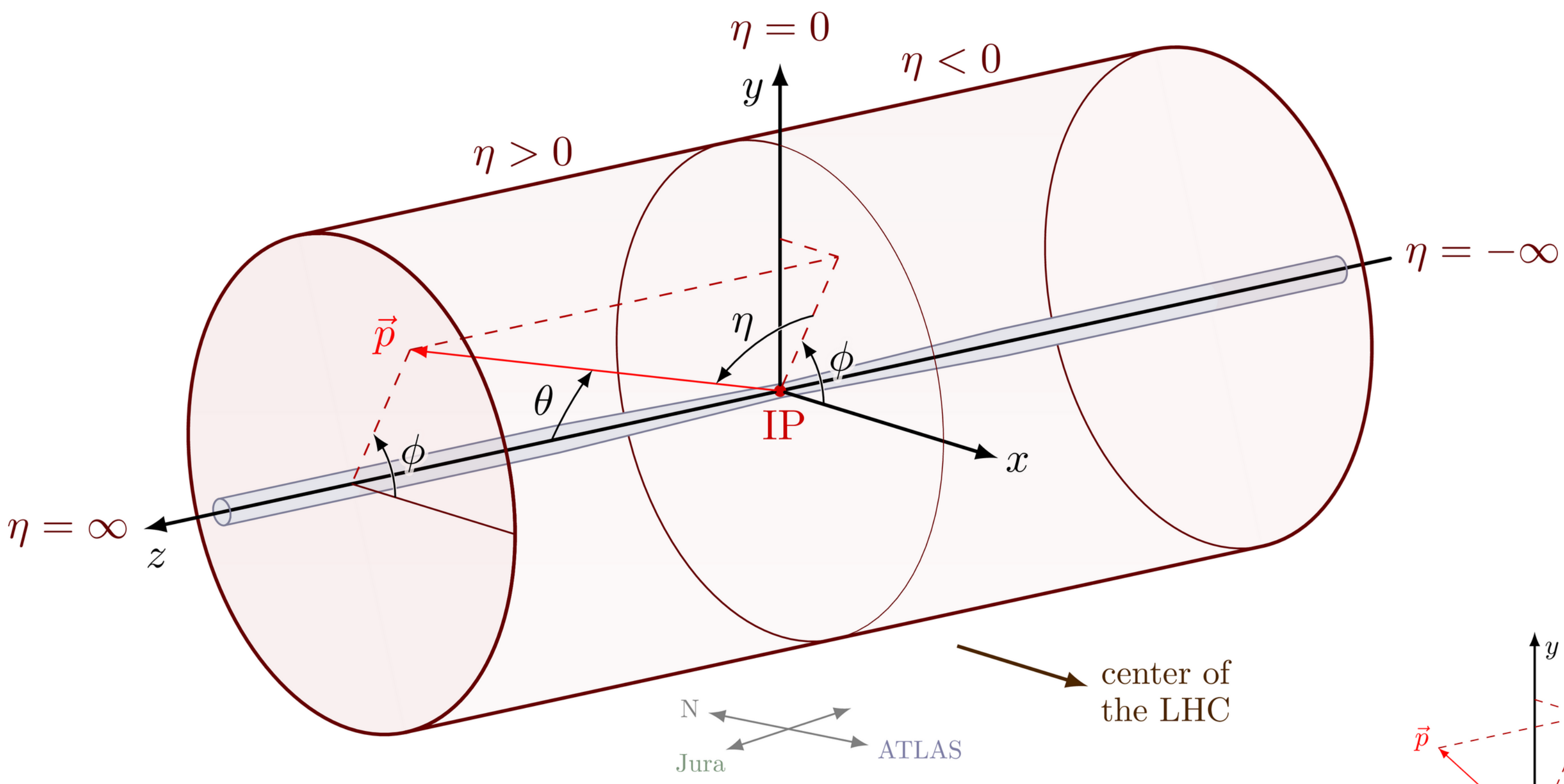
Angle transverse to beamline (ϕ)

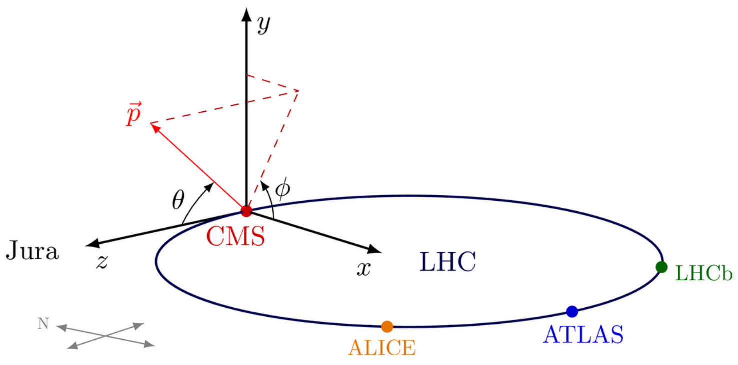
Angle with respect to beamline (θ , or $\eta = -\ln[\tan(\theta/2)]$)

Impact parameters (offset along beamline, offset in plane transverse to beamline)

$p_{T[GeV]} = 0.3 \times B_{[T]} \times r_{[m]}$

Typical coordinate system

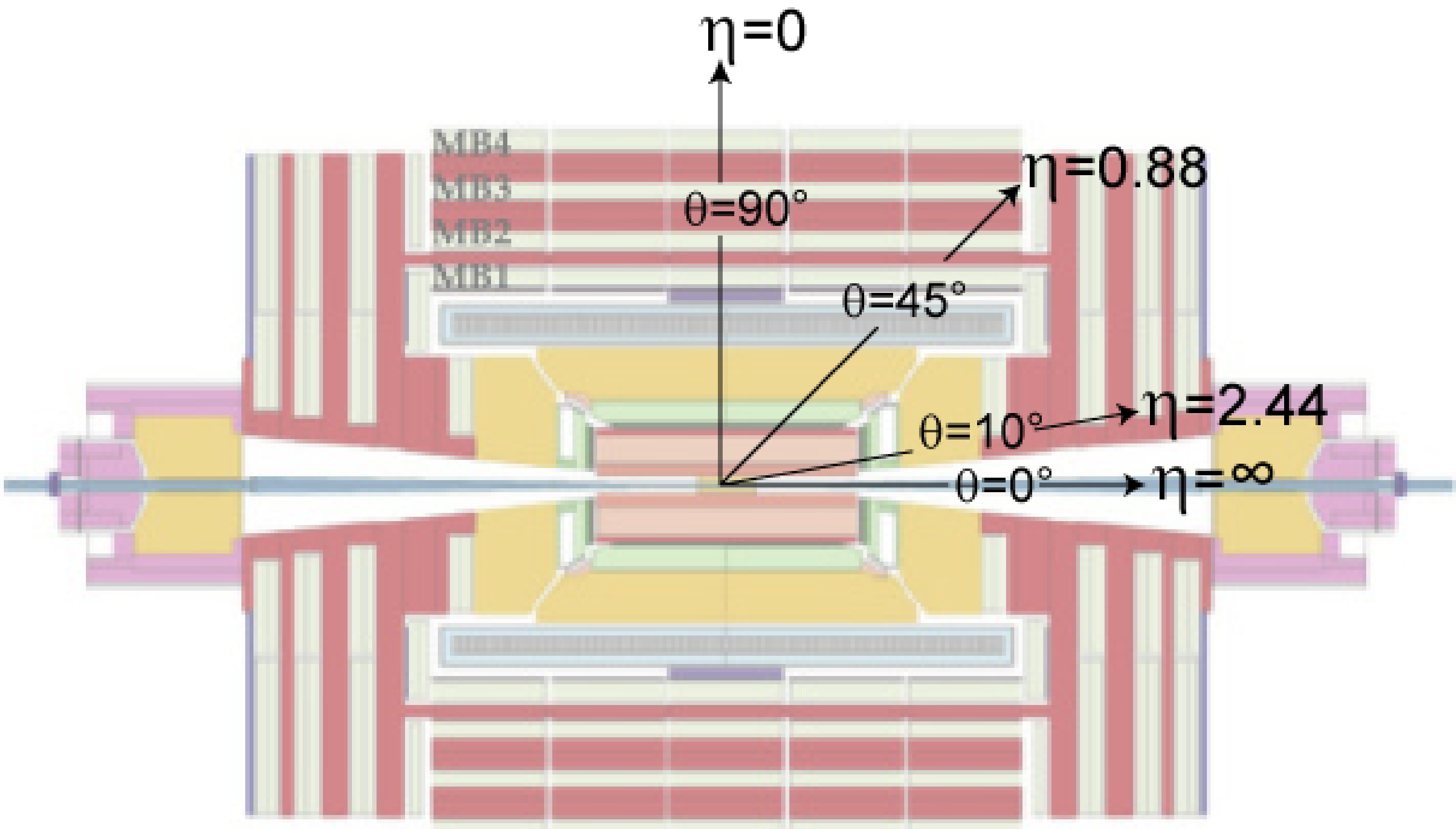




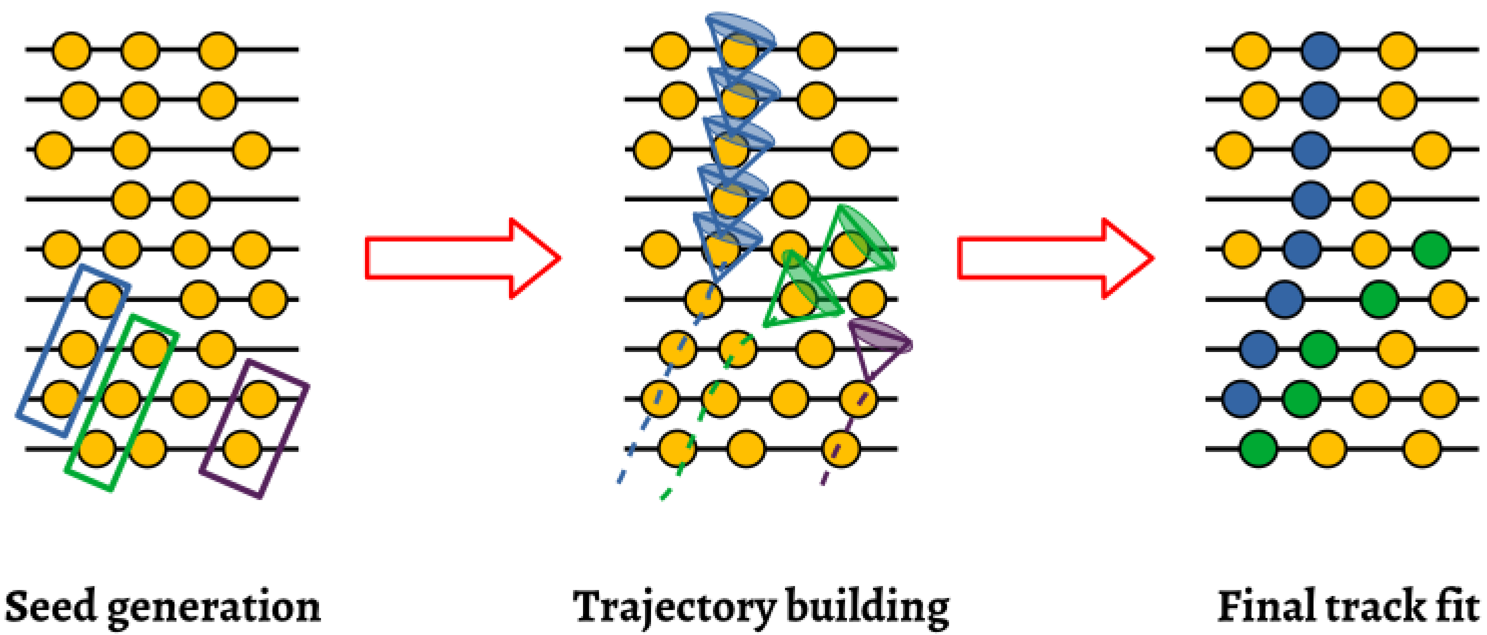
- It is convenient to use (z, θ, ϕ) coordinate system instead of (*x, y, z*)
- θ is converted to η (pseudorapidity).
- Measurement of η and ϕ gives the location of where a particle hits the detector.

Pseudorapidity from θ :

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



Tracking specifics

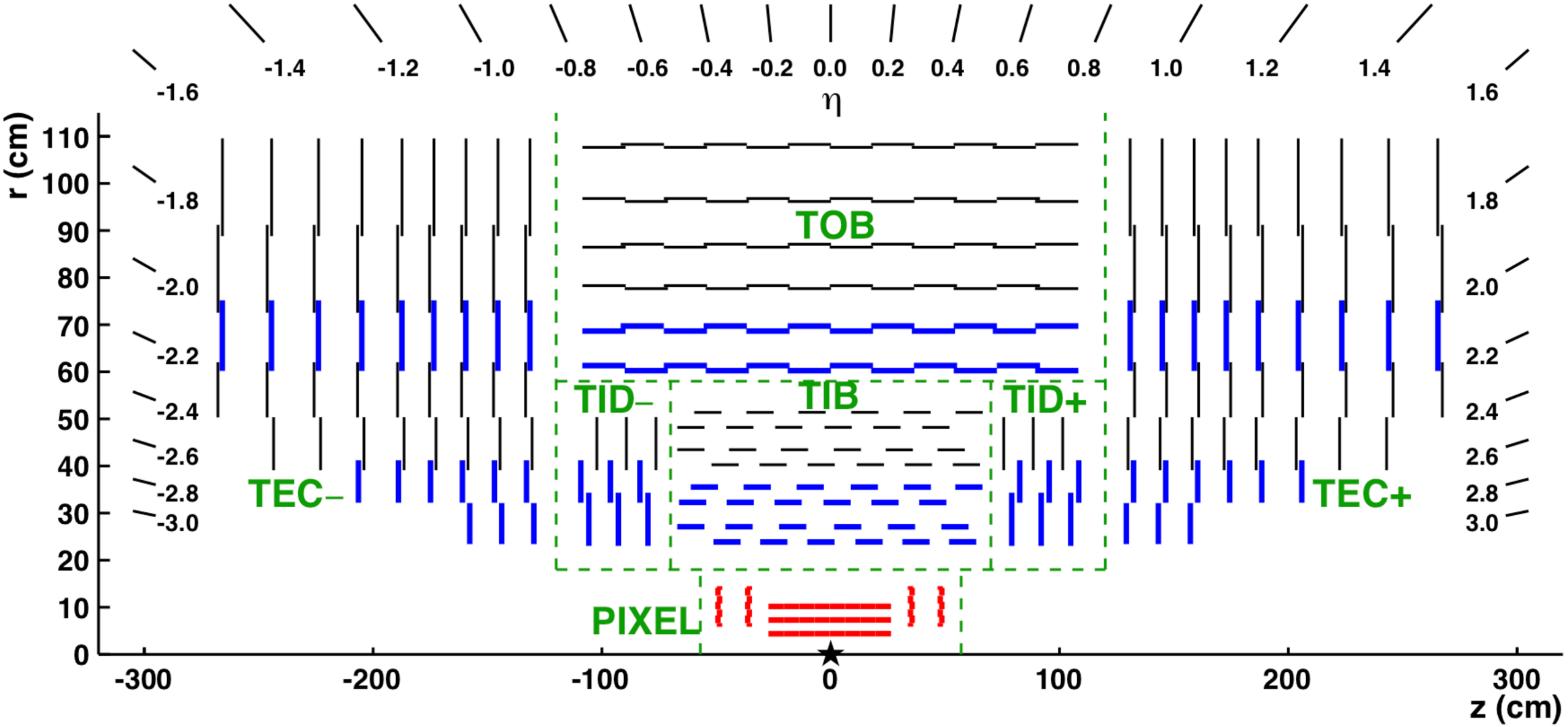


Exceptionally challenging due to combinatorics

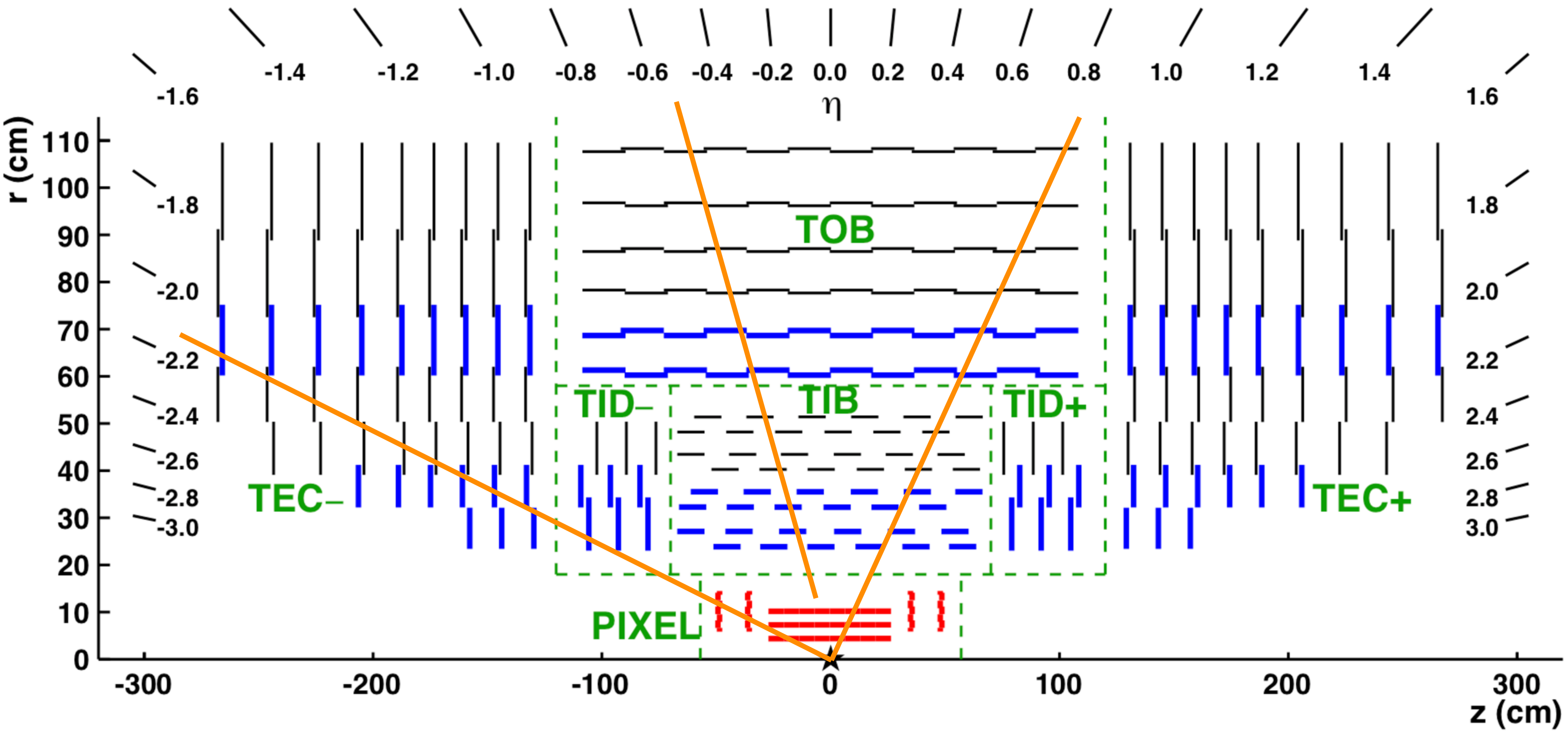
Very compute intensive

Rastogi, A 2022, PhD thesis

CMS Tracker


-1.6
-1.4
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
η
-1.8
-2.0
-2.2
-2.4
-2.6
-2.8
-3.0
1.8
2.0
2.2
2.4
2.6
2.8
3.0
r (cm)
110
100
90
80
70
60
50
40
30
20
10
0
TOB
TID–
TIB
TID+
TEC–
TEC+
PIXEL
-300
-200
-100
0
100
200
300
z (cm)

CMS Tracker



-1.6
-1.4
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
η
r (cm)
110
100
90
80
70
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50
40
30
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10
0
-1.8
-2.0
-2.2
-2.4
-2.6
-2.8
-3.0
1.8
2.0
2.2
2.4
2.6
2.8
3.0
TOB
TID–
TIB
TID+
TEC–
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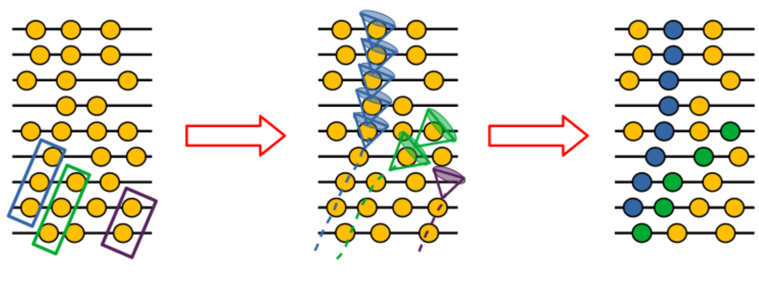
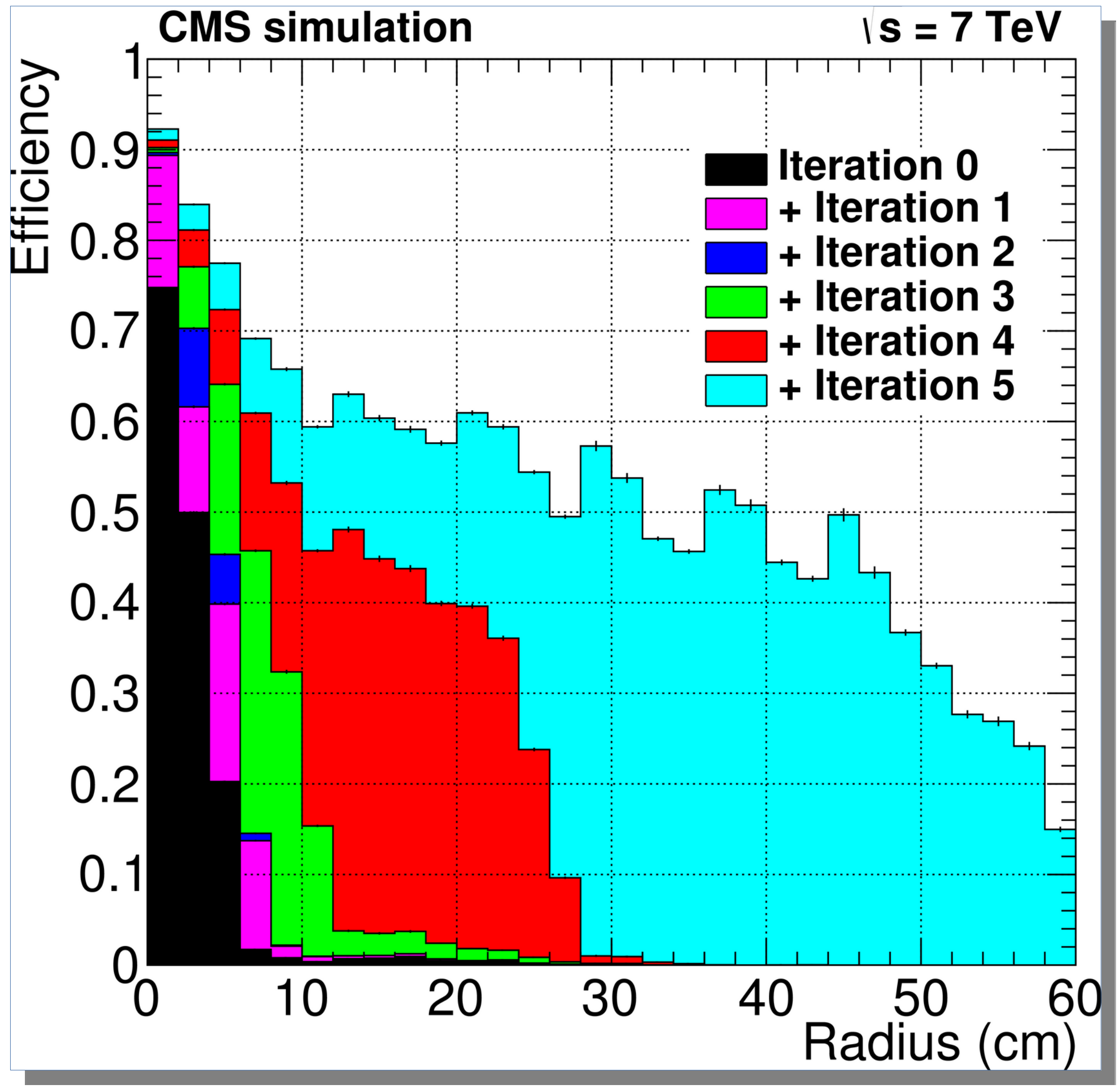
PIXEL
-300
-200
-100
0
100
200
300
z (cm)

Tracking specifics

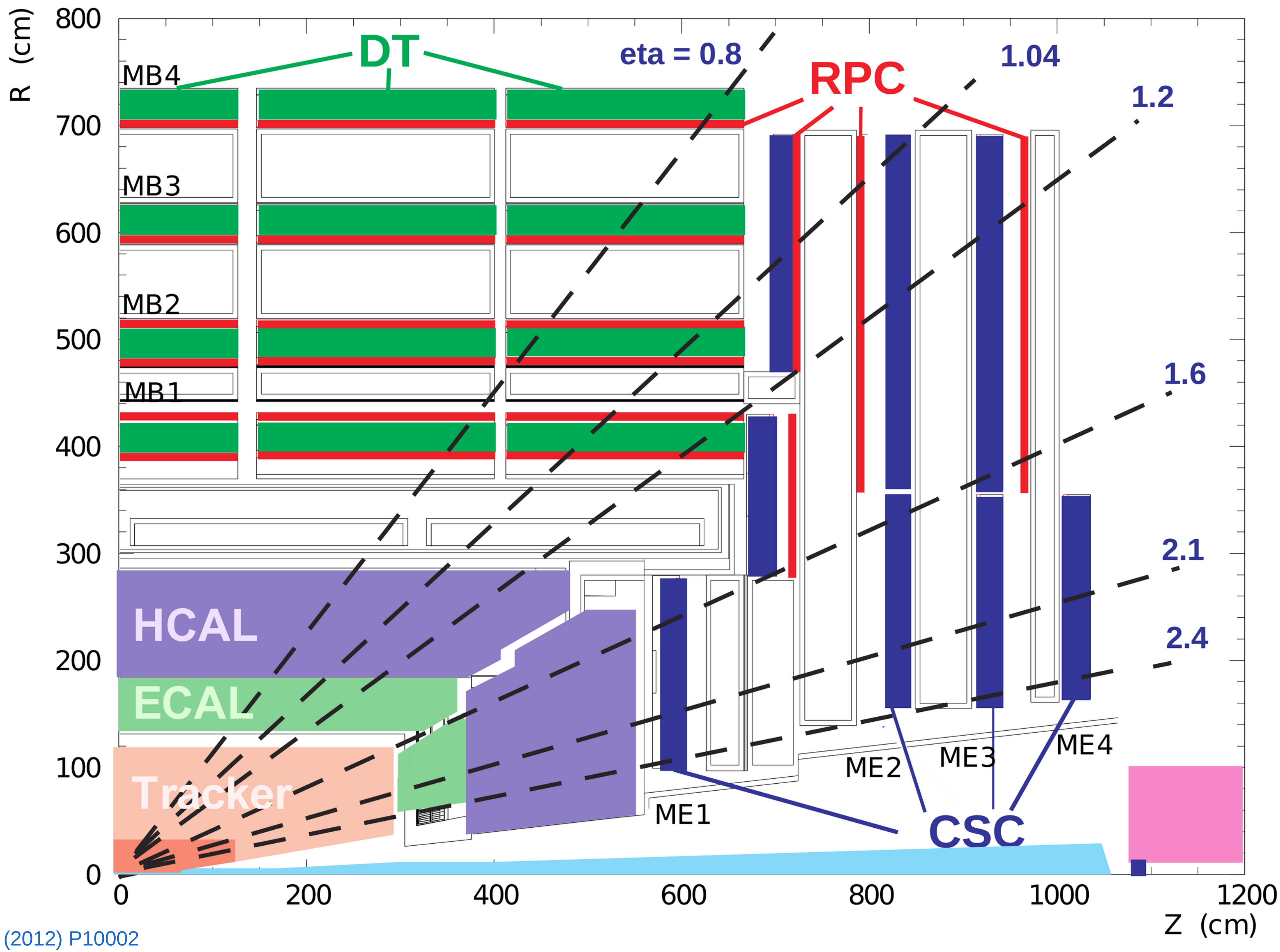


Track reconstruction is iterative. Starts from prompt tracks, and proceeds to finding more and more displaced tracks.



J. Instrum. 9 (2014) P10009

CMS Muon Detector



J. Instrum. 7 (2012) P10002

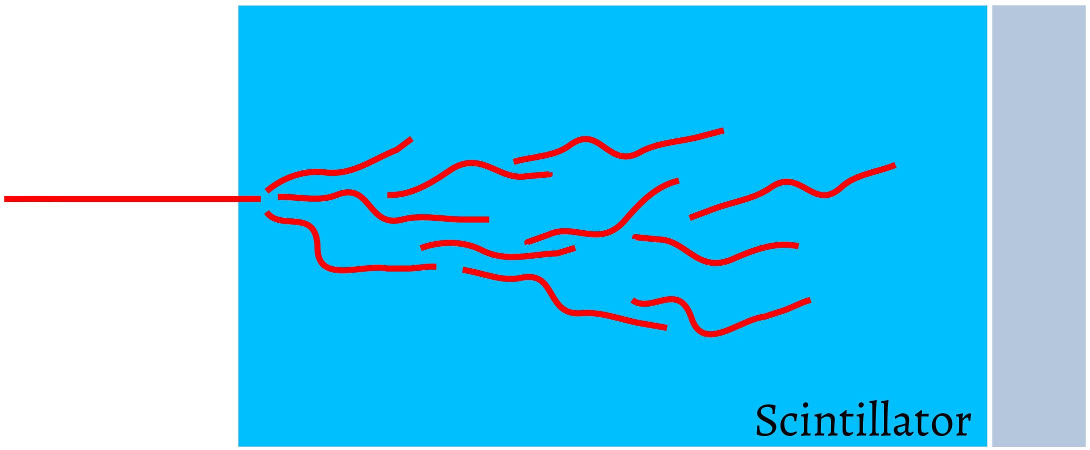
Trackers measure charge, momentum, trajectory

They do not stop the particle!

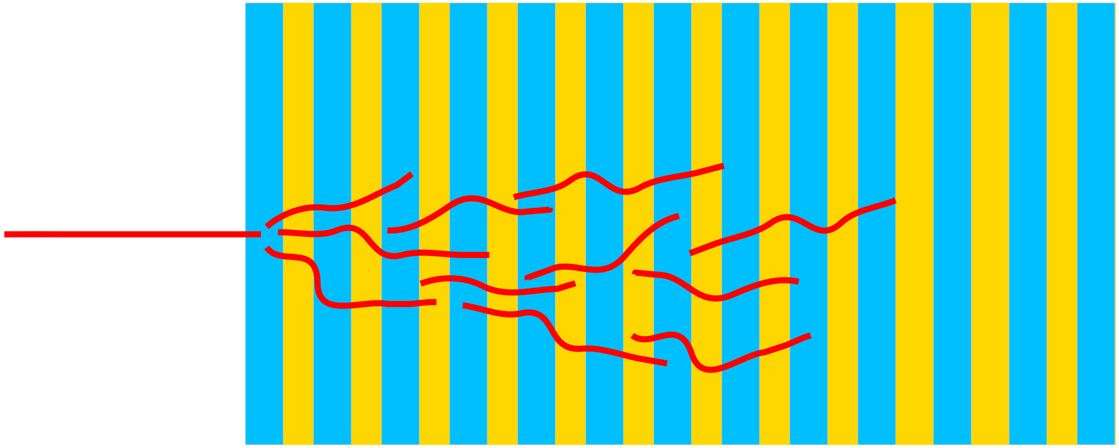
Calorimeters measure energy of particle.

They need to stop the particle (thus measuring complete energy!)

Calorimeters

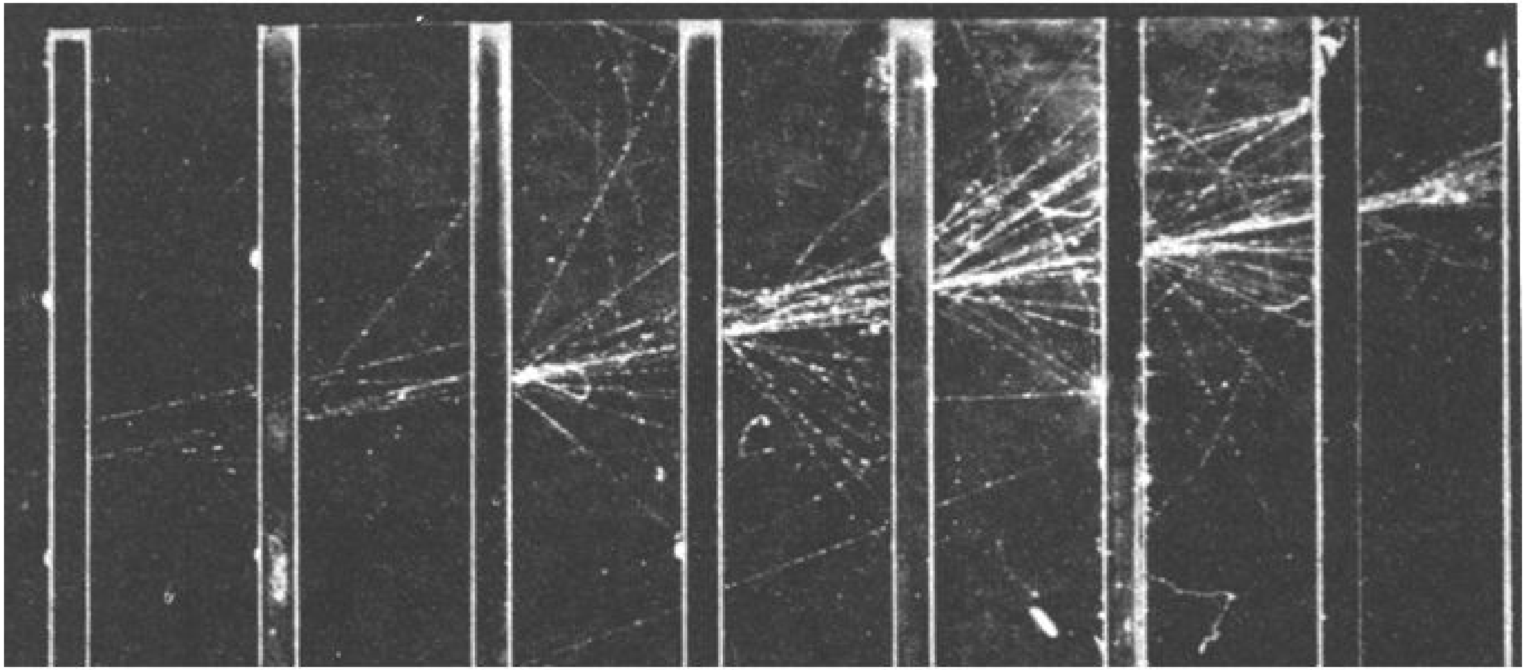


Homogenous calorimeter
The absorber is also the detector, with typically light being collected by a sensor.



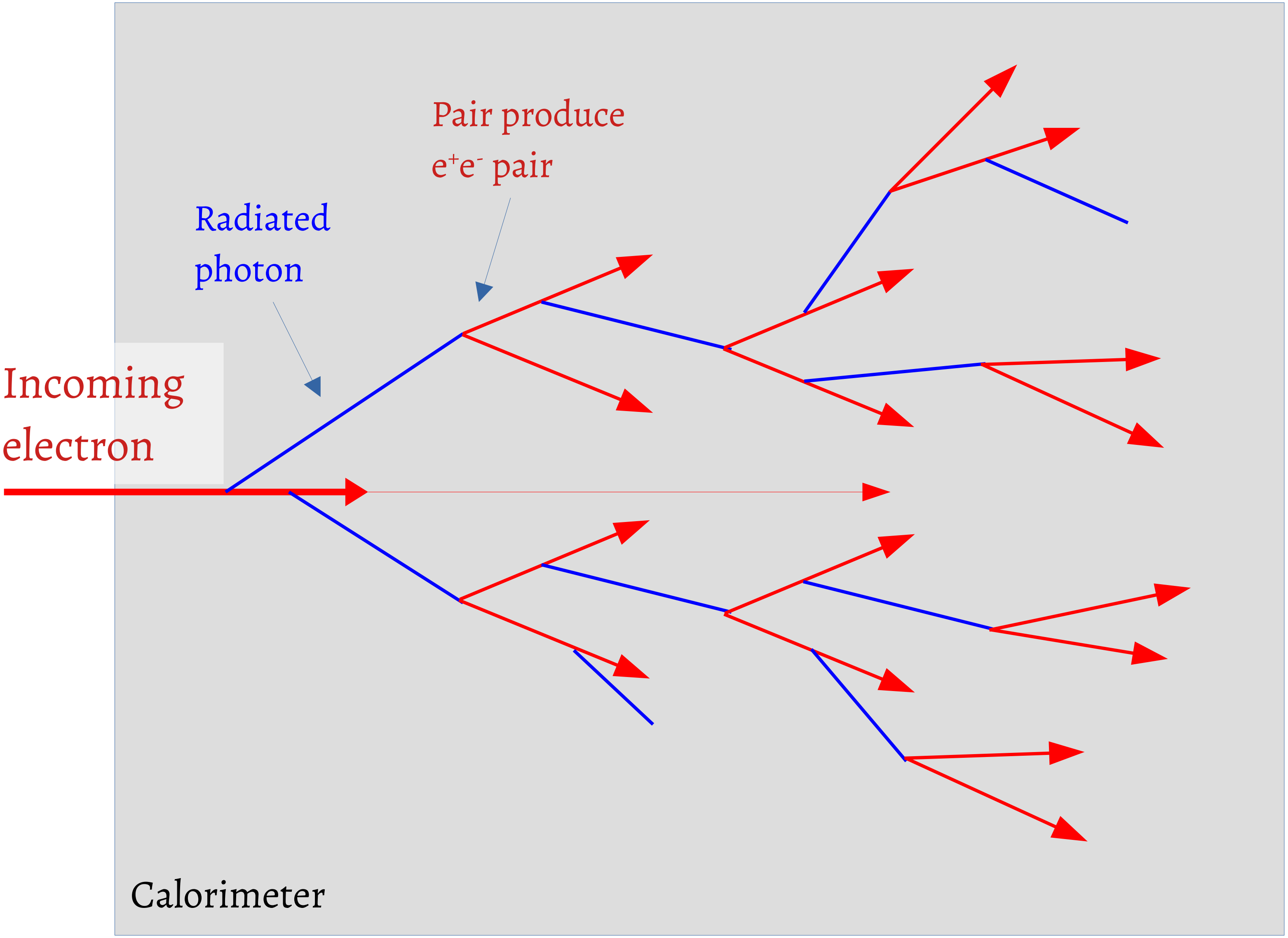
Sampling calorimeter
Passive heavy material layers interspersed with the active layers that detect energy deposited.

Calorimeter shower



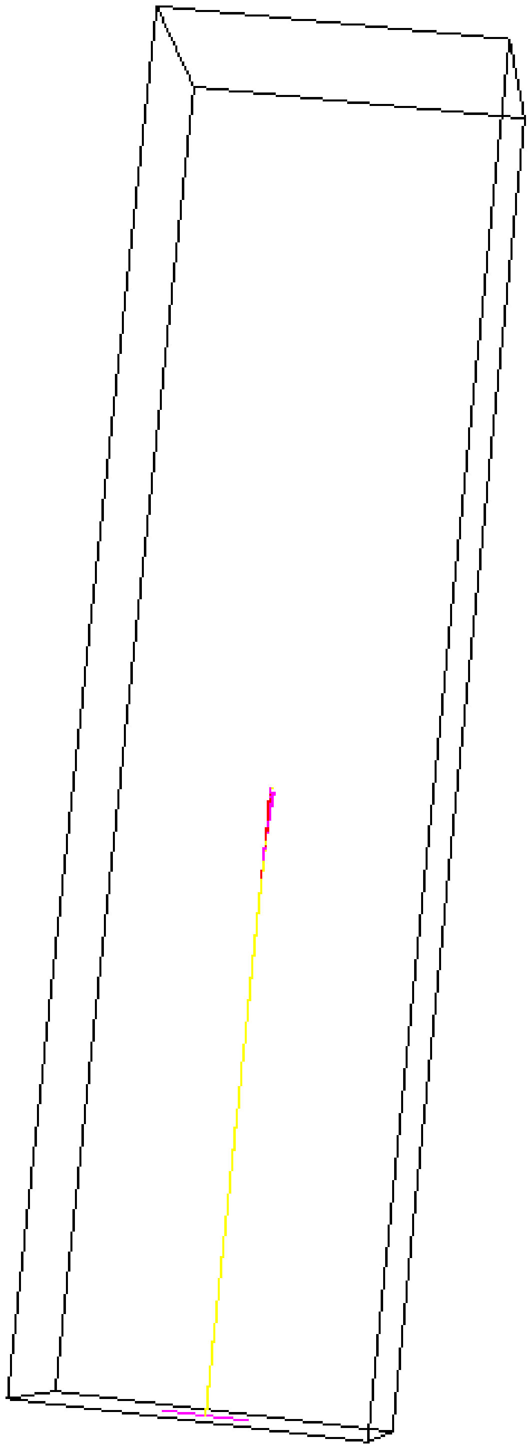
Electron in a cloud chamber with lead absorbers

Electromagnetic shower



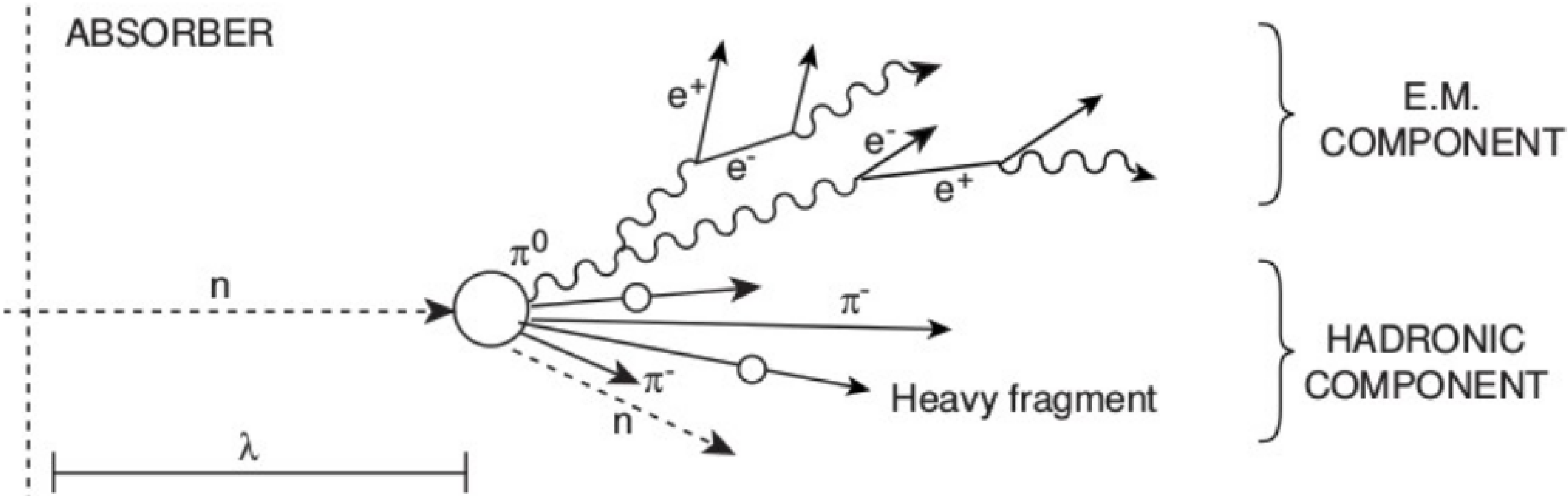
Bremsstrahlung
Pair-production
Collisions with atomic electrons
Ionization

40 GeV electron in a lead glass block.



ELSS The Electromagnetic Shower Simulator
https://www.mpp.mpg.de/~menke/elss/home.shtml

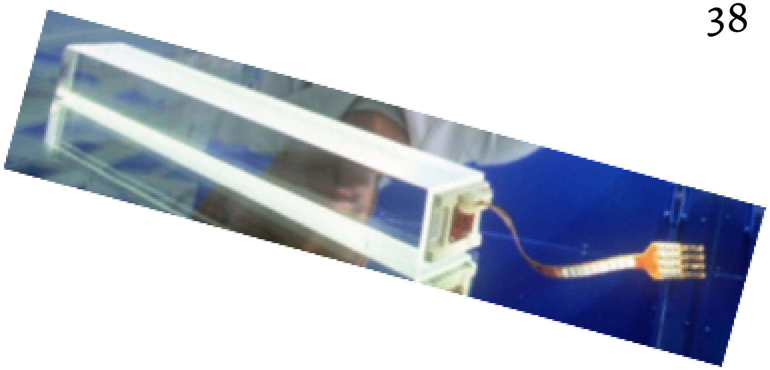
Hadronic shower

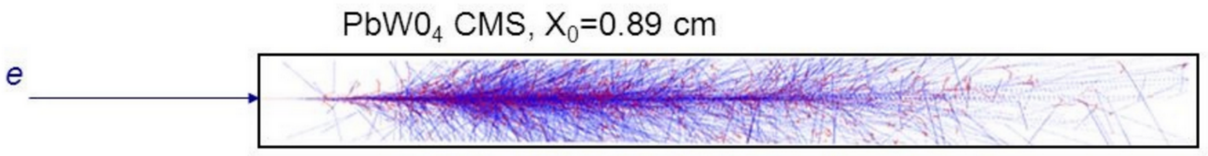


ECAL (Electromagnetic Calorimeter) :

PbWO4 crystals connected to photomultipliers.

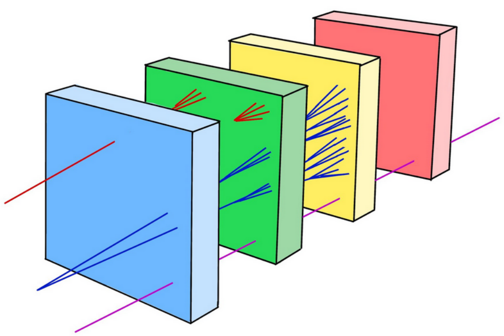
The crystal "scintillates" when electrons/photons pass through it.

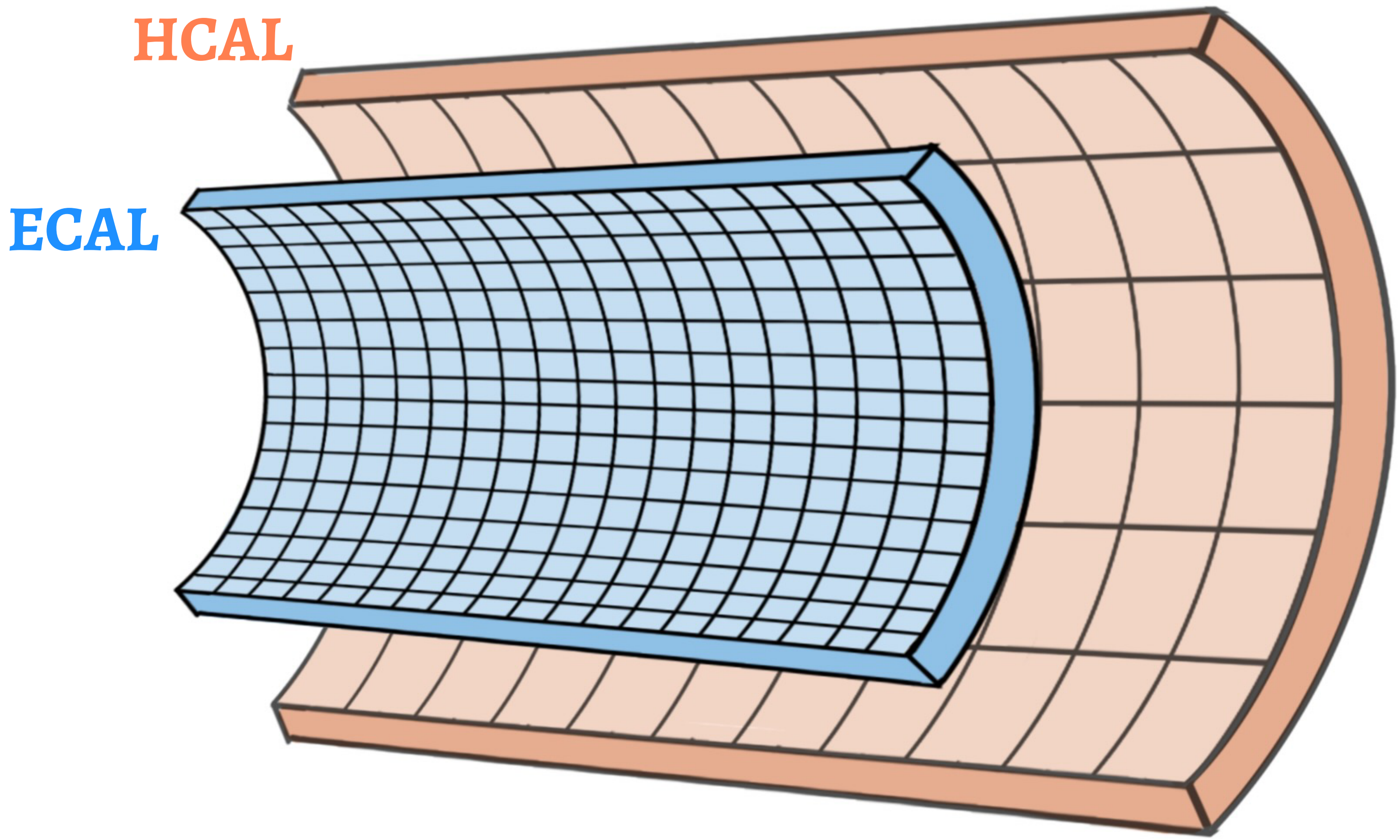


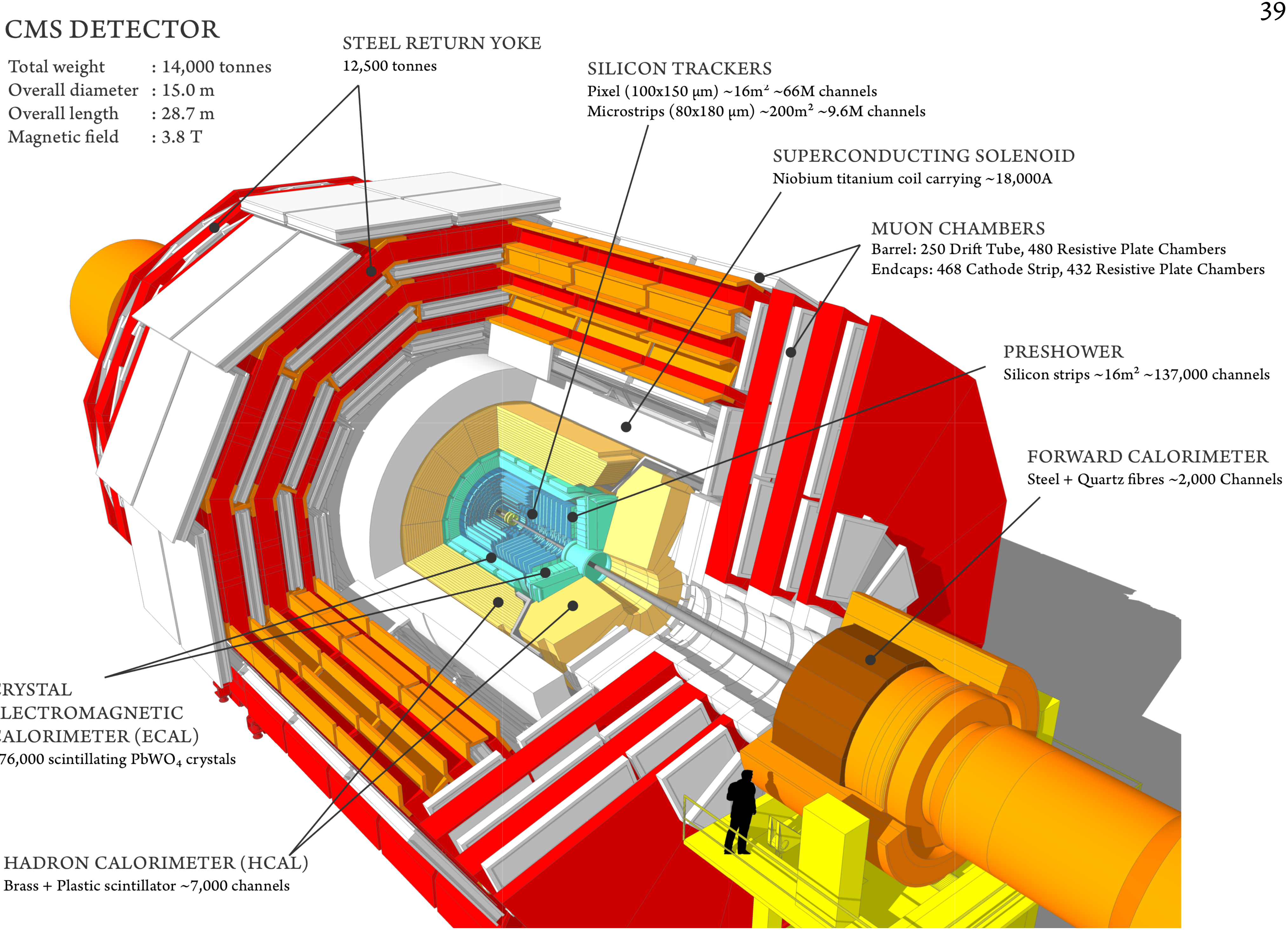


HCAL (Hadronic Calorimeter) :

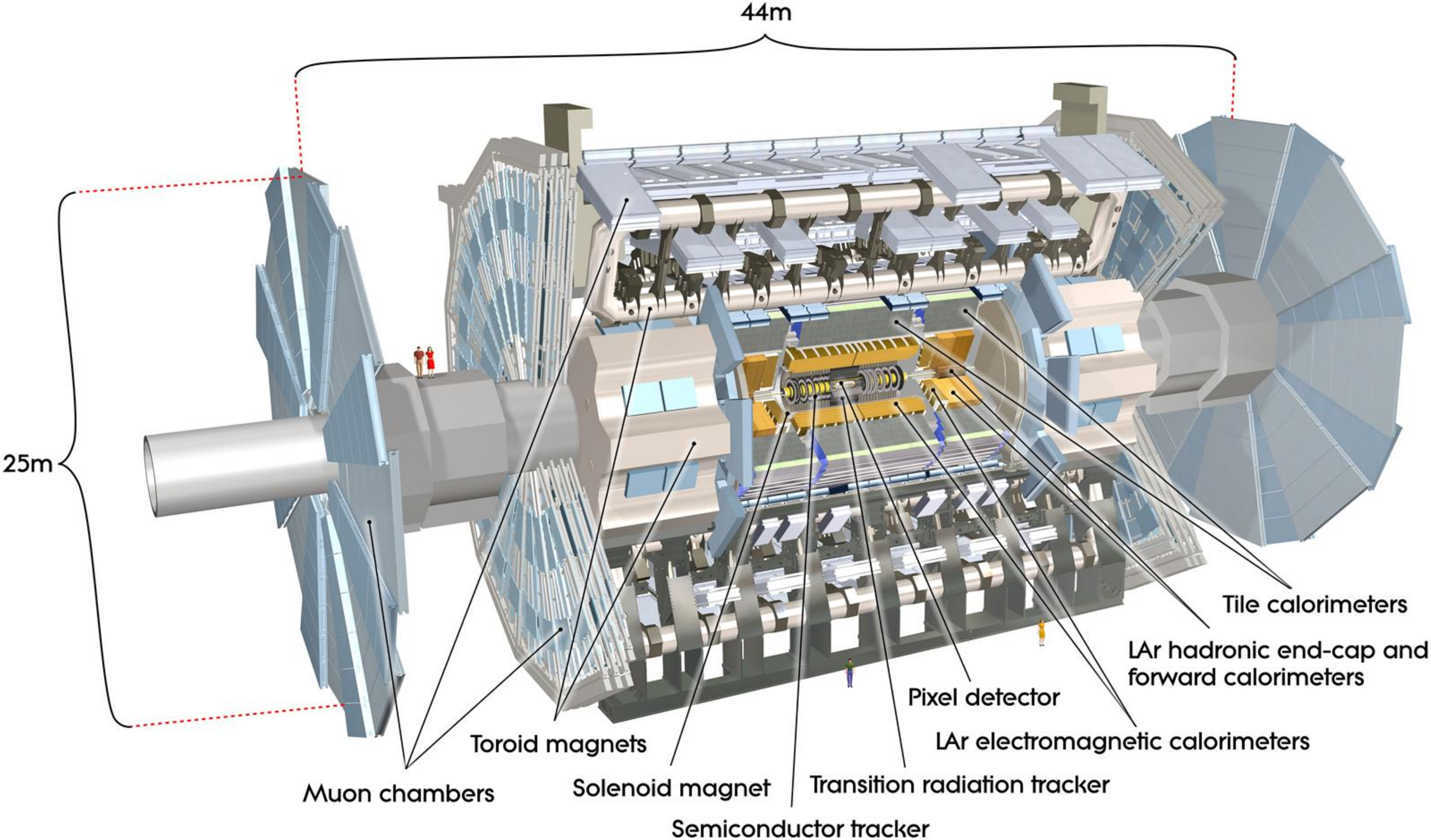
Sampling calorimeter with brass sandwiched with plastic scintillator.



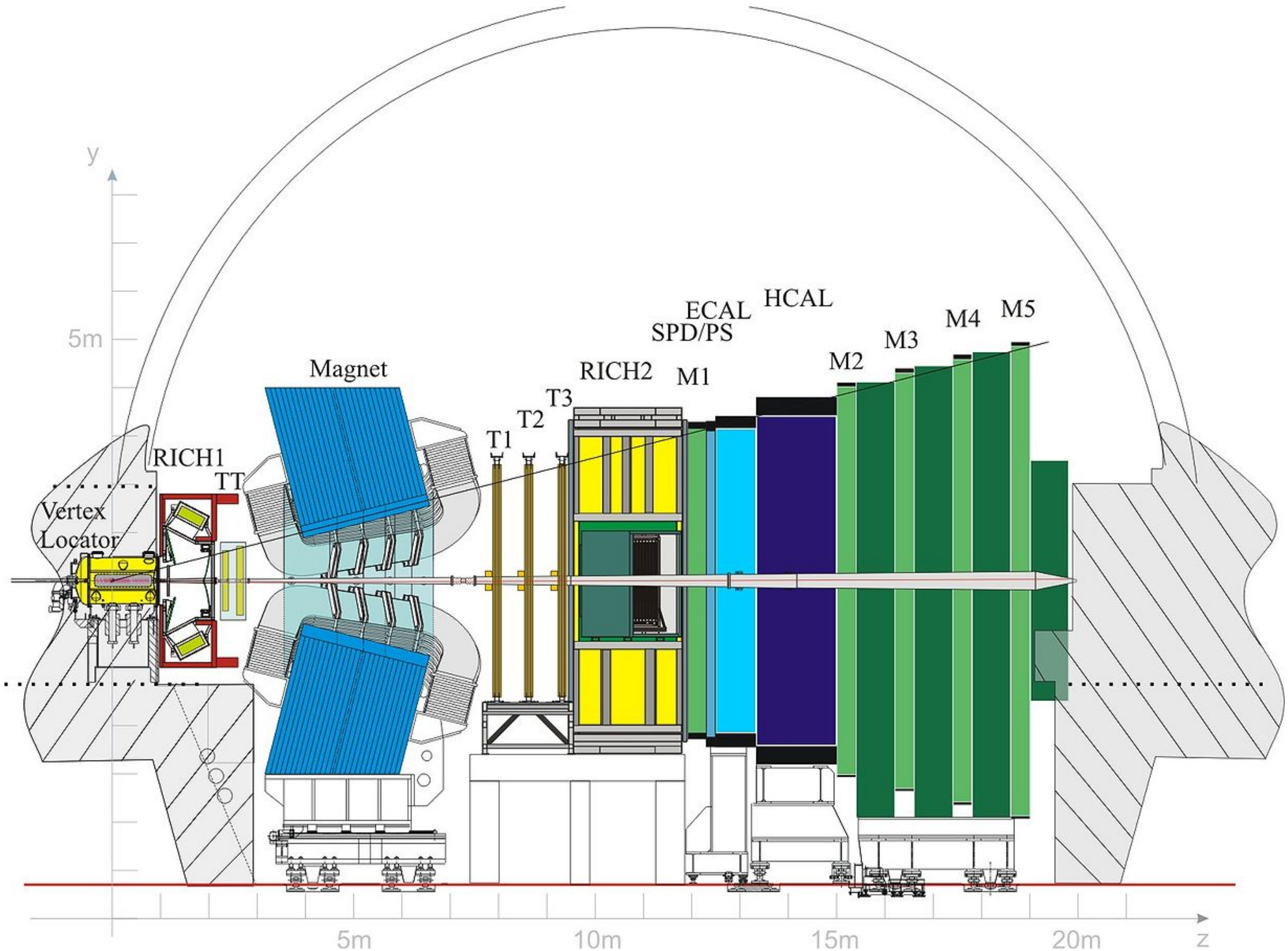



CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

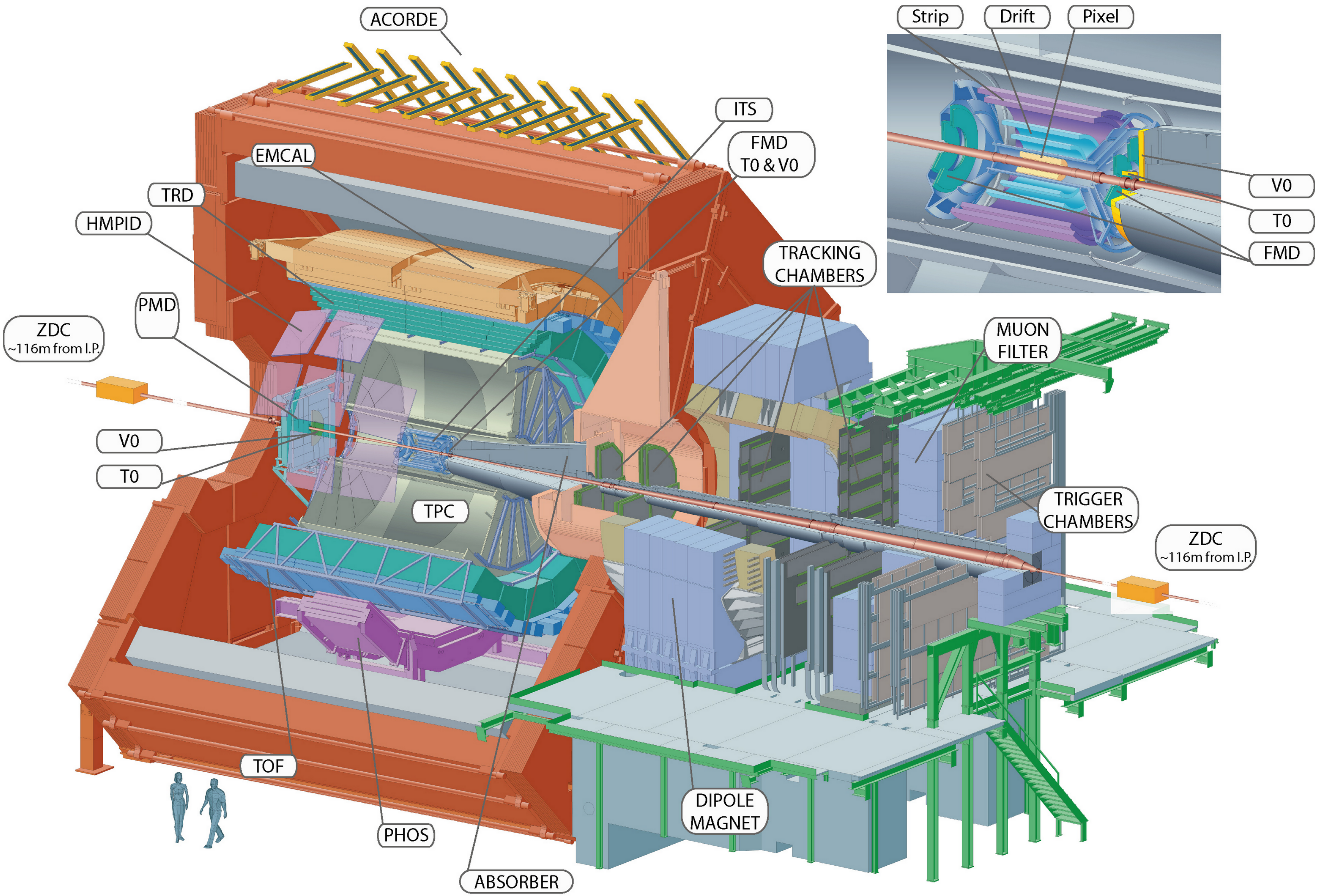
ATLAS detector

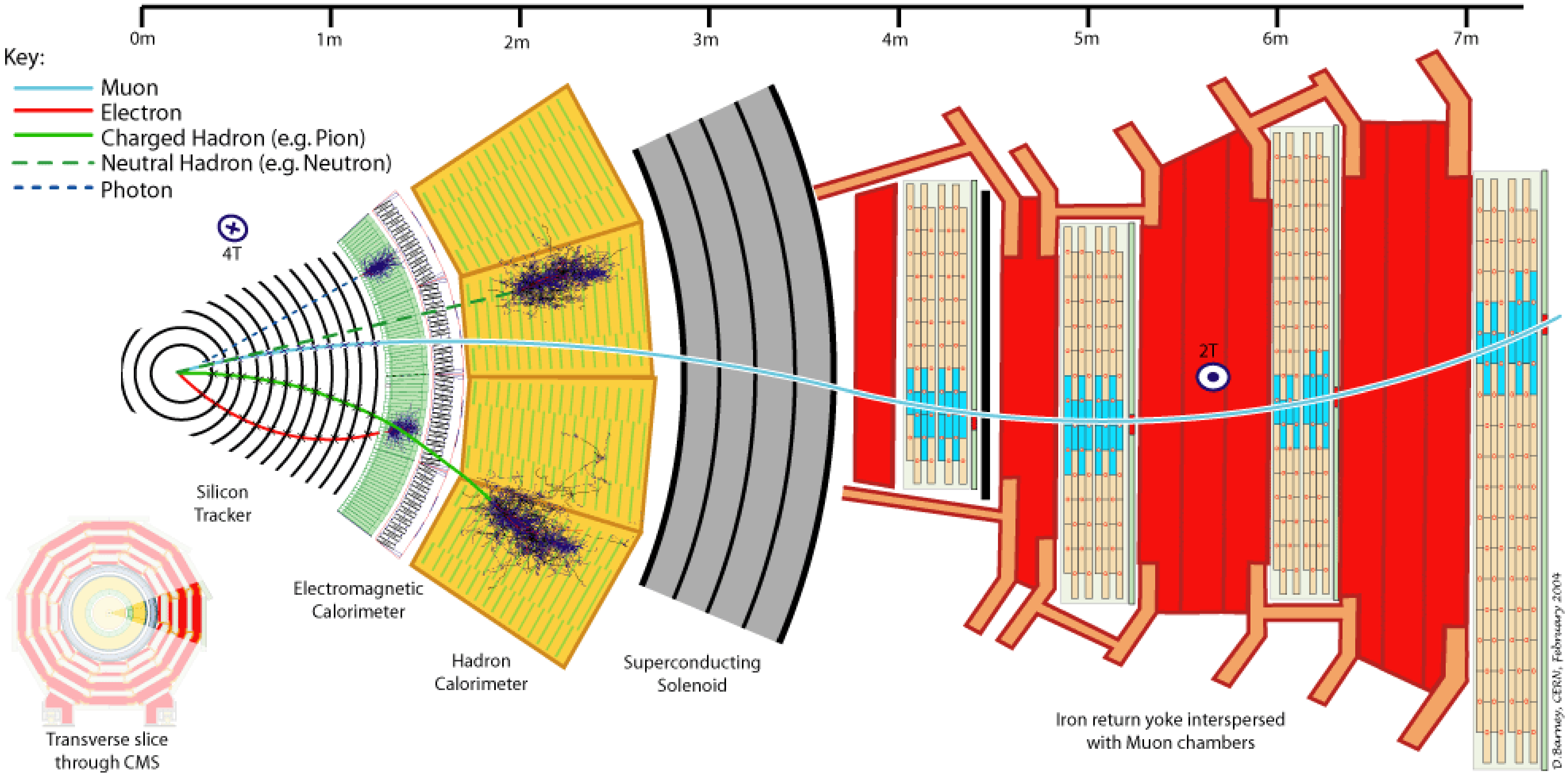


LHCb detector



ALICE detector

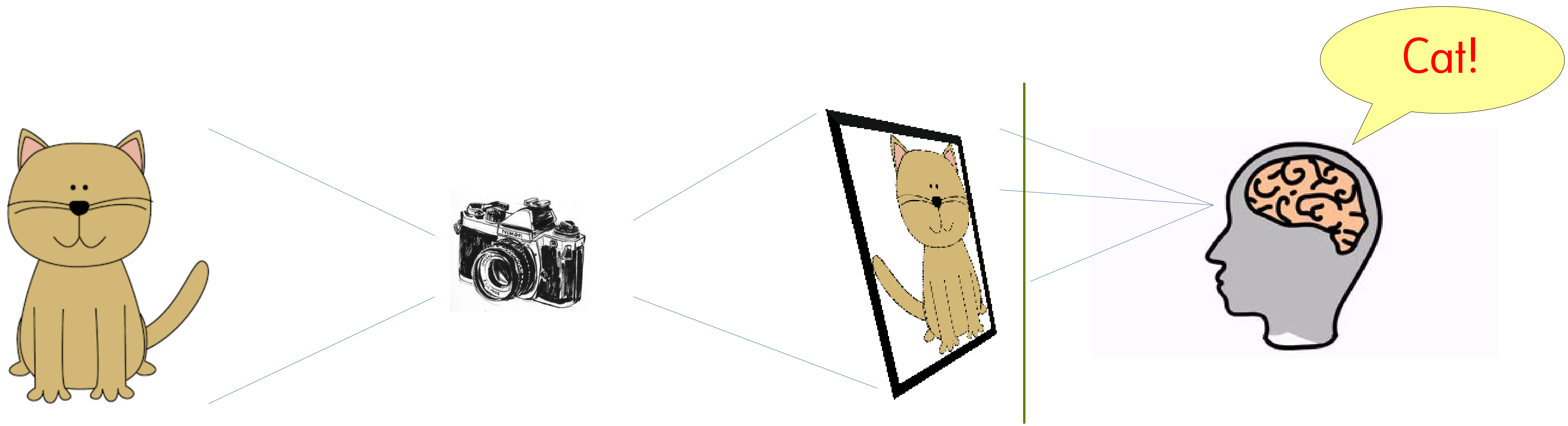




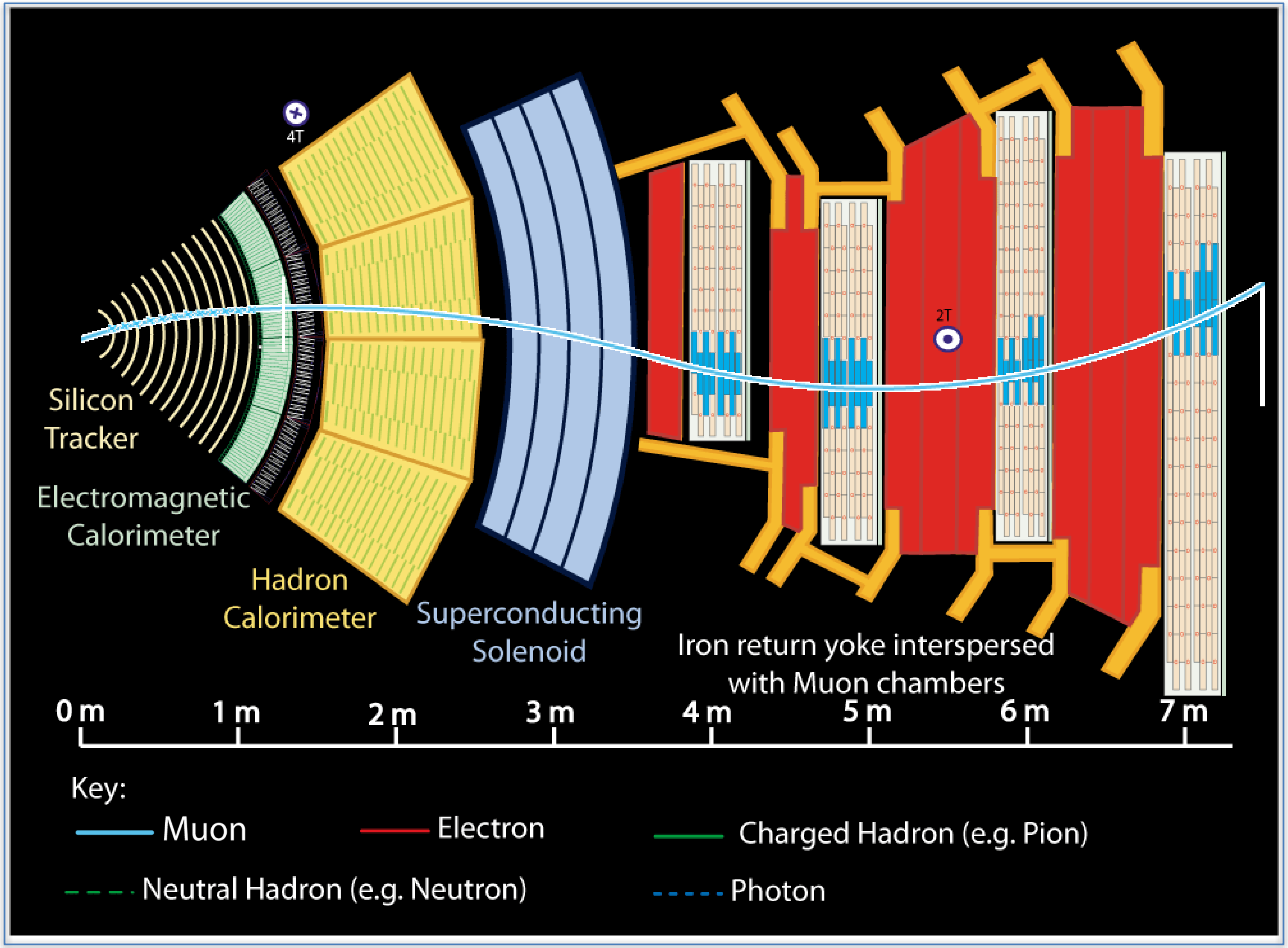
This is how the detector responds to different particles passing through it.

Lecture 3: Object Reconstruction

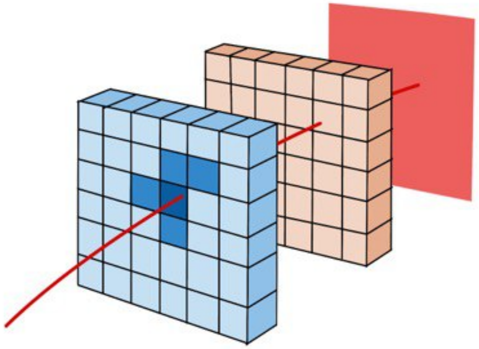
Object Reconstruction and Identification



Object Detector Data collected Data analyzed

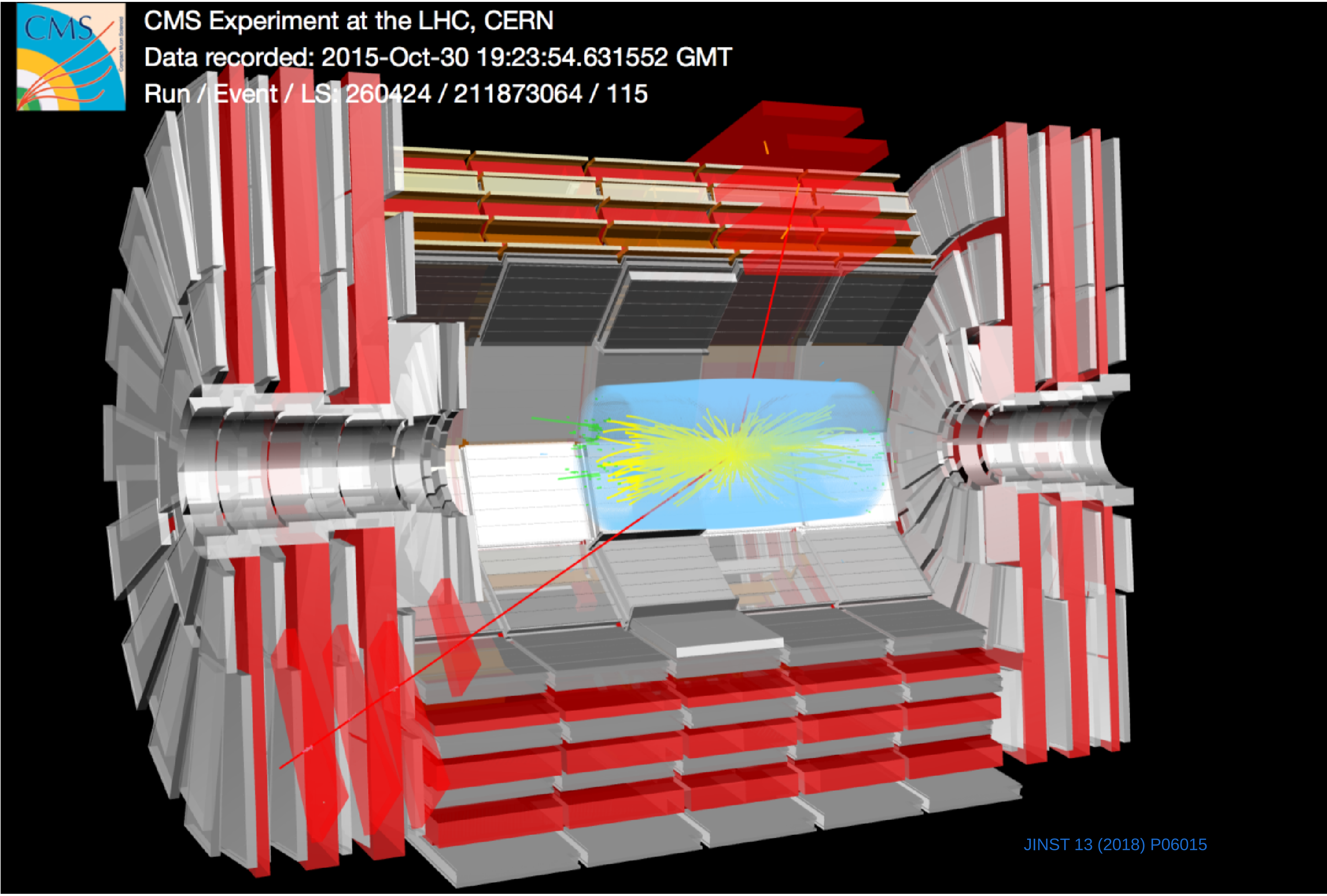


Muons

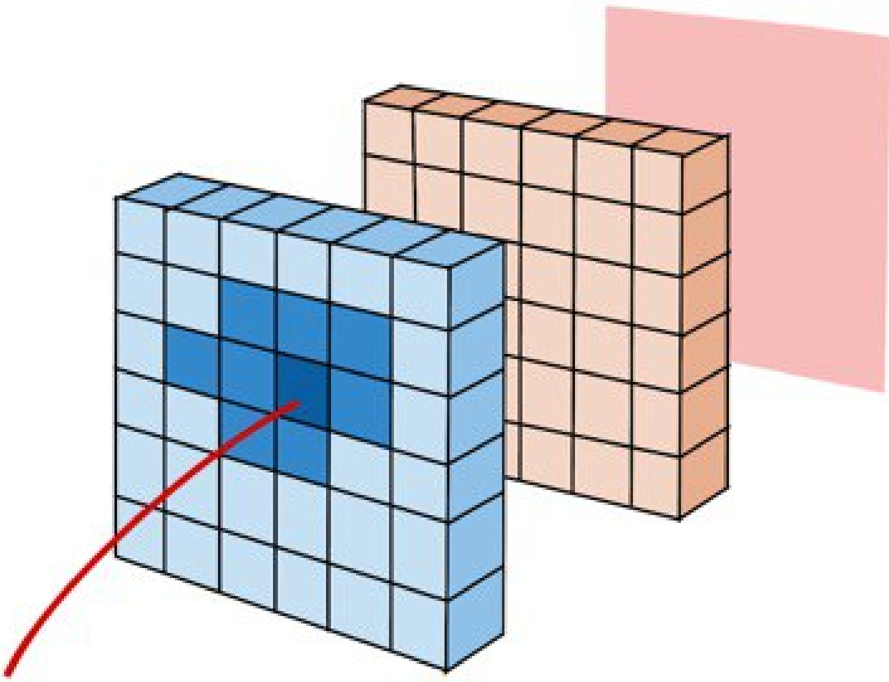


Match up tracks in the inner tracker and the outer muon chambers.

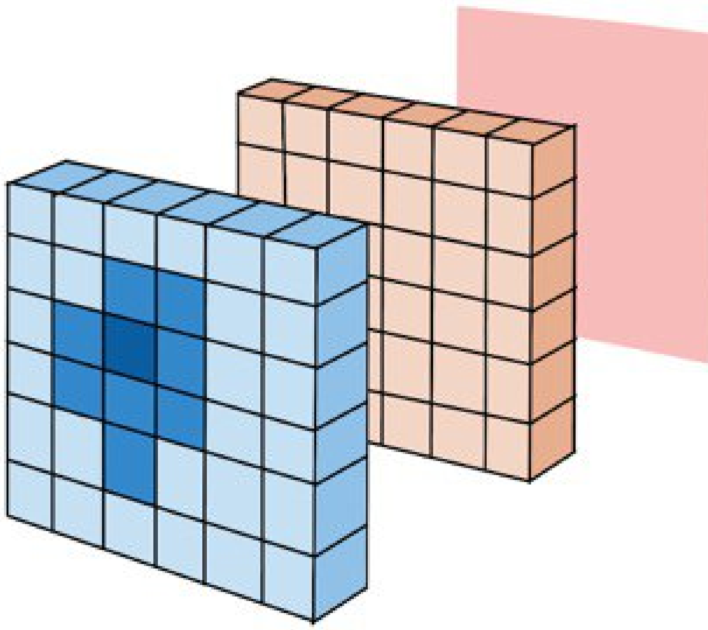
1. How good is the match? Spatially, and in momentum
2. How good are the individual tracks (inner and outer)
3. Is the calorimeter deposit low/negligible ?


CMS Experiment at the LHC, CERN
Data recorded: 2015-Oct-30 19:23:54.631552 GMT
Run / Event / LS: 260424 / 211873064 / 115
JINST 13 (2018) P06015

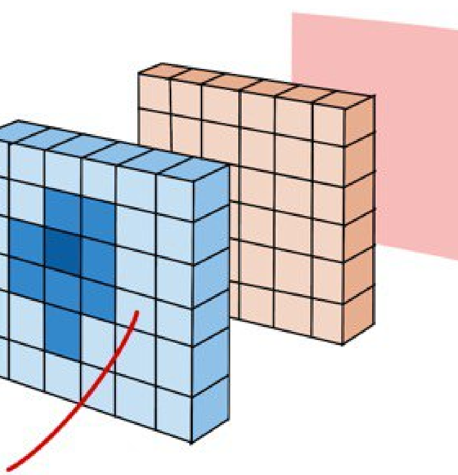
Electrons and Photons



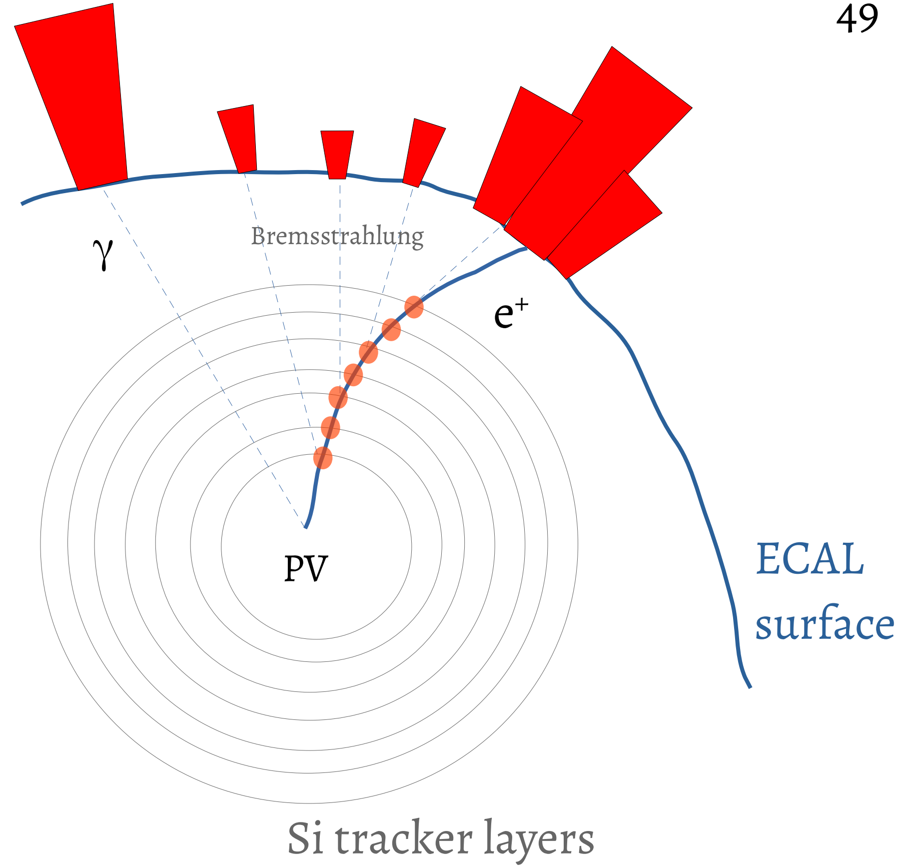
Electron



Photon



Electrons

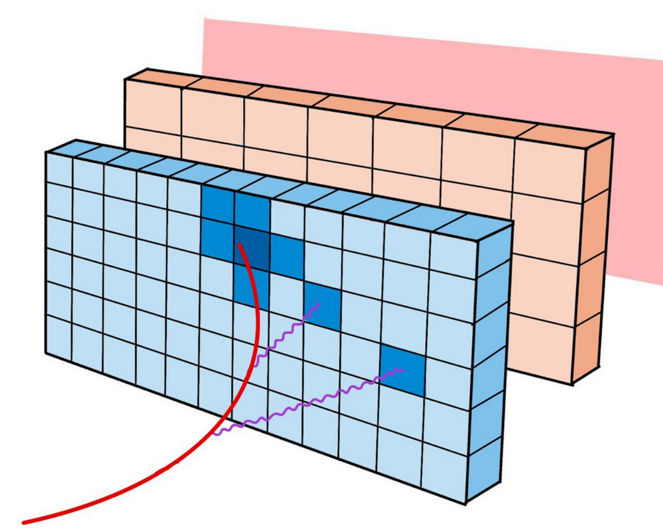


Electrons are tricky.
Low mass means they interact a lot, and lose energy by bremsstrahlung.

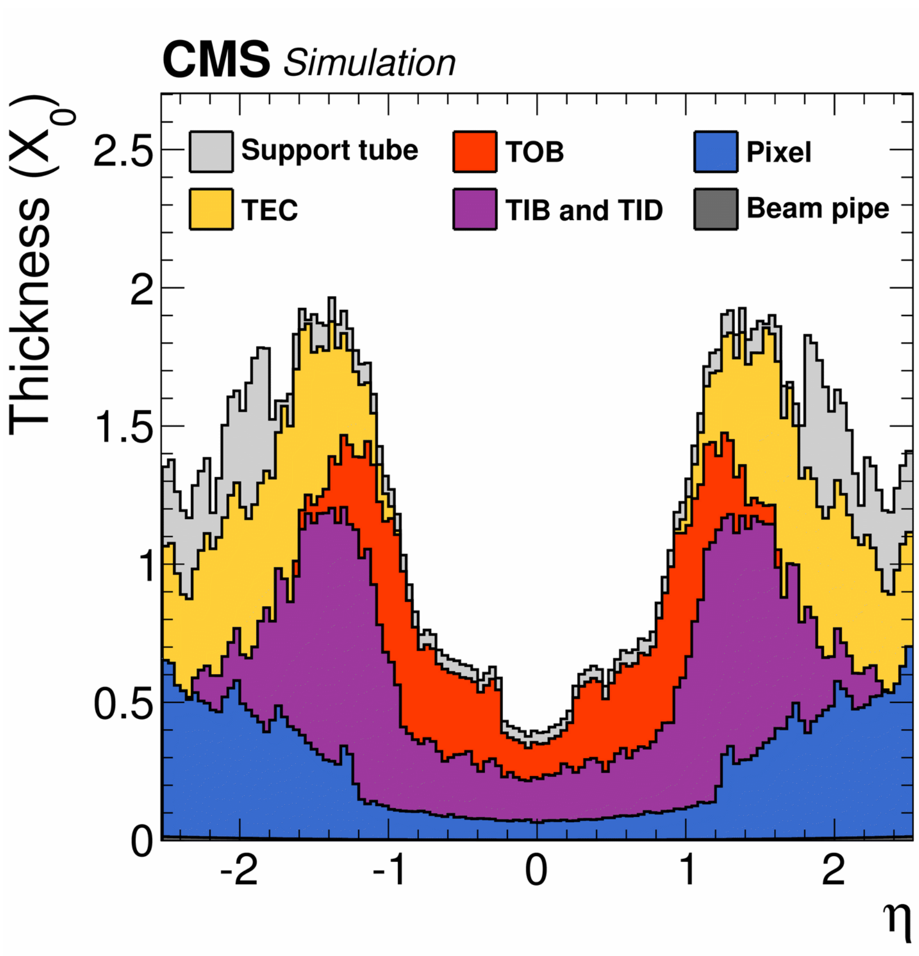
The energy lost has to be accounted for, to obtain the true energy of the electron.

Recover brem photons along the direction.

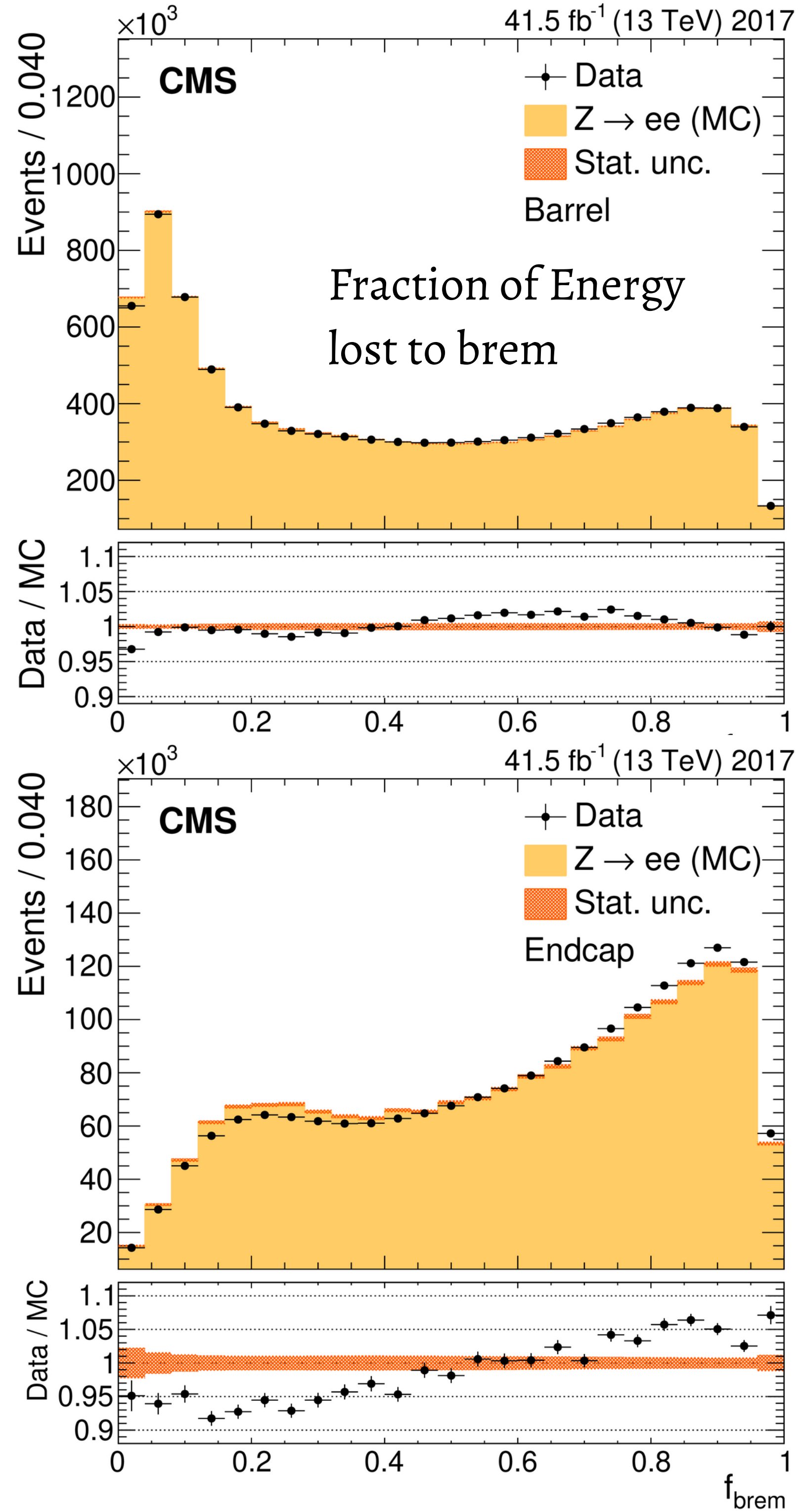
Have dedicated algorithms to do electron tracks
GSF = Gaussian Sum Filter



Bremsstrahlung



Material budget of the tracker

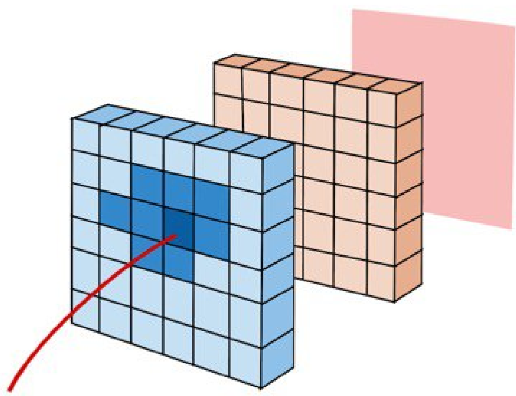


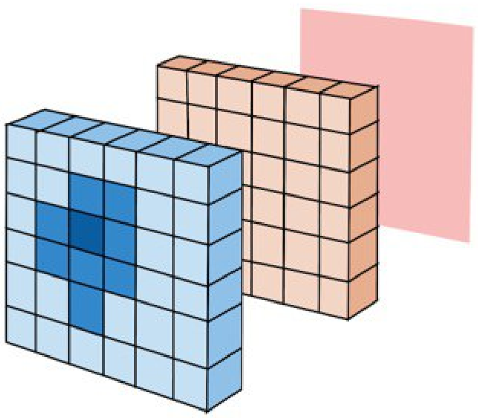
Fraction of Energy lost to brem

JINST 10 (2015) P06005

JINST 16 (2021) P05014

Electrons and Photons





A track that matches a calorimeter cluster

Energy/Momentum close to 1

Negligible HCAL deposit

Shape of shower as expected

Isolated

No track that matches deposit

Energy/Momentum close to 1

Negligible HCAL deposit

Shape of shower as expected

Isolated

In practice, many photons convert to e^+e^- pair

Isolation

Crucial for electrons, muons, photons and taus

Typically e, μ, γ get classified into two types Prompt and non-prompt

By prompt, usually we mean that they arise from the collision directly, or from the decay of a gauge boson (W, Z) or from some BSM particle.

By non-prompt, we mean everything else – typically that occur in hadron decay (and are thus inside a jet)

Prompt