IISER PUNE

Detectors in high energy physics

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1st National Workshop on GEANT4 and its Application to High-Energy Physics and Astrophysics

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Numbers

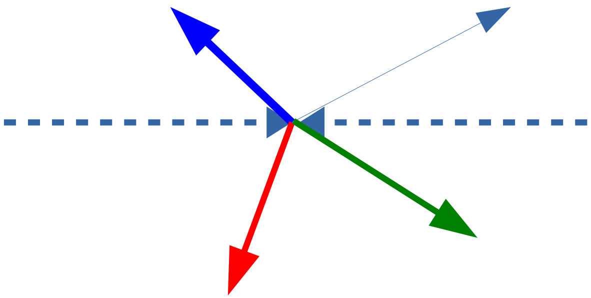
We have the de Broglie relation

$\lambda = h/p = hc/E$

And

$hc = 1.24$ eV.μm

Proton is ~ 1 fm, thus we need energy of ~ 1.24 GeV to "peek inside" a proton.



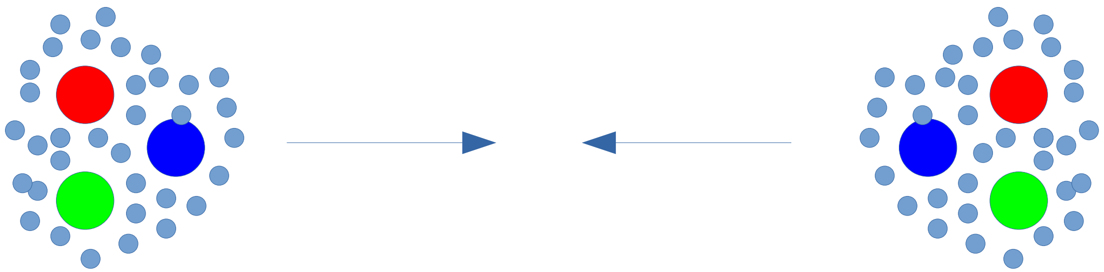
Collisions

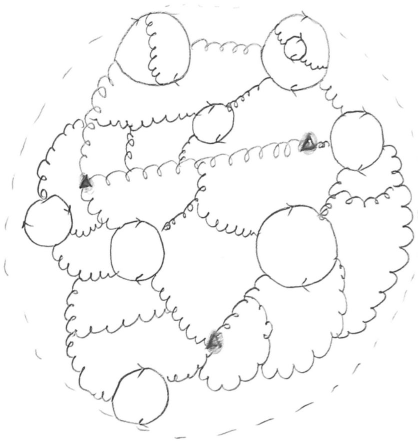
We also have

$E = mc^2$

A Higgs boson has a mass of 125 GeV, to produce it we would need collisions at COM energy of at least 125 GeV

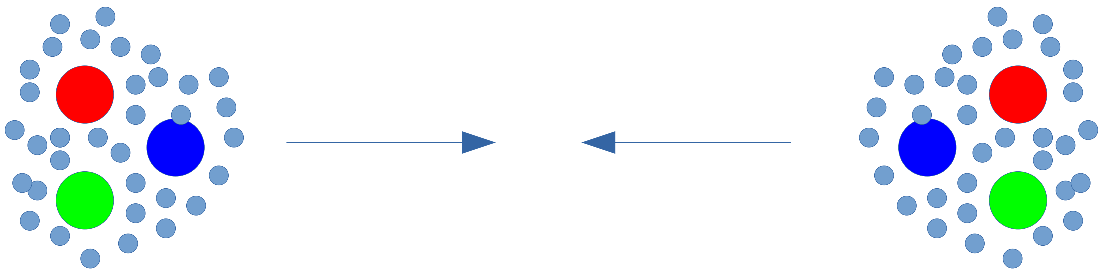
pp collisions and hadronization

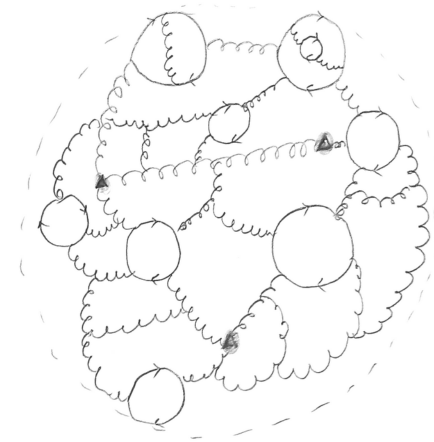




My sketch of the innards of a proton at high energy

pp collisions and hadronization





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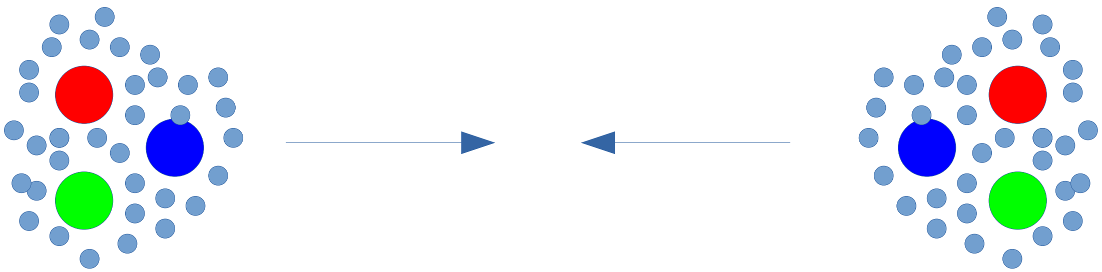
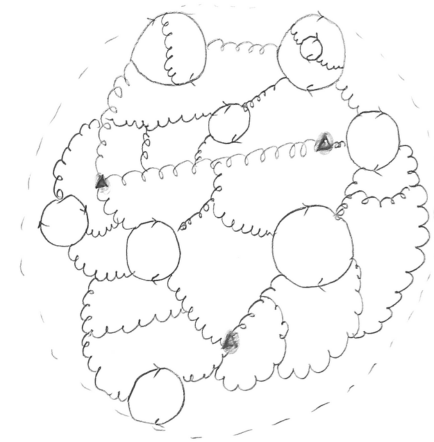
Proton-proton collision

pp collisions and hadronization

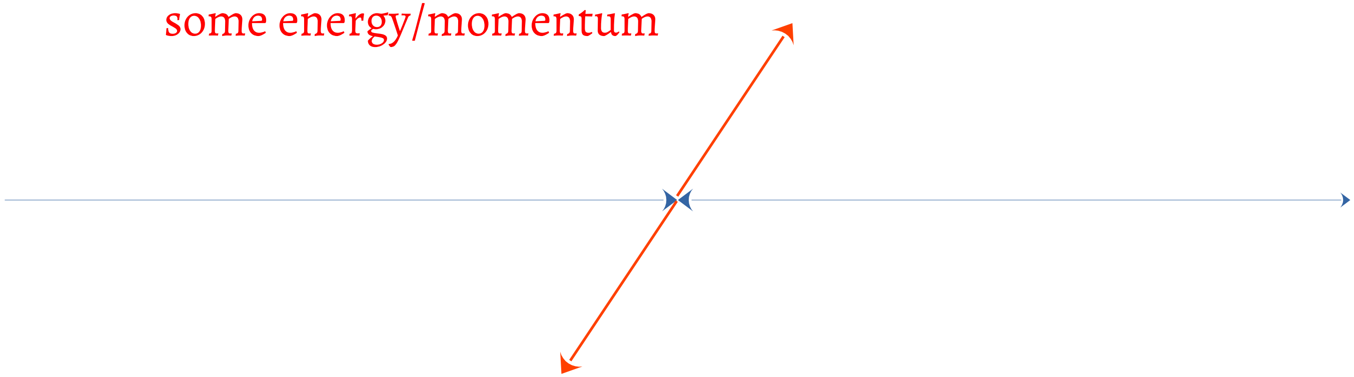




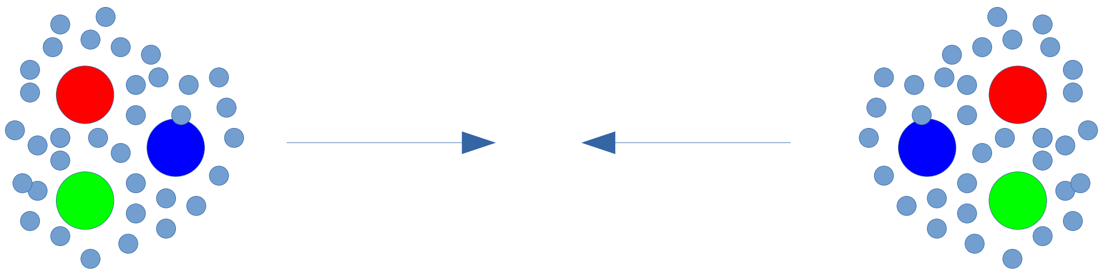
My sketch of the innards of a proton at high energy

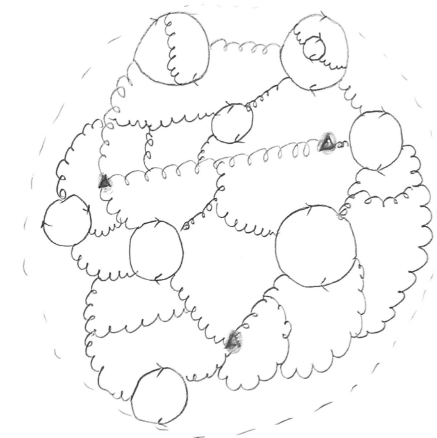
Quarks or gluons produced with some energy/momentum

Proton-proton collision



pp collisions and hadronization

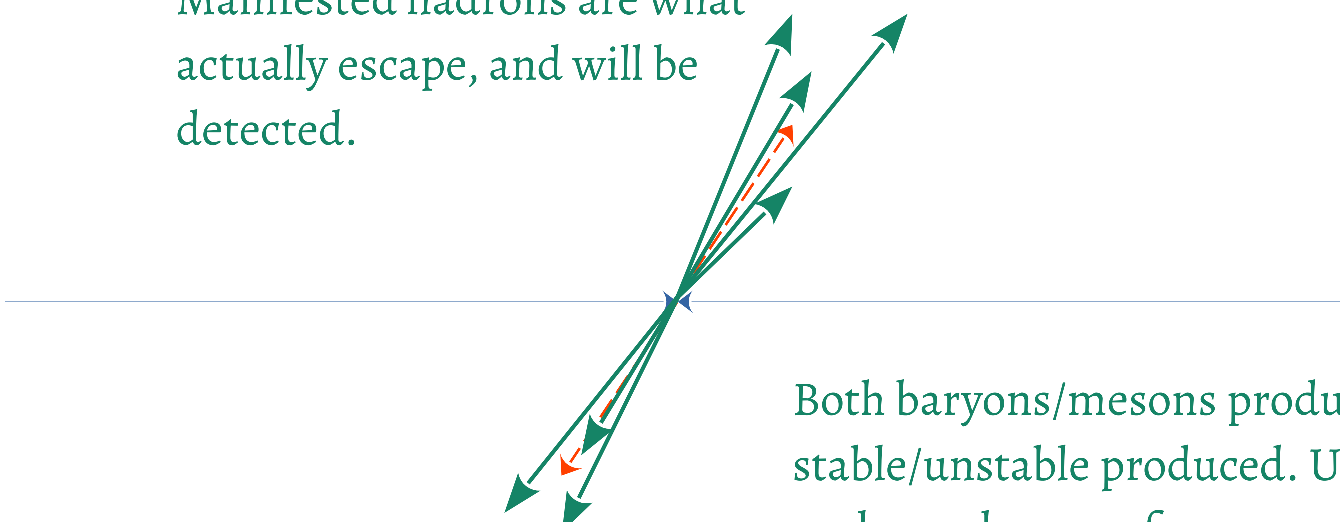




My sketch of the innards of a proton at high energy

Manifested hadrons are what actually escape, and will be detected.

Proton-proton collision



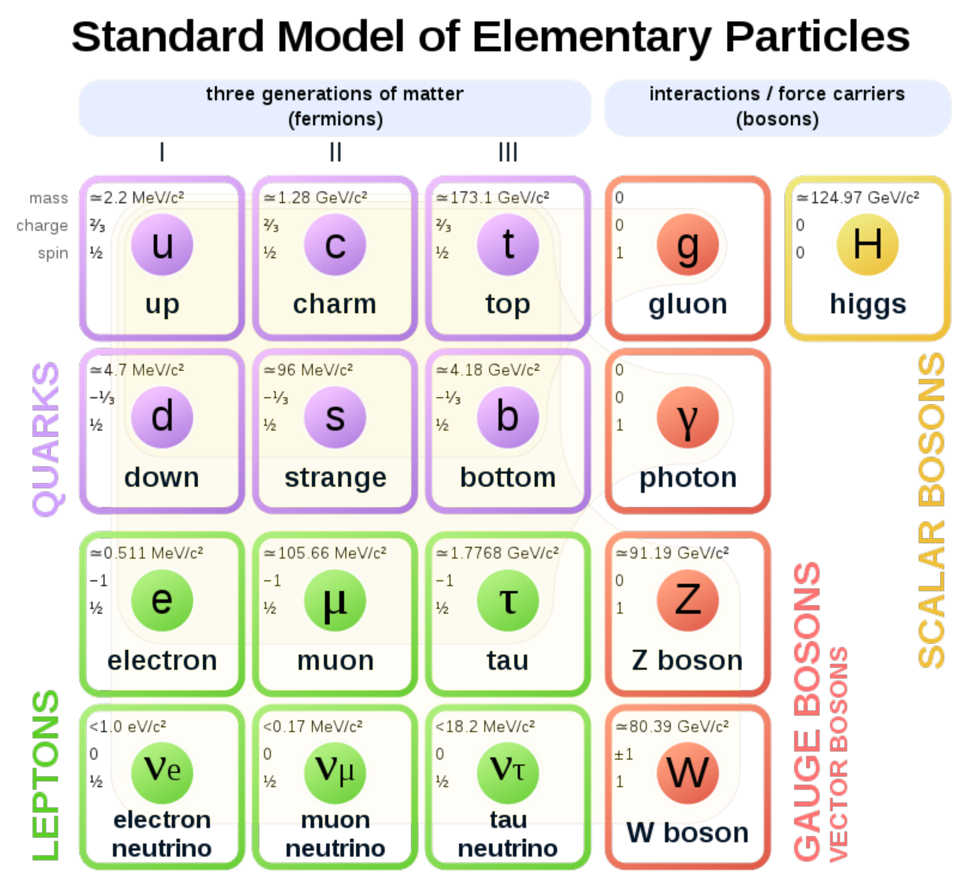
Both baryons/mesons produced, both stable/unstable produced. Unstable hadrons undergo decays, of course.
(Different ways to hadronize 'same' initial state)

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?



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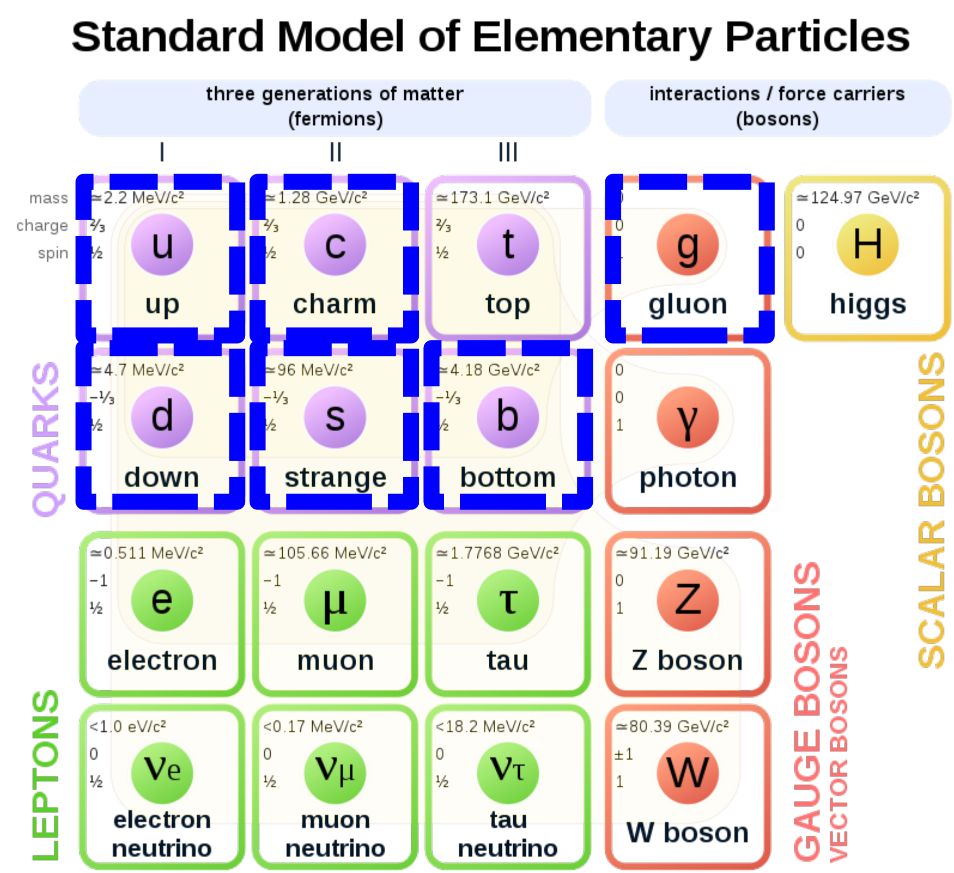
These hadronize, producing hadrons such as pions, kaons, neutrons etc.



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

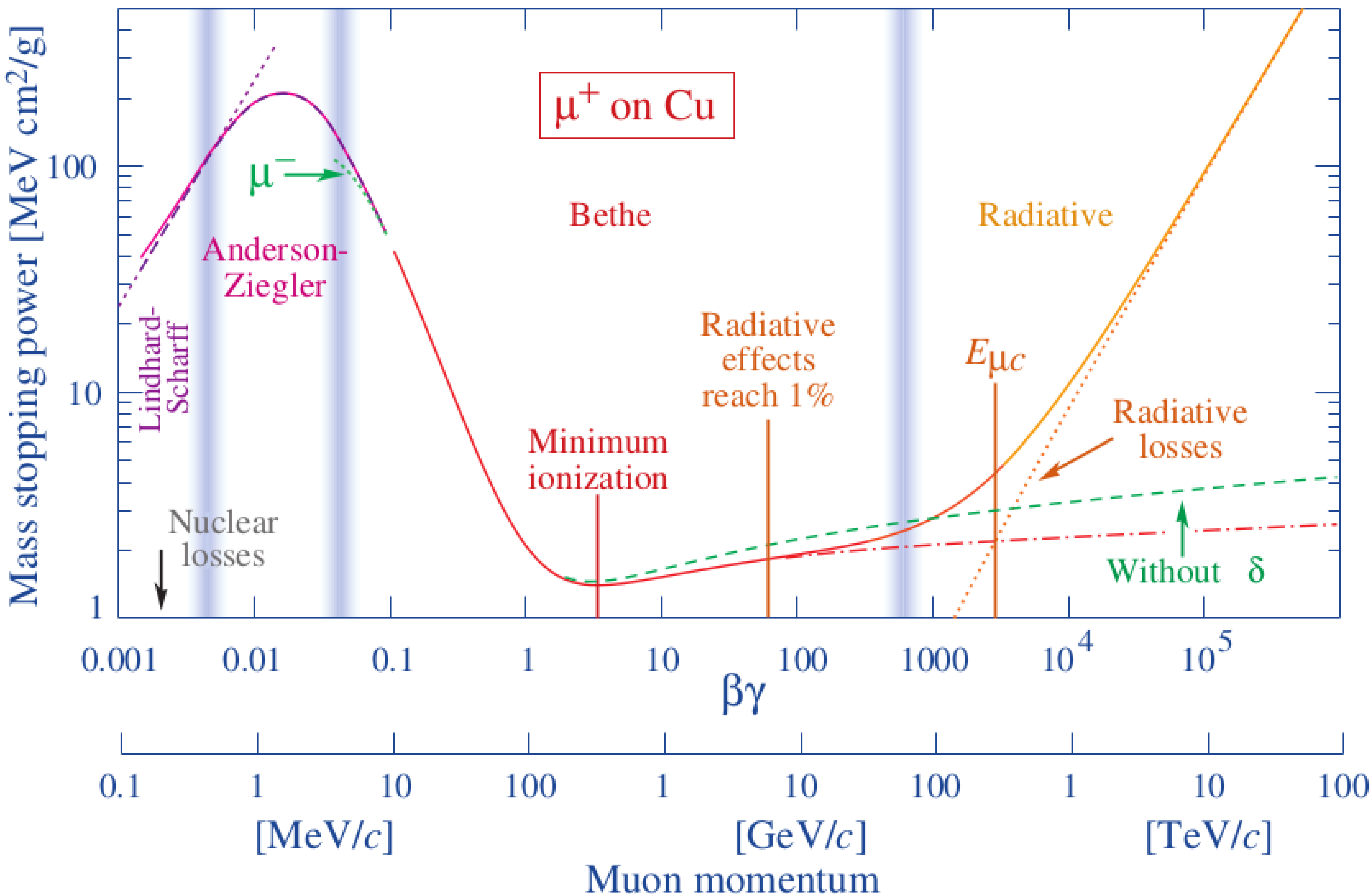
A beam of particles passes through a slab of material –
(a) many small interactions (b) All-or-nothing

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

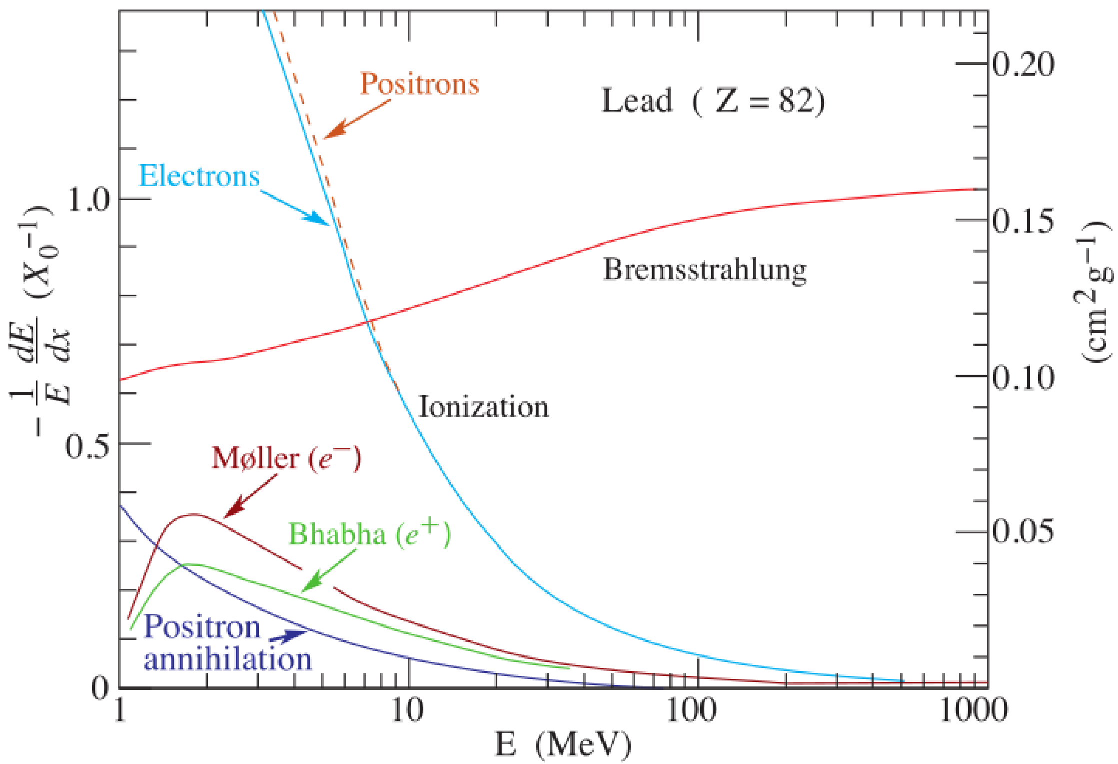
Heavy charged particles lose energy through ionization or excitation of atoms of material, with the energy loss dE/dx given by the Bethe-Bloch equation
dE/dx is proportional to Z^2 of absorber, q^2 of the particle, and inversely proportional to speed of incoming particle.

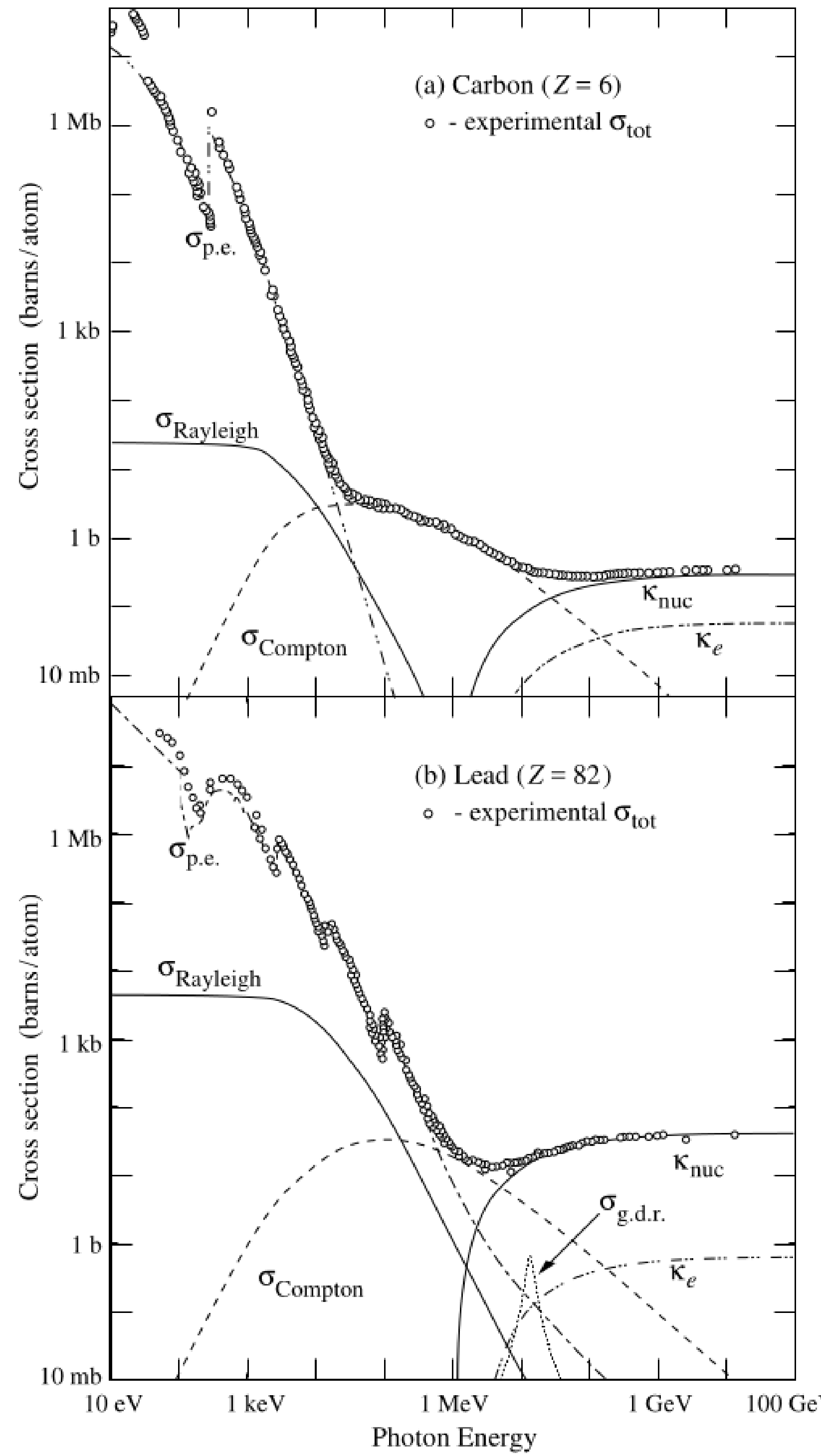
At high energies, radiative losses and pair production dominate energy loss.
In addition we have Cerenkov radiation (particle velocity > phase velocity of light in that medium) and Transition Radiation (when particle traverses materials of different optical properties)

Interactions with matter



Electrons and photons





$X_\circ$ = radiation length
The mean distance over which energy will decrease to 1/e of its value.

The bremsstrahlung loss goes as ~ E/Xo

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.

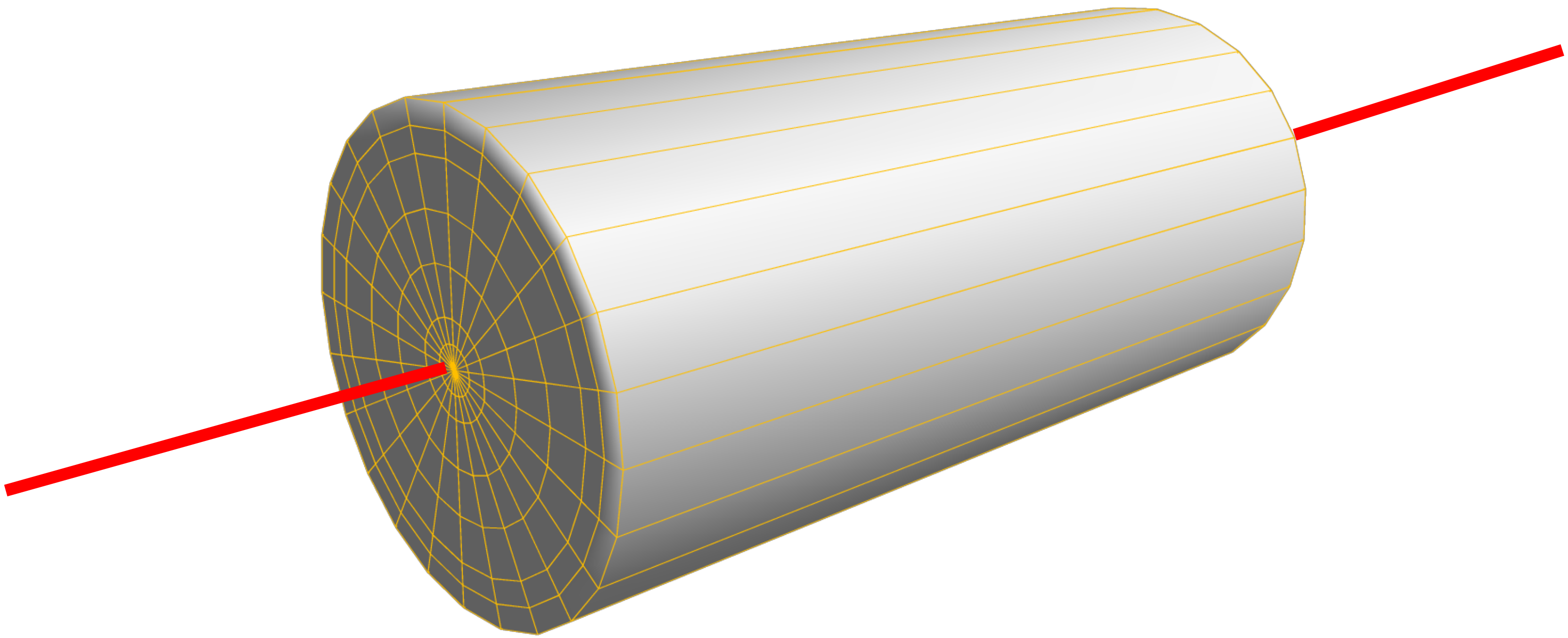
2. Charge

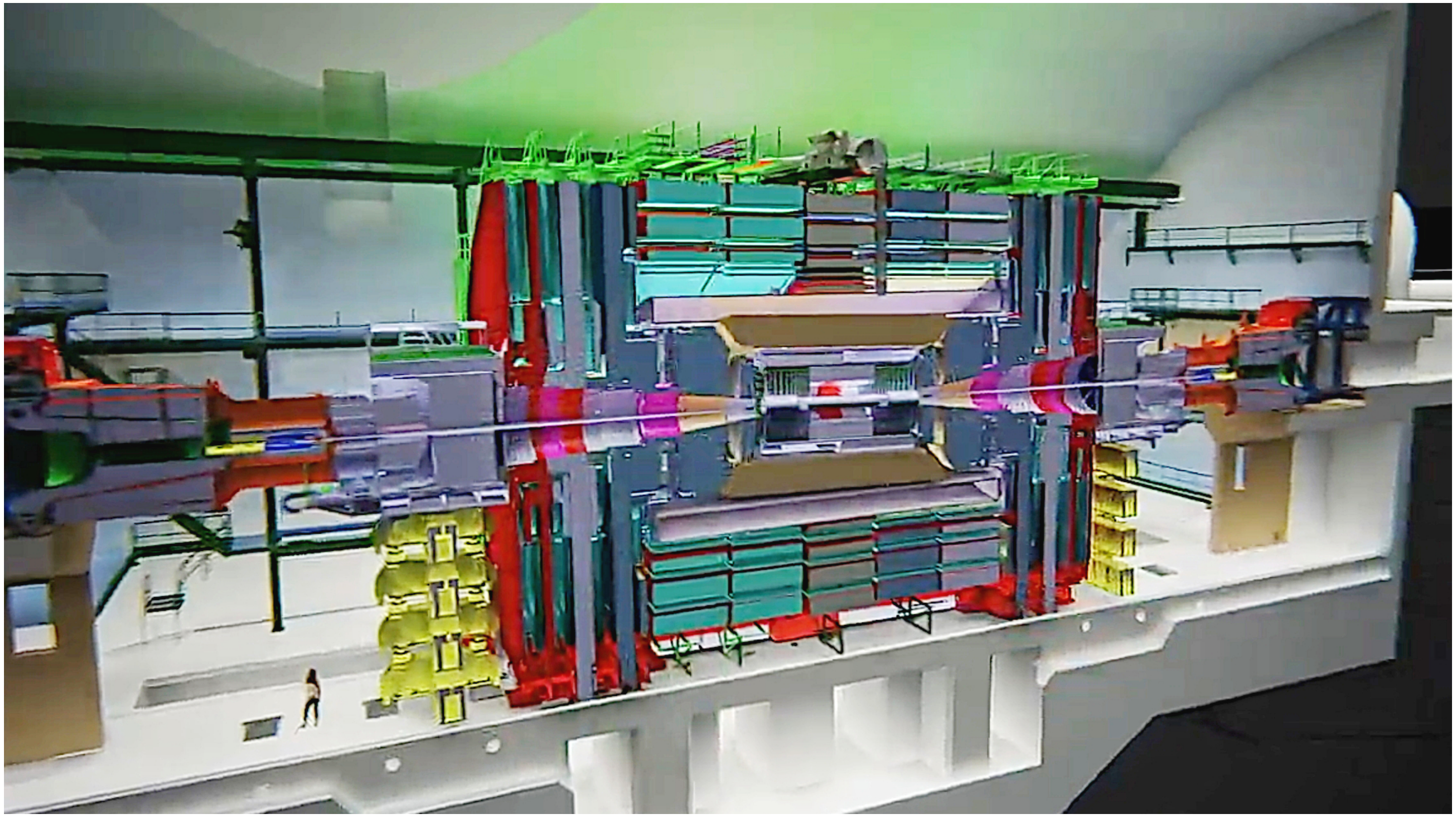
3. If it decays, then where? Its lifetime?

4. How many particles of each kind

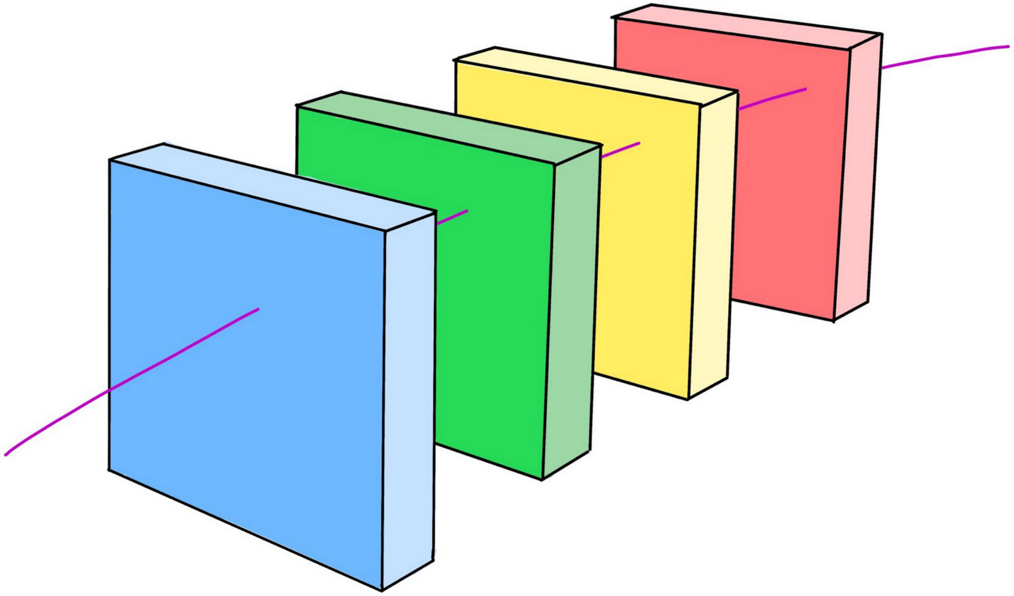
5. Anything special? Did the particle interact unusually with our detector?

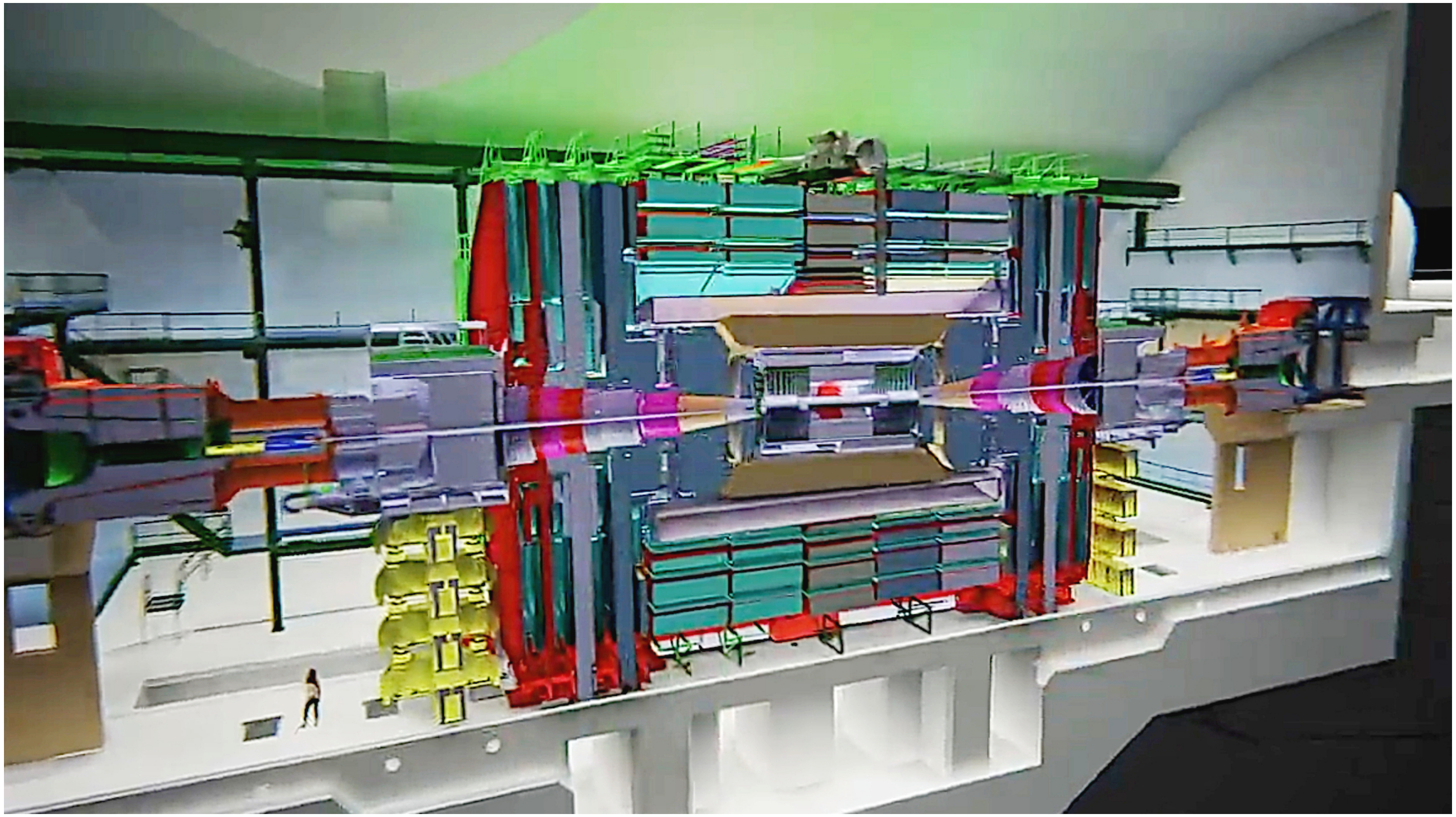
Typical detector design



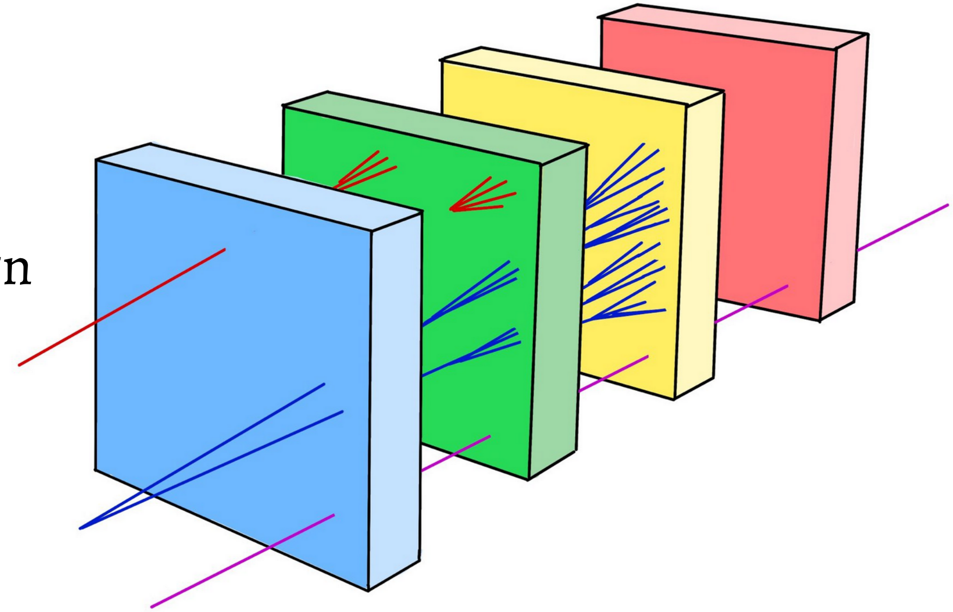


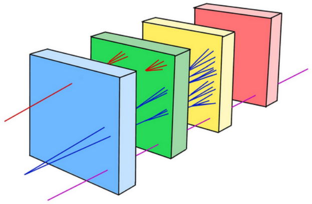
A particle produced in a collision will traverse the different sub detectors where it will interact.





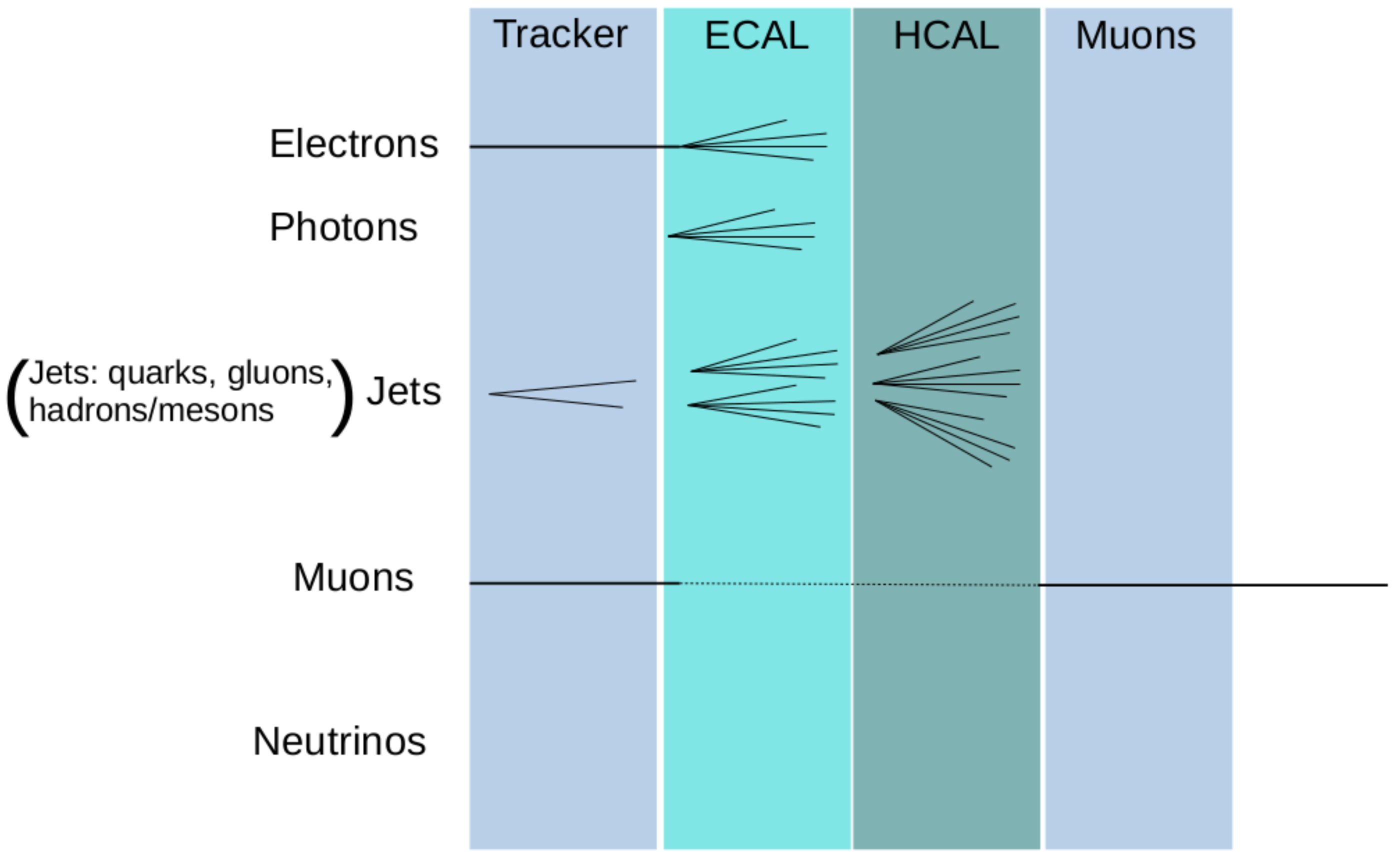
Different particles will interact differently (!!) since that is how we design the detector





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.



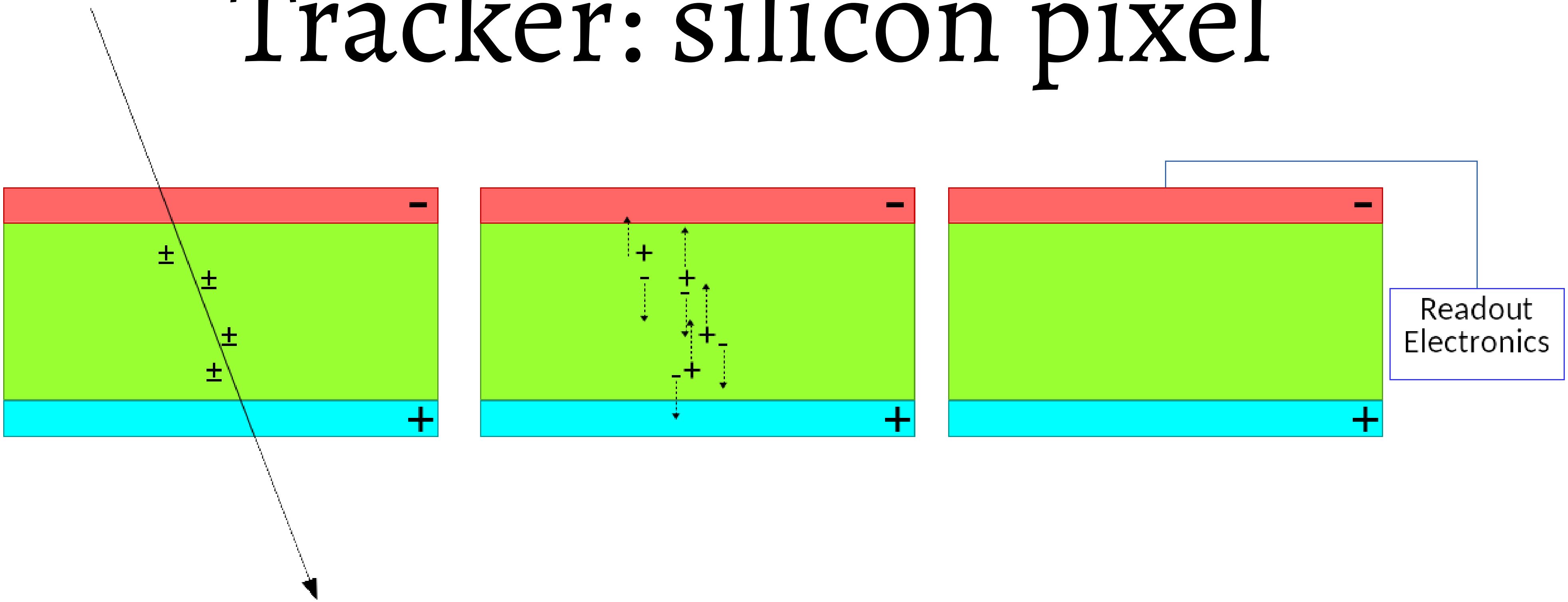
Radially outward from the collision point

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.

Tracker: silicon pixel



Consider a silicon diode, with reverse bias applied.

A passing charged particle created electron-hole pairs.

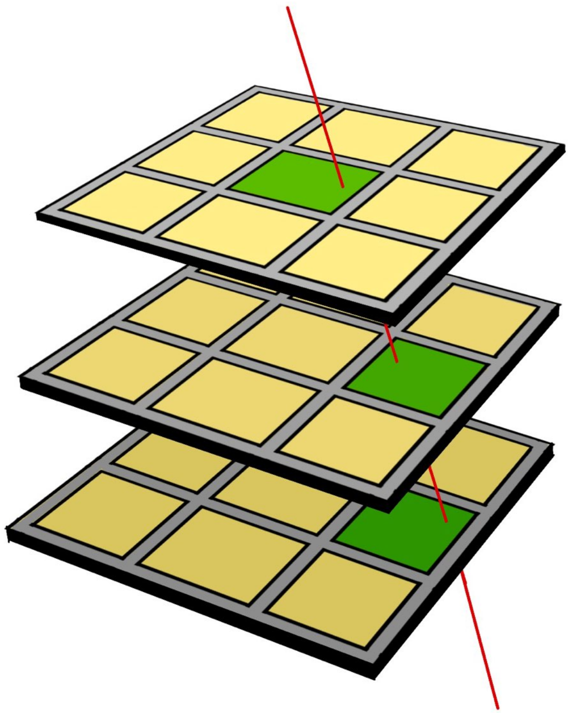
These electrons drift to the end where the total charge is read out.

The typical size of a pixel is 150×150 μm² 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.



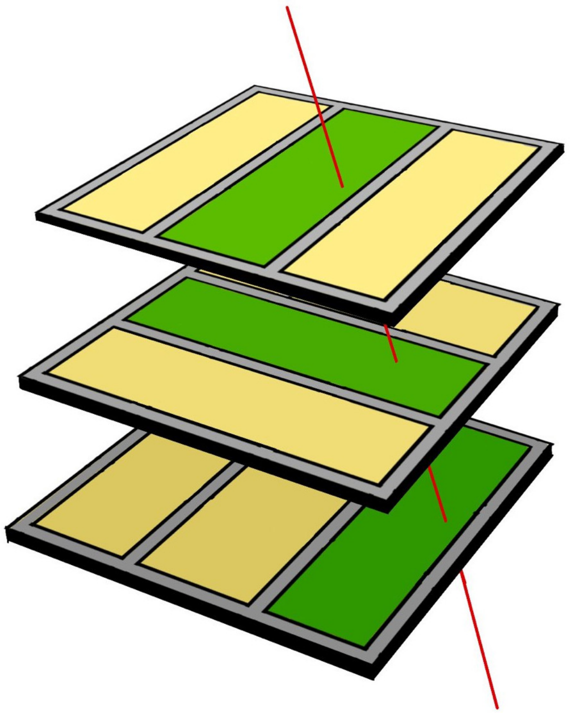
Tracker: silicon strip

Imagine a stack of pixel layers.

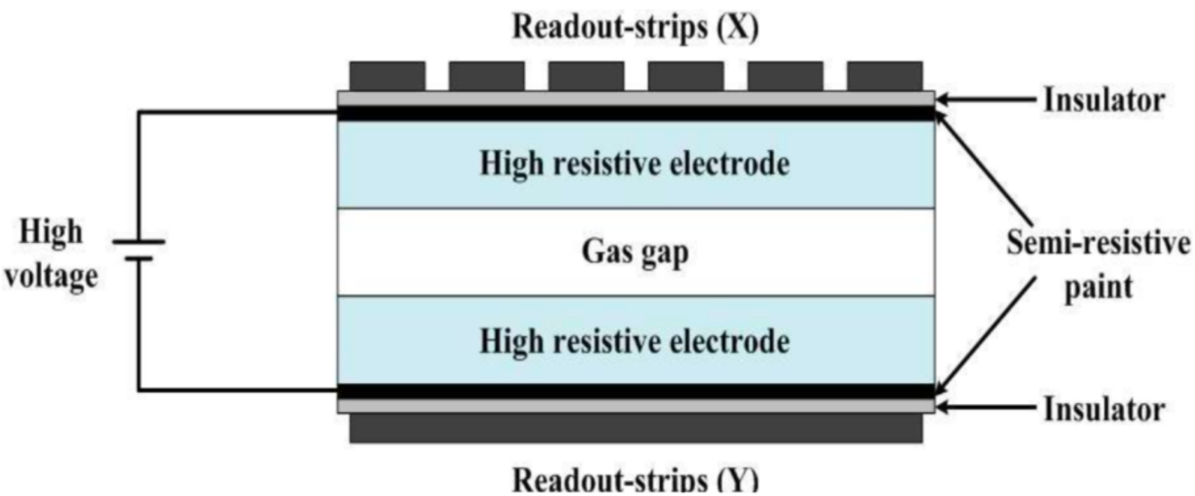
As a particle goes through, we can trace its path based on which pixels are lit up.

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.

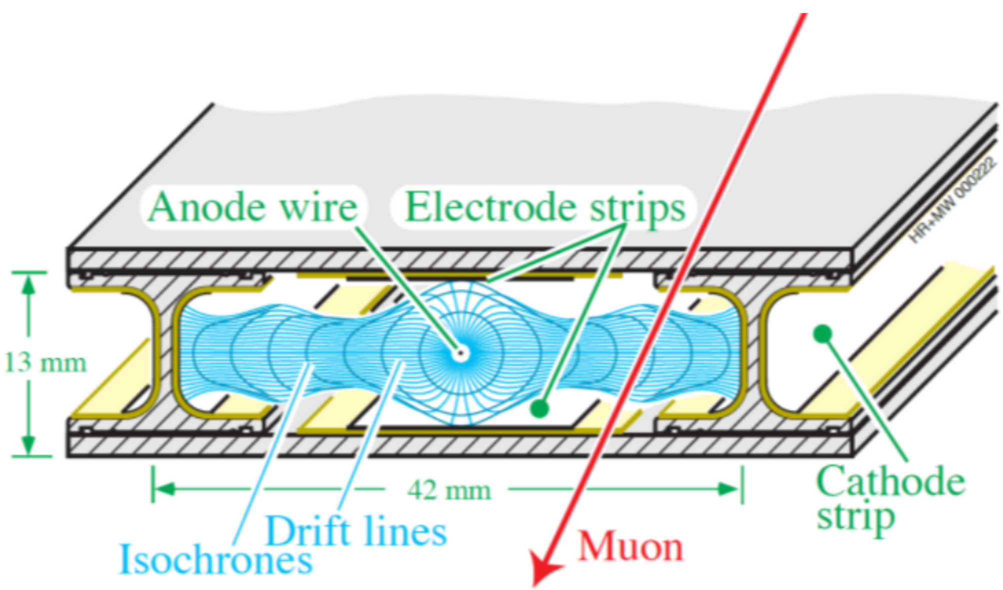


Tracker: for muons



RPCs: Resistive plate chambers

DTs: Drift tubes



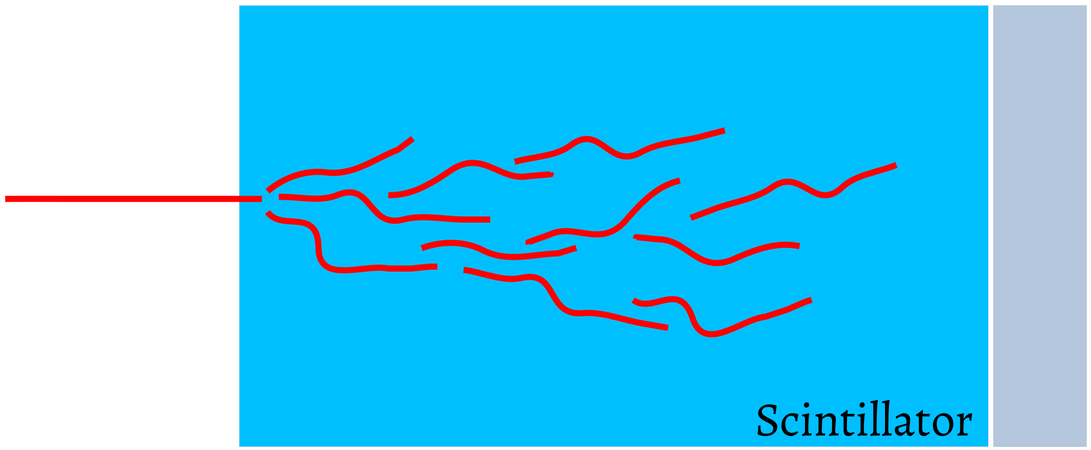
Trackers measure charge, momentum, trajectory

They do not stop the particle!

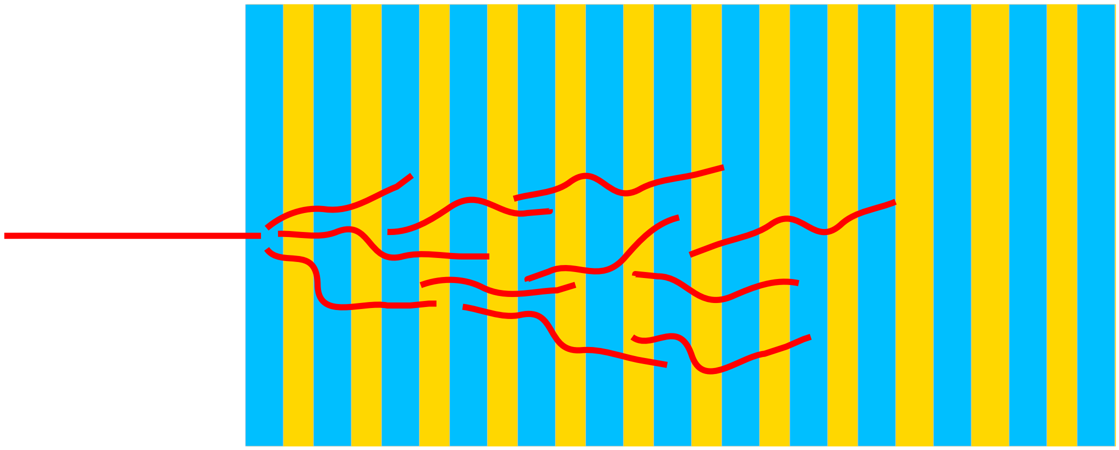
Calorimeters measure energy of particle.

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

Calorimeters

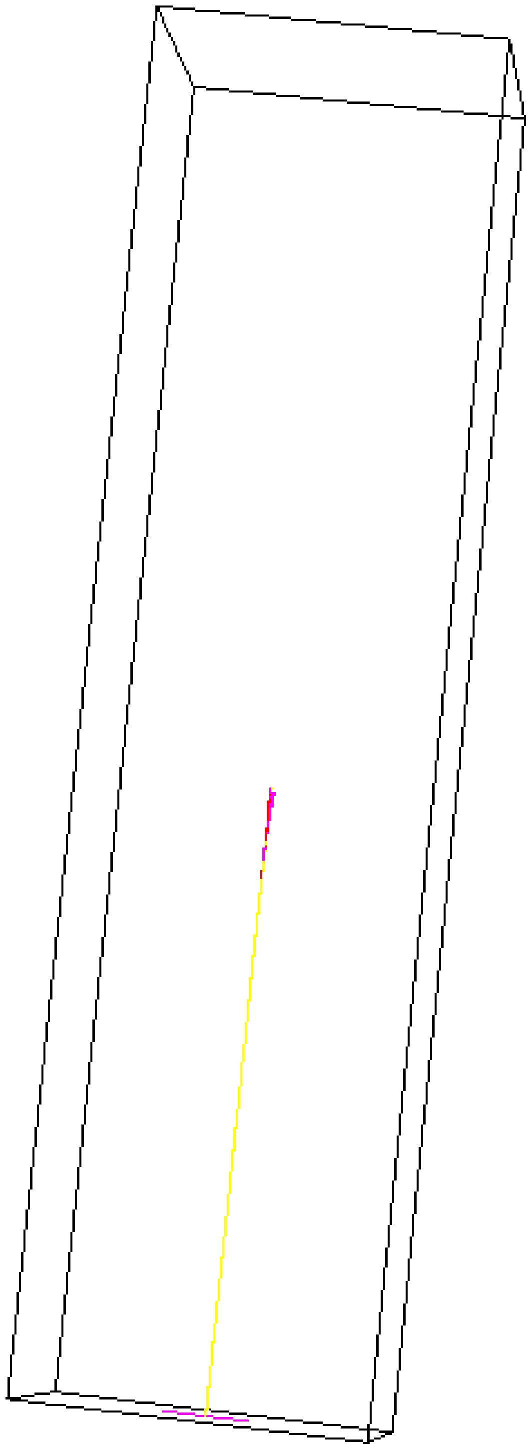


Homogenous calorimeter
The absorber is also the detector, with typically light being collected by a sensor.



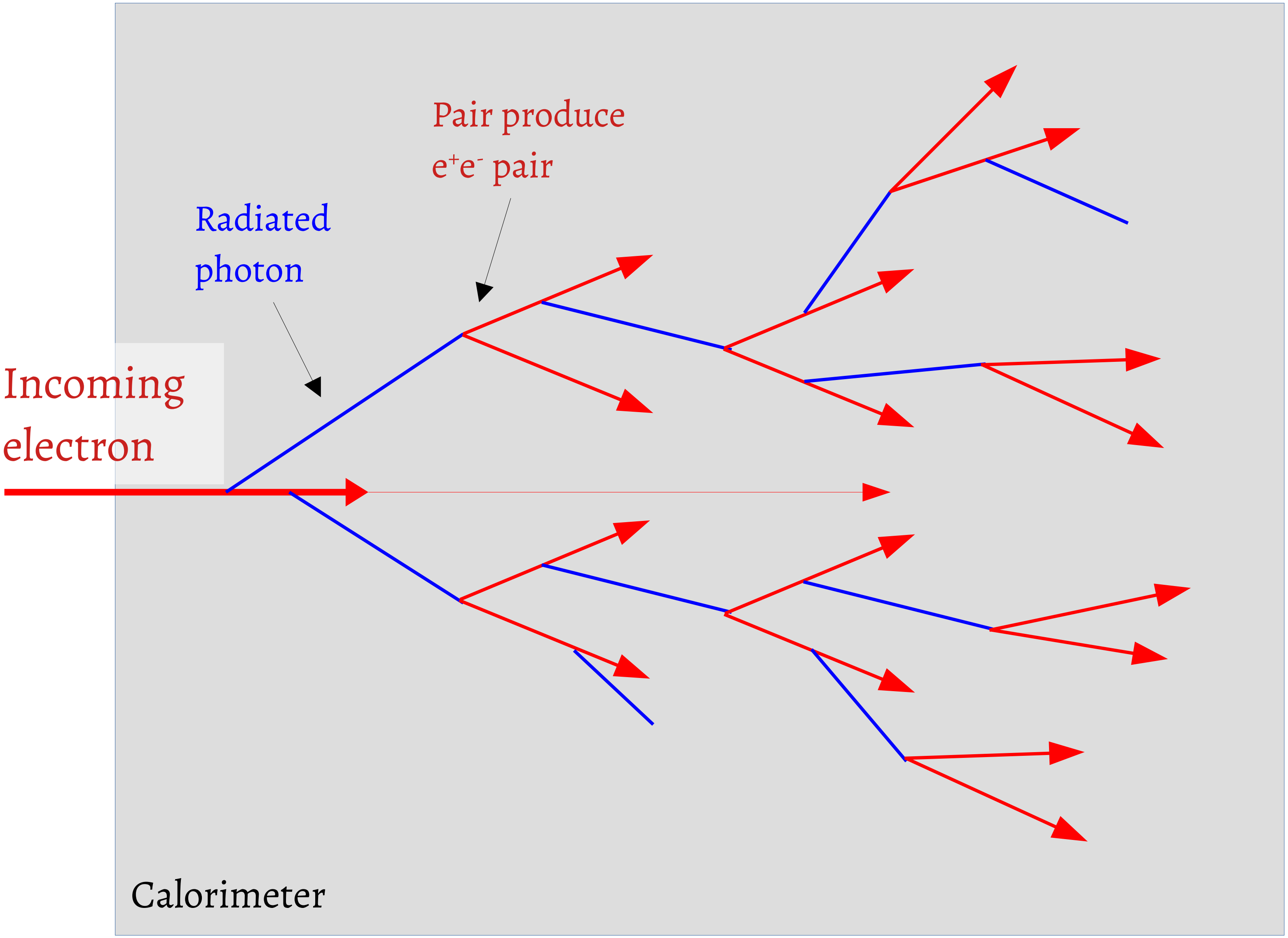
Sampling calorimeter
Passive heavy material layers interspersed with the active layers that detect energy deposited.

40 GeV electron in a lead glass block.



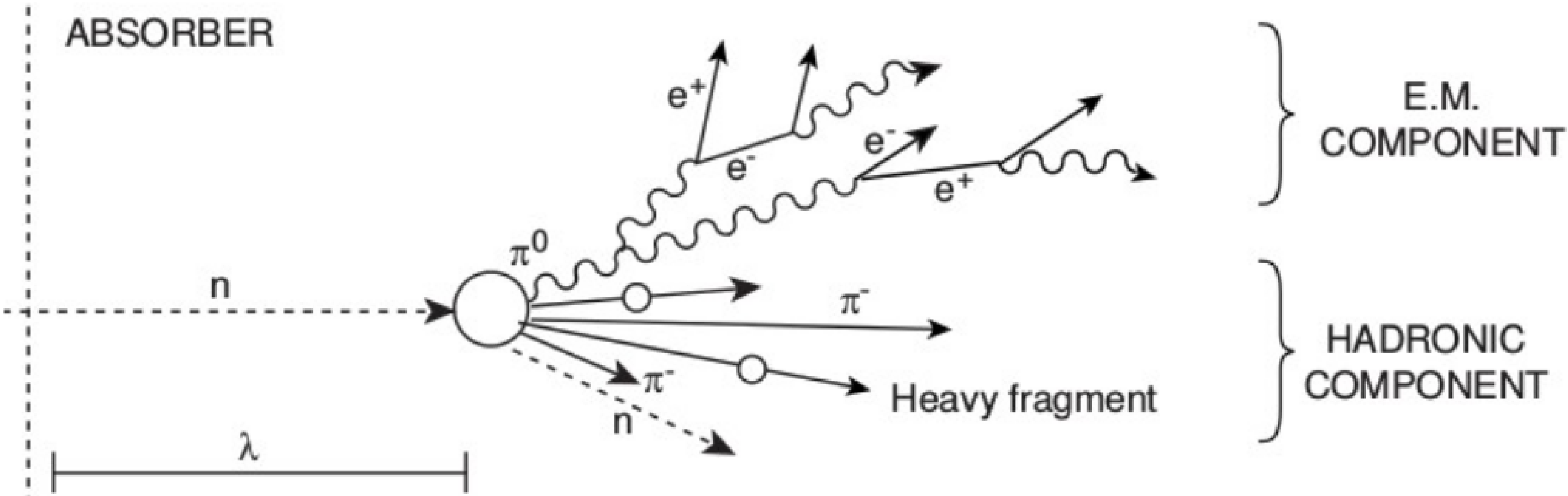
ELSS The Electromagnetic Shower Simulator
https://www.mpp.mpg.de/~menke/elss/home.shtml

Electromagnetic shower



Bremsstrahlung
Pair-production
Collisions with atomic electrons
Ionization

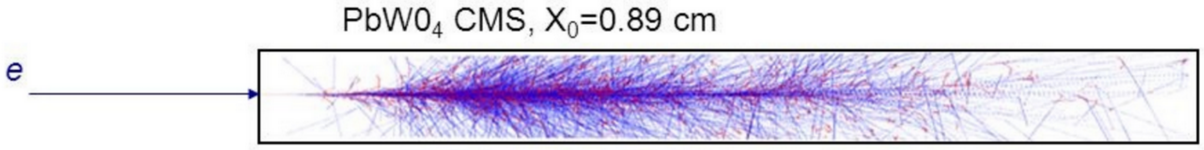
Hadronic shower



Elastic and inelastic scattering,
Nuclear excitations, disassociations
Fission, capture,
(Secondary decays)

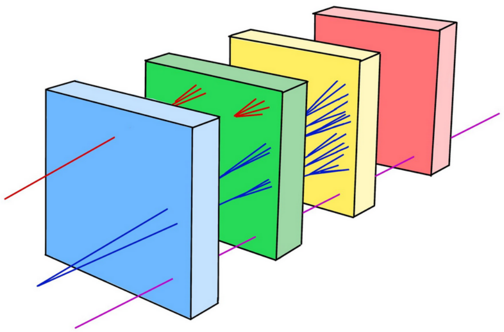
ECAL (Electromagnetic Calorimeter) :

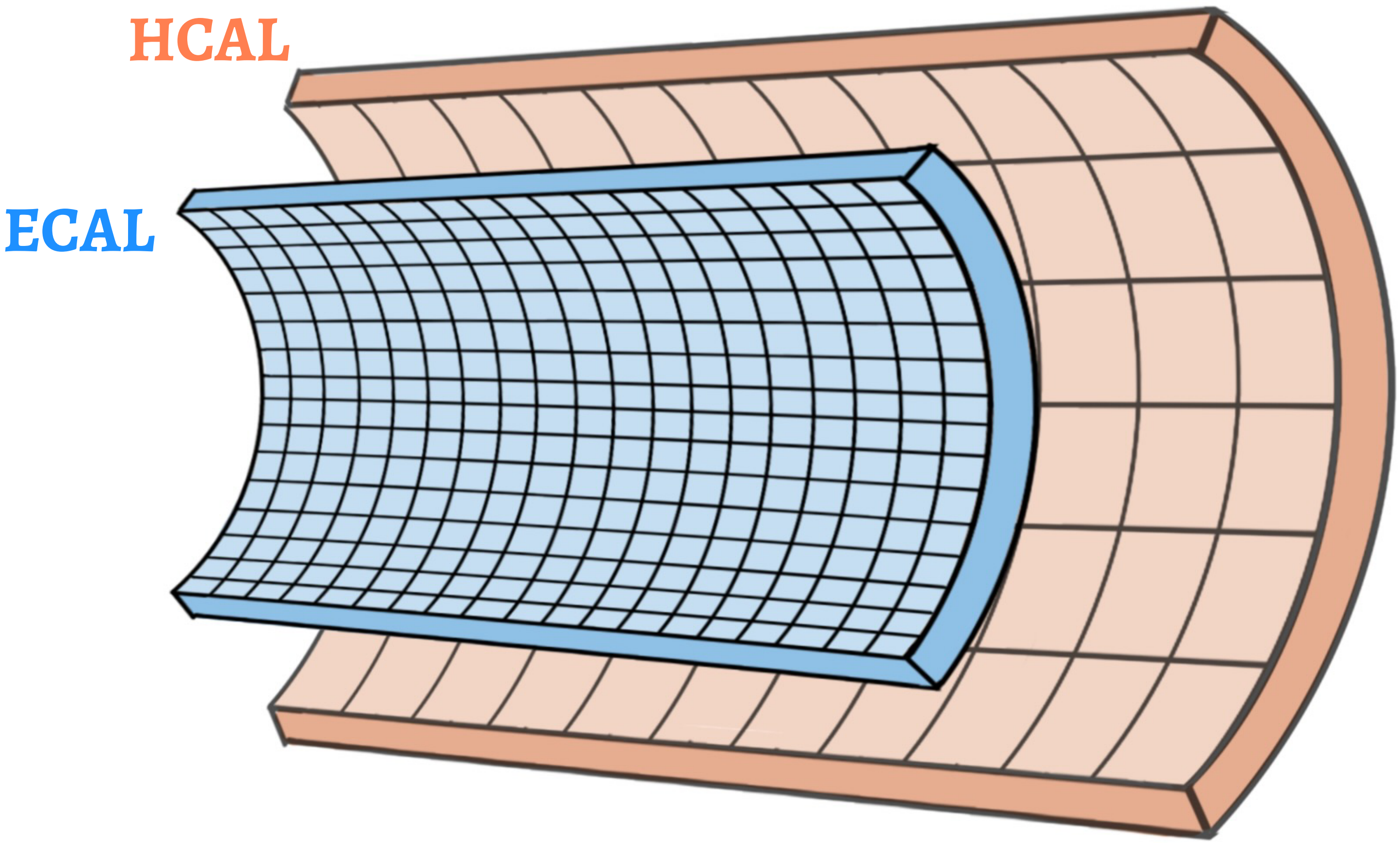
PbWO4 crystals connected to photomultipliers.
The crystal "scintillates" when electrons/photons pass through it.



HCAL (Hadronic Calorimeter) :

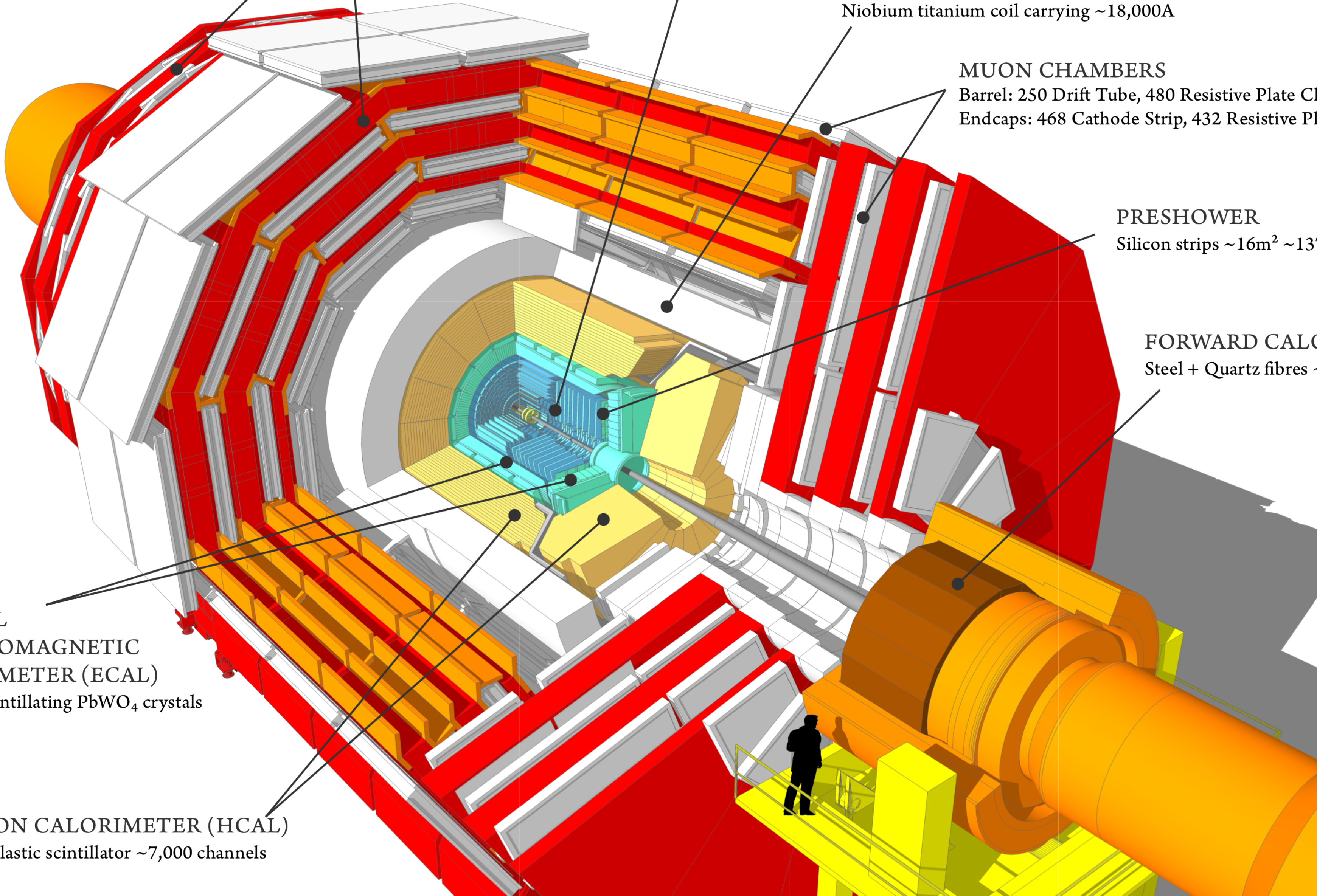
Sampling calorimeter with brass sandwiched with plastic scintillator.



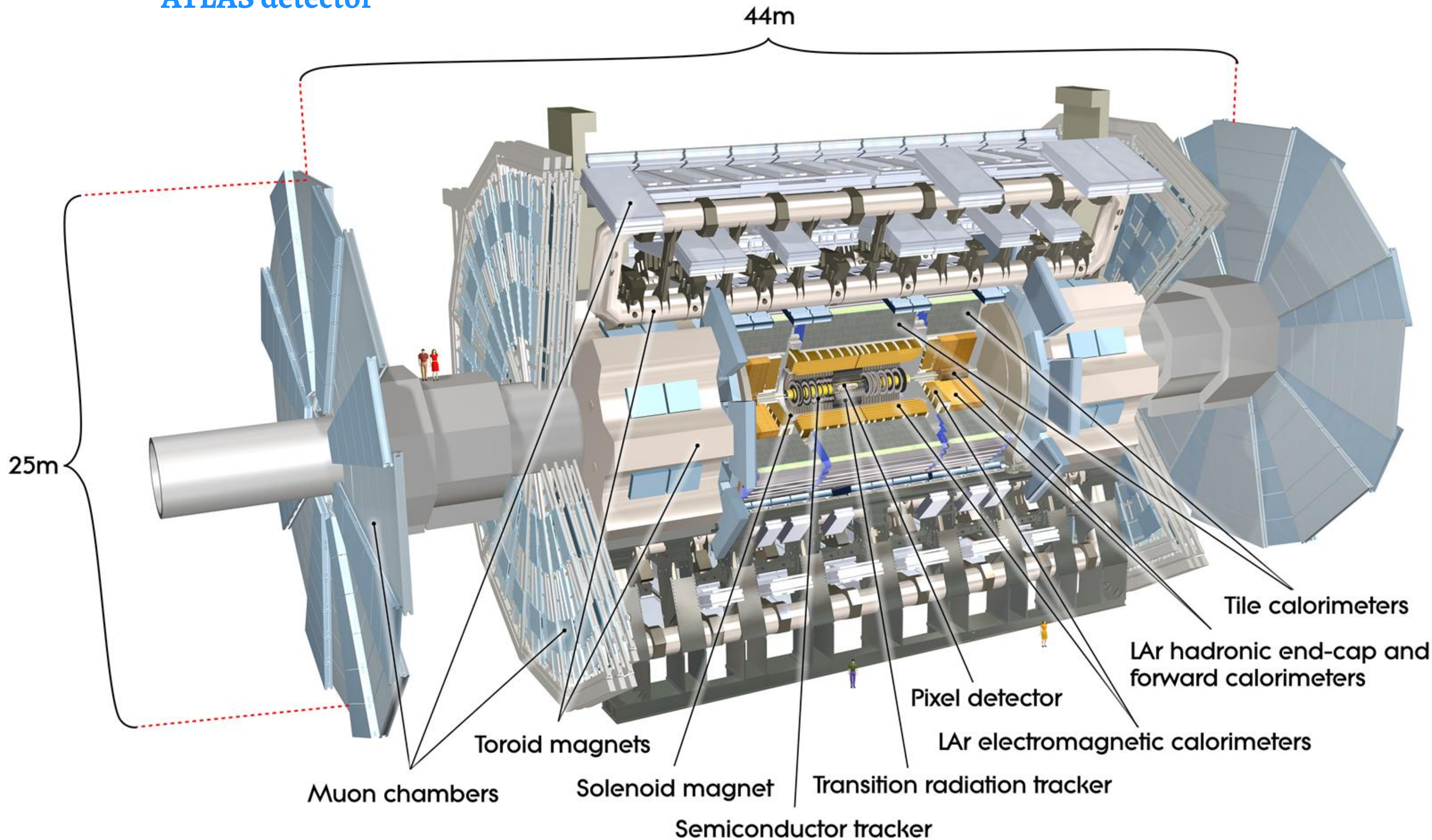


CMS DETECTOR

Total weight	: 14,000 tonnes
Overall diameter	: 15.0 m
Overall length	: 28.7 m
Magnetic field	: 3.8 T



ATLAS detector



Particle Identification

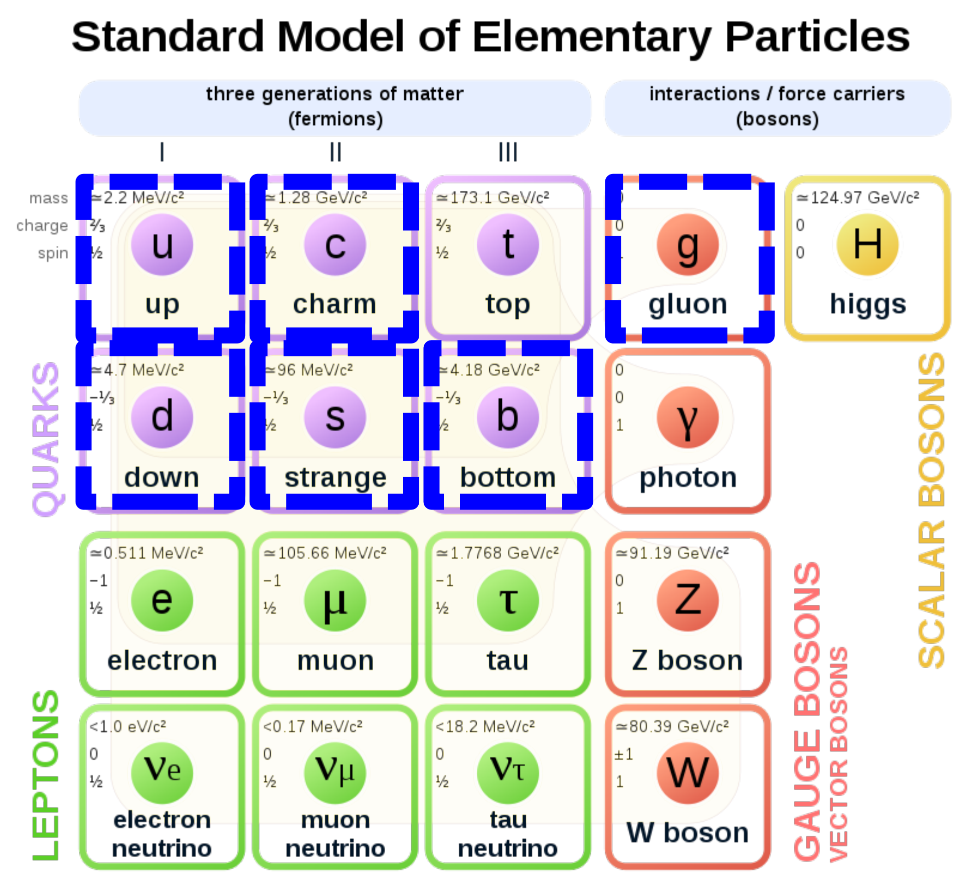
Which particles can we detect directly?

Electrons, Muons, Taus, Photons,

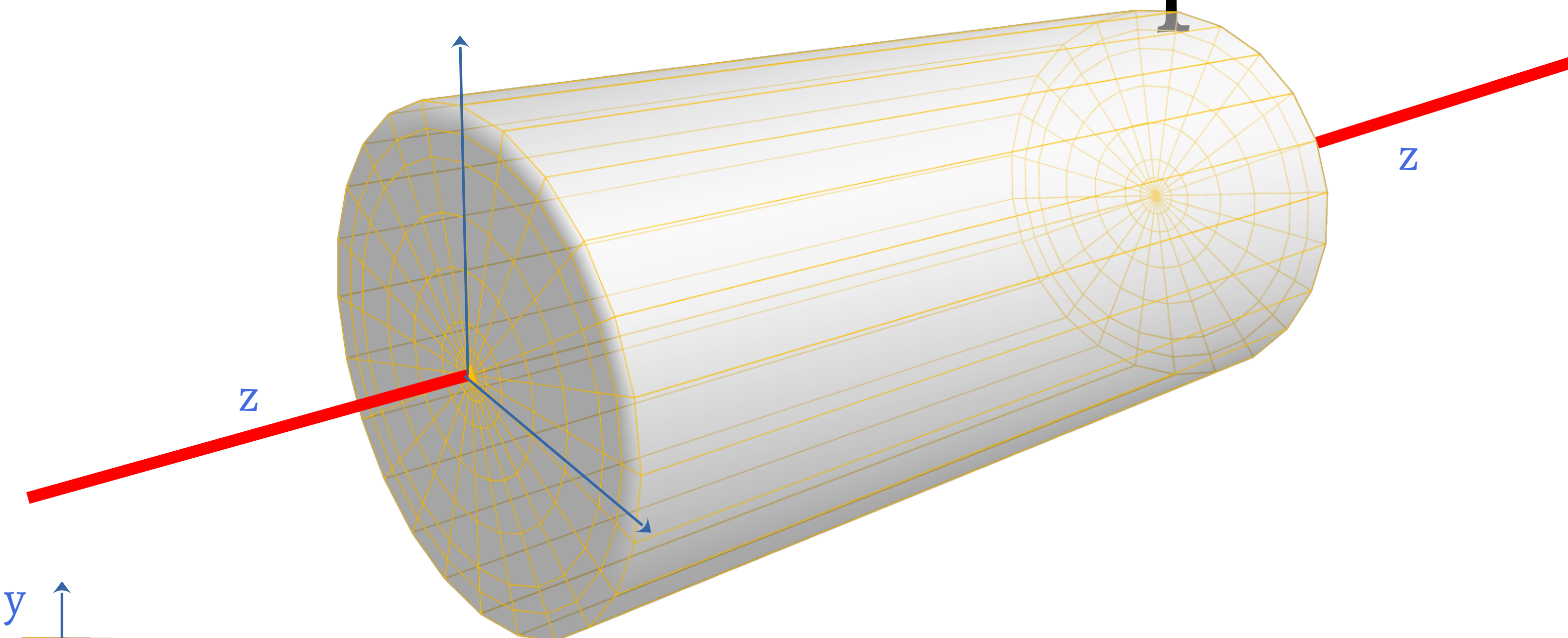
Quarks, gluons manifest as jets (of hadrons)

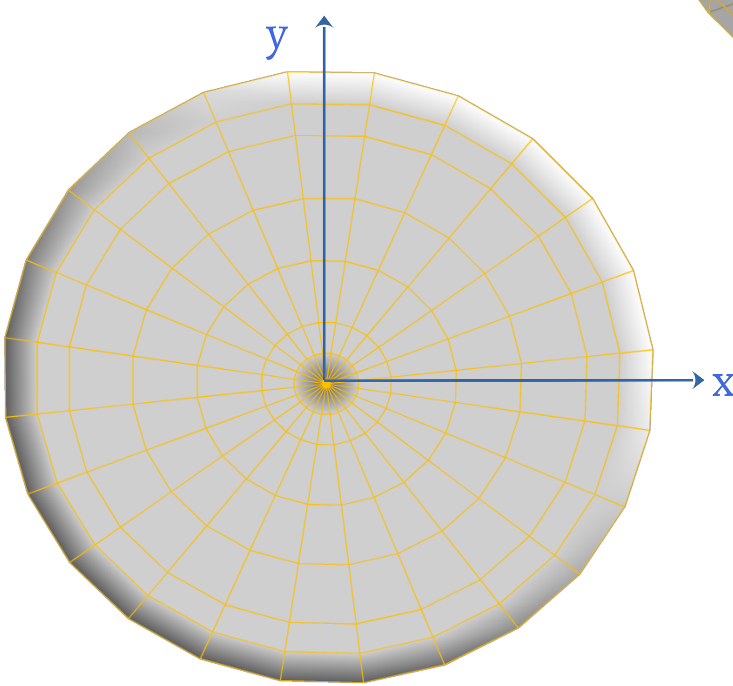
(*b*-jet, *c*-jet, q-g discrimination)

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

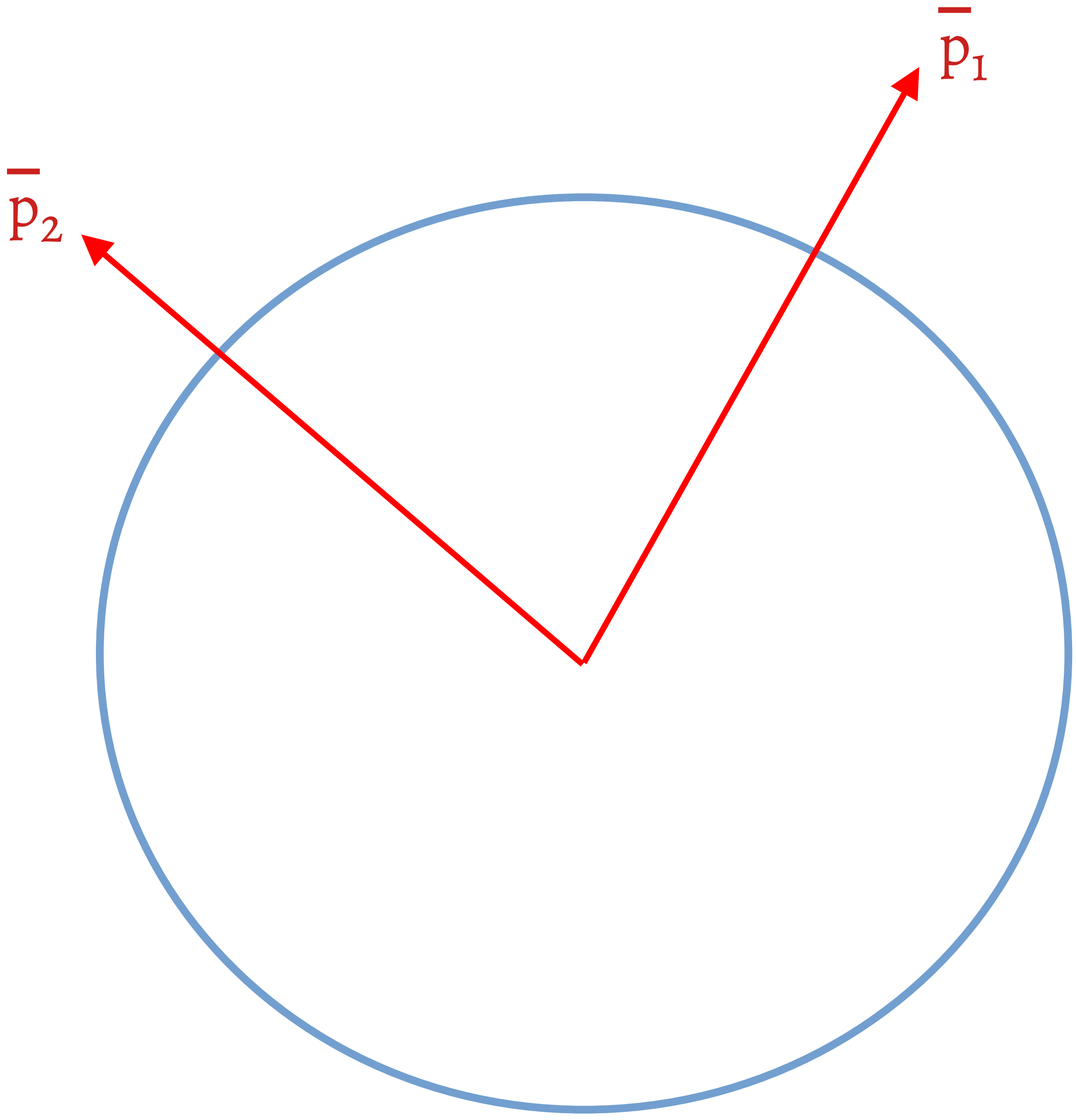


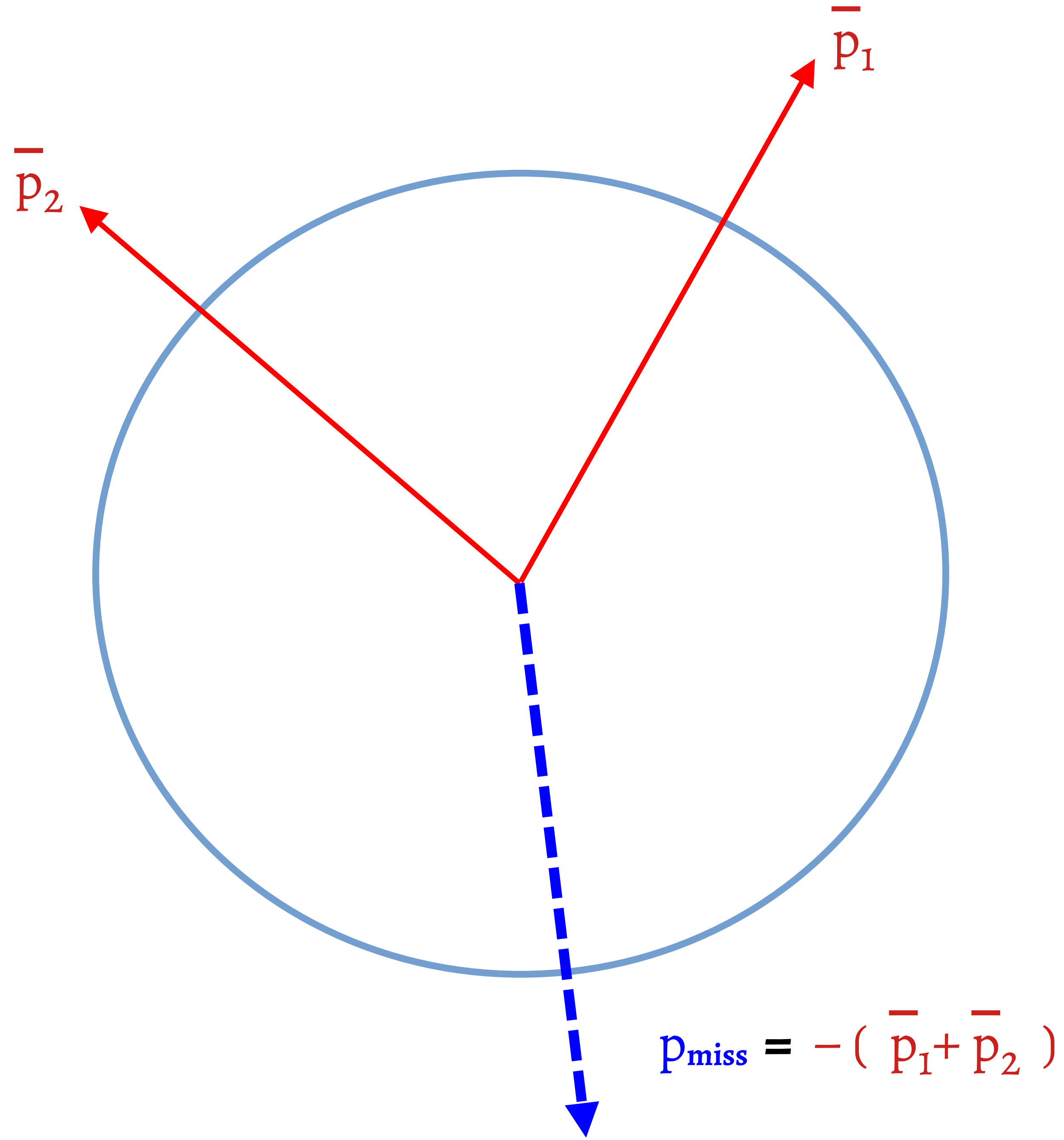
Consider the transverse plane





The beam is in & out of page at the center.


$\bar{p}_1$
$\bar{p}_2$


$\bar{p}_1$
$\bar{p}_2$
$p_{miss} = -(\bar{p}_1 + \bar{p}_2)$

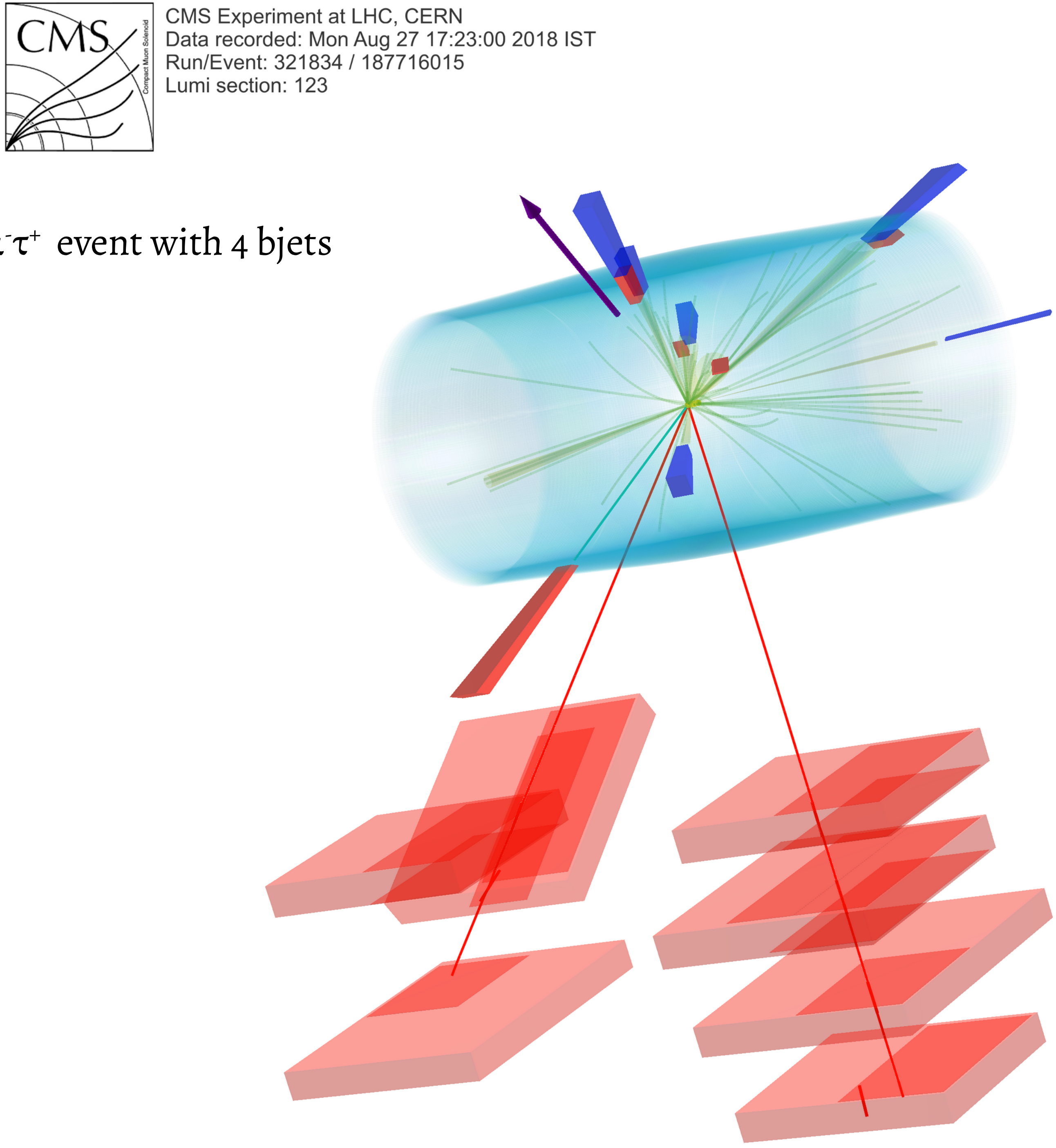
Missing momentum

Defined as the negative of the vector sum of p_T of all observed particles.

This means one has to understand all the observed particles well.

Mismeasurements in measuring existing particle 4-vectors will impact missing momentum.

These mismeasurements have to be modeled well in simulations!



This is a $\mu^{+}e^{-}\mu^{-}\tau^{+}$ event with 4 bjets

Thank you!