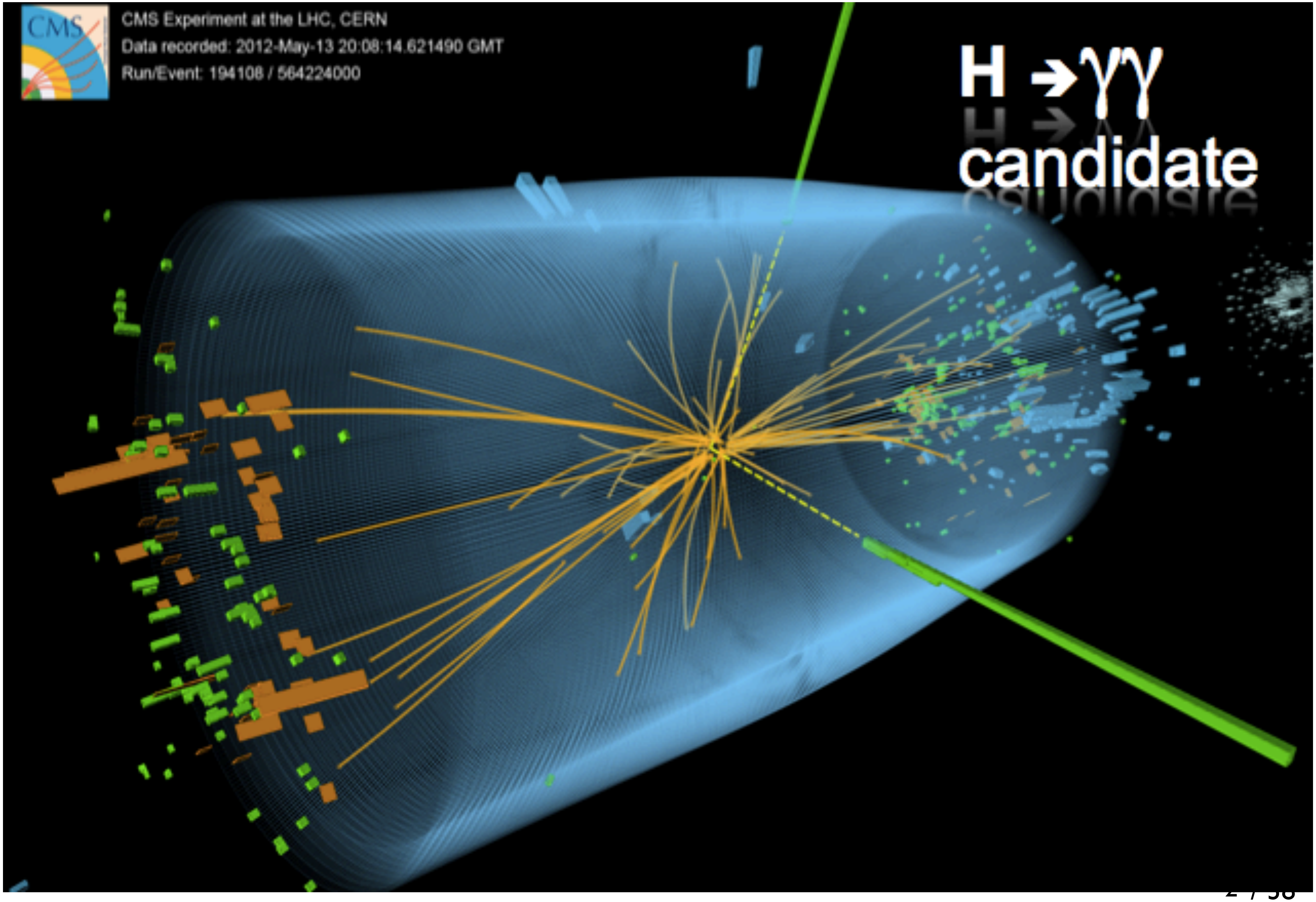
THE PICOSEC MC-NET PROJECT

MARIE CURIE ACTIONS

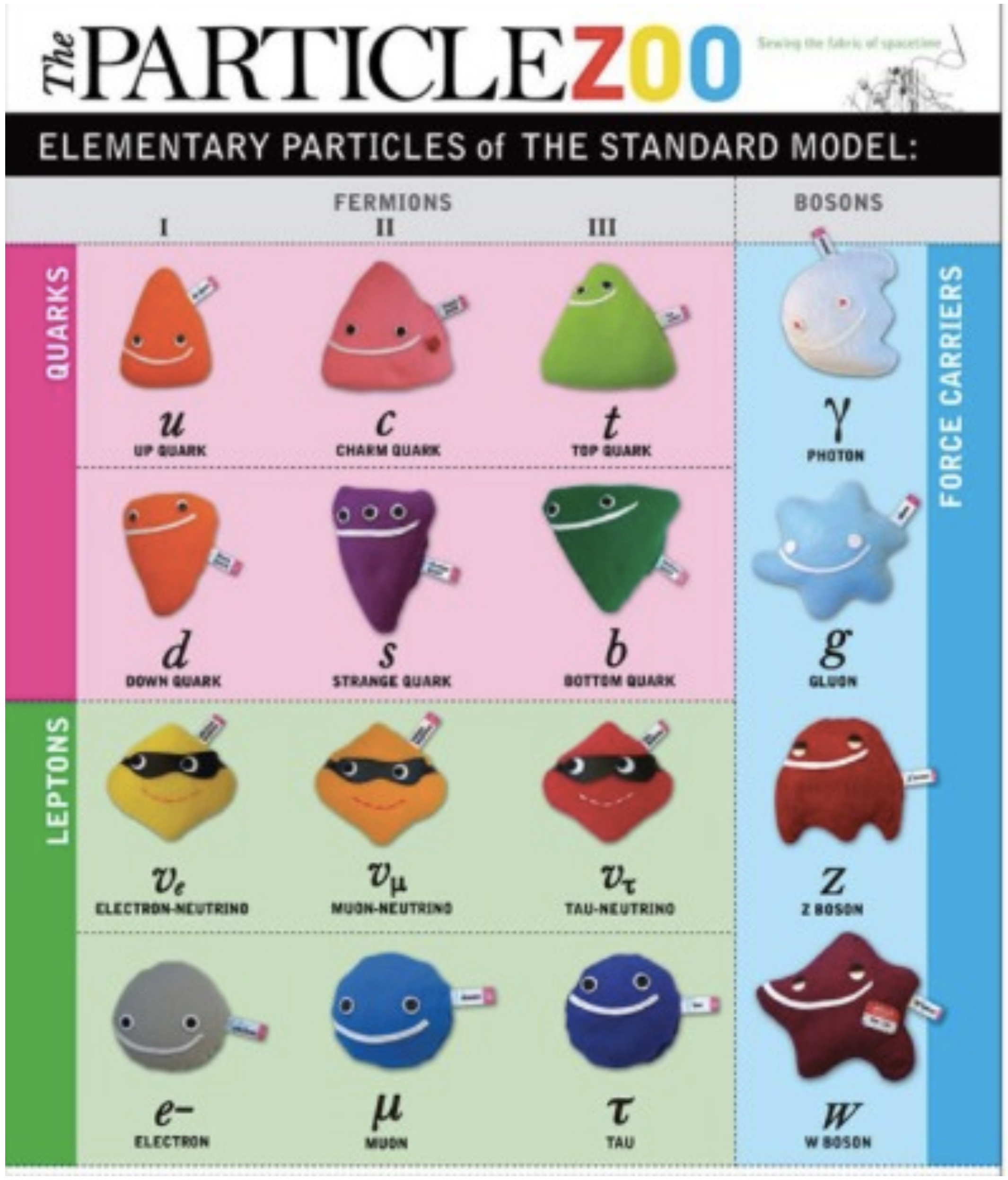
Interaction and detection of particles

Erika Garutti

A “typical” high energy physics event …



The Standard Model



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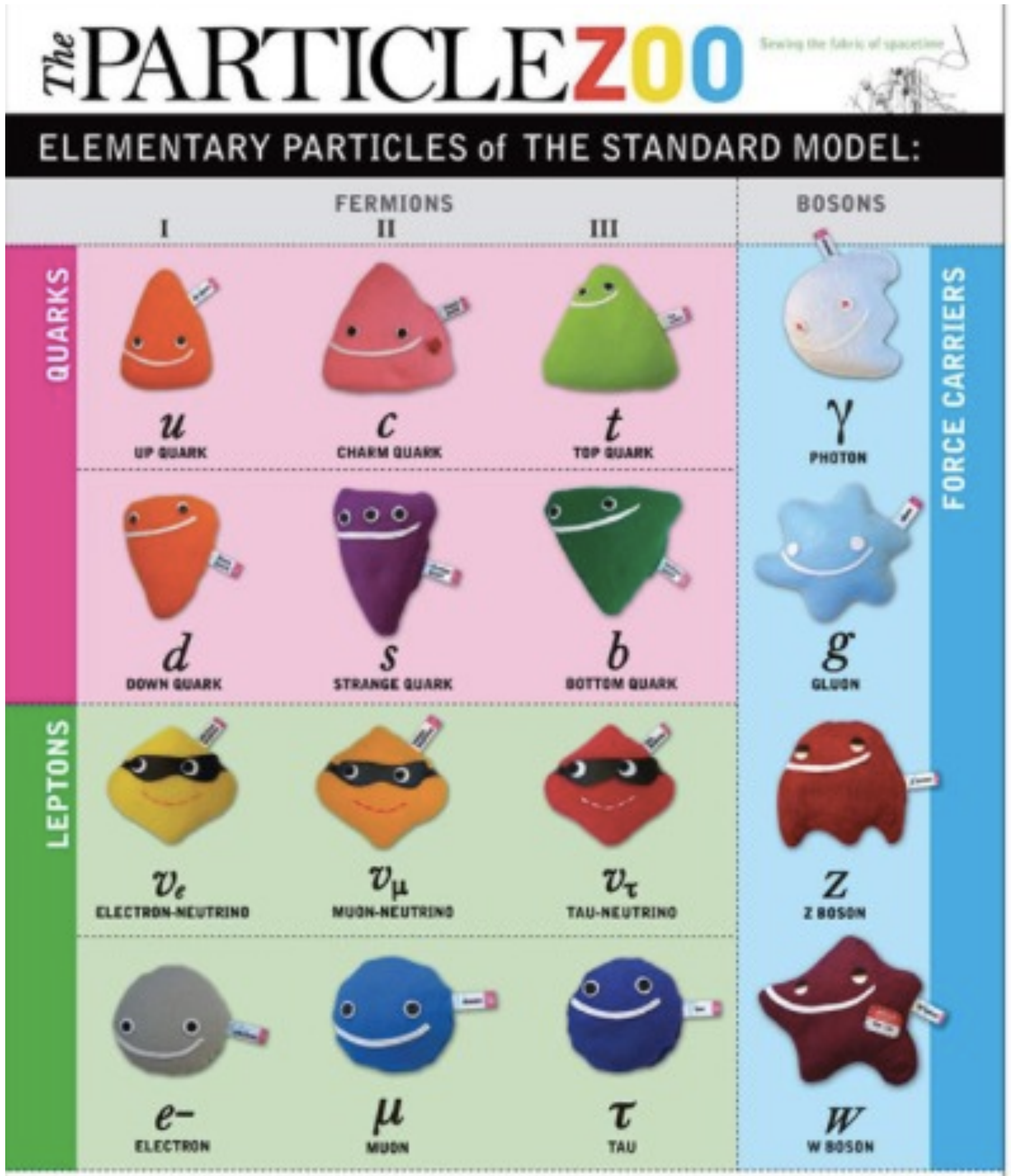

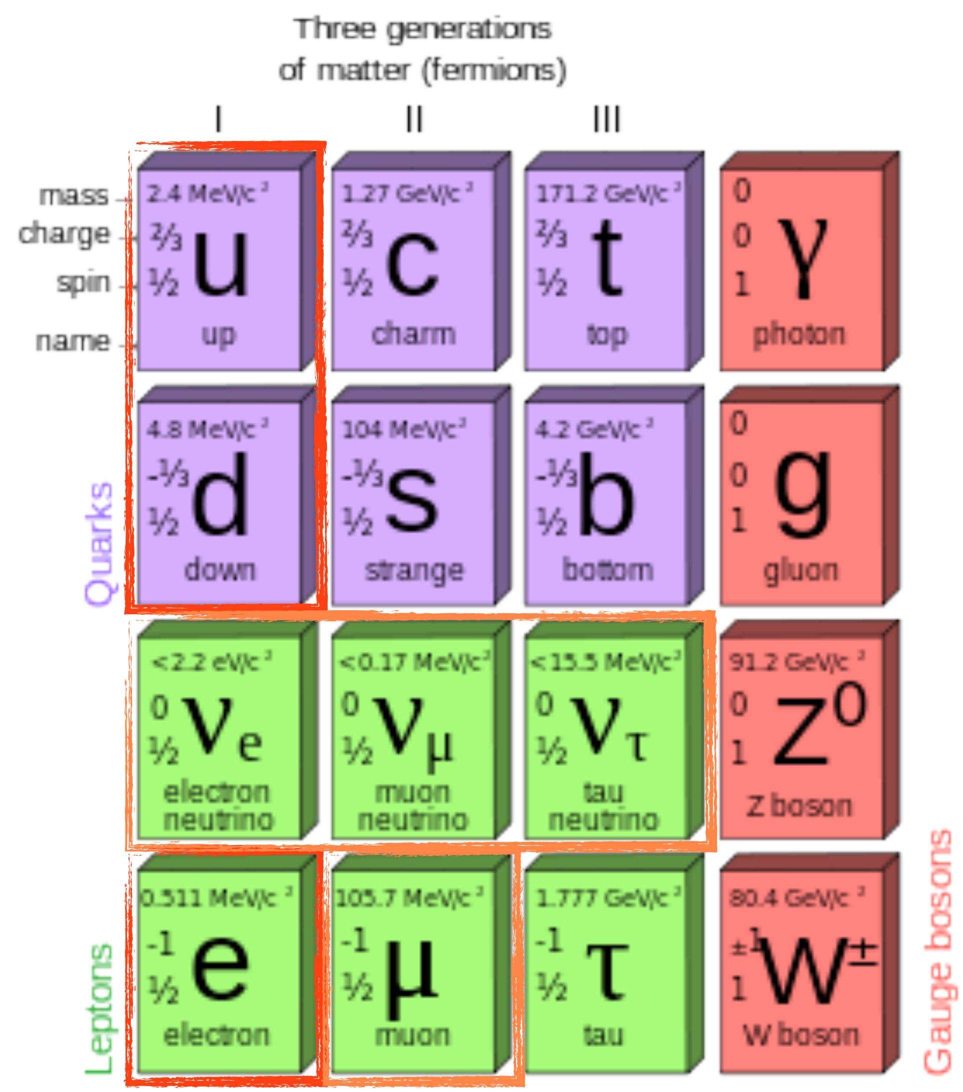

What particles can be detected?

In order for a particle to be detected, it has to interact and deposit energy

heavy charged particles
(with masses>$m_{electron}$)

electrons/positrons

photons

neutrons

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stable particles ($c\tau$ > 500μm): $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$, K^{0}, n, γ

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stable particles ($c\tau > 500\mu m$): $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$, K^0, n, γ

- Ultimately, the signals are obtained from the interactions of charged particles
- Neutral particles (photons, neutrons) have to transfer their energy to charged particles to be measured calorimeters
- what does detecting mean?

To be detected particles need to interact with matter...

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What do we measure of a particle?

- A particle is uniquely identified by its

  mass and charge

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

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- particle mass determination

$$m^2c^2 = E^2 - \vec{p}^2$$

requires **energy** and **momentum**

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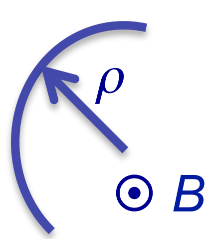
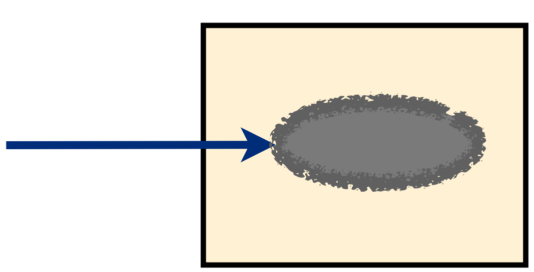


momentum determination via Lorenz relation

$$p = \rho Z e B$$



energy determined via calorimetric measurements

$$E = \gamma m c^2$$

What do we measure of a particle?

$$m^2c^2 = E^2 - \vec{p}^2$$

E = Energy
p = Momentum

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	Units
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Note: 1 GeV = 1.000 MeV = 1.000.000 keV

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$$\Delta \sim \frac{\lambda}{2\pi}$$

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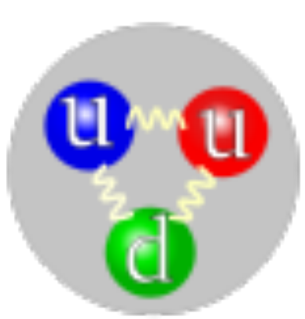
why such a high energy?
think about the microscope resolution:

$$\Delta \sim \frac{\lambda}{2\pi} = \frac{\hbar c}{E}$$

$$\frac{200 \text{ MeV fm}}{200 \text{ GeV}} = 10^{-3} \text{ fm} = 10^{-18} \text{ m}$$

Proton radius = 1 fm = 10^{-15} m (need E > 200 MeV)



Quark radius < 10^{-19} m

How do particles interact with matter?

stable particles: $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$, K^0, n, γ

1) photons
2) heavy charged particles ($m > m_e$)
3) electron / positron
4) neutrons

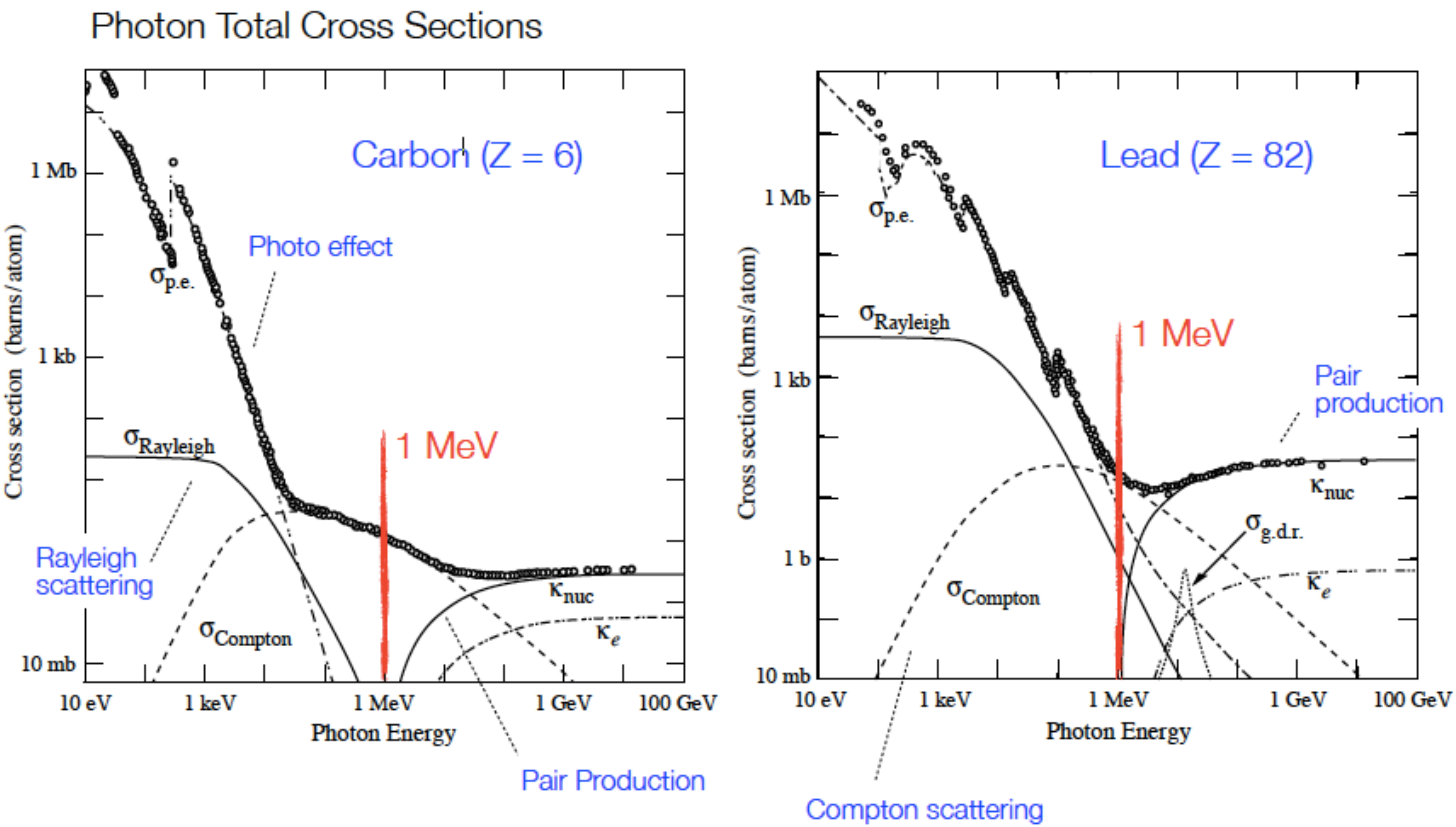
Jets: collimated bunch of (mainly heavy charged) particles from the hadronization of a quark

Neutrinos: react very weakly with matter

Cross section for $\nu_e + n \rightarrow e^- + p$ is around 10^{-43} cm^{-2}

in 1m Iron interaction probability 10^{-17}

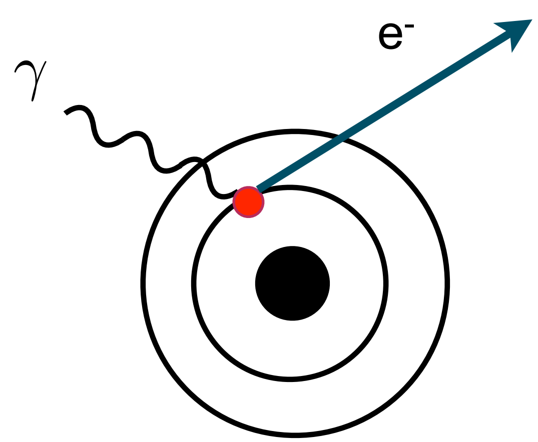
1) Photons


Photon Total Cross Sections
Carbon (Z = 6)
Lead (Z = 82)
Cross section (barns/atom)
1 Mb
1 kb
1 b
10 mb
10 eV
1 keV
1 MeV
1 GeV
100 GeV
Photon Energy
Photo effect
$\sigma_{p.e.}$
$\sigma_{Rayleigh}$
$\sigma_{Compton}$
κ_{nuc}
κ_e
$\sigma_{g.d.r.}$
1 MeV
Rayleigh scattering
Pair Production
Pair production
Compton scattering

Interaction of photons with matter

- Most dominating effects - dependence on E_γ and material (Z)

Photo-Effect



Cross-section largest for
$E_\gamma \approx$ K-shell energy
Strongest E dependence
for $I_0 < E_\gamma < m_ec^2$

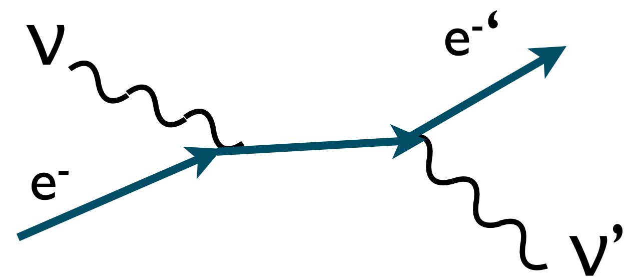
$$\sigma_{ph} = \alpha\pi a_B Z^5 (I_0 / E_\gamma)^{7/2}$$

$a_B = 0.53$ Å
$I_0 = 13.6$ eV

Softer for $E_\gamma > m_ec^2$

$$\sigma_{ph} = 2\pi r_e^2 \alpha^4 Z^5 (mc)^2 / E_\gamma$$

Compton-Scattering

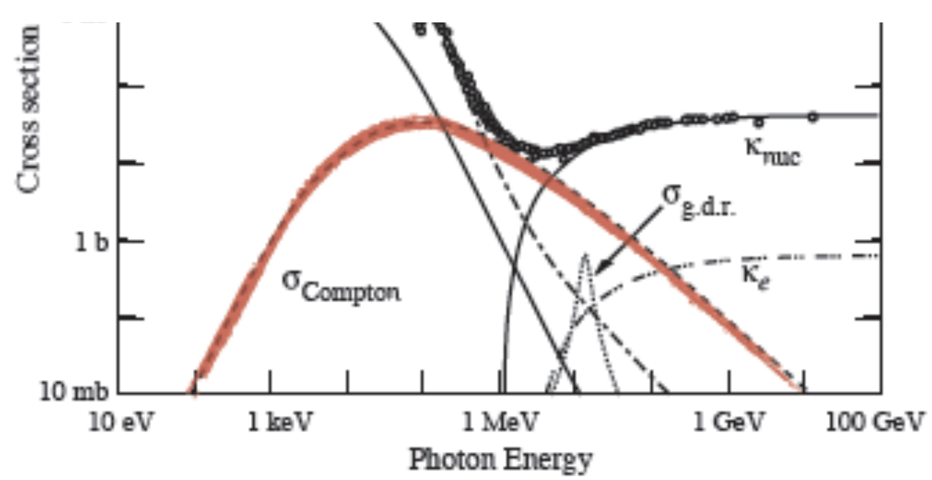


for $E_\gamma << m_ec^2$ $\quad \sigma_c \propto \sigma_{Th}(1 - 2\varepsilon + \frac{26}{5}\varepsilon^2)$

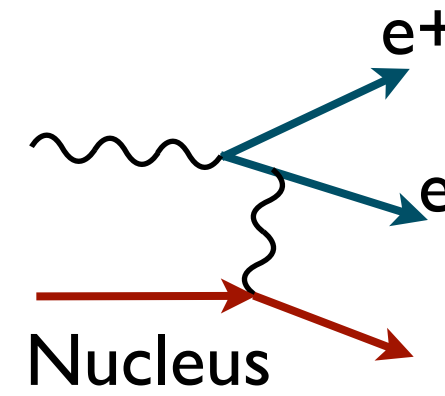
Thompson cross-section:
$\sigma_{Th} = 8\pi/3\, r_e^2 = 0.66$ barn

$$\varepsilon = \frac{E_\gamma}{m_ec^2}$$

for $E_\gamma >> m_ec^2$ $\quad \sigma_c \propto \frac{\ln\varepsilon}{\varepsilon} Z$



Pair creation



Only possible if
$E_\gamma \geq 2m_ec^2$ ~1 MeV

$\sigma_{pair} \sim \ln(E_\gamma)$

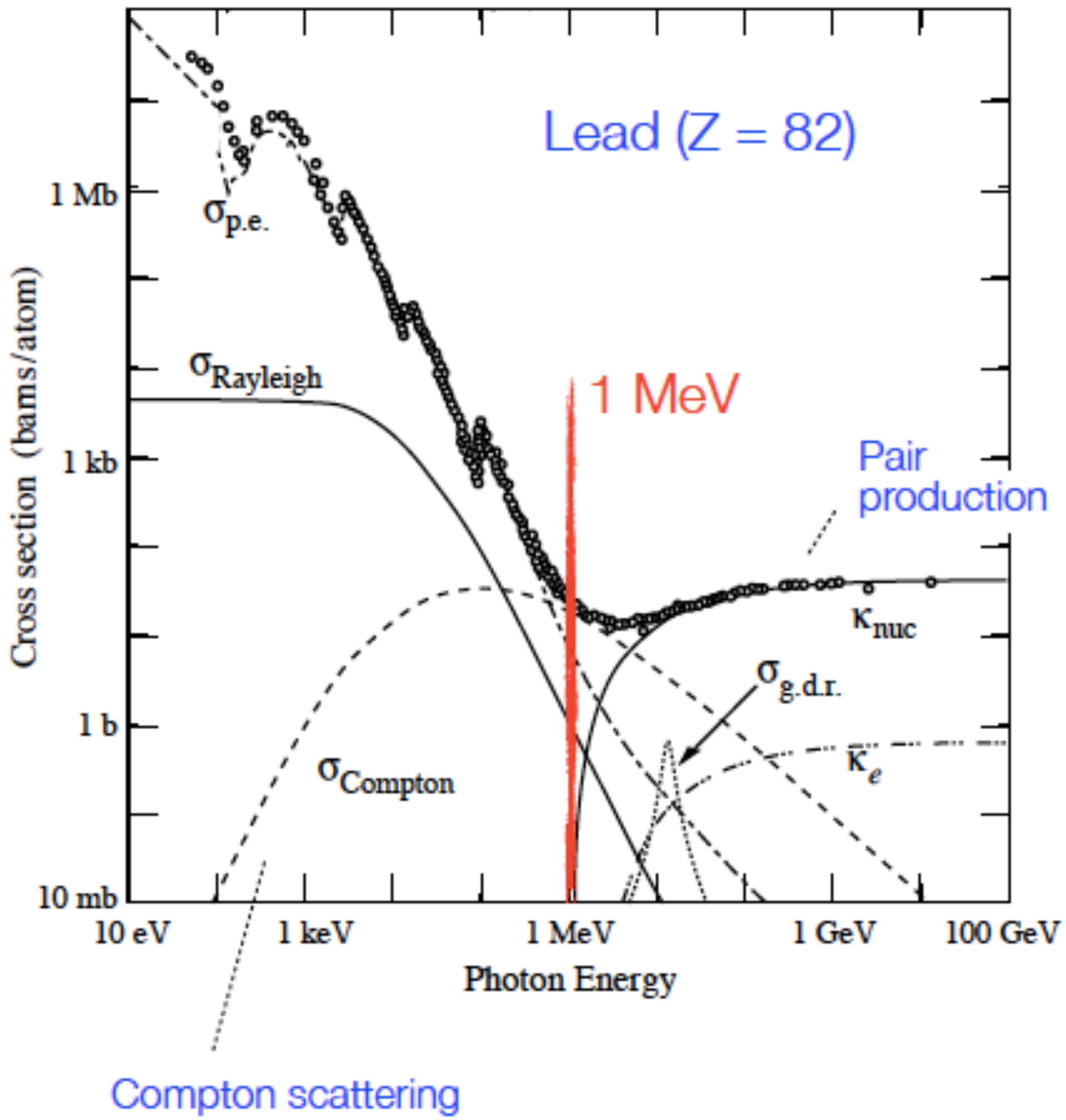
$\sigma_{pair} \sim Z^2$

$$\sigma_{pair} = \frac{7}{9}\frac{N_A}{A}\cdot\frac{1}{X_0}$$

X_0: Radiation length
Radiation length /38

Interaction of photons with matter

- Most dominating effects - dependence on E_γ and material (Z)



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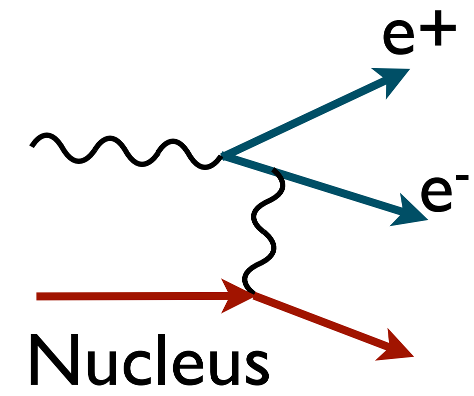

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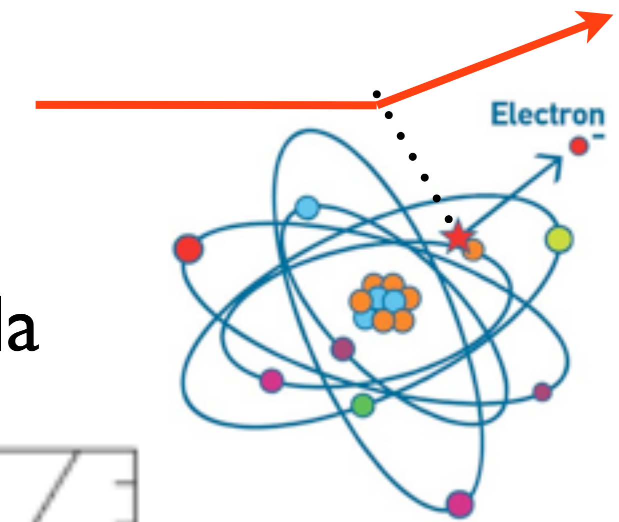
Radiation length

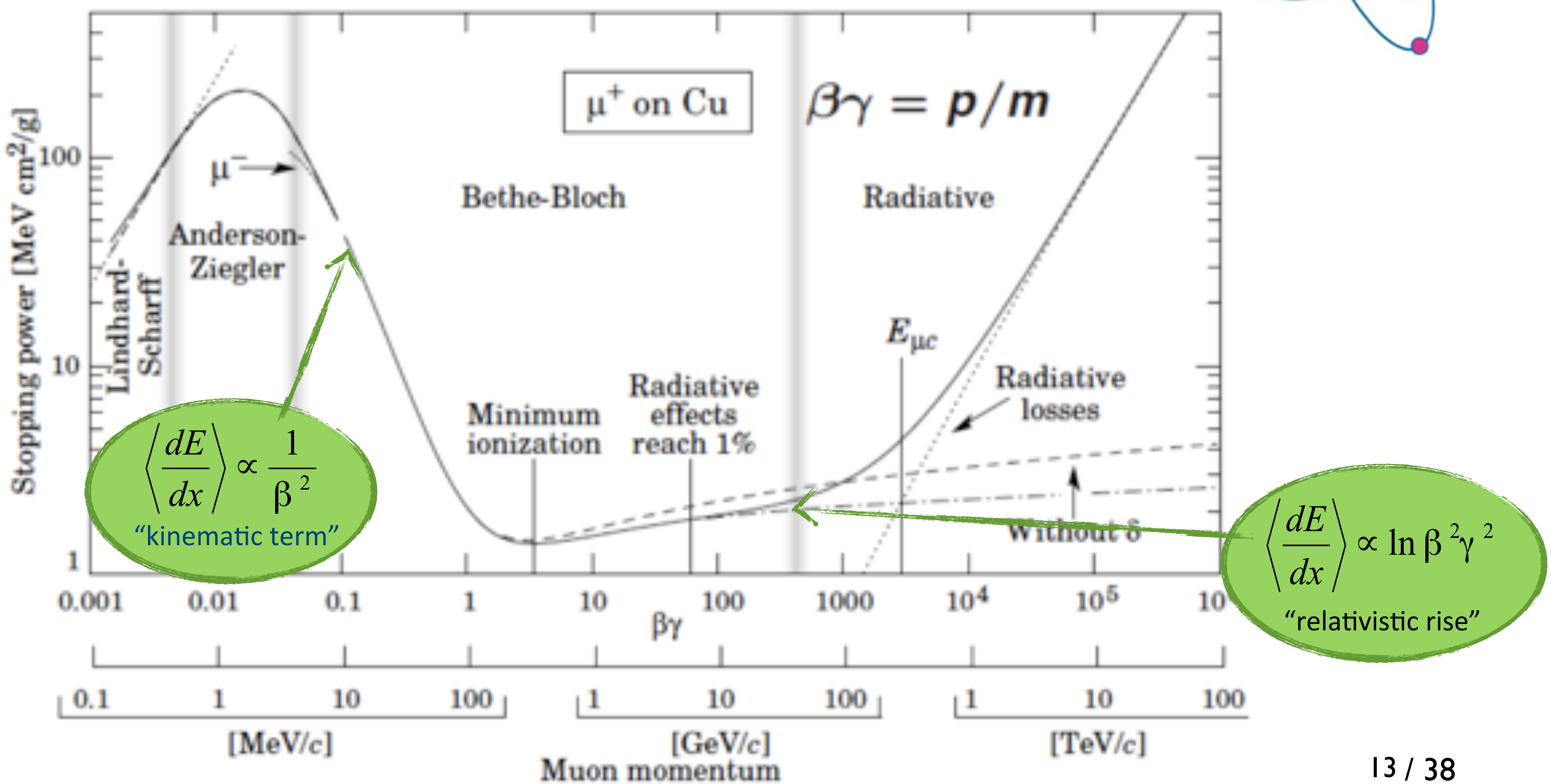
2) Heavy charged particles

$\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$

Mostly energy transfer to the atomic electrons causing ionization and excitation

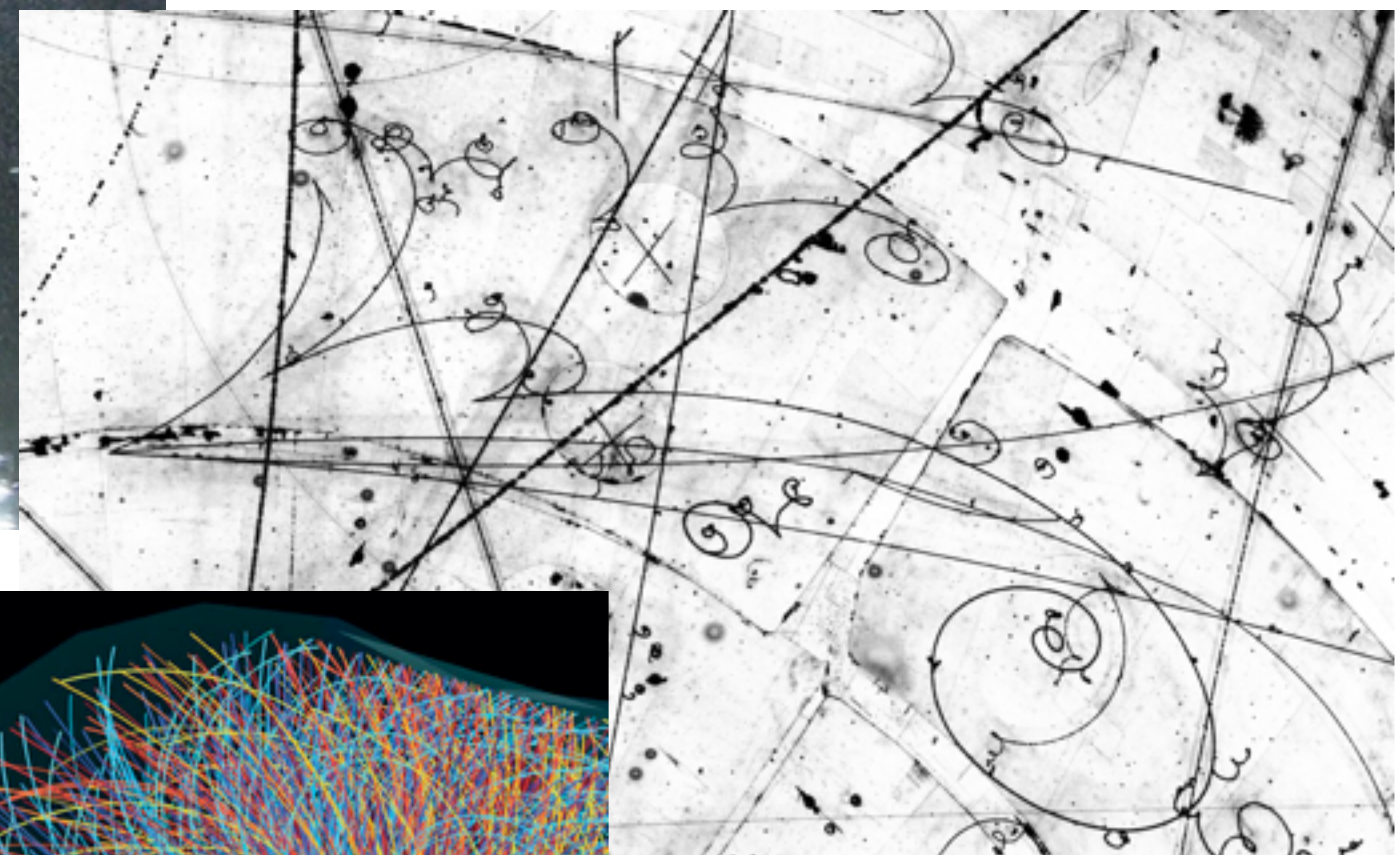


Mean energy loss is described by the Bethe-Bloch formula



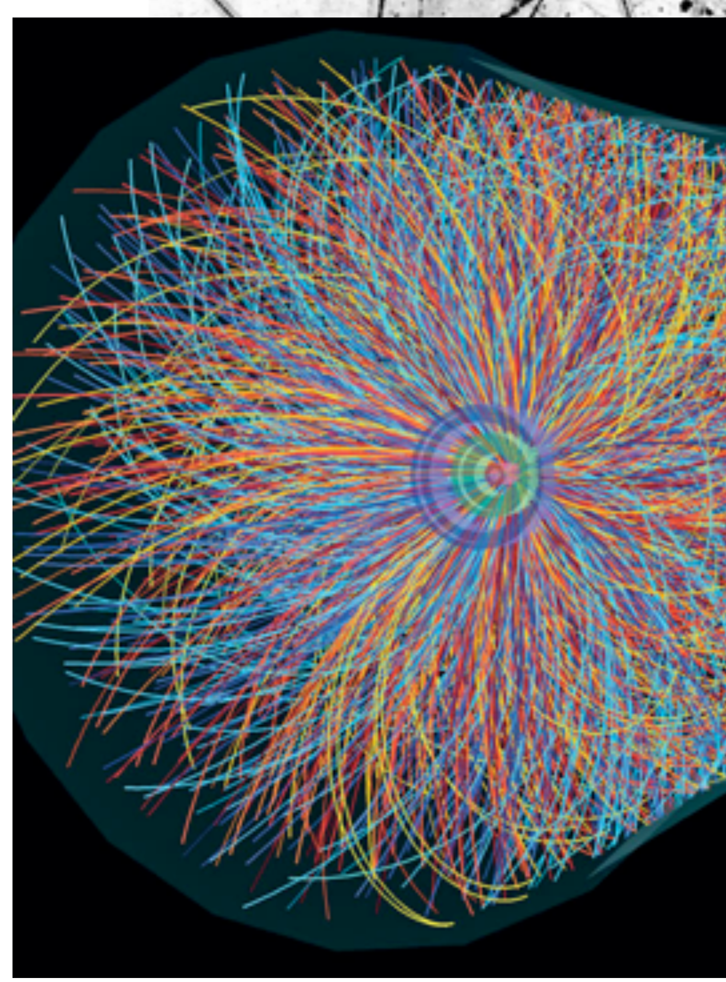
Detection via ionization

Radon220 decay in a cloud chamber



bubble chamber

spark chamber



ALICE
time projection chamber

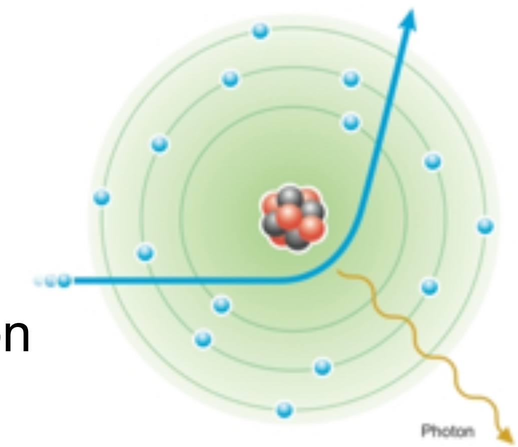
3) Electron / positron

e±

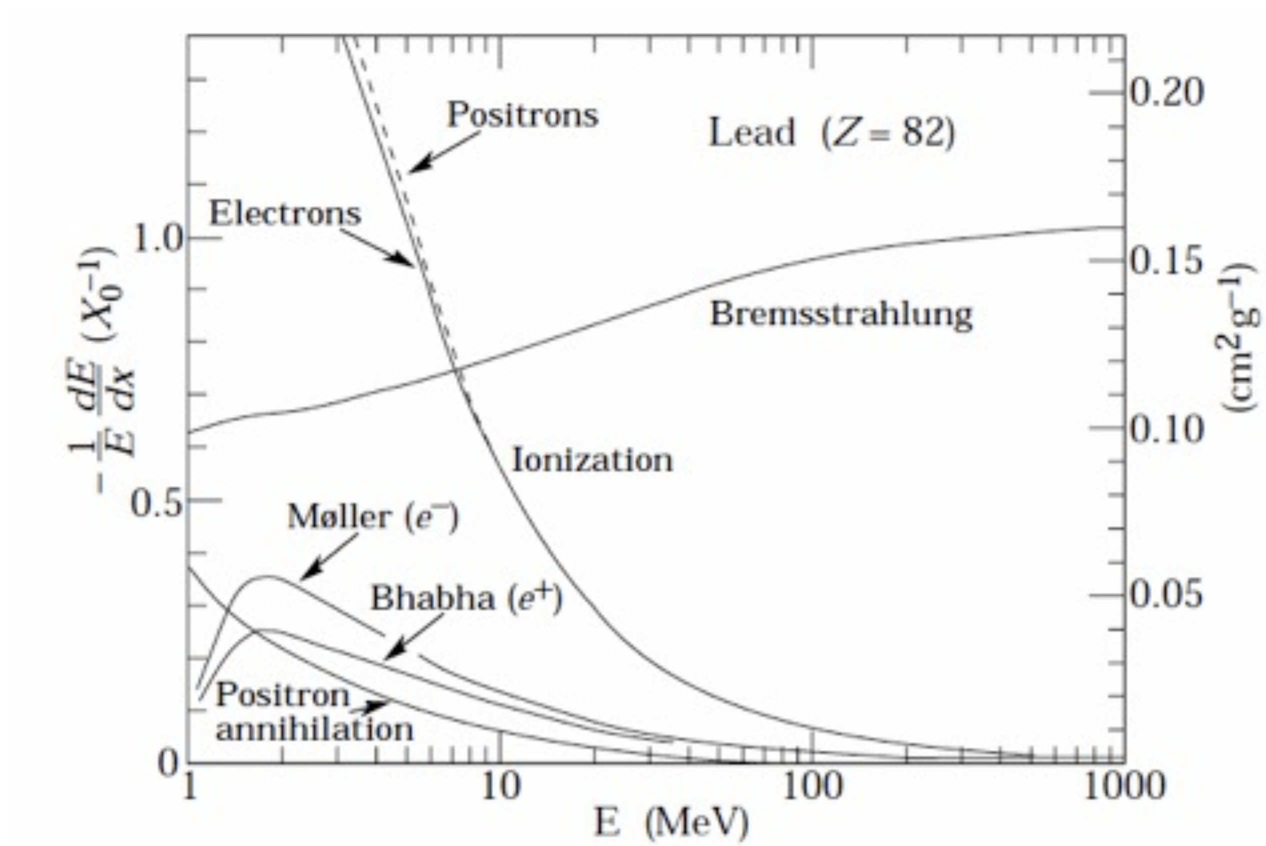
Deflection of a charge in a strong nuclear E-field ➔ emission of a photon

$$-\frac{dE}{dx} \propto \frac{E}{m^2}$$

Incident electron and Bremsstrahlung photon



Effect plays a role only for e± and ultra-relativistic μ (>1000 GeV)



Bremsstrahlung dominates for energies > O(10 MeV)

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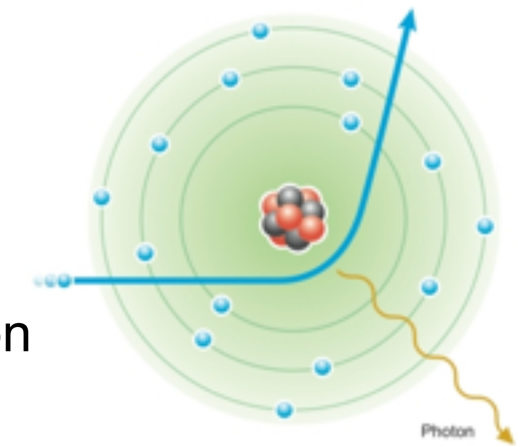

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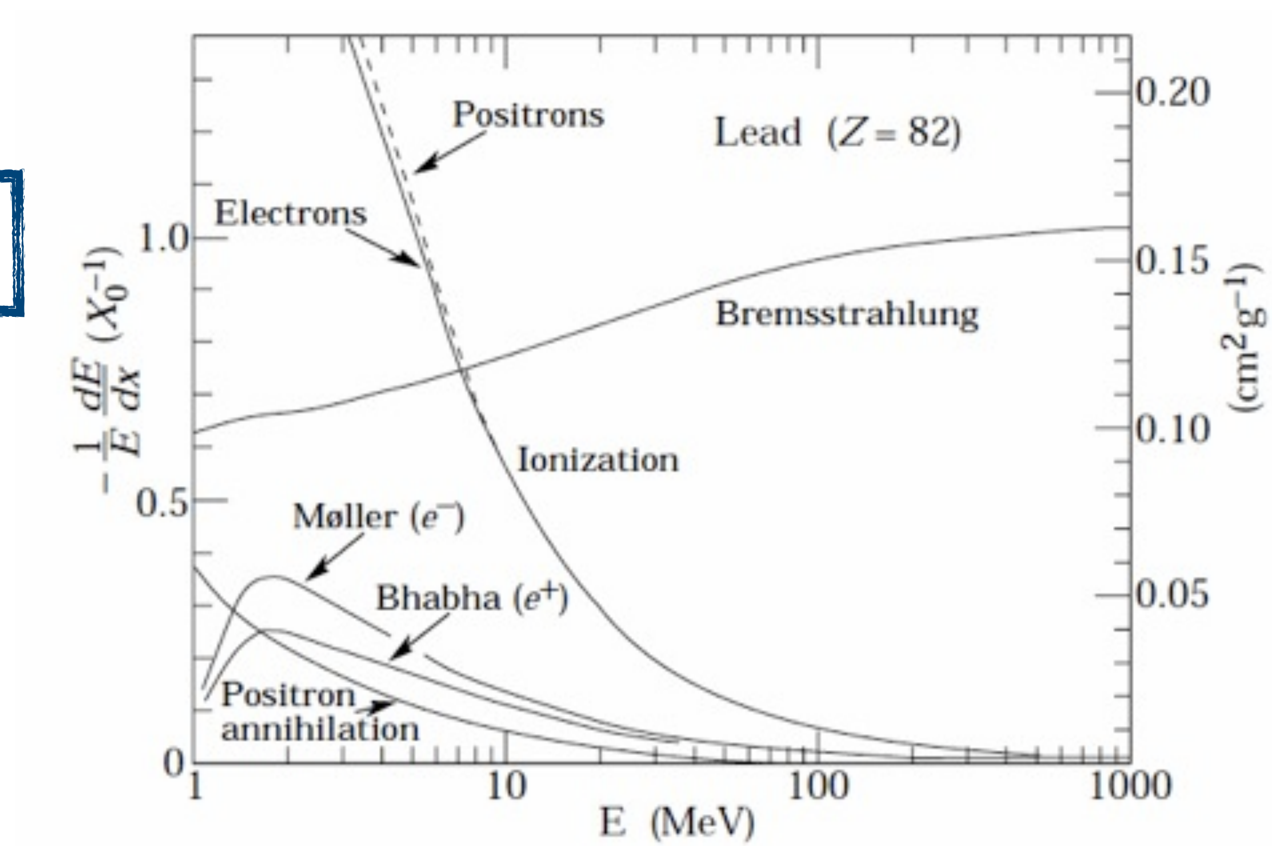
$$-\frac{dE}{dx} = \frac{E}{X_0} \quad \rightarrow \quad E = E_0 \, e^{-x/X_0}$$

$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln \frac{183}{Z^{1/3}}}$$

Radiation length

- crucial parameter for detector design
- thickness of material an electron traverses till its energy is reduced by 1/e (~37%)
- depends only on material



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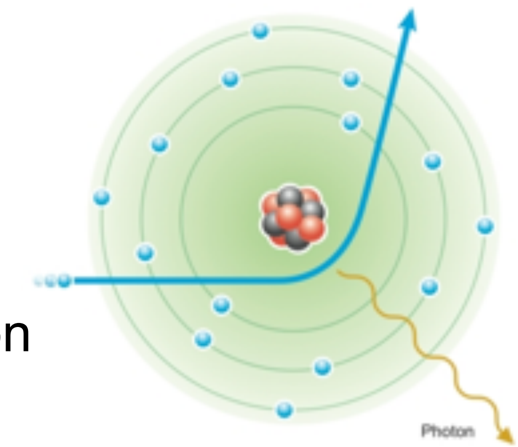

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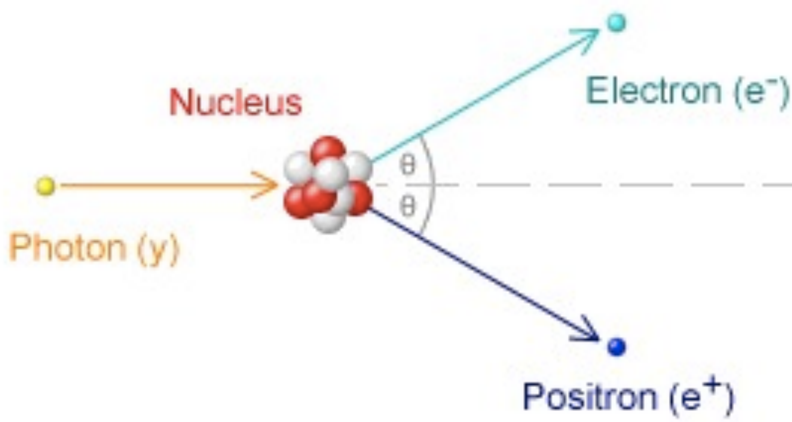
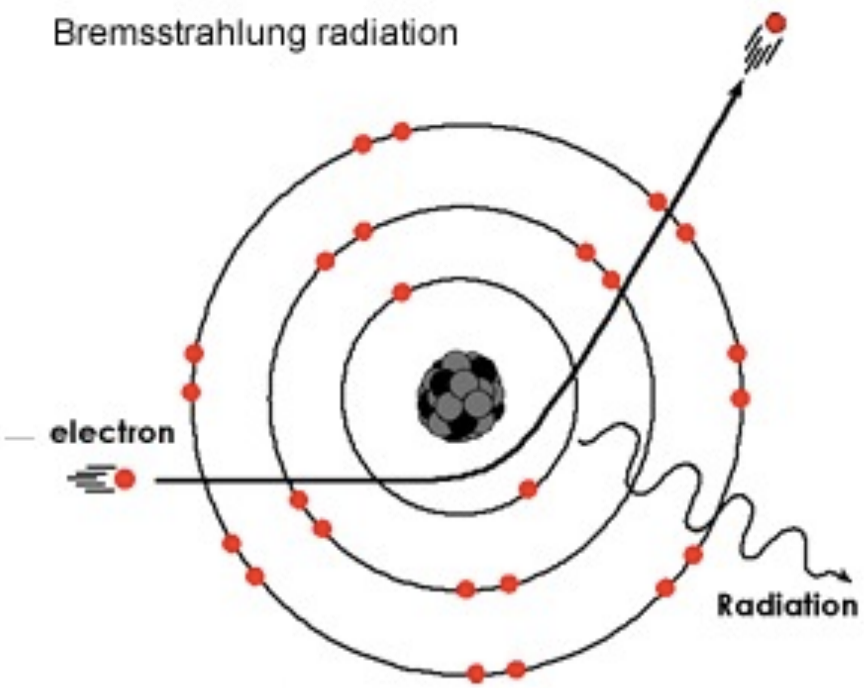
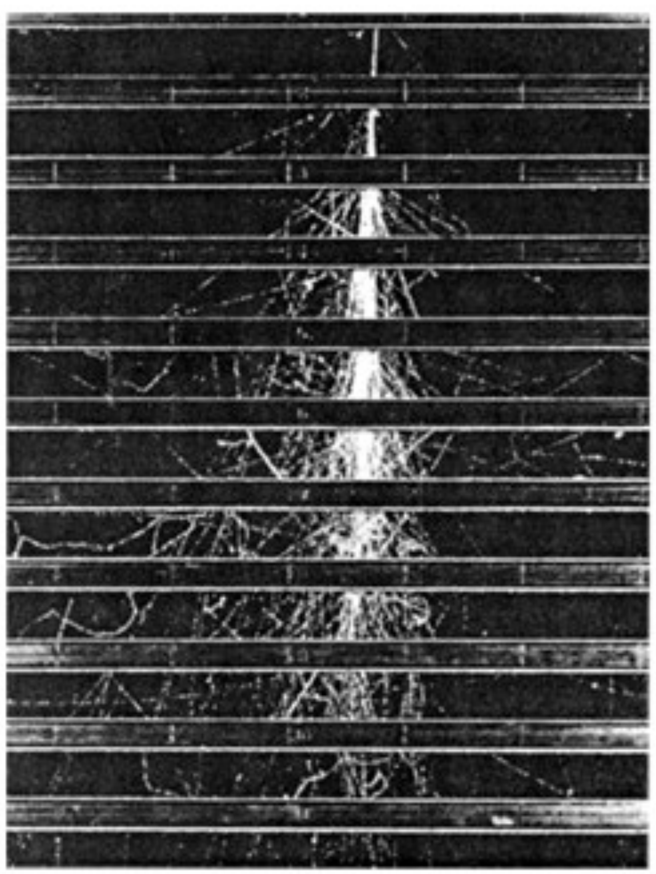
- Usually quoted in [g/cm²], typical values are:
  - Air: 36.66 g/cm² ->~ 300 m
  - Water: 36.08 g/cm² -> ~ 36 cm
  - Silicon: 21.82 g/cm² -> 9.4 cm
  - Aluminium: 24.01 g/cm² -> 8.9 cm
  - Tungsten: 6.76 g/cm² -> 0.35 cm

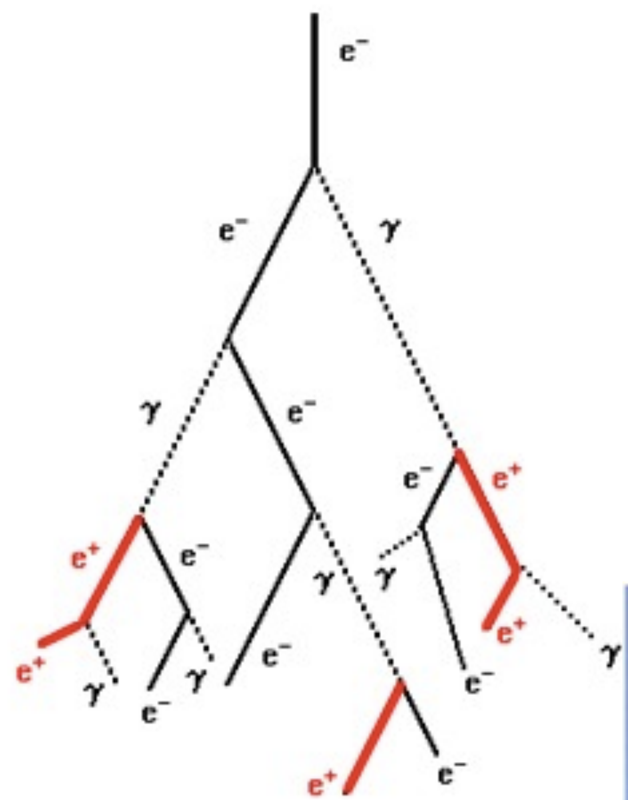
Electromagnetic shower

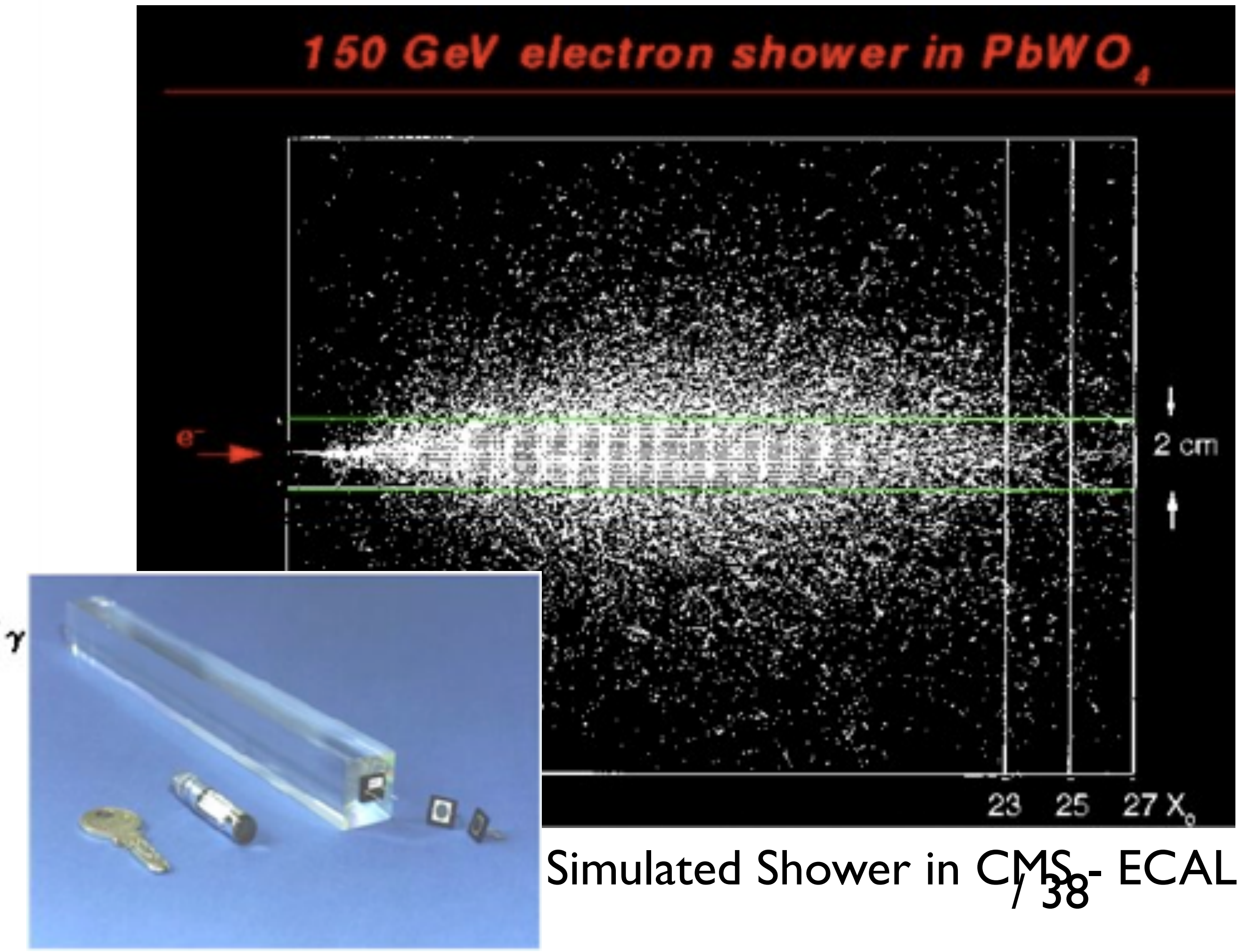




~ ln(E) !!!
~ X_0







[cloud chamber](#) photograph (MIT cosmic ray group) of a particle traversing a series of brass plates

Simulated Shower in CMS - ECAL

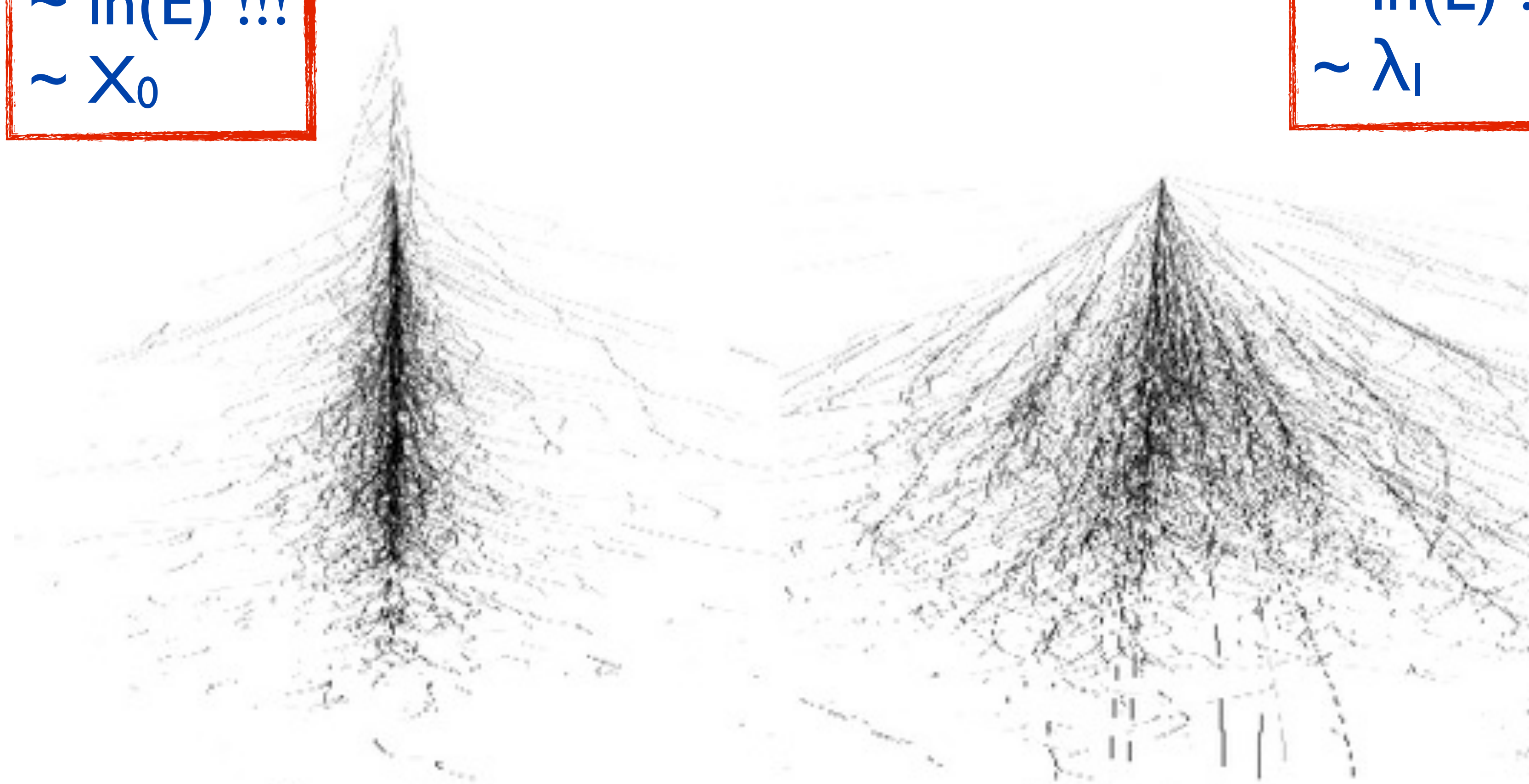
4) Neutrons (and charged hadrons)

- Neutron interaction is based only on strong (and weak) nuclear force
- To detect neutrons, one has to create charged particles
- In high energy physics fast neutrons (E_n>100 MeV) mainly elastic / inelastic interactions → hadronic cascades

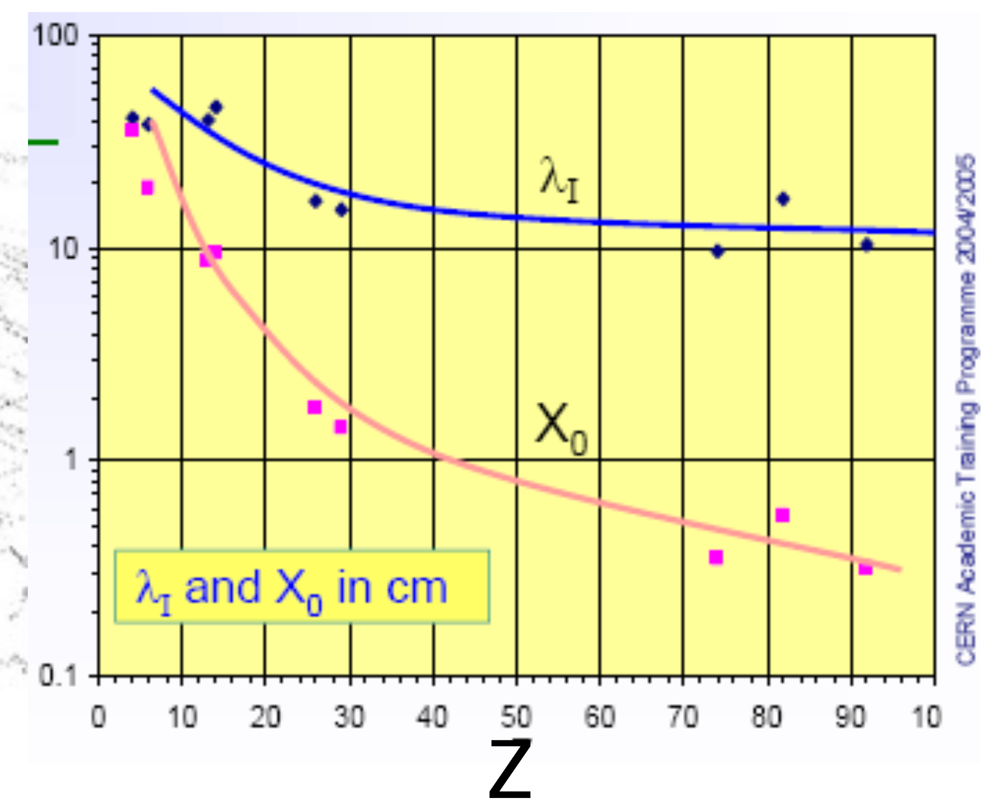
~ ln(E) !!!
~ X_0

~ ln(E) !!!
~ λ_I

Interaction length:
λ_I (g cm^{-2}) ∝ $A^{1/3}$



Gamma shower Hadronic shower



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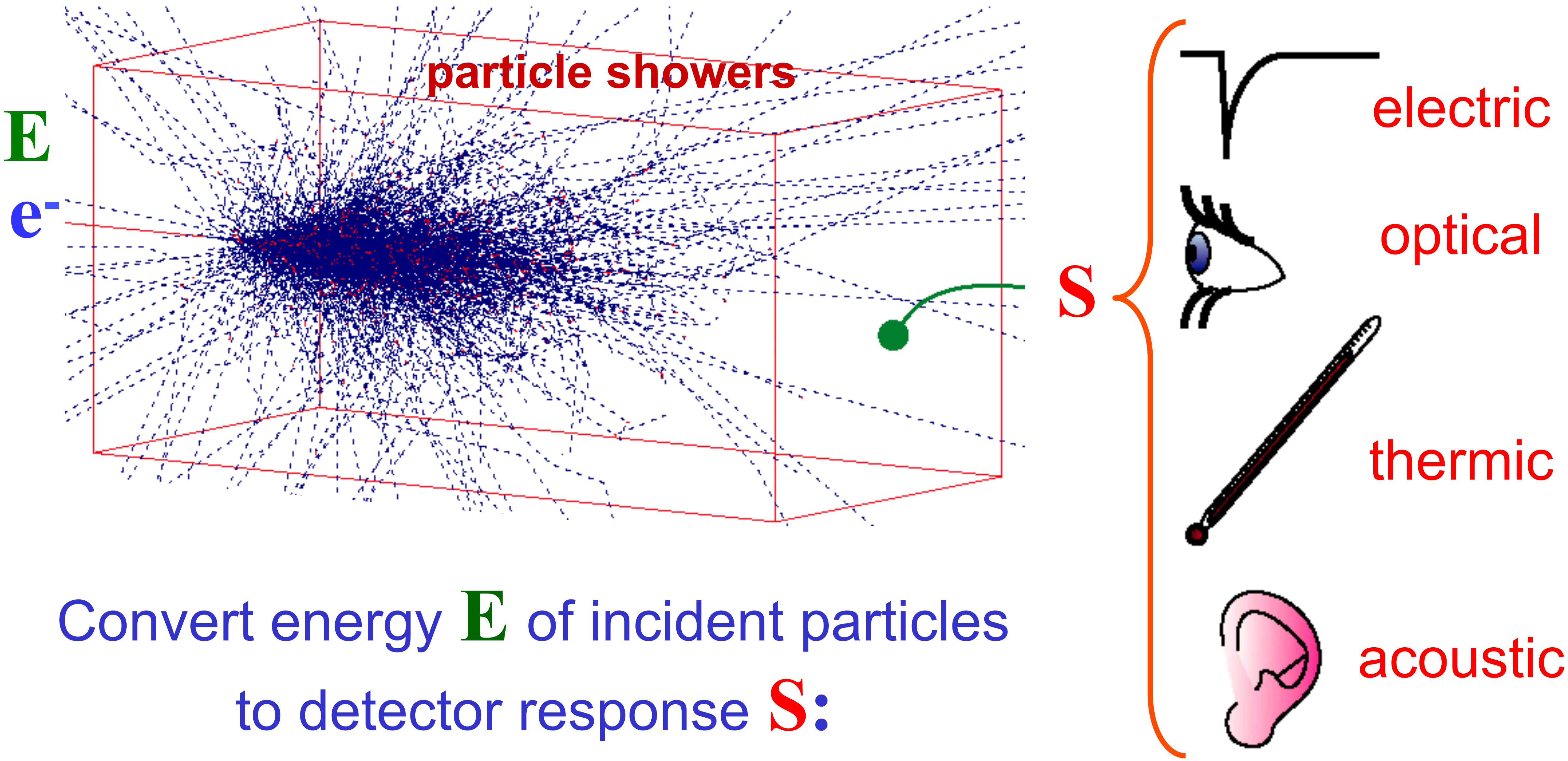


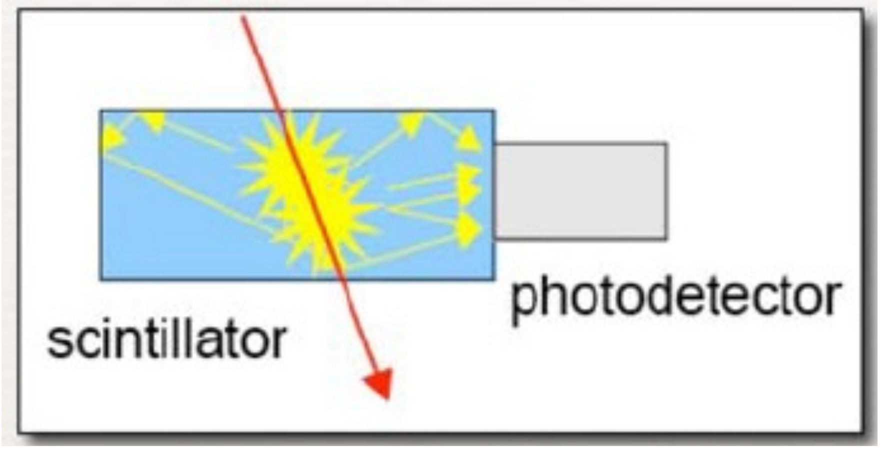
Convert energy **E** of incident particles to detector response **S**:

$$S \propto E$$

How do we measure a particle?

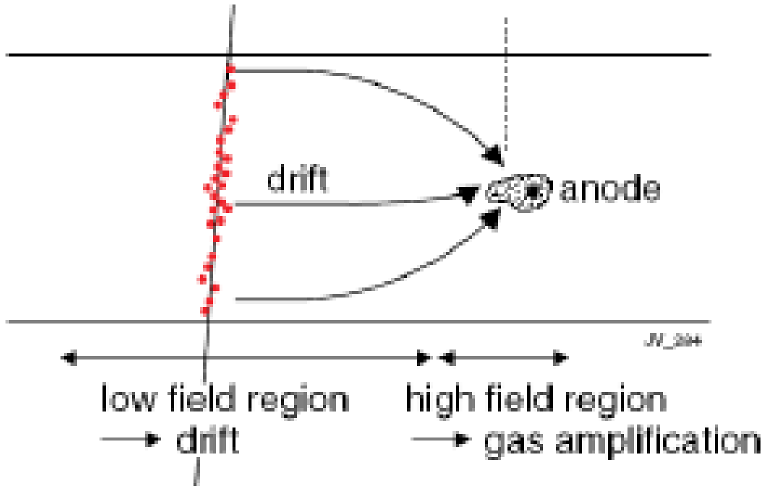
1) Convert particle energy to light:
scintillator (org. / in-org.)

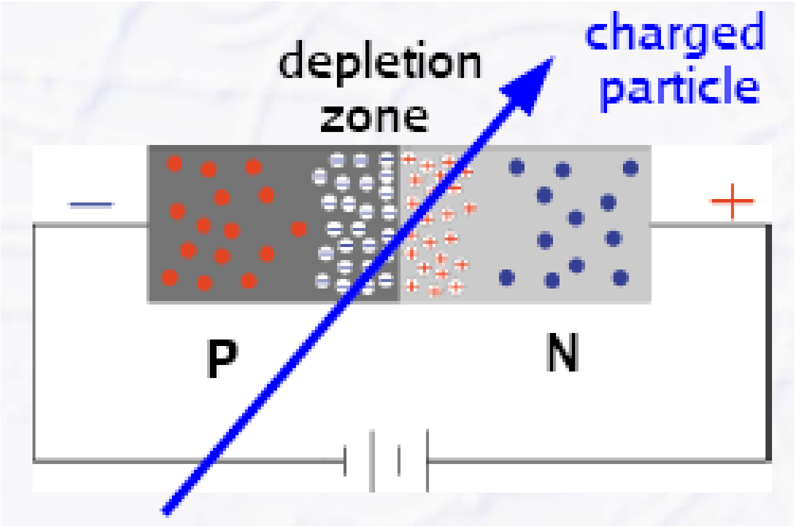
& measure light:
PMT / APD / HPD / SiPM …



2) Measure ionization E:
gas
noble liquids
semiconductors

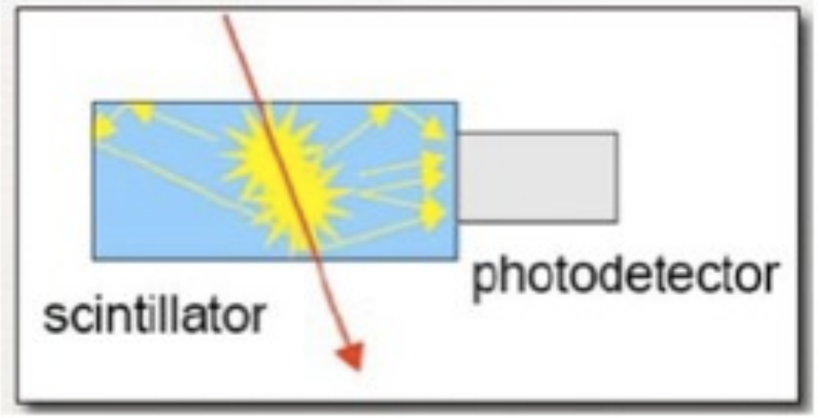
& measure charge signal

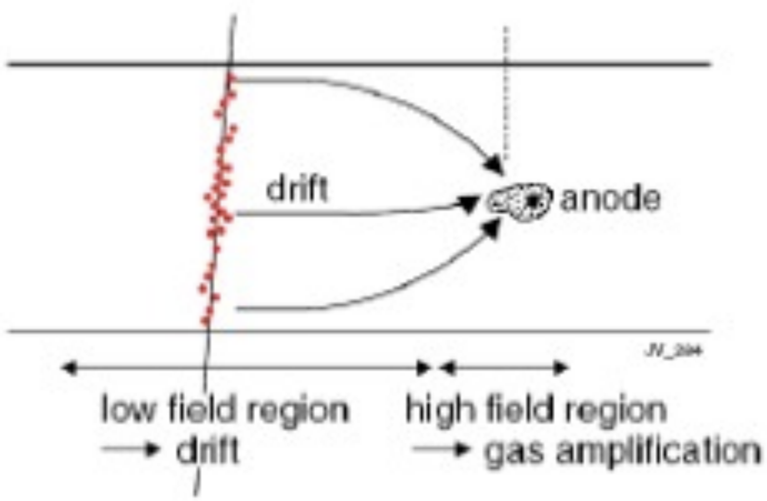


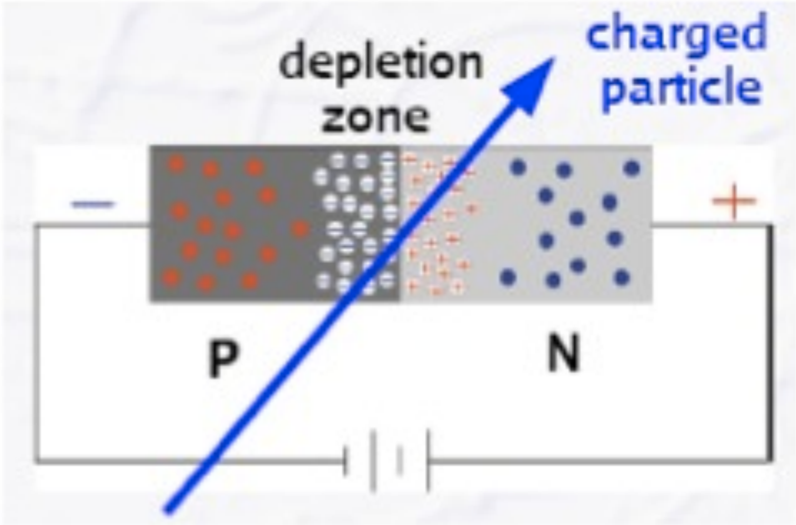


3) Measure temperature:
specialized detectors for: DM, solar νs, magnetic monopoles, double β−decay
very precise measurements of small energy deposits
phenomena that play a role in the 1 Kelvin to few milli-Kelvin range

Measurement of ionization charge







Relevant parameter:
ionization energy (I_0) = energy needed to create a detectable quantum

semiconductors I_0 = 1-5 eV per e-hole pair
gas detectors I_0 = 20-40 eV per e-ion pair
scintillators I_0 = 400-1000 eV to create a photon (need to convert photon!)

Historically

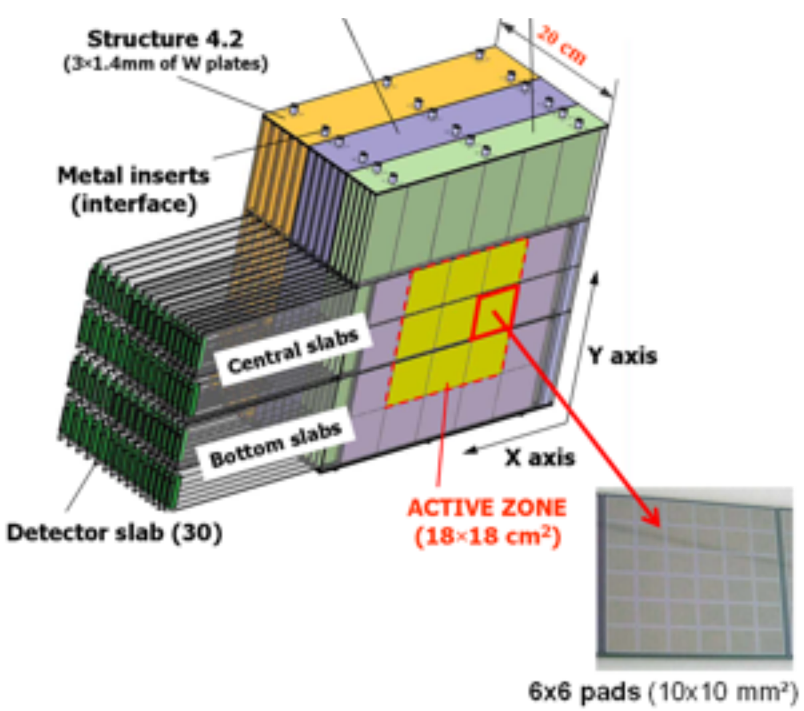
- semiconductors & gas mainly used in tracker detectors
  ➔ p measurement (+ dE/dx)

- scintillators (organic/inorganic) mainly used in calorimeters
  ➔ E measurement

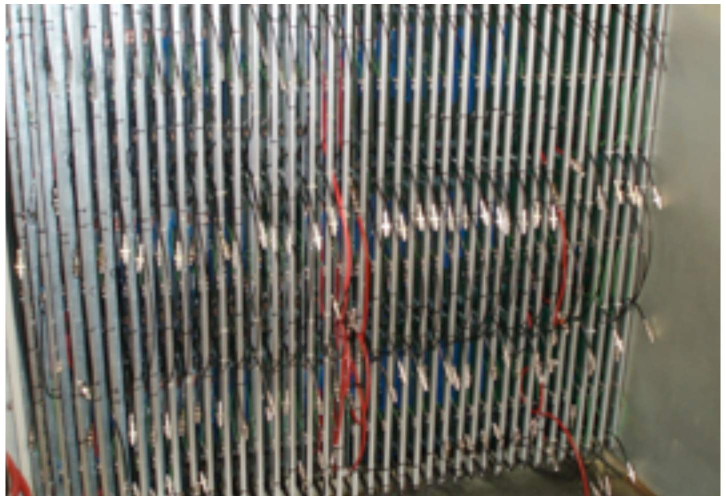
- ... but exceptions exist

> as detector developer be always open minded and daring !

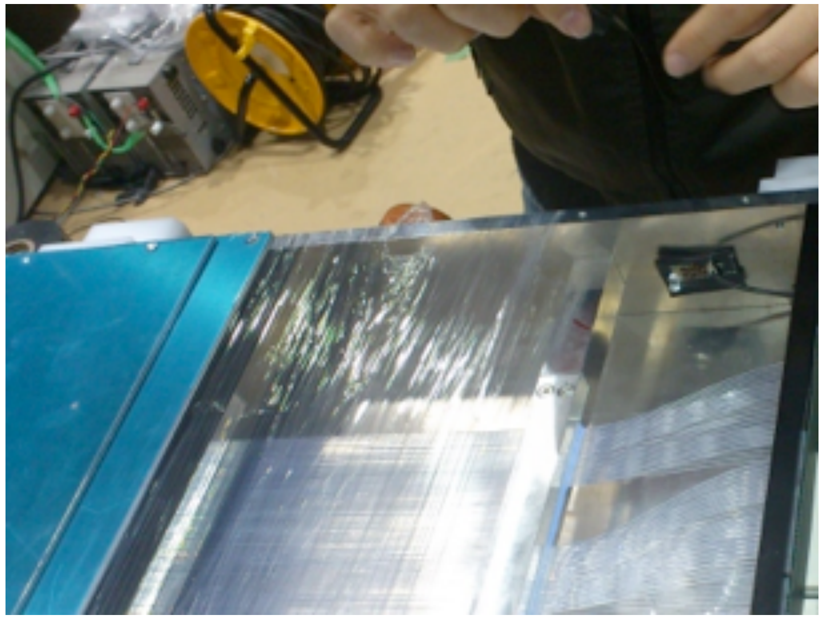
Silicon - ECAL



Gas readout for HCAL

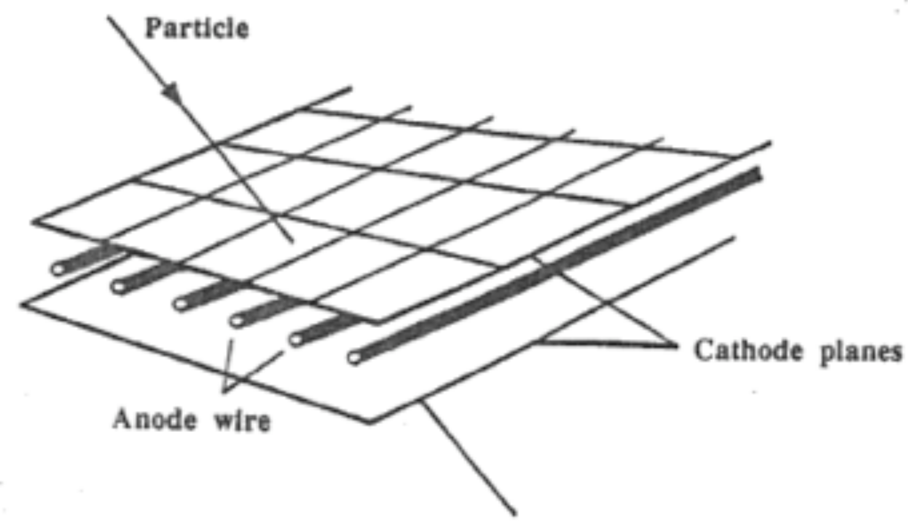


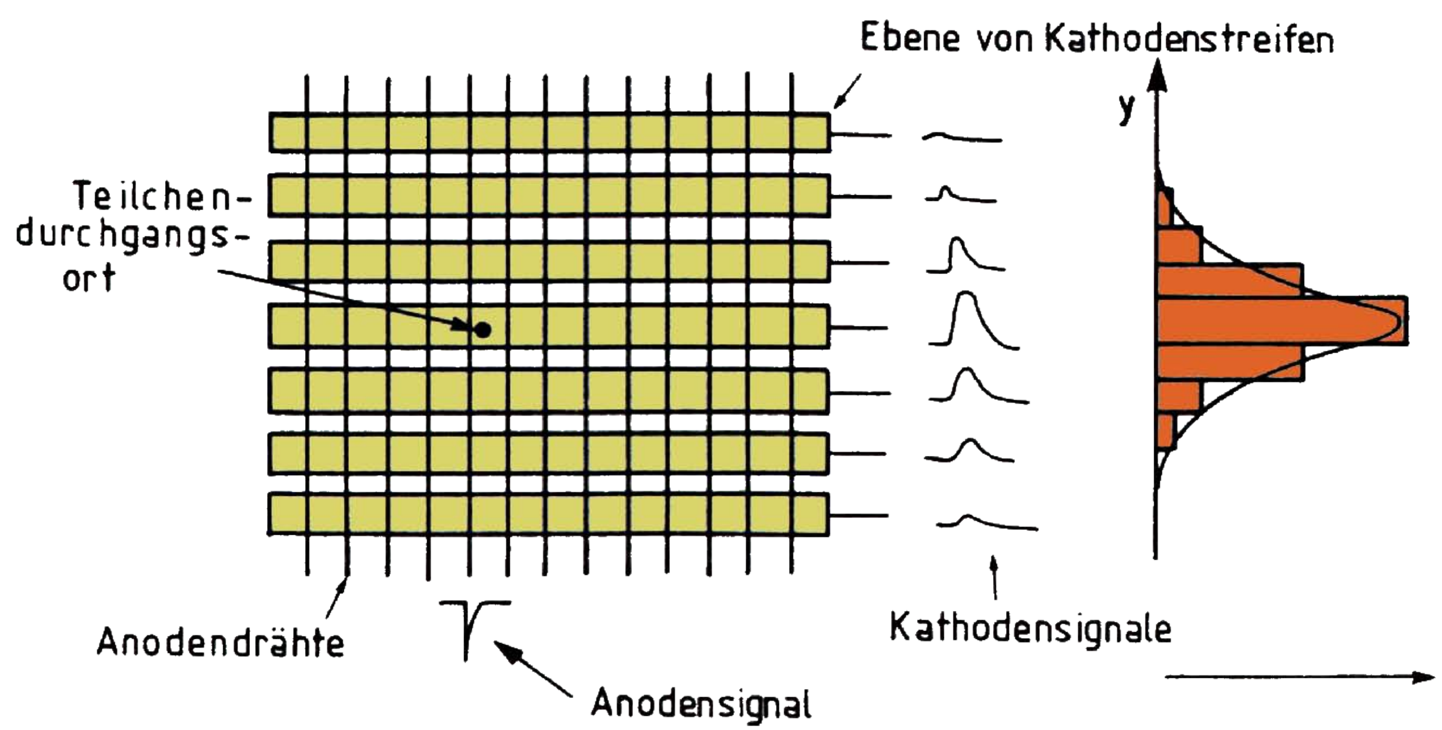
Fiber tracker



Track position: ionization chambers

- Extreme successful approach to provide good spatial resolution with gas detectors
- Multi wire proportional chamber (MWPC)
- Gas-filled box with a large number of parallel detectors wires, each connected to individual amplifiers
- G. Charpak 1968 (Nobel-Preis 1992)





Adding time: drift chamber

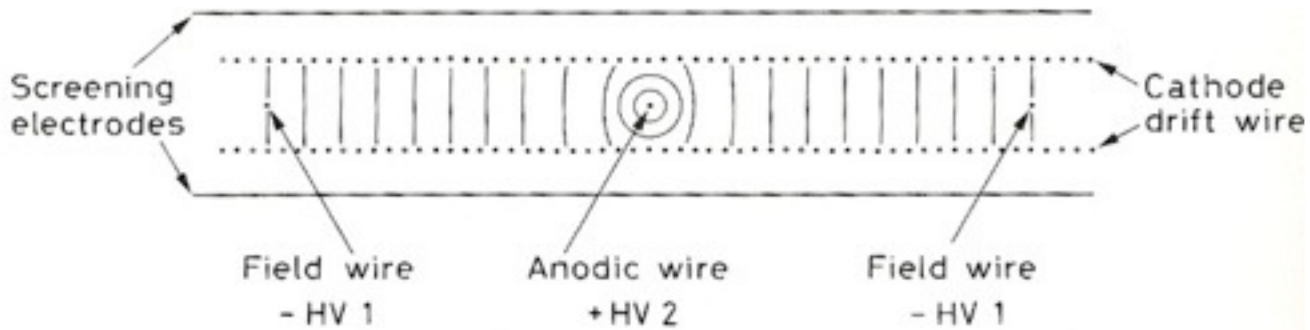
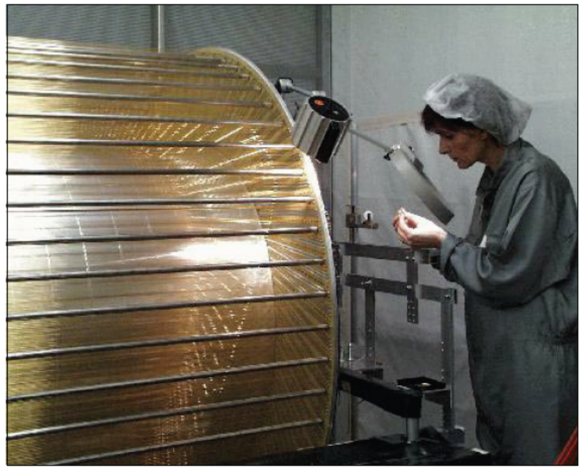


Fig. 6.16. Drift chamber design using interanode field wires (from *Breskin* et al. [6.22])

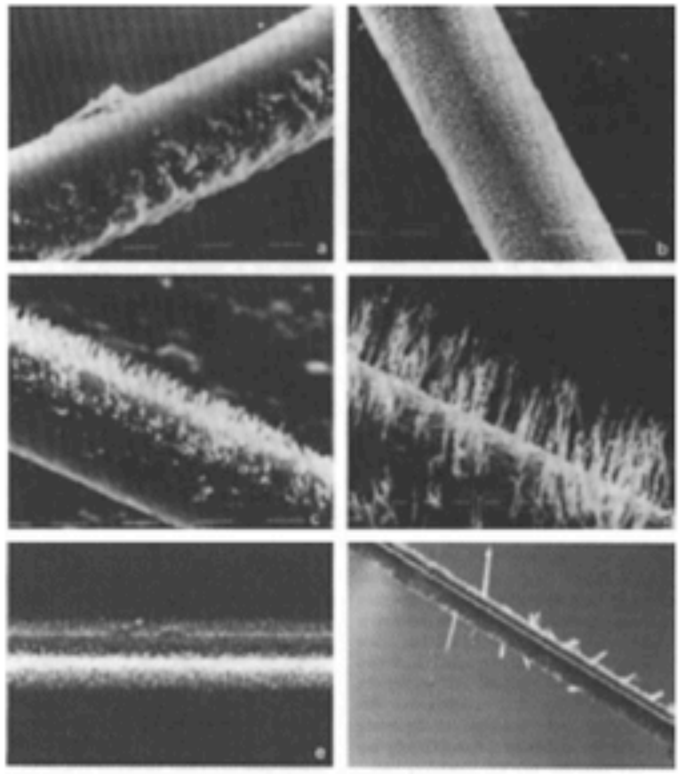
Cylindrical
Drift Chamber

[H1 Experiment]

Number of wires: ~ 15000
Total force from wire tension: ~ 6 t



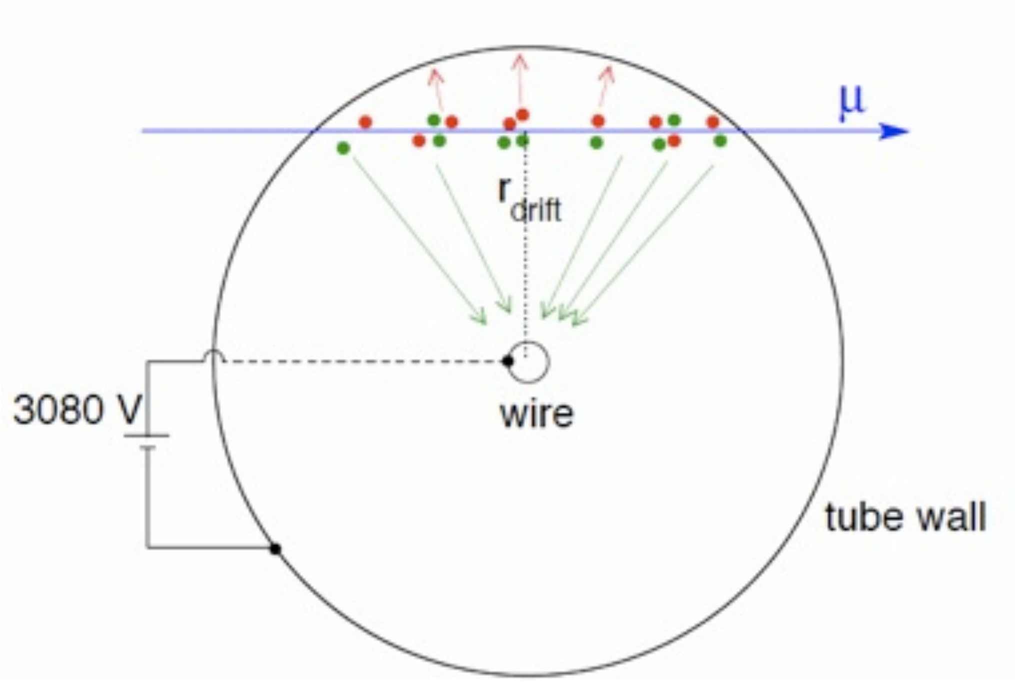
- Electric field is designed in a way that electrons drift with a constant velocity and only amplify very close to the wire
- If time of arrival of a particle is known (trigger), one can derive from the signal arrival time at the anode the position of the track
- Condition: the HV field distribution and therefore the drift velocity within the gas is well known



Wire aging due to gas contamination

Commonly used: Drift Tube

- Example: ATLAS Muon-System



Measurement of the drift time: defines the smallest distance of the track to the wire

➩ right/left ambiguity: multiple layers shifted to each other necessary

➩ spacial resolution typically ~100 μm

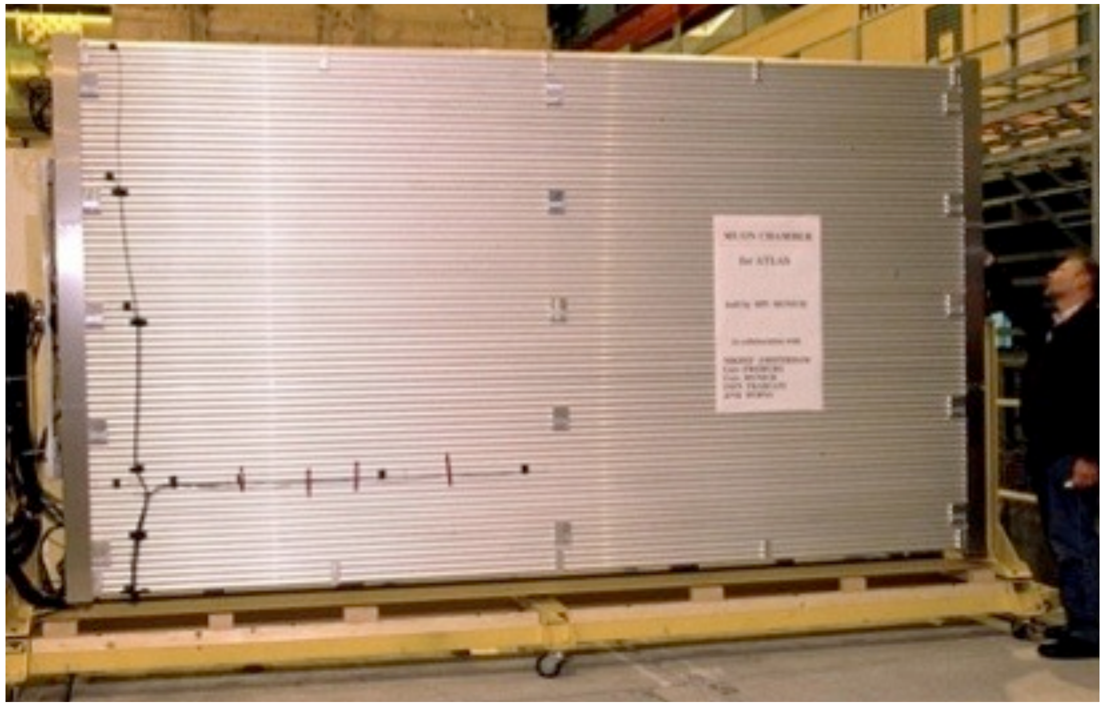
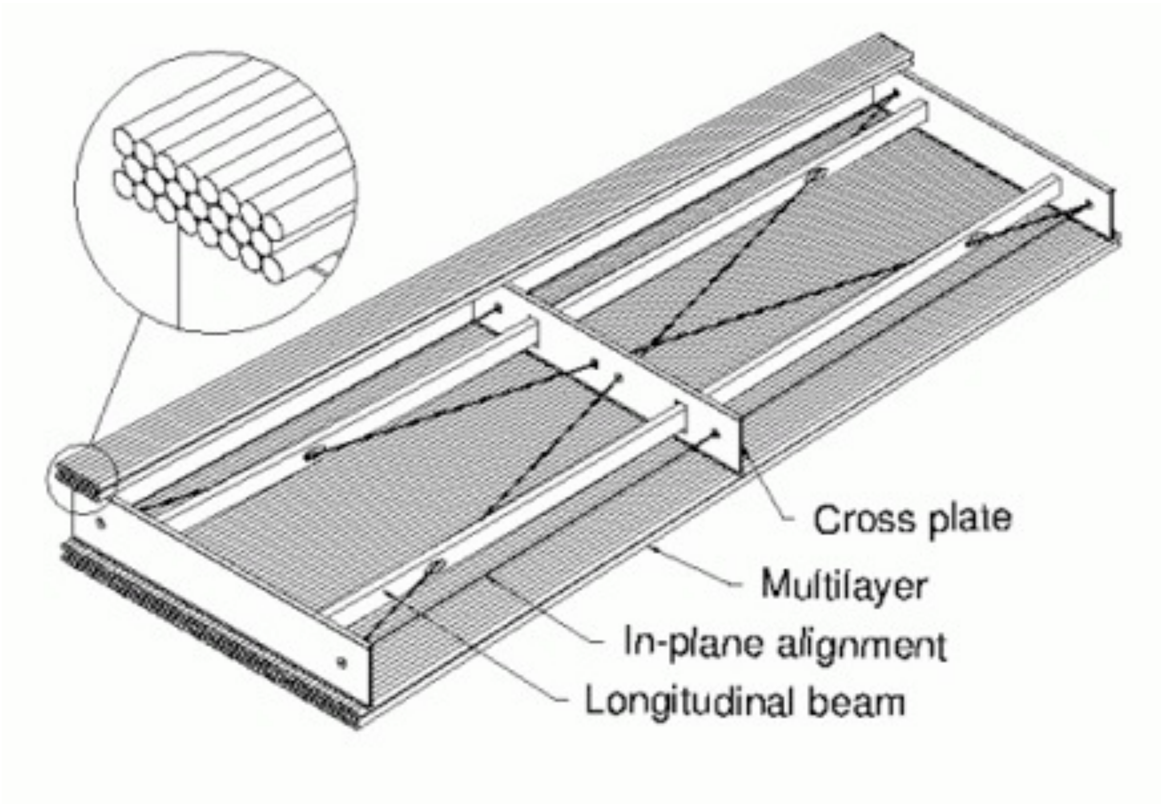


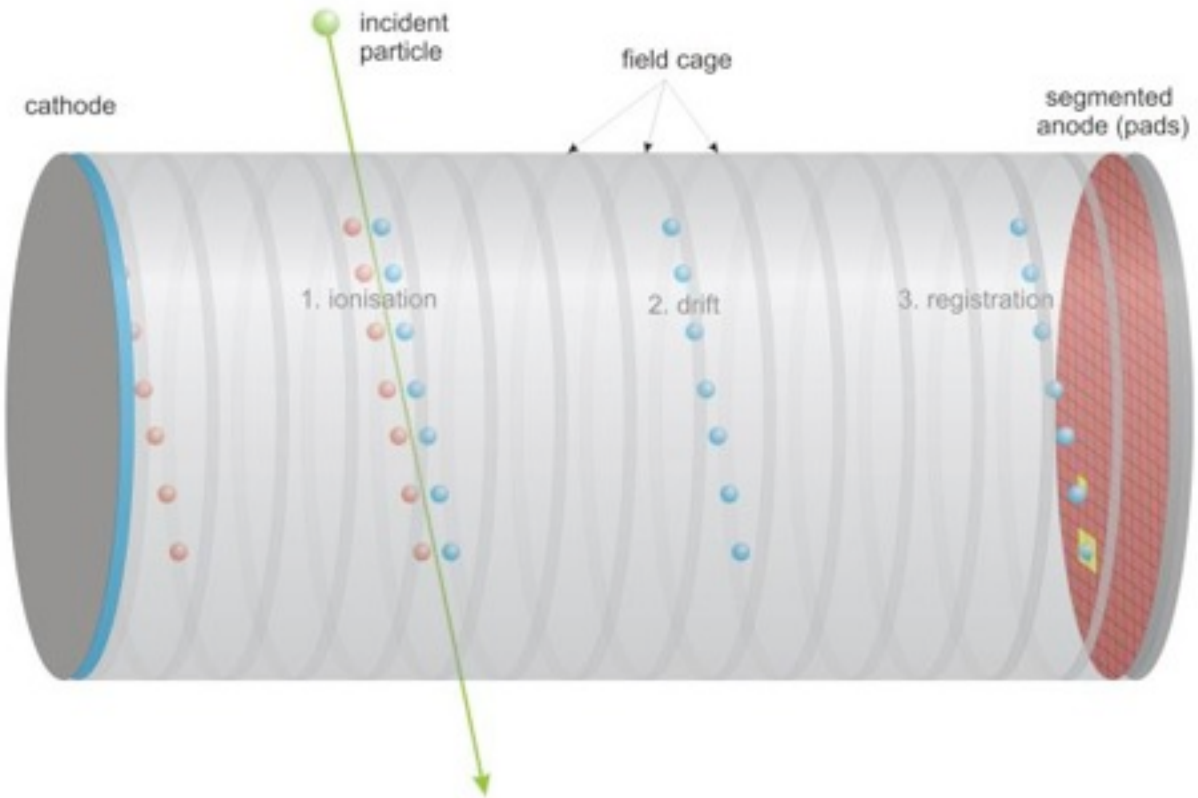
Foto: CERN



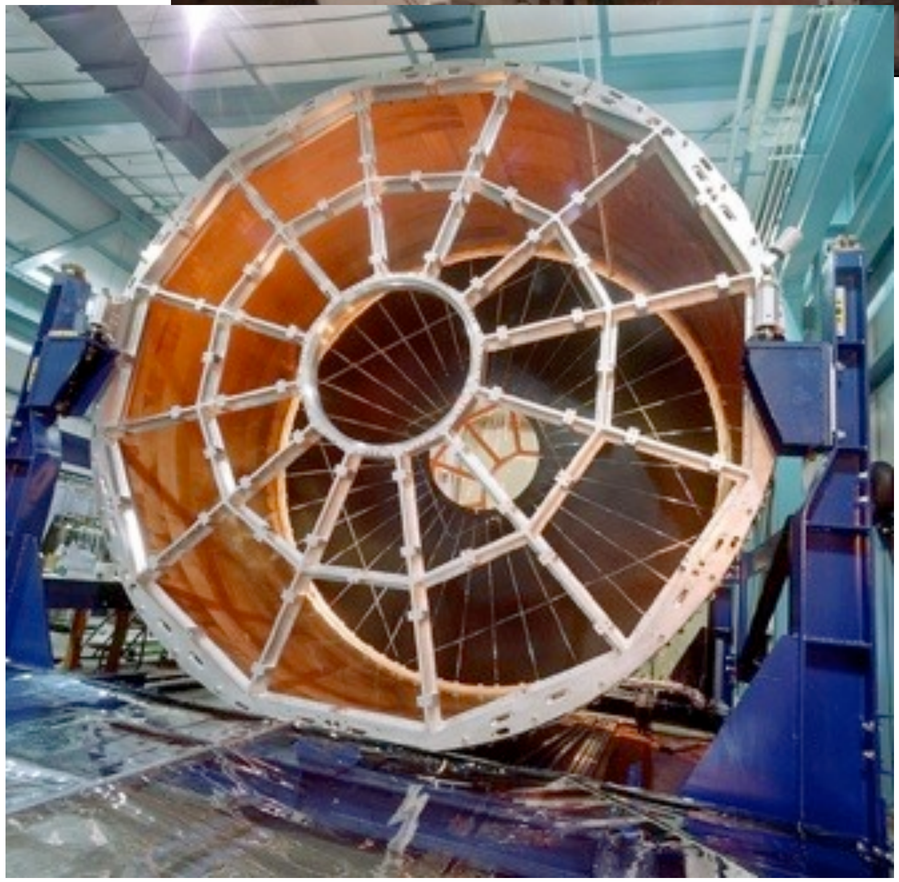
TPC- Time Projection Chamber: 3D

- Combination of the the 2D track information and the time results in a real 3D point

Pic: O. Schäfer



Pic: DESY



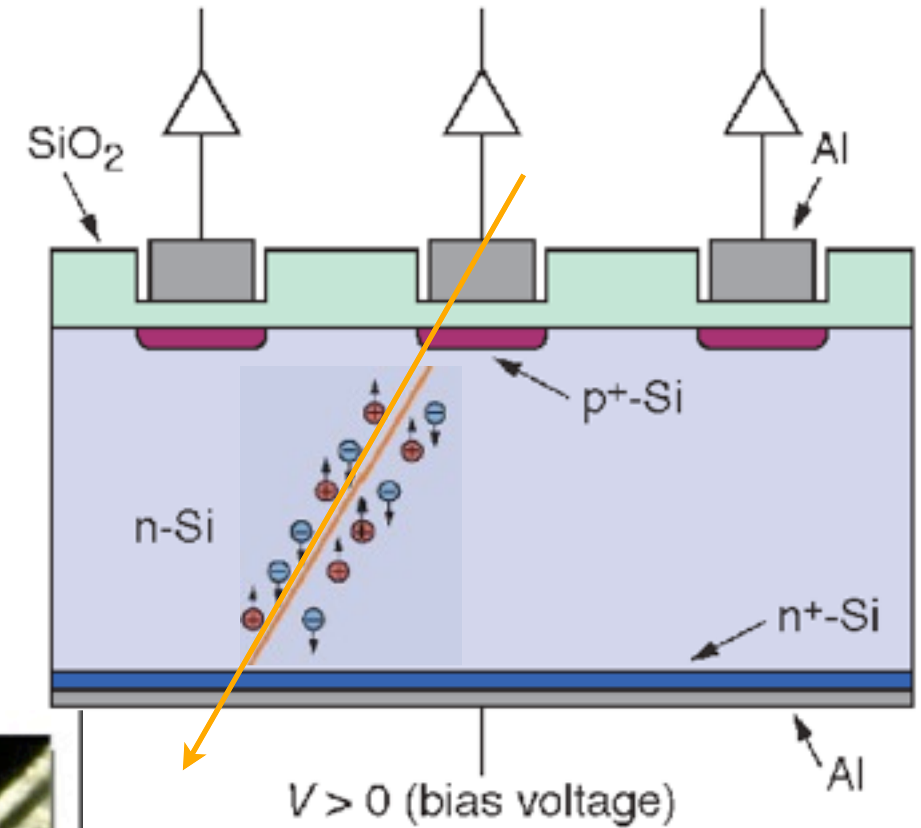
Pic: ALICE Collaboration

- Readout of the anode usually with multi-wire projection chambers
- Nowadays new developments for the readout: **Micro-Pattern Gas Detectors** i.e. gas electron multipliers (GEMs), micromegas, ...

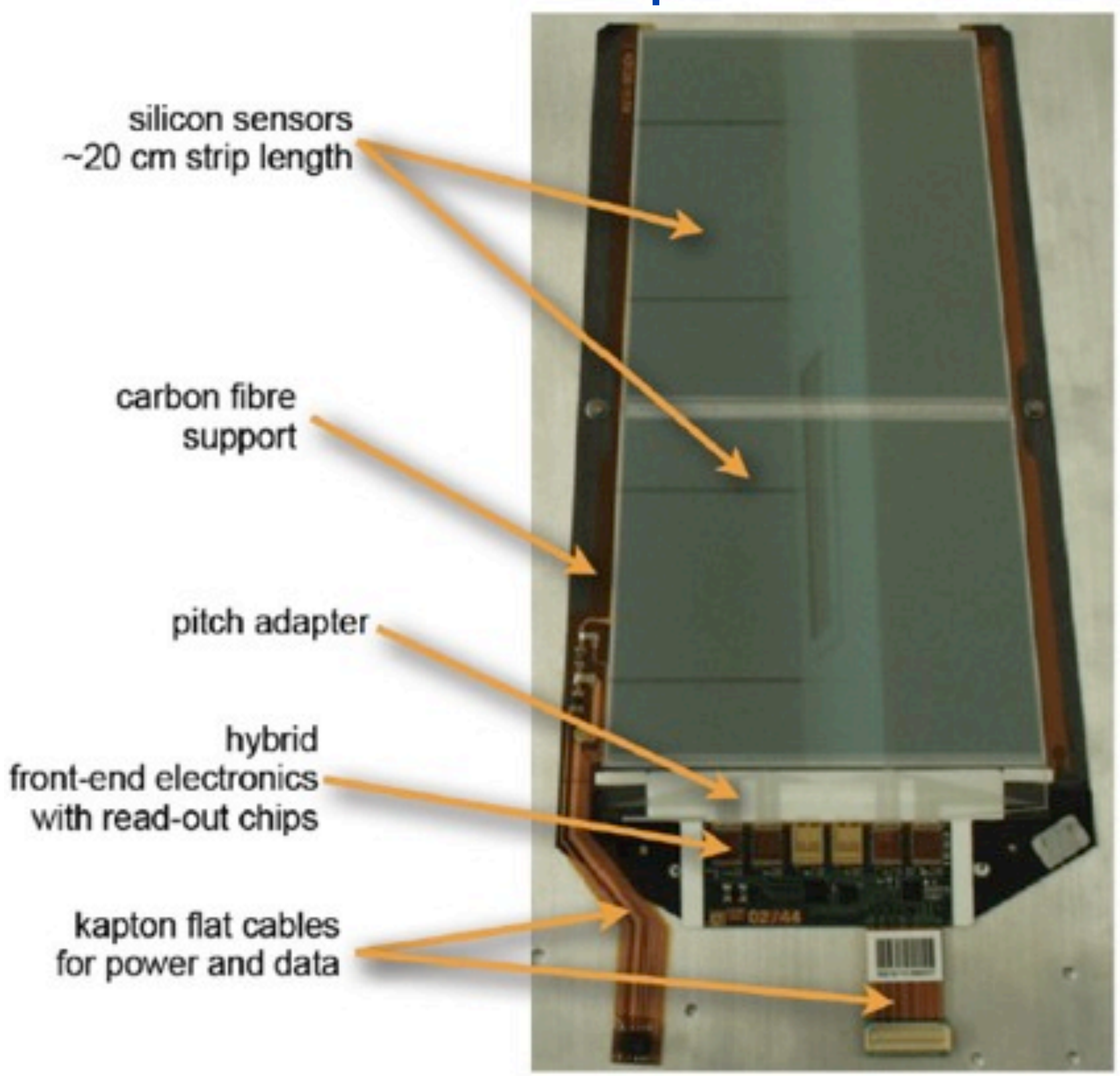
Track position: 1D silicon detectors

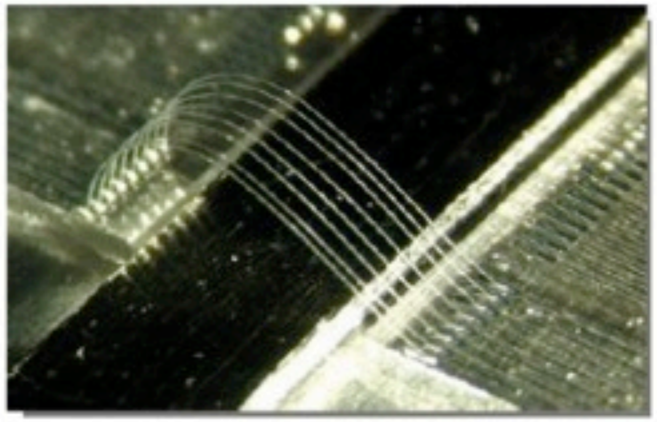
Charge carrier drift to electrodes and induce signal

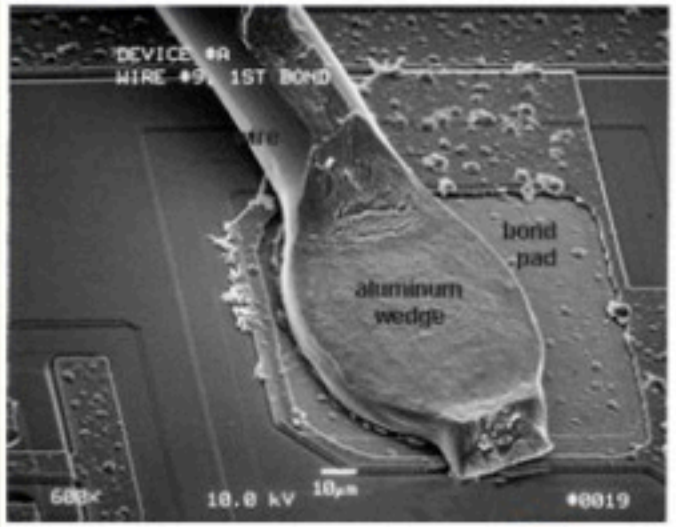
By segmenting the implant we can reconstruct the position of the traversing particle in one dimension



Strip module CMS

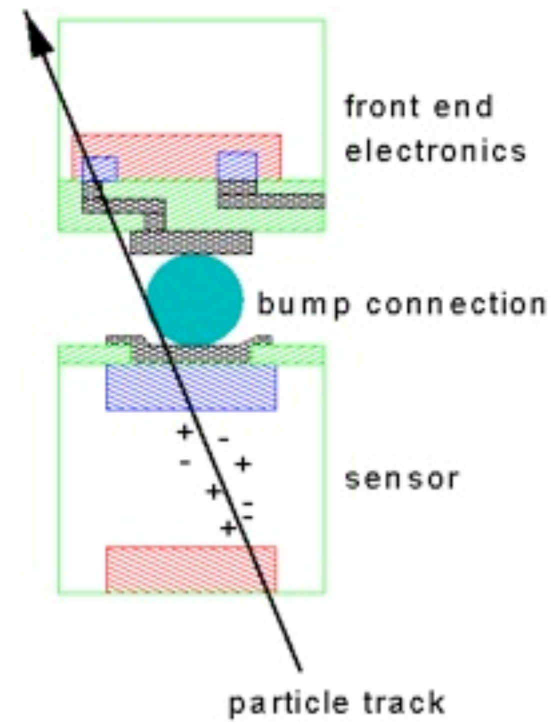


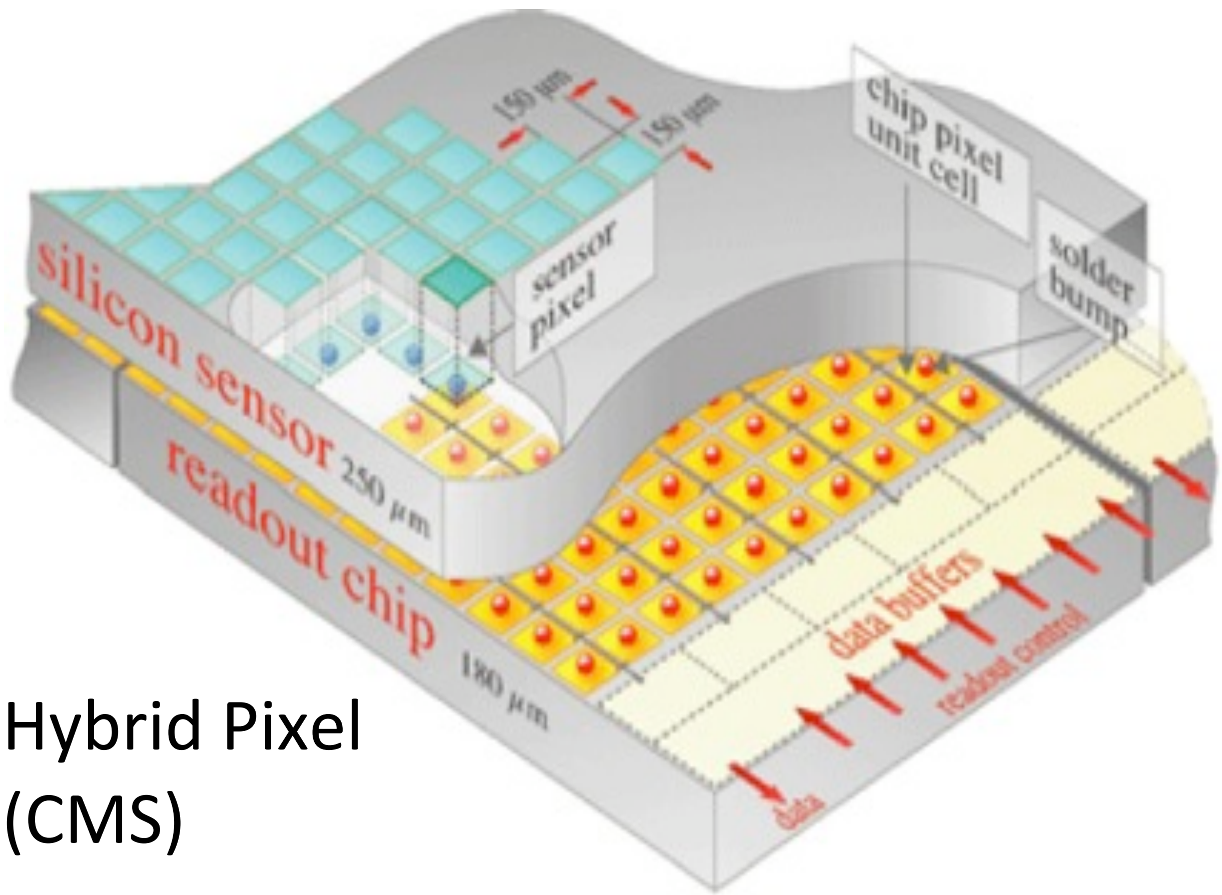




Track position: 2D silicon detectors

- 2D segmented implants = pixels
- Read-out chip mounted directly on top of the pixels (bump-bonding)
- Each pixel has its own read-out amplifier
- Fast read-out and radiation-tolerant
- **... but:**
- Pixel area defined by the size of the read-out chip
- High material budget and high power dissipation





Hybrid Pixel (CMS)

- CMS Pixels: ~65 M channels 150 μm x 150 μm
- ATLAS Pixels: ~80 M channels 50 μm x 400 μm (long in z or r)
- Alice: 50 μm x 425 μm
- LHCb
- Phenix
- ….

Alternative designs

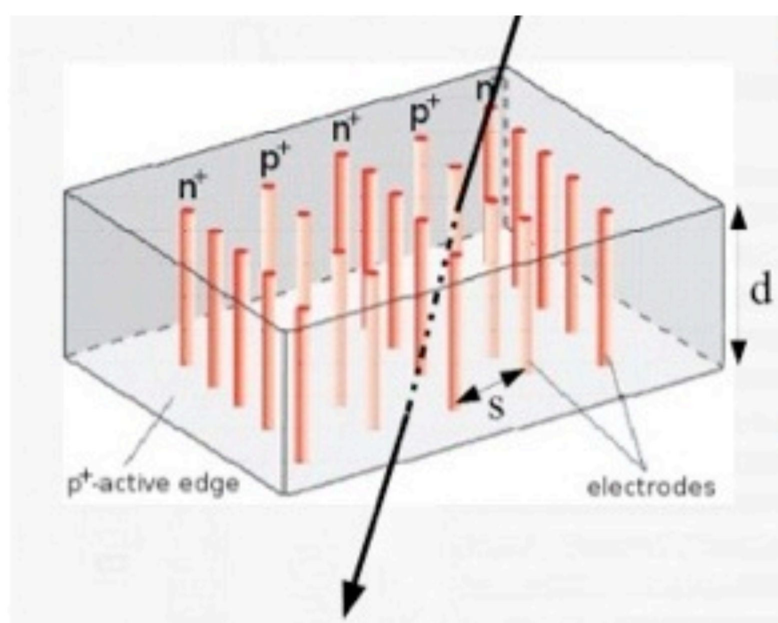
Planar Sensor

- current running horse for HEP experiments
- radiation hardness proven up to LHC requirements
- problem: HV might need to exceed 1000V

Very strong R&D efforts to develop sensors for future LHC/ILC applications!

3D Silicon

- Both electrode types are processed inside the detector bulk instead of being implanted on the wafer's surface.
- Max. drift and depletion distance set by electrode spacing
- Reduced collection time and depletion voltage



CVD (Diamond)

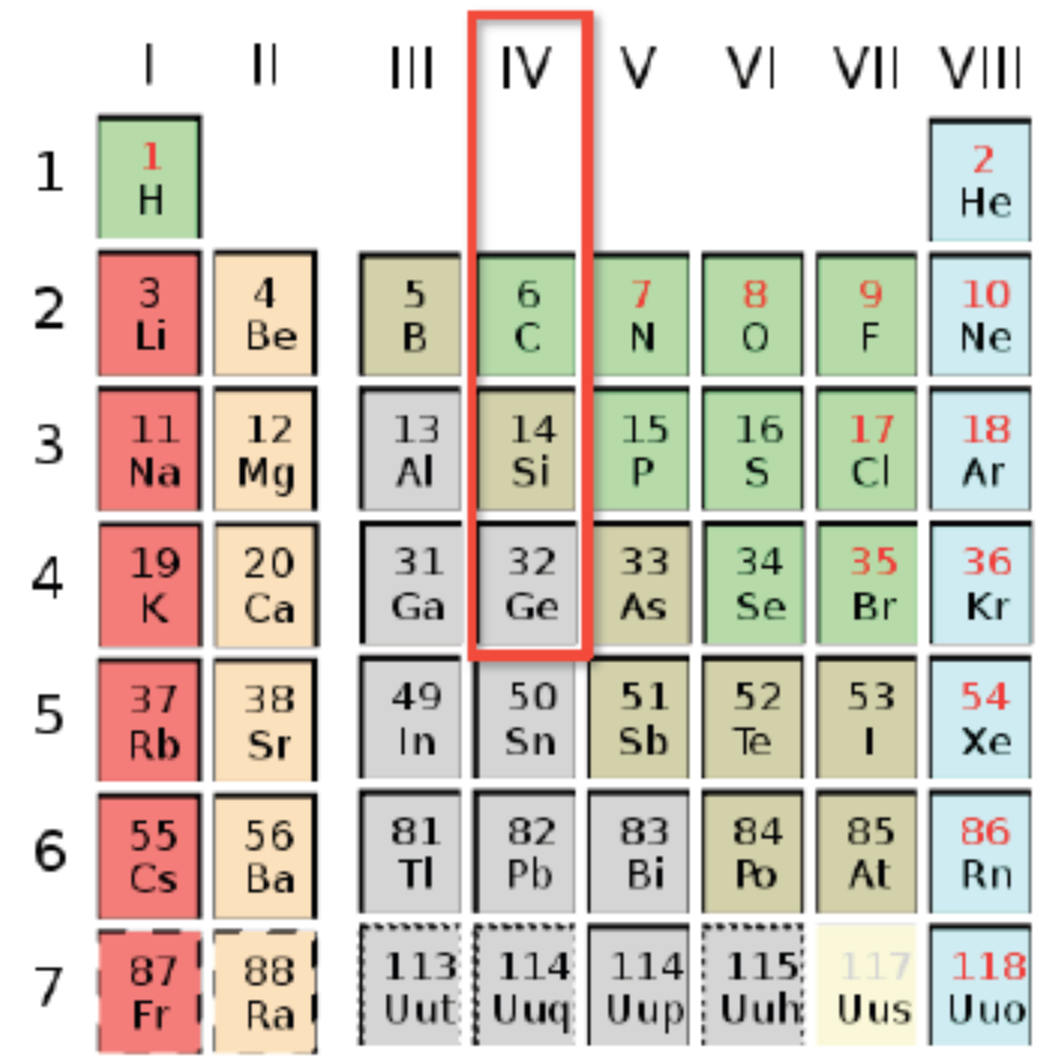
- Large band gap 5.5 eV (no depletion zone required)
- Operation at room temperature possible
- Radiation hard material
- Drawback: 50% signal compared to silicon for same X_0, but better S/N ratio (no dark current)

Alternative semiconductors

- **Compound semiconductors**
  two or more elements of the periodic table

- **important IV-IV compounds:**
  - ***SiGe, SiC***

- **important III-V compounds:**
  - ***GaAs***: Faster and probably more radiation resistant than Si. Drawback is less experience in industry and higher costs.
  - GaP, GaSb, InP, InAs, InSb, InAlP



- **important II-VI compounds:**
  - ***CdTe***: High atomic numbers (48+52) hence very efficient to detect photons
  - ZnS, ZnSe, ZnTe, CdS, CdSe, Cd1-xZnxTe, Cd1-xZnxSe

Calorimetry: Overview

In nuclear and particle physics calorimetry refers to the detection of particles, and measurements of their properties, through total absorption in a block of matter: the calorimeter

Common feature of all calorimeters:
the measurement process is destructive
i.e. the particles are no longer available for inspection after the calorimeter

The only exception concerns muons
➔ mean for muon identification

Calorimetry works both for charged (e± and hadrons) and neutral particles (γ, n) !

Principle:

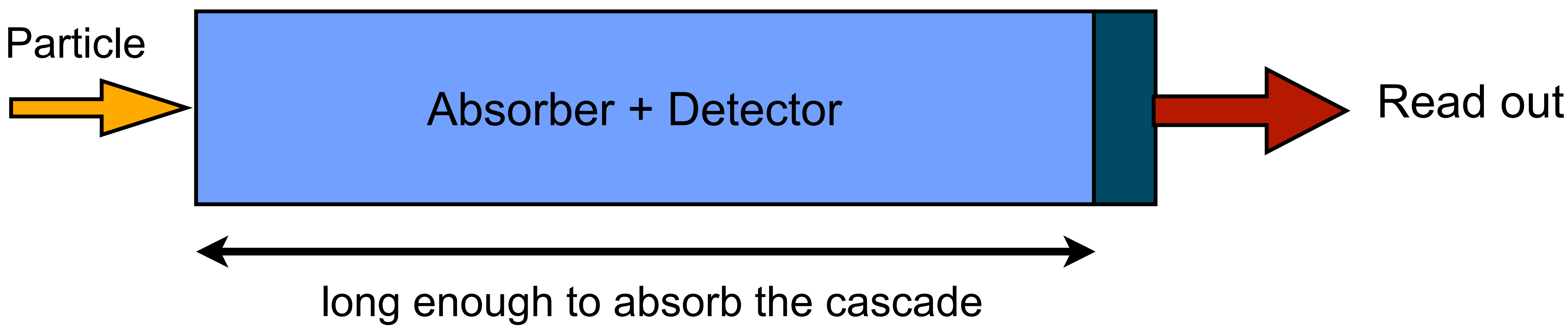
- formation of electromagnetic
- or hadronic showers

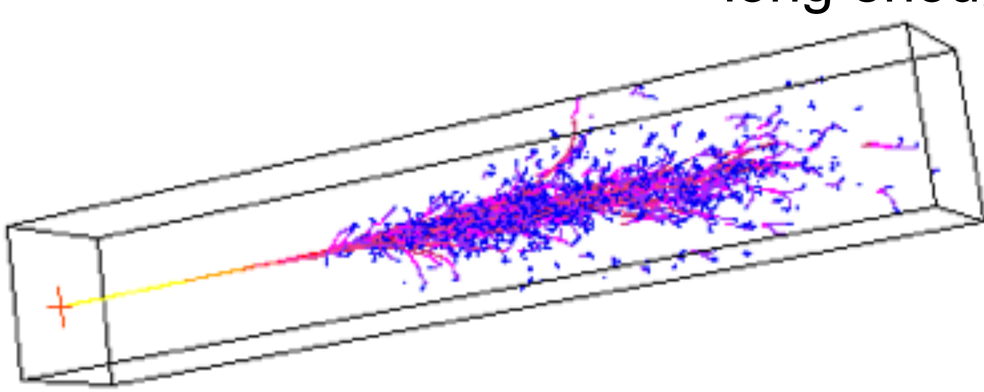
Calorimeter Types

Most commonly used: Homogeneous and Sampling Calorimeter

Homogeneous Calorimeter

- The absorber material is active; all deposited energy is converted into signal
- Pro: very good energy resolution
- Contra: segmentation difficult, selection of material is limited, expensive





Pic: Cornell

Example: CMS electromagnetic calorimeter

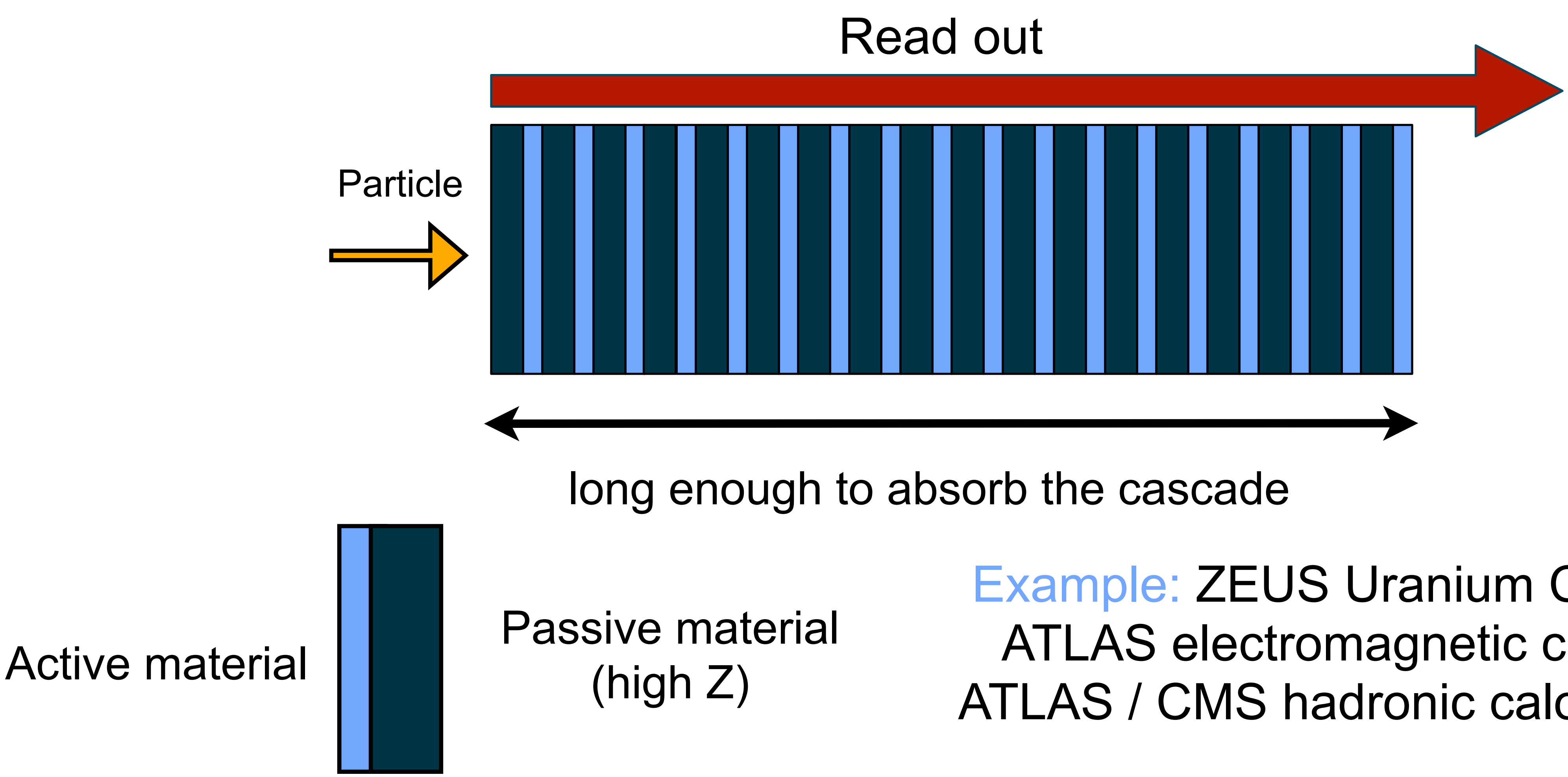
design not suitable for hadronic calorimeters

Calorimeter Types

Most commonly used: Homogeneous and Sampling Calorimeter

Sampling Calorimeter

- A structure of passive and active material; a fraction (**Sampling Fraction, f_S**) of the deposited energy is detected (1-5%)
- Pro: Segmentation, compact detectors by the usage of dense materials (W, U)
- Contra: Energy resolution is limited by fluctuations

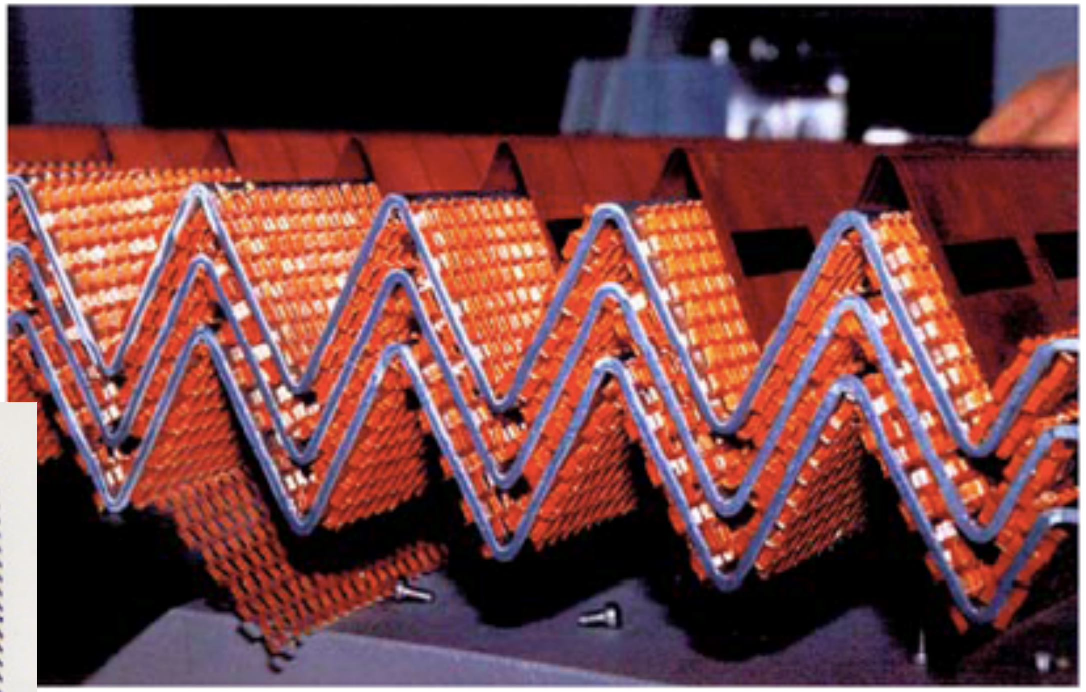


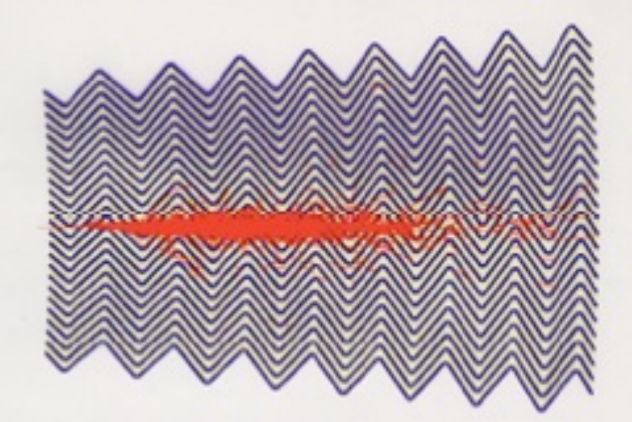
Example: ZEUS Uranium Calorimeter, ATLAS electromagnetic calorimeter ATLAS / CMS hadronic calorimeters, ...

Examples of electromagnetic calorimeters

ATLAS EM barrel calorimeter

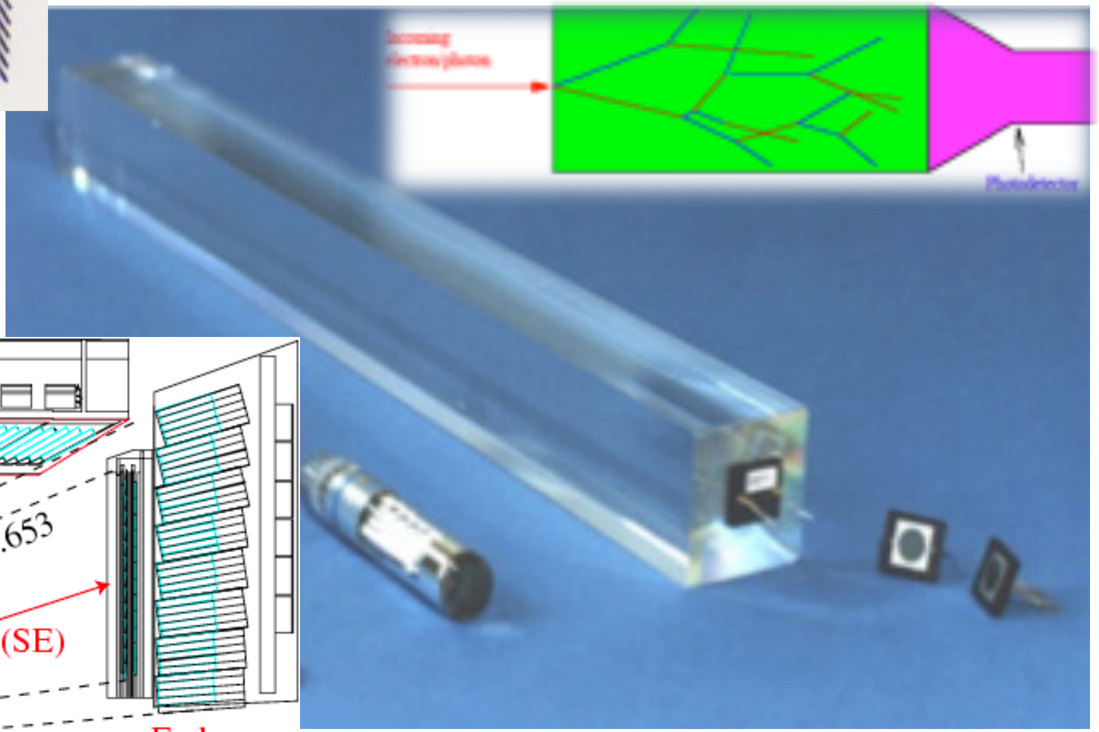
- Honeycomb spacers position the electrodes between the lead absorber plates
- Liquid Argon at 90°K flows through.
- Radiation resistant, no cracks in η
- Accordion structure with Pb-LAr sampling

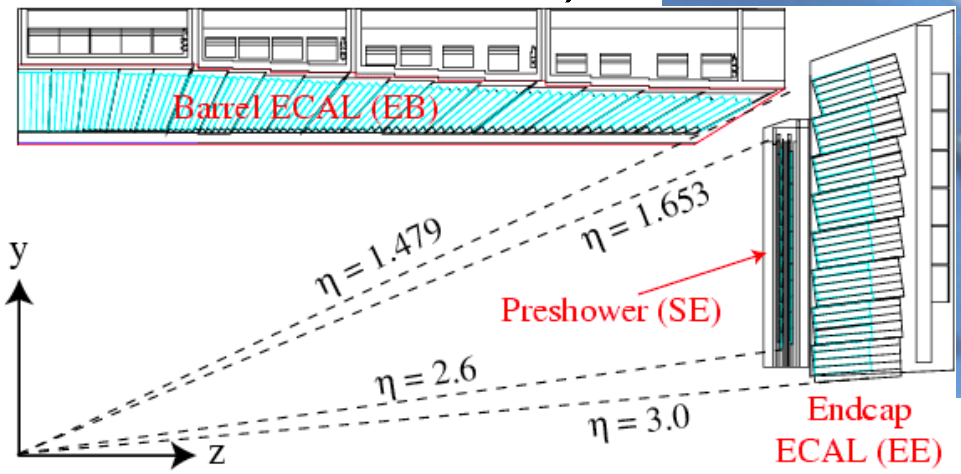




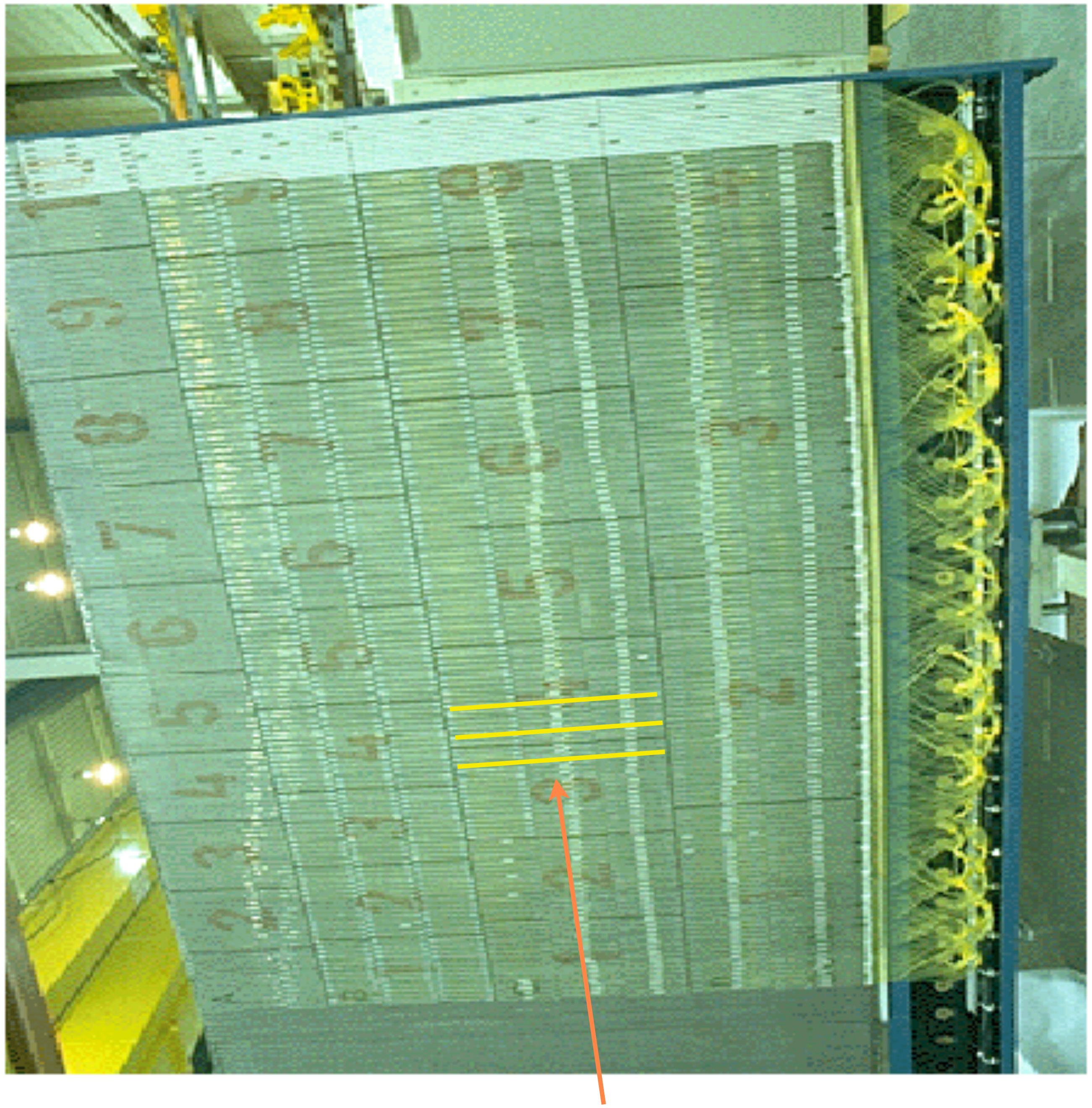
CMS EM barrel calorimeter

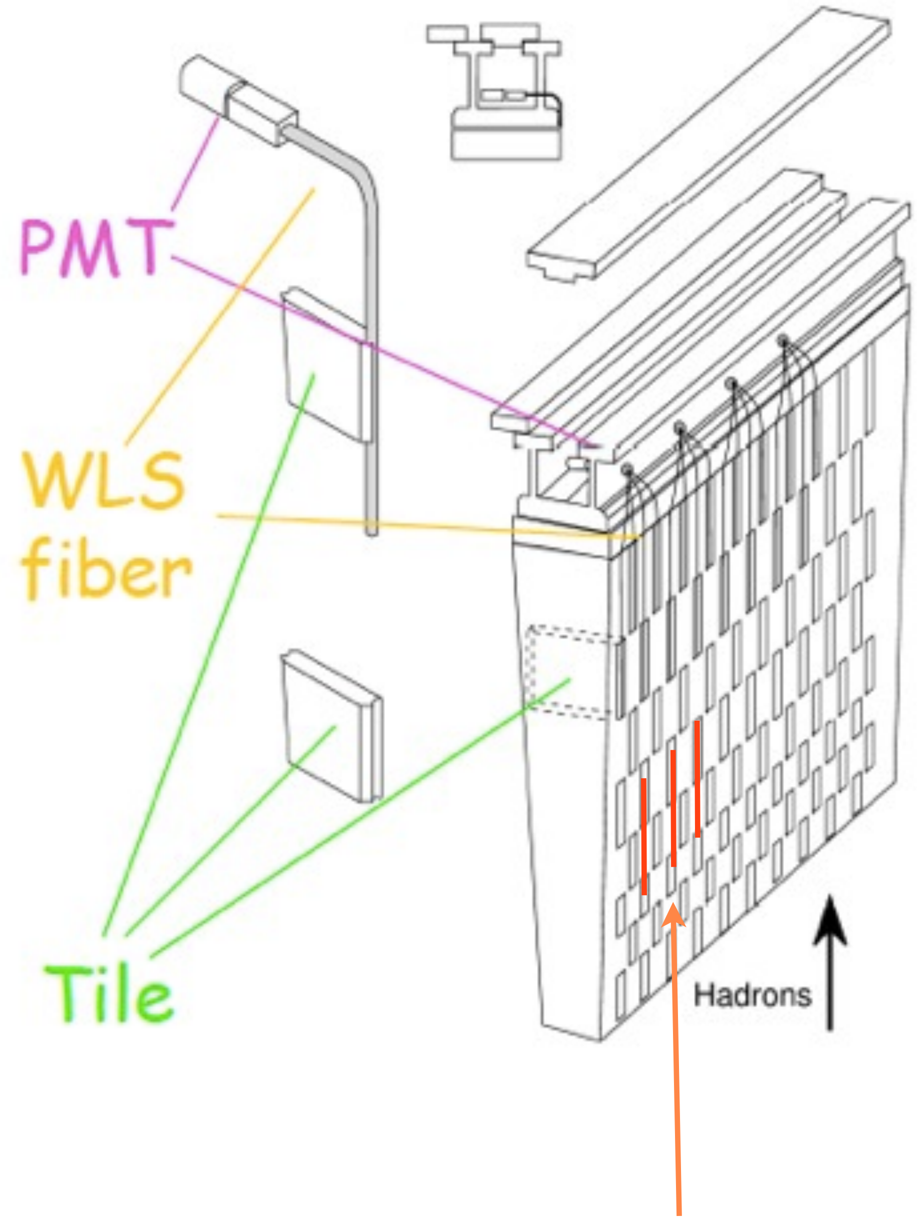
- PbWO4 crystals (230x22x22 mm^3)
- Read out by APD (Avalanche PhotoDiodes)
- Homogeneous





Examples of hadronic calorimeters

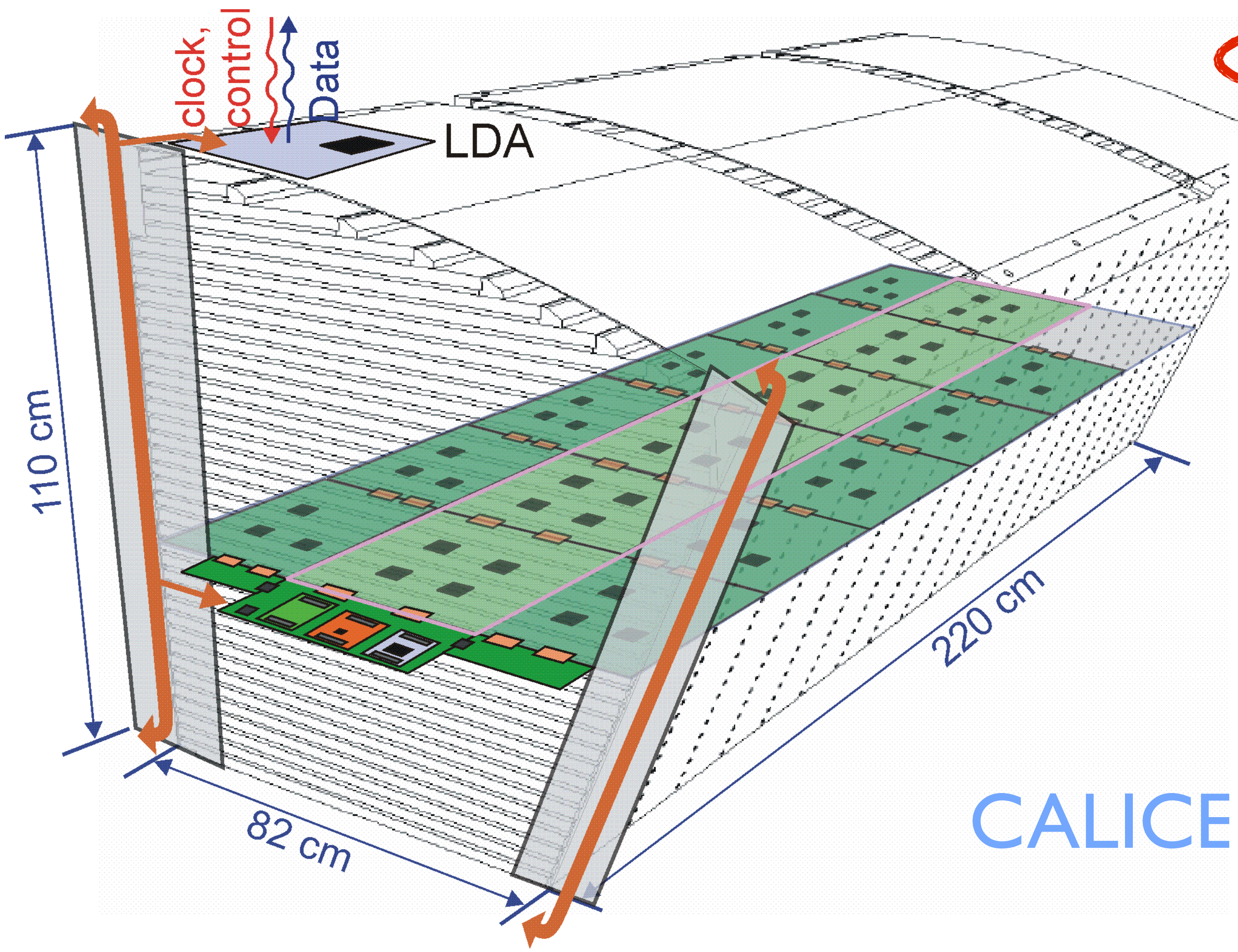




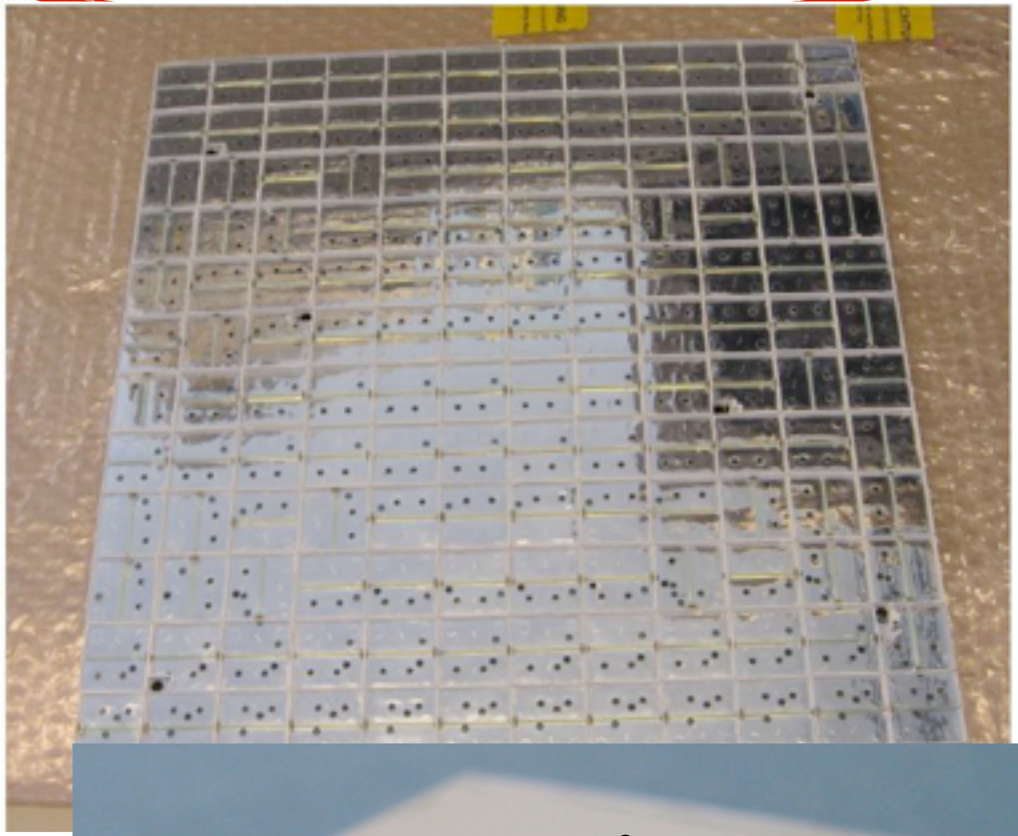
CMS: Brass/scintillator
longitudinal orientation

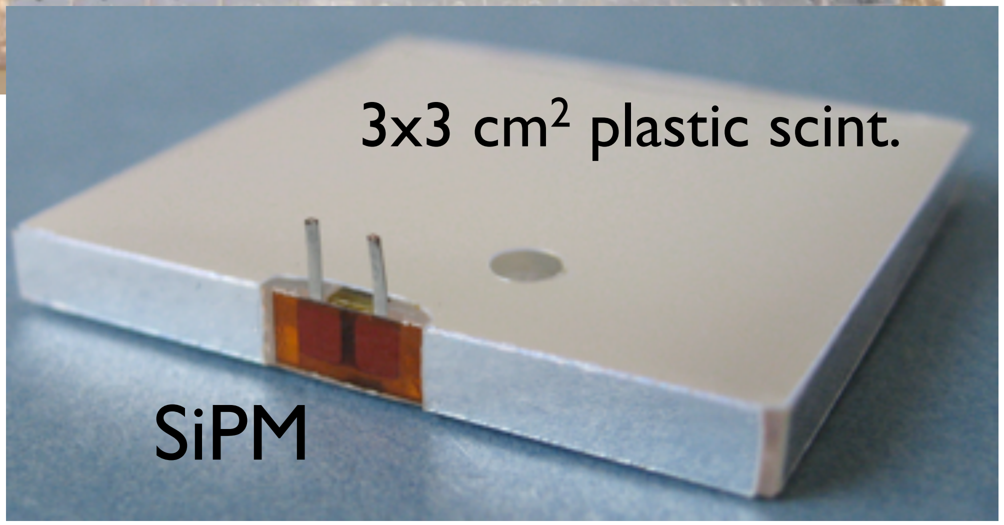
ATLAS: Fe/scintillator
vertical orientation

New Concepts: highly-integrated granular calorimeters



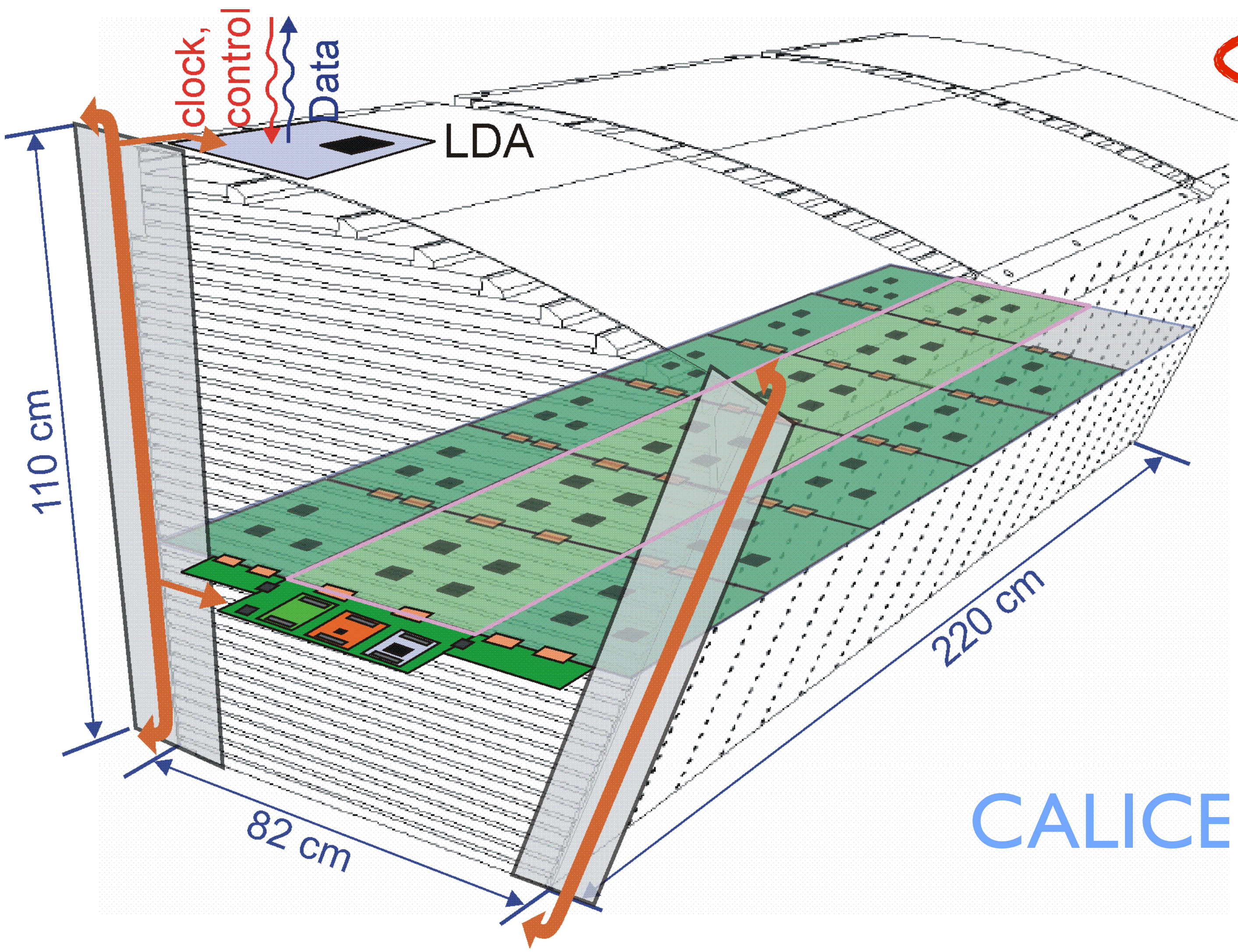
~ 1,000 calorimeter cells / m^2



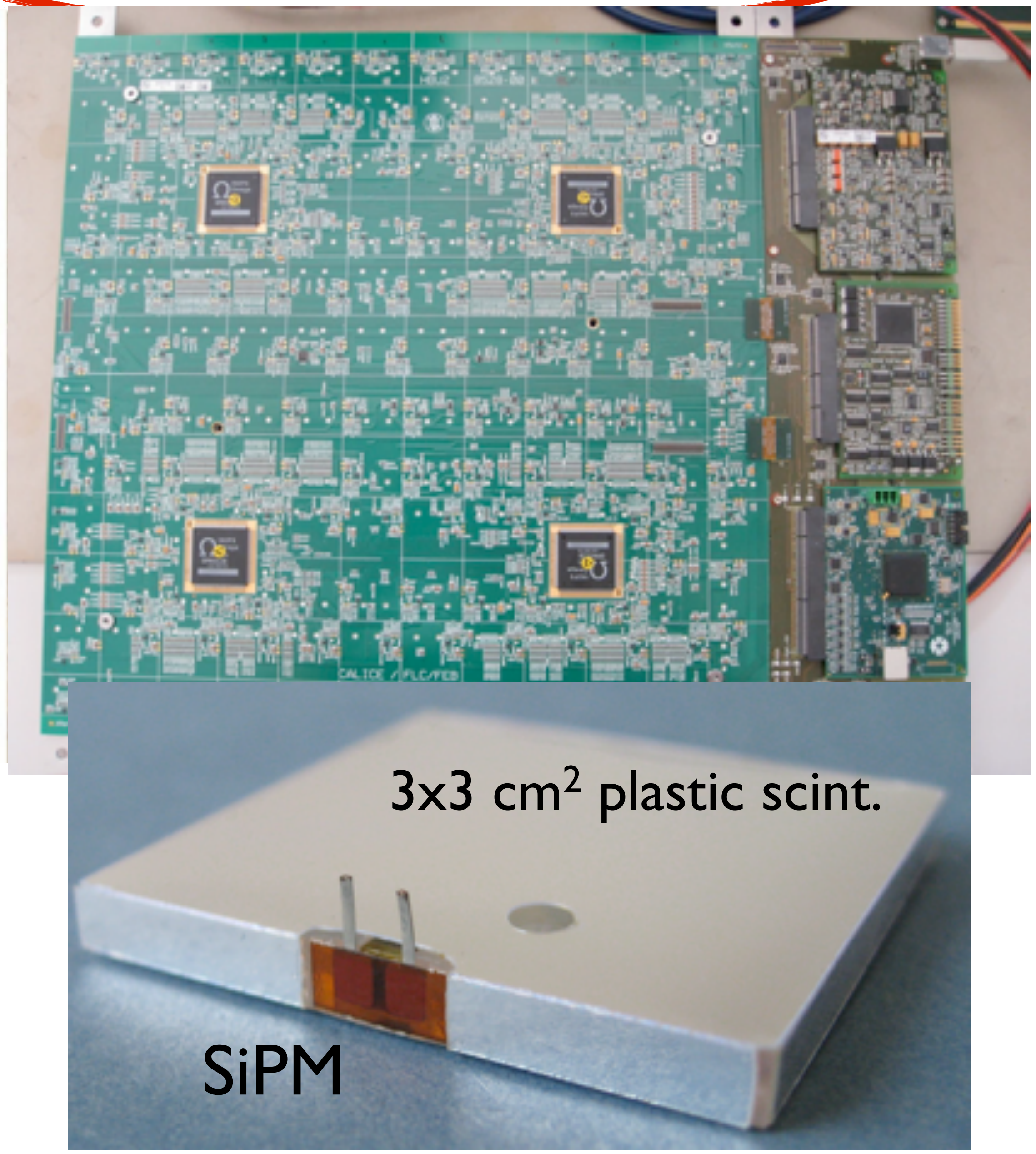


- sampling calorimeter Fe / plastic scintillator
- ~ 48 layers ~ 6 λ
- Front end electronics integrated in active layer

New Concepts: highly-integrated granular calorimeters



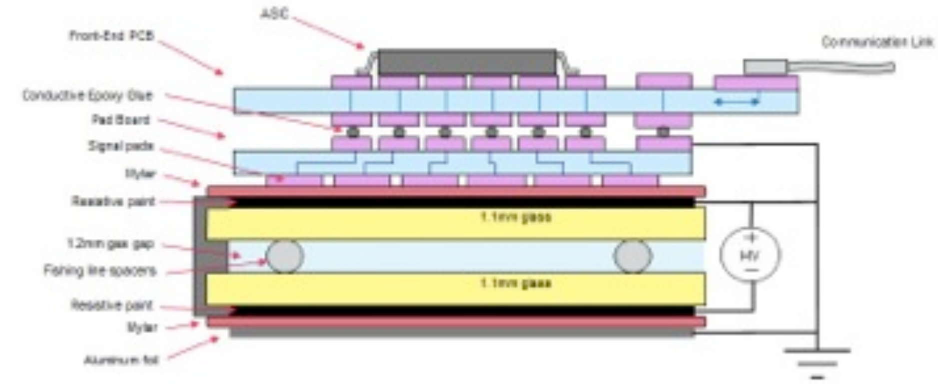
~ 1,000 calorimeter cells / m^2



- sampling calorimeter Fe / plastic scintillator
- ~ 48 layers ~ 6 λ
- Front end electronics integrated in active layer

New Concepts: highly-integrated granular calorimeters

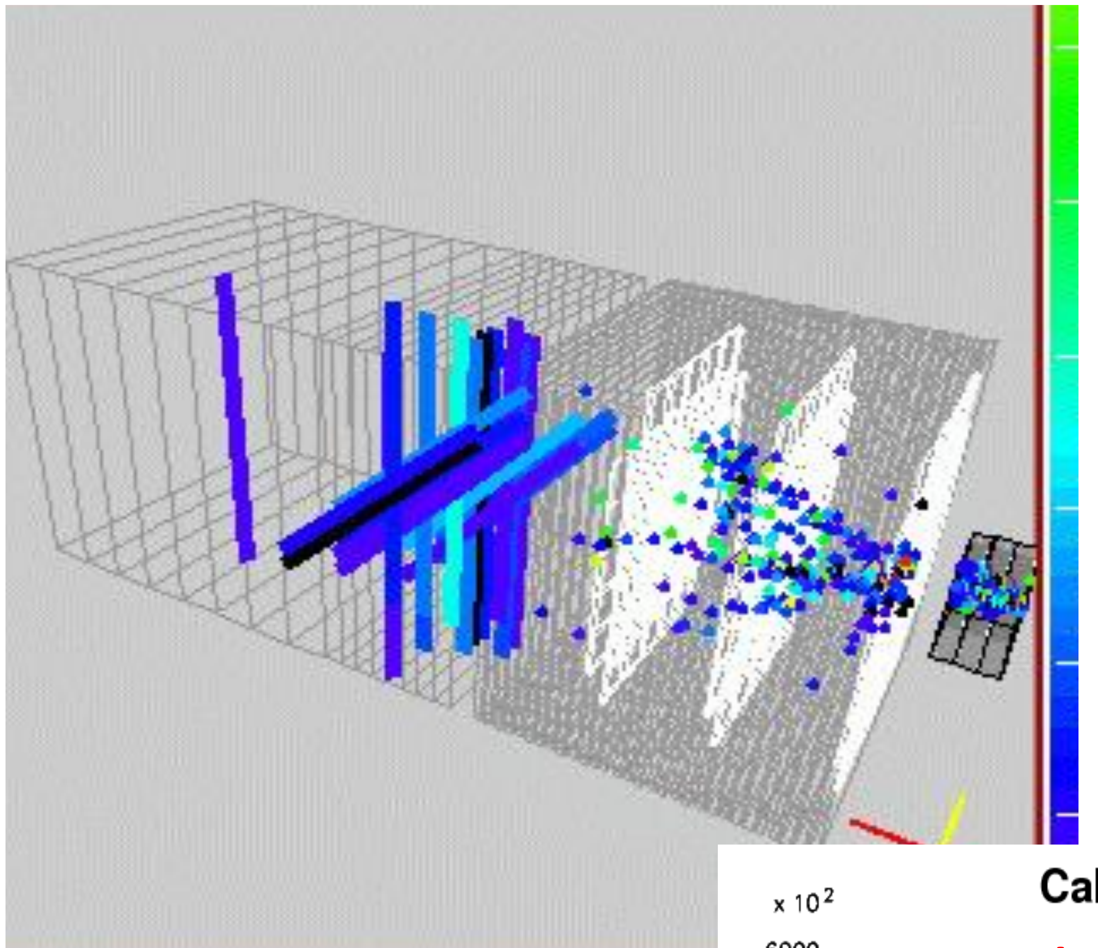
~ 10,000 calorimeter cells / m^2



- sampling calorimeter Fe / gas layer (RPC)
  ~ 48 layers ~ 6 λ
- Front end electronics integrated in active layer

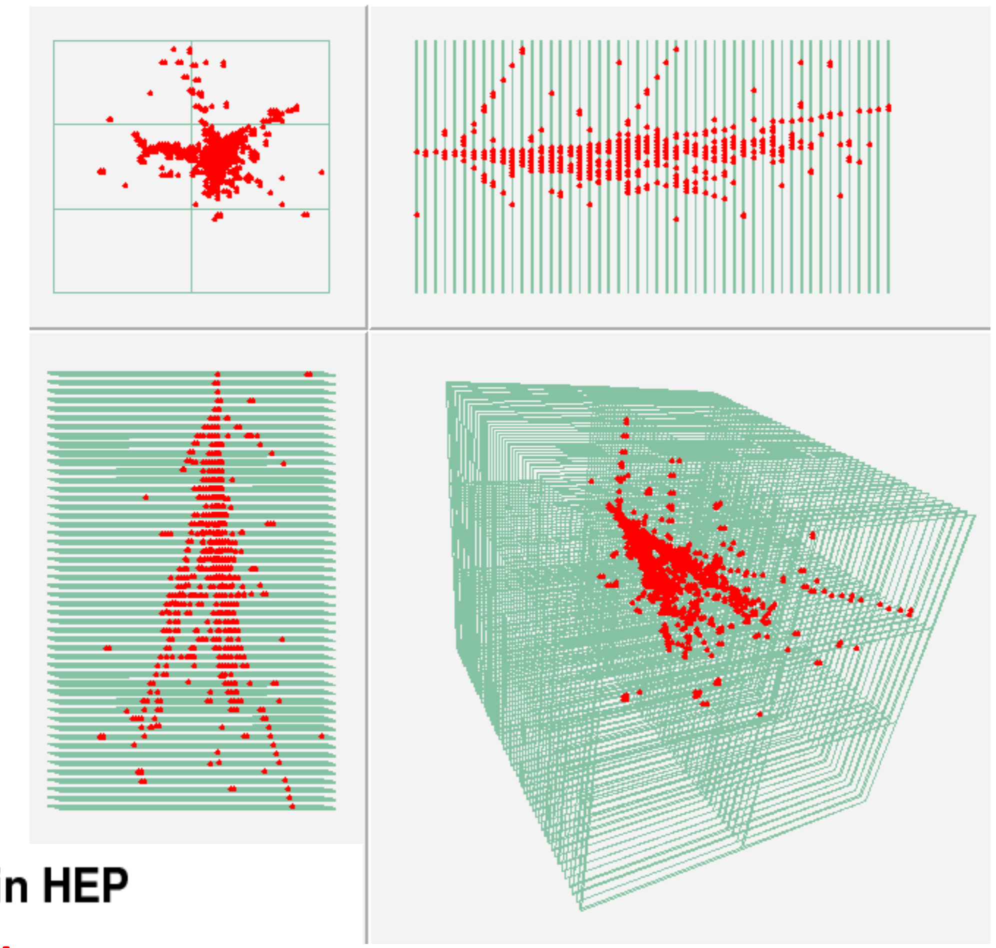
Single pion reconstruction with high granularity

Fe/scintillator with analog readout

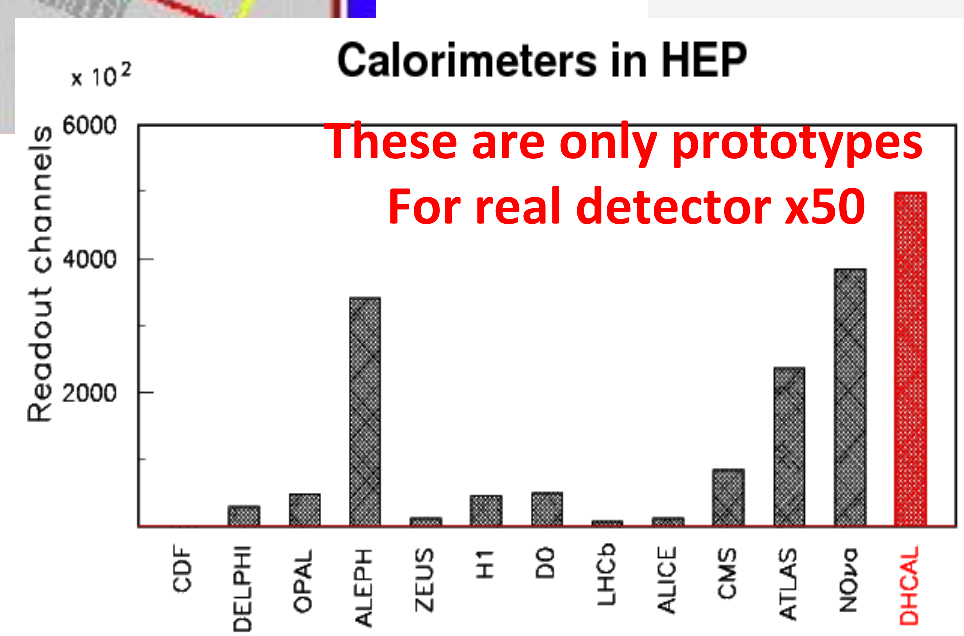


Energy scale [MIP]

Fe/gas with digital readout



CALICE



Summary & conclusions

- Stable particle detection = **measurement of** particle **E and p**
- Main interaction of high energetic particles with matter
  - heavy charged particles: **ionization** (Bethe-Block)
  - electrons (>10 MeV): **Bremsstrahlung**
  - photons (>1 MeV): **pair-production**
  - neutrons (> 20 MeV): **elastic and inelastic n-p scattering**
- p meas. : segmented gaseous or semiconductor detectors
- E meas. : calorimeters (homogeneous / inhomogeneous)