Particle Detectors

Chapters to study:
Ch.1, Interactions of particles and photon with matter.
Ch.5, Main physical phenomena used for particle detection and basic counter types
Ch.7, Track detectors
Ch.8, Calorimetry
Ch.9, Particle identification
Ch.14, Electronics
Ch.15, Data analysis
Ch.16, Applications of particle detectors outside of particle physics

Chapters to read through
Ch.2, Characteristic properties of detectors
Ch.3, Units of radiation measurements and radiation sources
Ch.4, Accelerators
Ch.6, Historical track detectors
Ch.10, Neutrino detectors
Ch.11, Momentum measurement and muon detection
Ch.12, Aging and radiation effects
Ch.13, Example of a general-purpose detector: ATLAS, CMS

Particle Detectors

Chapters to study:

Ch.1, Interactions of particles and photon with matter

- Electromagnetic interactions of charged particles (electron, muon, pion, kion, proton).
- Photon specific interactions.
- Strong interactions of hadrons (pion, kion, proton, neutron).
- Mechanical interactions specific to gaseous detectors: drift and diffusion in gases.

Ch.5, Main physical phenomena used for particle detection and basic counter types

Ch.7, Track detectors

Ch.8, Calorimetry

Ch.9, Particle identification

Ch.14, Electronics

Ch.15, Data analysis

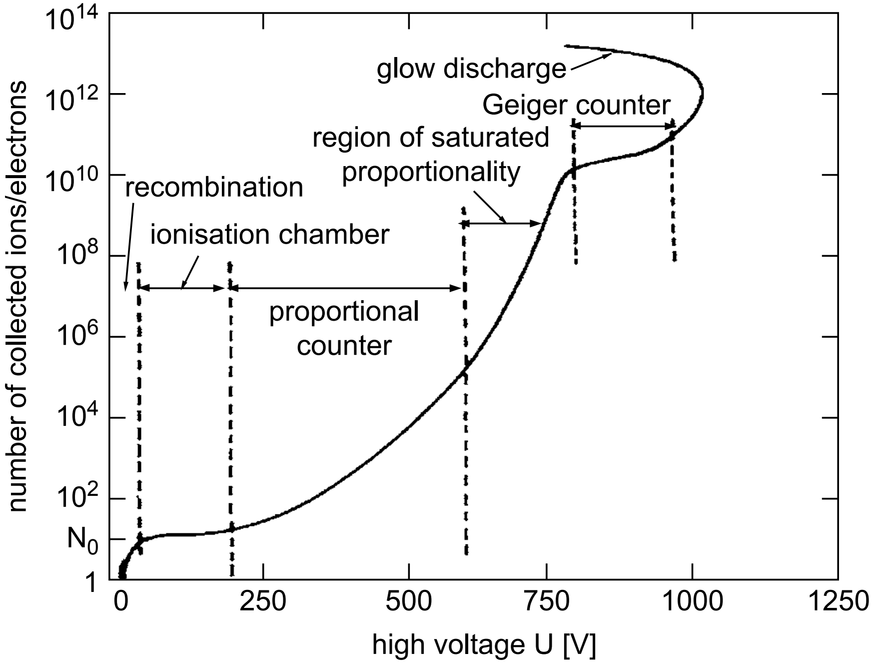
Ch.16, Applications of particle detectors outside of particle physics

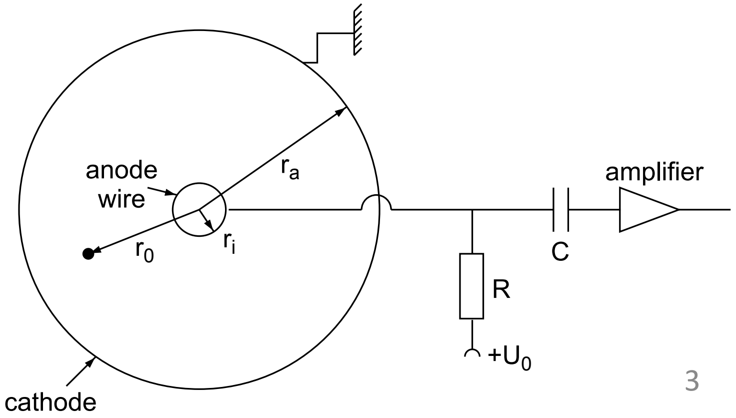
Particle Detectors

Chapters to study:

Ch.5, Main physical phenomena used for particle detection and basic counter types

- Ionization counters (of charges)
  - With gas mixtures:
    1. Ionization chamber (no gas amplification)
    2. Proportional chamber/tube
    3. Geiger counter
    4. Streamer tubes
  - With liquids (LAr, LXe), mostly in calorimeters.
  - With solid-state crystals, count electron-holes.
    1. Most commonly used: si p-n junction
    2. Others: Germanium, C (diamond), etc.



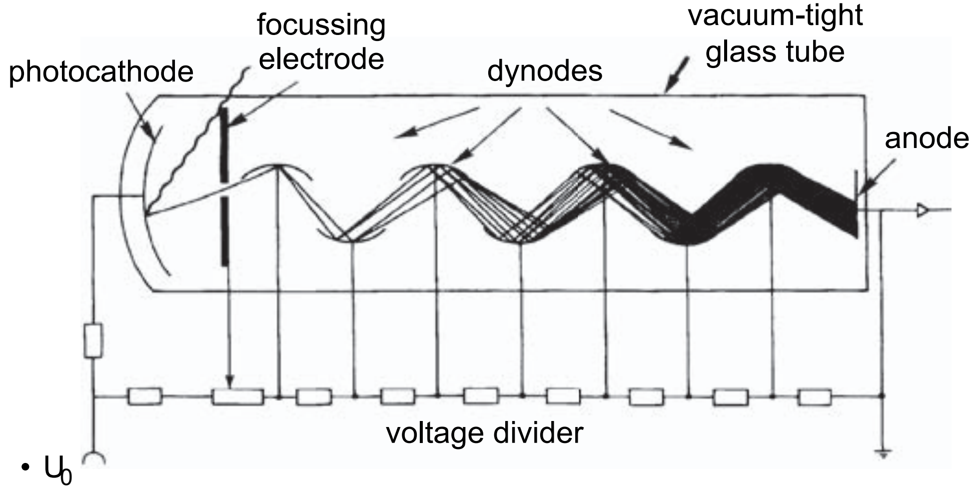


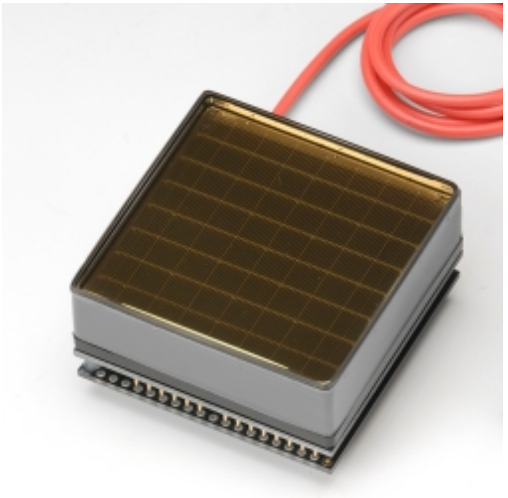
Particle Detectors

Chapters to study:

Ch.5, Main physical phenomena used for particle detection and basic counter types

- Scintillation counters (of UV to visible photons), PMTs, APDs, SiPM, devices that convert photons to electrons and lineally amplify them.
    1. Inordanic: sodium-iodide NaI(Tl), BGO, Lead-Tungsten, … … often for total absorption energy measurement
    2. Organic: plastic, liquid, or water base doped with scintillating agents, for total absorption energy measurement or fast counting/triggering use.
    3. Gas scintillation counters
    4. Photon conversion and amplification, some with position sensitivity





Particle Detectors

Chapters to study:

Ch.5, Main physical phenomena used for particle detection and basic counter types

- Cherenkov counters (of deep UV photons), <u>mostly for particle ID</u>
  - Need a tracker to know the trajectory of the particle
  - Need a photon detector to measure the ring and then θ_c

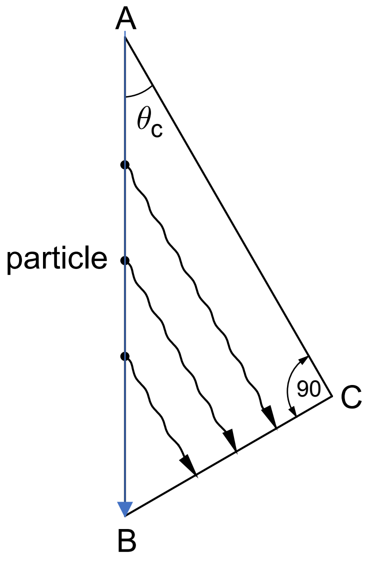
$$\cos\theta_\mathrm{c} = \frac{c}{n\beta c} = \frac{1}{n\beta} \qquad \theta_\mathrm{c}^\mathrm{max} = \arccos\frac{1}{n}$$

  - Not always a ring is measured. There is also the threshold type

$$\frac{\mathrm{d}N}{\mathrm{d}x} = 2\pi\alpha z^2 \int_{\lambda_1}^{\lambda_2}\left(1 - \frac{1}{(n(\lambda))^2\beta^2}\right)\frac{\mathrm{d}\lambda}{\lambda^2}$$

- Transition-radiation detectors (TRD), particle ID at high energy
  - Radiation emitted when particles pass boundary between media with different dielectrics.

$$N_\gamma(\hbar\omega > \hbar\omega_0) \approx \frac{\alpha z^2}{\pi}\left[\left(\ln\frac{\gamma\hbar\omega_\mathrm{p}}{\hbar\omega_0} - 1\right)^2 + \frac{\pi^2}{12}\right]$$

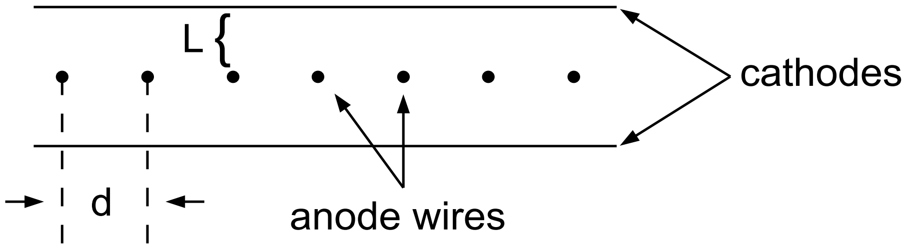


Particle Detectors

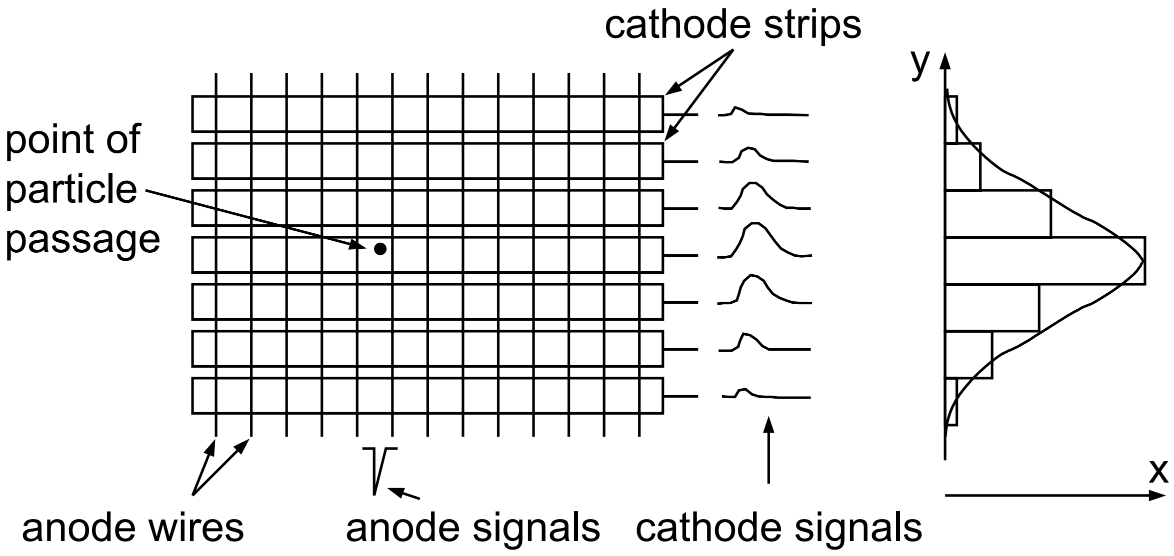
Chapters to study:

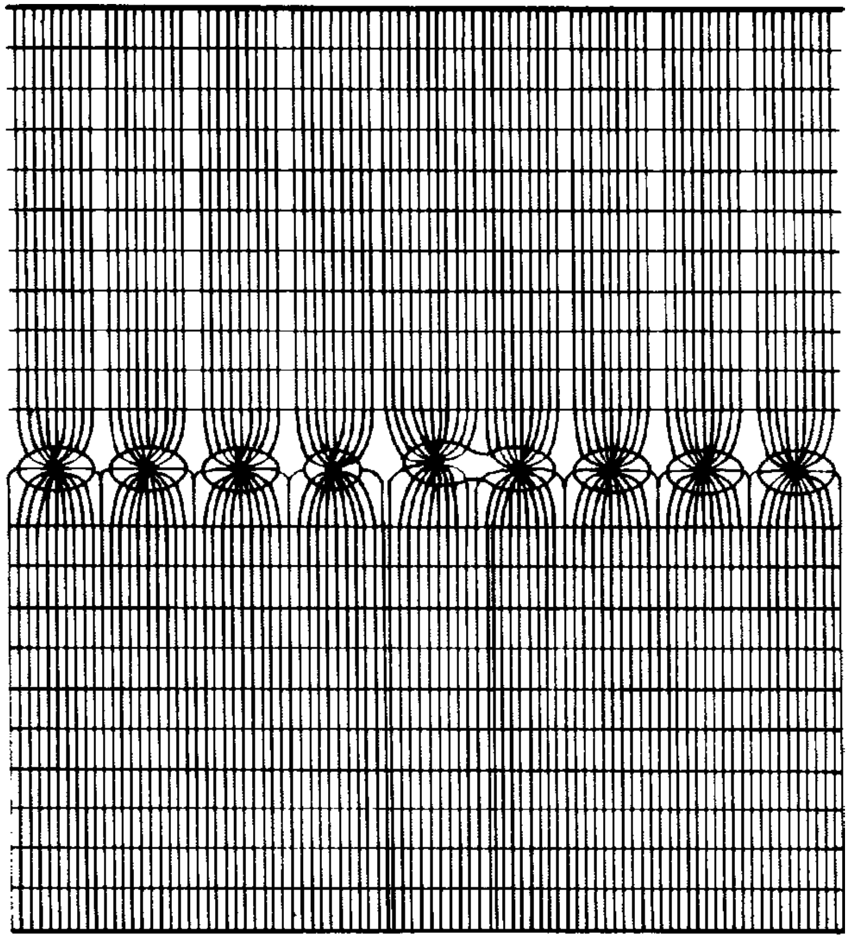
Ch.7, Track detectors

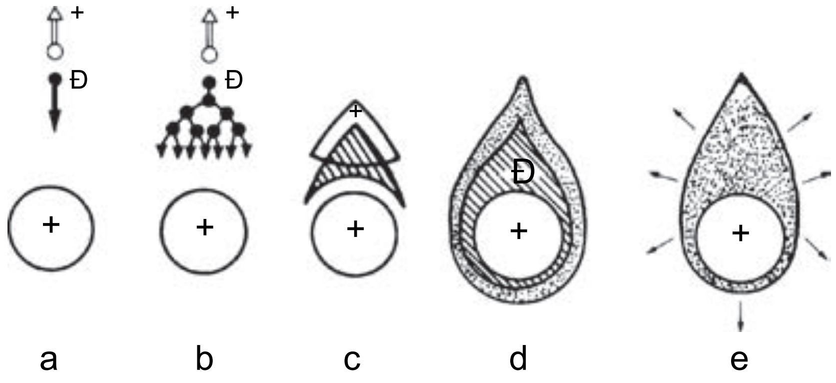
- Multiwire proportional chamber (MWPC)



- Readout and spatial resolution ~0.5 mm





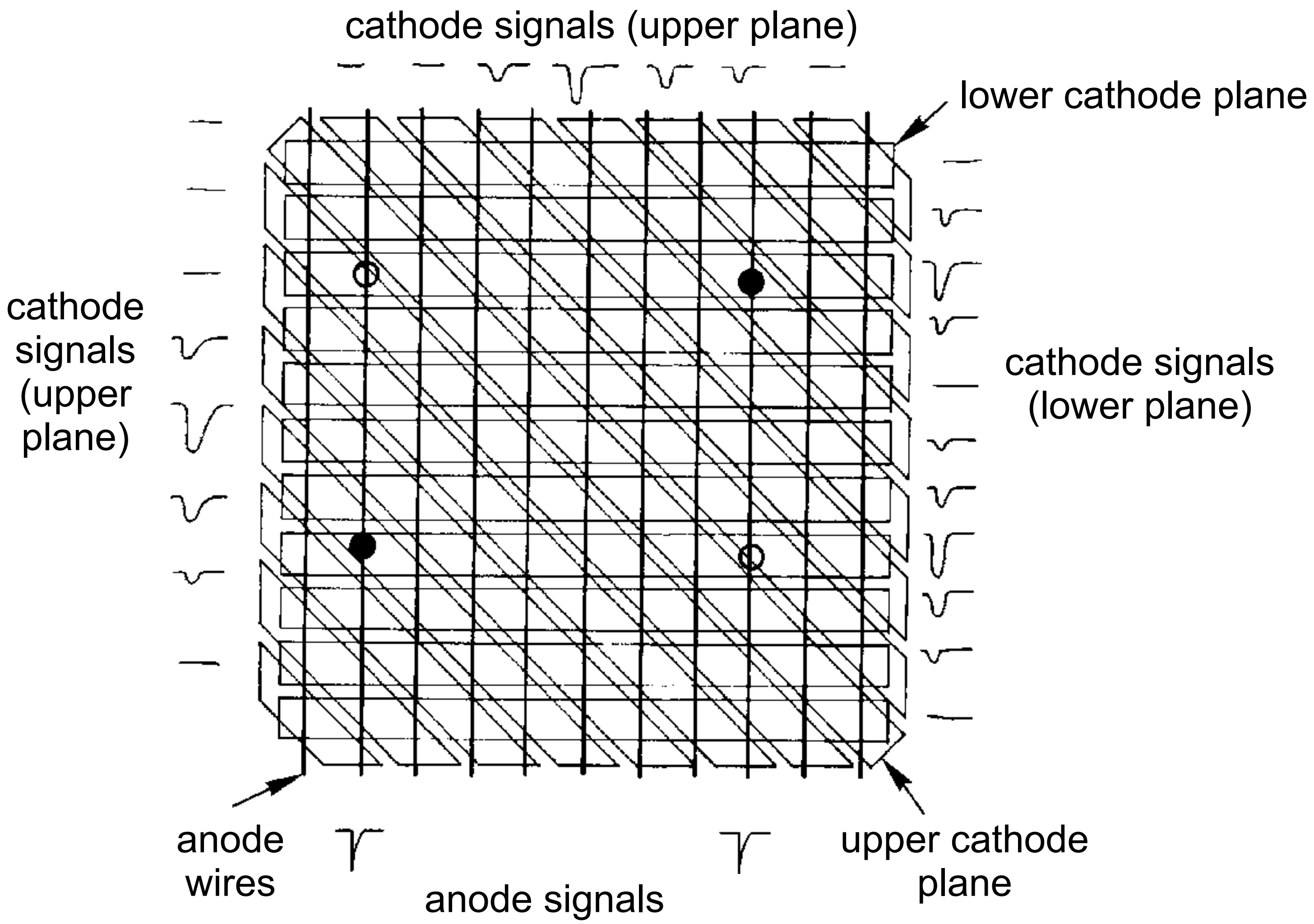


Particle Detectors

Chapters to study:

Ch.7, Track detectors

- More readout



Currently I am developing a pad readout. Join in me if you like to build a prototype, and develop a detector out of that.

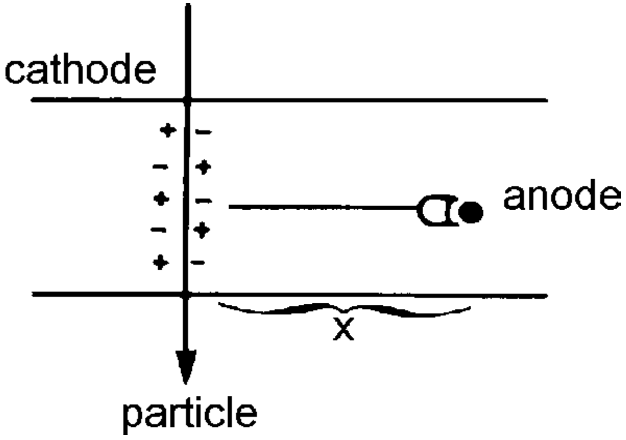
MWC is very rather economical when large detectors are needed.

Particle Detectors

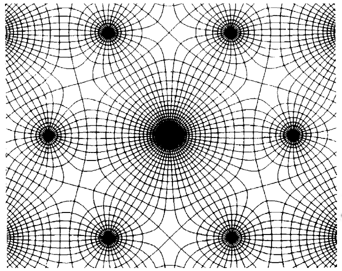
Chapters to study:

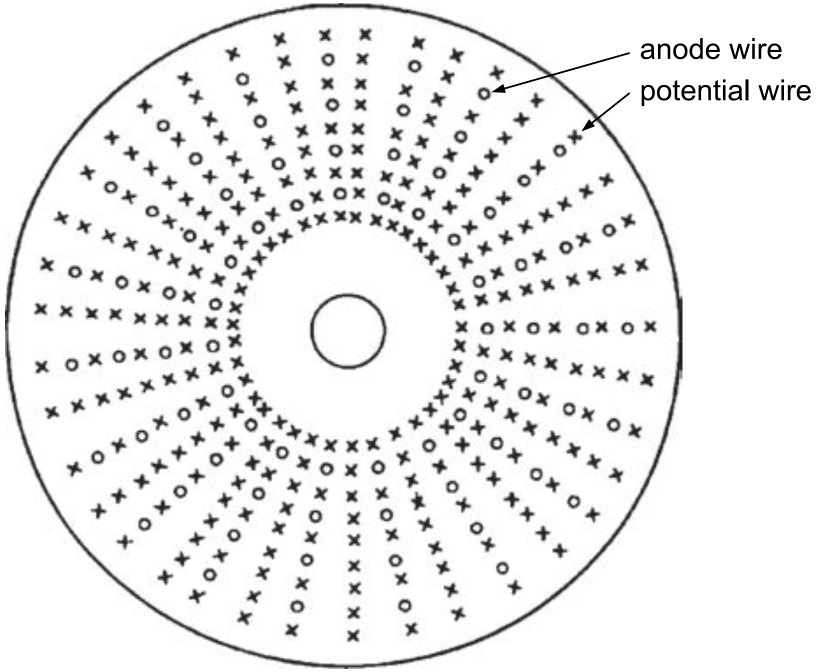
Ch.7, Track detectors

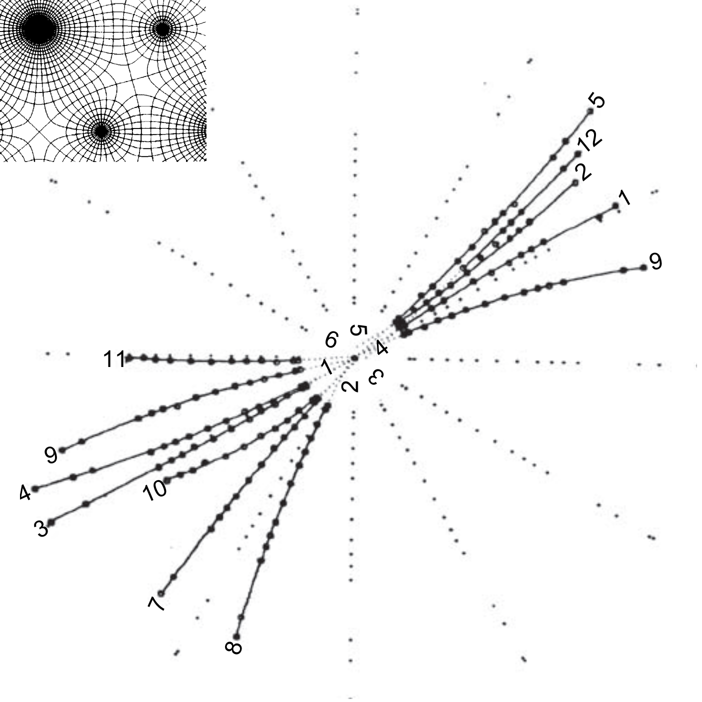
- Planar drift chambers: need constant drift velocity
  - Resolution can be ~0.05 mm
  - Variations, TEC (time expansion chamber), separate drift volume and gas amplification region.
- Cylindrical wire chambers

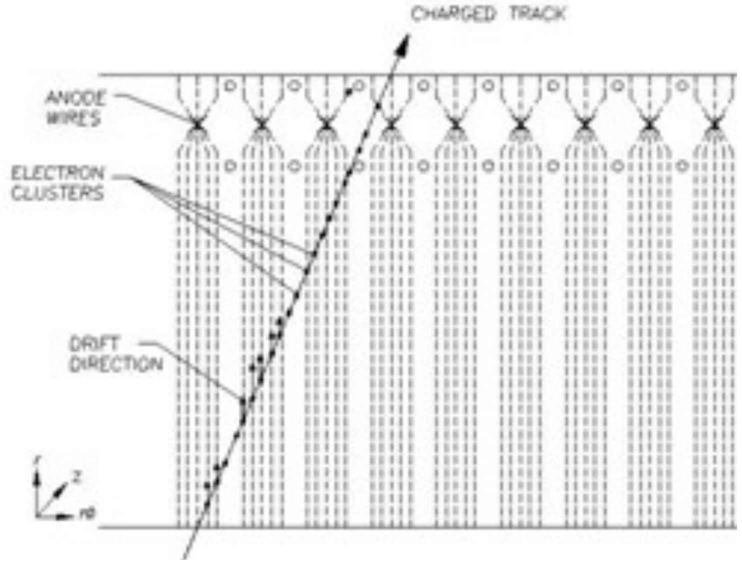


$$x = v^{-} \cdot \Delta t$$







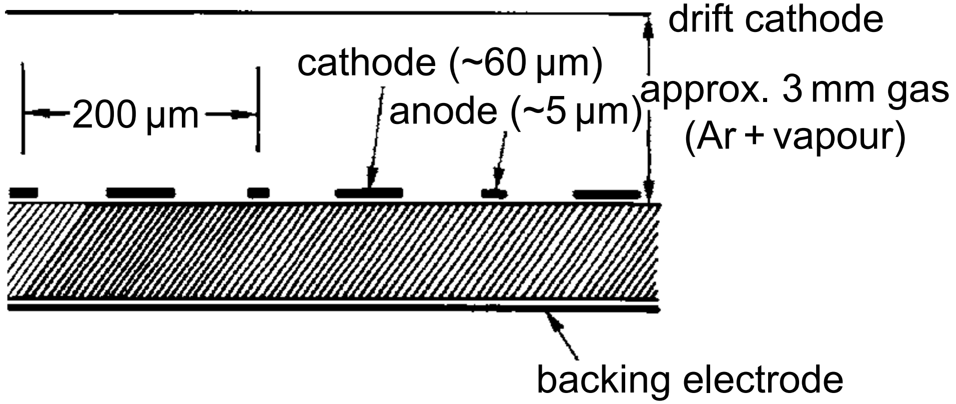


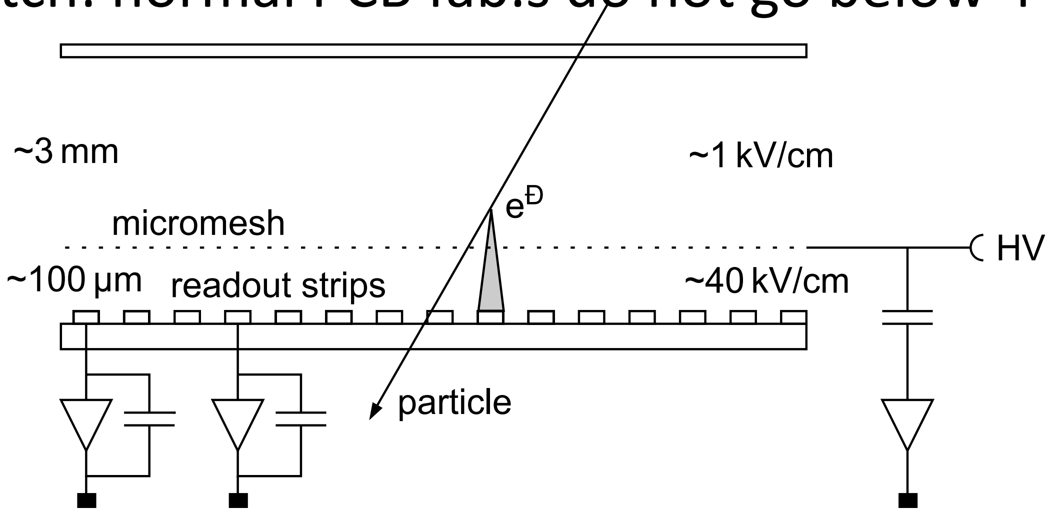
Particle Detectors

Chapters to study:

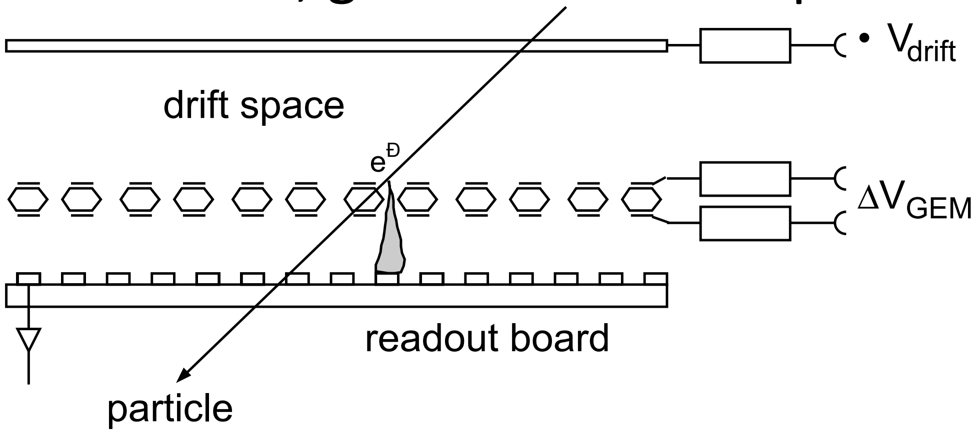
Ch.7, Track detectors

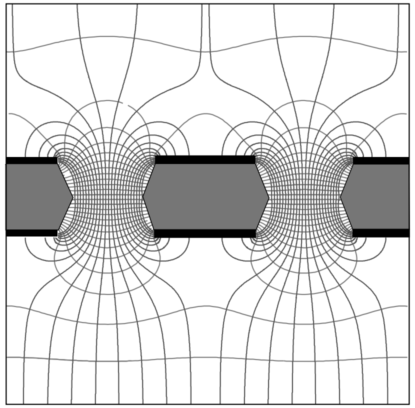
- Micropattern: no need to pull 20 μm gold-plated tungsten wires. Rely on PCB manufacturers to make detector. The catch: normal PCB fab.s do not go below 4 mils.





- A GEM, gas electron multiplier





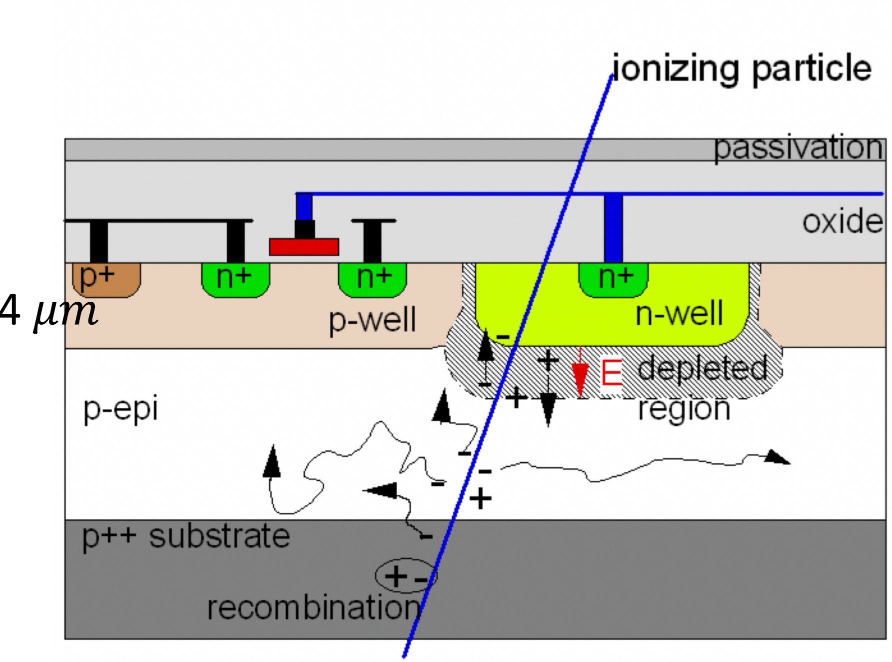
GEM and THGEM. A rich field of detector development and complementary to silicon pixel detector, especially when large area is needed.

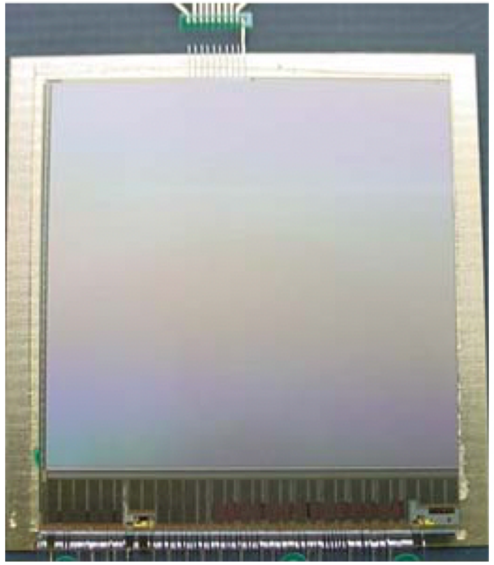
Particle Detectors

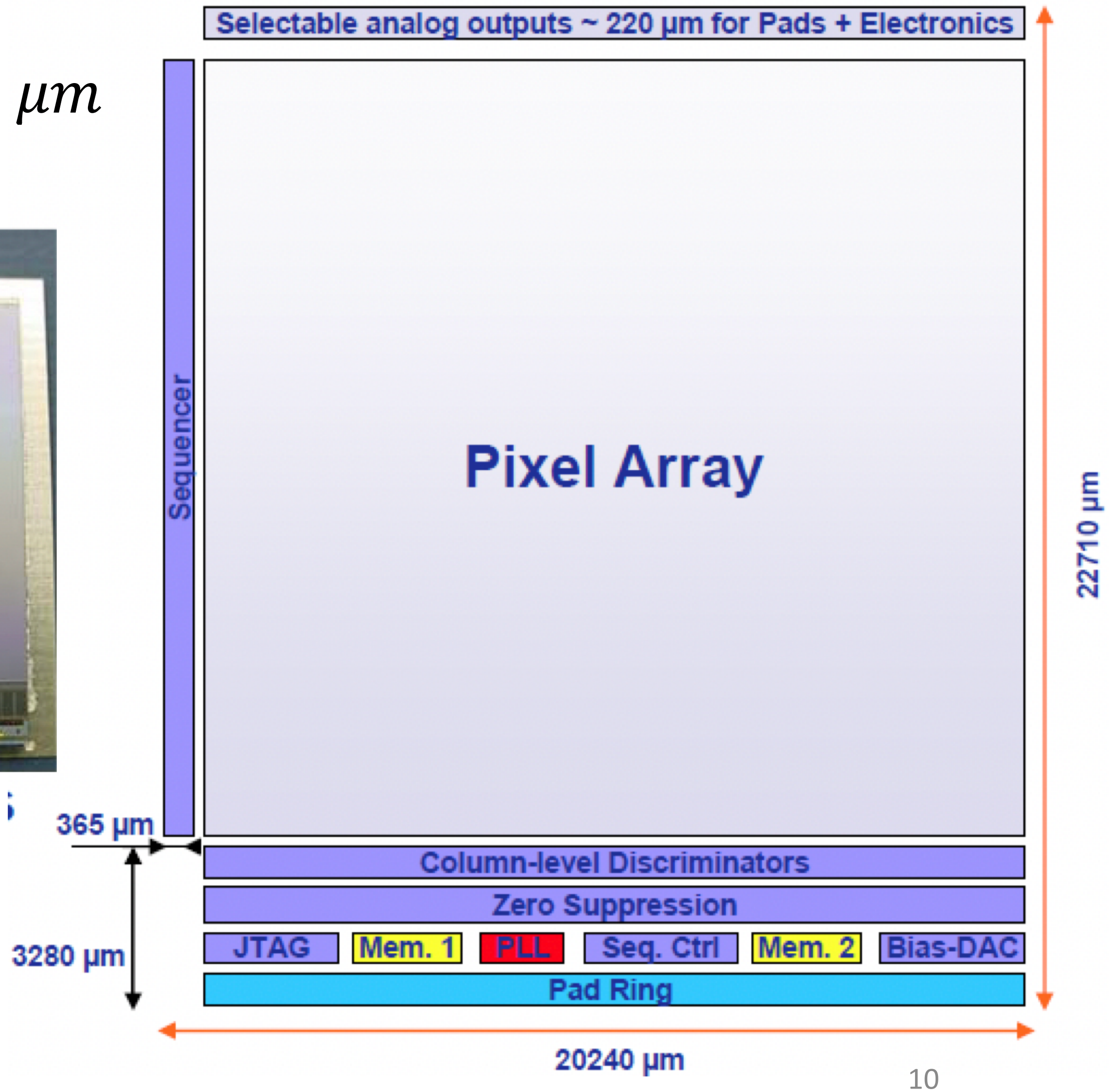
Chapters to study:

Ch.7, Track detectors

- Semiconductor trackers, resolution down to ~ 5 μm
  - Fundamentally a PN junction
  - Pixel or strip
  - Hybrid or MAPS







Particle Detectors

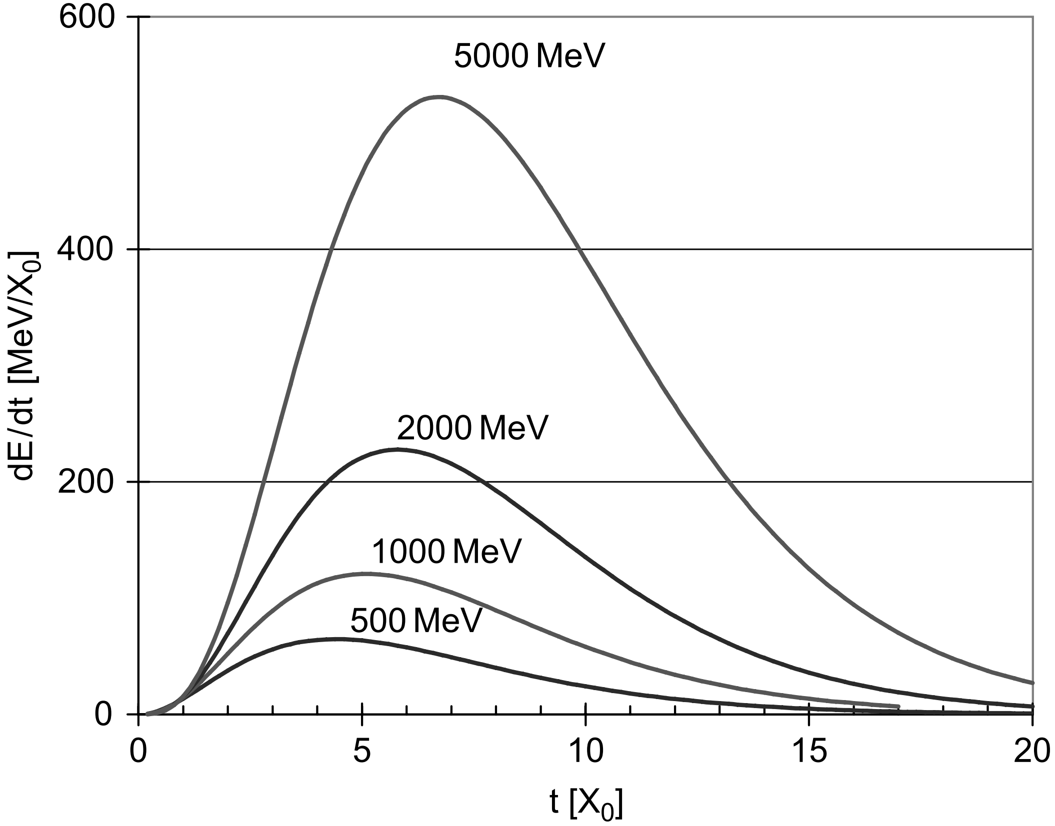
Chapters to study:

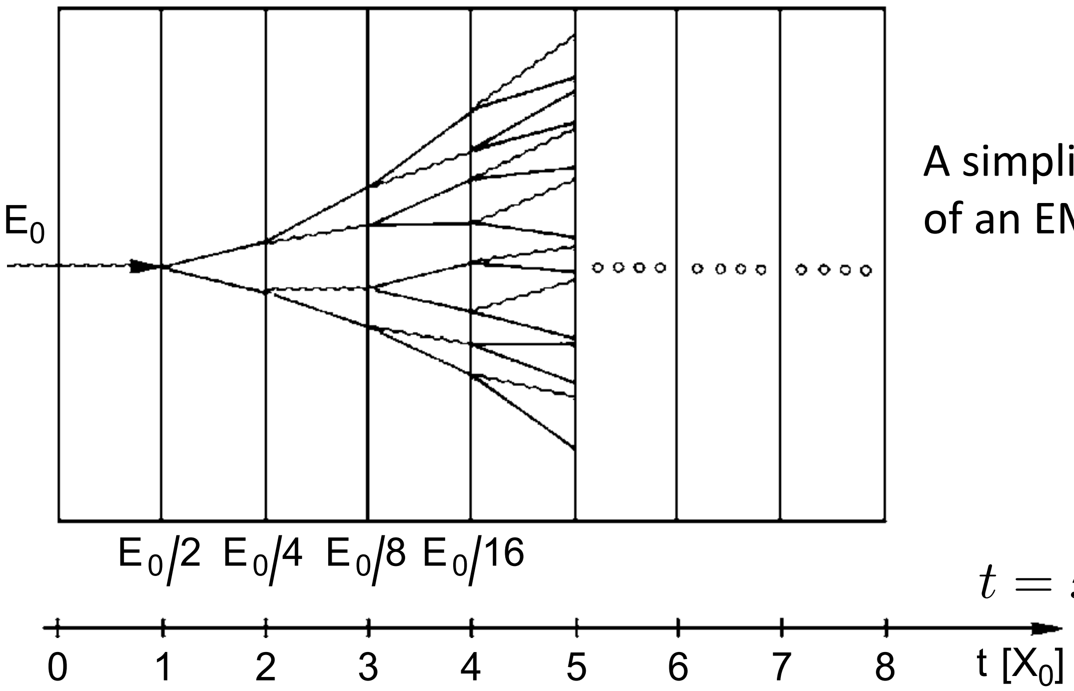
Ch.8, Calorimetry

- Electromagnetic

$$-\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\mathrm{rad}} = \frac{E}{X_0}$$

X_0 is the radiation length





A simplified view of an EM shower

$$t = x/X_0$$

The number of shower particles $N(t) = 2^t$

the energy of the individual particles in generation t

$$E(t) = E_0 \cdot 2^{-t} \qquad E_\mathrm{c} = E_0 \cdot 2^{-t_\mathrm{max}}$$

$$t_\mathrm{max} = \frac{\ln(E_0/E_\mathrm{c})}{\ln 2} \propto \ln(E_0/E_\mathrm{c})$$

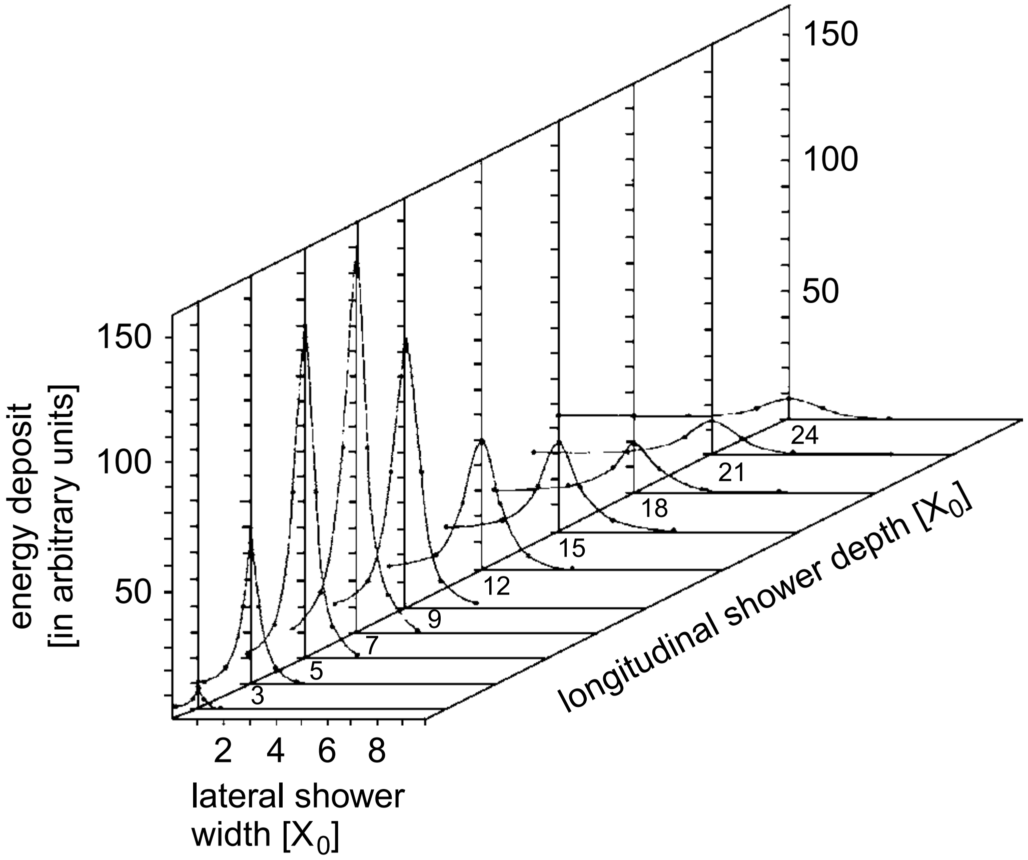
To contain the shower (electron and photon) $t \sim 14 - 24\ X_0$

Particle Detectors

Chapters to study:

Ch.8, Calorimetry

- Electromagnetic



Longitudinal and lateral development of an electron shower (6 GeV)

The actual shower development is usually simulated by GEANT4, and can be parameterized as

$$\frac{\mathrm{d}E}{\mathrm{d}t} = E_0 b \frac{(bt)^{a-1}\,\mathrm{e}^{-bt}}{\Gamma(a)}$$

$$t_{\max} = \frac{a-1}{b} = \ln\left(\frac{E_0}{E_\mathrm{c}}\right) + C_{\gamma e}$$

Particle Detectors

Chapters to study:

Ch.8, Calorimetry

- Electromagnetic
  - Homogeneous calorimeter: absorber = detector (the whole volume is sensitive to energy deposition)
  - Detectors: scintillators, ionization detectors (example: liquid noble elements, diamond, Ge, Si/PN), Cherenkov light detector (lead glass).
  - Energy resolution

$$\sigma^2_{Total} = \sigma^2_{1st-int} + \sigma^2_{rear-leak} + \sigma^2_{lateral-leak} + \sigma^2_{photon-leak}$$

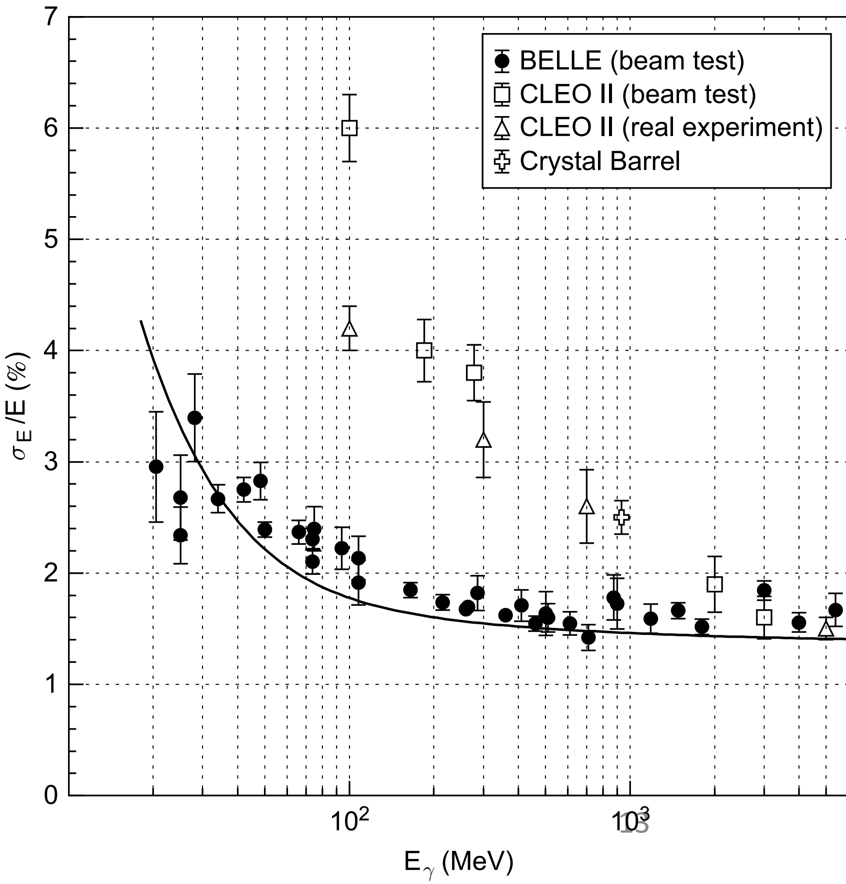
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

a: photoelectron statistics (the stochastic term)

b: electronics noise

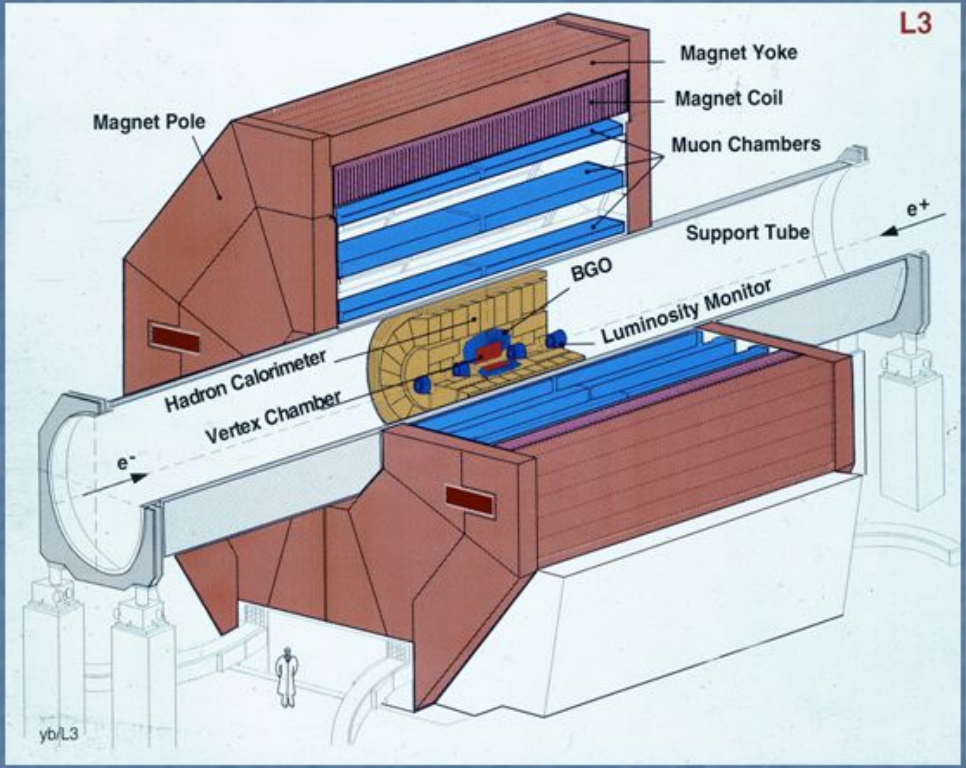
c: calibration, crystal non-uniformity, etc, (the constant term)

$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{0.066\%}{E_\mathrm{n}}\right)^2 + \left(\frac{0.81\%}{\sqrt[4]{E_\mathrm{n}}}\right)^2 + (1.34\%)^2}\ , \quad E_\mathrm{n} = E/\mathrm{GeV}$$



  - Position resolution: usually no longitudinal segmentation (information). Photon angles measured by center of gravity of energy.

L3 BGO calorimeter



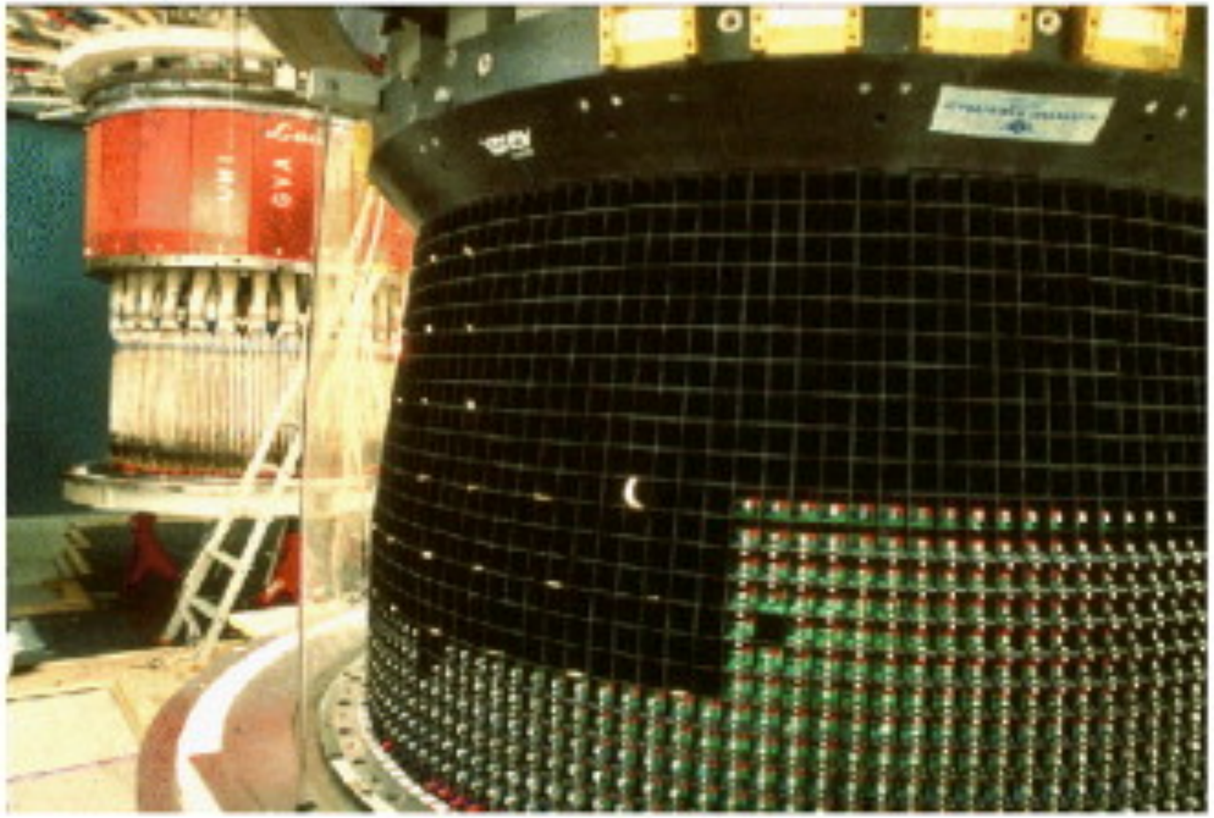
Number of crystals:
- Barrel – 7680
- Endcaps – 2×1527

Thickness – $22X_0$

Photodotector – Si PD

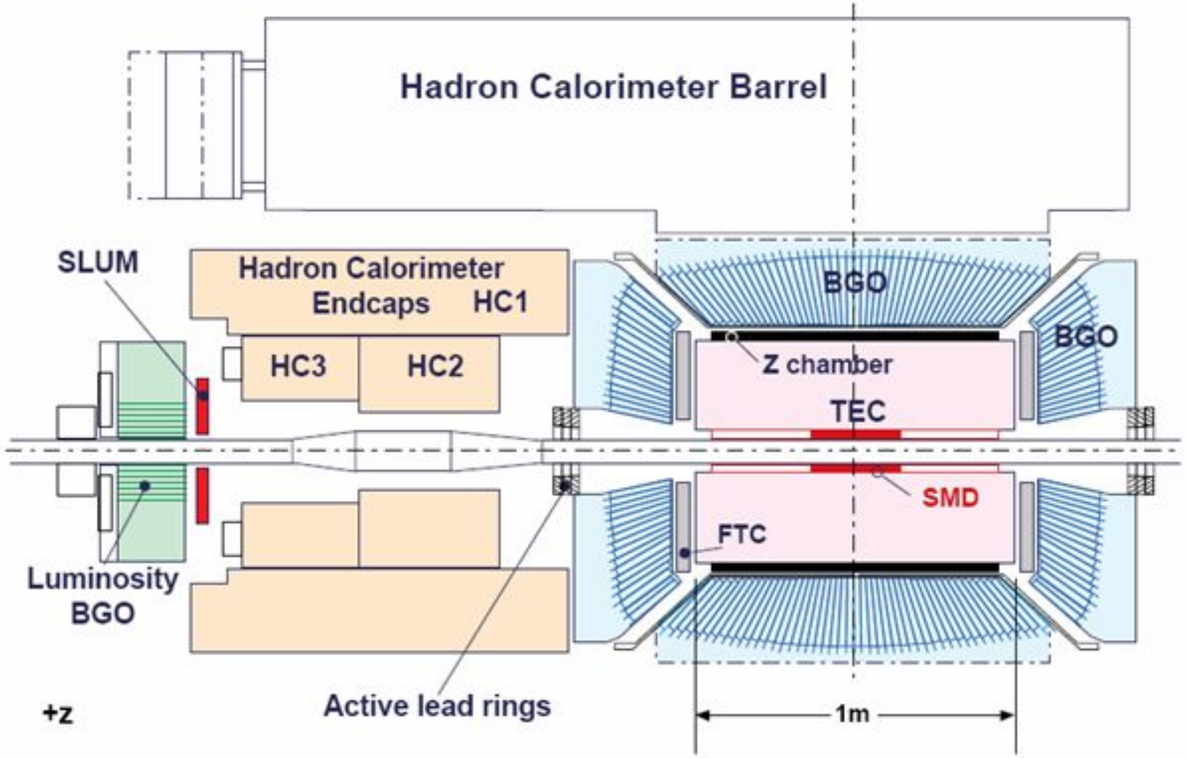
L3 detector at LEP 1980-2000

03.03.2008 V. Golubev, INSTR08

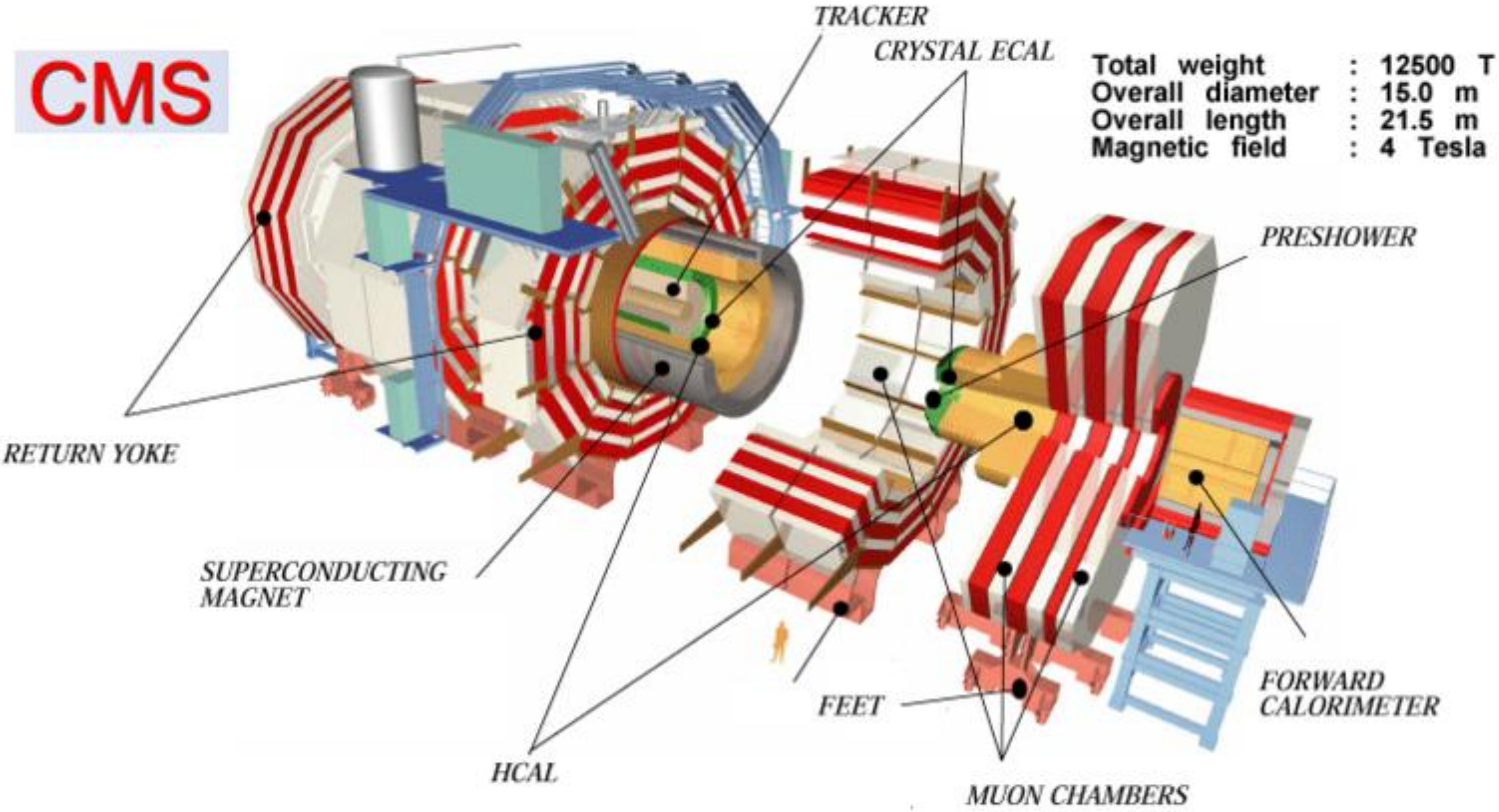


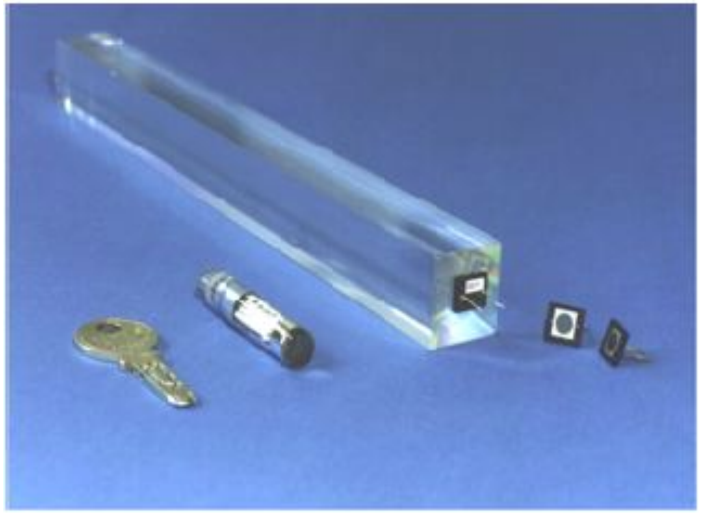
12000 BGO crystals
1.5 m^3, 11 tons

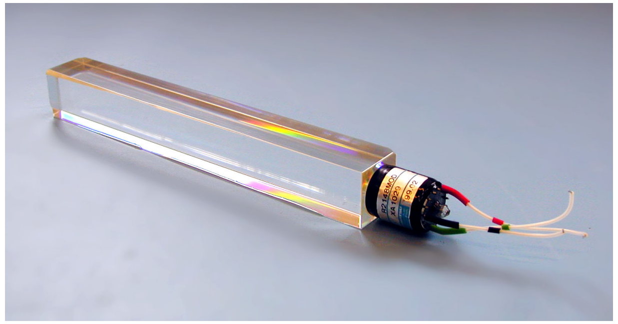
LEP L3 Experiment Detector / 1

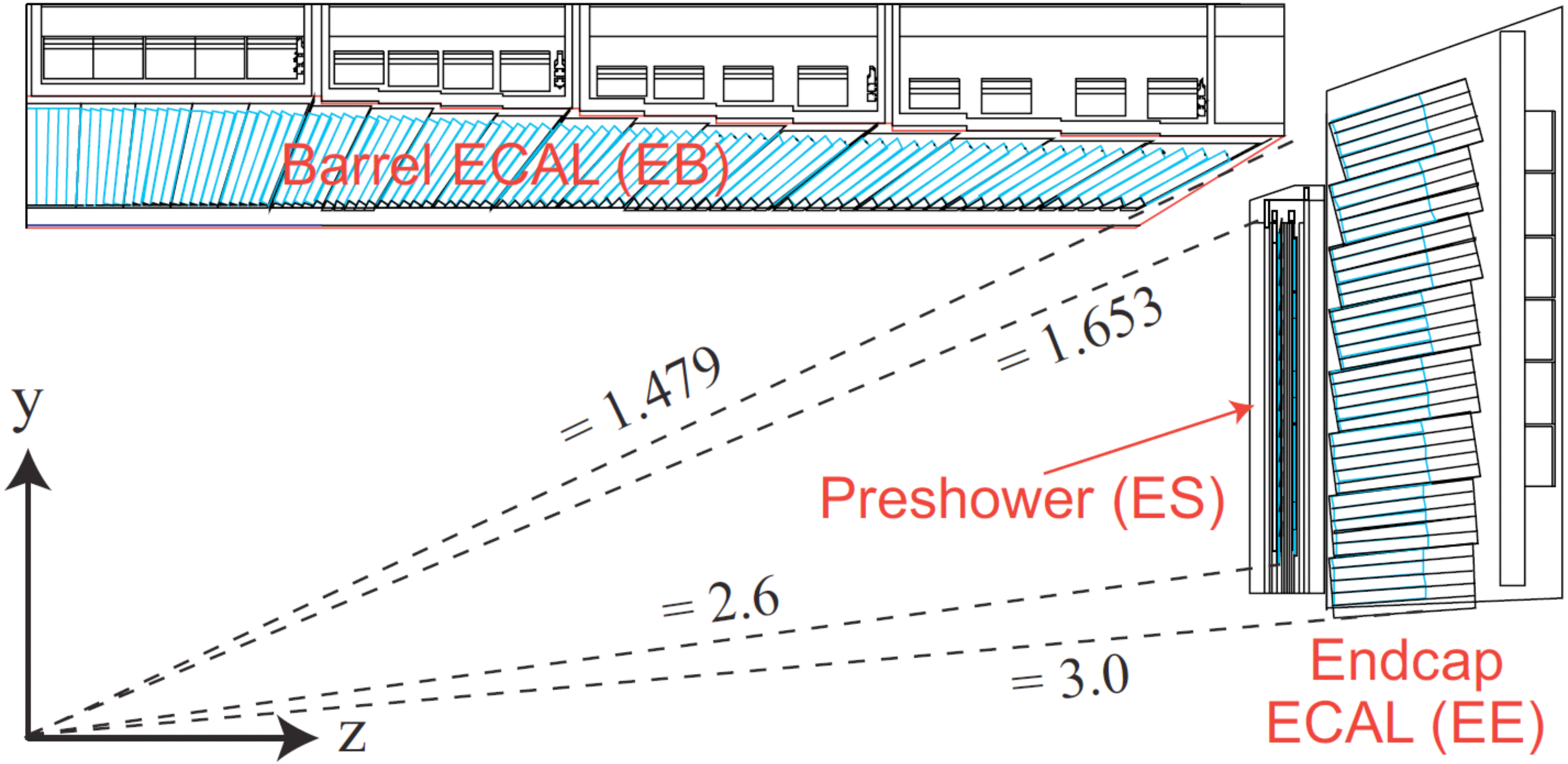


- A Silicon track detector (SLUM) for precise impact/angle measurements.
- A scintillating crytal (BGO) electro-magnetic calorimeter to measure the energy of the particle, optimized for electrons and photons.


CMS
TRACKER
CRYSTAL ECAL
Total weight : 12500 T
Overall diameter : 15.0 m
Overall length : 21.5 m
Magnetic field : 4 Tesla
PRESHOWER
RETURN YOKE
SUPERCONDUCTING MAGNET
FORWARD CALORIMETER
FEET
HCAL
MUON CHAMBERS






Barrel ECAL (EB)
= 1.479
= 1.653
Preshower (ES)
= 2.6
= 3.0
Endcap
ECAL (EE)
y
z

Particle Detectors

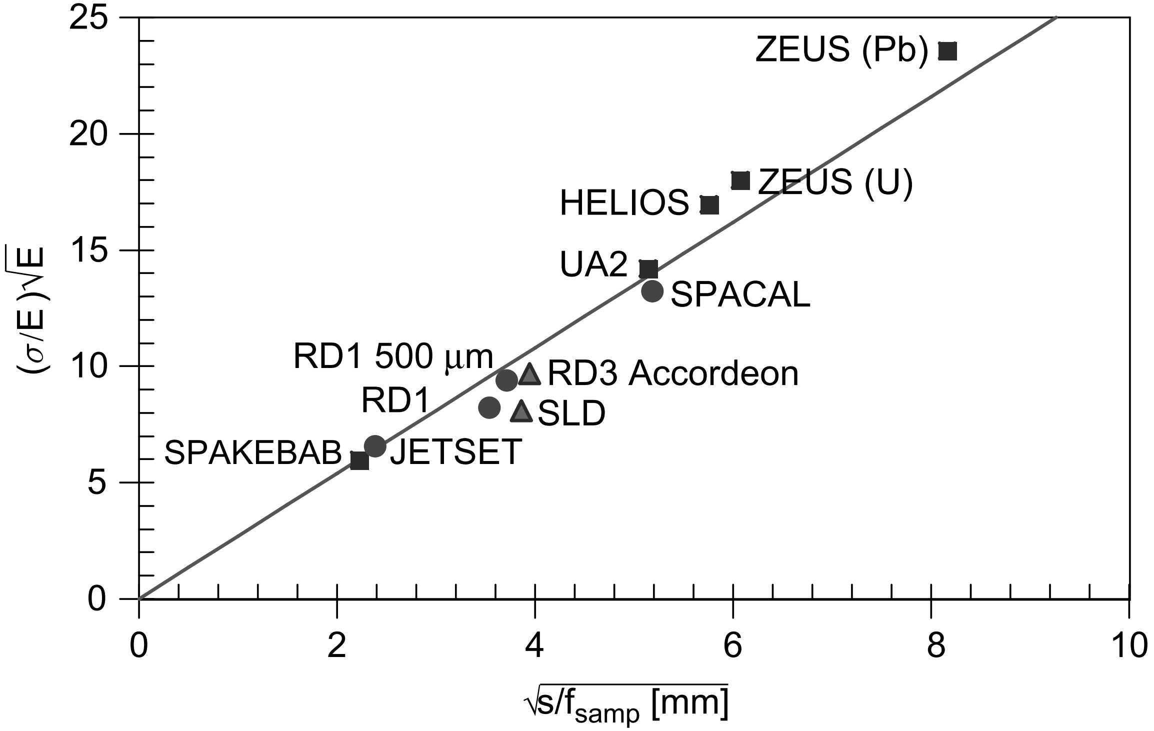
Chapters to study:

Ch.8, Calorimetry

- Electromagnetic
  - Sampling calorimeter: absorber + detector. For practical reasons (example: need a large inner tracker, the energy of the particle to be stopped is high) when a homogenous calorimeter is not economically feasible.
  - Price on the resolution: additional term from sampling fluctuation.
  - An empirical expression:

$$\frac{\sigma_{\mathrm{samp}}}{E} = \frac{2.7\%}{\sqrt{E\ [\mathrm{GeV}]}}\sqrt{\frac{s\ [\mathrm{mm}]}{f_{\mathrm{samp}}}}$$

s is the thickness of the detector
f_{samp} is the sampling ratio
This ratio benefits from the density of the detector medium, a reason we usually see liquids and solids, but not gases to be used as the samplers.

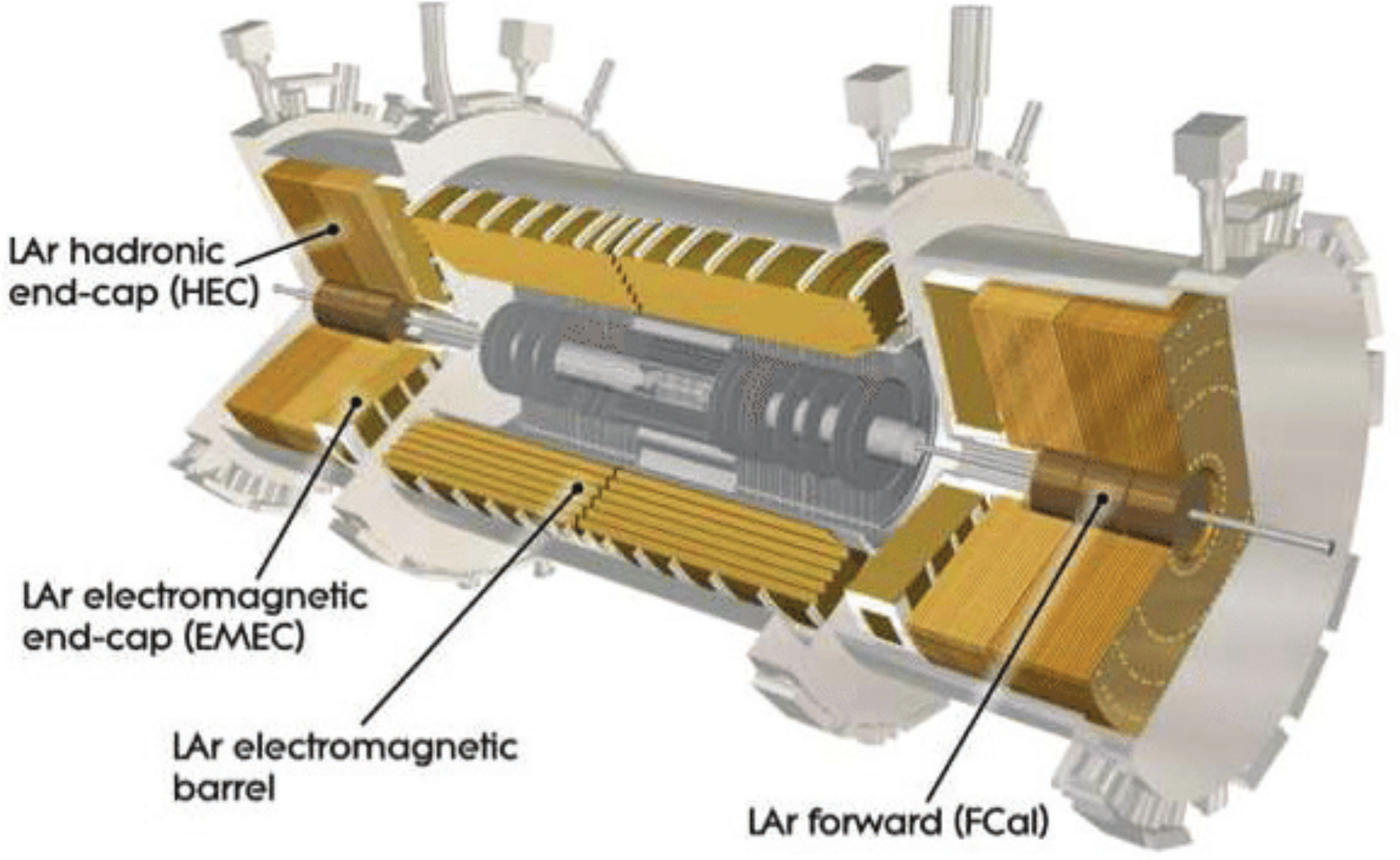


Particle Detectors

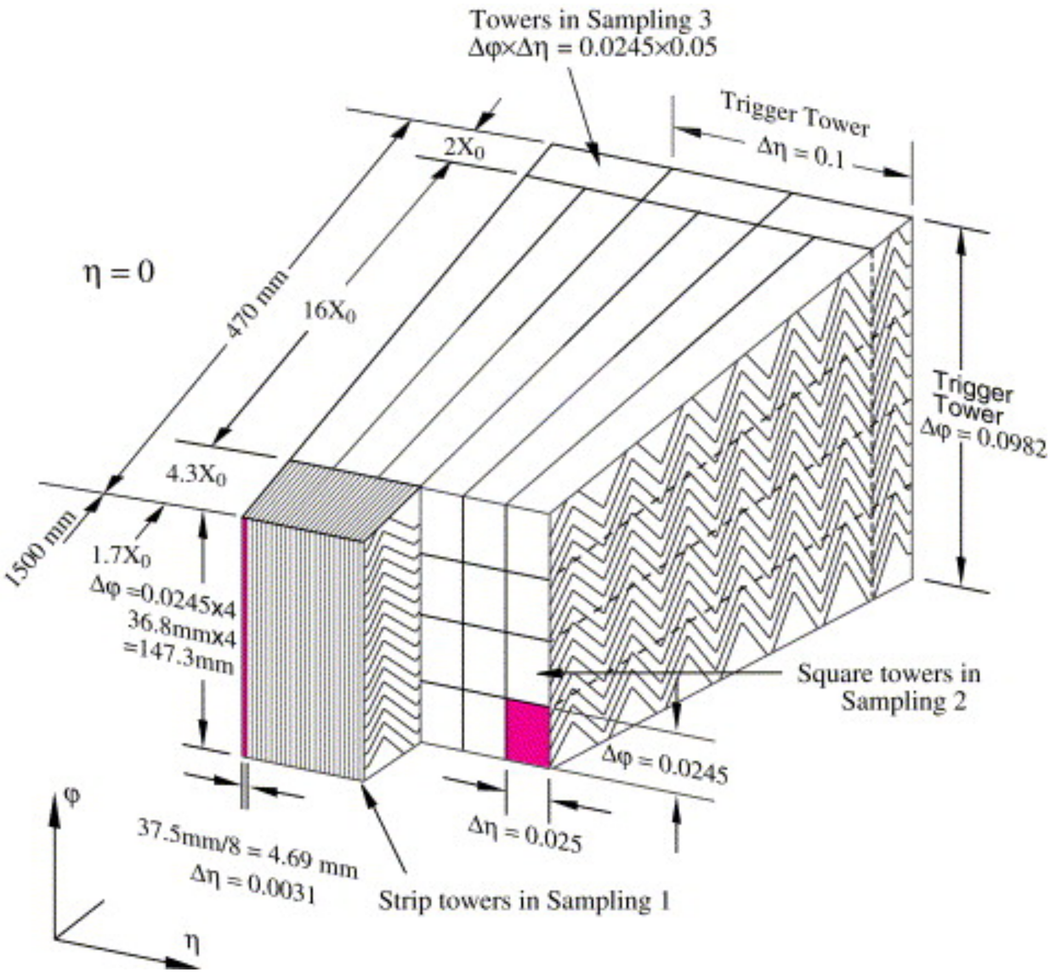
Chapters to study:

Ch.8, Calorimetry

- Sampling ECALs and HCALs



ATLAS Liquid Argon Calorimeters (LAr)



One module, accordion type

Particle Detectors

Chapters to study:

Ch.8, Calorimetry

- Sampling ECALs and HCALs

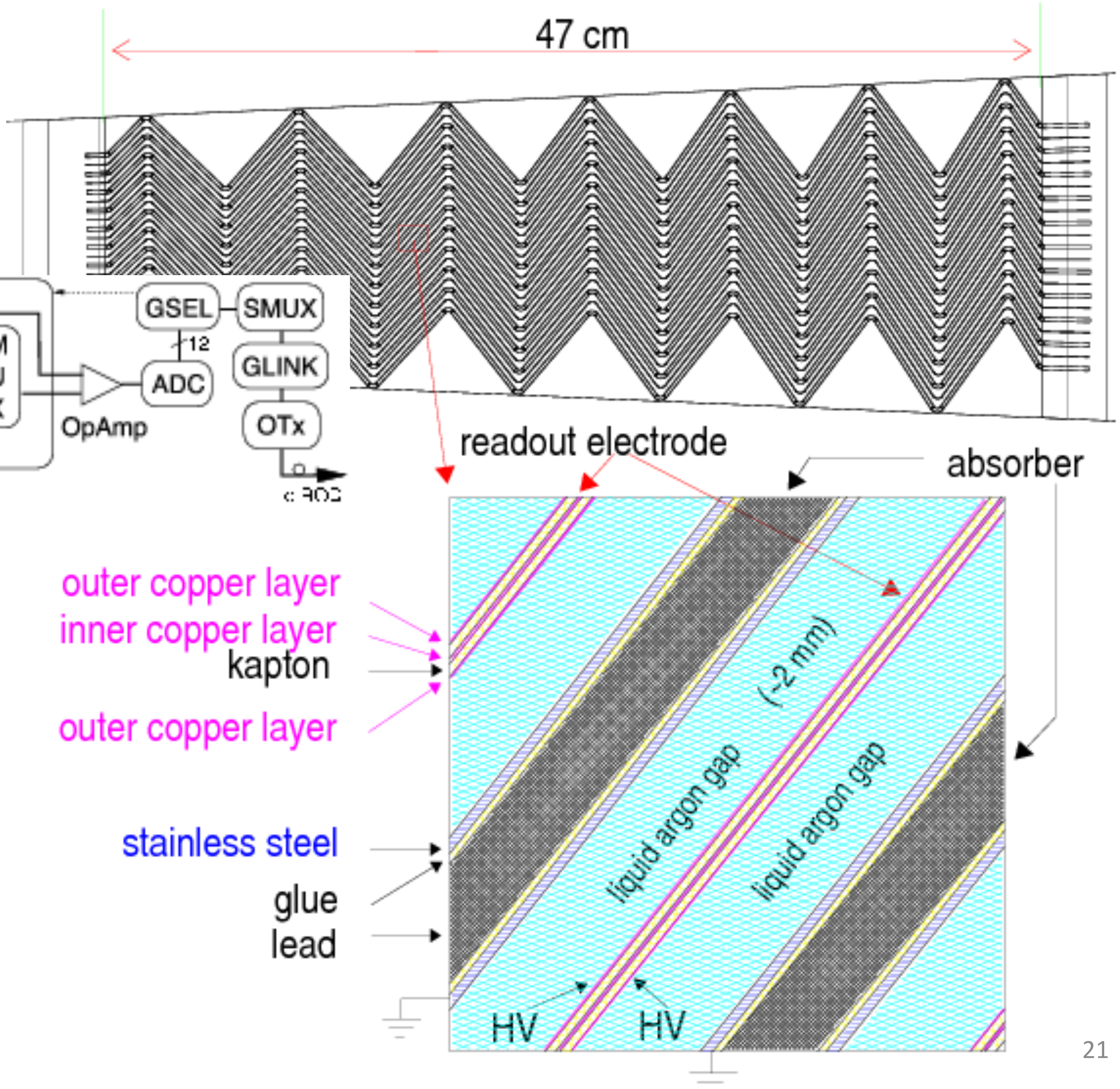
	ATLAS	CMS	ALICE	LHCb
Materials used	Cu-LAr	$PbWO_4$	Pb-PS	Pb-PS
Detector Depth (X_0)	27.6	25.8	20.1	25
R_M (cm)	1.9	2.2	3.2	3.5
Granularity (cm)	3.0	2.2	6.0	2.02
Designed Resolution ($\%/\sqrt{E}$)	28.5	2.8	10	10

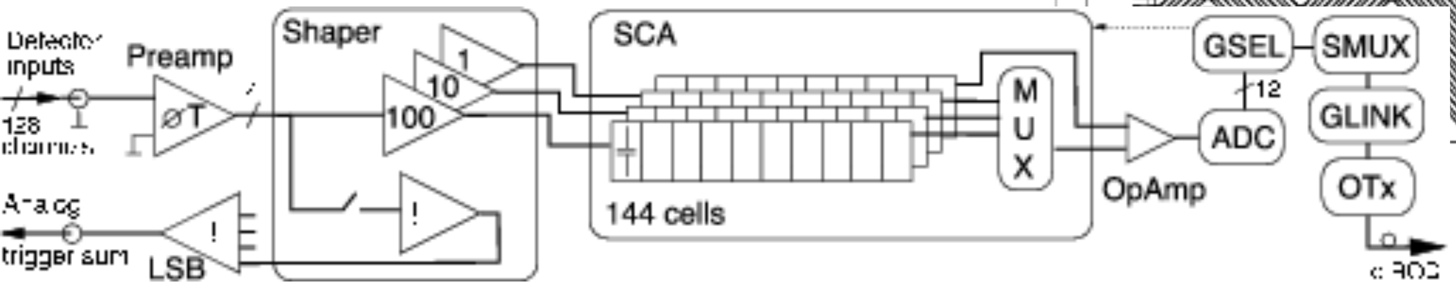
Particle Detectors

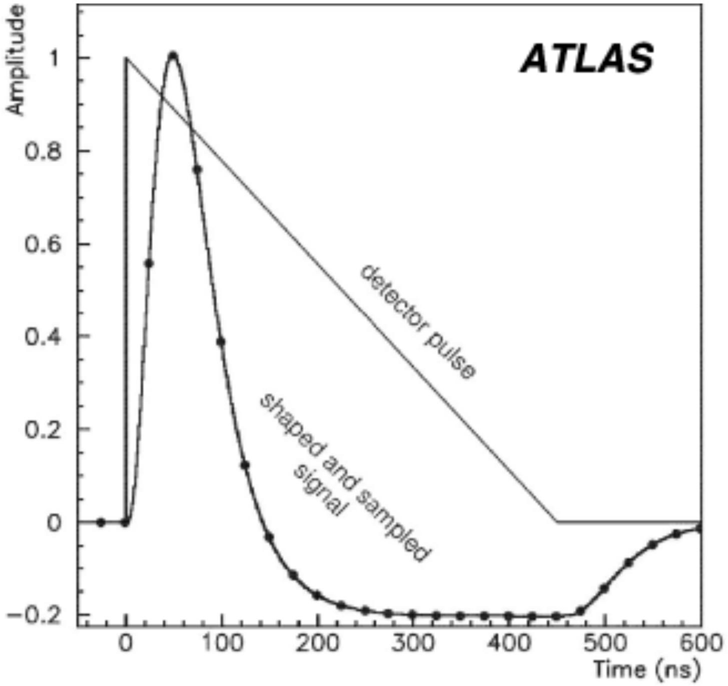
Chapters to study:

Ch.8, Calorimetry

- Sampling ECALs and HCALs





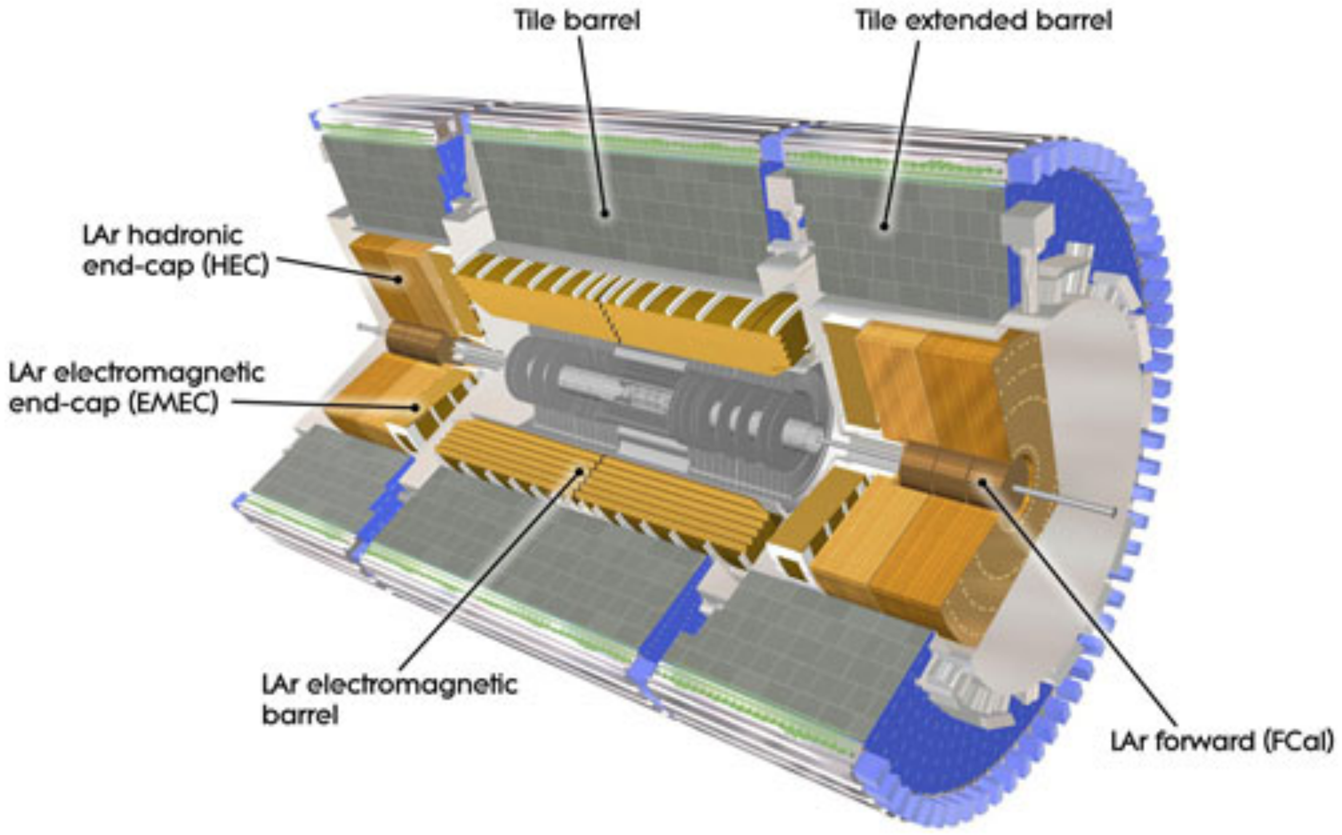


Particle Detectors

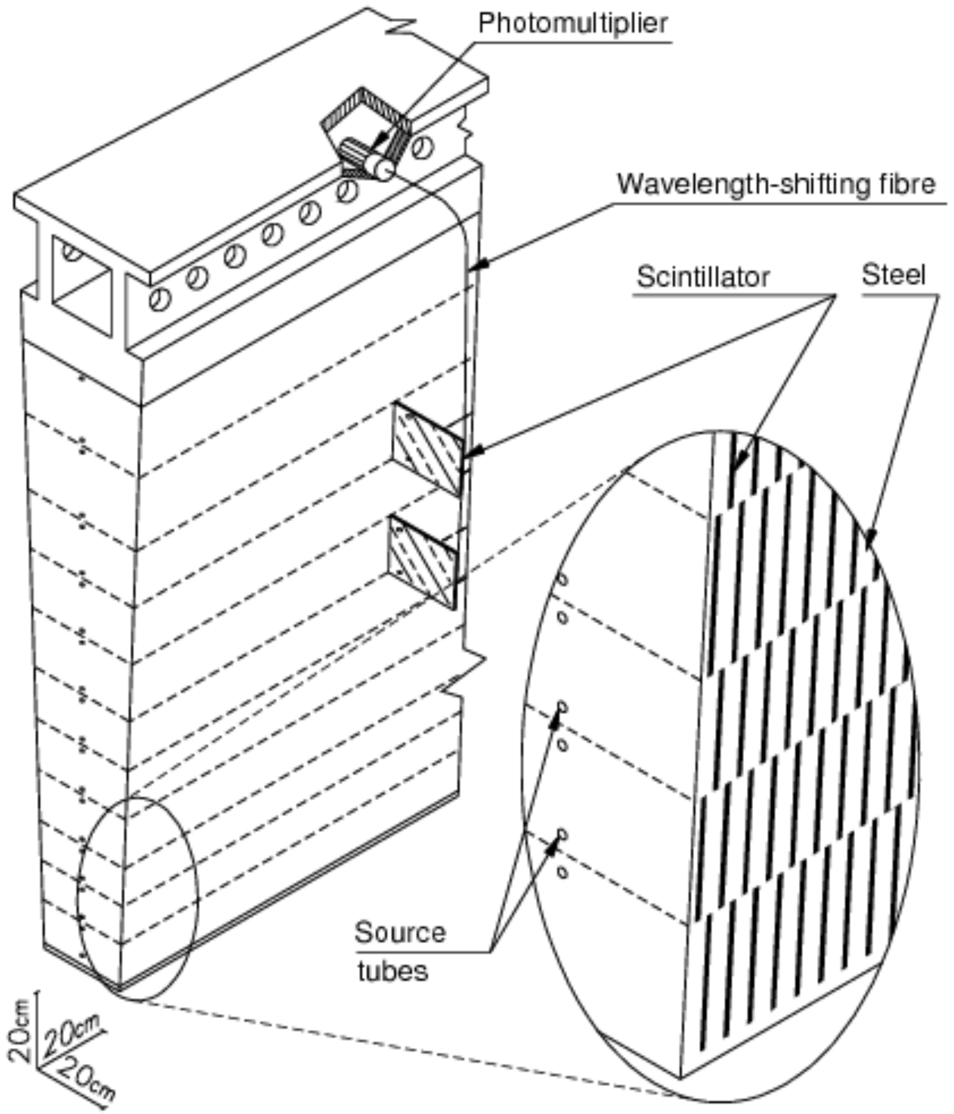
Chapters to study:

Ch.8, Calorimetry

- Sampling ECALs and HCALs



ATLAS Tile Calorimeters

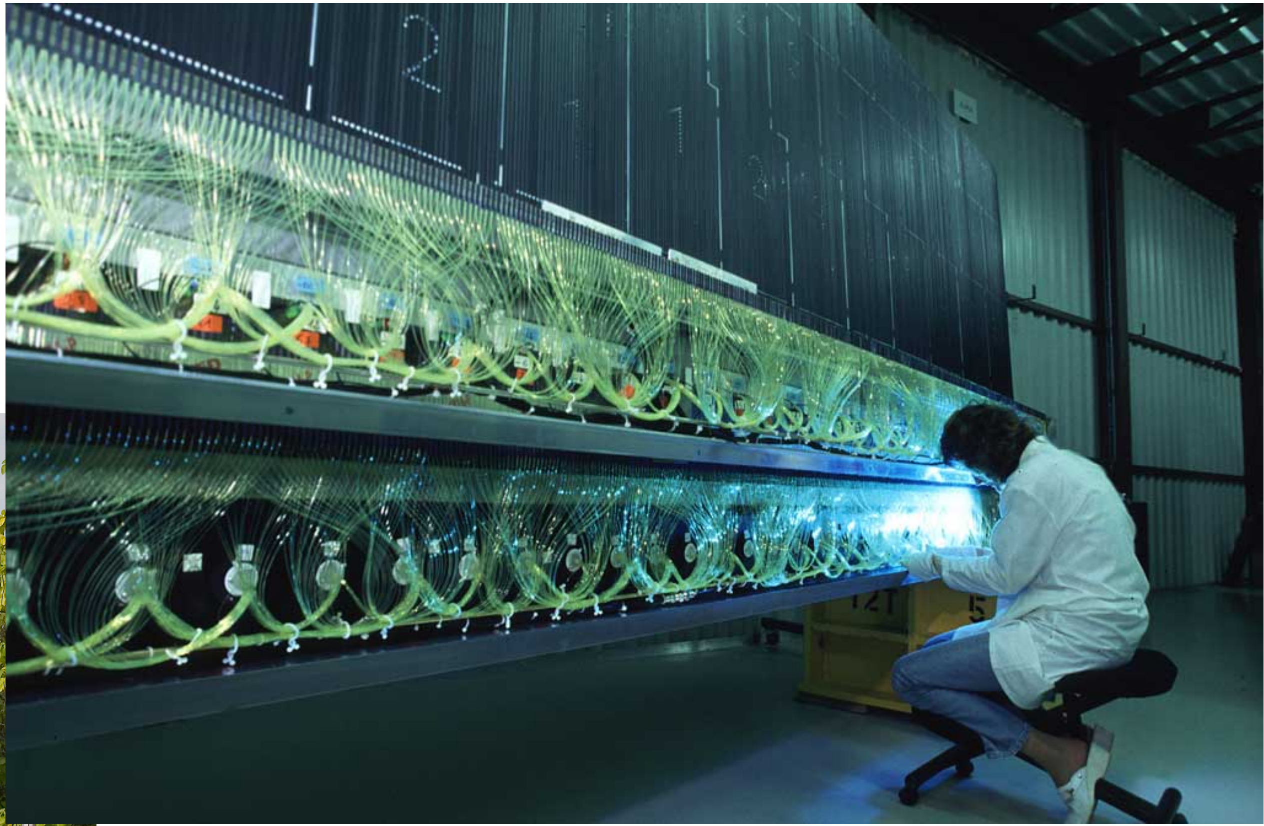


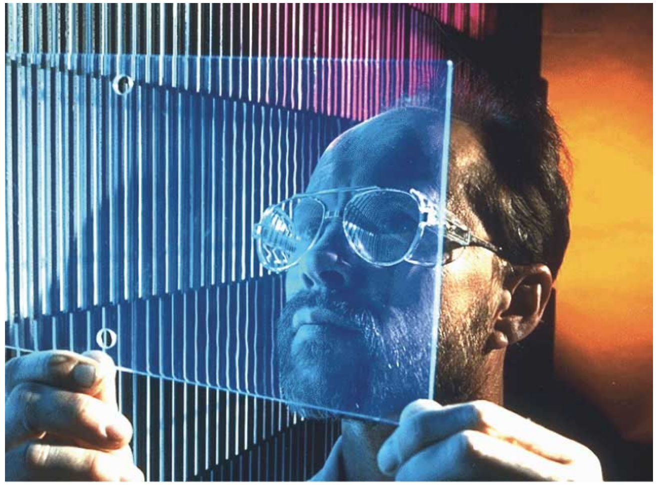
Particle Detectors

Chapters to study:

Ch.8, Calorimetry

- Sampling ECALs and HCALs



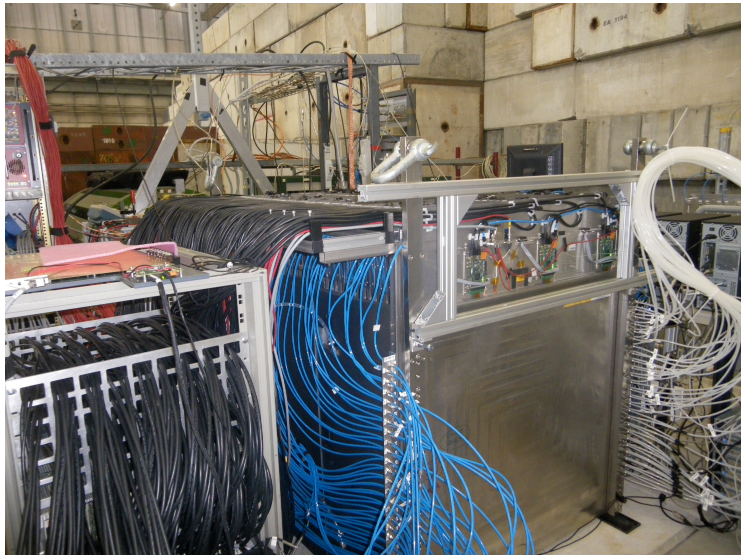


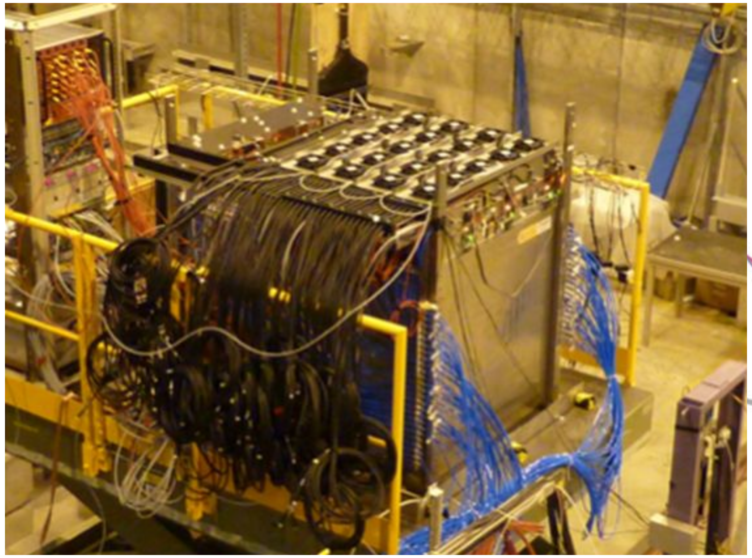
Particle Detectors

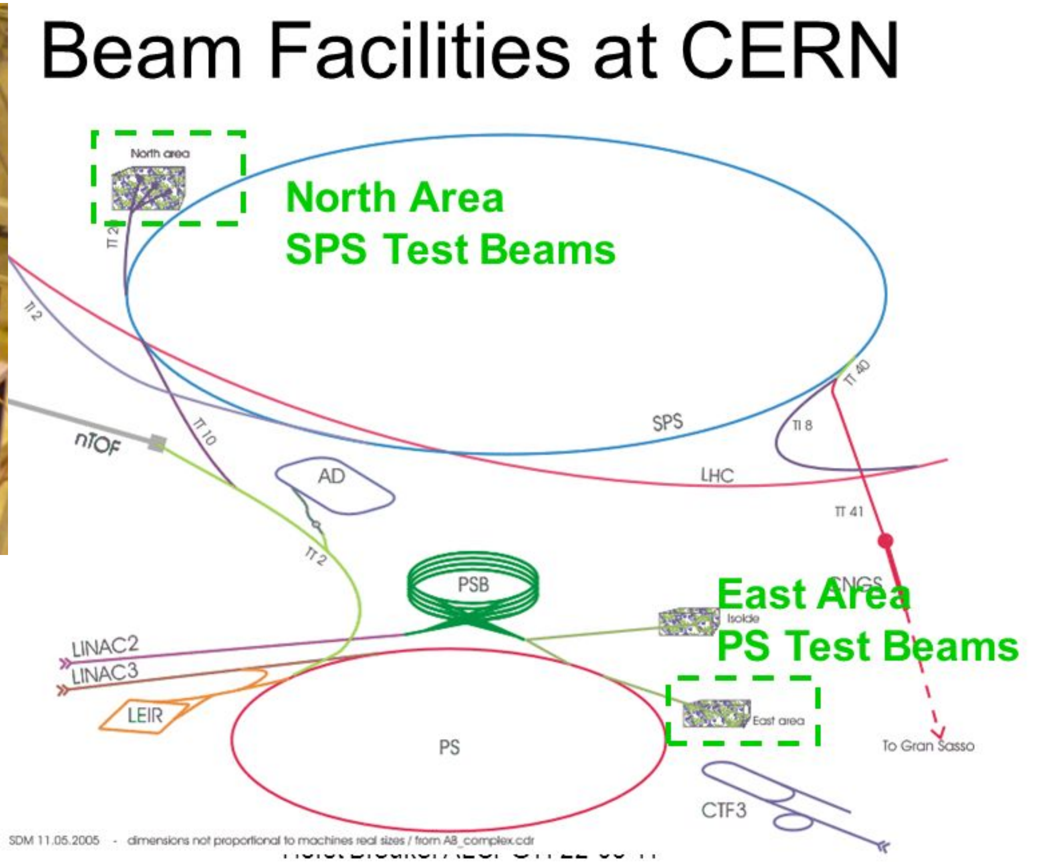
Chapters to study:

Ch.8, Calorimetry

- Calibrations
  - Beam tests on one module, with particles ($e, \mu, \gamma, \pi^{\pm}$, etc) and known energy (momentum)







  - With known physics processes
    pion or keon decays
    $^{J}/_{\psi}$ decays
    Z decays

Particle Detectors

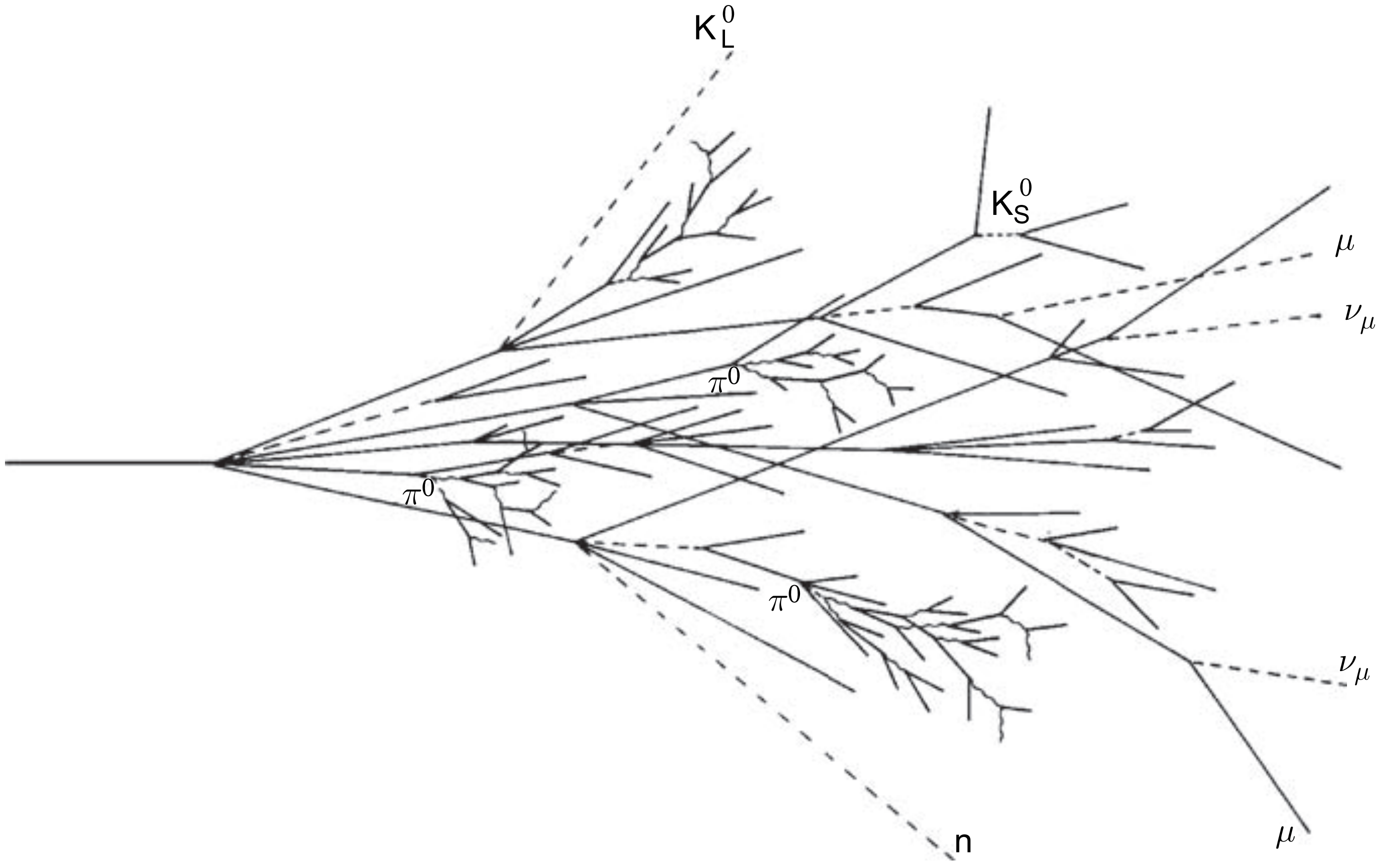
Chapters to study:

Ch.8, Calorimetry

- Hadron Calorimeters or HCALs

  The absorption (average nuclear interaction length) $\lambda_{\mathrm{I}} \approx 35\,\mathrm{g/cm^2}\,A^{1/3}$

  The shows from a hadron contains particles interact electromagnetically or hadronically



HCAL is usually behind the smaller ECAL. While electrons and photons are fully contained in the ECAL which is calibrated to these particles, a hadron show is in both ECAL and HCAL, making the calibration more difficult. The EM part of the show inside the ECAL will stay inside the ECAL. The fluctuation of the EM components and their locations inside a hadron shower contribute to the energy resolution of hadron show measurement. A typical formula

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E(\mathrm{GeV})}}$$

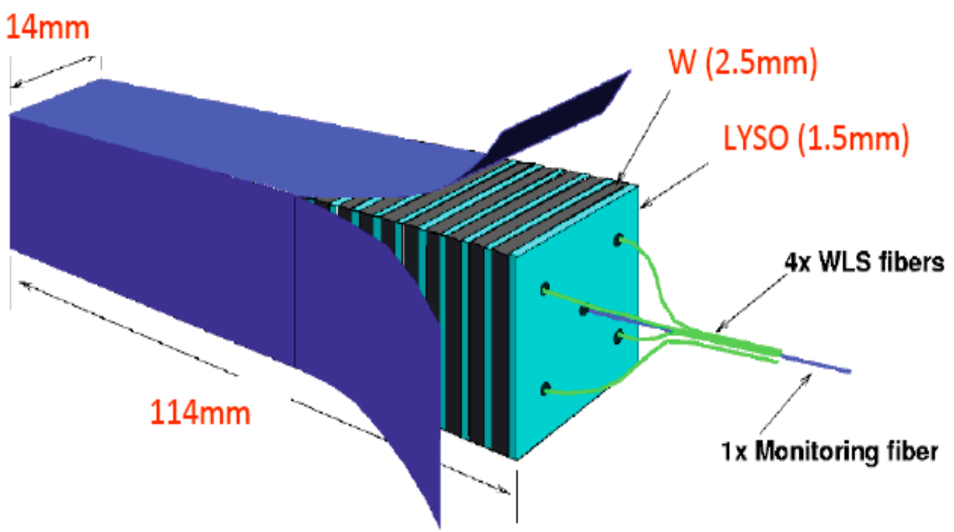
Where *a* is around 40-50%

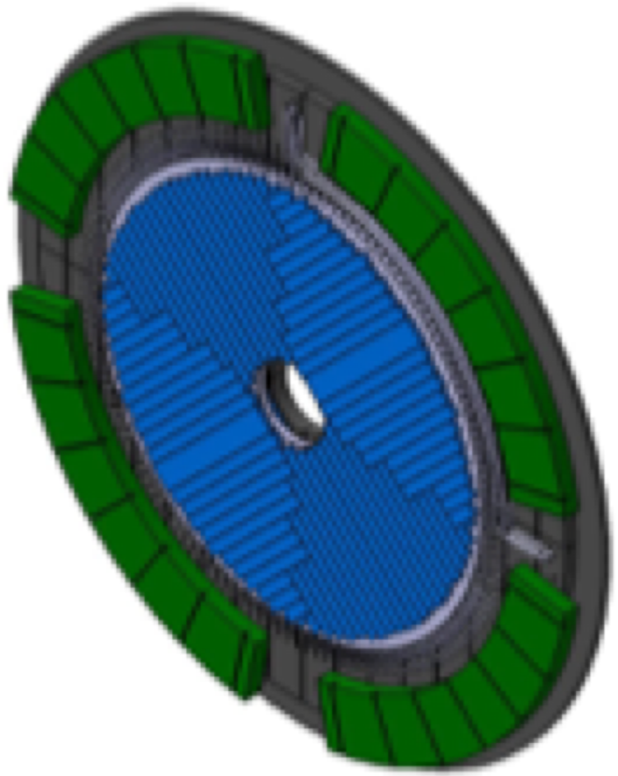
Particle Detectors

Chapters to study:

Ch.8, Calorimetry

- Efforts to improve resolution: measure each secondary particle – a digital calorimeter, usually with Si pixel sensors. Other sensors such as RPC, for example in the Cornel DHCAL, are also under R&D. Recent trend also includes the HGC (CMS) and HGTD (ATLAS). Timing information from a calorimeter, or, as an added information to a calorimeter is the newest direction in particle detectors.





Particle Detectors

Chapters to study:
Ch.1, Interactions of particles and photon with matter.
Ch.5, Main physical phenomena used for particle detection and basic counter types
Ch.7, Track detectors
Ch.8, Calorimetry
Ch.9, Particle identification
Ch.14, Electronics
Ch.15, Data analysis
Ch.16, Applications of particle detectors outside of particle physics

Chapters to read through
Ch.2, Characteristic properties of detectors
Ch.3, Units of radiation measurements and radiation sources
Ch.4, Accelerators
Ch.6, Historical track detectors
Ch.10, Neutrino detectors
Ch.11, Momentum measurement and muon detection
Ch.12, Aging and radiation effects
Ch.13, Example of a general-purpose detector: ATLAS, CMS