Experimental methods in particle physics

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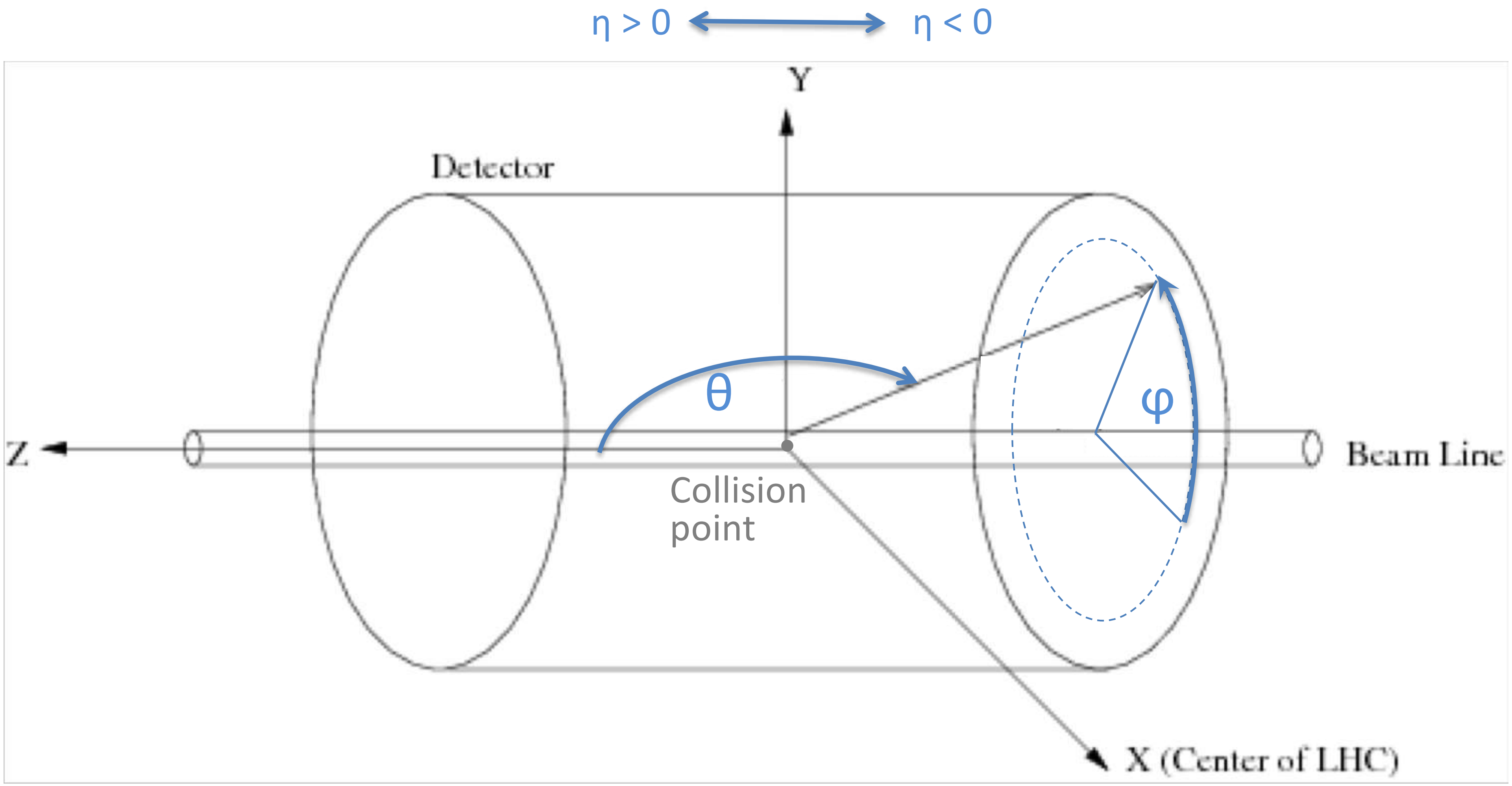
Webpage of lecture:
http://atomfizika.elte.hu/rfkm/rfkm2019.html

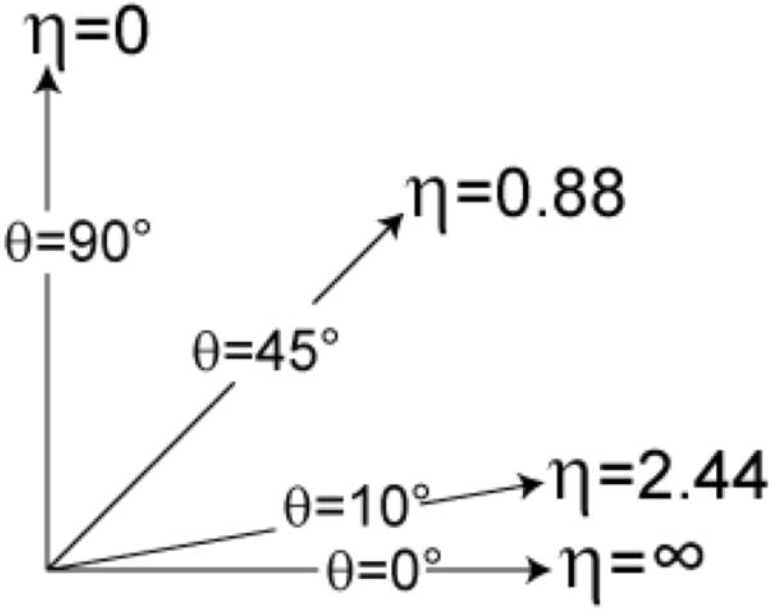
Coordinate system of large detectors at colliders



pseudorapidity: $\eta = -\ln \tan(\theta/2)$

Pseudorapidity (η)

- Spatial coordinate
- Angle measured from beam line
- Θ: ∢(particle ***p***, beam ***z***)
- p_{L}: longitudinal momentum (p_z)
- If v→c, η→y (rapidity)
- Particle production distribution roughly constant as a function of η
- (Pseudo)rapidity difference Lorentz invariant
- Δ*R*: Lorentz-invariant quantity to measure the angular distance of two particles
- ϕ: azimuth angle
- "Forward" direction: large η, close to beam direction
- "Backward" –*z* direction (when distinguished from "forward" +*z* direction)



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

$$\theta = 2\arctan\left(e^{-\eta}\right)$$

$$\eta = \frac{1}{2}\ln\left(\frac{|\mathbf{p}|+p_{\mathrm{L}}}{|\mathbf{p}|-p_{\mathrm{L}}}\right) = \operatorname{artanh}\left(\frac{p_L}{|\mathbf{p}|}\right)$$

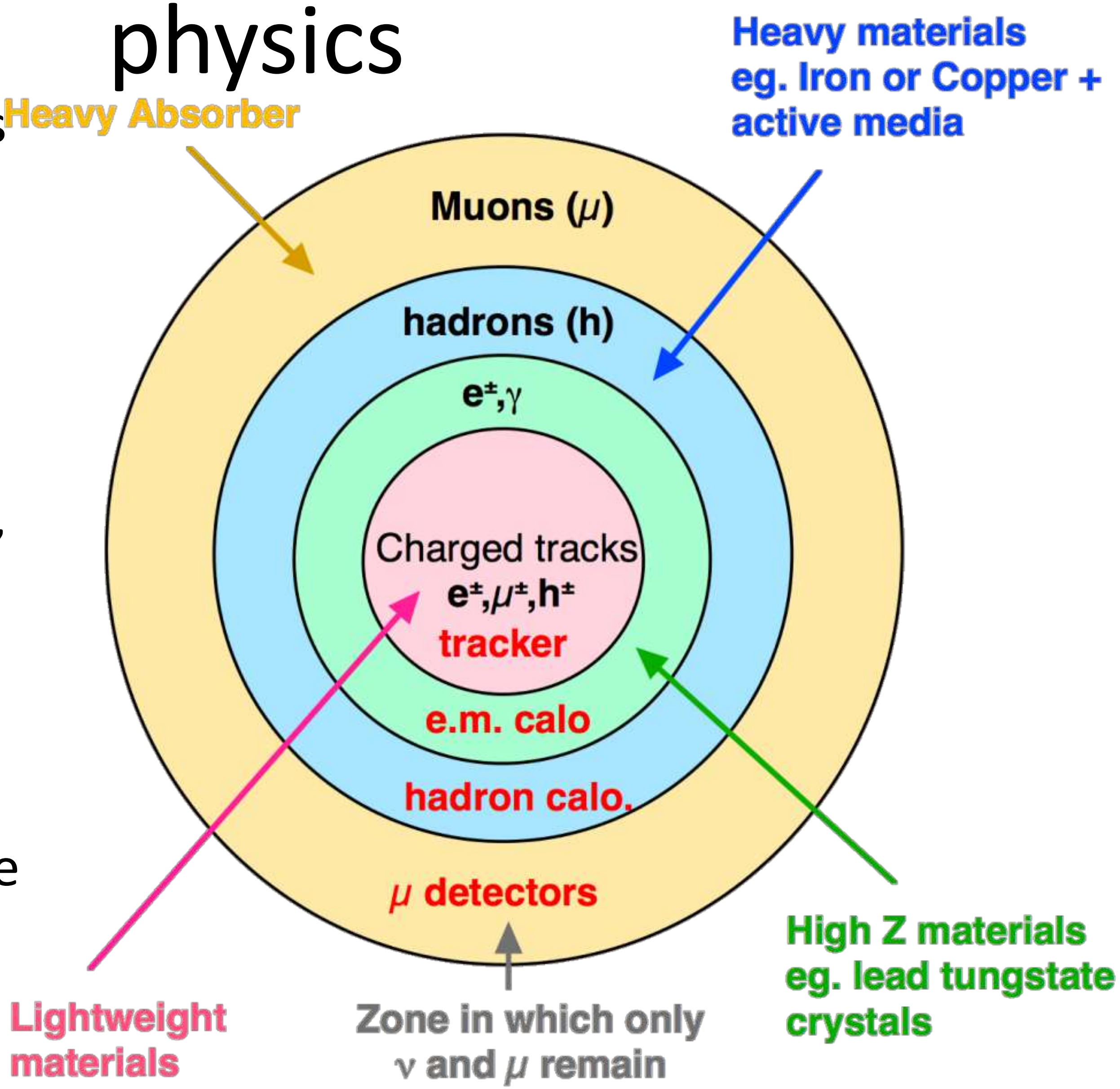
$$y \equiv \frac{1}{2}\ln\left(\frac{E+p_{\mathrm{L}}}{E-p_{\mathrm{L}}}\right)$$

$$m \ll p \Rightarrow E \approx p \Rightarrow \eta \approx y$$

$$(\Delta R)^2 \equiv (\Delta\eta)^2 + (\Delta\phi)^2$$

Detector systems in high energy physics

- Detector: an apparatus that measures a particle's position, arrival time, momentum, energy, properties (m, lifetime, quantum numbers…) and identifies it
- There is no detector that could measure / identify , all kind of particles
- Onion-style structure: each layer brings new information
- Comparing the signals of the various detectors, one can identify the particles and measure their momentum, energy



Heavy Absorber

Heavy materials
eg. Iron or Copper +
active media

Muons (μ)

hadrons (h)

$e^\pm,\gamma$

Charged tracks
$e^\pm,\mu^\pm,h^\pm$
tracker

e.m. calo

hadron calo.

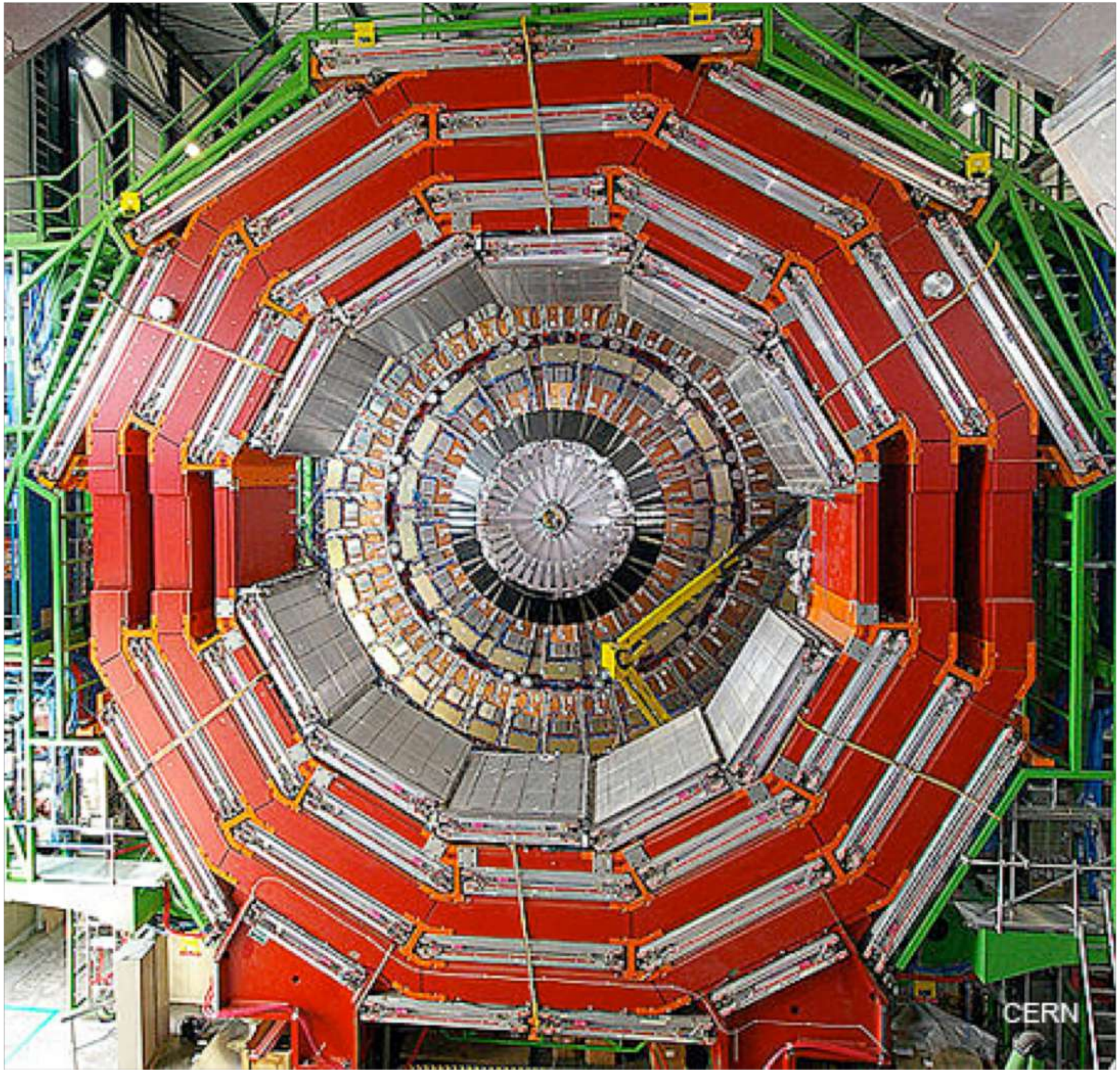
μ detectors

Lightweight
materials

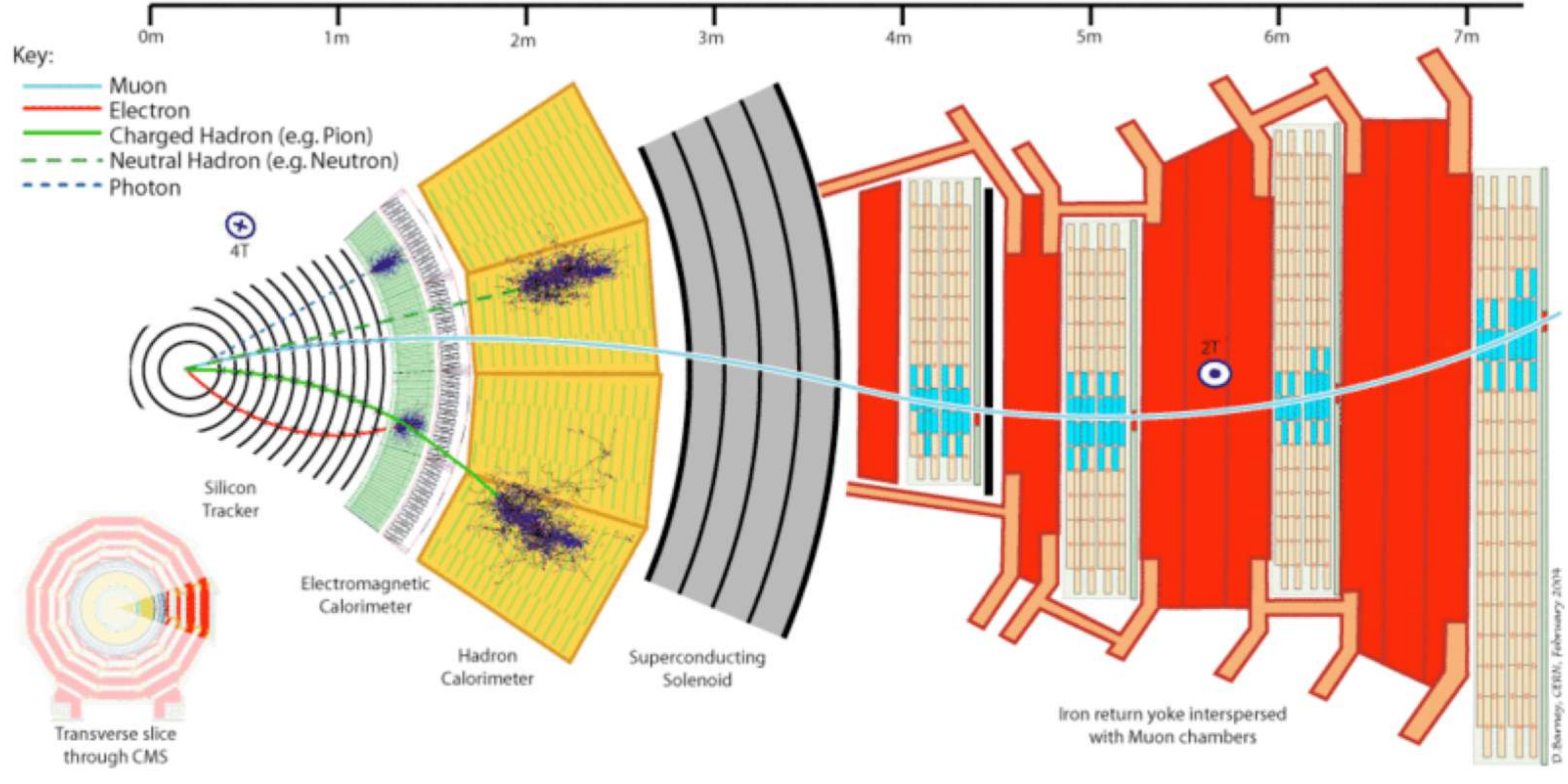
Zone in which only
ν and μ remain

High Z materials
eg. lead tungstate
crystals

CMS detector



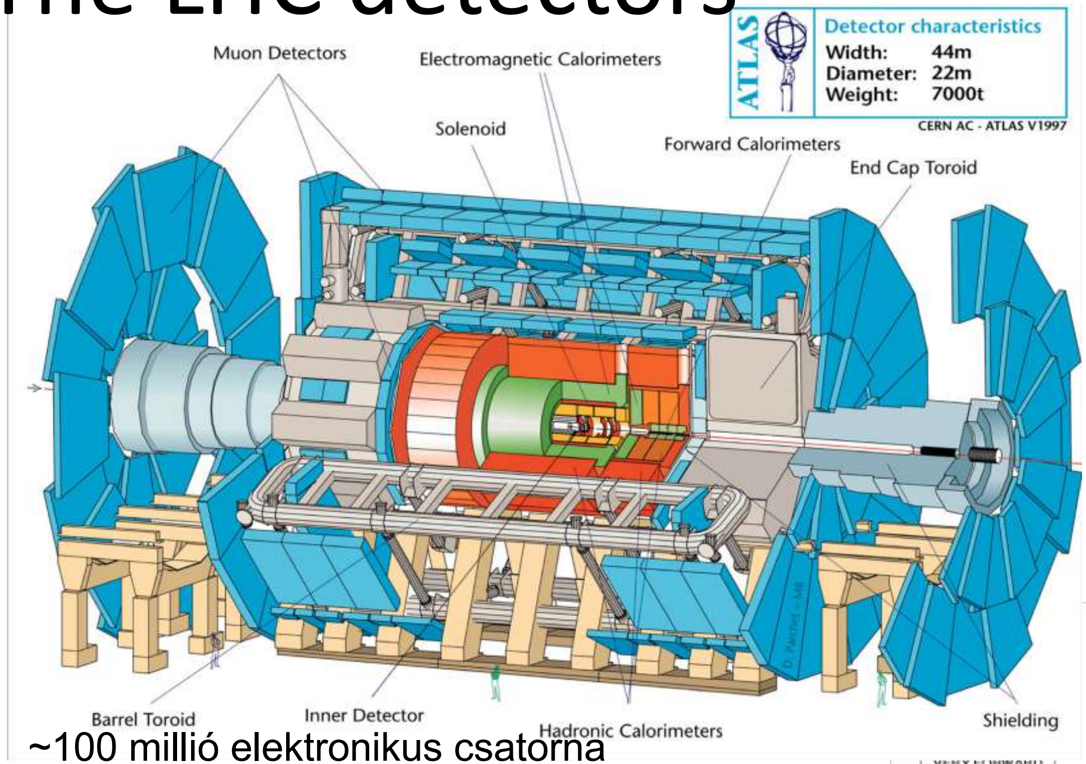
CMS detector



Comparing the signals left by the particles in different detector layers,
we can identify the particles and measure their momentum / energy

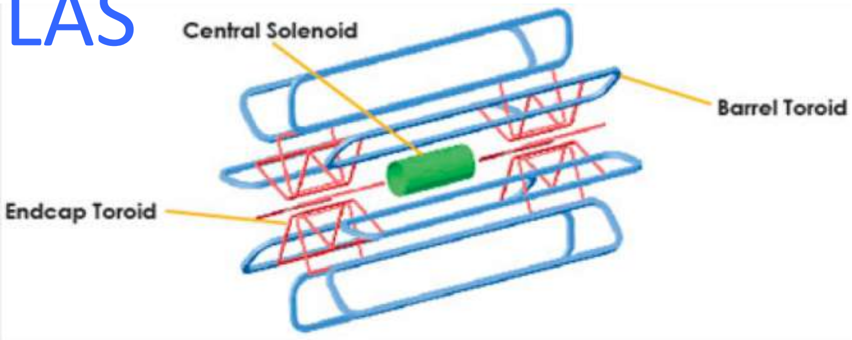
The LHC detectors

Solenoid: 2T
Toroid: 4T on superconductor
non-uniform field



~100 millió elektronikus csatorna

ATLAS



Different design philosophy
Similar resolution, efficiency

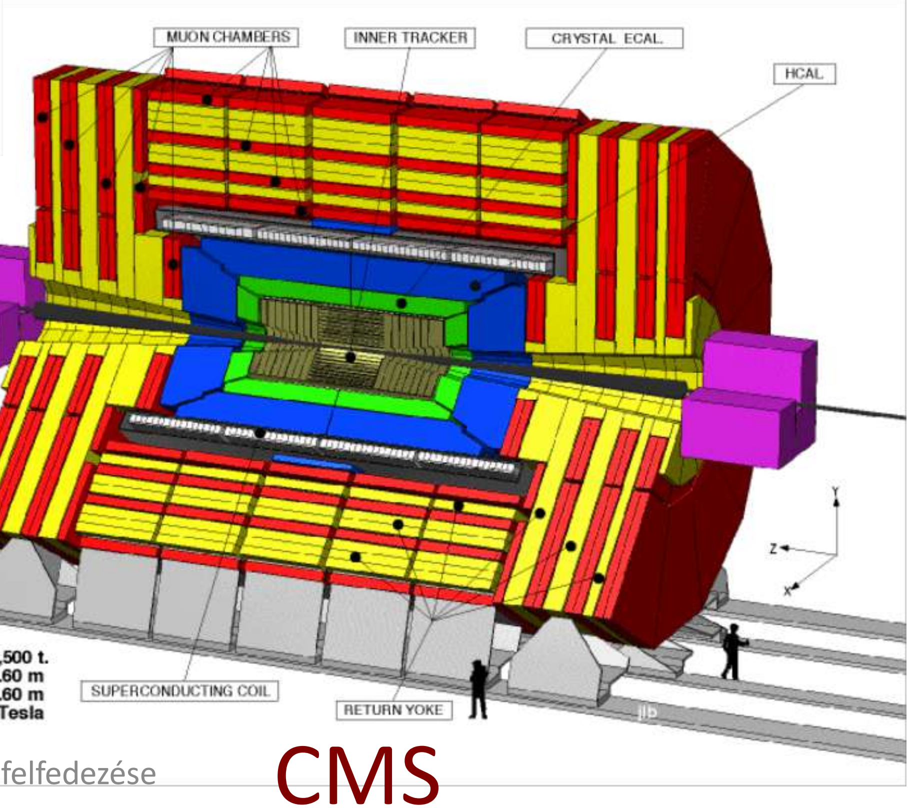
Hungarian technical contribution

CMS:

- *Alignment system of muon chambers*
- *Pixel detector reconstruction, calibration*
- *Wigner FK Grid Tier2*
- *Hadron calorimeter (VFCAL) assembly*
- *High-level trigger*
- *Luminosity detector calibration, monitoring*
- *Zero Degree Calorimeter calibration*

ATLAS:

- *Electromagnetic calorimeter simulation*
- *Electron-photon reconstruction, trigger*

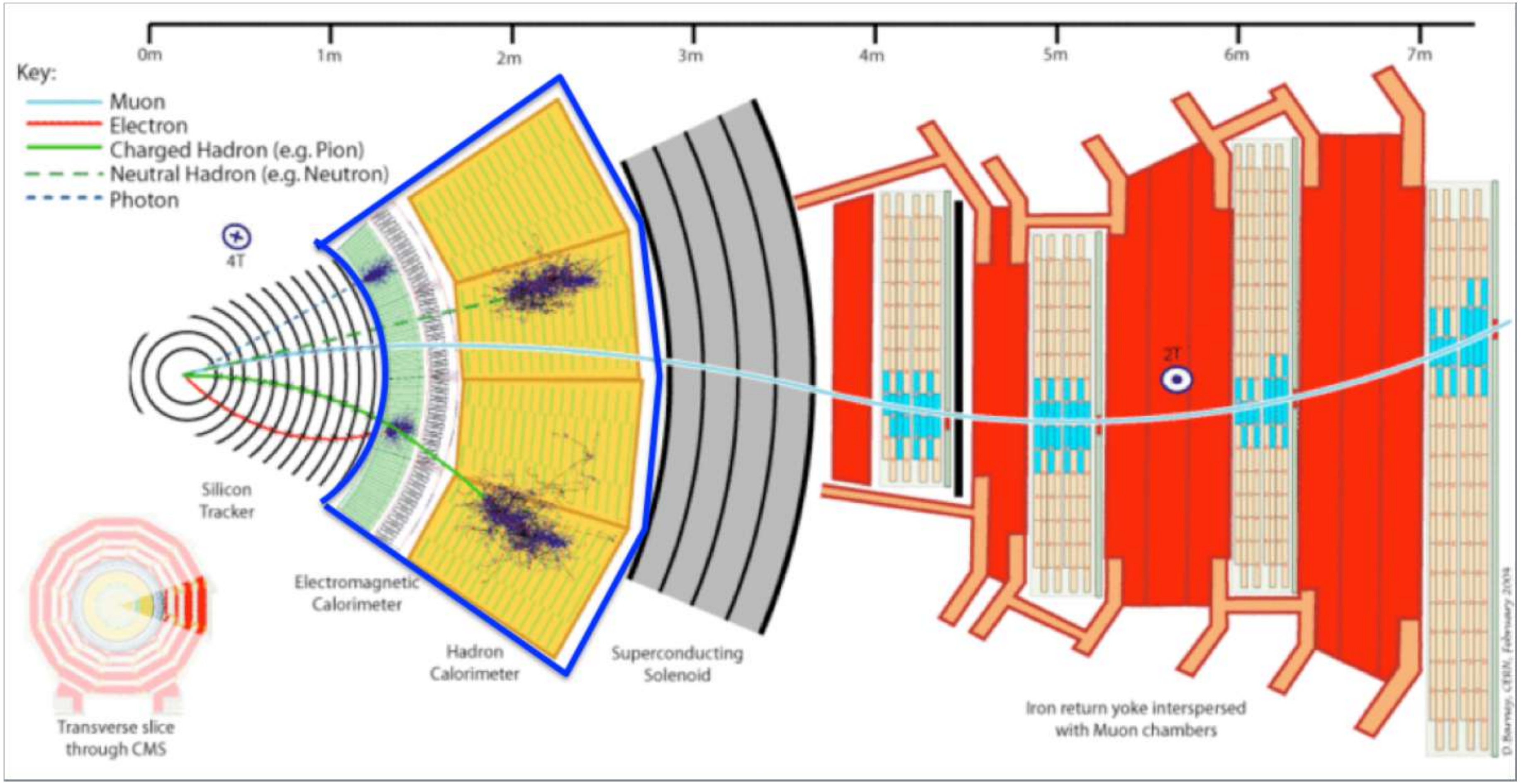


Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

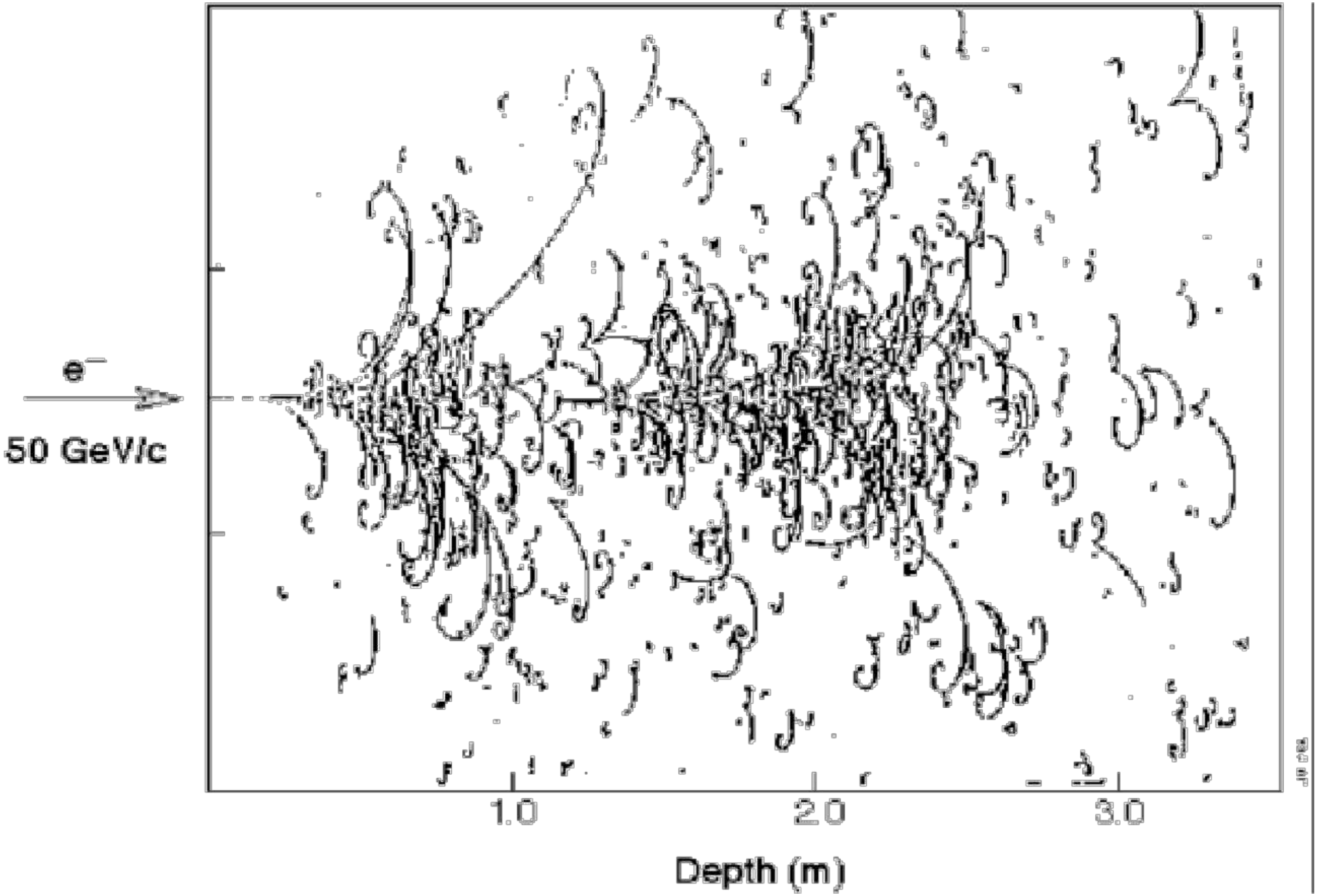
CMS

Calorimeters

- Stop particle (absorb its full particle energy), measure the absorbed energy
  - Thick, high density material placed to the particles' path
- Destructive for almost all particles (except μ, ν) → helps to identify muons
- Indispensable to detect neutral particles (photons, neutral hadrons)
- Incoming charged or neutral particles interact electromagnetically with the detector material or create hadronic showers
- Secondary particles ionise or produce excited states in the active material, giving measureable signal



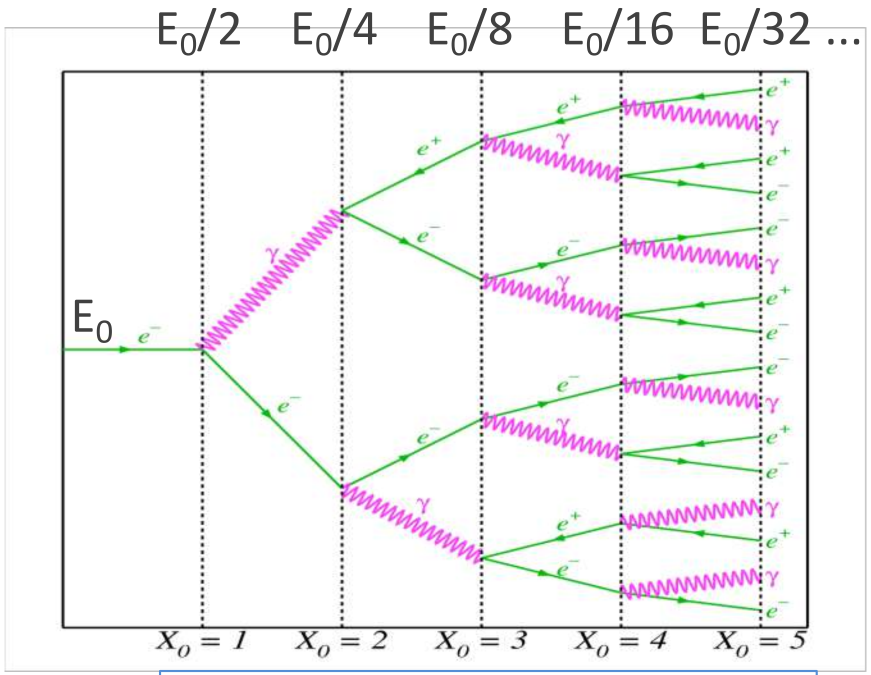
Electromagnetic shower



Homogeneous calorimetry – illustration of bremsstrahlung and photon conversion mechanism: Electromagnetic shower created by a 50 GeV electron in 3 T magnetic field in the BEBC bubble chamber using Ne/H_2 (70%-30%) gas mixture

Electromagnetic calorimeters

- $E \gtrsim 100$ MeV:
  - Electron: bremsstrahlung
    $-(dE/dx)_{rad} = E/X_0$ (X_0: radiation length)
    energy of $e^{\pm}$ drops to E/e in X_0 distance
  - Photon: e^+e^- pair productions
    $-(dI/dx) = e^{-x/\lambda} / \lambda$ ($\lambda = 9 X_0 / 7$)
    λ: photon mean free path for pair production
  - EM shower develops until $E > E_{critical}$
- At lower ($E < E_{critical} \sim$ MeV) energy, the absorption processes dominate
  - Electron (charged particle): ionisation and excitation of atomic states
  - Photon: photoelectric effect and Compton

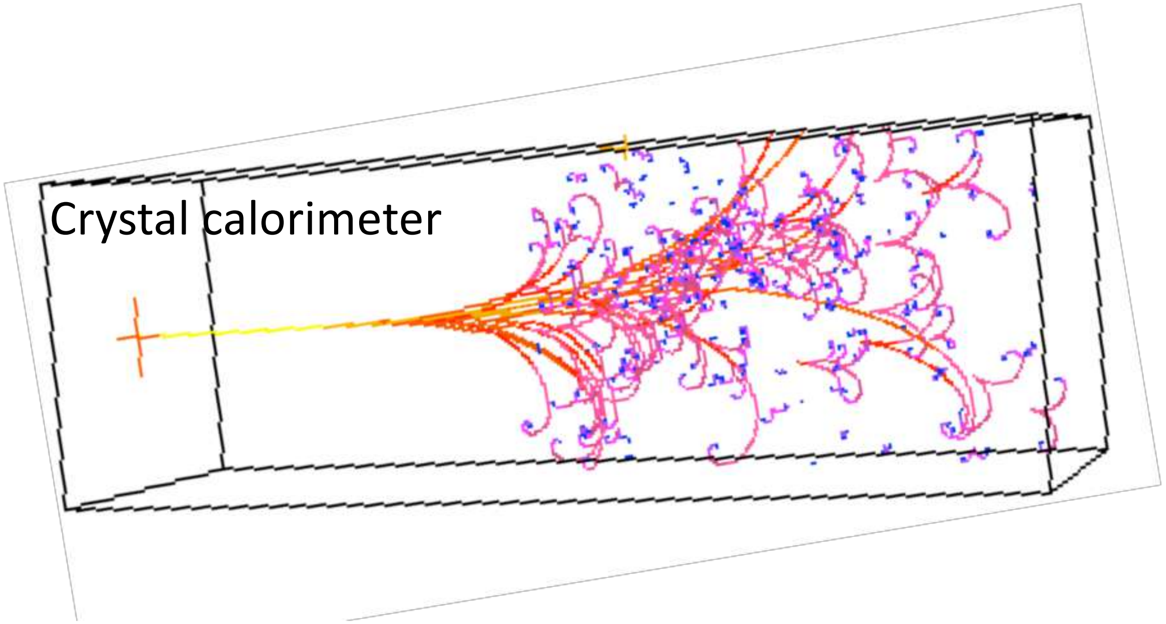


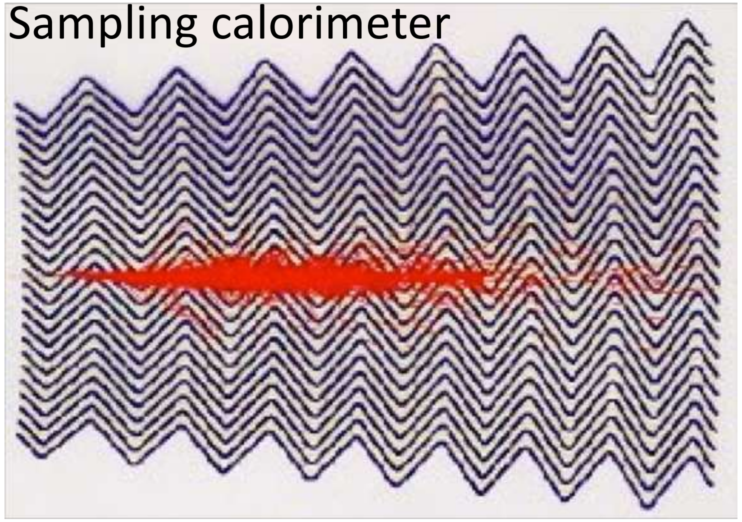
Example:
Into a CsI crystal (E_c~10 MeV) a 1 GeV electron enters
Shower maximum: $N_{max} = E_0/E_c = 100$, $t_{max} = 6.6$
Electron with E_c energy fully absorbed in ~1 X_0 distance but ~7-9 X_0 material is needed to absorb 95% of the energy of such a photon
→ Calorimeter depth > 15 X_0 to cover the full shower

Simple shower model:
X_0 as generation length
Distance: $t = x / X_0$
Particle multiplicity: $N(t) = 2^t$
Energy / particle:
$E(t) = E_0 / 2^t$
Shower maximum:
$t_{max} = \ln(E_0/E_c) / \ln 2$

Electromagnetic calorimeters

- Most important properties:
  - Minimum ~15 X_0 thickness (typically ~25 X_0)
  - Position of shower maximum depends slowly on energy, calorimeter depth depends logarithmically on energy
  - Energy leakage mostly due to low energy photons escaping the calorimeter cell on the sides (lateral leakage) or behind it (rear / longitudinal leakage)
- In reality shower modelling is much more complicated, modelled by Monte Carlo simulation (ex. GEANT4 program package)


Crystal calorimeter


Sampling calorimeter

Calorimeter types and processes

- Homogeneous (EM) calorimeters: full volume sensitive (contributes to the signal)
  - Usually inorganic (high density, high Z) crystal scintillators or non-scintillator Cherenkov-radiators (e.g. lead-glass)
  - Excellent energy resolution, but expensive and high quality mass-production challenging
  - E.g. CMS lead-tungstate EM calorimeter:

$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997

- Sampling (EM or hadron) calorimeters: absorber metal layers, pl. Fe, Cu (hadron) and Pb (EM), alternate with active detector layers
  - Active material could be scintillator, ionizing liquid noble gas, Cherenkov-radiator, semi-conductor or gas detector
  - Cheap, provides fine segmentation (better vertex determination precision, more e/γ identification information), but not whole shower visible (worse energy resolution)
  - E.g. ATLAS EM calorimeter:

Liquid Ar/Pb accordion	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

- Energy resolution: $(\sigma_E / E)^2 = (a/E)^2 + (b/\sqrt{E})^2 + c$ b: stochastic (sampling) term
  - Fluctuation of first interaction point a: noise term, c: constant term (→ Calo quality)
  - Sampling fluctuations
  - Fluctuation of energy leakage in longitudinal direction
  - crystal non-uniformity
  - Electronic noise
  - …
- Spatial resolution

Energy resolution

Ideally, if all shower particles counted: $E \sim N, \quad \sigma \sim \sqrt{N} \sim \sqrt{E}$

In practice:

absolute $\sigma = a\sqrt{E} \oplus b\,E \oplus c$

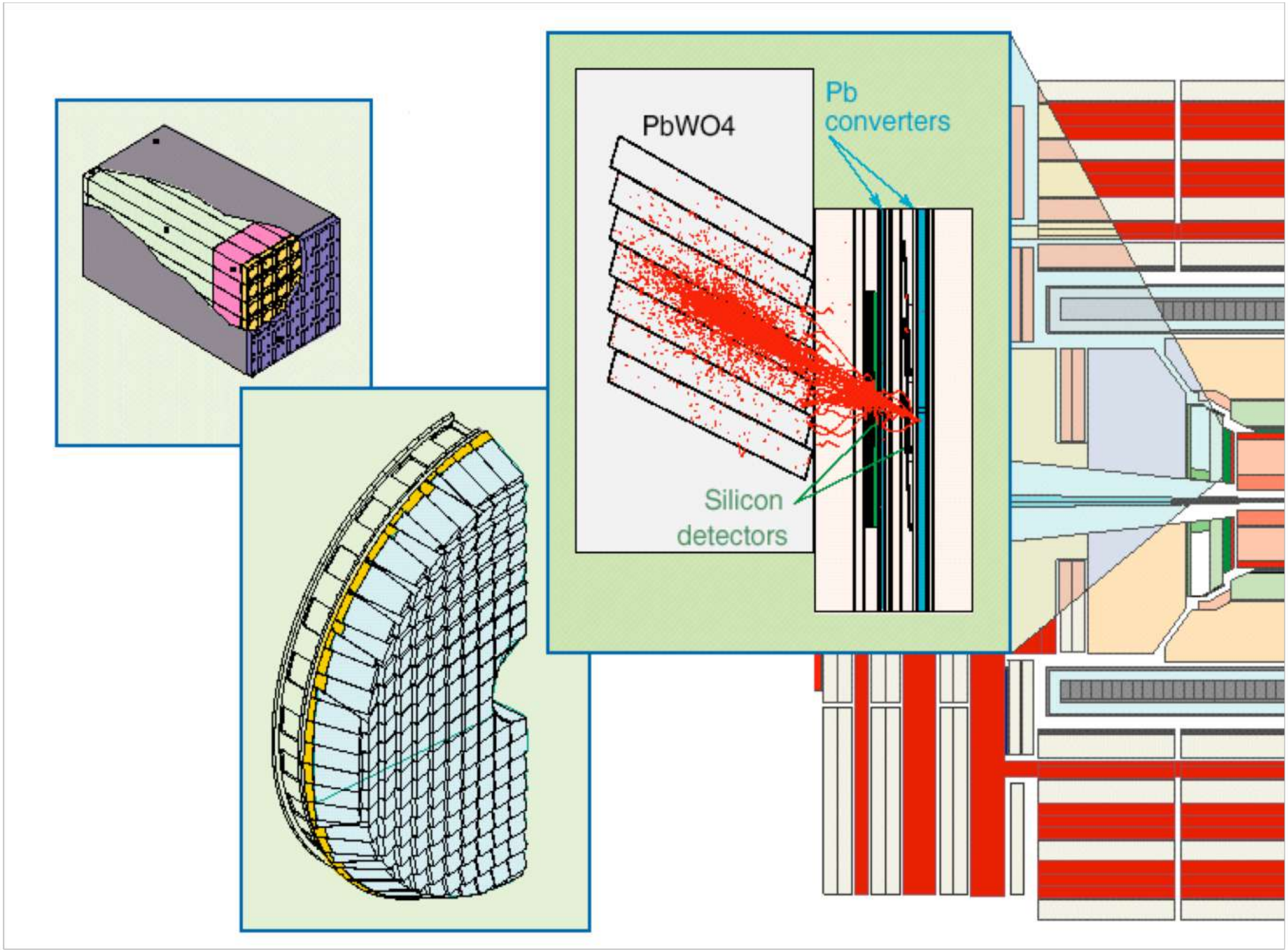
relative $\boxed{\sigma / E = a / \sqrt{E} \oplus b \oplus c / E}$

a: stochastic term
    intrinsic statistical shower fluctuations
    sampling fluctuations
    signal quantum fluctuations (e.g. photo-electron statistics)

b: constant term
    inhomogeneities (hardware or calibration)
    imperfections in calorimeter construction (dimensional variations, etc.)
    non-linearity of readout electronics
    fluctuations in longitudinal energy containment (leakage can also be ~ $E^{-1/4}$)
    fluctuations in energy lost in dead material before or within the calorimeter

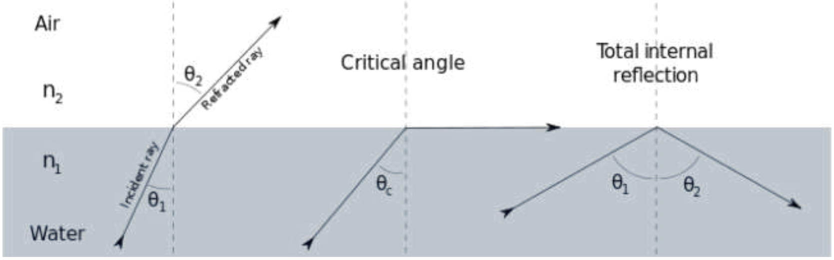
c: noise term
    readout electronic noise
    Radio-activity, pile-up fluctuations

CMS ECAL

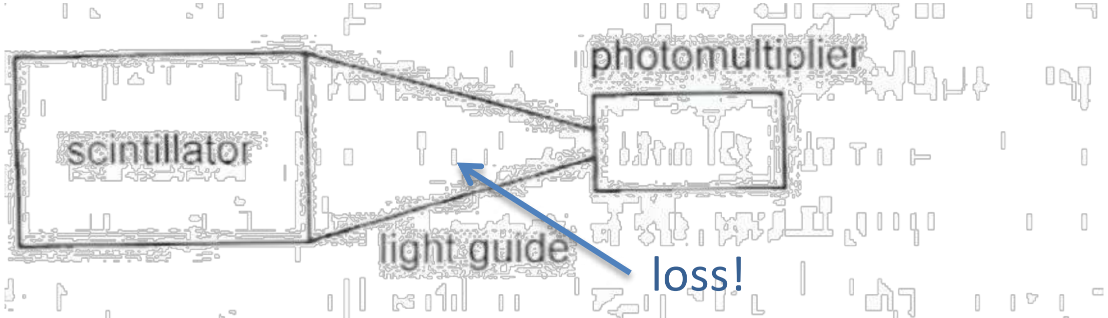


Light collection

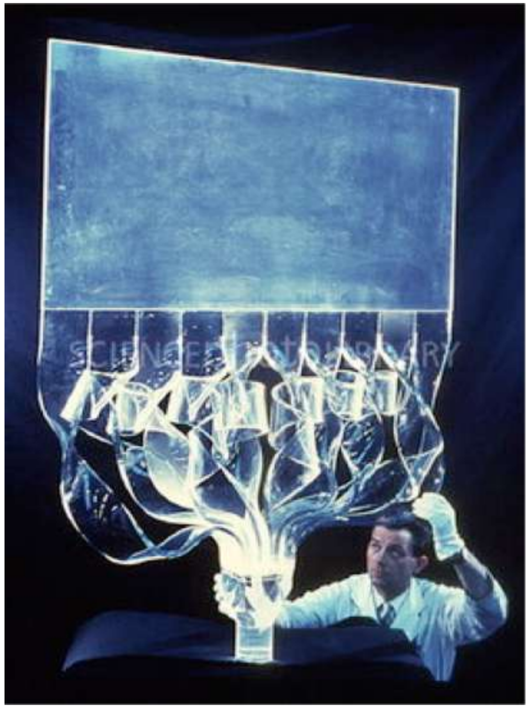
- Usually scintillation counters read out through one or two surfaces
  - Area significantly smaller than the full surface of the scintillator
- For small detectors, the rest of the surface is coated with a reflective diffuse layer (MgO powder or porose Teflon film)
- For large detectors (especially for long rods) total reflection gives the best result (finely polished smooth surface!)



- Plastic scintillators are usually produced in plates
  - The light passing through the edges need to be guided to the photo-detector, fitting there shapes → light guides
  - The cross-section can not be reduced without light loss when matched to the photocathode



Light readout with a 'fish-tail' light guide



Adiabatic lightguide
(no flight loss)
Only small bending
allowed

Photoelectron multiplier (PM tube)

- Measure fast light signal: light → electric signal
- Visible or UV light frees electrons from photocathode via photoelectric effect
- Usually semi-transparent photocathode: very thin semiconductor (SbCs, SbKCs, SbRbKCs) layer on the inner surface of the transparent input window
- The large kinetic energy electron kicks out several others when hitting the dynode (<25 e / 200 eV)

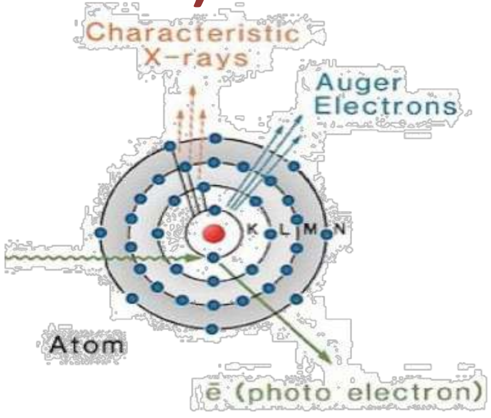
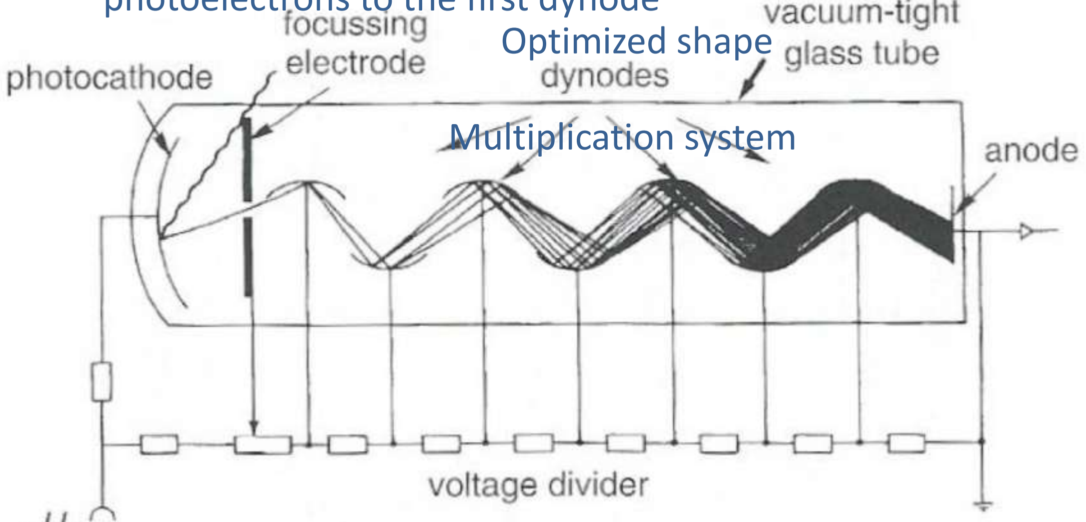


Illustration of the photoelectric effect.

Provides guiding field to focus photoelectrons to the first dynode



Optimized shape

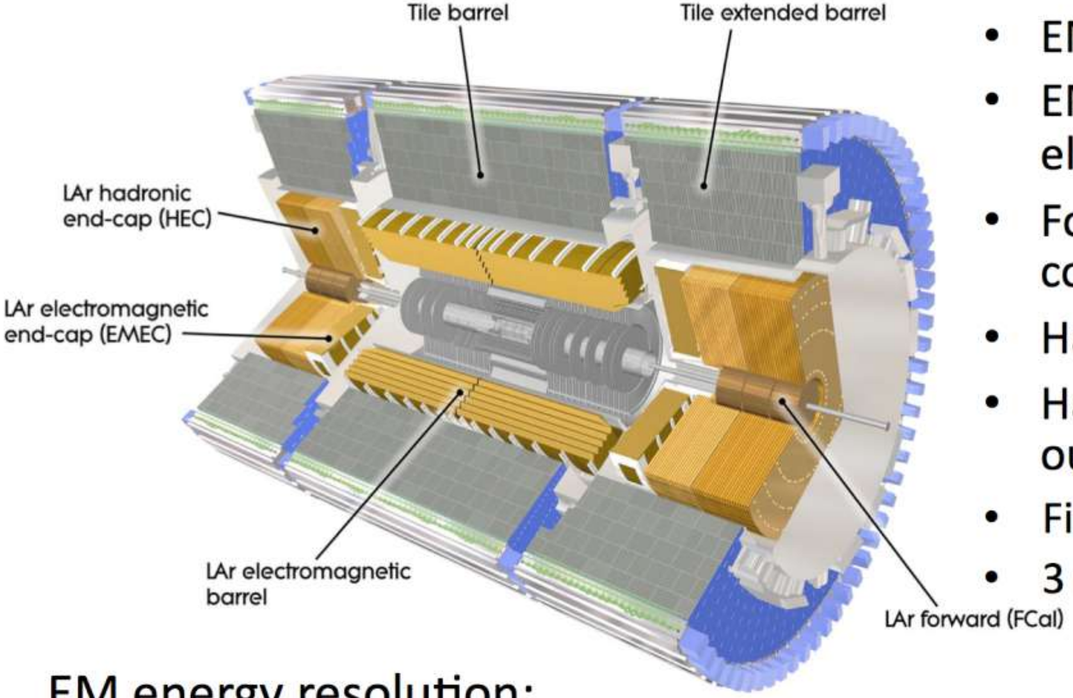
Multiplication system

-2000 V

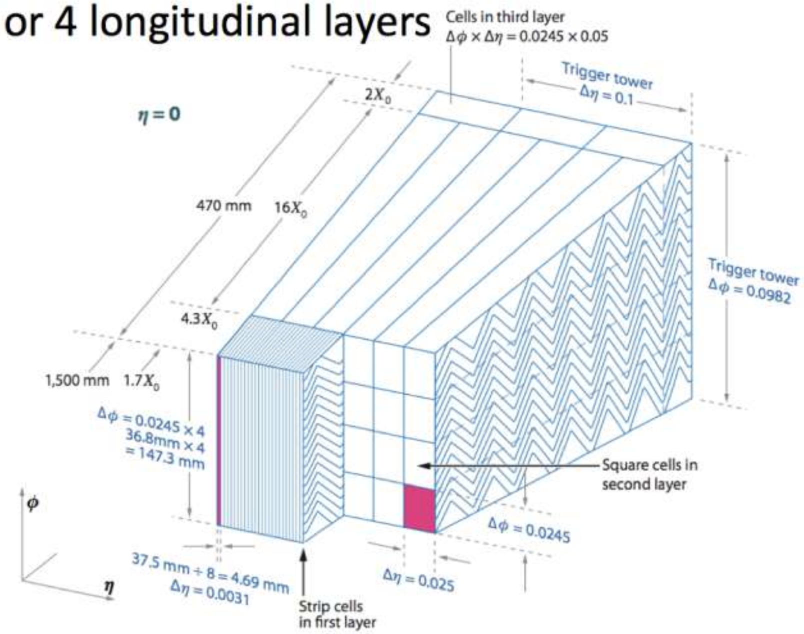
Fig. 5.29. Working principle of a photomultiplier. The electrode system is mounted in an evacuated glass tube. The photomultiplier is usually shielded by a mu-metal cylinder made from high-permeability material against stray magnetic fields (e.g. the magnetic field of the Earth).

- Quantum efficiency – average number of photo-electrons produced by an incoming photon: ~25%, max. 50% (GaAs, GaInAsP)
- Secondary emission coefficient (g ~ 4)
  → current amplification: $A=g^n$ (n dynodes)
  variance: $(\sigma/A)^2=1/(g-1)$
- Total amplification: $>10^6$
- Total transit time: ~10-40 ns
  Rise time: 1-3 ns

The ATLAS Calorimeter System



- EM presampler, |η|<1.8: active LAr layer
- EM calorimeter, |η|<3.2: accordion shaped electrodes and lead absorbers in LAr
- Forward calorimeter, 3.1<|η|<4.9: copper/tungsten-LAr
- Hadronic end-cap, 1.5<|η|<3.2: copper/LAr
- Hadronic tile calorimeter, |η|<1.7: outside LAr cryostats
- Fine lateral segmentation
- 3 or 4 longitudinal layers



EM energy resolution:

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

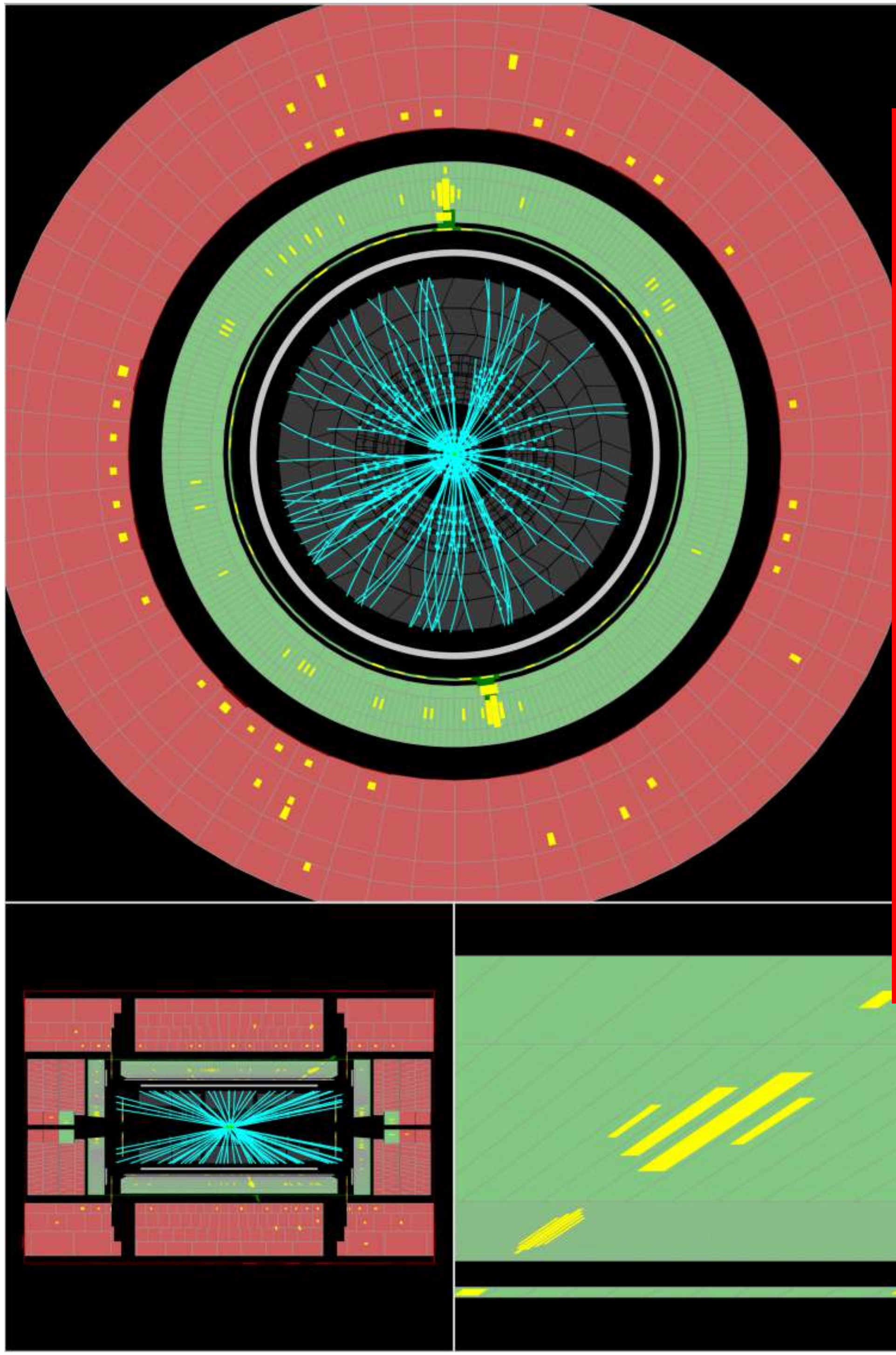
a≈10%, b≈170 MeV, c≈0.7%

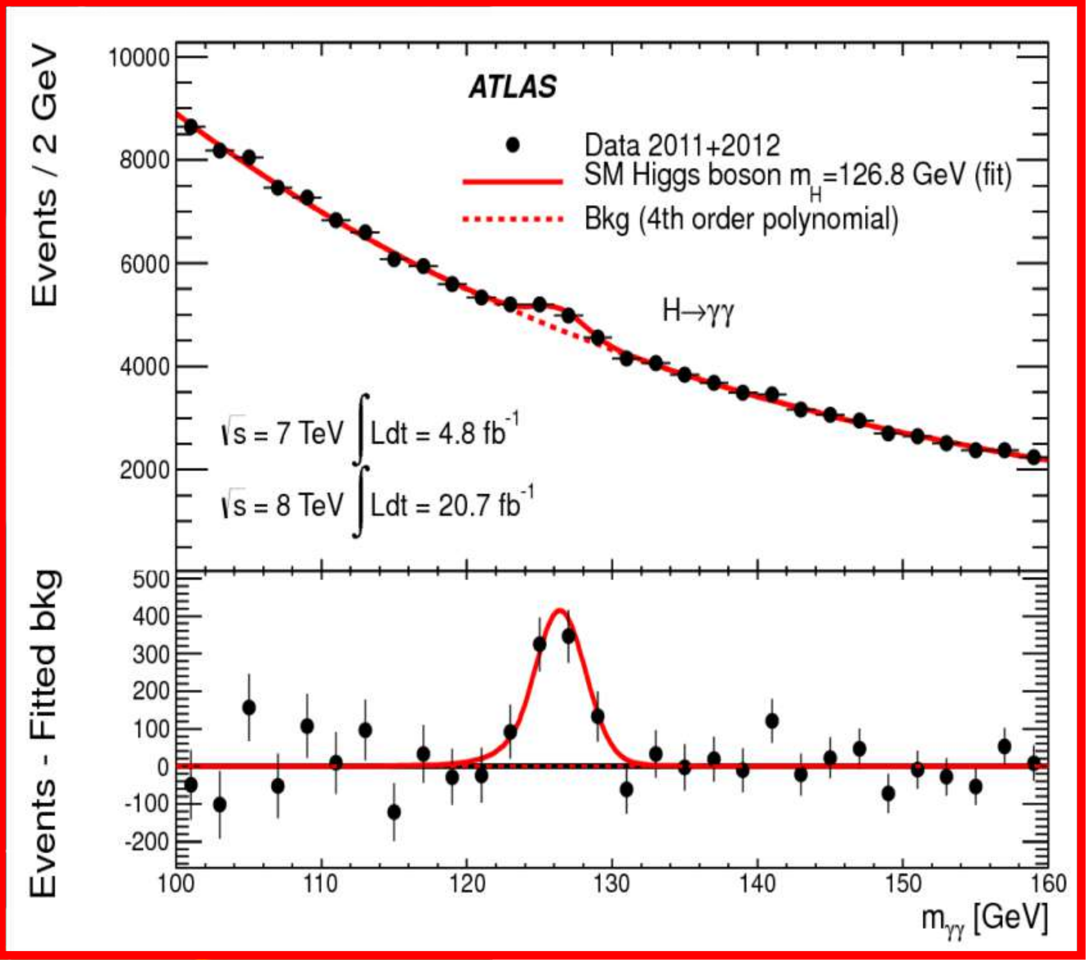
Hadronic energy resolution:

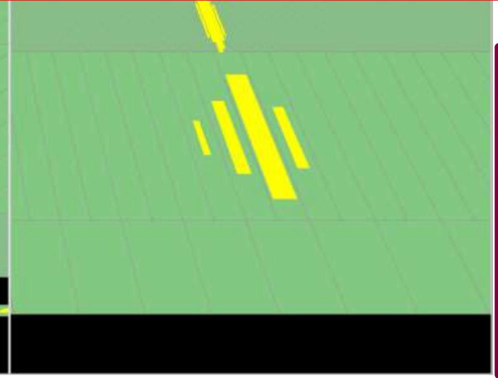
a≈50%, c≈3%

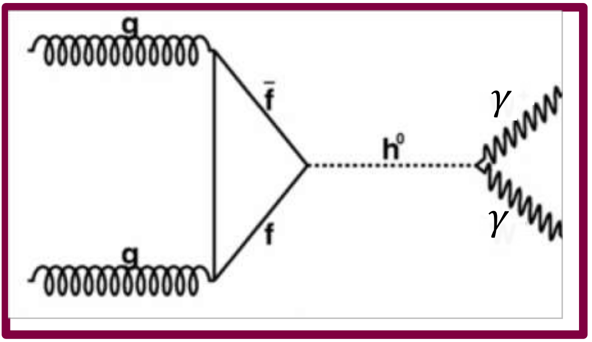
Compare with CMS crystal size:
22 x 22 x 230 mm^3 (1 R_M x 1 R_M x 26 X_0) (barrel),
30 x 30 x 220 (endcap)

H→$\gamma\gamma$

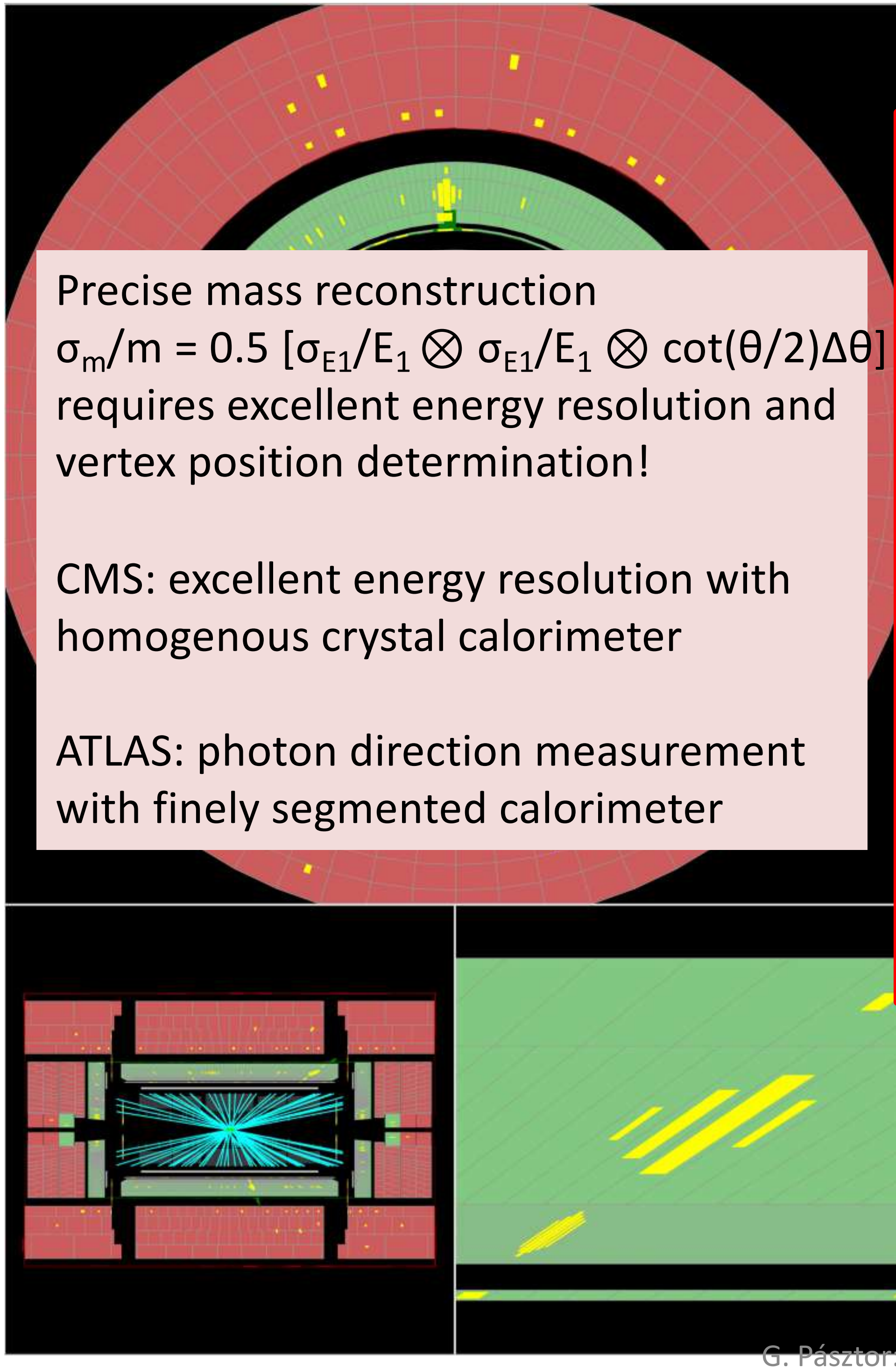








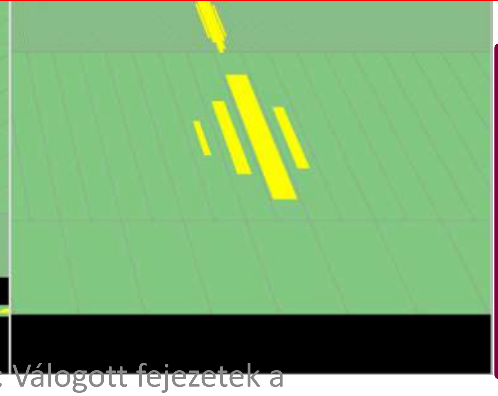
H→$\gamma\gamma$

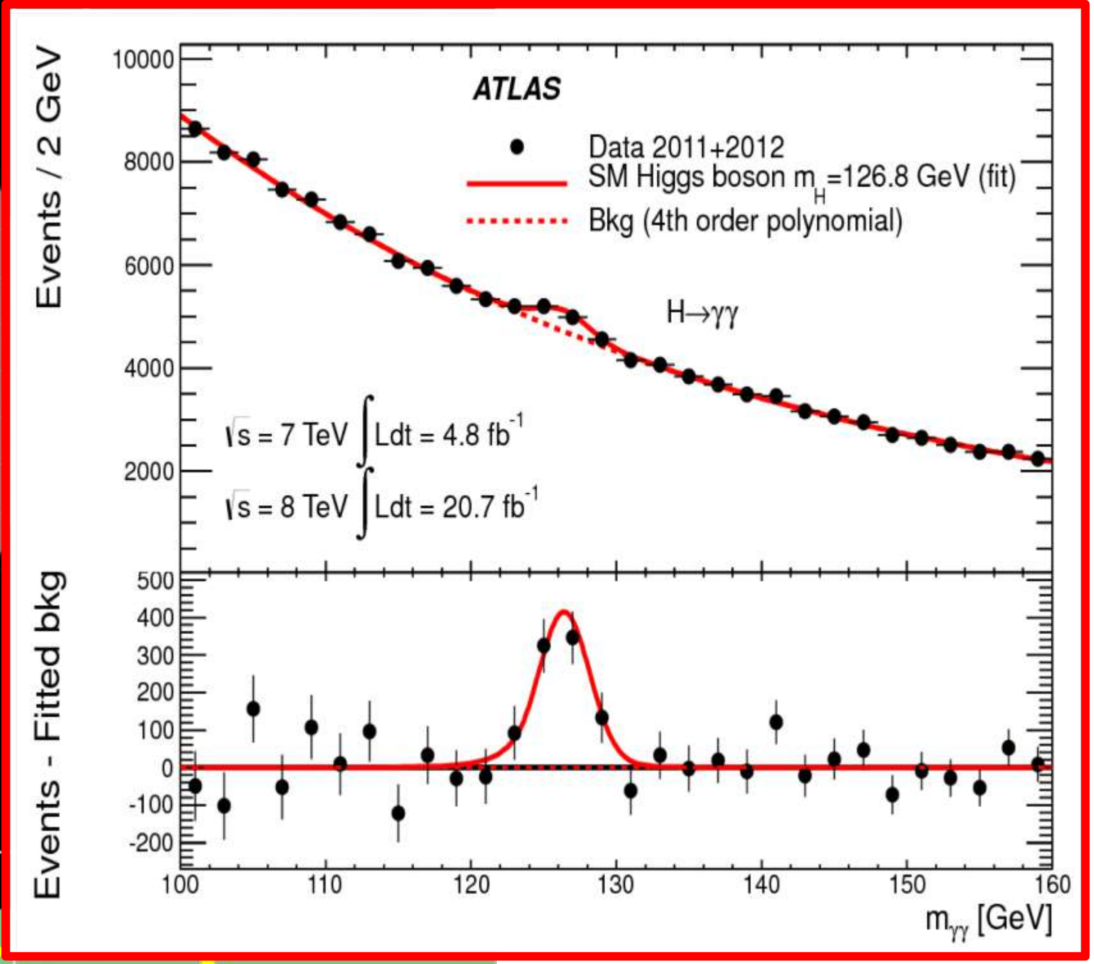


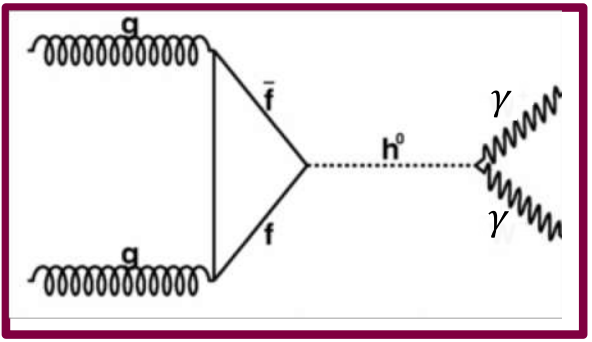
Precise mass reconstruction
$\sigma_m/m = 0.5\,[\sigma_{E1}/E_1 \otimes \sigma_{E1}/E_1 \otimes \cot(\theta/2)\Delta\theta]$
requires excellent energy resolution and vertex position determination!

CMS: excellent energy resolution with homogenous crystal calorimeter

ATLAS: photon direction measurement with finely segmented calorimeter







Homework

- 100 GeV electron enters (a) a Copper or (b) an Iron absorber. Where will be the shower maximum? How many particles will form the shower at its maximum? What is the average energy of the particles there?
- Compare the electromagnetic calorimeters of the ATLAS and CMS experiments. What technologies are used? How the energy and spatial resolutions compare? What do you think the arguments were when justifying the experiment's own designs?
- EM calorimeter has a stochastic term to its energy resolution of 0.05/sqrt(E). How can we ensure that the energy resolution for a E = 40 GeV photon does not exceed 1%?
- How will interact a muon with the detector material when it traverses through the CMS detector? How can we use the signals to identify the muon? Do the calorimeters play any role?
- A multi-purpose detector system using the traditional layered structure has a relative track momentum resolution of 0.00015 pT [GeV] $\oplus$ 0.005, an EM calorimeter energy resolution of 0.2/E[GeV] $\oplus$ 0.03/sqrt(E[GeV]) $\oplus$ 0.005 and a hadron calorimeter energy resolutions of 0.7/sqrt(E[GeV]) $\oplus$ 0.08. At what electron and pion energy will the tracking and the calorimeter measurements have the same precision for highly relativistic particles at pseudorapidity of 0? Which measurement is more precise at low / high momentum?