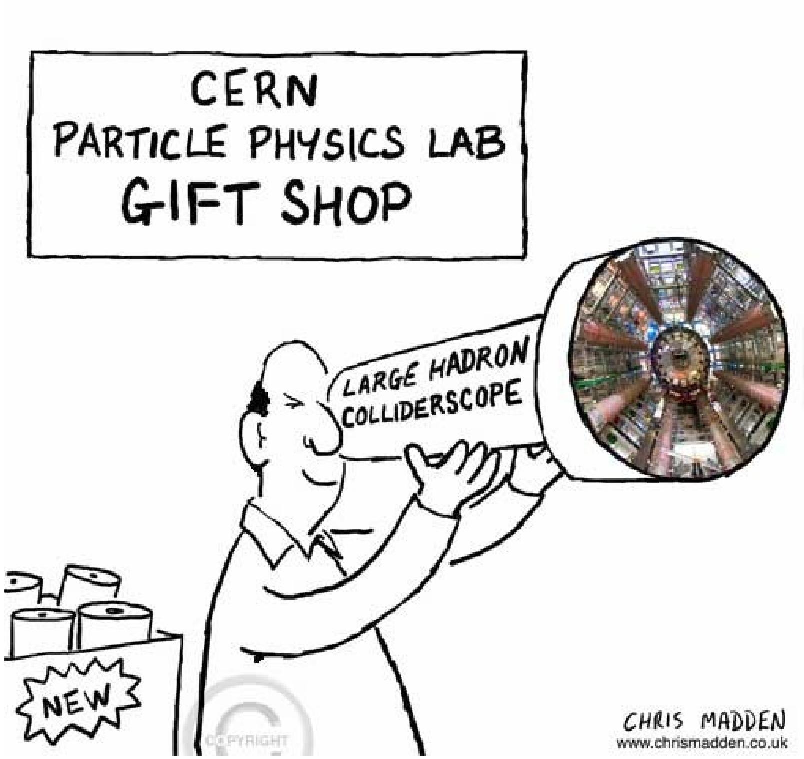
GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

Detector Physics – Part 2



Jörn Grosse-Knetter

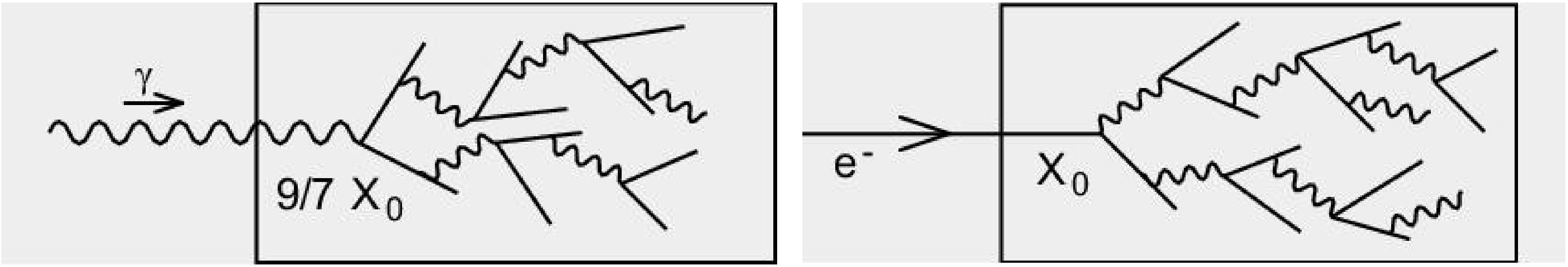
HASCO Summer School 2021

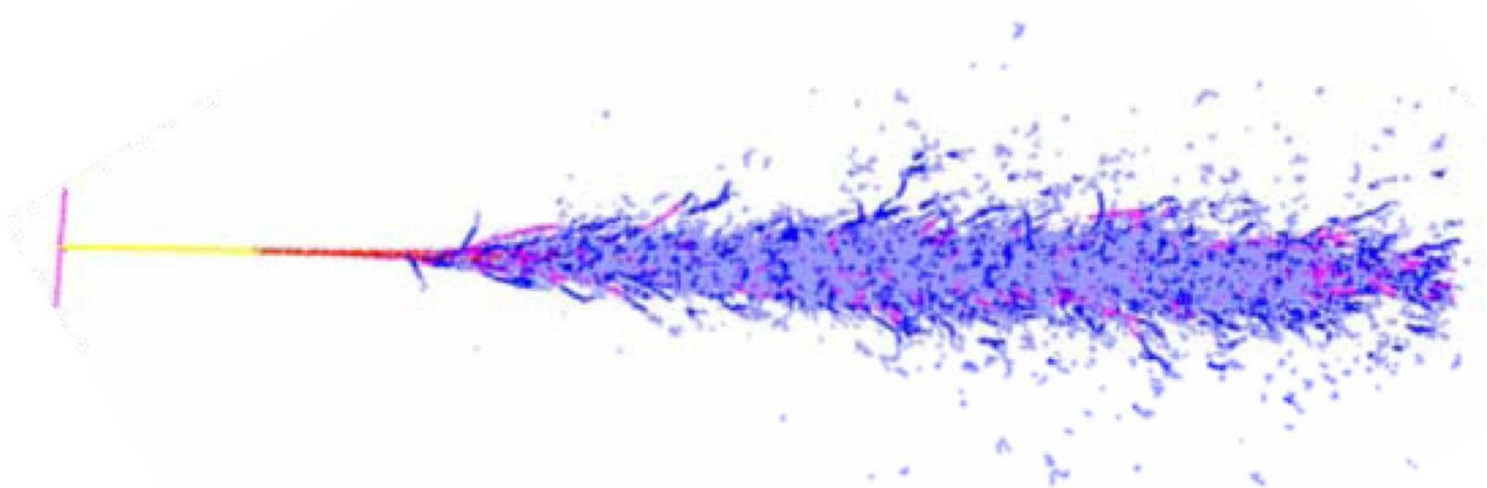
Overview

- 1st part (prev. talk):
  - Particle detection concepts: detection vs identification
  - Interaction radiation/matter: charged vs neutral particles
  - Ionisation detectors: electronic detectors
  - Excitation and scintillation: light detectors
  - Tracking concepts: from track reconstruction to vertex finding
- 2nd part (this talk):
  - Calorimeters: electromagnetic and hadronic showers
  - Overall detector system concepts

Calorimeters

Electromagnetic Shower (1)



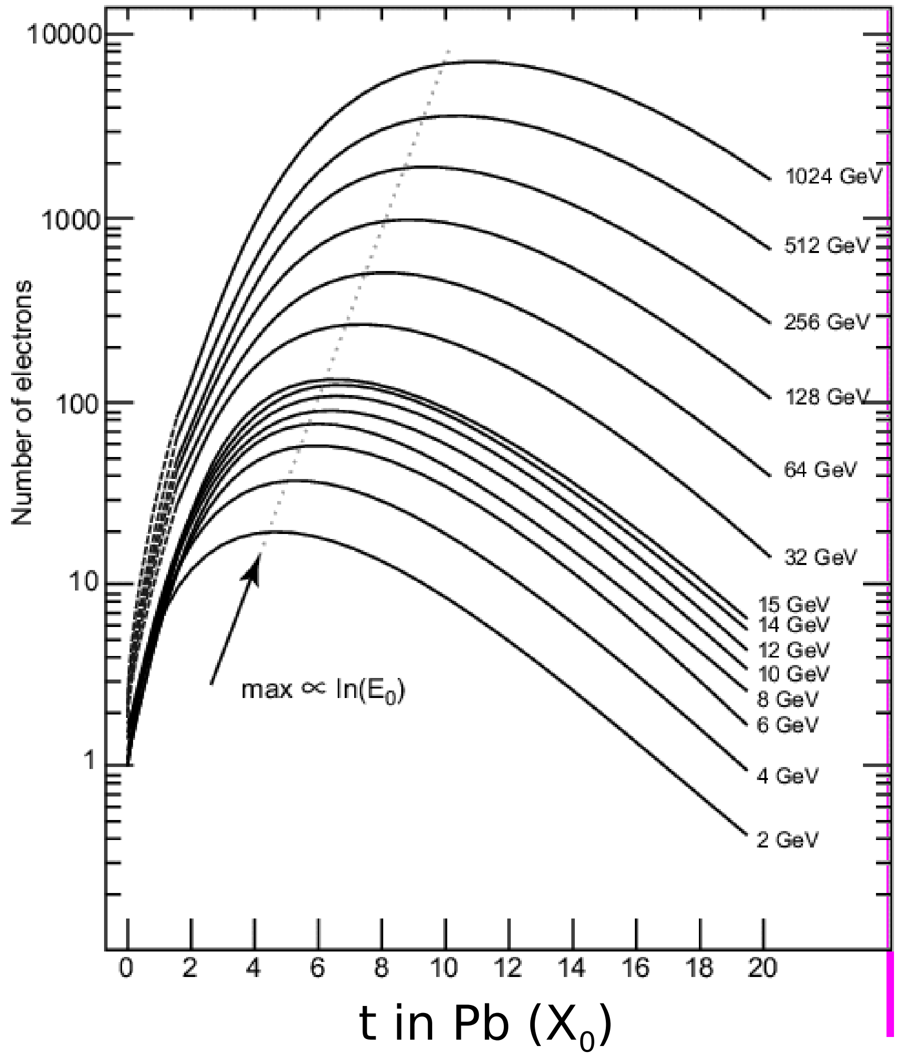


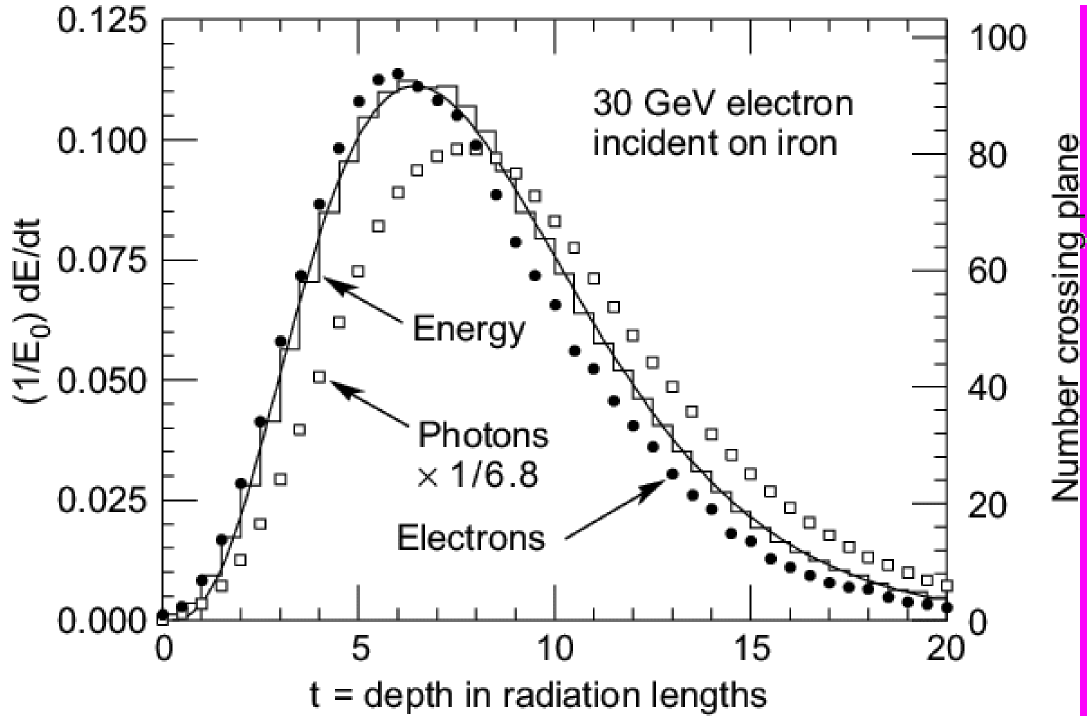
- Alternating Bremsstrahlung and pair creation
- Every ~X_0: doubling of no. particles N, ~halves energy per particle → N ∝ incid. Energy E_i

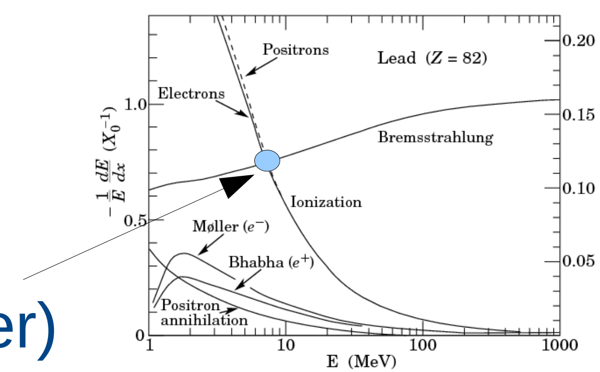
Electromagnetic Shower (2)

- Need to drive shower process and at the same time measure shower particles
- Measurement via ionisation charge or (scitillation/Čerenkov/…) light:
  - Signal is proportional to “track length” ~ N
  - With N ∝ $E_i \rightarrow$ **Signal ∝ E_i**
- Shower scales
  - Longitudinally with X_0, but only logarithmically in E_i
  - Laterally: scales with $R_M \sim ZX_0$

Longitudinal Profile

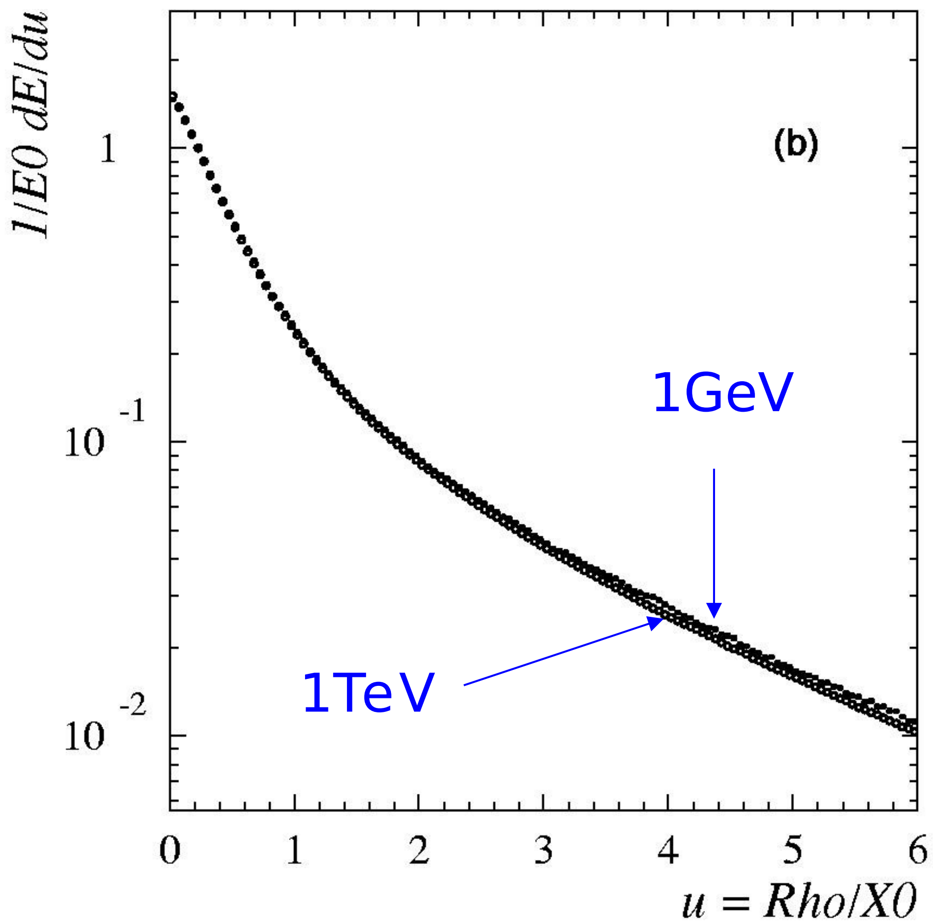


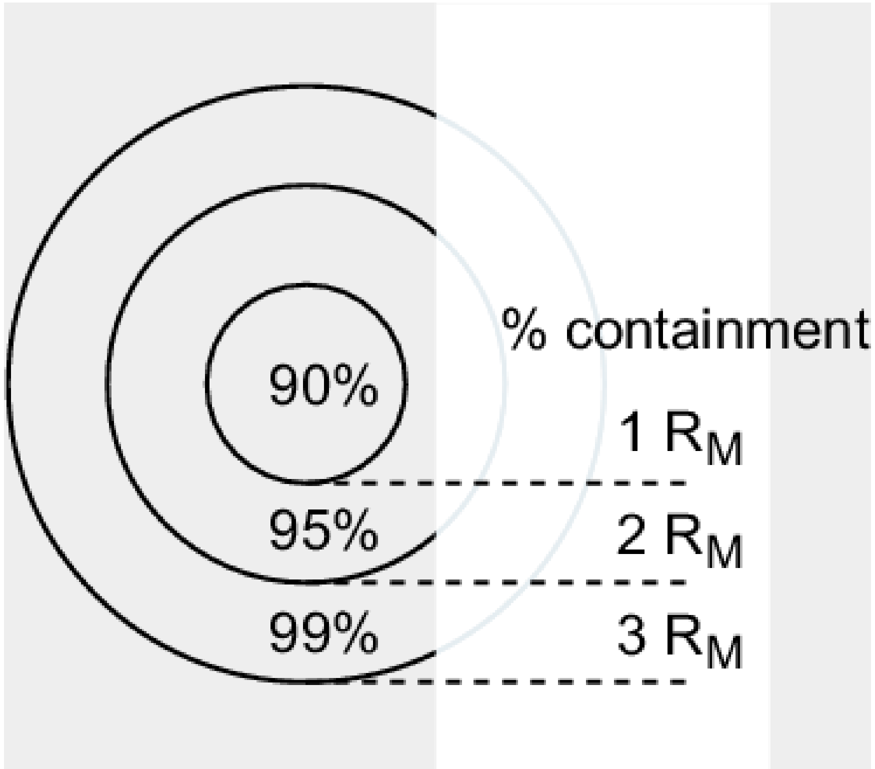




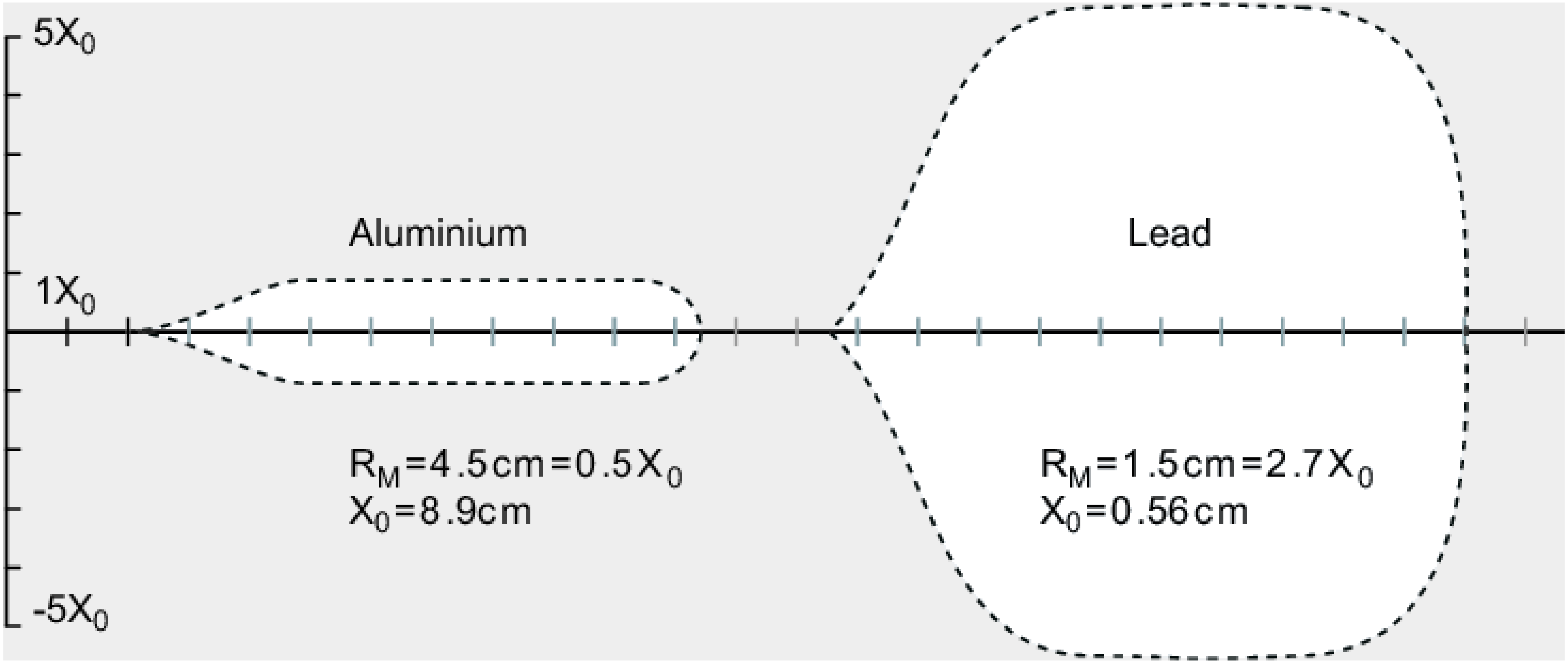
Shower proceeds until $E_e < E_c$ (ionisation takes over)

Transverse Profile





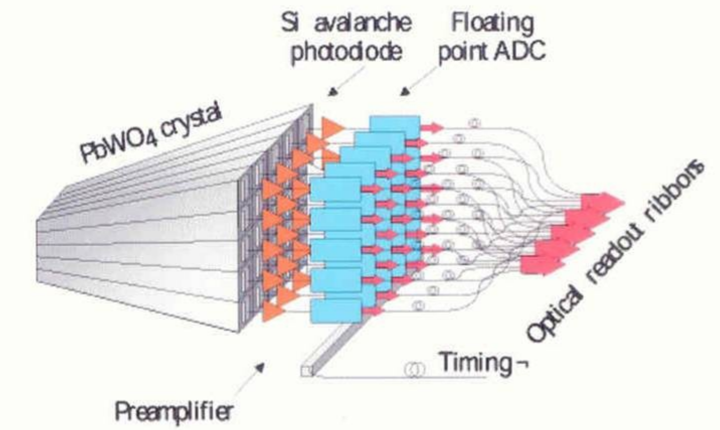
Overall Profile

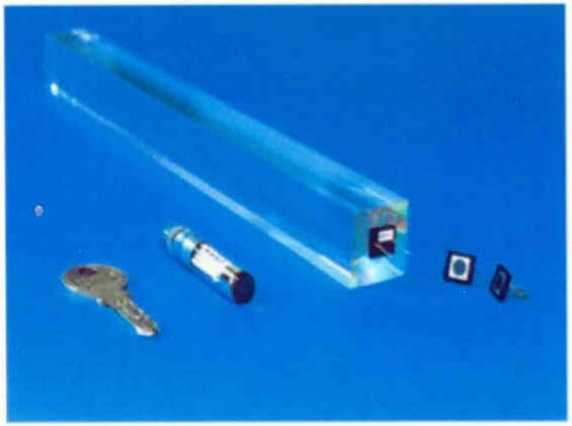


Calorimeter Types (1)

absorber & detector: the same

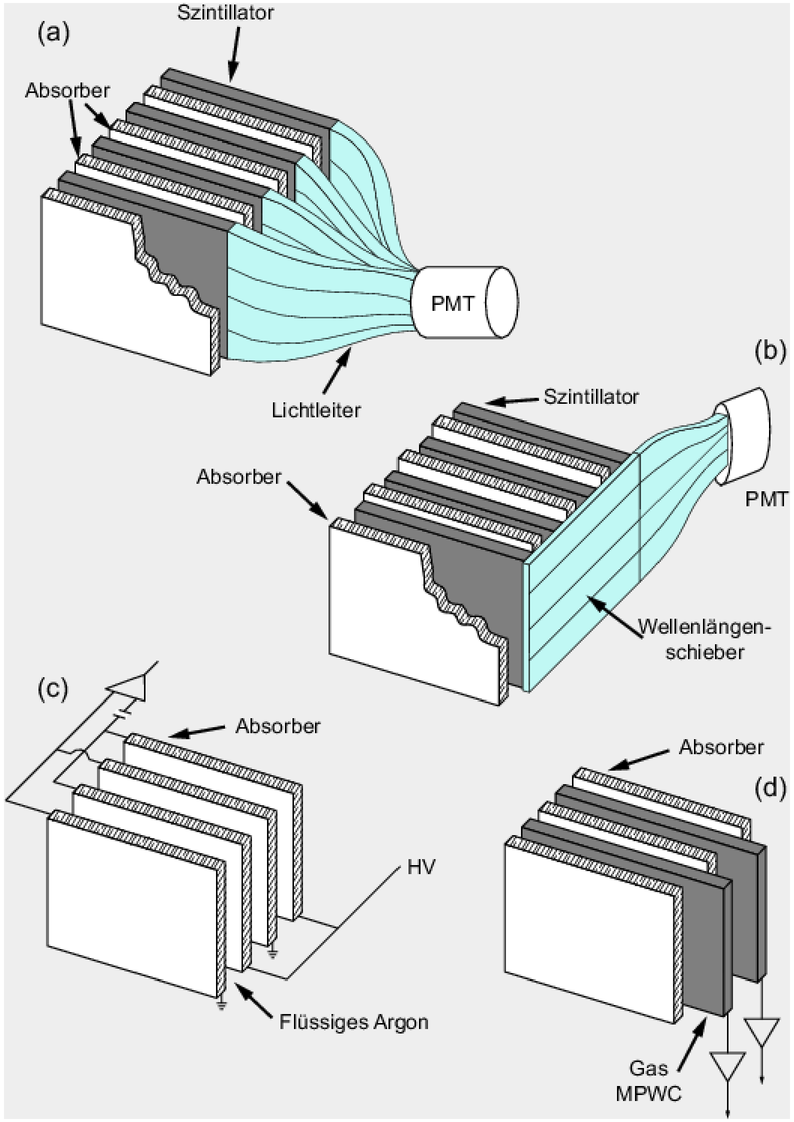
homogeneous





separate absorber and detector

sampling



Calorimeter Types (2)

Homogeneous

- Material:
  - Scintillators (crystals)
  - Čerenkov-Radiators
  - (Semiconductors)
  - (Liquid gases)
- Good Resolution
- Small X_0: difficult
- Segmentation?

Sampling

- altern. detector material:
  - Scintillators (plastic)
  - (Liquid)gases
  - (Semiconductors)

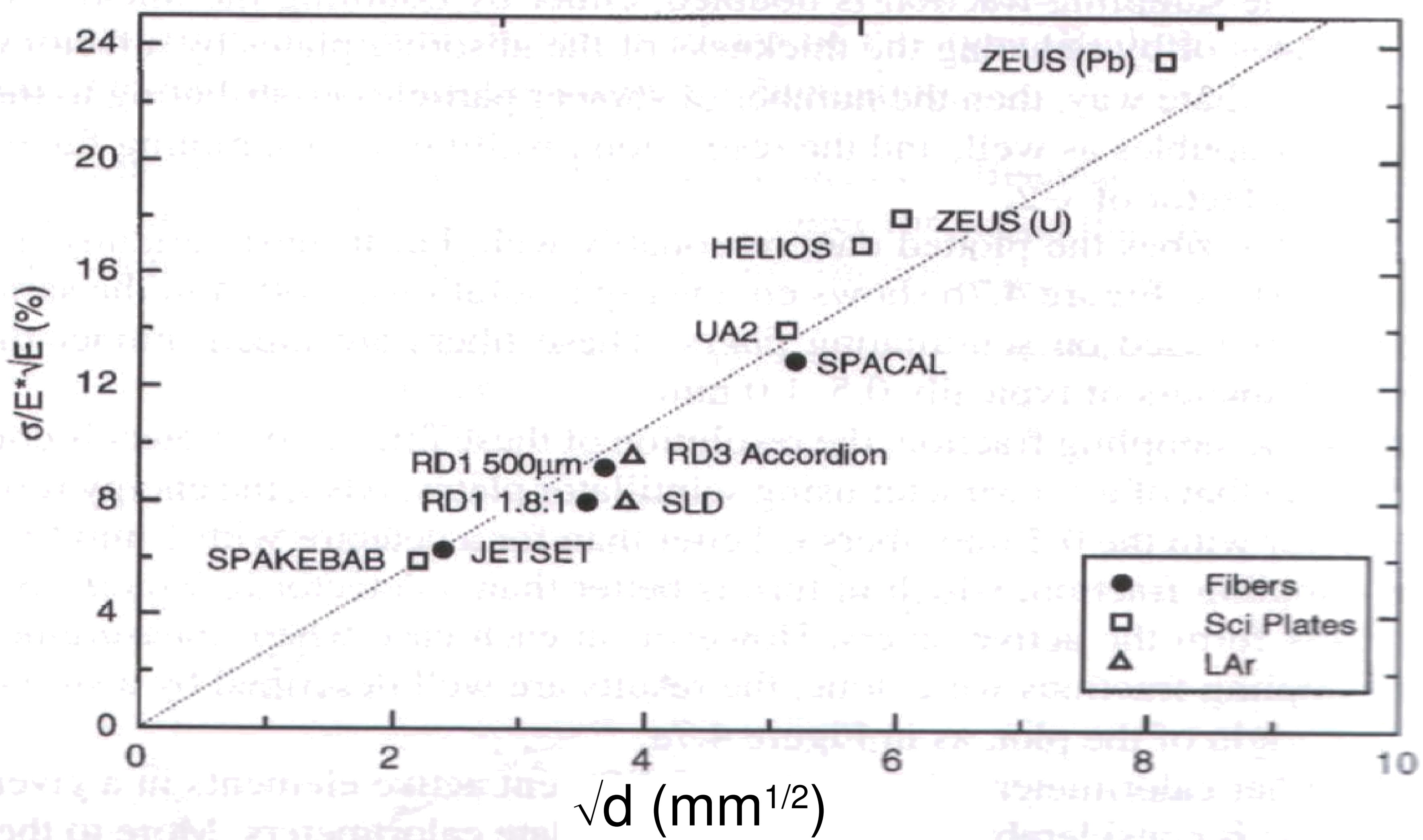
  \+ Absorber:
  - Fe, Pb, W, U
- Compact, easily segmented
- Poorer resolution

Energy Resolution (1)

- Intrinsic ("stochastic") fluctuations:
  - Shower processes have intrinsic fluctuations (QM nature of processes) → N follows Poisson statistics
  - → $\sigma_N = \sqrt{N}$
  - With $N \propto E$ → $\sigma_E \propto \sqrt{E}$ or $\frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E}}$
- Sampling fluctuations
  - Homogeneous calorimeters: observe entire signal, sampling: only a fraction is observed → poorer stat.
  - Absorber thickness d → observed signal $\propto E/d$ →

$$\frac{\sigma_E}{E} \propto \sqrt{\frac{d}{E}}$$

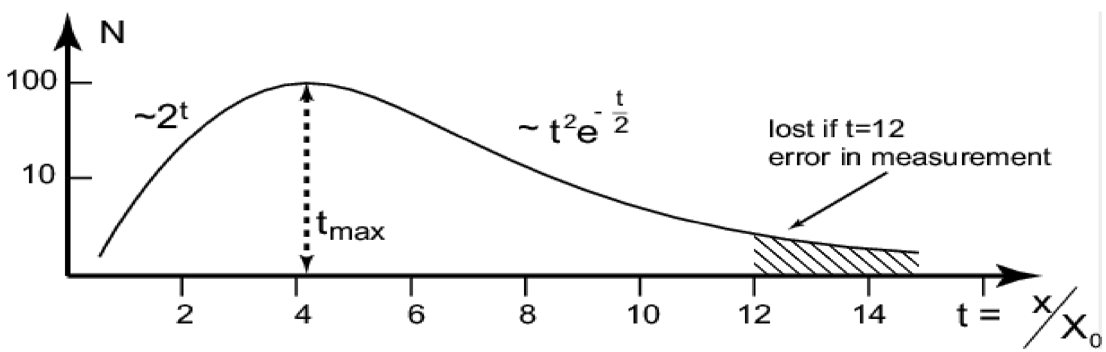
Sampling Fluctuations

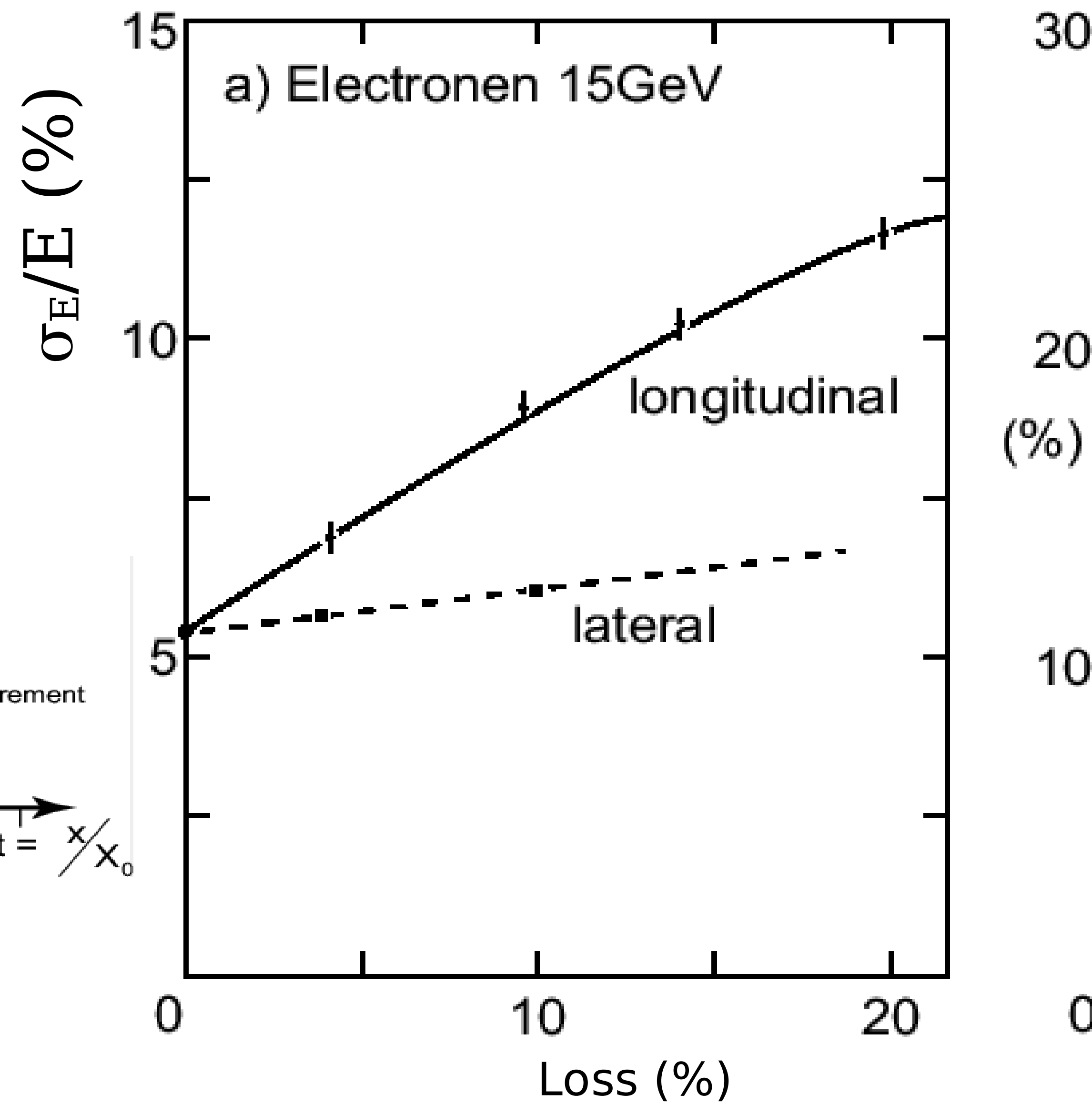


Energy Resolution (2)

- Similar to sampling effect, also $\frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E}}$:
  - Missing (fluctuating) parts of signal due to leakage effects
  - Intrinsic fluctuations in measured signal (Landau and path length fluctuation) – typ. “thin” media like gas
- Noise from read-out (electronics, PMT, …)
  - Size of noise independent of shower → const. in E → $\frac{\sigma_E}{E} \propto \frac{1}{E}$
- Signal ∝ E must be calibrated → limited precision scales with E, leads to $\frac{\sigma_E}{E} \propto \text{const.}$

Leakage Effects

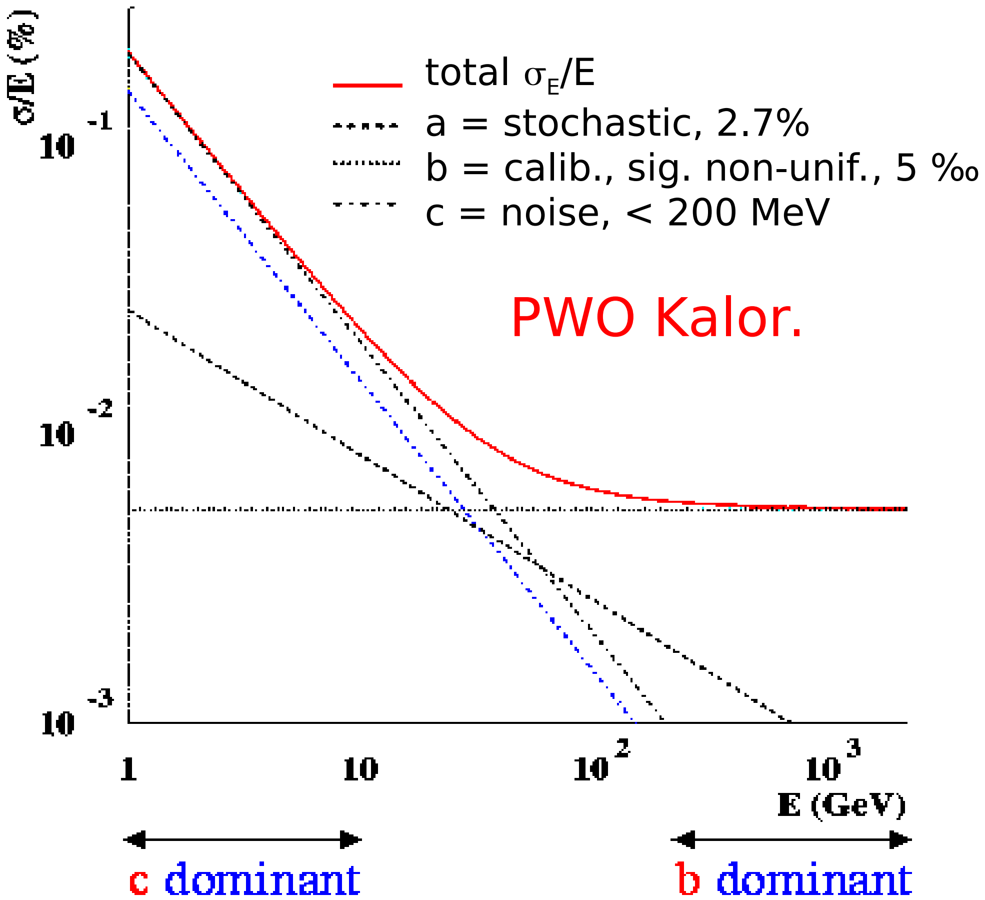




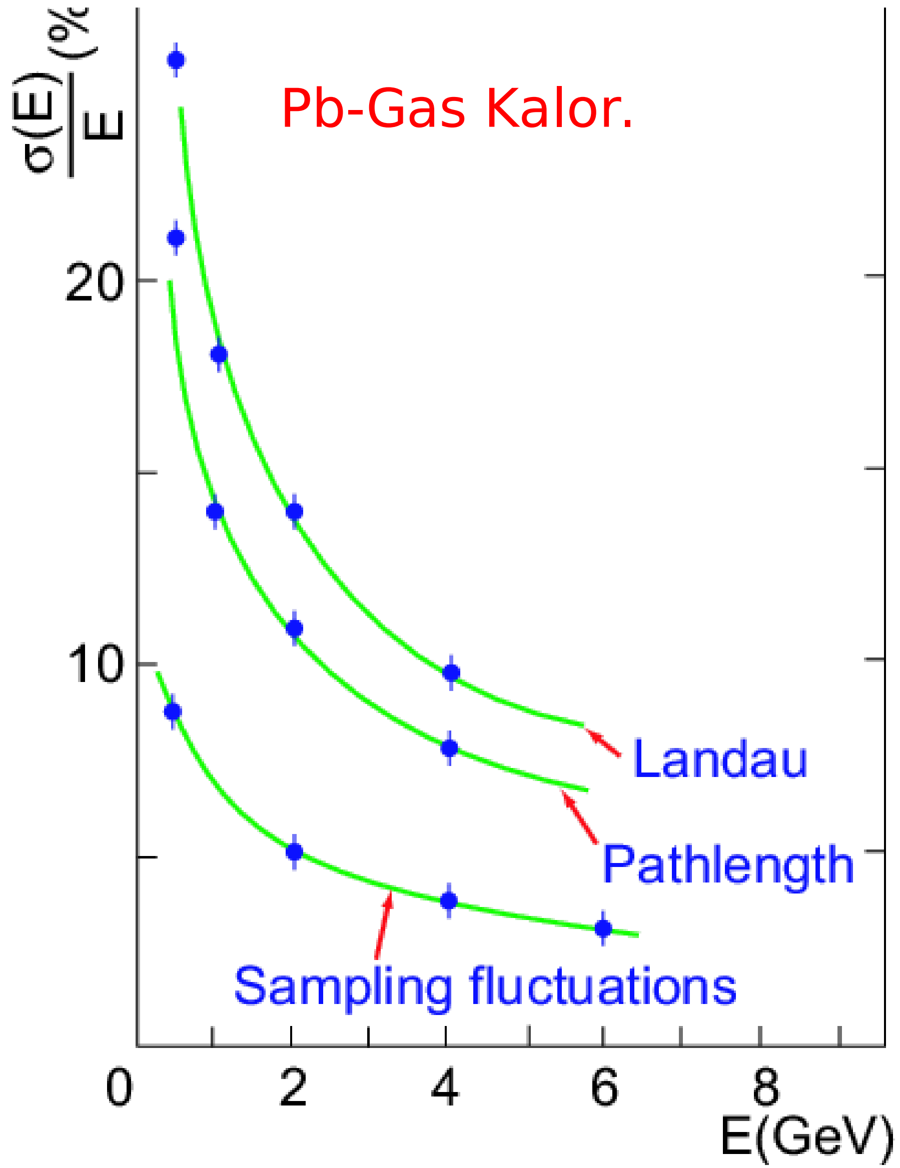
Energy Resolution (3)

In total, we get:

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



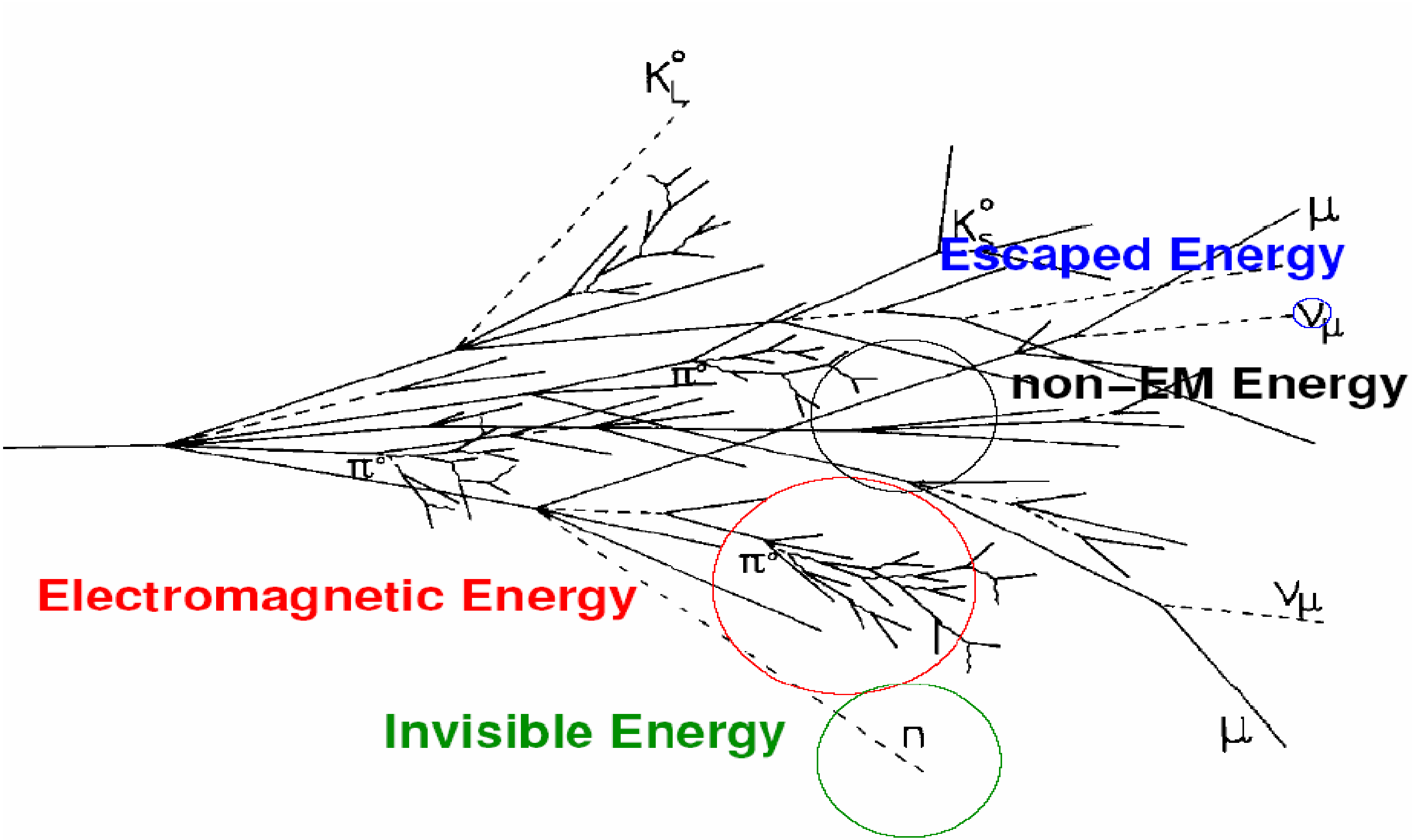
dominating term dep. on calor. type:



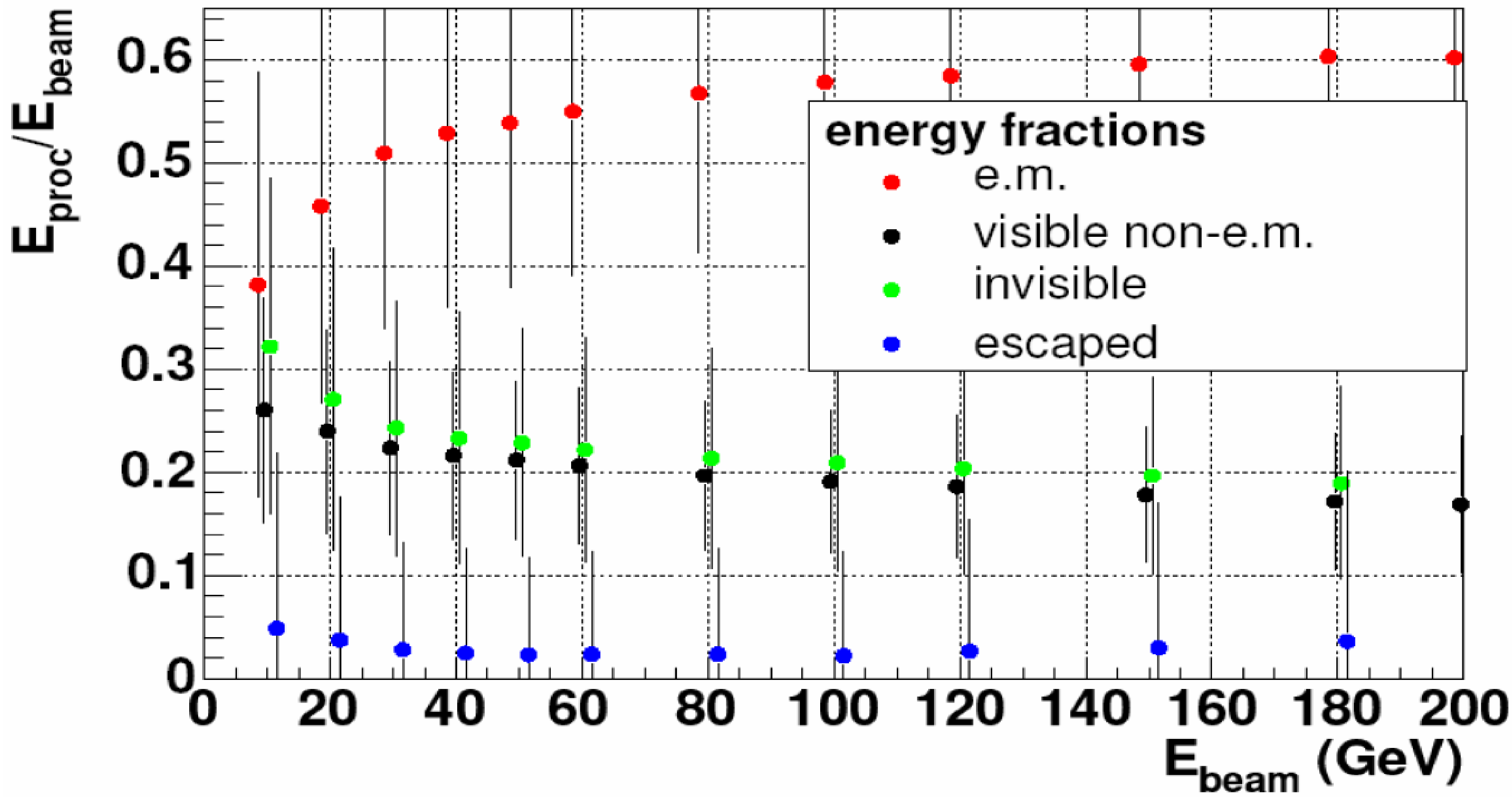
Hadron Showers

- Similar to em shower, hadronic processes lead to a shower of particles → same concepts as before (also resolution)
- Generally, much larger due to $\lambda \gg X_0$, no good homogenous calorimeter → only sampling
- Additional complication:
  - em showers are simple: just γ, $e^{\pm}$
  - Hadron showers are more complex:
    - Pure hadronic part, visible ($\pi^{\pm}$, p, …)
    - Electromagnetic (large fraction due to e.g. $\pi^0 \to \gamma\gamma$)
    - Invisible (n, nuclear fragments)
    - Escaped (ν)

Content of a had. Shower (1)



Content of a had. Shower (2)

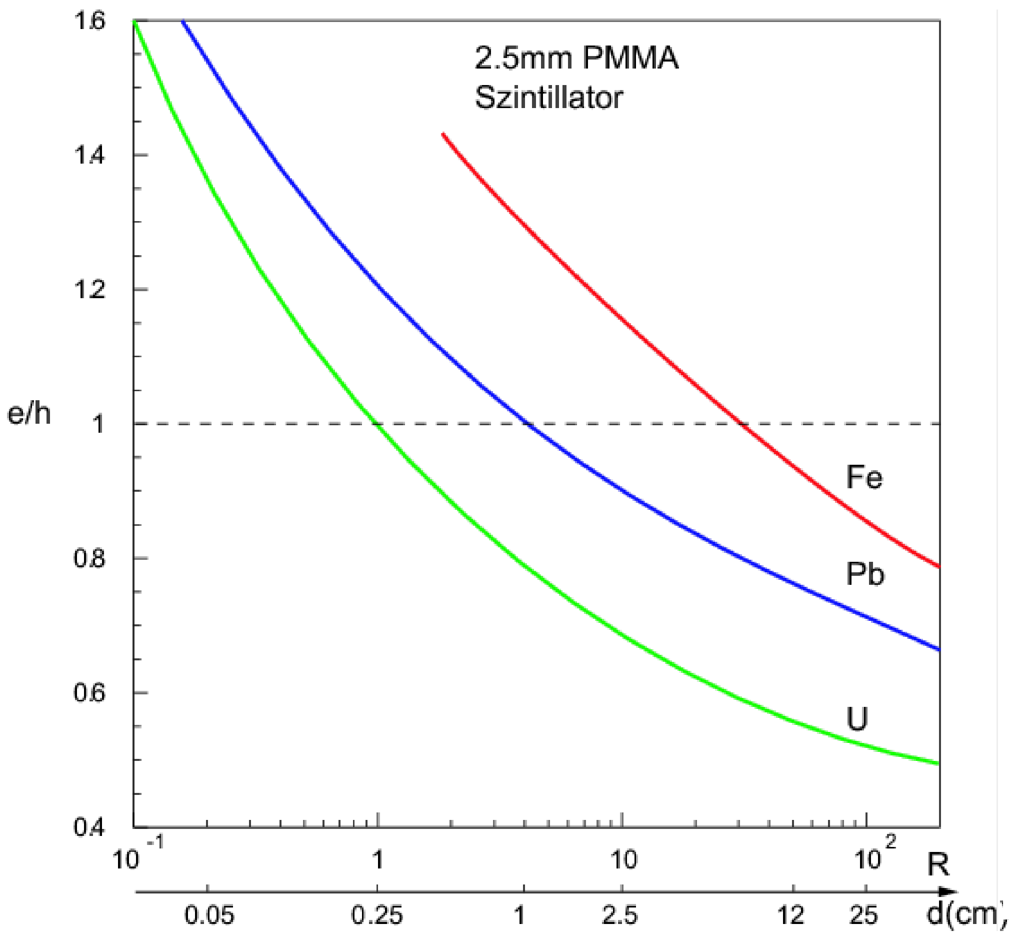


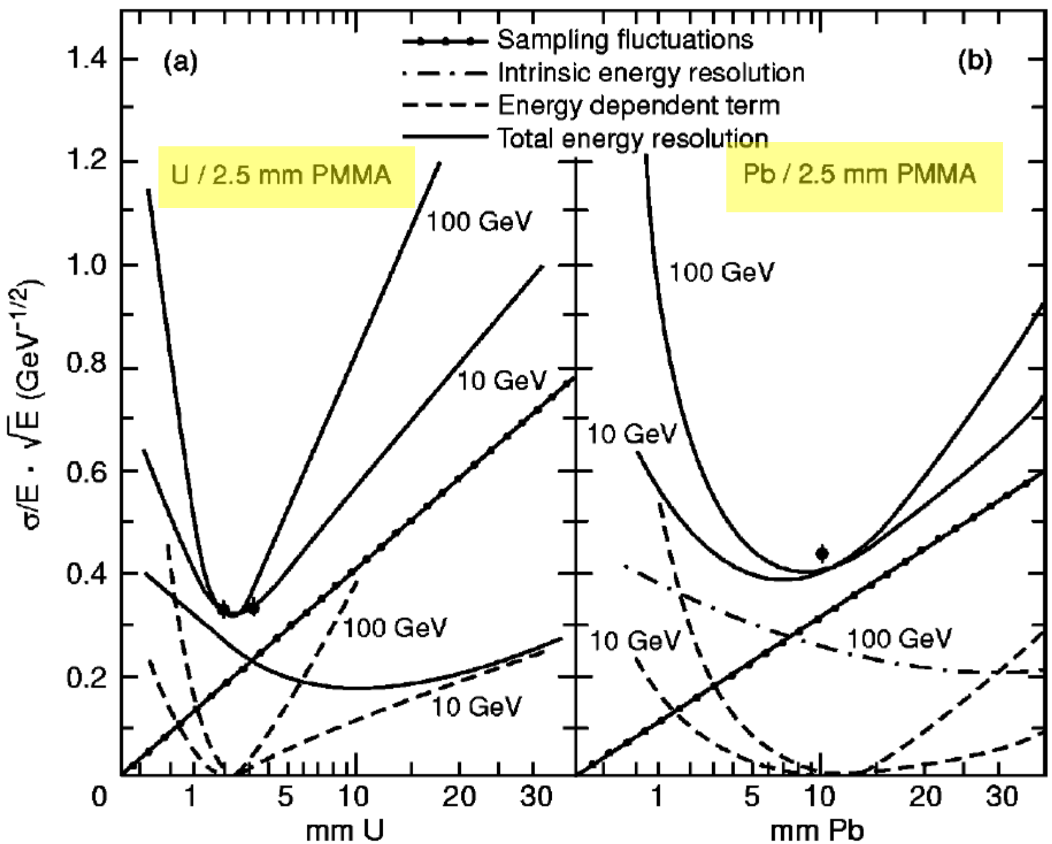
- Composition varies with energy → non-linearity
- Stat. variation in composition (shown by "error bars")
  → fluctuations in resolution

Compensation

- Net result: different response from calorimeter to electromagnetic shower, e.g. from e, and to hadronic shower, e.g. from $\pi^{\pm}$
- Ratio of response often noted as e/h (>1 w/o any further action)
- Cure: compensation to achieve e/h=1
  - Enhance h signal, e.g. by recovering n-contribution
    - Plastic scintillators well suited for n detection
    - Tune effect by thickness ratio absorber/plastic → also affects resolution due to sampling effect
  - Reduce e-signal, e.g. by identifying “compact” shower and post-processing

Hardware Compensation



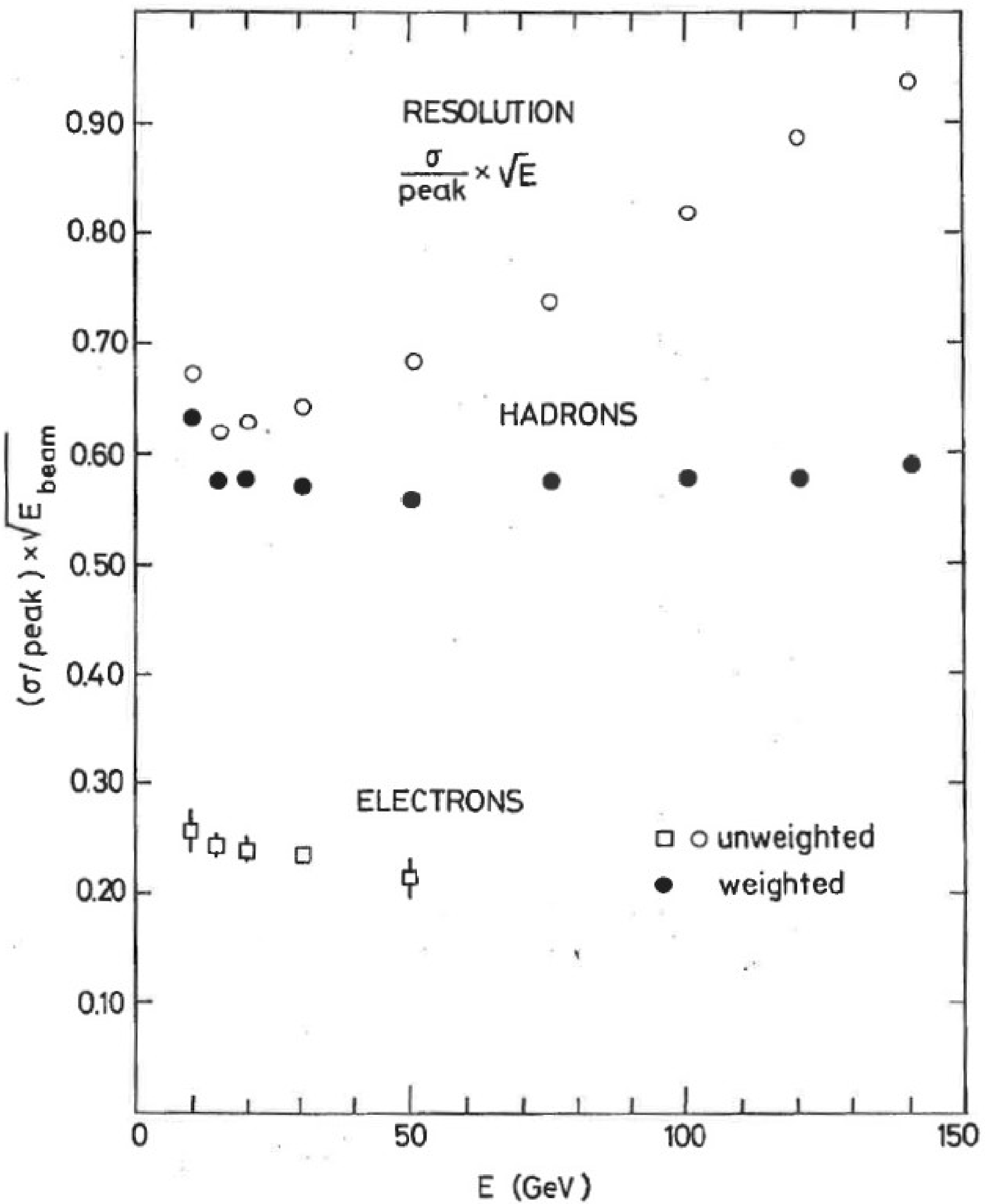


- Tuning e/h and the resolution by adjusting absorber thickness for fixed plastic scintillator (PMMA) thickness
- Depends on absorber → different nuclear processes

Software Compensation

- Aim: identify em sub-showers → need a fine segmentation of calorimeter
- Identify cells with high energy density and re-weight cell energy E_i:

  $E_i' = E_i \cdot (1 - C \cdot E_i)$
- Parametrise C as function of (un-weighted) jet energy

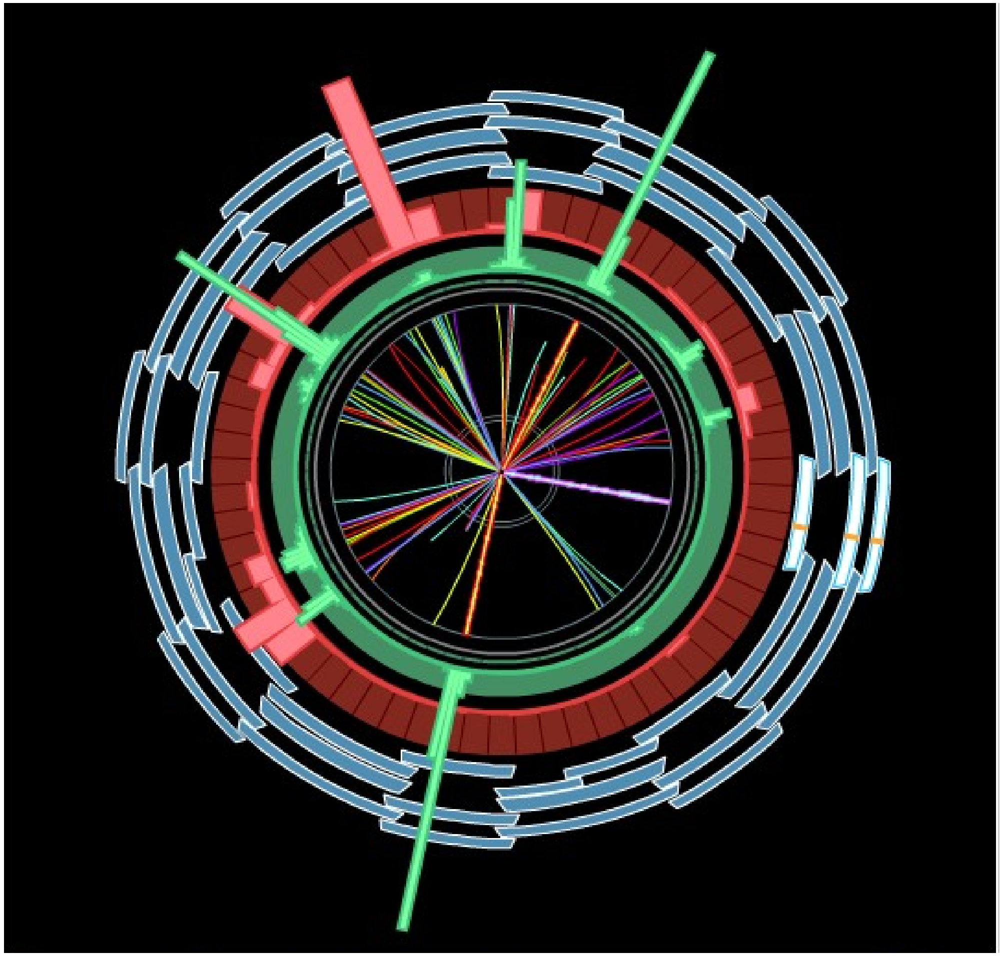


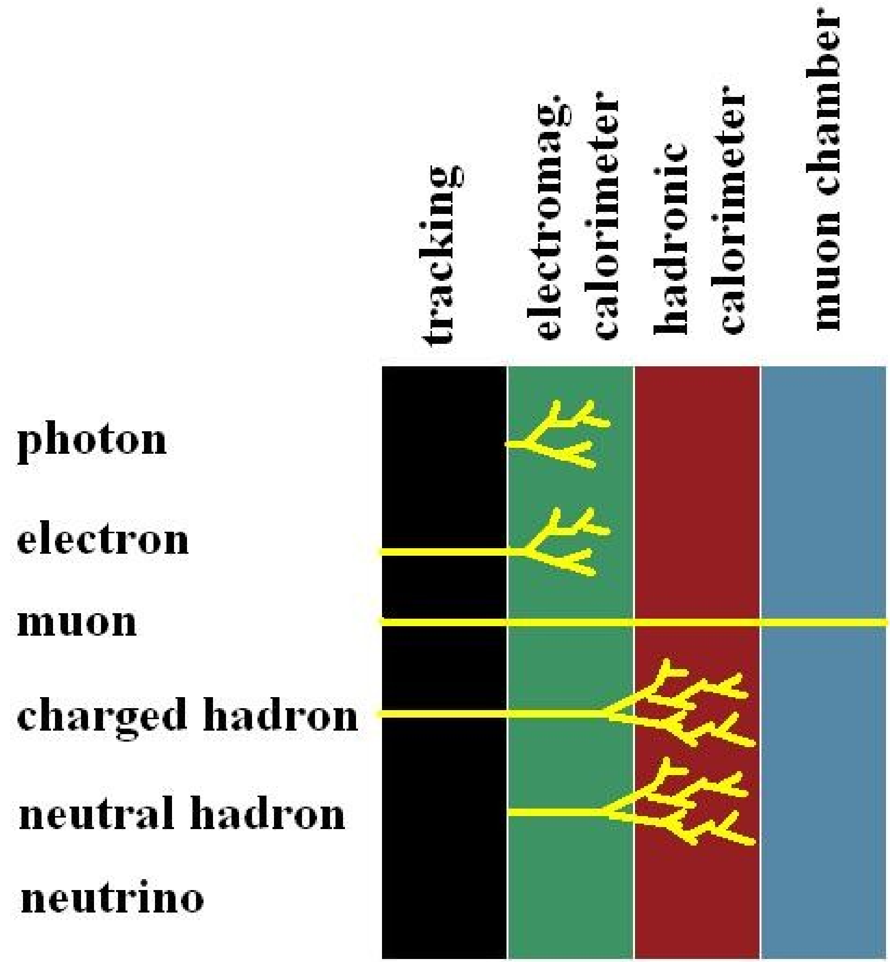
Calorimeter Design

- Inner part: tuned for em showers ($\lambda \gg X_0$)
  - Homogeneous: only few crystals with useful X0 available
  - Sampling: variety of material
  - Choice drives resolution, but also other requ.: read-out speed, radiation hardness,…
  - Segmentation: separation of individual particles, e.g. photons from $\pi^0 \rightarrow \gamma\gamma$
- Outer part: tuned for had. showers
  - Size is critical: avoid leakage problems
  - Decide if sw/hw-compensation is required $\rightarrow$ e.g. fine segmentation

Overall detector system concepts

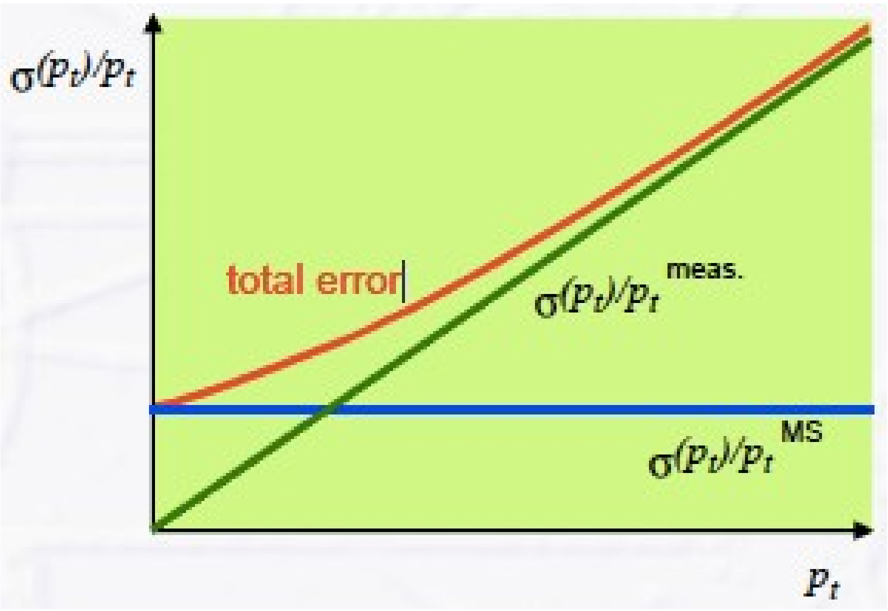
Multi-layer HEP Detector



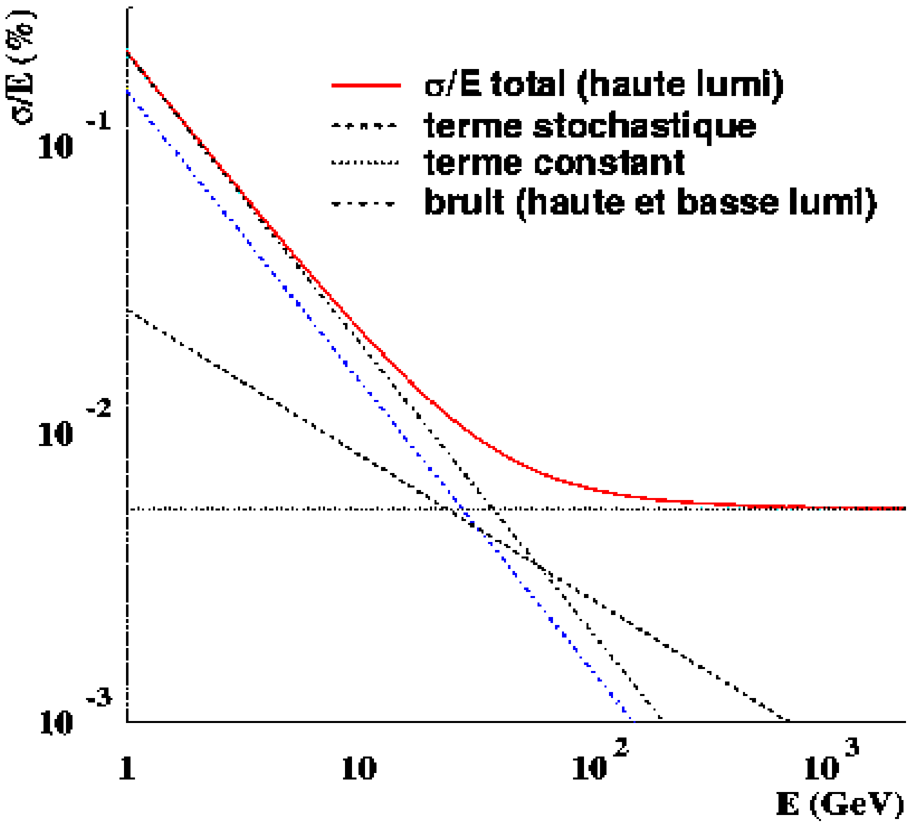


Complementary Measurements

- Tracking: measure momentum p
- Resolution degrades with rising p



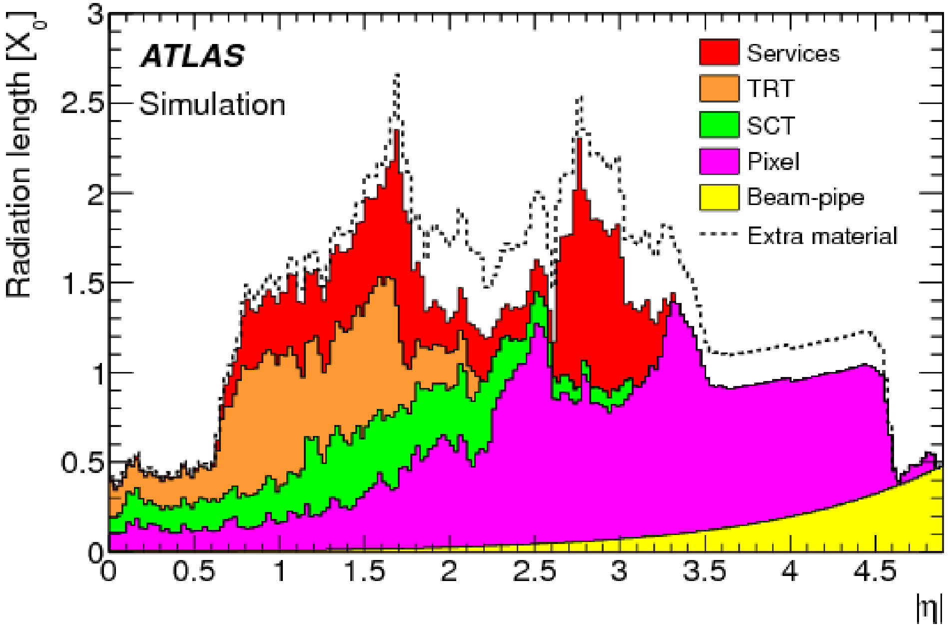
- Calorimeter: measure energy E
- Resolution improves with rising E



Material Budget

- Inner detector layers influence outer layers
  - Multiple scattering: influence on tracking itself, but also on track-calo. matching
  - Possible photon-conversion and Bremsstrahlung → calorimeter doesn't measure “original” e, γ

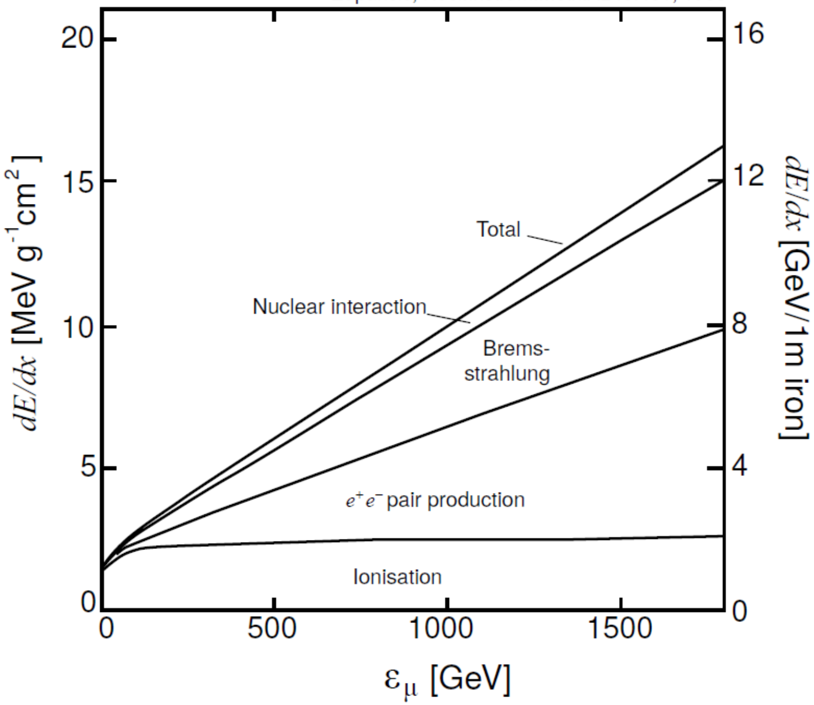
    → keep material as low as possible
- Material budget is not just the pure detector (gas or silicon): cables, cooling pipes, support structures,… contribute as well



Muon Detectors (1)

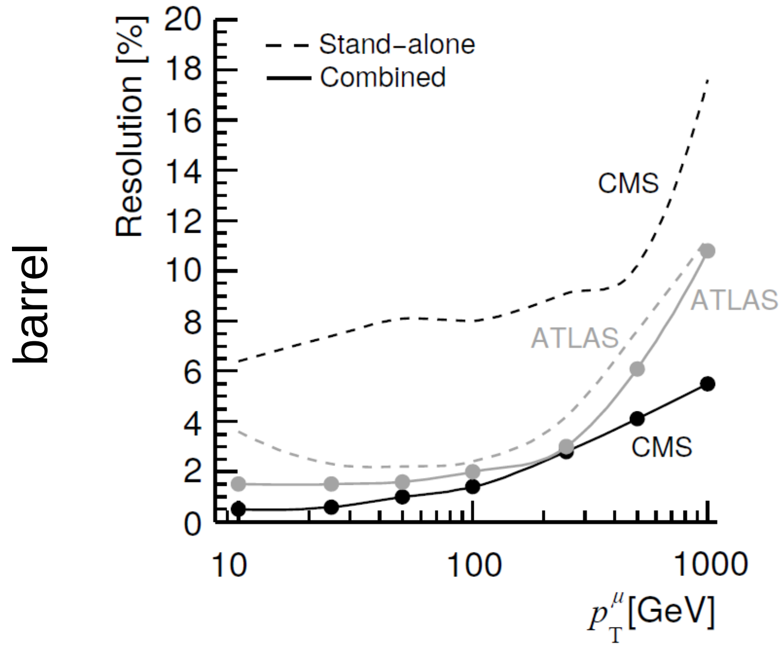
- Muons penetrate calorimeter layers → detector in outermost layer
- Independent tracking system
  - Magnetic field: return yoke from inner tracking system (CMS), or additional magnets (ATLAS)
  - Complementary momentum measurement
  - Adjust for energy loss in calorimeter: several processes, contribution is energy dependent

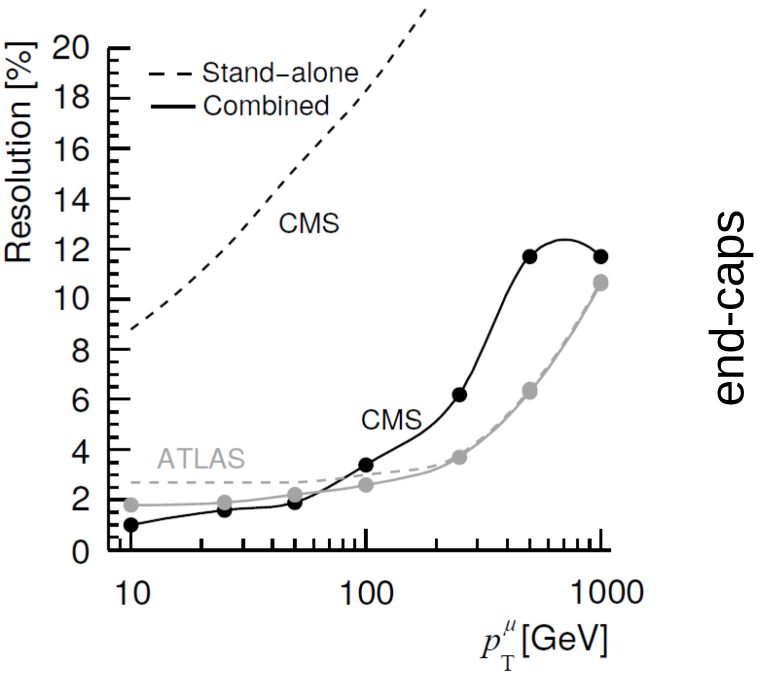
Zupančič, Nucl.Instrum.Meth.A248:461, 1986



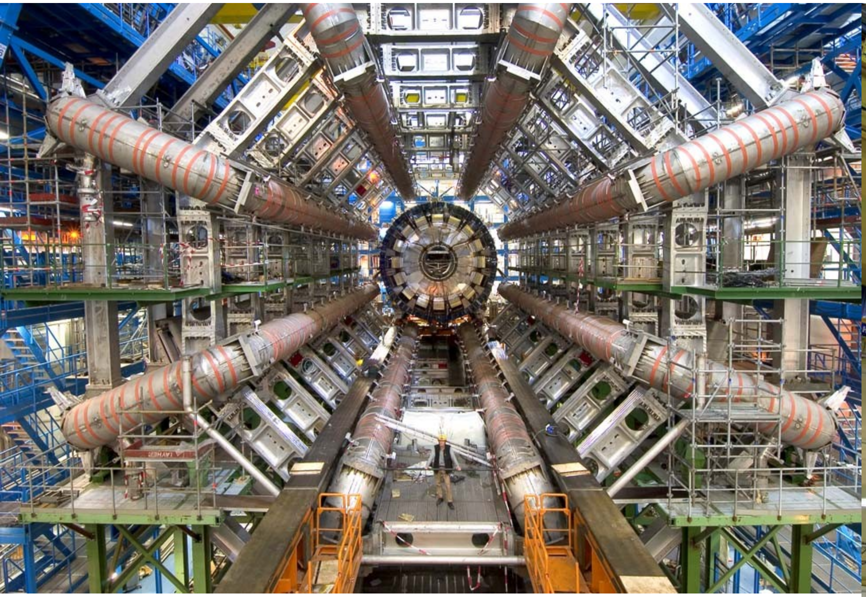
Muon Detectors (2)

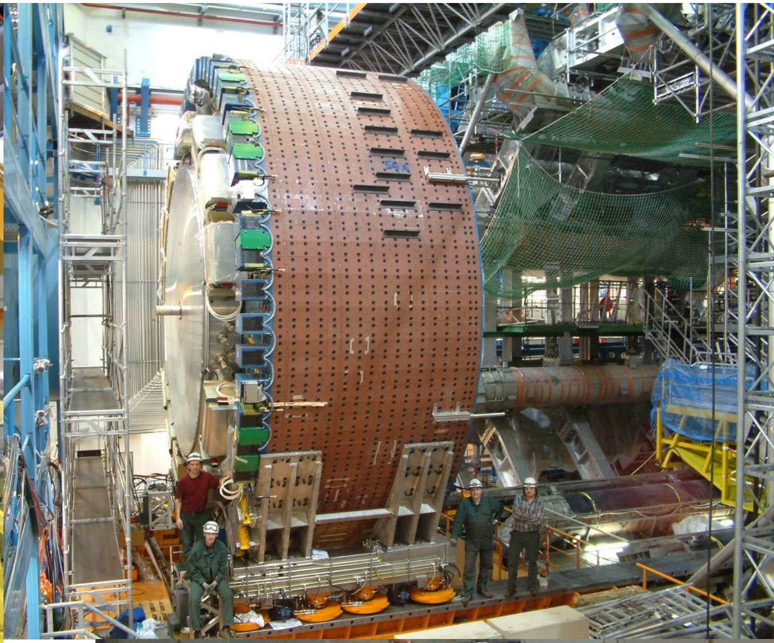
- Combine measurement with inner tracking system:
  - Each provides independent momentum measurement → reduce syst. error
  - More hits and larger L improves resolution

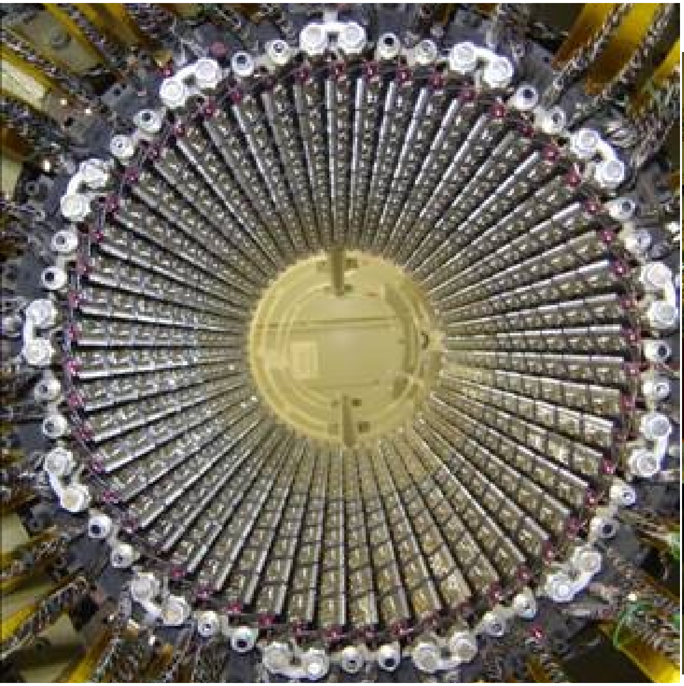


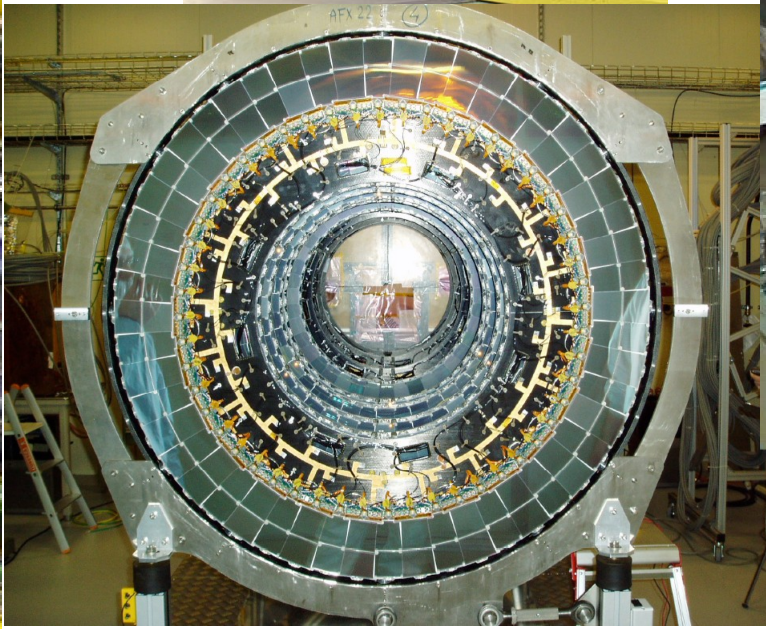


Real Detectors

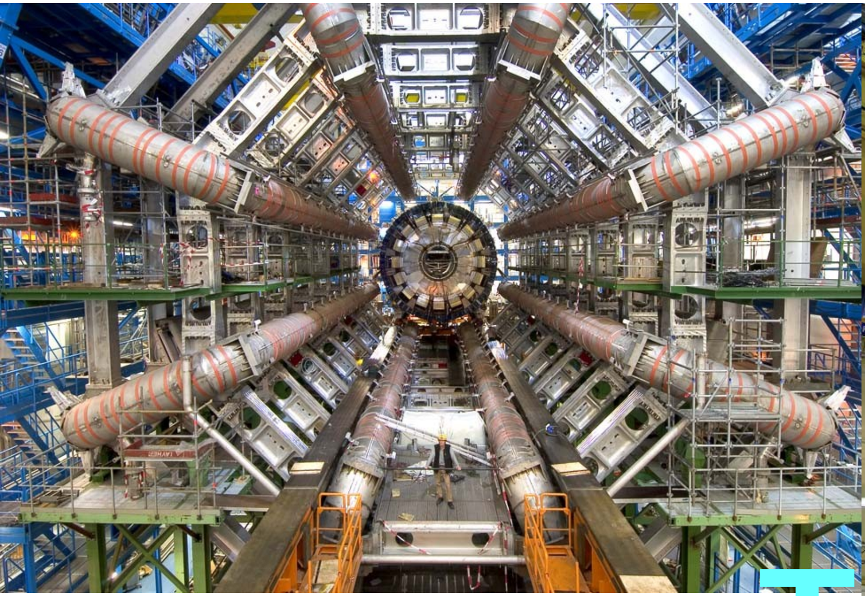


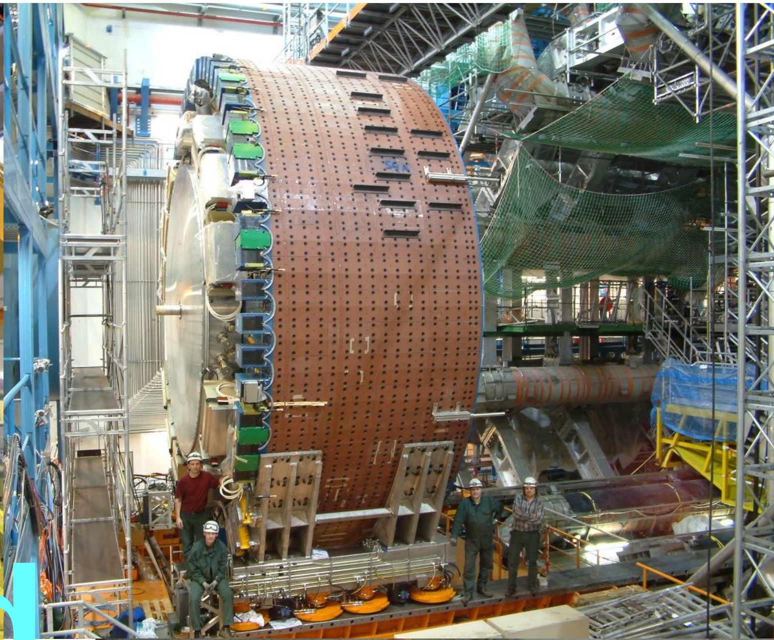






Real Detectors





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