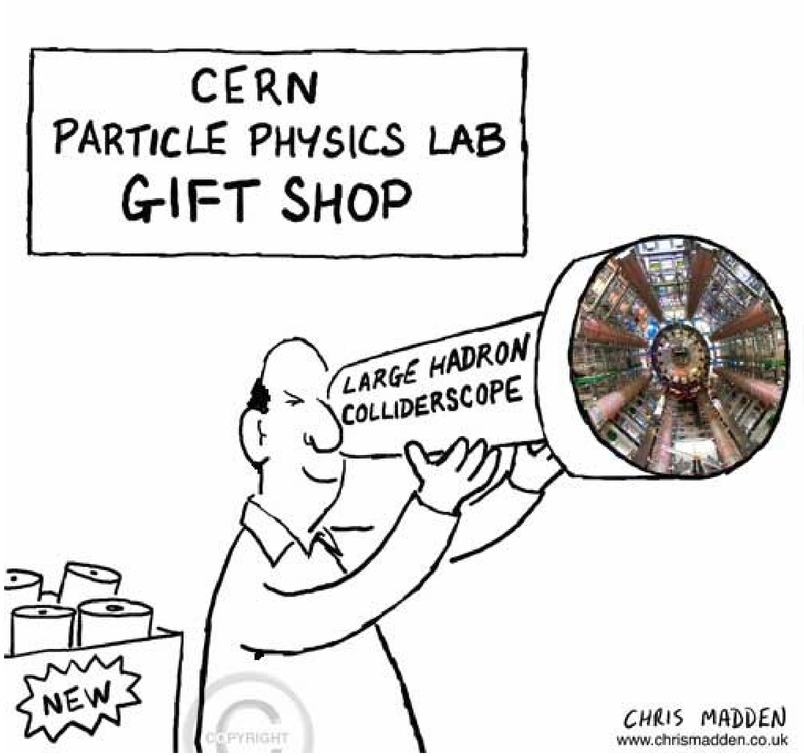
Detector Physics



Jörn Grosse-Knetter

HASCO Summer School 2022

Overview

- Basic concepts
  - Interaction of particles with matters
  - Ionisation detectors
  - Light-based detectors
- Tracking
  - Momentum and vertex measurement
- Calorimeters
  - Electromagnetic and hadronic showers
- Overall concepts

Interaction of particles with matters

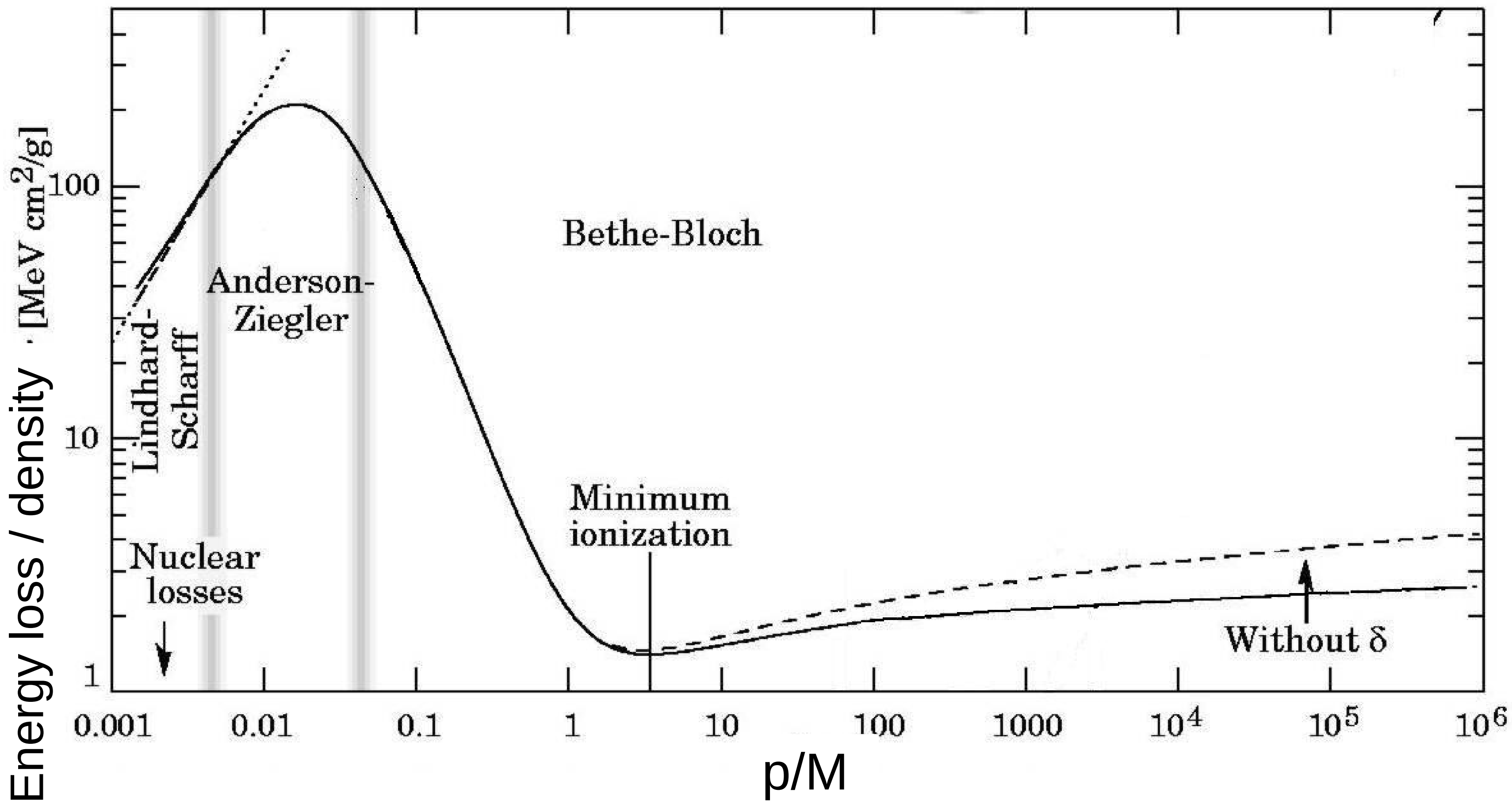
Energy Loss: Charged Particles (1)

(Heavy) charged particles:

- Interact with shell electrons → energy is transferred – or lost by inc. particle: dE/dx
- dE/dx can be described by Coulomb interaction and simple kinematics

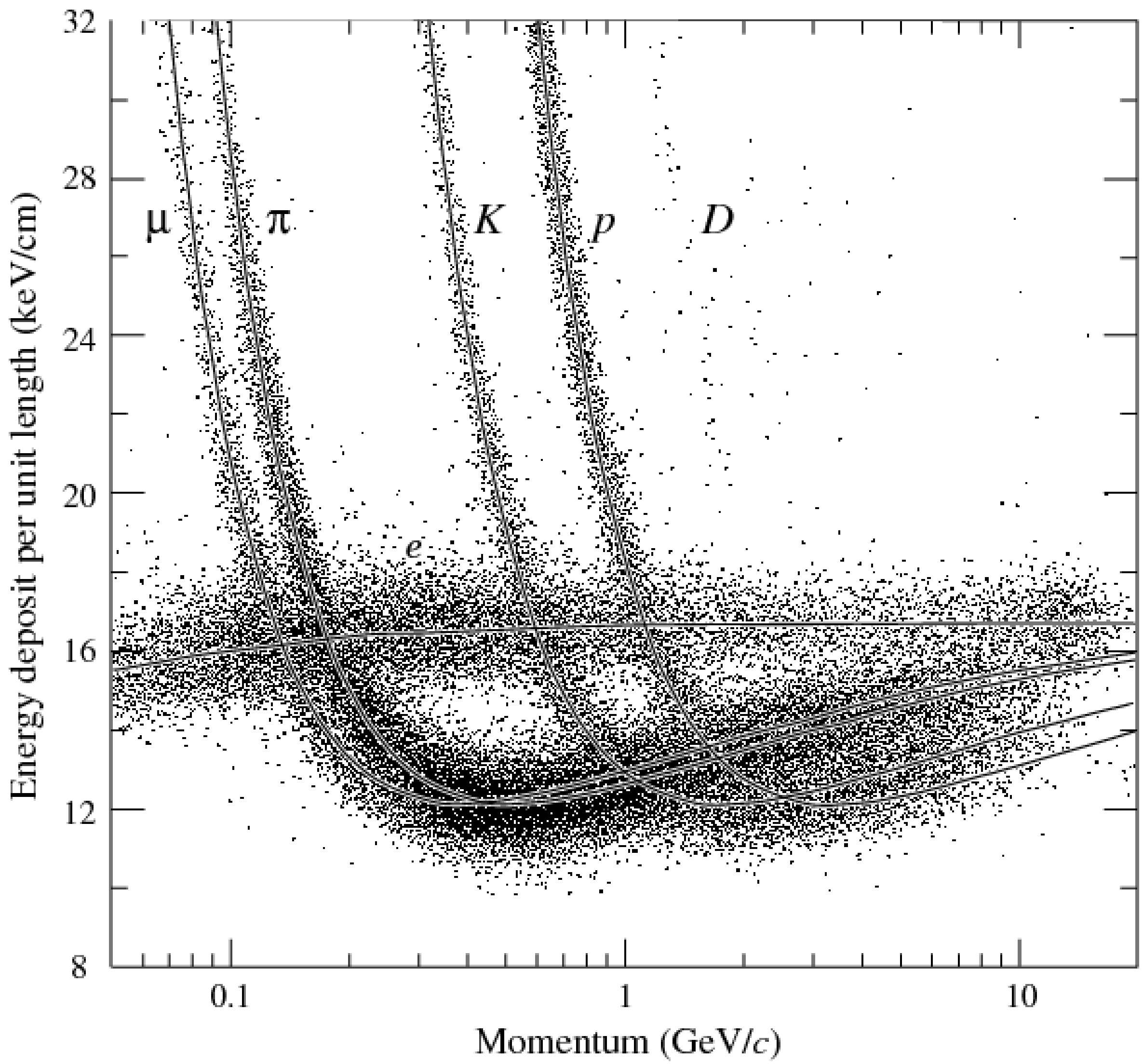
  → Bethe-Bloch-mechanism
- Transferred energy can excite or ionise medium → charge or light (from de-excitation) for detection

Energy Loss: Charged Particles (2)



- dE/dx: steeply falling towards p/M~3...4
- Modest rise afterwards → highly relativistic particles very similar in dE/dx

Energy Loss: Charged Particles (3)



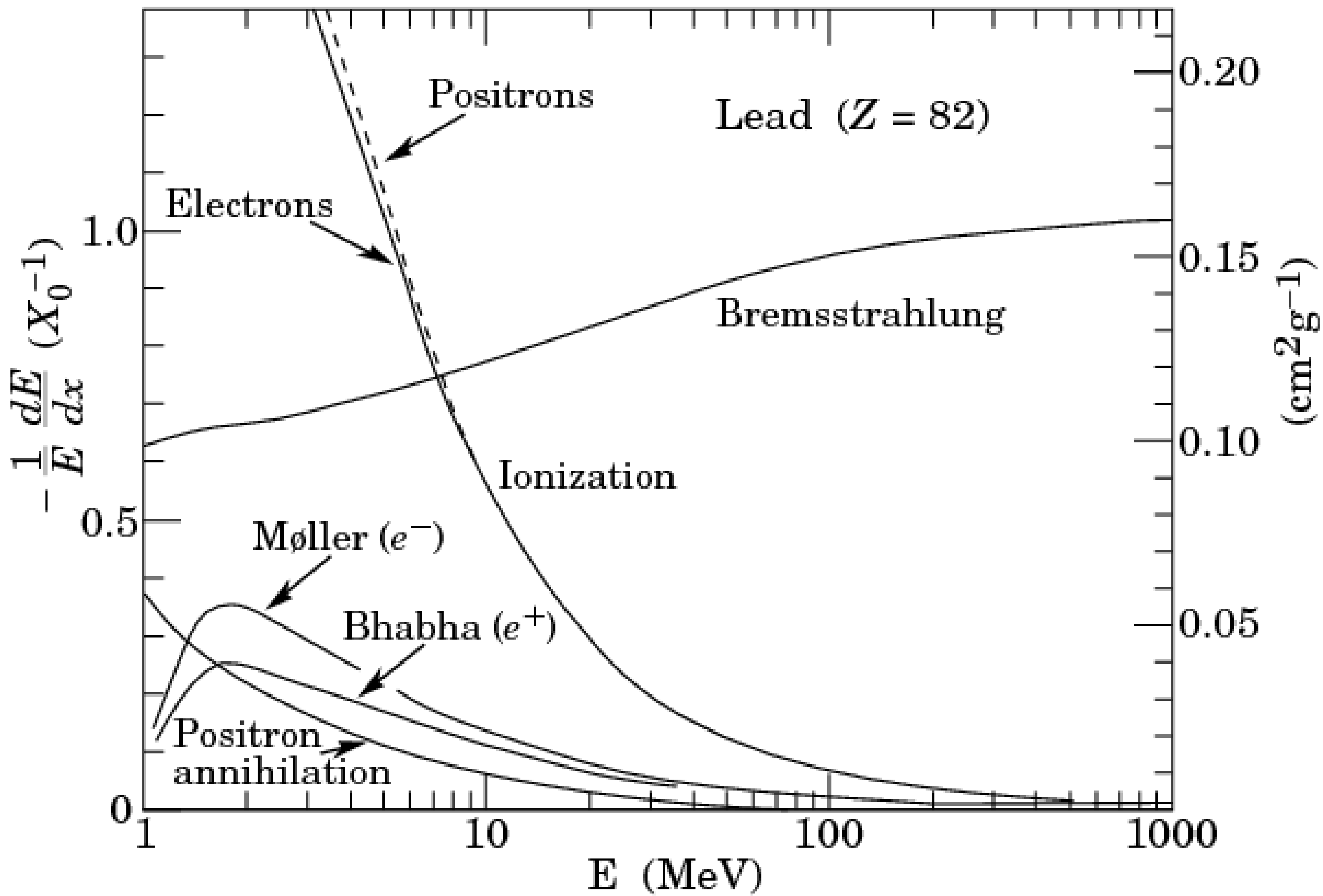
- dE/dx: identical in p/M, but different vs momentum → allows particle ID if momentum is known

“Light” charged particles: $e^\pm$

- Excitiation/ionisation loss similar to Bethe-Bloch, but corrections due to scattering partners with same mass
- Additional effect: Bremsstrahlung
  - Emission of photon in field of nucleus
  - $dE/dx \propto Z^2/m^2 \cdot E$ → dominant only for low mass m and high energy E, need high-Z material
  - Def. of X_0 (material-dependent radiation length):

    $$dE/dx := E/X_0$$

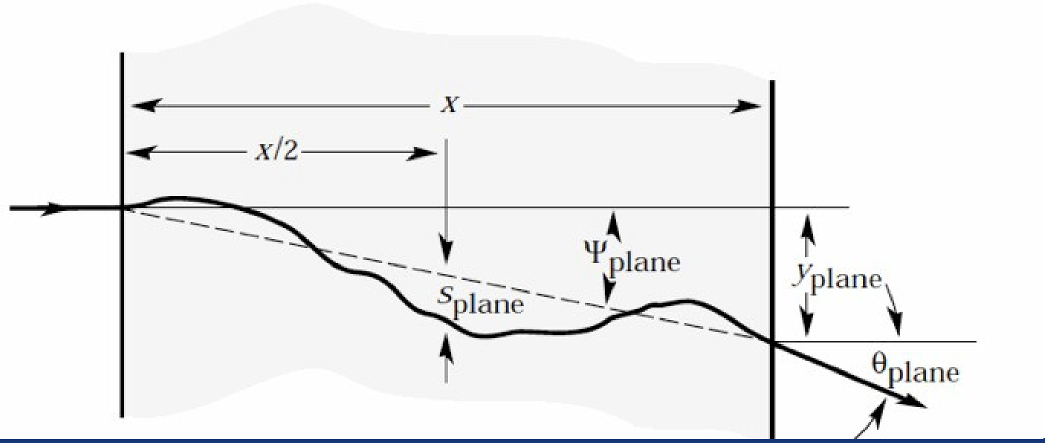
Bremsstrahlung

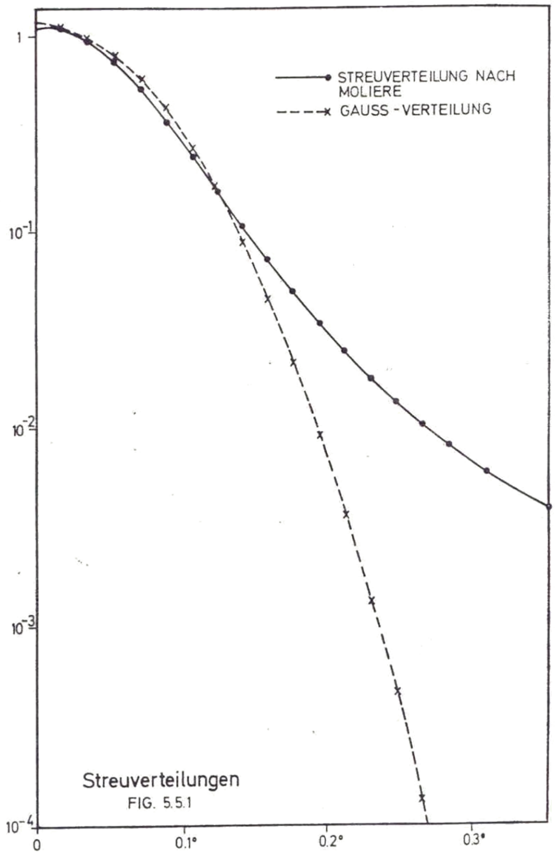


Multiple Scattering

- Multiple scattering of charged particles on medium without energy transfer
  - No measurable signal
  - But: deflection of particle → disturbance that needs to be considered
    - Mostly change in direction described by angle θ_0 (1-σ-value of distribution):

$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p} z \sqrt{x/X_0}\left[1+0.038\ln\left(x/X_0\right)\right]$$



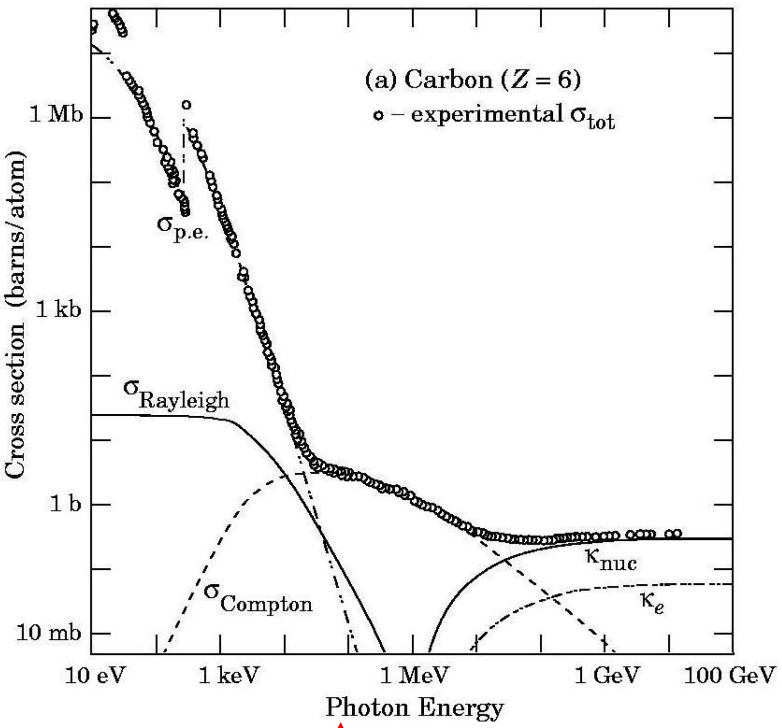


Absorption of Photons (1)

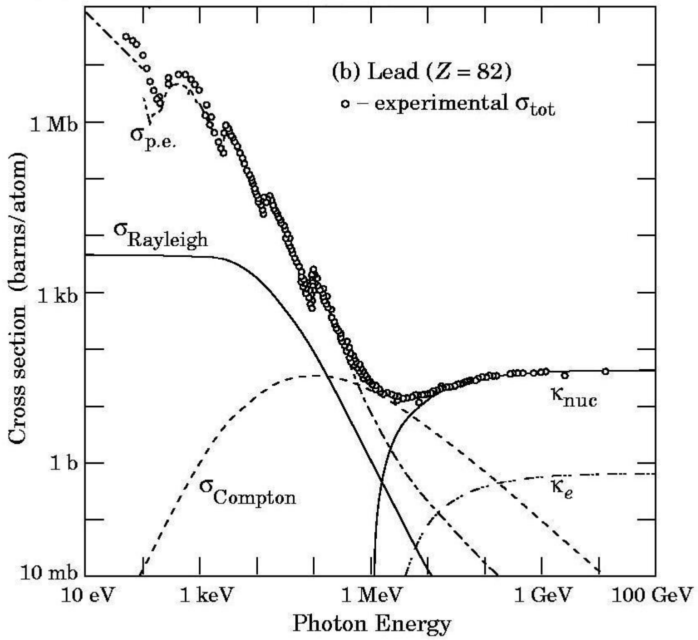
- Most processes involving photons absorb them (in contrast to dE/dx as before):
  - Photo effect: photo electron is released with $E_e \sim E_\gamma$
  - Compton effect: $E_\gamma \gg$ binding energy → electron quasi-free → scattering
  - Pair creation: $E_\gamma > 2m_e$ allows $\gamma \rightarrow e^{+-} e^-$ in the field of a nucleus
    - Process similar to Bremsstrahlung

      → mean free path: $9/7\ X_0$
    - Relevant process at high E_γ → in HEP

Absorption of Photons (2)



Absorption cross-section in lead



Absorption cross-section in carbon

- None of the above applies to neutrons
  - Can measure it indirectly: knocking off nuclei, measure charged object
  - Ideally: scattering partner of same mass → p

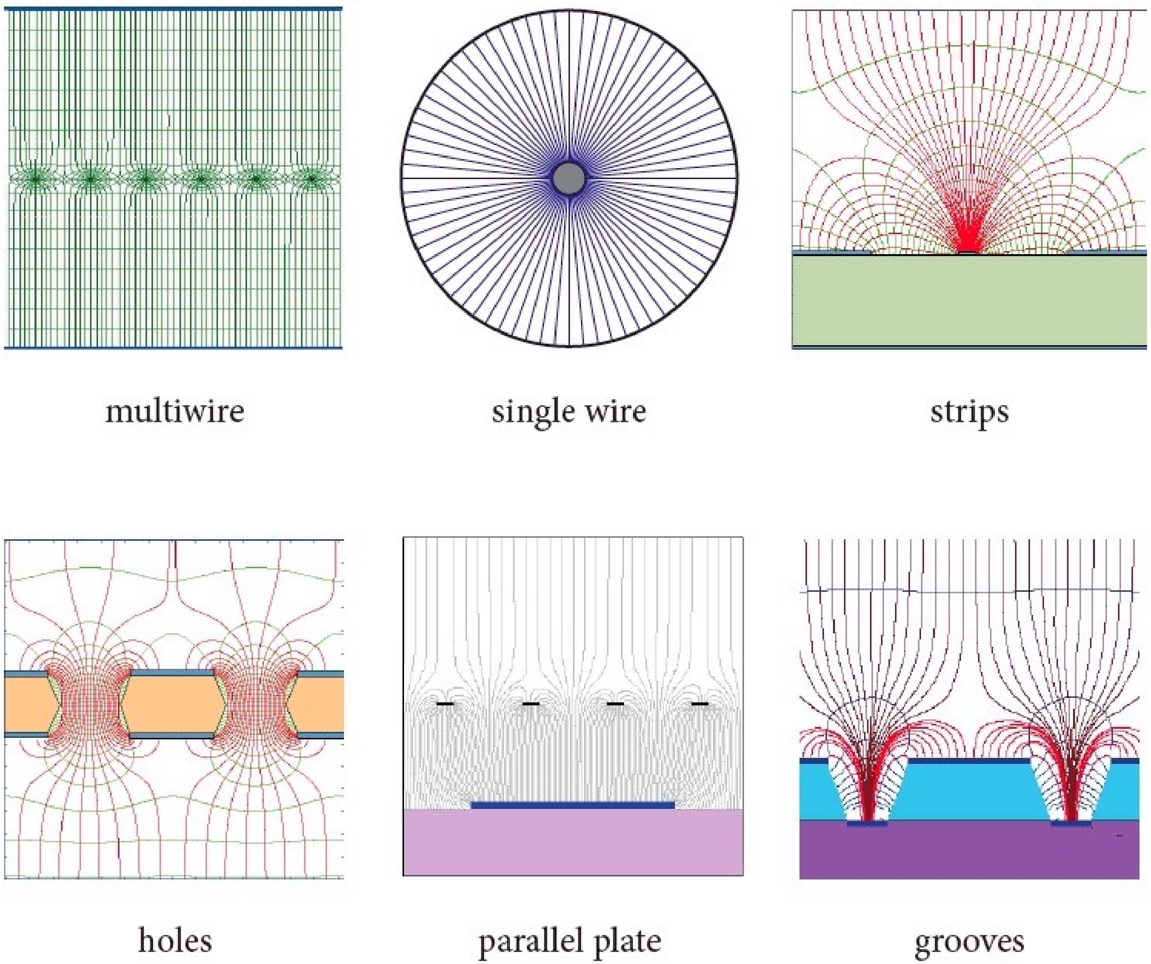
    → use organic material (significant H-content)
- p,n,π,K at high energies: additional processes possible
  - Creation of further hadrons
  - Nuclear interactions → new γ, n, p (+nuclear fragments)
  - Avg. had. interaction length $\lambda \gg X_0$

Ionisation detectors

Ionisation Detectors: Concept

- General idea of ionisation detectors:
  - Deposited energy E_{dep} causes ionisation, for which on avg. energy W is needed → release of E_{dep}/W charge carriers
  - Apply electric field to extract and read charge pulse
  - Typical media:
    - Gas: e-ion pairs, W ~ few 10eV
    - Semiconductor: e-hole pairs, W ~ few eV
  - Bethe-Bloch signal ∝ density →
    - Gas: too little charge for meas. → amplification
    - Semiconductors: charge detectable, but competes with intrinsic charge carriers

Gas-filled Det.: Field Configuration



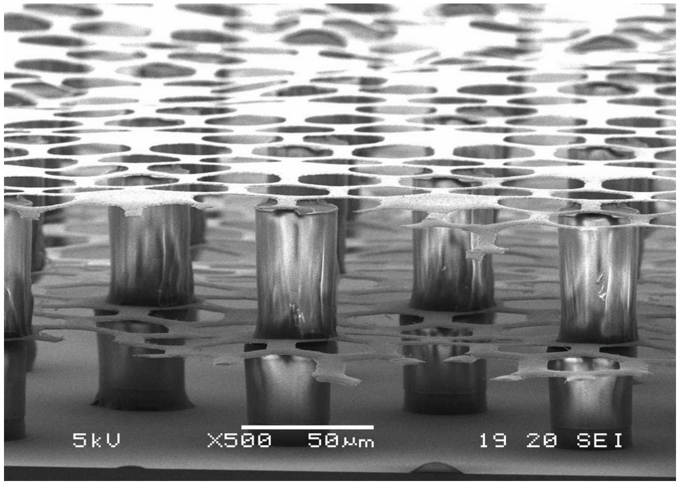
- Internal charge amplification achieved by high electric field

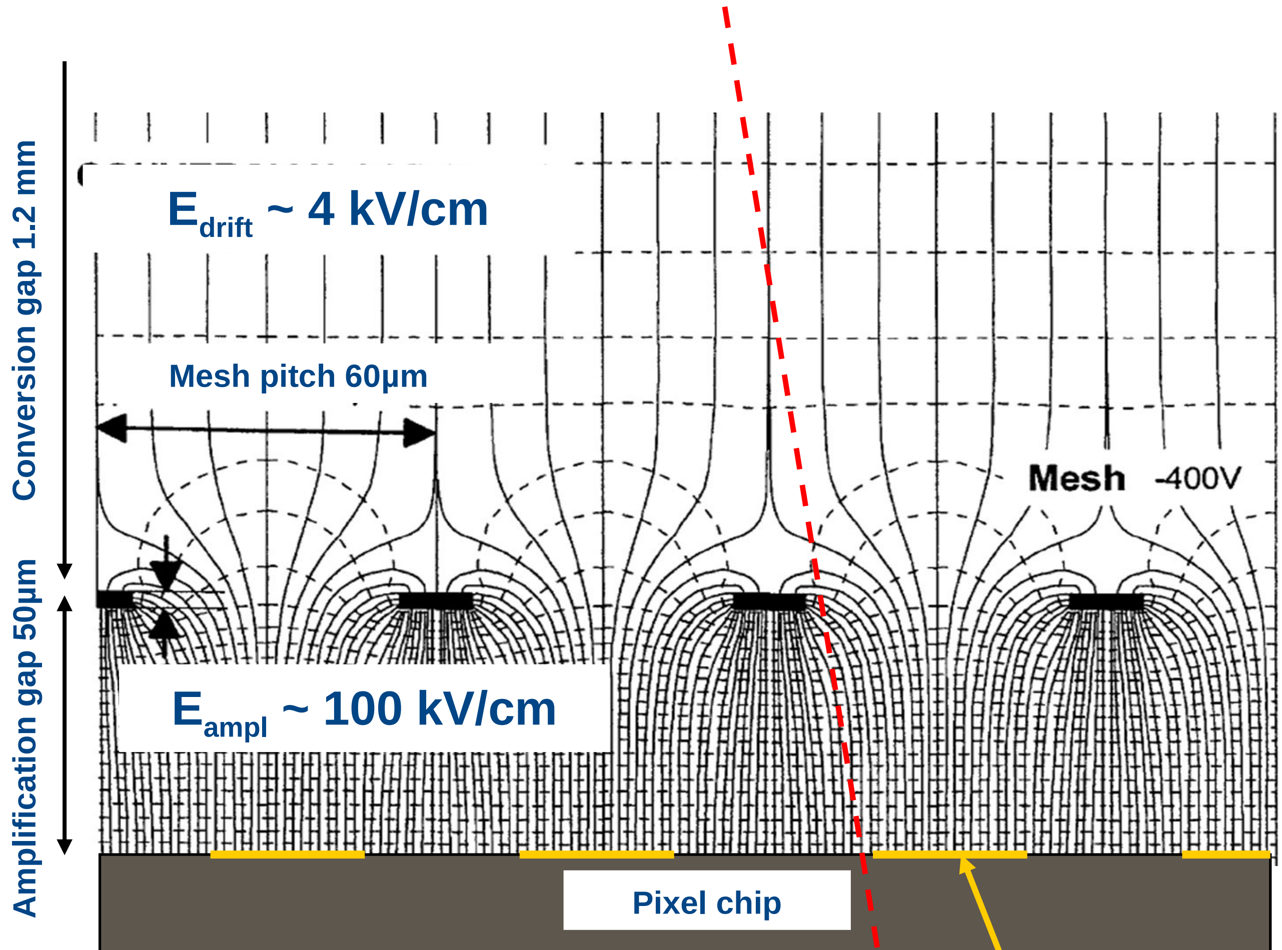
  → need small or close electrodes

  - Small read-out segments, e.g. wires
  - Specific perforated foils

- Operate in proportional mode → can measure dE/dx

Gas Amplification: Example

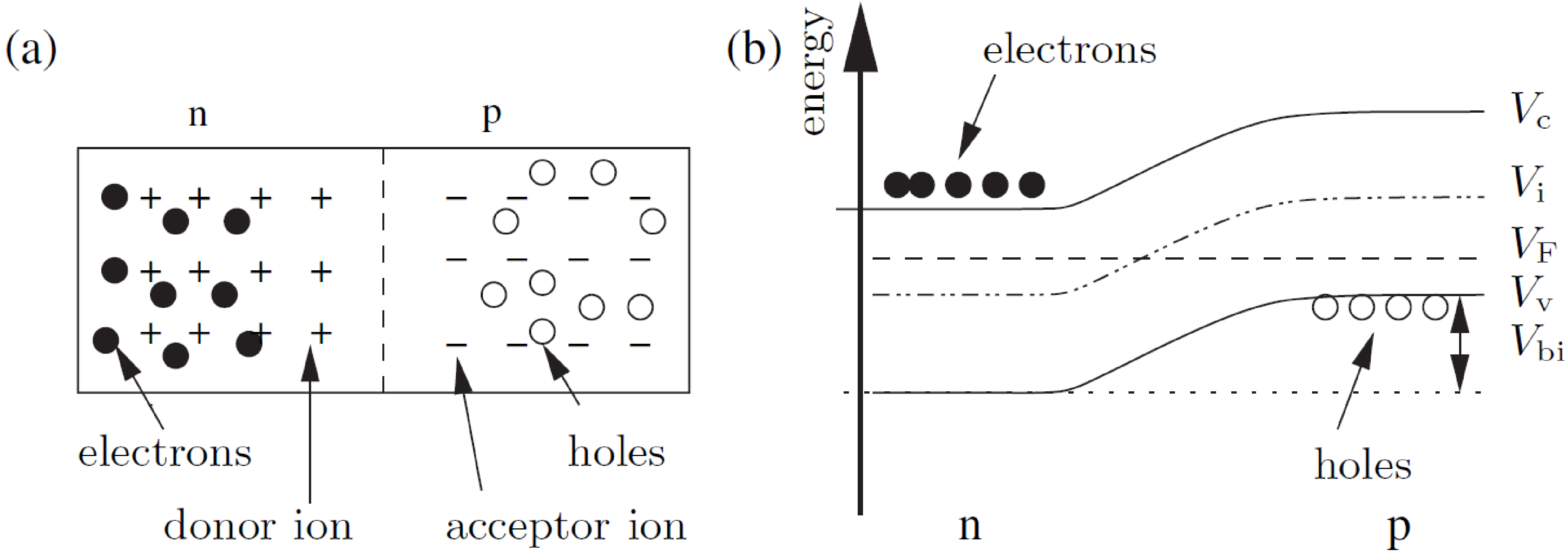




- Perforated foil supported by pillars
- Pixel electrodes beneath

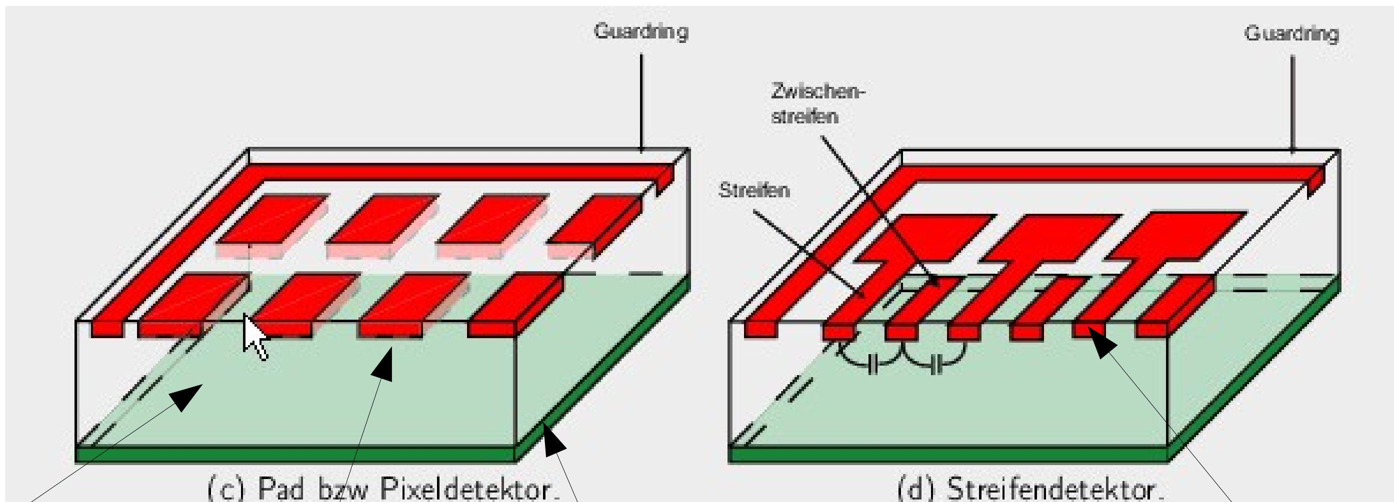
  → amplification and read-out separated

Semiconductor: pn-junction



- pn-junction under reverse bias:
  - Extract electrons or holes present from doping
  - Provides electric field needed for charge drift and read-out

- Segmenting pn-junctions → position sensitivity



Detector volume (substrate)

Pixel electrodes

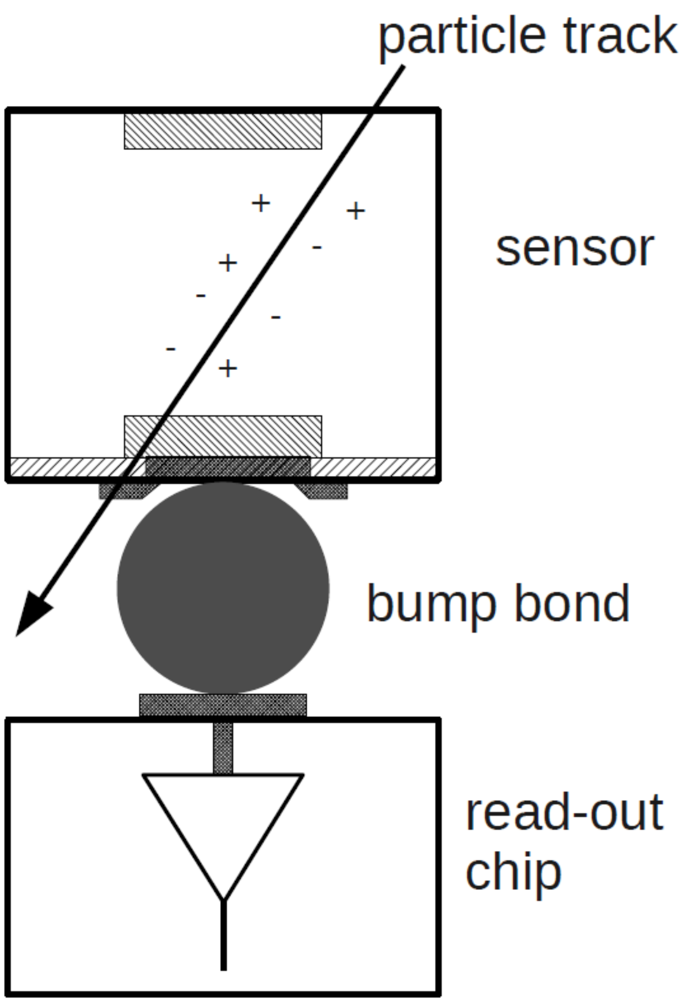
Backside electrode

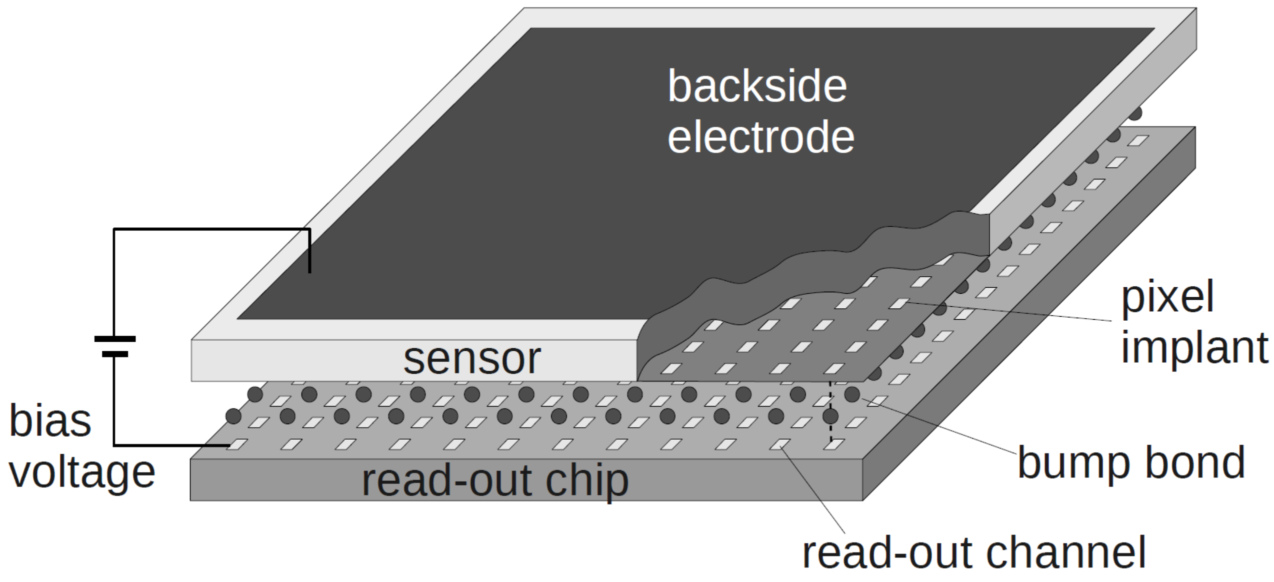
Strip electrodes

- NB: implants isolated from each other due to depletion zone around junction

Pixel Detector Read-out

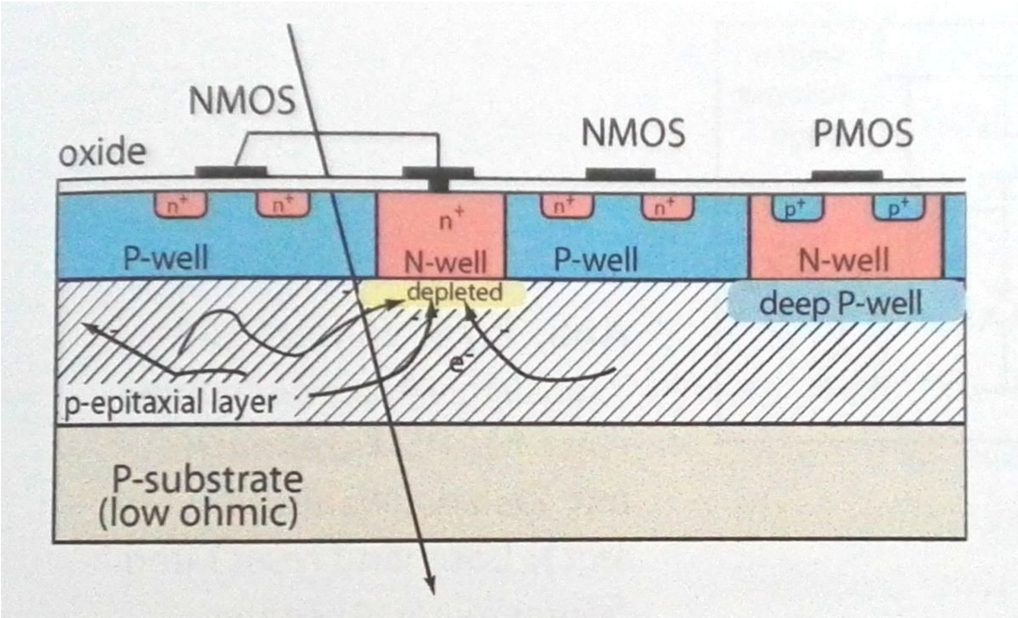
- 1:1 connection sensor segment to read-out cell
  → bump bonding





Active Pixel Detectors

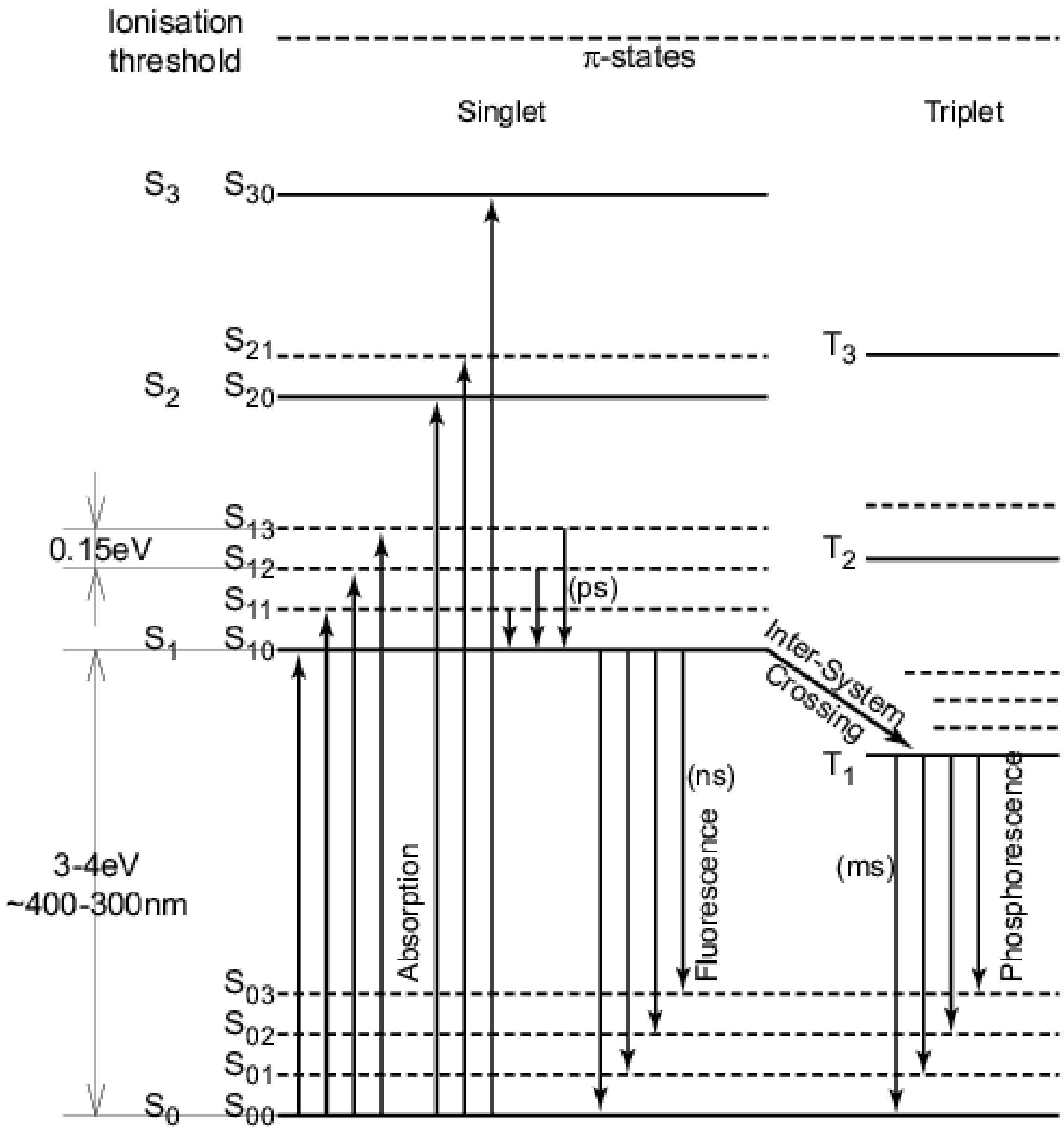
- Integrate detection into read-out chip: one device for sensing, amplification and digitisation
  - Based on standard electronics technology (CMOS transistors)
  - Add epitaxial Si layer (low doping) on top of highly doped layer



  - Layer with MOS transistors and collecting implant on top
  - e/h trapped in epi-layer to due doping differences → collected by diffusion into depletion zone → measurement → direct connection to amplifier

Light-based Detectors: Scintillation & Čerenkov Radiation

Scintillation

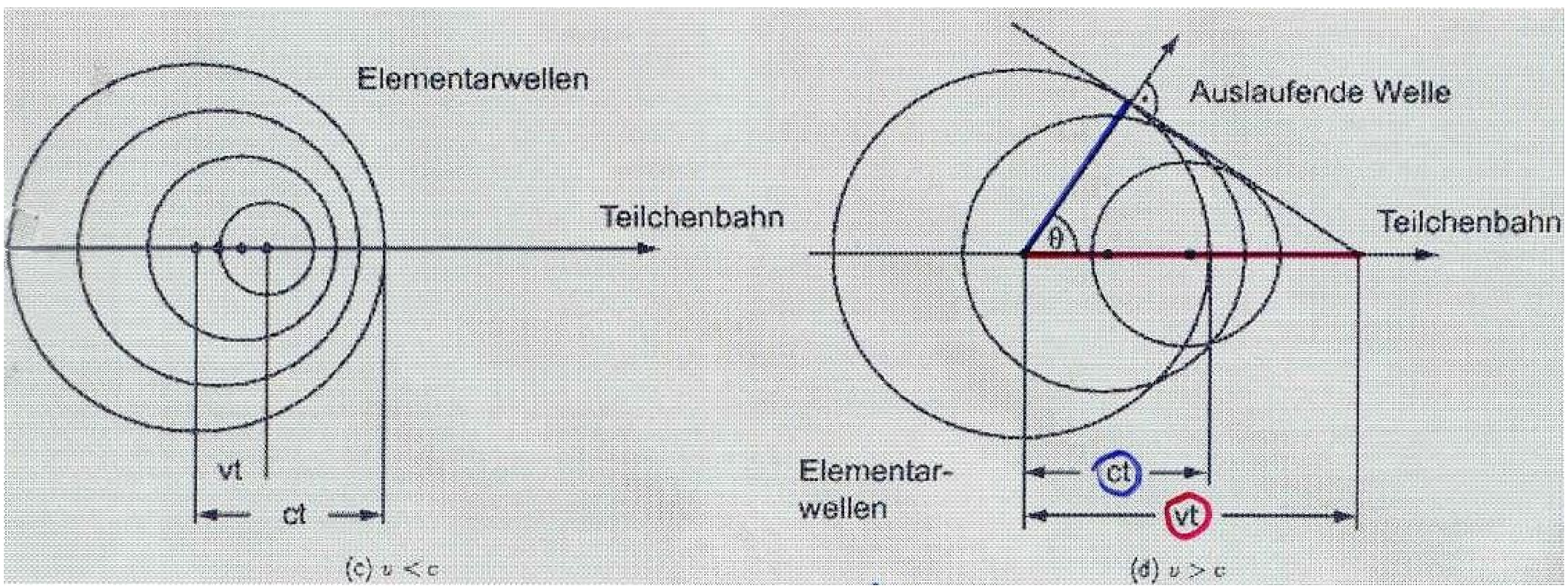


- Excitation from
  - Bethe-Bloch (chg. Particles)
  - Photo-electrons (→ detection of gammas)
  - Neutrons knocking off protons

results in de-excitation → scintillation light

- Particle travels with speed $v>c_m=c/n$ (speed of light in medium) → light is emitted

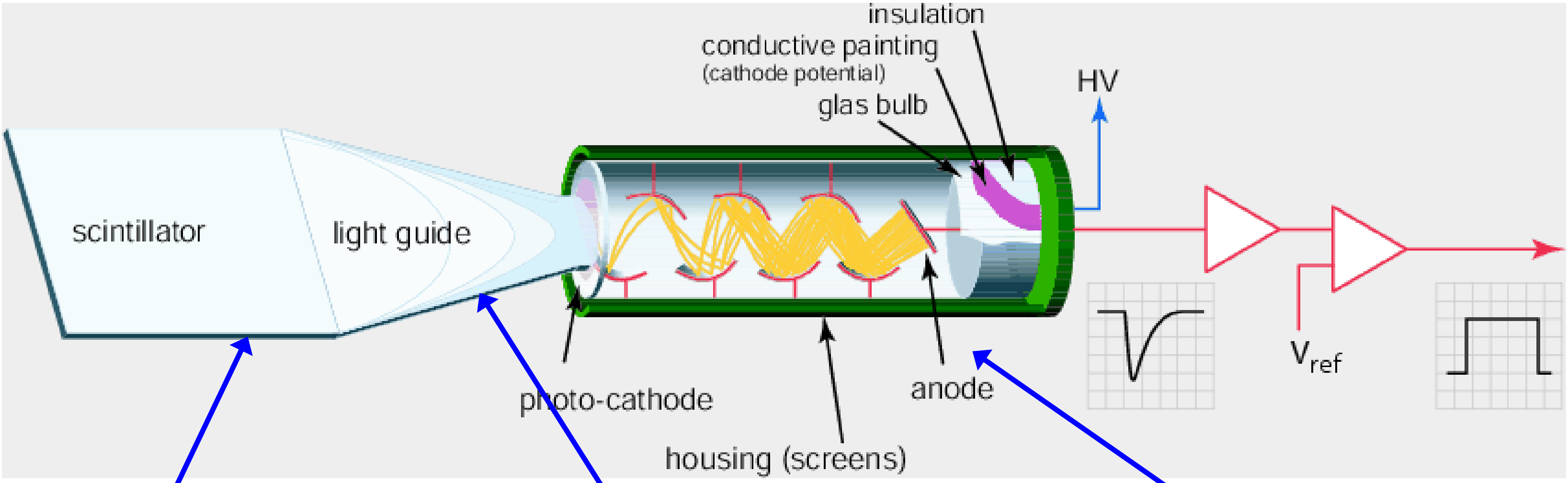
$v \ll c_m$ $v > c_m$



destructive interference

Mach-like shock wave → constructive interference

Light Readout: PMT, APD

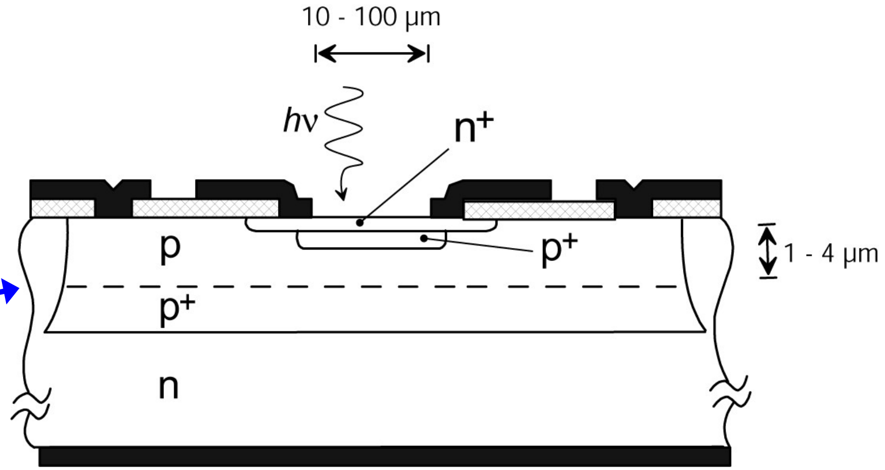


(in-)organic material → scintillation or Čerenkov light

Light guide → connection to PMT

Photo multiplier tube (PMT) → signal amplification

Alternative to PMT: silicon pn-junction with amplification (avalanche photo diode, APD)

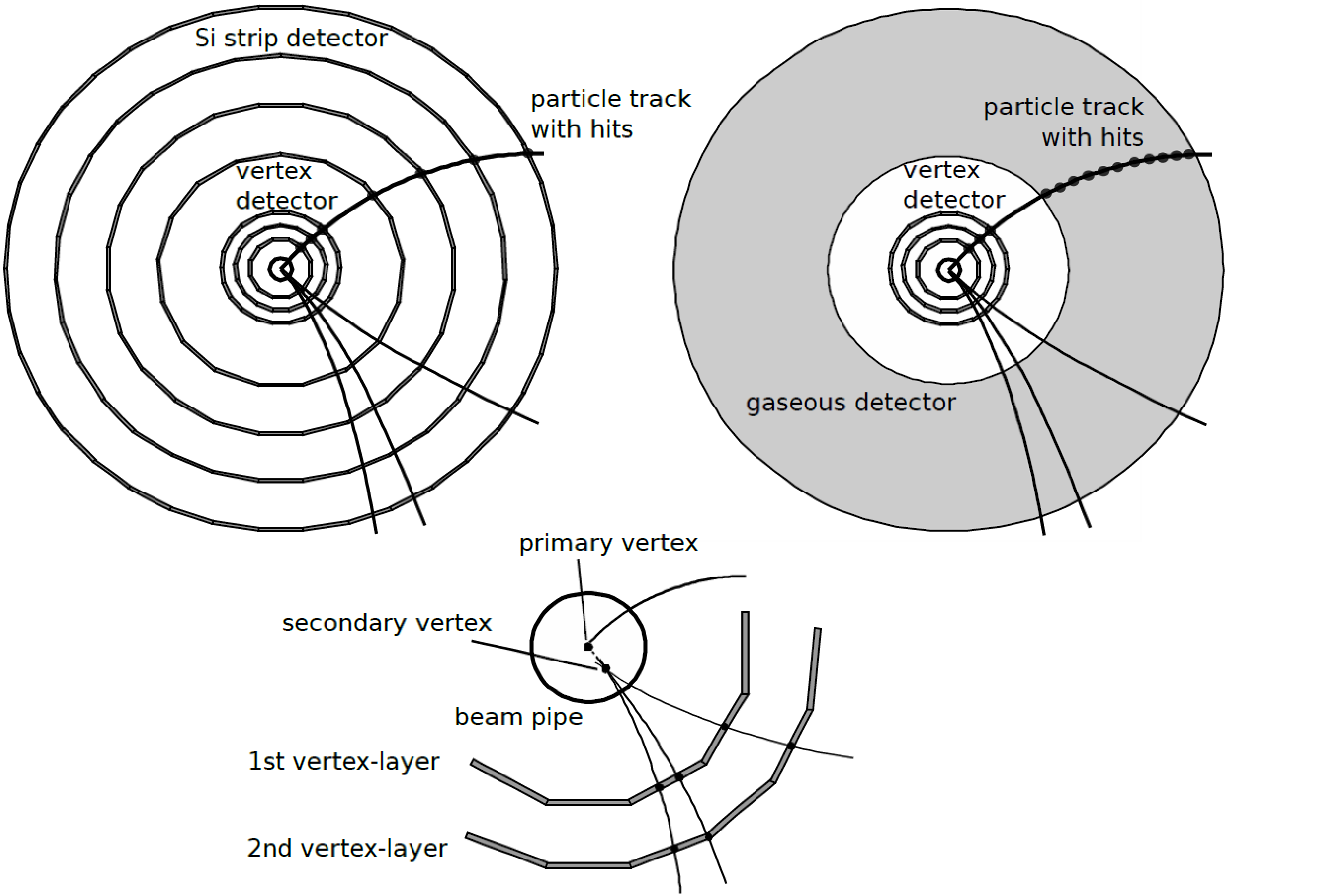


Tracking

Aim of Trackers

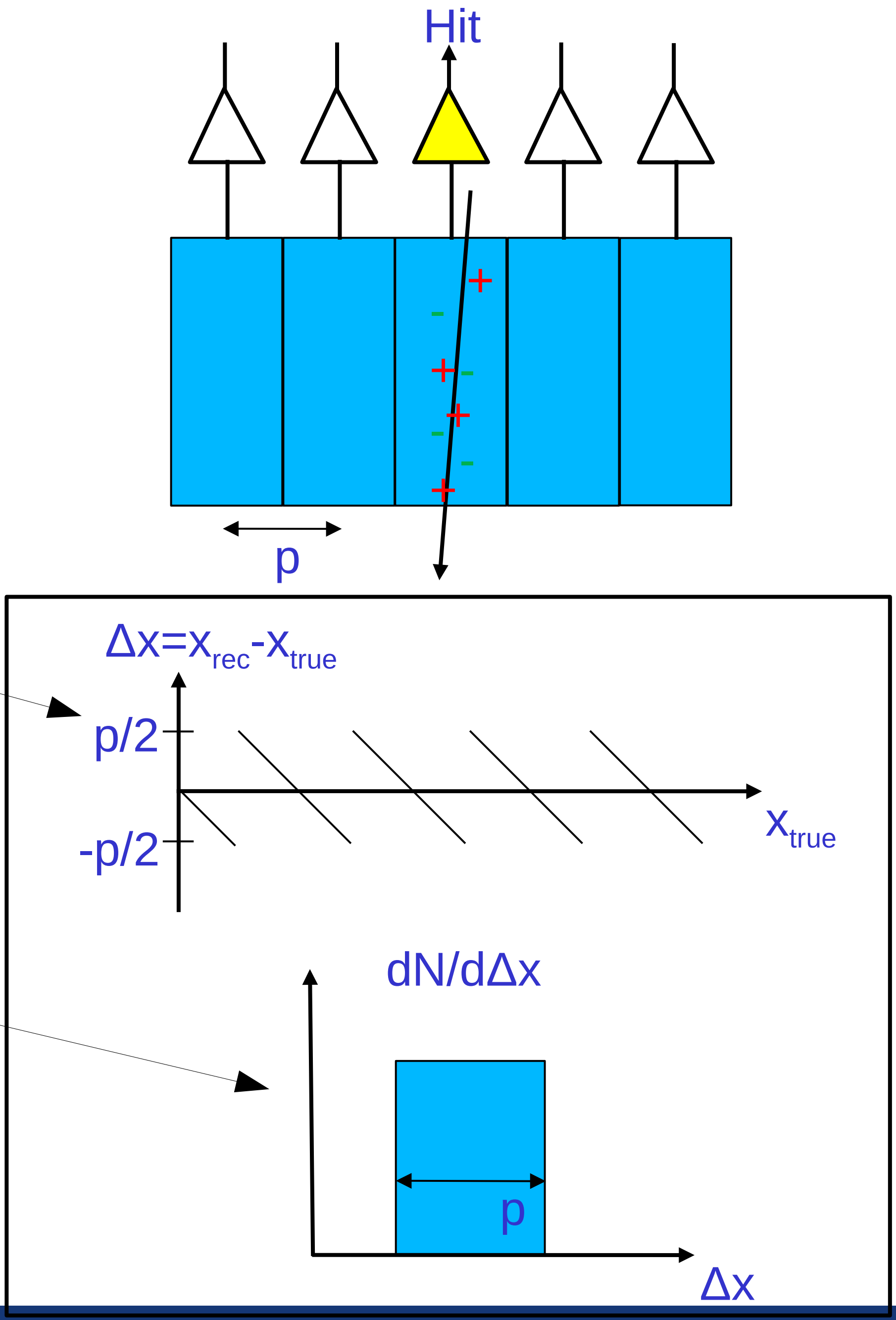
- Measure trajectory of charged particles
  - Measure several points along the track ("hit") and fit curves to the points (helix)
- Use the track curvature in magnetic field to determine the particle momentum and charge
- Extrapolate tracks to the point of origin
  - Determine positions of primary vertices and identify collision vertex
  - Find secondary vertices from decay of long-lived particles (lifetime tagging)

Tracking Concepts



Single Point Resolution (1)

- Simple case: only single hit segment
- Default hit position: centre of segment
- Reconstruction error ("residual") varies with true hit position
- Flat hit probability: residual distribution is a box diagram



Single Point Resolution (2)

- Reconstruction error = std. deviation defined by probability distribution
- Normalised box distribution centred around 0 with width p:

$$\sigma_x = \sqrt{\frac{1}{p} \int_{-p/2}^{p/2} x^2 \, dx} = \frac{p}{\sqrt{12}}$$

- Worst possible resolution with pure binary readout
  - Value improves if several segments are hit per track: weighting with pulse height information

Pulse Height Weighting

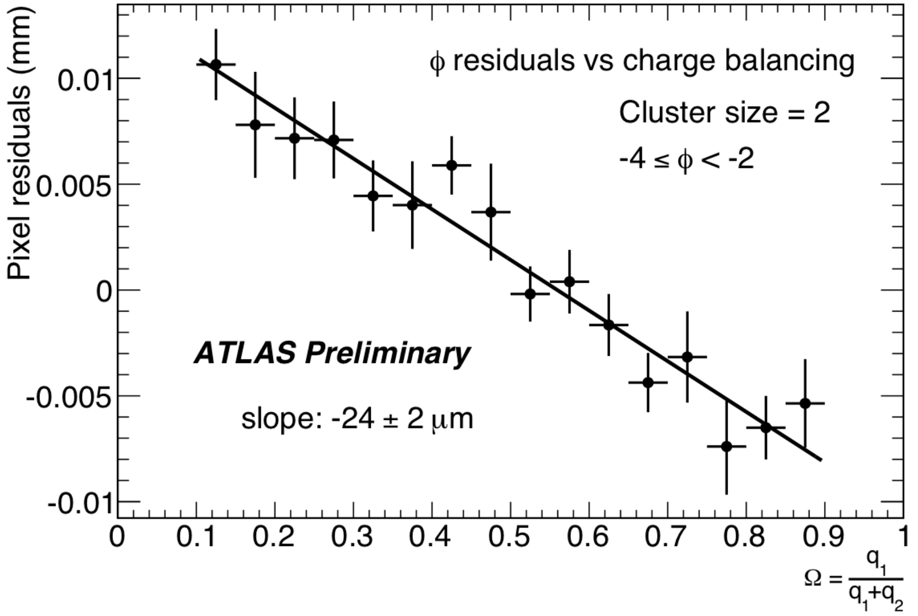
- Simplest method: linear interpolation, using the charge deposited in the edge pixels of the cluster:

$$\Omega = \frac{q_{last}}{q_{first} + q_{last}}$$

- Hit position: reconstructed from geometrical centre of the cluster and Ω:

$$x = x_{centre} + \Delta_x \left(\Omega_x - \frac{1}{2} \right)$$

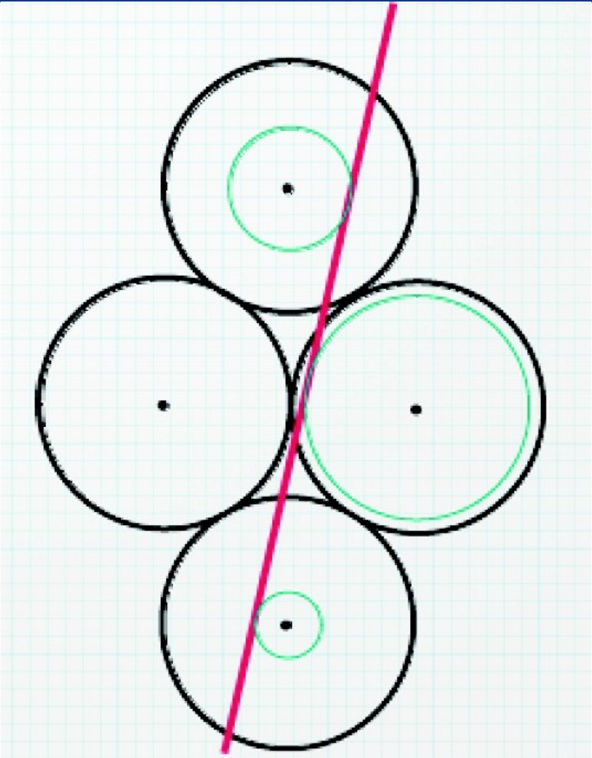
- Δ_x calibrated from data (plotting residual vs. charge sharing)

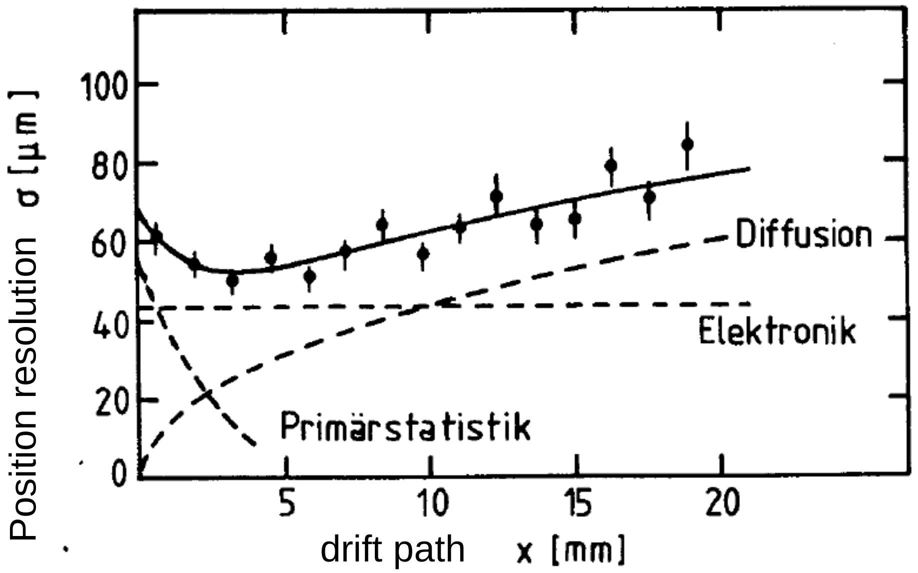


Drift detectors

- Resolution < $p/\sqrt{12}$ if using drift time:
  - Precise measurement of arrival time of charge signal
  - Known electric field → drift velocity $\vec{v} = \mu \vec{E}$ is known

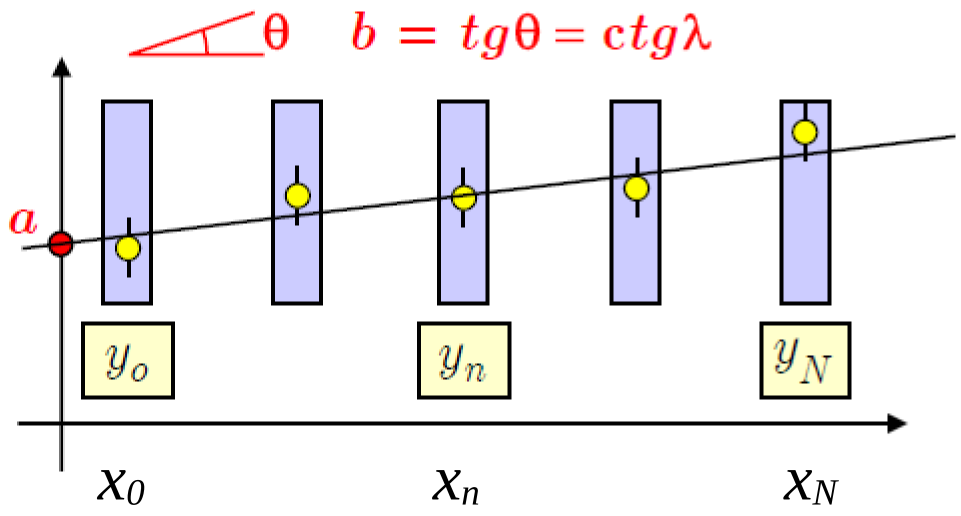
    → determine distance of ionisation location from electrode
  - Precision driven by timing resolution and smearing due to diffusion





From Hits to a Track

- Simple example: straight line fit
  (a track is of course more complex)
  - Measured positions y_i with single point resolution as before
  - χ^2 minimisation with $y_n = a + bx_n$: $\chi^2 = \sum_{n=0}^{N} \frac{(y_n - a - b x_n)^2}{\sigma_n^2}$
  - Errors on a, b from covariance matrix
- Similar approach for real tracks → allows error calculation on track parameters



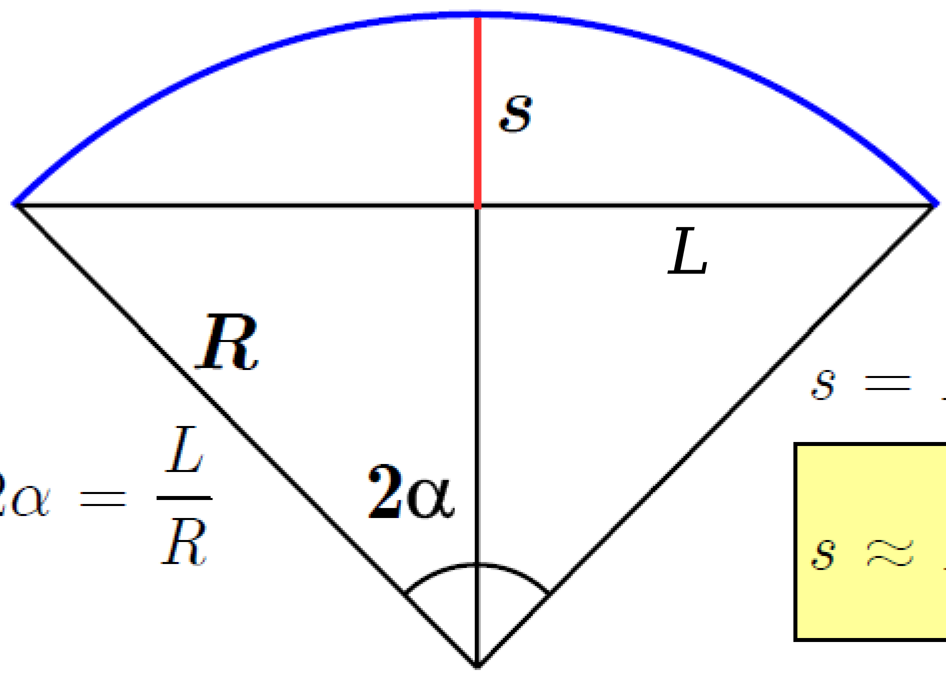
Momentum Resolution

- Bending in B-field

  → p_T (GeV/c) = 0.3·B(T)·R(m)

- Determine curvature from fit to N hit points → resolution in p_T?

described by sagitta s



$$2\alpha = \frac{L}{R}$$

$$s = R\,(1 - \cos\alpha\,)$$

$$s \approx R\frac{\alpha^2}{2} = \frac{L^2}{8R}$$

Gluckstern Formula

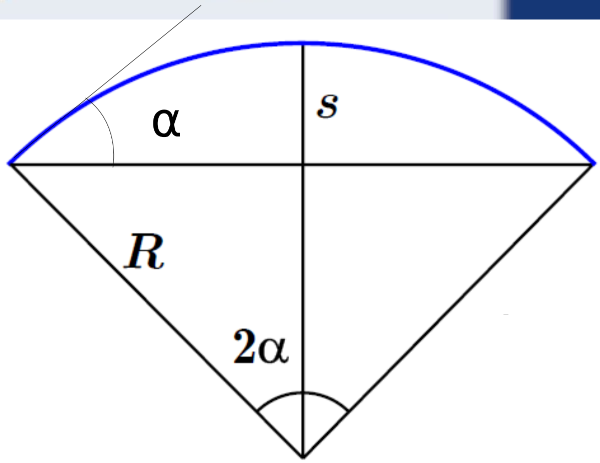
- Error calculation by Gluckstern: approximate curved track by parabolic fit
  - Points on track (x,y) with $y = ½\, k\, x^2$
  - From picture: $s = ½\, k\, (L/2)^2 \rightarrow R = k^{-1}$

    $\rightarrow p_T = 0.3 \cdot B/k \rightarrow \sigma_{pT} = 0.3 \cdot B \cdot \sigma_k / k^2 = p_T^2 / 0.3 \cdot B \cdot \sigma_k$
  - For large N and equal errors σ_{point} on spatial hit position:

$$\sigma_k = \frac{\sigma_{\text{point}}}{L^2}\sqrt{\frac{720}{N+4}}$$

$$\rightarrow \quad \frac{\sigma_{pT}}{p_T} = \frac{p_T \sigma_{\text{point}}}{0.3\, B\, L^2}\sqrt{\frac{720}{N+4}}$$

Momentum: Multiple Scattering



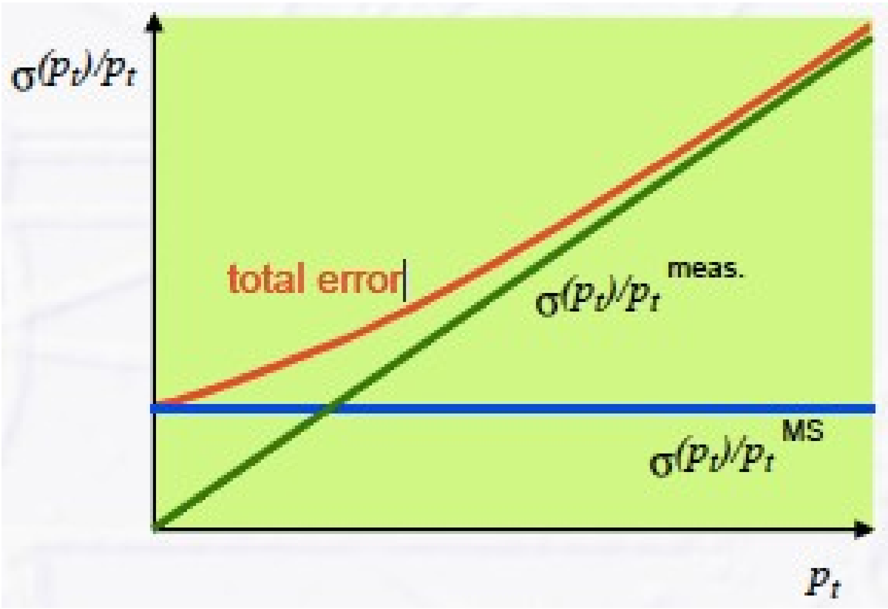
- Adds in quadrature to intrinsic resolution → MS dominates at low p_T, intrins. part at high p_T

- $p_T = 0.3 \cdot B \cdot R = 0.3 \cdot B \cdot L/(2\alpha)$

- $\sigma_\Theta \propto 1/p_T$ from MS translates into σ_α

$$\sigma_{pT}^{MS} = \frac{0.3\,BL}{2\,\alpha^2}\sigma_\alpha \rightarrow \frac{\sigma_{pT}^{MS}}{p_T} = \frac{27.2\,\mathrm{MeV}}{0.3\,B\sqrt{L\,X_0}}$$

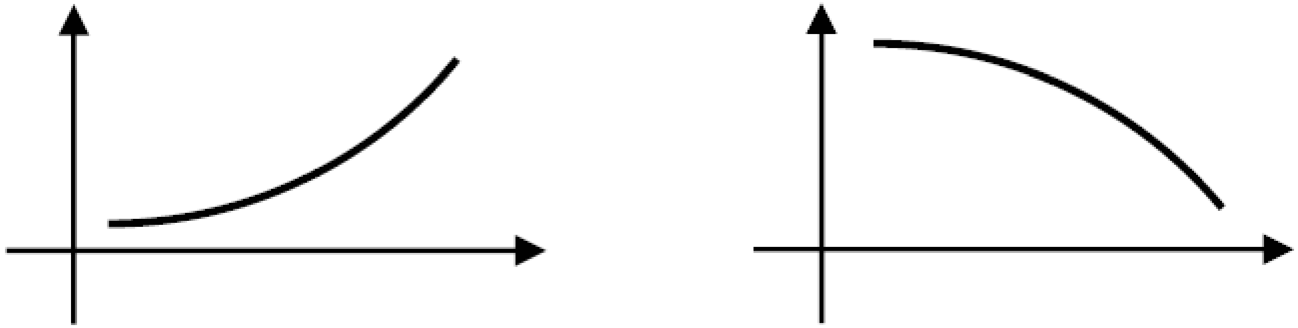
const. in p_T



Sign of Charge

- Sign of charge is defined by the sign of 1/R=k:

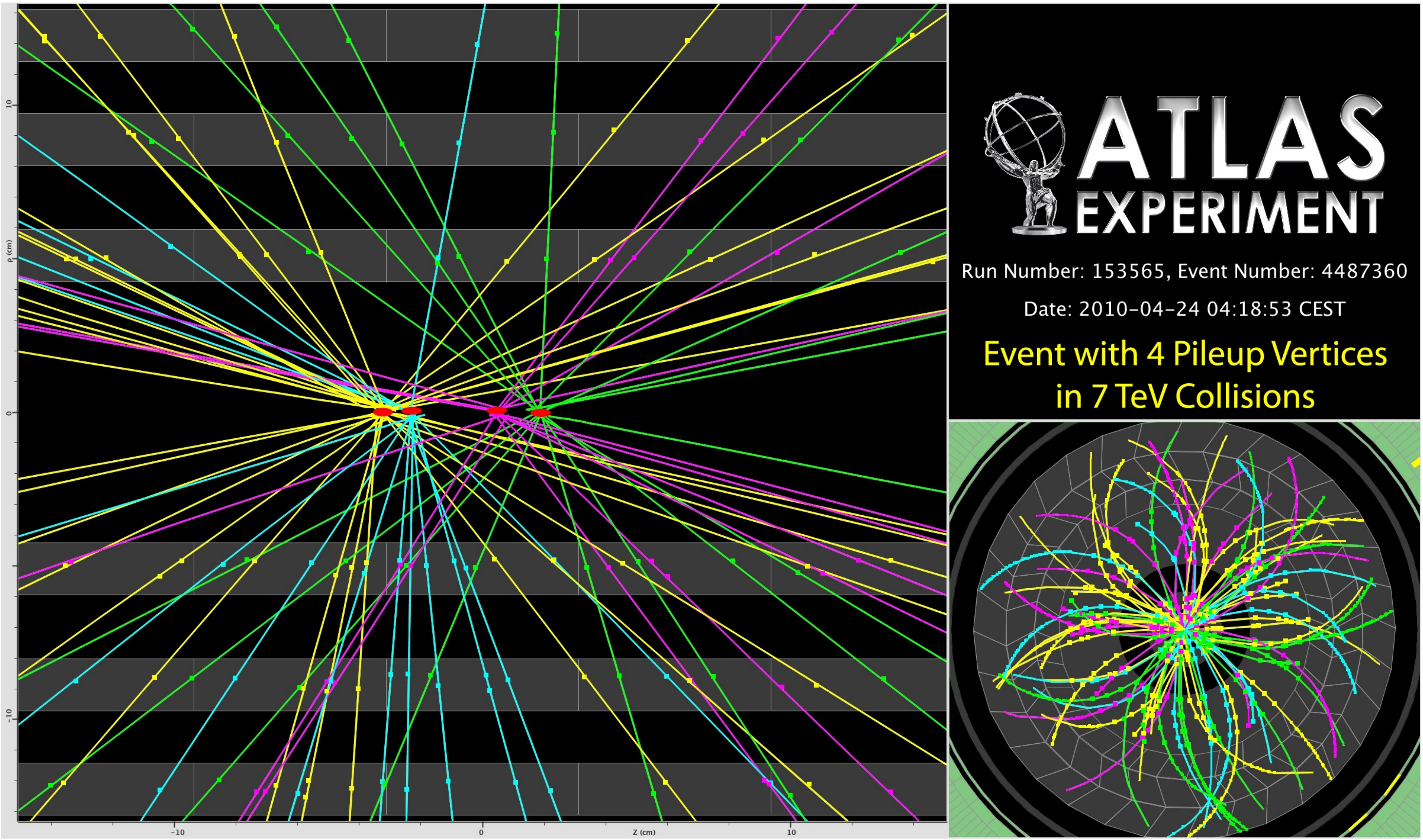
$$Q = +1 \quad \frac{1}{R} > 0 \qquad\qquad Q = -1 \quad \frac{1}{R} < 0$$



- Precision on k from Gluckstern: $\sigma_k = \frac{\sigma_{\text{point}}}{L^2}\sqrt{\frac{720}{N+4}}$
- Requiring 3σ identification → upper lim. in p:

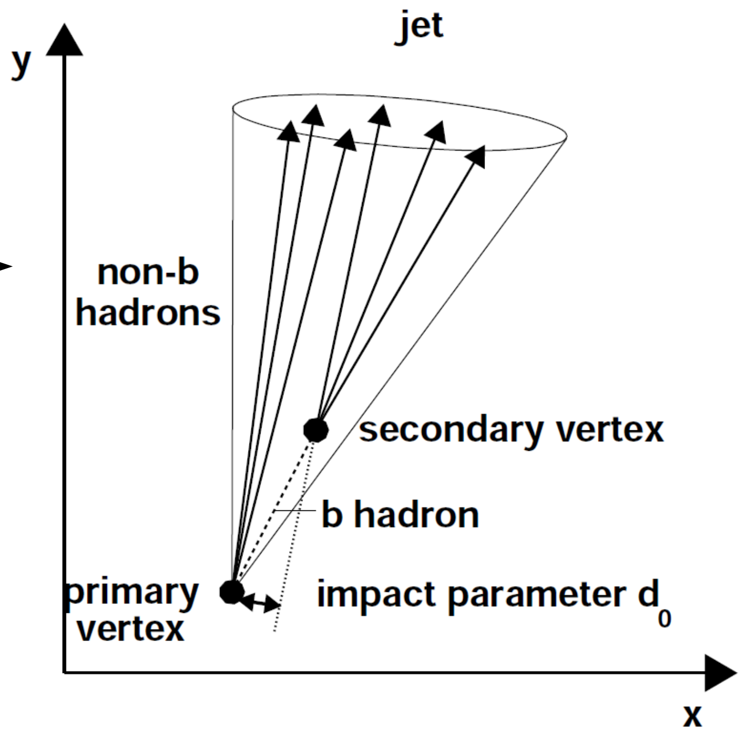
$$\left|\frac{1}{R}\right| > 3\sigma_k = \frac{3\sigma_{\text{point}}}{L^2}\sqrt{\frac{720}{N+4}} \Rightarrow p < \frac{0.3 B L^2}{3\sigma_{\text{point}}}\sqrt{\frac{N+4}{720}}$$

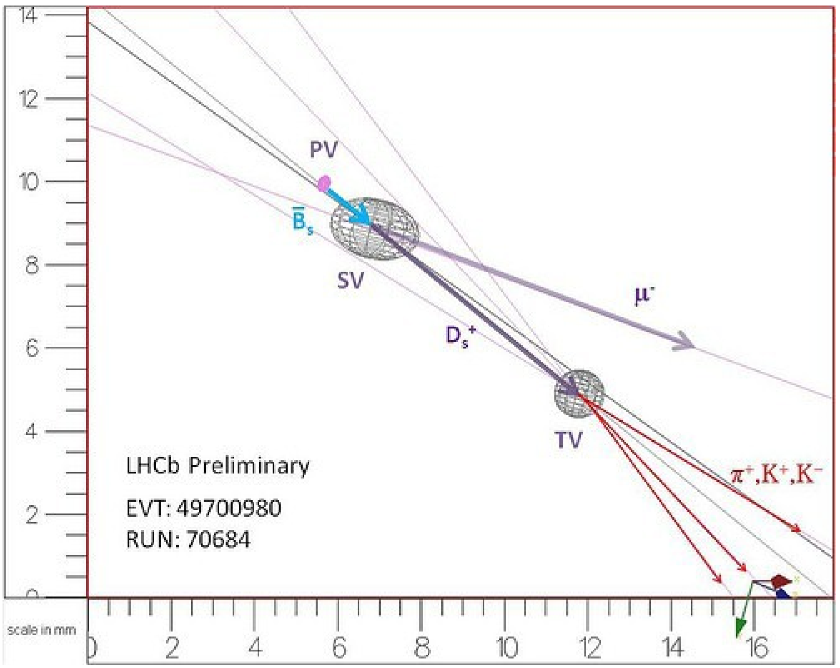
Primary vertices



Lifetime Tagging

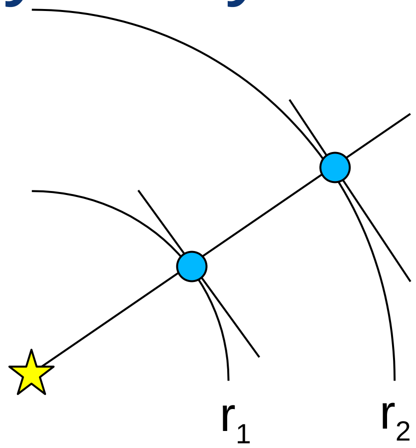
- Tracks from secondary vertex have significant impact parameter with respect to primary vertex





- Example of a fully reconstructed event from LHCb with primary, secondary and tertiary vertex

- Simple case: Two tracking layers at radii r_1 and r_2, extrapolation to r = 0 (intercept theorem) – if uncertainty in layer 1 only:



$$\sigma_{d_0} = \frac{r_2 \sigma_1}{r_2 - r_1}$$

similarly from layer 2 only:

$$\sigma_{d_0} = \frac{r_1 \sigma_2}{r_2 - r_1}$$

- Added in quadrature:

$$\sigma_{d_0}^2 = \frac{r_2^2 \sigma_1^2 + r_1^2 \sigma_2^2}{(r_2 - r_1)^2}$$

Vertex: Multiple Scattering

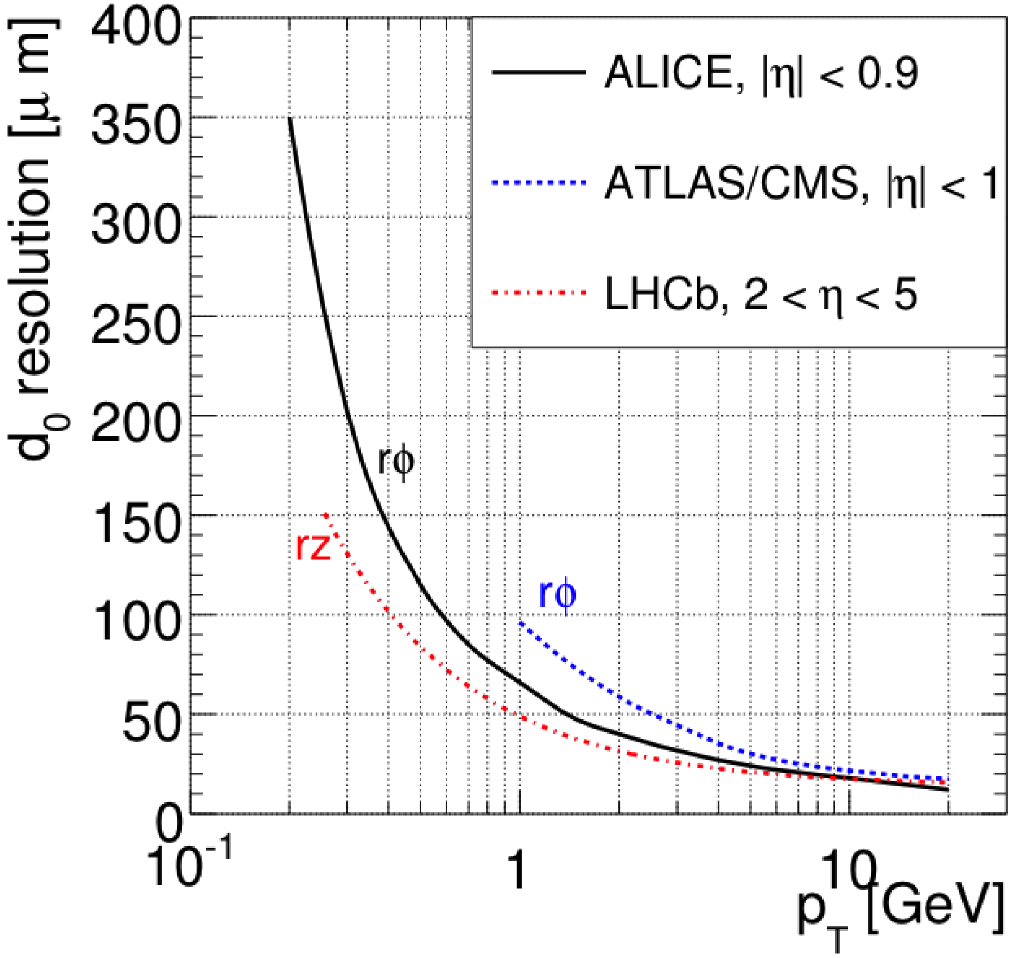
- Additional contribution due to multiple scattering

$$\sigma_i \rightarrow \sigma_i \oplus \Delta r\, \sigma_\theta$$

with σ_Θ as for momentum

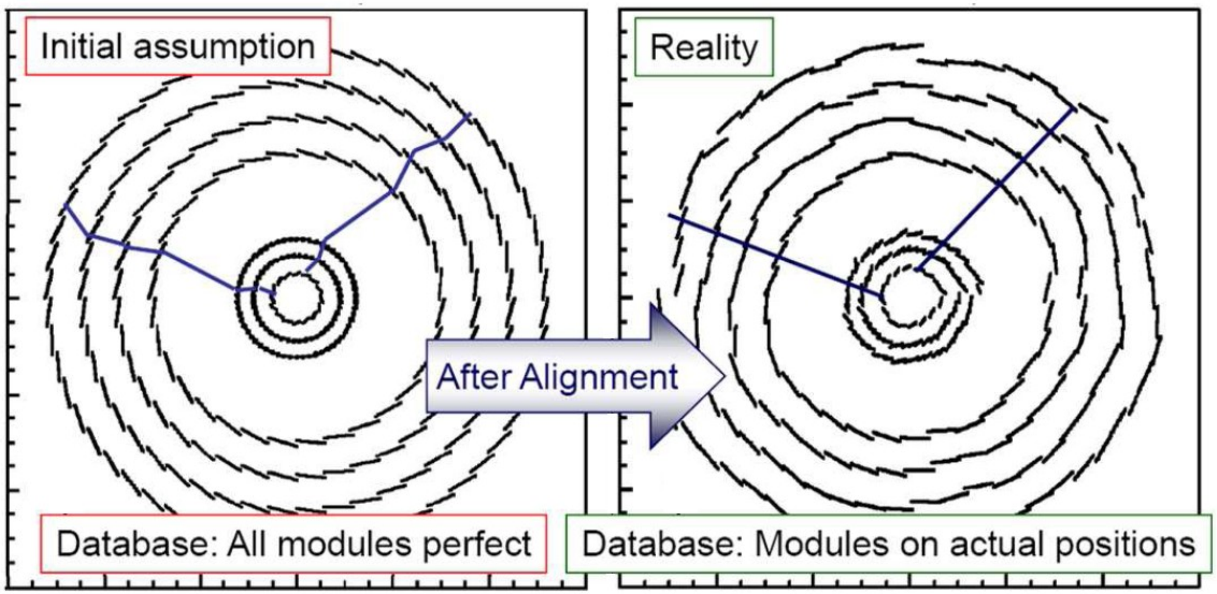
- Results in

$$\sigma_{d_0} = \frac{\sqrt{r_2^2 \sigma_1^2 + r_1^2 \sigma_2^2}}{r_2 - r_1} \oplus \frac{\text{const.}}{p} \sqrt{\frac{x}{X_0}}$$



(Mis-)Alignment

- Track fit assumes a known position of detector elements
  - Typ. have systematic shifts due to distortion in mech. structures (twist, sagging, bending, …)
  - Impact on momentum and vertex reconstruction
- Correct for "broken" tracks → alignment

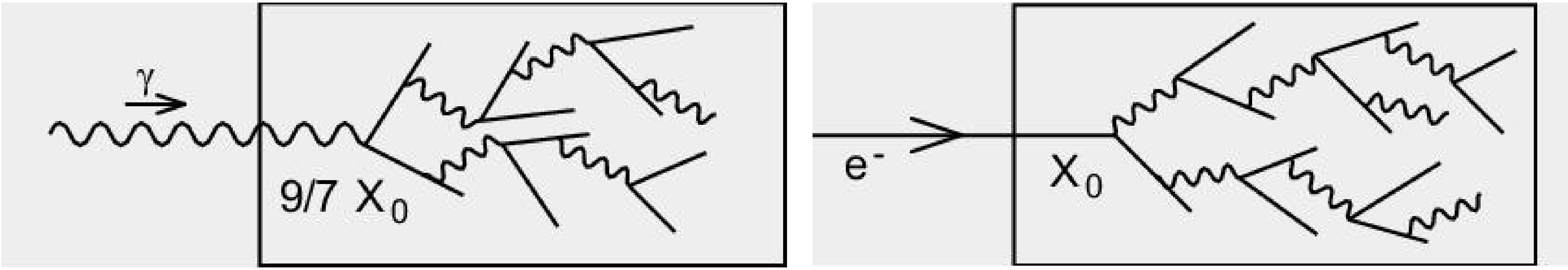


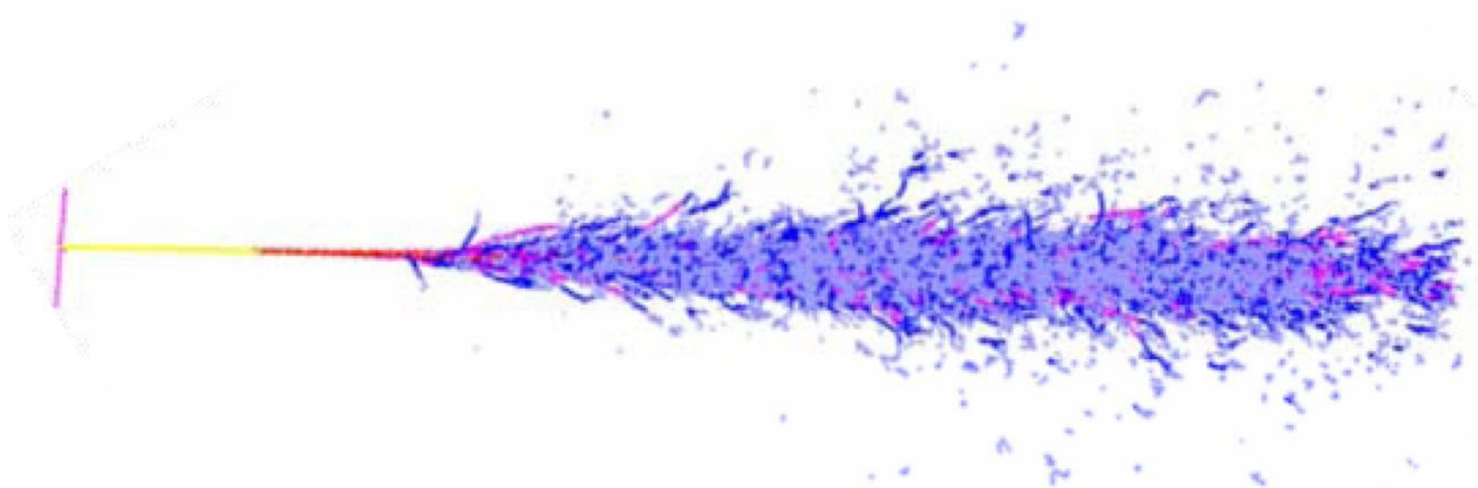
$$\sigma_{d_0} = \frac{\sqrt{r_2^2 \sigma_1^2 + r_1^2 \sigma_2^2}}{r_2 - r_1} \oplus \frac{\text{const.}}{p} \sqrt{\frac{x}{X_0}} \qquad \frac{\sigma_{pT}}{p_T} = \frac{p_T \sigma_{pt}}{0.3 B L^2} \sqrt{\frac{720}{N+4}} \oplus \frac{27.2\,\text{MeV}}{0.3 B \sqrt{L X_0}}$$

- Tracker design:
  - Vertex resolution: inner radius as small as possible with best point resolution, outer radius as large as possible
  - Momentum resolution: many points and long lever arm L
  - Both: as little material as possible
  - Limit 1 (Inner radius): Beam pipe, track density, radiation damage
  - Limit 2 (Outer radius): Cost

Calorimeters

Electromagnetic Shower (1)



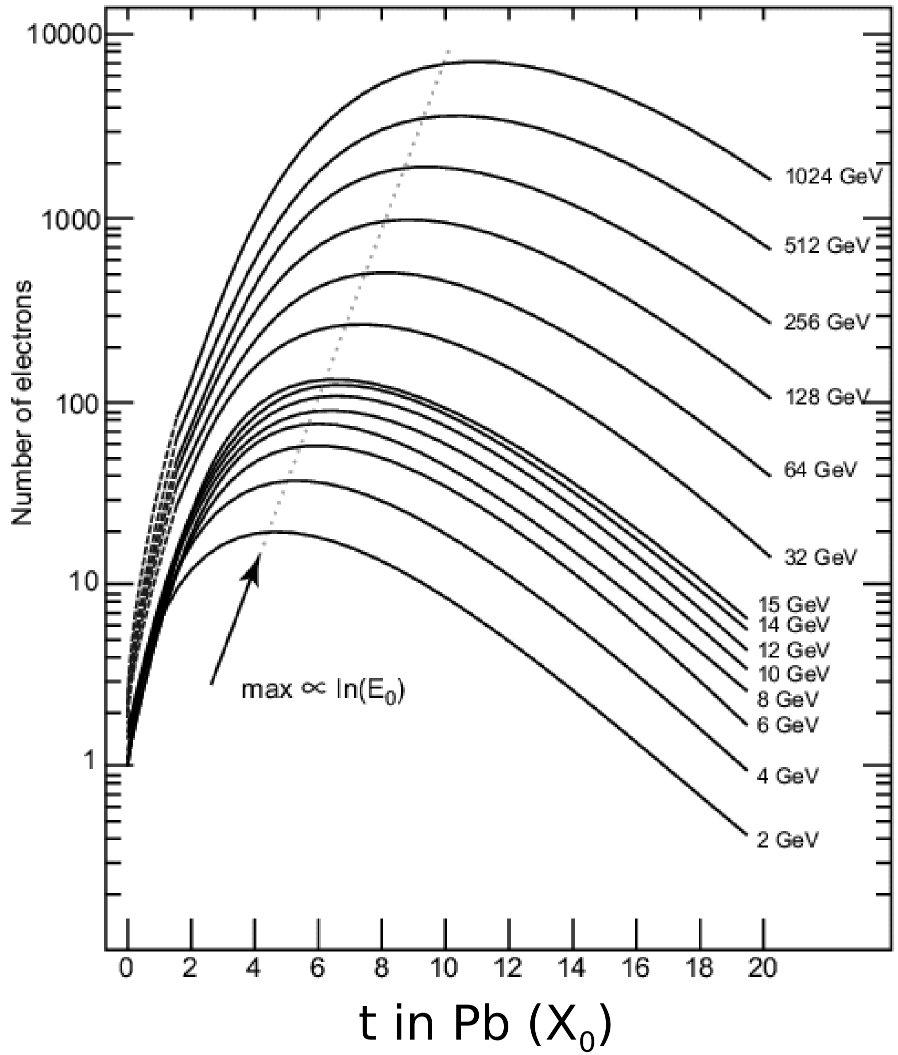


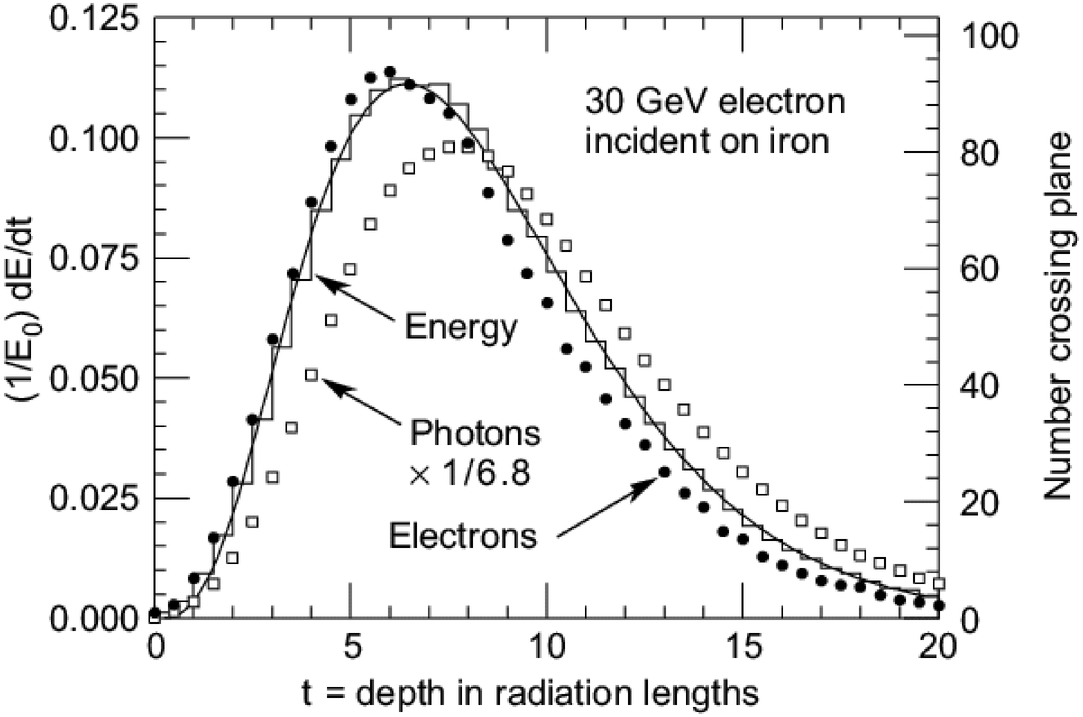
- Alternating Bremsstrahlung and pair creation
- Every ~X_0: doubling of no. particles N, ~halves energy per particle → N ∝ incid. Energy E_i

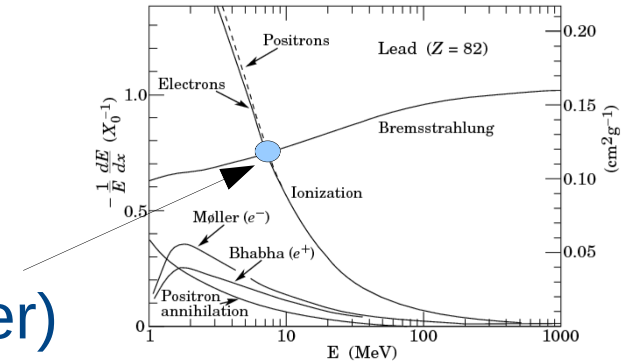
Electromagnetic Shower (2)

- 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 $N \propto E_i \rightarrow$ **Signal $\propto E_i$**
- Shower scales
  - Longitudinally with X_0, but only logarithmically in E_i
  - Laterally: scales with $R_M \sim ZX_0$

Longitudinal Profile

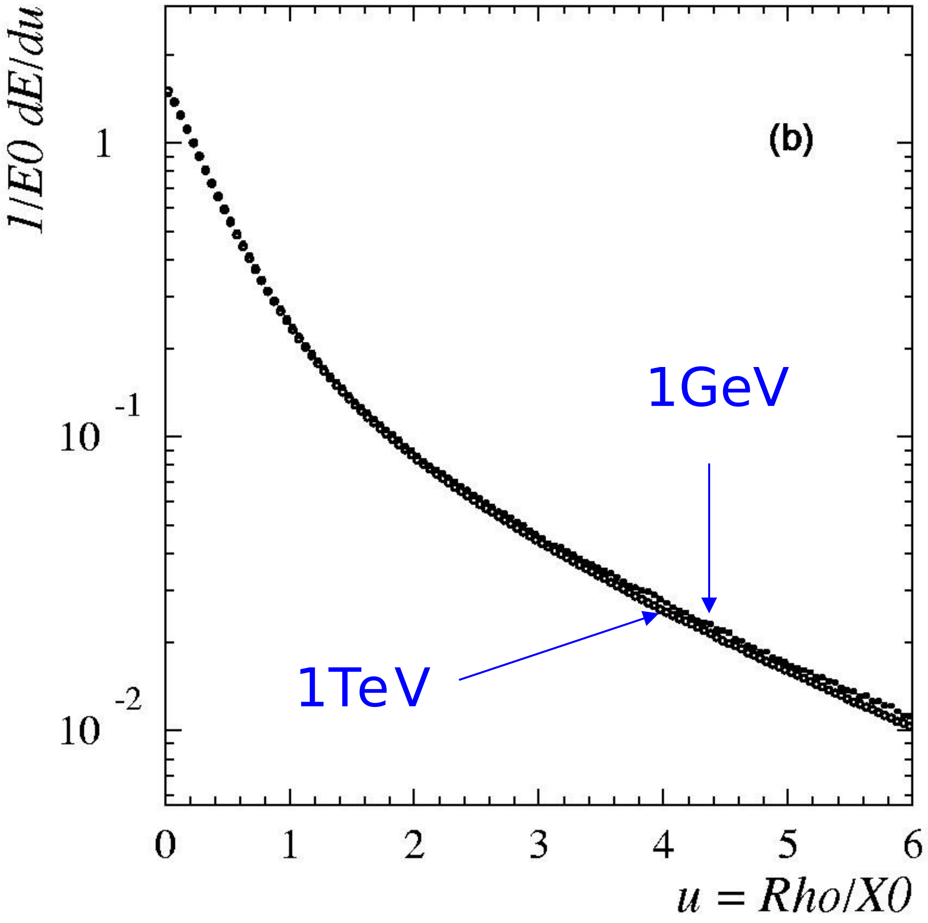


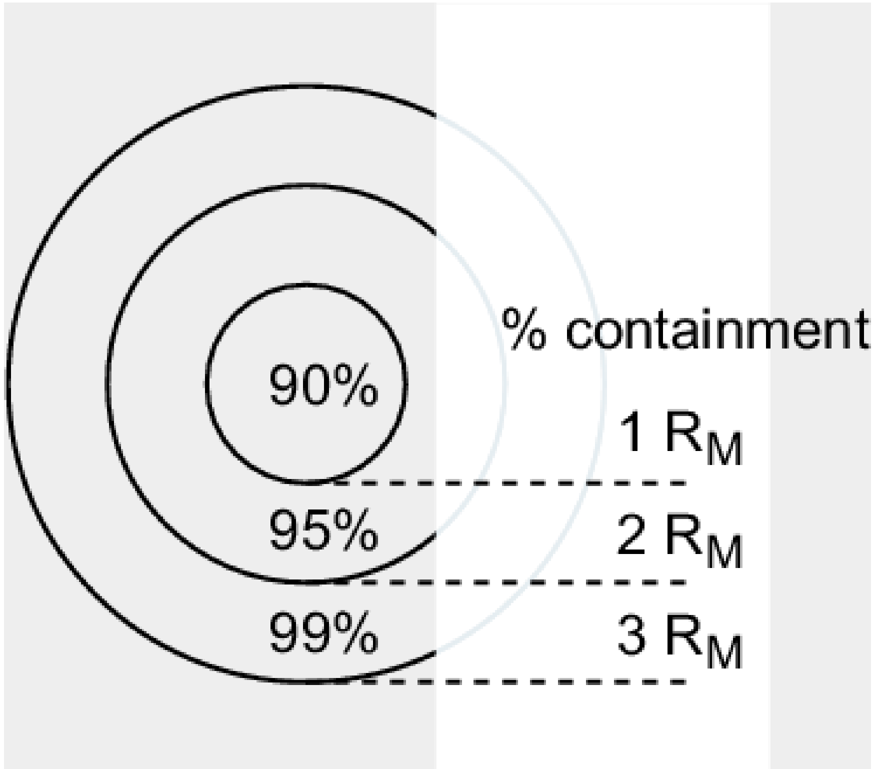




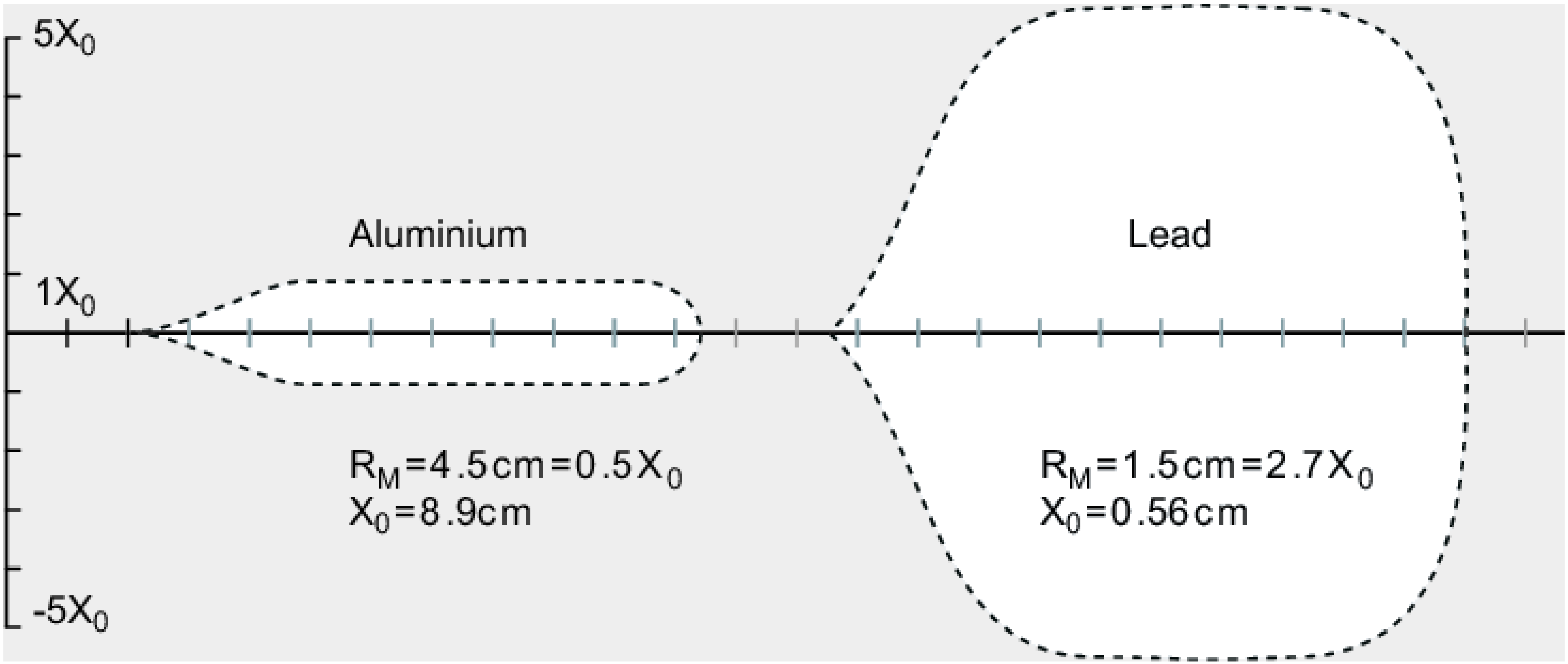
Shower proceeds until $E_e < E_c$ (ionisation takes over)

Transverse Profile





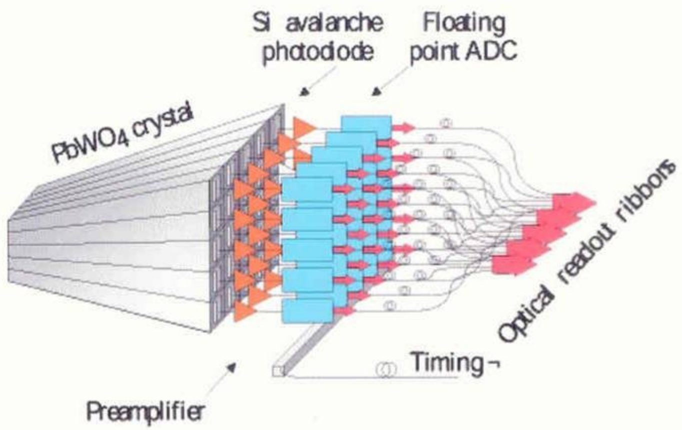
Overall Profile

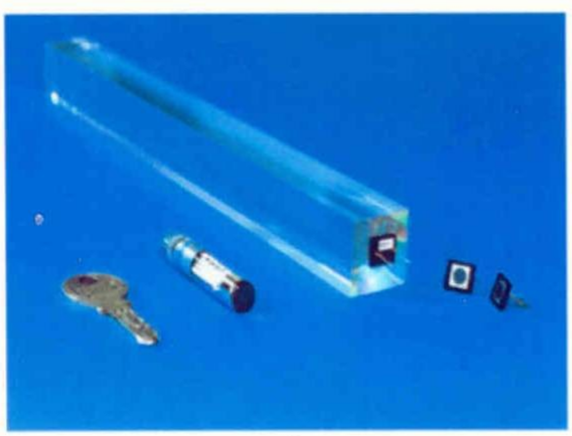


Calorimeter Types (1)

absorber & detector: the same

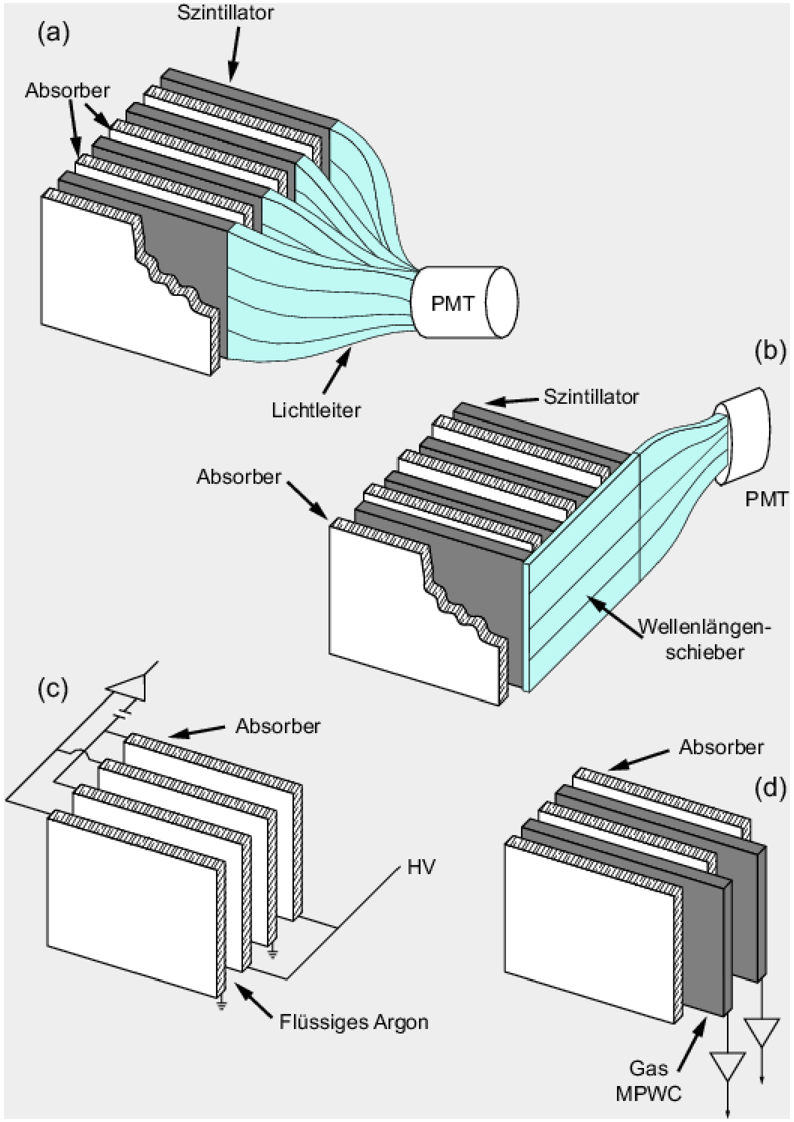
homogeneous





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)

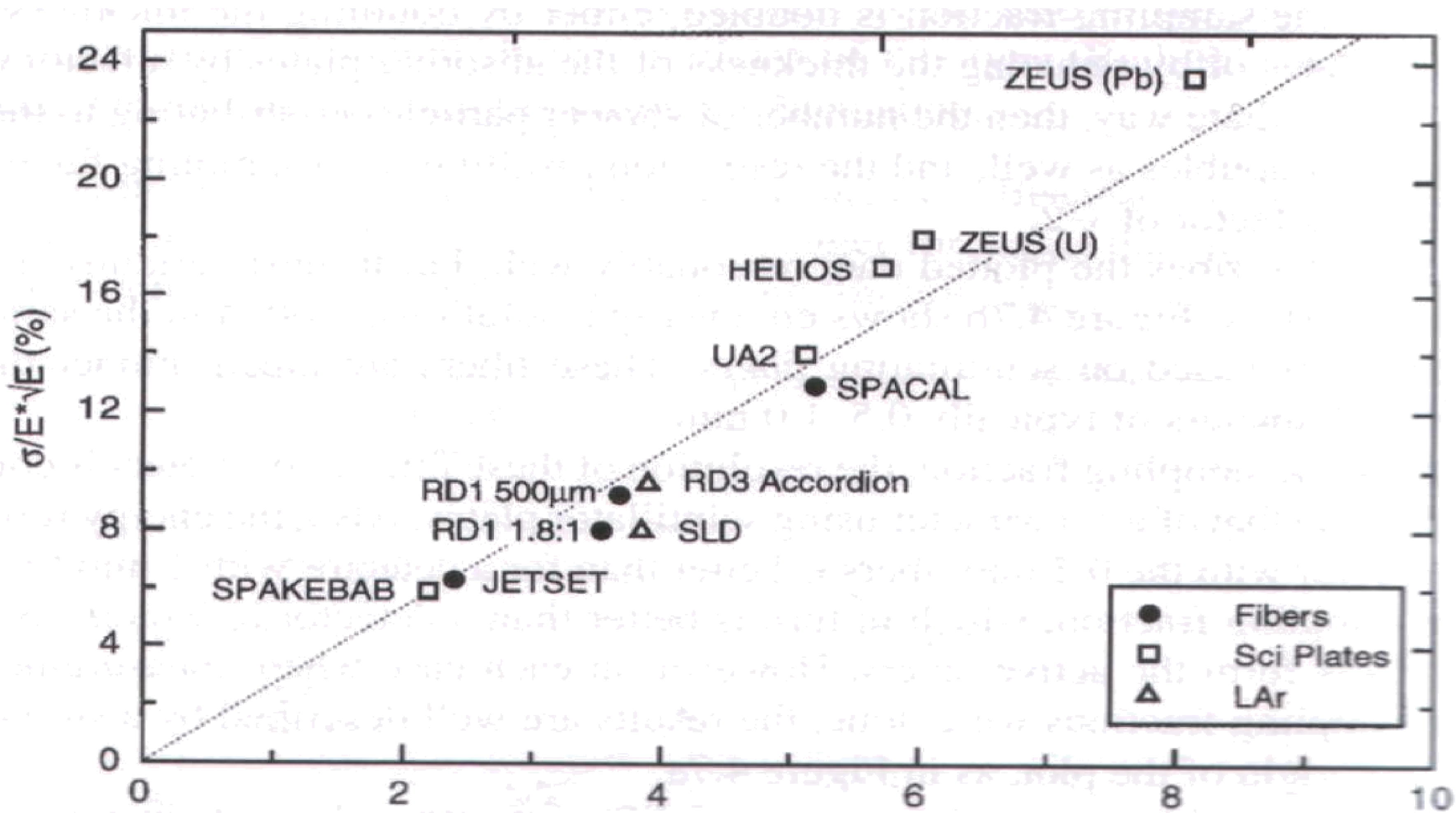
  \+ Absorber:
  - Fe, Pb, W, U
- Compact, easily segmented
- Poorer resolution

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

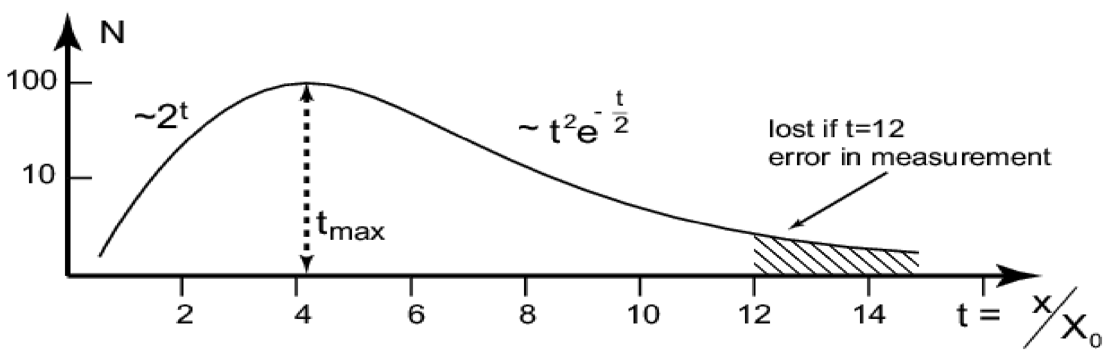


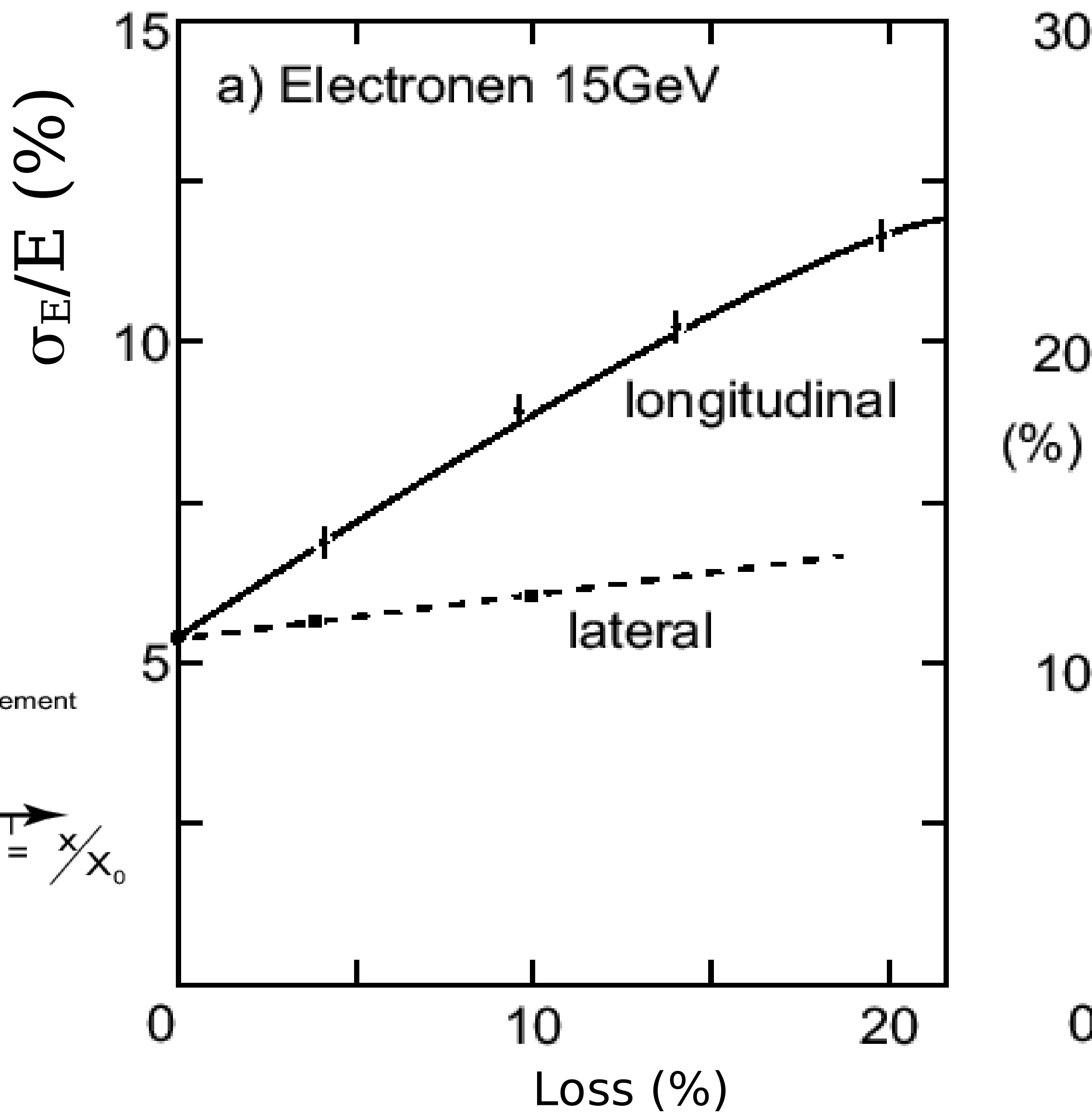
$\sqrt{d}$ (mm$^{1/2}$)

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 $\frac{\sigma_E}{E} \propto \text{const.}$

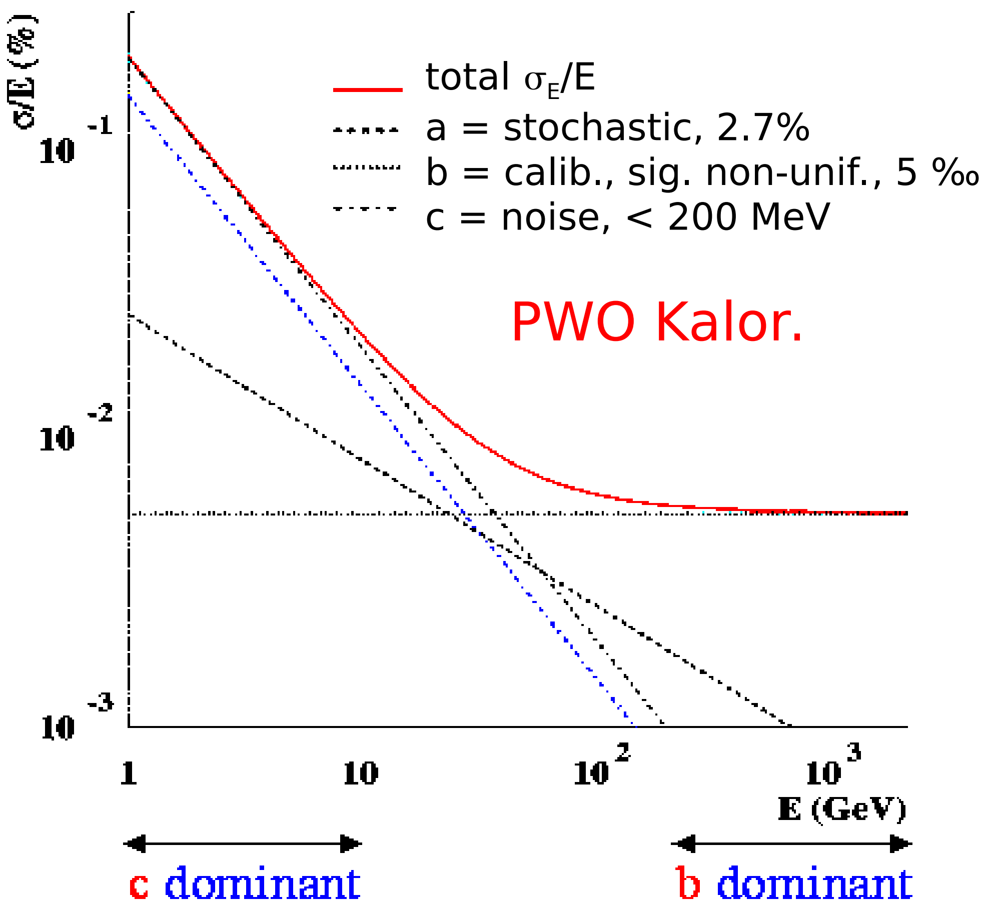
Leakage Effects



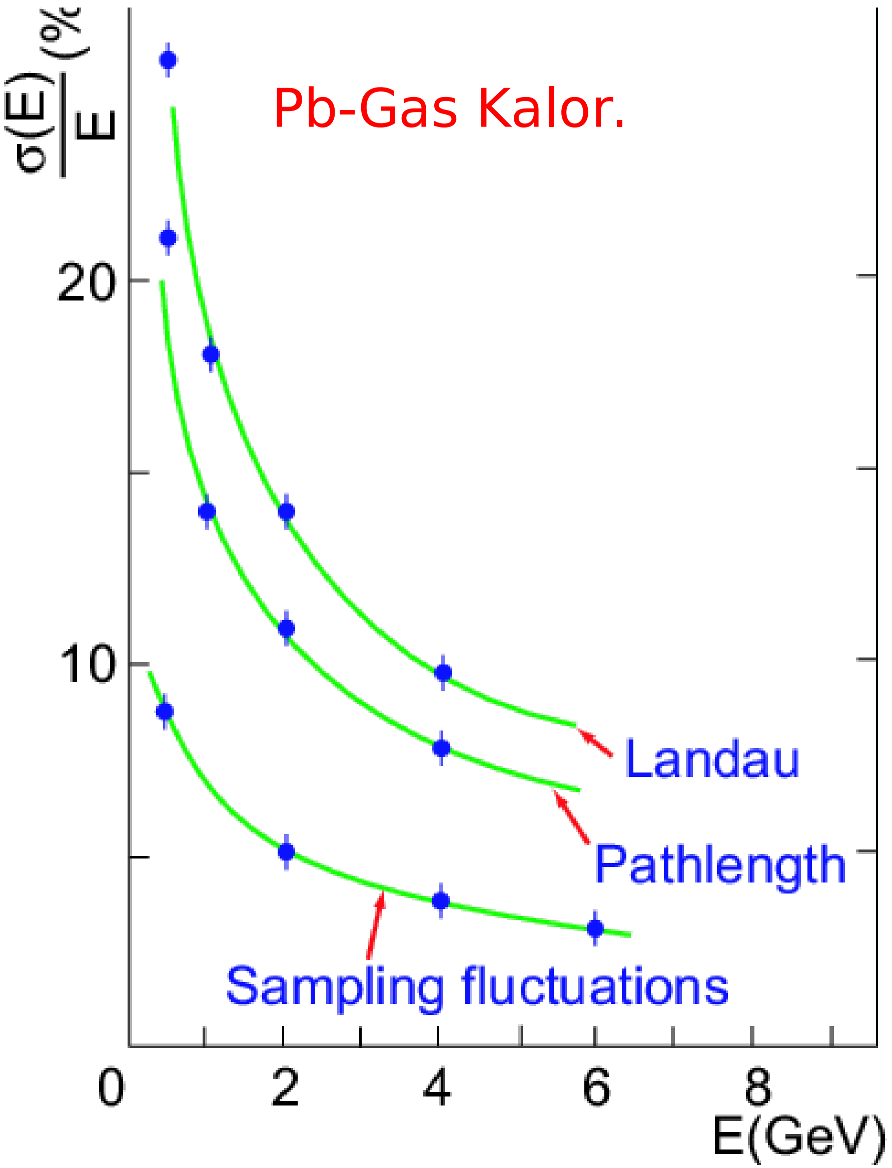


In total, we get:

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



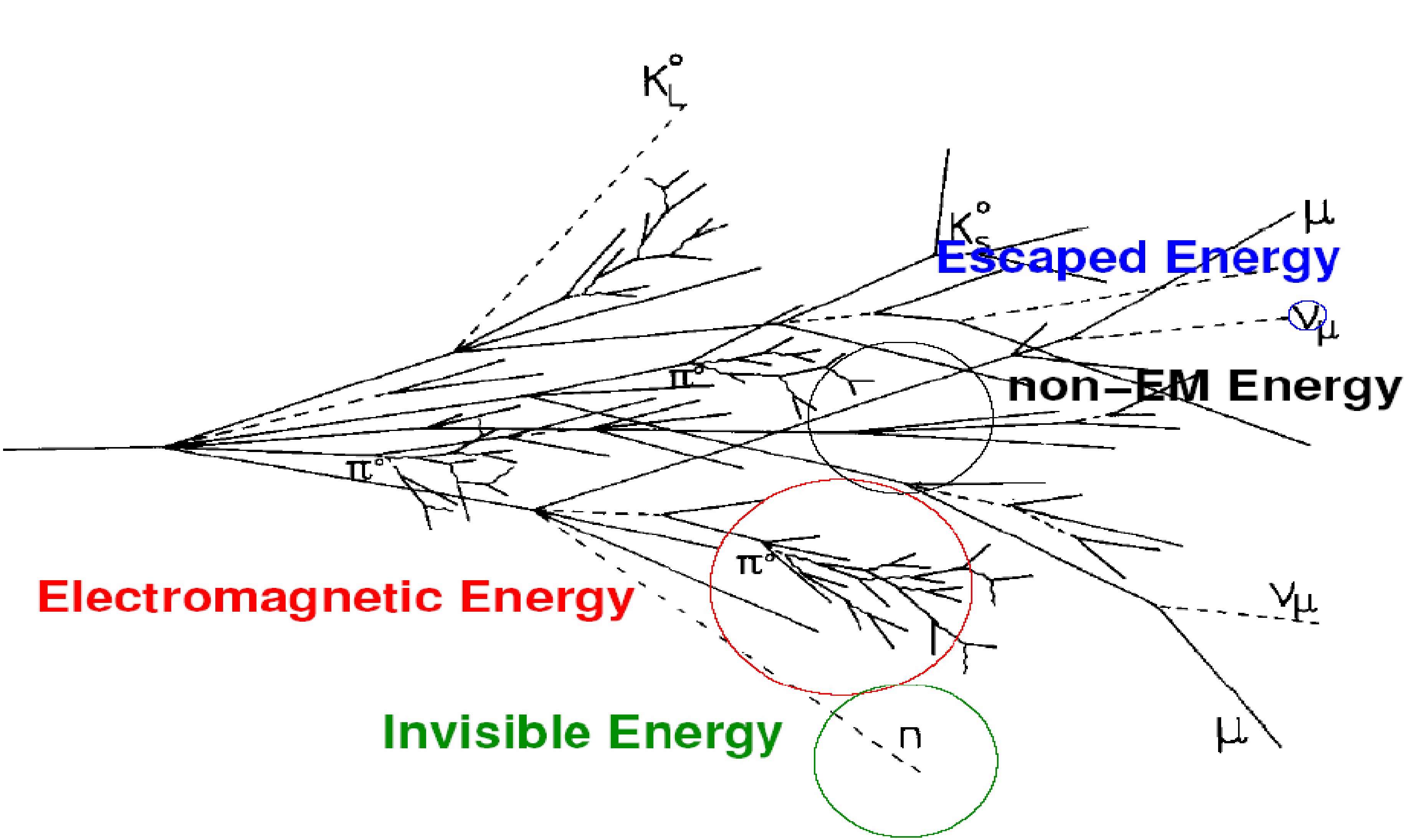
dominating term dep. on calor. type:



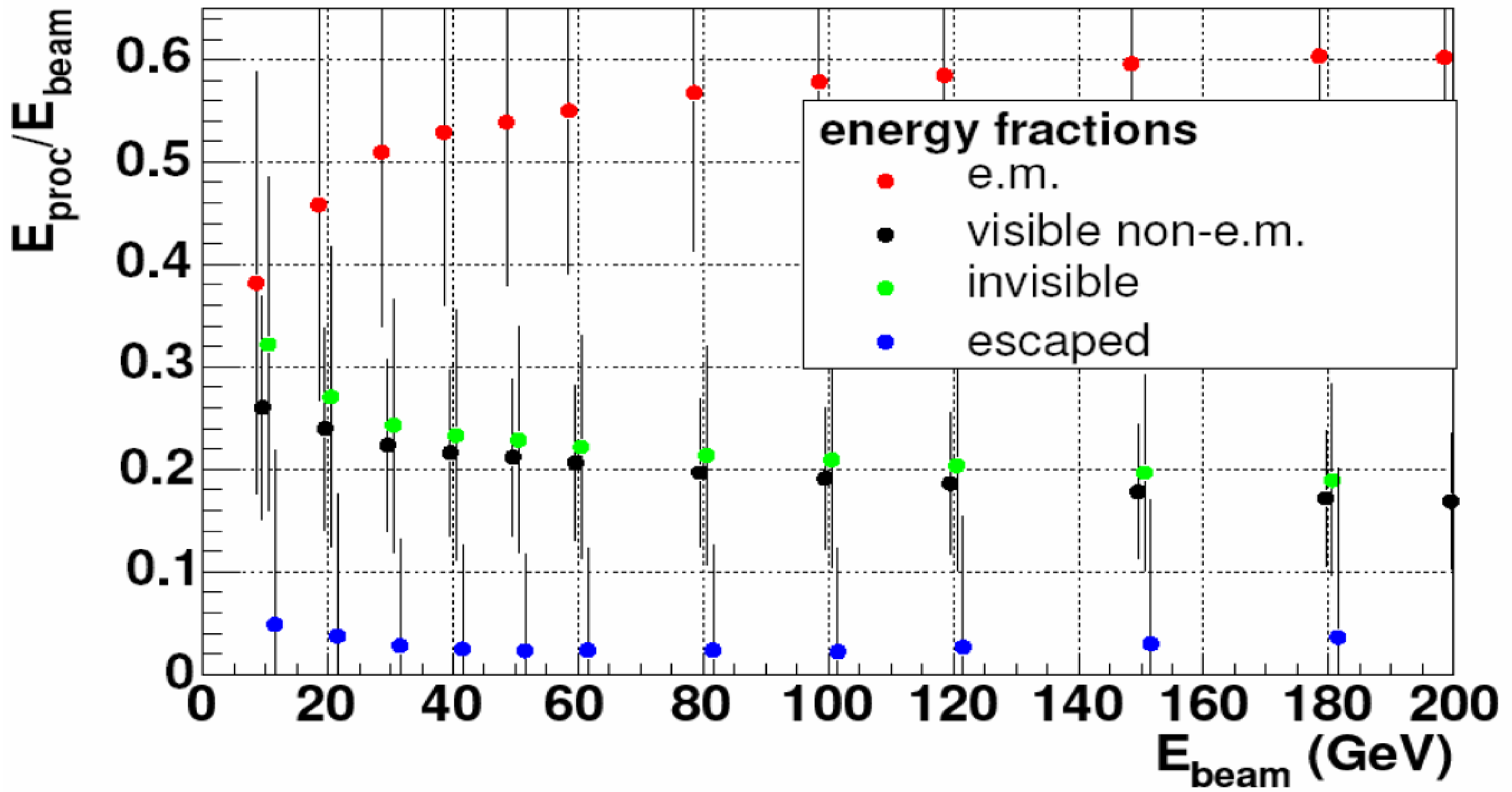
Hadron Showers

- 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. $\pi^0 \rightarrow \gamma\gamma$)
    - Invisible (n, nuclear fragments)
    - Escaped (ν)

Content of a had. Shower (1)



Content of a had. Shower (2)

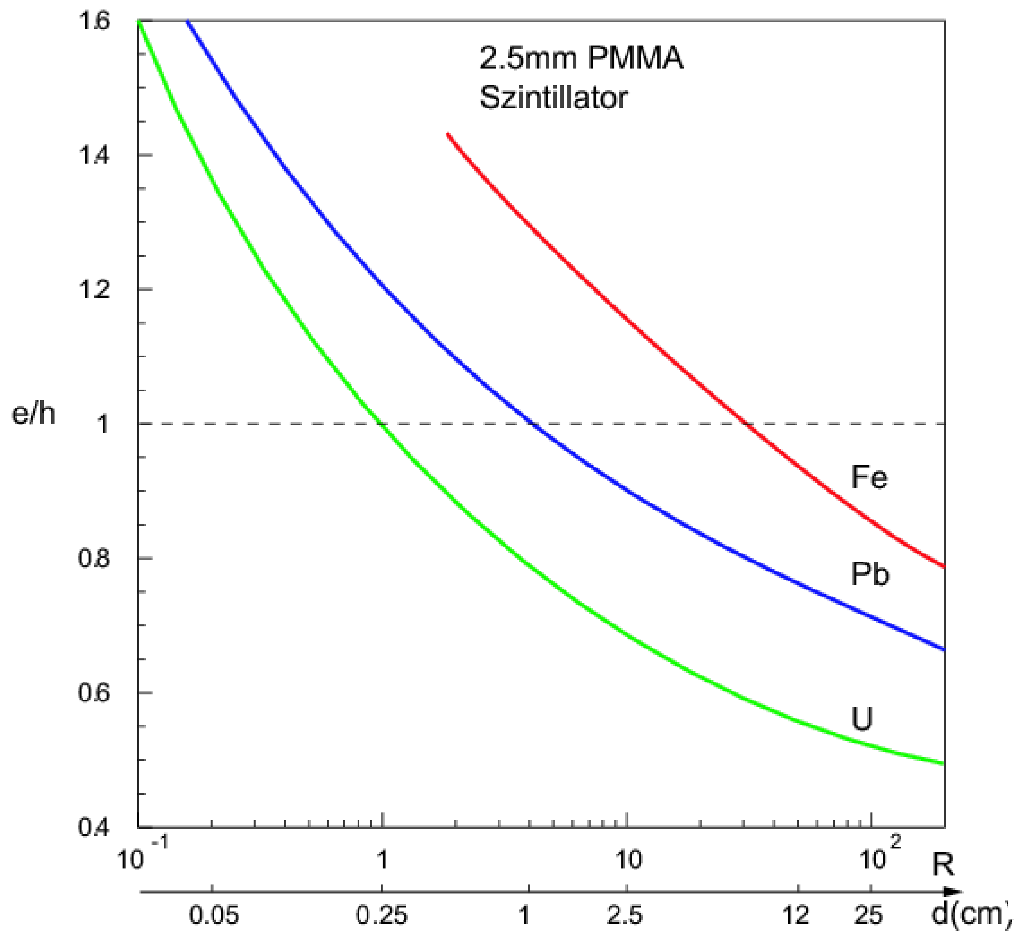


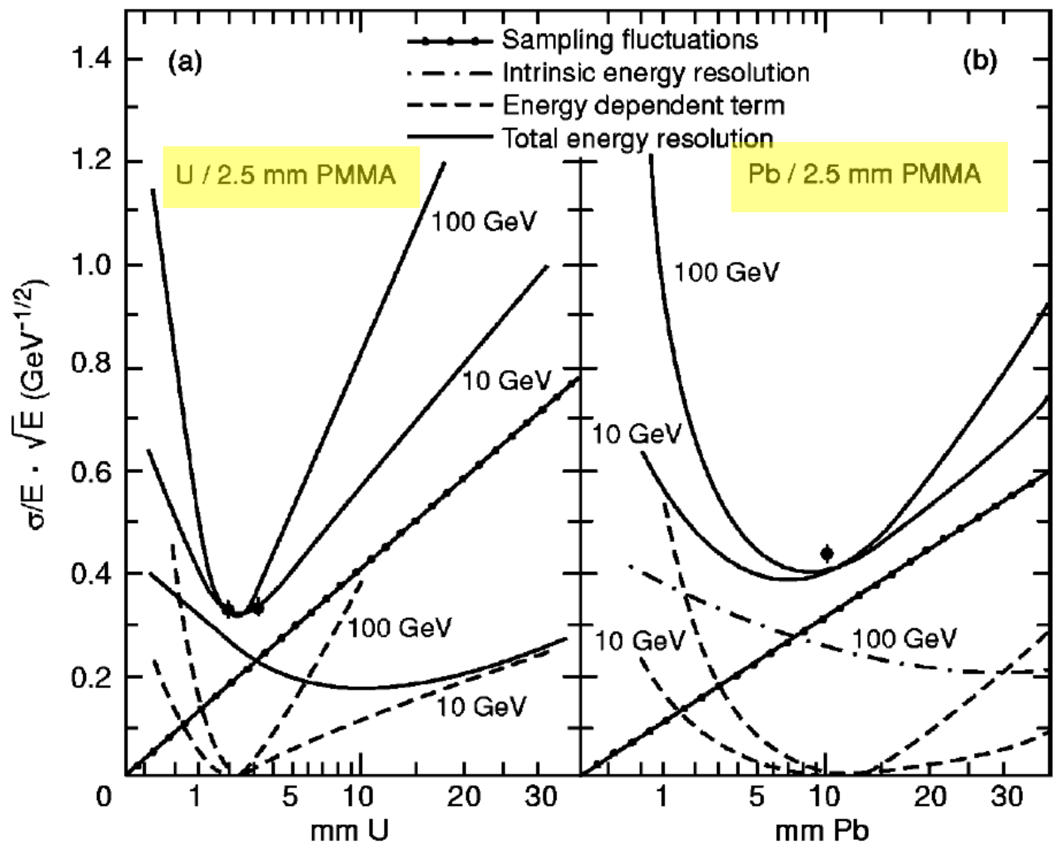
- Composition varies with energy → non-linearity
- Stat. variation in composition (shown by “error bars”) → fluctuations in resolution

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)
- Mitigation: 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



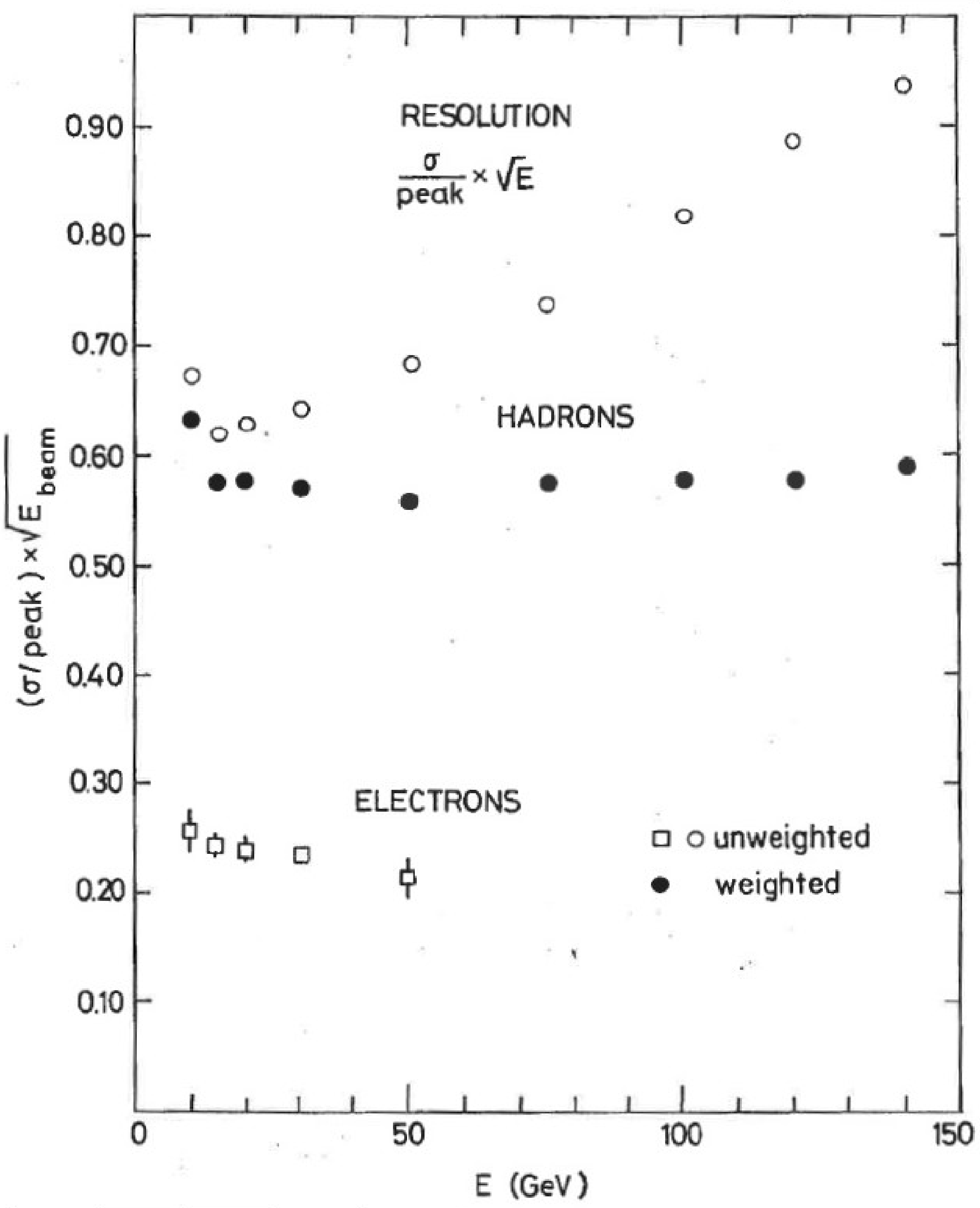


- Tuning e/h and the resolution by adjusting absorber thickness for fixed plastic scintillator (PMMA) thickness
- Depends on absorber → different nuclear processes

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:

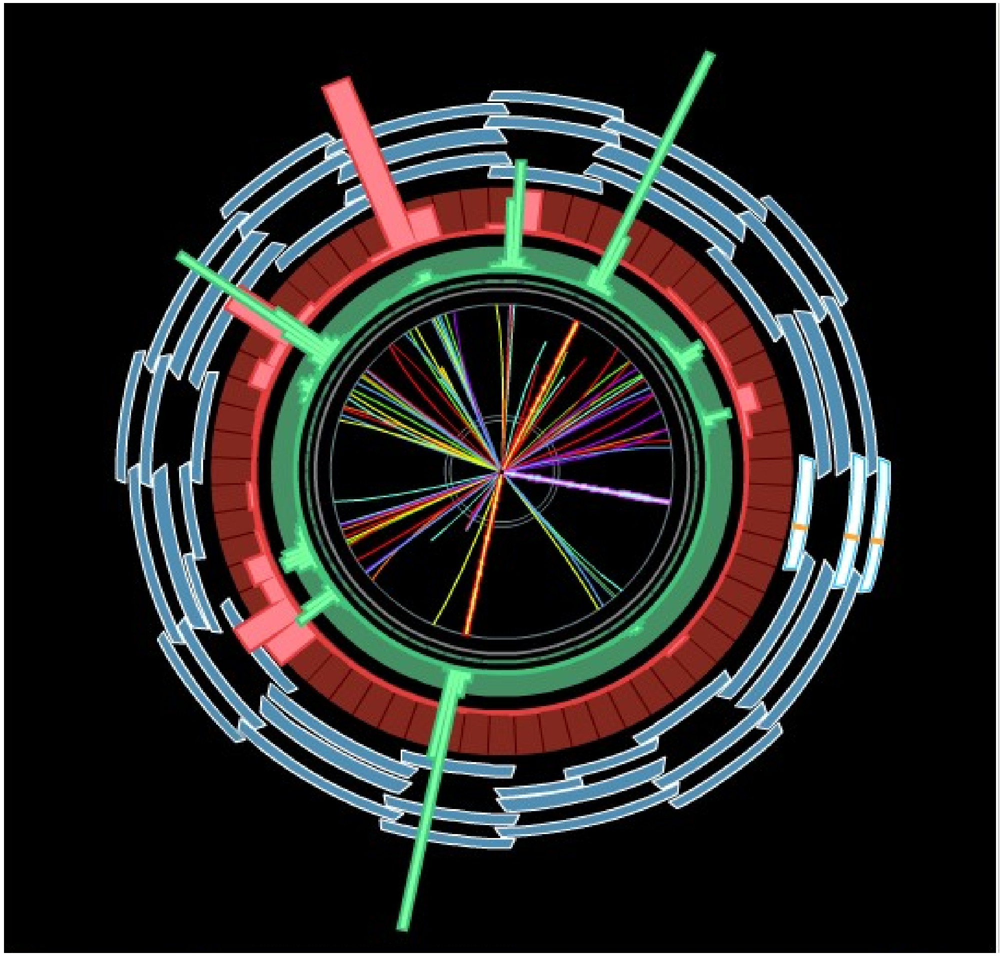
  $E_i' = E_i \cdot (1 - C \cdot E_i)$
- Parametrise C as function of (un-weighted) jet energy

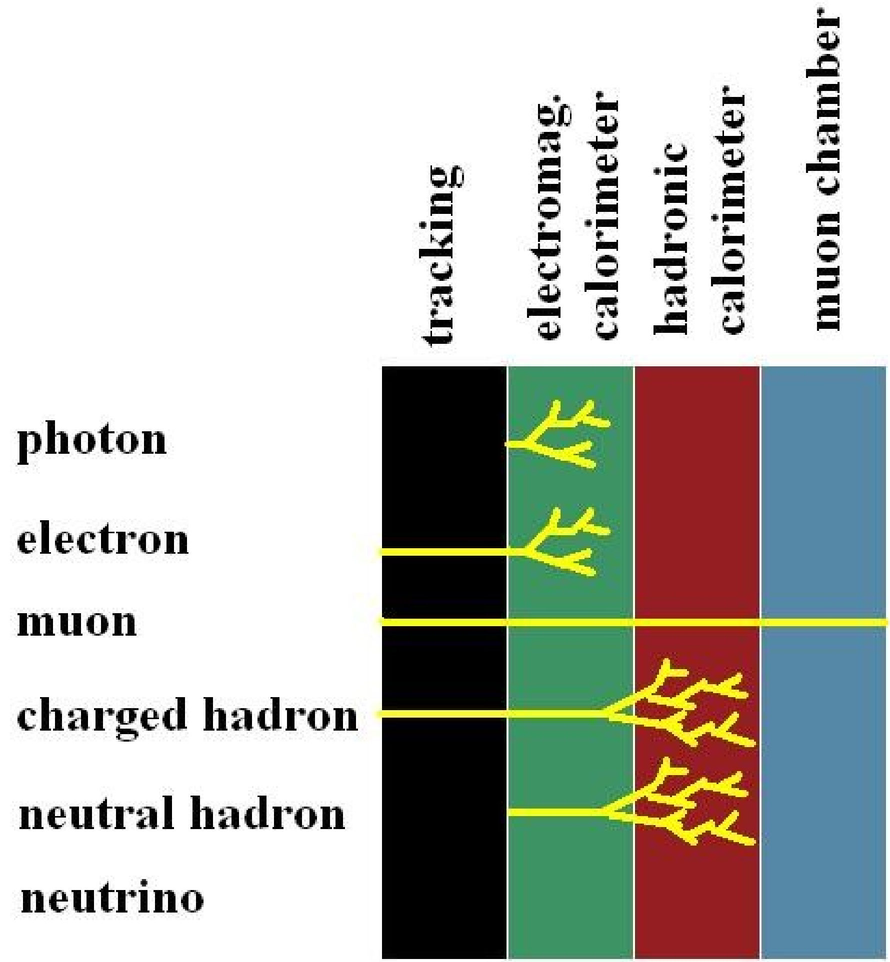


- Inner part: tuned for em showers ($\lambda \gg X_0$)
  - Homogeneous: only few crystals with useful X_0 available
  - Sampling: variety of material
  - Choice drives resolution, but also other requ.: read-out speed, radiation hardness,…
  - Segmentation: separation of individual particles, e.g. photons 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 → e.g. fine segmentation

Overall Concepts

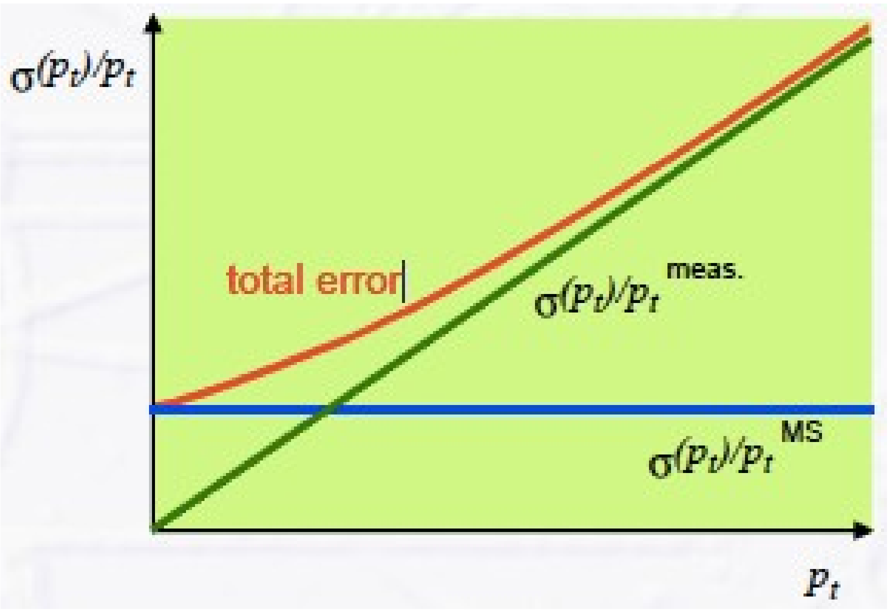
Multi-layer HEP Detector



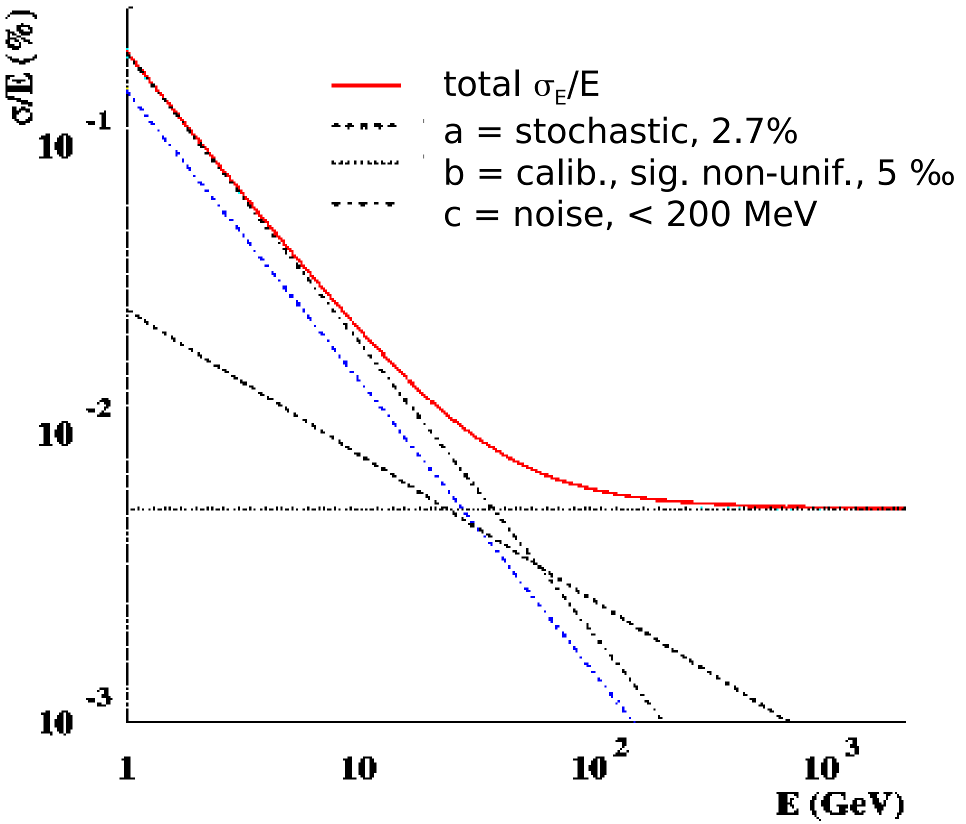


Complementary Measurements

- Tracking: measure momentum p
- Relative resolution *degrades* with rising p



- Calorimeter: measure energy E
- Relative resolution *improves* with rising E

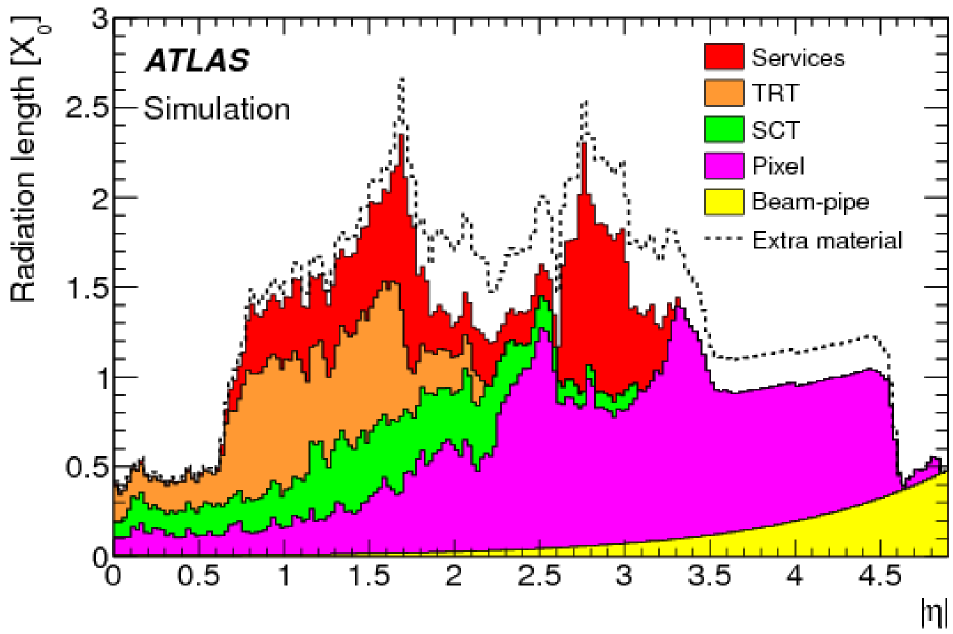


Material Budget

- 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

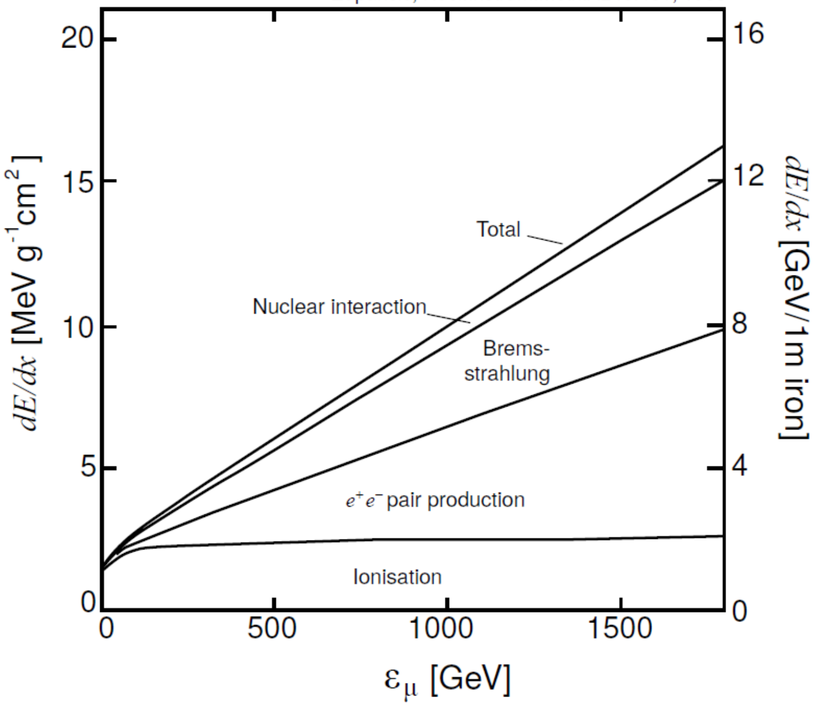
- Material budget is not just the pure detector (gas or silicon): cables, cooling pipes, support structures,… contribute as well



Muon Detectors (1)

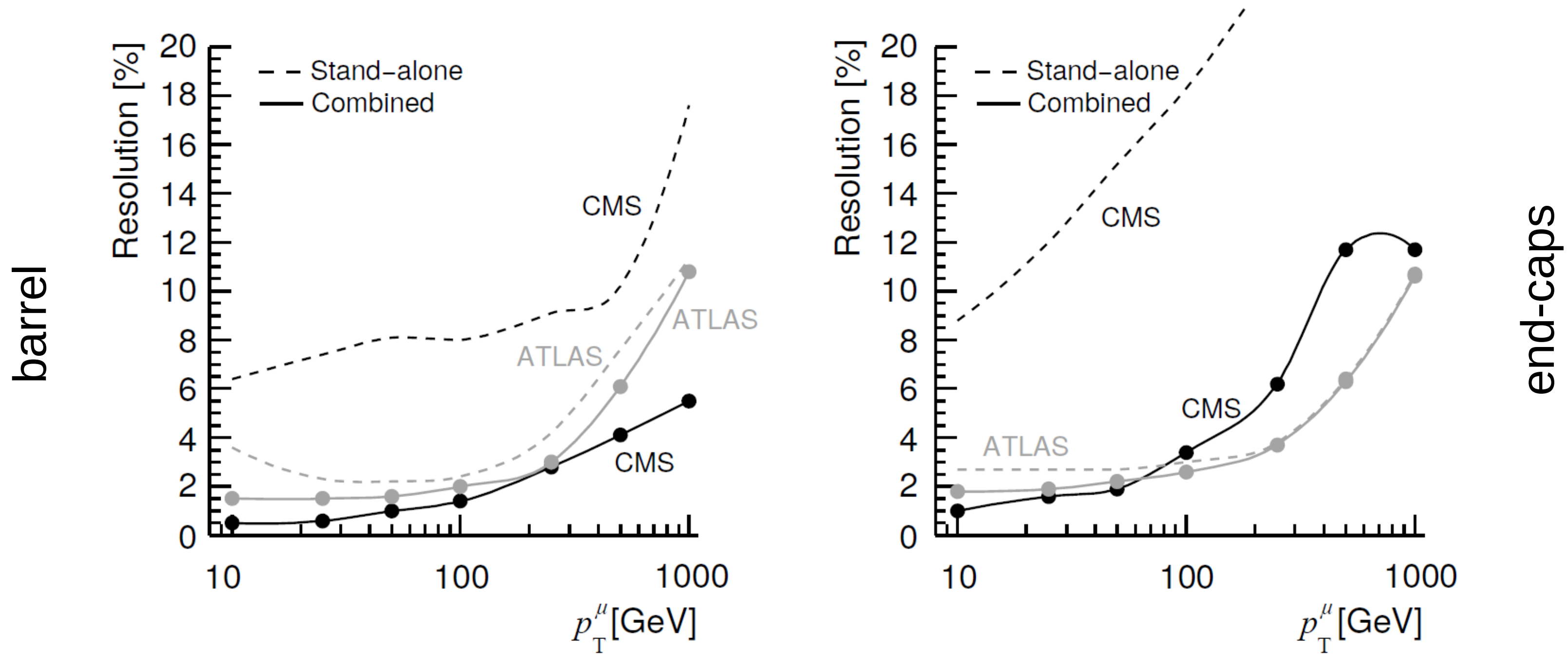
- Muons penetrate calorimeter layers → detector in outermost layer
- Independent tracking system
  - Magnetic field: return yoke from inner tracking system (CMS), or additional magnets (ATLAS)
  - Complementary momentum measurement
  - Adjust for energy loss in calorimeter: several processes, contribution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

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

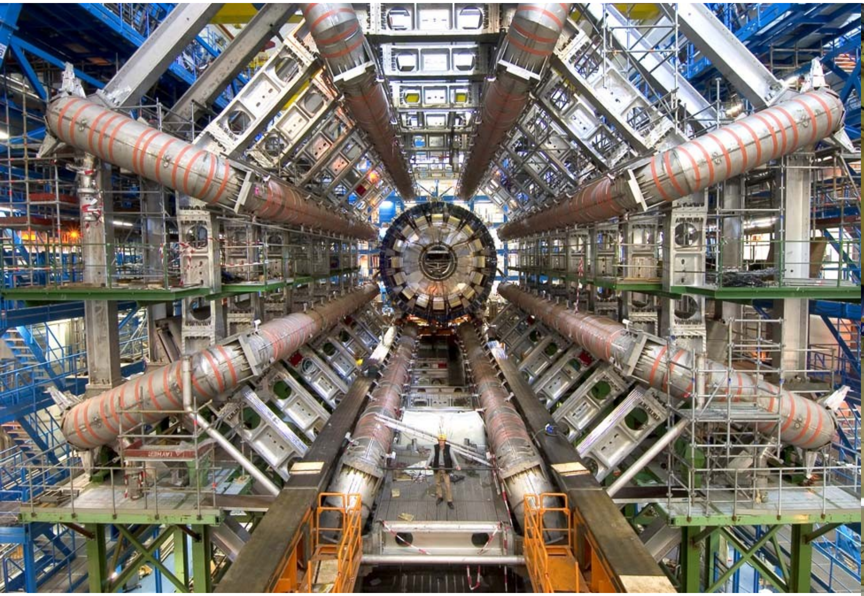


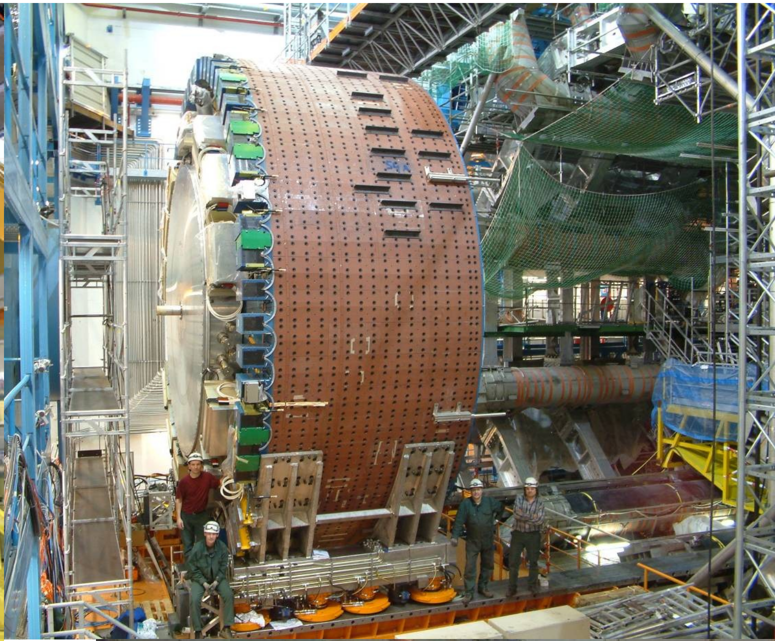
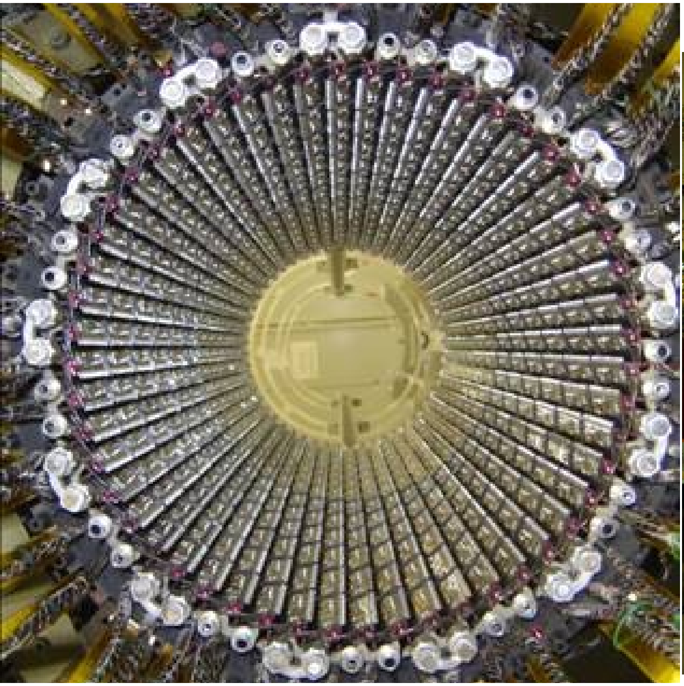
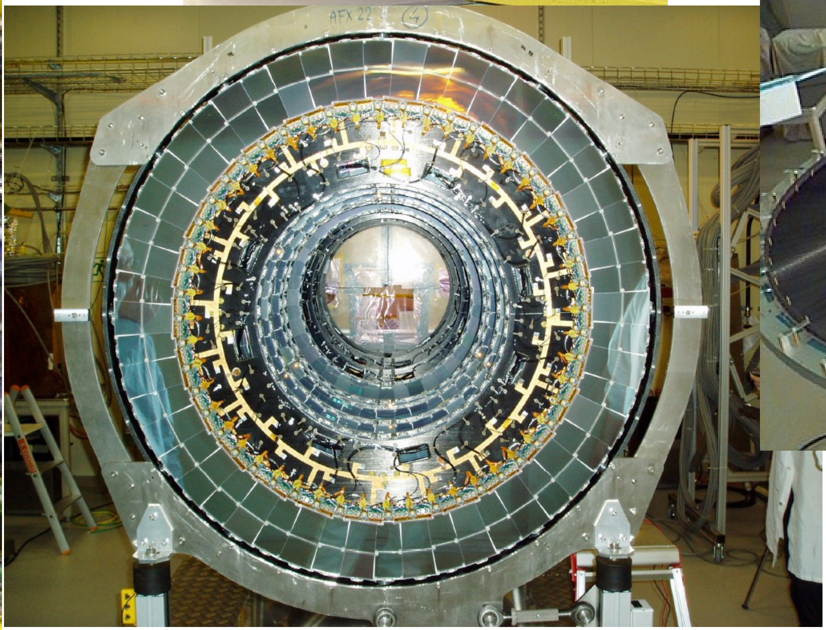
Muon Detectors (2)

- 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

Thanks for your attention!