Calorimetry and Jet reconstruction

C. Zeitnitz

Bergische Universität Wuppertal

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    - Charged particles
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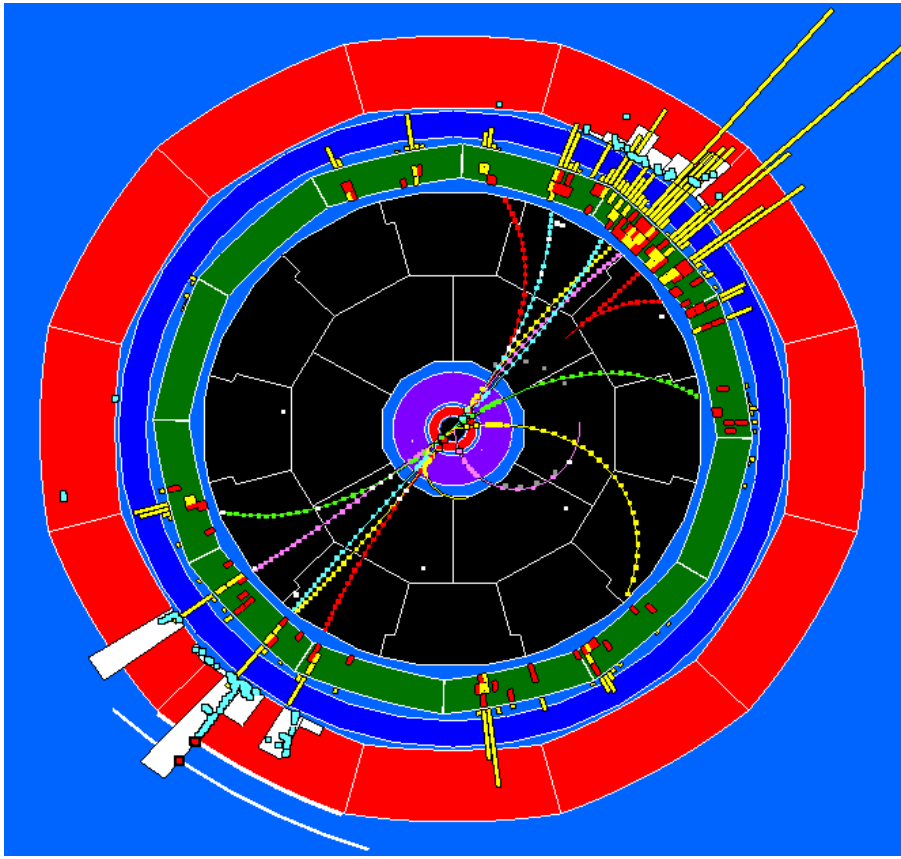
- **Literature**
  - Richard Wigmans, *Calorimetry,* Oxford University Press
    - most pictures taken from this book
  - Detector Physics text books

Introduction

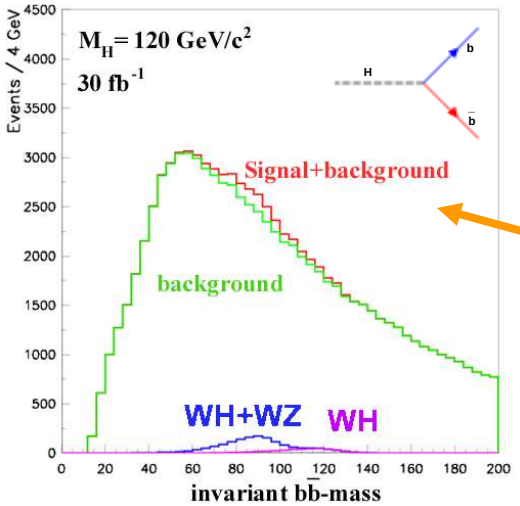
- **Calorimeter measures the energy of**
  - Charged and neutral particles
    - Only means to measure neutrals!
  - Jets
    - Composed of charged and neutral hadrons
    - Secondary leptons
    - Only means to measure the total energy of a jet!
- **Requirements**
  - Linear response with the energy
  - Good energy resolution
  - Spatial resolution
  - Particle identification



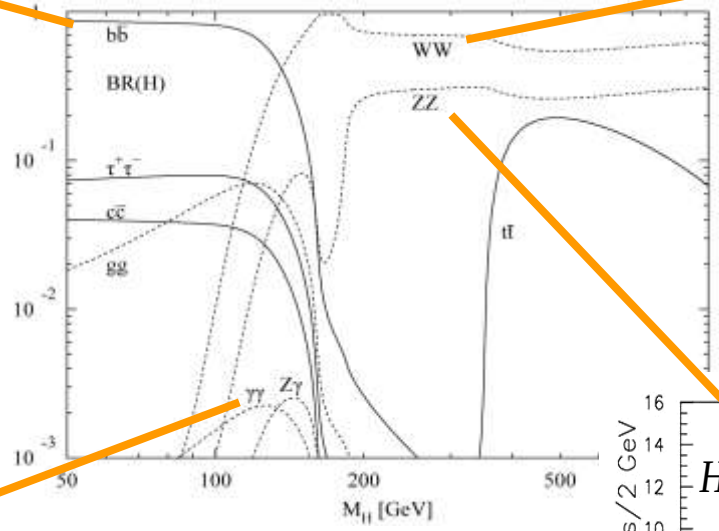
Physics with Calorimeters

- **Energy measurements of different particle types (leptons, hadrons, jets) required by physics**
  - Standard Model physics
    - W and t-quark mass
  - Higgs search
    - Signatures of production and decay
    - Couplings
  - No-Higgs models
    - Study in detail W and Z-events to understand symmetry breaking
  - New physics
    - Often undetectable particles in the final state (e.g. SUSY)
    - Requires good measurement of **missing energy**
    - Cover full solid angle and measure ALL particles

LHC: Search for the Higgs



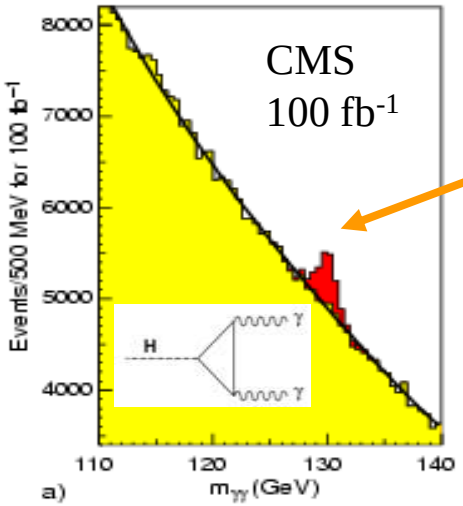
Higgs branching ratio



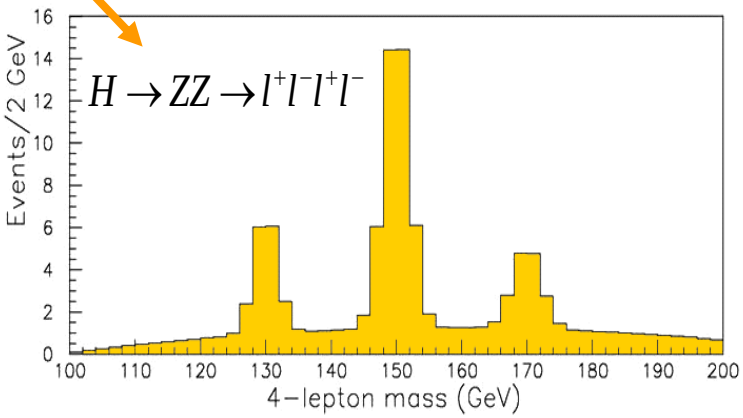
$$H \rightarrow WW^* \rightarrow l^+ \nu l^- \bar{\nu}$$

Signature

- missing transfer momentum
- two leptons

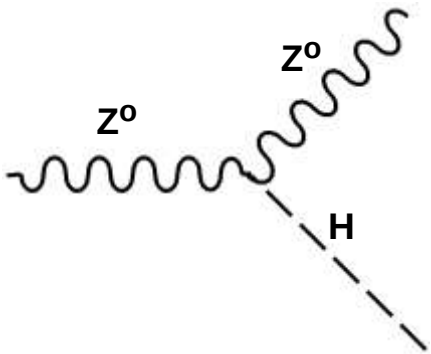


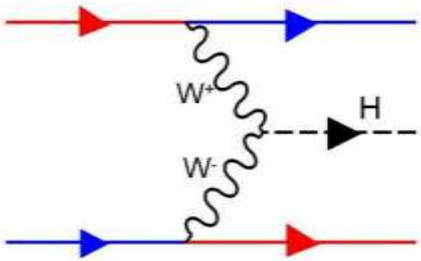
3 different Higgs masses

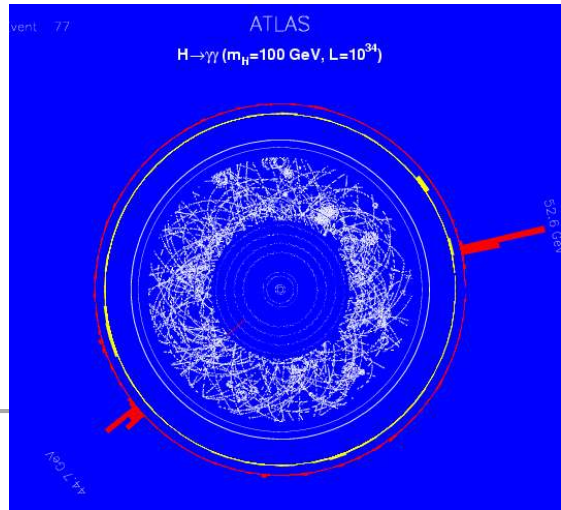


LHC: Search for the Higgs (2)

- **Distinguish signal and background by signatures during production**
  - Associated production of Higgs with W and Z
    - Lepton(s) in the final state from $W \rightarrow l\nu$ or $Z \rightarrow l^+l^-$ decay
    - Constraint from W (M_T) or Z mass
  - Vector-Boson Fusion
    - Additional jets at small angle
- **Utilize decay signatures**
  - Decay of b-quarks: Jets+secondary vertex
  - Decay to photons: isolated hiegh energetic photons
  - Decay to W or Z: leptons in the final state





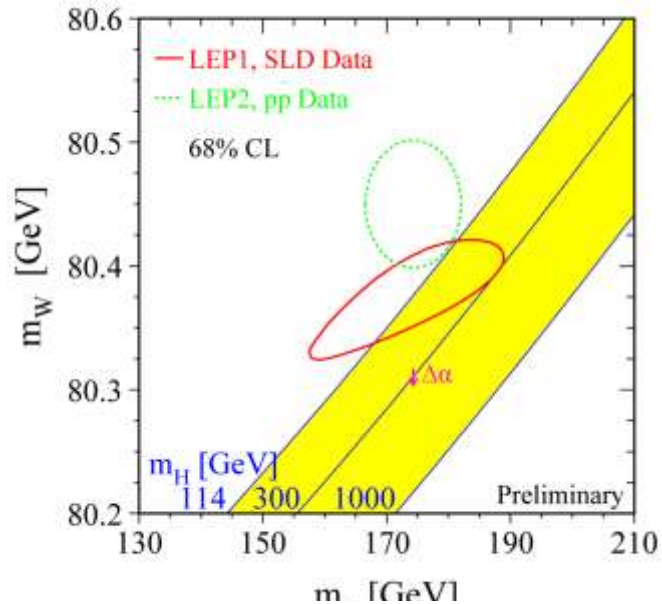


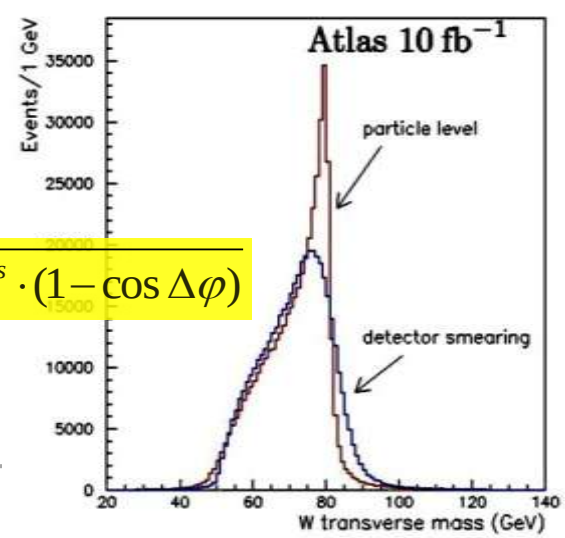
Higgs: Requirements for Calorimetry

- **Hermeticity**
  - Calorimeter should cover (nearly) the full solid angle
  - Typical coverage up to $\eta = 5$ (0,8° to the beam axis)
- **Good electron identification**
  - Utilize the difference in the **shower shape** between electron/hadron
  - Requires high longitudinale/laterale granularity
- **Good energy resolution for photons/electrons**
  - Very good **Sampling-Calorimeter** or
  - **Homogeneous** calorimeter
- **Good resolution for missing transverse momentum**
  - Vectorial energy sum (granularity)
  - Good jet energy resolution
  - Good **hadronic** calorimeter
  - Essential for new physics signatures like SUSY !

Standard Model Physics

- **Measurement of the W mass**
  - Important for the indirect measurement of the Higgs mass through loop corrections
  - Aim at LHC: $\Delta M_W \sim 15 MeV/c^2$
  - Signature: leptons in the final state
  - ➡ **Precise elektromagnetic energy scale of 0.02% !**
- **Measurement of the top-quark mass**
  - Signature: 4 Jets
  - Aim: $\Delta M_{top} \sim 1 GeV/c^2$
  - ➡ Very good hadronic energy measurement
  - ➡ **1% precision for jetc energy scale**
- **Requires very good calibration of the calorimeters with known decays**
  - example $Z \rightarrow e^+e^-$





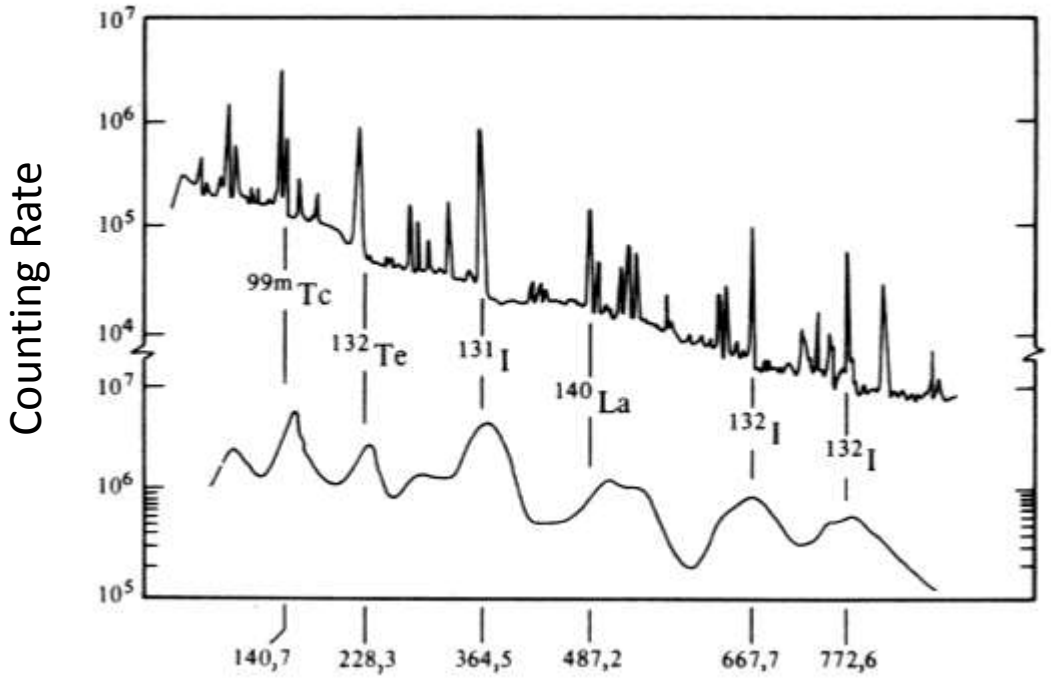
$$M_T = \sqrt{2 \cdot P_T^e \cdot P_T^{mis} \cdot (1 - \cos\Delta\varphi)}$$

Different Calorimeters

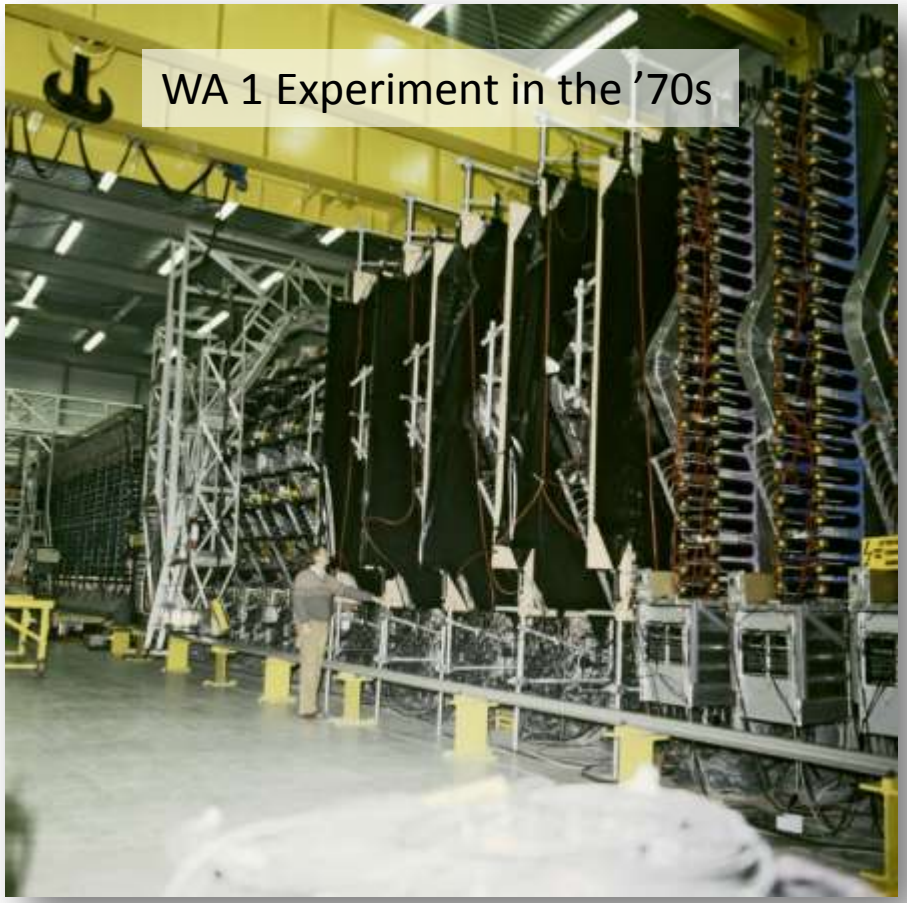
Nuclear Physics

- Detectors for Gamma-spectroscopy

Germanium detector



High Energy Physics

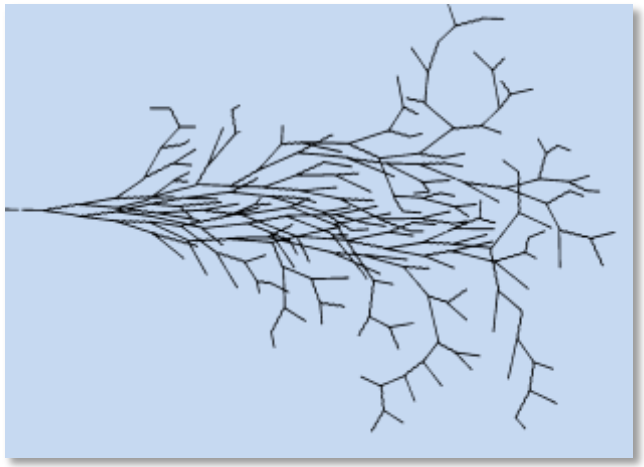


Very different materials, read-out, sizes

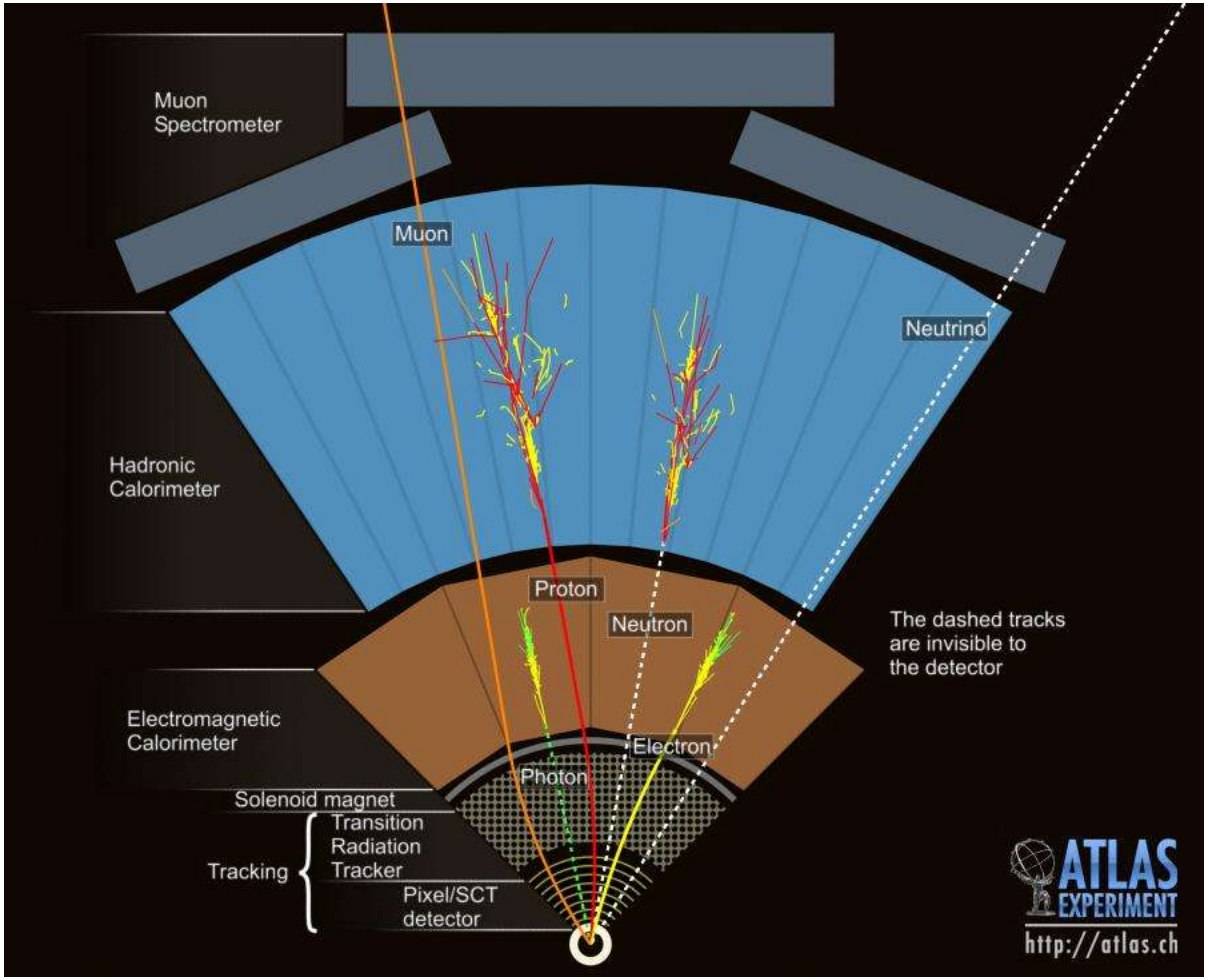
Energy Measurement

- **Energy measurement of particles**
  - Absorption of a particle in a block of material
  - Measure the energy loss
    - so-called *deposited energy*
    - Only charged particles produce a direct and measureable signal
    - Signal consists of
      - Charge from ionization
      - Light from scintillation or Cerenkov effect
  - Measureable signal depends substantially
    - Material choice
    - Type of detector
    - Energy spectrum of secondary particles
    - Type of particle
  - Measured signal is proportional to the energy of the particle

electron →



Passage of Particles through Matter



Electromagetic Interactions in Matter

Energy Loss

- Continuous energy loss in the medium due to
  - Excitation

$$e^- + atom \rightarrow e^- + atom^* \rightarrow e^- + atom + \gamma$$

  - Ionization

$$e^- + atom \rightarrow e^- + atom^+ + e^-$$

- Happens for all charged particles
- Example
  - Argon gas

$$\frac{dE}{dx} \approx -2\frac{MeV}{g/cm^2} \qquad \rho = 1.8 \cdot 10^{-3}\frac{g}{cm^3}$$

$$\Rightarrow \quad \frac{dE}{dx} = -3600\frac{eV}{cm}$$

$$\text{need W} = 26\text{eV per e}^- \text{-ion pair} \Rightarrow \quad \sim 140\,\text{e}^- \text{-ion pairs/cm}$$

Average Energy Loss (Ionization)

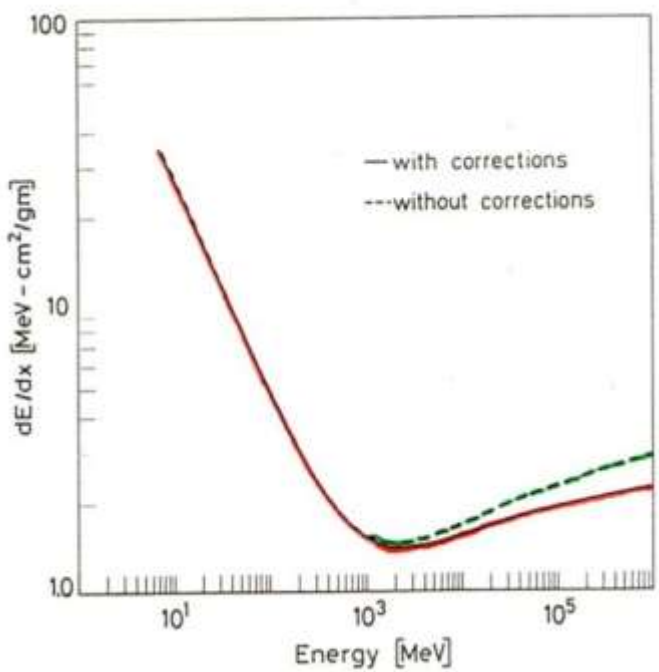
Heavy charged particles

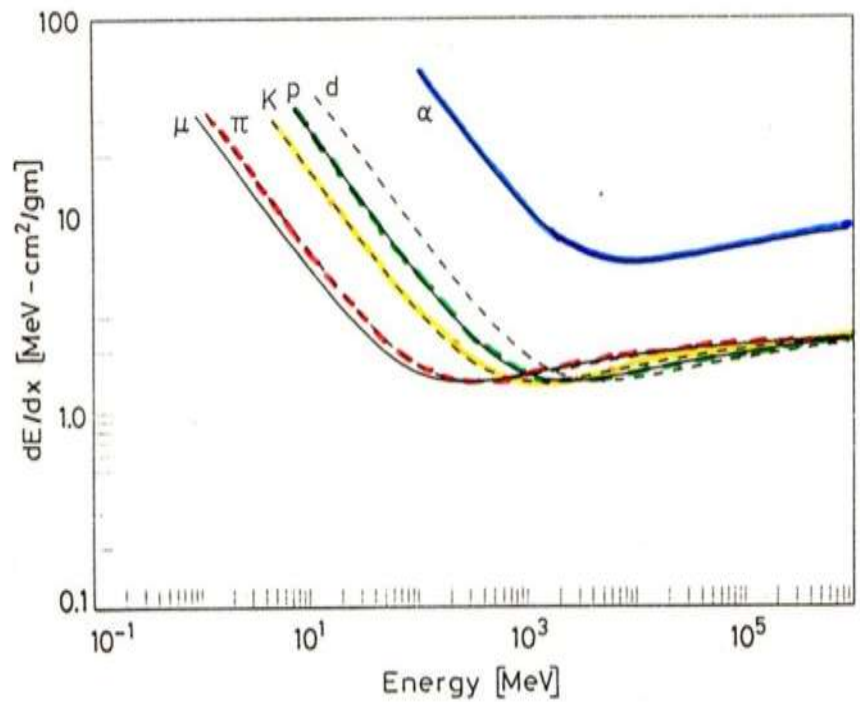
Bethe-Bloch formula

$$-\frac{dE}{dx} = 4\pi N_A \cdot r_e \cdot m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I}\right) - \beta^2 - \frac{\delta}{2}\right]$$

N_A : Avogadros number ; Z, A : charge and atmic mass

r_e : classical electron radius ; $I = Z^{0.9} \cdot 16eV$: ionization potential





Average Energy Loss (2)

- **For electrons is the energy transfer different**
  - Different energy loss

$$-\frac{dE}{dx} = 4\pi N_A \cdot r_e \cdot m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\ln\left(\frac{\gamma m_e c^2 \beta\sqrt{\gamma-1}}{\sqrt{2}I}\right) - \frac{1}{2}\left(1-\beta^2\right) - \frac{2\gamma-1}{2\gamma^2}\ln 2 + \frac{1}{16}\left(\frac{\gamma-1}{\gamma}\right)^2\right]$$

- **Positrons**
  - slightly different energy loss wrt electrons
  - Stopped positrons will annihilate to two photons with 511keV
- **Dependence of the energy loss**
  - Proportional to z^2 (charge of the particle)
  - Proportional to $1/\beta^2$ for slow particles
- **Minimal energy loss at approx $\beta \cdot \gamma = P/m = 4$**
  - Parametrization

$$-\frac{dE}{dx} = 6\frac{Z}{A} - 1.25\frac{MeV}{g/cm^2} \quad (10\% \text{ for } Z > 4)$$

  - MIP: Miniminal Ionising Particle

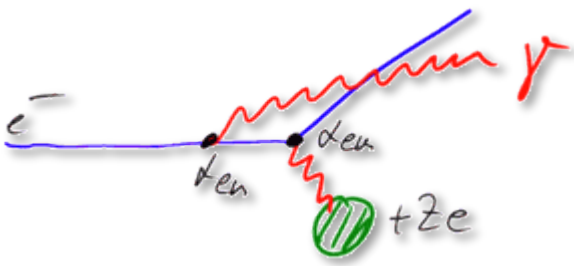
Bremsstrahlung

High energetic charged particle in the Coulomb field of a nucleus

$$-\frac{dE}{dx} = 4\alpha N_A \left(\frac{1}{4\pi\varepsilon_0} \frac{e^2}{mc^2} \right)^2 z^2 \frac{Z^2}{A} E \cdot \ln \frac{183}{Z^{1/3}}$$

N_A : Avogadros number ; Z, A : charge and atomic mass

α : fine structure constant 1/137



- Energy loss is
  - proportional to E and z^2
  - material dependent : Z^2/A
  - proportional to $1/m^2$
    - Only important for light particles (electron)
    - For $e^{\pm}$ dominant at high energies

$$-\left.\frac{dE}{dx}\right|_{\mu} \approx \frac{1}{40000} \left.\frac{dE}{dx}\right|_{e}$$

Radiation Length

- **Bremsstrahlung for electrons**
  - Parametrization (valid for high energy)
  - Radiation length X_0
    - The energy of an electron is reduced to E/e within $1X_0$ due to Bremsstrahlung

$$-\left.\frac{dE}{dx}\right|_{Brem} = \frac{E}{X_0}$$

$$E = E_0 \cdot e^{-x/X_0}$$

    - Depends only on the material (A/Z²)
  - 1/E energy spectrum of the photons
- **Radiation length allows for a material independent description of absorption processes for $e^{\pm}$ and photons**
- **Examples**
  - Al – X_0=18.8cm
  - Fe – X_0=1.76cm
  - Pb – X_0=0.56cm

Parametrization

$$X_0 = \frac{716.4 \cdot A}{Z(Z+1)\ln(287/\sqrt{Z})}\left[\frac{g}{cm^2}\right]$$

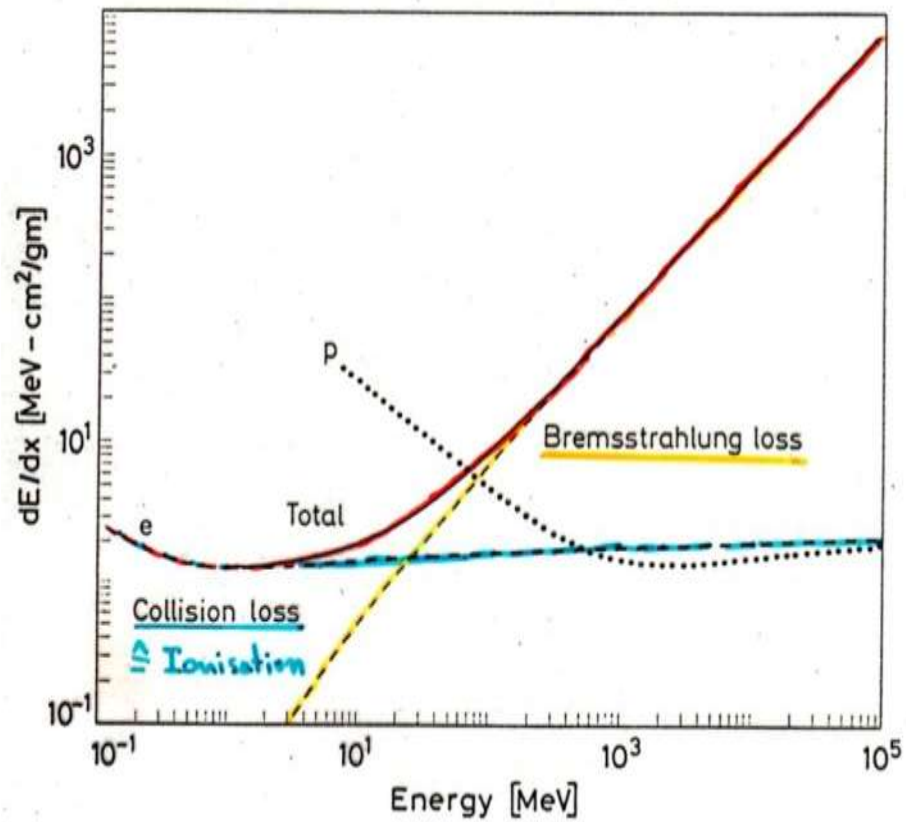
Energy Loss vs. Energy

- **Critical Energy E_c**
  - Equal energy loss due to ionization and Bremsstrahlung

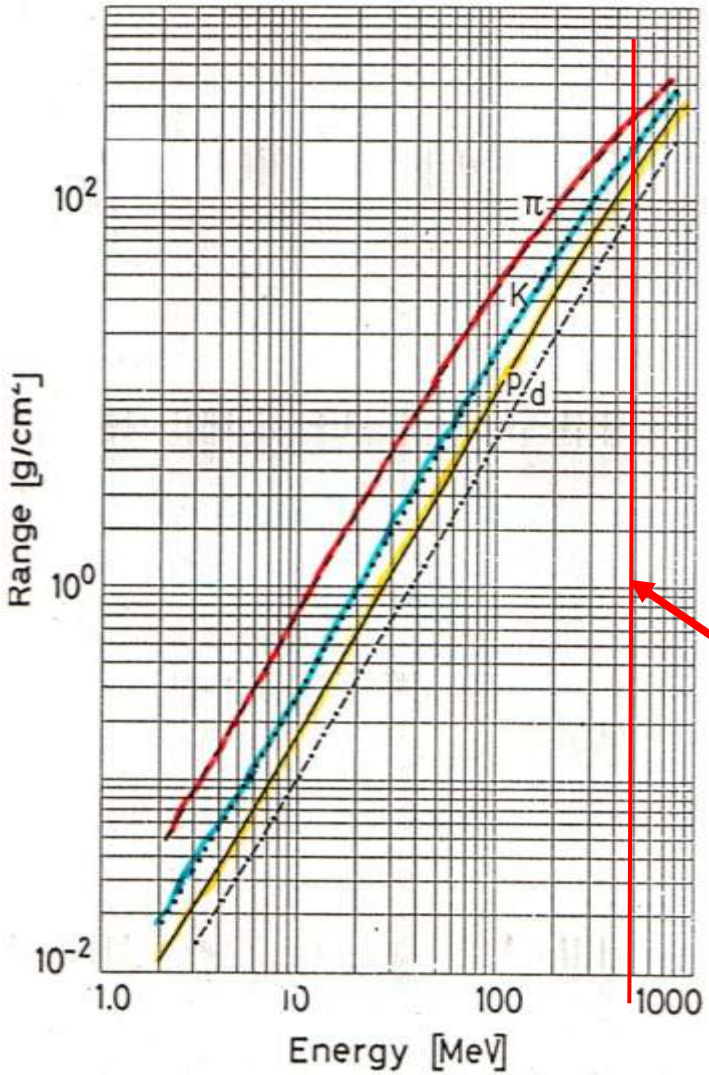
$$\left.\frac{dE}{dx}(E_c)\right|_{Brem} = \left.\frac{dE}{dx}(E_c)\right|_{ion}$$

  - Material dependent
    - Parametrization

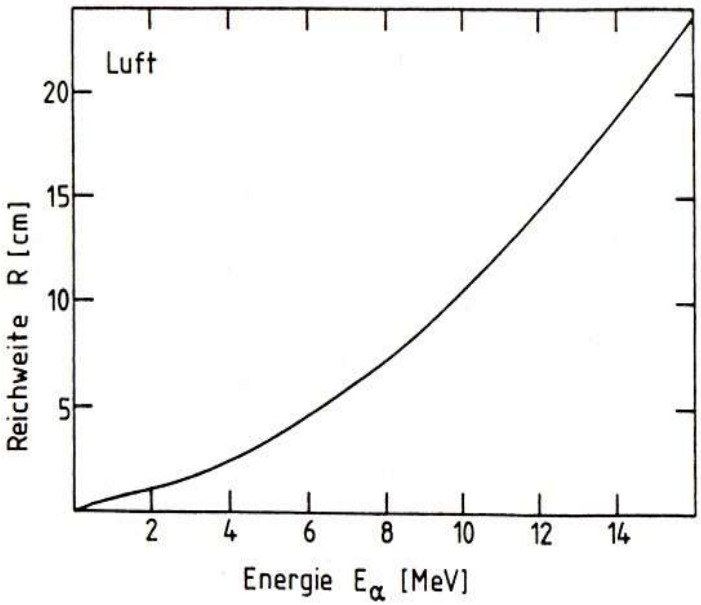
$$E_c = \frac{800\,\mathrm{MeV}}{Z+1.2}$$



Range of heavy charged particles



α-Particle in air

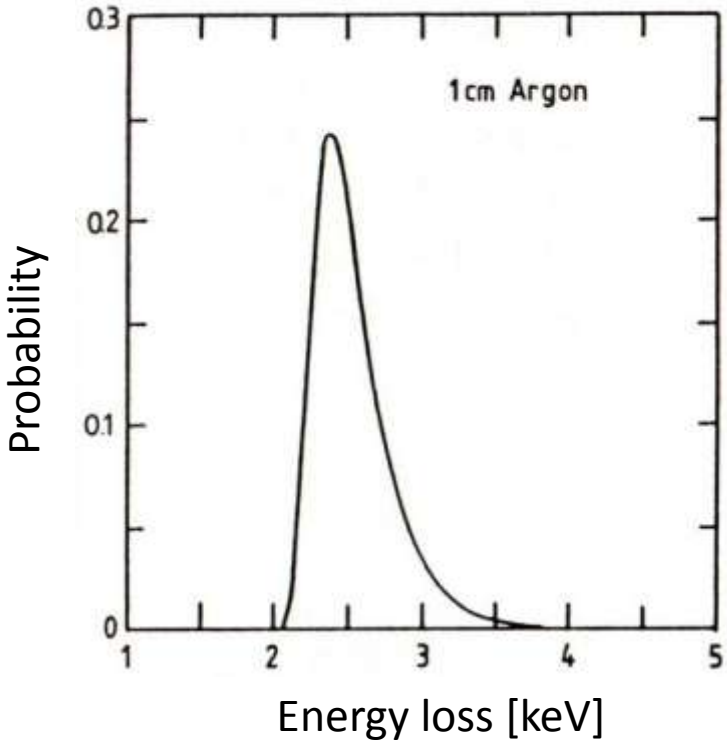


Example for E=500MeV in water

- Proton : 150cm
- Kaon : 200cm
- Pion : 300cm

Fluctuations of the energy loss

- **Energy loss is varying substantially**
  - Statistical fluctuation of the energy transfer to the electron
  - In thin detectors a Landau distribution represents the energy loss
  - In thick layers of material the distribution will converge to a Gaussian due to the central limit theorem



Multiple Scattering

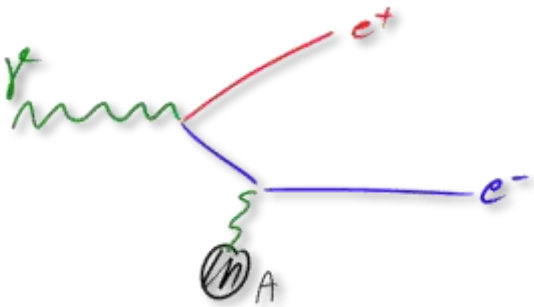
- **Coulomb scattering**
  - Many scatterings with small energy transfer
  - Rarely large energy transfers (δ-electrons)
  - Asymmetric dE/dx-distribution (Landau-fluctuations)
  - Most scatterings happen under small angle (θ^{-4} dependence)
  - Parametrization of the width of the scattering angle θ as function of the thickness x

$$\phi_{rms} \approx \frac{13.6}{\beta c p}\sqrt{\frac{x}{X_0}}$$

- **Charged particle track will deviate from the straight line**

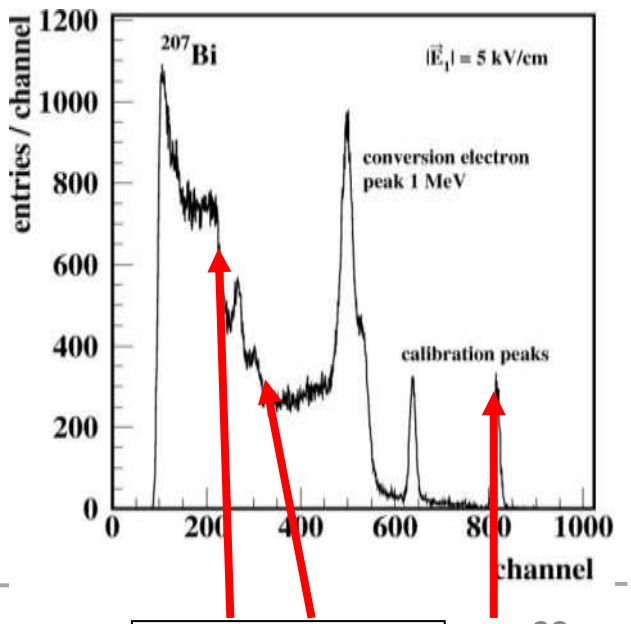
Interaction of Photons in Matter

- **Photon interacts with the electric field of the atoms (nucleus) or the electrons in the shell**
  - Pair-production in matter
    - Threshold: 2 x electron mass = 1 MeV
    - The intensity of a photon beam is reduced to 1/e within 9/7 X_0
  - Compton Scattering
    - Scattering off a bound electron in the shell
    - Electron is liberated
    - Cross section is proportional to Z and m_e/E (for E above the electron mass)
    - Maximal energy of electron $E_{kin}^{\max} = E_\gamma - \frac{m_e}{2}$



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

$$\text{Intensity}: I(x) = I_0 \cdot e^{-\frac{7x}{9X_0}}$$



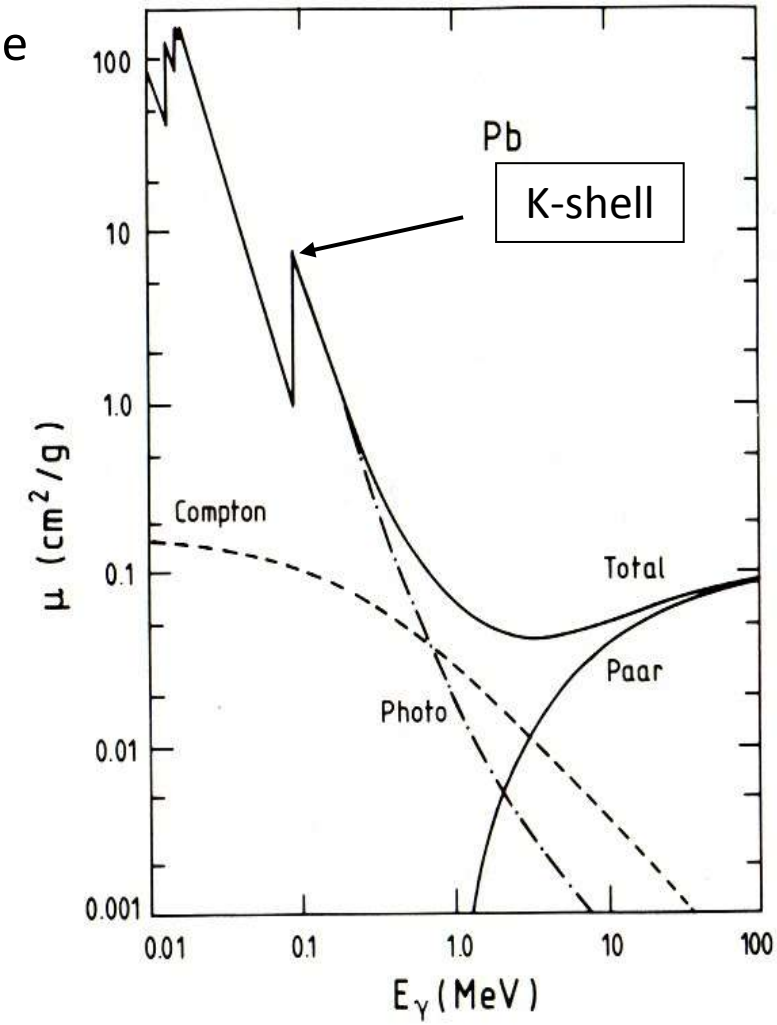
Compton edges

Interaction of Photons in Matter (2)

- Photoeffect
  - Photon is absorbed by an electron in the shell
  - Electron is liberated
  - Cross section is proportional to Z^5 !!

$$\sigma_{Photo} = 4\pi \cdot r_e^2 \cdot Z^5 \cdot \alpha^4 \cdot \frac{m_e}{E_\gamma}$$

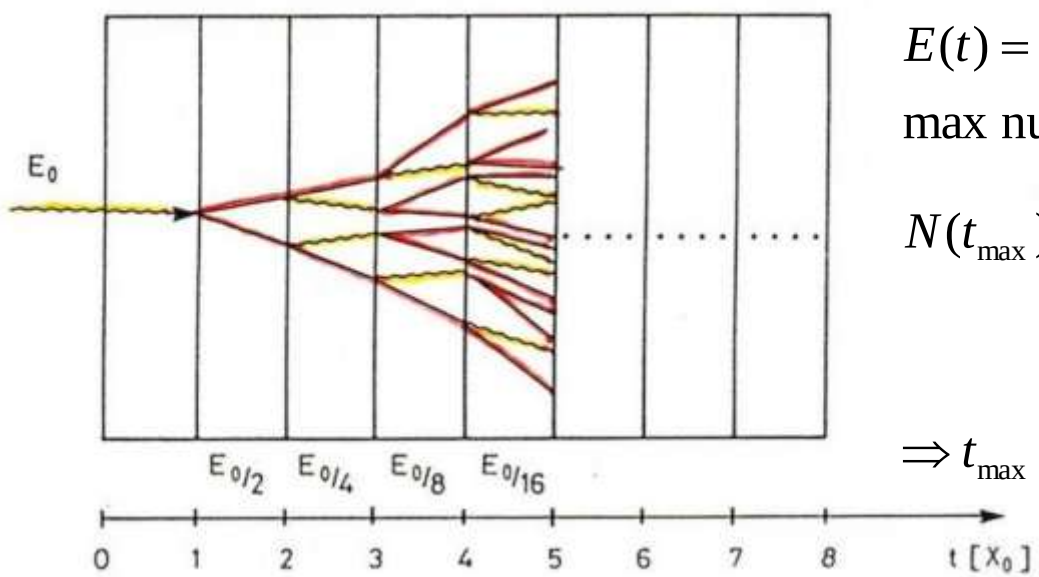
- Rayleigh Scattering
  - Scattering off an electron in the shell without energy loss
  - Only the direction of the photon is changed
- Different effects have different material dependence



Electromagnetic Cascade

Simple Model of an *em shower*

- An electron entering a block of material will radiate a photon after 1 X_0 due to Bremsstrahlung
  - The electron and photon carry half the energy
- One X_0 later the photon will produce an e^+e^- pair, each with ½ of the energy and the electron radiates another photon
- In each step the number of particles doubles and the energy of the particles is halved
- The process stops, when the energy is reduced to the critical energy



$$E(t) = E_0 \cdot 2^t \text{ and } N(t) = 2^t$$

$$\text{max number of particles at } E(t_{\max}) = E_c$$

$$N(t_{\max}) = \frac{E_0}{E_c}$$

$$\Rightarrow t_{\max} = \frac{\ln \frac{E_0}{E_c}}{\ln 2}$$

Attributes of em Showers

- **Simple model yields the following features**
  - Only logarithmic dependence of the shower maximum with E_0
  - Number of produced particles is proportional to the energy of the primary particle $N=E_0/E_c$
  - Energy spectrum of particles reduces quickly with depth
- **Reality**
  - Energy of particles is differently distributed
    - Bremsstrahlung creates 1/E spectrum
    - Pair production, compton and photo effect produce wide range of electron (positron) energies
    - Most charged particles (~90%) are electrons
  - Material dependence breaks exact X_0 scaling
    - Shower max shifted for high Z
    - Slow decay in high Z materials

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  - with E_0
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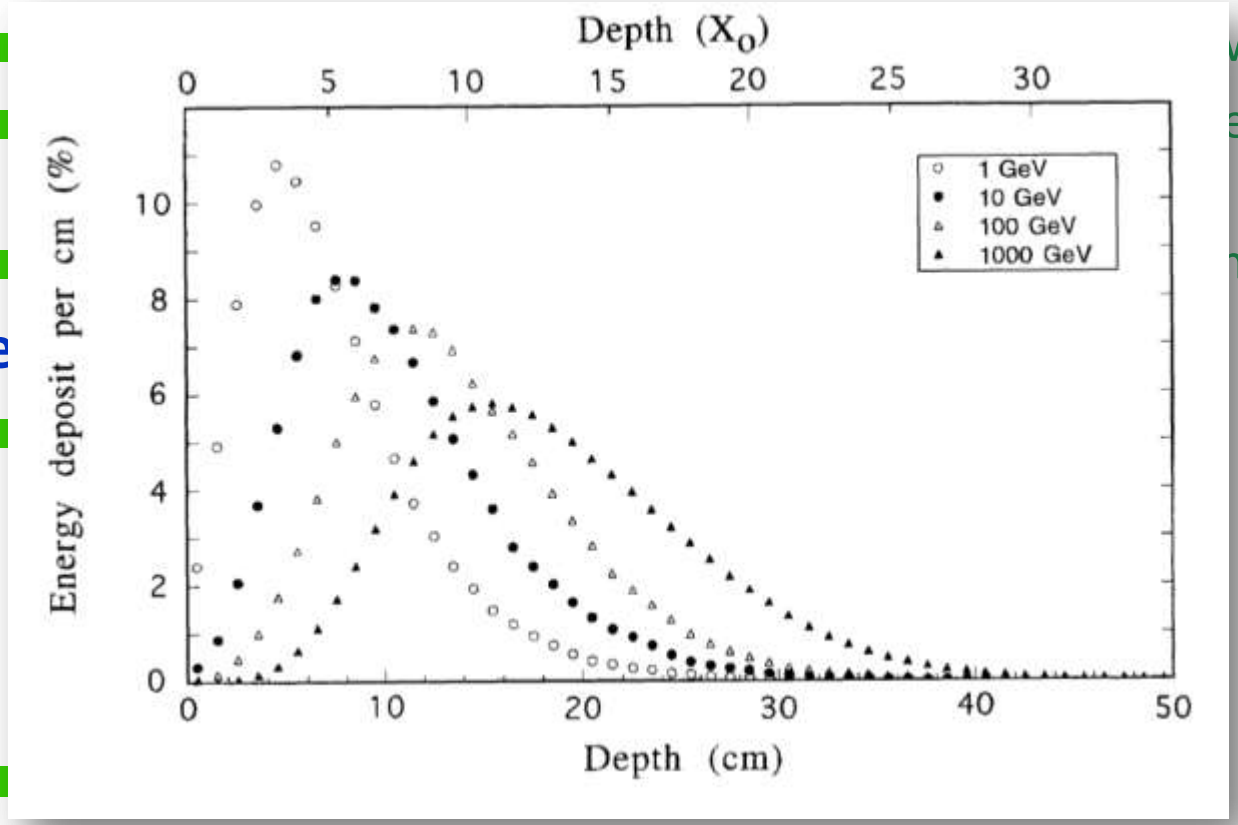

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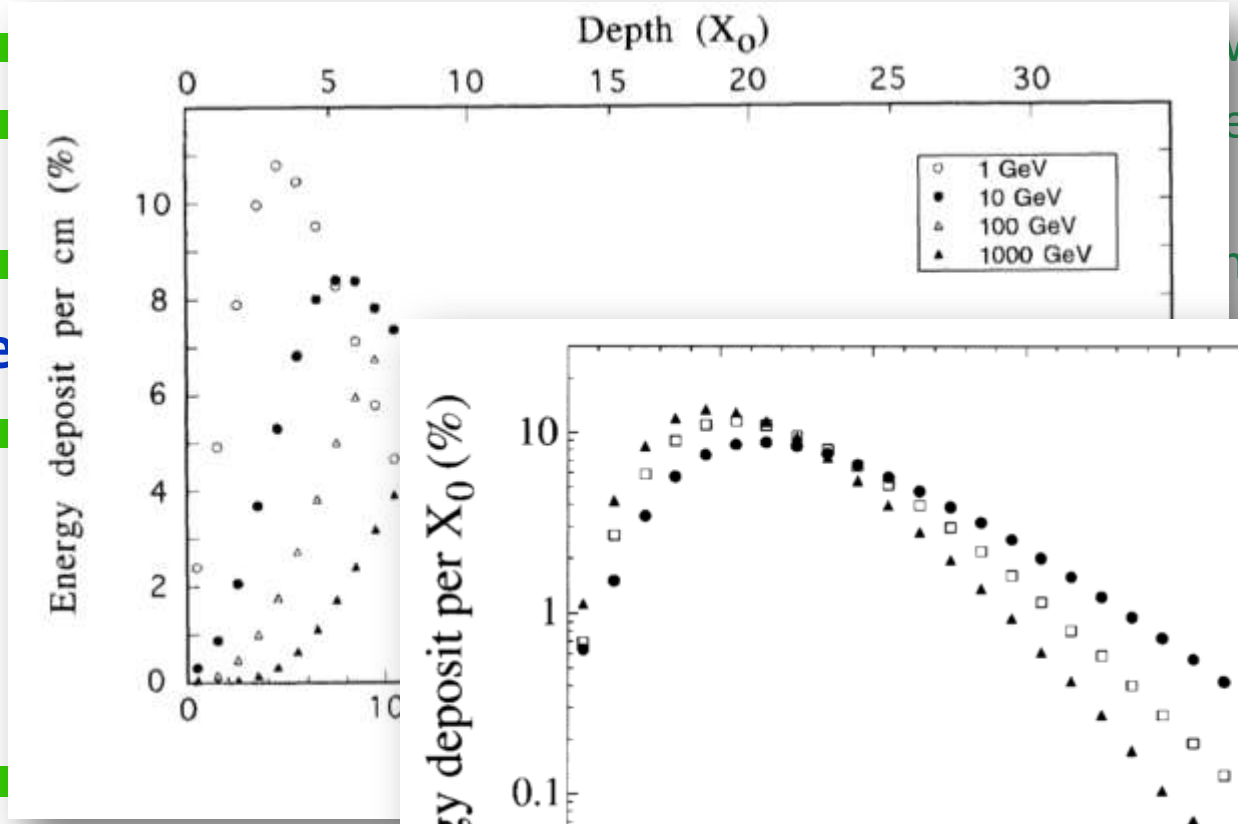
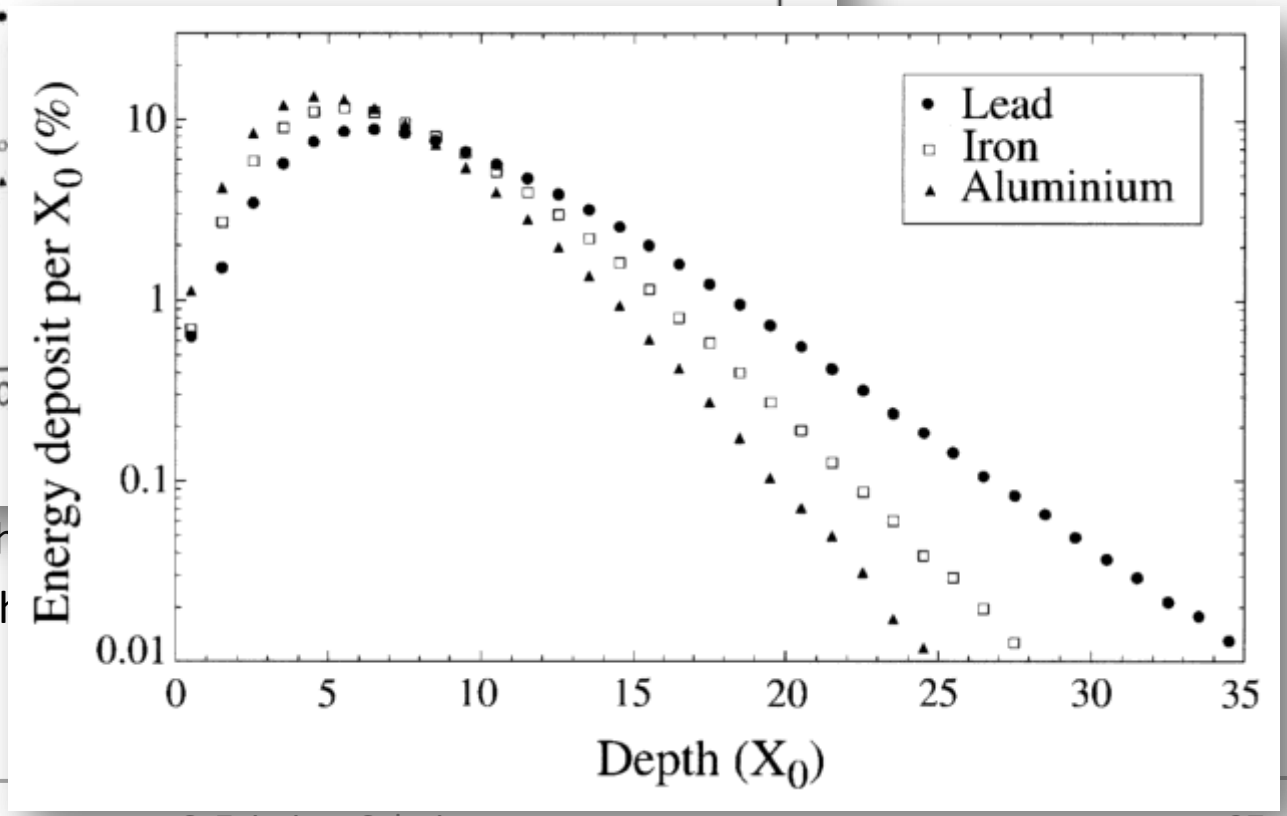
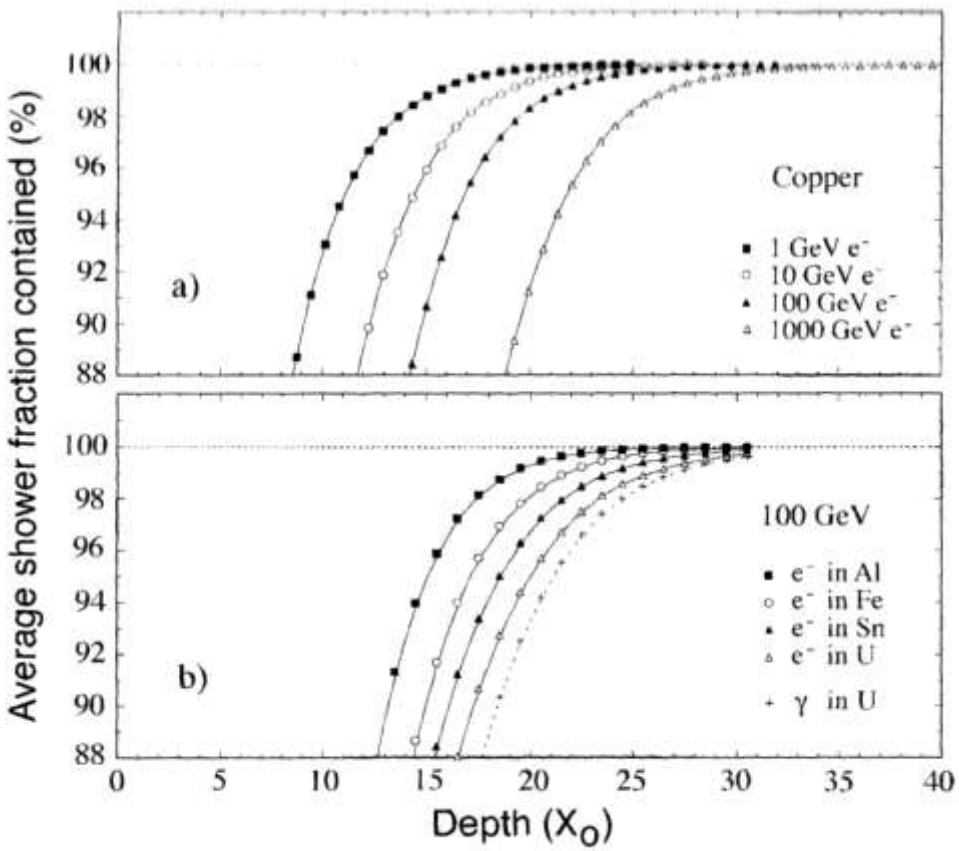
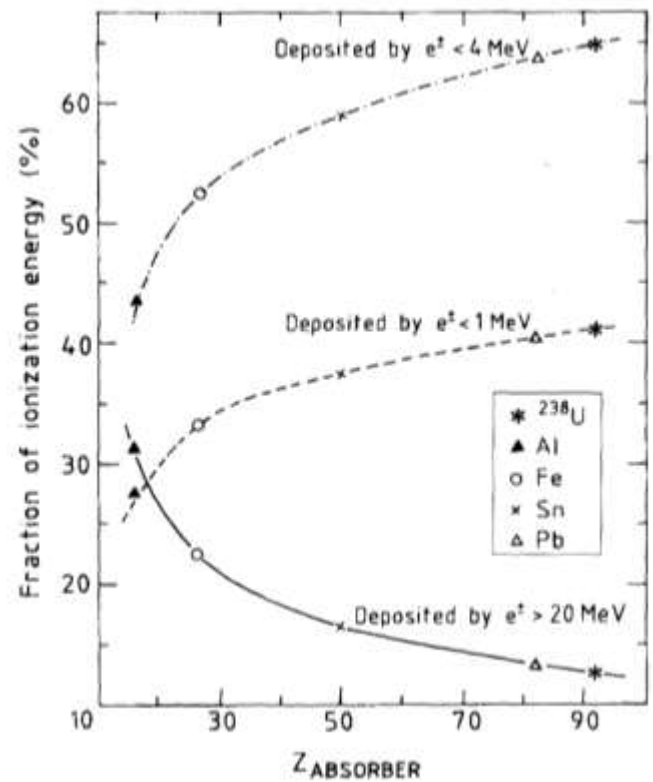




Containment of em shower

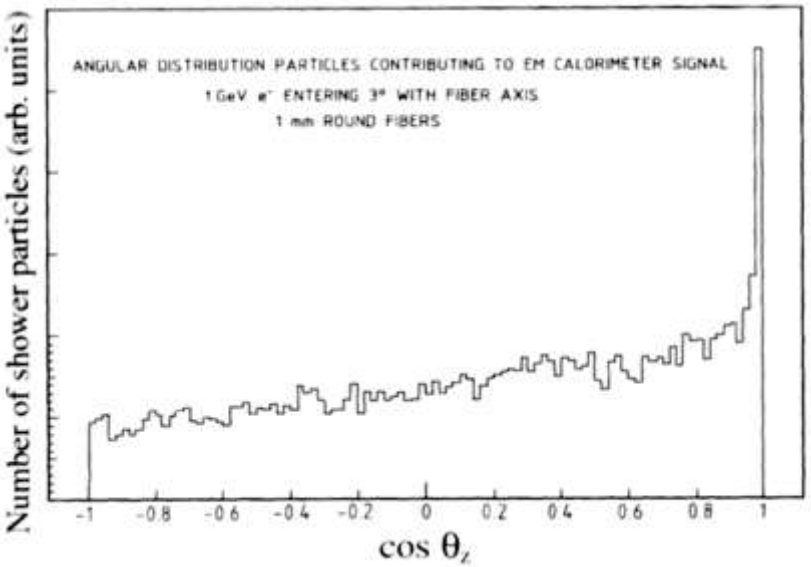


Composition of em shower



Lateral Shower Shape

- **Angular distribution in scattering (pair production)**
  - Spread of the particles perpendicular to the direction of the incoming particle
  - The energy carried by particles falls exponentially wrt. the shower axis
  - The width depends on the shower depth



- **Parameter: Molière Radius**

$$\rho_M = m_e c^2 \sqrt{4\pi/\alpha}\,\frac{X_0}{E_c} = 21.2MeV\,\frac{X_0}{E_c}$$

  - 90% energy is deposited in a cylinder with radius ρ_M around the shower axis
  - Molière radius has no real physical meaning!

Examples

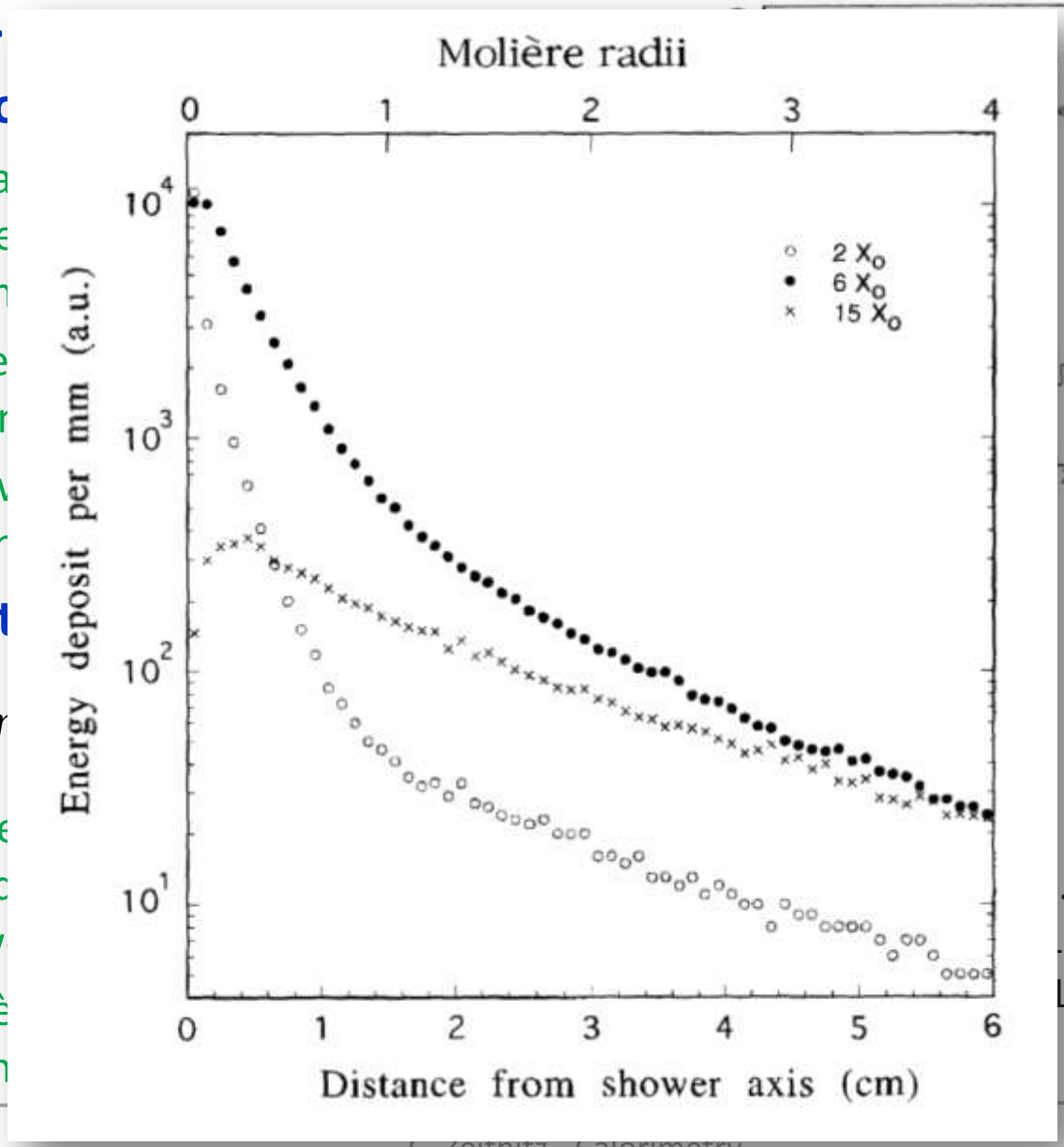
Al – ρ_0=4.7cm
Fe – ρ_0=1.8cm
Pb – ρ_0=1.6cm

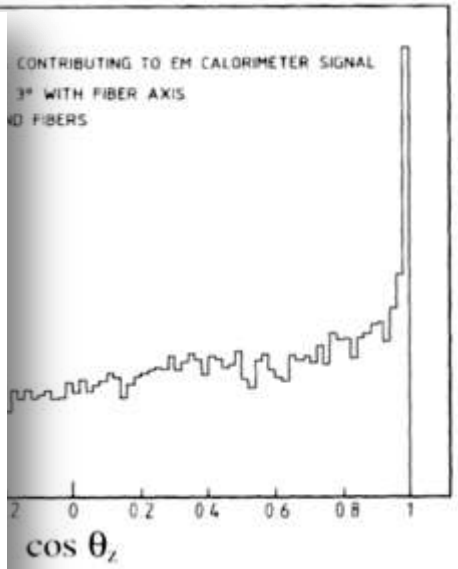
Lateral Shower Shape

- **Angular (pair pro**
  - Sprea perpe the in
  - The e expor
  - The v depth
- **Paramet**

$$\rho_M = m$$

  - 90% e cylinc show
  - Molliè mean





.7cm
..8cm
L.6cm

Myons

- **Nearly no Bremsstrahlung (1/40000 of e^-)**
  - Energy loss of μ mainly due to ionization
  - High energetic μ pass through thick layers of material
  - Myons with high energies are close to minimal ionizing (mip)
  - Example: 2m Pb
    - Minimal energy loss

$$-\frac{dE}{dx} = 1.13 \frac{MeV}{g/cm^2} \cdot \rho_{Pb} \Rightarrow -dE \approx 13 \cdot 200 MeV = 2.6 GeV$$

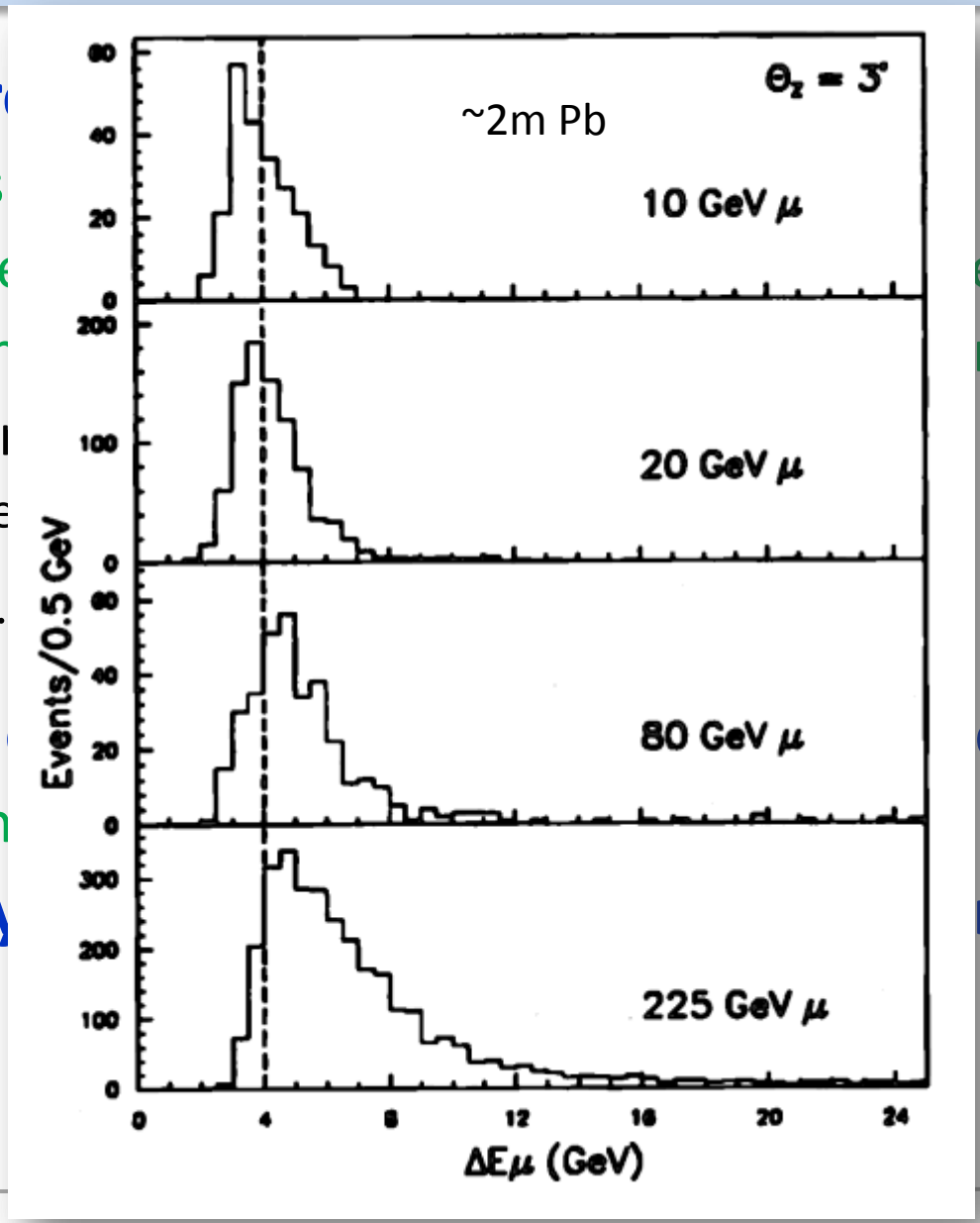
- **At very high energies Bremsstrahlung get important**
  - E_c is as high as 200GeV!
- **Myon energy NOT measureable in calorimeters with limited size**
  - Need for μ spectrometer

Myons

- **Nearly no Br**
  - Energy loss
  - High energe
  - Myons with
  - Example: 2
    - Minimal e

$$-\frac{dE}{dx} = 1.$$

- **At very high**
  - E_c is as high
- **Myon energy limited size**
  - Need for μ



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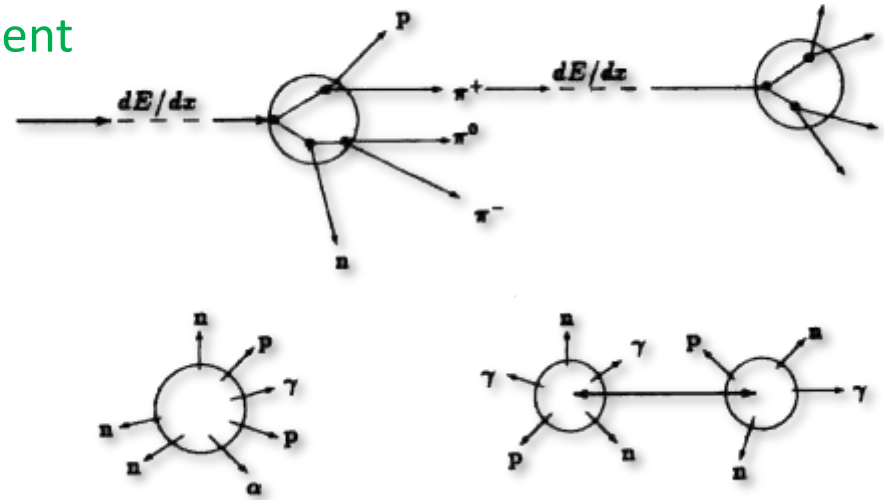
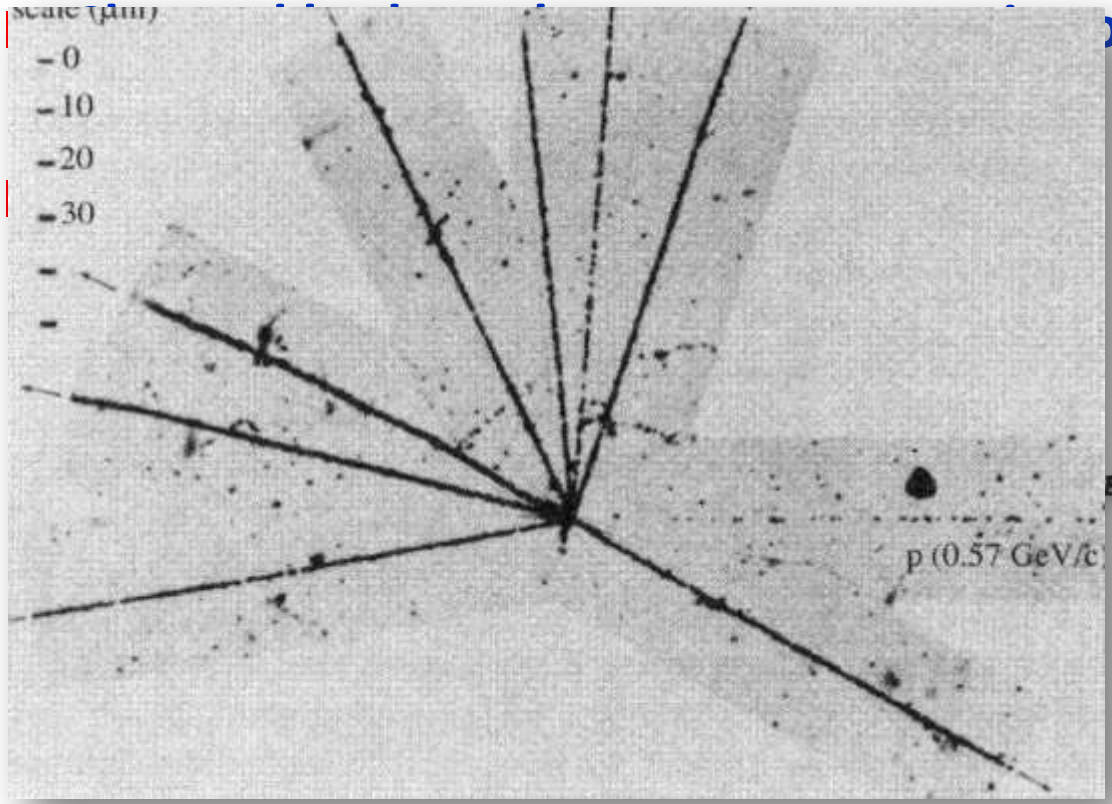
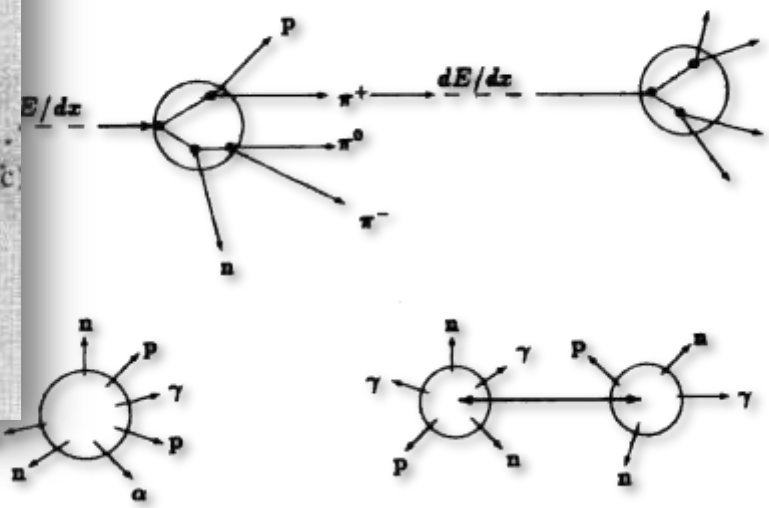
Hadronic Interactions

- **Charged hadrons loose energy continuously due to ionization/excitation of atoms**
- **Inelastic Interactions (spallation)**
  - Hadron interacts with a nucleon within the nucleus
  - Momentum transfer leads to subsequent scatterings off other nucleons
    - Intranuclear Cascade
  - Nucleons might leave the nucleus
    - slow Protons stopped quickly
  - Secondary particles are produced
    - mainly pions, rarely kaons
  - Electromagnetic component from neutral pion decays
  - Residual nucleus will very likely evaporate nucleons and emit photons



Hadronic Interactions





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- Residual nucleus will very likely evaporate nucleons and emit photons

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  - N
  - S
  - E d
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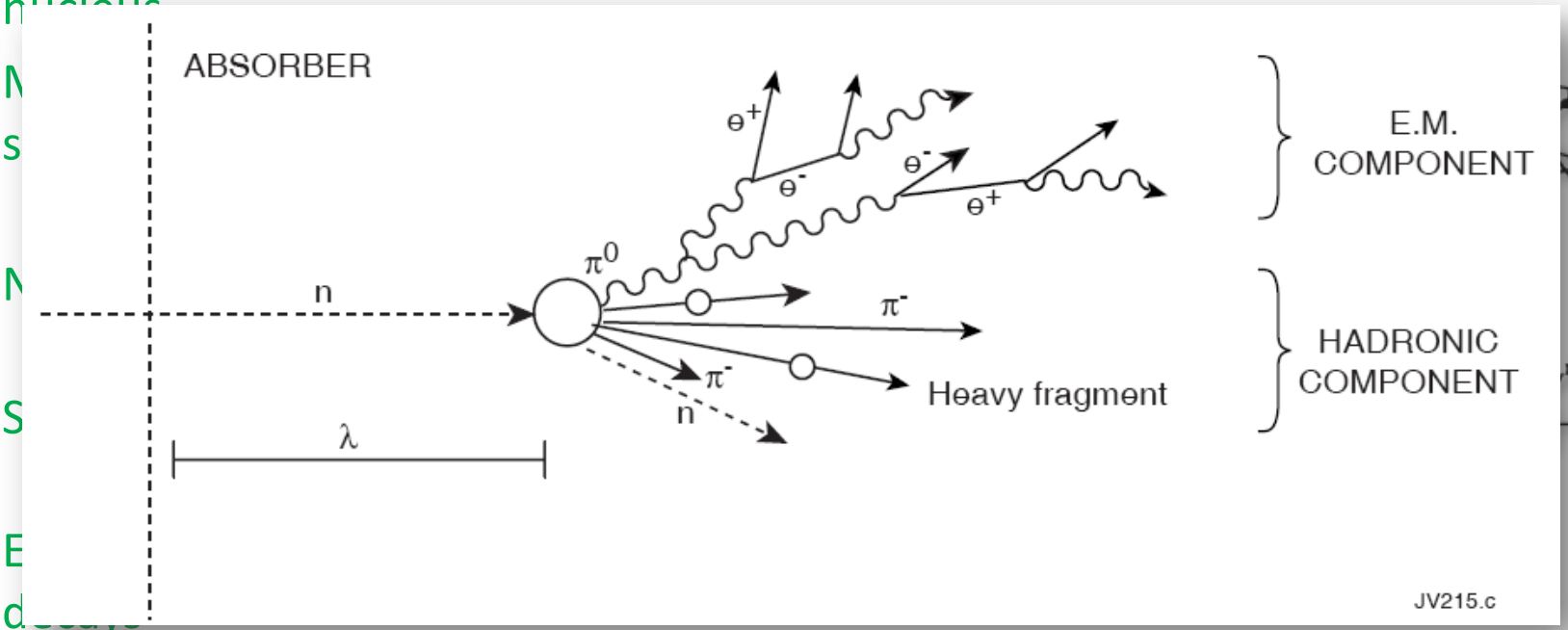

Hadronic Interactions

- **Charged hadrons loose energy continuously due to io**
- **Inelastic**
  - Hadro
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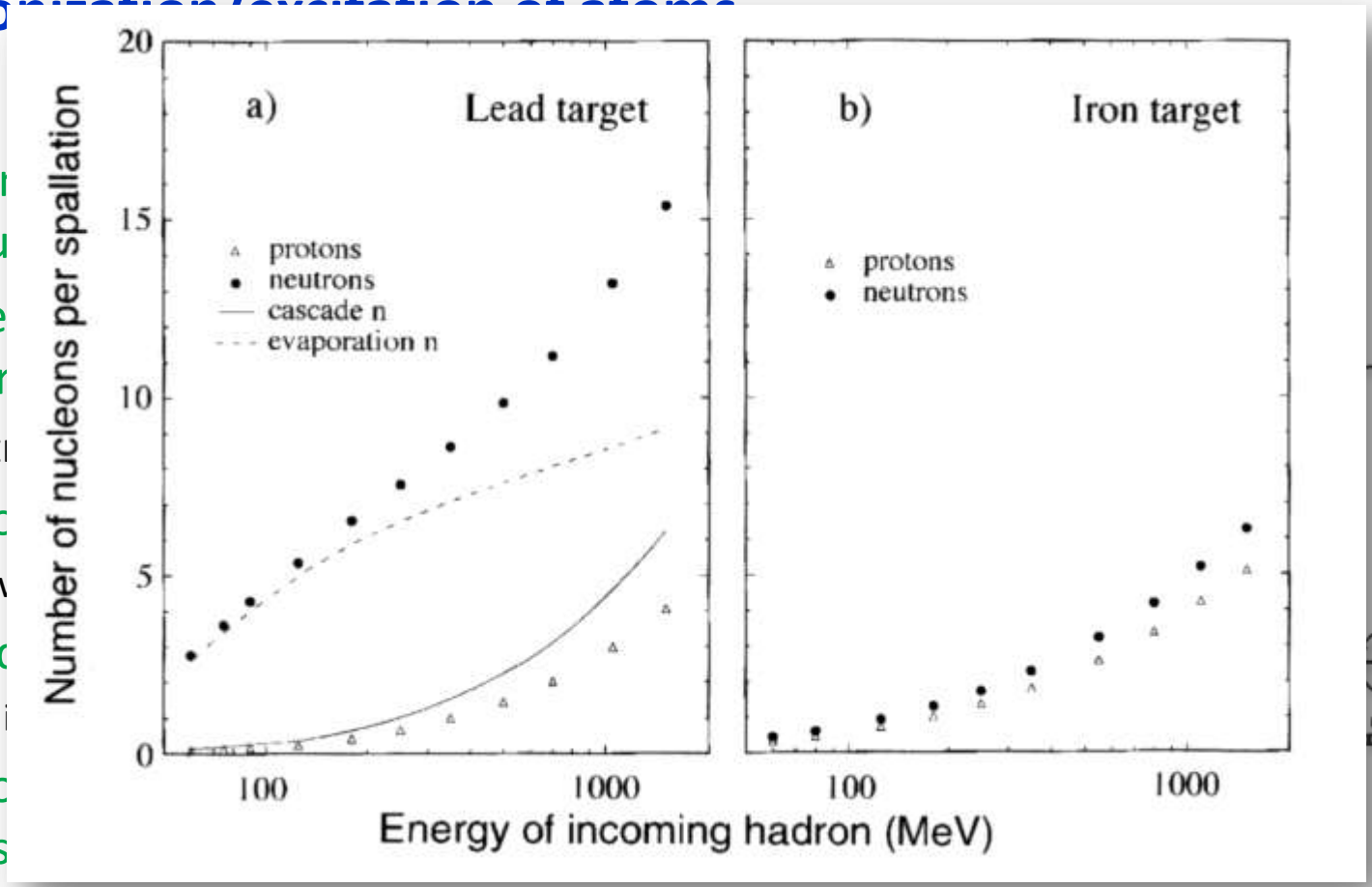
    decays
  - Residual nucleus will very likely evaporate nucleons and emit photons



Hadronic Interactions (2)

- **Secondary particles**
  - Energy is required to generate secondaries
    - Approx. 1.3 GeV (0.7GeV) for a single pion in Pb (Fe)
  - Composition of particles depends on the type of the primary particle and the material
  - Large fluctuations of number of secondaries and particle types
  - Extreme case is the charge exchange reaction

$$\pi^+ n \rightarrow \pi^0 p$$

    - Nearly no energy into nucleons and no charged hadrons
    - The neutral pion decays to two photons
- **Lost energy**
  - Spallation with the emission of nucleons leads to lighter nuclei
    - Binding energy is lost
  - Neutrons and decay products (myons & neutrinos) might escape the volume of the calorimeter
    - Pion and Kaon decays

Hadronic Interaction Length

- **Mean free Path Length**
  - Distance a proton travels on average without having a hadronic interaction

$$\lambda_{\text{int}} = N_A \cdot \rho \frac{A}{\sigma_{inel}} \quad \text{with } \sigma_{inel} \propto A^{2/3}$$

$$\Rightarrow \lambda_{\text{int}} \propto A^{1/3}$$

  - Parametrization for Protons

$$\lambda_{\text{int}} = 20 \cdot A^{0.4} + 32 \left[\frac{g}{cm^2} \right]$$

    - Larger for pions!

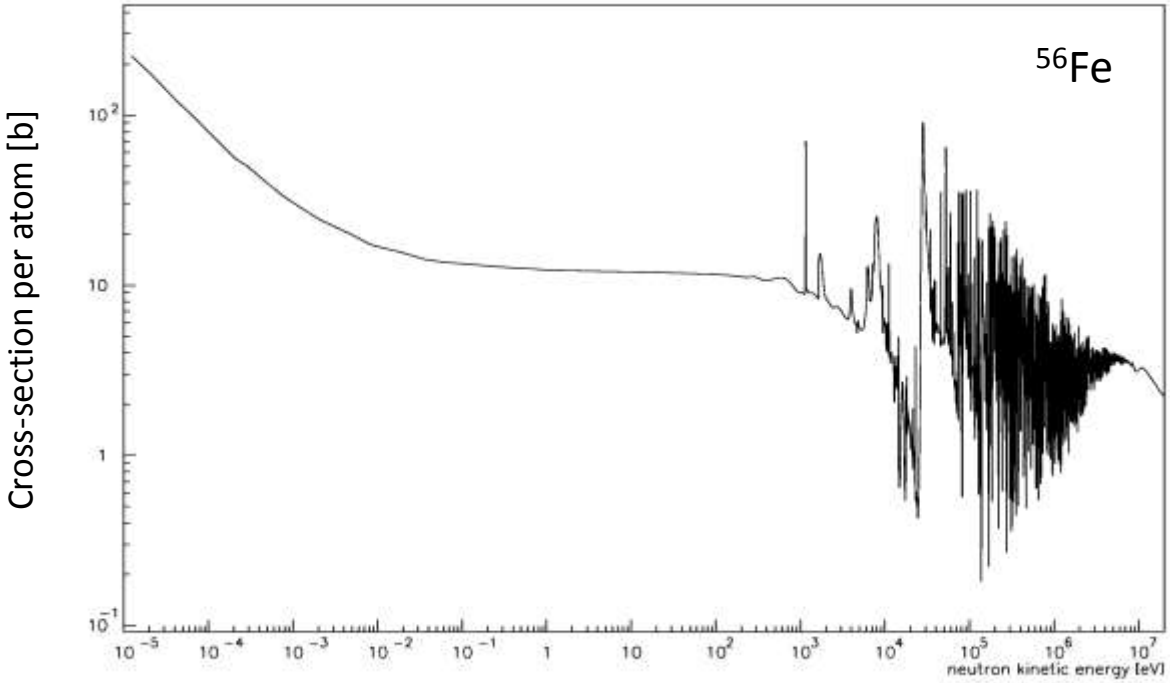
- **Examples**
  - Be– λ_{int}= 42.10cm (X_0= 35.3cm)
  - Al – λ_{int}= 39.70cm (X_0=18.8cm)
  - Fe – λ_{int}= 16.77cm (X_0=1.76cm)
  - Pb – λ_{int}= 17.59cm (X_0=0.56cm)
- **For small A is the mean free path length nearly the same for hadrons and electrons**

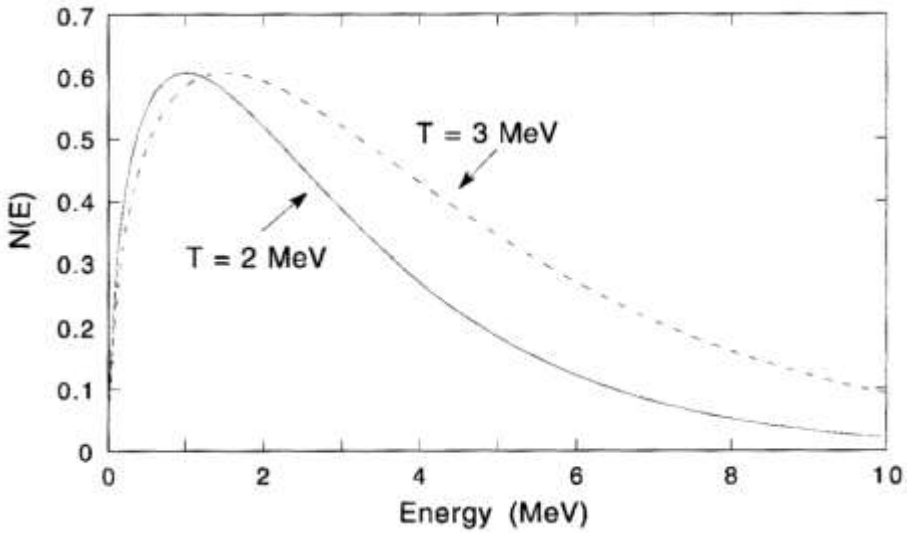
Interaction of Neutrons

- **Inelastic hadronic interactions**
  - Same as for charged hadrons for high energies
  - Strong energy and material dependence for energies in the MeV range
- **Elastic scattering (1eV < E < 1MeV)**
  - Energy loss due to elastic scattering depends heavily on the material
    - Average per collision
      - Target: H - 50% , Fe – 3.4% , Pb – 1%
  - Hydrogen rich materials very good for slowing neutron down (thermalization)
  - Mean free path length in high A materials can be huge
- **Low energy neutrons (E < 1eV)**
  - Capture
    - High cross section for very low energies (thermal)
    - Very high cross section for some materials (e.g. Cd, B)
    - Example Hydrogen

$$n + p \rightarrow D + \gamma(2.2MeV)$$

Total cross-section in Iron





Hadronic Cascades

- **The absorption of a hadron will start with an inelastic interaction (spallation)**
  - The further development depends crucially on this first interaction
    - Number of produced neutral pions (electromagnetic component f_{em})
    - Number of produced charged pions
    - Energy going into neutrons
    - Number of slow protons
  - The multiplicities depend on the target nucleus as well as the projectile
    - Cascade development different for pion and proton!
      - Baryon conservation reduces the pion production for protons
- **Subsequent collisions of secondary high energetic hadrons lead to a cascade or shower of particles**
  - Center of mass energy is decreasing rapidly within the cascade

Hadronic Cascades

- **The absorption of a hadron will start with an inelastic interaction (spallation)**
  - The [illegible] st inte[illegible]
    - [illegible] ent f_{em})
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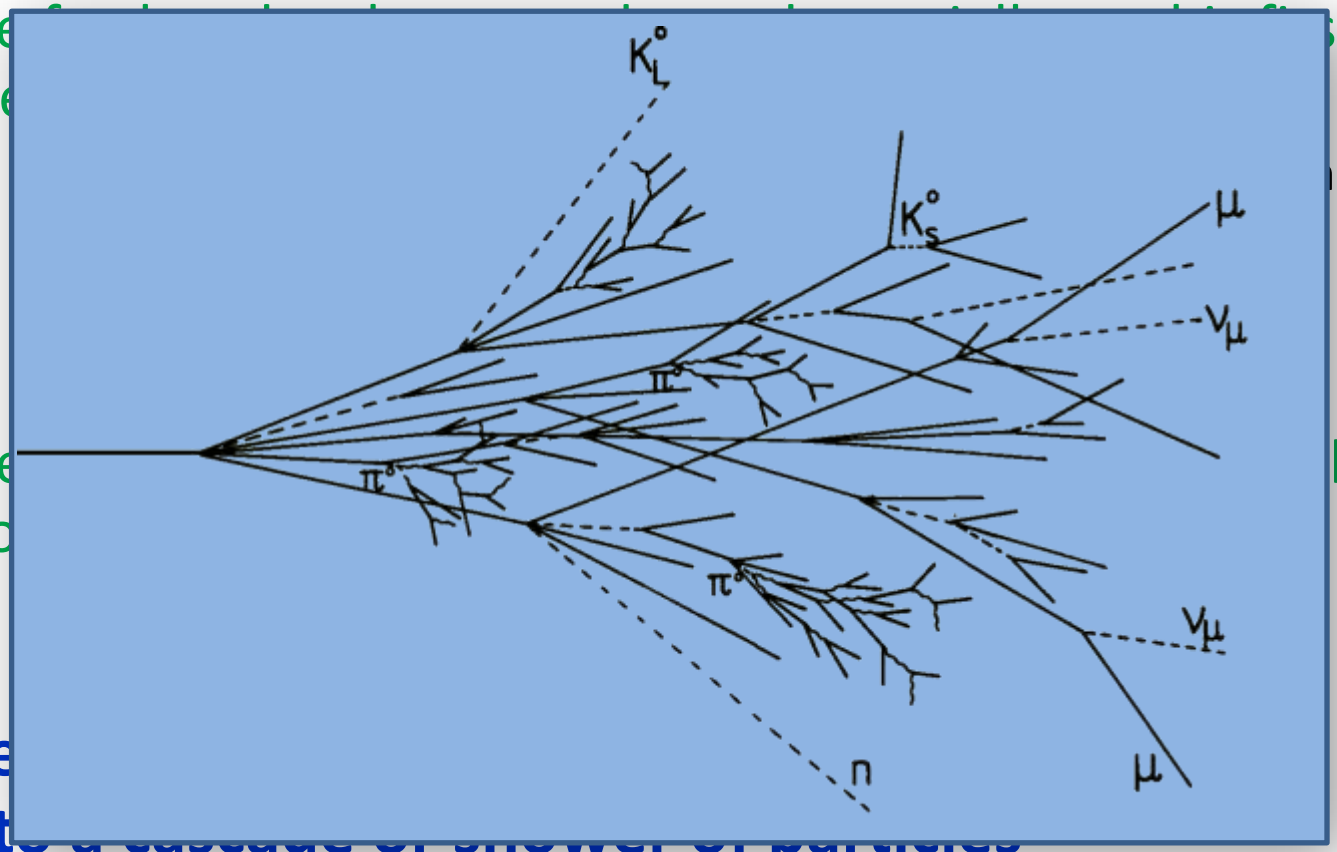
    - [illegible]
- **Subse[illegible] hadrons lead t[illegible]**
  - Center of mass energy is decreasing rapidly within the cascade



Hadronic Shower Composition

- **Hadronic Part: Example Pb and Fe**
  - Energy deposit (loss) for the non-electromagnetic component
  - Pions
    - Equal number of π^+, π^-, π^0
  - Nucleons
    - Binding energy is smaller in Pb
    - More neutrons in Pb due to Coulomb barrier for protons

	Lead	*Iron*
Ionization by pions	19%	21%
Ionization by protons	37%	53%
Total ionization	56%	74%
Nuclear binding energy loss	32%	16%
Target recoil	2%	5%
Total invisible energy	34%	21%
Kinetic energy evaporation neutrons	10%	5%
Number of charged pions	0.77	1.4
Number of protons	3.5	8
Number of cascade neutrons	5.4	5
Number of evaporation neutrons	31.5	5
Total number of neutrons	36.9	10
Neutrons/protons	10.5/1	1.3/1

Particles per GeV

Hadronic Shower Composition (2)

- **Electromagnetic component**
  - Production of π^0
    - Energy dependent (log increase)
    - Material dependent
    - Subject to large fluctuations
  - π^0 decay to photons generates electromagentic sub-shower (scales with X_0 and NOT λ_{int})
    - For high Z materials these are very different (Fe by a factor 10)!
- **Resolution of em component better than hadronic**
  - Dominates resolution at very high energies

Hadronic Shower Composition (2)

- Ele
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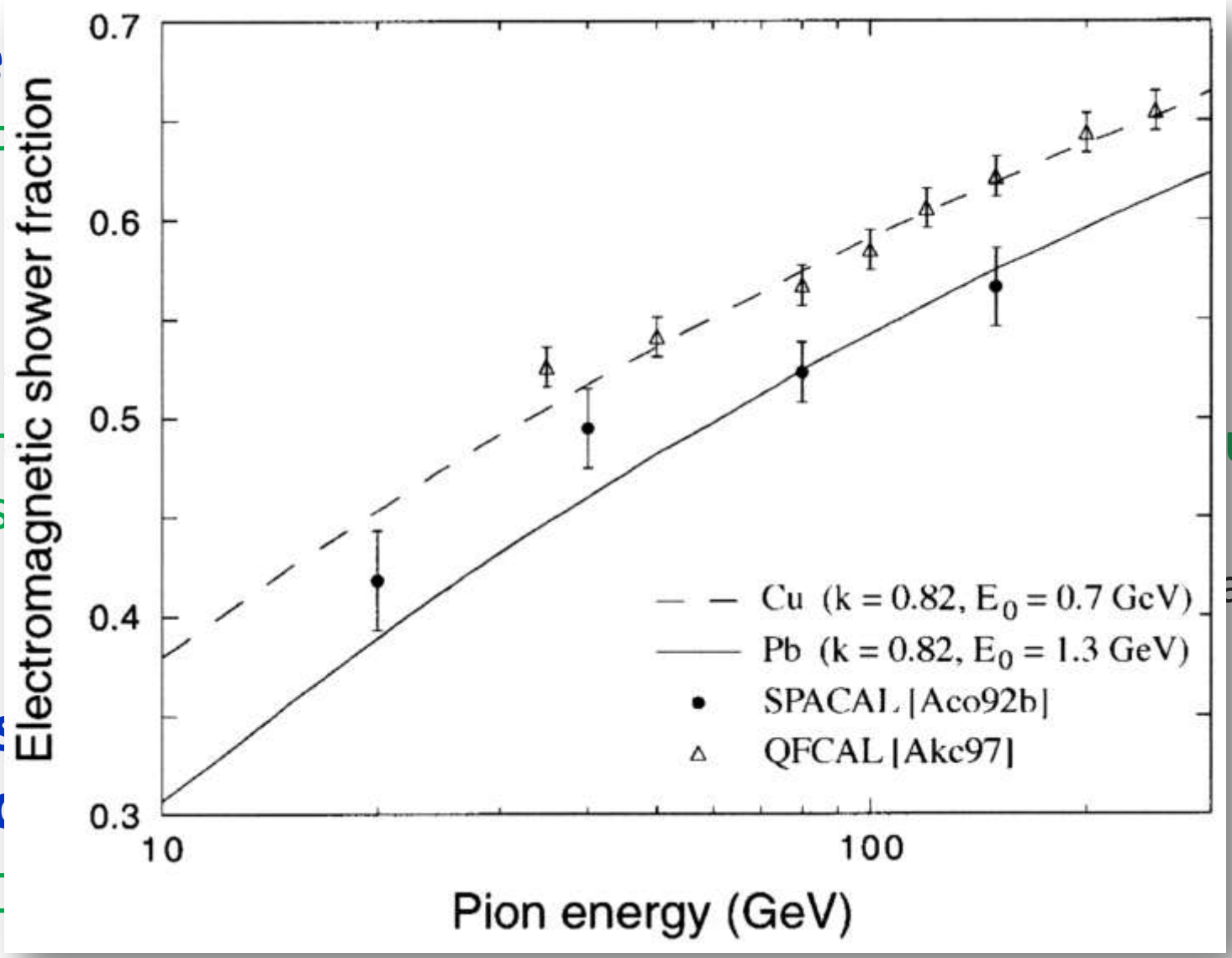

Hadronic Shower Shape

- **Shower Shape can be studied by means of radio nuclide analysis**
  - Detect radioactive isotopes produced in different depth of the material and distance from particle impact
  - Uranium well suited
    - Fast neutrons induce fission (1.5MeV threshold) of ^{238}U creates ^{99}Mo
    - High energetic photons: $^{238}U(\gamma,n)\ ^{237}U$
    - Slow neutrons are captured $^{238}U+n \rightarrow {}^{239}U \rightarrow {}^{239}Np$
- **Longitudinal shower development**
  - Each individual shower will look very different
    - Fluctuation of the different shower components
  - Average shape similar to em-shower
    - Scales with hadronic interaction length λ_{int}

Hadronic Shower Shape

- **Shower Shape can be studied by means of radio nuclide an**
  - Detect ra ent depth of the mate t
  - Uranium
    - Fast ne ^{238}U creates ^{99}Mo
    - High er
    - Slow ne o
- **Longitudir**
  - Each indi t
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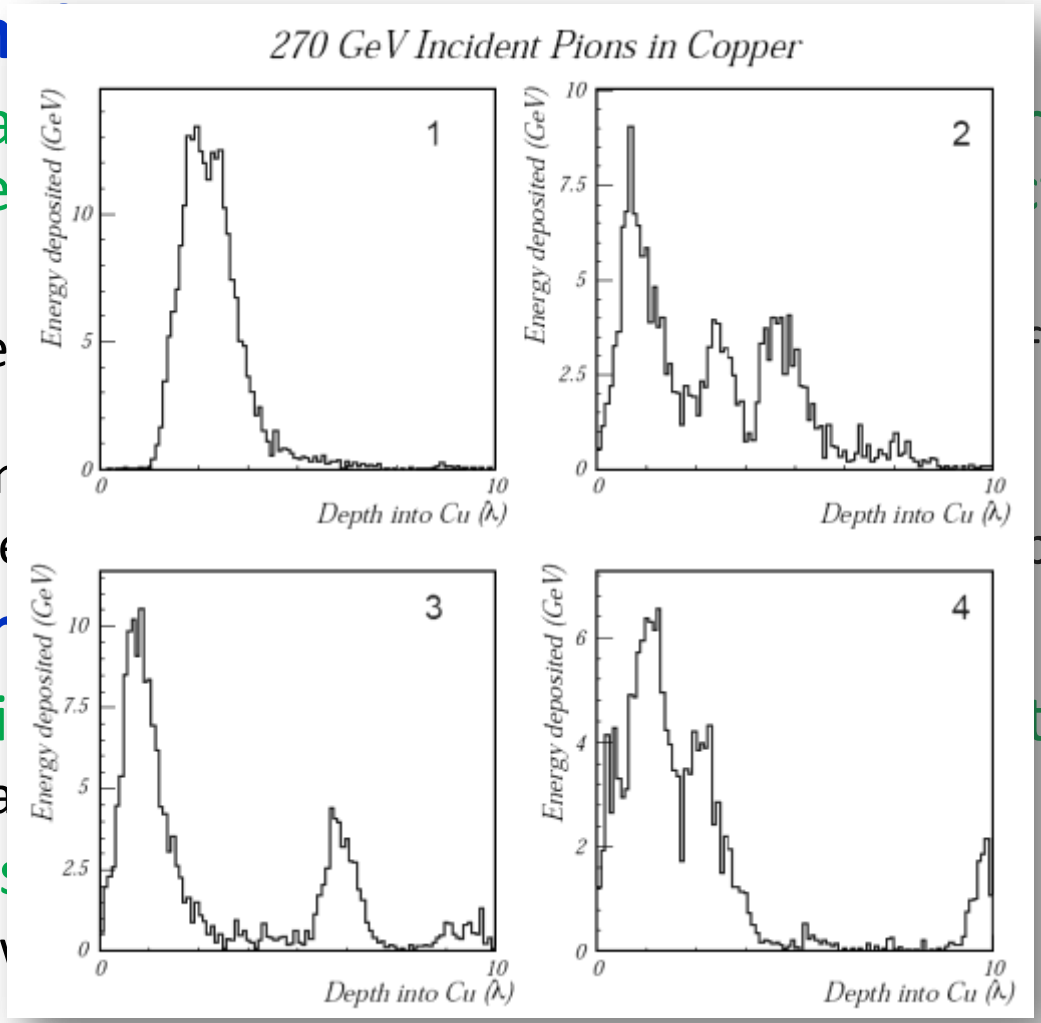

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  - Detect radioactive isotopes produced in different depth of the material and distance from particle impact
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      ^{99}M
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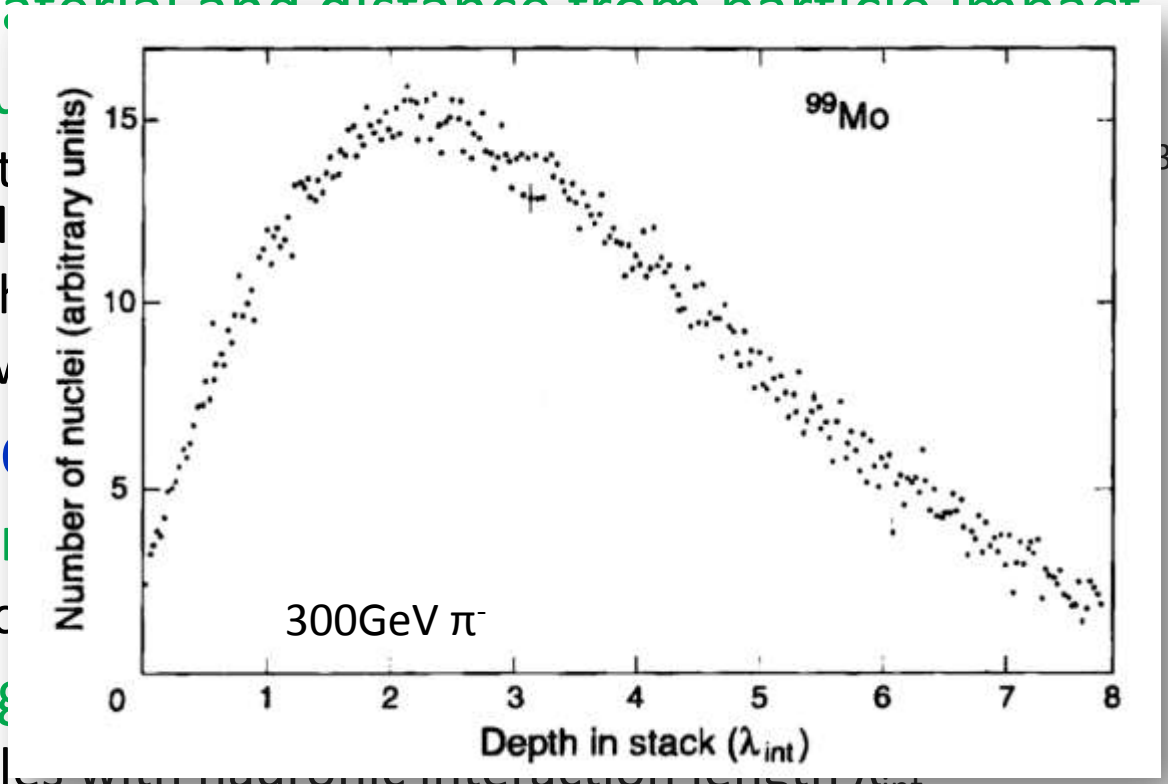
  - Averag
    - Scal

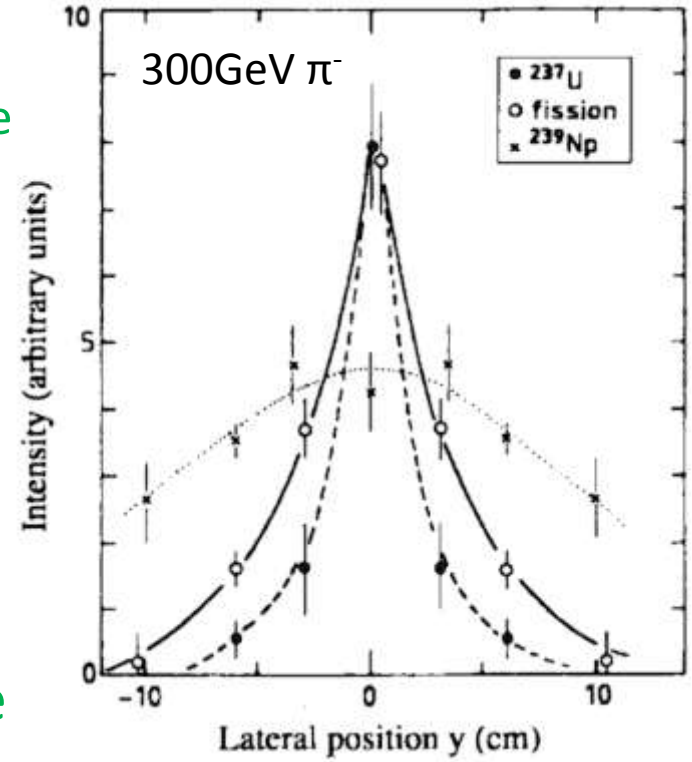


^{238}U creates

with hadronic interaction length λ_{int}

Lateral Shower Shape

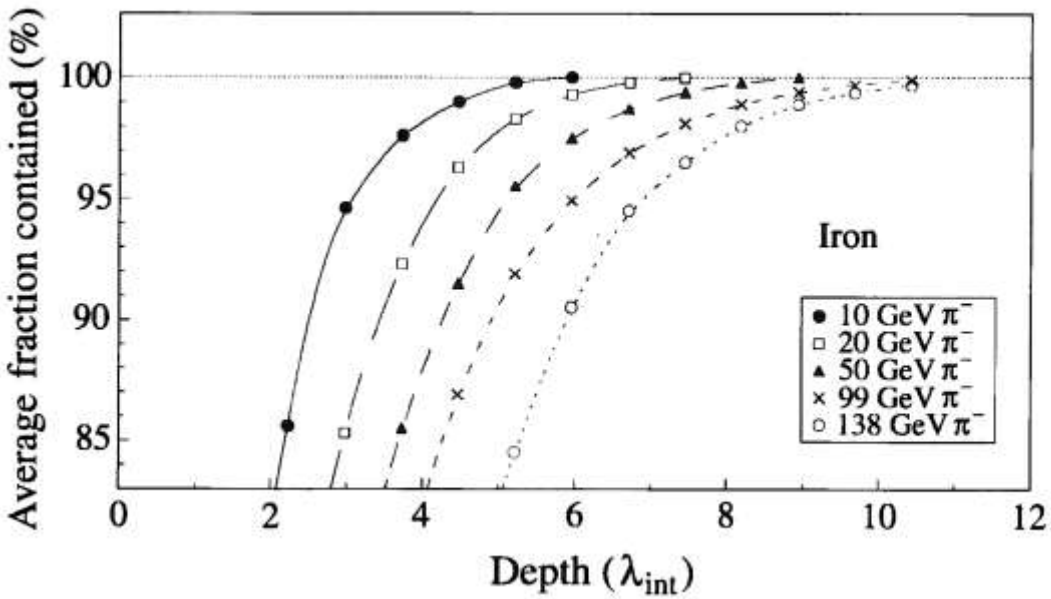
- **Particle composition depends on distance from shower axis**
  - Fast particles (neutrons, γ) found close to the axis
    - ^{237}U samples the em component
    - ^{99}Mo samples fast neutrons
  - Slow (thermalized) neutrons travel far off axis
    - ^{239}Np samples thermal neutrons
- **Result from Uranium slab block**
  - Exponential lateral shape, with a core of high energetic particles



~1λ_{int}

Containment

- **Longitudinal containment**
  - Particles leaving the calorimeter (leakage) are lost for energy measurement
    - Large fluctuation of the lost particles event by event
    - Deteriorated energy resolution
  - Each event has a different composition, which leads to a very different requirement for containment
  - Energy dependence adds to the requirement for the depth



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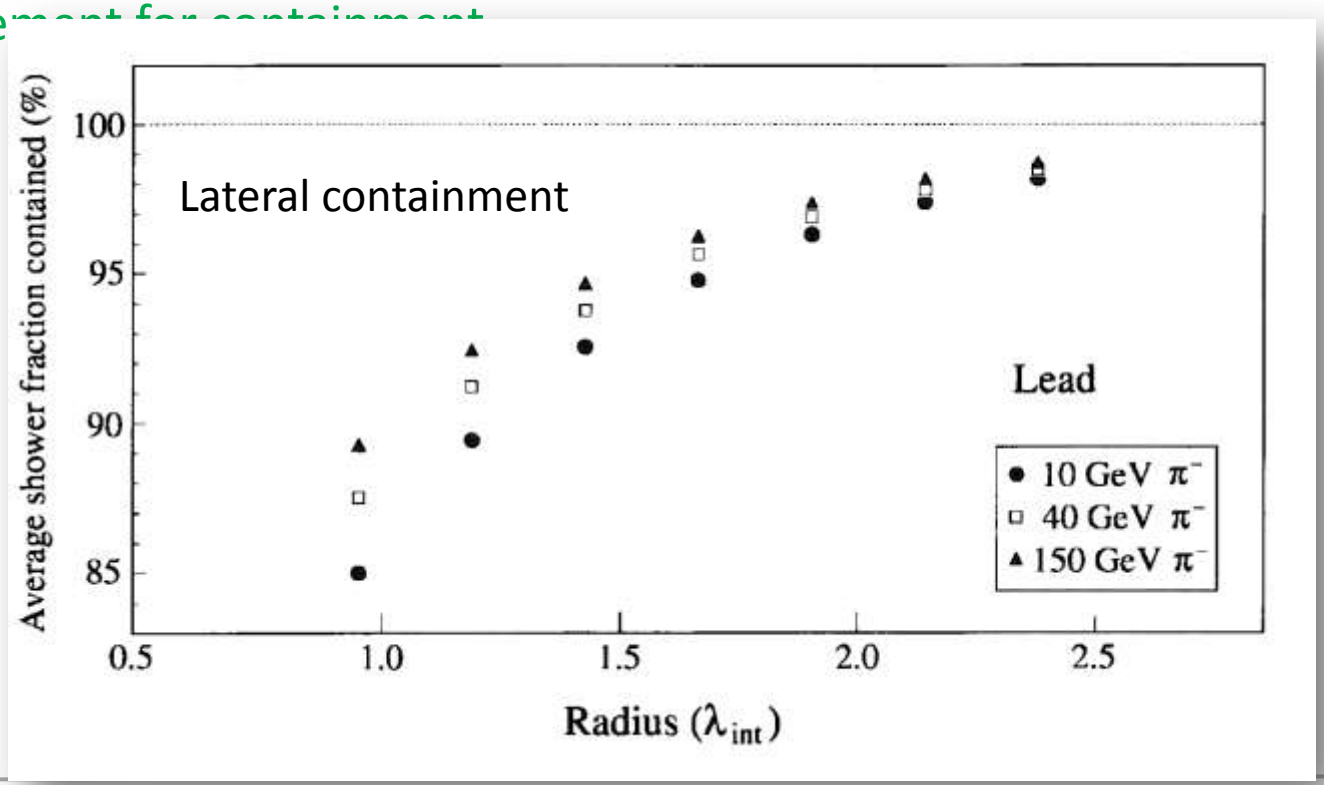
  - Energy



Summary of Showers

- **Electromagnetic**
  - Bremsstrahlung and Pair-production produces multitude of secondary particles
    - Electrons, positrons and photons down to very small energy
  - Scales with X_0
    - Small X_0 for high Z materials
    - Requires roughly 25-30 X_0 for full containment (Pb ~ 17cm)
- **Hadronic**
  - Electromagnetic sub-showers originating from neutral pion decays
  - Hadrons
    - Charges pions, charged and neutral kaons
    - Slow protons from inelastic interactions with nuclei
    - Fast and slow neutrons
  - Energy lost due to binding energy and escaping particles
  - Large fluctuations of different components
  - Scales with λ_{int}
    - Small λ_{int} for high A material
    - Requires 8-9 λ_{int} for containment (Fe ~150cm)

Response of Calorimeters

- **Assumptions**
  - Absorb the particle in a dense medium (compact calorimeter)
  - Infinite absorber size (no leakage)
  - Ideal materials
- **How to measure the energy deposition in the absorber**
  - Absorber itself provides a signal (e.g. light or charge) which is proportional to the deposited energy
    - Liquid noble gas (LAr, LKr), dense crystals (NaI, Pb-glas, $PbWO_4$)

    Homogeneous calorimeter
  - "Sample" the deposited energy by interleaving absorber and an "active" medium
    - Only a fraction of the energy is measured → reduced response and resolution
    - High Z and A materials as absorber
    - Standard particle detector as active medium (e.g. scintillator, semi conductor, gas …)

    Sampling calorimeter

Response of Calorimeters

CMS: $PbWO_4$ calorimeter

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. light or charge) which is

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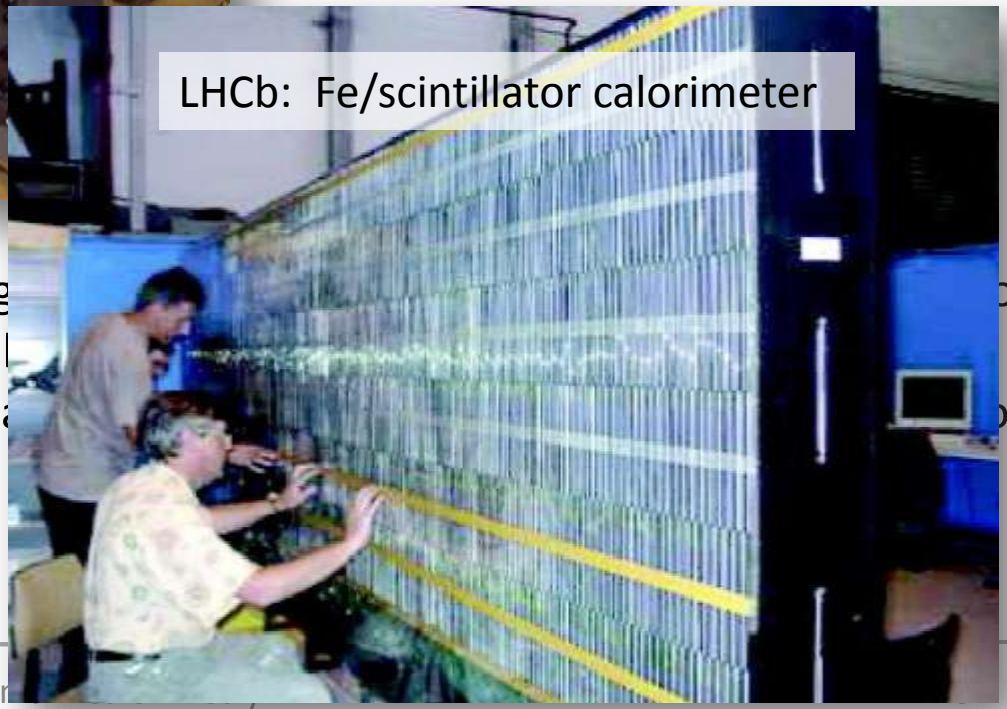

LHCb: Fe/scintillator calorimeter

"active" medium

- Only a fraction of the energ on
- High Z and A materials as al
- Standard particle detector a r, gas …)

Sampling calorimeter

Homogeneous Calorimeter Crystals

- **$PbWO_4$ crystal**
  - High density ρ=8.3 g/cm3
  - Small radiation length X_0=8.9mm
  - Small Molièreradius R_m=2.2cm
  - Fast signal: 80% of the light in 25ns
  - Radiation hard
  - Excellent energy resolution
- **Disadvantages**
  - Small light yield: ca. 80 γ/MeV (NaI : 40000 γ/MeV)
  - Temperature dependent yield (-1.9%/°C @ 18°C)
  - expensive

Homogeneous Calorimeter Crystals

- **PbWO crystal**
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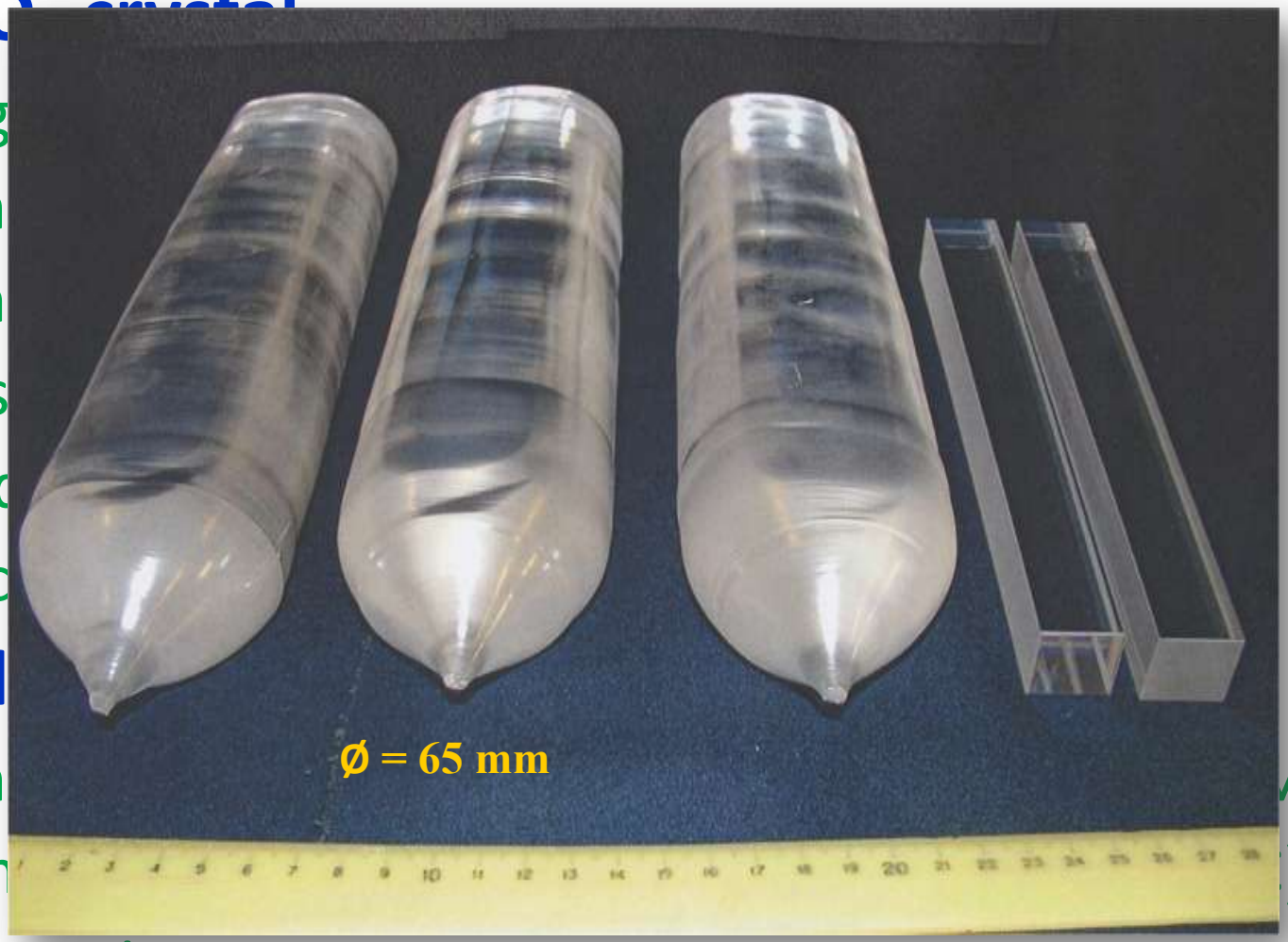
  - expensive



Signal of a MIP

- **Energy deposition by a minimal ionizing particle (MIP)**
  - Energy loss given by minimum of Bethe-Bloch Formula
  - Can easily be calculated for different material combinations
  - Example
    - 20 layers of 5cm Fe+ 1cm scintillator

$$dE_{Fe} = 1.451 \frac{MeV}{g/cm^2} \cdot 7.8 \frac{g}{cm^3} \cdot 5cm \cdot 20 = 1131.8 MeV$$

$$dE_{sci} = 1.936 \frac{MeV}{g/cm^2} \cdot 1.03 \frac{g}{cm^3} \cdot 1cm \cdot 20 = 39.9 MeV$$

$$\text{total energy loss } dE = 1171.7 MeV$$

    - In this case only 39.9MeV are actually measured in the scintillator → *visible* energy

Signal of a MIP (2)

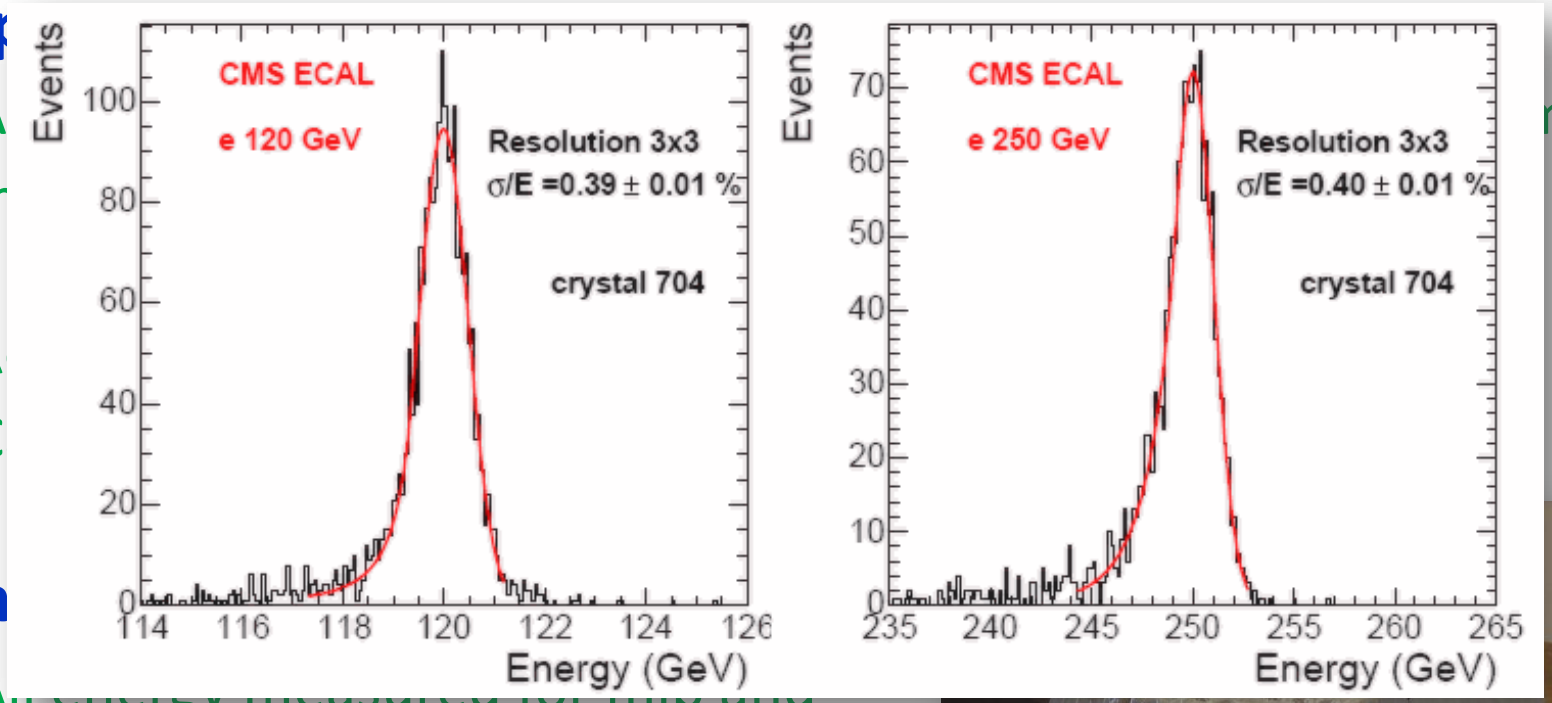
- **MIP signal is commonly used as a reference for all other particles**
  - X/mip: signal of a particle X with energy equal the dE/dx of a MIP
  - e/mip, γ/mip, n/mip, p/mip, π/mip
  - Ratios are often energy dependent!
- **Measure the MIP signal**
  - Myons provide best estimate for a MIP
    - Needs correction (energy dependent)
- **The response of a calorimeter can be estimated from the known X/mip ratios**

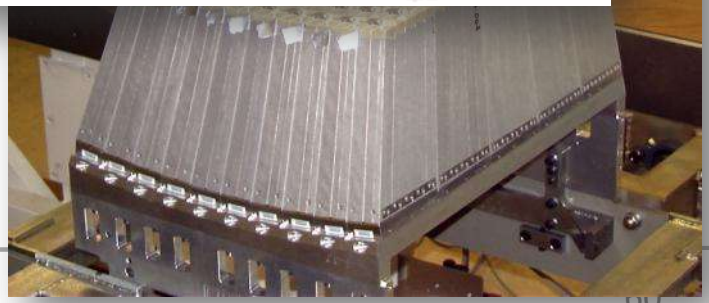
Homogeneous Calorimeter

- **Practically only used in high energy physics for electromagnetic calorimeters**
- **Response**
  - All the energy is deposited AND measured in the active volume
  - Intrinsically linear response
    - Reality: local ionization density leads to saturation
  - Readout usually not 100% efficient
  - Calibration with known energy required
    - Electrons with known energy
- **e/mip=1**
  - All energy measured for mip and electron
  - Response identical!

Homogeneous Calorimeter

- **Practically only used in high energy physics for electromagnetic calorimeters**
- **Resp**
  - A
  - Ir
  - R
  - C
- **e/m**
  - A
    electron
  - Response identical!





Response of homogeneous Calorimeters

- **Response to hadrons (assume full containment)**
  - $e/\pi > 1$
    - Energy loss in hadronic showers (e.g. binding energy) reduces the visible energy
  - Fraction of neutral pions (f_{em}) increases with energy → e/π decreases with E
- **Intrinsic pure hadronic response**
  - e/h (electron/hadronic) > 1
    - Pure hadronic consists of pions, kaons, neutrons, recoil nuclei
    - Response (nearly) energy independent
    - Lost energy leads to smaller response of hadrons
  - Range $1.5 < e/h < 2.5$
- **Calorimeters with $e/h \neq 1$ are called "non-compensating"**

Determination of e/h-ratio

- **Only e/π can be measured**
  - Pion response depends on e/h

$$\pi = f_{em} \cdot e + (1 - f_{em}) \cdot h$$

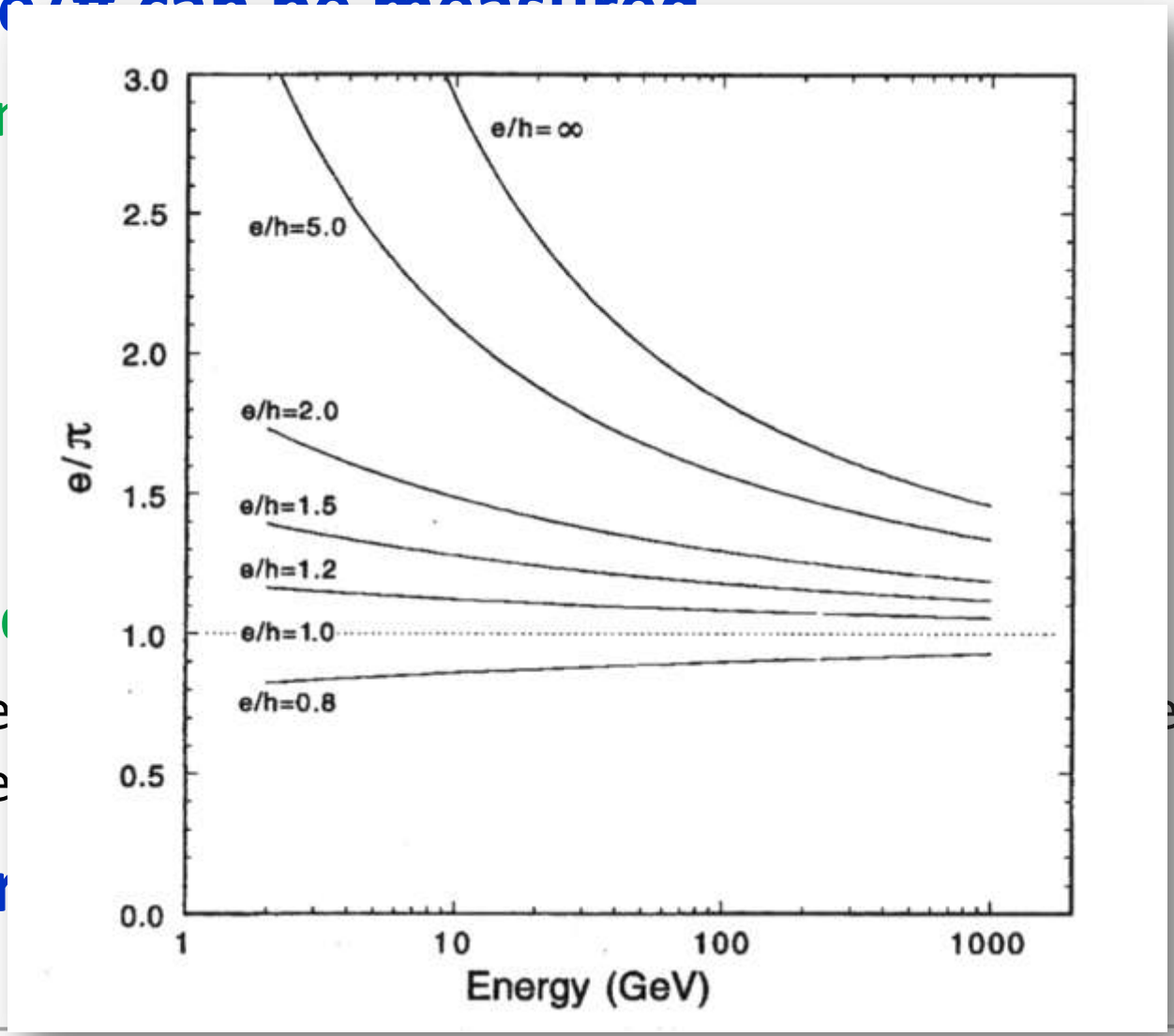
$$\frac{\pi}{e} = f_{em} + (1 - f_{em}) \cdot \frac{h}{e}$$

$$\Rightarrow \frac{e}{\pi} = \frac{e/h}{1 - f_{em}(1 - e/h)}$$

  - f_{em} depends logarithmically on the energy
    - e/π changes with energy and approaches 1 for very high energies
- **Pion response for e/h≠1 is NOT linear!**

Determination of e/h-ratio

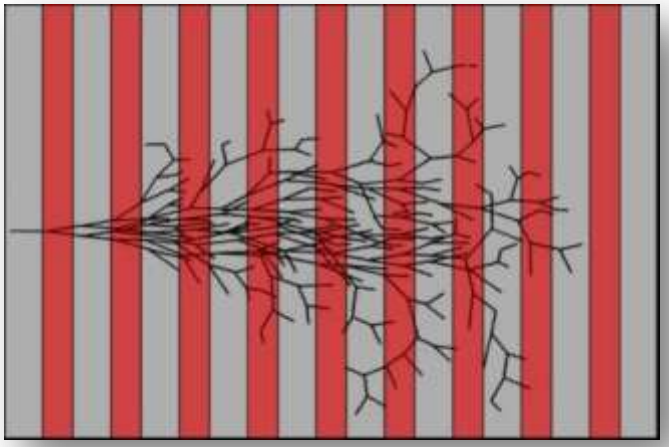
- **Only e/π can be measured**
  - Pion
  - f_{em}
    - e
      e
- **Pion r**



ery high

Sampling Calorimeter

- **Absorber material (high Z) interleaved with active medium**
- **Sampling fraction**
  - Fraction of energy deposited in active medium
    - Calculates for a MIP
    - Example again: 20 layers of 5cm Fe+ 1cm scintillator

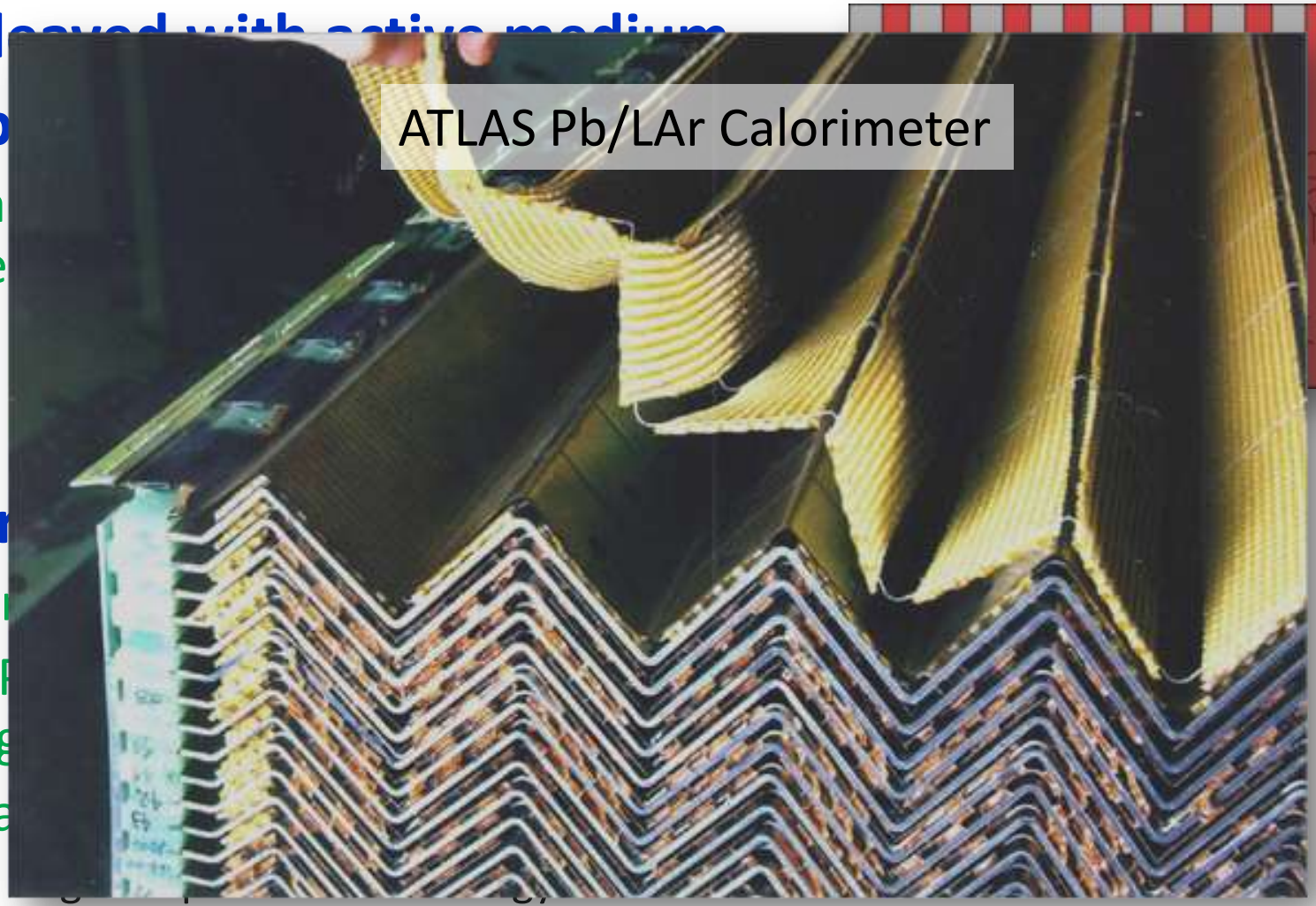


$$f_{samp} = \frac{39.9}{1131.8 + 39.9} = 3.4\%$$

- **Calibration**
  - Signal (ADC counts) to energy scaling
  - MIP signal has to be scaled by $1/f_{samp}$ to get correct energy
  - In addition scale with X/mip
    - Might depend on the energy itself!

Sampling Calorimeter

- **Absorber material (high Z) interl**
- **Samp**
  - Fra me
    -
    -
- **Calibr**
  - Sig
  - MI to g
  - In a
    -

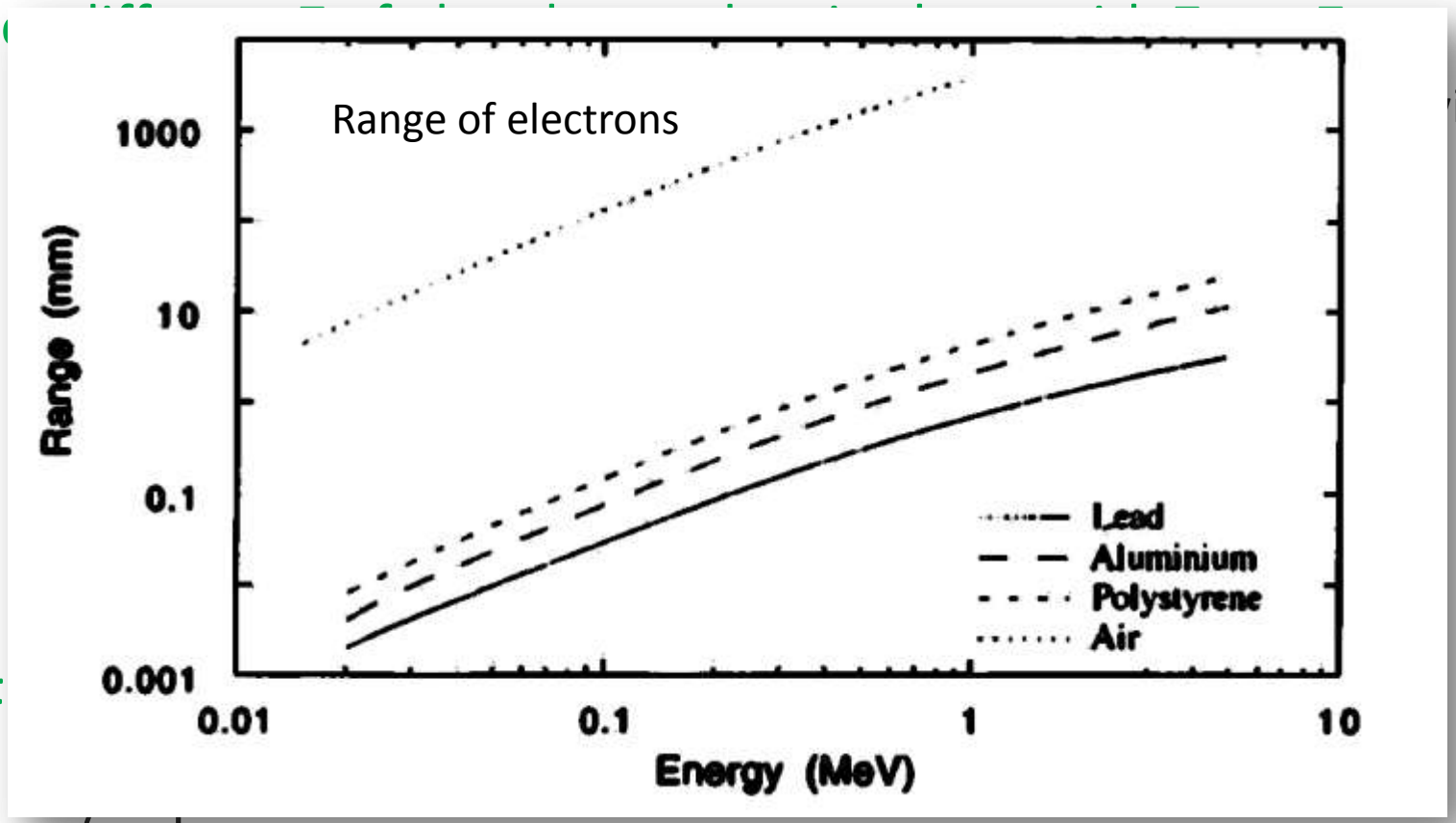


Electrons and Photons

- **e/mip and γ /mip**
  - For different Z of absorber and active layer with $Z_{abs} > Z_{act}$
    - Most shower particles ($e^{\pm}$, γ) are produced in the high Z absorber with low energy (Bremsstrahlung, photo effect, Compton)
    - Range of particles is smaller than thickness of absorber plates
    - Particles do not reach the active layer
    - e/mip < 1 and γ /mip < 1
    - Depends on difference in Z
    - Depends on shower depth
      (particles get softer)
  - For light absorbers (Al) and heavy active media
    - e/mip > 1
- **Response depends on thickness of sampling layers**

Electrons and Photons

- **e/mip and γ /mip**
  - F
  - F



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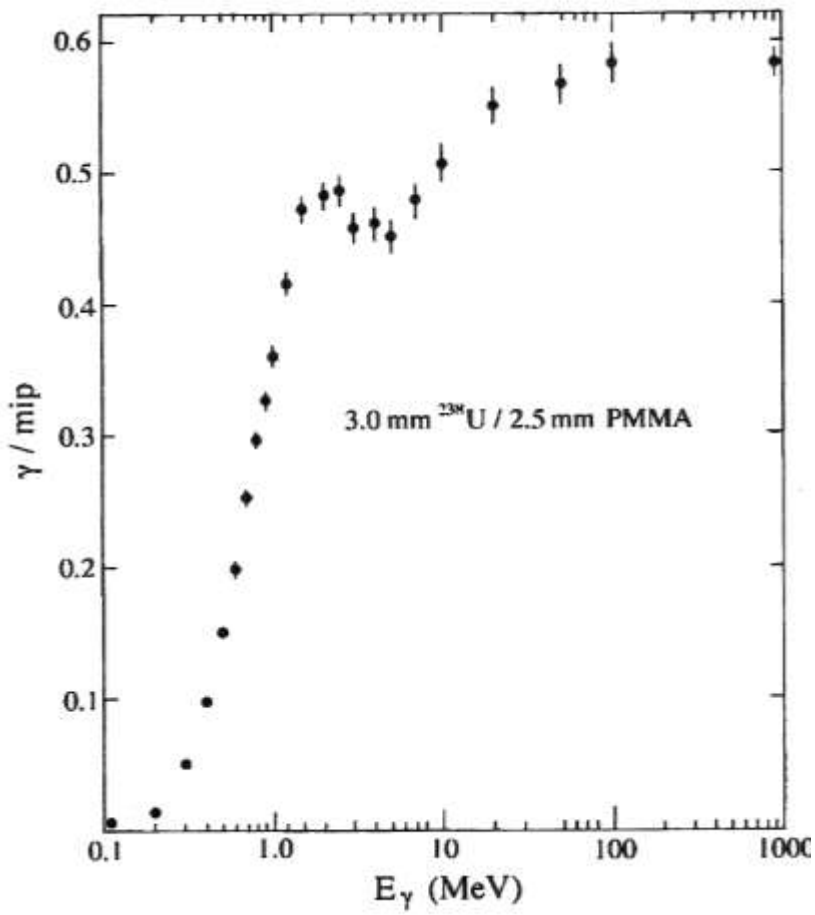
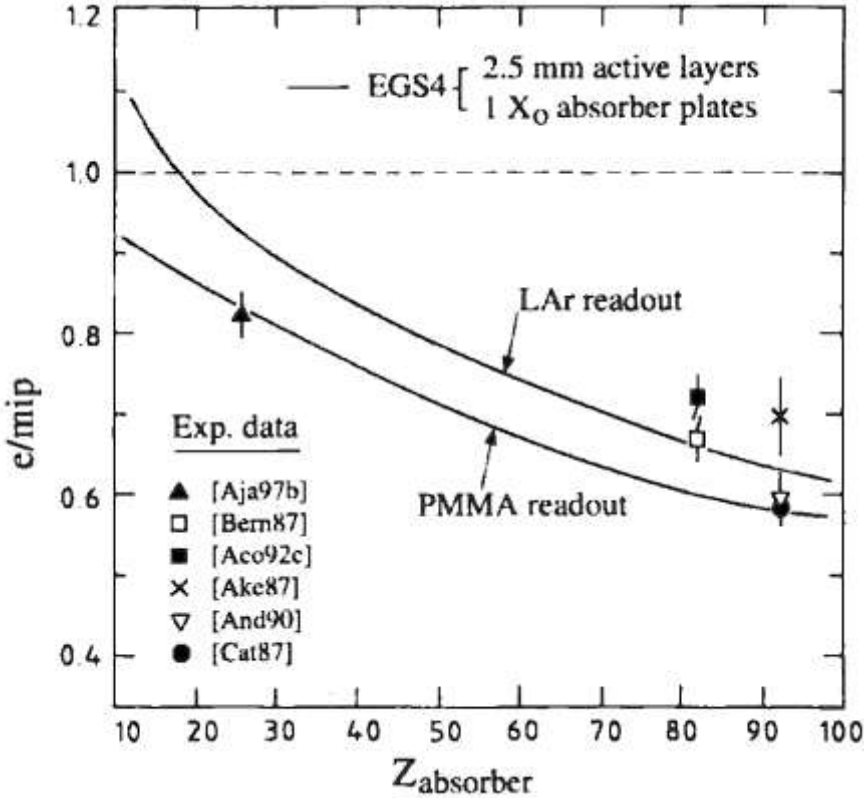
Electrons and Photons





- Response depends on thickness of sampling layers

Electrons and Photons

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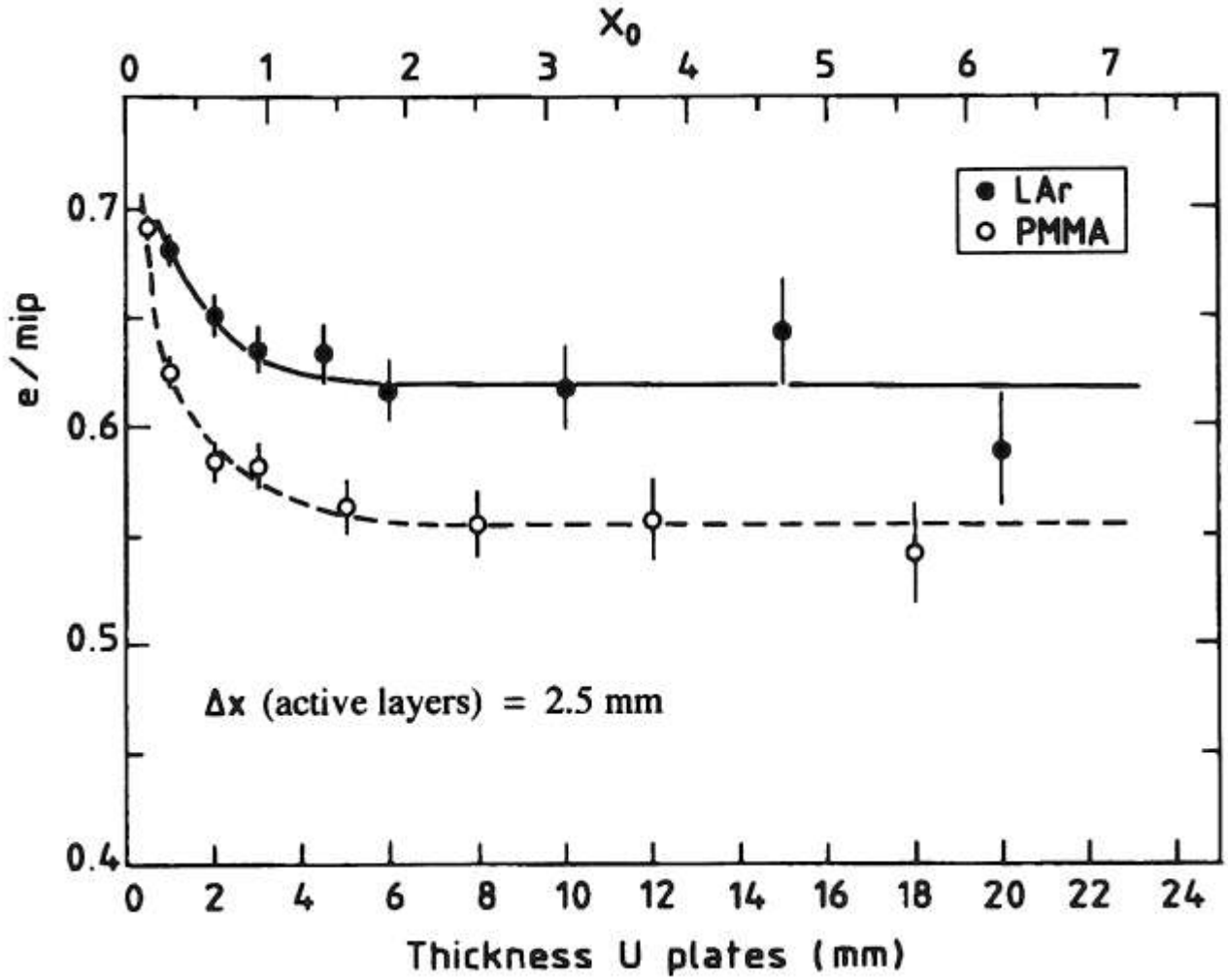
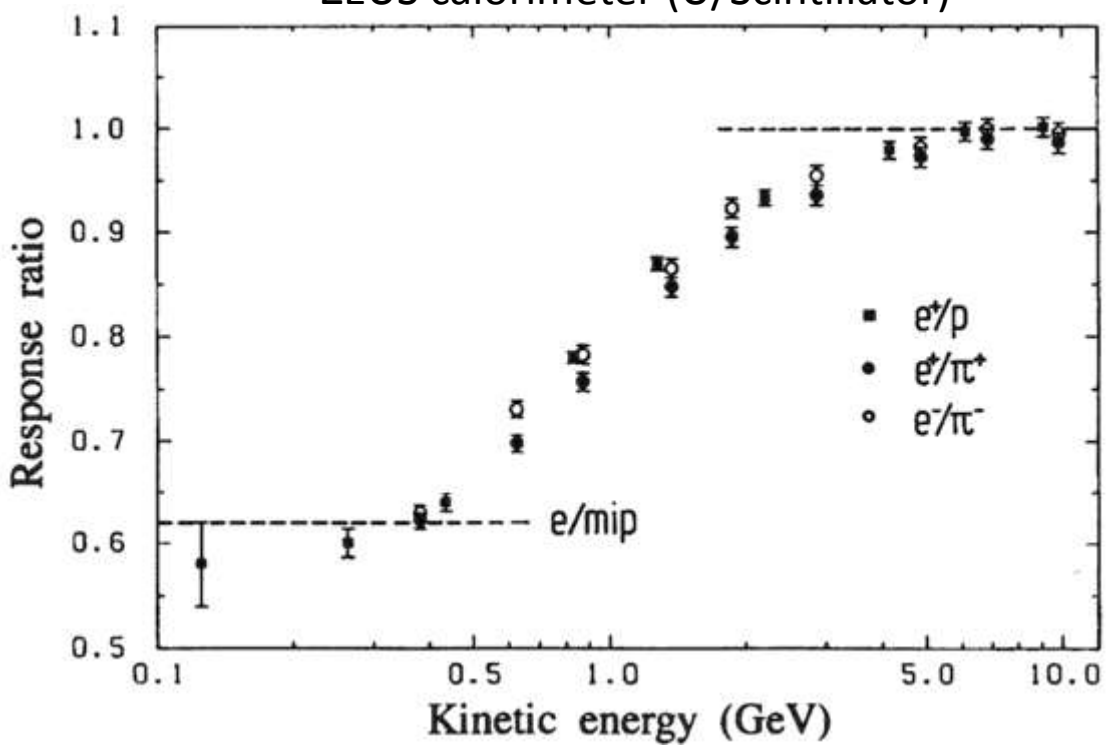


Hadrons

- **Low energy hadrons (below 1GeV)**
  - Mainly ionization loss (nearly MIP like)
- **High energy hadrons**
  - For very high energies e/π=1 (as for homogeneous case)
  - Transition region up to 5GeV

ZEUS calorimeter (U/Scintillator)



e/h of Sampling Calorimeters

- **Intrinsic e/h is a constant!**
  - Describes the response of non-electromagnetic part of the shower
- **ZEUS calorimeter (HERA experiment) achieved e/h=1 → "compensated" calorimeter**
- **Most calorimeters are non-compensating**
  - Wide range of e/h values
  - e/h≠1: energy response is not linear

$$\frac{\pi(E_1)}{\pi(E_2)} = \frac{f_{em}(E_1) + [1 - f_{em}(E_1)] \cdot e/h}{f_{em}(E_2) + [1 - f_{em}(E_2)] \cdot e/h} \neq 1$$

- **Calculation of e/h requires the response of different hadronic shower components**
  - Ionizing particles (pions, slow protons…), neutrons

e/h of Sampling Calorimeters

- **Intrinsic e/h is a constant!**
  - the
- **ZEU** **h=1**
  →
- **Mo**
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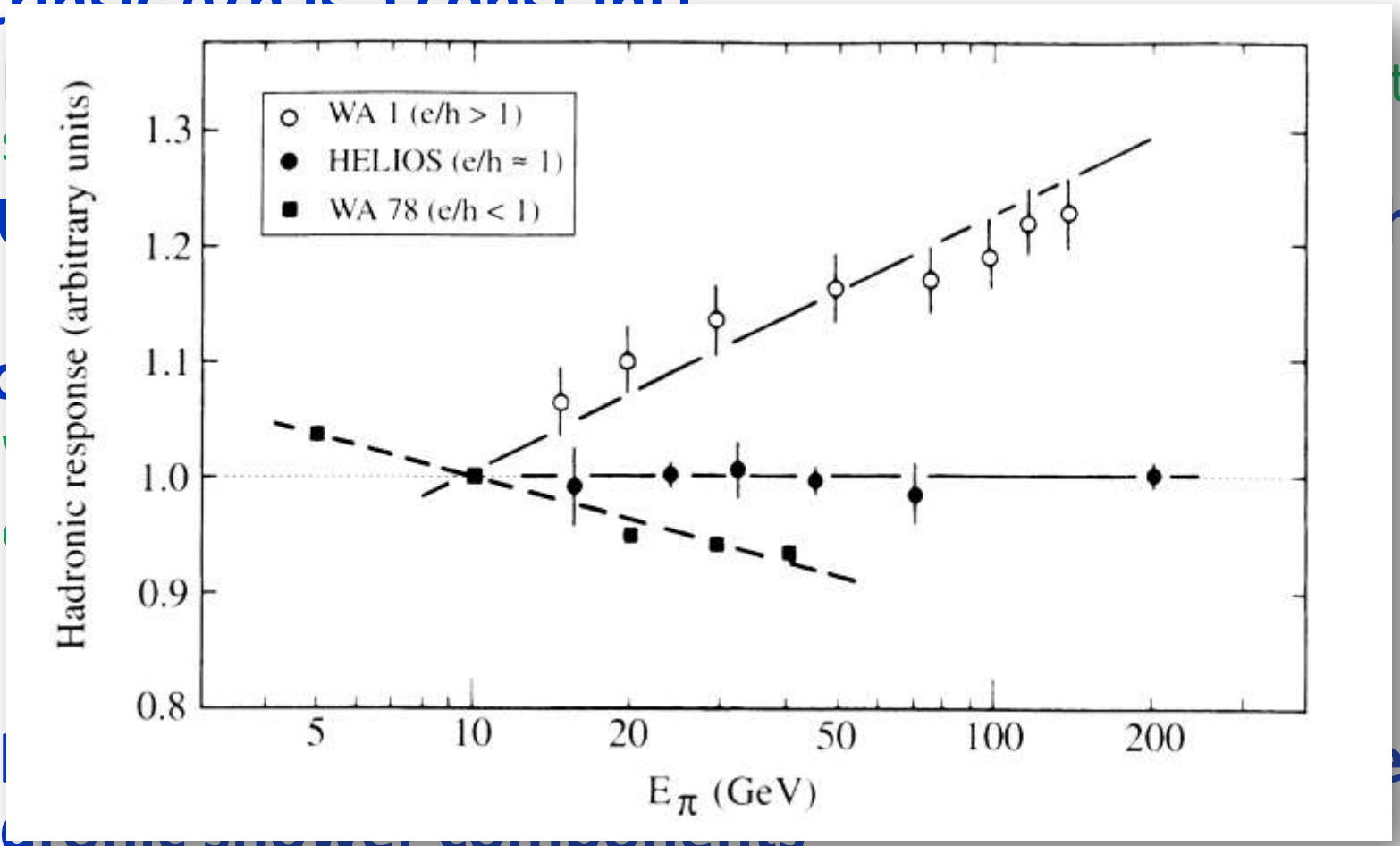
  had
  - Ionizing particles (pions, slow protons…), neutrons



Pure hadronic response

- **All response components expressed wrt MIP**
- **e/h calculation**

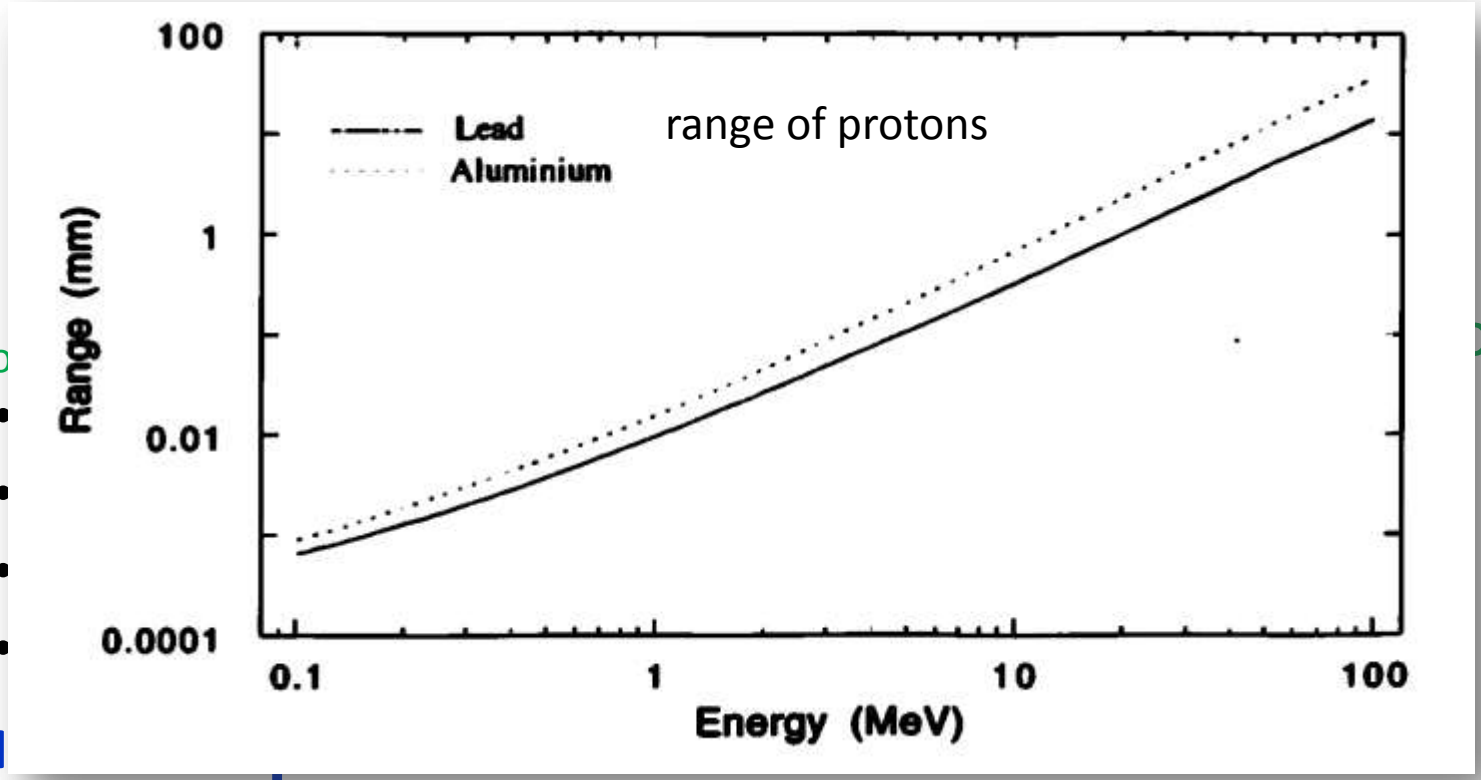
$$\frac{e}{h} = \frac{e/mip}{f_{ion} \cdot ion/mip + f_n \cdot n/mip}$$

$$f_{ion} + f_n + f_{inv} = 1$$

  - f_{ion} contains fast charged hadrons as well as slow protons
    - Range of slow protons limited
    - Might not reach active material
    - Saturation effects in active medium reduces response
    - Material, energy and plate thickness dependence
- **Neutron response**
  - Depends substantially on material and energy

Pure hadronic response

- All response components expressed wrt MIP
- e/h calculation
  - f_{io} ... ons
- Neu
  - Depends substantially on material and energy



Response of a hadrons

- **Pure hadronic response + em response**

$$\frac{\pi}{e} = f_{em} + (1 - f_{em}) \frac{f_{ion} \cdot ion/mip + f_n \cdot n/mip}{e/mip}$$

- f_{em} is energy dependent → response is non-linear

Response of Jets

- **Jet composition**
  - Energy of a jet distributed over different particle types
    - Baryons, mesons, neutrals
  - f_{em} depends on the composition and particle multiplicity
- **Electromagnetic fraction for jets**
  - Initial photons from π^0 (from jet fragmentation)
  - Intrinsic em fraction f_{em} from individual hadrons
  - Depends substantially on the jet composition
- **Response**
  - e/jet > 1
  - Resolution is usually worse than for single hadron
  - Response is energy dependent

Compensation

- **Linear energy response only for e/h=1**
- **Intrinsically compensating calorimeters**
  - Requires right choice of materials, sampling and readout
  - Two possibilities
    - Reduce electron response (e/mip)
    - Recuperate f_{inv} (lost energy)
- **e/mip reduction**
  - Increased absorber (high Z) thickness reduces electron signal
    - Caused by range of low energetic shower particles in the absorber
    - Sampling fraction is reduced
  - e/h=1 NOT achievable for all materials!
  - Energy resolution gets worse

Compensation

- **Linear energy response only for e/h=1**
- **Intrinsi**
  - Requi … l readout
  - Two p
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- **e/mip r**
  - Increa … lectron signal
    - Cau … the absorber
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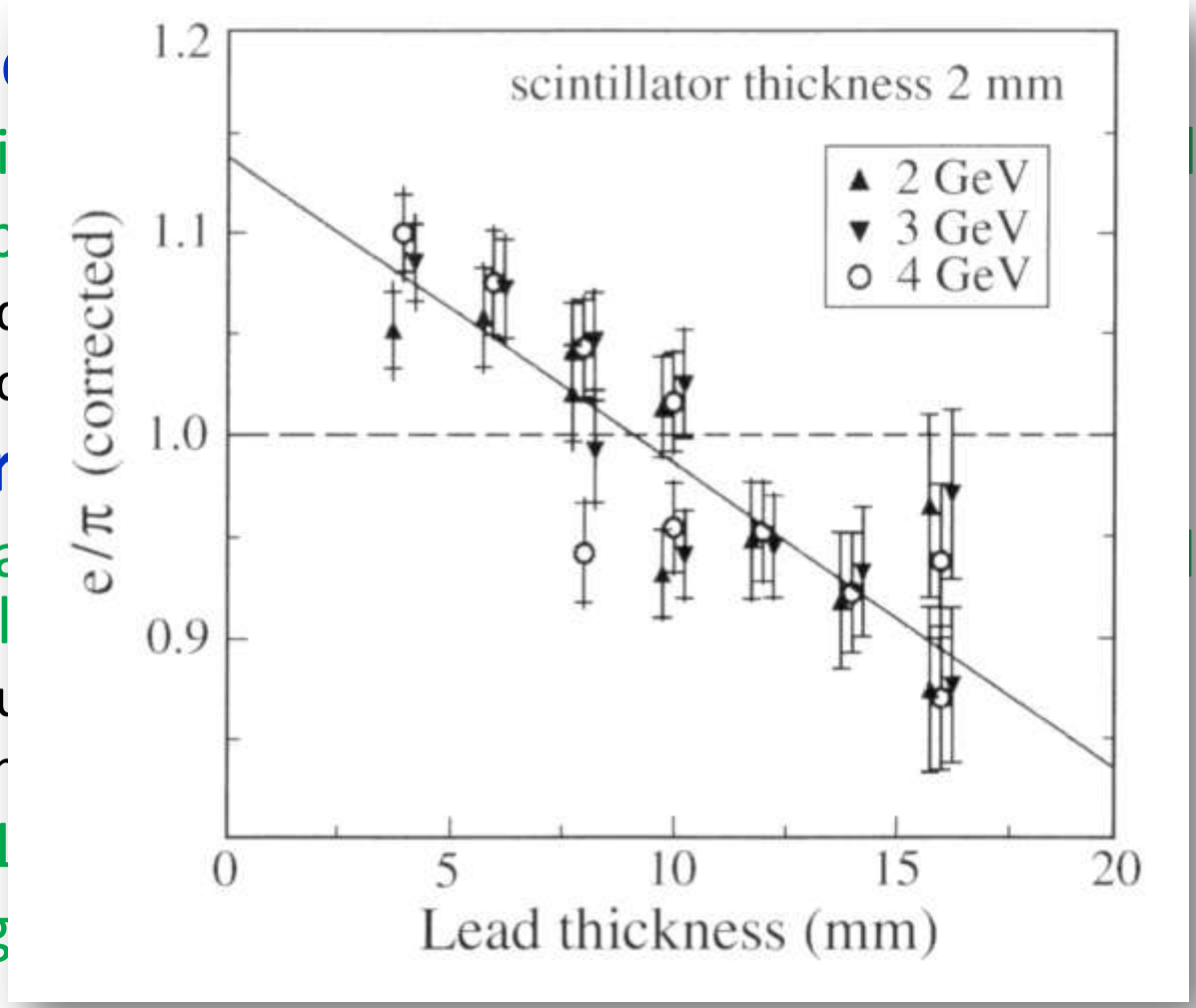
  - e/h=1
  - Energ



Compensation (2)

- **Recuperate f_{inv}**
  - Neutron multiplicity correlated with the invisible energy
  - Increase f_n
    - Use absorber with high neutron yield (Pb, U)
  - Increase n/mip
    - Signal from neutrons comes late due to the required thermalization, capture and γ emission (~200nsec)
    - n/mip can be tuned by changing the integration time of the readout
      - ZEUS U/scintillator calorimeter from e/pi=1.12 (50nsec) down to 1.04 (600nsec)
  - Best: do both
- **Optimally applied in the ZEUS calorimeter**
  - DU plates (3.3mm) cladded in stainless steel and scintillator (2.6mm) readout
    - Scintillator provides hydrogen for the effective thermalization of the neutrons
  - 200nsec integration time
  - Calorimeter with the best performance for hadrons up to date

Compensation (2)

- **Recuperate f_{inv}**
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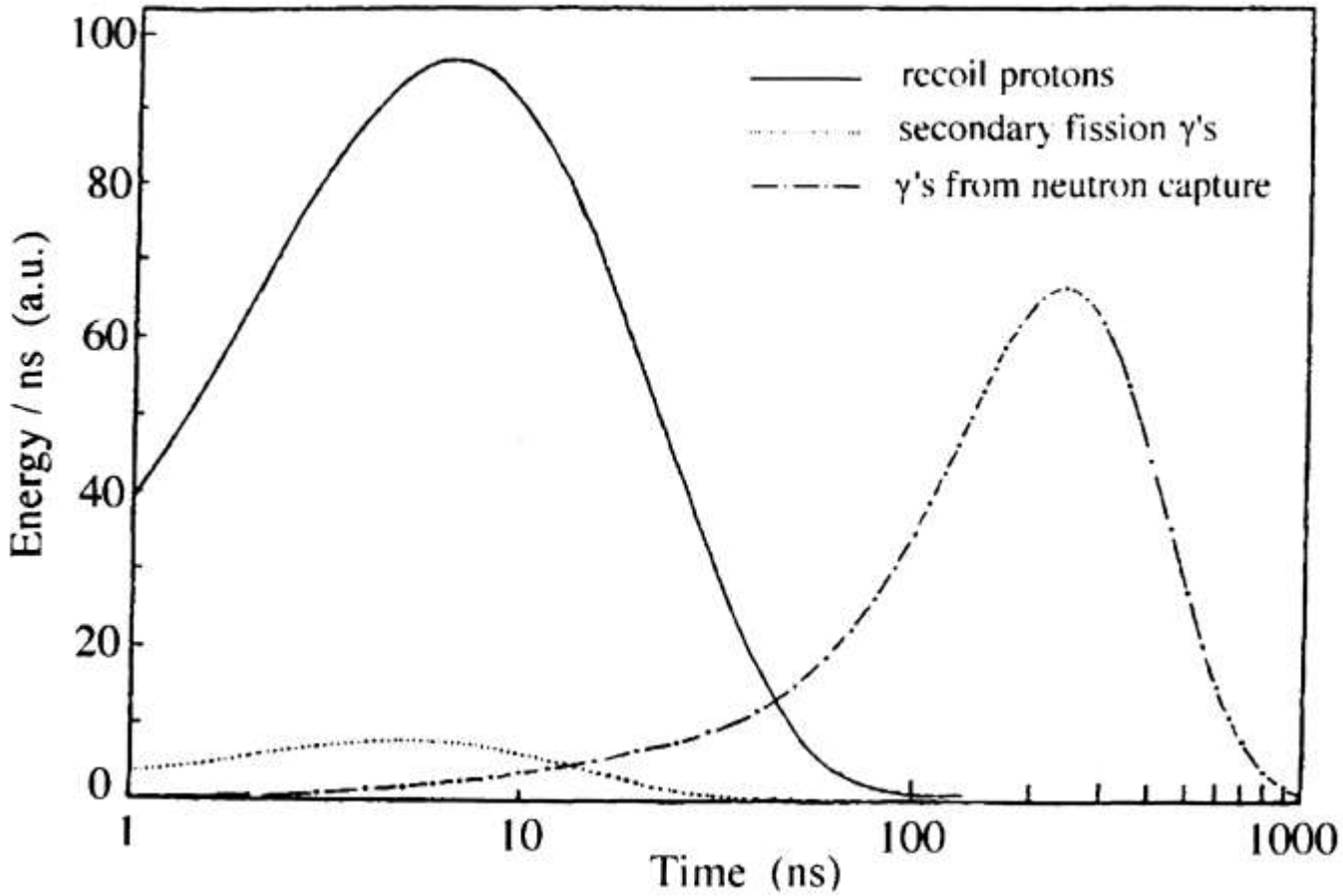

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e

Compensation (2)

- **Recuperate f_{in}**
  - Neutron mul … le energy
  - Increase f_n
    - Use absorb
  - Increase n/n
    - Signal from … ed thermalization, capture and γ emis
    - n/mip can … me of the readout
      - ZEUS U …) down to 1.04 (600nsec)
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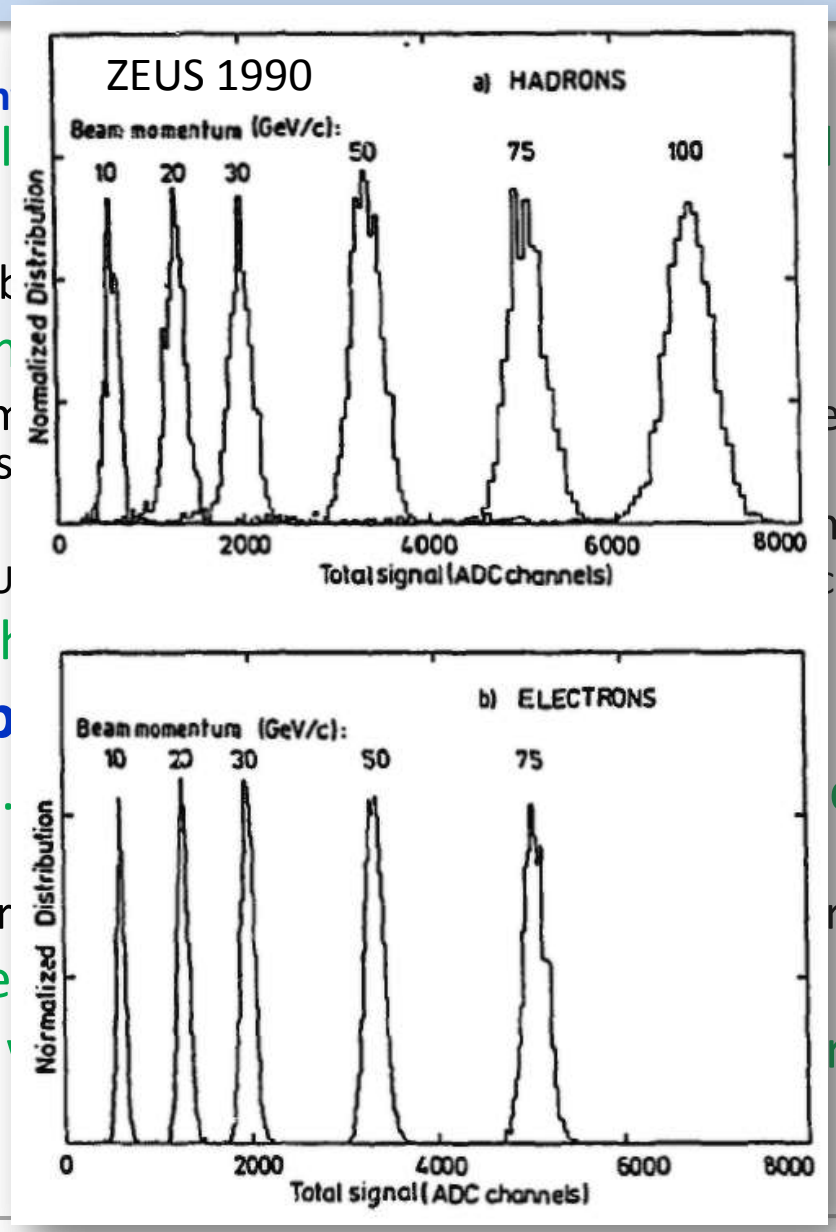

Software Compensation

- **High granularity of a calorimeter allows to locate em sub-showers**
  - em shower very localized with high energy density
    - Shower maximum within $10X_0$ and contained in $1R_m$
  - Weighting of local em energy can correct e/mip to achieve $e/\pi=1$
- **Problem**
  - Weighting is energy dependent
  - Weighting might depend on the location
  - Complicated multi dimensional problem!
    - Leads to complicated weighting functions
- **Method pioneered by CDHS experiment at CERN (1981)**
  - Improved in the 1990s by H1 at HERA
  - Further optimized by ATLAS at the LHC

Energy Resolution of Calorimeters

- **Intrinsic fluctuations**
  - Signal in the active medium
    - photo statistics, charge fluctuations
    - Saturation effects, recombination
  - Shower composition (hadrons)
  - $e/h \neq 1$ in conjunction with the fluctuation of f_{em} (hadrons)
- **Sampling calorimeters**
  - Fluctuation of the visible signal (sampling fluctuations)
- **Instrumental effects**
  - Inhomogeneities (e.g. variation of plate thickness)
  - Incorrect calibrations of different channels (intercalibration)
  - Electronic noise

Resolution of Calorimeters

- **A calorimeter signal *S* is composed of multiple individual processes *N***
  - Photo electrons, electron-ion pairs …
- **Fluctuation of N can be described by Poisson statistics (stochastic term)**
  - Relative resolution of the signal $\frac{\sigma_S}{S} = \frac{\sigma_E}{E} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$
  - assume linearity

$$E \rightarrow 2E \Rightarrow N \rightarrow 2N \Rightarrow \frac{\sigma_E}{E} = \frac{1}{\sqrt{2N}}$$

  - Relative resolution $\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}}$
- **Resolution improves with energy**
  - Spectrometers always get worse with increasing momentum!
- **Constant *A* gives the purely statistical fluctuations**

More Fluctuations

- **Instrumental effects**
  - Non-uniformities of the absorber/active layer
    - Scales with energy ($\sigma_{uni} = C \cdot E$)
  - Electronic noise
    - Depends on the number of considered electronic channels
    - For constant number of channels it's a constant contribution ($\sigma_{Noise} = B$)
- **Adding the contributions in quadrature**

$$\sigma_{samp}^2 + \sigma_{noise}^2 + \sigma_{uni}^2 \Rightarrow \frac{\sigma_E}{E} = \sqrt{\frac{A^2}{E} + \frac{B^2}{E^2} + C^2} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$$

Resolution and Sampling Fraction

- **Signal depends on low energy particles reaching the active material**
  - Higher signal leads to smaller fluctuations
- **How to increase the signal**
  - Add more active layers with thickness d (increased sampling frequency)
  - Increase the thickness d of the active layers (increased sampling fraction f_{samp})
- **Resolution depends on d/f_{samp}**
  - Empirical formula (Wigmans)

$$\frac{\sigma_E}{E} = 2.7\% \frac{\sqrt{d / f_{samp}}}{\sqrt{E}} \Rightarrow A = 2.7\% \sqrt{d / f_{samp}}$$

  - Example ZEUS

$$f_{samp} = \frac{dE(sci)}{dE(sci) + dE(U)} = 7\% \quad d(sci) = 2.6mm$$

$$\Rightarrow A = 16.5\% \sqrt{GeV} \quad A_{true} = 18\% \sqrt{GeV}$$

Resolution and Sampling Fraction

- **Signal depends on low energy particles reaching the acti**
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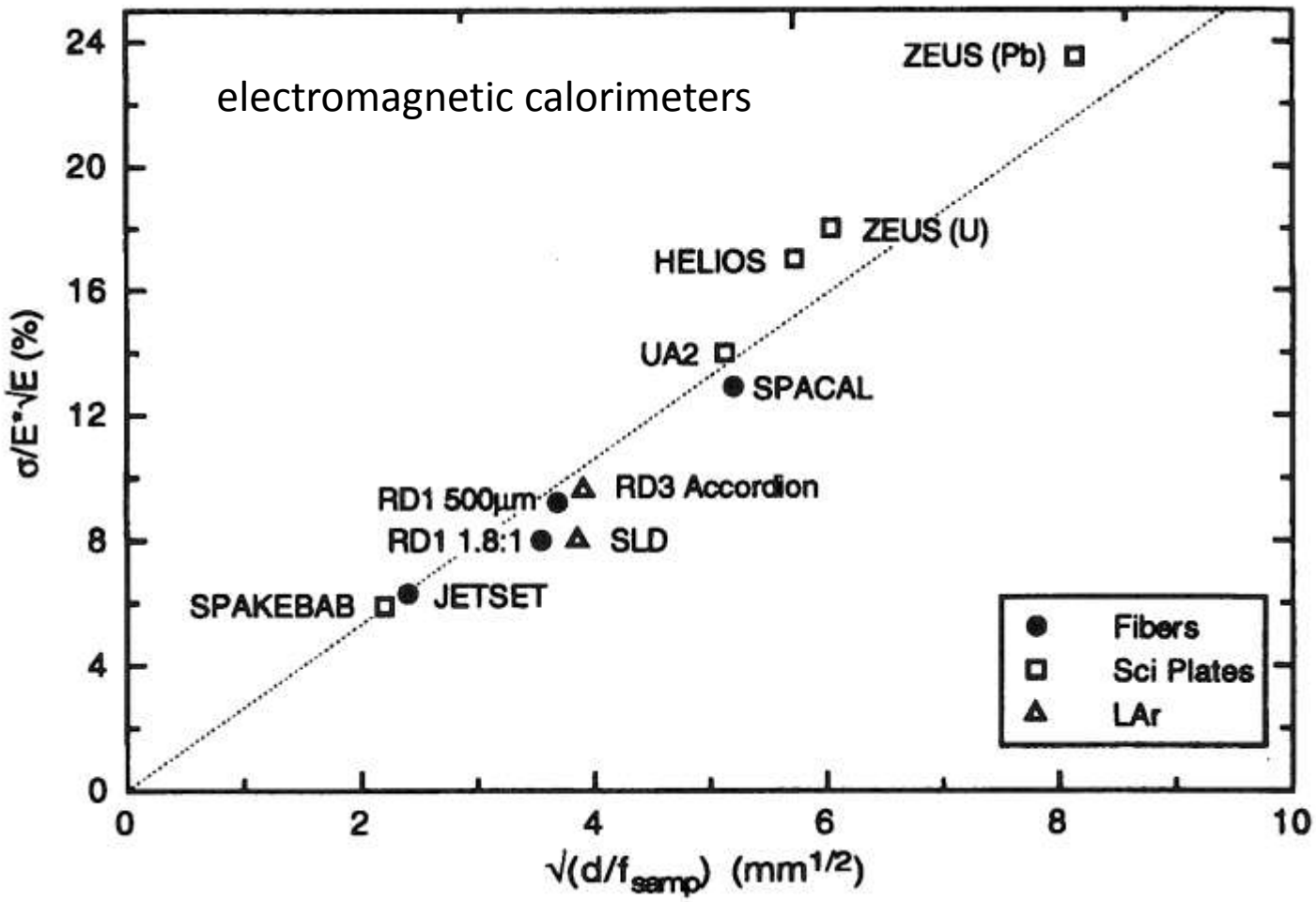


$/ f_{samp}$

$$\Rightarrow A = 16.5\%\sqrt{GeV} \quad A_{true} = 18\%\sqrt{GeV}$$

Hadronic Calorimeters

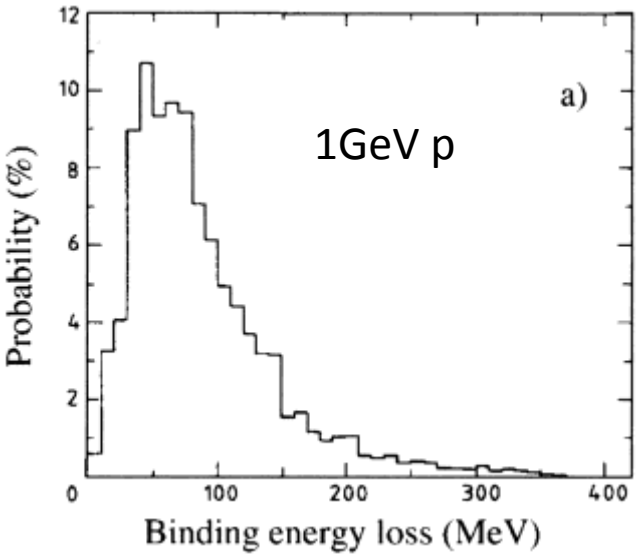
- **Complexity of hadronic showers makes it difficult to estimate the resolution**
  - Pure sampling fluctuations of hadronic part (ZEUS)

$$\frac{\sigma_E}{E} = \frac{11.5\%\sqrt{\Delta E}}{\sqrt{E}} \text{ where } \Delta E \text{ is the energy lost by a MIP in one sampling}$$

  - Resolution often dominated by other effect!
- **Effects on the resolution (non-compensating)**
  - Fluctuations of the binding energy E_B

$$\frac{\sigma_E}{E_B} = \frac{15\%}{\sqrt{E_B}} \text{ for high Z materials}$$

  - Fluctuations of the em fraction f_{em}
    - Substantial effect for pion induced shower
    - Reduced effect for protons due to baryon numbe conservation (reduced pion production)



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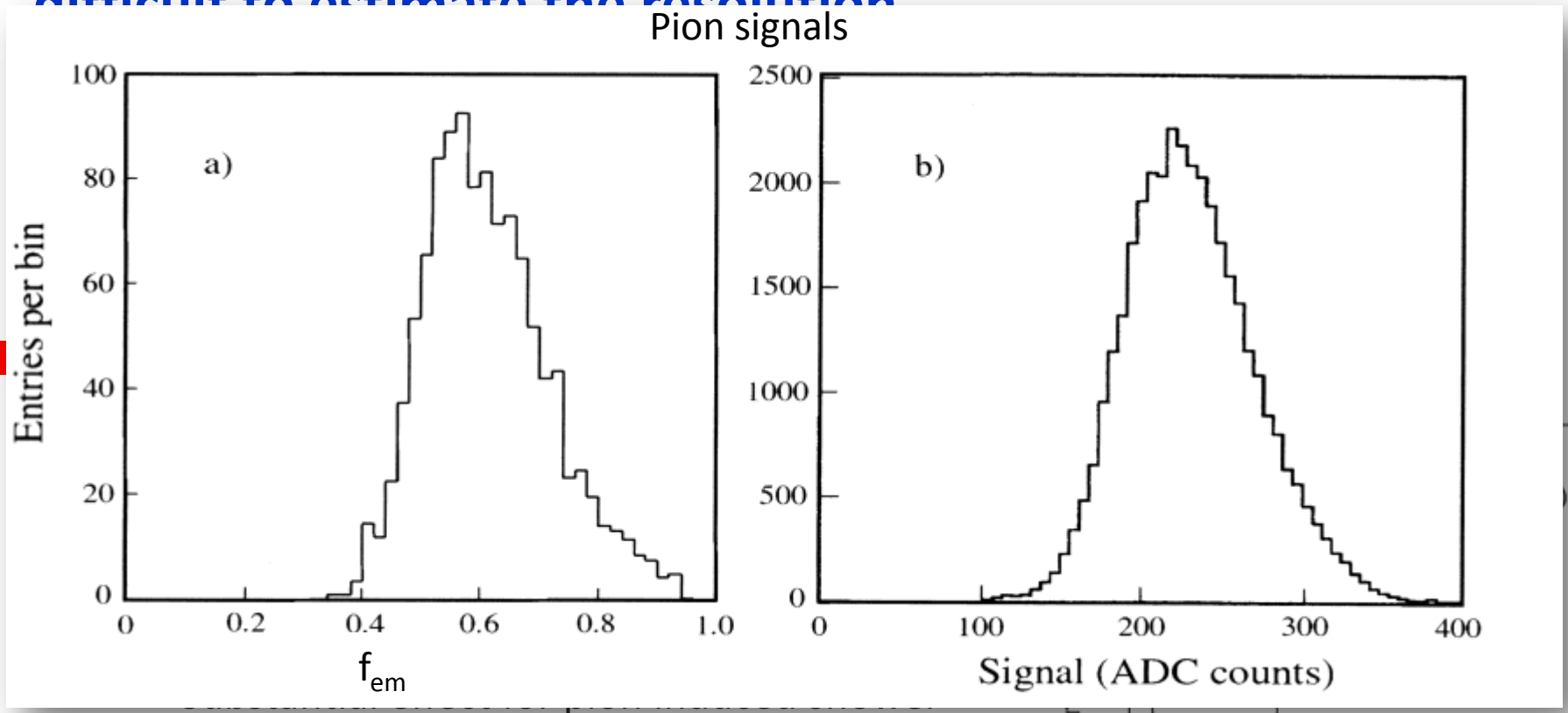

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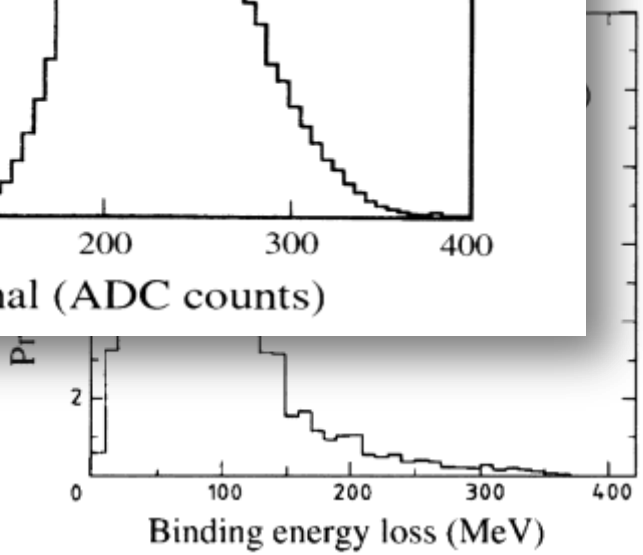

Hadronic Calorimeters

- **Complexity of hadronic showers makes it difficu**
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- **Effects**
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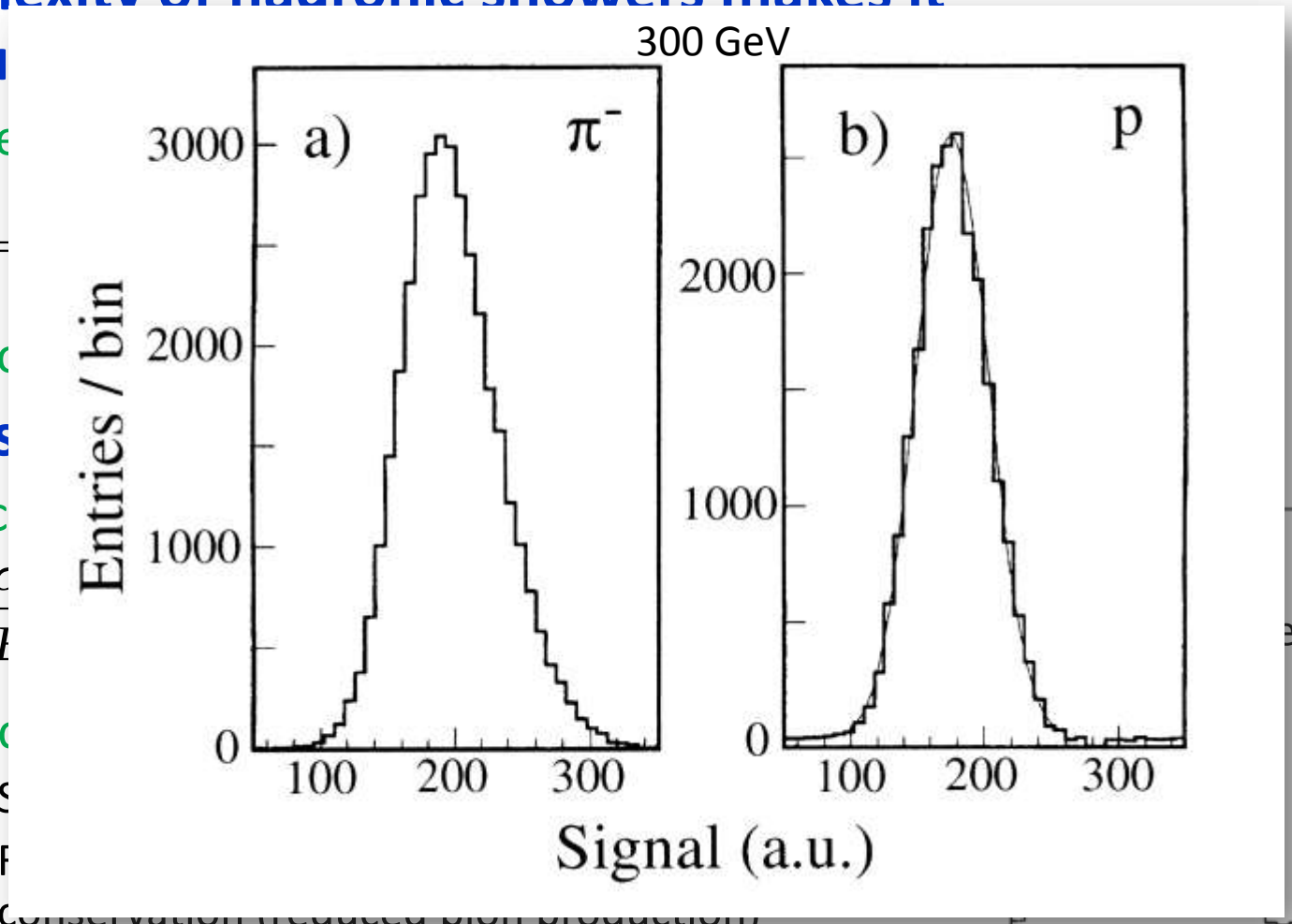

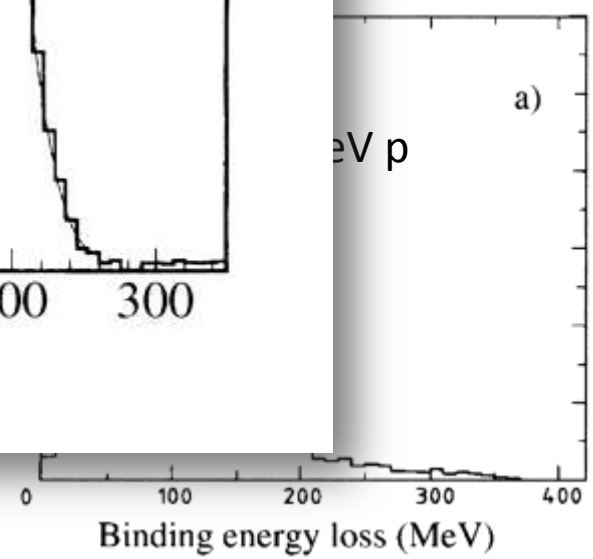

Spatial Resolution

- **Spatial resolution based on energy sharing of neighboring cells**
  - Calculate energy weighted average requires correction

$$\bar{x} = \frac{\sum_i x_i \cdot E_i}{\sum_i E_i}$$

  - Cells size (Δx) smaller than characteristic width of shower
    - $1R_m$ for em-shower
    - $1\lambda_{int}$ for hadronic shower
  - Resolution scales with $1/\sqrt{E}$
    - Wigmans parameterization for em-shower (square cells)

$$\sigma_{x,y} \approx \frac{17.8\% \cdot \Delta x[mm]}{\sqrt{E[GeV]}} \Rightarrow \sigma_{x,y} = \frac{17.8\% \cdot 30mm}{\sqrt{10GeV}} = 1.7mm$$

- **Angular resolution possible with longitudinal segmentation**

Spatial Resolution

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  - Calculate
    requires c
  - Cells size (
    - 1R_m for
    - 1λ_{int} for
  - Resolution
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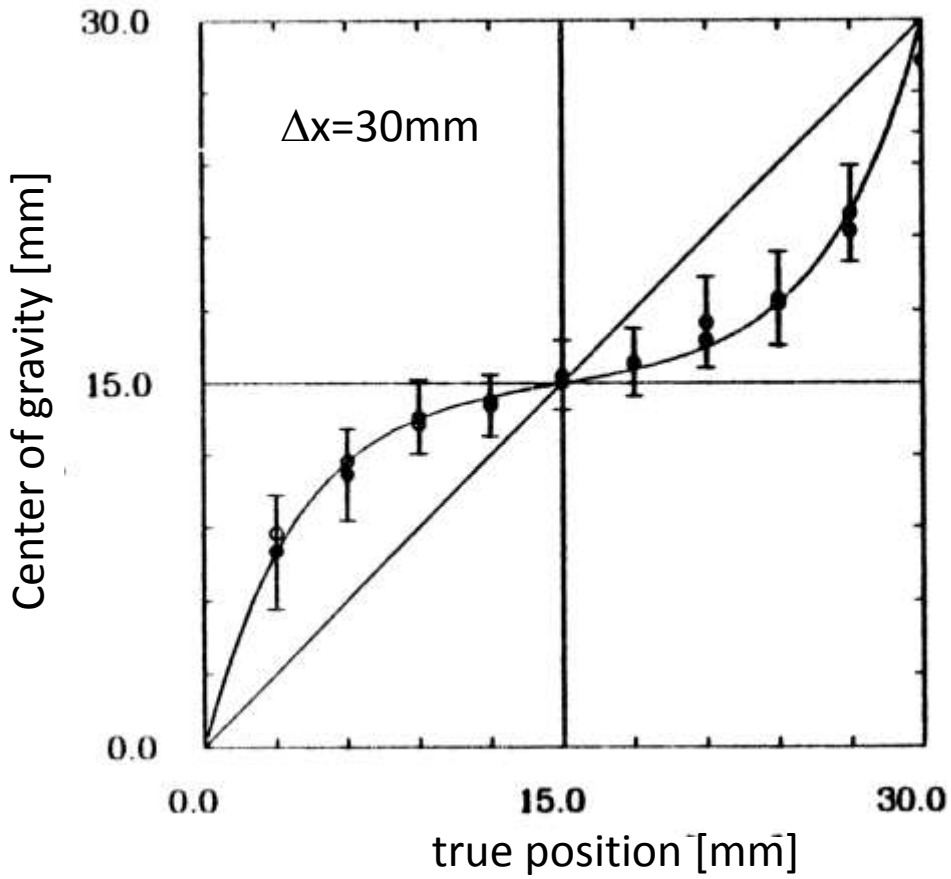
$$\sigma_{x,y} \approx$$

- **Angular res**
  segmentation



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- **Angular resolution possible with longitudinal segmentation**

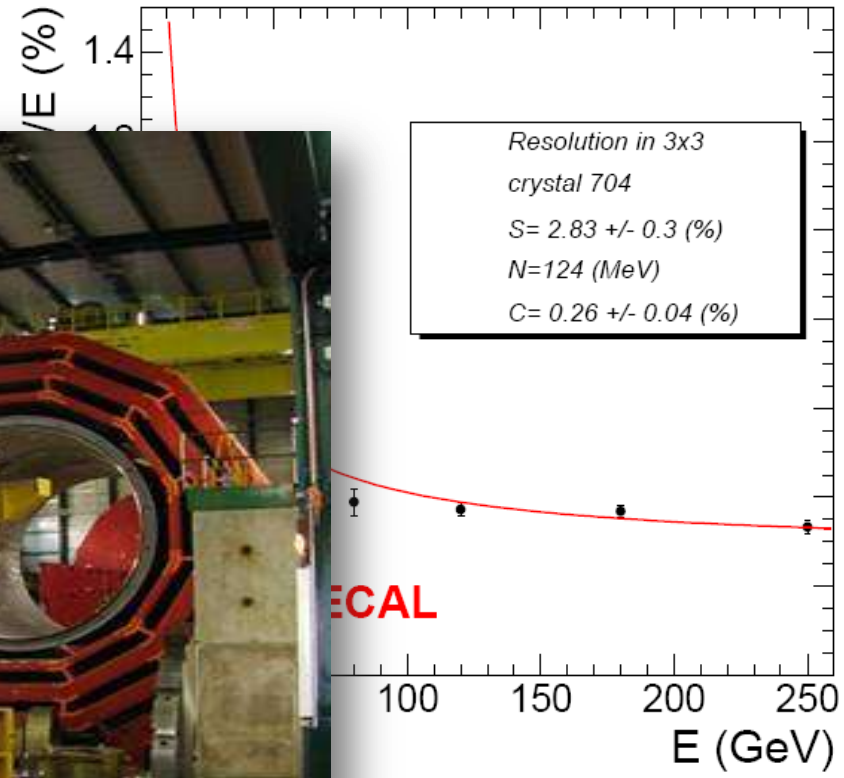
Example: homogeneous Calorimeter

- **CMS $PbWO_4$ homogeneous em calorim**
  - Electron r
  - Expectatic

$$\frac{\sigma_E}{E} = \frac{1}{\sqrt{xE}} = \frac{}{\sqrt{420}}$$

  - Resolution photo elec
    - Leakage
    - Cracks b


61200 $PbWO_4$ Kristalle (22x23x230 mm^3)

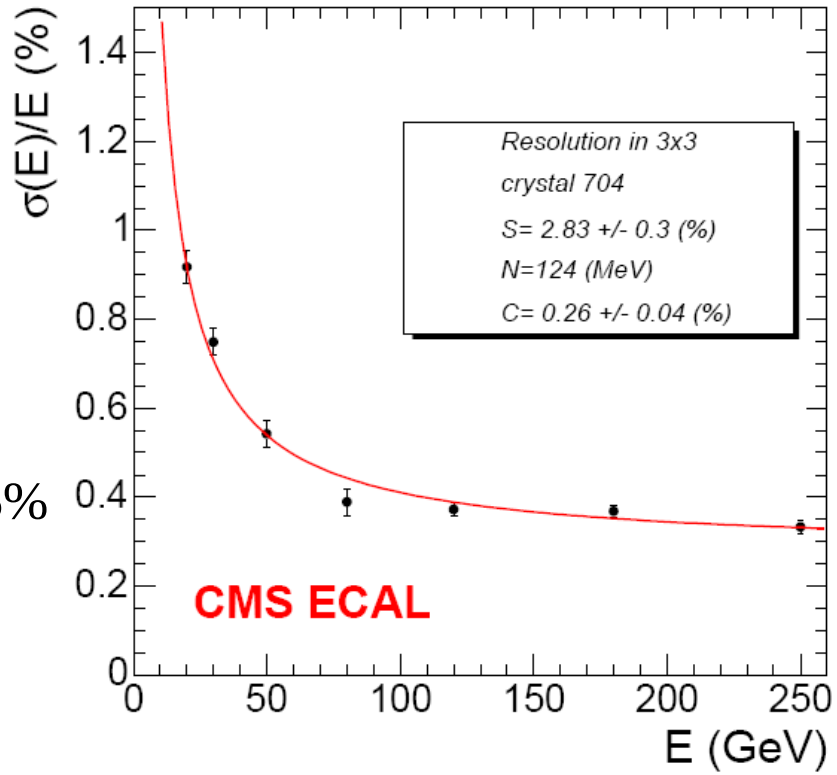


Example: homogeneous Calorimeter

- **CMS $PbWO_4$ homogeneous em calorimeter**
  - Electron resolution $\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E}}$
  - Expectation

$$\frac{\sigma_E}{E} = \frac{1}{\sqrt{xE}} = \frac{1}{\sqrt{4200\,pe \cdot E}} \Rightarrow A = \frac{1}{\sqrt{4200}} = 1.5\%$$

  - Resolution not dominated by photo electron statistics
    - Leakage
    - Cracks between crystals



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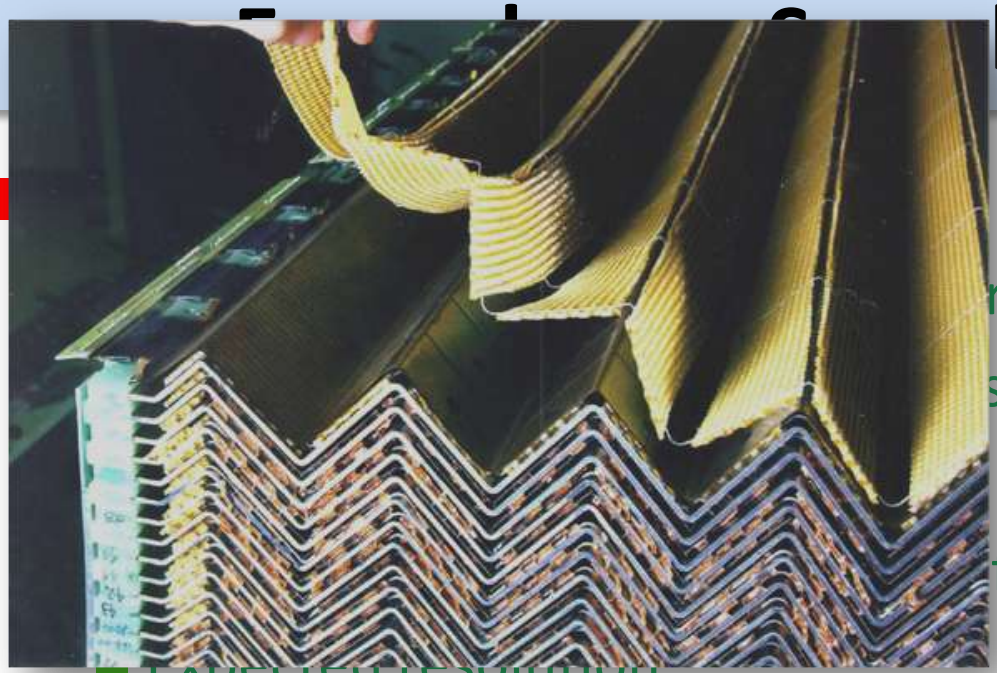

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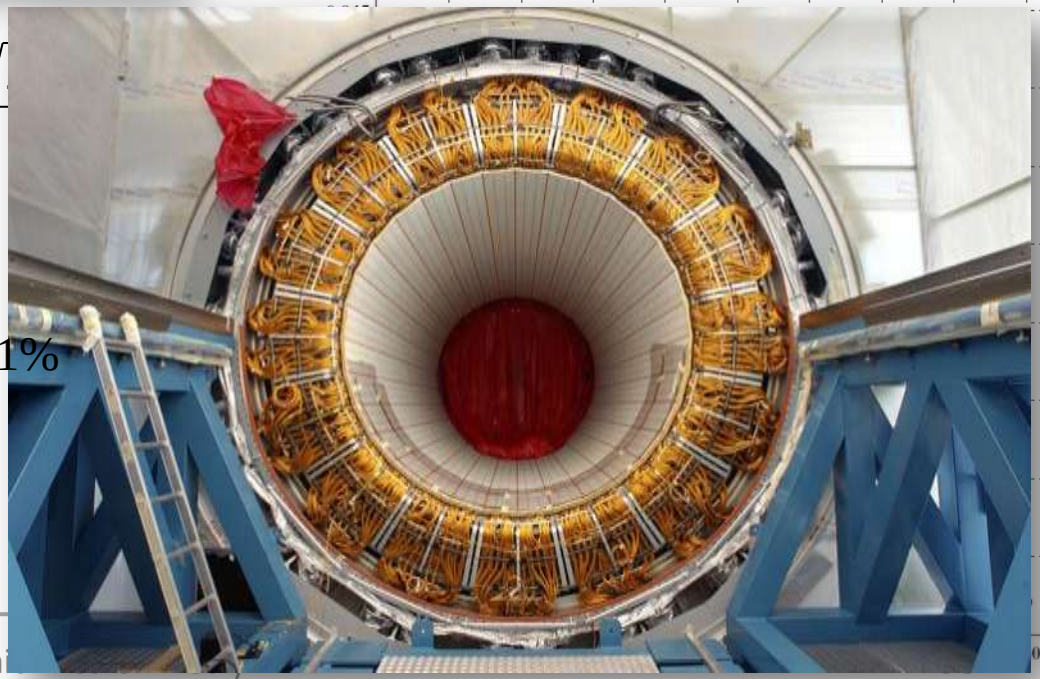
- Expected resolution

$$\frac{\sigma}{E} = 2.7\% \frac{\sqrt{d / f_{samp}}}{\sqrt{E}} = 2.7\% \frac{\sqrt{}}{}$$

$$\Rightarrow A = 9.8\%$$

- Measured $\frac{\sigma}{E} = \frac{9.4\%}{\sqrt{E}} \oplus 0.1\%$



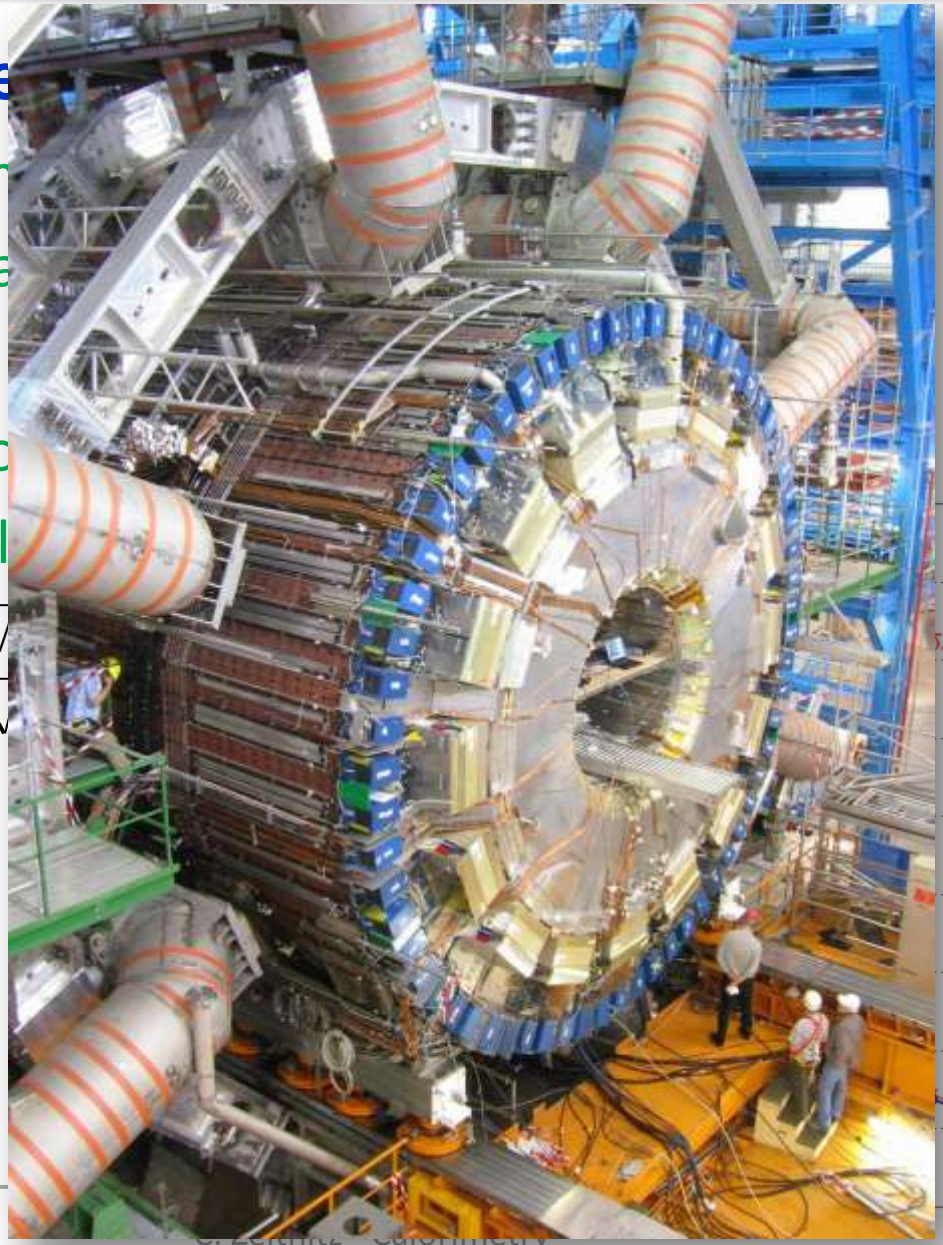
Example: em Sampling Calorimeter

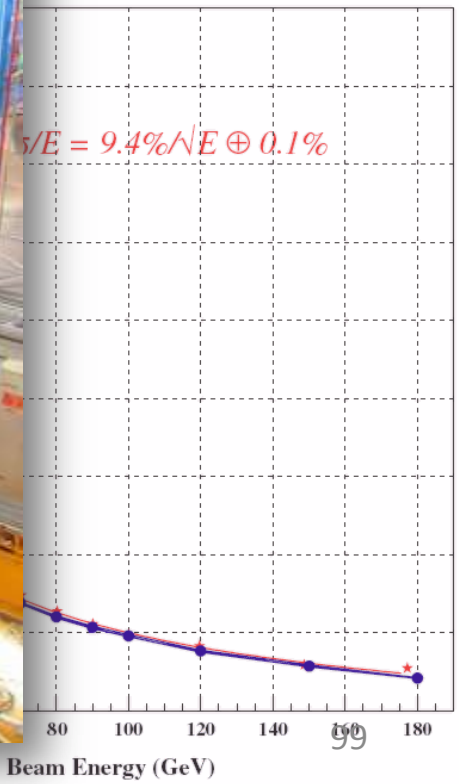
- **ATLAS Pb/LAr e**
  - Complex geom
  - 1.53mmPb (cla
  - 2.1mm LAr
  - Average impac
  - Expected resol

$$\frac{\sigma}{E} = 2.7\% \frac{\sqrt{d/}}{\sqrt{}}$$

$$\Rightarrow A = 9.8\%$$

  - Measured





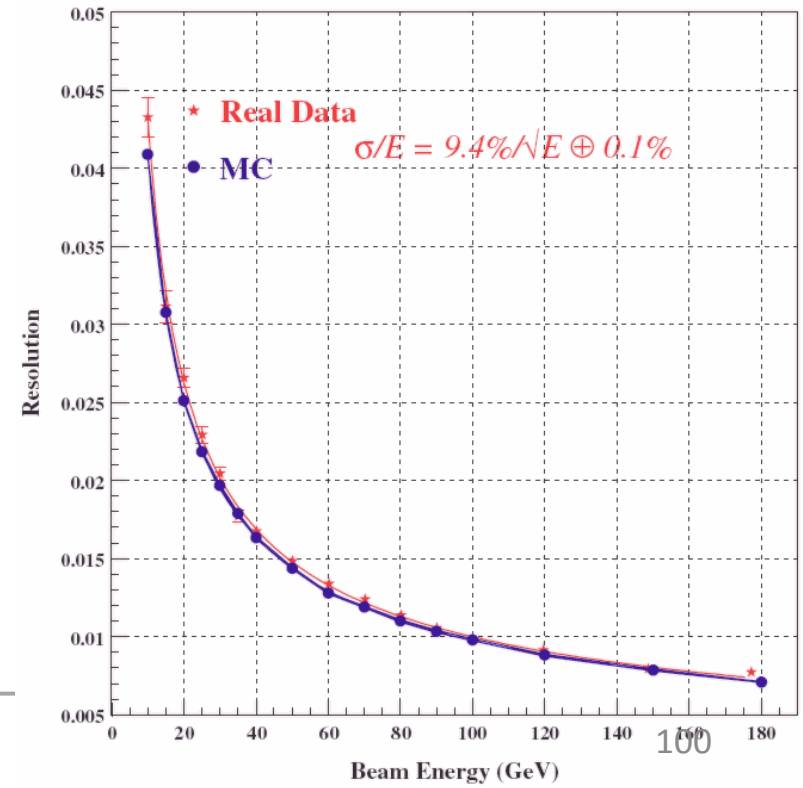
Example: em Sampling Calorimeter

- **ATLAS Pb/LAr em calorimeter**
  - Complex geometry (accordion structure)
  - 1.53mmPb (cladded with stainless)
  - 2.1mm LAr
  - Average impact angle 45° (simplified)
  - Expected resolution

$$\frac{\sigma}{E} = 2.7\% \frac{\sqrt{d / f_{samp}}}{\sqrt{E}} = 2.7\% \frac{\sqrt{2.1mm / 0.16}}{\sqrt{E}}$$

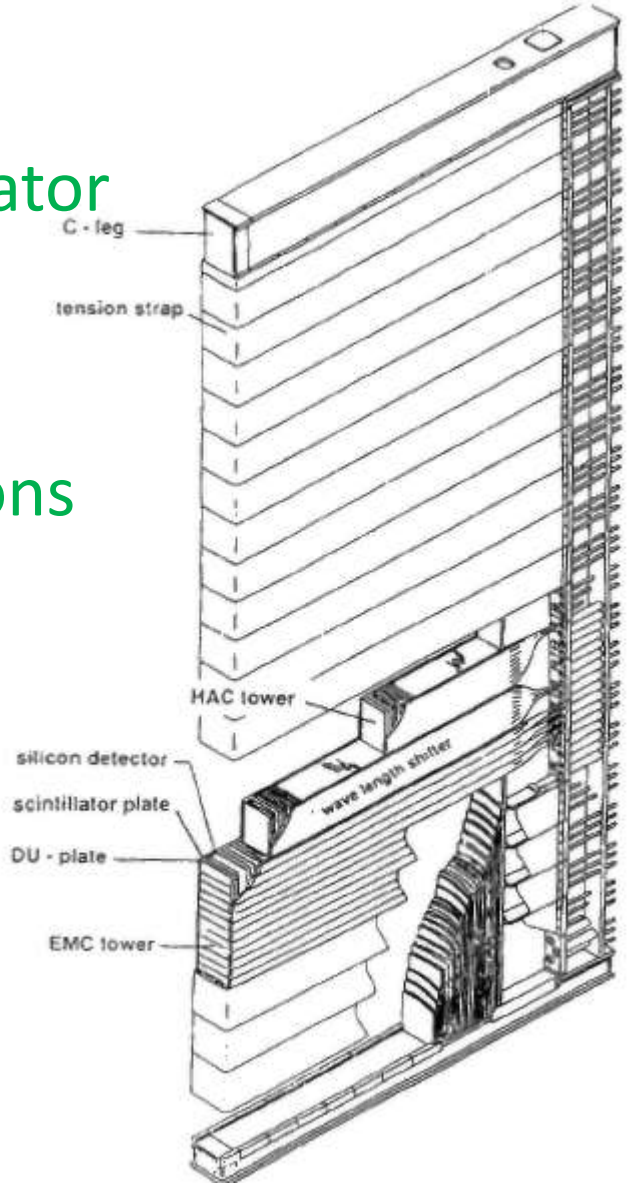
$$\Rightarrow A = 9.8\%$$

  - Measured $\frac{\sigma}{E} = \frac{9.4\%}{\sqrt{E}} \oplus 0.1\%$



Example: hadronic sampling Calorimeter

- **ZEUS U/scintillator**
  - Towers of DU (3.3mm) and scintillator plates (2.6mm)
  - Intrinsically compensating e/h=1
  - Best resolution obtained for hadrons up to now



Example: hadronic sampling Calorimeter

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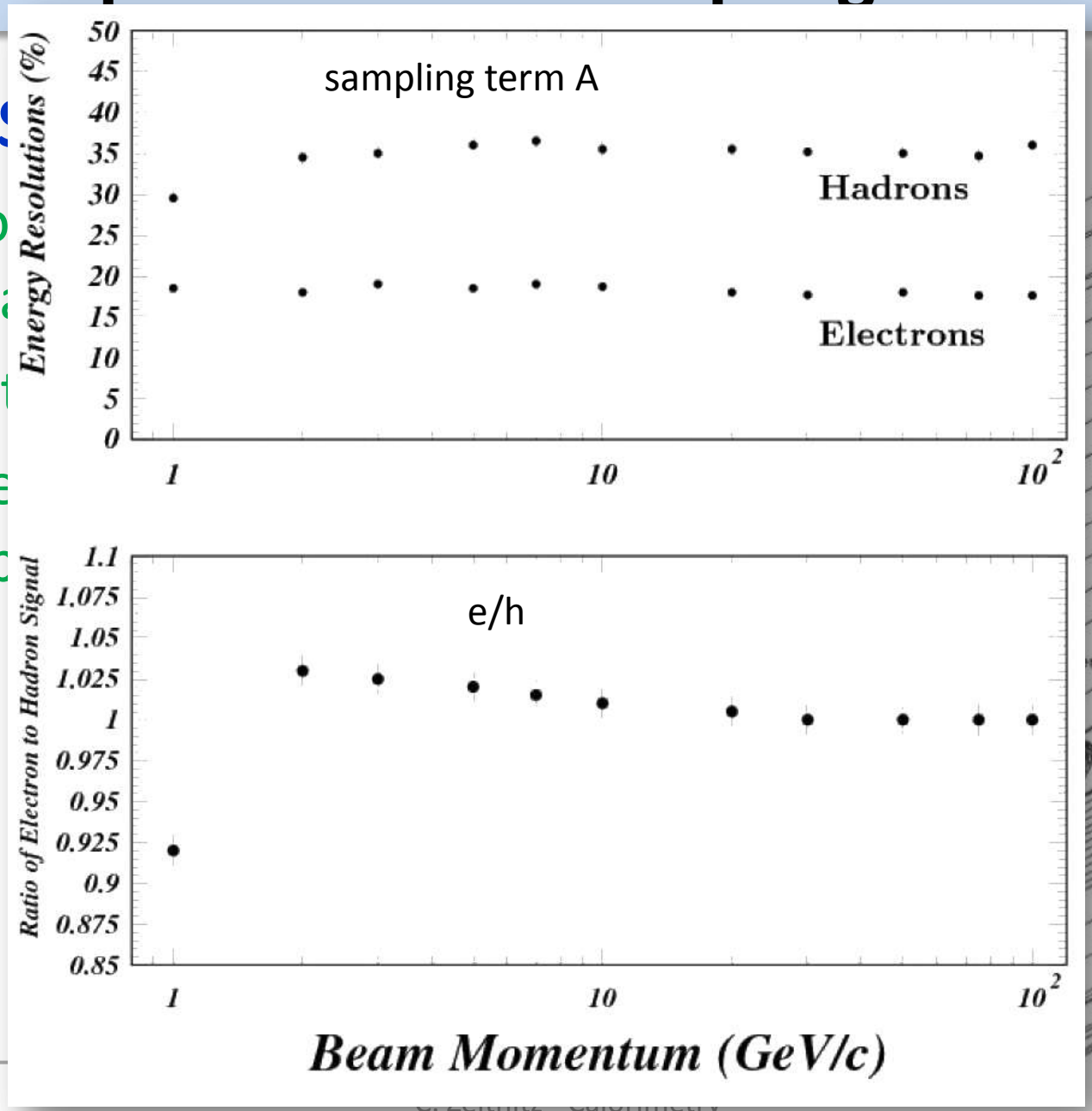
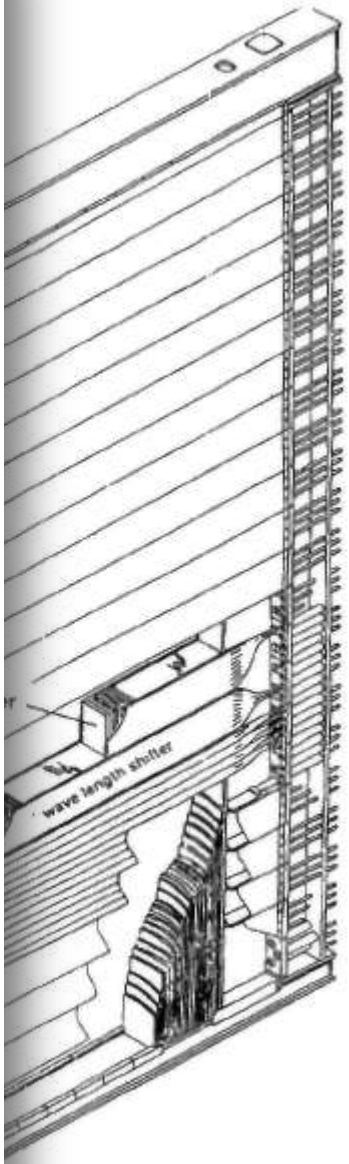




Overview

Comparison of single particle resolutions

Experiment		absorber	active	resolution	type
CMS	em	$PbWO_4$	Scint.	$2.8\%/\sqrt{E}$	homogeneous
CMS	had.	Fe	Scint.	$77\%/\sqrt{E}$	sampling
ATLAS	em	Pb	LAr	$10\%/\sqrt{E}$	sampling
ATLAS	had.	Cu	LAr	$66\%/\sqrt{E}$	SW compensation 46%
NA48	em	LKr	LKr	$3.5\%/\sqrt{E}$	homogeneous
BaBar	em	CsI	CsI	$2.3\%/E^{1/4}$	homogeneous

Energy Resolution of Jets

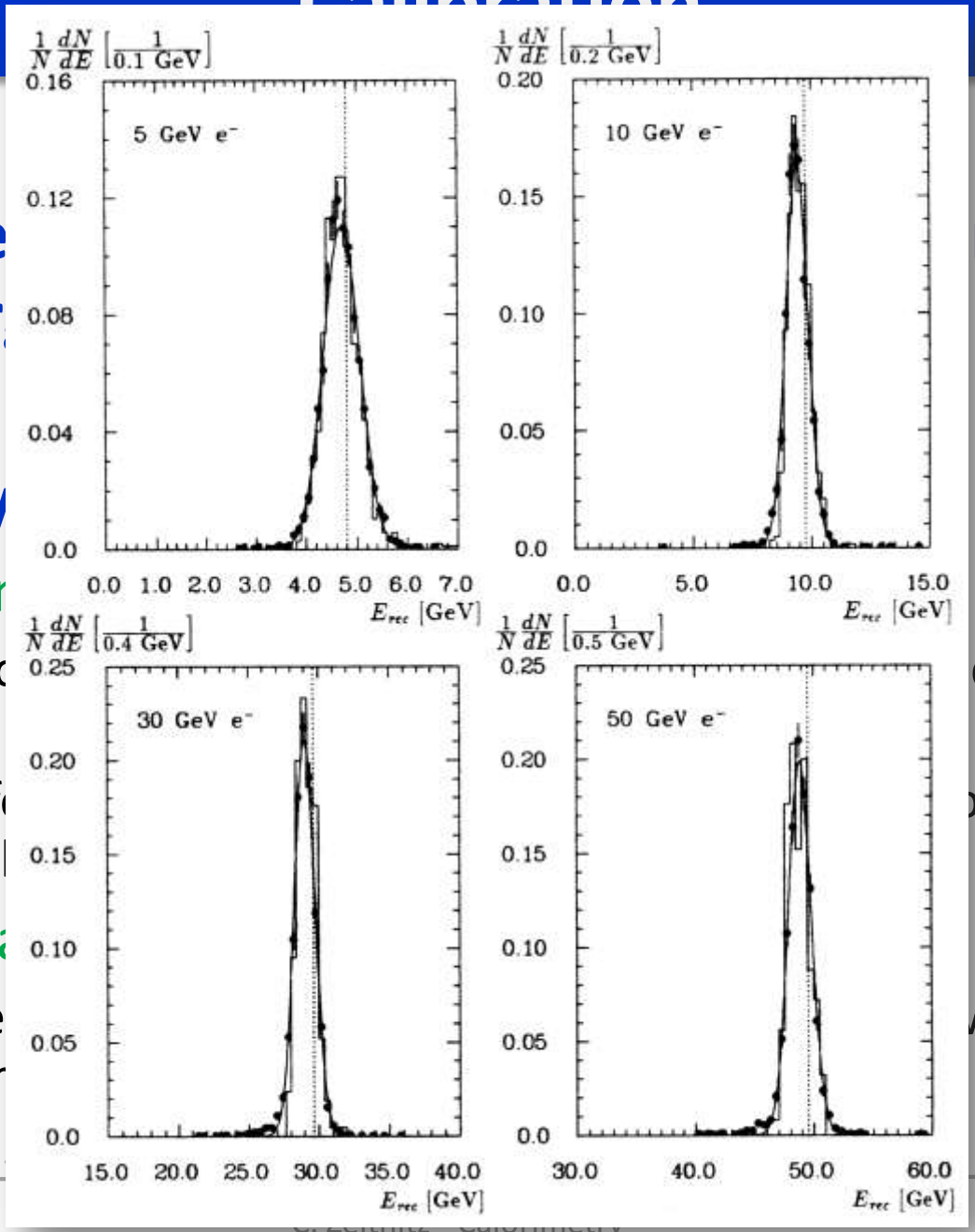
- **Electromagnetic fraction**
  - Neutral pions as primary particles
  - em-fraction from hadronic interactions
- **Hadrons**
  - Mixture of pions, kaons, nucleons
- **Multiplicity usually higher than for single particle with same energy as the whole jet**
  - More interactions and less fluctuations
  - Would expect better resolution
- **Fluctuation of particle composition spoils resolution**
  - In most cases dominant and not easy to predict
  - Depends strongly on the studied physics!
- **Material in front of calorimeter deteriorates the em resolution**
- **No simple rule of thumb**

Calibration

- **Read-out calibration done electronically**
- **Signal measured in charge or photo electrons and NOT energy**
  - Need calibration constant or function
- **Relatively simple for single particles**
  - Testbeam
    - Electrons/pions/protons with known energy provide reference signal
    - Transfer of calibration to the actual experiment not always easy (e.g. changes in electronics)
  - In-situ calibration
    - Utilize momentum measurement in comparison with energy in calorimeter
    - Reconstruct the mass of known particles

Calibration

- **Read-out**
- **Signal me** … **rons and NOT ener**
  - Need ca
- **Relatively**
  - Testbear
    - Electro … de reference signal
    - Transf … ot always easy (e.g. cl
  - In-situ ca
    - Utilize … with energy in calorir
    - Recon



Calibration

- **Read-out**
- **Signal me** … **rons and NOT ener**
  - Need ca
- **Relatively**
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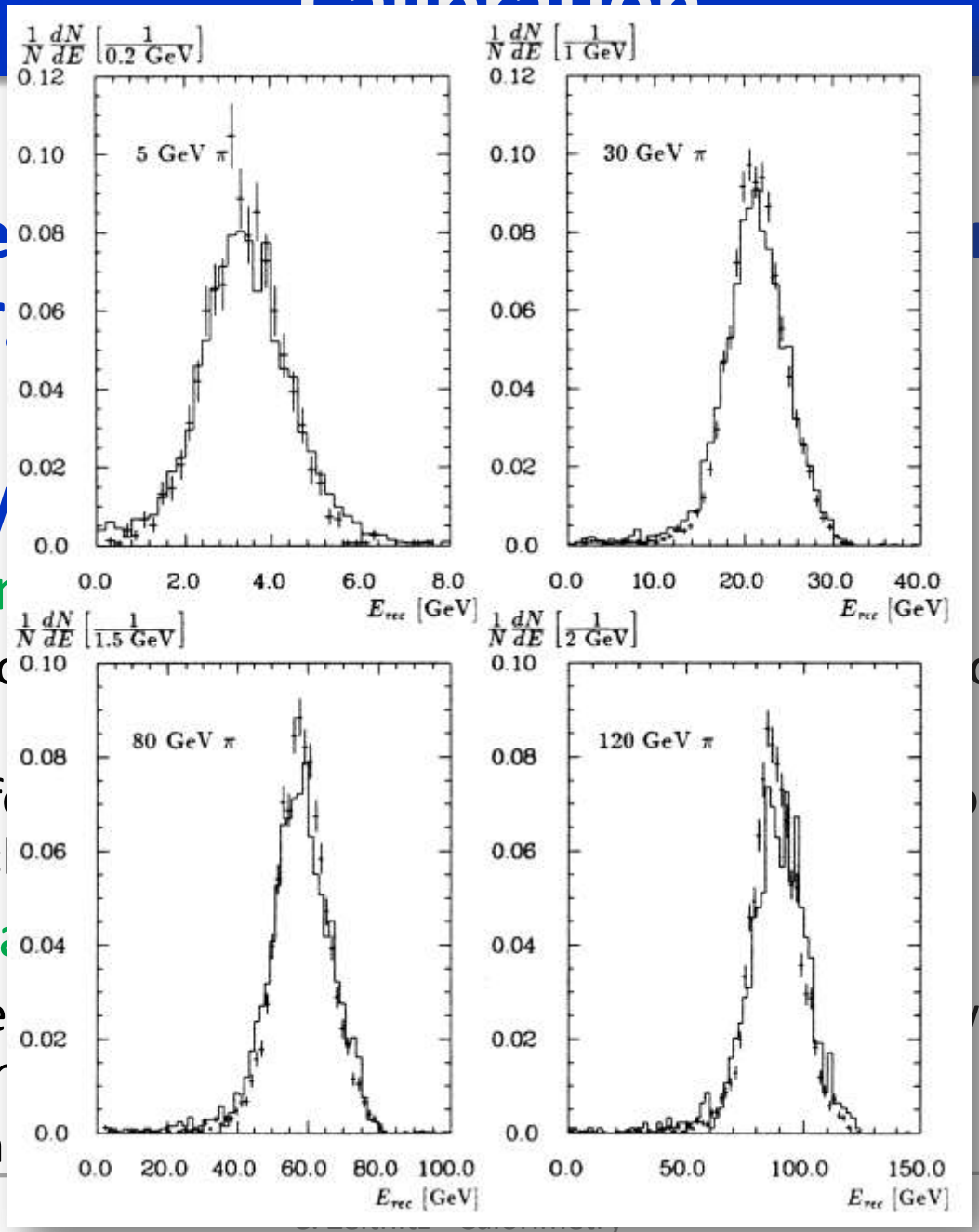
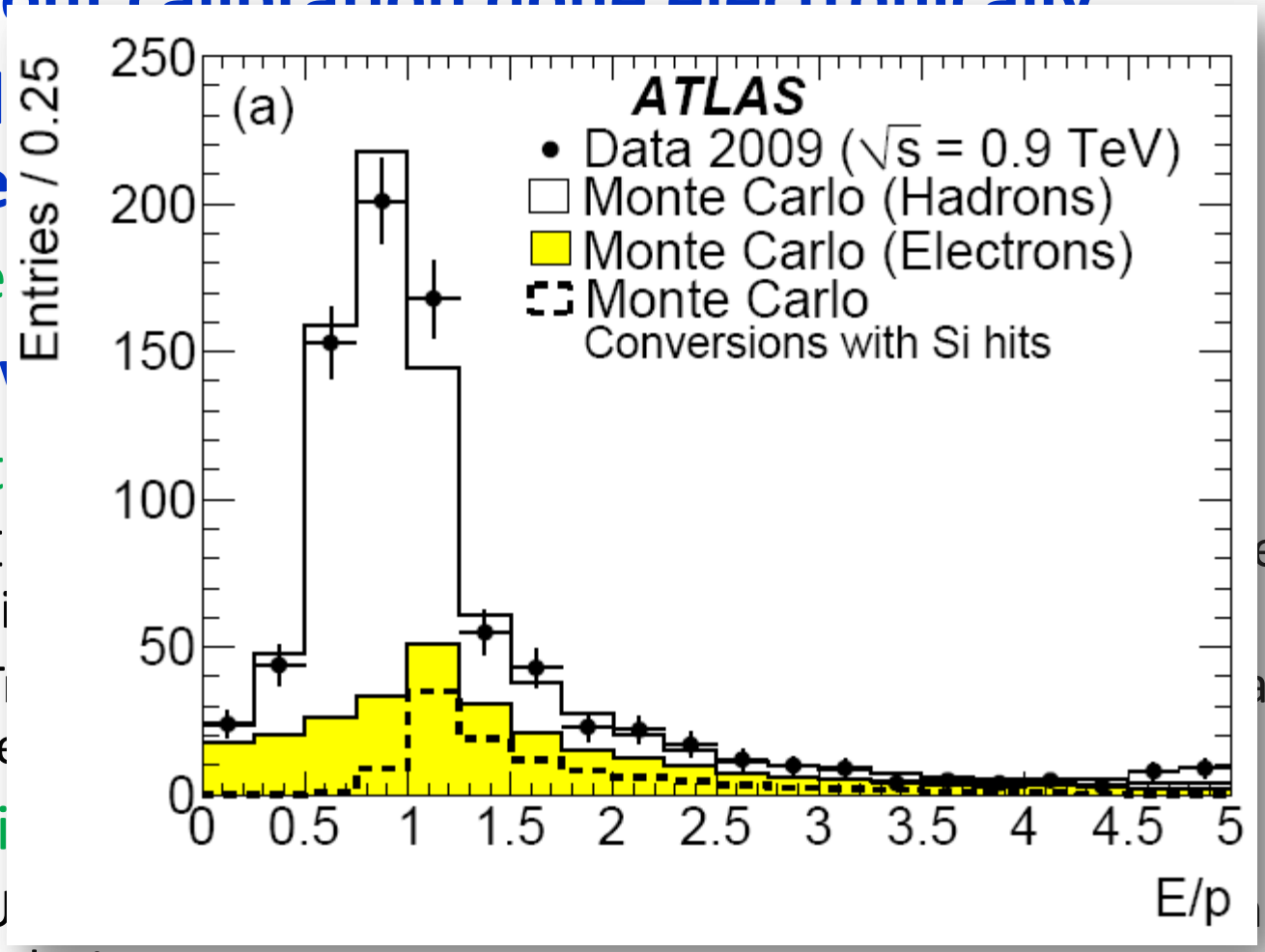


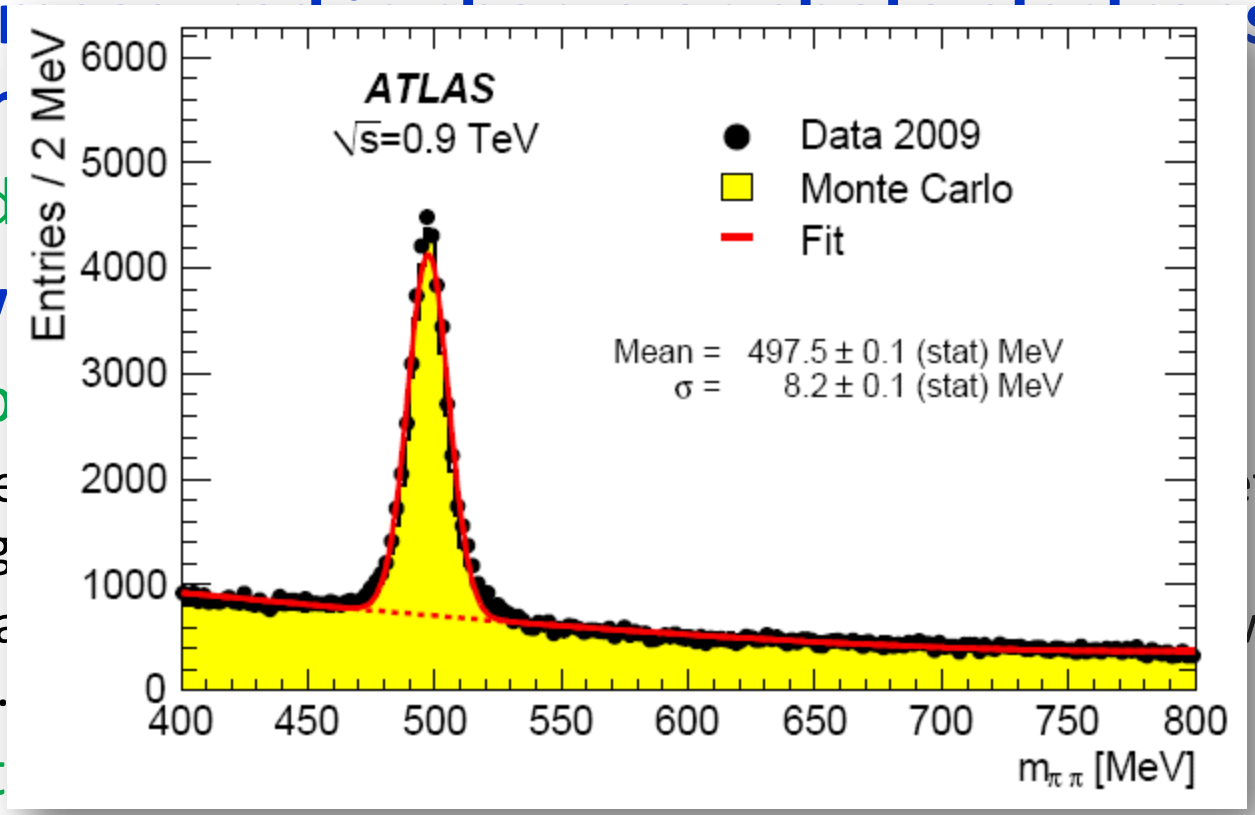
Calibration

- Read-out calibration done electronically
- Signal and NOT e
  - Nee
- Relati
  - Test
    - E erence si
    - T ys easy (e
  - In-si
    - U ergy in calorimeter
    - Reconstruct the mass of known particles



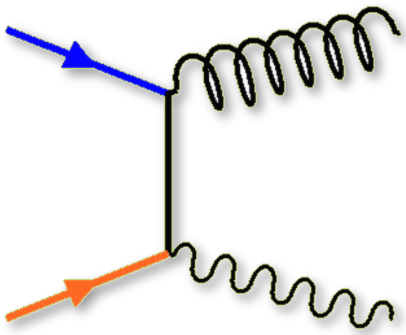
Calibration

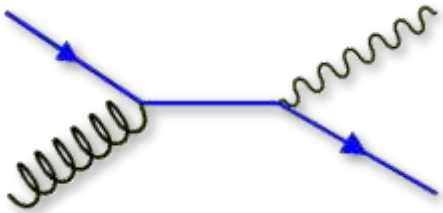
- **Read-out calibration done electronically**
- **Signal** [illegible] **s and NOT er**
  - Need
- **Relativ**
  - Testb
    - Ele [illegible] eference sig
    - Tra [illegible] ays easy (e.
  - In-sit
    - Utilize momentum measurement in comparison with energy in calorimeter
    - Reconstruct the mass of known particles



Calibration (2)

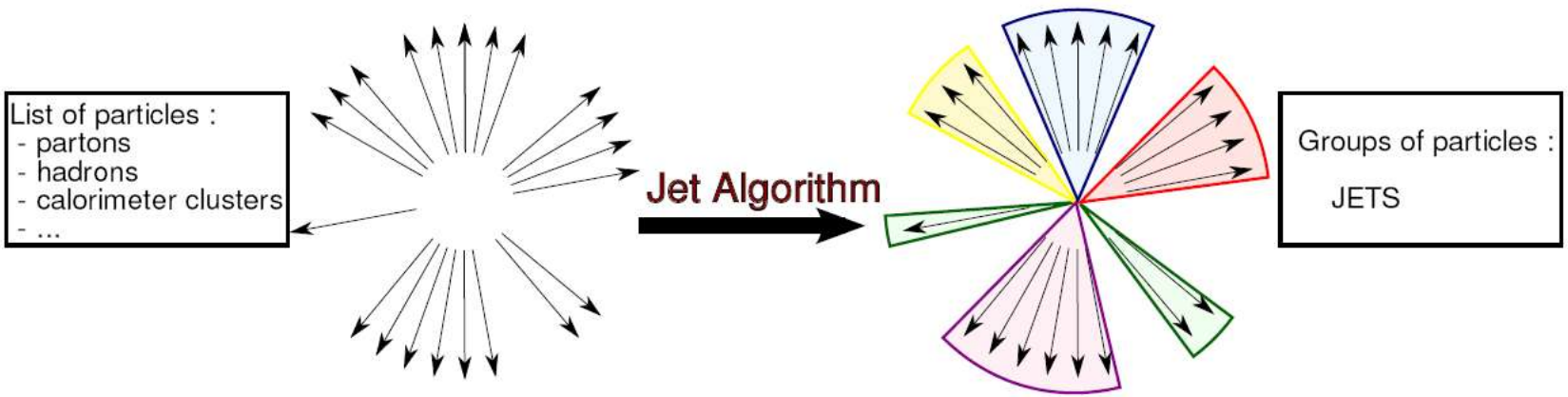
- **Jet calibration**
  - No universal calibration exists
    - Depends on physics process (multiplicity and composition)
      - Need different calibration for different event types
    - Depends on jet definition (algorithm)
  - In-situ calibration
    - Example for Tevatron/LHC: Jets+γ events
      - Photon calibration known
      - Jets have to balance momentum in transverse plane
    - Hadronic decays of Z and W into 2 jets
  - Calibration is usually dependent on η





Jet Reconstruction

- **Initially parton fragmentate to hadrons**
  - Multiple hadrons (Jet) enter the detectors
  - Reconstruction of parton 4 vectors requires to find the hadrons belonging to the jet
  - Jet clustering (find groups of particles)

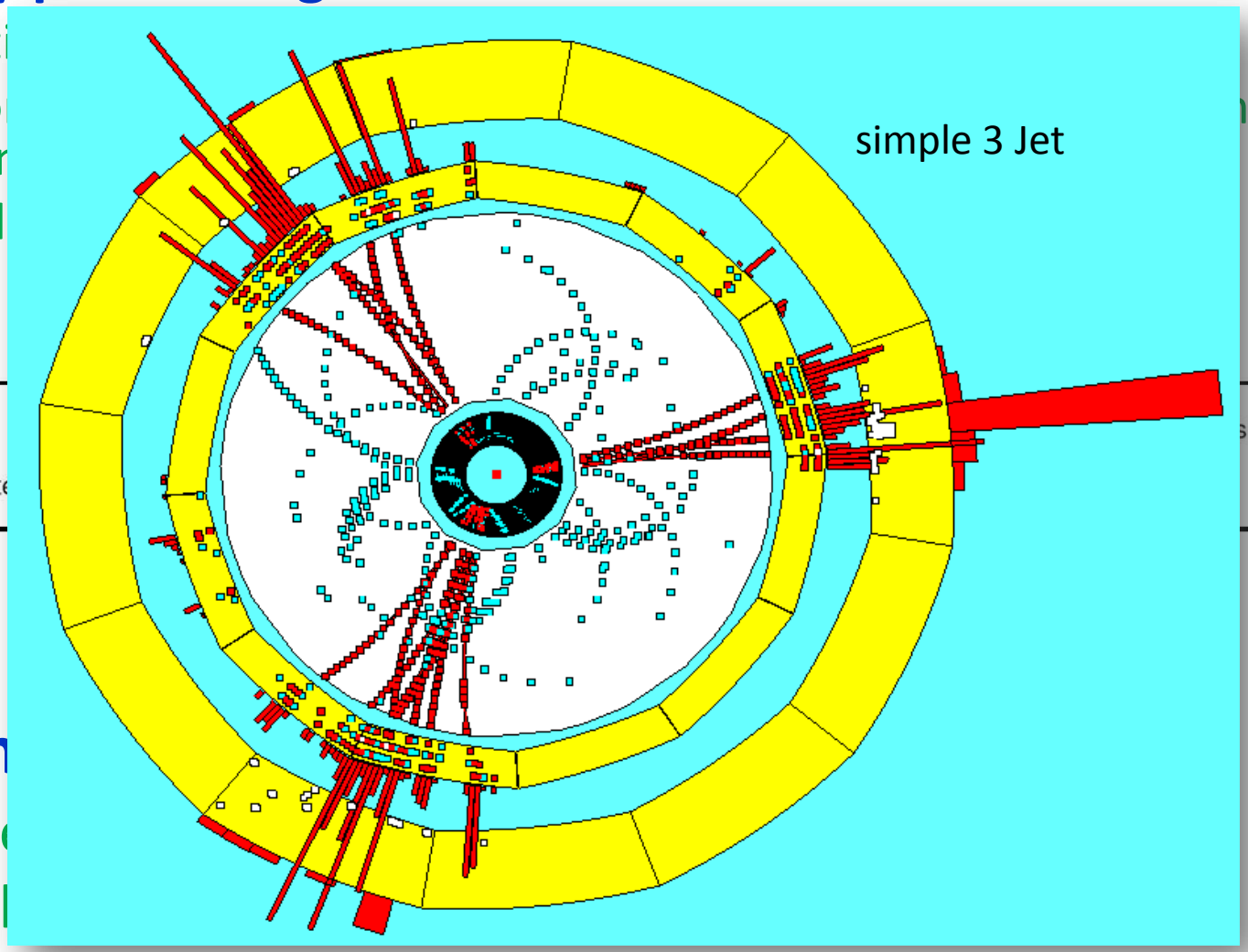


- **Commonly used algorithms**
  - Cone
  - kT clustering, anti-kT

Jet Reconstruction

- **Initially parton fragmentate to hadrons**
  - Multi
  - Reco
    belor
  - Jet cl

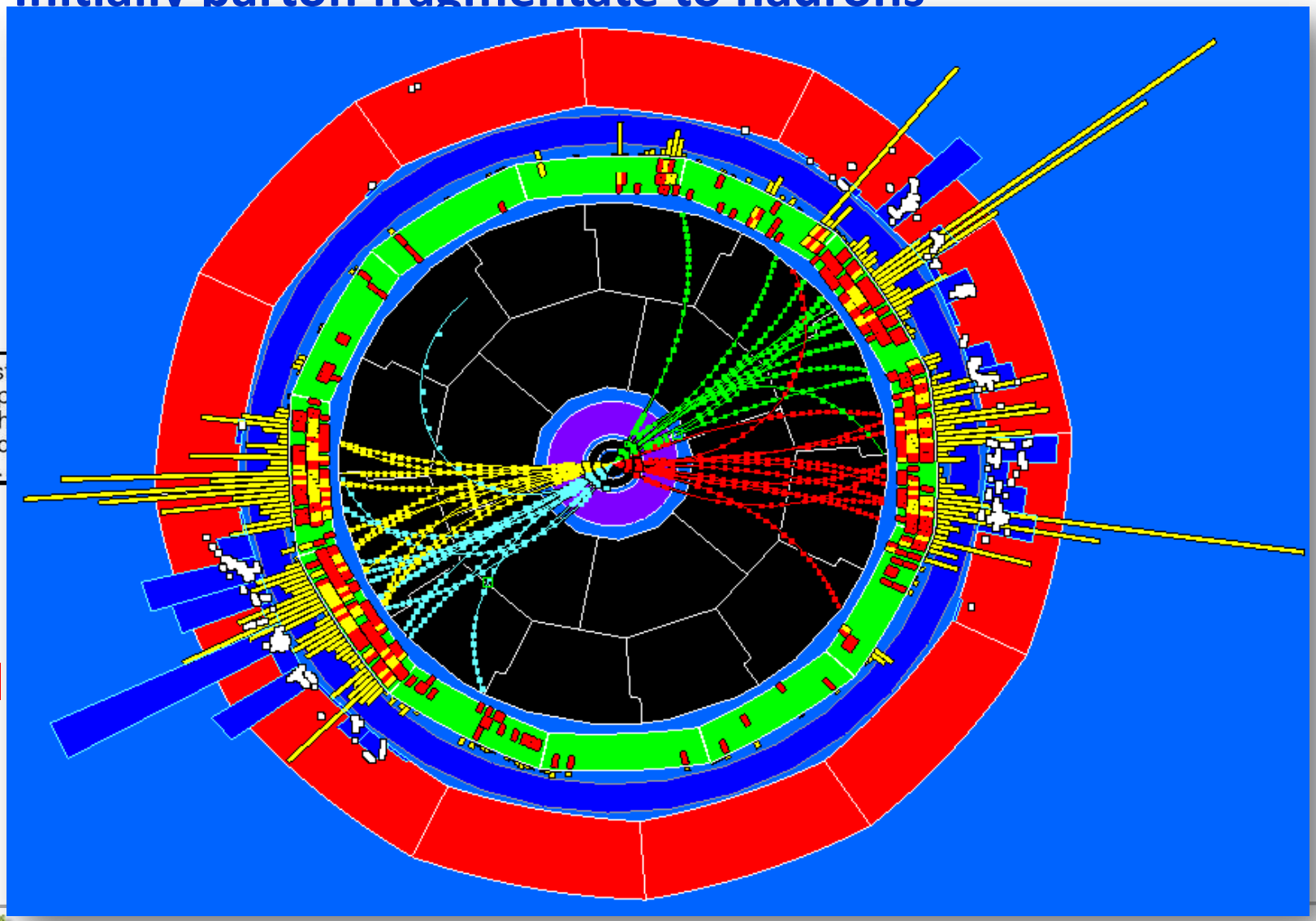
List of particles :
- partons
- hadrons
- calorimeter cluste
- ...



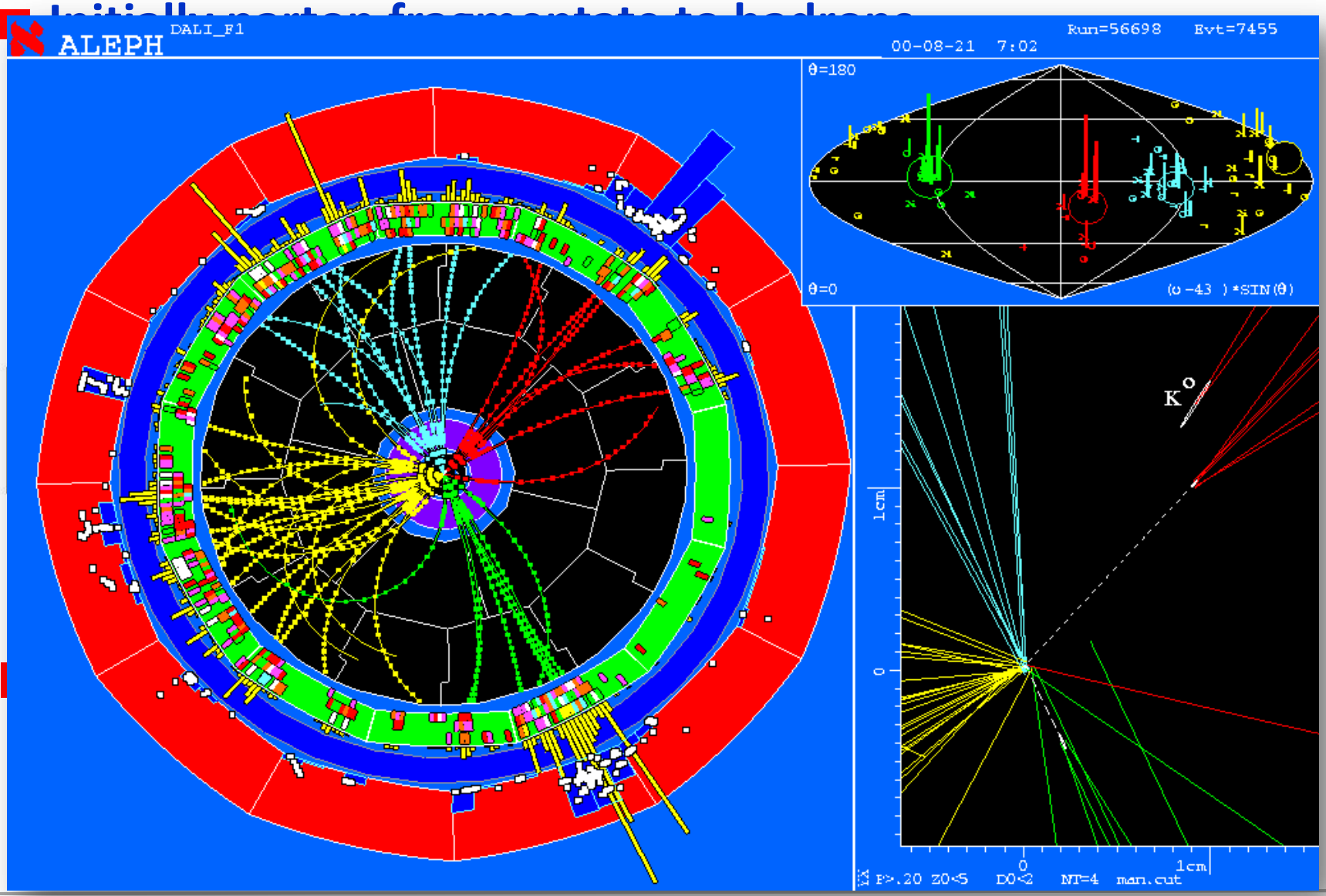
- **Comm**
  - Con
  - kT cl

Jet Reconstruction

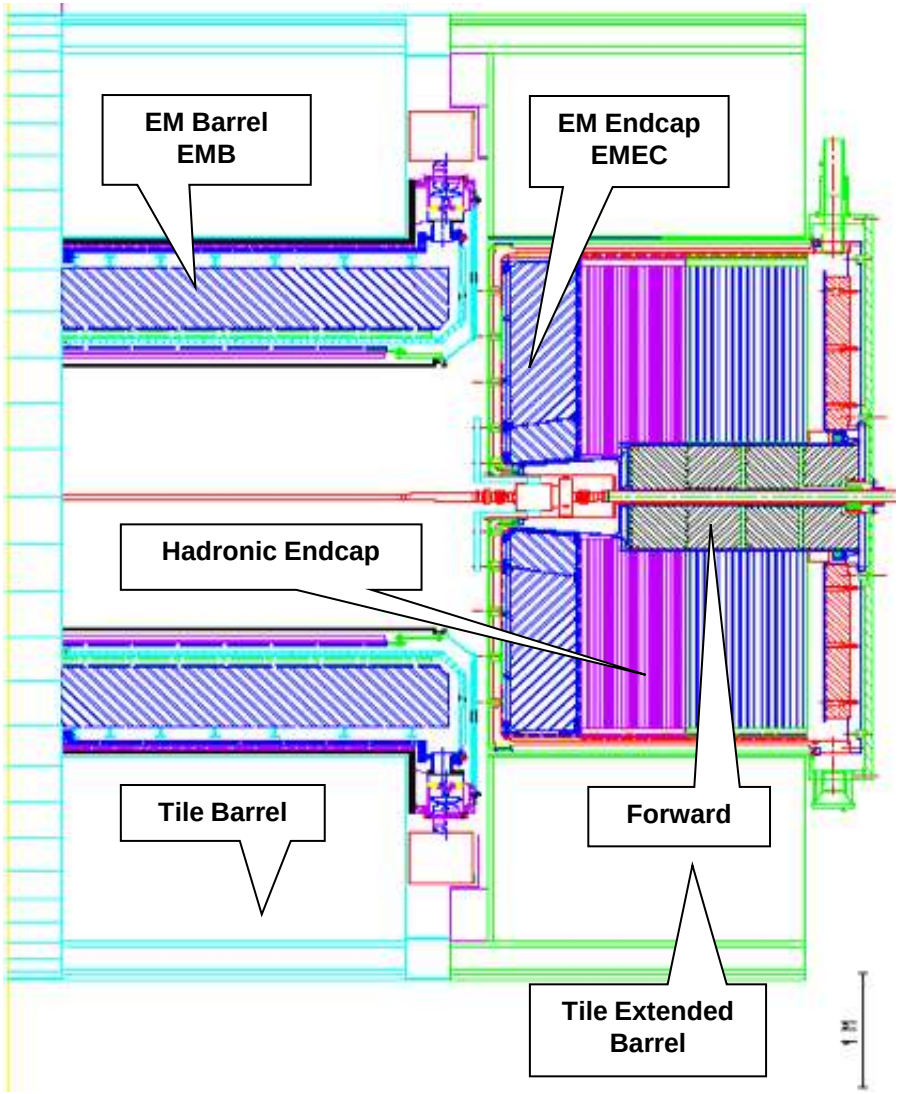
- Initially parton fragmentate to hadrons



Jet Reconstruction



Example: ATLAS Detector



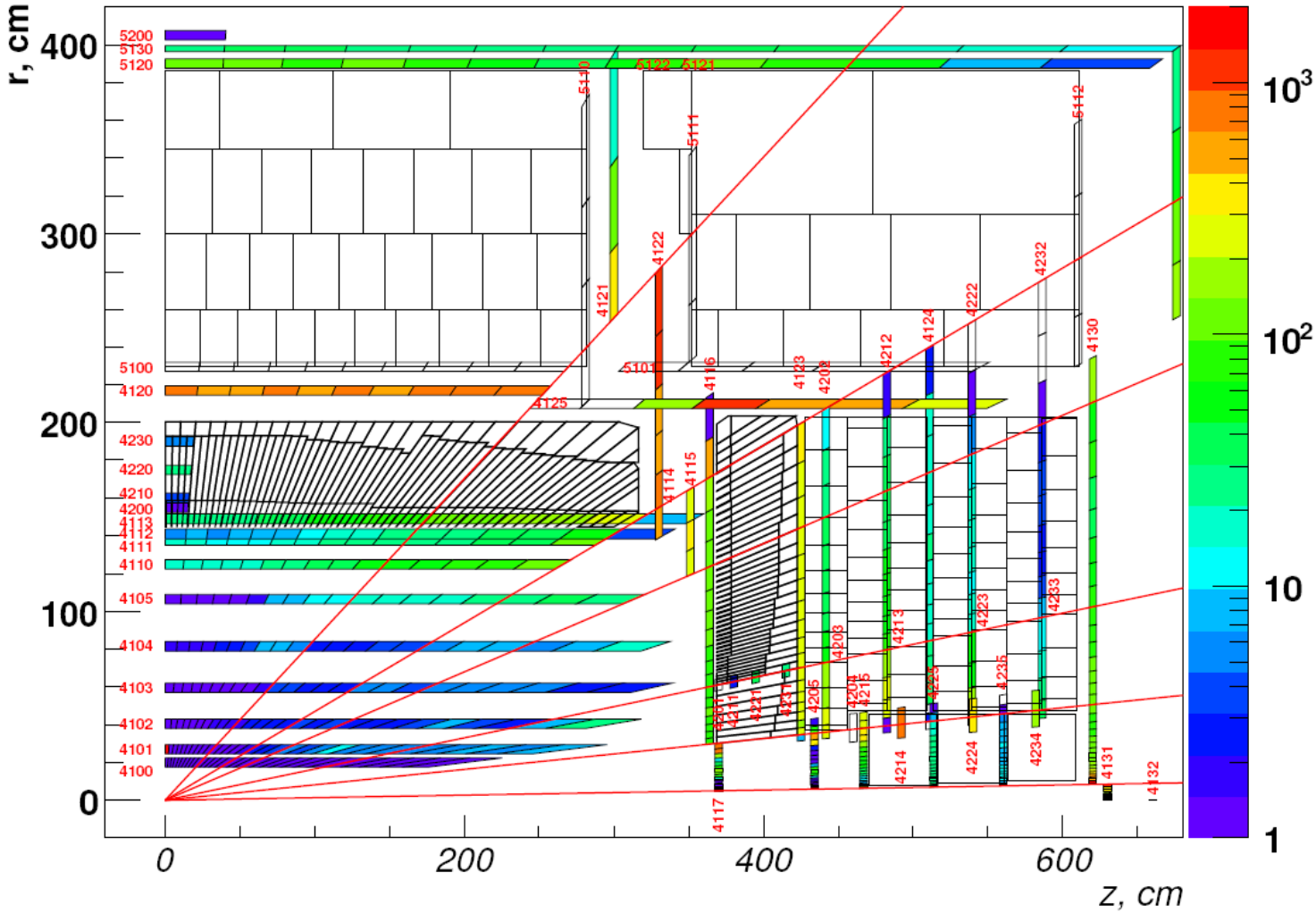
ATLAS Calorimeters

- EM: $|\eta| < 3.2$,
  - Pb/LAr calorimeter,
  - 22-26 X_o, 1.2 λ,
  - 3 longitudinal sections,
  - $\Delta\eta \times \Delta\Phi = 0.025 \times 0.025 - 0.1 \times 0.1$
  - $\sigma/E \simeq 10\%/\sqrt{E}$.
- Central Hadronic: $|\eta| < 1.7$,
  - Fe/Scintillator sampling calorimeter
  - 7.4 λ,
  - 3 longitudinal sections,
  - $\Delta\eta \times \Delta\Phi = 0.1 \times 0.1 - 0.2 \times 0.1$,
  - $\sigma/E \simeq 50\%/\sqrt{E} \oplus 0.03$.
- EndCap Hadronic: $1.7 < |\eta| < 3.2$,
  - Cu/LAr sampling calorimeter,
  - 4 longitudinal sections,
  - $\Delta\eta \times \Delta\Phi = 0.1 \times 0.1 - 0.2 \times 0.2$
- FCAL: $3 < |\eta| < 4.9$,
  - EM: Cu/LAr, HAD: W/LAr calorimeter,
  - 10 λ,
  - 1 EM + 2 HAD longitudinal sections,
  - $\Delta\eta \times \Delta\Phi = 0.75 \times 0.65 - 5.4 \times 4.7$

P. Loch

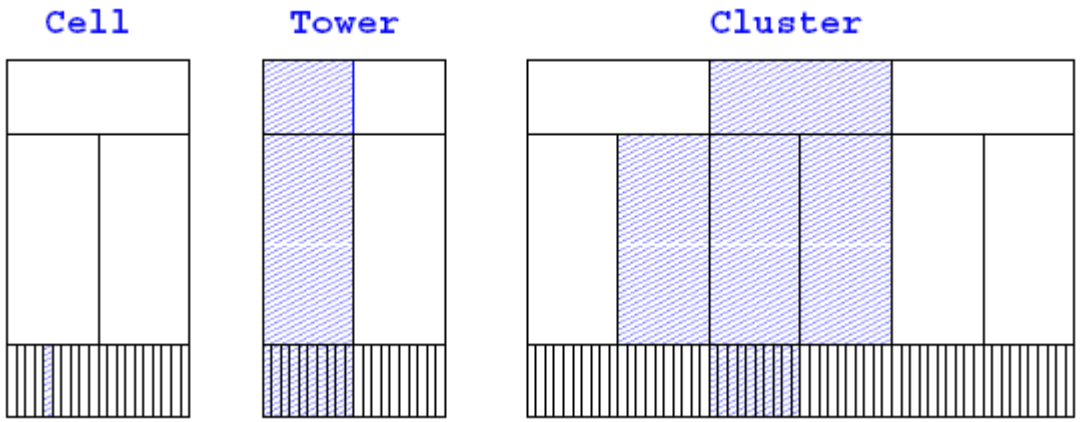
Jet Finding in ATLAS

Calorimeter towers, cells and dead material



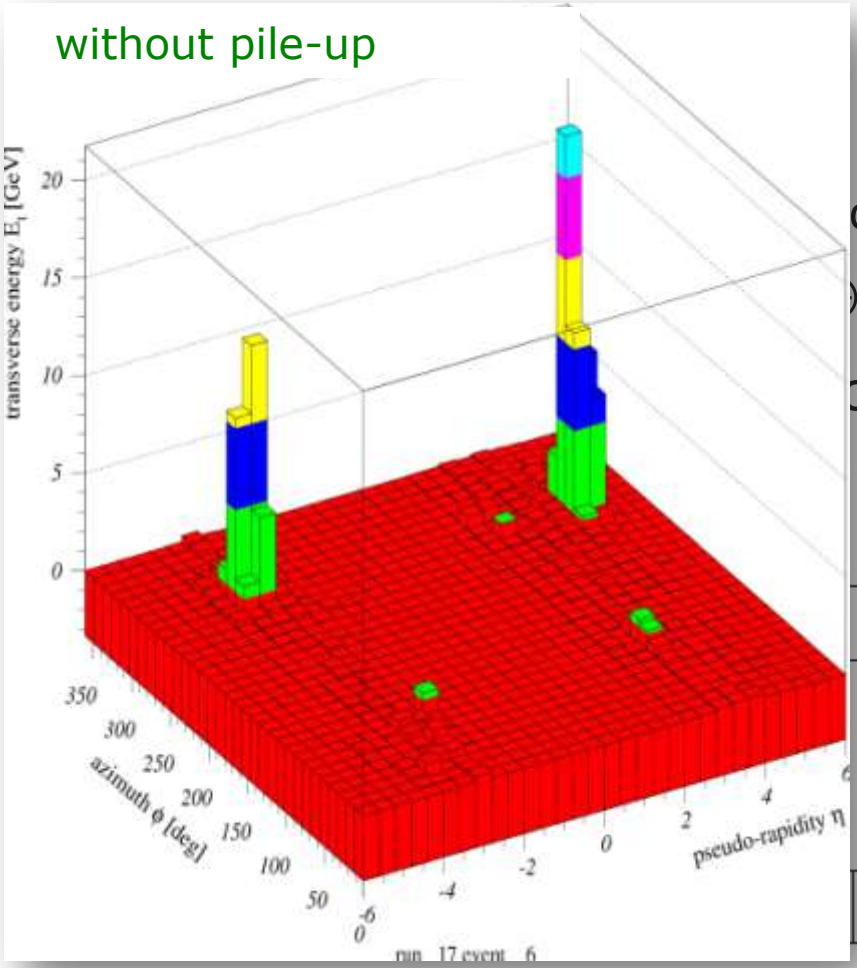
Clustering

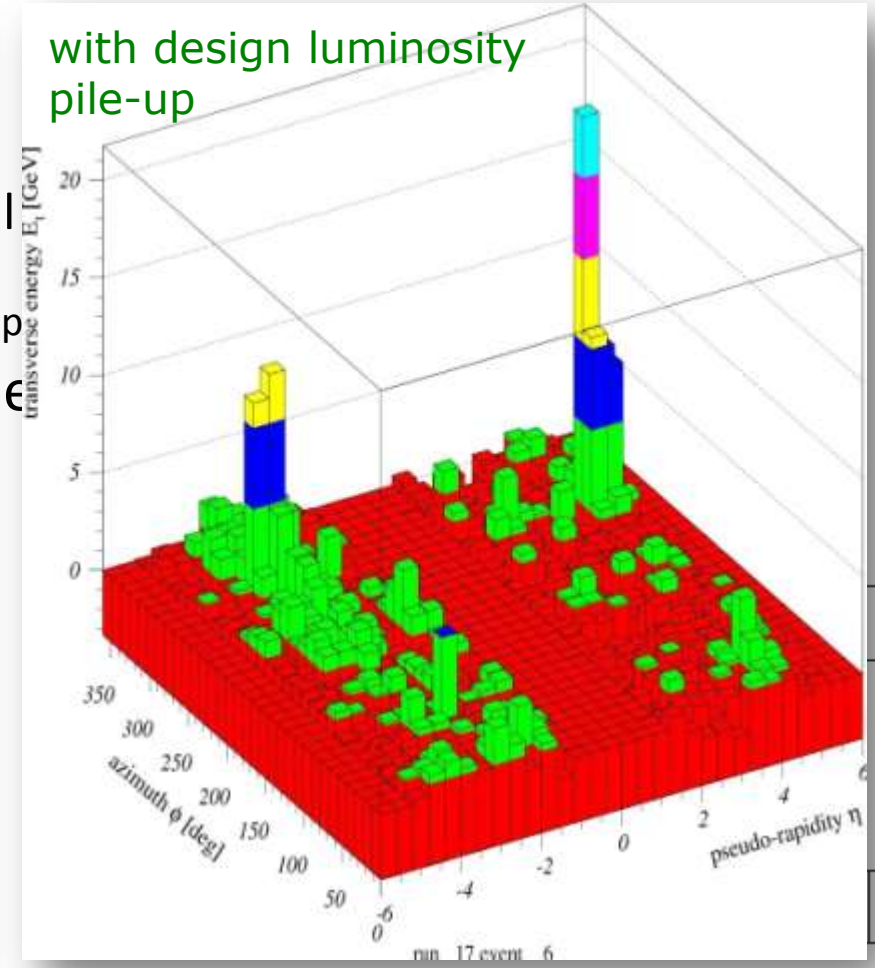
- **Signal in calorimeter**
  - In a cell, tower or cluster
  - Cluster
    - Group of cells around a seed cell
    - Seed cell with $E > \sigma_{noise} \oplus \sigma_{pileup}$
    - Scan neighboring cells for energy above noise
    - Add cells together



Clustering

Signal in calorimeter





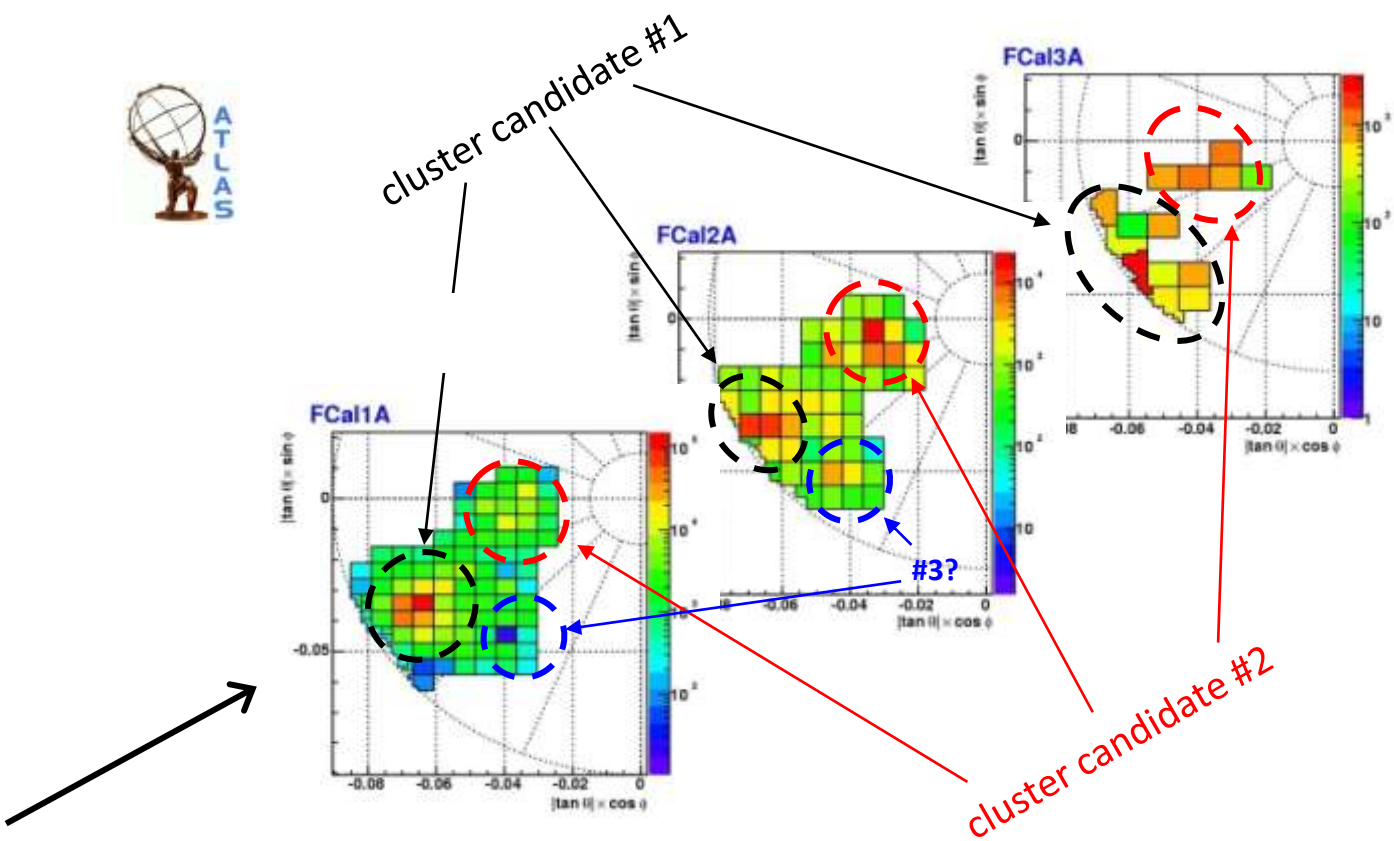
cell

σ_p

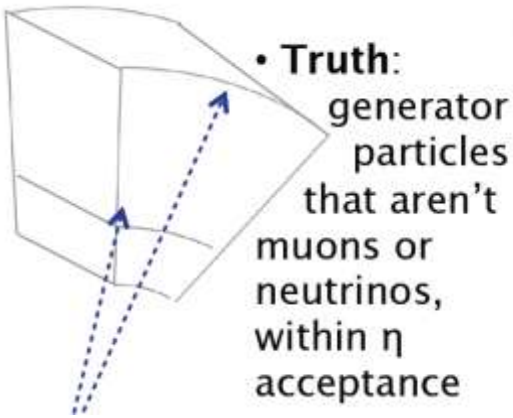
or ϵ

Clustering (2)

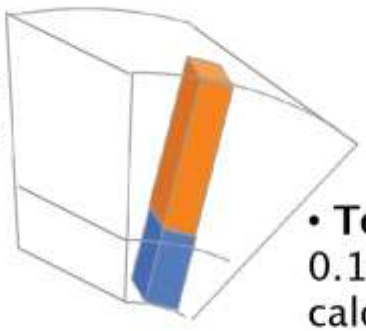
- **Might have to split clusters, if local maxima found**



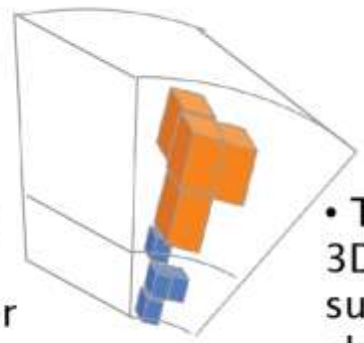
Clustering (3)



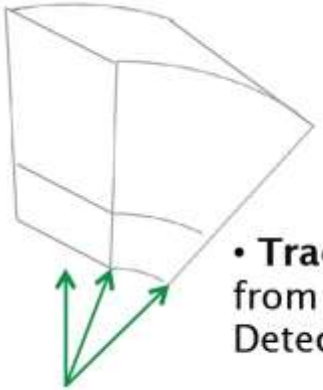
• **Truth**: generator particles that aren't muons or neutrinos, within η acceptance



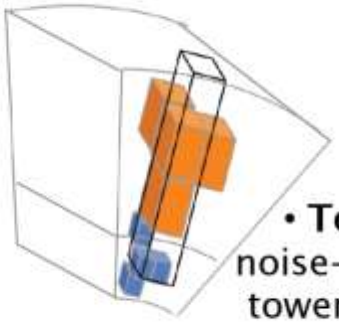
• **Towers**: 0.1x0.1 calorimeter towers



• **TopoClusters**: 3D noise-suppressed clusters of cells



• **Tracks**: from Inner Detector



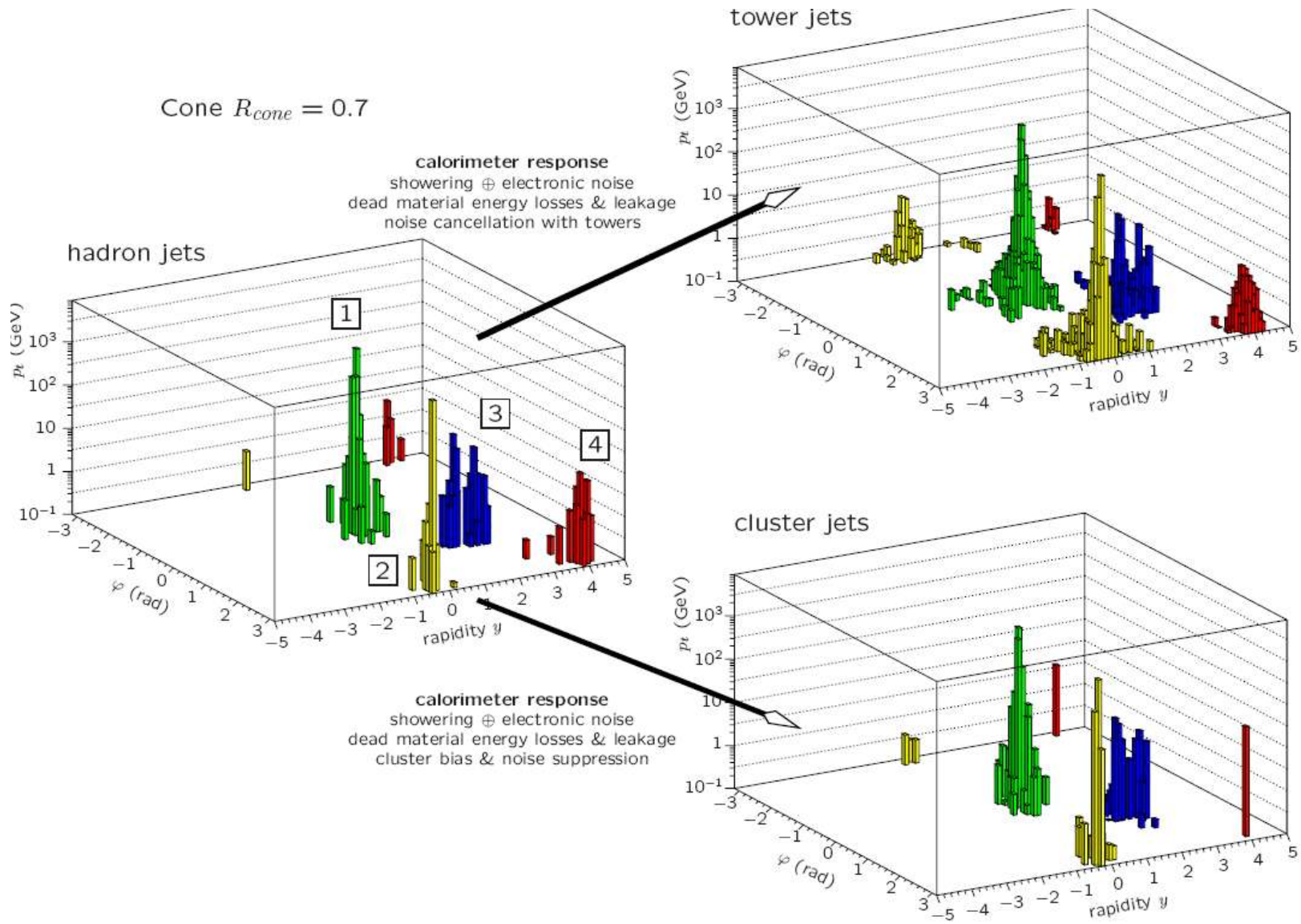
• **TopoTowers**: noise-suppressed towers built from topoclusters

from K. Perez, Columbia U.

Jets and Jet Energy

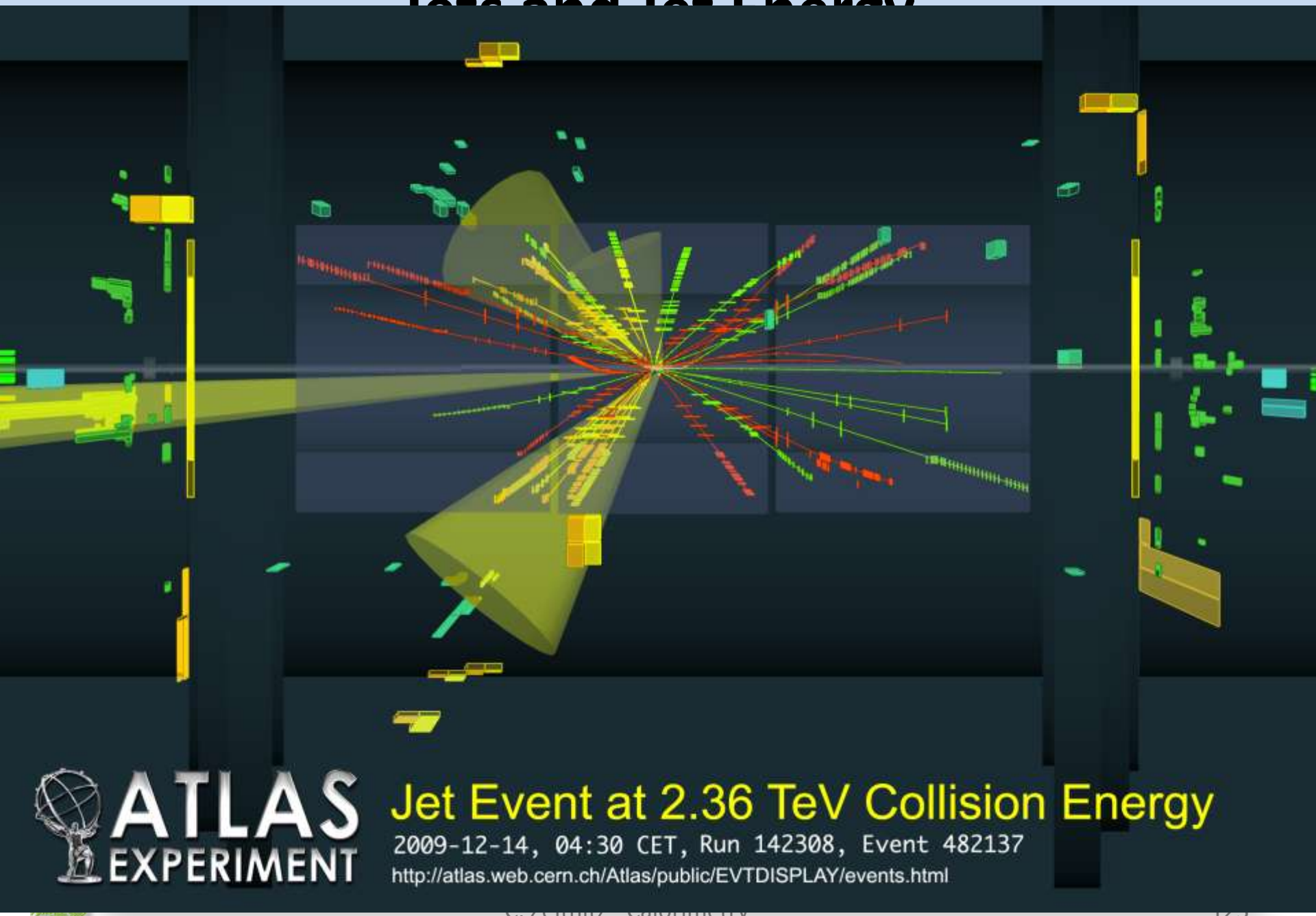
- **Found clusters used as input to Jet algorithm**
  - Clusters are combined to a Jet
    - Criterion for combination very different
      - Distance (cone), energy weighted distance …
    - Iteractive process (stop condition depends on jet algorithm)
- **Shape and number of jets depend on algorithm**
- **Measured energy**
  - Cell energy
    - Apply energy calibration
    - Weighting: em or hadronic energy
  - Cluster energy
    - Corrections
      - Out of cluster energy
      - Dead material in front
      - Linear response

Jets and Jet Energy



S.D. Ellis, J. Huston, K. Hatakeyama, P. Loch, M. Toennesmann, **Prog.Part.Nucl.Phys.60:484-551,2008**

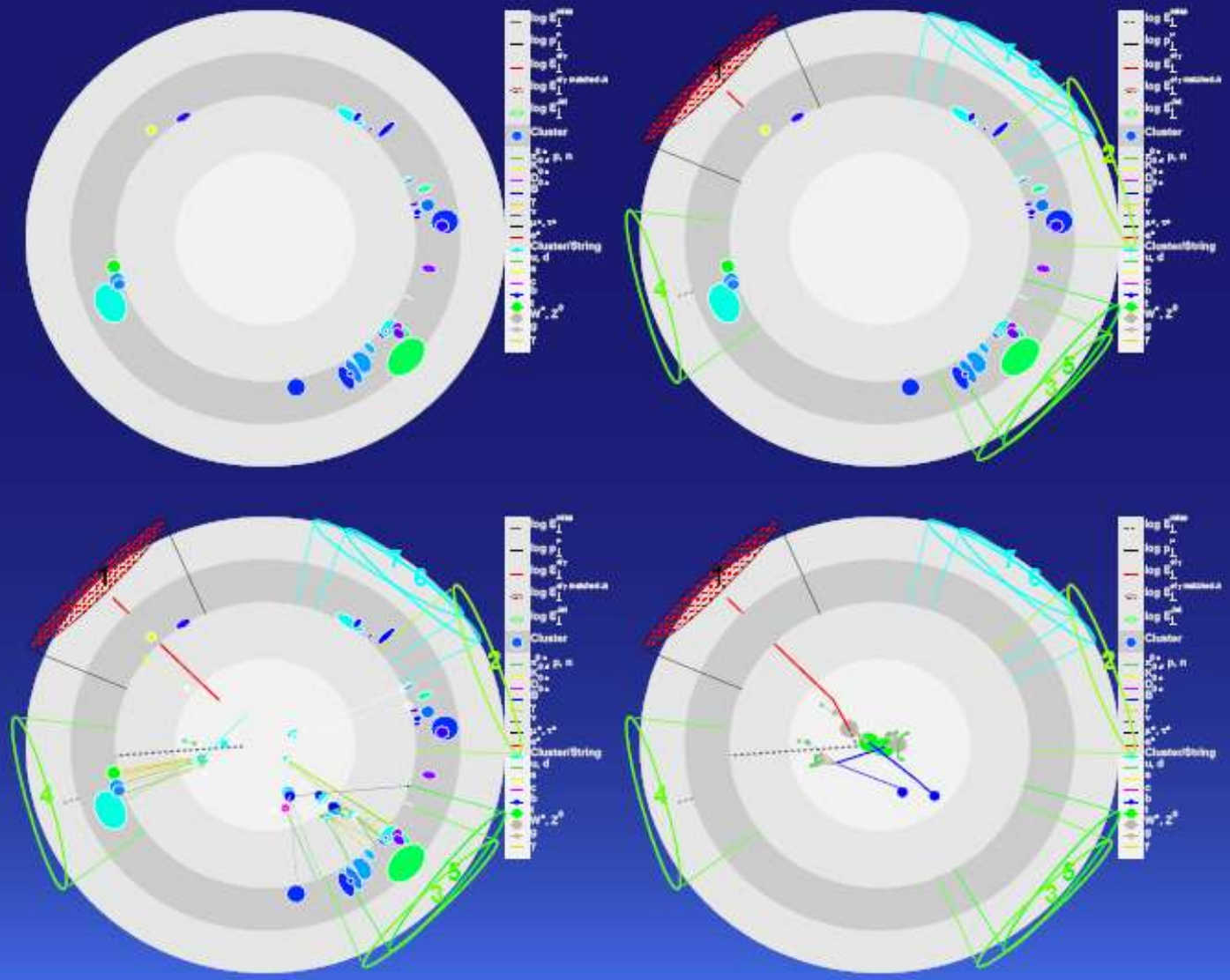
Jets and Jet Energy



Topo Clusters as Input to Jets

- Jet reconstruction and calibration can be divided in 4 steps

1. calorimeter tower/cluster reconstruction
2. jet making
3. jet calibration from calorimeter to particle scale
4. jet calibration from particle scale to the parton scale

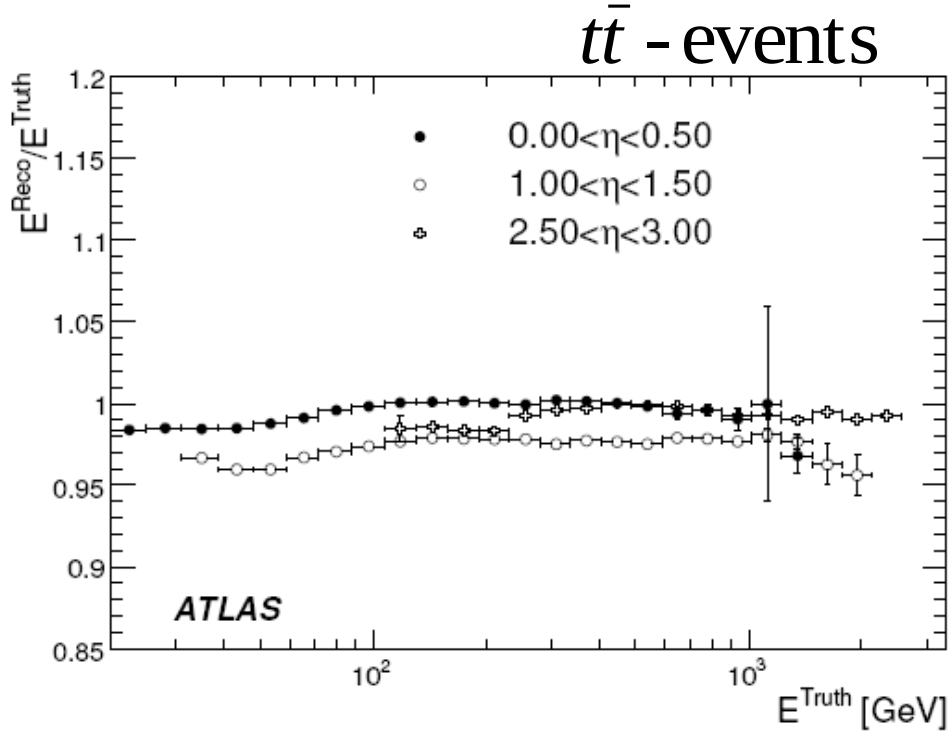


Jet Energy Scale

- **Jet energy should reflect the "true" energy**
  - "true" no really defined!
  - Compare with parton energy
- **Uncertainty of energy scale is important**
  - Top mass measurement

$$\frac{\Delta m_{top}}{m_{top}} < 1GeV \Rightarrow \frac{\Delta E_{Jet}}{E_{Jet}} < 1\%$$

- **Scale depends on multiple parameters**
  - Real signal composition (em/had)
  - Pile-up events
  - Noise
  - Jet algorithm



Conclusions

- **Calorimeters cover a wide range of application**
  - Medicine PET (511keV)
  - Nuclear physics (10keV range)
  - HEP (TeV range)
- **Calorimetry is a main ingredient of HEP detectors**
  - Measurement of neutral and charged particles
  - Measurement of jet energies
  - Measurement of missing energy
  - Measurement of the luminosity (small angle detectors)
- **High resolution calorimeters will be a central part of future experiments**
  - Precise energy measurement required to measure properties of new particles (Higgs?)

Topics not covered in the lecture

New Concepts for hadron Calorimeters

- **Dual Readout (DREAM)**
  - Measure the em-shower fraction separately
    - Even low energetic electron/positron (1MeV) are fast (0.94c)
    - Slow protons (1MeV) are really slow (0.05c)

    Exploit Cerenkov detector to determine f_{em} in each event
    - Atomic excitation more likely done by hadrons

    Scintillation light more likely to come from hadrons
  - Requires material with scintillation and Cerenkov signal
    - Special fibers, doped Pb-glas
    - Sampling fraction not important
  - Results from testbeam measurements very promising

New Concepts for hadron Calorimeters

- **Dual Reado**
  - Measure t
    - Even lov
    - Slow pro
    - Exploit Ce
    - Atomic e
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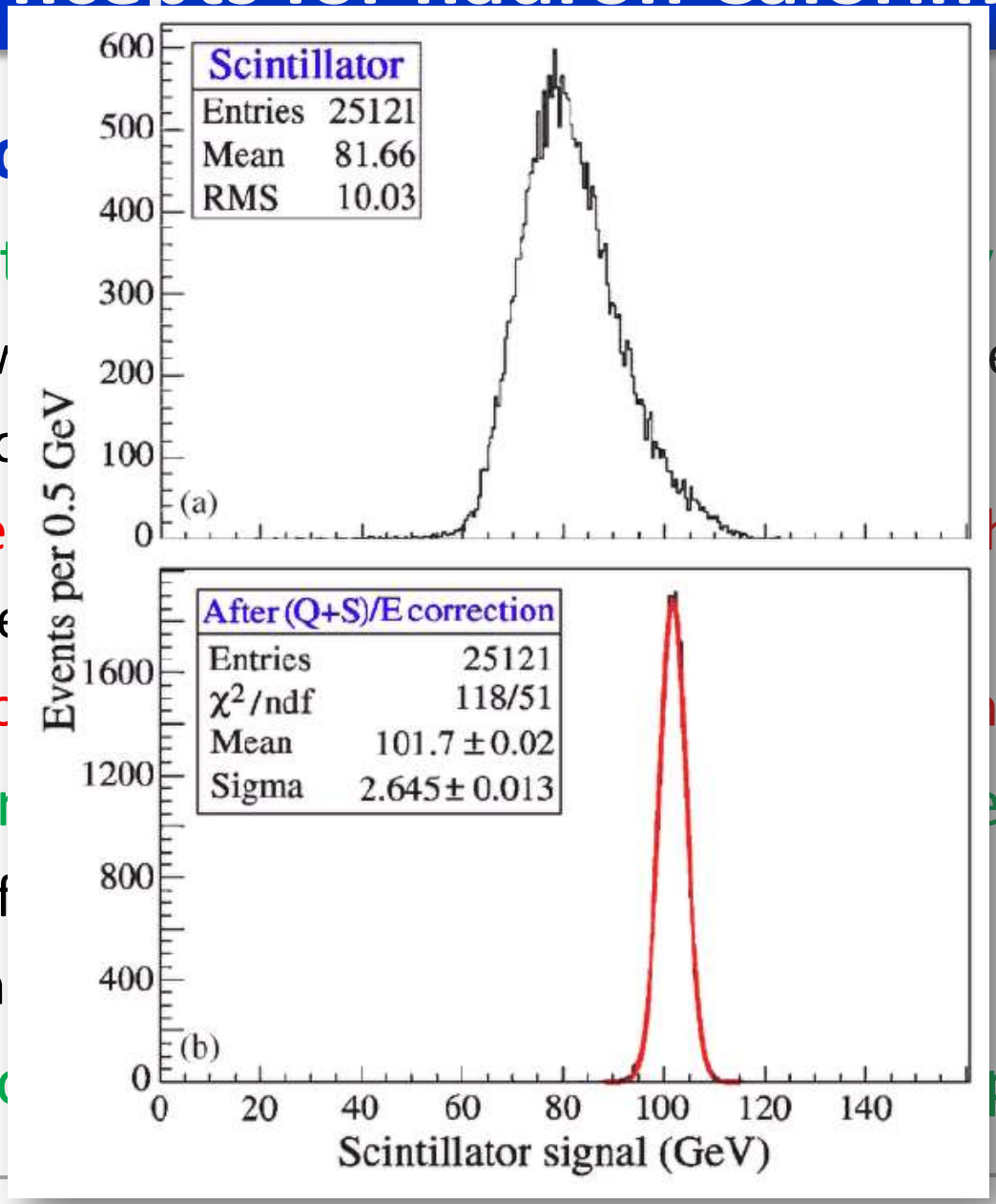
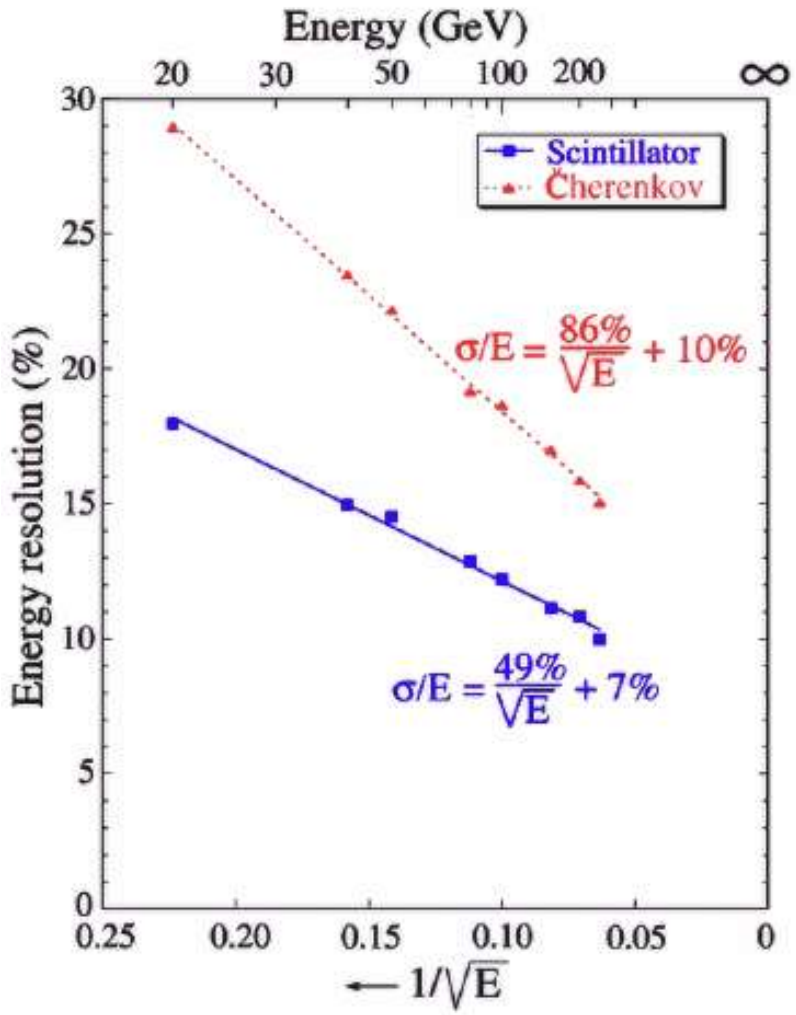
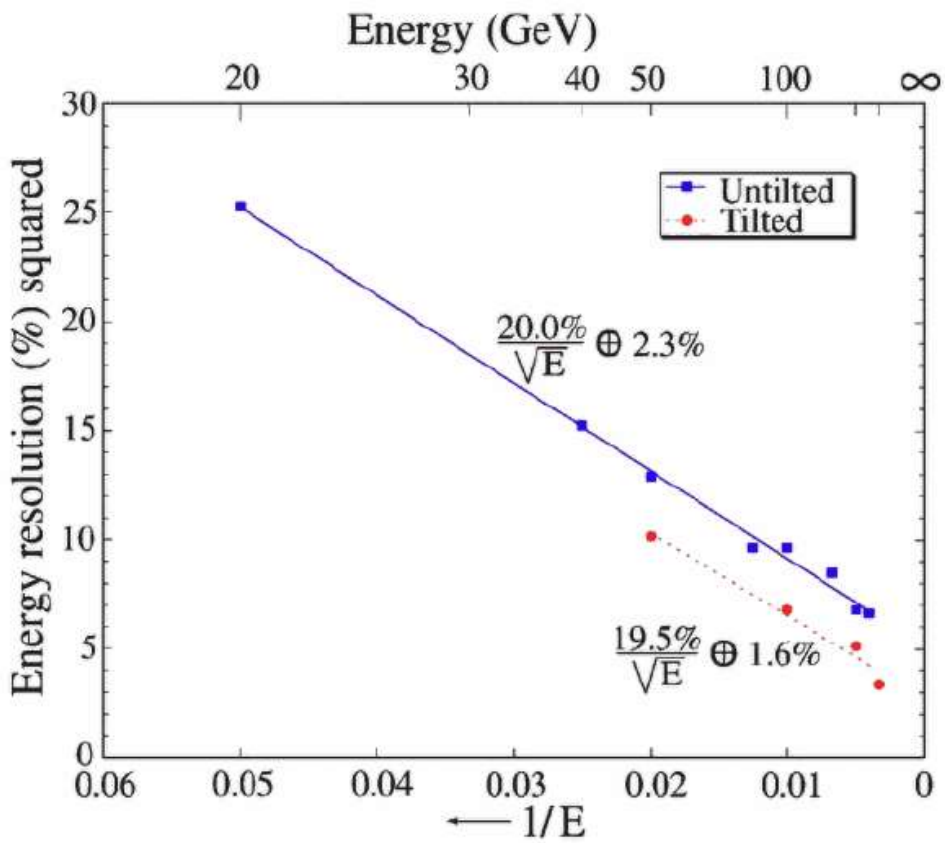


New Concepts for hadron Calorimeters





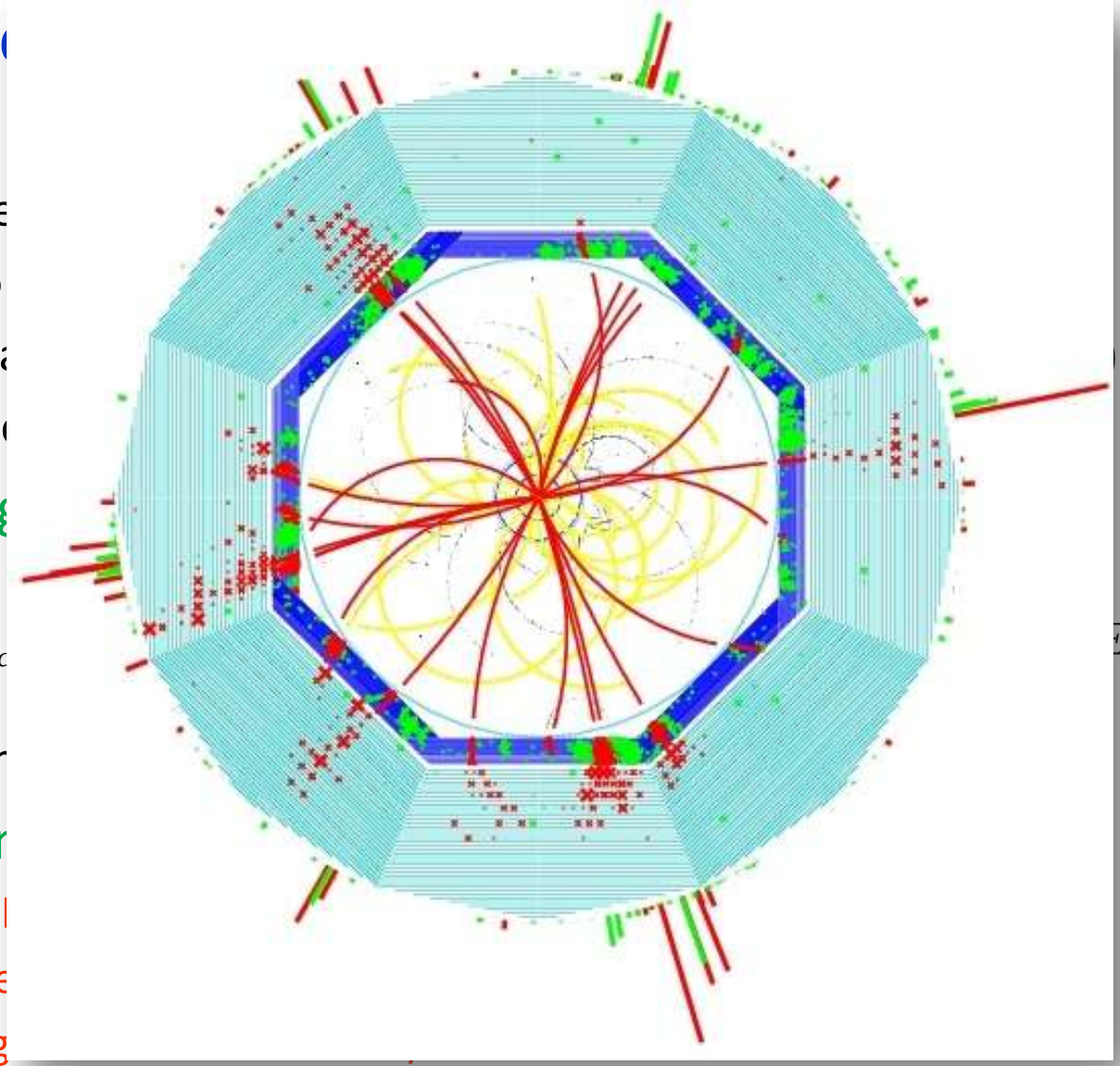
Particle Flow for Jets

- **Combine**
  - Method
    - Mome
    - Photo
    - Neutra
    - All fra
  - Jet energ

$$\sigma^2 = \sigma^2_{trac}$$

$$E_{Jet}$$

    - Domir
  - Requiren
  - ➡ High granul
  - ➡ Hadronic re
  - ➡ Elektromag



Particle Flow for Jets

Combine different detectors

Method based on

- Momentum measurement of charegd particles (~65% E_{jet})
- Photons measured in em-calorimeter (~25% E_{jet})
- Neutral hadrons measured in hadronic calorimeter (~10% E_{jet})
- All fractions energy dependent!

Jet energy resolution

$$\sigma^2 = \sigma^2_{track} + \sigma^2_{h\_neutral} + \sigma^2_{photon} + \sigma^2_{mix} = (0.14)^2 \cdot E_{Jet} + \sigma^2_{mix} \approx (0.3)^2 \cdot E_{Jet}$$

- Dominant is the mix-up term σ_{mix}!

Requirements

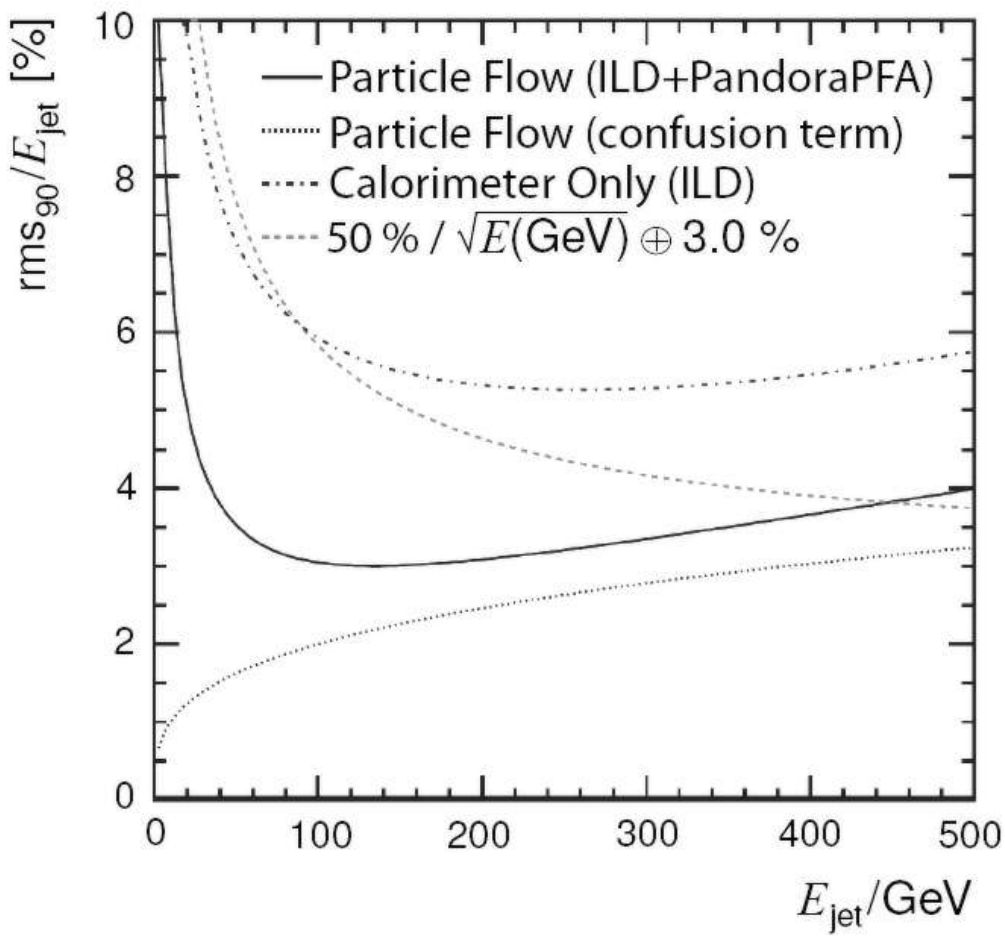
➡ High granularity lateral/longitudinal

➡ Hadronic resolution ~40%/√E

➡ Elektromagnetic resolution ~10%/√E

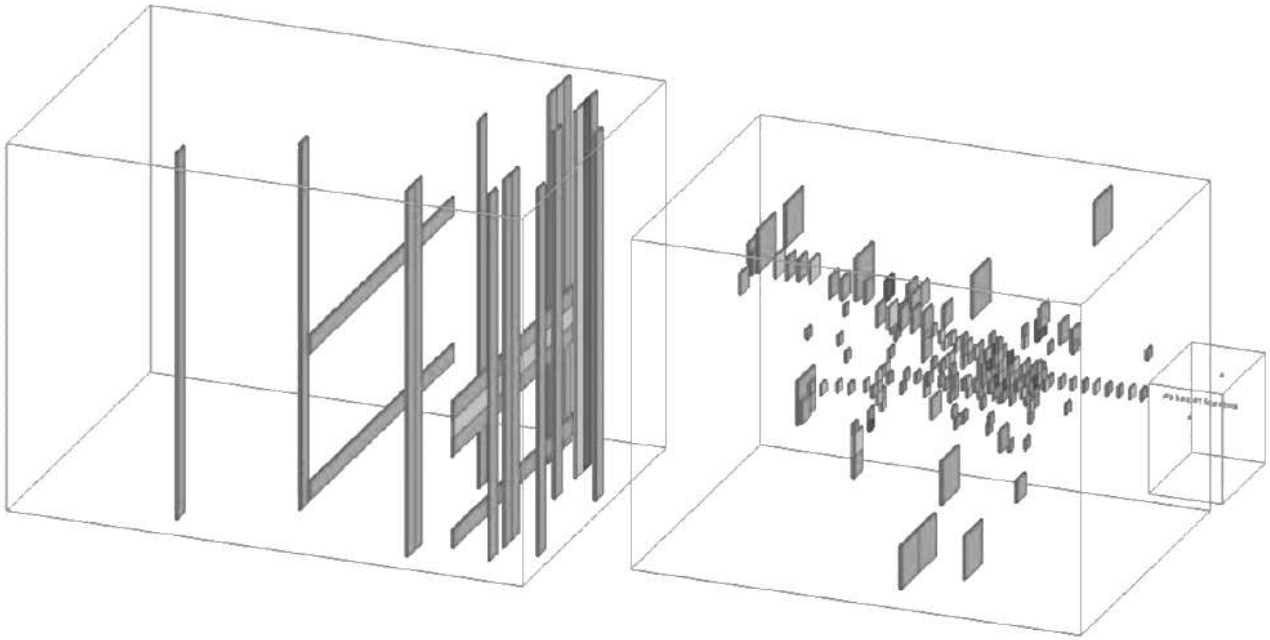
Particle Flow Jet Resolution

- **Resolution scales no longer with 1/√E**



CALICE Collaboration

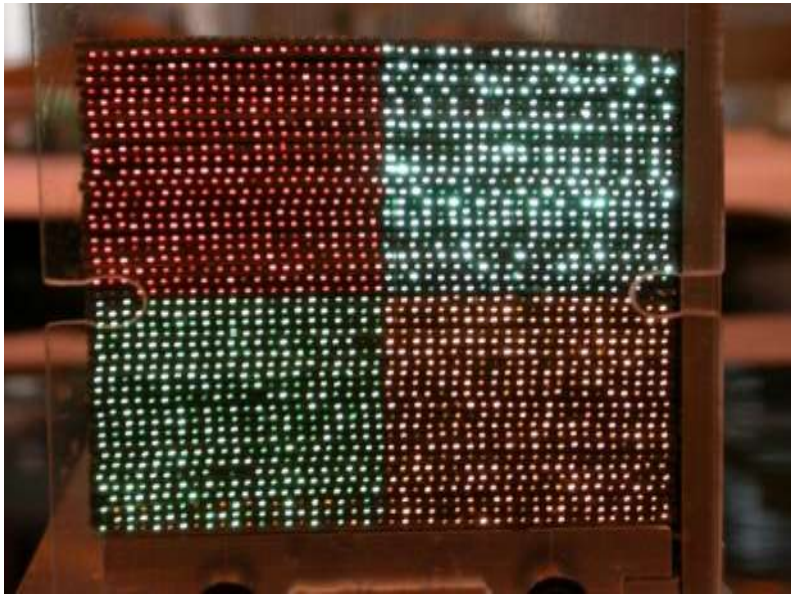
- **CALorimeter for LInear Collider for Electrons**
  - Development of highly granular calorimeters with exceptional energy resolution
  - Different read-out technologies are under investigation
    - Silicon for em- part
    - Silicon and scintillating tiles (SiPM readout) for hadronic part



Other Calorimeters

- **ALICE zero degree calorimeter**
  - Extreme high energy
  - Radiation hard
  - Quartz fiber/tungsten and copper
  - e/h=2
  - Resolution 10% at 1TeV

$$\frac{\sigma_E}{E} = \frac{234\%}{\sqrt{E}}$$



- **And more**
  - Luminosity calorimeters
  - Ice at the south pole
  - Athmosphere

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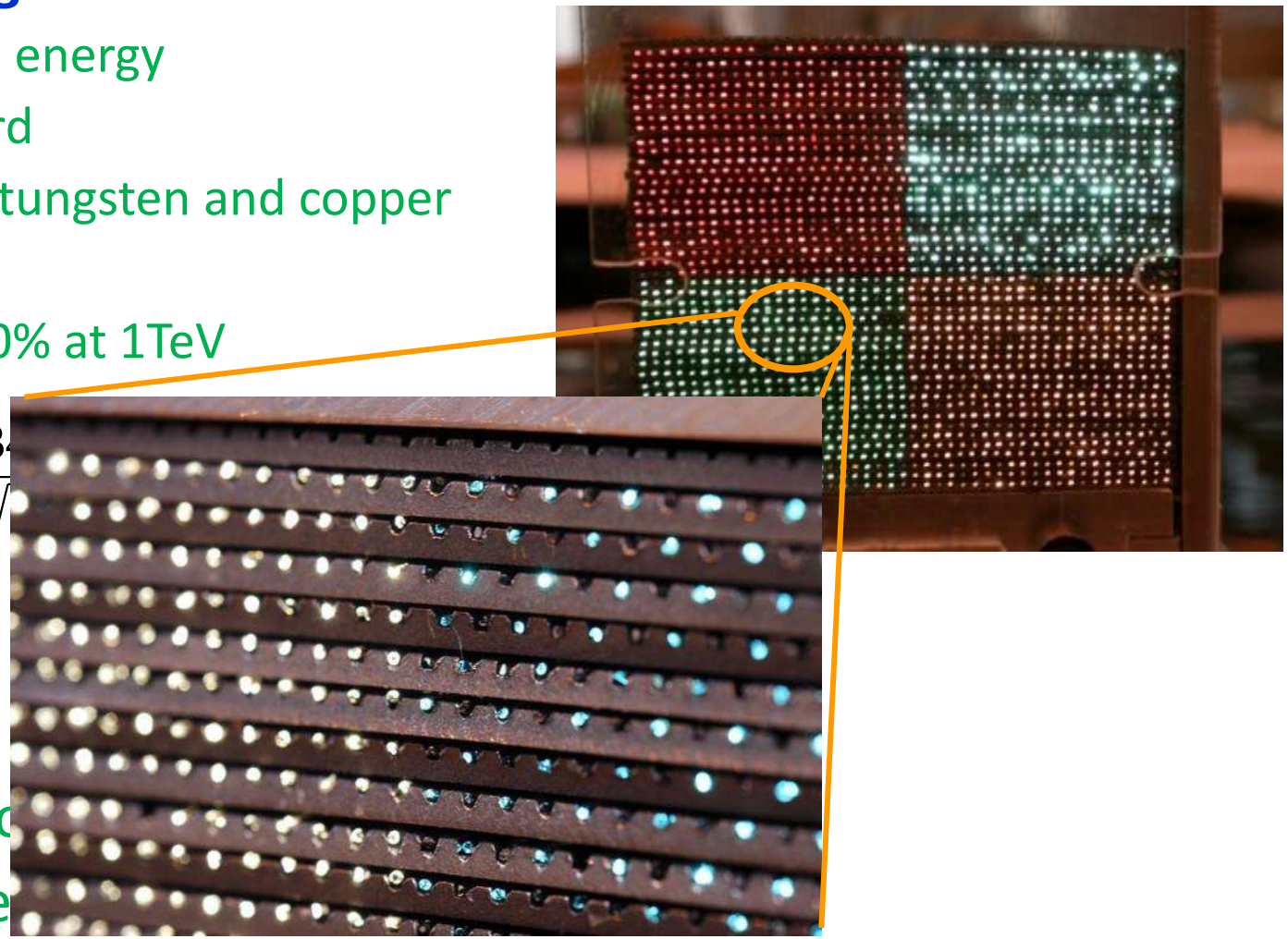

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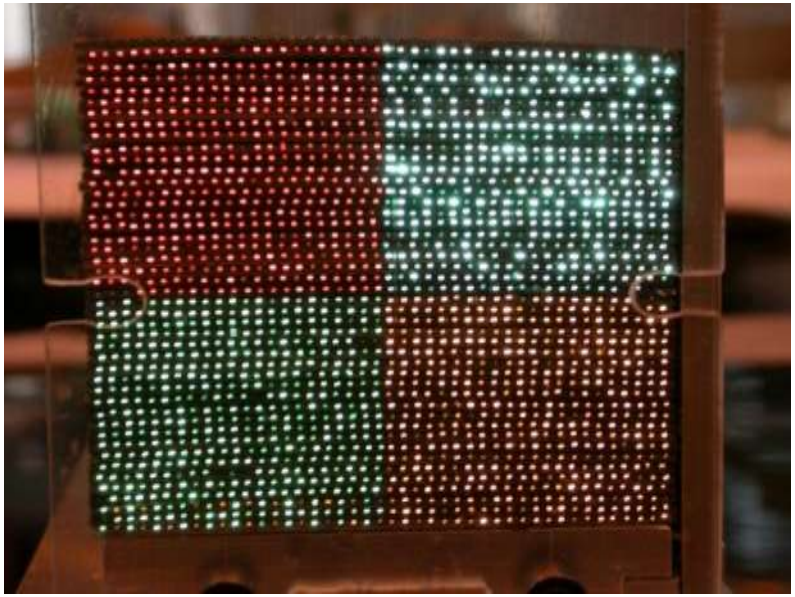

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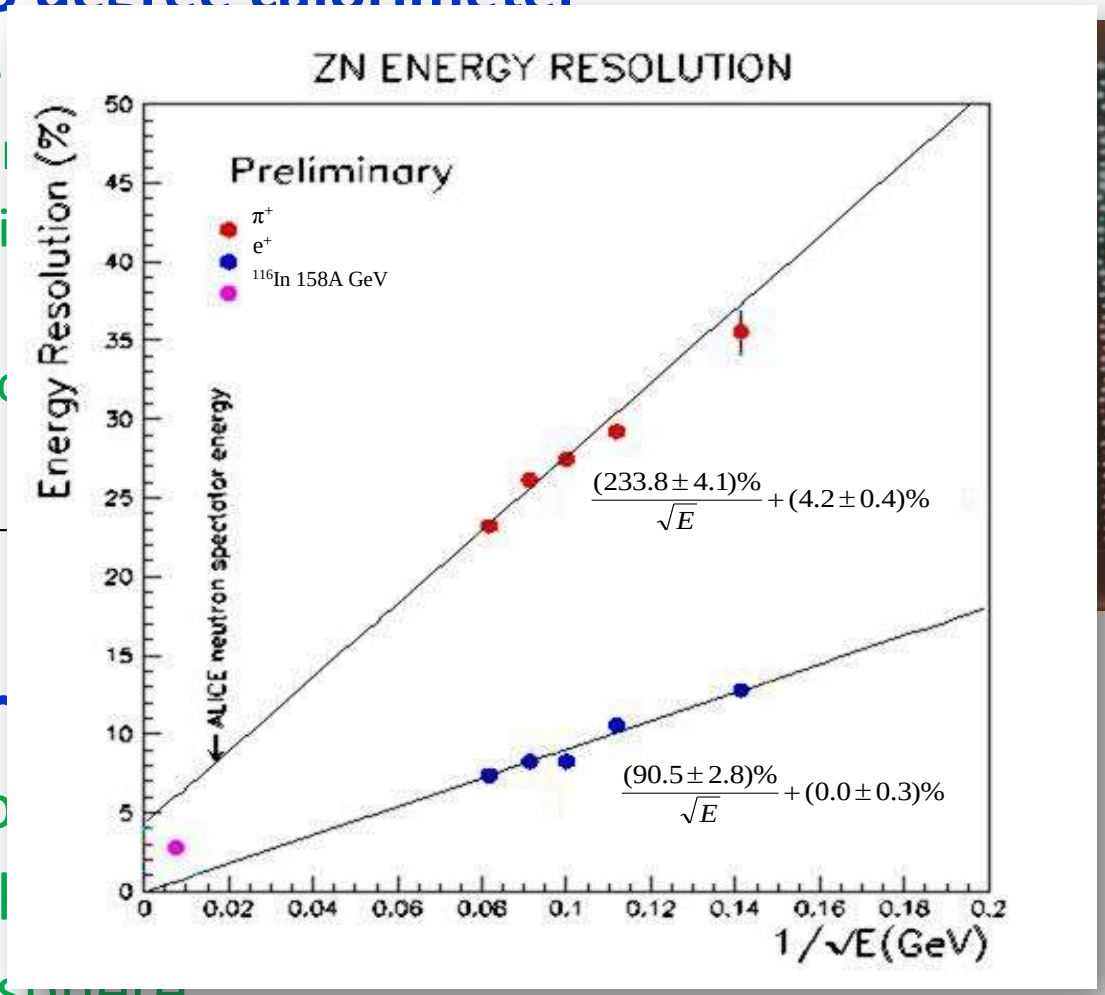

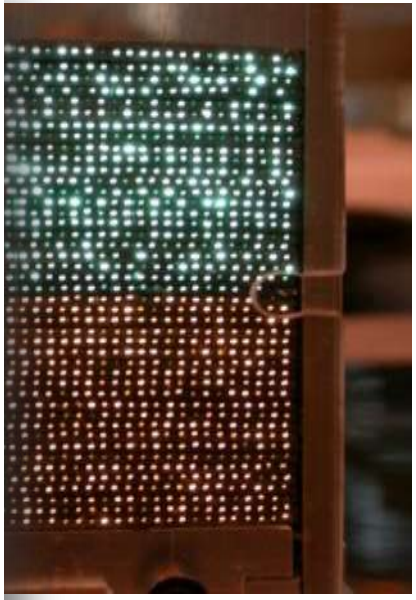

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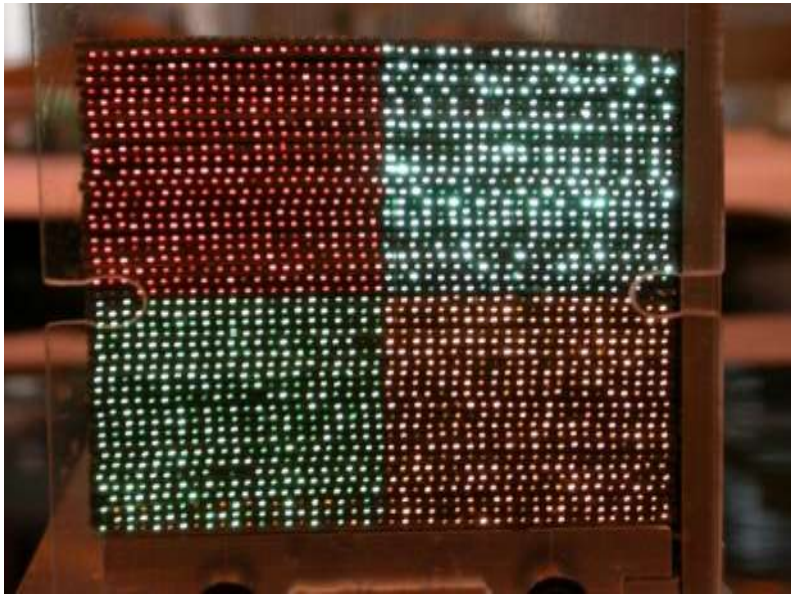

- **And more**
  - Luminosity calorimeters
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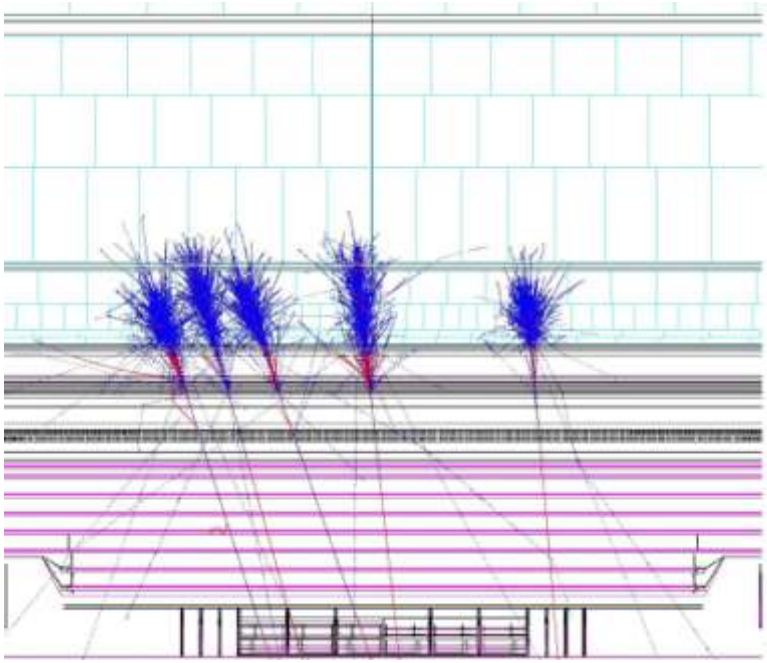
Simulation

Electromagnetic Showers

- QED provides very precise decription of all processes
- Need detailed description of geometry and materials
- Simulation describes the measured calorimeter response well, but need a lot of CPU time
- Programs
  - EGS (THE reference)
  - GEANT 4 (em-Package)



Simulation of Hadrons

- **Hadronic Models**
  - Much more complicated due to complexity of hadronic interactions (nuclear physics), required measured cross-sections
  - Simulation of neutrons tricky
    - Requires precise description of material composition (elements)
  - Comparison with data usually only reasonable
  - Programs
    - GEANT 4
    - FLUKA
    - HETC (ORNL/LANL)
    - Programs for special applications (shielding …)

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