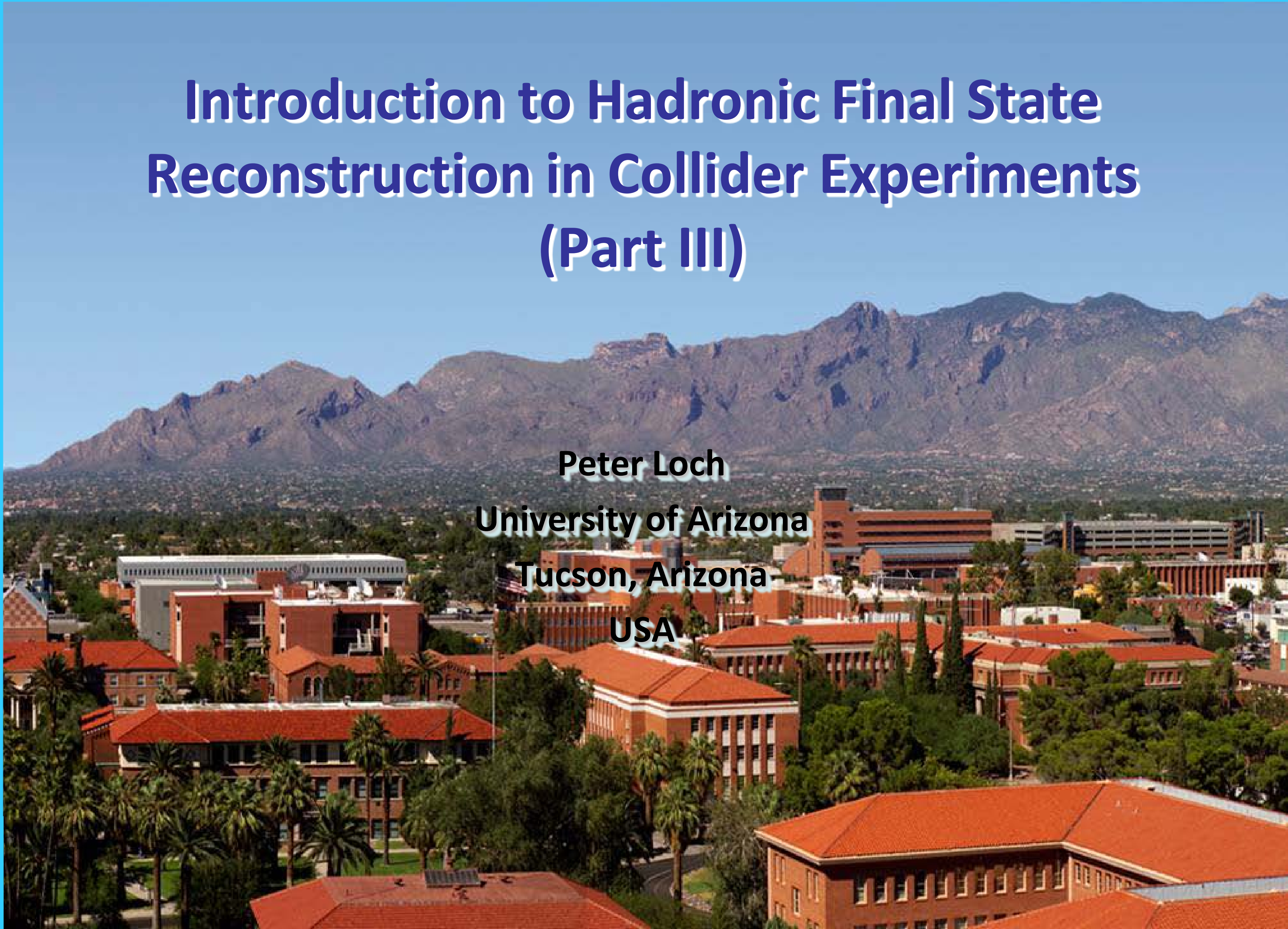
Introduction to Hadronic Final State Reconstruction in Collider Experiments

(Part III)



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Calorimeter Basics

Full absorption detector

- Idea is to convert incoming particle energy into detectable signals
  - Light or electric current
  - Should work for charged and neutral particles
- Exploits the fact that particles entering matter deposit their energy in particle cascades
  - Electrons/photons in electromagnetic showers
  - Charged pions, protons, neutrons in hadronic showers
  - Muons do not shower at all in general

Principal design challenges

- Need dense matter to absorb particles within a small detector volume
  - Lead for electrons and photons, copper or iron for hadrons
- Need "light" material to collect signals with least losses
  - Scintillator plastic, nobel gases and liquids
- Solution I: combination of both features
  - Crystal calorimetry, BGO
- Solution II: sampling calorimetry

Calorimeter Basics (2)

Sampling calorimeters

- Use dense material for absorption power…
  - No direct signal
- …in combination with highly efficient active material
  - Generates signal
- Consequence: only a certain fraction of the incoming energy is directly converted into a signal
  - Typically 1-10%
- Signal is therefore subjected to sampling statistics
  - The same energy loss by a given particle type may generate different signals
  - Limit of precision in measurements

Need to understand particle response

- Electromagnetic and hadronic showers

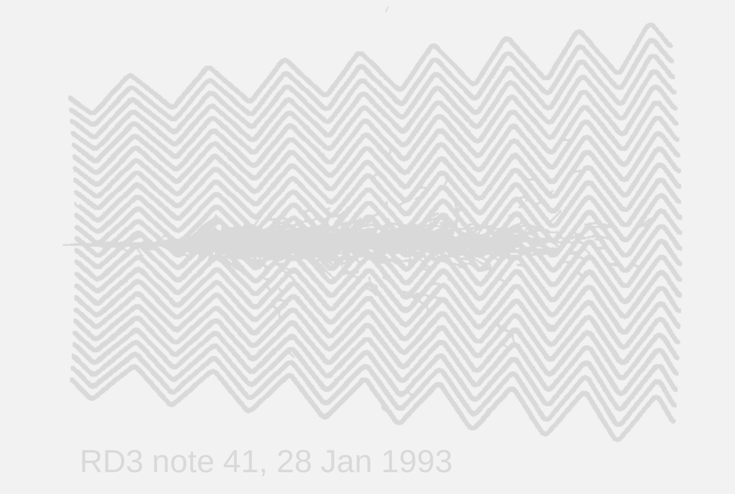
Electromagnetic Cascades in Calorimeters

Electromagnetic showers

- Particle cascade generated by electrons/positrons and photons in matter
- Developed by bremsstrahlung & pair-production

Compact signal expected

- Regular shower shapes
  - Small shower-to-shower fluctuations
- Strong correlation between longitudinal and lateral shower spread



RD3 note 41, 28 Jan 1993

Shower depth scales in radiation length X_0 :

$$X_0 \approx \frac{716.4 \cdot A}{Z(Z+1)\ln\frac{278}{\sqrt{Z}}} \text{ g} \cdot \text{cm}^{-2}$$

Approximation good within $\pm 2\%$ for all materials except Helium (5% low)

Shower width scales in Moliere Radii R_M :

$$R_M \approx \frac{E_s}{E_c} X_0 \approx \frac{21 \text{ MeV} \cdot (Z+1.2)}{800 \text{ MeV}} X_0$$

$$= 0.0265 \cdot X_0 (Z+1.2)$$

(90% energy containment radius)

$$\text{with } \begin{cases} E_s \approx 21 \text{ MeV} \\ E_c \approx \dfrac{800 \text{ MeV}}{Z+1.2} \end{cases}$$

C. Amsler *et al.* (Particle Data Group), Physics Letters **B667**, 1 (2008) and 2009 partial update for the 2010 edition

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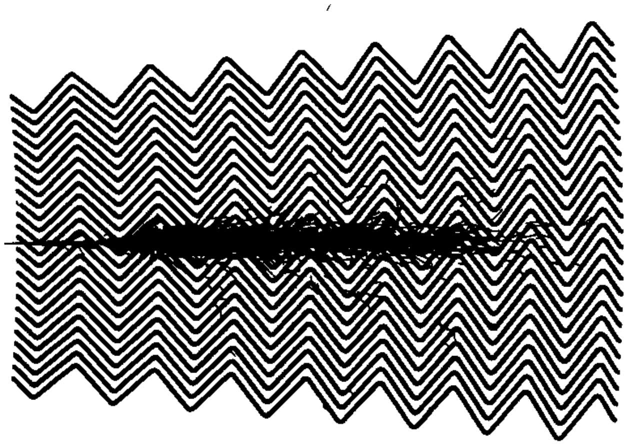

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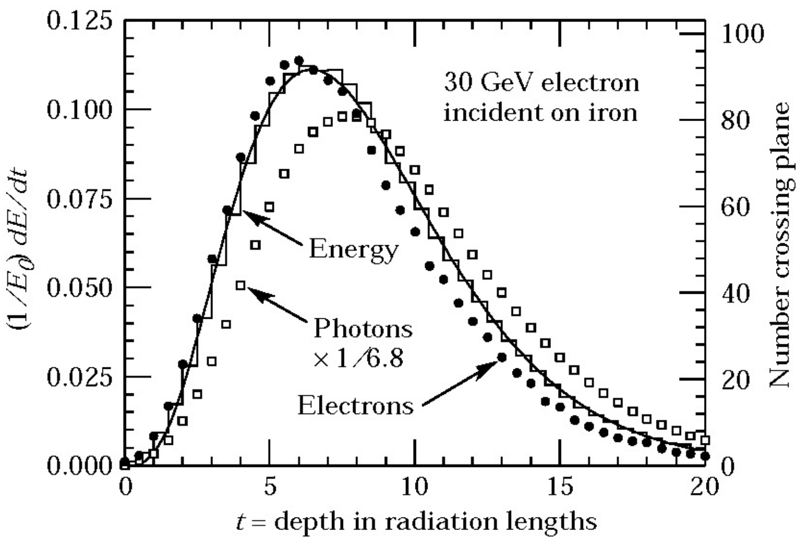

$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}, \text{ with } t = x/X_0$$

$$t_{\max} = (a-1)/b = 1.0 \times (\ln y + C_j),$$

$$\text{with } y = E/E_c \text{ and}$$

$$C_j = \begin{cases} -0.5 & \text{for } e^{\pm} \\ +0.5 & \text{for } \gamma \end{cases}$$

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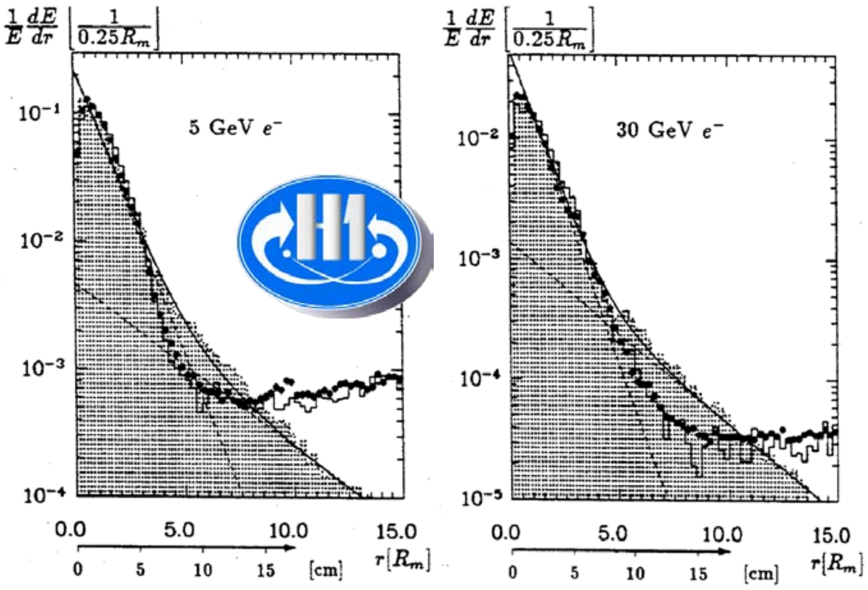

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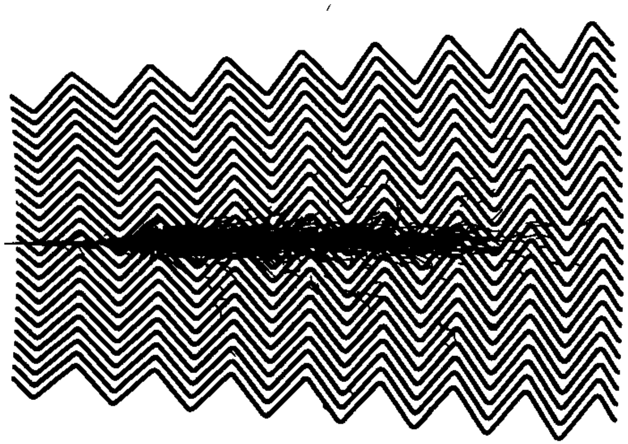
$$\frac{1}{E}\frac{dE}{dr} = a(E)\cdot e^{-\alpha(E)r} + b(E)\cdot e^{-\beta(E)r}$$

G.A. Akopdzhanov *et al.* (Particle Data Group), Physics Letters **B667**, 1 (2008) and 2009 partial update for the 2010 edition



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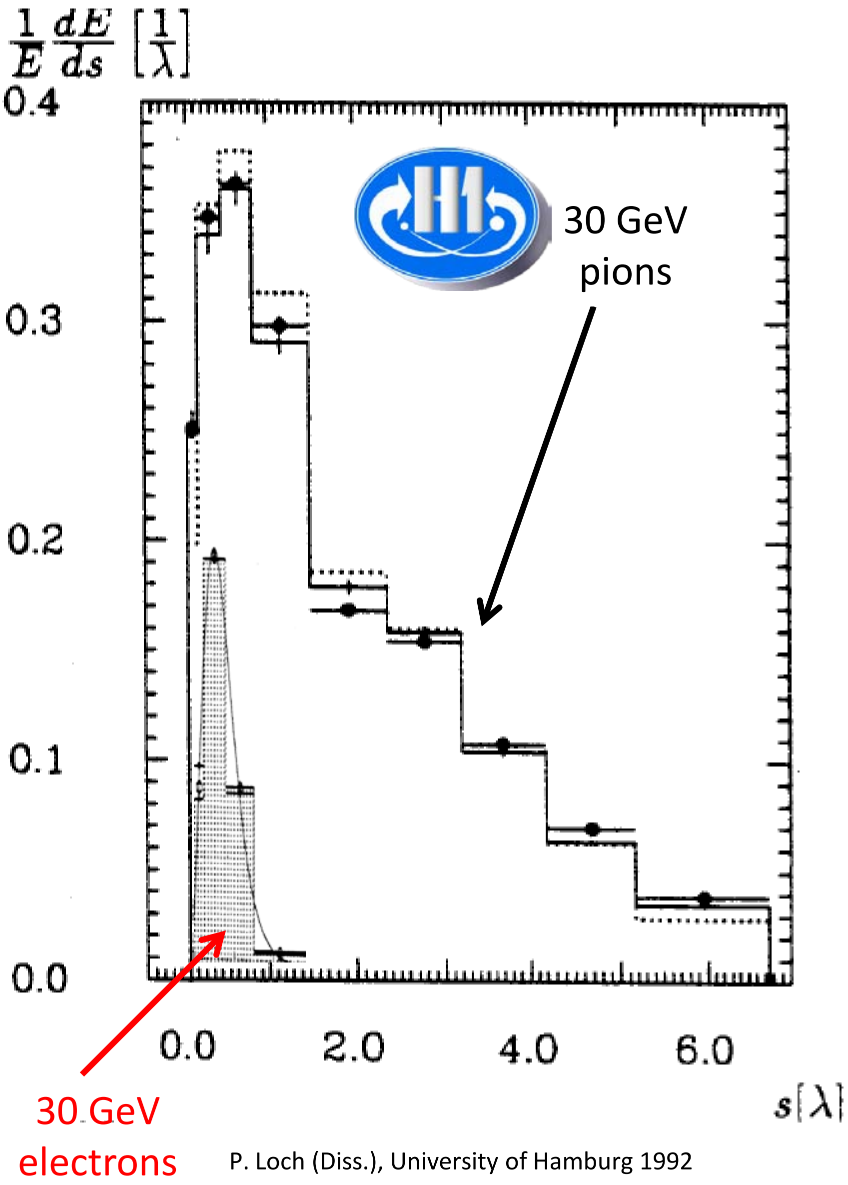
Hadronic Cascades in Calorimeters

Hadronic signals

- Much larger showers
  - Need deeper development
  - Wider shower spread
- Large energy losses without signal generation in hadronic shower component
  - Binding energy losses
  - Escaping energy/slow particles (neutrinos/neutrons)
- Signal depends on size of electromagnetic component
  - Energy invested in neutral pions lost for further hadronic shower development
  - Fluctuating significantly shower-by-shower
  - Weakly depending on incoming hadron energy

Consequence: non-compensation

- Hadrons generate less signal than electrons depositing the same energy



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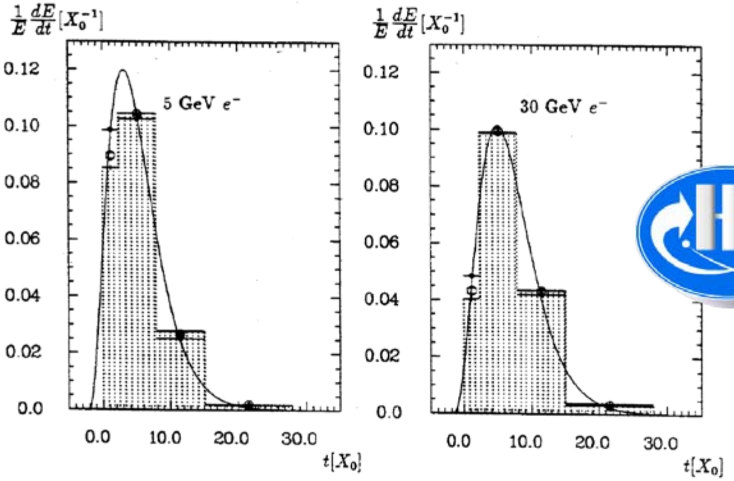
Shower Features Summary

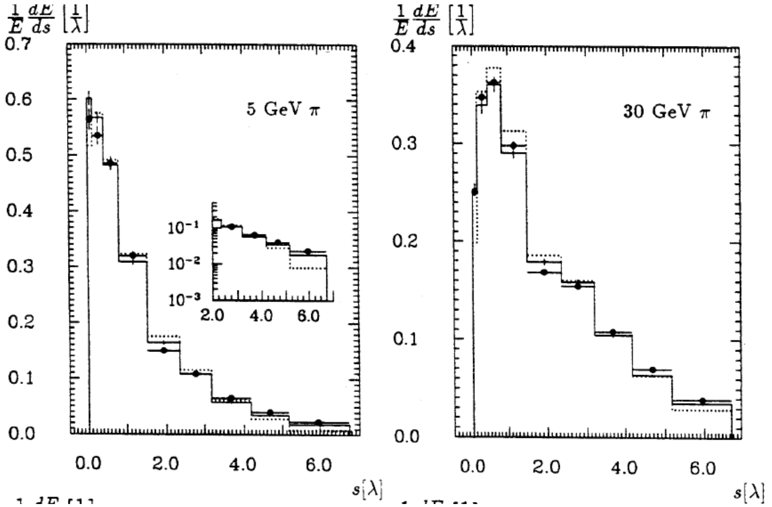
Electromagnetic

- Compact
  - Growths in depth ~log(E)
- Longitudinal extension scale is radiation length X_0
  - Distance in matter in which ~50% of electron energy is radiated off
  - Photons 9/7 X_0
- Strong correlation between lateral and longitudinal shower development
- Small shower-to-shower fluctuations
  - Very regular development
- Can be simulated with high precision
  - 1% or better, depending on features



Hadronic

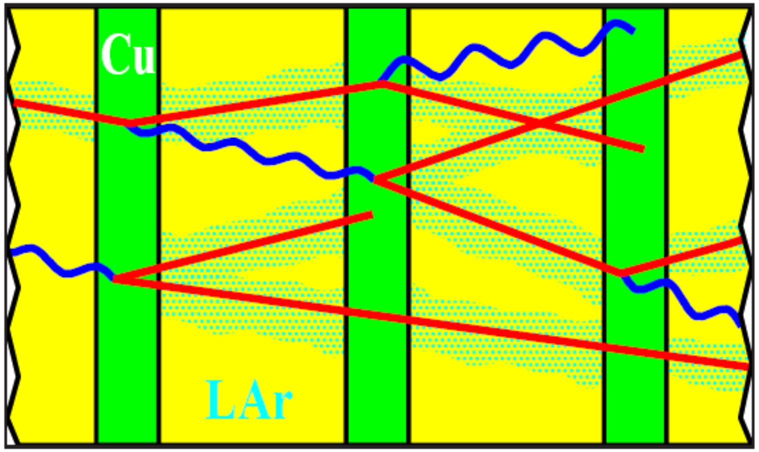
- Scattered, significantly bigger
  - Growths in depth ~log(E)
- Longitudinal extension scale is interaction length λ >> X_0
  - Average distance between two inelastic interactions in matter
  - Varies significantly for pions, protons, neutrons
- Weak correlation between longitudinal and lateral shower development
- Large shower-to-shower fluctuations
  - Very irregular development
- Can be simulated with reasonable precision
  - ~2-5% depending on feature



Electromagnetic Signals

Signal features in sampling calorimeters

- Collected from ionizations in active material
    - Not all energy deposit converted to signal
- Proportional to incoming electron/photon
    - C.f. Rossi's shower model, Approximation B
        - Only charged tracks contribute to signal
        - Only pair-production for photons
        - Energy loss is constant
    - Signal proportional to integrated shower particle path
- Stochastical fluctuations
    - Sampling character
- Sampling fraction
    - Describes average fraction of deposited energy generating the signal



Integrated shower particle track length:

$$T=\int_0^{t_{\max}} N(t)dt \Rightarrow T_c=\frac{2}{3}T=\frac{2}{3\ln 2}\frac{E_0}{E_c}$$

(only charged tracks ionize!)

Number of crossings of active material:

$$N_\times=\frac{T_c}{d_{\text{active}}}\propto E_0$$

Deposited energy contributing to the signal:

$$E_{\text{vis}}=N_\times\int_0^{d_{\text{active}}}\frac{dE}{dx}dx=N_\times\Delta E\propto E_0$$

Stochastic nature of sampling:

$$\sigma(N_\times)=\sqrt{N_\times}\Rightarrow\sigma(E_{\text{vis}})\propto\sqrt{N_\times\Delta E}\propto\sqrt{E_0}$$

Signal Formation: Sampling Fraction

Characterizes sampling calorimeters

- Ratio of energy deposited in active material and total energy deposit
- Assumes constant energy loss per unit depth in material
  - Ionization only
- Can be adjusted when designing the calorimeter
  - Material choices
  - Readout geometry

Multiple scattering

- Changes sampling fraction
  - Effective extension of particle path in matter
  - Different for absorber and active material

Showering

- Cannot be included in sampling fraction analytically
  - Need measurements and/or simulations

$$S = \frac{E_{\text{vis}}}{E_{\text{dep}}} = \frac{dE/dx|_{\text{active}} \cdot d_{\text{active}}}{dE/dx|_{\text{active}} \cdot d_{\text{active}} + dE/dx|_{\text{absorber}} \cdot d_{\text{absorber}}}$$

$$= \frac{dE/dx|_{\text{active}}}{dE/dx|_{\text{active}} + dE/dx|_{\text{absorber}} \cdot d_{\text{absorber}}/d_{\text{active}}}$$

(with Rossi's assumption $dE/dx|_{\text{active}} = const$

and $dE/dx|_{\text{absorber}} = const$)

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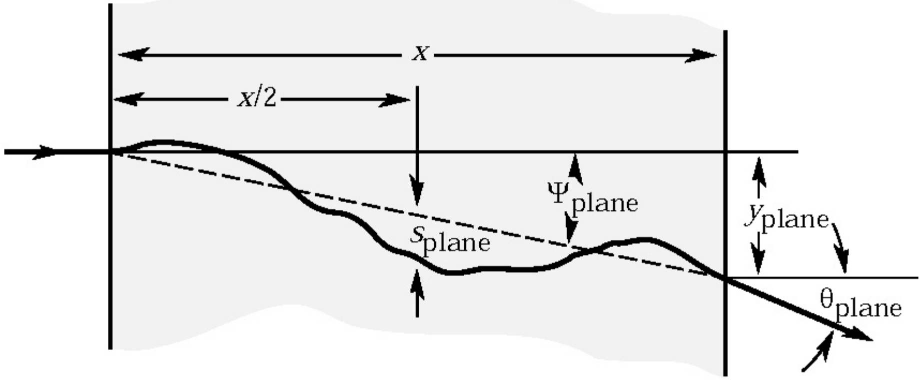

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$$S = \frac{E_{\text{vis}}}{E_{\text{dep}}} = \frac{dE/dx|_{\text{active}}}{dE/dx|_{\text{active}} + dE/dx|_{\text{absorber}} \cdot d_{\text{absorber}}/d_{\text{active}} \cdot \cos\theta_{\text{active}}/\cos\theta_{\text{absorber}}}$$

Approximation:

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

$$\text{with} \begin{cases} \beta c & \text{particle velocity} \\ p & \text{particle momentum} \\ z & \text{particle charge number} \\ x/X_0 & \text{material thickness in radiation length} \end{cases}$$

(good to 11% for singly charged particles with $\beta = 1$ for all matter and within $10^{-1} < x/X_0 < 100$)

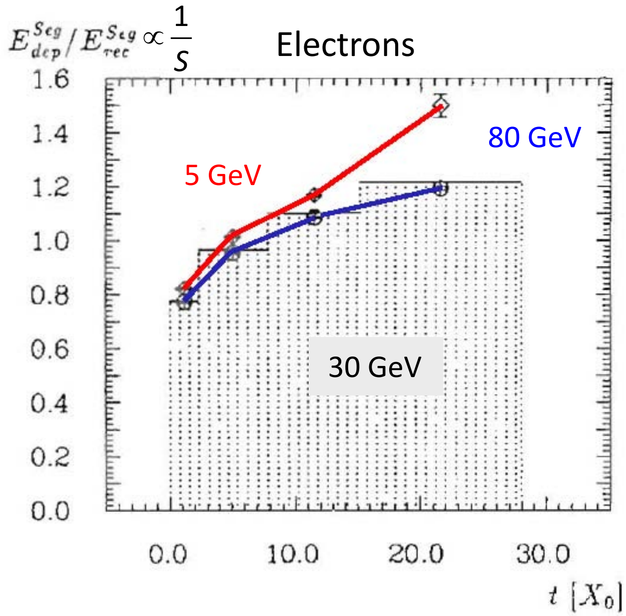
Signal Formation: Sampling Fraction

- **Characterizes sampling calorimeters**
  - Ratio of energy deposited in active material and total energy deposit
  - Assumes constant energy loss per unit depth in material
    - Ionization only
  - Can be adjusted when designing the calorimeter
    - Material choices
    - Readout geometry
- **Multiple scattering**
  - Changes sampling fraction
    - Effective extension of particle path in matter
    - Different for absorber and active material
- **Showering**
  - Cannot be included in sampling fraction analytically
    - Need measurements and/or simulations

$$S = \frac{E_{\text{vis}}}{E_{\text{dep}}} \propto \frac{A(E_0)}{E_0}$$

$A(E_0)$ is the calorimeter signal from test beams or simulation, converted to energy units.

Showering changes the electron sampling fraction mostly due to the strong dependence of photon capture (photo-effect) on the material (cross-section ~Z^5) leading to a non-proportional absorption of energy carried by soft photons deeper in the shower!



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Signal Extraction

Example: charge collection in noble liquids

- Charged particles ionizing active medium when traversing it
  - Fast passage compared to electron drift velocity in medium
- Electrons from these ionizations are collected in external electric field
  - Similar to collection of 1-dim “line of charges” with constant charge density
- Resulting (electron) current is base of signal
  - Positive ions much slower
  - Can collect charges or measure current

Characteristic features

- Collected charge and current are proportional to energy deposited in active medium

$$Q(t=t_{\mathrm{d}})=\frac{N_e e}{2};\ I(t=t_0)=\frac{N_e e}{t_{\mathrm{d}}};\ N_e=\frac{E_{\mathrm{vis}}}{E_{\mathrm{ion}}}$$

- Drift time for electrons in active medium
  - Determines charge collection time
  - Can be adjusted to optimize calorimeter performance