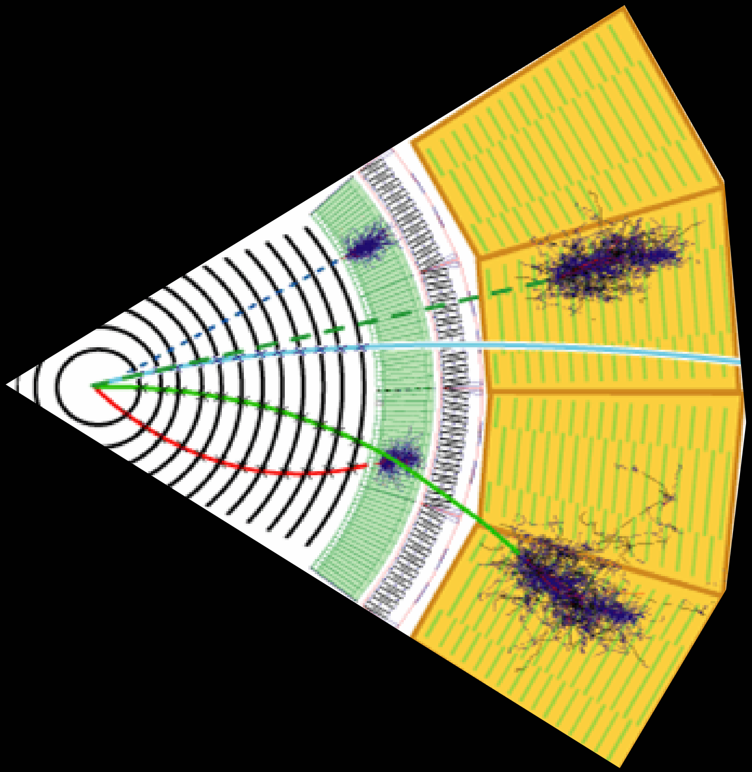
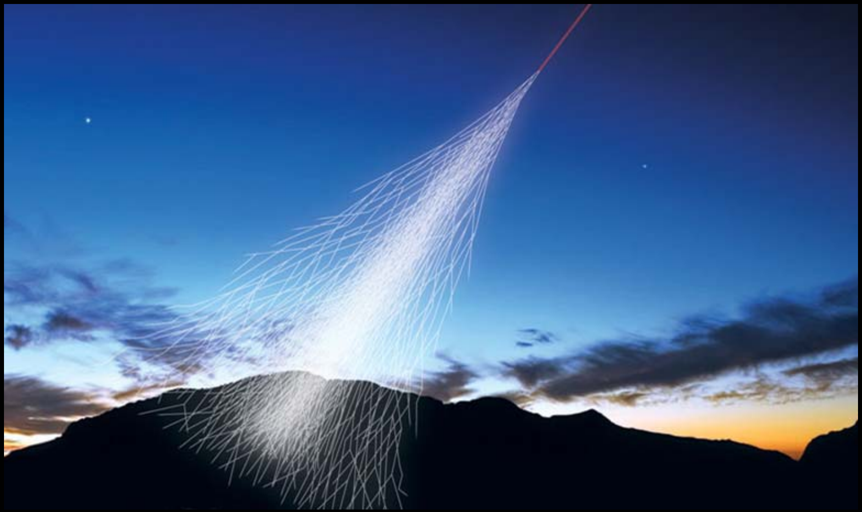
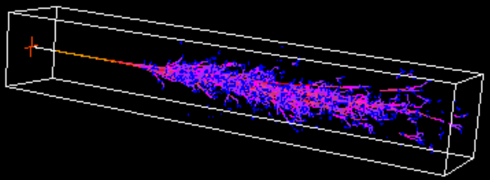
Physics of Particle Showers for High-Energy Calorimetry

Part II: Hadrons

Hermann Kolanoski
Humboldt-Universität zu Berlin and DESY







High-Energy Calorimetry: Physics of Particle Showers

1. Introduction
2. Electromagnetic Showers
3. Construction Criteria for Calorimeters
4. Electromagnetic Calorimeters
5. Hadron Showers
6. Hadron Calorimeters
7. Examples for Calorimeters for Hadrons and Jets

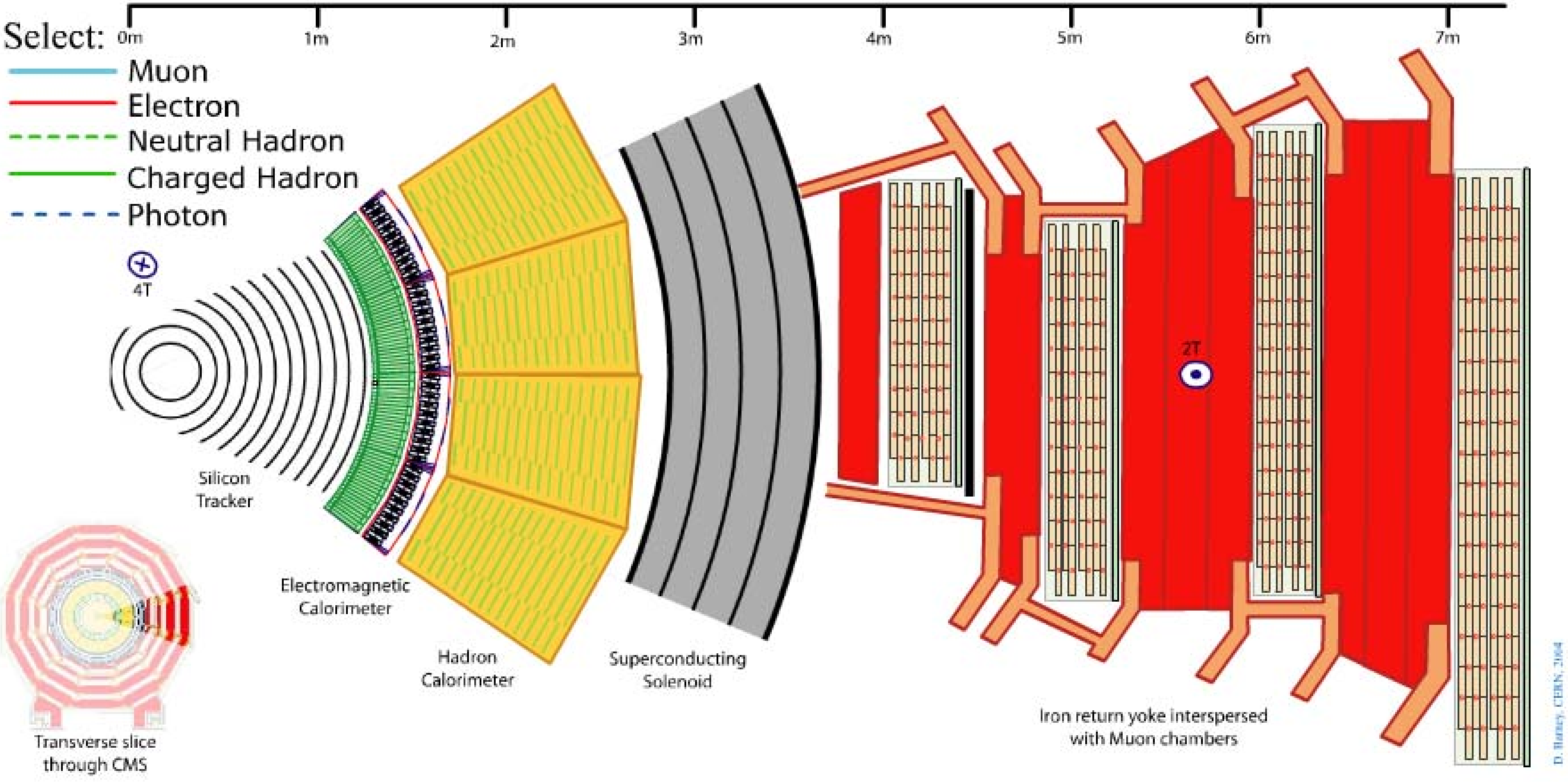
1^{st} lecture (EM): items 1–4

2^{nd} lecture (HAD): items 5–7

1. Introduction

Transverse slice through CMS detector

Click on a particle type to visualise that particle in CMS



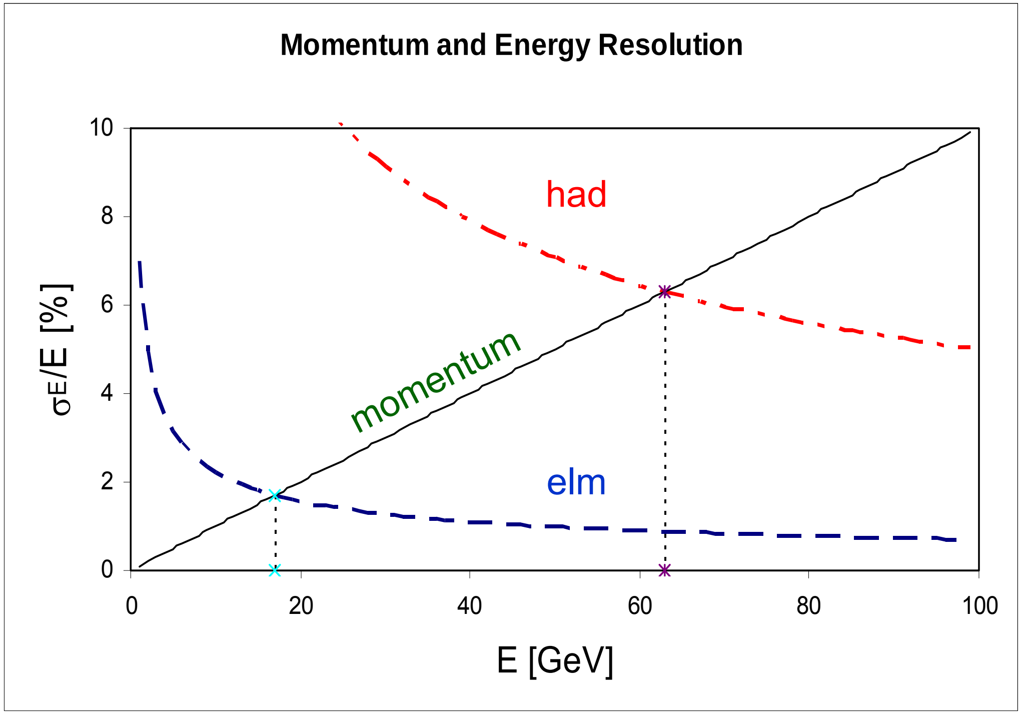
Momentum and Energy Resolutions

Momentum

$$\frac{\sigma_p}{p} \approx 0.1 \ldots 1\,\% \cdot p/\mathrm{GeV}$$

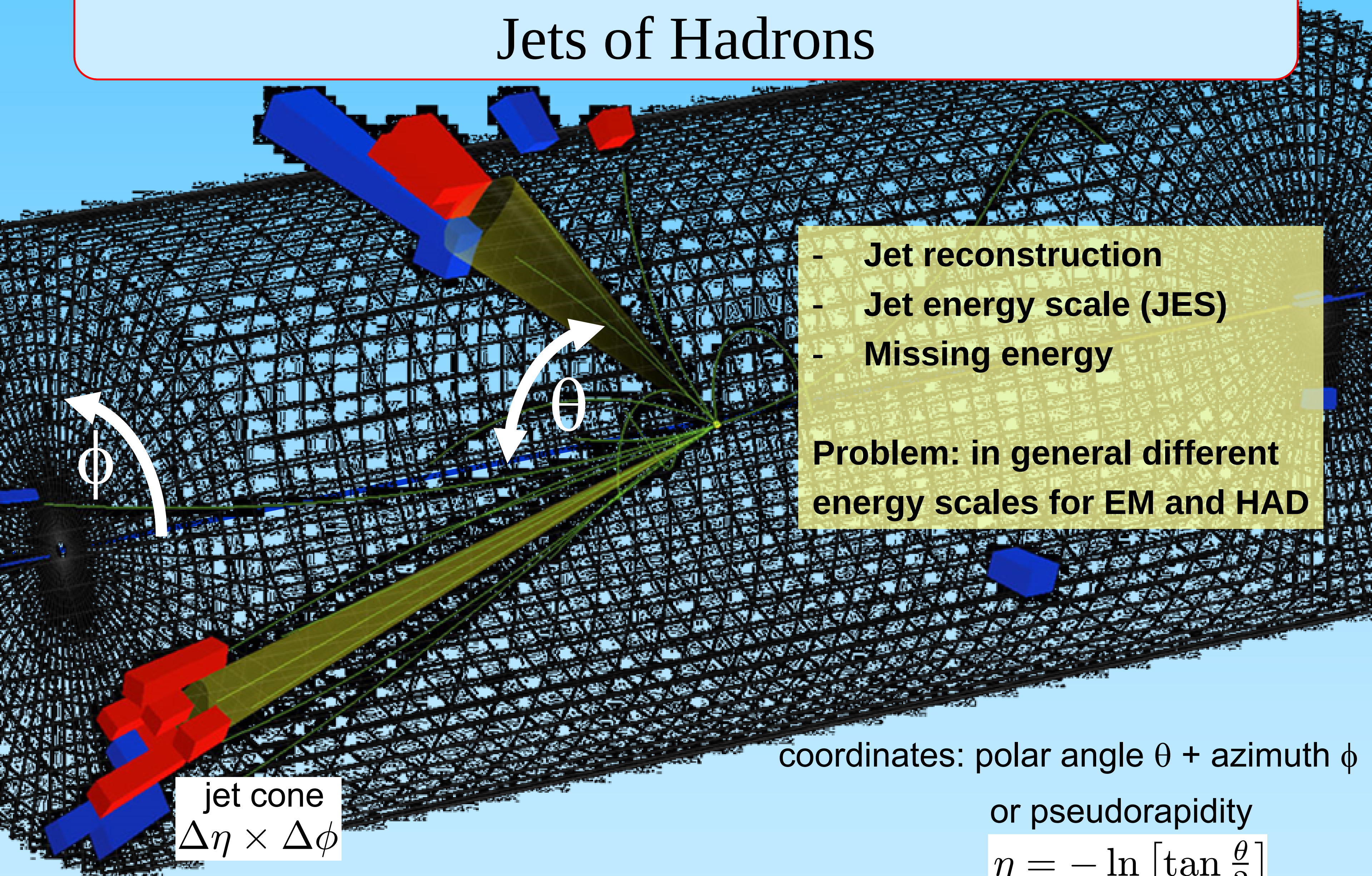
Energy

$$\frac{\sigma_E}{E} \approx \begin{cases} \dfrac{2\text{–}15\,\%}{\sqrt{E/\mathrm{GeV}}} & \text{elm.} \\[2ex] \dfrac{35\text{–}120\,\%}{\sqrt{E/\mathrm{GeV}}} & \text{had..} \end{cases}$$



Important for Calorimetry:

Jets of Hadrons



- **Jet reconstruction**
- **Jet energy scale (JES)**
- **Missing energy**

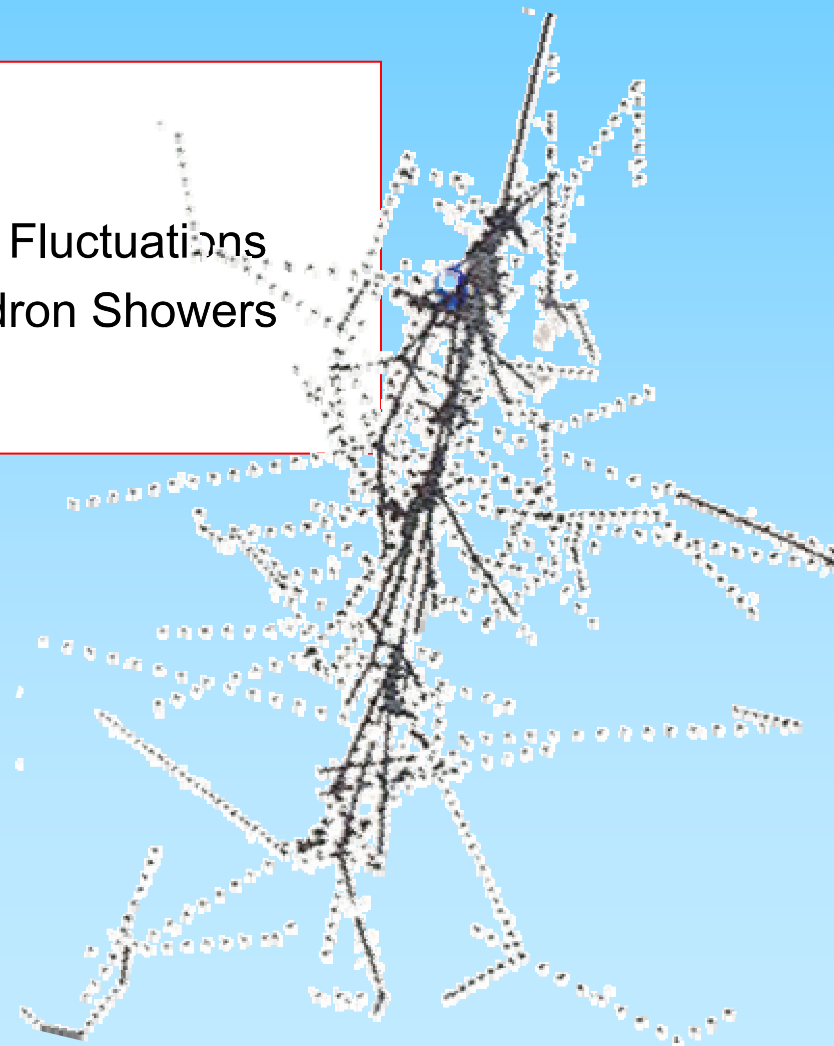
Problem: in general different energy scales for EM and HAD

coordinates: polar angle θ + azimuth ϕ

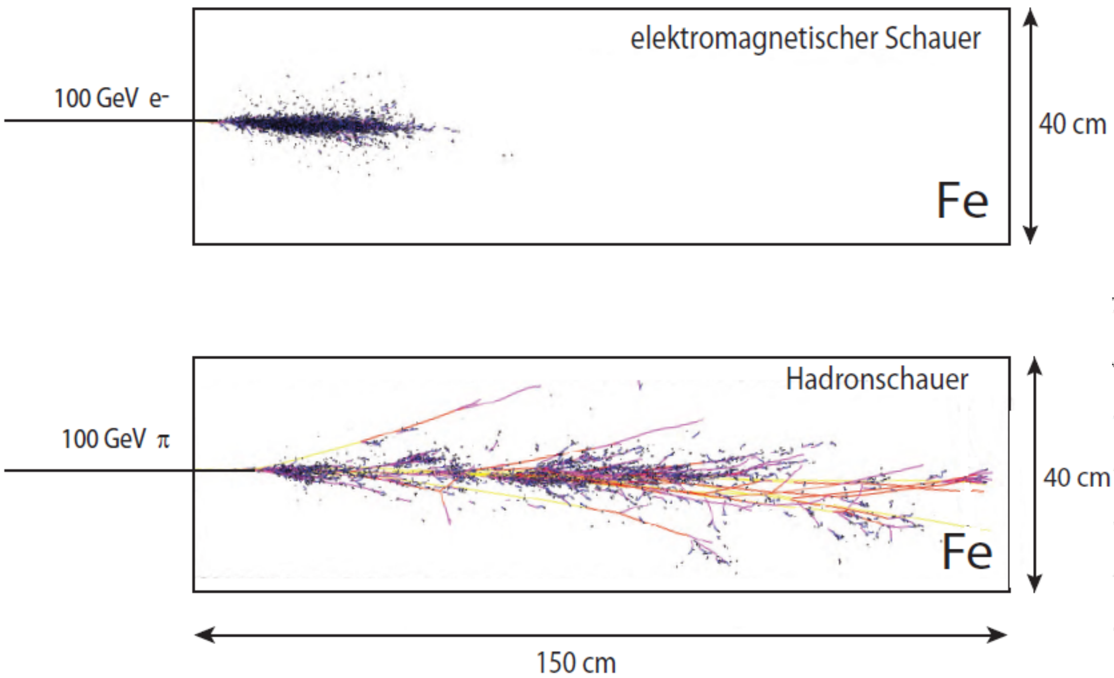
or pseudorapidity

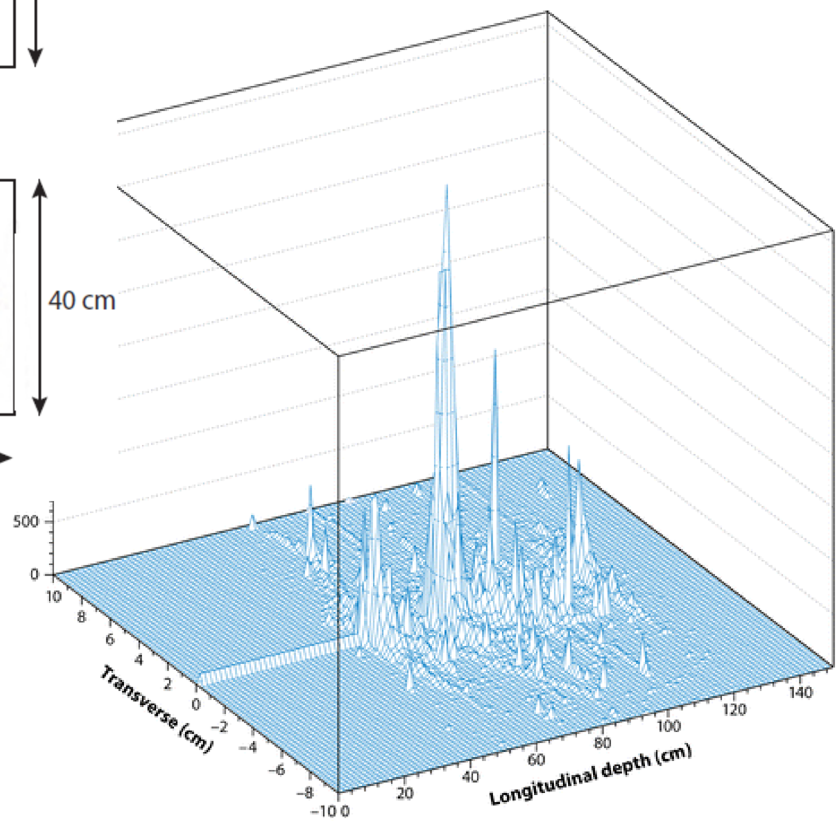
$$\eta = -\ln\left[\tan\frac{\theta}{2}\right]$$

5 Hadron Showers



5.1 Hadronic Showers Development





Brau JE, et al. 2010.
Annu. Rev. Nucl. Part. Sci. 60:615–44

Hadronic Interactions

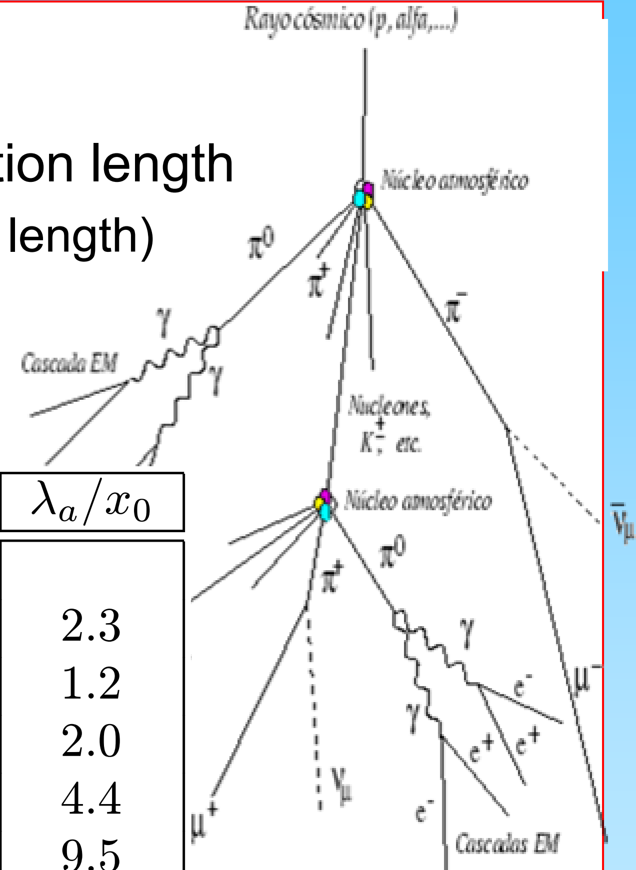
$$N(x) = N_0\, e^{-x/\lambda_a}$$

nuclear absorption length

(≠ interaction length)

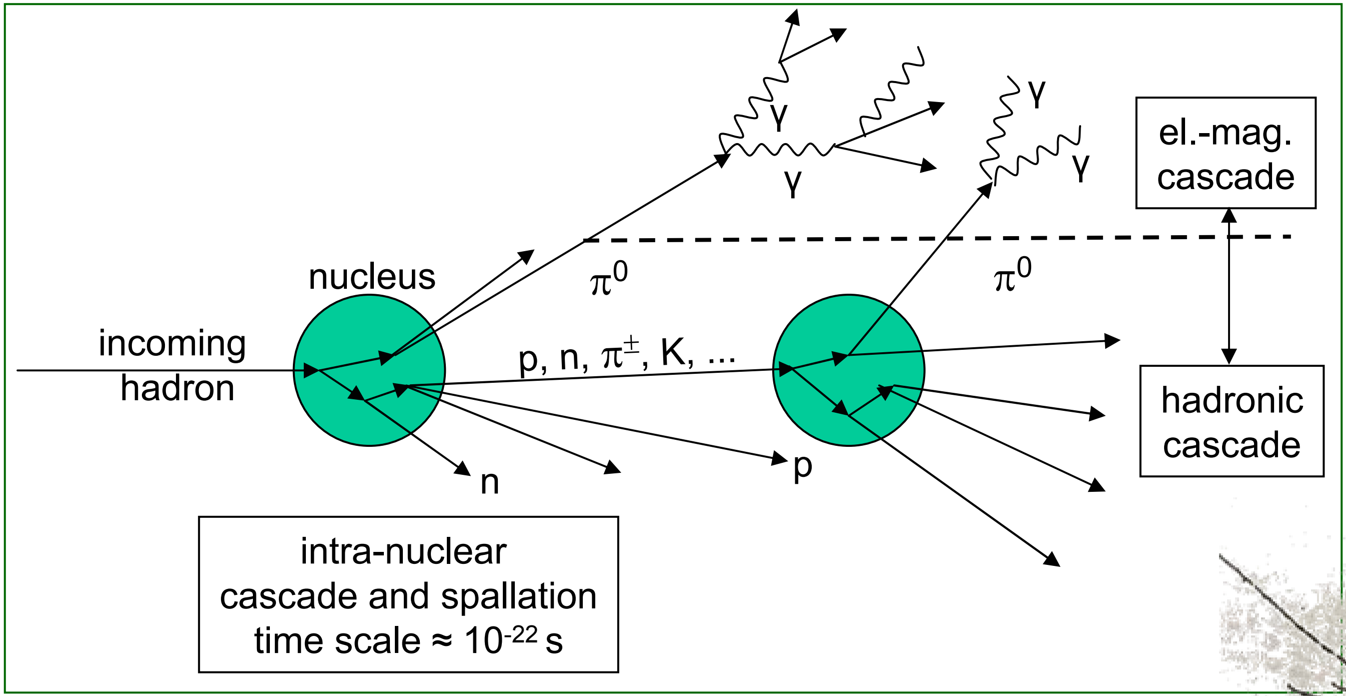
$$\lambda_a = \frac{A}{N_A\, \rho\, \sigma_{inel}} \approx 35\,\mathrm{g\,cm^{-2}}\, A^{\frac{1}{3}}$$

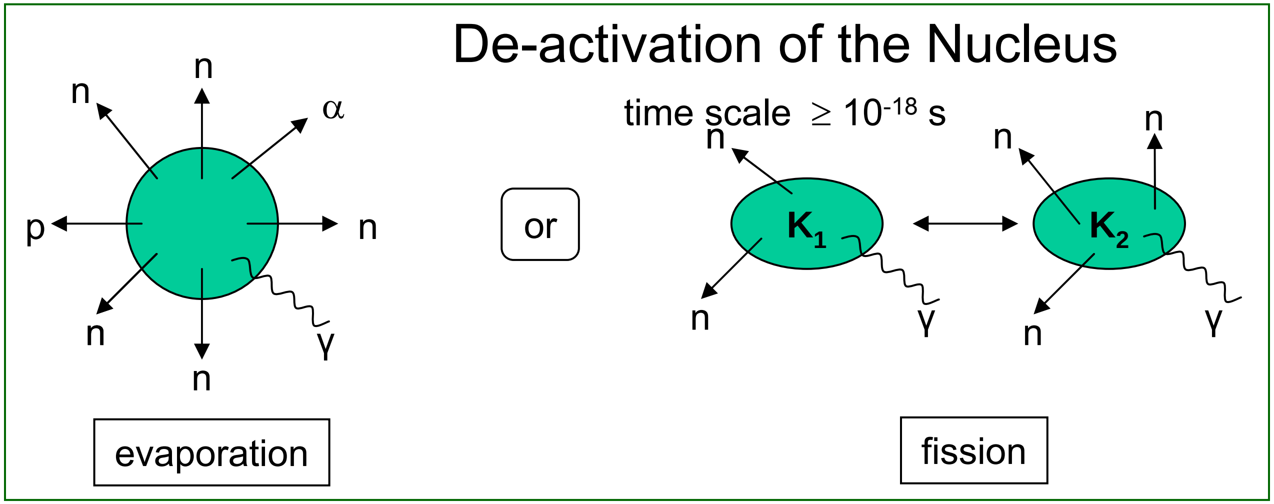
many reactions contribute

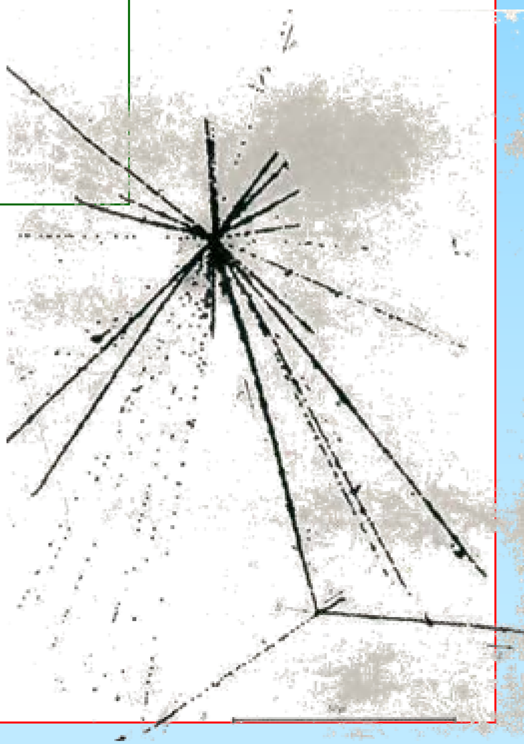


Material	Z	x_0 [mm]	E_k [MeV]	A	λ_a [mm]	λ_a/x_0
H_2O	1, 8	361	92	18	836	2.3
Be	4	353	116	9	407	1.2
C	6	188	84	12	381	2.0
Al	13	89	43	27	394	4.4
Fe	26	17.6	22	56	168	9.5
Cu	29	14.3	20	64	151	10.6
W	74	3.5	8.1	183	96	27.4
Pb	82	5.6	7.3	207	171	30.5
U	92	3.2	6.5	238	105	32.8

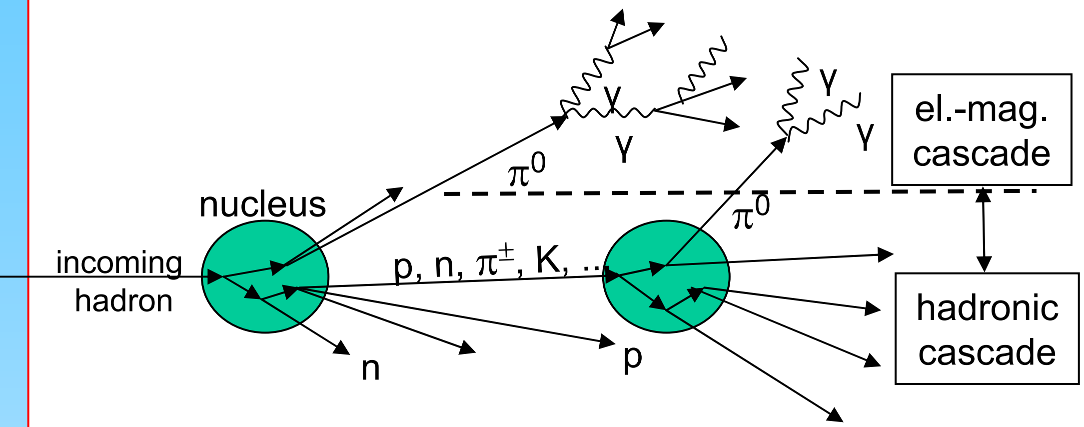
Nuclear and High-Energy Cascades

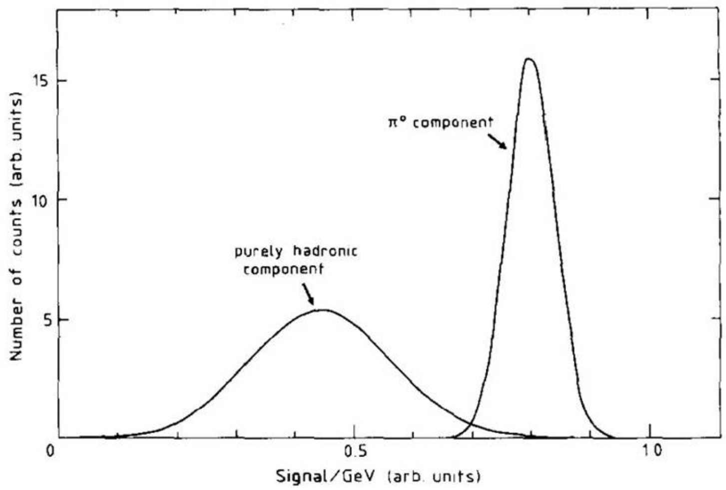






5.2 Shower Components and Fluctuations





$$\pi^0 \to \gamma\gamma : \quad c\tau \approx 25\,\text{nm} \;\Rightarrow\; \text{spontaneous decay}$$

Problem of hadron calorimetry: - many contributions - with different signals + strong fluctuation between

$$E_{dep} = \left(f_{em} + \underbrace{f_{ion} + f_n + f_\gamma + f_B}_{f_h} \right) E$$

EM Contribution to E_{dep}

$$f_{em} \approx 1 - \left(\frac{E}{E_0}\right)^{k-1}$$

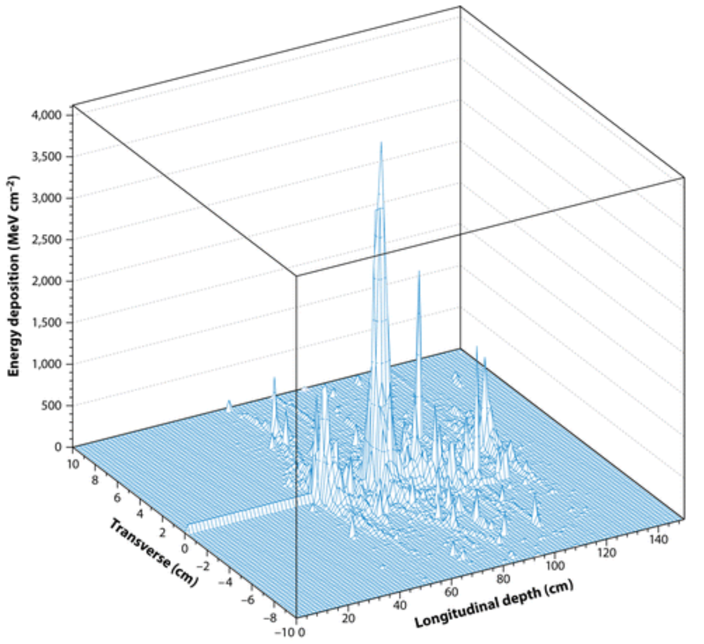
k depends on particle multiplicity in cascade

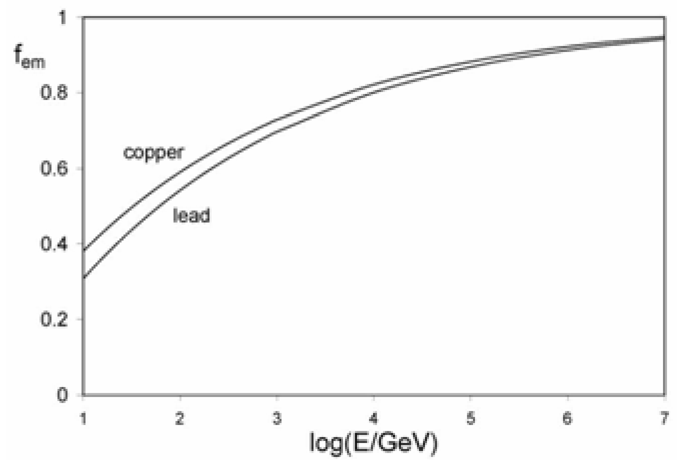
$k \approx 0.82$

E_0 is the mean energy to create a π^0

$$E_0 = \begin{cases} 0.7 \text{ GeV for Cu} \\ 1.3 \text{ GeV for Pb} \end{cases}$$

fluctuations in f_{em}: $$f_{em} \approx 0....1$$





HAD Contribution to E_{dep}

$$f_h = 1 - f_{em} = f_{ion} + f_n + f_\gamma + f_B$$

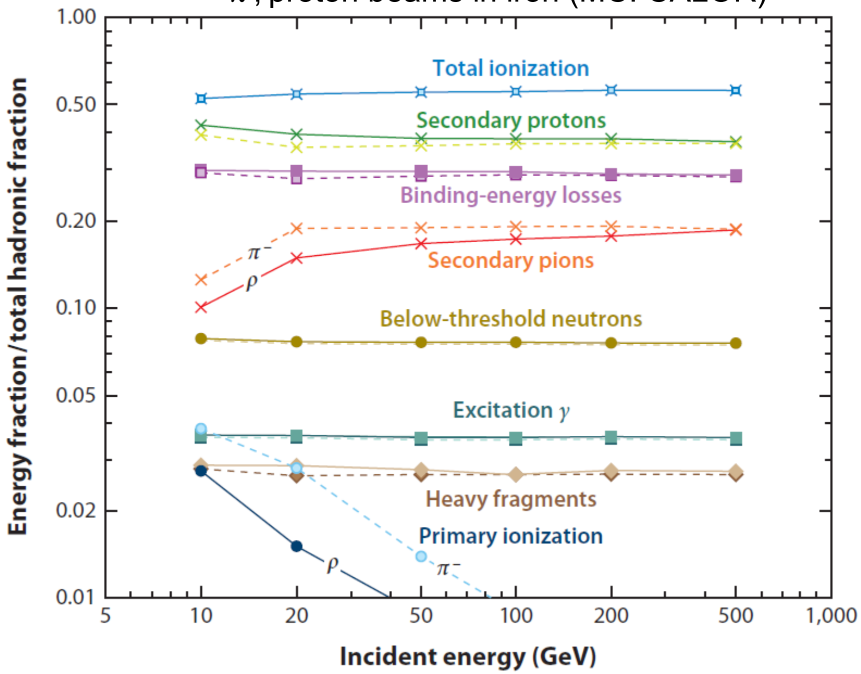
f_{ion} - ionisation of charged particles
- relativistic/non-rel

f_n - high energy: contributes to hadronic cascade
- medium energy: elastic scattering transfers energy to nuclei (most efficient for small A)
- low energy: thermalised n capture $\Rightarrow$ delayed γ's

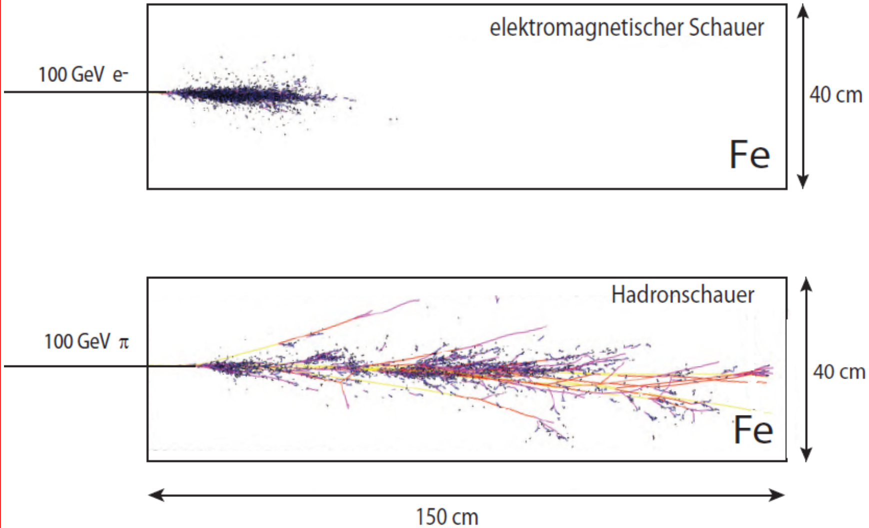
f_γ - photo- and Compton effect

f_B - binding energy lost to break up the nucleus; not detectable/ invisible

π^-, proton beams in iron (MC: CALOR)



3.3 Characteristic Size of Hadron Showers



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t = length in units of λ_a

$$t_{max} \approx 0.2 \ln(E/\mathrm{GeV}) + 0.7$$

$$t_{95\%} \approx t_{max} + 2.5\,\lambda_a \left(\frac{E}{\mathrm{GeV}}\right)^{0.13}$$

$$R_{95\%} \approx \lambda_a$$

much larger than EM showers (and more fluctuations)

Exercise (HAD) I

[Find the exercises here.]

6 Hadron Calorimeters

6.1 Signals of Electrons and Hadrons

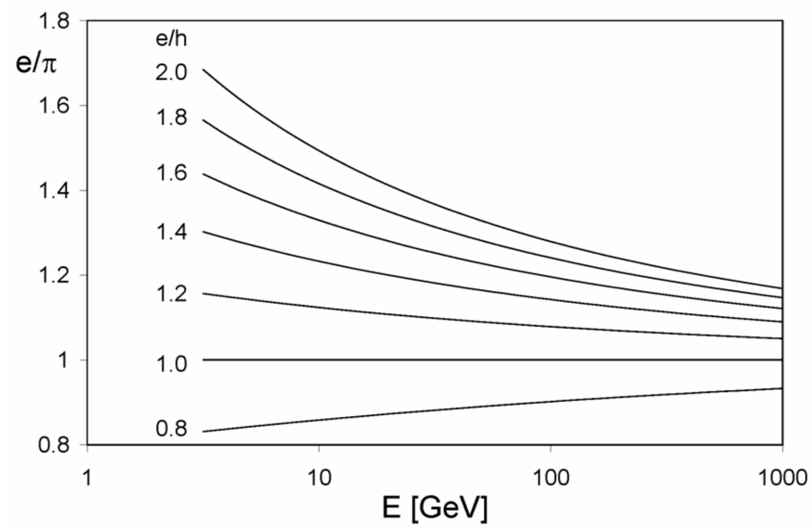
$$S(\pi) = \left(f_{em}\,\epsilon_{em} + \underbrace{f_{ion,r}\,\epsilon_{ion,r} + f_{ion,nr}\,\epsilon_{ion,nr} + f_n\,\epsilon_n + f_\gamma\,\epsilon_\gamma + f_B\,\epsilon_B}_{f_h\,\epsilon_h} \right) E$$

$$\frac{S(e)}{S(\pi)} = \frac{\epsilon_{em}\,E}{(f_{em}\epsilon_{em}+f_h\epsilon_h)\,E} = \frac{\epsilon_{em}/\epsilon_h}{1-f_{em}\left(1-\frac{\epsilon_{em}}{\epsilon_h}\right)}$$

$$\frac{S(e)}{S(\pi)} \stackrel{def}{=} \frac{e}{\pi} \quad \text{from } e^\pm \text{ and } \pi^\pm \text{ beams}$$

$$\frac{\epsilon_{em}}{\epsilon_h} \stackrel{def}{=} \frac{e}{h} \quad \text{intrinsic cal. property.}$$

$$\frac{e}{h} = 1 \implies \frac{e}{\pi} = 1$$



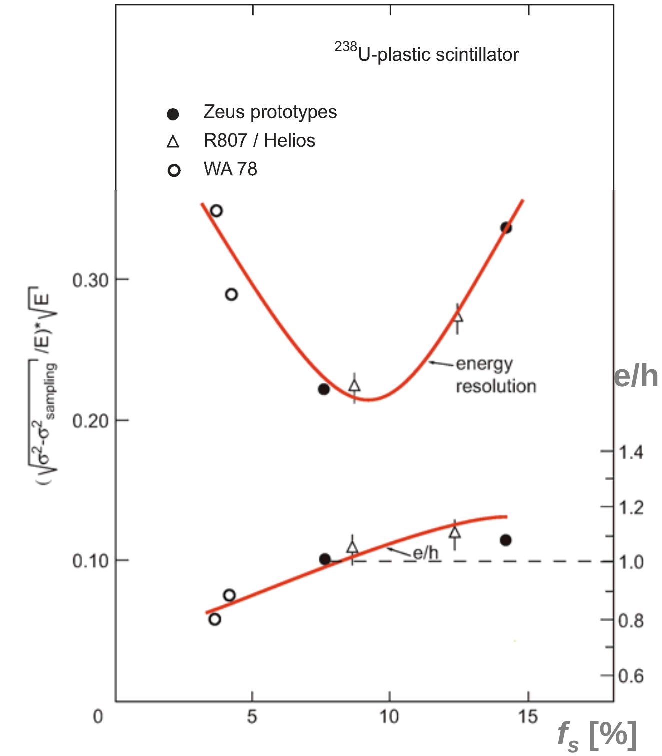
e/h Dependence of Resolution and Linearity

resolution:

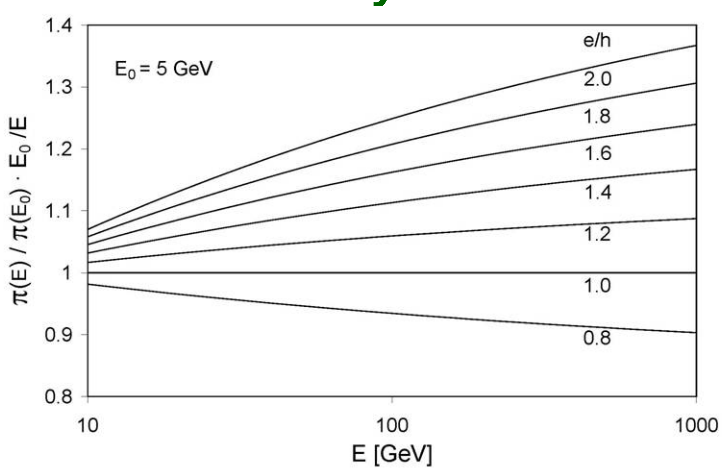
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E/\mathrm{GeV}}} \oplus b\left(\frac{e}{h} - 1\right)$$

sampling: $a \approx 0.35$ for U
e/h dep.: $b \approx 1$

e/h = 1⇒ 'fully compensated'



non-linearity:



$$\frac{S(\pi(E))/E}{S(\pi(E_0)/E_0} = \frac{f_{em}(E)+(1-f_{em}(E))\,(e/h)^{-1}}{f_{em}(E_0)+(1-f_{em}(E_0))\,(e/h)^{-1}}$$

mip Signal as Reference

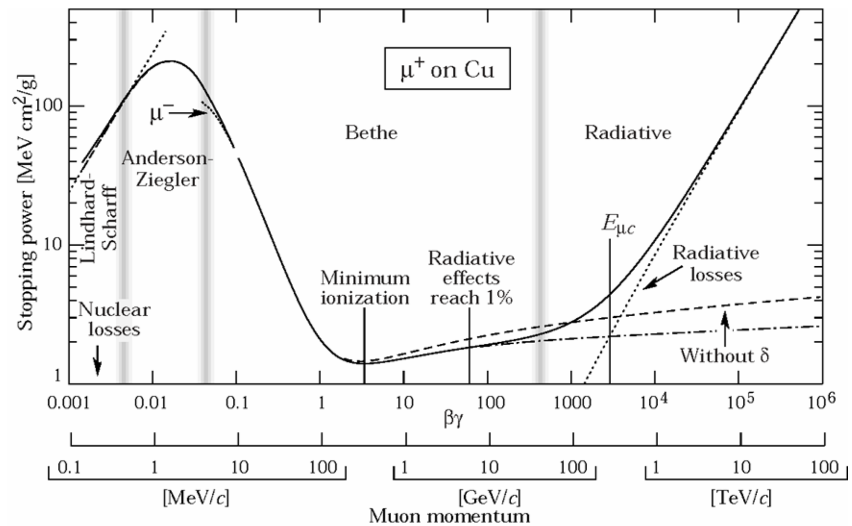
$$\frac{S(\pi)}{S(mip)} = \frac{\pi}{mip} = f_{em}\frac{e}{mip} + f_{ion,r}\frac{r}{mip} + f_{ion,nr}\frac{nr}{mip} + f_n\frac{n}{mip} + f_\gamma\frac{\gamma}{mip}$$

fractions

efficiencies

mip = minimum ionizing particle as reference.

A *mip* is artificial, not directly measurable, usually inferred from muon beams + MC



Signal Contributions (1)

e/mip: < 1 about 0.5 to 0.7 for reasons discussed in EM part;
becomes larger for lower Z absorber (e.g. Fe, Cu vs. Pb, U)

r/mip: ≈ 1 the relativistic particles behave like *mips*

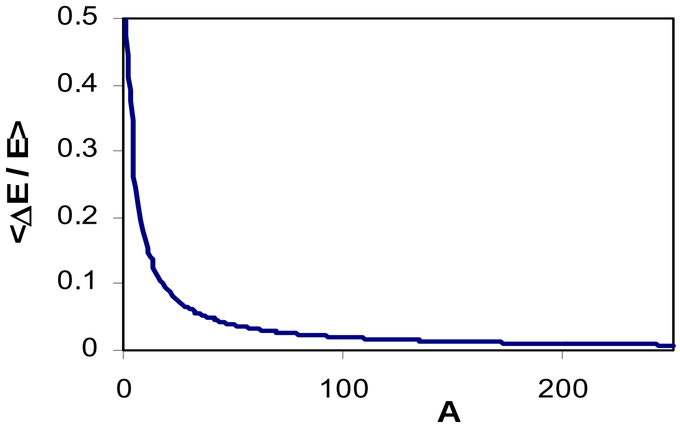
nr/mip: < 1 the non-relativistic particles are preferentially stopped in the absorber

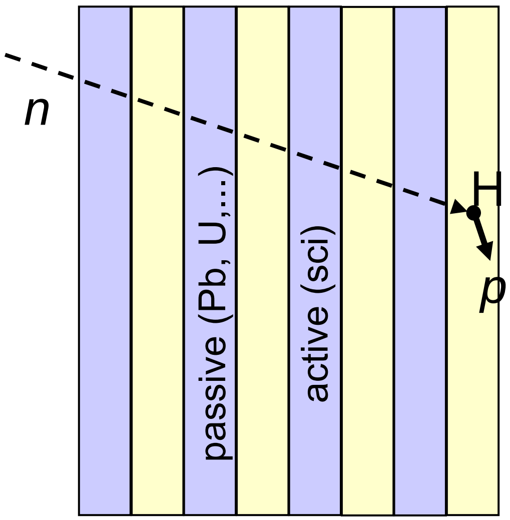
γ/mip: < 1 the nuclear gammas are mostly generated in the absorber
and transfer energy to non-relativistic particles

Signal Contributions (2)

n/mip: >> 1 possible with light active media (H, ..)

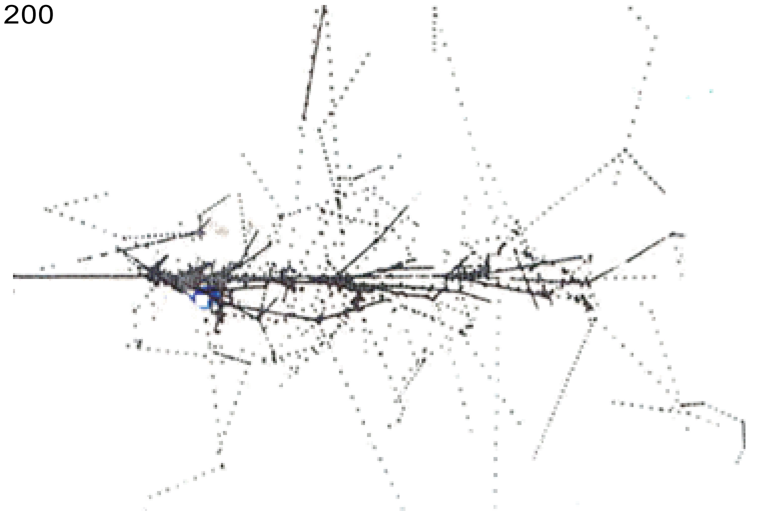
$$\left\langle \frac{\Delta E}{E_n} \right\rangle = \frac{2\,A}{(A+1)^2}$$





mean free path: *n* some cm

p some 10 μm

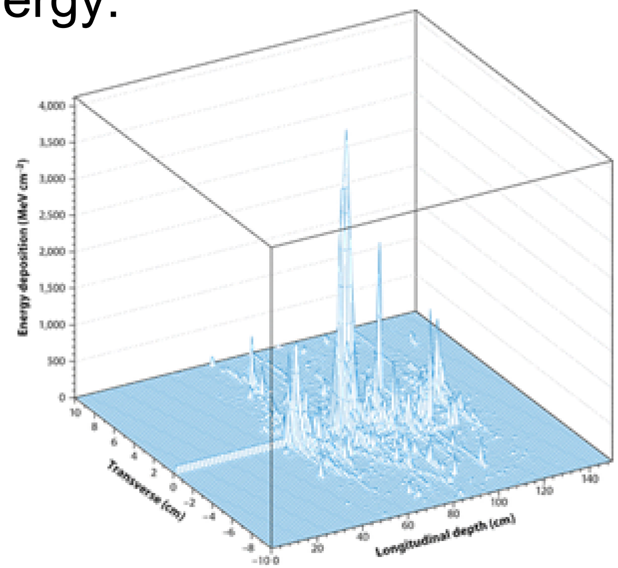


⇒ n/mip tunable between 0 and O(1000)

6.2 ‚Compensation'

Matching of signals from EM and HAD deposited energy:

- 'measure' EM energy separately
- make signals for EM and HAD equal: ***e/h*** $\rightarrow$ ***1***



1. Software correction: weighting of EM clusters
2. Hardware compensation: make *e/h* $\approx$ 1 by design
3. Dual Readout (DR): measure signal with 2 readouts with different sensitivity to EM and HAD (e.g. Cerenkov + Scintillator)
4. Particle Flow Analysis (PFA): distinguish single particles

will concentrate in this lecture on 1 and 2

Exercise (HAD) II

Find the exercises here.

6.2.1 Hardware Compensation

Idea: f_n, f_γ **and** f_B are positively correlated via spallation processes
compensate with high ε_n, ε_γ, and low ε_e

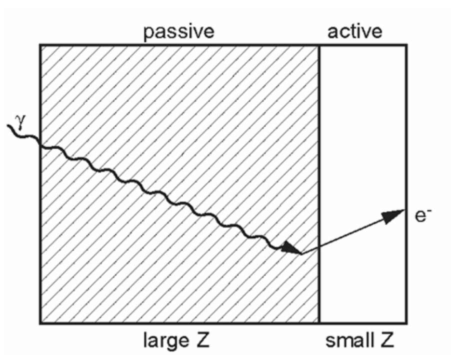
$$\Rightarrow e/h \approx 1$$

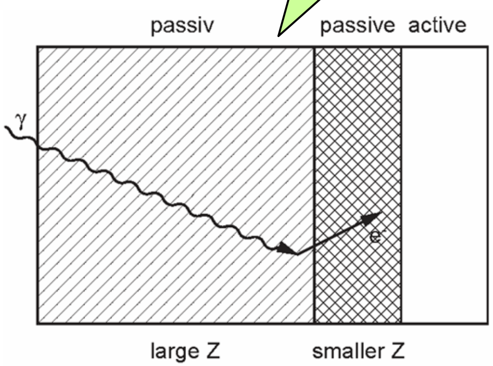
increase ε_h : compensate E_B losses with high ε_n and/or ε_γ

decrease ε_e : high Z of passive medium,
low Z of active medium

ZEUS: ^{238}U with Fe cladding

Example:

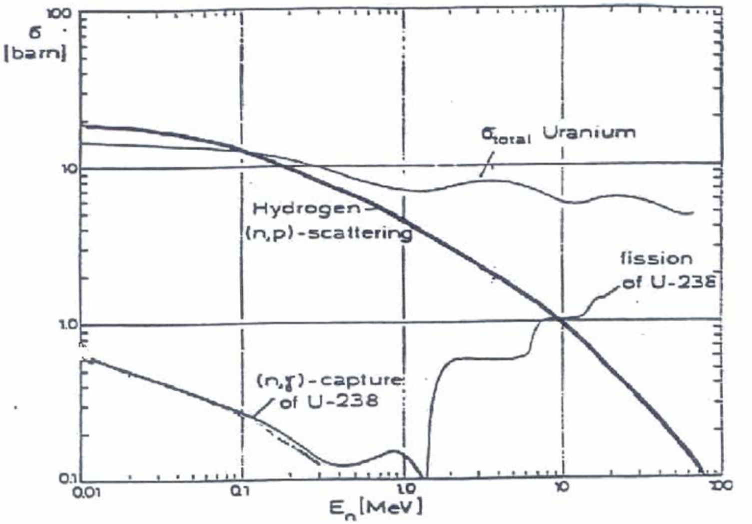


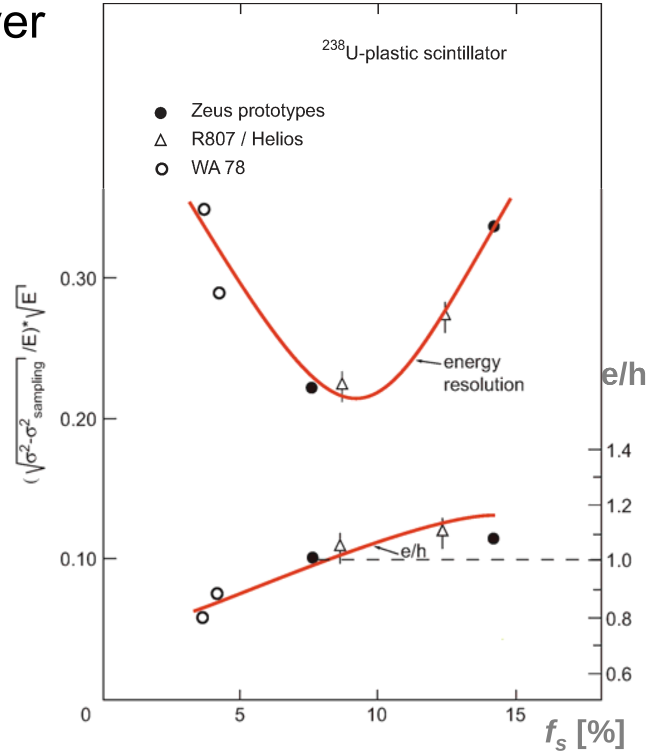


Elastic n-H Scattering in Active Layer

increase ε_n to compensate for invisible E_B

Conditions: - large n-production rate in passive layer (U, Pb, ...)
- small n-absorption cross section in passive layer
- sufficient light elements (H) in active layer





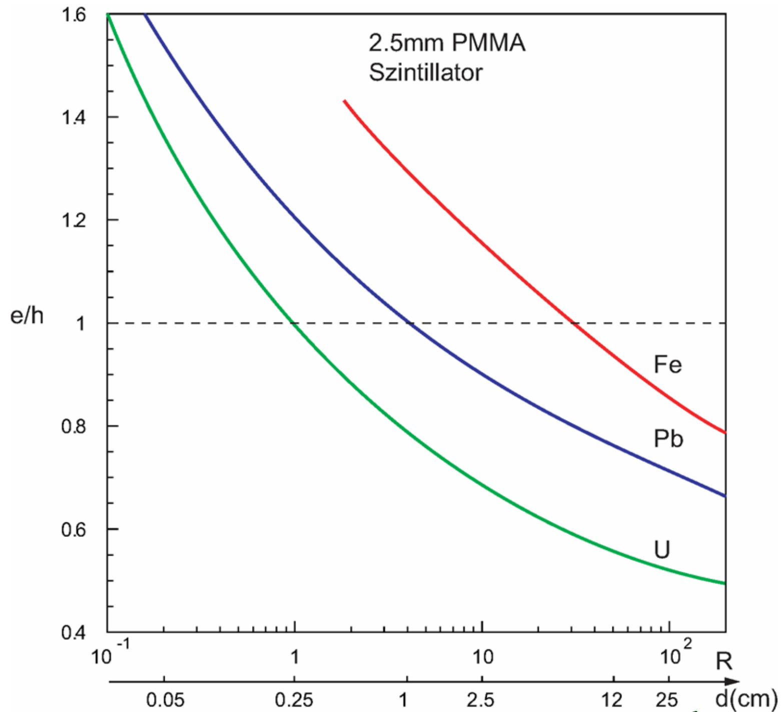
Does Compensation Work for non-Uranium?

$$R = \frac{\text{passive layer thickness}}{\text{active layer thickness}} \sim \frac{1}{f_S}$$

$R \uparrow \;\Rightarrow\; \varepsilon_{em} / \varepsilon_n \downarrow$

	^{238}U	Pb	Fe
R	1:1	4:1	40:1
d_a [cm]	0.25	1.0	10.0
a_{samp} [%]	27	43	125
a_{intr} [%]	22	13	?

even better for Pb than U!



d_p for 2.5 mm scint.

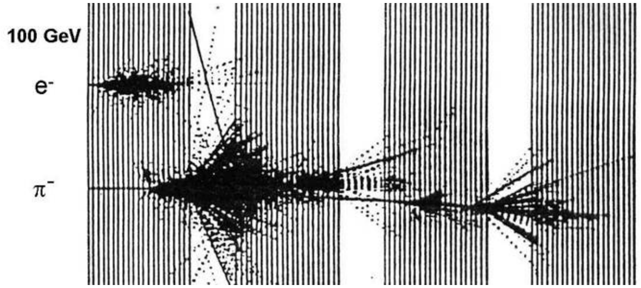
But: large R destroys resolution:

$$\frac{\sigma_{sampling}}{E} \sim \frac{1}{\sqrt{f_s\, E}} \sim \sqrt{\frac{R}{E}}$$

scintillator thickness technically limited to ~ 2 mm (possible with SPACAL Pb-Sci)

6.2.2 Software Compensation

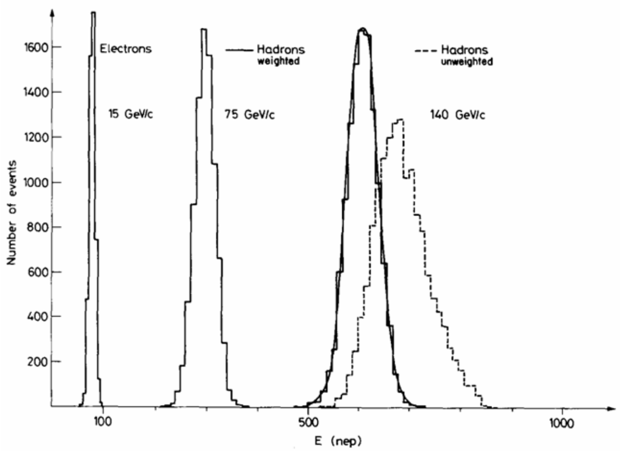
EM part develops ‘subshowers’ with higher density
⇒ suppress relatively high energy per cell volume

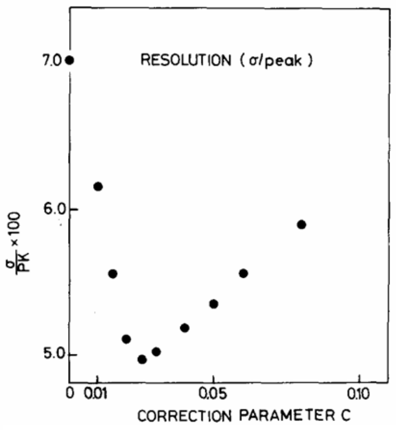


Method pioneered by CDHS:

$$E_i' = E_i(1 - C\,\frac{E_i}{\sqrt{E_{tot}}})$$

$$\frac{\sigma_E}{E} \approx \frac{85\%}{\sqrt{E}} \rightarrow \approx \frac{60\%}{\sqrt{E}}$$





(CDHS, H1, ATLAS, CMS, ...)

Lar Calorimeter of H1:

$$E^i_{rec} = \left\{a_0 + a_1 \exp(-\alpha E^i_0/V^i)\right\} E^i_0$$

$$\Rightarrow \quad \frac{\sigma_E}{E} = \frac{50.7\%}{\sqrt{E/\mathrm{GeV}}} \oplus \frac{90\%}{E/\mathrm{GeV}} \oplus 1.6\%.$$

6.3 Energy Resolution of Hadron Calorimeters

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

samp — noise — const

$$\left(\frac{\sigma_{stoch}}{E}\right)^2 = \left(\frac{a}{\sqrt{E}}\right)^2 = \left(\frac{a_{intr}}{\sqrt{E}}\right)^2 + \left(\frac{a_{sampl}}{\sqrt{E}}\right)^2$$

$$\frac{a_{sampl}}{\sqrt{E}} = 11.5\% \frac{\sqrt{\Delta\epsilon_{mip}/\mathrm{MeV}}}{\sqrt{E/\mathrm{GeV}}}$$

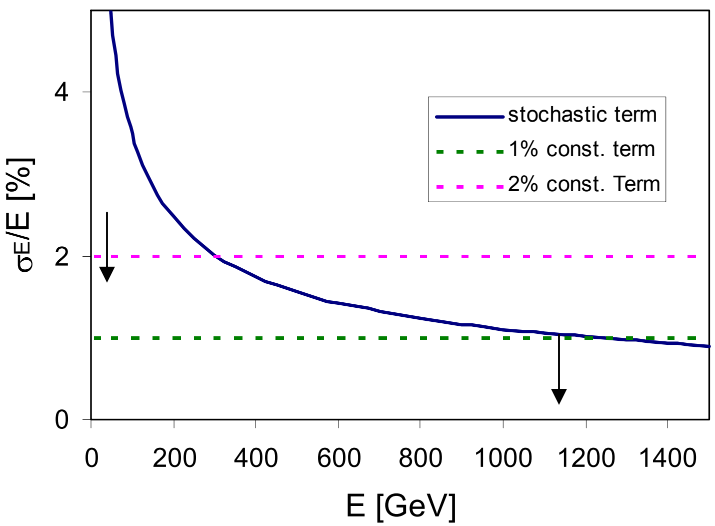
Constant Term and Leakage

constant term:

leakage,

mechanical and electronic tolerances,

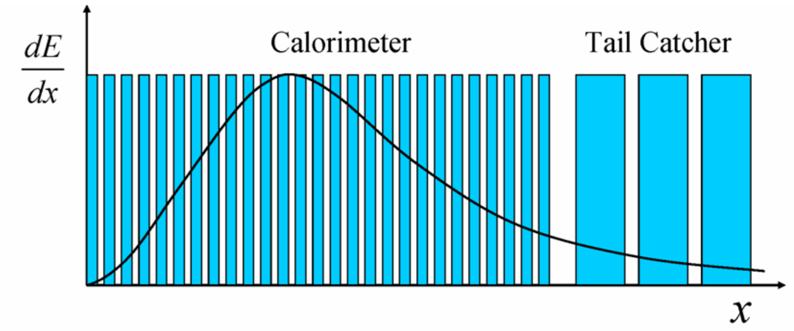
intercalibration errors, ...

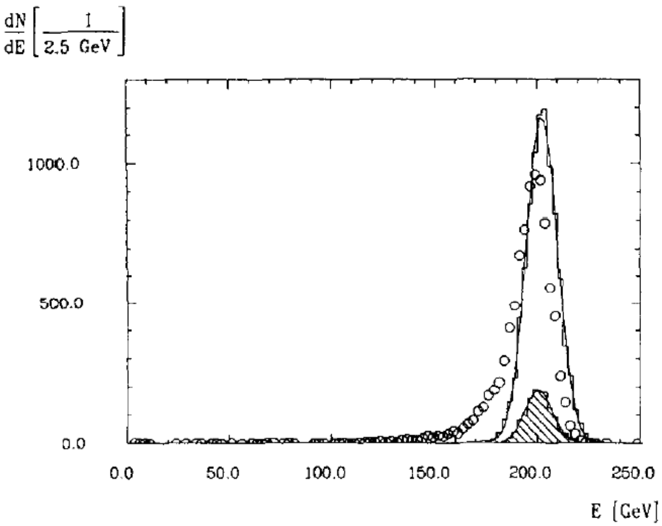


leakage is major problem because of size of calorimeters and fluctuations

cures: - tail catcher

- remove late first interactions





7 Examples for Calorimeters for Hadrons and Jets

7.1 Hadron Calorimetry in Neutrino Experiments

7.2 Calorimetry in LEP Experiments

7.3 HERA: Calorimetry in H1 und ZEUS

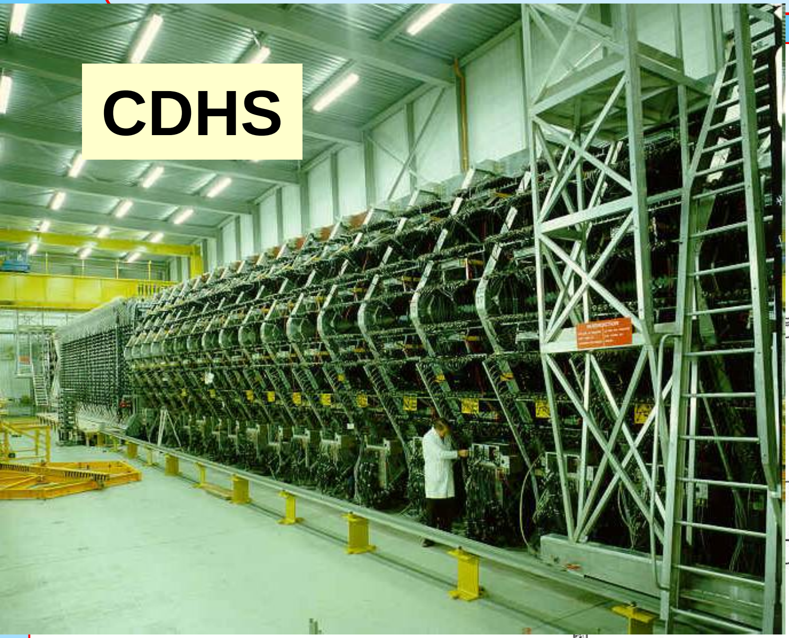
7.4 Tevatron

7.5 LHC

Calorimeter Systems

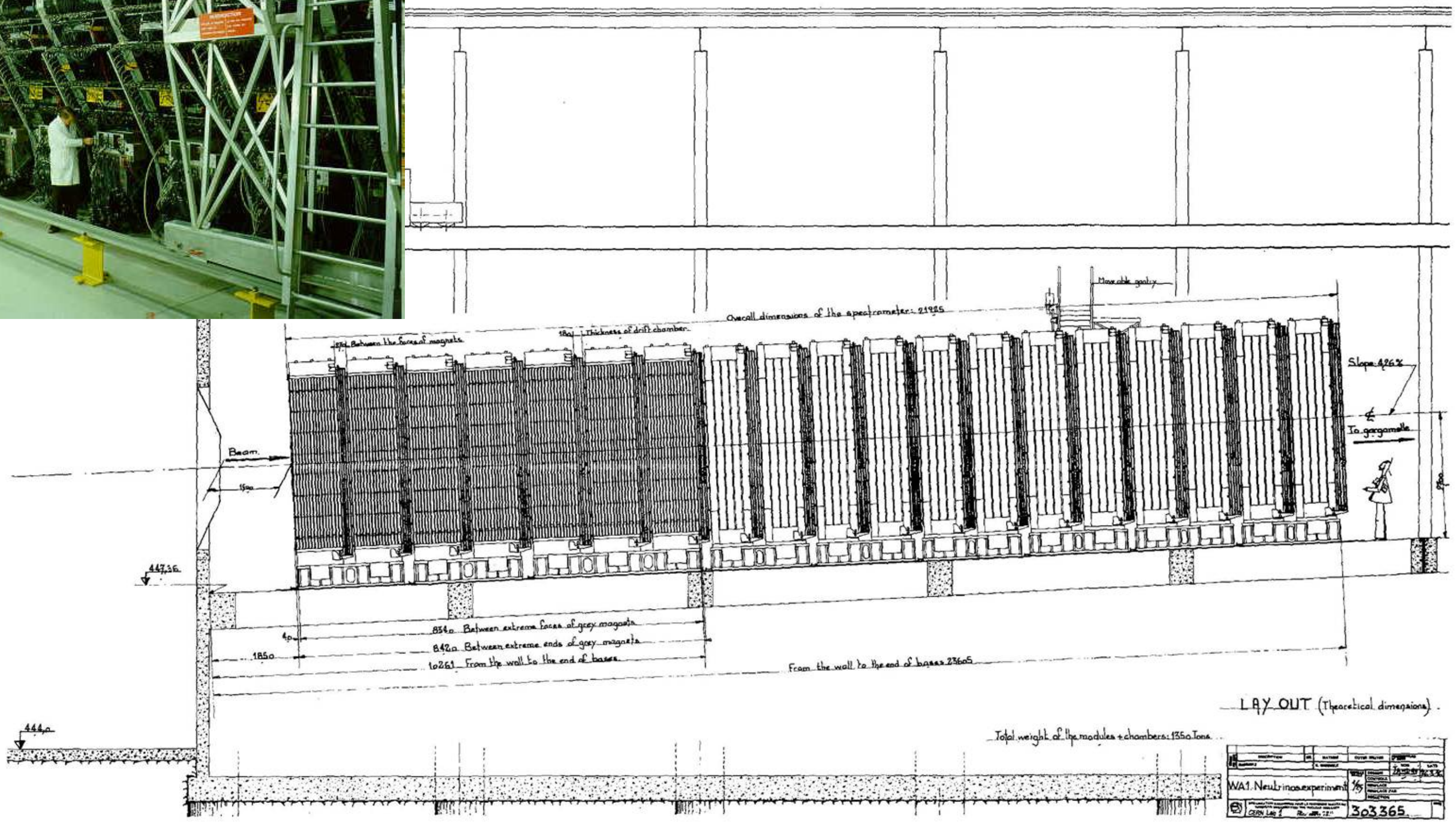
exp.	cal.	structure	e/h	resolution $\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$		
				a [$\sqrt{\mathrm{GeV}}$]	b [MeV]	c
ZEUS	EM	U/scin.	-	0.18	$<$?	0.?
	HAD	U/scin.	1.00	0.35	< 500	0.02
H1	EM	Pb/LAr	-	0.11	250	0.01
	HAD	Fe/LAr	1.4?	0.507	900	0.016
CDF	EM	Pb/scin.		0.135	?	?
(Run I)	HAD	Fe/scin.	?	0.80	?	?
D0	EM?	U/LAr	1.08?	0.157	1.30	0.003
(Run I)	HAD	U/LAr	1.08	0.45	1.30	0.04
CMS	EM	$PbOW_2$	-	0.028	120	0.003
	HAD	brass/scin.	1.40	1.25	0.56	0.03
ATLAS	EM	Pb/LAr	-	0.10	245	0.007
	HAD	Fe/scin.	1.30	0.56	1.80	0.03

7.1 Calorimetry in Neutrino Experiments



driven by the need to kinematically reconstruct invisible energy, e.g. in NC events:

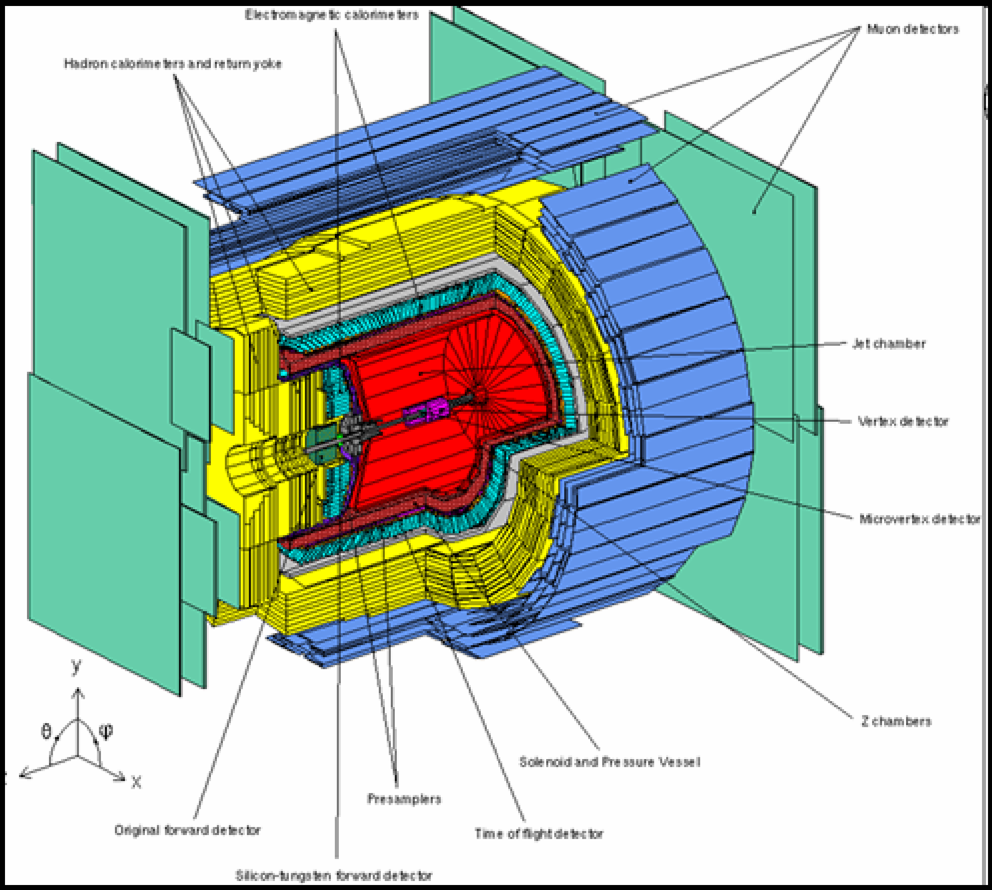
$$\nu + nucleus \rightarrow \nu + X$$

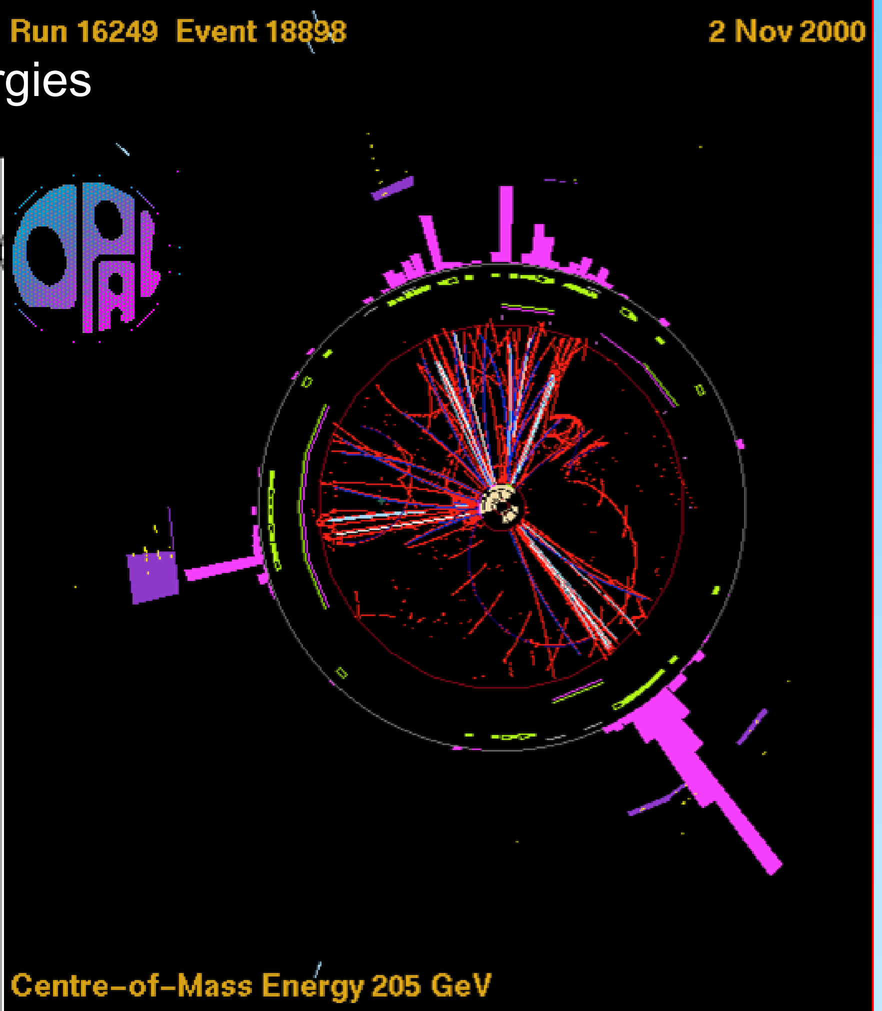


7.2 Calorimetry in LEP Experiments

requirement on hadron cal. modest

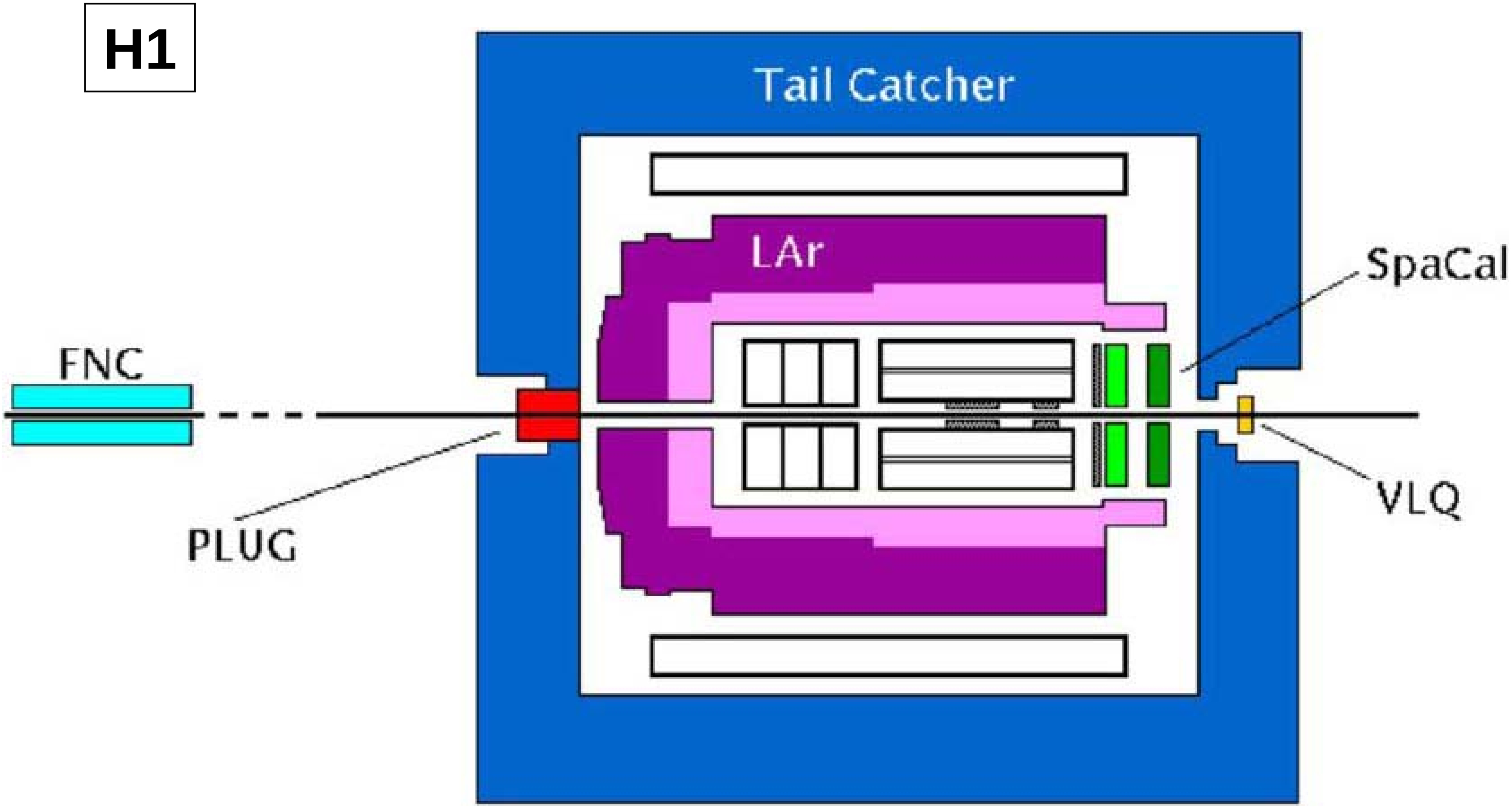
'particle flow' concept still works at these energies



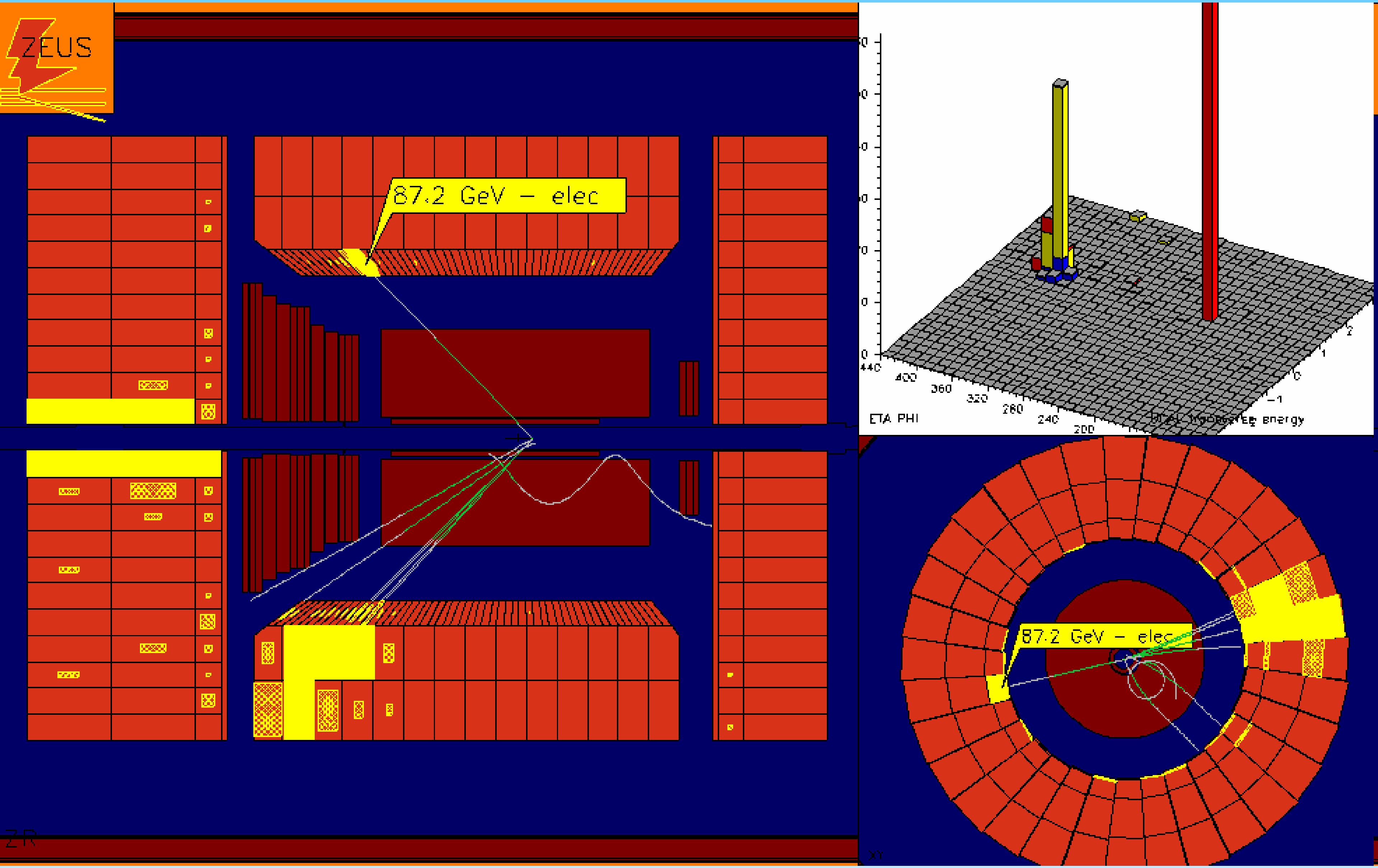


7.3 Calorimetry in HERA Experiments

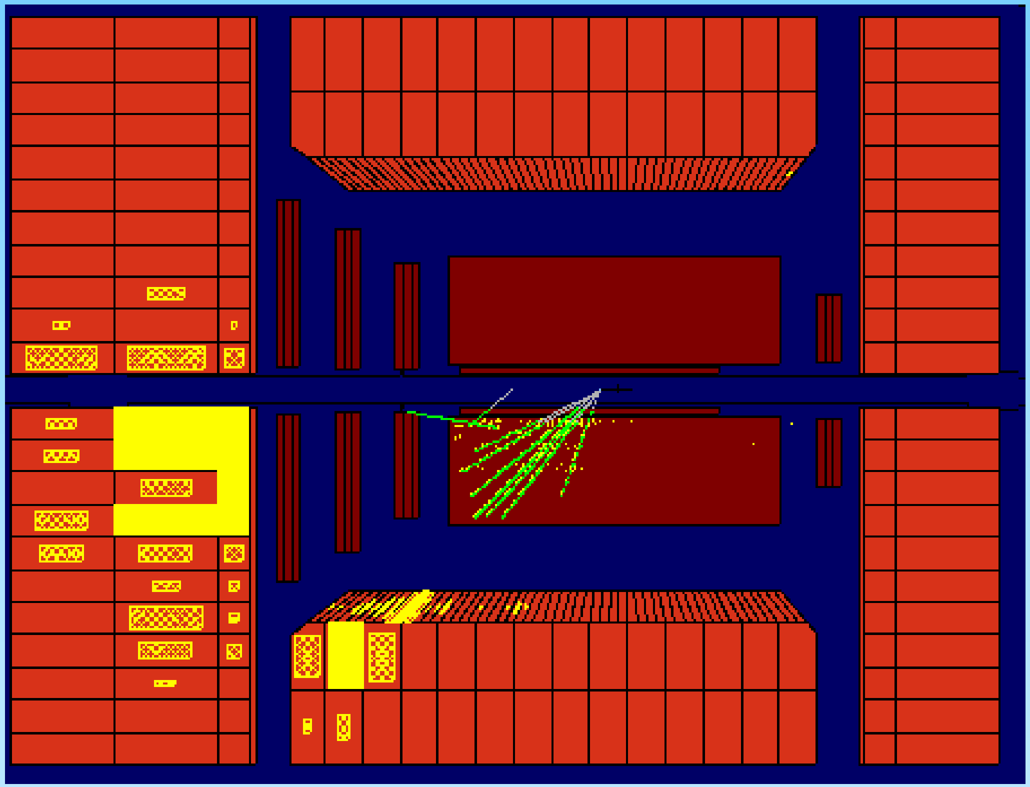
Large efforts to improve hadron calorimetry,
important for reconstruction and energy calibration of deep-inelastic events

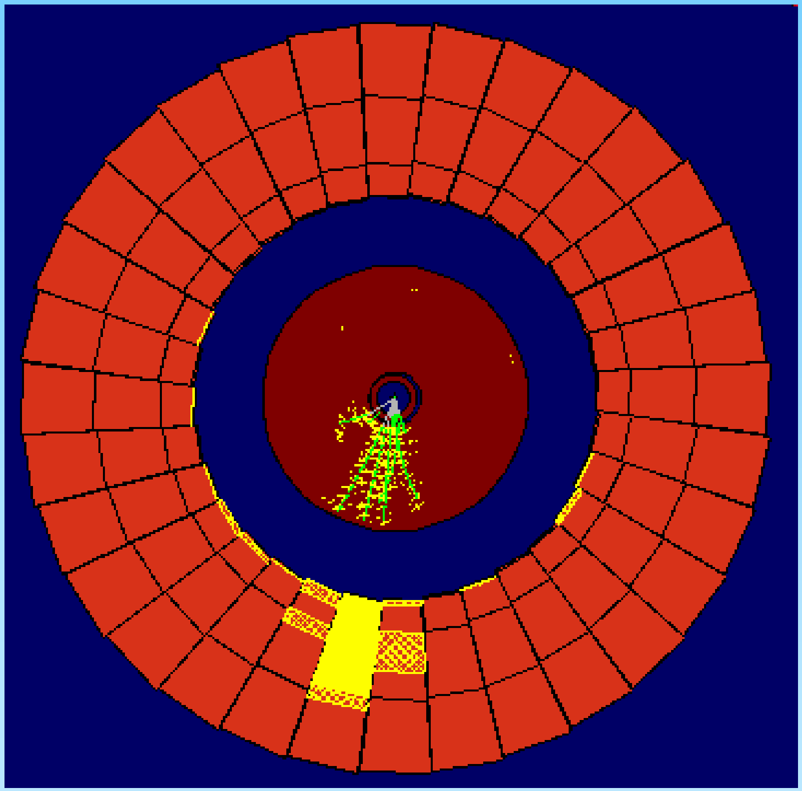


Uran Calorimeter of ZEUS

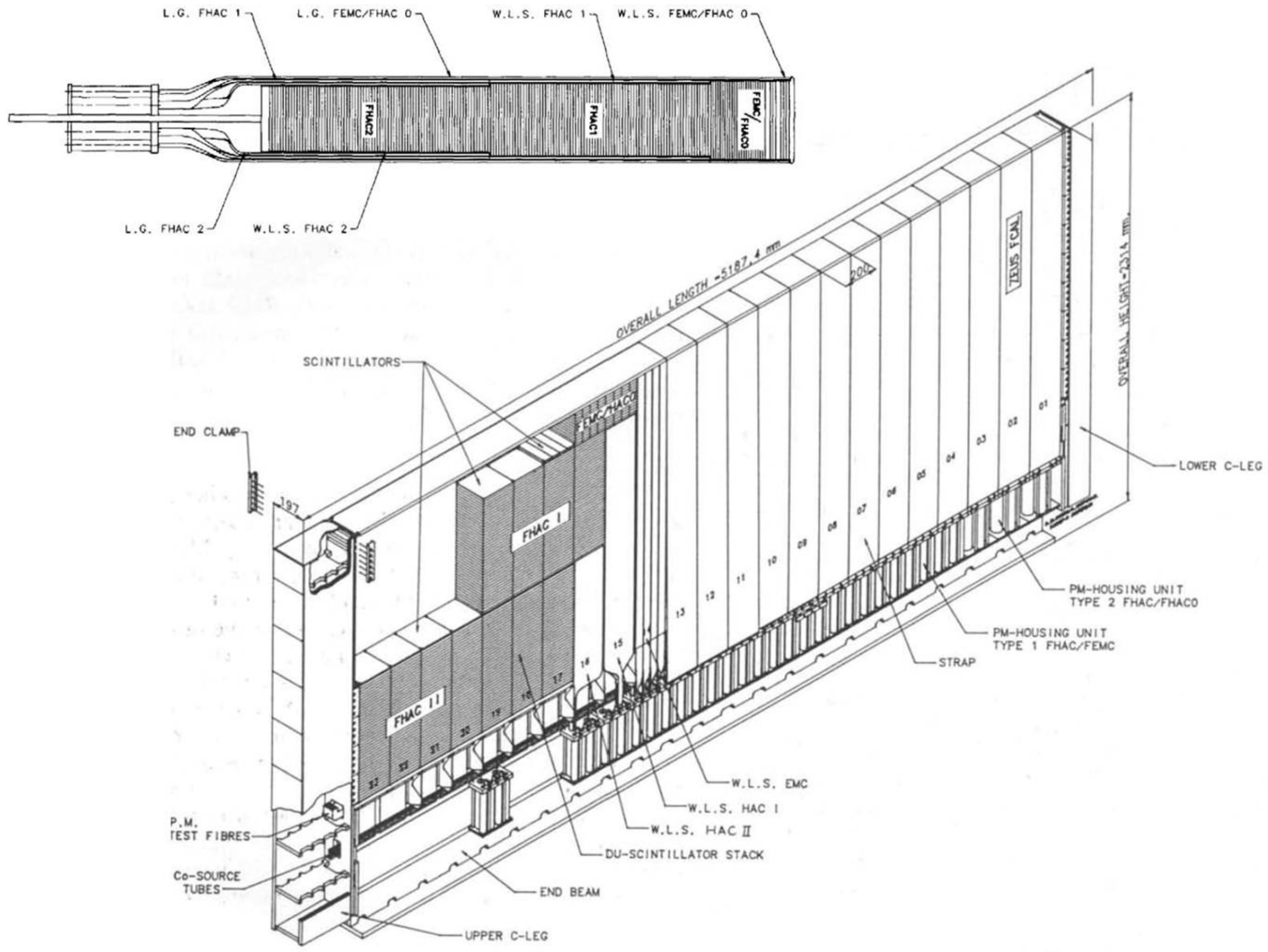


E^{miss} Measurement



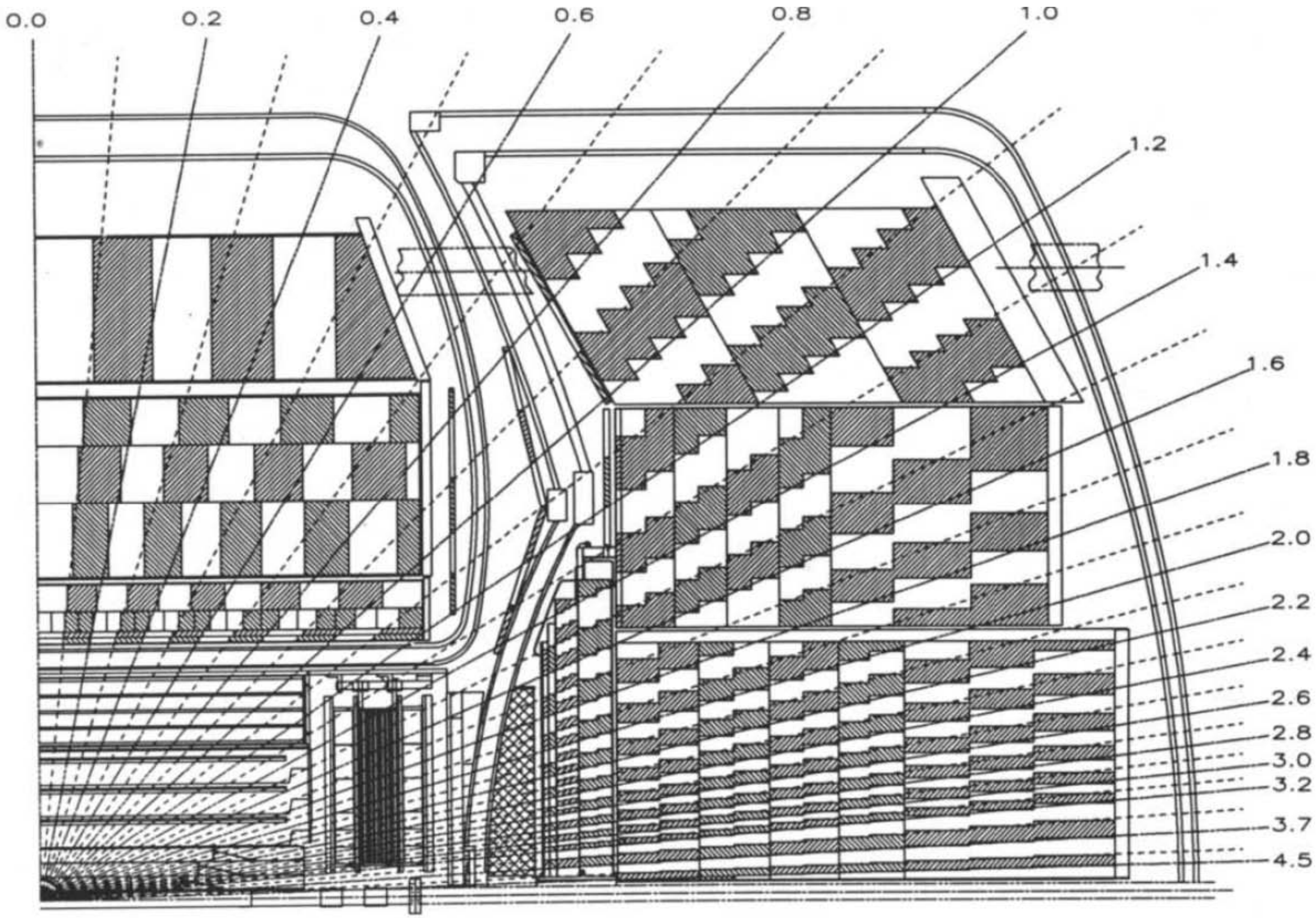


Construction of the ZEUS Calorimetere

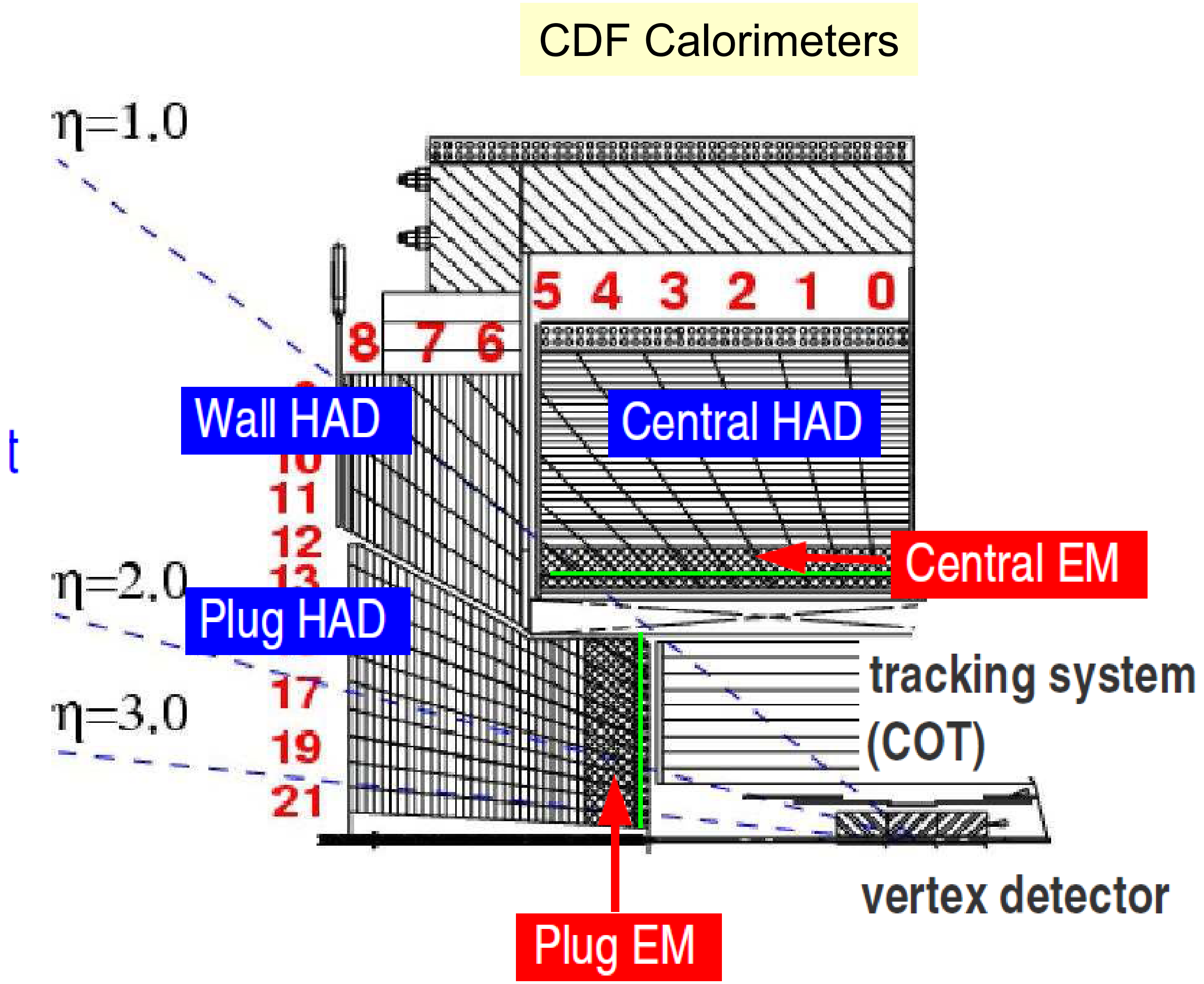


7.4 Calorimetry in Tevatron Experiments

Example of a trigger tower structure (D0)

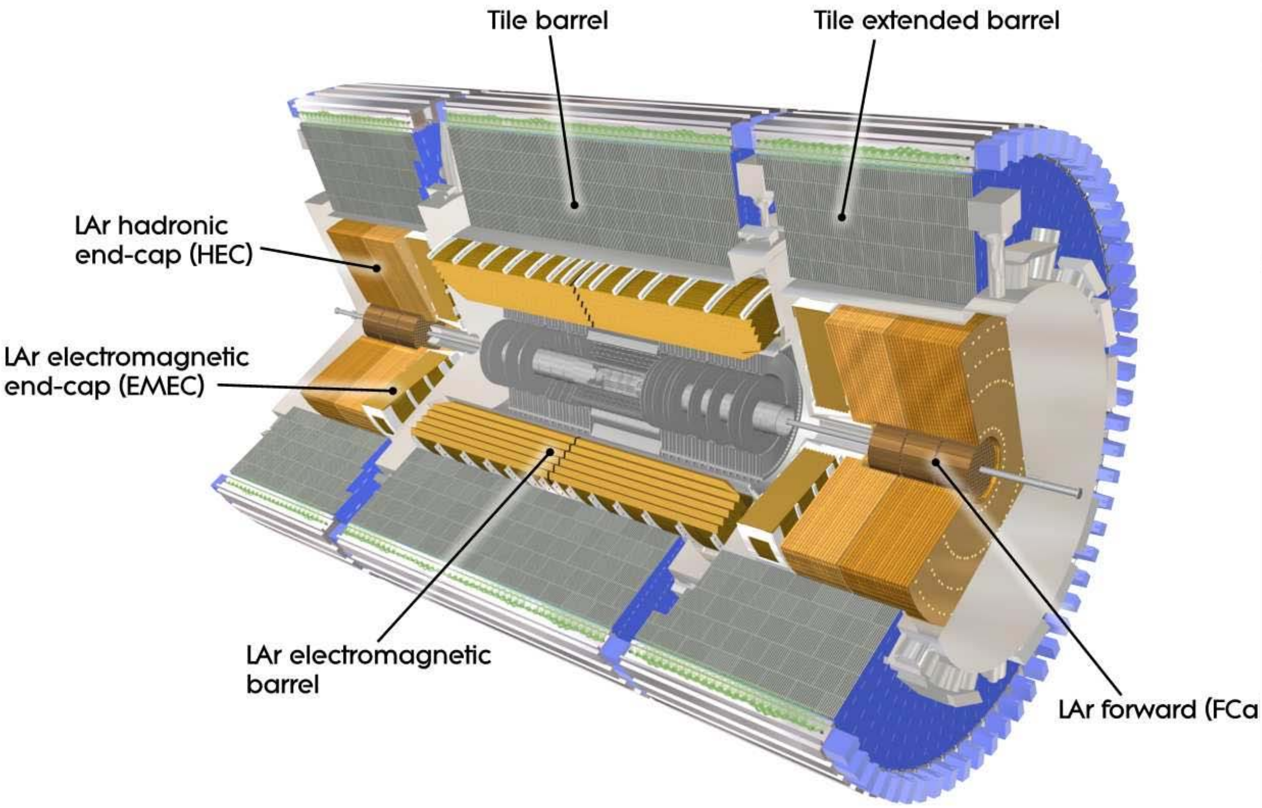


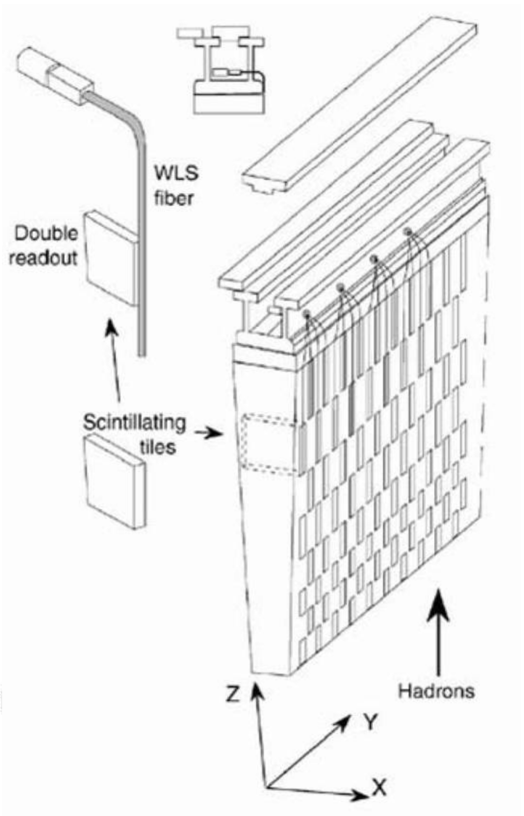
Calorimetry at the Tevatron: CDF



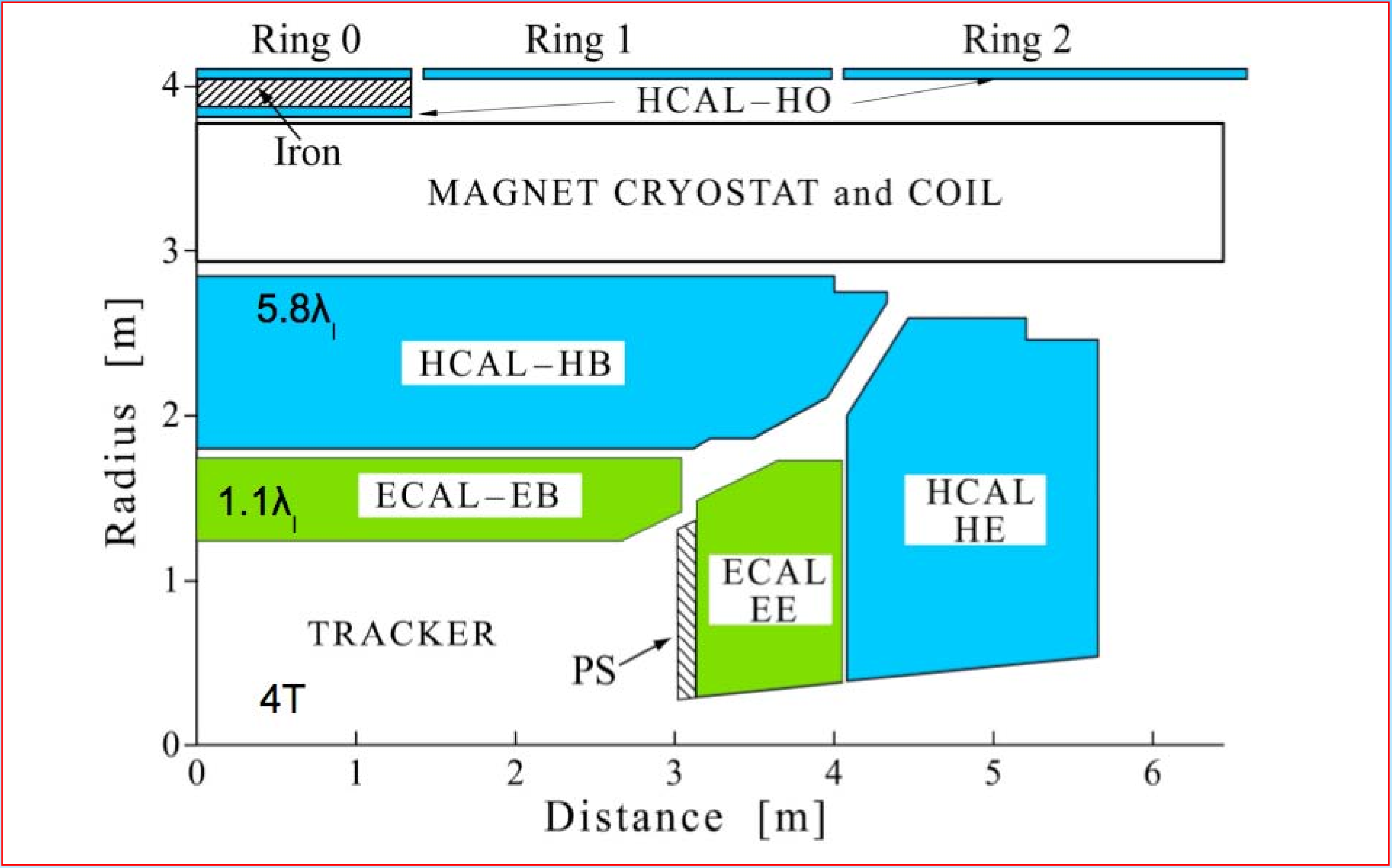
7.5 Calorimetry in LHC Experiments

ATLAS Calorimeters





Calorimetry in LHC Experiments: CMS



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