Calorimetry in Particle Physics

Lecture IV

Hadronic Calorimeters

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Hadronic Calorimetry: History

Pioneering papers

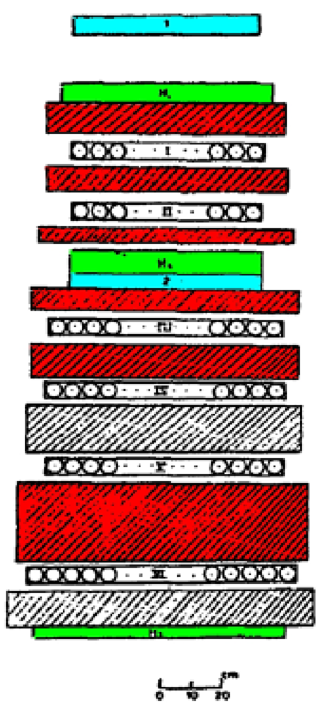
V. S. Marzin	Progr.Elem.Part. and Cosm.Ray Physics 9 (1967) 245
J. Engler et al.	Phys. Lett. 27B (1968) 599
J. Engler, W. Flauger, B. Gibhard, F. Mönnig, K. Runge, H. Schopper	NIM 106 (1973) 189
V. Böhmer et al.	NIM 122 (1974) 313
J. Moritz et al.	KfK report 1936 (1974)

Cosmic Ray Physics : *V. S. Marzin et al.*

propose to exploit

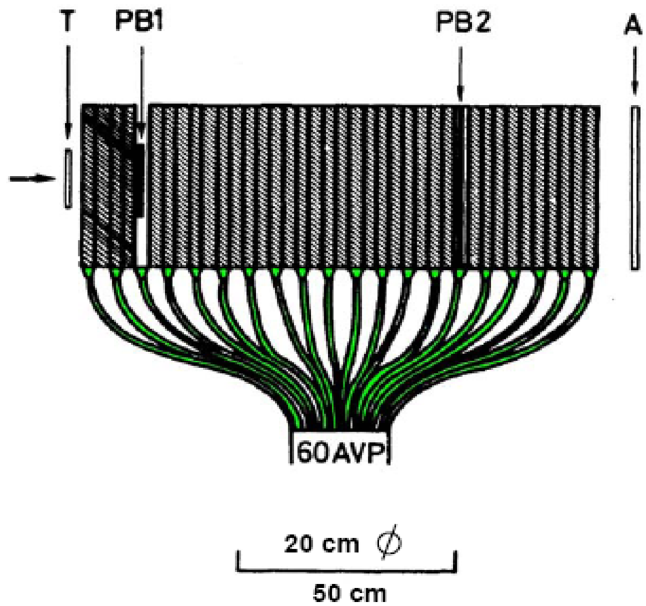
$$\frac{\sigma}{E} \sim \frac{1}{\sqrt{E}}$$

Basic understanding:



- Sampling structure
- $L > 6\ \lambda_{abs}$
- converter plates thickness $< 6\ X_o$ in order to detect π^o
- not b properly considered : transverse leakage

Hadronic Calorimetry: History



n–Calorimeters

H. Schopper et al.

- Transverse dimension of shower λ_{int}

Systematic study of hadron calorimeters

Questions addressed:

- $S \sim E$
- $\frac{\sigma}{E} \sim \frac{1}{\sqrt{E}}$
- Shape of signal for monoenergetic particle

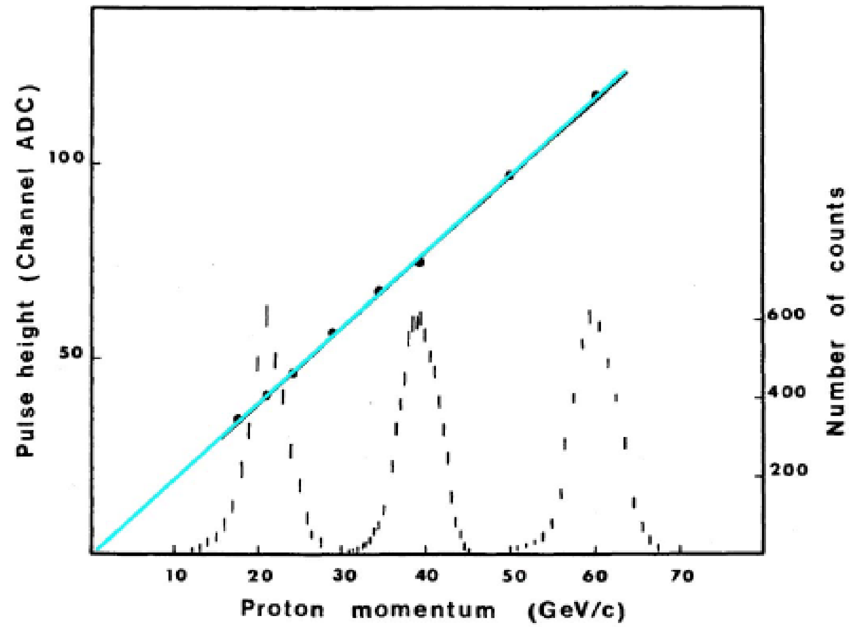
$$n + p \rightarrow p + n$$

  inclusive n–spectra

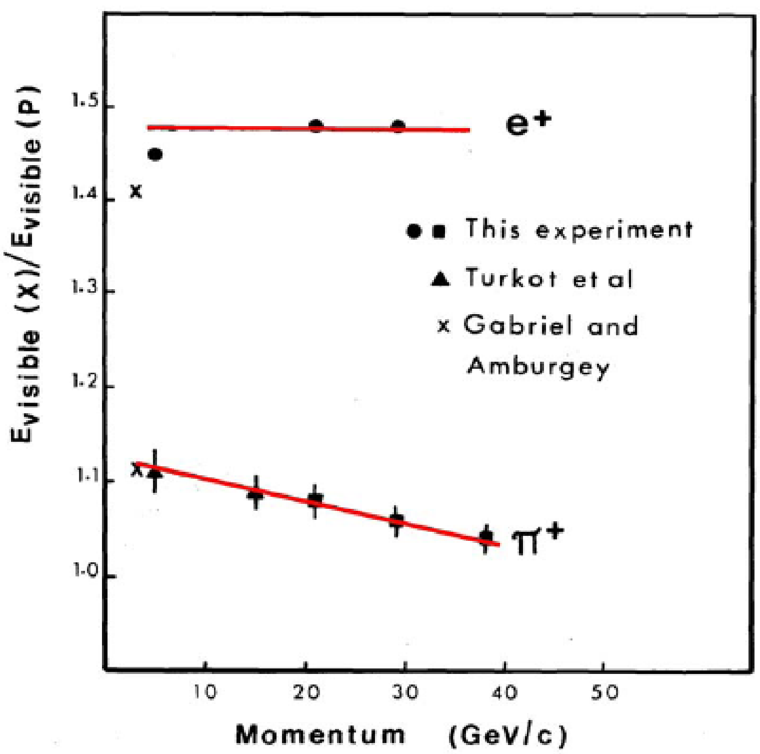
- parameters influencing resolution
- particle identification
- spatial information
- first crude simulation of detector response

Hadronic Calorimetry: History

- Linearity and ∼Gaussian shape



- Different response for e^- and hadrons

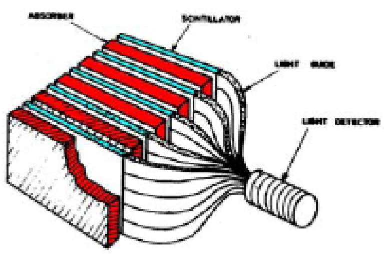


Hadronic Calorimetry: History

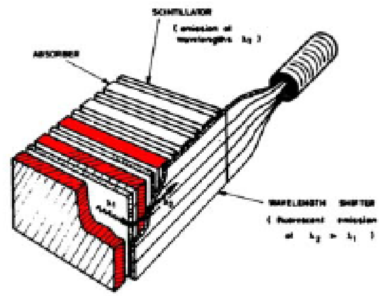
Next step: New read out types

LAr calorimeter : Willis et al., Engler et al.

WLS technique : Garwin, Keil, Hofmann et al.



a)



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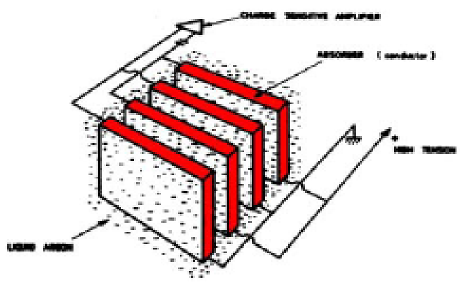
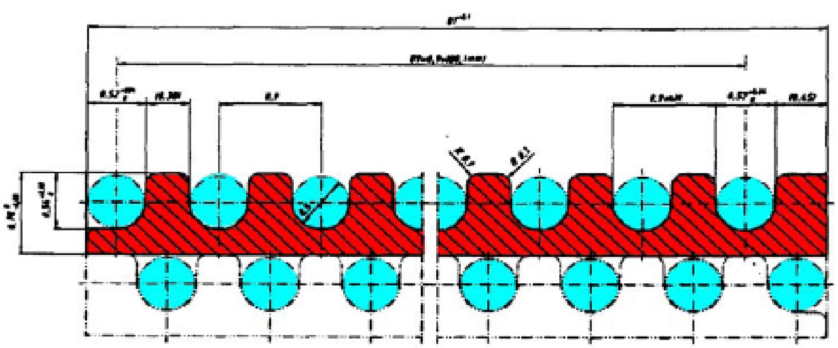
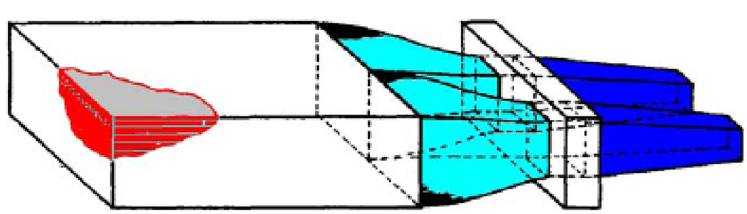


c)

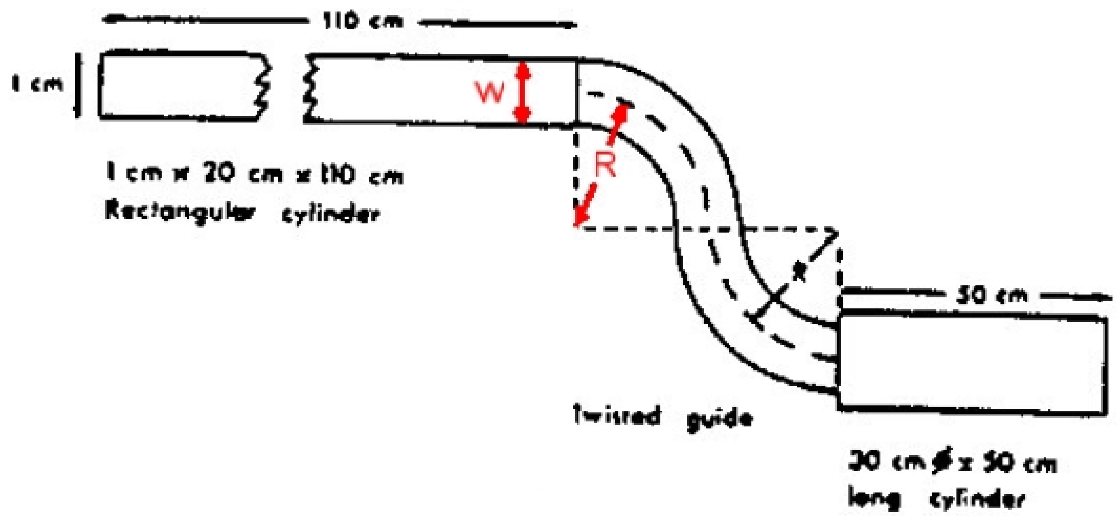
Read–out by scintillating fibres :



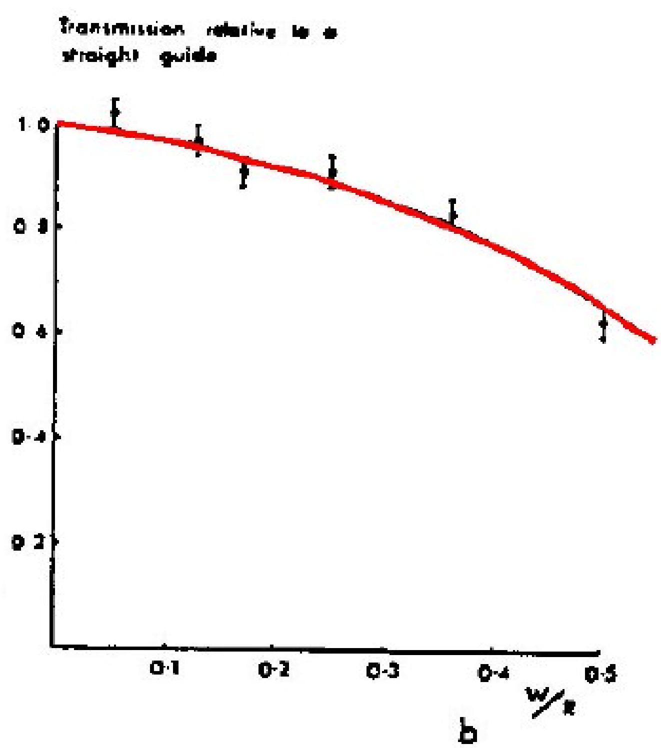


Hadronic Calorimetry: History

Transport of light



Transmission depends on radius of curvature

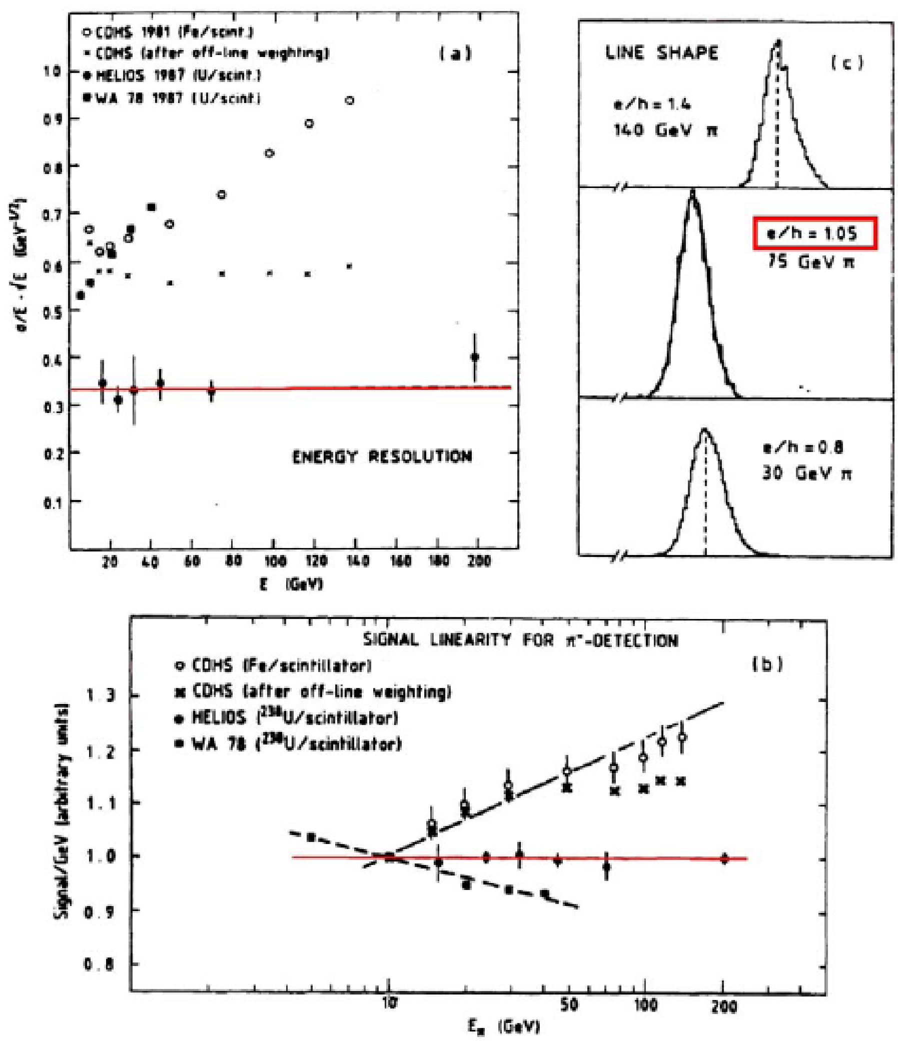


Basic Observations

Aim :

- $S \sim E$
- $\frac{\sigma}{E} \sim \frac{1}{\sqrt{E}}$
- Gaussian shape of signal (unfolding!)
- Signal (e) = Signal (π)

1. Generation of experiment s: conditions fulfilled in first approximation, but small deviations:



Basic Observations

These experiments observed

- weak non linearity $\frac{S}{E} \neq const$
- $\frac{\sigma}{E} \cdot \sqrt{E} \neq const$
- non Gaussian tails of signal
- $\frac{S(e)}{S(\pi)} \neq 1$ for $e(\pi)$ of same energy

Detailed studies proved

- Localized energy due to electromagnetic component

$$V_{em} \approx (10X_o \cdot R_M^2) << V_{had}(6\ \lambda_{int}^3)$$

- $S(e)/S(\pi) \neq 1$ important limitation of energy resolution and linearity

Contributions to Hadron Signal

Energy deposited by a particle i	$E_{dep}(i)$
Visible energy	$E_V(i)$
Non visible energy (recombination, nuclear binding)	$E_{NV}(i)$

$$a(i) = \frac{E_V(i)}{E_V(i) + E_{NV(i)}} \qquad (1)$$

Compare signal with those of min. ionizing particles (mip)
High energy μ good approximation to mip

$$\frac{e}{mip} = \frac{a(e)}{a(mip)} \qquad (2)$$

Hadronic component of hadronic shower, i.e. electro–magnetic component due to $\pi^o \rightarrow \gamma\gamma, \omega \rightarrow \pi^o\gamma, \ldots$ excluded

$$\frac{h_i}{mip} = \frac{a(h)}{a(mip)} \qquad (3)$$

Signal of

$$S(e) = k \cdot E \cdot \frac{e}{mip} \qquad (4)$$

$$S(h) = k \cdot E \left\{ f_{em} \frac{e}{mip} + (1 - f_{em}) \frac{h_i}{mip} \right\} \qquad (5)$$

Calibration constant k : record signal of particles
with well defined energy

$$f_{em} \approx 0.1 \cdot \ell n \frac{E}{1\ GeV} \qquad (6)$$

Contributions to Hadron Signal

If

$$\frac{e}{mip} \neq \frac{h_i}{mip} \swarrow\searrow \frac{S(h)}{E} \neq const \qquad (7)$$

Discuss ratio

$$\frac{S(e)}{S(h)} = \frac{e/mip}{f_{em}\frac{e}{mip} + (1 - f_{em})\frac{h_i}{mip}} \qquad (8)$$

Conclusions

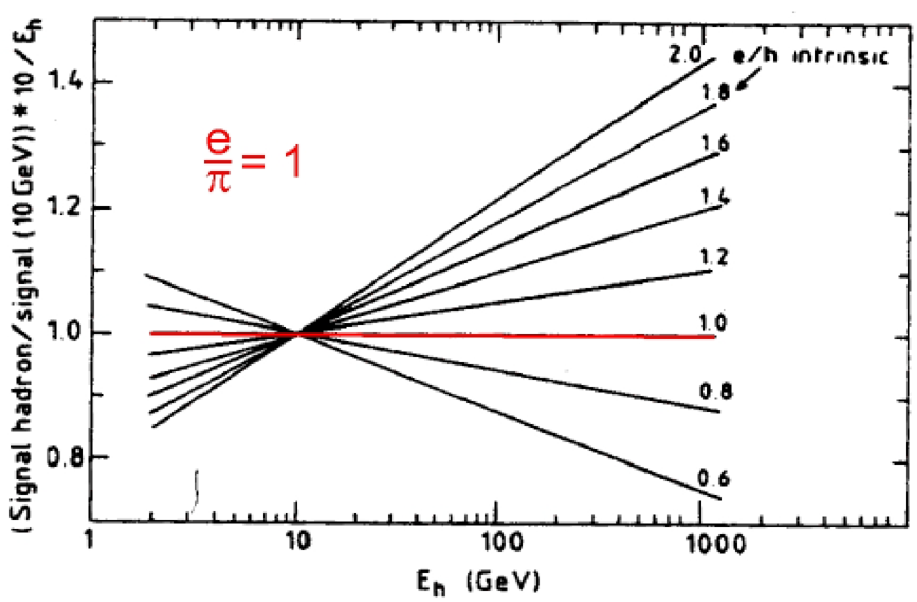
- Since $f_{em} \sim \ln\frac{E}{1GeV}$ energy resolution and signal distribution deteriorate with increasing signal, if

$$\frac{e}{mip} \neq \frac{h_i}{mip}$$

- Deviation from linear dependence

$$S \sim E$$

  expected



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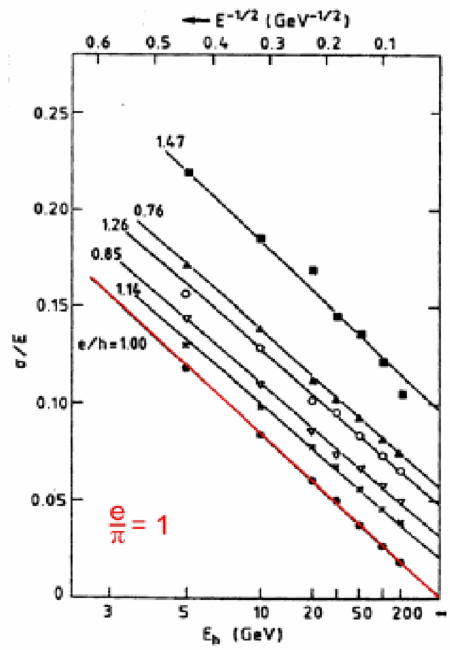
Contributions to Hadron Signal



Aim of detector lay out

$$\boxed{\frac{e}{mip} = \frac{h_i}{mip}} \qquad (9)$$

Different components contribute to $\frac{h_i}{mip}$:

$$\boxed{\frac{h_i}{mip} = f_{ion} \cdot \frac{ion}{mip} + f_n \cdot \frac{n}{mip} + f_\gamma \cdot \frac{\gamma}{mip} + f_B \cdot \frac{b}{mip}}$$

f_{ion} : fraction of hadronic component deposited by charged particles $(\mu^\pm, \pi^\mp, p)$

f_n : fraction deposited by neutrons (n)

f_γ : fraction deposited by photons (γ) from nuclear deexcitation

f_B : fraction deposited as nuclear binding energy

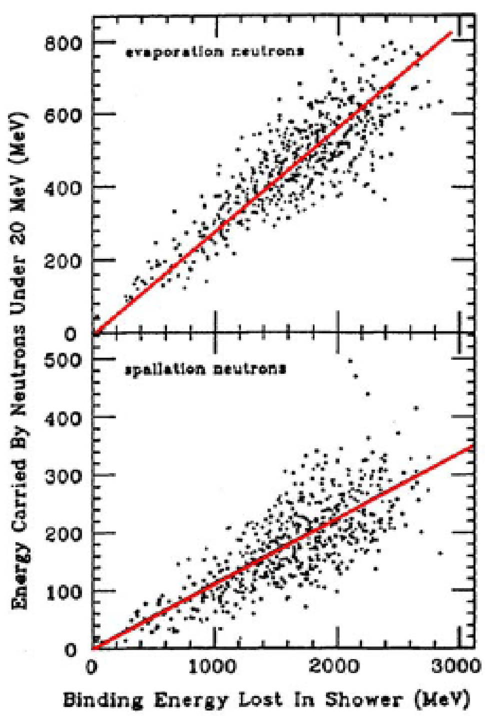
Typical values (Monte Carlo simulation, Wigmans)

Contributions to Hadron Signal

		Fe	U
f_{ion}	total	57 %	38 %
	spallation	42 %	27 %
f_γ		3 %	2 %
f_n		8 %	15 %
f_B		32 %	45 %

	Fe/Sz	Fe/Ar	U/Sz	U/Ar	dependence
$\frac{ion}{mip}$	0.83	0.88	0.91	1	d_{act}
$\frac{n}{mip}$	0.5 ... 2	0	0.8 ... 2.5	0	d_{act}/d_{pas}
$\frac{\gamma}{mip}$	0.7	0.95	0.4	0.4	d_{pas}
$\frac{e}{mip}$	0.9	0.95	0.55	0.55	

Strong correlation of f_B, f_n and f_B, f_γ :



Contributions to Hadron Signal

$$f_B \sim f_n$$

Nuclei excited by n–capture

$$f_\gamma \sim f_n$$

Since for many calorimeters

$$\frac{h_i}{mip} < \frac{e}{mip}$$

$\rightsquigarrow$ increase $\frac{h_i}{mip}$ by

- increase f_n, f_γ
- increase $\frac{n}{mip}, \frac{\gamma}{mip}$

  or
- decrease $\frac{e}{mip}$

Applying this condition and achieving

$$\boxed{\frac{e}{mip} = \frac{h_i}{mip}}$$

is the aim of compensation calorimetry

Exploit Monte Carlo Simulation:

Pioneers	H. Brückmann	DESY
	R. Wigmans	CERN
	Gabriel	Oak Ridge
2 procedures	Software weighting :	CDHS, H1
	Hardware weighting :	Helios, ZEUS

Software Compensation: H1 Method

Highly segmented calorimeter allows to identify regions of high energy deposition (electromagnetic subshowers). Derive from Monte Carlo simulations proper weights

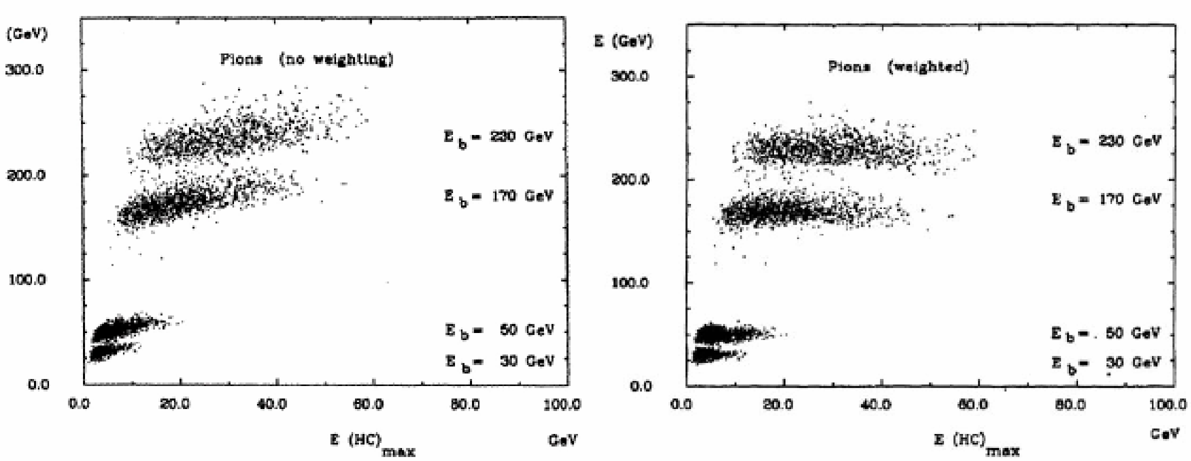
$$\frac{E(Q)}{Q} = \left(A_1 \ \exp\left\{-A_2\frac{Q}{V}\right\} + A_3\right)_{EMC} + \left(B_1 \ \exp\left\{-B_2\frac{Q}{V}\right\} + B_3\right)_{HAC}$$

Optimized with MC for different θ, E

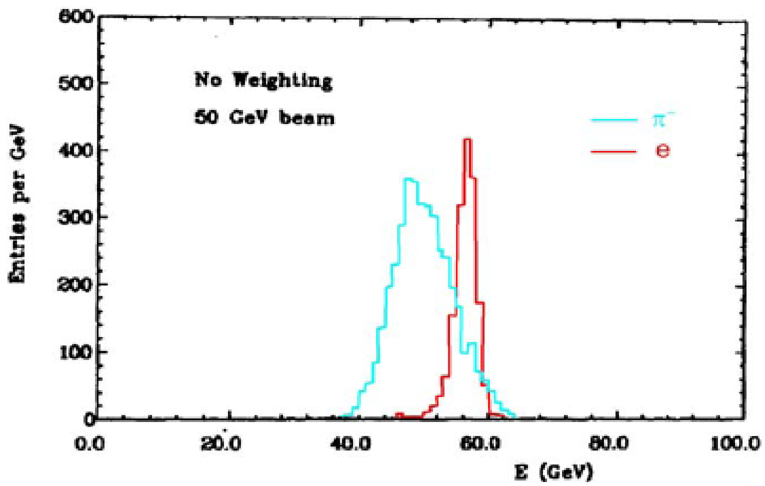
Parametrize

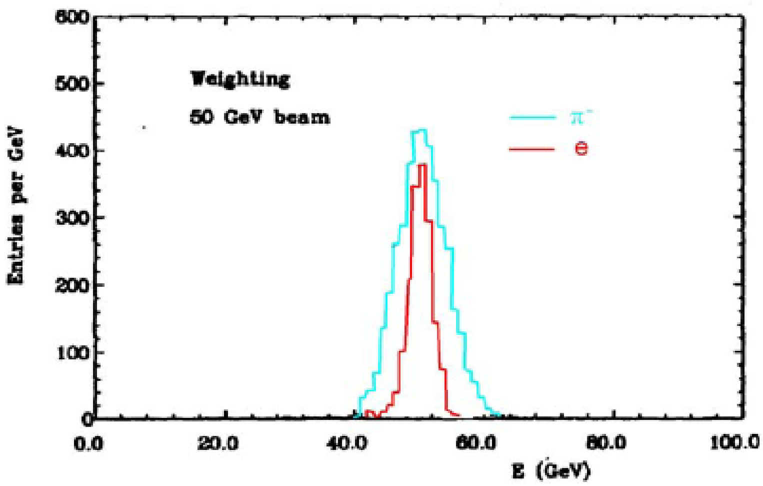
$$\begin{aligned} A_i &= A_i(Q) \qquad i = 1,2 \\ A_3 &= A_3(Q,\theta) \end{aligned}$$

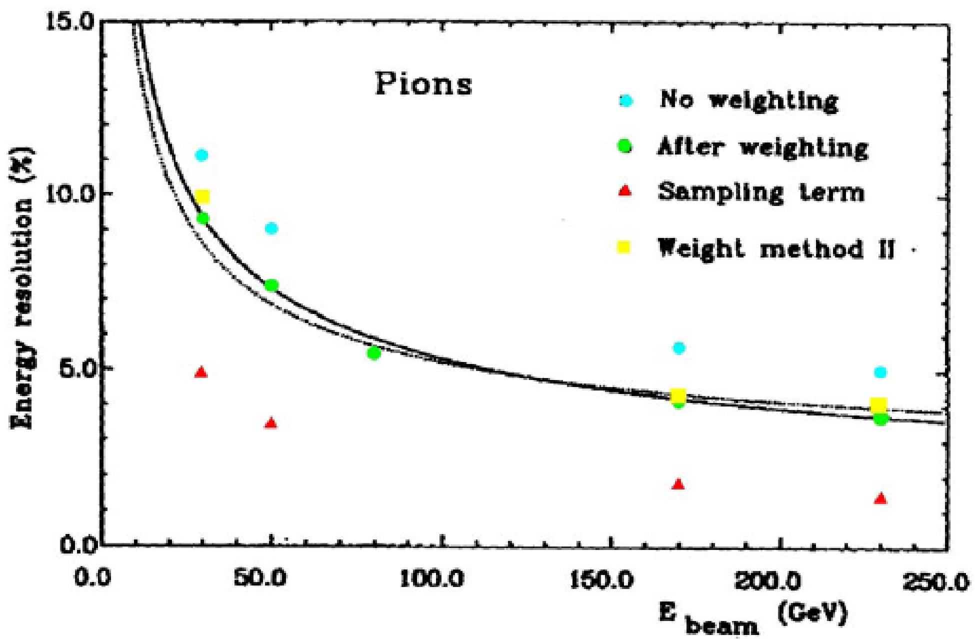
Result:



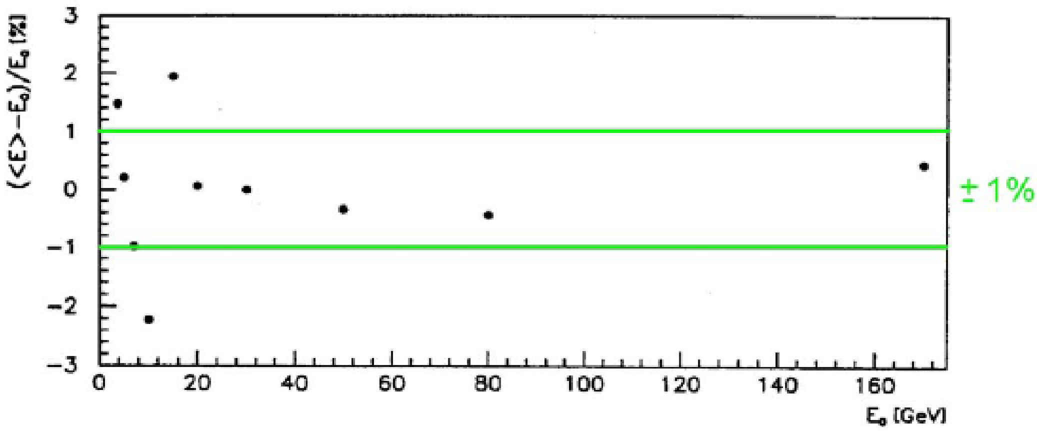
Software Compensation: H1 Method

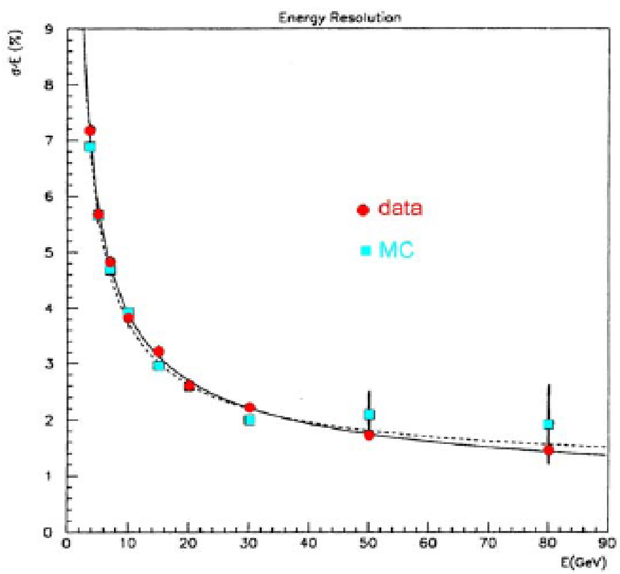


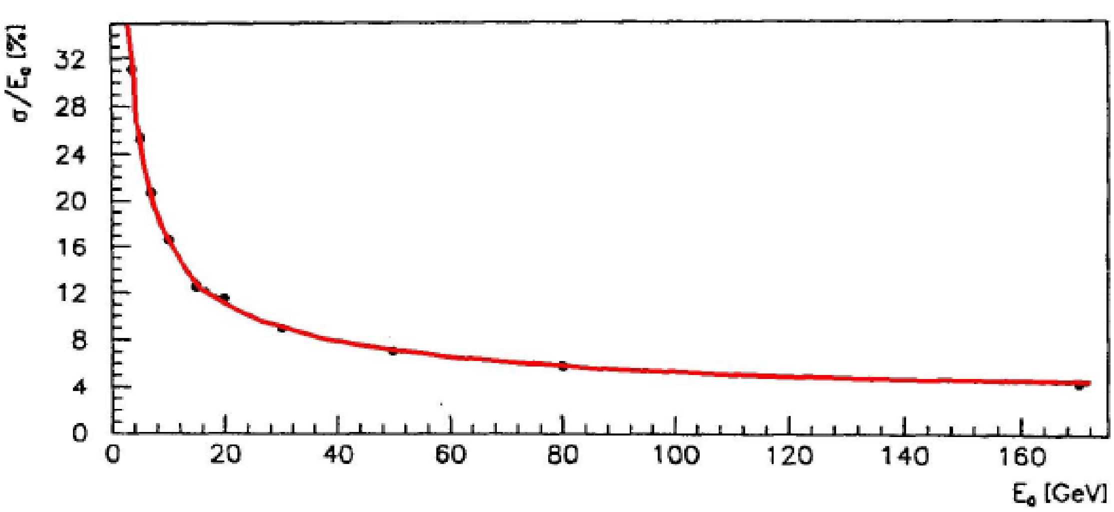




Software Compensation: H1 Method



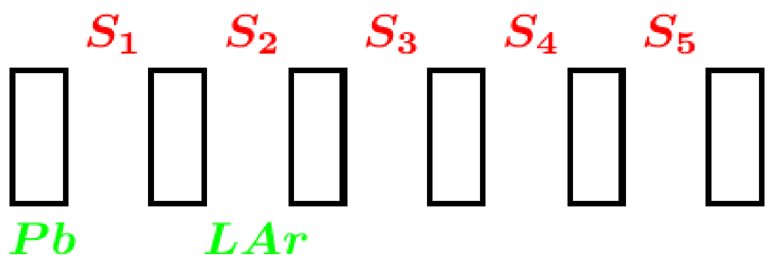




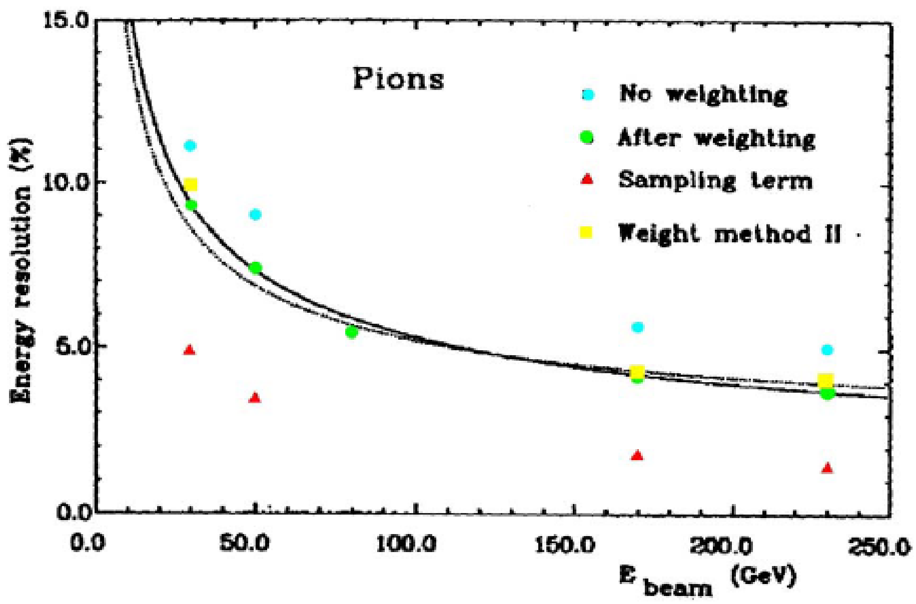
Software Compensation: H1 Method

- Linearity within 1%
- $S(e)/S(\pi) = 1$
- $\left(\frac{\sigma}{E}\right)_h = \frac{0.46\ GeV^{1/2}}{\sqrt{E}} \oplus \frac{0.73\ GeV}{E} \oplus 0.026$

Measurement of sampling fluctuations



$$
\begin{aligned}
S_\Sigma &= S_1 + S_3 + S_5 + \ldots S_2 + S_4 + S_6 \ldots \\
S_\Delta &= S_1 - S_2 + S_3 - S_4 + S_5 - S_6 \\
\sigma_\Sigma &= \sigma_{2n} \oplus \sigma_{2n+1} \oplus \sigma_{bind} \\
\sigma_\Delta &= \sigma_{2n} \oplus \sigma_{2n+1}
\end{aligned}
$$

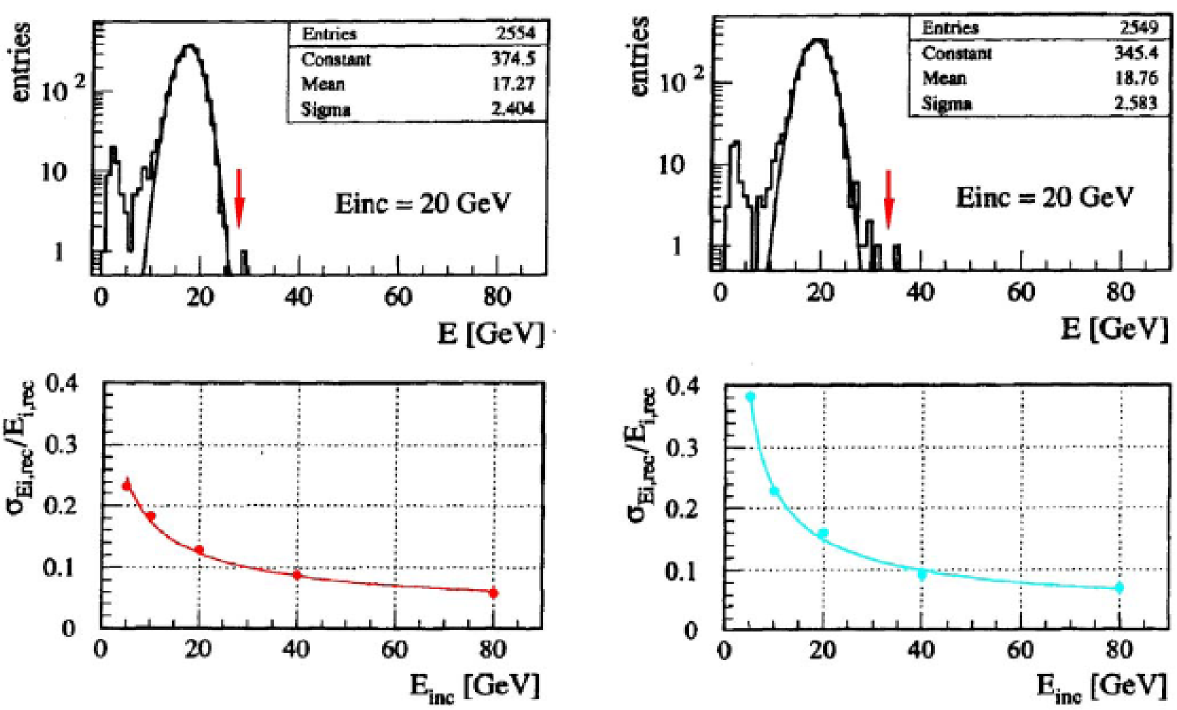


Nuclear binding fluctuations dominate

Software Compensation: H1 Method

Improvements possible

Apply weights via neural network tuned with Monte Carlo data :



Got better linearity and resolution for $E < 10\ GeV$; for $E > 10\ GeV$ same results as standard weighting

Hardware Compensation: ZEUS

Aim
$$\frac{e}{mip} = \frac{h_i}{mip}$$

Qualitative discussion of result backed by Monte Carlo simulation (Wigmans, Brückmann)

- $E_n > 1\ GeV$
  $f_{ion},\ f_\gamma,\ f_n,\ f_B$ independent of hadron energy
- spallation protons dominant contribution to
  $$f_{ion} \quad \rightsquigarrow$$
  f_{ion} decreases for increasing $Z\,(\frac{Z}{A}\searrow)$
- f_n increases, if Z_{abs} increases $(\frac{A-Z}{Z}\nearrow)$
  Can only be exploited, if $\frac{n}{mip} \neq 0$
  Efficient use only if active material containes
  H–atoms
  This signal is delayed !

Choice of optimal detector material :
$$\frac{h_i}{mip} = \frac{ion}{mip} \cdot f_{ion} + f_n\,\frac{n}{mip} + f_\gamma\,\frac{\gamma}{mip} + f_B\,\frac{b}{mip}$$

Hardware Compensation: ZEUS

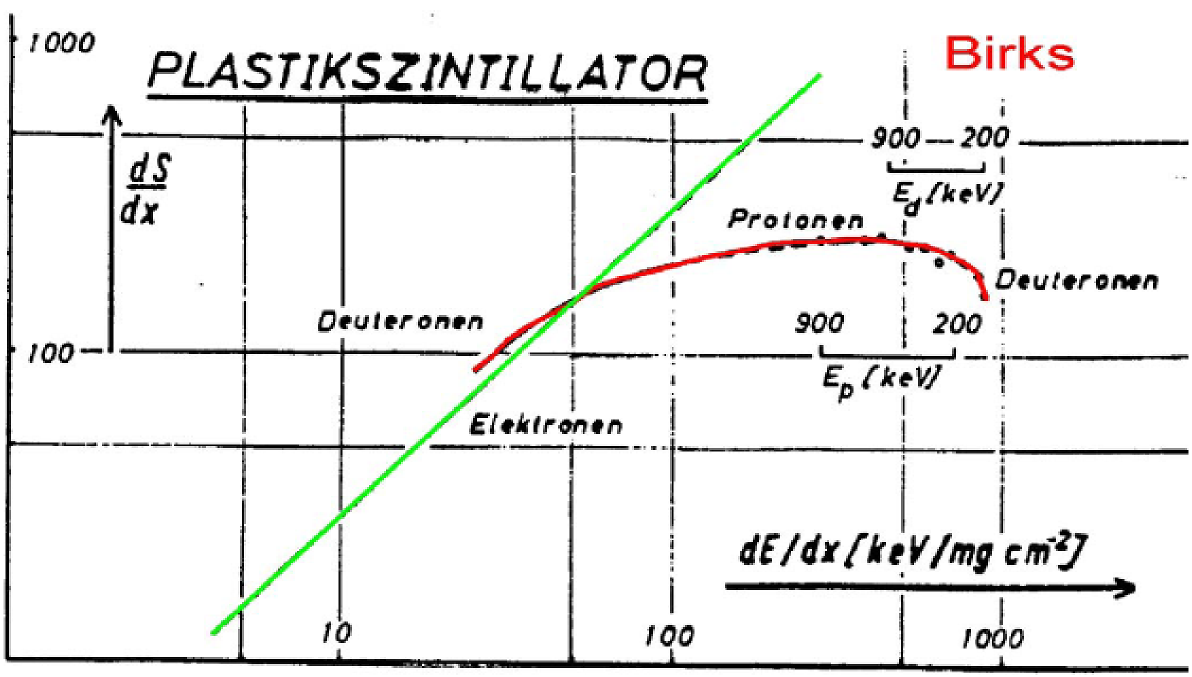
- $\frac{ion}{mip} = 0.8 \ldots 1$

Ratio depends on energy spectrum of spallation protons

Ratio depends on $\frac{dE}{dx}$

Birks :

$$\frac{dS}{dx} = \frac{A\frac{dE}{dx}}{1 + k_B\frac{dE}{dx}} = \begin{cases} A\frac{dE}{dx} & E_n >> m_n \\ A/B & \text{slow particles} \end{cases}$$



Hardware Compensation: ZEUS

$\frac{ion}{mip} \searrow$, if $d_{act} \nearrow$, since $\frac{dE}{dx}$ rises at end of track

If $\qquad d_{abs} \ll R_{Spallation}$

$\rightsquigarrow$ all spallation protons enter active medium

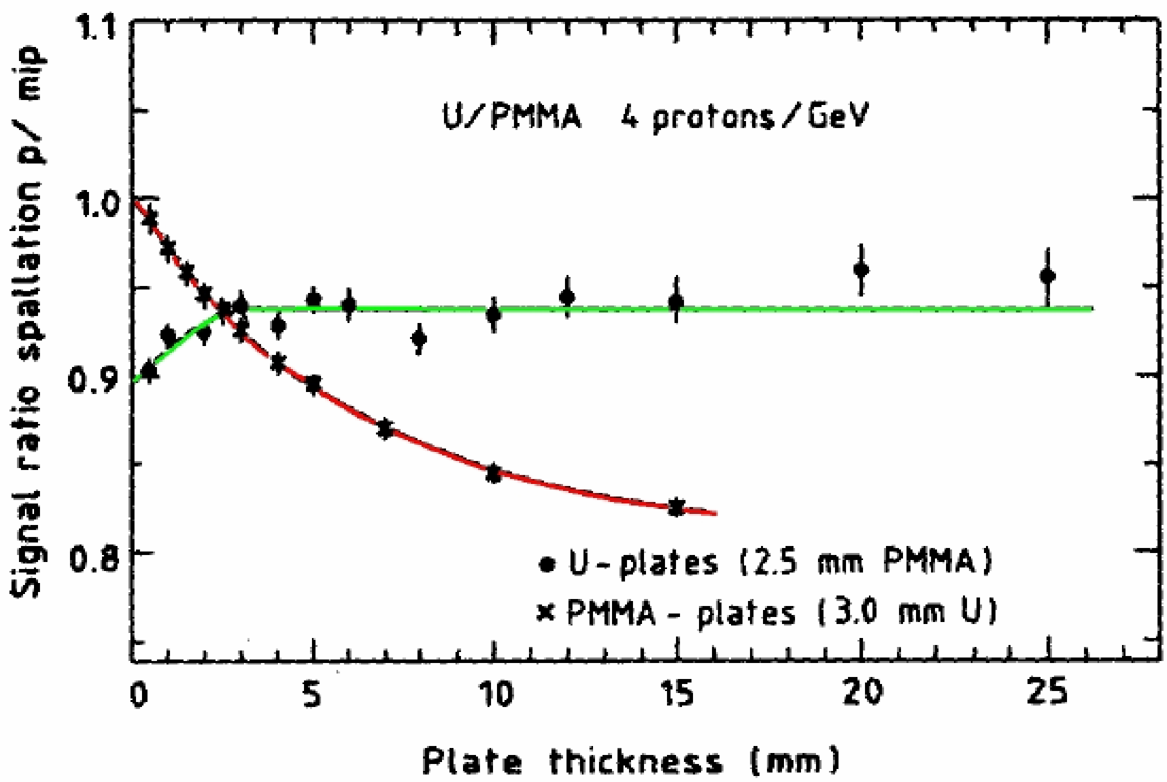
$$\frac{ion}{mip} \nearrow \quad \text{if} \quad d_{abs} \nearrow$$

If $\qquad d_{abs} \gg R_{Proton}$

$\rightsquigarrow$ only protons of surface region contribute

$\rightsquigarrow$ saturation expected

Simulation:



Hardware Compensation: ZEUS

- $\frac{n}{mip}$

  Neutrons have to be detected in active medium
  Since energy transfer

  $$\Delta E \sim \frac{E_n}{M_{act}}$$

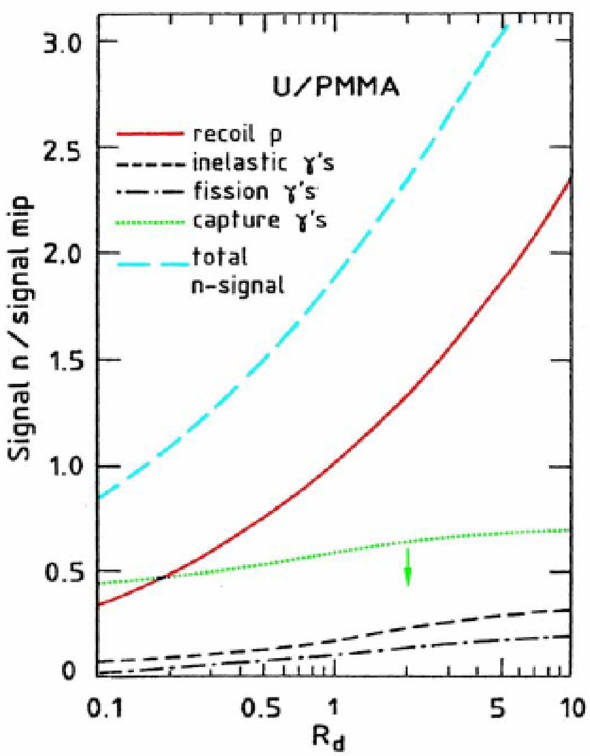
  Low mass media necessary (Birks!)
  Scintillator optimal detection material

  $$\frac{n}{mip} \nearrow \quad \text{if} \quad \frac{d_{act}}{d_{pas}} = R_d^{-1} \searrow$$

  since n are only stopped in active medium $\rightsquigarrow$ independent of d_{pas}, while

  $$mip \nearrow \quad \text{if} \quad \frac{d_{act}}{d_{pas}} \nearrow$$

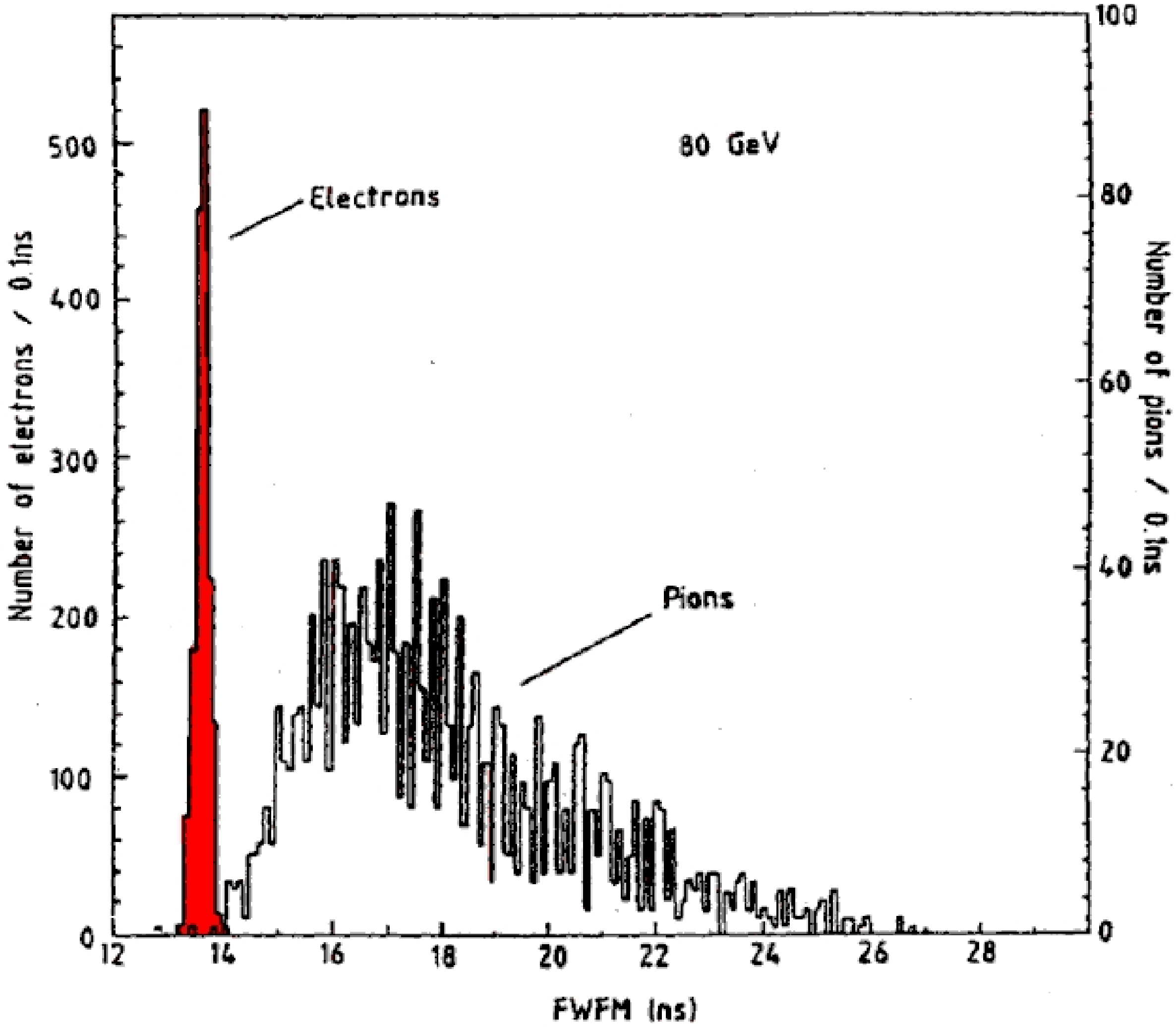
  Monte Carlo simulation:



Hardware Compensation: ZEUS

Time dependence of signal complicated :

recoil protons	"prompt" signal
capture gammas	"delayed" signal

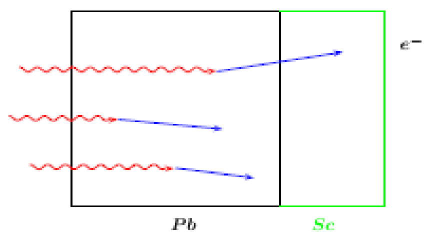


Hardware Compensation: ZEUS

- $\frac{e}{mip}$

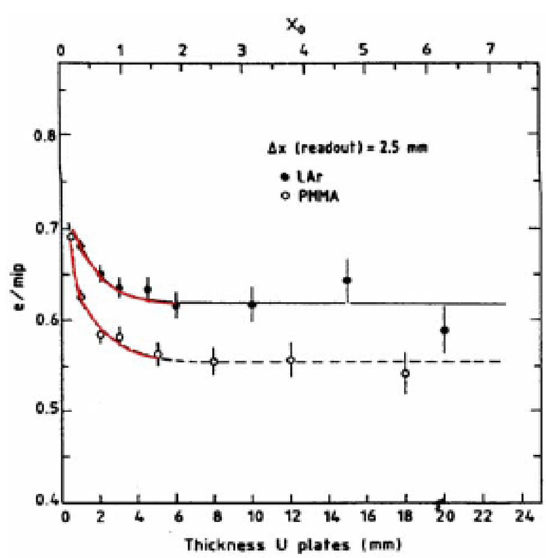
  Instead of increasing $\frac{h_i}{mip}$ one can also decrease $\frac{e}{mip}$ to achieve
  $$\frac{e}{mip} = \frac{h_i}{mip}$$

  $\frac{e}{mip}$ decreases, if d_{abs} increases



$$\mu_{abs} \sim Z^4$$

Photons deposit energy dominantly in converter, low energy electrons $\rightsquigarrow$ small range $\rightsquigarrow$ only contribution from absorber surface region



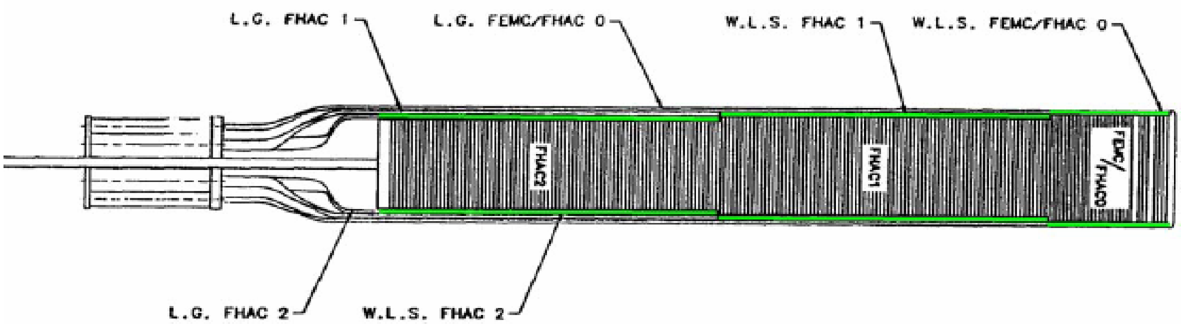
ZEUS: achieved compensation for Pb–Sc–Calorimeter

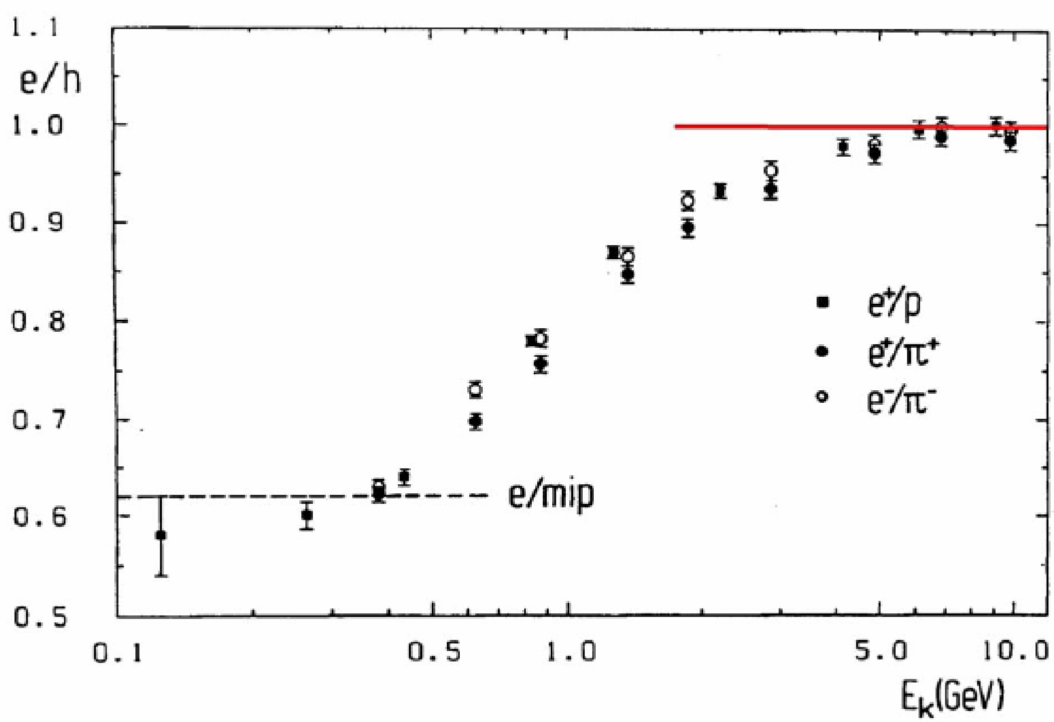
linearity $\frac{\sigma}{E} = \frac{0.442 \ GeV^{1/2}}{\sqrt{E}}$

Hadron Calorimeter Systems: ZEUS

- Scintillator–U Compensating Calorimeter ZEUS

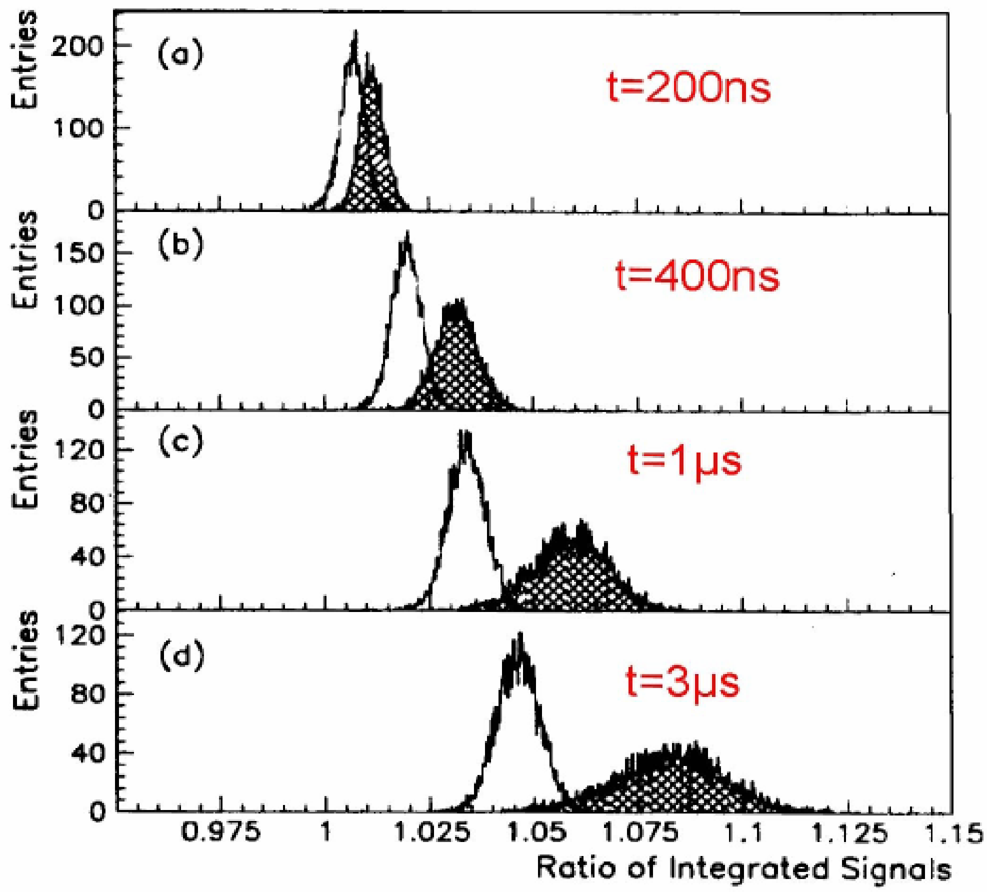
Module



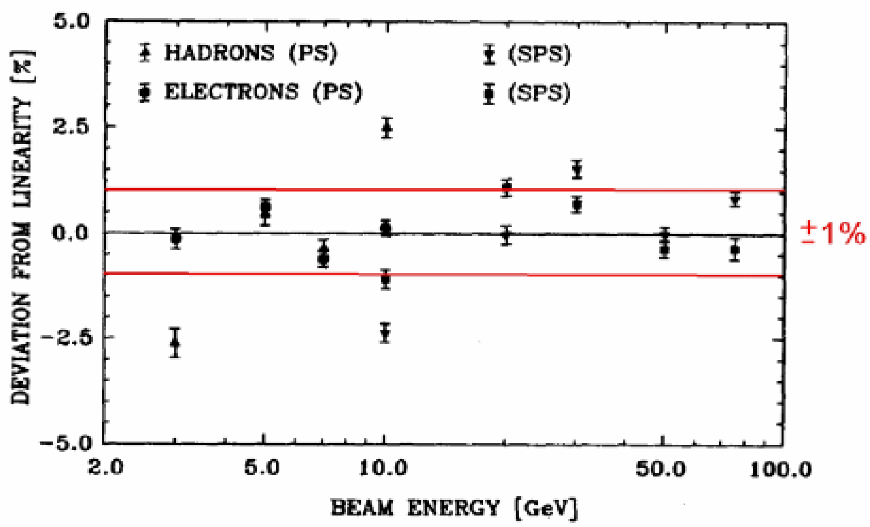


Hadron Calorimeter Systems: ZEUS

n–Contribution delayed

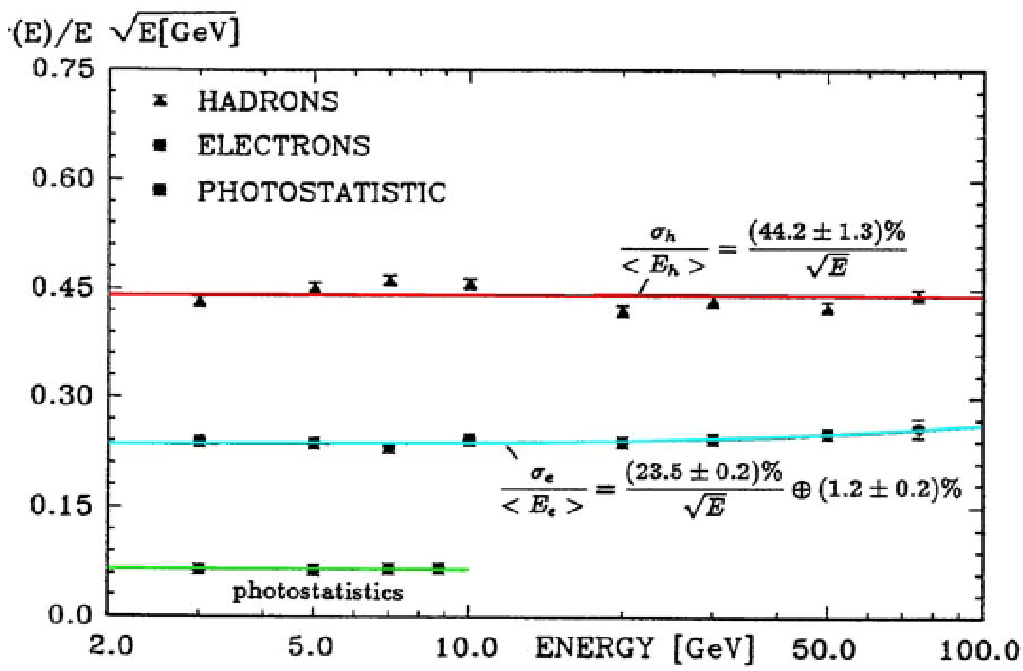


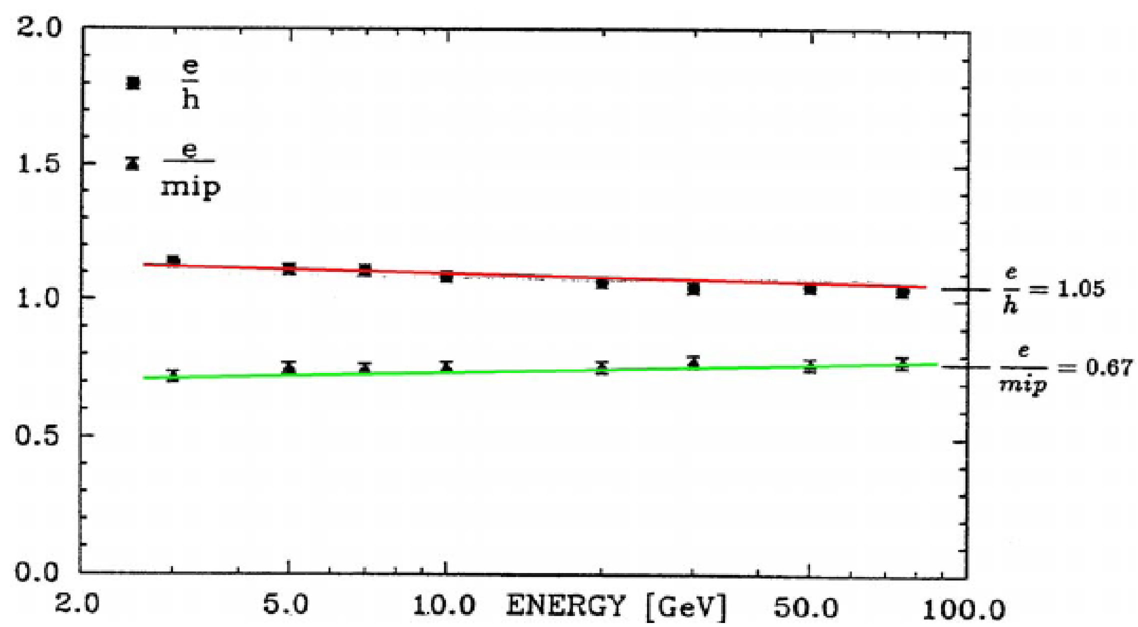
Linearity



Hadron Calorimeter Systems: ZEUS

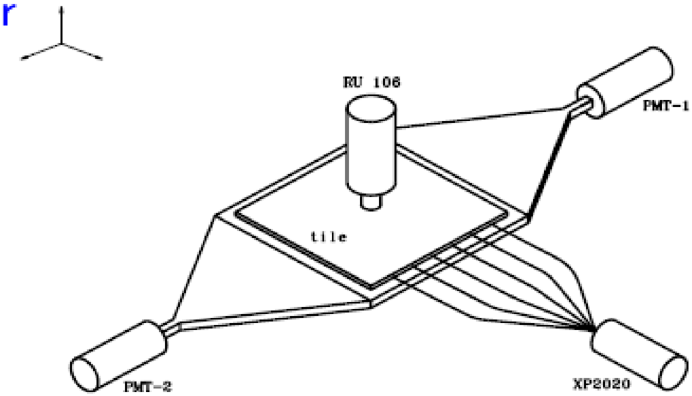
Resolution

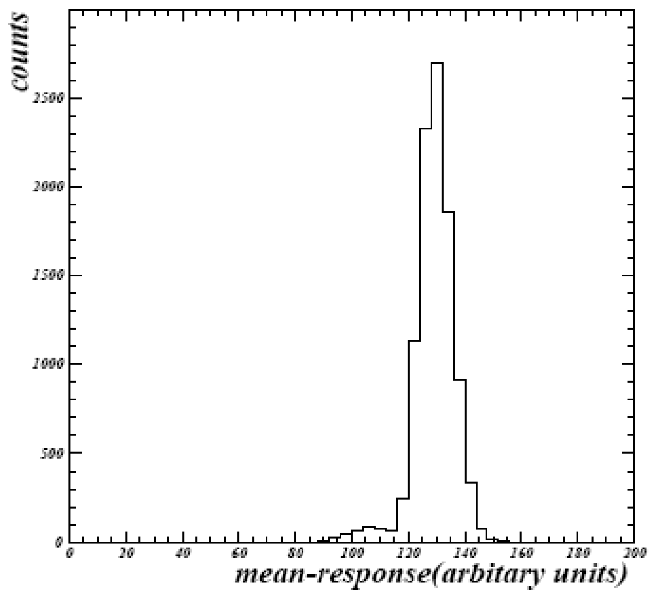


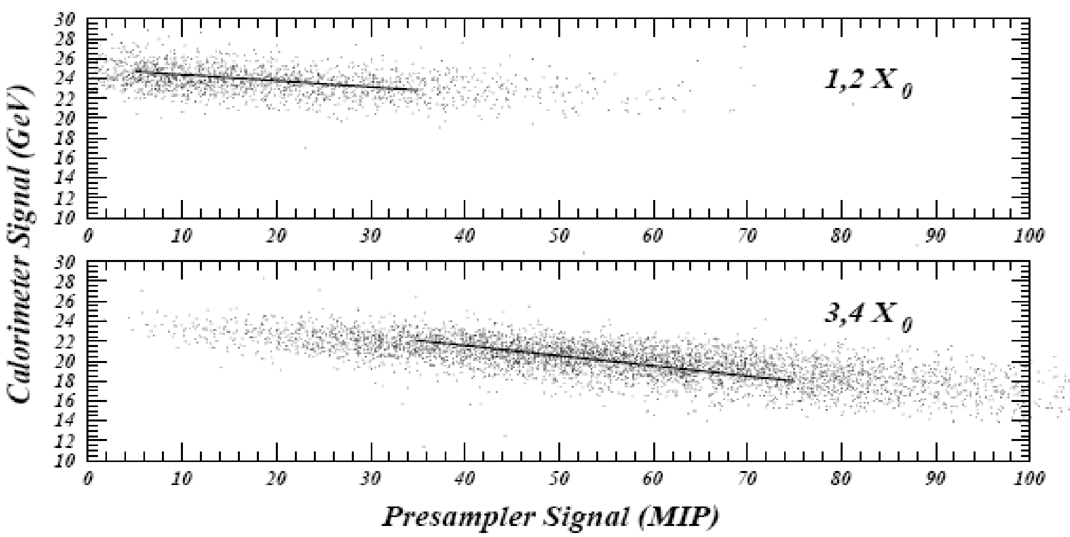


Hadron Calorimeter Systems: ZEUS

Presampler

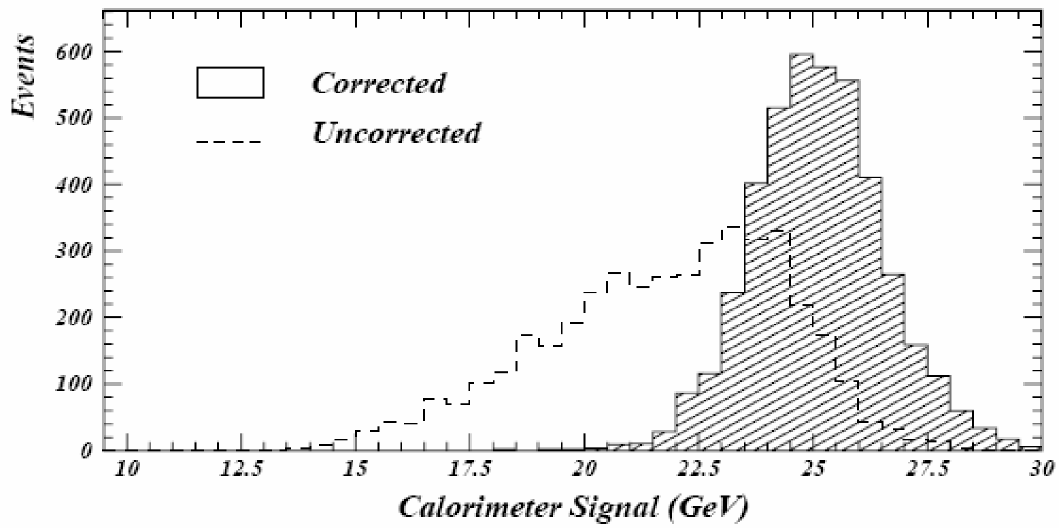


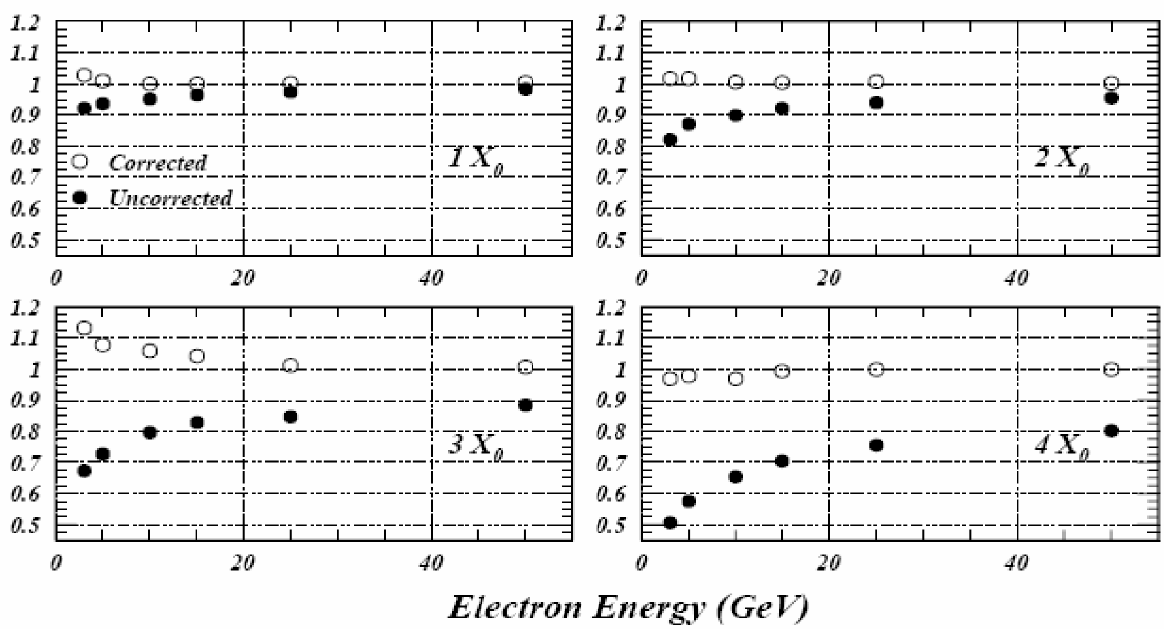




Hadron Calorimeter Systems: ZEUS

Achieve Gaussian shape

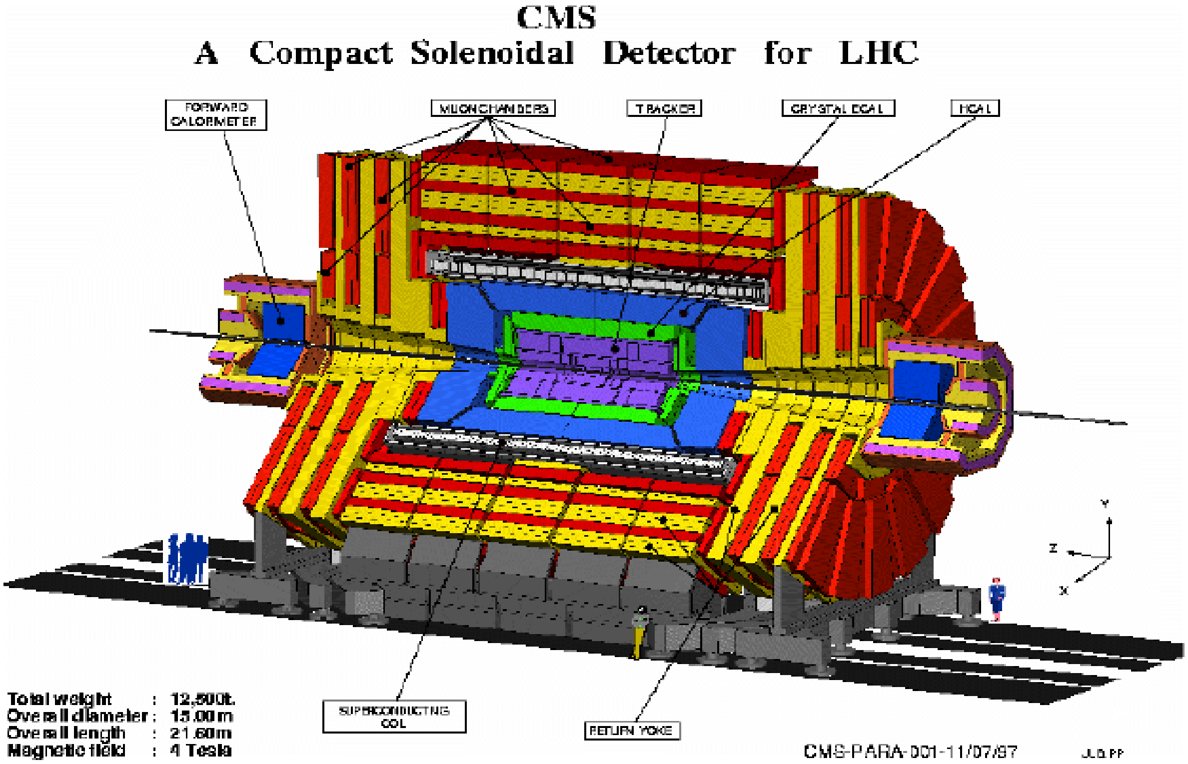




Further Optimization : Presampler
Hadron Electron Separator

Hadron Calorimeter Systems: CMS

Electromagnetic	$PbWO_4$
Hadronic	tile–calorimeter $(Sc + Cu)$



Technique : Calorimeter inside coil

$PbWO_4$: electromagnetic

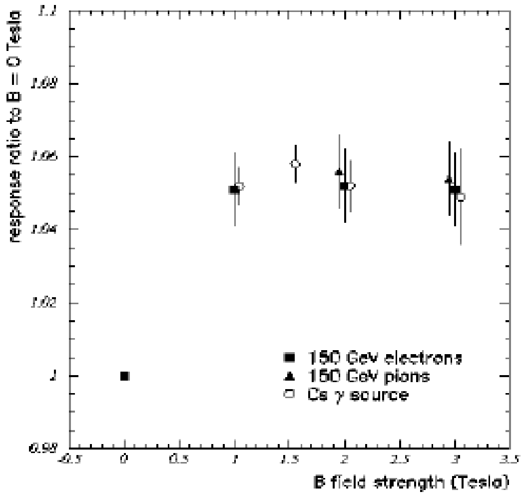
Scintillator – Tile calorimeter : hadronic

Hadron Calorimeter Systems: CMS

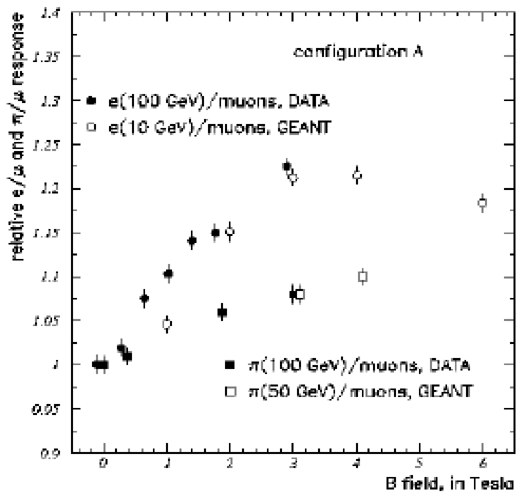
Results

- Dependence on B–field

$B_\perp$

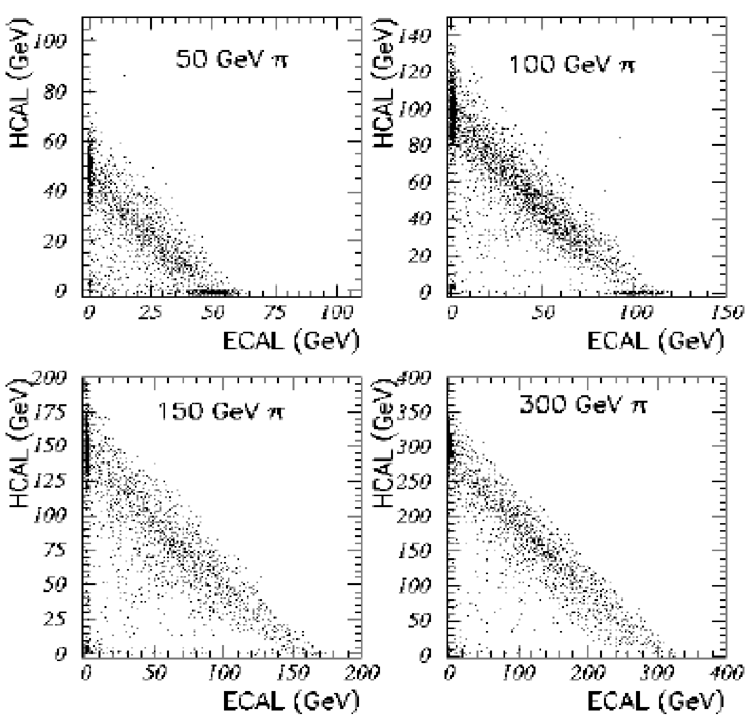


$B_{||}$



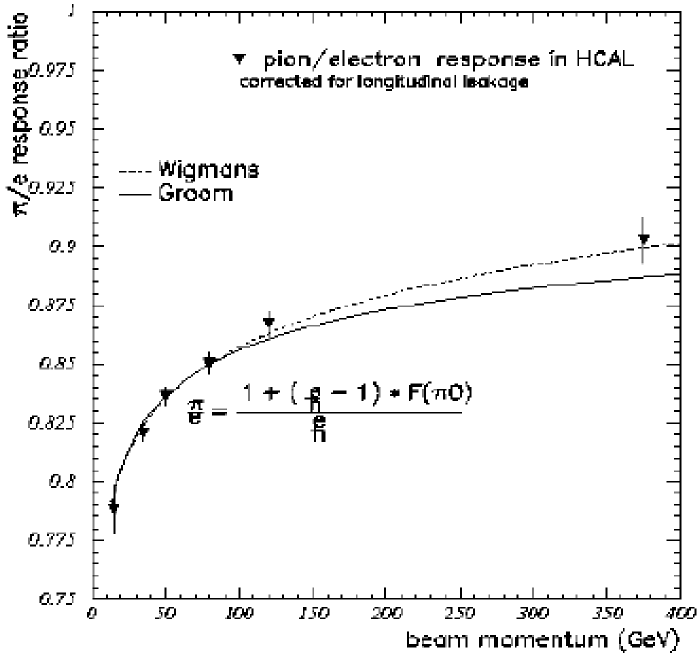
Explanation : $B_\perp$ ^3S *to* ^1S mixing

- Energy sharing between ECAL and HCAL :

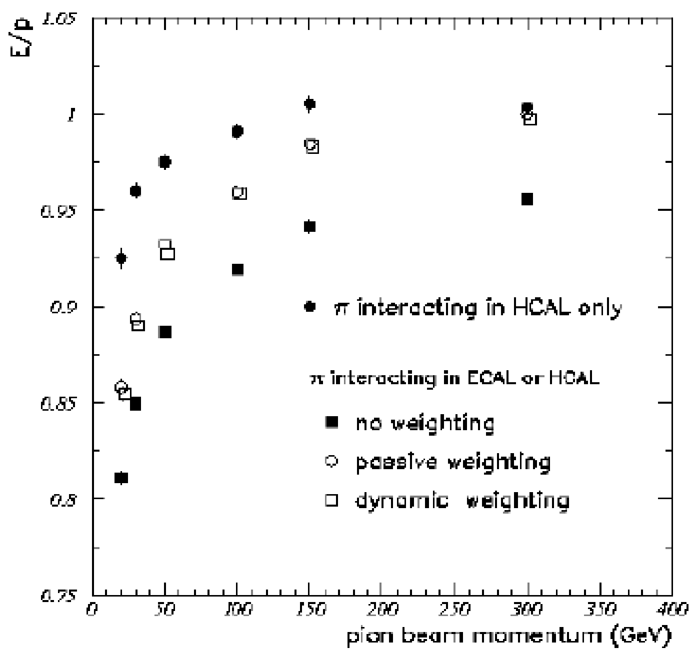


Hadron Calorimeter Systems: CMS

- $\frac{e}{\pi} \neq 1$

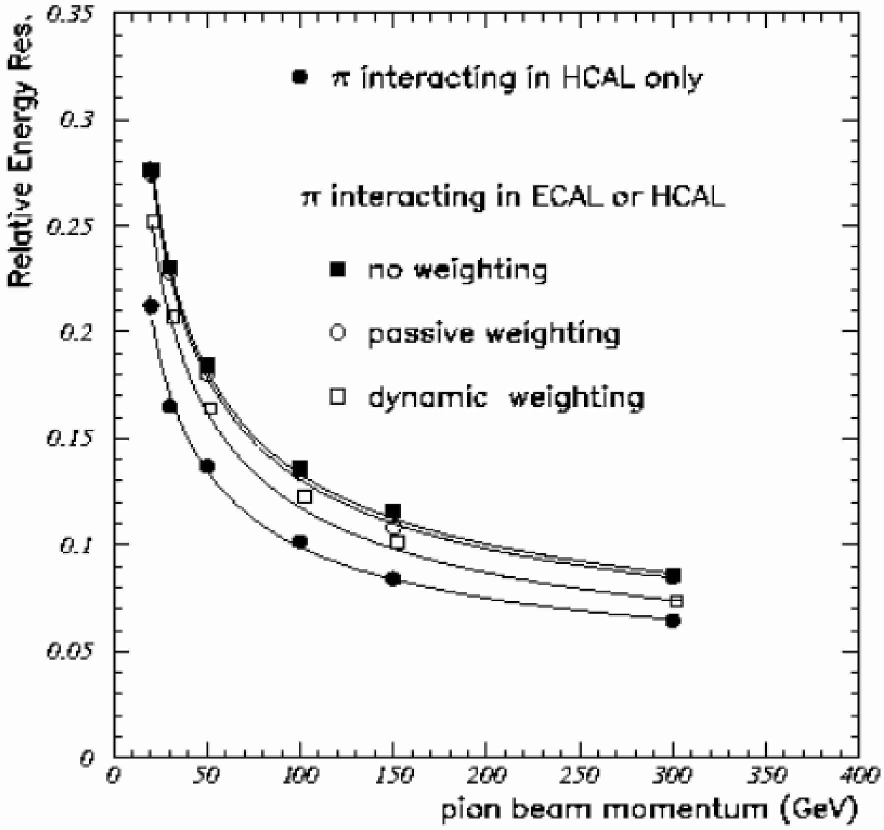


- Nonlinearity



Hadron Calorimeter Systems: CMS

- Resolution



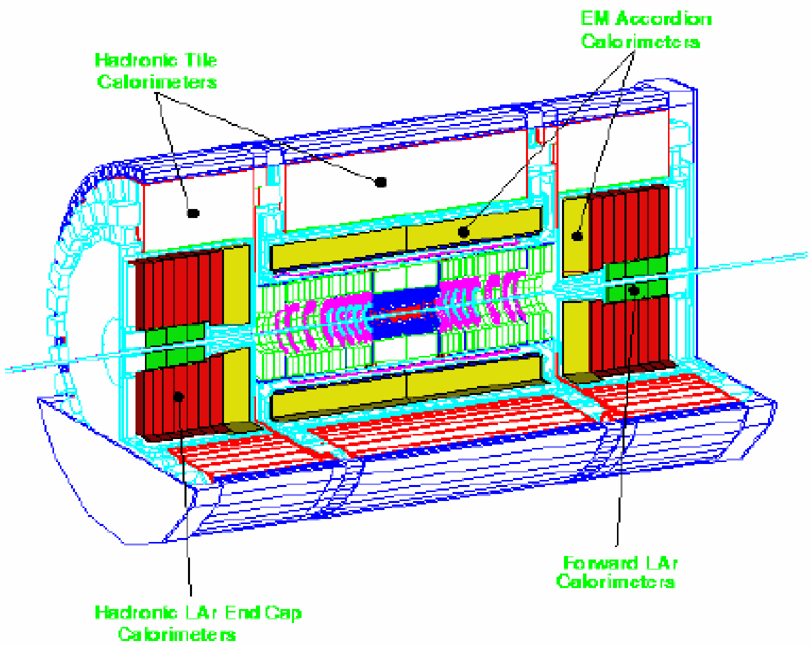
Remark :
- Excellent energy resolution
  for γ, e^- : $H \to \gamma\gamma$
- Poor hadron energy measurement

$$\left(\frac{\sigma}{E}\right)_{tile} = \frac{100\,\%}{\sqrt{E}} \oplus 4\,\%$$

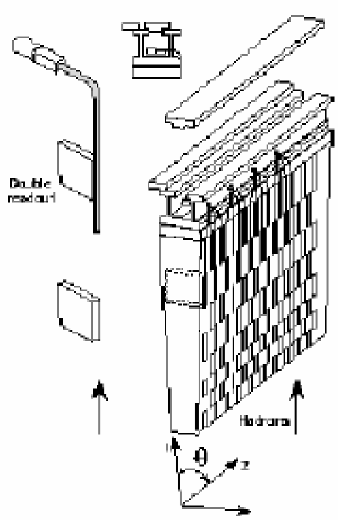
$$\left(\frac{\sigma}{E}\right)_{all} = \frac{127\,\%}{\sqrt{E}} \oplus 6.5\,\%$$

Hadron Calorimeter Systems: ATLAS

Detektor



Tile–calorimeter : hadron detection

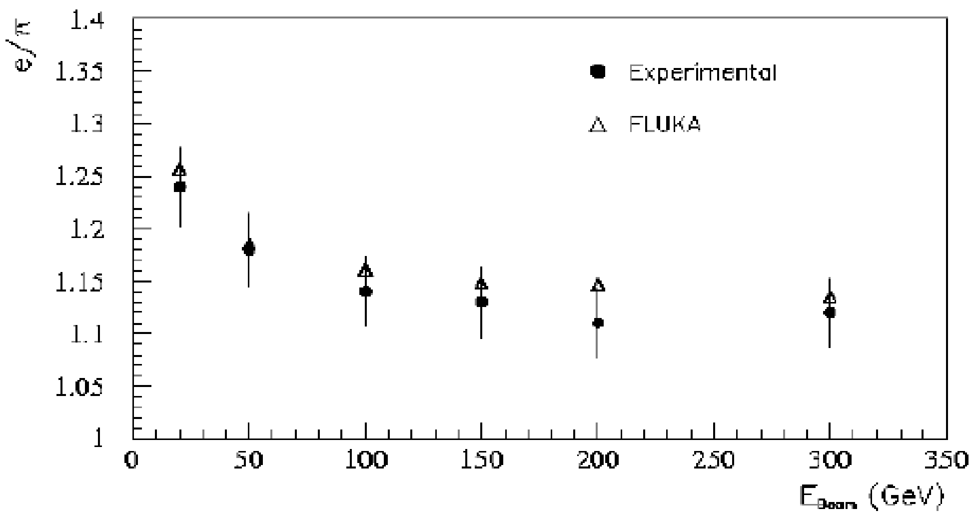


Hadrons

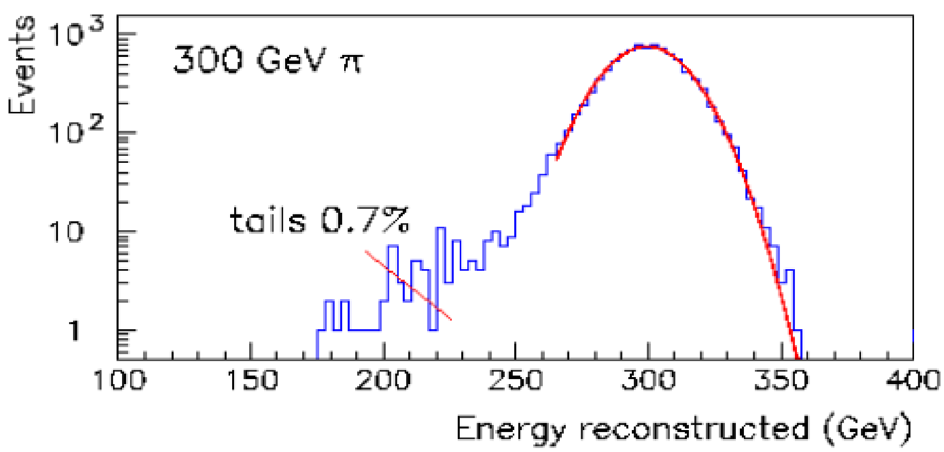
e/π–ratio :

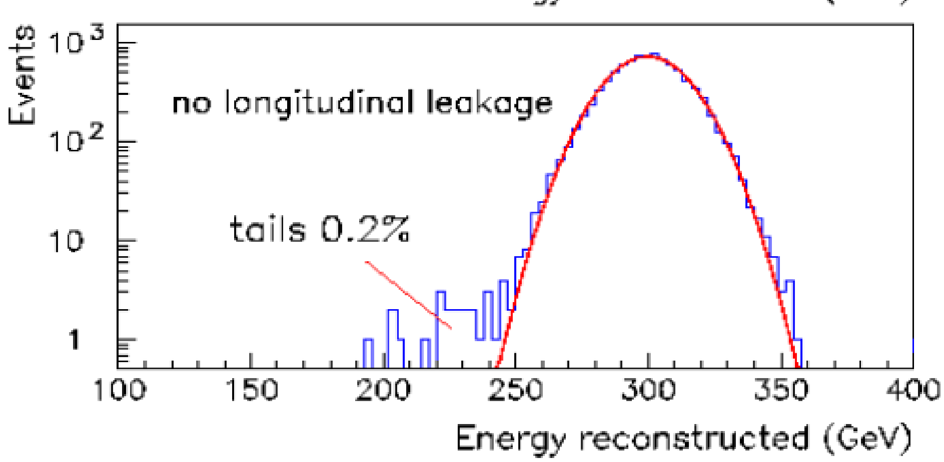
$$\frac{e}{\pi} = \frac{\frac{e}{h}}{1 + (\frac{e}{h} - 1) 0.11 \, ln \, E}, \quad \frac{e}{h} = 1.37$$

Hadron Calorimeter Systems: ATLAS



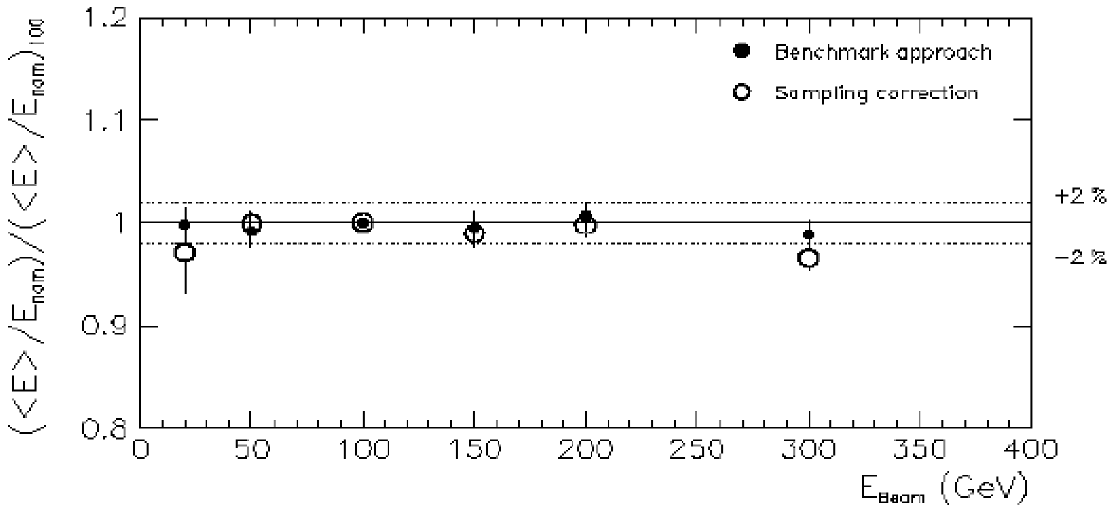
Gaussian–shape of signal



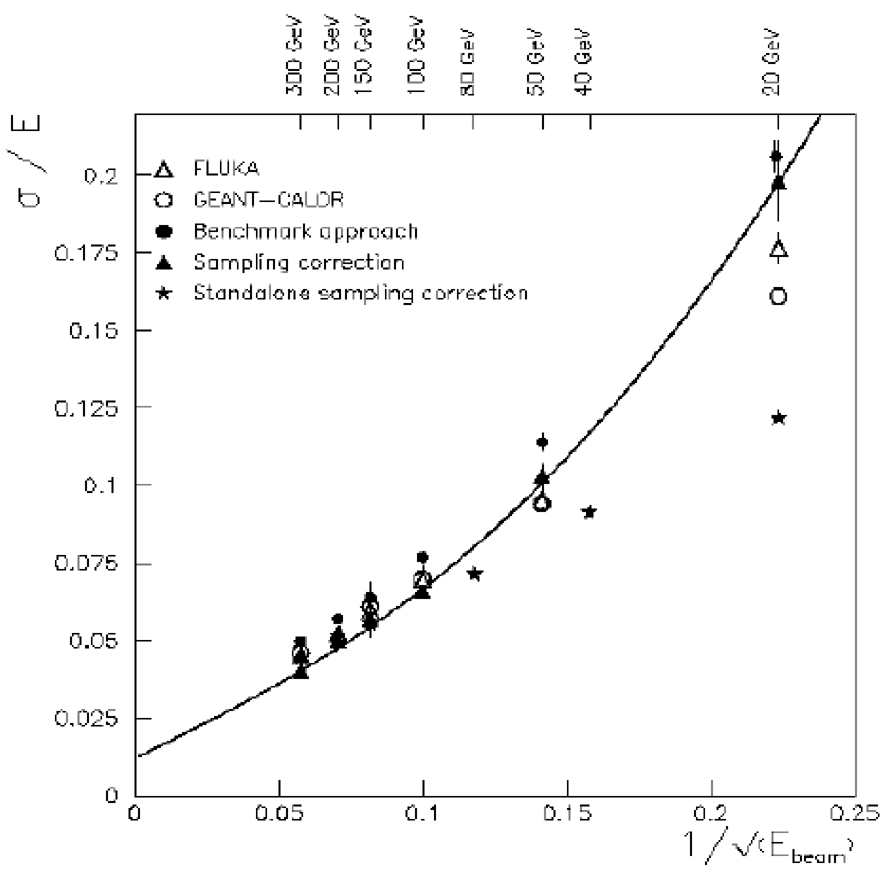


Hadron Calorimeter Systems: ATLAS

Linearity



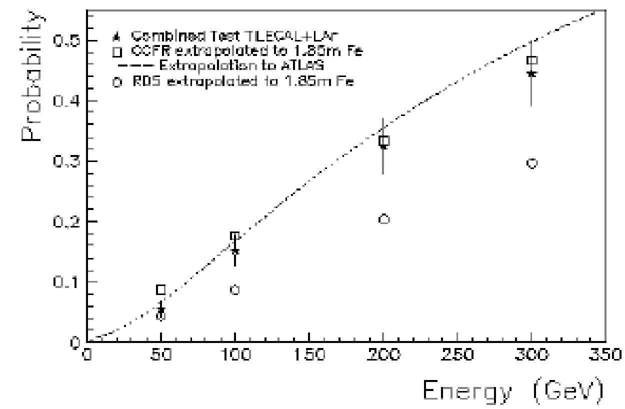
Energy resolution

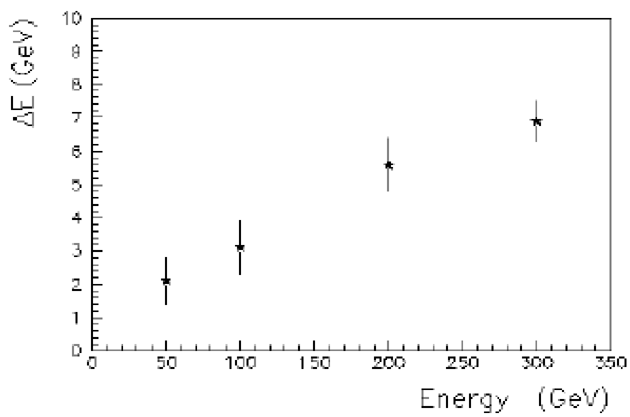


Hadron Calorimeter Systems: ATLAS

Punch through

Probability large at 300 GeV :





Comparison : LHC–detectors

	ATLAS	CMS
$\left(\frac{\sigma}{E}\right)_{em}$	$\frac{10\,\%}{\sqrt{E}} \oplus 0.35\,\%$	$\frac{4\,\%}{\sqrt{E}} \oplus 0.45\,\%$
$\left(\frac{\sigma}{E}\right)_{had}$	$\frac{42\,\%}{\sqrt{E}} \oplus 1.8\,\%$	$\frac{127\,\%}{\sqrt{E}} \oplus 6.5\,\%$
$\sigma_{\varphi\, had}$	$\frac{68\,mrad}{\sqrt{E}} \oplus 0.91\,mrad$	

Good/excellent electromagnetic calorimetry

$$H \rightarrow \gamma\gamma$$