Toward meaningful simulations of hadronic showers*

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HSSW, Fermilab, 8 September 2006

Outline:

- The practical importance of reliable simulations
- The crucial elements of such simulations
  - *How do we know that these elements are crucial?*
  - *How do we test if they are correctly implemented? ("generic validation")*
- Conclusions

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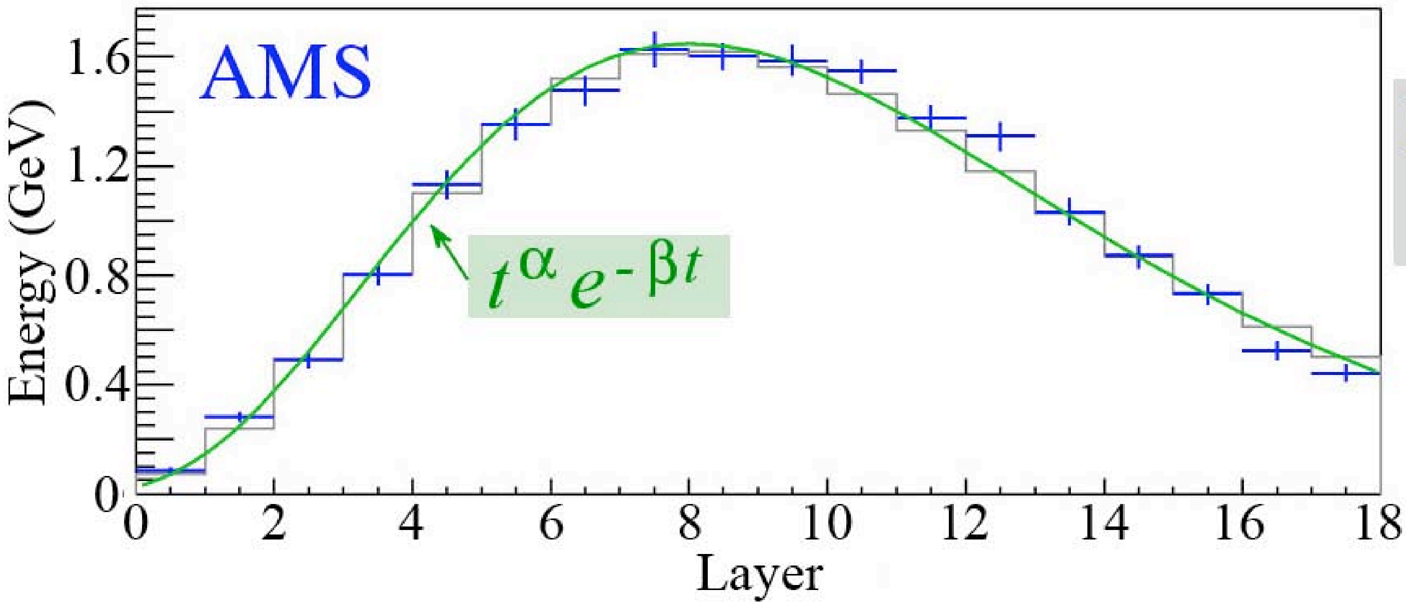
* *for purposes of calorimetry*

The importance of reliable simulations for calorimetry (1)

Leakage estimates in the AMS calorimeter

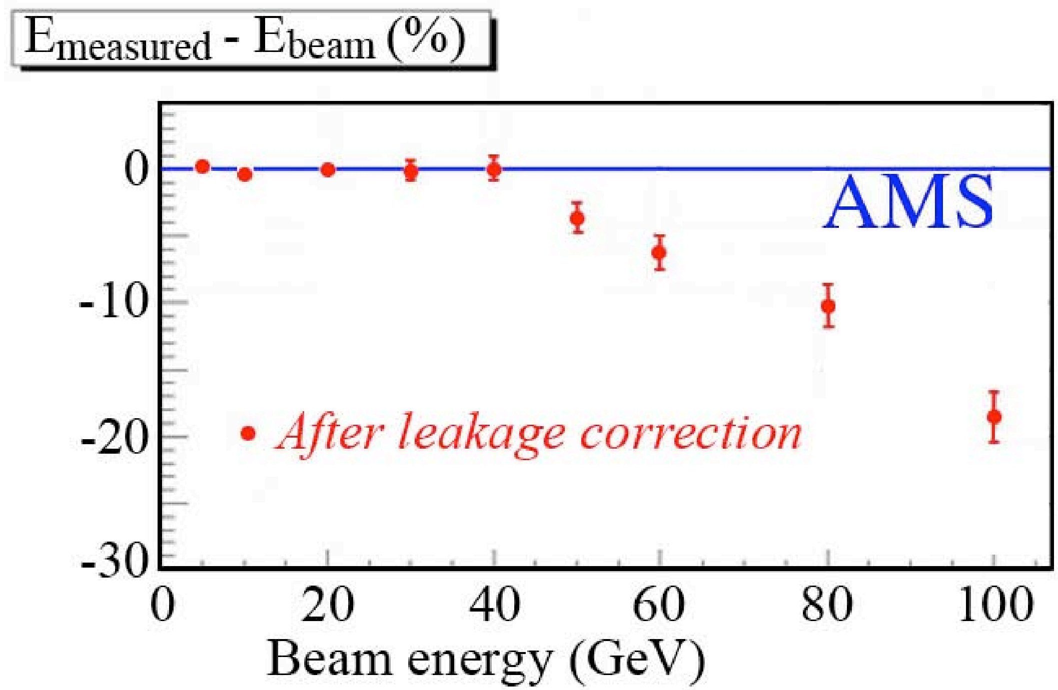


NIM A490, 132 (2002)

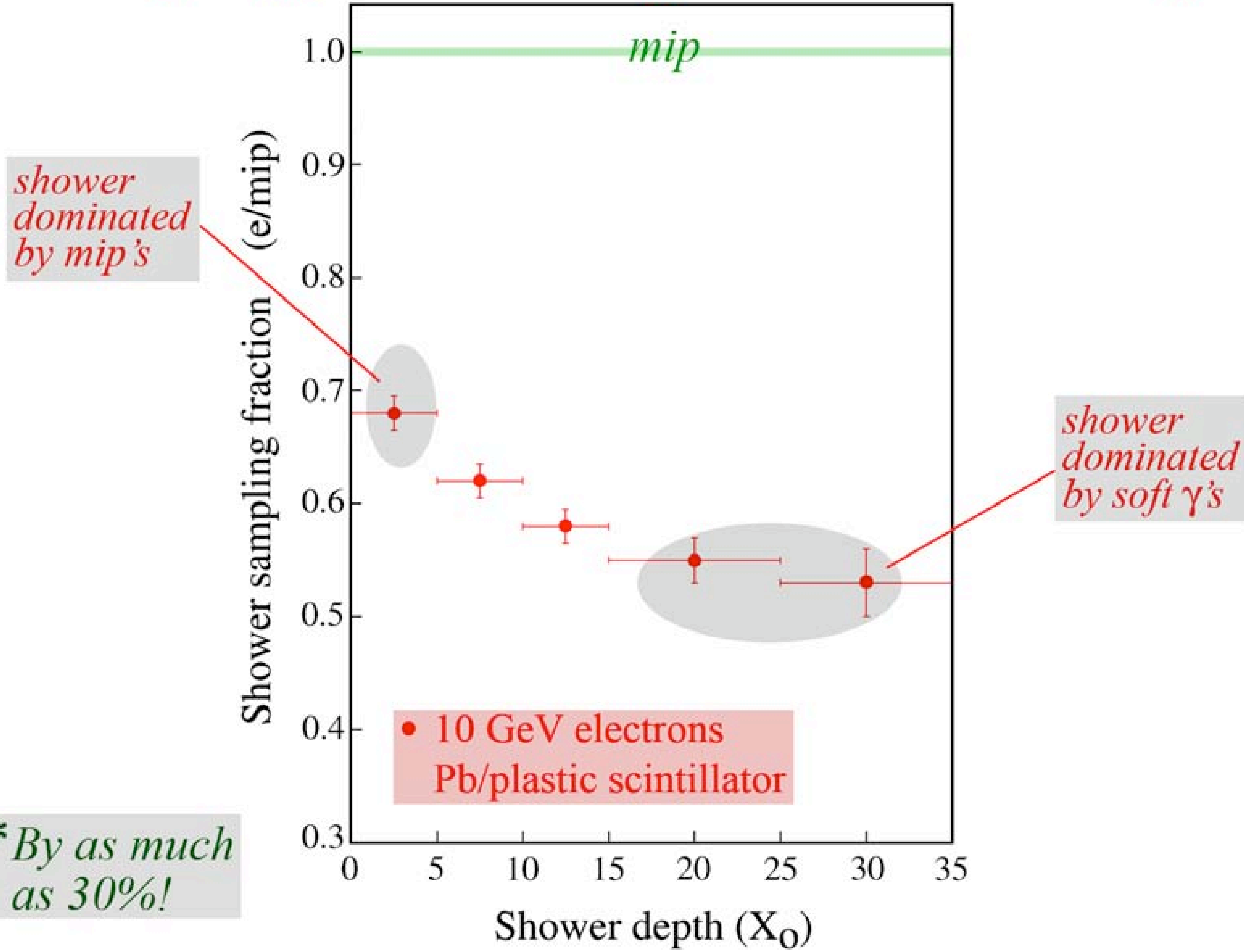
Pb/scintillating fiber
18 layers (17 X_0)

Calibrated with mip's:
11.7 MeV/layer

Shower leakage:
(Under)estimated on the basis of fits to longitudinal profile



*The sampling fraction changes as shower develops**



**By as much as 30%!*

The importance of reliable simulations for calorimetry (2)

- In most sampling calorimeters, the electromagnetic sampling fraction *decreases* as the shower develops

- In practice, this may have important consequences, *e.g.*:

Systematic mismeasurement of energy	- NIM A490 (2002) 132
Electromagnetic signal non-linearity	- NIM A262 (1987) 243
Differences in response to e, γ, π^o	- NIM A485 (2002) 385
etc.	

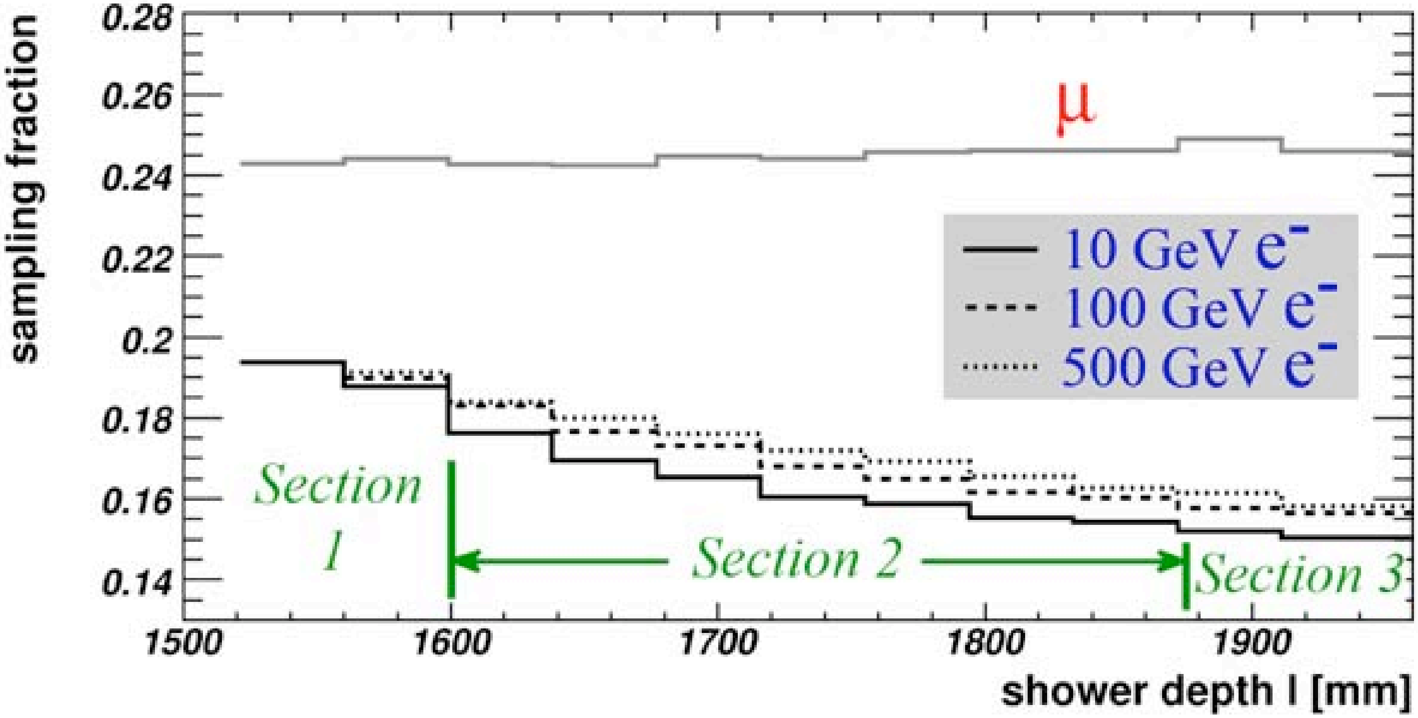
- These issues are especially relevant in *longitudinally segmented* devices. To avoid them, one has to solve the non-trivial problem of *intercalibrating* the segments.

  A modern example: The ATLAS ECAL

The importance of reliable simulations for calorimetry (3)

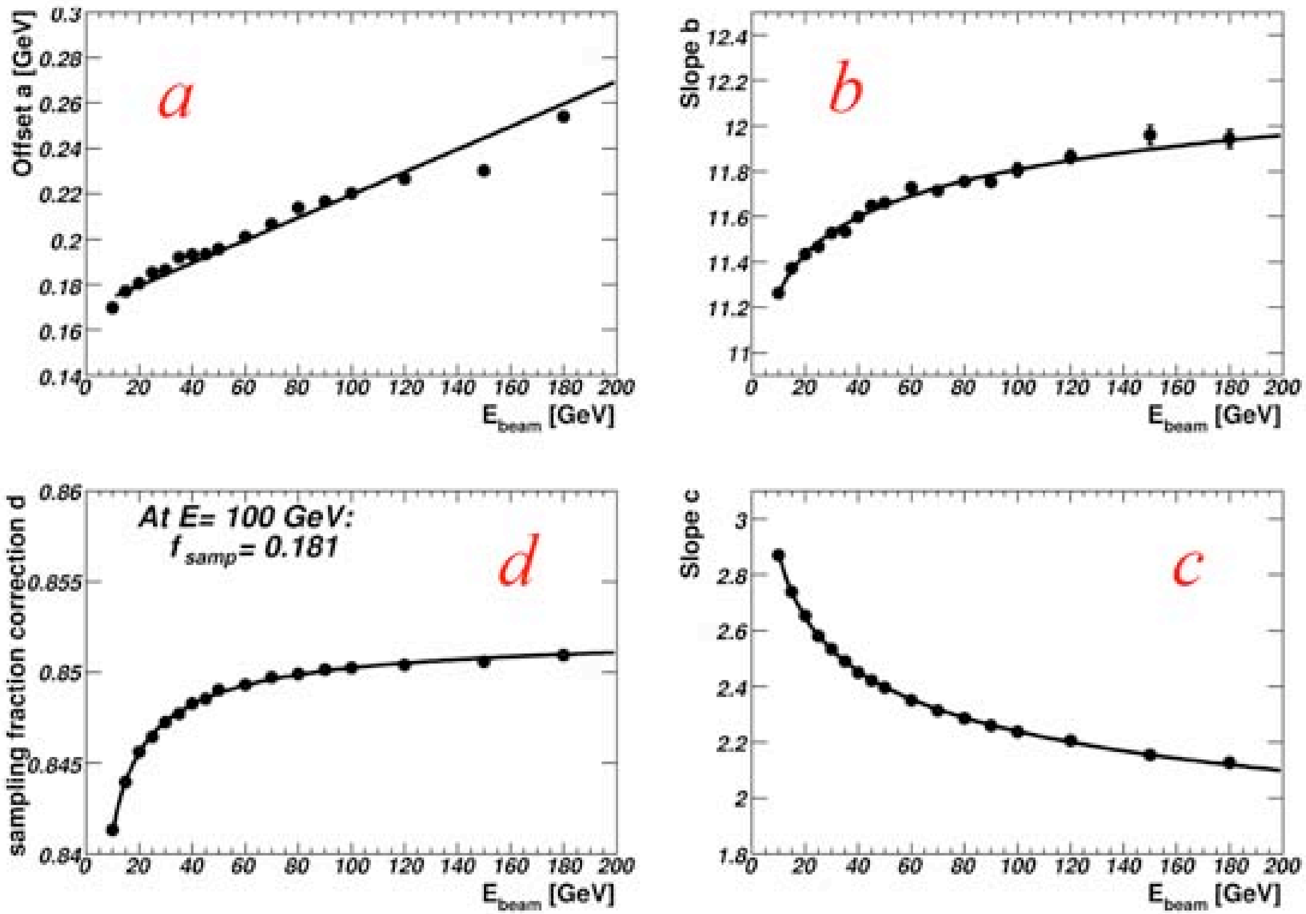
The ATLAS electromagnetic calorimeter (Pb/LAr)

The relationship between signal and energy is different for each of the 3 sections, in an energy dependent way!!



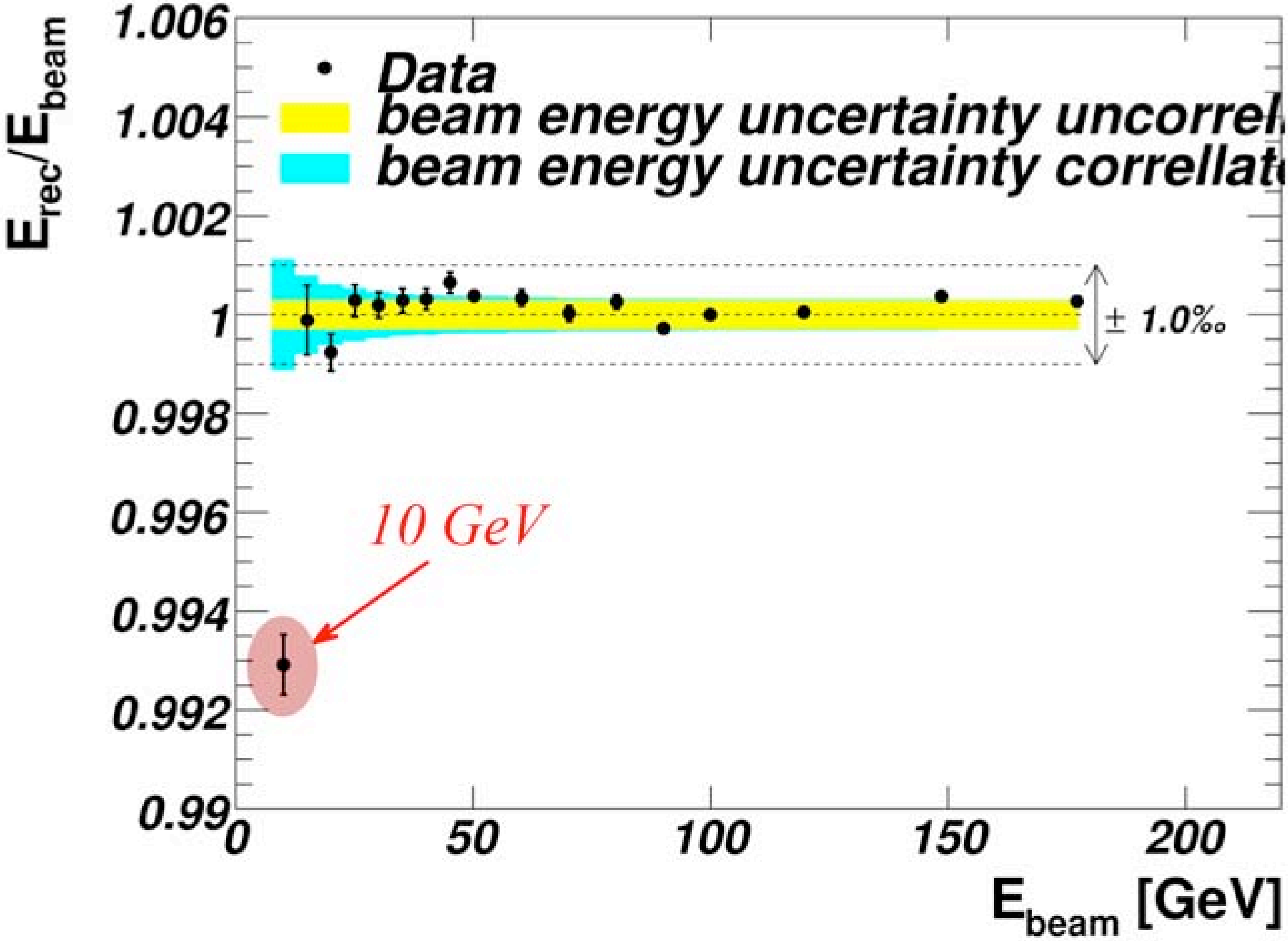
→ *How to (inter)calibrate these sections?*
How to achieve good linearity/energy resolution?

ATLAS: Energy reconstruction ECAL
(developed & optimized with MC simulations)



$$E^{rec} = \left(a(E) + b(E)\, E_0^{vis} + c(E)\, (E_0^{vis} \cdot E_1^{vis})^{0.5} + \frac{1}{d(E)\, f_{samp}} \sum_{i=1,3} E_i^{vis} \right) \cdot f_{\mathrm{cell\,impact}}(\Delta\Phi) \cdot (1 + f_{\mathrm{leakage}})$$

ATLAS: Electromagnetic signal linearity



Shower simulations and calorimetry

- Absorption of high-energy particles in dense matter is a very complicated process. However, for the purpose of calorimetry, only very few aspects of this process are of critical importance.

- In the previous examples, what mattered was the fact that the soft-γ component is sampled with a different efficiency than the mip component. There is no need to simulate in detail what happens below 100 keV to get this aspect right.

- Also for hadron calorimetry, only a few aspects of the shower development process are of crucial importance.
  It is important to get these aspects right in the simulations.
  For example, application of the laws of conservation of energy and baryon number is essential. On the other hand, hadronic reactions with a relative probability < 1% can be safely ignored, except for some very specific applications (e.g., μ *production in hadronic shower development)*

- In the following, the crucial aspects of hadronic shower simulations are discussed. *I will only show experimental data* (to illustrate the cruciality).

The crucial elements of hadronic shower simulations (1)

Hadronic showers consist of two distinctly different components:

- An *electromagnetic* component
  (γs from π^0 and η decay generate electromagnetic showers)
- A *non-electromagnetic* component
  (The rest)

The main difference (for purposes of calorimetry):

Some fraction of the energy carried by the non-em component does *not* contribute to the calorimeter signals *("invisible" energy)*

Let the *response (average signal per GeV)* to the em component be e and the response to the non-em component h

Then, the e/h ratio quantifies this effect

(e.g. in crystal calorimeters, $e/h \sim 2 \longrightarrow$ 50% of non-em energy invisible)

The crucial elements of hadronic shower simulations (2)

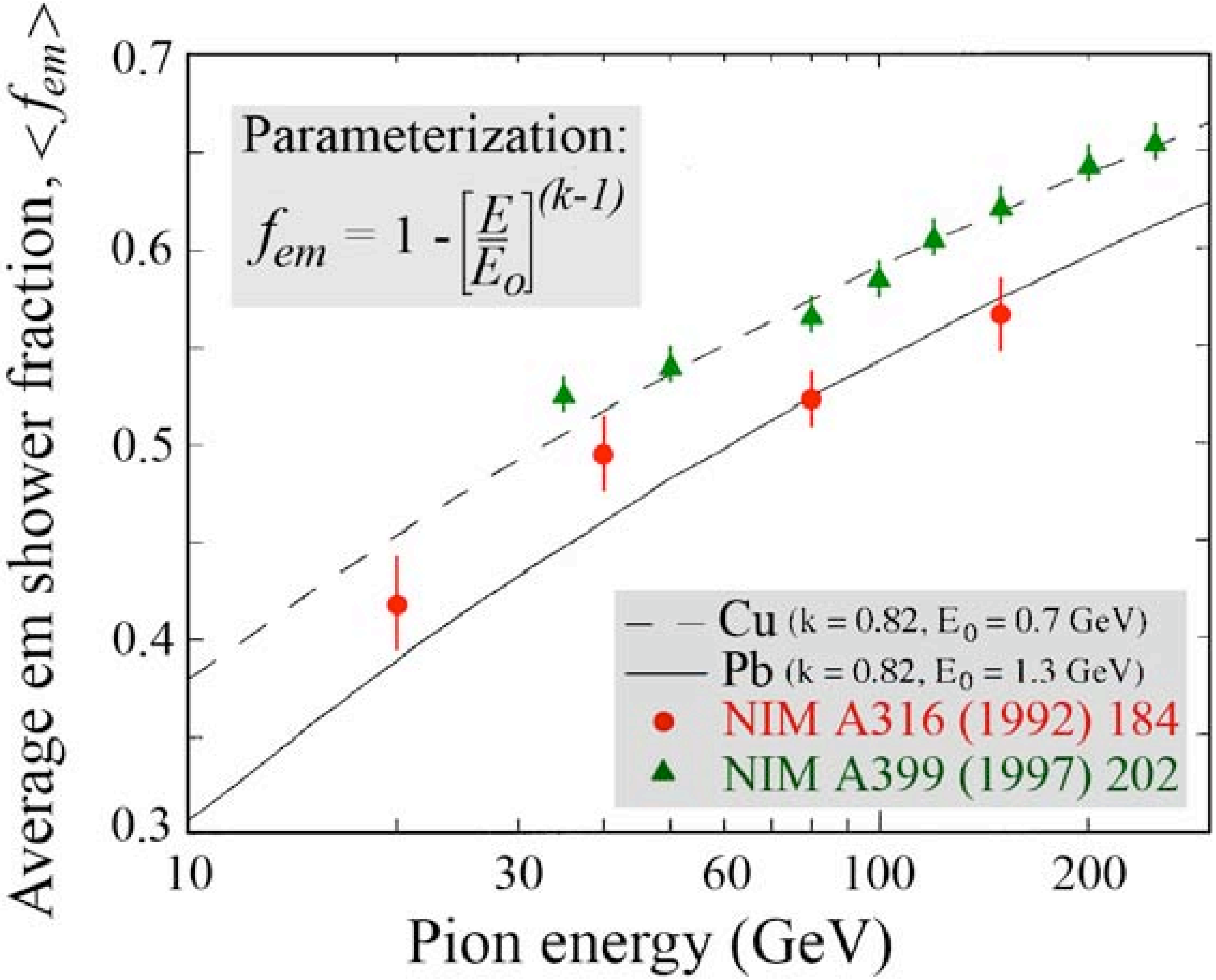
The electromagnetic shower component

Characteristics affecting calorimeter performance in crucial ways

Let f_{em} (= E_{em}/E_{tot}) be the *em shower fraction*

Characteristic	*Consequence for calorimetry*
• $\langle f_{em} \rangle$ increases with energy	Hadronic signal non-linearity

The em shower fraction, f_{em} (1)



$<f_{em}>$ is *large, energy dependent* and *material dependent*

The crucial elements of hadronic shower simulations (2)

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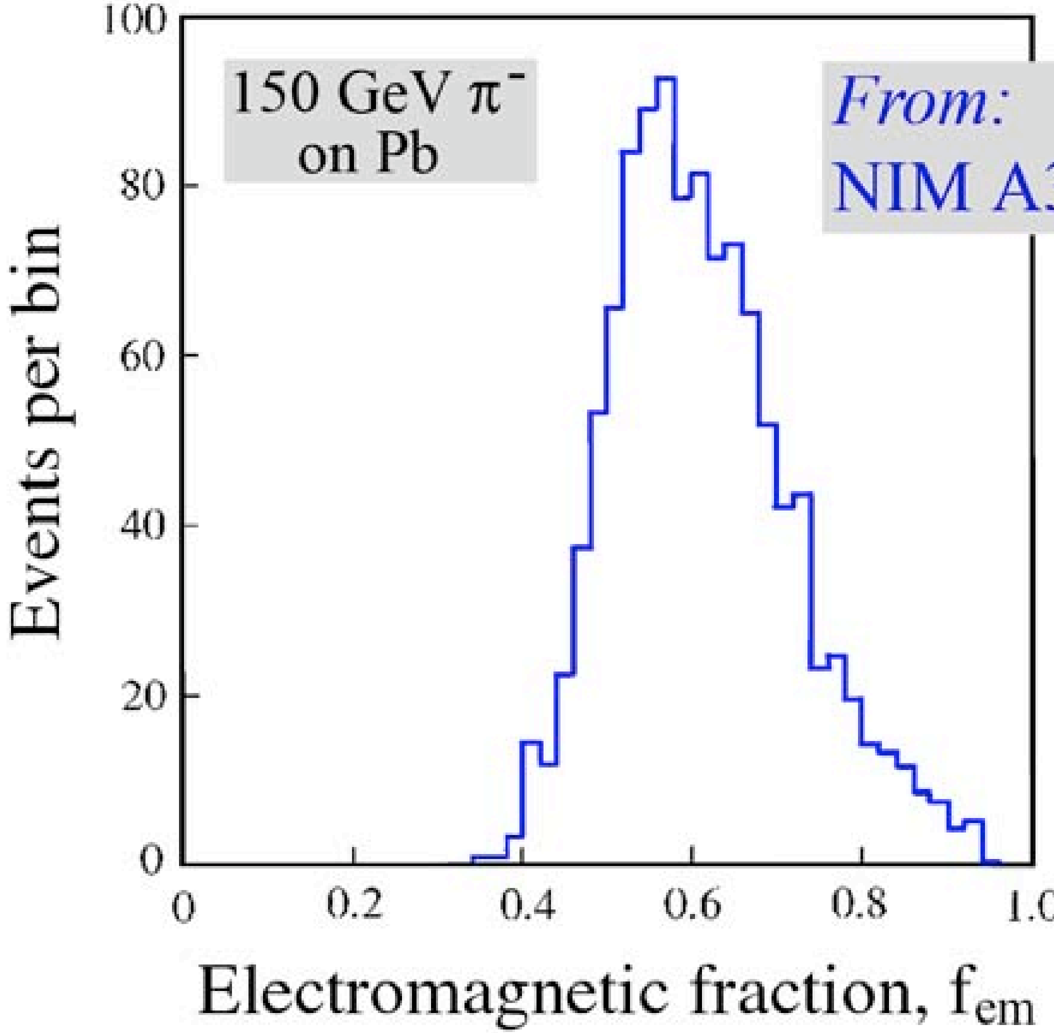
• $\langle f_{em} \rangle$ increases with energy	Hadronic signal non-linearity
• Fluctuations in f_{em} non-Poissonian	Non-Gaussian response function Deviations from $E^{-1/2}$ scaling

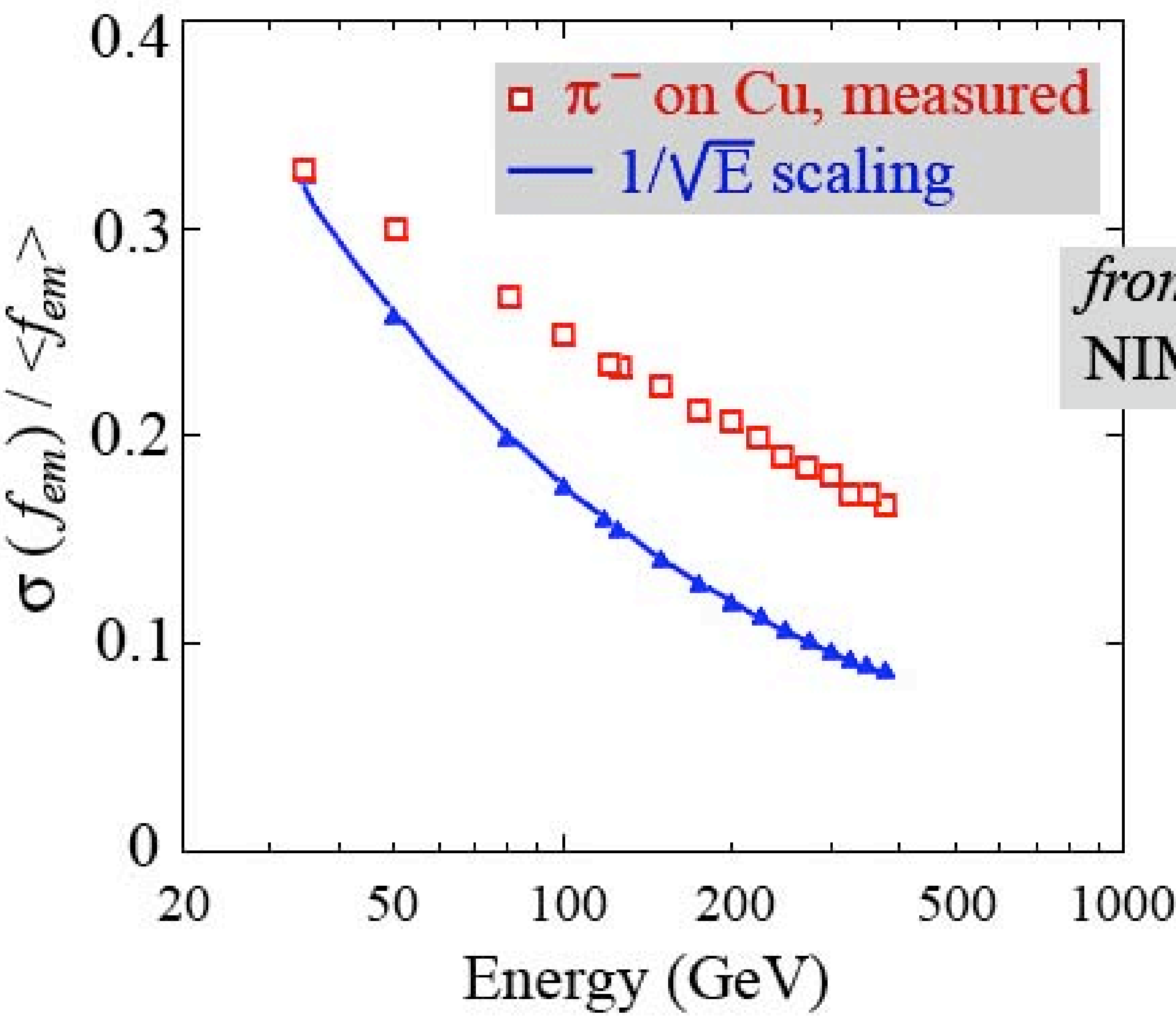
The em shower fraction, f_{em} (2)



From:
NIM A316 (2002) 184

Fluctuations in f_{em} are *large and non-Poissonian*

The em shower fraction, f_{em} (3)



from
NIM A399 (1997) 202

Fluctuations in f_{em} are non-Poissonian

The crucial elements of hadronic shower simulations (2)

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• $\langle f_{em} \rangle$ increases with energy	Hadronic signal non-linearity
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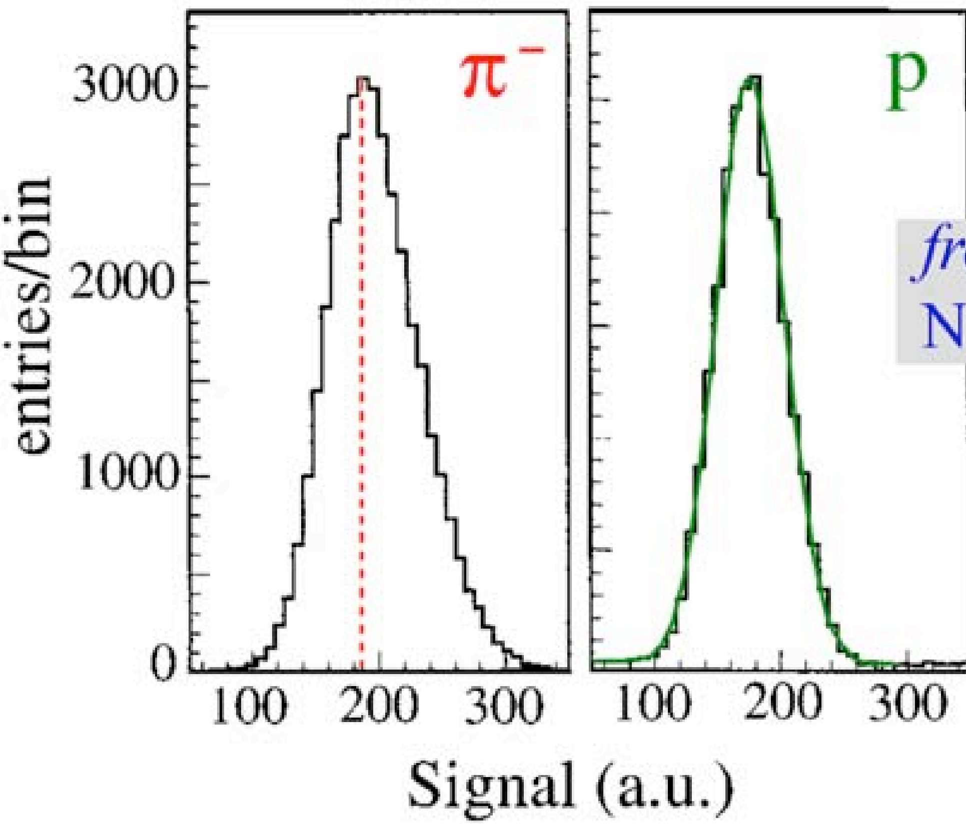
• Differences between p and π	Differences in response Differences in response function

The em shower fraction, f_{em} (4)

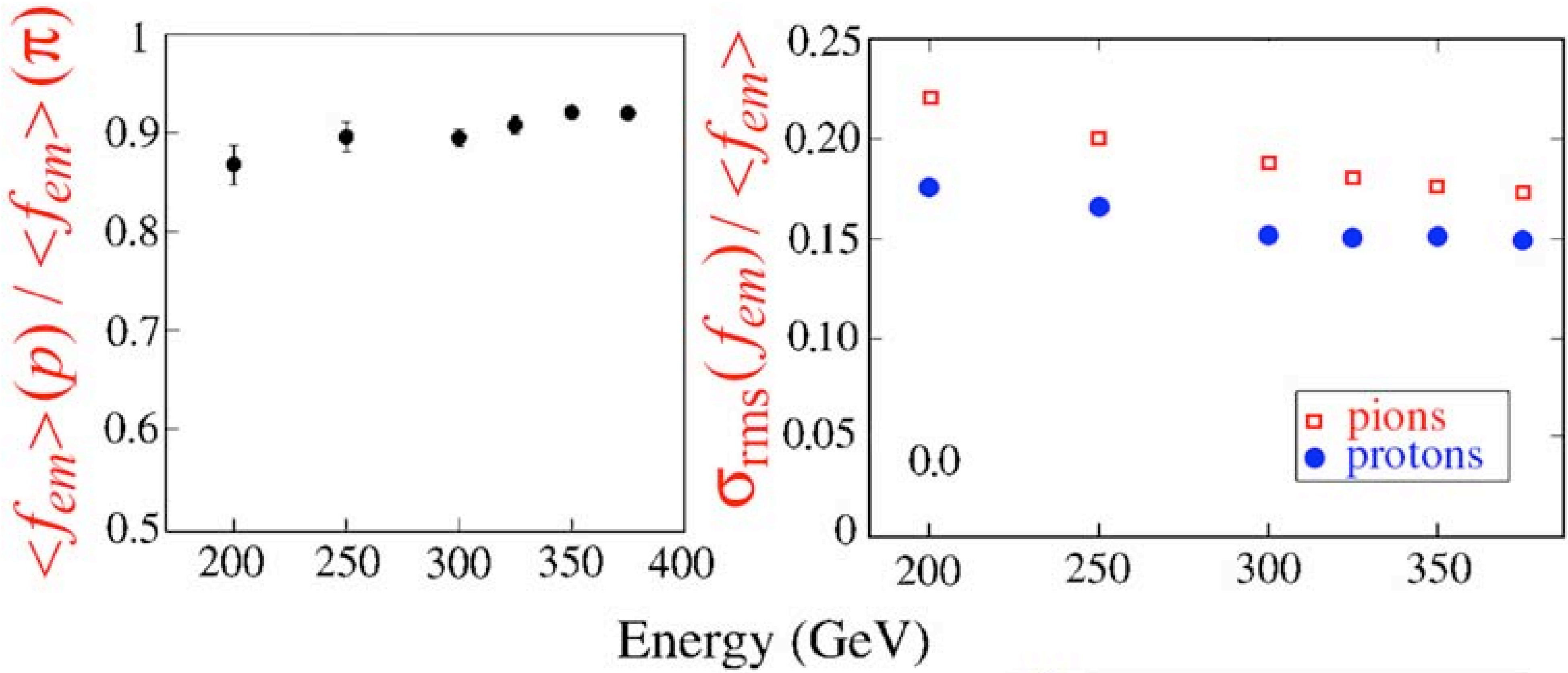


300 GeV showers
in Cu

from:
NIM A408 (1998) 380

f_{em} fluctuations are different in π- and *p*-induced showers

The em shower fraction, f_{em} (5)



from:
NIM A408 (1998) 380

$<f_{em}>$ and the fluctuations in f_{em} are different in π- and p-induced showers

The crucial elements of hadronic shower simulations (2)

The electromagnetic shower component

Characteristics affecting calorimeter performance in crucial ways

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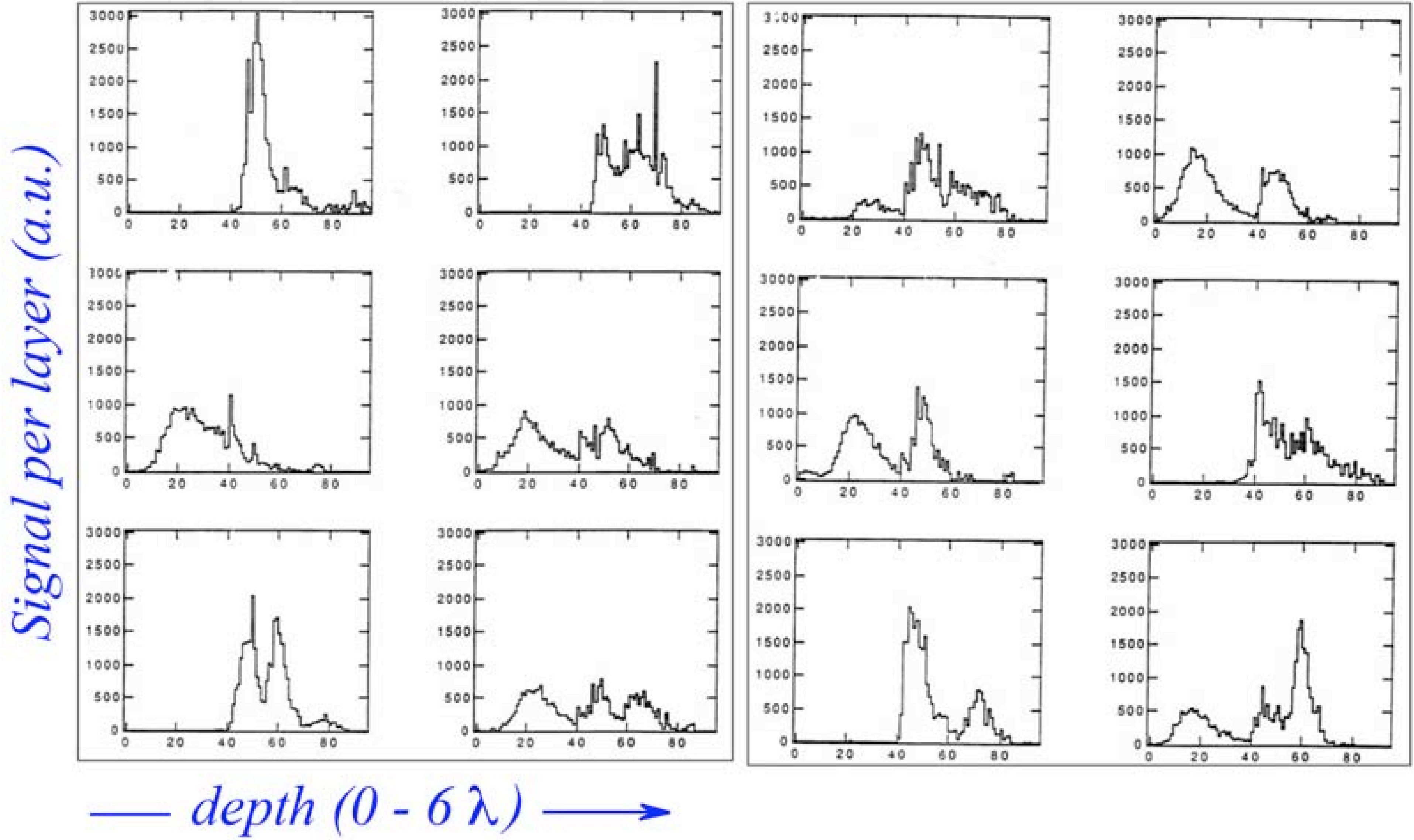
Characteristic	*Consequence for calorimetry*
• $<f_{em}>$ increases with energy	Hadronic signal non-linearity
• Fluctuations in f_{em} non-Poissonian	Non-Gaussian response function Deviations from $E^{-1/2}$ scaling
• Differences between *p* and π	Differences in response Differences in response function
• Em component distributed over entire shower development	No “characteristic” profiles

"Characteristic" hadronic shower profile does NOT exist



270 GeV π in Pb/scintillator
(hanging-file experiment)

The crucial elements of hadronic shower simulations (3)

The *non-electromagnetic* shower component

A very large fraction (> 80%) of the calorimeter signal from this component is caused by *protons* and other nuclear fragments. Pions and other mips play, at best, only a minor role.

It is, therefore, crucial to simulate the processes in which these protons are being produced, as accurately as possible.

→ *Nuclear breakup* processes determine many aspects of the hadronic calorimeter performance

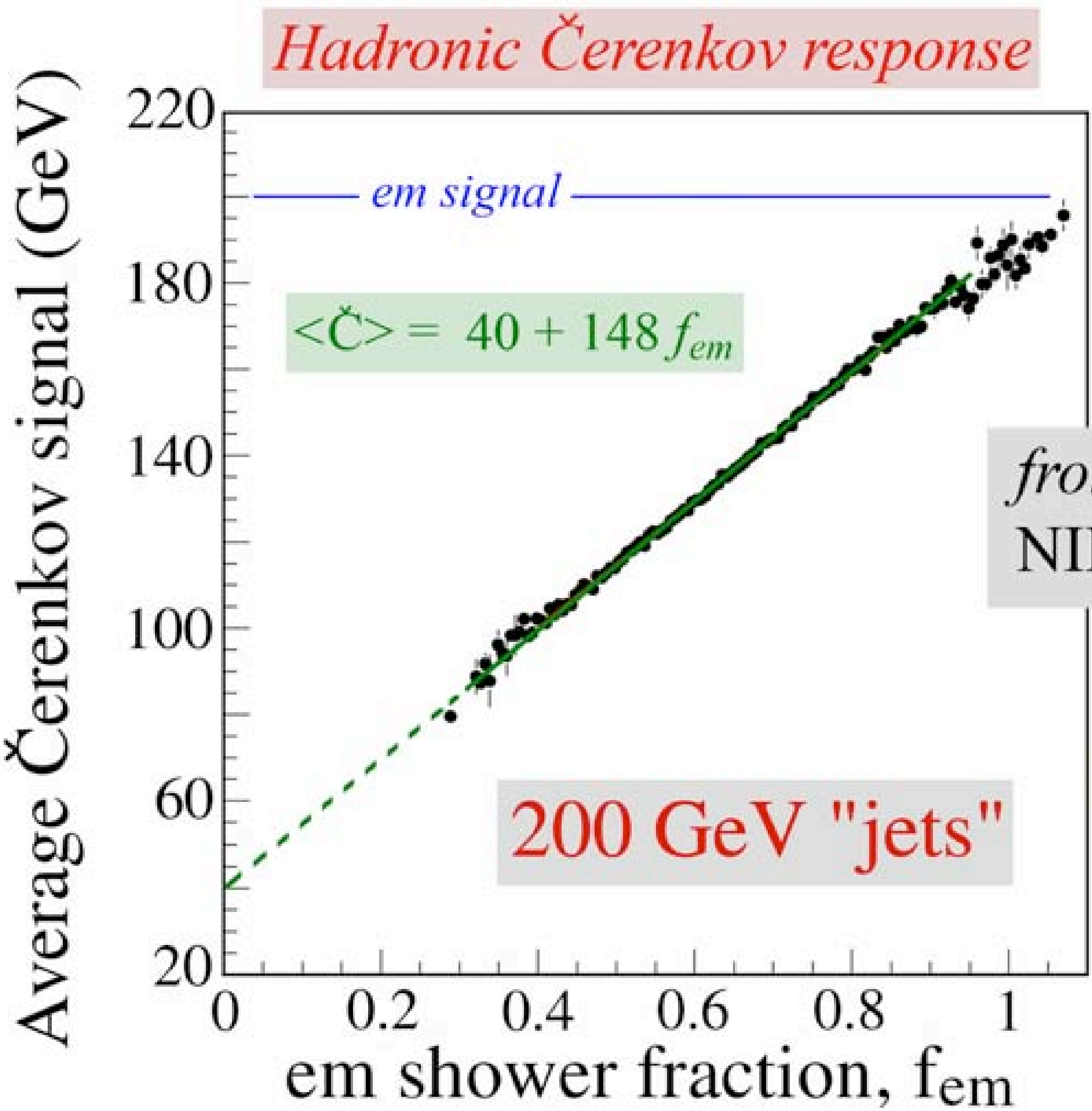
The non-electromagnetic shower component (1)

How do we know that protons dominate non-em signal?

1) Because of the small hadronic signals (i.e. large e/h values) of calorimeters that are blind to these protons.

In quartz-fiber calorimeters ($n = 1.46$), only particles with $\beta > 0.69$ emit Čerenkov light, i.e. $E_{kin} > 0.2$ MeV for electrons and > 350 MeV for protons

DREAM: Measure f_{em} event-by-event



$$R = f_{em} \cdot e + (1-f_{em}) \cdot h$$
$$= p_0 + p_1 f_{em}$$

from:
NIM A537 (2005) 537

$$f_{em} = 0 \longrightarrow R_h = 0.2\, R_{em}$$
$$< 0.2\, R_{mip}$$

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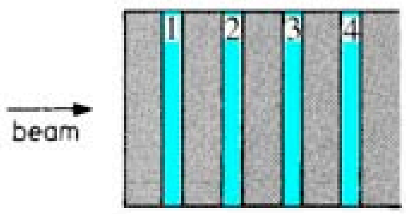
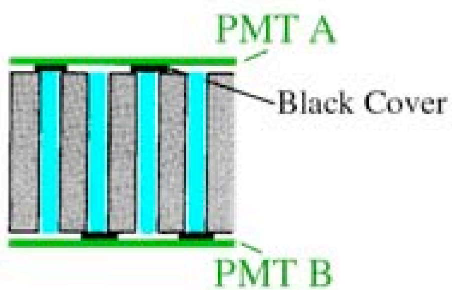
2) Because of the absence of correlations between the signals from adjacent active layers in fine-sampling hadron calorimeters

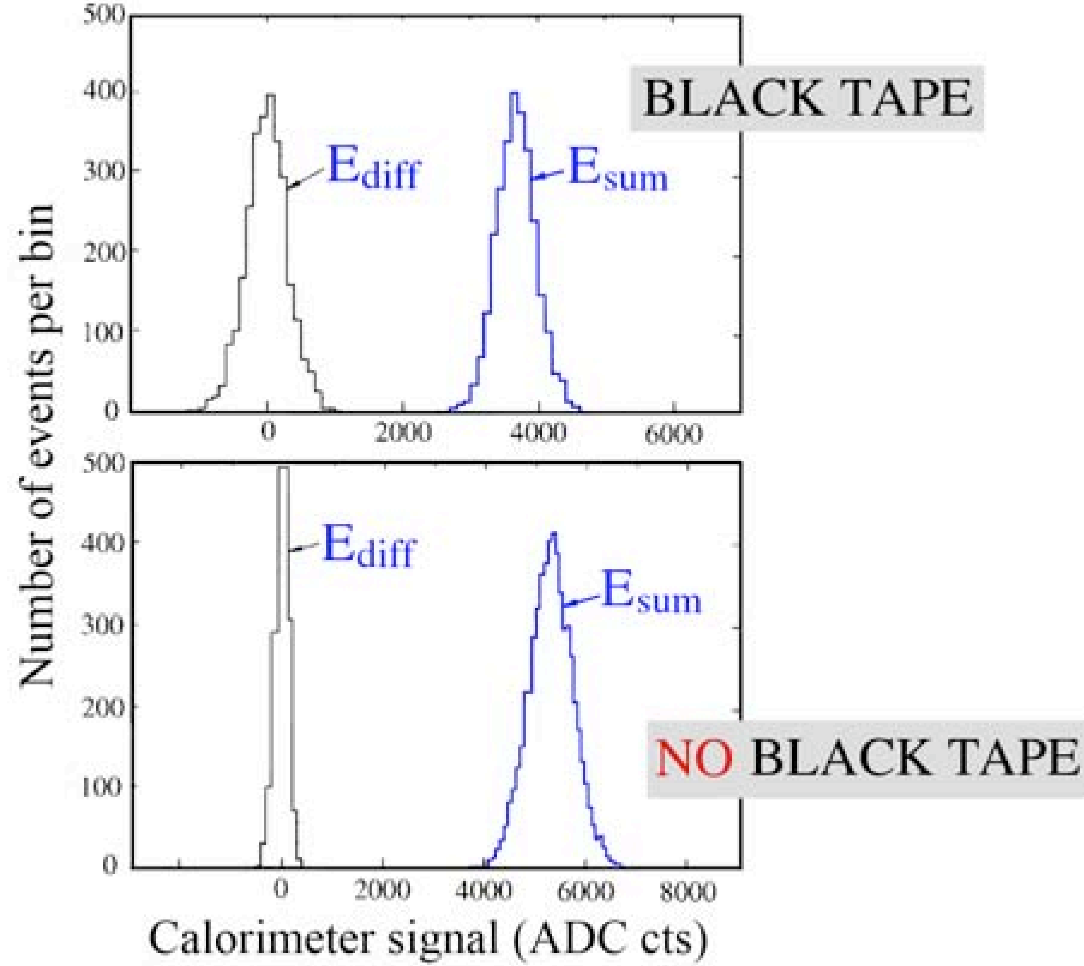
The calorimeter from the example had 0.06 λ_{int} thick sampling layers. A mip would lose on average 12.7 MeV traversing these layers.

Correlations between signals from different sampling layers



$$E_a = E_1 + E_3 + \ldots$$
$$E_b = E_2 + E_4 + \ldots$$
$$E_{sum} = E_a + E_b$$
$$E_{diff} = E_a - E_b$$





Fluctuations (%)	*10 mm lead / 2.5 mm plastic* Electrons	Pions
σ_A, σ_B	36.0±1.0	60.5±1.0
σ_{sum}	24.5±1.0	43.5±1.0
σ_{diff}	25.8±1.0	42.3±1.0

from:
NIM A290 (1990) 335

The crucial elements of hadronic shower simulations (4)

Where do these protons come from?

1) Nuclear spallation.

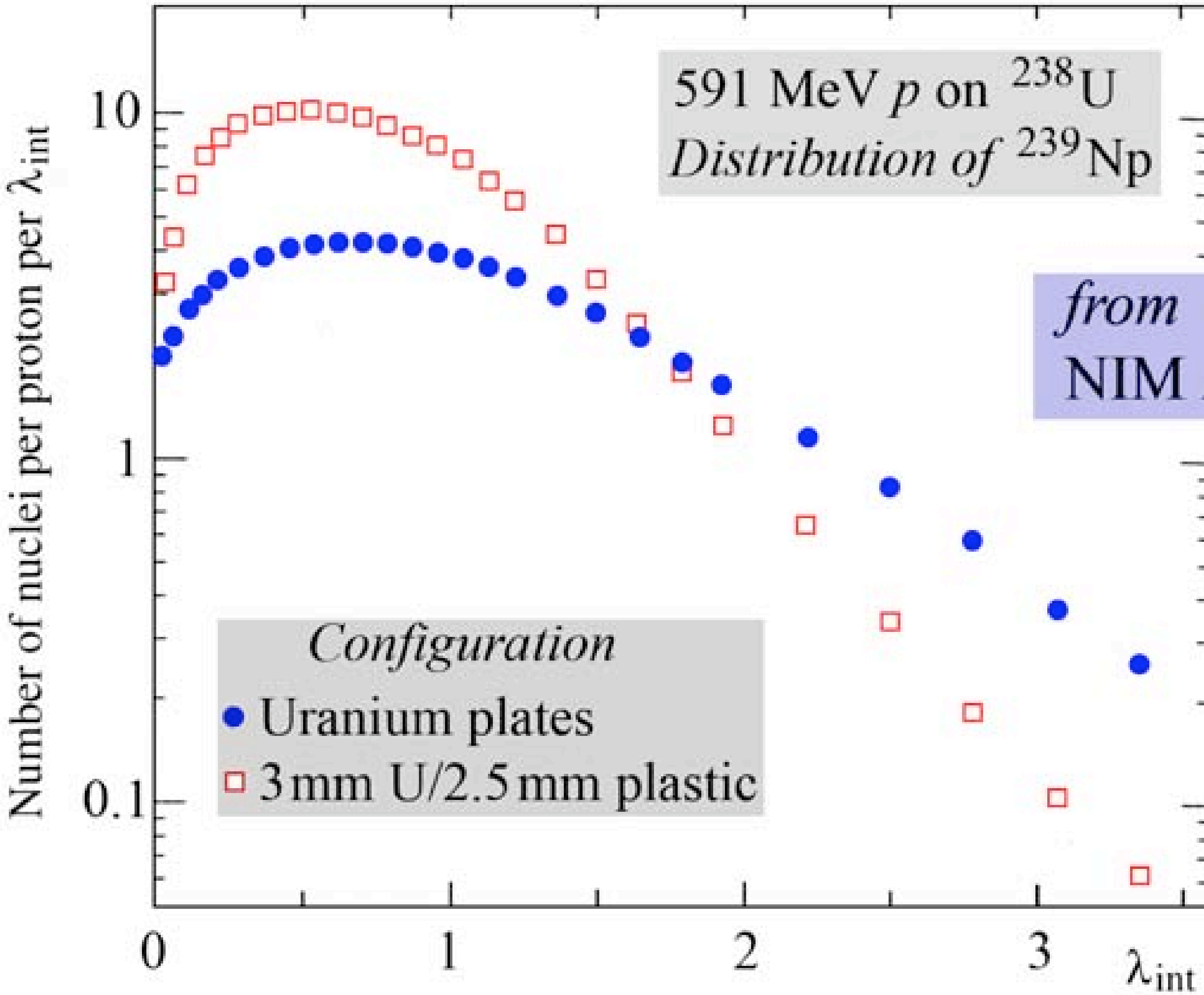
Spallation protons typically carry ~ 100 MeV kinetic energy.
Their range is typically of the order of the thickness of sampling layers in hadron calorimeters.

2) Nuclear reactions induced by neutrons, e.g. (*n,p*) reactions

These protons have kinetic energies comparable to those of the (evaporation) neutrons that generated them (< 10 MeV)
These neutrons outnumber spallation protons by an order of magnitude

Measurements of neutron production in hadronic showers:
> 40 per GeV in some materials (NIM A252 (1986) 4)

The importance of hydrogen in the absorbing structure



from
NIM A252 (1986) 4

(Nuclear evaporation) neutrons are typically produced with E_{kin} ~ few MeV.
Elastic *n-p* scattering slows these neutrons down.
^{239}Np is produced by thermal neutron capture in uranium

The special role of neutrons in calorimetry

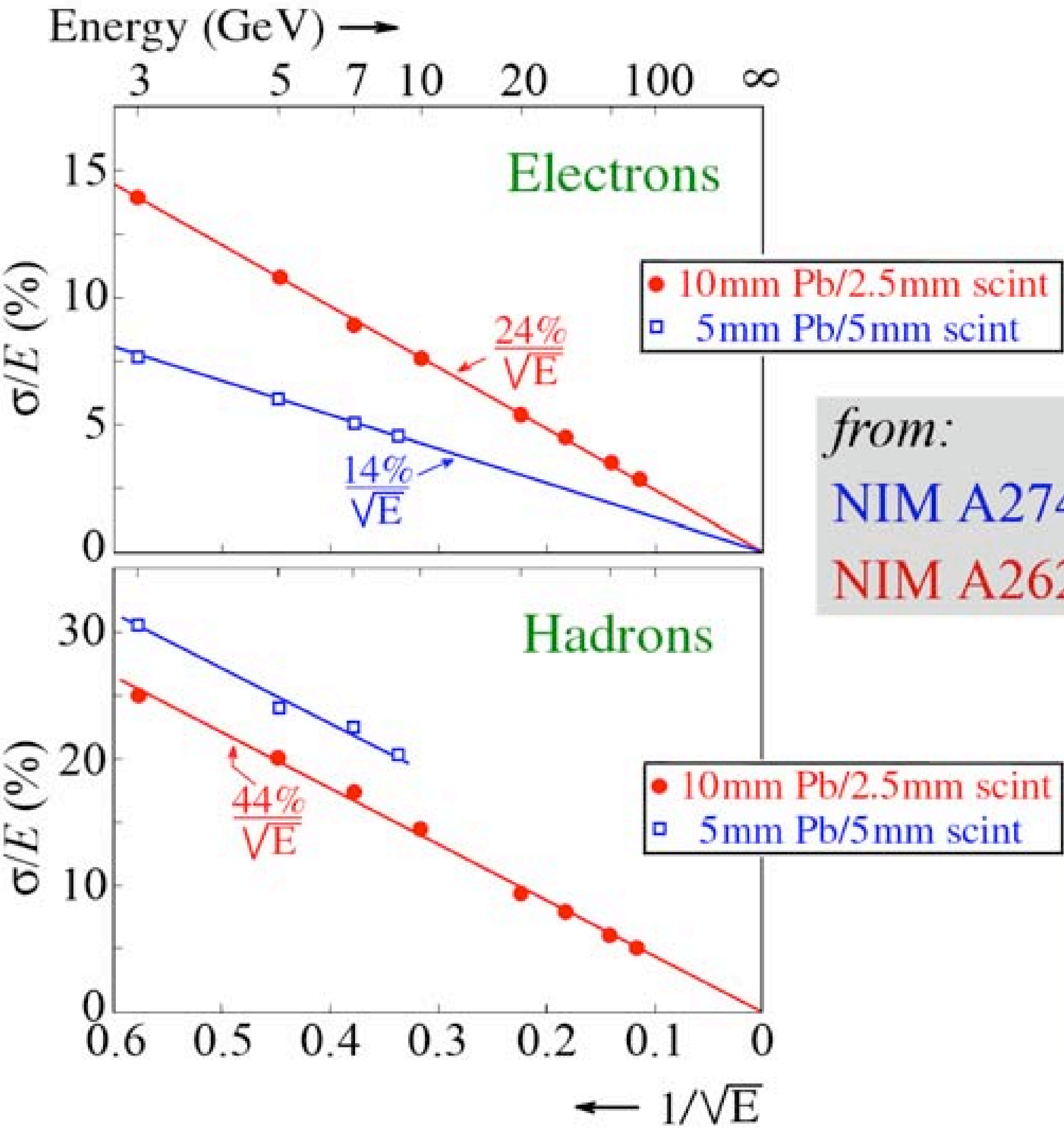
In calorimeters with hydrogenous active material, neutrons lose a major fraction of their kinetic energy through elastic *n-p* scattering in that material.

The recoil protons may contribute to the signals.

Therefore, the *neutron component may be very efficiently sampled* in such calorimeters.The sampling fraction may be much larger than for the other shower particles .

This is the key element of *compensation*.

Calorimetric effects of efficient neutron sampling



from:

NIM A274 (1989) 134 $e/h \sim 1.5$

NIM A262 (1987) 229 $e/h = 1.05$

The response to neutrons is increased (relative to the other shower particles) by a factor of 4 in the more crudely sampling calorimeter

Are the crucial elements correctly implemented in simulations?

How to test this?

- Use experimental data that are specifically sensitive to one element

"Generic Validation"

- Čerenkov calorimeter data for (the consequences of) π^o production
- ZEUS Pb/scintillator data for the signal contributions from nuclear reactions
- ^{239}Np data for neutron transport

etc.

- Use preferably data from longitudinally *unsegmented* calorimeters

Weighting factors introduce an element of arbitrariness into the results

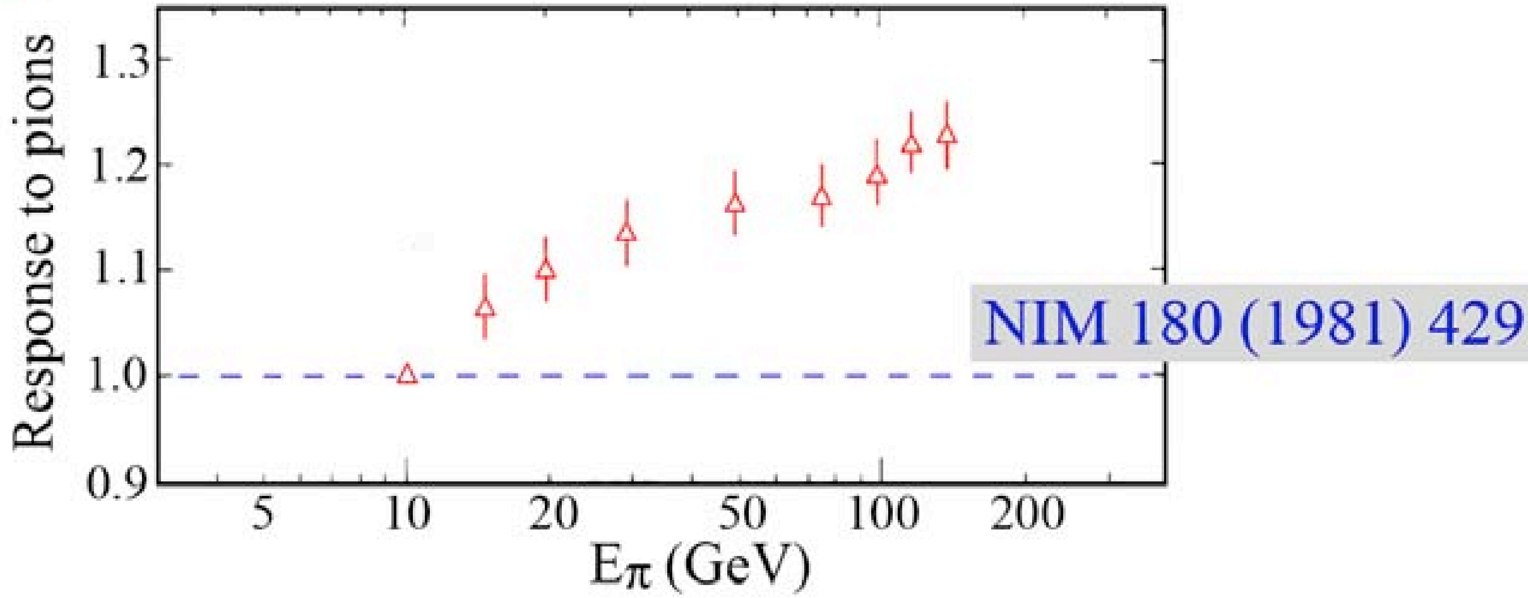
Are the crucial elements correctly implemented in simulations?

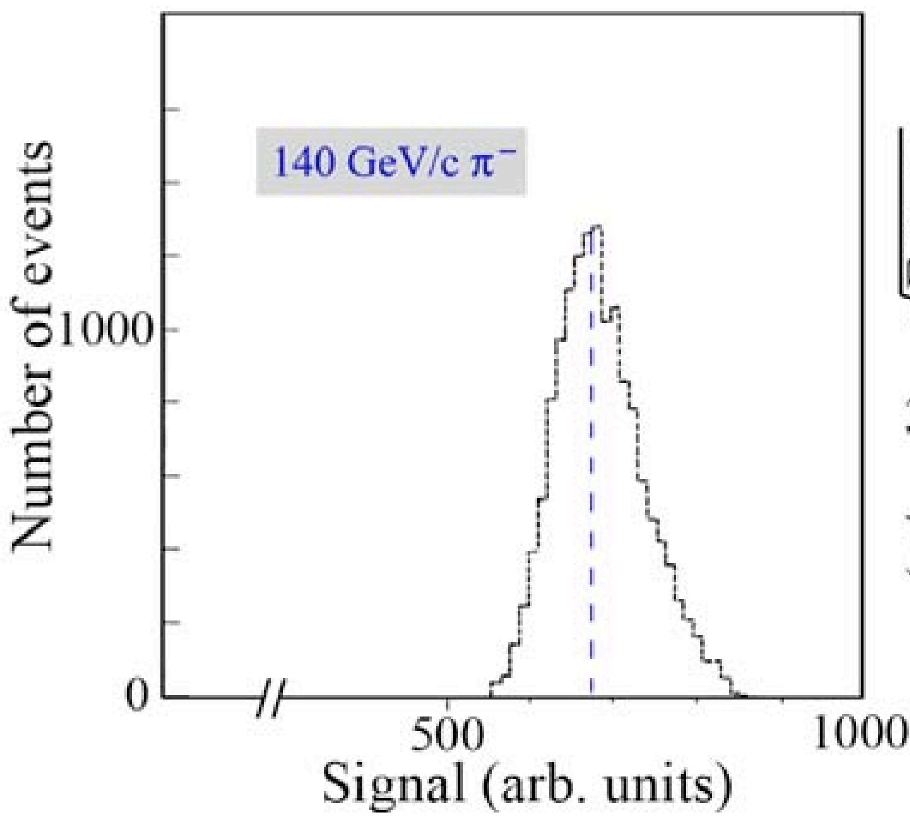
The described effects are also observed in other types of calorimeters

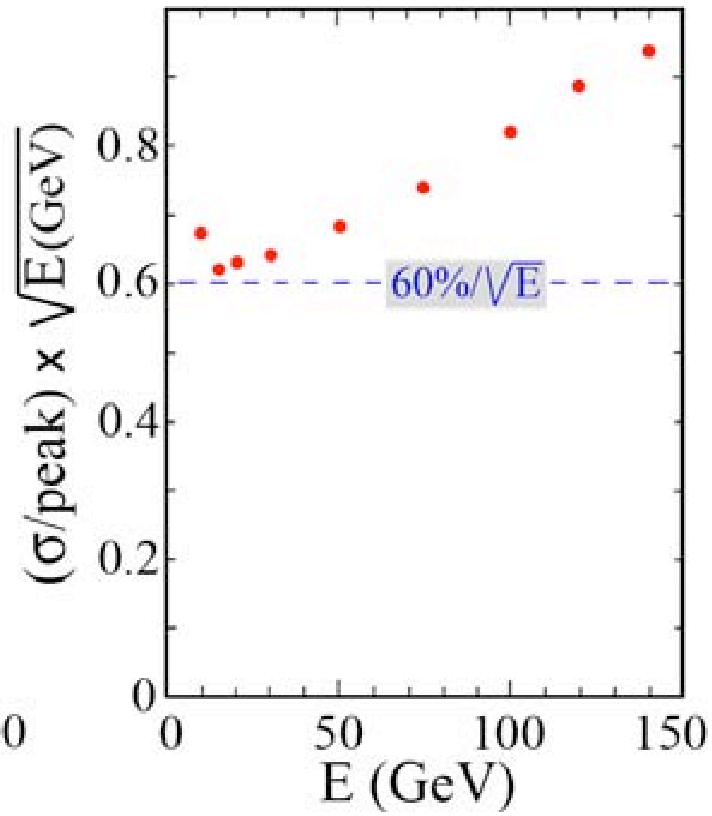
- For example, any non-compensating calorimeter ($e/h \neq 1$) exhibits the consequences of the peculiarities of π^{o} production:
  - Hadronic signal non-linearity
  - An asymmetric response function for pion showers
  - Deviations from $1/\sqrt{E}$ scaling (energy resolution)
  - Proton/pion differences (response, response function, energy resolution)

However, the closer e/h to 1, the less pronounced these effects become. Therefore, it is best to test simulations for the case that maximizes the effects (Čerenkov calorimeters)

π^o effects in a calorimeter with e/h = 1.5







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  However, the closer e/h to 1, the less pronounced these effects become. Therefore, it is best to test simulations for the case that maximizes the effects (Čerenkov calorimeters)

- Effects of the sampling fraction on the *e/h* value and related performance characteristics can also be observed in calorimeters with *non-hydrogenous* active material. However, the effects are much smaller than in the ZEUS Pb/scintillator case, where they are maximized, also because of the "inertness" of the lead nucleus.

CONCLUSIONS

- *The performance of hadron calorimeters depends sensitively on some very specific aspects of the shower development process :*
  - π^{o} *production, nuclear component, neutron transport*
- *Many sets of experimental data document this sensitivity in precise, quantitative ways*
- *Unfortunately, none of these data sets were considered in the context of the "grand validation"*
- *Reliable hadronic shower simulations are absolutely essential for designing, optimizing, calibrating, operating and understanding calorimeters*
- *The reliability of available codes leaves (very) much to be desired*