

# Energy Resolution

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## Calorimeter energy resolution determined by fluctuations ...

Homogeneous calorimeters:

|                                                                 |   |                      |
|-----------------------------------------------------------------|---|----------------------|
| Shower fluctuations                                             | ] | Quantum fluctuations |
| Photo-electron statistics                                       |   |                      |
| Shower leakage                                                  |   |                      |
| Instrumental effects (noise, light attenuation, non-uniformity) |   |                      |

In addition for

Sampling calorimeters:

Sampling fluctuations  
Landau fluctuations  
Track length fluctuations

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

|                           |                        |
|---------------------------|------------------------|
| Quantum fluctuations      | $\sim 1/\sqrt{E}$      |
| Electronic noise          | $\sim 1/E$             |
| Shower leakage*           | $\approx \text{const}$ |
| Sampling fluctuations     | $\sim 1/\sqrt{E}$      |
| Landau fluctuations       | $\sim 1/\sqrt{E}$      |
| Track length fluctuations | $\sim 1/\sqrt{E}$      |

\* Different for longitudinal and lateral leakage ...  
Complicated; small energy dependence ...

# Energy Resolution

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## Shower fluctuations: [intrinsic resolution]

Ideal (homogeneous) calorimeter without leakage: energy resolution limited only by statistical fluctuations of the number  $N$  of shower particles ...

i.e.:

$$\frac{\sigma_E}{E} \propto \frac{\sigma_N}{N} \approx \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}} \quad \text{with } N = \frac{E}{W}$$

$$\frac{\sigma_E}{E} \propto \sqrt{\frac{W}{E}}$$

$E$  : energy of primary particle

$W$  : mean energy required to produce 'signal quantum'

Examples:

Silicon detectors :  $W \approx 3.6 \text{ eV}$

Gas detectors :  $W \approx 30 \text{ eV}$

Plastic scintillator :  $W \approx 100 \text{ eV}$

Resolution improves due to correlations between fluctuations (Fano factor; see above) ...

$$\frac{\sigma_E}{E} \propto \sqrt{\frac{FW}{E}} \quad [\text{F: Fano factor}]$$

# Energy Resolution

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## Photo-electron statistics:

For detectors for which the deposited energy is measured via light detection inefficiencies converting photons into a detectable electrical signal (e.g. photo electrons) contribute to the measurement uncertainty ...

i.e.:

$$\frac{\sigma_E}{E} \propto \frac{\sigma_{N_{pe}}}{N_{pe}} \approx \frac{1}{\sqrt{N_{pe}}} \quad N_{pe}: \text{number of photo electrons}$$

This contribution is present for calorimeters based on detecting scintillation or Cherenkov light; important in this context are quantum efficiency and gain of the used photo detectors (e.g. Photomultiplier, Avalanche Photodiodes ...)

Also important: losses in light guides and wavelength shifters ....

# Energy Resolution

## Shower leakage:

Fluctuations due to finite size of calorimeter; shower not fully contained ...

Lateral leakage: limited influence

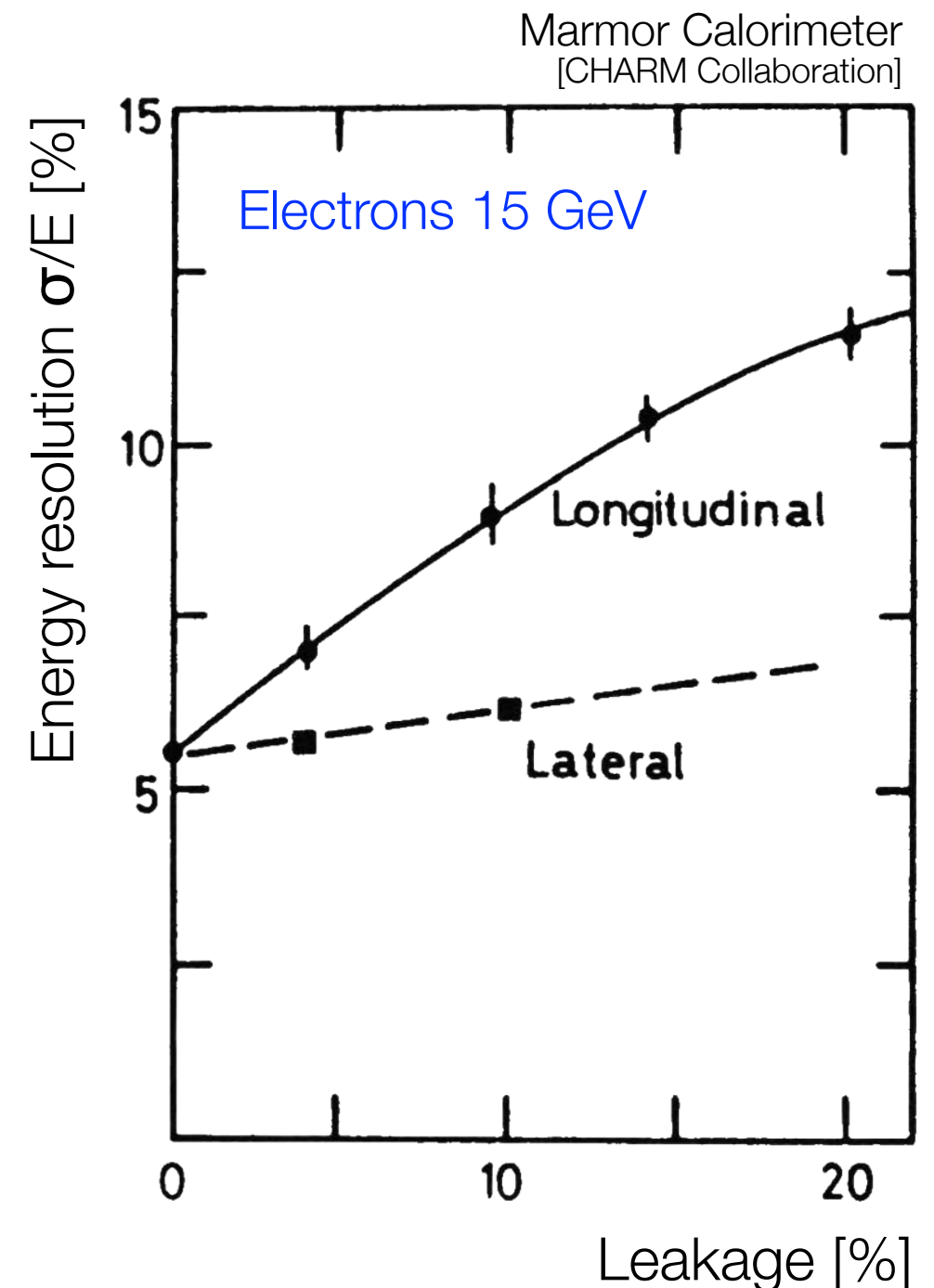
Longitudinal leakage: strong influence

Typical expression when including leakage effects:

$$\frac{\sigma_E}{E} \propto \left( \frac{\sigma_E}{E} \right)_{f=0} \cdot \left[ 1 + 2f\sqrt{E} \right]$$

[ $f$ : average fraction of shower leakage]

Remark: other parameterizations exist ...



# Energy Resolution

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## Sampling fluctuations:

Additional contribution to energy resolution in sampling calorimeters due to fluctuations of the number of (low-energy) electrons crossing active layer ...

Increases linearly with energy of incident particle and fineness of the sampling ...

$$N_{\text{ch}} = \frac{E}{E_c t_{\text{abs}}}$$

$N_{\text{ch}}$  : charged particles reaching active layer

$N_{\text{max}}$  : total number of particles =  $E/E_c$

$t_{\text{abs}}$  : absorber thickness in  $X_0$

Reasoning: Energy deposition dominantly due to low energy electrons; range of these electrons smaller than absorber thickness  $t_{\text{abs}}$  and only few electrons reach active layer ...

Thus: fraction  $f \sim 1/t_{\text{abs}}$  lost before active medium

Resulting  
energy resolution:

$$\frac{\sigma_E}{E} \propto \frac{\sigma_{N_{\text{ch}}}}{N_{\text{ch}}} = \sqrt{\frac{E_c t_{\text{abs}}}{E}}$$

Choose:  $E_c$  small (large  $Z$ )  
 $t_{\text{abs}}$  small (fine sampling)

Semi empirical:

$$\frac{\sigma_E}{E} = 3.2\% \sqrt{\frac{E_c [\text{MeV}] \cdot t_{\text{abs}}}{F \cdot E [\text{GeV}]}}$$

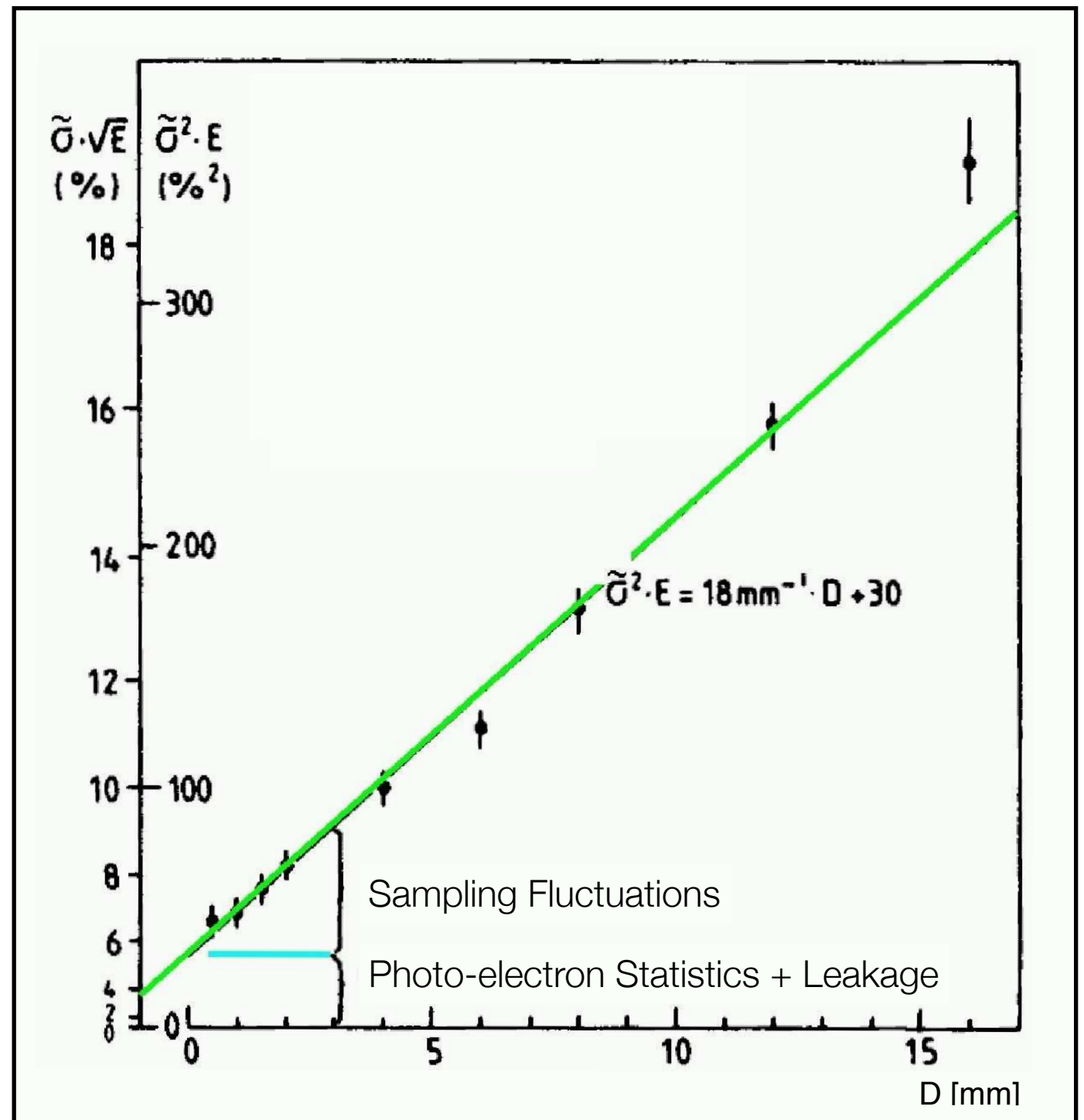
where  $F$  takes detector threshold effects into account ...

# Energy Resolution

Measure energy resolution  
of a sampling calorimeter  
for different thicknesses

Sampling  
contribution:

$$\frac{\sigma_E}{E} = 3.2\% \sqrt{\frac{E_c [\text{MeV}] \cdot t_{\text{abs}}}{F \cdot E [\text{GeV}]}}$$



# Energy Resolution

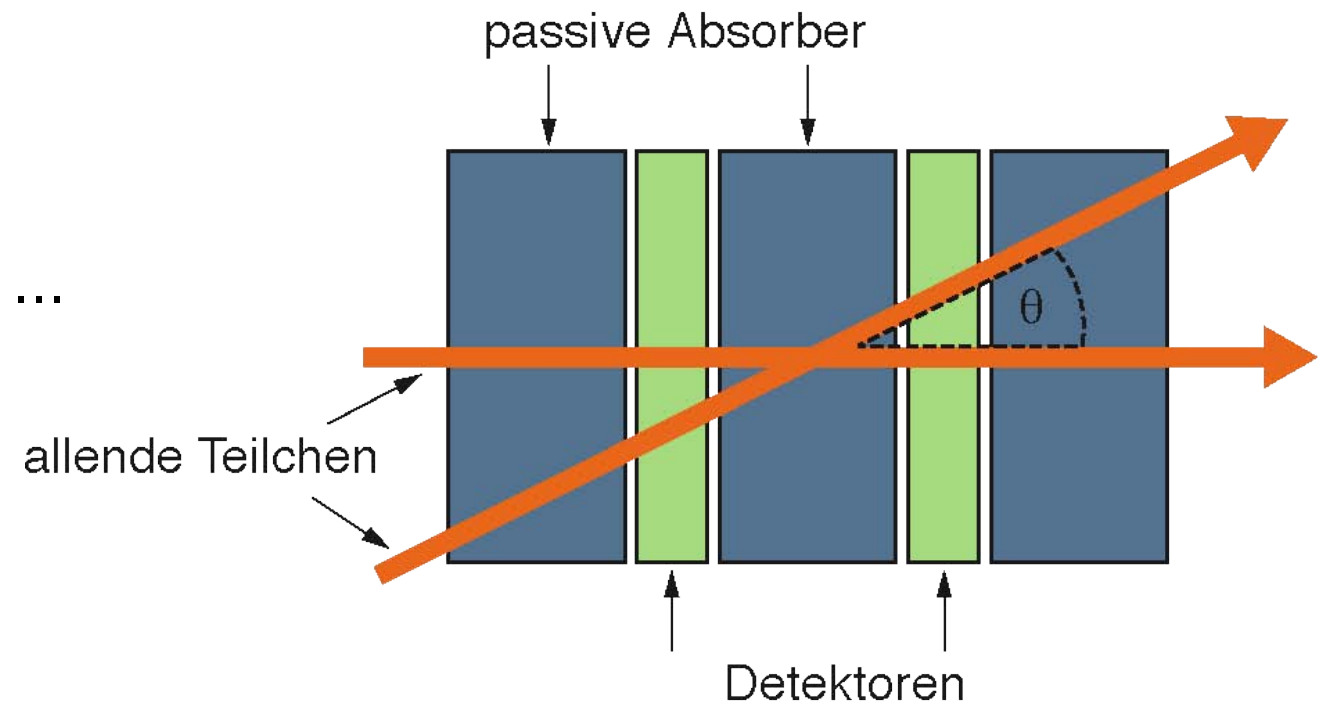
## Track length fluctuations:

Due to multiple scattering particles traverse absorber at different angles ...

→ Different effective absorber thickness:

$$t_{\text{abs}} \rightarrow t_{\text{abs}} / \cos \theta$$

[Enters sampling (and Landau) fluctuations]



## Landau fluctuations:

Asymmetric distribution of energy deposits in thin active layers yields correction [Landau instead of Gaussian distribution]:

$$\frac{\sigma_E}{E} = \frac{1}{\sqrt{N_{\text{ch}}}} \cdot \frac{3}{\ln(k \cdot \delta)}$$

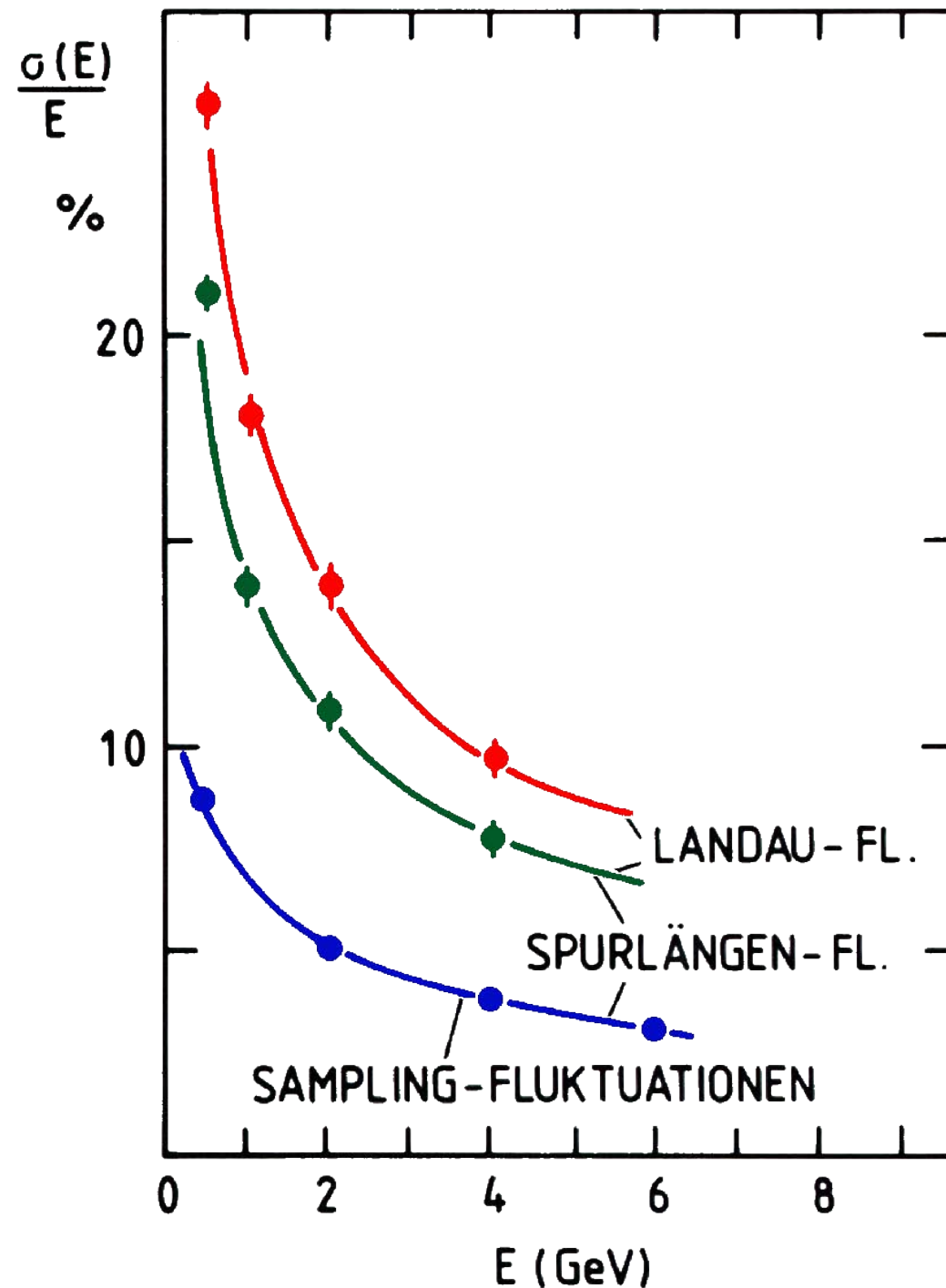
[semi empirical]

with:

k : constant;  $k = 1.3 \cdot 10^4$  if  $\delta$  measured in MeV

$\delta$  : average energy loss in active layer ('thickness')

# Energy Resolution



Calculated contributions  
from

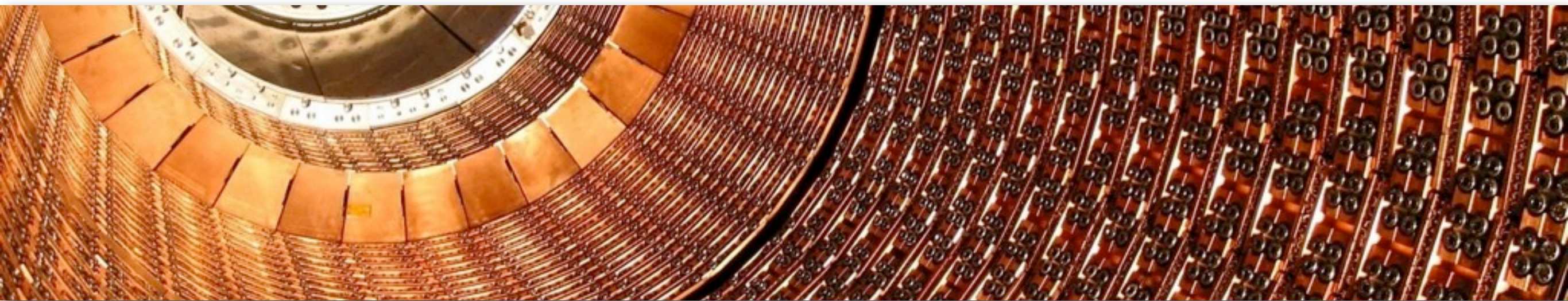
Track Length fluctuations  
Sampling fluctuations  
Landau fluctuations

Calorimeter:

1 mm lead absorber  
5 mm scintillator  
Total thickness:  $12.5 X_0$

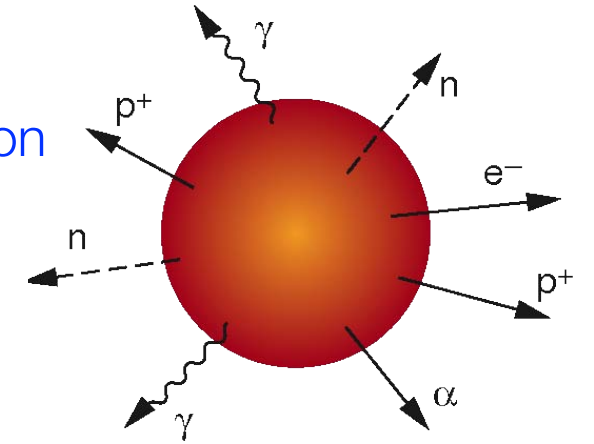
# Calorimetry II

## Hadronic Calorimeters

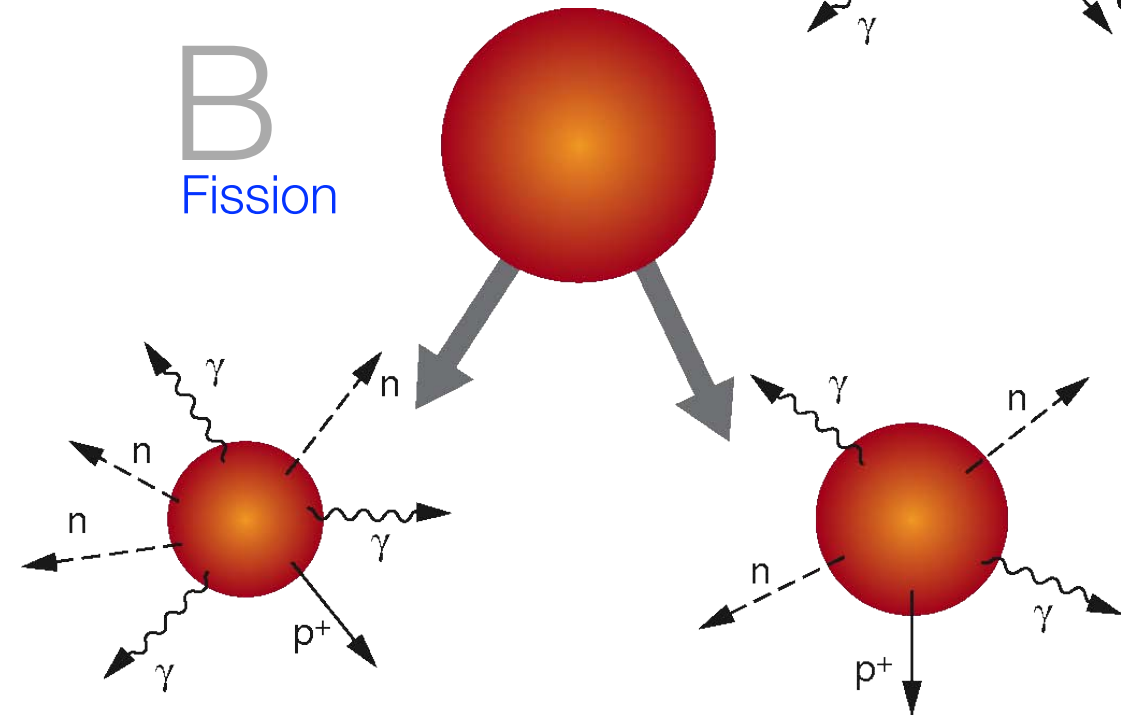


# Hadronic Showers

C Nuclear evaporation

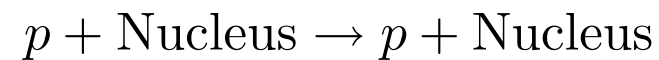


B Fission

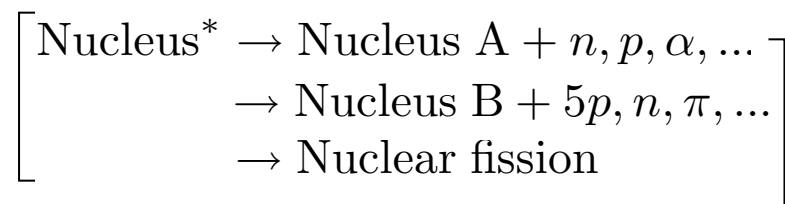
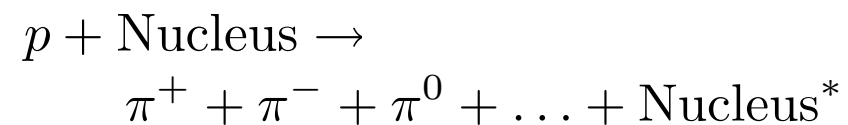


Hadronic interaction:

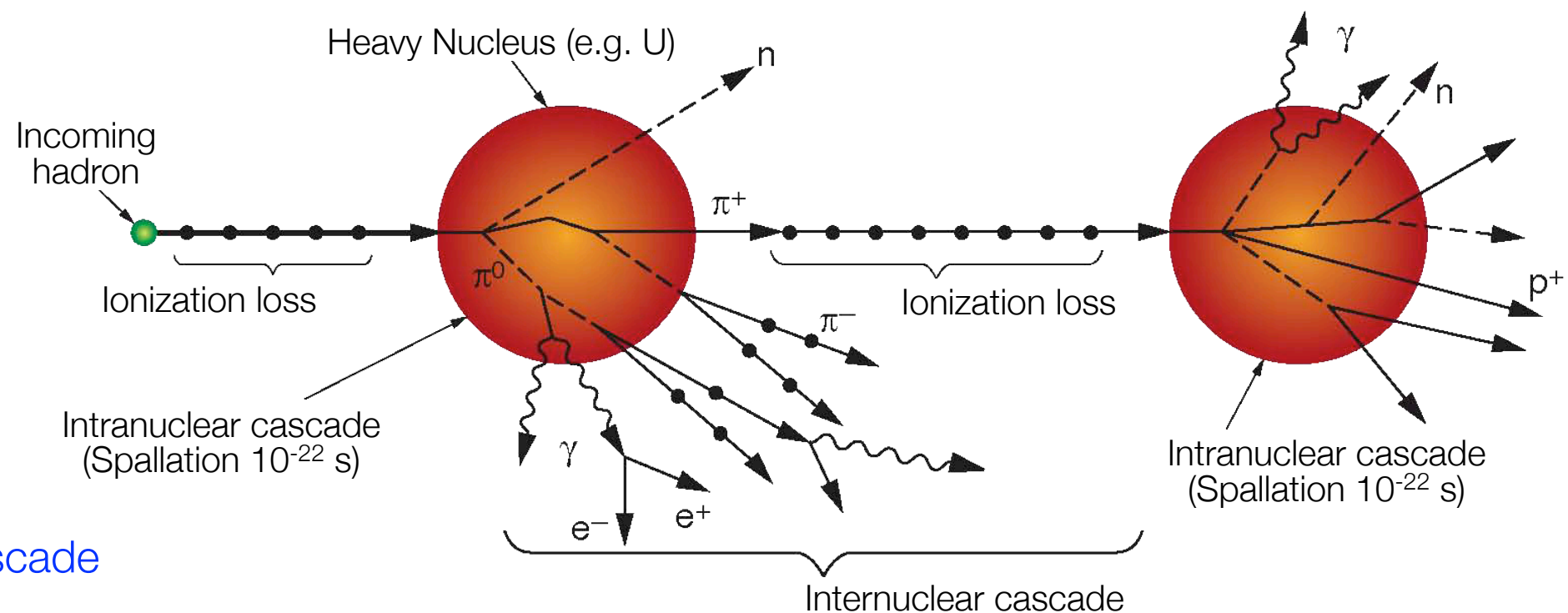
Elastic:



Inelastic:



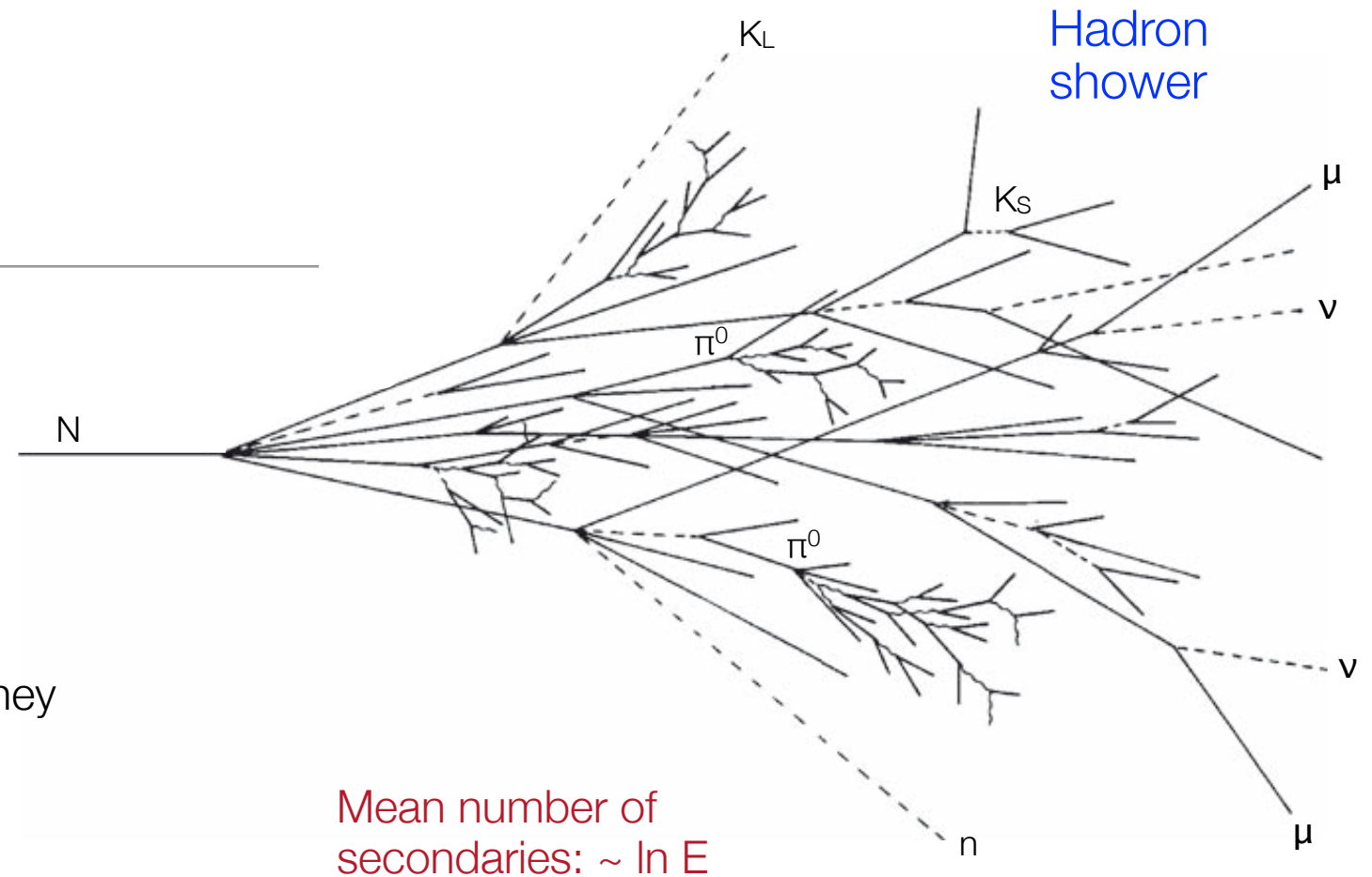
A Inter- and intranuclear cascade



# Hadronic Showers

## Shower development:

1.  $p + \text{Nucleus} \rightarrow \text{Pions} + N^* + \dots$
2. Secondary particles ...  
undergo further inelastic collisions until they fall below pion production threshold
3. Sequential decays ...  
 $\pi^0 \rightarrow \gamma\gamma$ : yields electromagnetic shower  
 Fission fragments  $\rightarrow \beta$ -decay,  $\gamma$ -decay  
 Neutron capture  $\rightarrow$  fission  
 Spallation ...



Mean number of  
secondaries:  $\sim \ln E$

Typical transverse  
momentum:  $p_t \sim 350 \text{ MeV}/c$

Substantial  
electromagnetic fraction

$f_{em} \sim \ln E$   
[variations significant]

## Cascade energy distribution:

[Example: 5 GeV proton in lead-scintillator calorimeter]

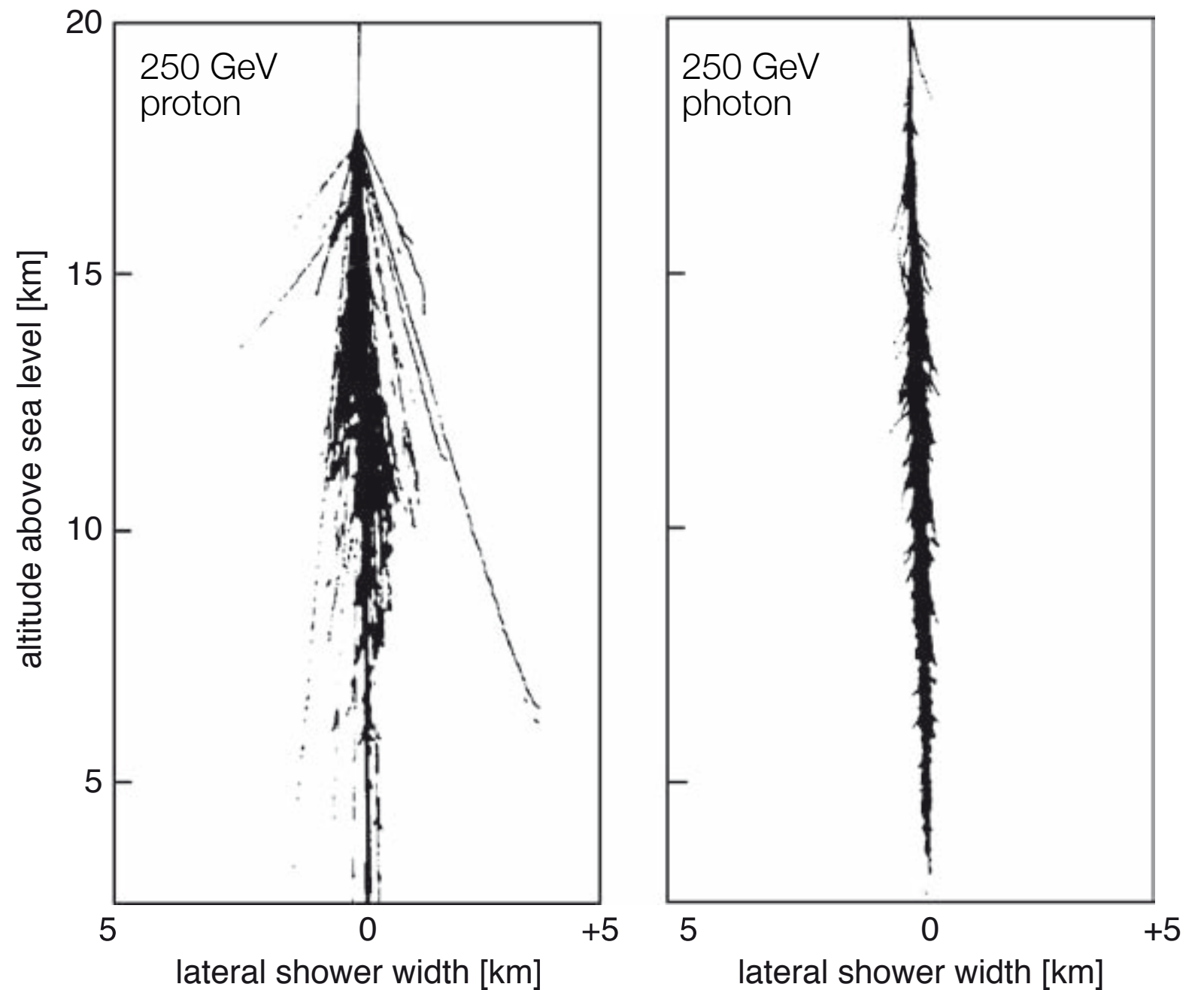
|                                                            |                |
|------------------------------------------------------------|----------------|
| Ionization energy of charged particles (p, $\pi$ , $\mu$ ) | 1980 MeV [40%] |
| Electromagnetic shower ( $\pi^0$ , $\eta^0$ , e)           | 760 MeV [15%]  |
| Neutrons                                                   | 520 MeV [10%]  |
| Photons from nuclear de-excitation                         | 310 MeV [ 6%]  |
| Non-detectable energy (nuclear binding, neutrinos)         | 1430 MeV [29%] |
|                                                            | <hr/>          |
|                                                            | 5000 MeV [29%] |

# Hadronic Showers

## Comparison

hadronic vs electromagnetic shower ...

[Simulated air showers]



# Hadronic Showers

## Hadronic interaction:

Cross Section:

$$\sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{inel}}$$

For substantial energies  
 $\sigma_{\text{inel}}$  dominates:

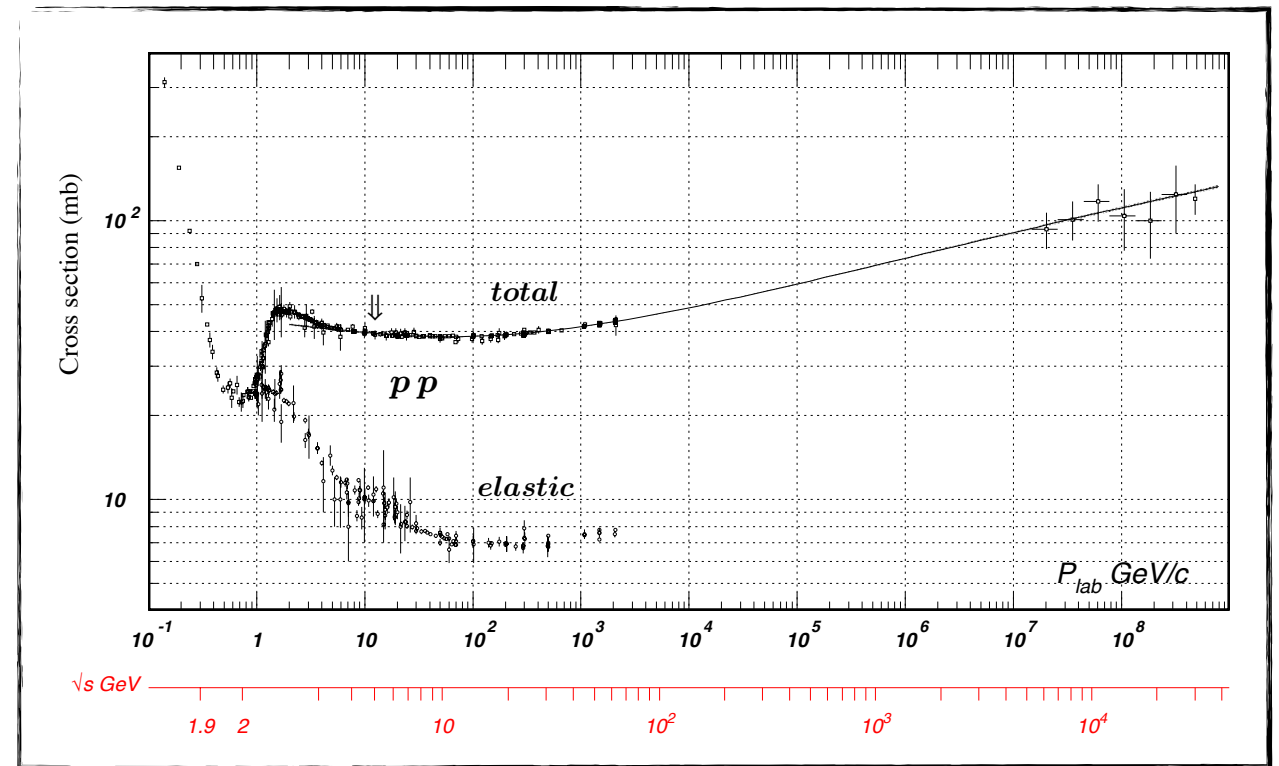
$$\sigma_{\text{el}} \approx 10 \text{ mb}$$

$$\sigma_{\text{inel}} \propto A^{2/3} \text{ [geometrical cross section]}$$

$$\therefore \sigma_{\text{tot}} = \sigma_{\text{tot}}(pA) \approx \sigma_{\text{tot}}(pp) \cdot A^{2/3}$$

[ $\sigma_{\text{tot}}$  slightly grows with  $\sqrt{s}$ ]

at high energies  
 also diffractive contribution



Total proton-proton cross section  
 [similar for p+n in 1-100 GeV range]

Hadronic interaction length:

$$\lambda_{\text{int}} = \frac{1}{\sigma_{\text{tot}} \cdot n} = \frac{A}{\sigma_{pA} A^{2/3} \cdot N_A \rho} \sim A^{1/3} \quad [\text{for } \sqrt{s} \approx 1 - 100 \text{ GeV}]$$

$$\approx 35 \text{ g/cm}^2 \cdot A^{1/3}$$

which yields:

$$N(x) = N_0 \exp(-x/\lambda_{\text{int}})$$

Remark: In principle one should distinguish between collision length  $\lambda_W \sim 1/\sigma_{\text{tot}}$  and interaction length  $\lambda_{\text{int}} \sim 1/\sigma_{\text{inel}}$  where the latter considers inelastic processes only (absorption) ...

Interaction length characterizes both,  
 longitudinal and transverse profile of  
 hadronic showers ...

# Hadronic Showers

Hadronic vs. electromagnetic interaction length:

$$\left[ \begin{array}{l} X_0 \sim \frac{A}{Z^2} \\ \lambda_{\text{int}} \sim A^{1/3} \end{array} \right] \rightarrow \frac{\lambda_{\text{int}}}{X_0} \sim A^{4/3}$$

$$\lambda_{\text{int}} \gg X_0$$

[ $\lambda_{\text{int}}/X_0 > 30$  possible; see below]

Typical

Longitudinal size:  $6 \dots 9 \lambda_{\text{int}}$   
[95% containment]

[EM:  $15-20 X_0$ ]

Typical

Transverse size: one  $\lambda_{\text{int}}$   
[95% containment]

[EM:  $2 R_M$ ; compact]

Hadronic calorimeter need more depth  
than electromagnetic calorimeter ...

Some numerical values for materials  
typical used in hadron calorimeters

|        | $\lambda_{\text{int}}$ [cm] | $X_0$ [cm] |
|--------|-----------------------------|------------|
| Szint. | 79.4                        | 42.2       |
| LAr    | 83.7                        | 14.0       |
| Fe     | 16.8                        | 1.76       |
| Pb     | 17.1                        | 0.56       |
| U      | 10.5                        | 0.32       |
| C      | 38.1                        | 18.8       |

# Hadronic Showers

Hadronic shower development:  
[estimate similar to e.m. case]

Depth (in units of  $\lambda_{\text{int}}$ ):

$$t = \frac{x}{\lambda_{\text{int}}}$$

Energy in depth  $t$ :

$$E(t) = \frac{E}{\langle n \rangle^t} \quad \& \quad E(t_{\text{max}}) = E_{\text{thr}} \quad \text{[with } E_{\text{thr}} \approx 290 \text{ MeV]}$$

$$E_{\text{thr}} = \frac{E}{\langle n \rangle^{t_{\text{max}}}}$$

Shower maximum:

$$\langle n \rangle^{t_{\text{max}}} = \frac{E}{E_{\text{thr}}}$$

Number of particles  
lower by factor  $E_{\text{thr}}/E_c$   
compared to e.m. shower ...

Intrinsic resolution:  
worse by factor  $\sqrt{E_{\text{thr}}/E_c}$

$$t_{\text{max}} = \frac{\ln(E/E_{\text{thr}})}{\ln \langle n \rangle}$$

But:

Only rough estimate as ...

energy sharing between shower particles  
fluctuates strongly ...

part of the energy is not detectable (neutrinos,  
binding energy); partial compensation possible  
(n-capture & fission)

spatial distribution varies strongly; different  
range of e.g.  $\pi^\pm$  and  $\pi^0$  ...

electromagnetic fraction, i.e. fraction of energy  
deposited by  $\pi^0 \rightarrow \gamma\gamma$  increases with energy ...

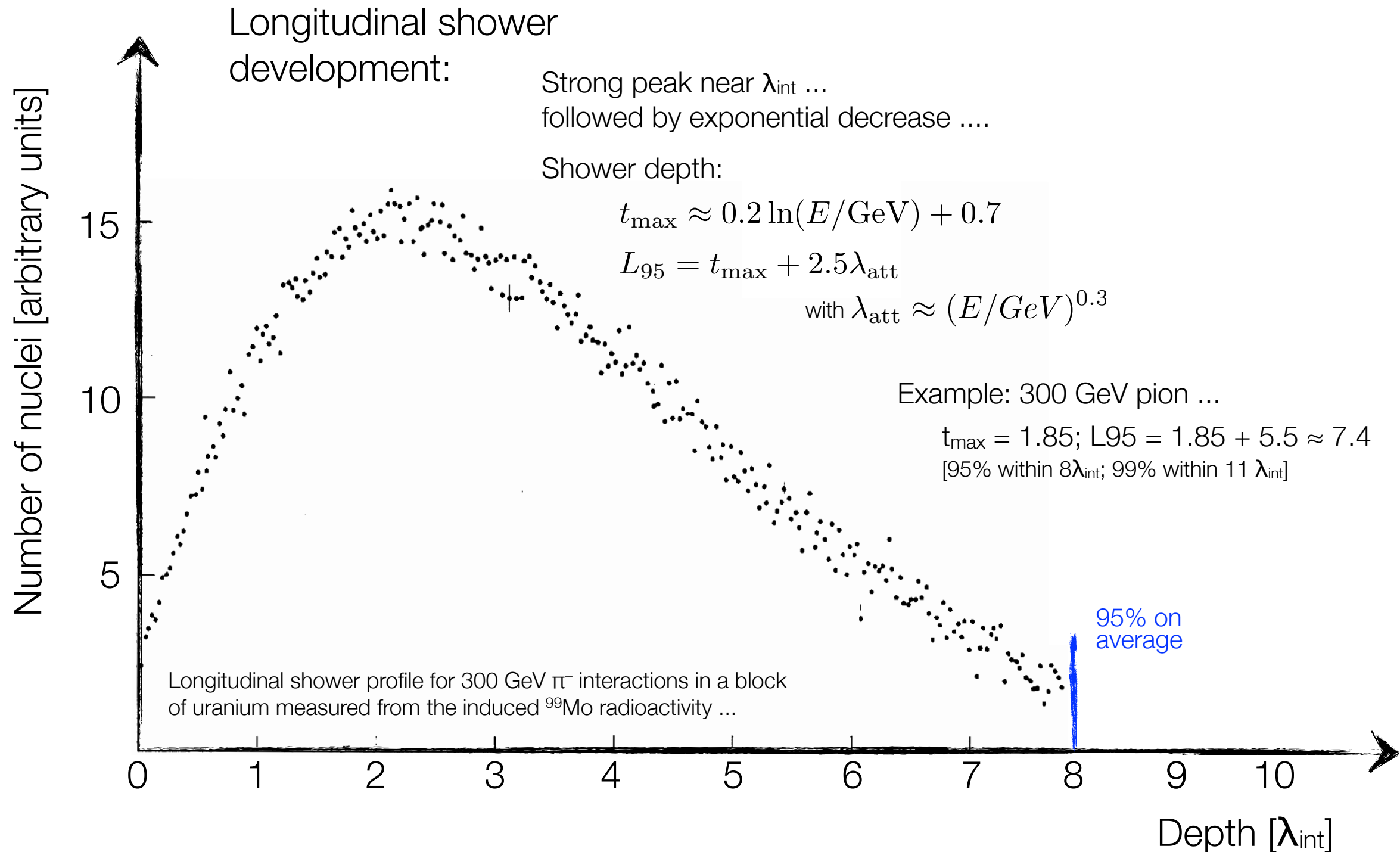
$$f_{\text{em}} \approx f_{\pi^0} \sim \ln E / (1 \text{ GeV})$$

Explanation: charged hadron contribute to electromagnetic  
fraction via  $\pi^\pm p \rightarrow \pi^0 n$ ; the opposite happens only rarely as  
 $\pi^0$  travel only  $0.2 \mu\text{m}$  before its decay ('one-way street') ...

At energies below 1 GeV hadrons lose their  
energy via ionization only ...

Thus: need Monte Carlo (GEISHA, CALOR, ...) to describe shower development correctly ...

# Hadronic Showers



# Hadronic Showers

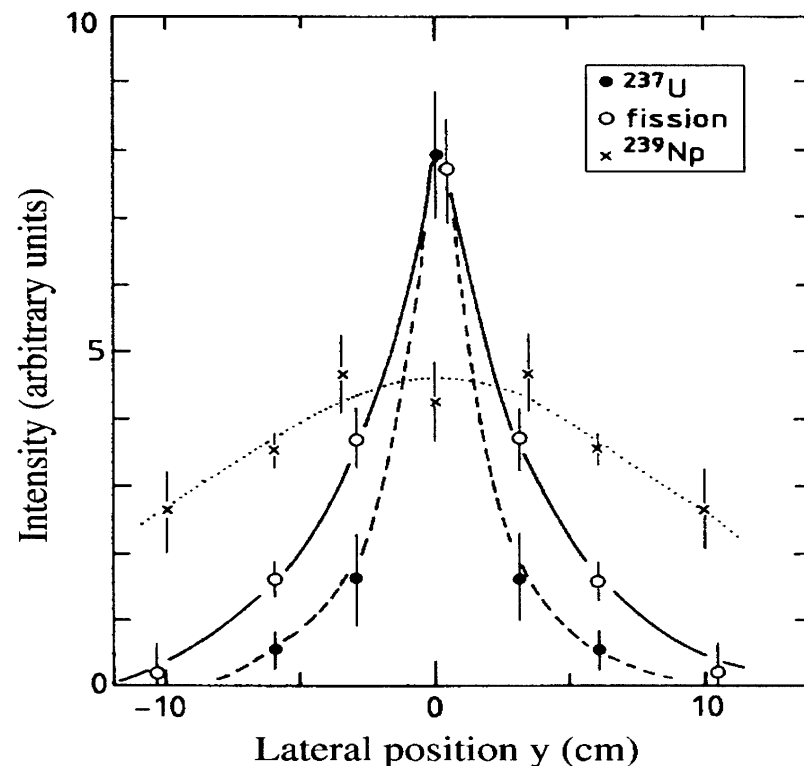
## Transverse shower profile

Typical transverse momenta of secondaries:  $\langle p_t \rangle \simeq 350 \text{ MeV}/c \dots$

Lateral extend at shower maximum:  $R_{95\%} \simeq \lambda_{\text{int}} \dots$

Electromagnetic component leads to relatively well-defined core:  $R \simeq R_M \dots$

Exponential decay after shower maximum ...

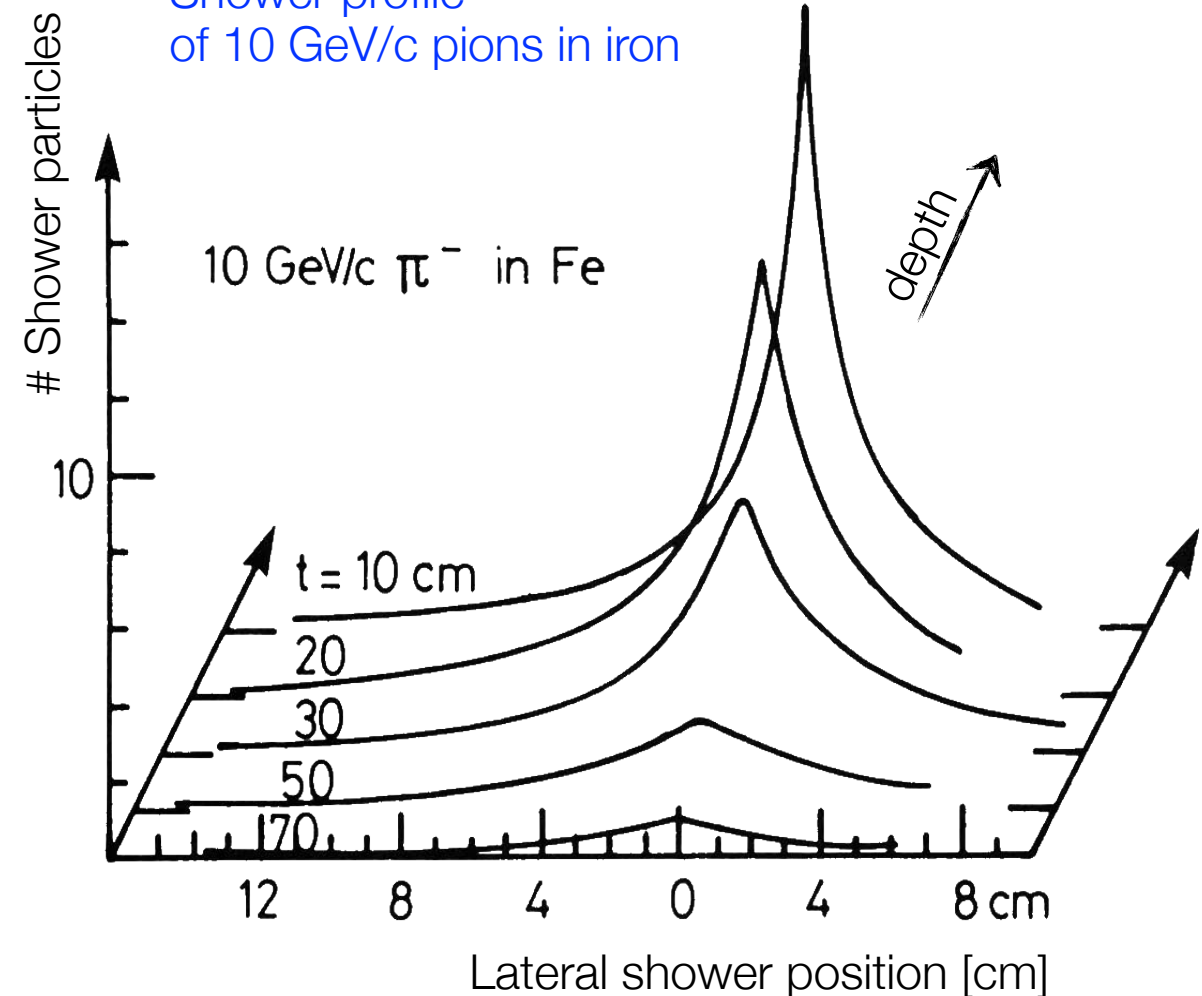


## Lateral profile for 300 GeV $\pi^-$

[target material  $^{238}\text{U}$ ]  
[measured at depth  $4 \lambda_{\text{int}}$ ]

More  $\pi^0$ 's and  $\gamma$  in core  
Energetic neutrons and charged pions form a wider core  
Thermal neutrons generate broad tail

## Shower profile of 10 GeV/c pions in iron



Measurement from induced radioactivity:

$^{99}\text{Mo}$  (fission): neutron induced ...  
[energetic neutron component]

$^{237}\text{U}$ : mainly produced via  $^{238}\text{U}(\gamma, n)^{237}\text{U} \dots$   
[electromagnetic component]

$^{239}\text{Np}$ : from  $^{239}\text{U}$  decay ...  
[thermal neutrons]

Ordinate indicates decay rate of different radioactive nuclides ...

# Hadronic Calorimeters

Most common realization: **Sampling Calorimeter**

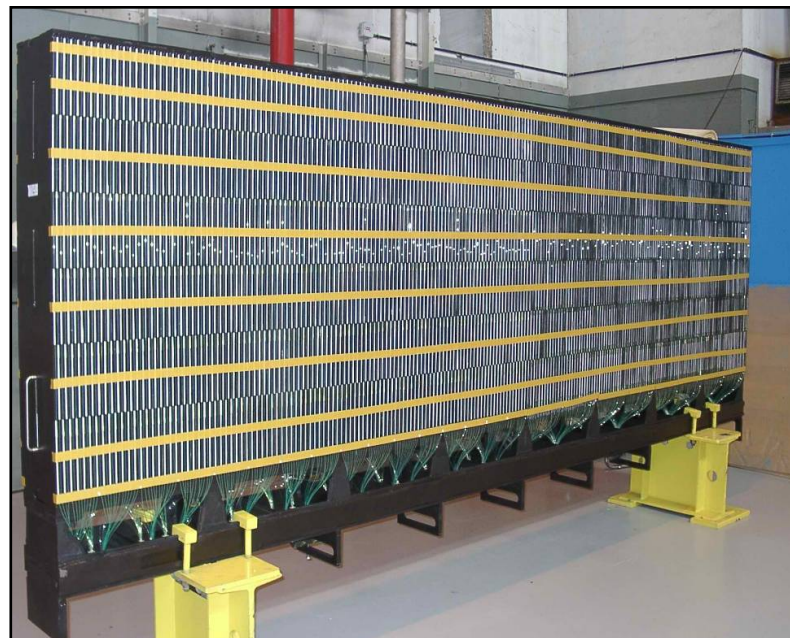
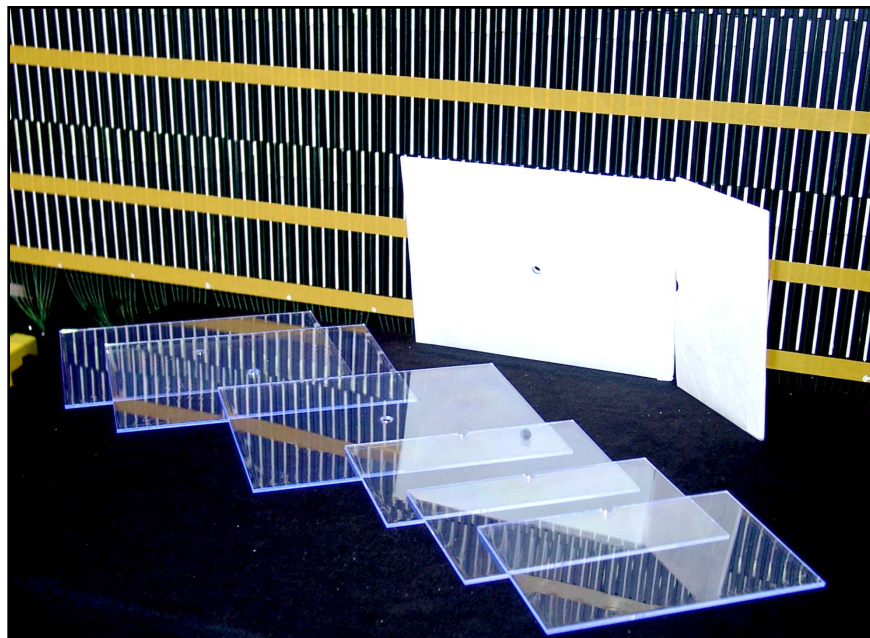
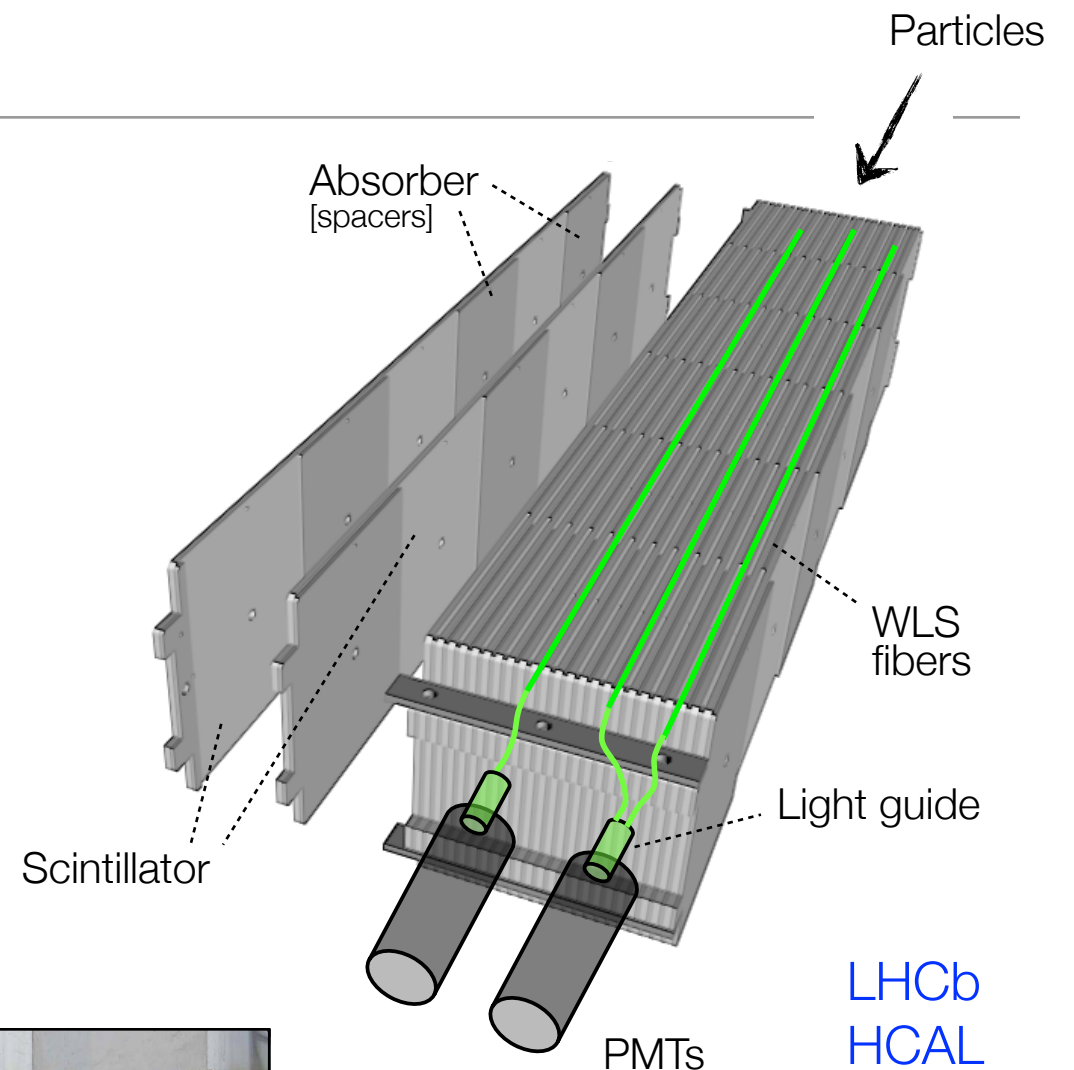
Utilization of homogenous calorimeters unnecessary (and thus too expensive) due to fluctuations of invisible shower components ...

Typical absorbers : Fe, Pb, U ...

Sampling elements : Scintillators, LAr, MWPCs ...

Typical setup:

Alternating layers of active and passive material  
[also: 'spaghetti' or 'shashlik' calorimeter]



Example:  
LHCb Hadron Calorimeter

# Hadronic Calorimeters

## Energy resolution:

### A. Intrinsic contributions:

Leakage fluctuations

Fluctuations of electromagnetic fraction

Nuclear excitations, fission, binding energy fluctuations ...

Heavily ionizing particles

All scale with  $1/\sqrt{E}$  as statistical processes ....

→ Fluctuations of invisible energy

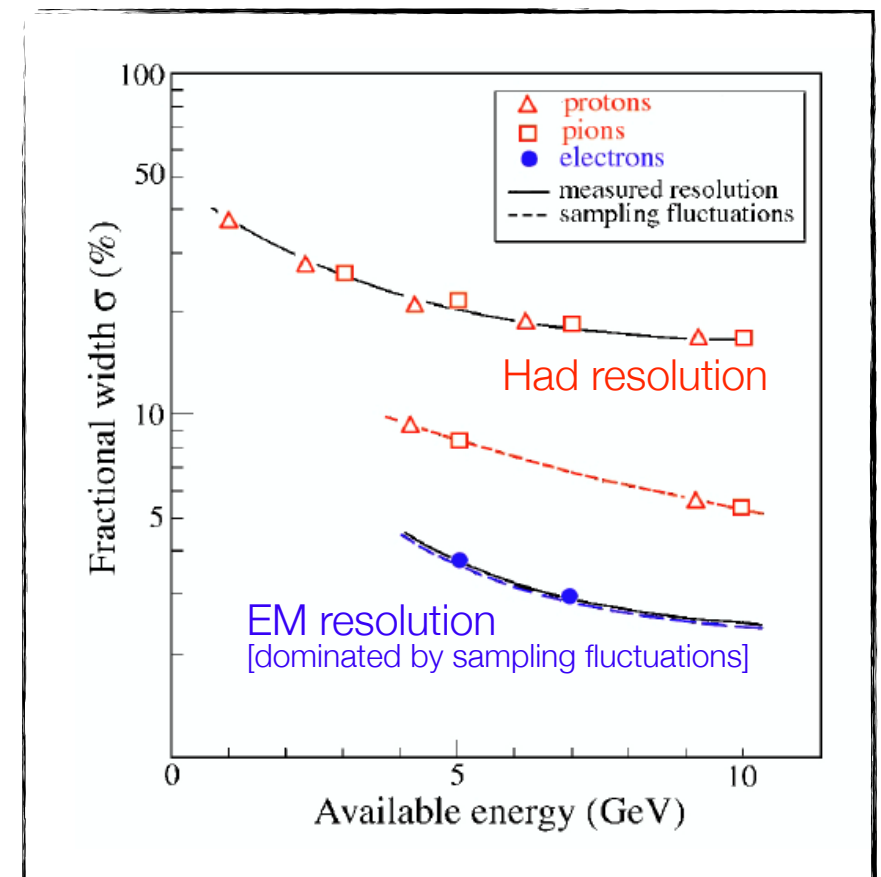
### B. Sampling fluctuations:

Dominate resolution in electromagnetic calorimeters ...

Only partially relevant in hadronic calorimeters; possibly even negligible ...

The electromagnetic and hadronic energy resolution of a sampling calorimeter

Sampling fluctuations only minor contribution to hadronic energy resolution  
[AFM Collaboration]



## Estimating sampling fluctuations:

Split calorimeter artificially into two interleaved parts and measure:

$$S_{\Sigma} = (S_1 + S_3 + S_5 + \dots) + (S_2 + S_4 + \dots)$$

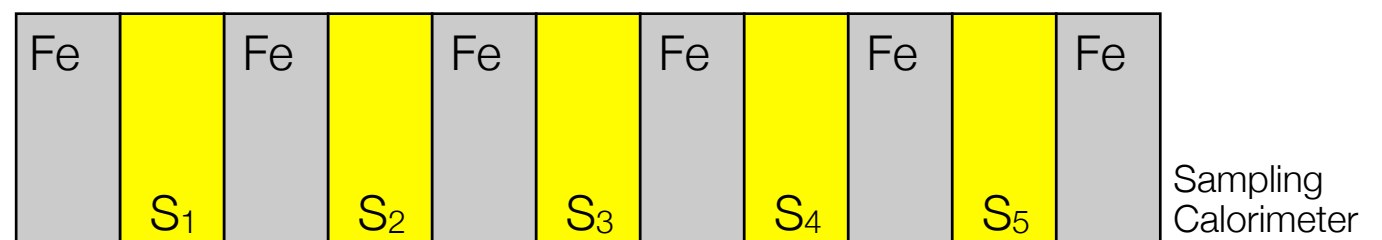
$$S_{\Delta} = (S_1 + S_3 + S_5 + \dots) - (S_2 + S_4 + \dots)$$

$$\rightarrow \sigma_{\Sigma}^2 = \sigma_{\text{odd}}^2 + \sigma_{\text{even}}^2 + \sigma_{\text{intr}}^2$$

$$\sigma_{\Delta}^2 = \sigma_{\text{odd}}^2 + \sigma_{\text{even}}^2$$

As sampling fluctuations are uncorrelated while invisible energy fluctuations are not ...

where  $\sigma_{\Delta}$  yields contribution from sampling fluctuations ...



# Hadronic Calorimeters

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Energy resolution:

$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus B \oplus \frac{C}{E}$$

e.g. inhomogeneities  
shower leakage

e.g. electronic noise  
sampling fraction variations

Fluctuations:

Sampling fluctuations

Leakage fluctuations

Fluctuations of electromagnetic  
fraction

Nuclear excitations, fission,  
binding energy fluctuations ...

Heavily ionizing particles

Typical:

A: 0.5 – 1.0 [Record:0.35]

B: 0.03 – 0.05

C: few %

# Hadronic Calorimeters

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Typical Calorimeter: to components ...

Electromagnetic (EM) +  
Hadronic section (Had) ...

Different setups chosen for  
optimal energy resolution ...

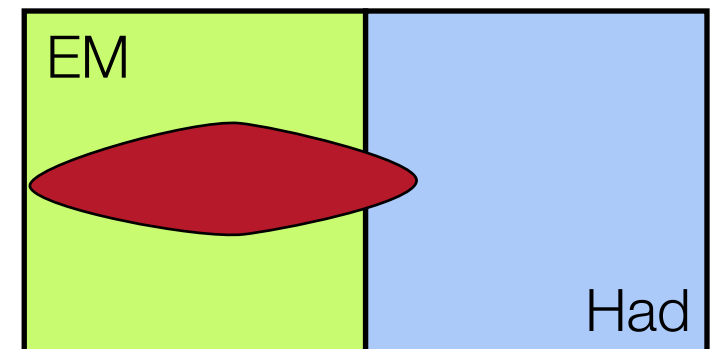
But:

Hadronic energy measured in  
both parts of calorimeter ...

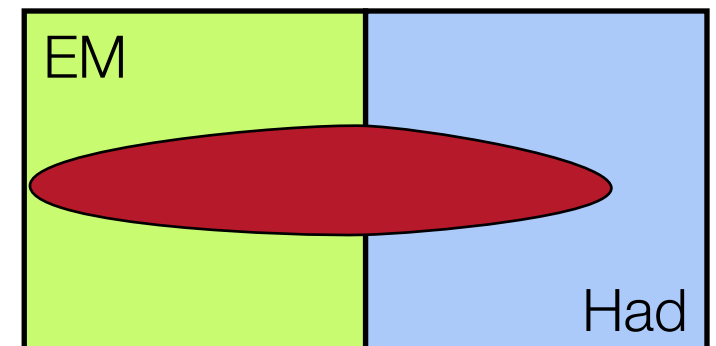
Needs careful consideration of  
different response ...

Schematic of a  
typical HEP calorimeter

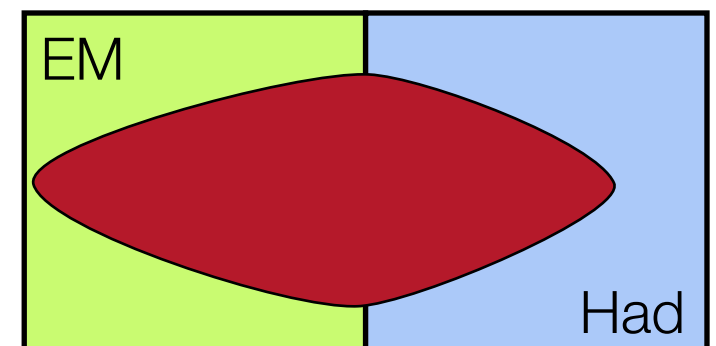
Electrons  
Photons



Taus  
Hadrons



Jets



# Hadronic Calorimeters

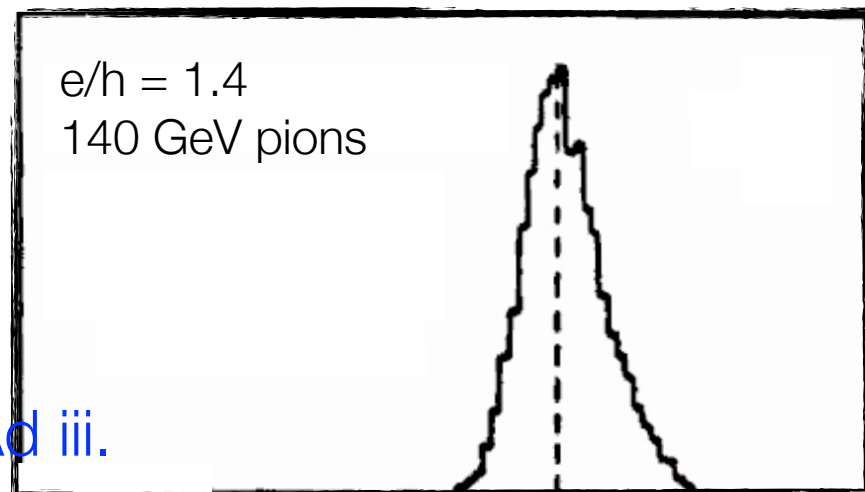
## Calorimeter requirements:

Signal :  $S \sim \text{Energy}$  (linearity)  
 Independent of particle type  
 Gaussian distributed

Resolution :  $\sigma/E \sim 1/\sqrt{E}$

## Reality:

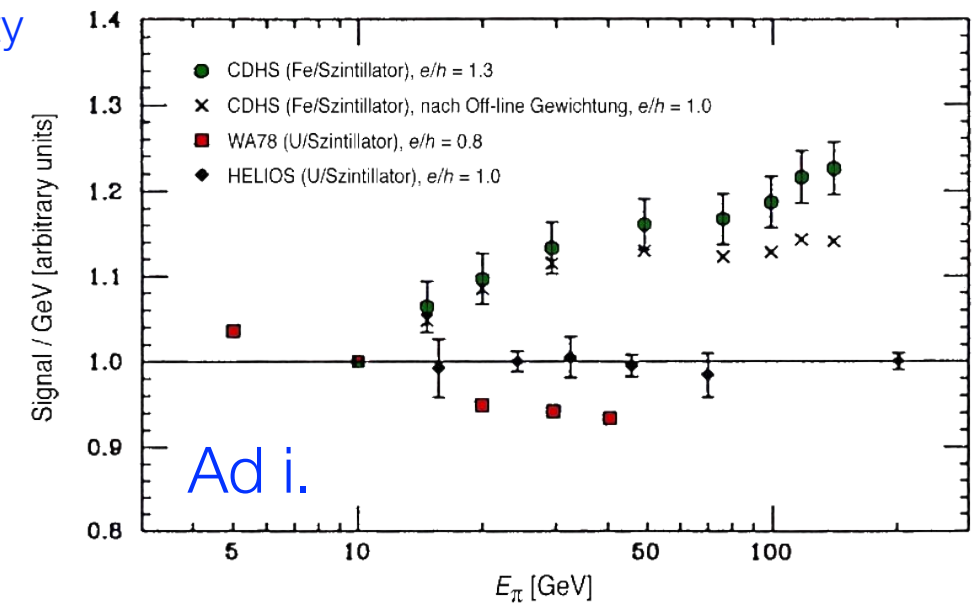
- Response not completely linear
- Resolution deviates from  $1/\sqrt{E}$  dependence
- Signal not completely gaussian
- $e/h$ -ratio greater 1



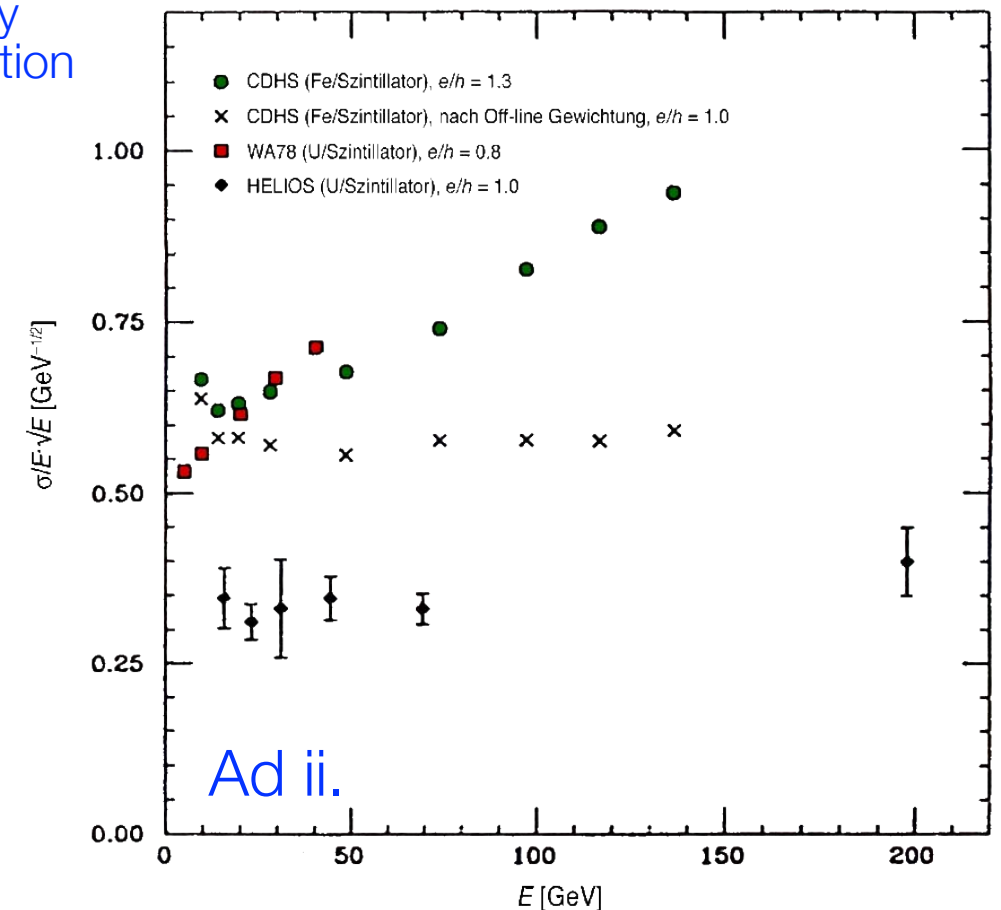
Ad iii.

Pulse height distribution

## Linearity



## Energy resolution



# Hadronic Calorimeters

$e/h$  ratio:

[This is what it is all about ...]

Generally ...

Response of calorimeters very different to electromagnetic and hadronic energy deposits ...

Usually higher weight for electromagnetic component  
i.e.  $e/h > 1$  ...

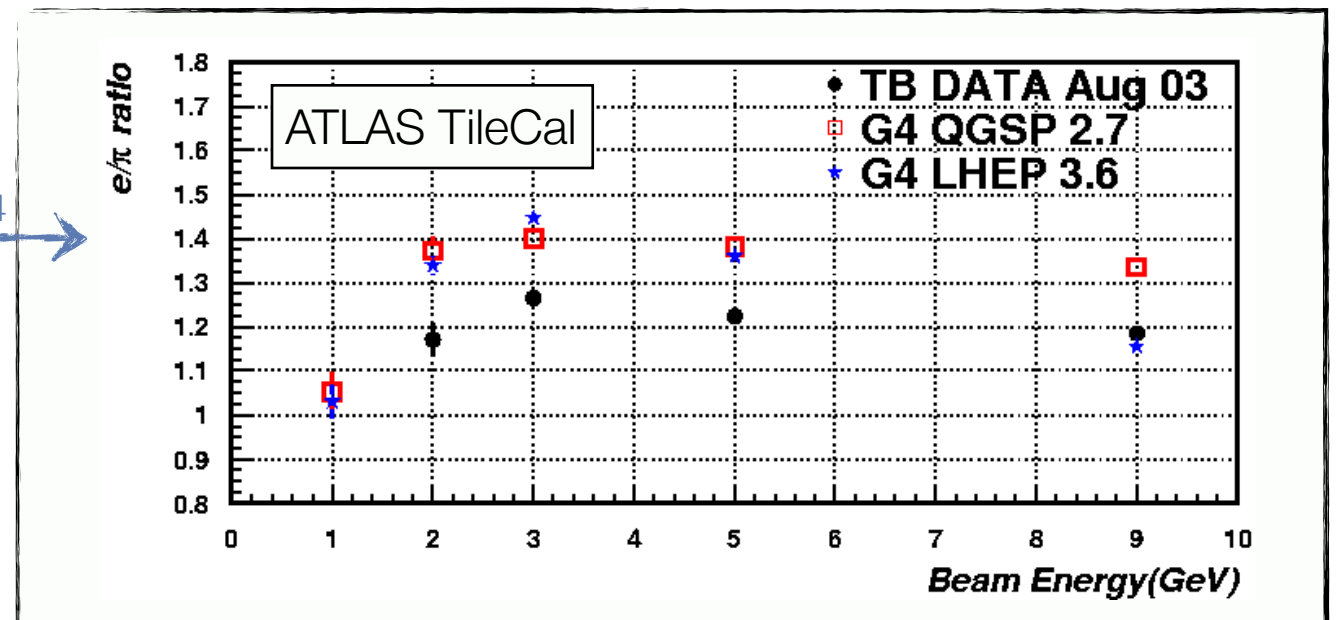
$e/h \neq 1$  leads to ...

Non-uniform energy response  
due to fluctuations in  $f_{em}$  ...

**Compensation important!**

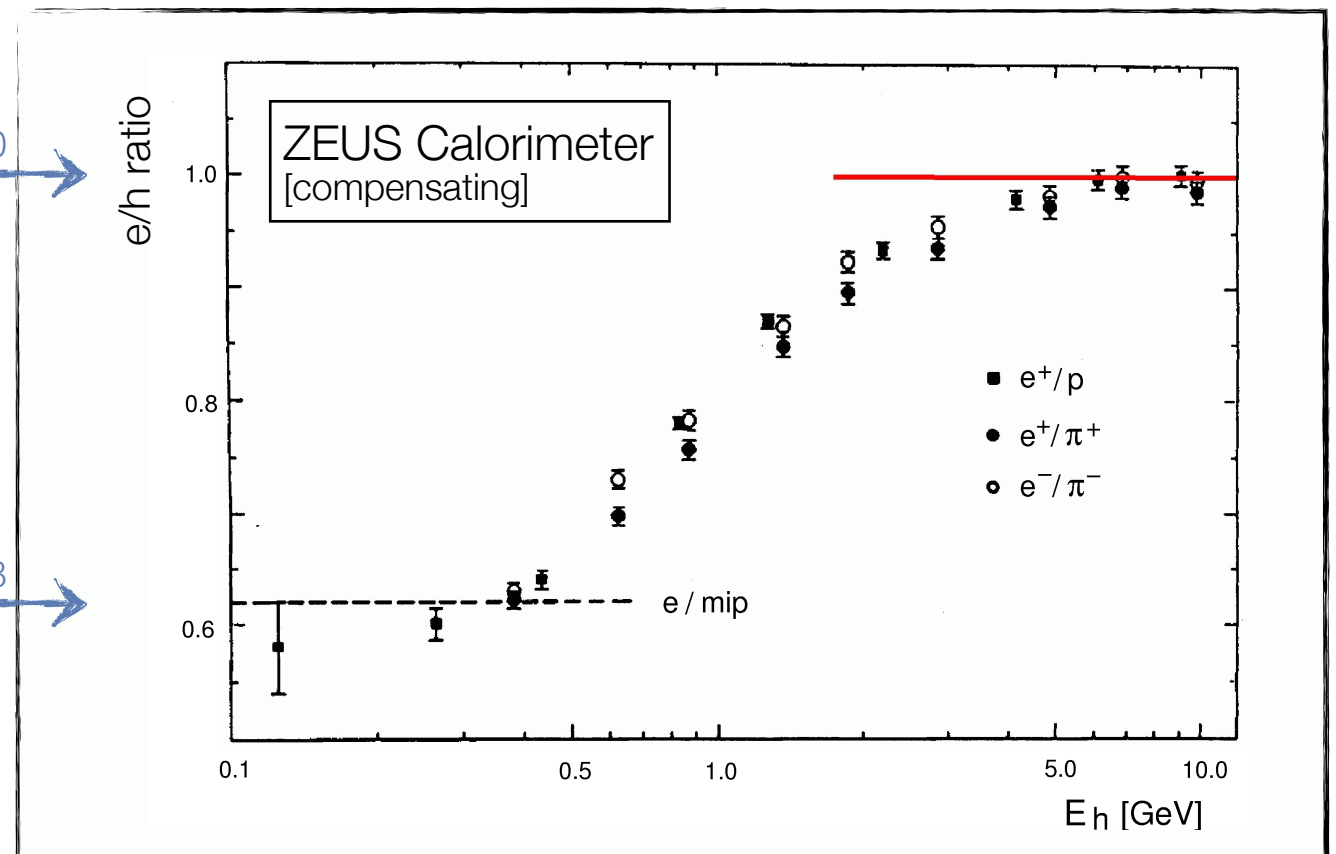
as one generally cannot resolve individual shower components when measuring the total energy flow ...

$e/h = 1.4$



$e/h = 1.0$

$e/h = 0.8$



# Compensation

e/h ratio:

[This is what it is all about ...]

Compensation:  $e/h > 1 \rightarrow e/h \approx 1$

[Understanding of e/h ration allows optimization]

Consider particle type  $i$  with energy  $E_i$ :

$$E_{\text{vis}}(i) = E_{\text{dep}}(i) - E_{\text{inv}}(i)$$

$E_{\text{vis}}$  : visible energy

$E_{\text{inv}}$  : invisible energy

$$a_i \equiv \frac{E_{\text{vis}}(i)}{E_{\text{vis}}(i) + E_{\text{inv}}(i)}$$

Visible energy fraction

Compare energy deposition of different particle types with that of minimum ionizing particle (mip):

$$\frac{e}{\text{mip}} = \frac{a_e}{a_{\text{mip}}} \quad [\text{Electrons}]$$

$$\frac{h}{\text{mip}} = \frac{a_h}{a_{\text{mip}}} \quad [\text{Hadronic components}]$$

$$S_e = \overset{\text{determined by calibration}}{k} \cdot E \frac{e}{\text{mip}} \quad [\text{Electrons signal}]$$

$$S_h = k \cdot E \left[ \underset{\substack{\text{electromagn.} \\ \text{energy fraction} \\ \text{[varies with } \ln E]}}{f_{\text{em}}} \frac{e}{\text{mip}} + (1 - f_{\text{em}}) \frac{h}{\text{mip}} \right] \quad [\text{Hadronic signal}]$$

# Compensation

## Consequences:

As energy response different for electromagnetic and hadronic energy deposits ...

[for non-compensating calorimeters]

$$\frac{e}{\text{mip}} \neq \frac{h}{\text{mip}}$$

### A. Non-linear behavior

Since  $f_{\text{em}}$  depends logarithmically on energy the calorimeter response will change with rising energy ...

### B. Worsening of resolution

The calorimeter response to the purely hadronic part of a hadron shower has a much broader distribution than the response to the e.m. part at the same energy. Fluctuations in  $f_{\text{em}}$  will worsen the energy resolution ...

### C. Deviation from $1/\sqrt{E}$ resolution dependence

Fluctuations in  $f_{\text{em}}$  will in addition cause the energy resolution not to scale with  $E^{-1/2}$  ...

$$S_e = k \cdot E \frac{e}{\text{mip}}$$

$$S_h = k \cdot E \left[ f_{\text{em}} \frac{e}{\text{mip}} + (1 - f_{\text{em}}) \frac{h}{\text{mip}} \right]$$

$\sim \ln E$

$$\frac{S_e}{S_h} = \frac{\frac{e}{\text{mip}}}{f_{\text{em}} \frac{e}{\text{mip}} + (1 - f_{\text{em}}) \frac{h}{\text{mip}}}$$

Total calorimeter response different for electrons and hadrons ...

Goal: Compensation, i.e.  $e/\text{mip} = h/\text{mip} \rightarrow S(e)/S(h) = 1$

# Compensation

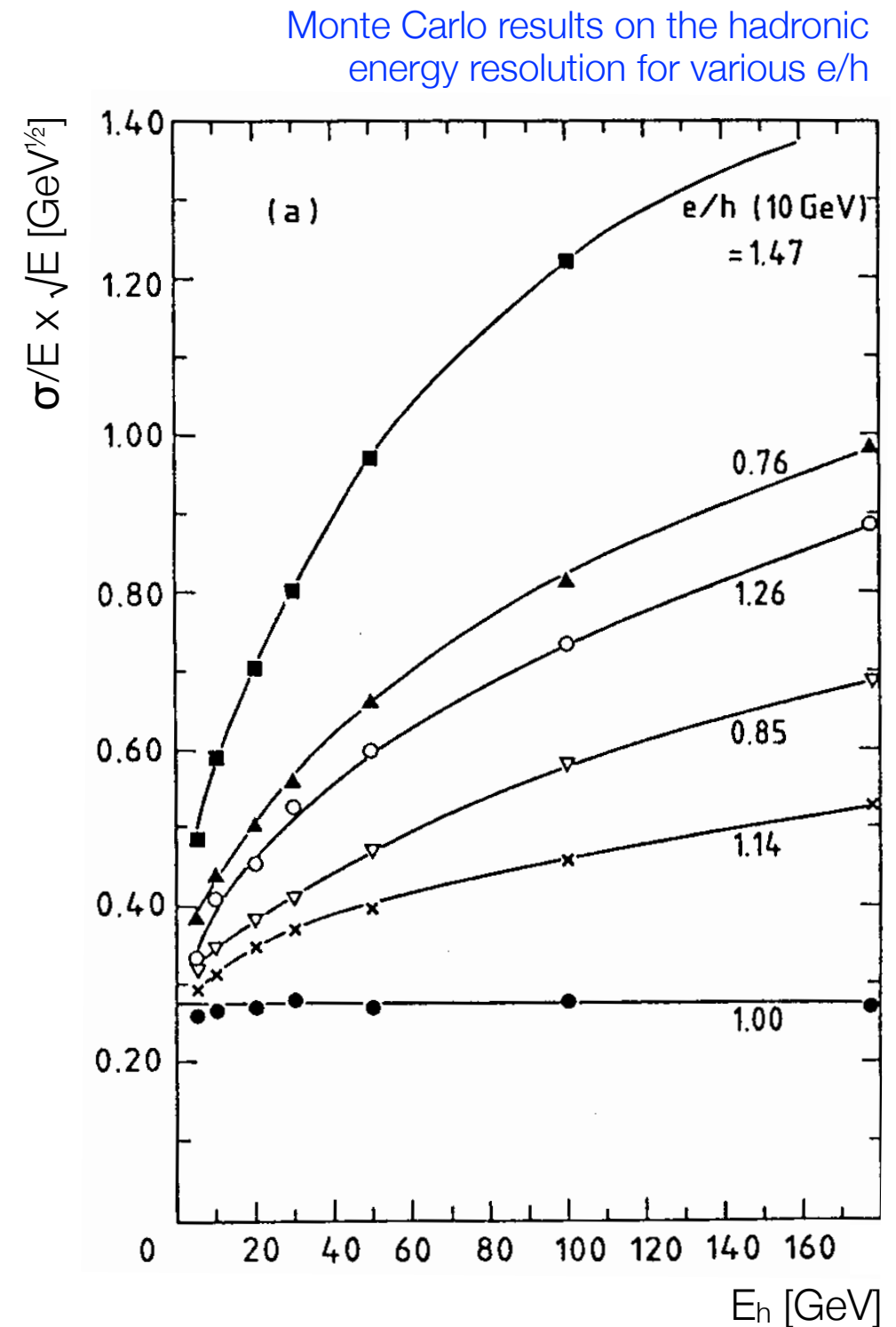
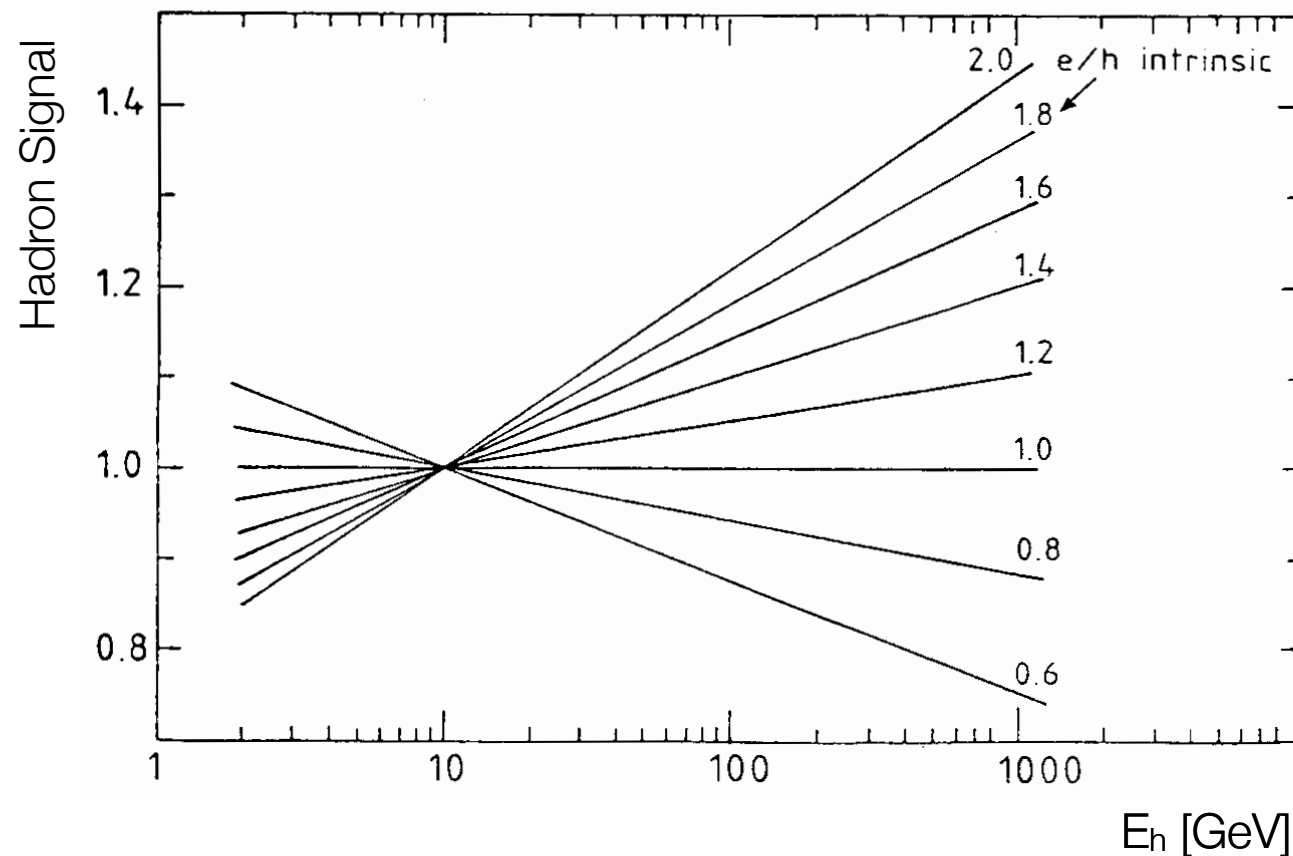
## Consequences of non-compensation ...

[Monte Carlo Simulation]

Fig A.: Hadron signals gets larger (smaller) with  $E_h$  energy if  $e/h > 1$  ( $e/h < 1$ ) as  $f_{em}$  increases ...

Fig B.: Energy resolution does not scale with  $\sqrt{E}$  for  $e/h \neq 1$  ...

Calorimeter signal per GeV for hadrons, normalized to a 10 GeV hadron signal, as a function of  $E_h$ , for various  $e/h$  ...



# Compensation

Contributions to  $h/mip$ :

$$\frac{h}{mip} = f_{ion} \cdot \frac{ion}{mip} + f_n \cdot \frac{n}{mip} + f_\gamma \cdot \frac{\gamma}{mip} + f_B \cdot \frac{B}{mip}$$

with:

$f_{ion}$  : fraction of hadronic component deposited by charged particles (ionization)

$f_n$  : fraction of hadronic component deposited by neutrons

$f_\gamma$  : fraction of hadronic component deposited by photons from nuclear reactions

$f_B$  : fraction of nuclear binding energy in hadronic component

Compensation:  
Increase  $h/mip$  via increase  
of  $f_{ion}, f_n, f_\gamma, f_B$

Typical values  
for a 5 GeV proton

|            | Fe  | U   |               | Fe/Sz     | Fe/Ar | U/Sz        | U/Ar | determined by     |
|------------|-----|-----|---------------|-----------|-------|-------------|------|-------------------|
| $f_{ion}$  | 57% | 38% | ion/mip       | 0.83      | 0.88  | 0.93        | 1    | $d_{act}$         |
| $f_n$      | 3%  | 2%  | n/mip         | 0.5 ... 2 | 0     | 0.8 ... 2.5 | 0    | $d_{act}/d_{abs}$ |
| $f_\gamma$ | 8%  | 15% | $\gamma$ /mip | 0.7       | 0.95  | 0.4         | 0.4  | $d_{abs}$         |
| $f_B$      | 32% | 45% | B/mip         | 0.9       | 0.95  | 0.55        | 0.55 | $d_{abs}$         |

$d_{act}$  : thickness of active medium  
 $d_{abs}$  : thickness of absorber

# Compensation

## Methods:

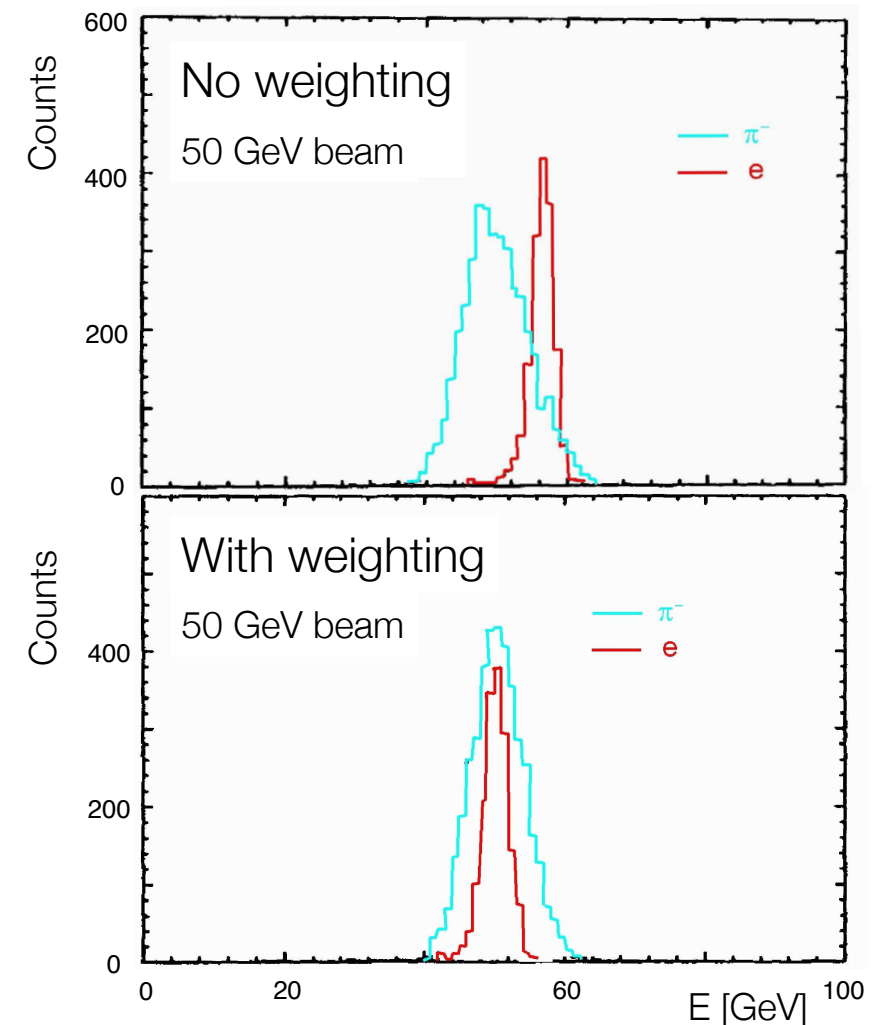
### A. Software compensation ...

Segmentation of calorimeter into cells/layers

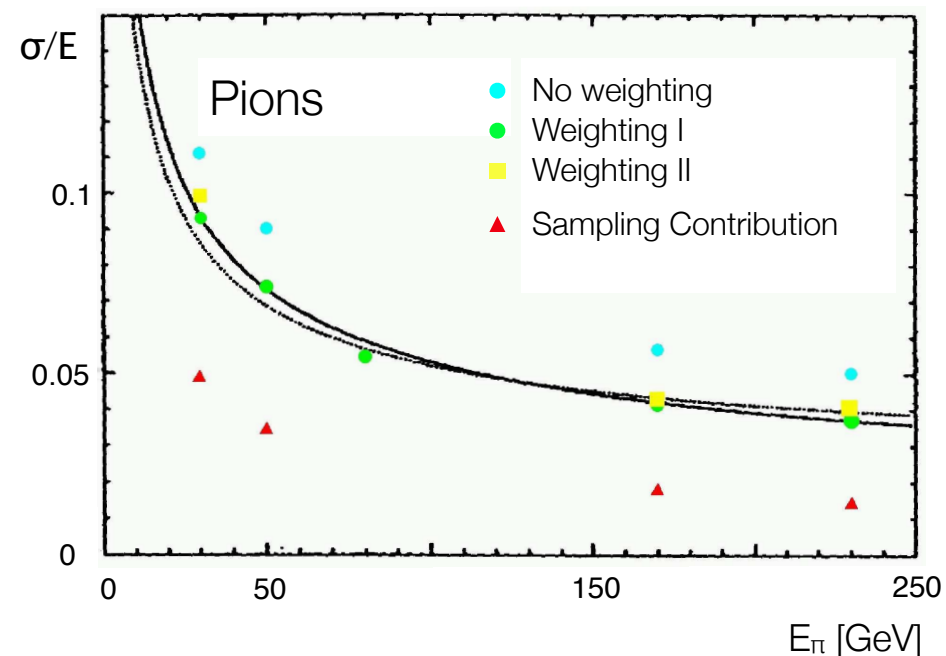
Identification of cells/layers with particularly large energy  
[considered as electromagnetic contribution from  $\pi^0$ ]

Give small weight to layers with larger energy density ...

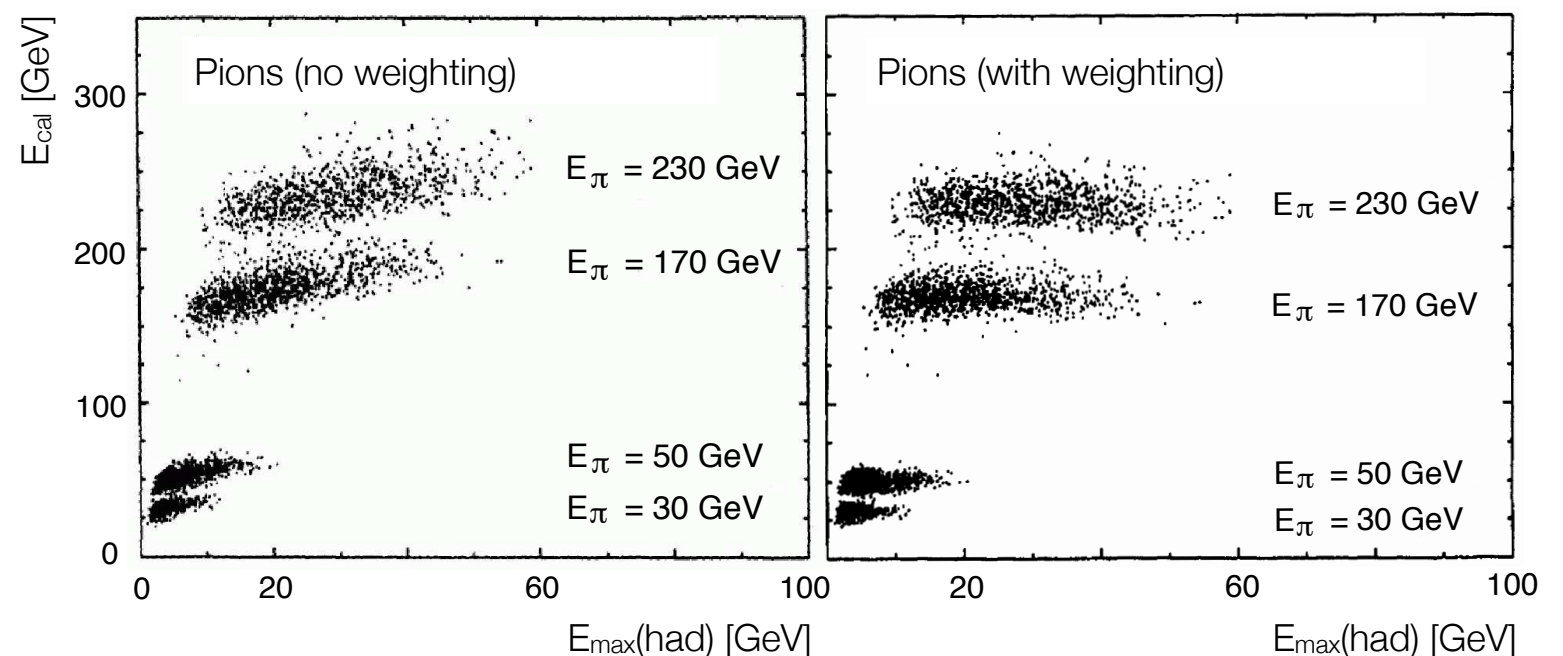
Measured  
pulse height spectrum



Energy resolution of LAr calorimeter  
with and without weighting ...



Energy measurement  
as function of  $E_{\max}(\text{had})$  ...



# Compensation

## Methods:

### B. Hardware compensation ...

Choose suitable hardware parameters to either increase  $h/mip$  or decrease  $e/mip$  ...

e.g.: Increase hadronic response by varying  $d_{abs}$  or  $d_{act}$  (absorber/active material thickness) ...

Increase hadronic response via fission and spallation of uranium ...

Increase neutron detection efficiency in active material [high proton content;  $H_2$ ] ...

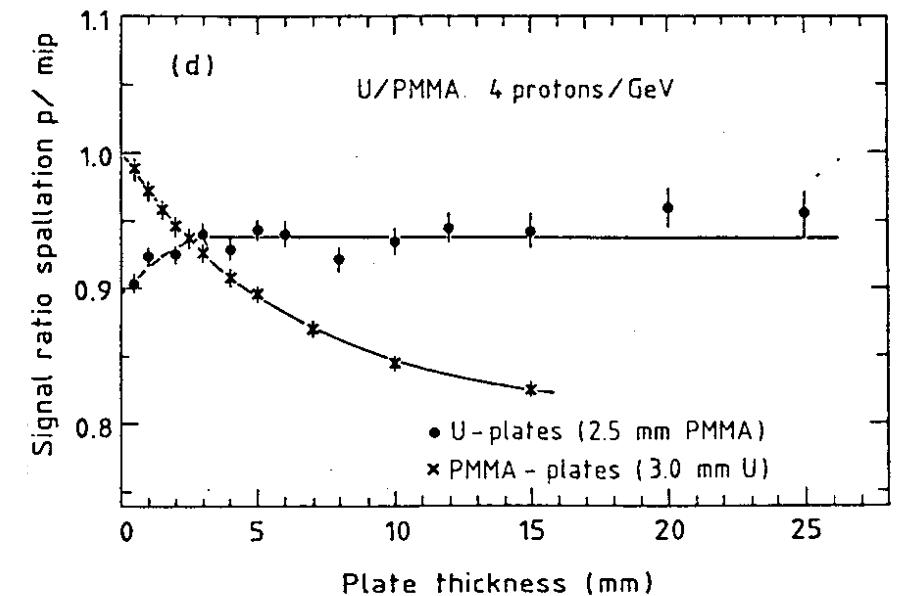
Reduction of  $e/mip$  via high-Z absorber and suitable choice of  $d_{abs}/d_{act}$  ...

Increase integration time for higher sensitivity to  $\gamma$ -capture after neutron thermalization ...

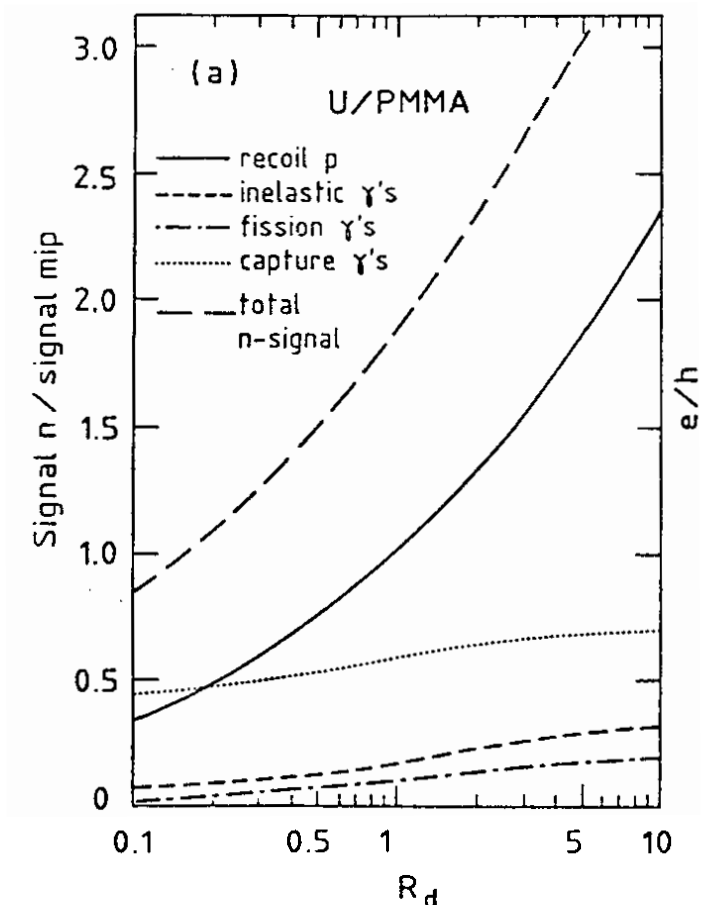
Modify  $f_n$  choosing larger  $Z_{abs}$  since fraction of spallation neutrons increases with  $Z/A$  ...

...

ion/mip signal in U/PMMA calorimeter as function of absorber/scintillator thickness



n/mip signal in U/PMMA calorimeter as function of  $R_d = d_{abs}/d_{act}$



# Compensation

## Methods:

### B. Hardware compensation ...

Choose suitable hardware parameters to either increase h/mip or decrease e/mip ...

e.g.: Increase hadronic response by varying  $d_{\text{abs}}$  or  $d_{\text{act}}$  (absorber/active material thickness) ...

Increase hadronic response via fission and spallation of uranium ...

Increase neutron detection efficiency in active material [high proton content;  $\text{H}_2$ ] ...

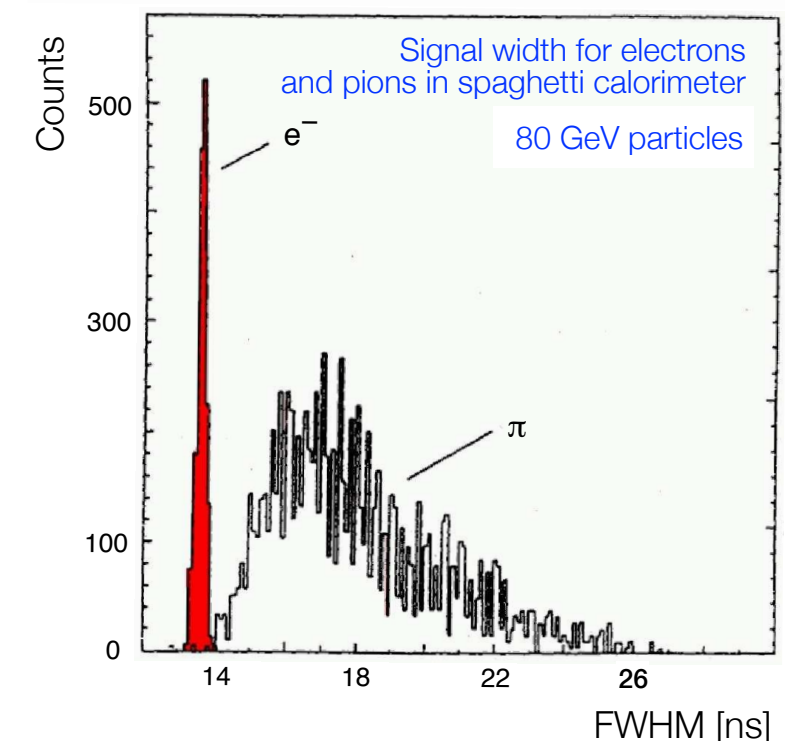
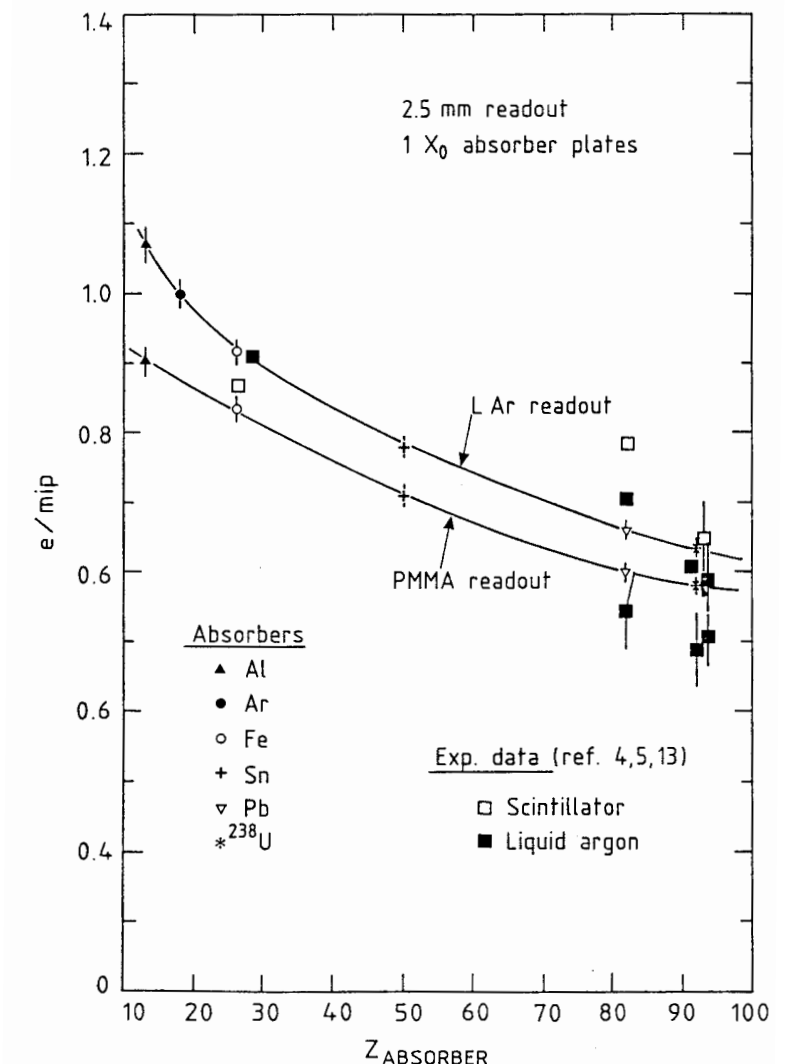
Reduction of e/mip via high-Z absorber and suitable choice of  $d_{\text{abs}}/d_{\text{act}}$  ...

Increase integration time for higher sensitivity to  $\gamma$ -capture after neutron thermalization ...

Modify  $f_n$  choosing larger  $Z_{\text{abs}}$  since fraction of spallation neutrons increases with  $Z/A$  ...

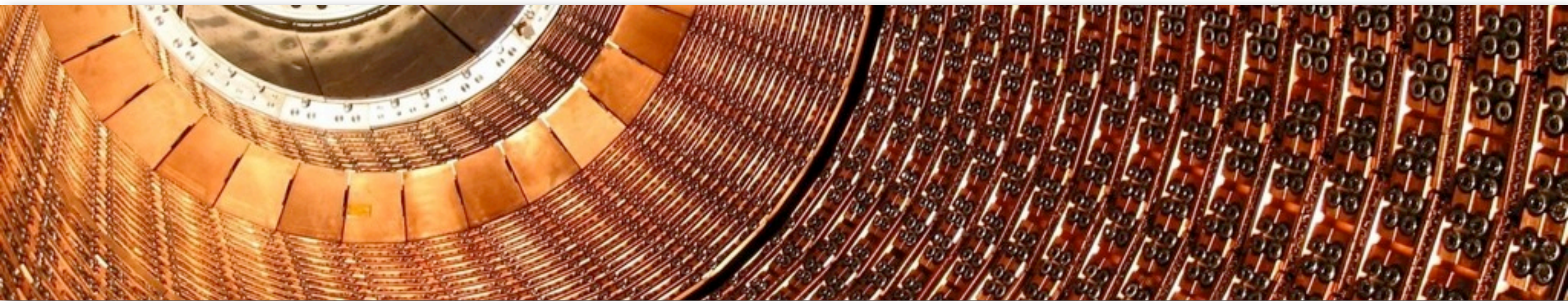
...

e/mip signal for a sampling calorimeter as a function of Z of absorber



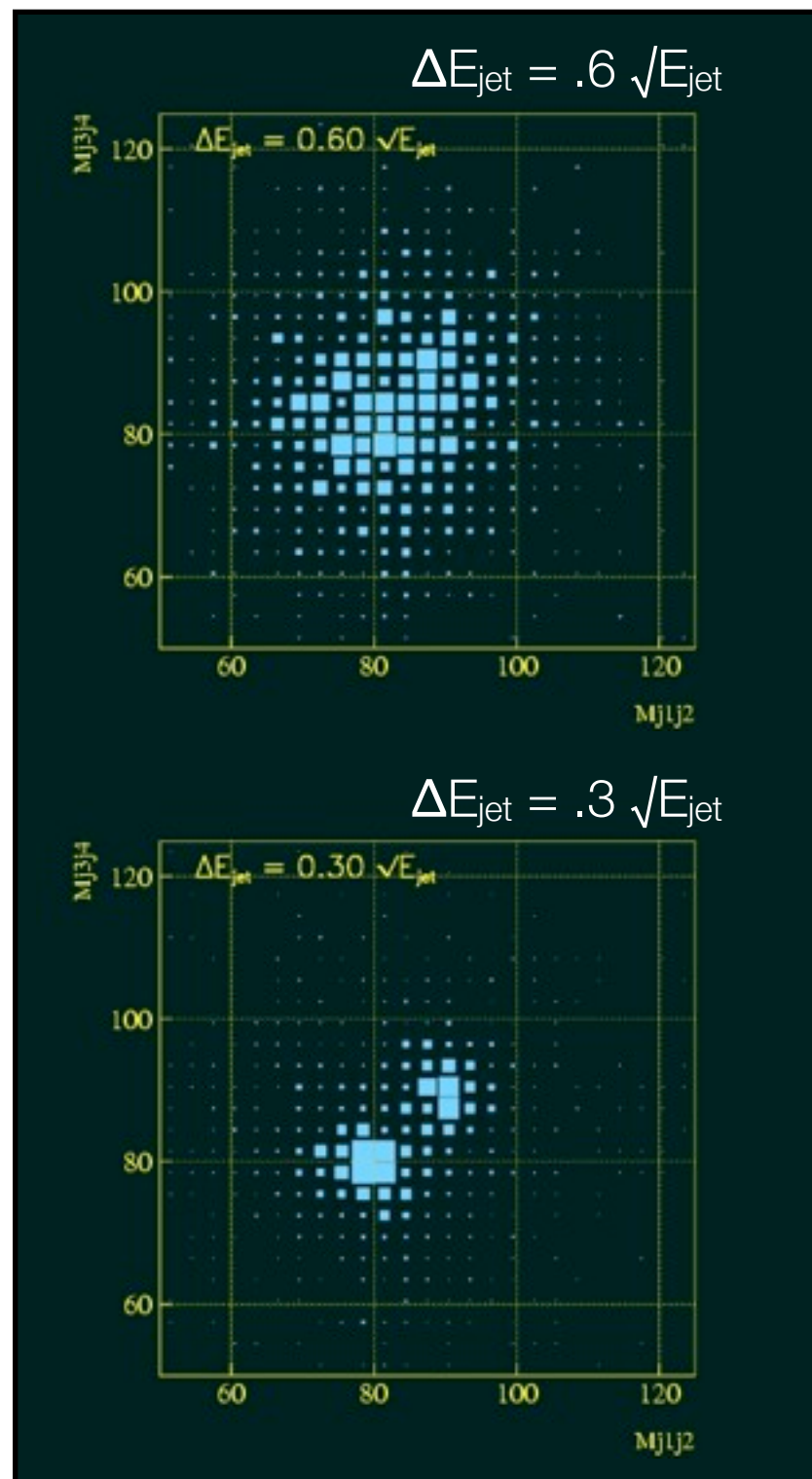
# Calorimetry III

Imaging Calorimeters for ILC ...



# ILC Physics and Calorimetry

$M_{j3j4}$



Separation  
of WW & ZZ  
final states

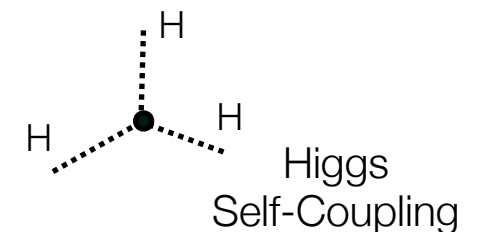
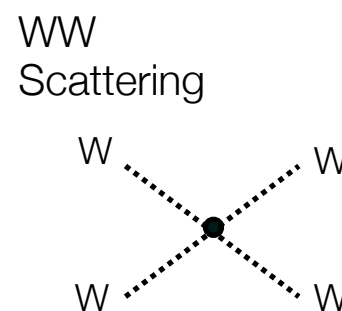
## Precision measurements

Higgs properties  
SUSY particle properties  
Rare SM processes

## Physics categorized by

Multi-Jet final states  
Small cross sections

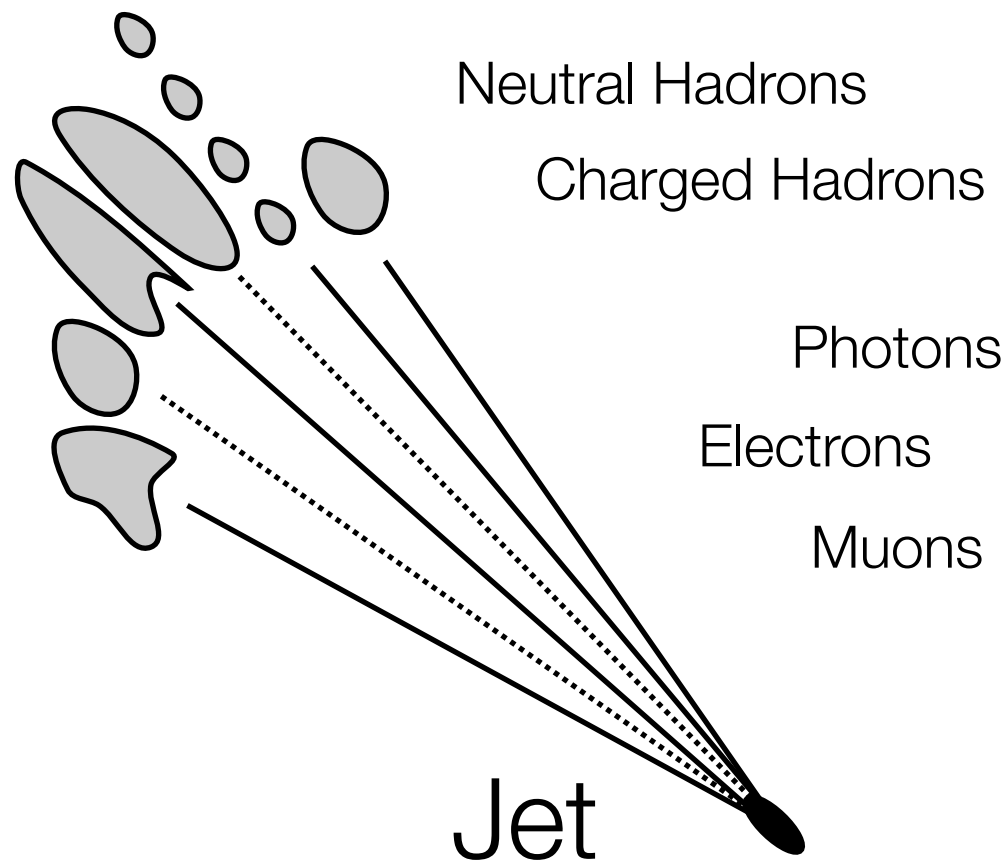
e.g.:  $e^+e^- \rightarrow ZHH$   
 $e^+e^- \rightarrow \nu\nu WW \rightarrow \nu\nu qqqq$   
 $e^+e^- \rightarrow \nu\nu ZZ \rightarrow \nu\nu qqqq$



Jet energy resolution  
directly impacts physics

$M_{j1j2}$

# Jet Energy Measurement



## Problems:

### Non-compensation

[hadronic vs. electromagnetic energy]

### Missing energy

[e.g. muon tracks]

### Double counting

[when using track momenta]

## Particle Flow Calorimetry

Reduce role of 'hadron' calorimetry  
to measurement of  $n$ ,  $K^0$

A

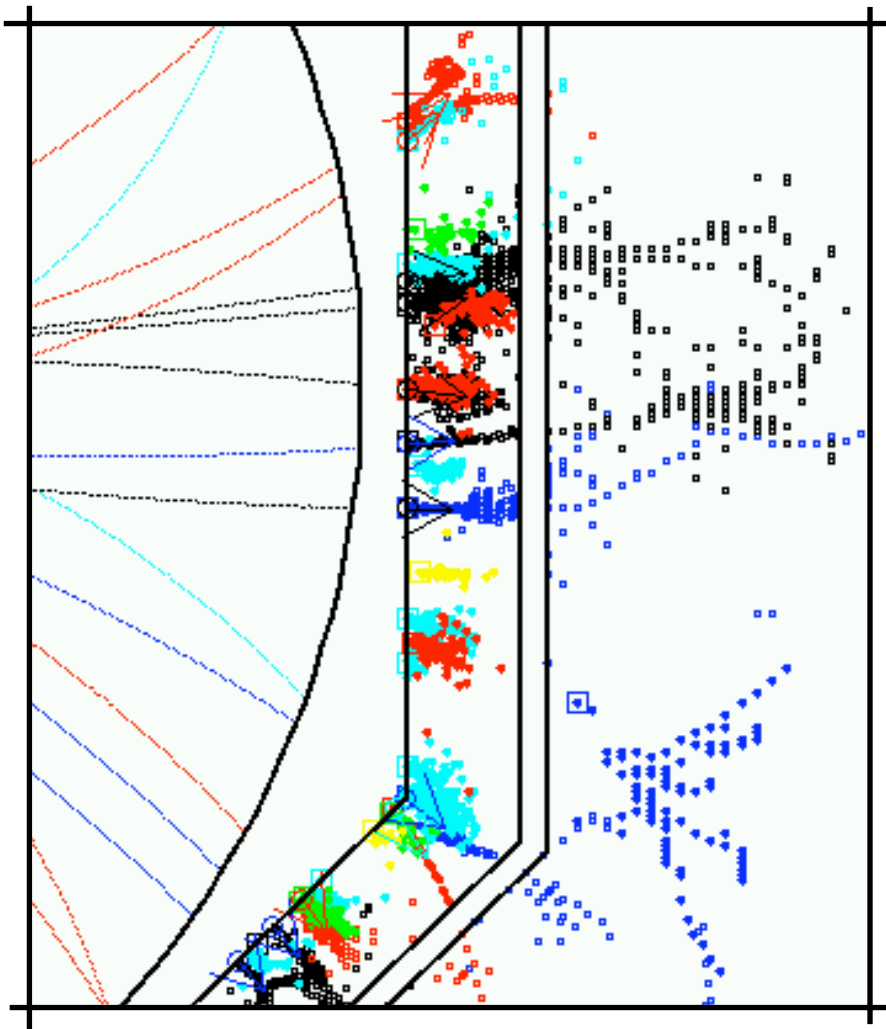
## Compensating Calorimetry

Correcting hadronic energy  
for nuclear-binding energy loss.

B

# No. 1 Approach: “Imaging Calorimetry”

| Component               | Detector | Fraction | Part. resolution            | Jet Energy Res.             |
|-------------------------|----------|----------|-----------------------------|-----------------------------|
| Charged ( $X^\pm$ )     | Tracker  | 60%      | $10^{-4} E_x$               | negligible                  |
| Photons ( $\gamma$ )    | ECAL     | 30%      | $0.1/\sqrt{E_\gamma}$       | $.06/\sqrt{E_{\text{jet}}}$ |
| Neutral Hadrons ( $h$ ) | E/HCAL   | 10%      | $0.5/\sqrt{E_{\text{had}}}$ | $.16/\sqrt{E_{\text{jet}}}$ |



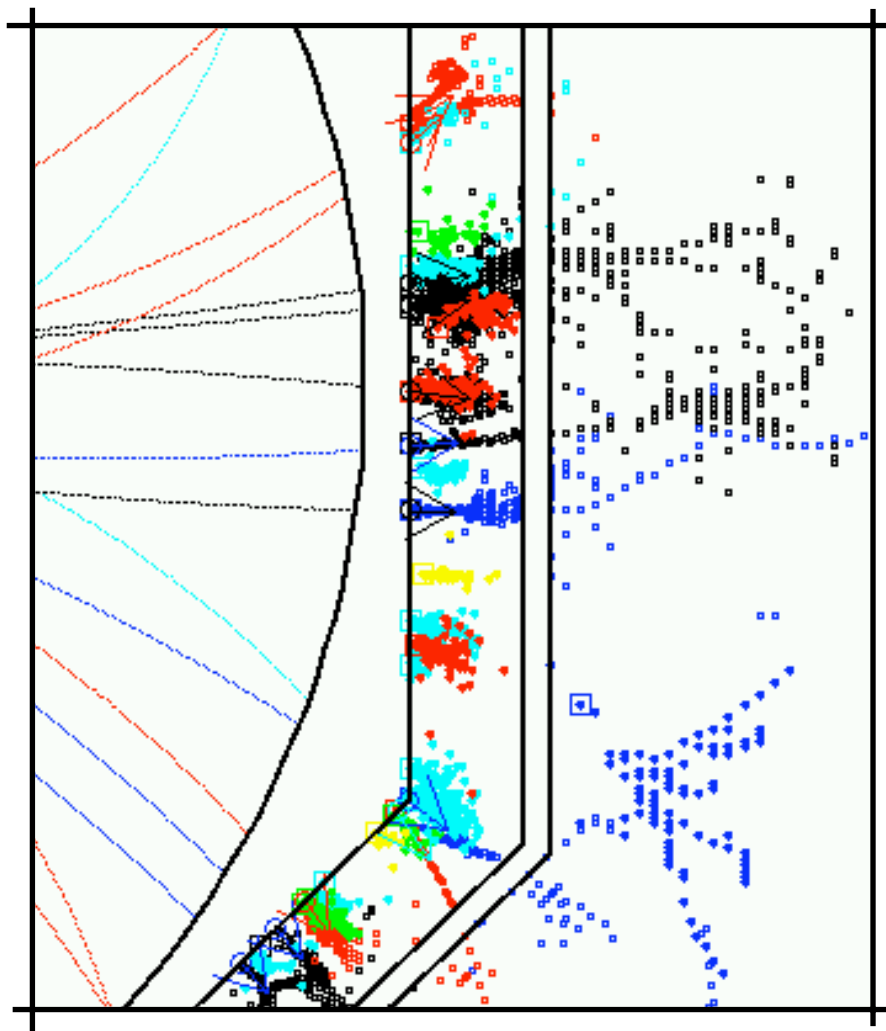
## Particle Flow (PFA):

Choose detector best suited for particular particle type ...

i.e.: use tracks and distinguish ‘charged’ from ‘neutral’ energy to avoid double counting  
distinguish electromagnetic and hadronic energy deposits for software compensation

# No. 1 Approach: “Imaging Calorimetry”

| Component               | Detector | Fraction | Part. resolution            | Jet Energy Res.             |
|-------------------------|----------|----------|-----------------------------|-----------------------------|
| Charged ( $X^\pm$ )     | Tracker  | 60%      | $10^{-4} E_x$               | negligible                  |
| Photons ( $\gamma$ )    | ECAL     | 30%      | $0.1/\sqrt{E_\gamma}$       | $.06/\sqrt{E_{\text{jet}}}$ |
| Neutral Hadrons ( $h$ ) | E/HCAL   | 10%      | $0.5/\sqrt{E_{\text{had}}}$ | $.16/\sqrt{E_{\text{jet}}}$ |



PFA – Energy Resolution:

$$\sigma_{\text{jet}}^2 = \sigma_X^2 + \sigma_\gamma^2 + \sigma_{\text{had}}^2$$

$$.17/\sqrt{E}$$

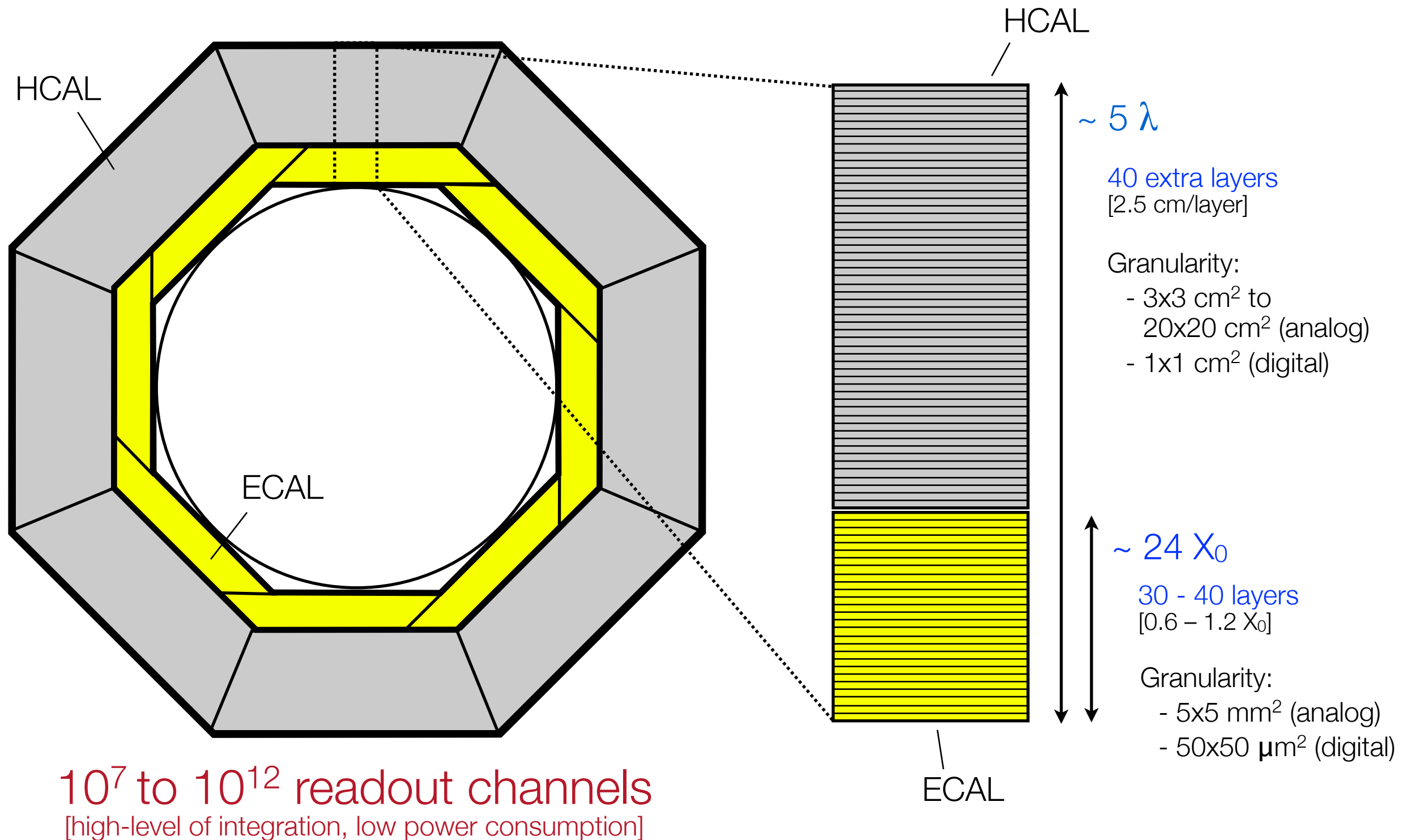
$$+ \sigma_{\text{confusion}}^2 + \dots$$

$$< .25/\sqrt{E}$$

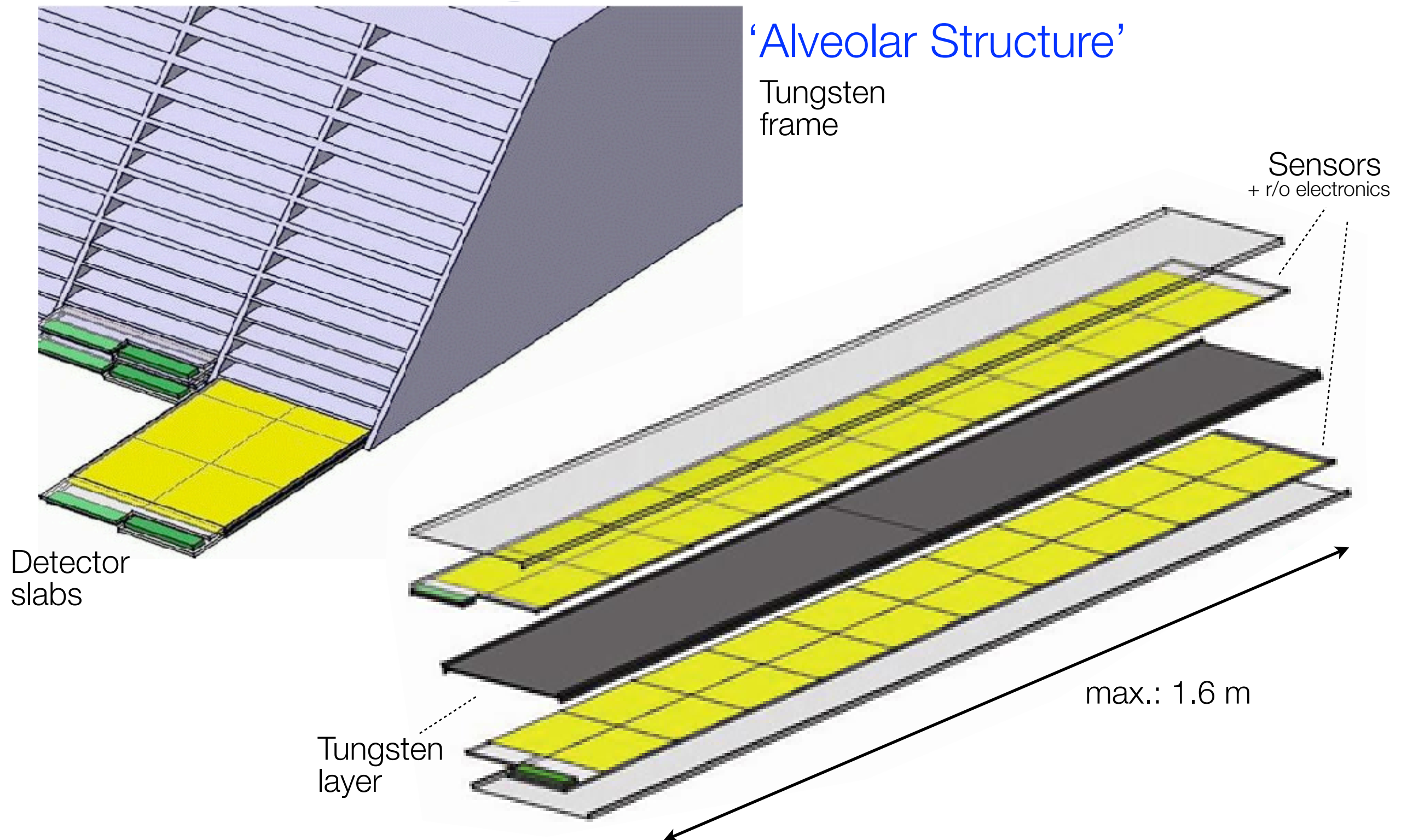
?

Granularity more important  
than energy resolution !?

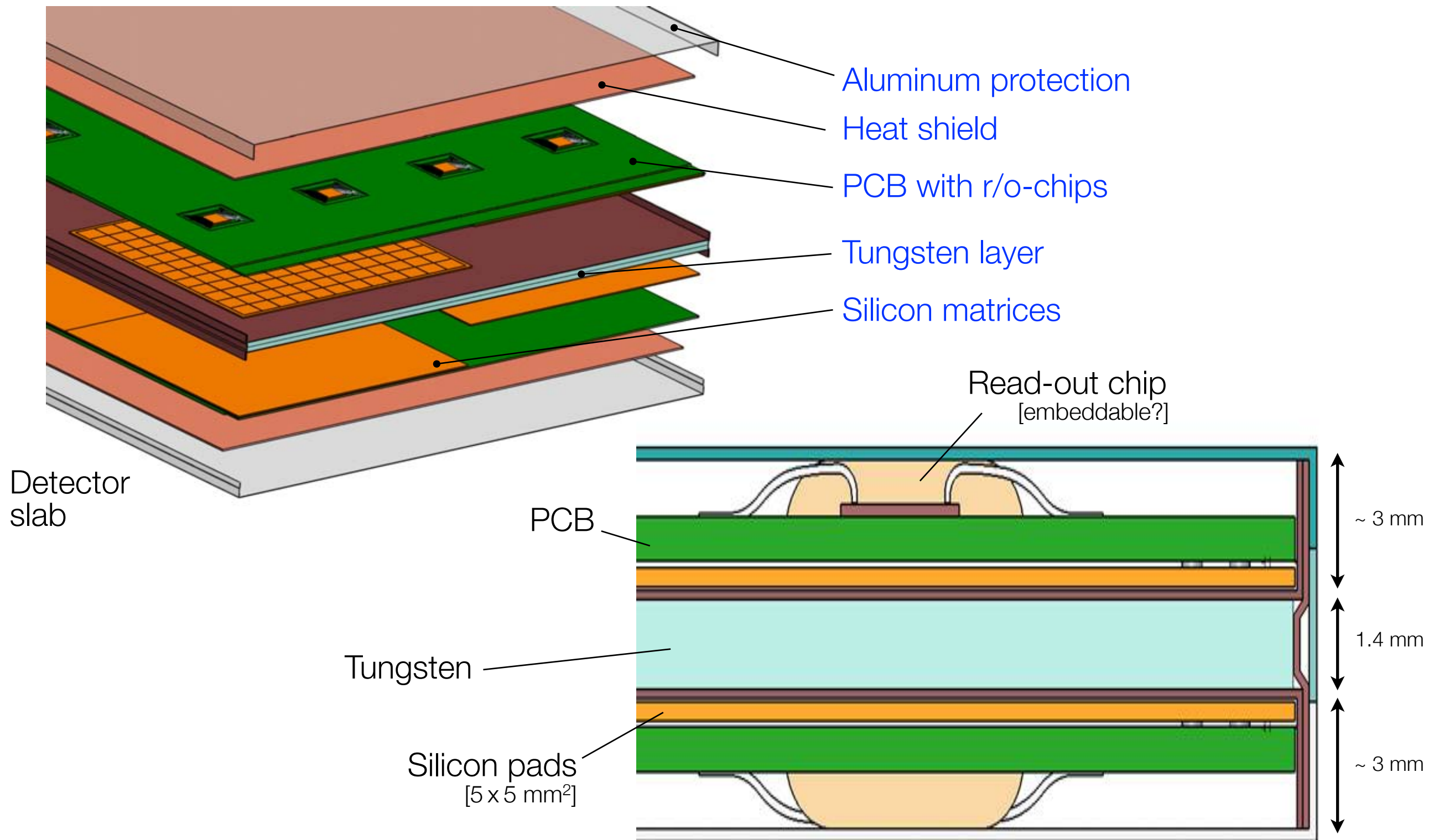
# Overall Calorimeter Design



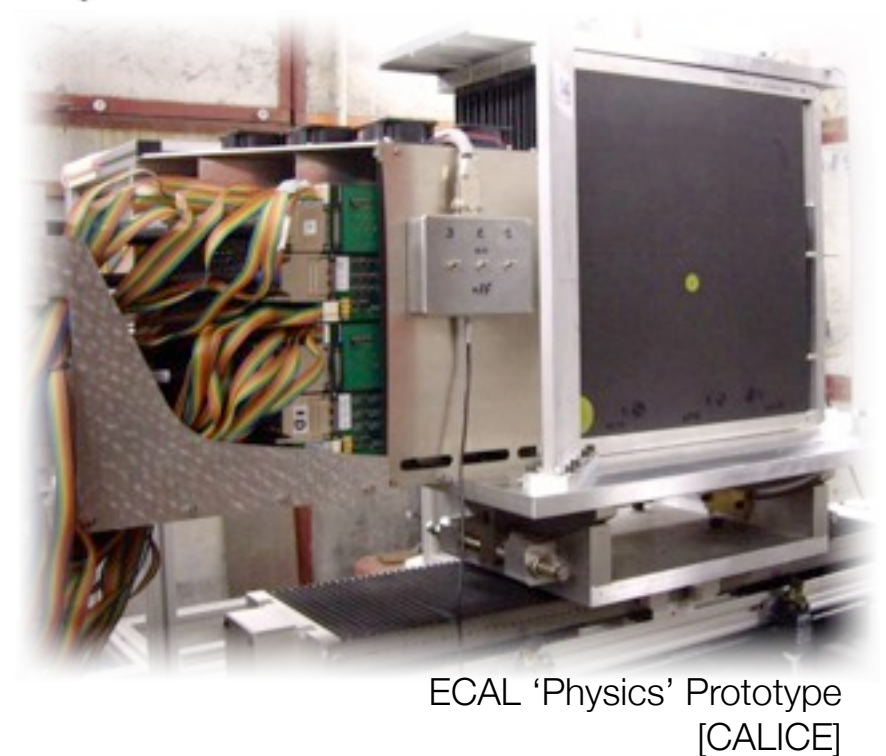
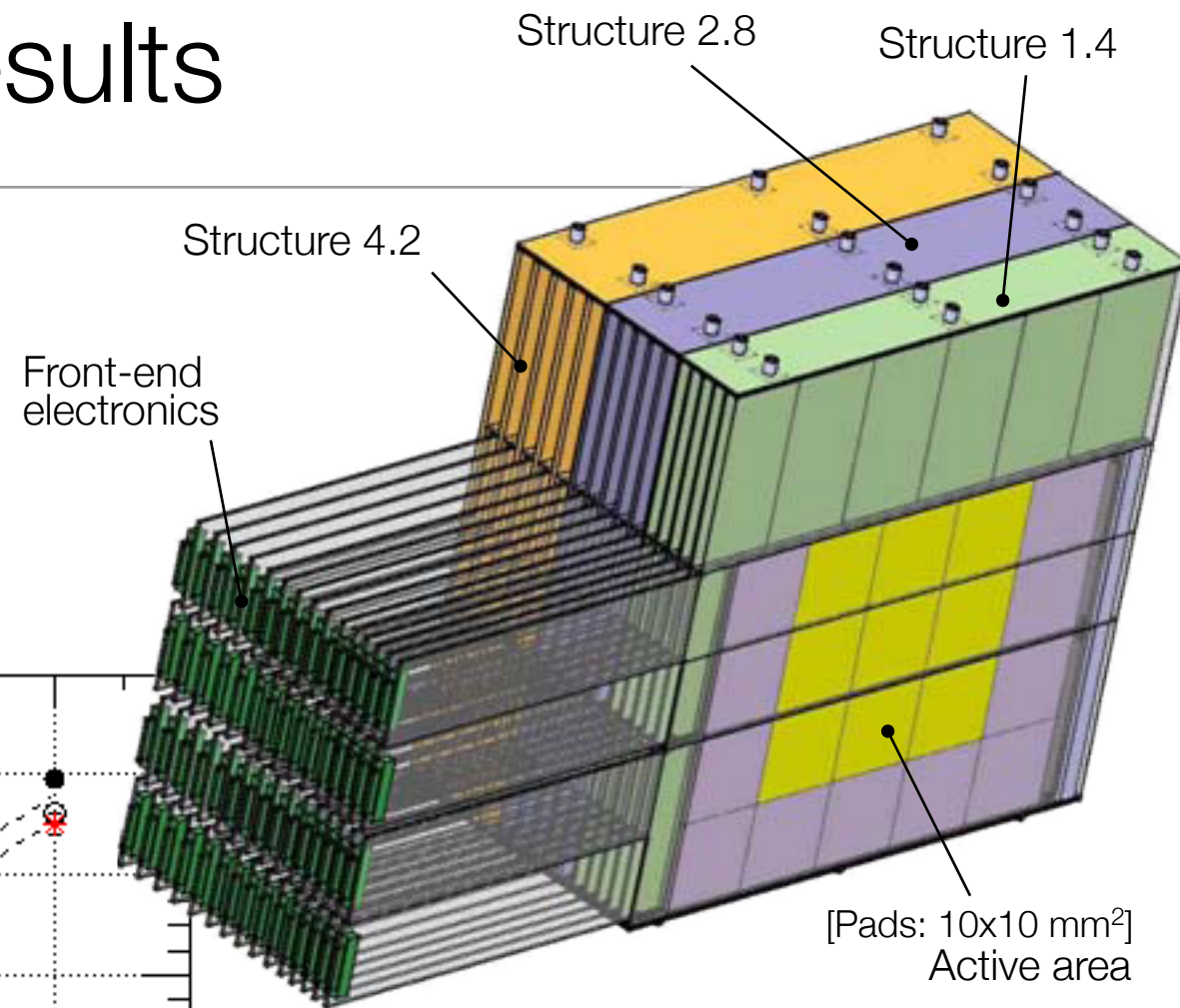
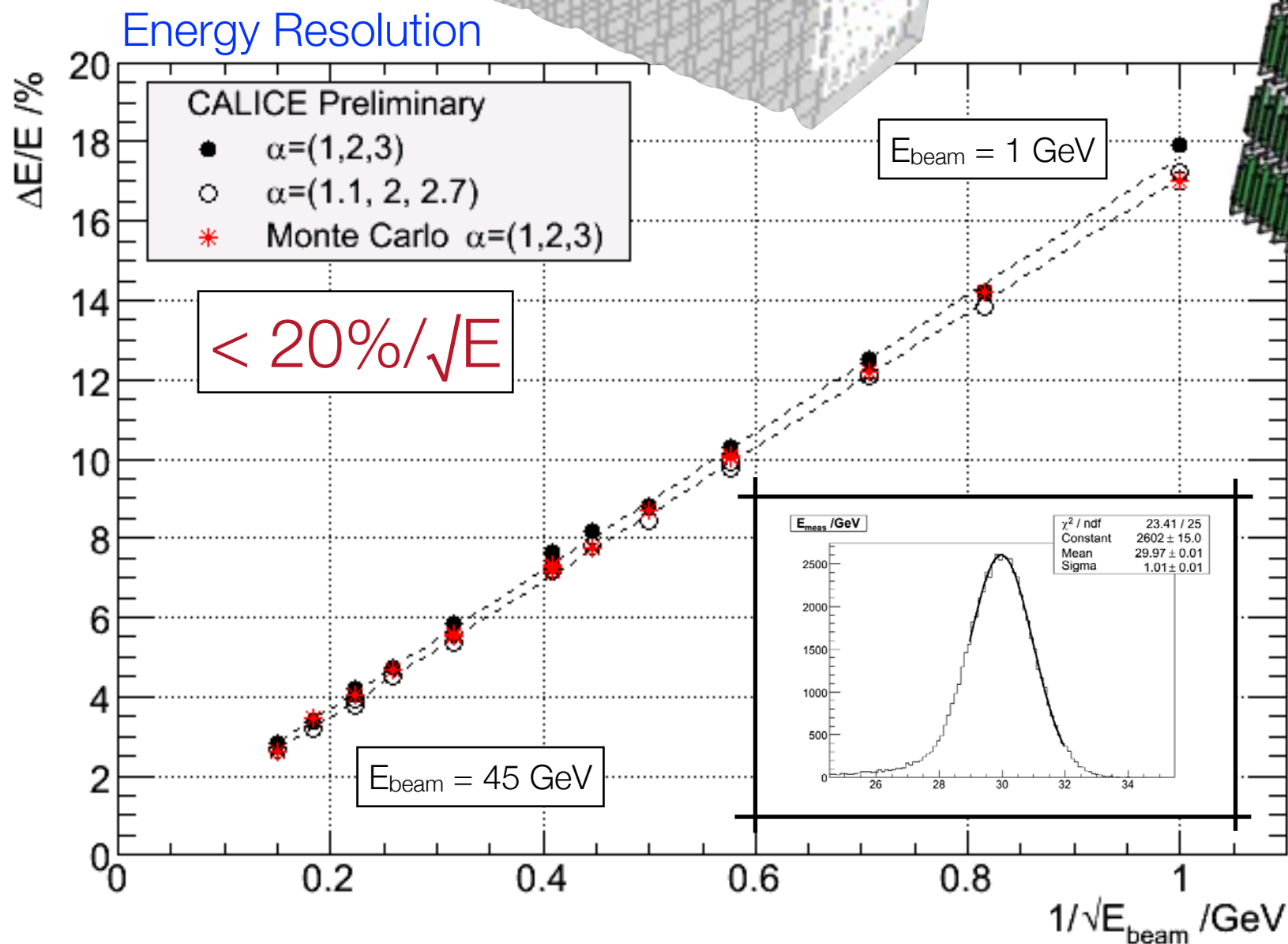
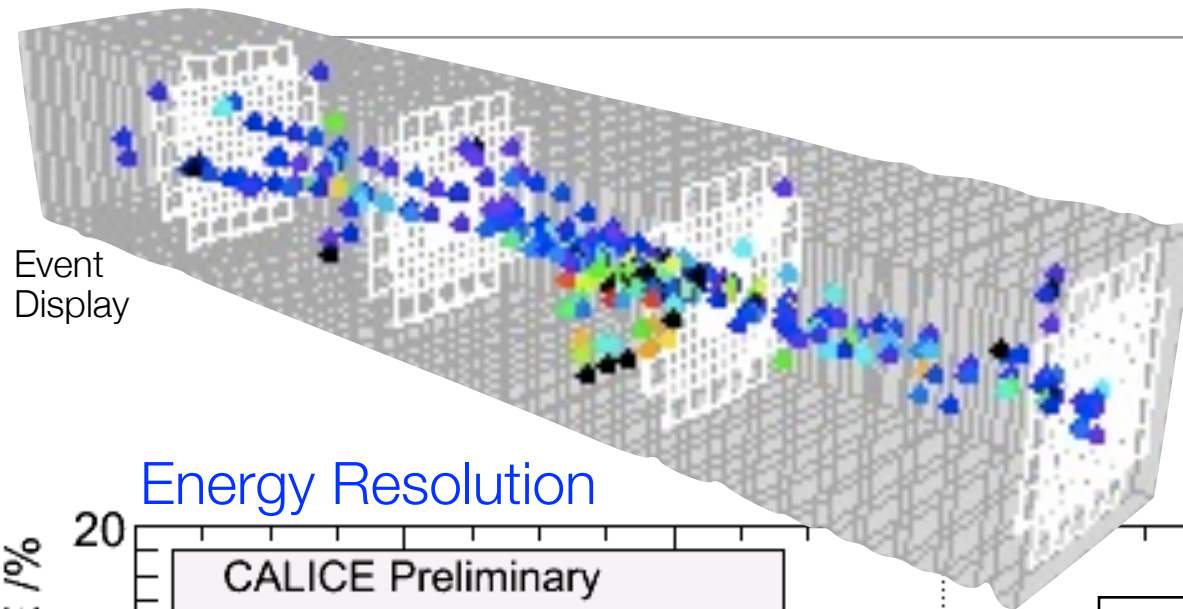
# Silicon Tungsten Calorimeters



# Basic CALICE ECAL Design



# CALICE ECAL Test Beam Results



# Monolithic Active Pixel Digital ECAL

## MAPS:

Monolithic  
Active Pixel Sensor

Pixel size:  $40 \times 40 \mu\text{m}^2$

Channel number:  $8 \times 10^{11}$

Absorber: Tungsten

Binary readout

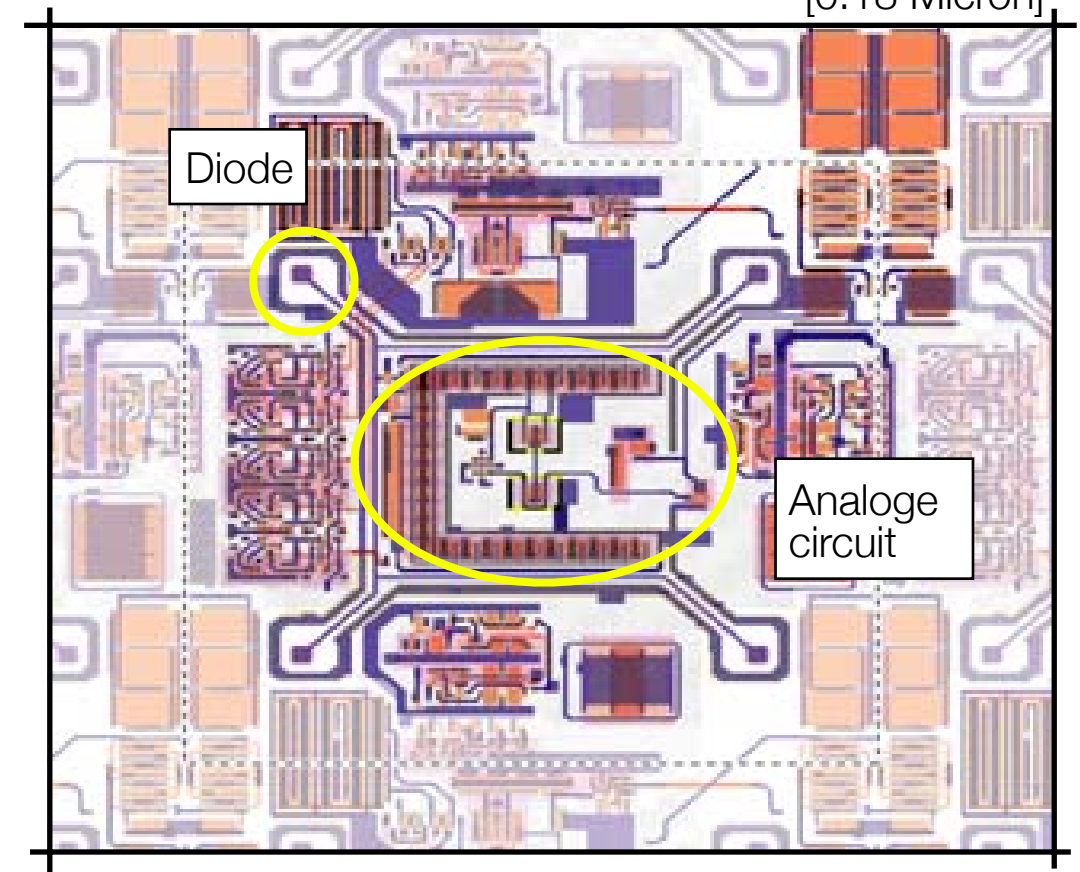
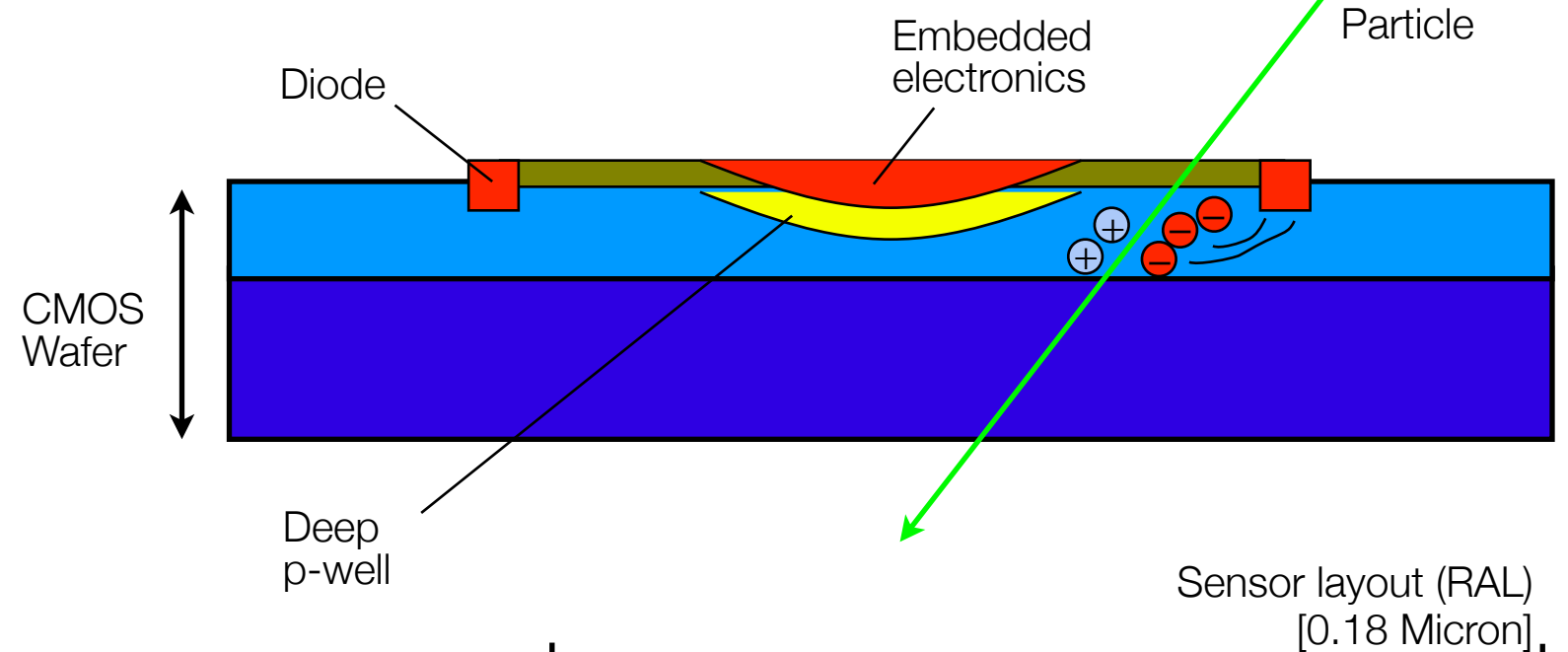
Integration of  
sensor and readout electronics

Manufactured in  
standard CMOS process

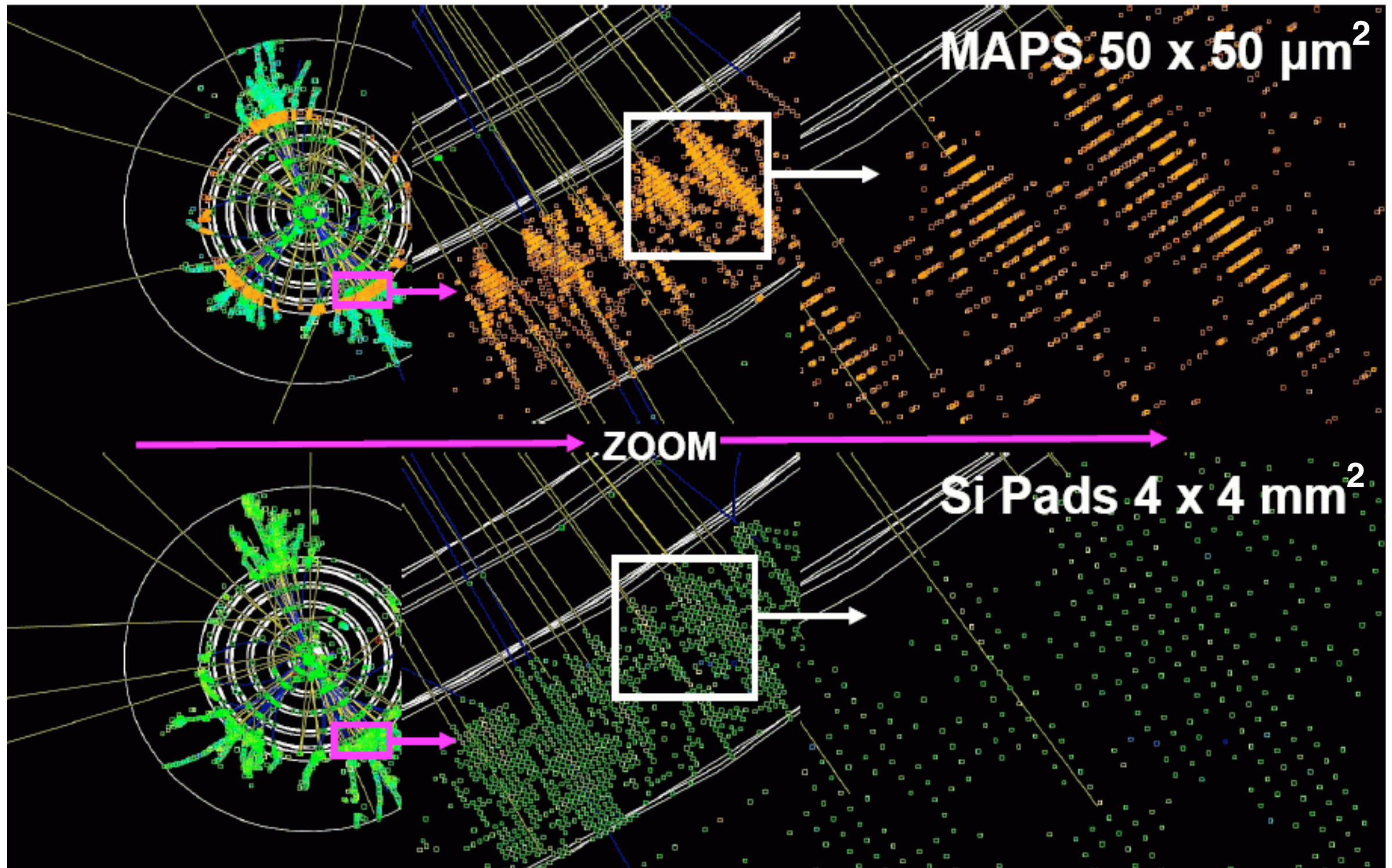
### Concerns:

Power consumption:  $40 \mu\text{W}/\text{mm}^2$

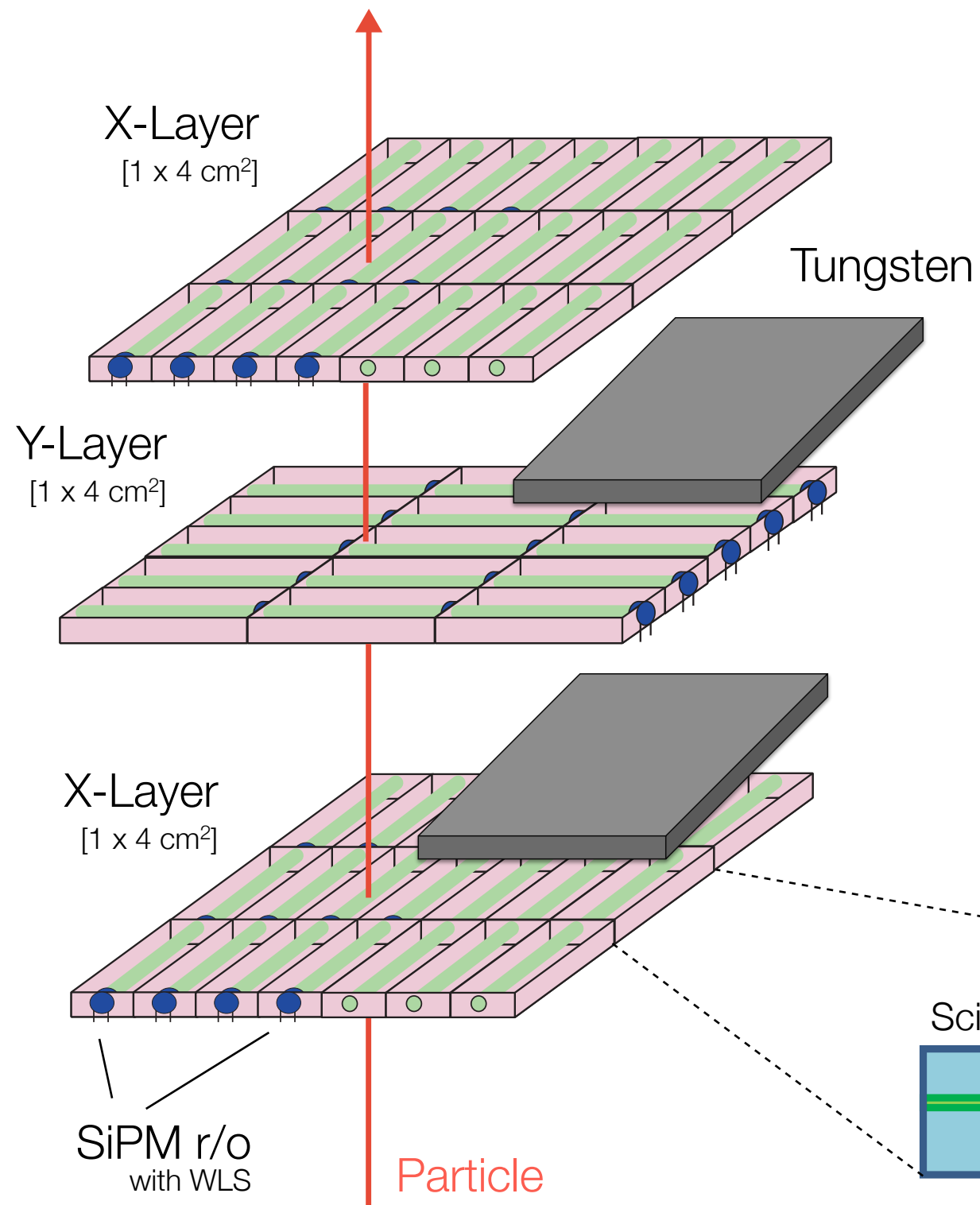
DAQ needs 400 Gbit/s



# Digital ECAL: Shower Imaging



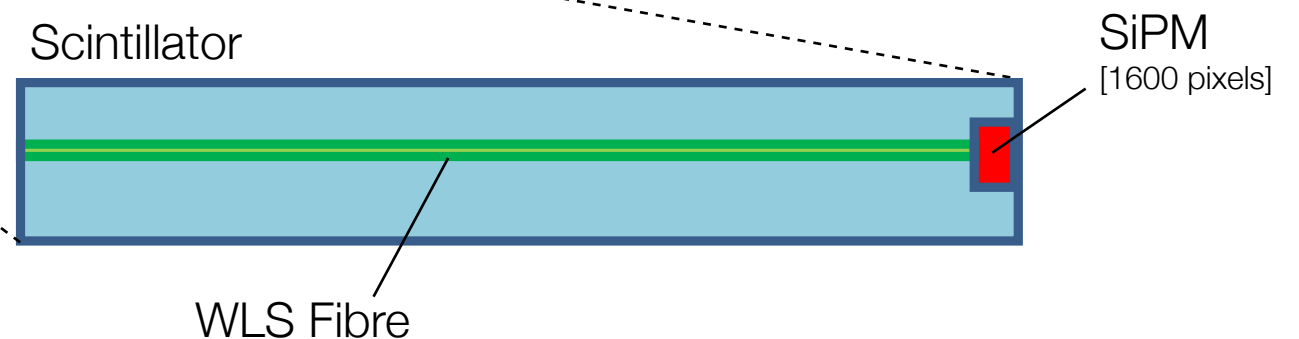
# Scintillator-Tungsten ECAL (Asia)



Scintillator layers: 2 mm  
Tungsten layers: 3 mm

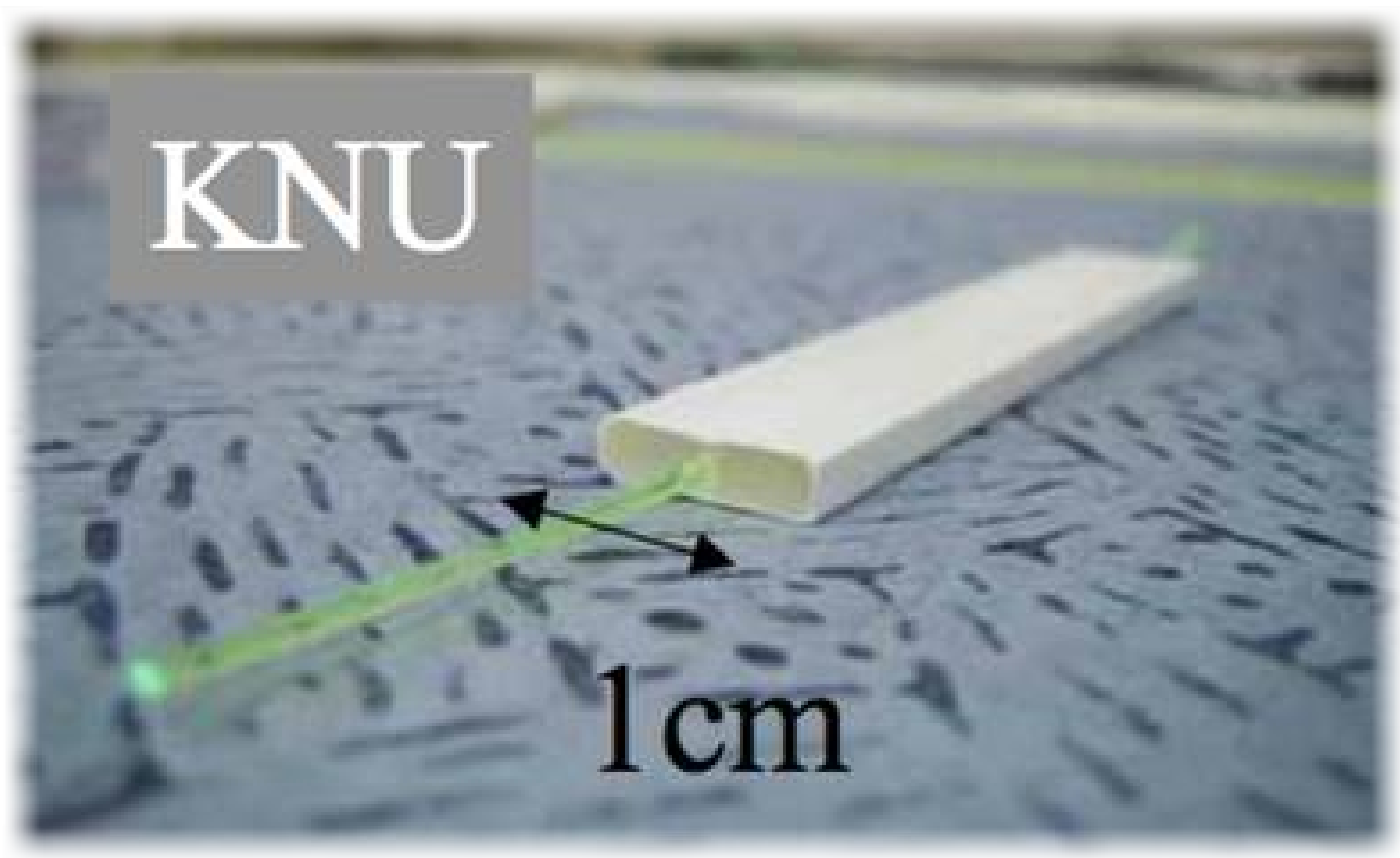
X/Y-Strips: 1 x 4 cm<sup>2</sup>  
Granularity: 1 x 1 cm<sup>2</sup>

Readout: MPPC  
Channels:  $\sim 10^7$



# Scintillator-Tungsten ECAL (Asia)

---



# Silicon Photomultipliers (SiPM)

## SiPMs:

Pixelated APDs  
operated in limited Geiger mode

Signal = sum of fired pixels

MEPhi/Pulsar : SiPMs  
Hamamatsu : MPPCs  
SENSL : SPMs  
Photonique : SSPMs  
Voxtel : MAPDs

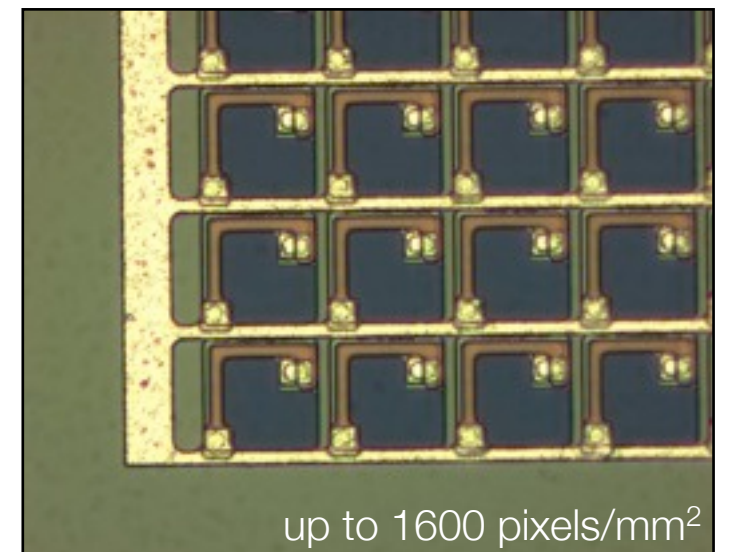
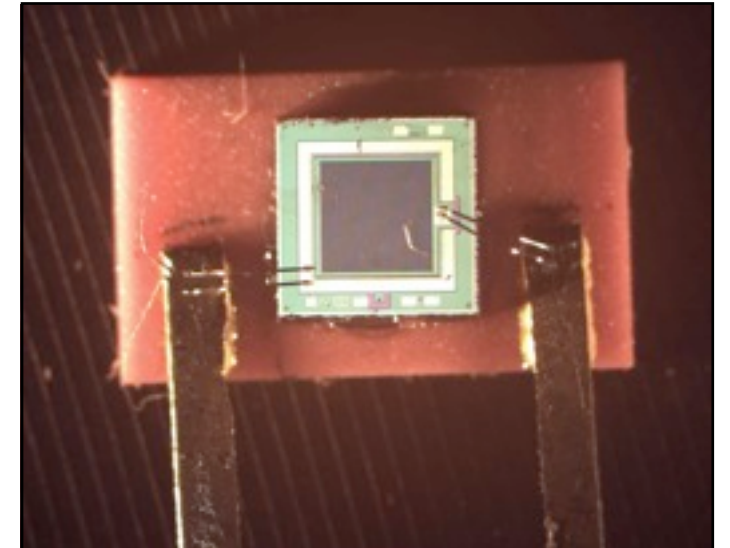
Pros: small size, cheap,  
work in magnetic field

Cons: temperature & voltage dep.,  
non-linearity, ...

Research in progress ...

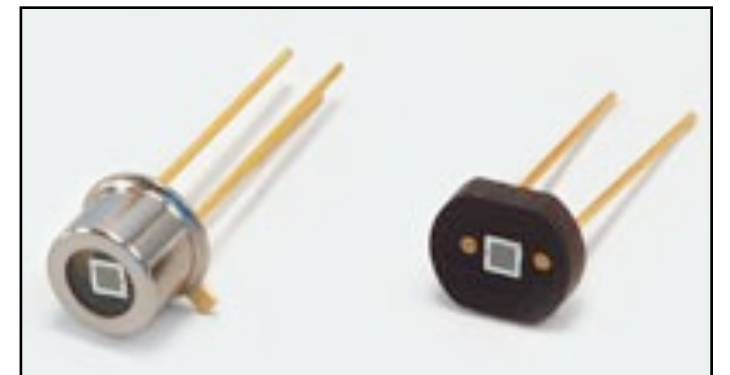
SiPM  
[MEPhi/Pulsar]

used for  
analog HCAL



MPPC  
[Hamamatsu]

used for  
analog ECAL

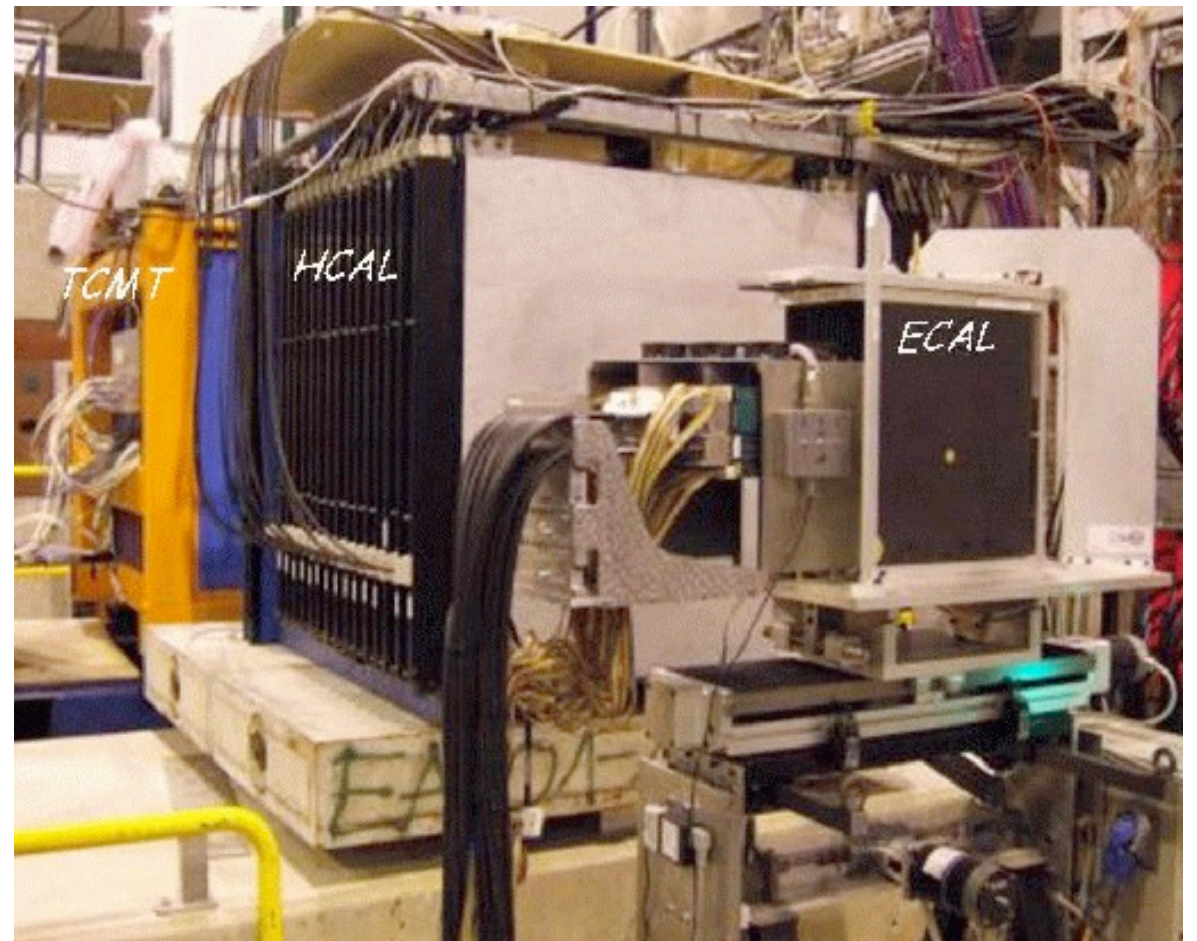
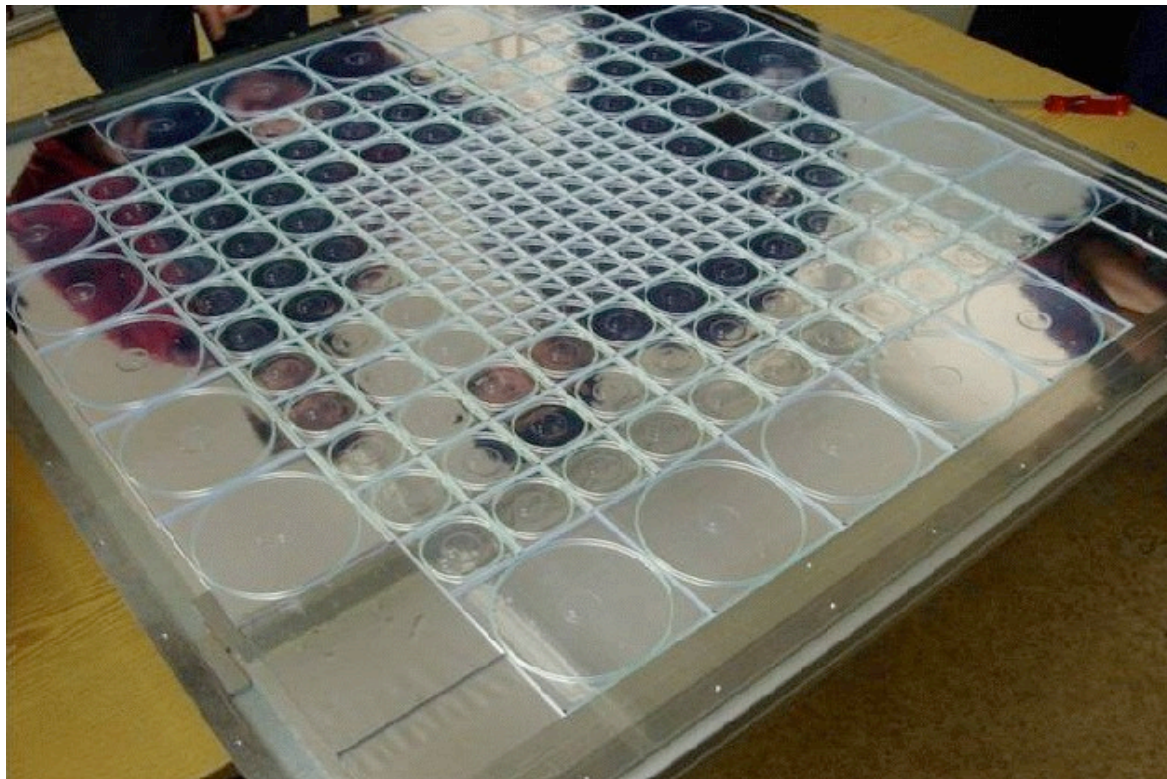


# CALICE – Analog HCAL

1 m<sup>3</sup> - Prototype  
38 layers

## Sandwich structure:

- Scintillator Tiles+WLS+SiPMs (.5 cm)
- Stainless steel absorber (1.6 cm)



2006/2007 CERN testbeam  
[2008 → Fermilab]

Combined

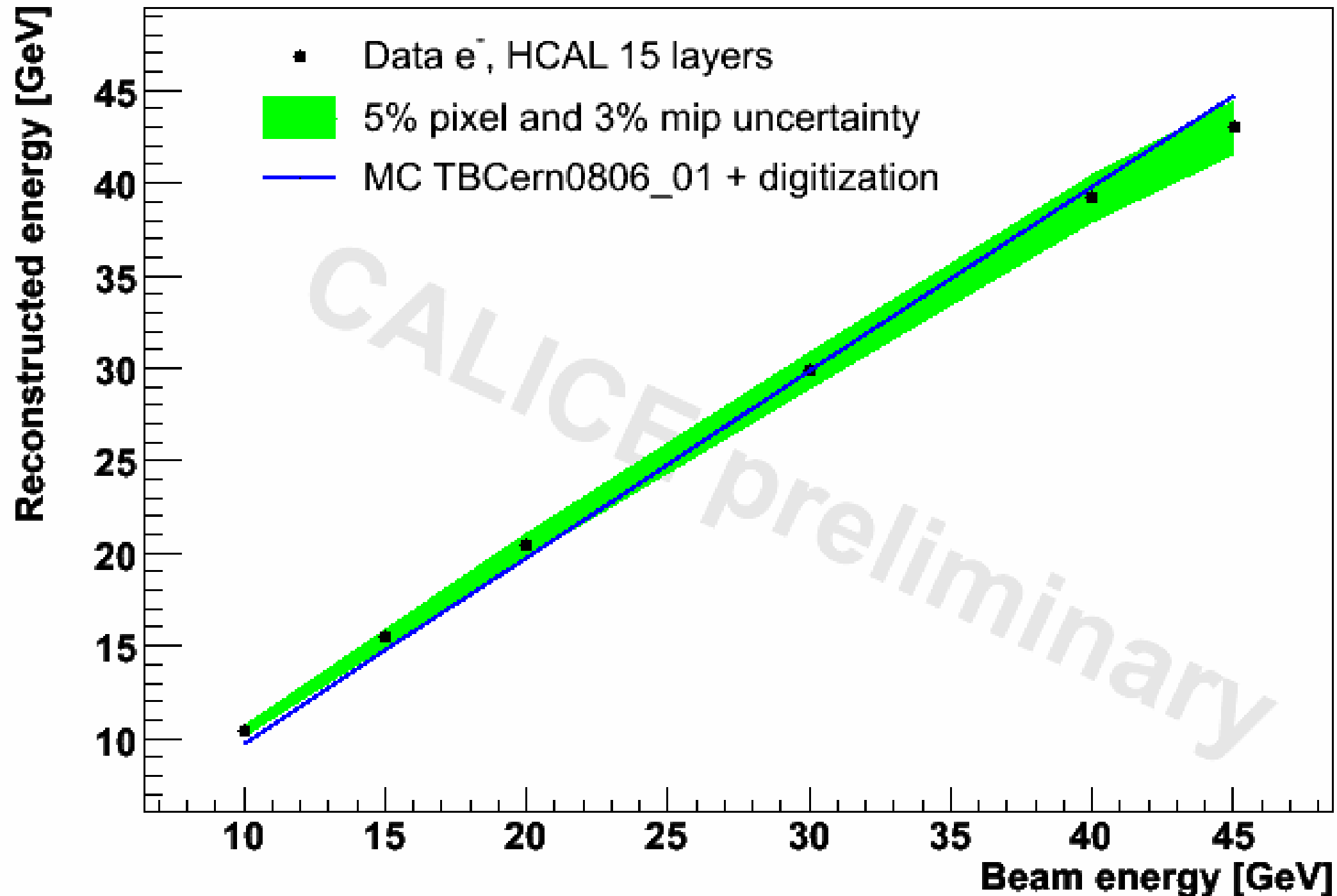
## Test Beam Data:

- 100 Million events collected
- Analysis ongoing

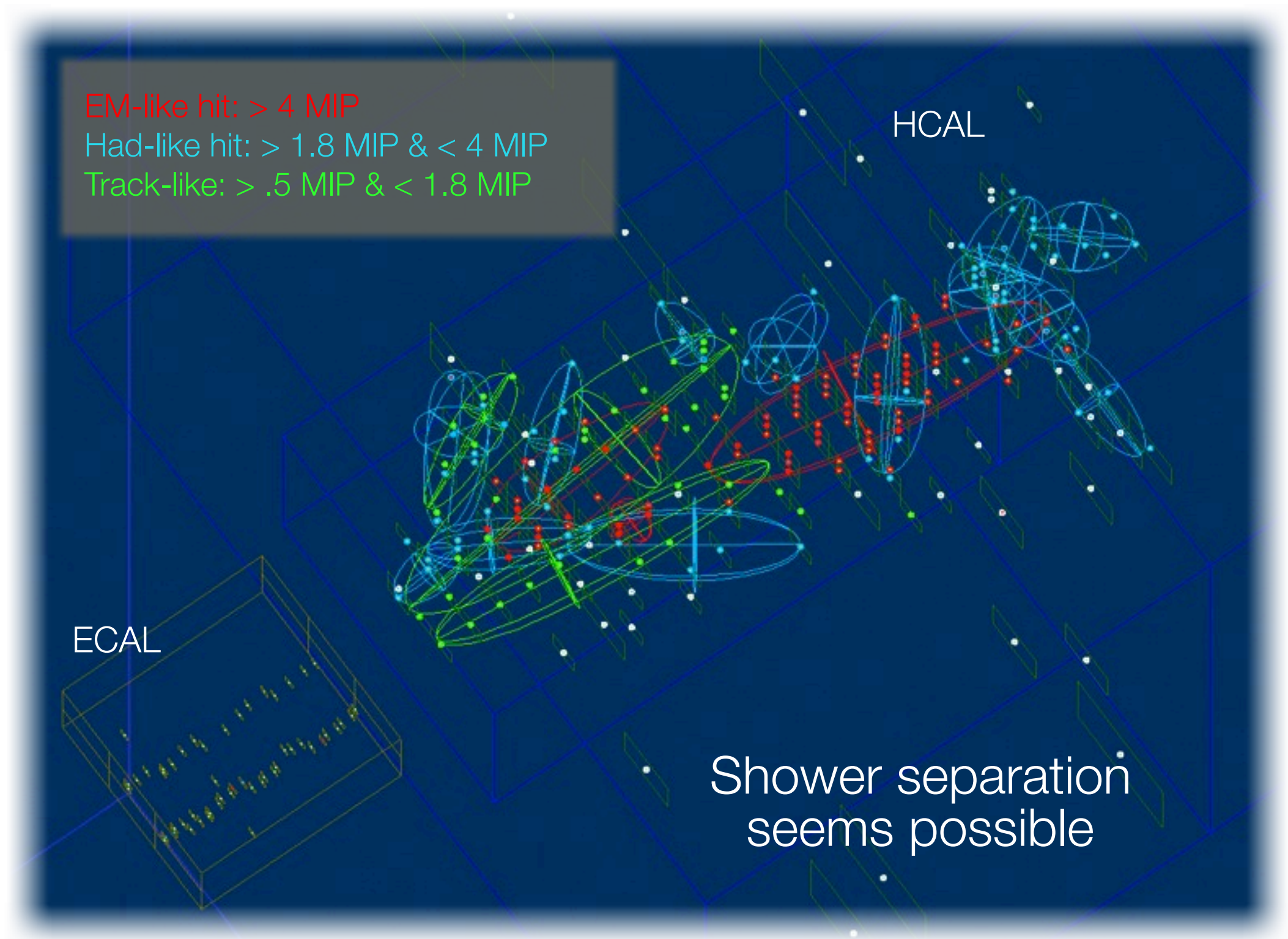
... next big step: technical prototype !

# Analog HCAL – Test Beam Result

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# Analog HCAL – Test Beam Result



# HCAL – The Digital Approach

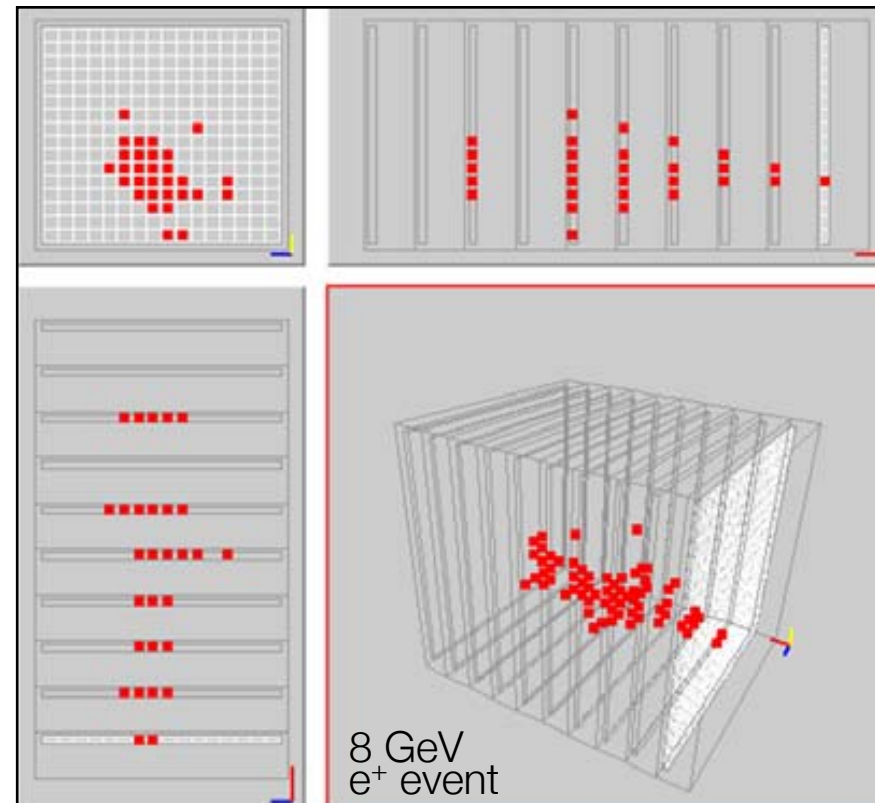
---

## Why digital ?

- better PFA performance
- cheap, robust detectors ...
- small total thickness ...

## Used Technologies:

- GEMs
- $\mu$ Megas
- RPCs



## Example RPCs:

Pad Size:  $1 \times 1 \text{ cm}^2$

Total thickness:  $< 6 \text{ mm}$  possible

Vertical Slice Test with  
9 small chambers successful

Large Prototype to be built

# Dual-Readout Calorimetry (4<sup>th</sup>)

Concept:

Cherenkov-assisted  
Hadron calorimetry

$$\frac{E_{\text{em}}}{E_{\text{tot}}} \sim \frac{E_{\text{Cherenkov}}}{E_{\text{Ionization}}}$$

EM: clear fibers, Č-light [ $E_{\text{Cherenkov}}$ ]

Charged: scintillation fibers [ $E_{\text{Ionization}}$ ]

Neutrons: time history measurement

"DREAM 3"

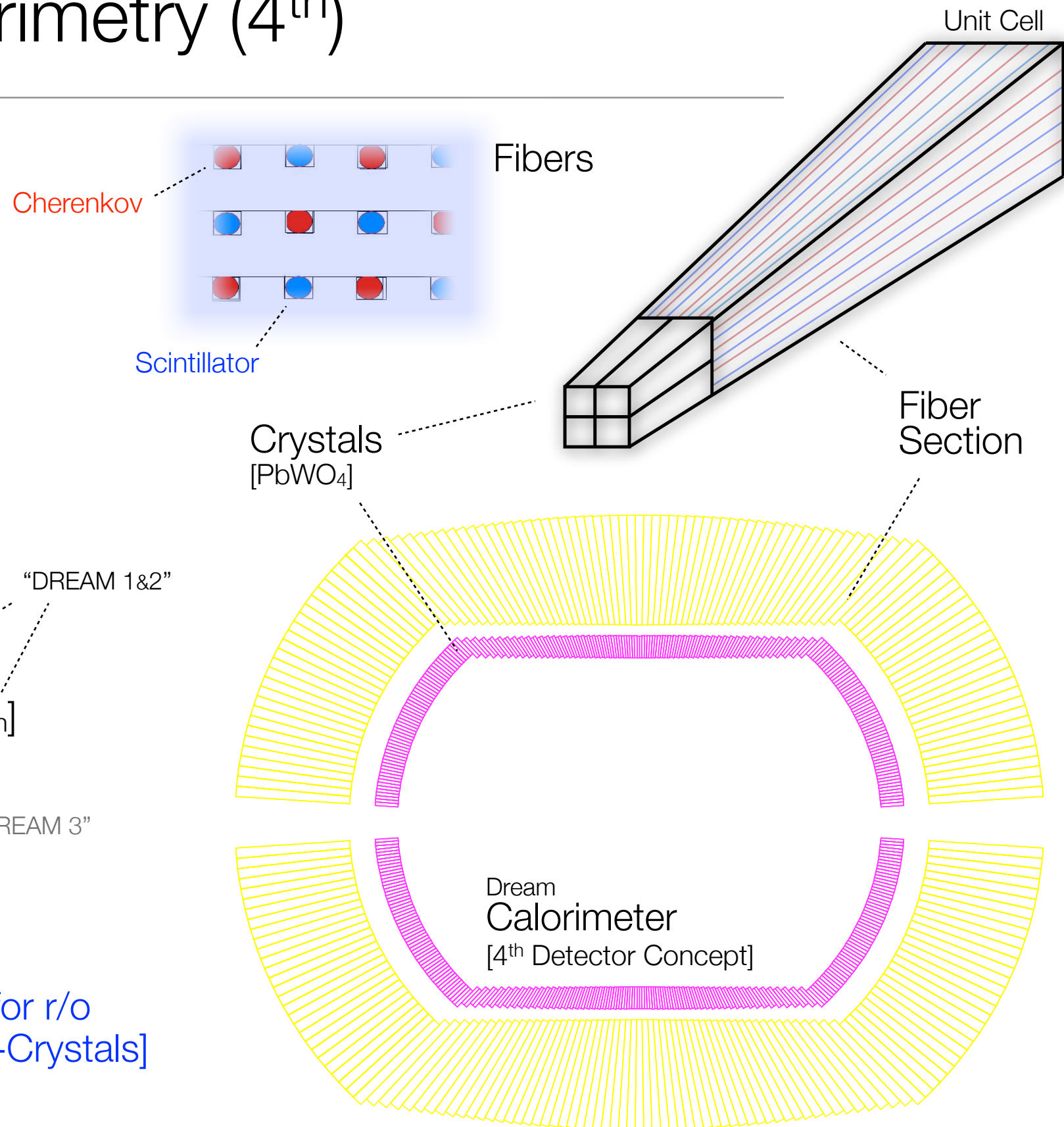
"DREAM 1&2"

Plans:

Scaleable module (unit cell)

Fiber Section: W absorber, MPPC for r/o

EM Section: Dual-readout [PbWO<sub>4</sub>-Crystals]



# Dual-Readout Calorimetry (4<sup>th</sup>)

