Counting calories at DØ

Jan Stark
Laboratoire de Physique Subatomique et de Cosmologie
Grenoble, France

500 kcal

300 kcal

490 kcal

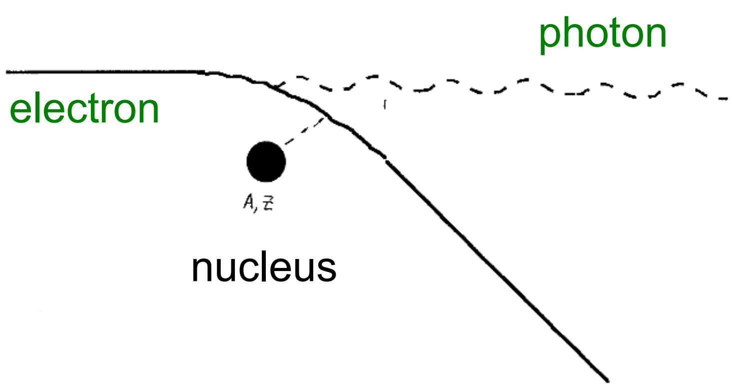
University of DØ, June 17th, 2010.

Why calorimeters ?

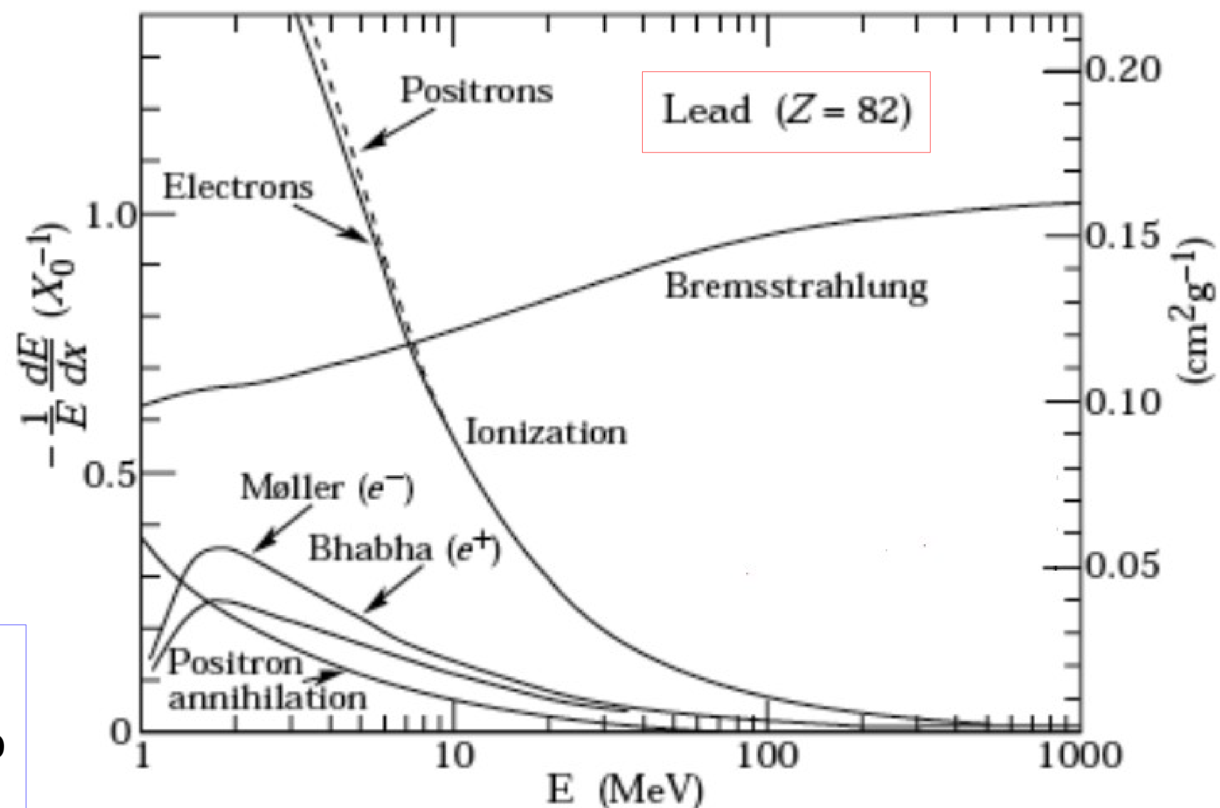
- Sensitive to both charged and neutral particles
- Differences in the shower patterns ⇒ some particle identification is possible (h/e/μ/ν(missing E_T) separation)
- Calorimetry based on statistical processes
  - ⇒ $\sigma(E)/E \propto 1/\sqrt{E}$
  - Magnetic spectrometers ⇒ $\Delta p/p \propto p$
- Increasing energy ⇒ calorimeter dimensions ∝ logE to contain showers
- Fast: response times < 100 ns feasible
- No magnetic field needed to measure E
- High segmentation possible ⇒ precise measurement of the direction of incoming particles

Interaction with matter: electrons

Bremsstrahlung:



$dE/dx|_{brems} \simeq E/X_0$

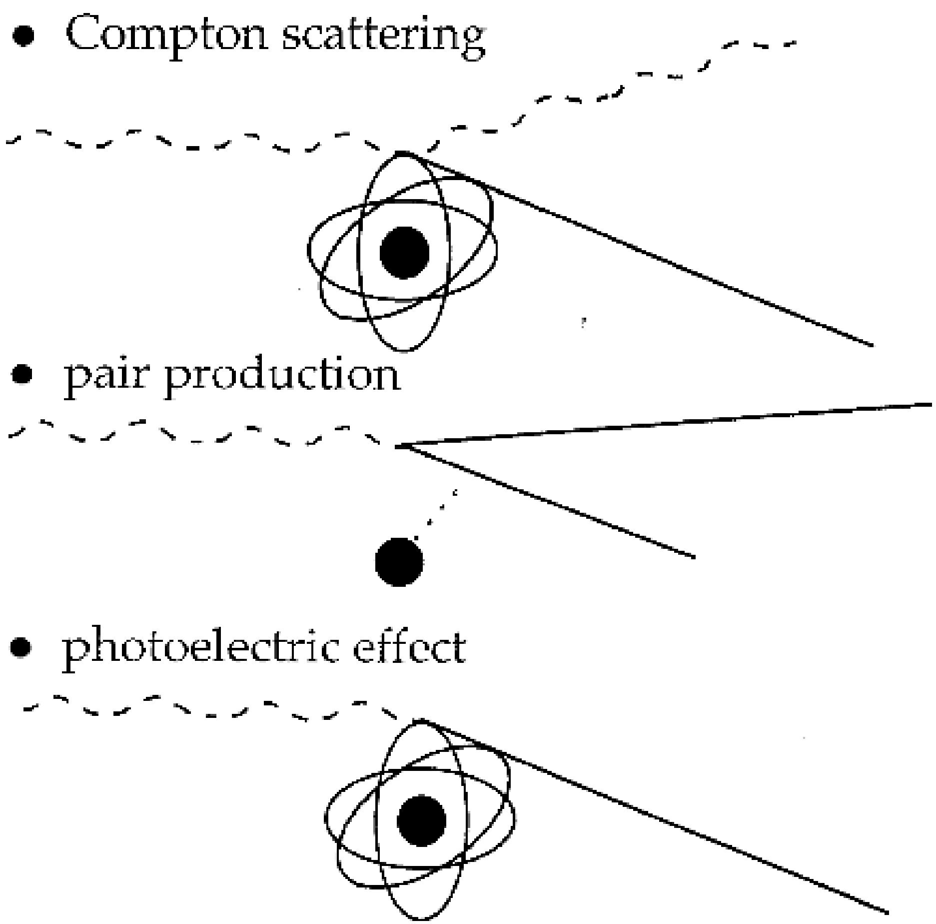


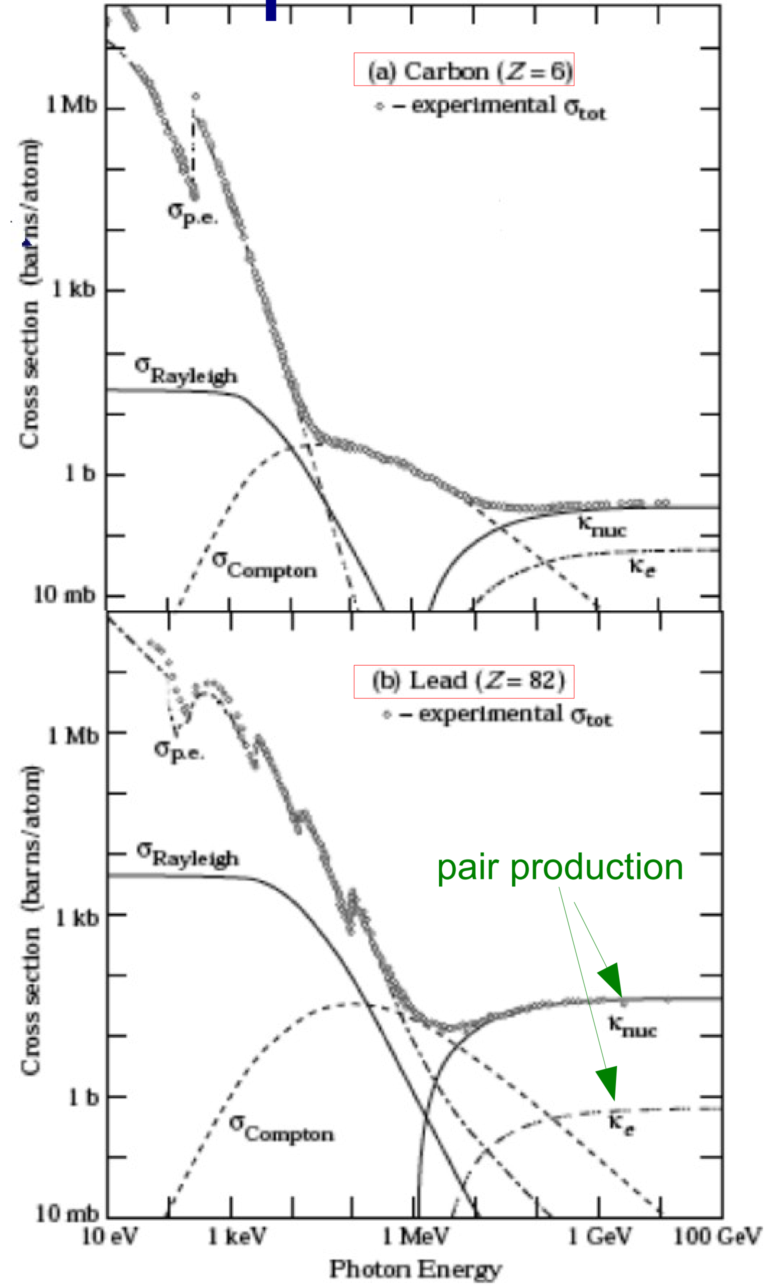
Critical energy E_c:

Electron energy where losses due to bremsstrahlung and ionisation are equal.

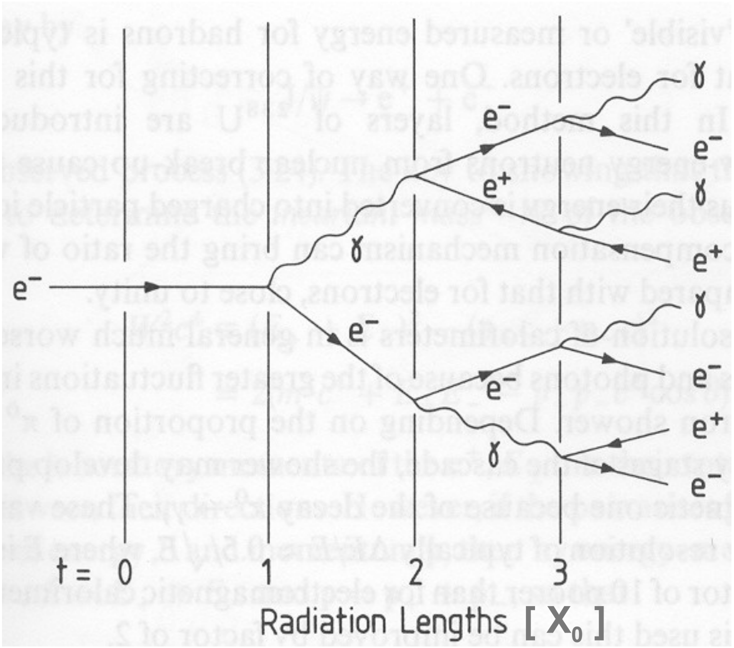
Empirically: $E_c \simeq \frac{580\,MeV}{Z}$

Interaction with matter: photons





A simple shower model



Shower development:

Start with an electron with $E_0 \gg E_c$

→ After $1X_0$: $1\ e^-$ and $1\ \gamma$, each with $E_0/2$

→ After $2X_0$: $2\ e^-$, $1\ e^+$ and $1\ \gamma$, each with $E_0/4$

→ After tX_0 :

$$N(t) = 2^t = e^{t \ln 2}$$

$$E(t) = E_0 / 2^t$$

→ Number of particles increases exponentially with t

→ equal number of e^+, e^-, γ

$$t(E') = \frac{\ln\left(E_0/E'\right)}{\ln 2}$$

→ Depth at which the energy of a shower particle equals some value E'

$$N(E > E') = \frac{1}{\ln 2} \frac{E_0}{E'}$$

→ Number of particles in the shower with energy > E'

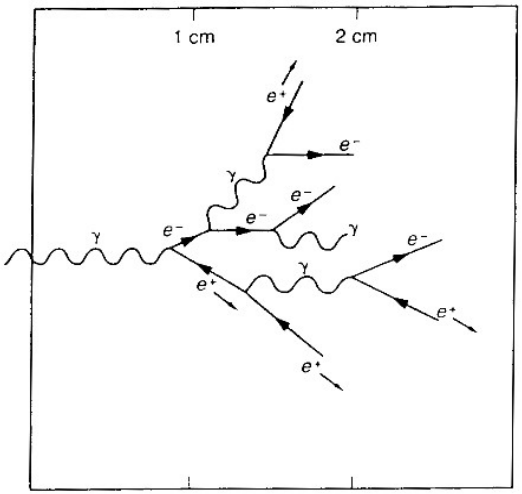
Maximum number of particles reached at $E = E_c$ →

$$t_{\max} = \frac{\ln\left(E_0/E_c\right)}{\ln 2}$$

$$N_{\max} = e^{t_{\max} \ln 2} = E_0/E_c$$

EM showers; MC techniques

Of course, real showers have a less "regular" (symmetric) development and shape, as illustrated below:



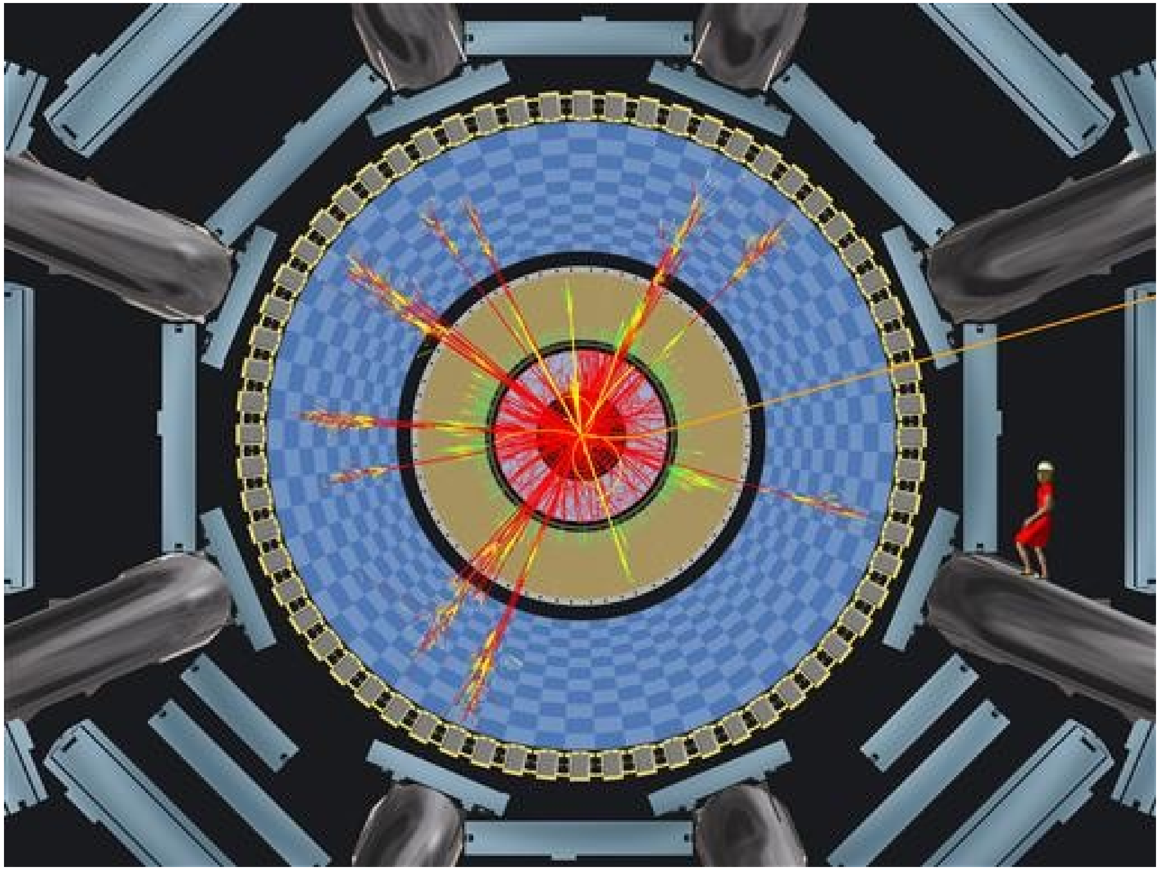
And we want more than a simple block of material. We want a geometrical representation of a complex detector, like e.g. on the right.

This is where MCC methods come in handy:

- set of initial particles from collision,
- model of EM processes,
- model of detector gemetry,

=> "step" particles through detector, drawing random interactions according to known probability laws

A simulated event in the ATLAS detector:



Given an accurate model of the detector, MC simulations of EM showers tend to be very accurate. But there ***are*** major pitfalls related to models of the EM processes. See: J.S., presentation at D0 MC Summit, June 20th, 2006.

(Longitudinal) Shower profile

Depth of shower max increases logarithmically with energy.

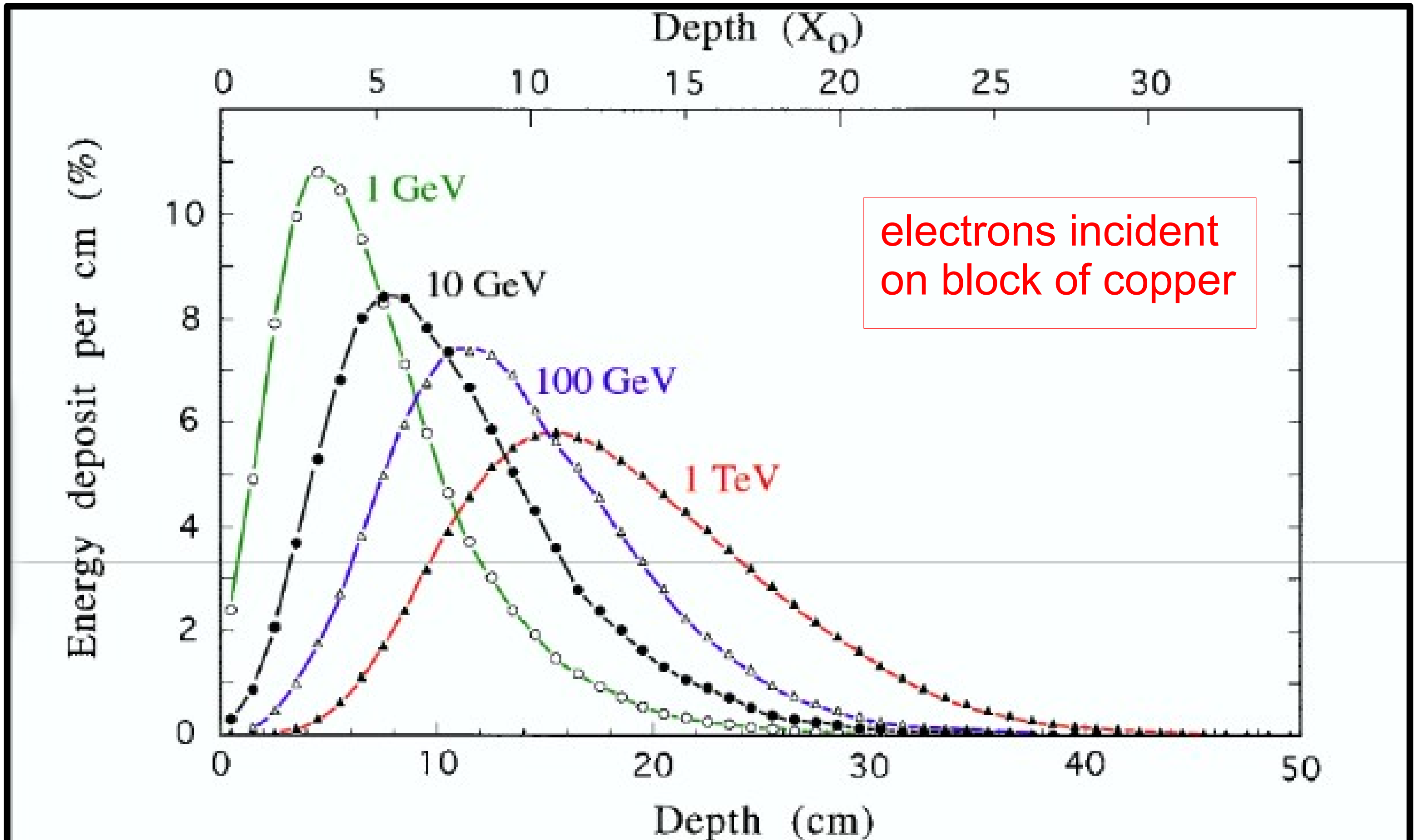


FIG. 2.9. The energy deposit as a function of depth, for 1, 10, 100 and 1000 GeV electron showers developing in a block of copper. In order to compare the energy deposit profiles, the integrals of these curves have been normalized to the same value. The vertical scale gives the energy deposit per cm of copper, as a percentage of the energy of the showering particle. Results of EGS4 calculations.

Signal generation

OK, so we know how EM showers work and how we can fully absorb electrons.

But we also need a process that gives us a signal that we can use to read out the amount of energy deposited
(we will not *literally* measure the temperature increase in our absorber ...)

In practice, essentially all calorimeters use one of only three effects for signal detection:

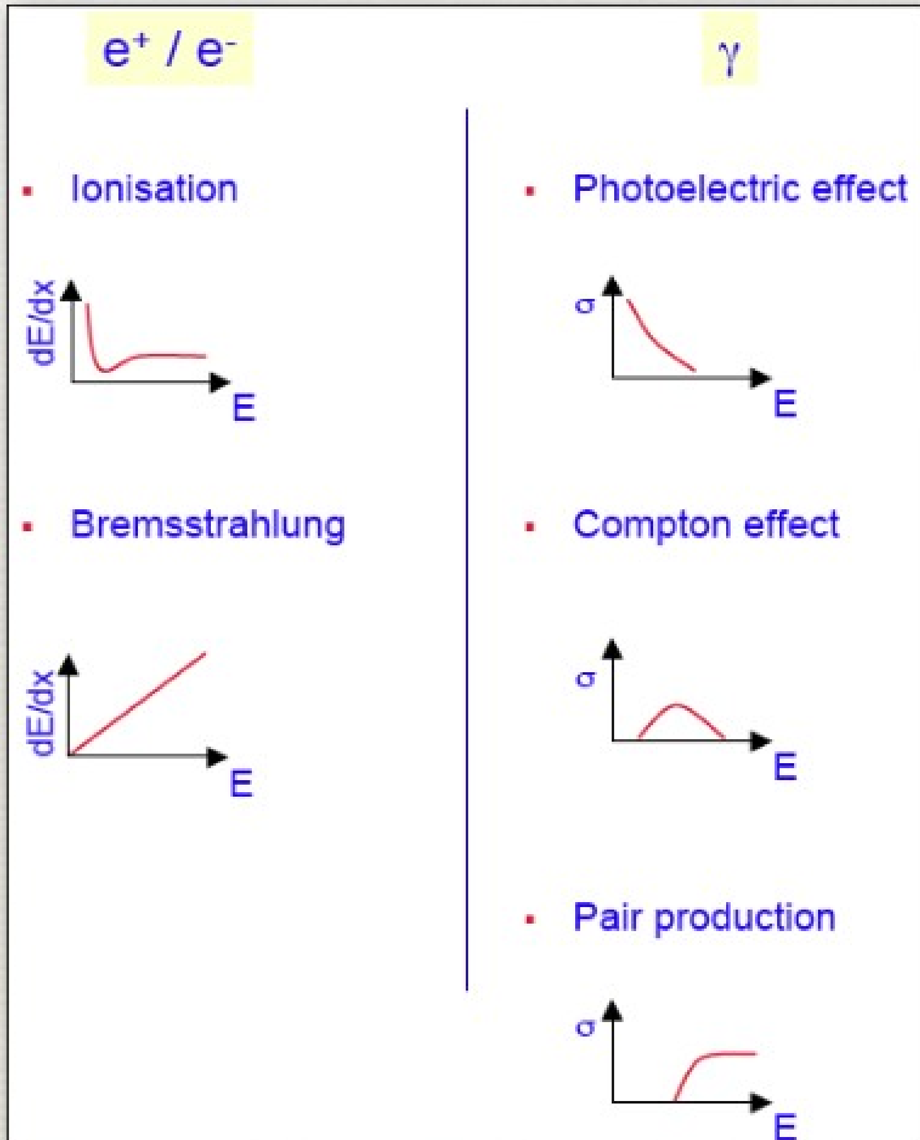
- Scintillation
  (charged particles in shower excite atoms in detector;
  atoms de-excite, emit light => light detected for readout)
- Ionisation
  (charged particles in shower ionise atoms in detector;
  => free charge => "collect" free charge for readout)

  D0 uses ionisation
- Čerenkov radiation
  (light emitted by charged particles faster than the speed of light in the medium; fast !)

EM processes (Z dependence)

Z

$Z(Z+1)$



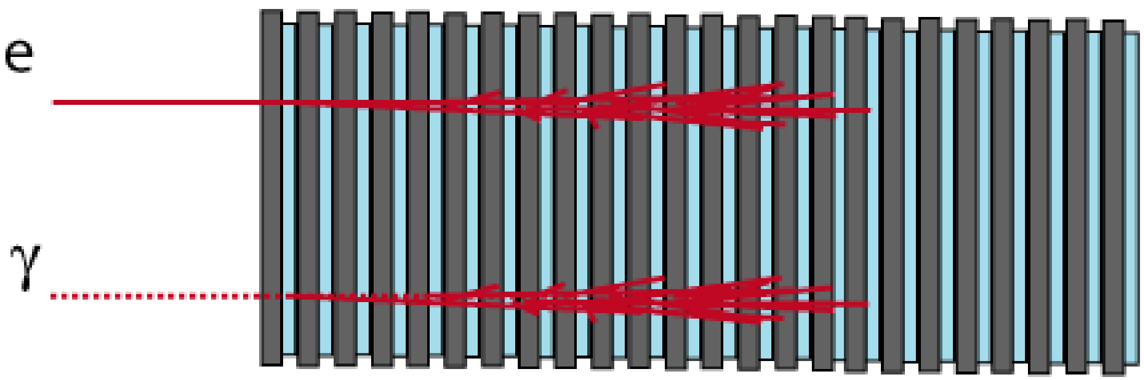
$Z^{4\div5}$

Z

$Z(Z+1)$

Homogeneous vs. sampling

- Sampling calorimeter:



Typical energy resolutions:

$$\Delta E/E \sim 15\%/\sqrt{E}$$

"Sandwich" of high-Z absorber plates (lead, uranium, ...) and low-Z active media (scintillator, liquid argon, ...)

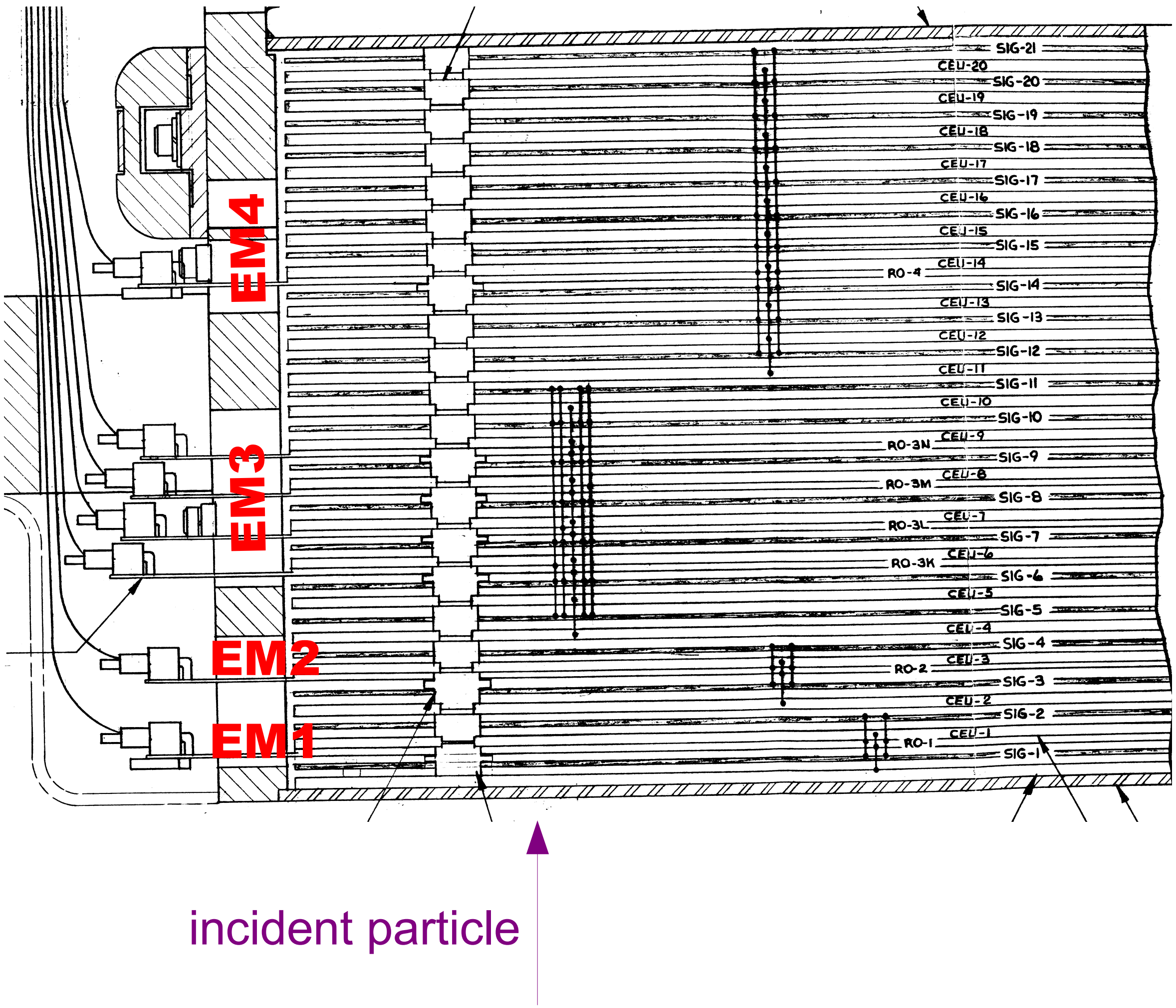
- exotic crystals (CsI, BGO, PbW, ...):

$$\Delta E/E \sim 1\%/\sqrt{E}$$

Homogeneous crystal that is, at the same time: dense enough to contain shower, scintillating, transparent (light transport for readout), radiation hard, ...

DØ: CC-EM module

More detailled view of one CC-EM module :



Basically a stack of Uranium plates with liquid Argon in between.
Shower develops in U and LAr (mainly U); charged shower particles
ionise the Argon atoms
=> current in Argon because of HV applied across each gap.
This current is measurable
(thanks to electronic charge amplifiers with very large gain).

EM1, EM2, EM3 and EM4 are read out separately; each one of these
layers regroups a number of digaps.

sampling fraction: 15 %

DØ: unit cell

Unit cell of CAL readout:

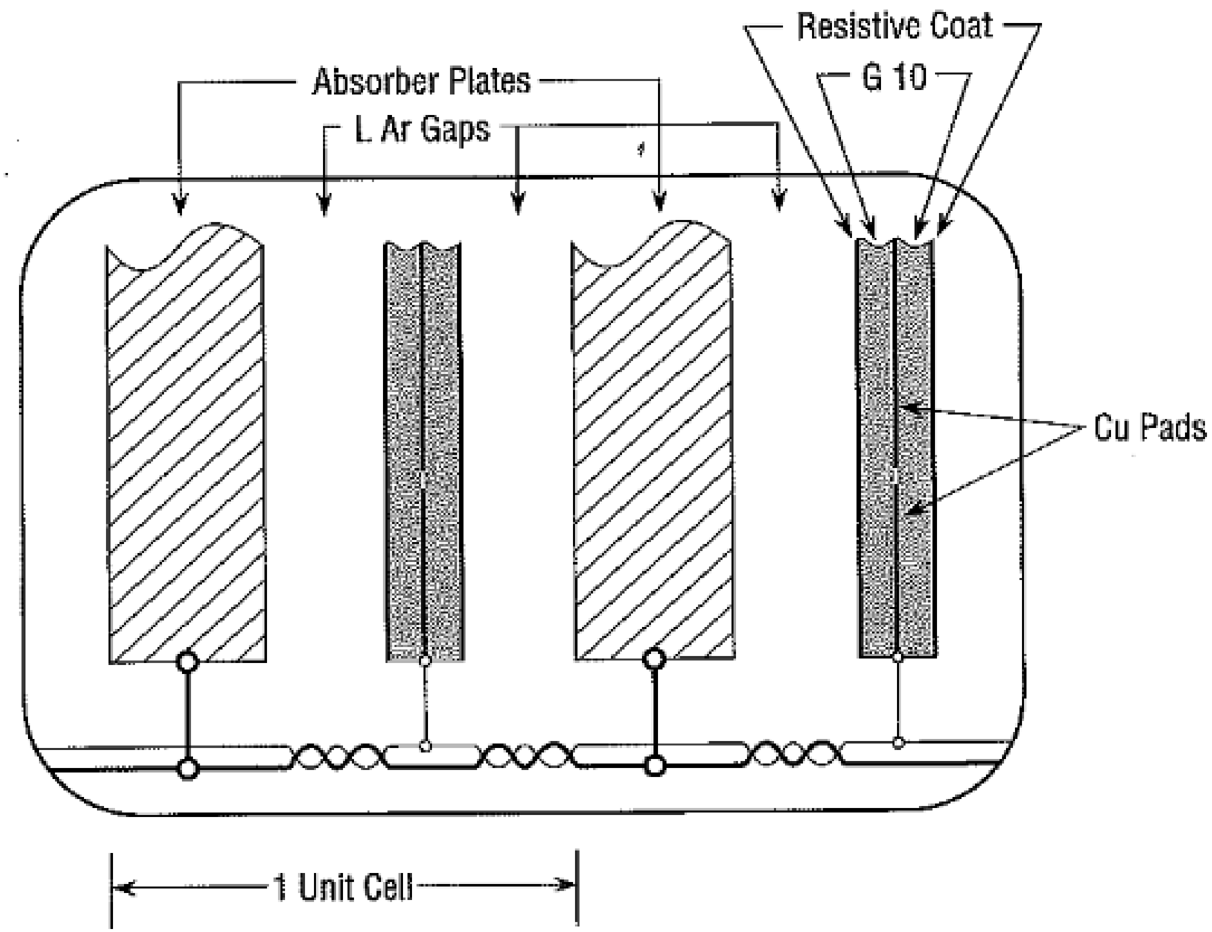


Fig. 27. Schematic view of the liquid argon gap and signal board unit cell.

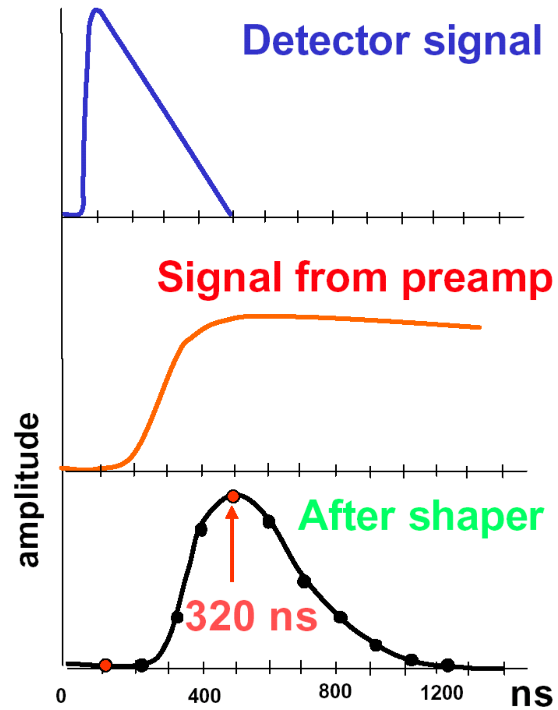
"As long as

- the LAr is pure,
- the high voltage is constant,
- and the geometry is unchanged,

there is little that can go wrong in term of stability of the gain."

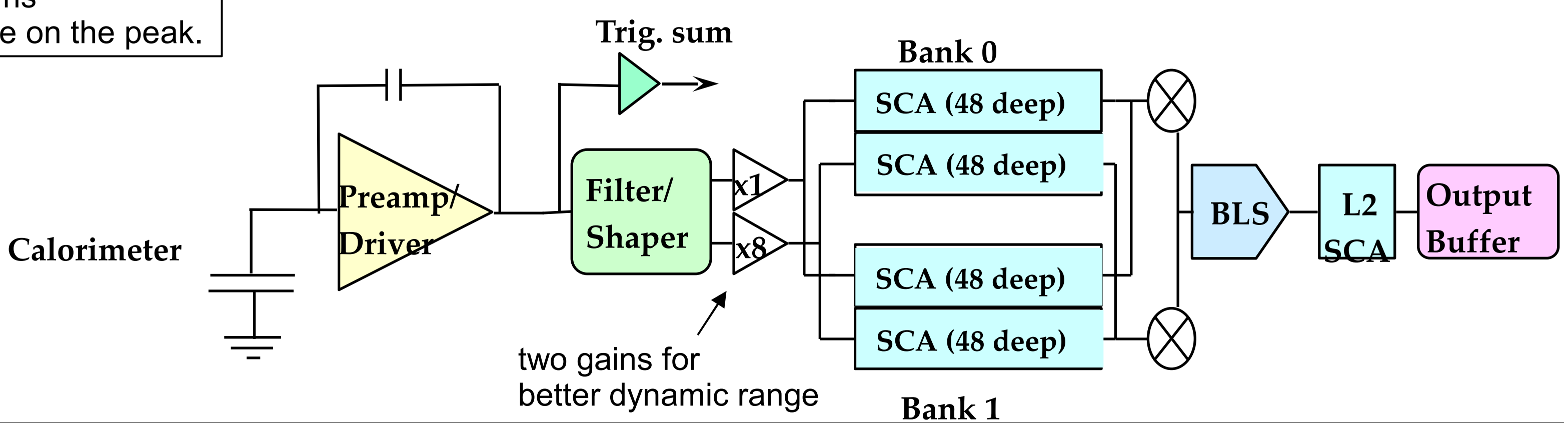
Fig. from D0 Run I NIM paper.

DØ: basics of the readout

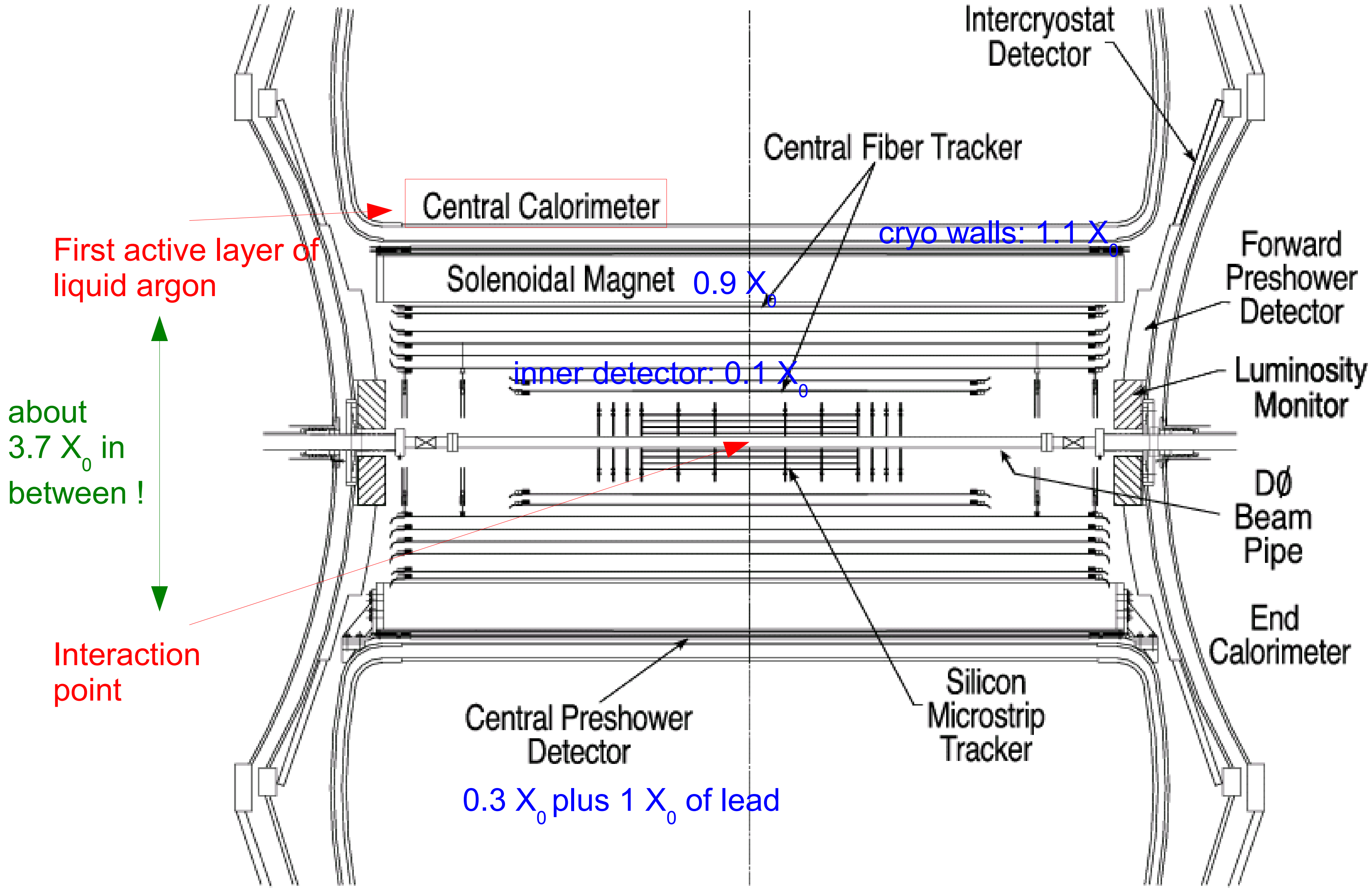


Have ability to sample and record the shaped signal also at (320 ± 120) ns to make sure we are on the peak.

- Detector signal ~ 450 ns long
  (bunch crossing time: 396 ns)
- Charge preamplifiers
- BLS (baseline subtraction) boards
  - short shaping of ~2/3 of integrated signal
  - signal sampled and stored every 132 ns in analog buffers (SCA) waiting for L1 trigger
  - samples retrieved on L1 accept, then baseline subtraction to remove pile-up and low frequency noise
  - signal retrieved after L2 accept
- Digitisation

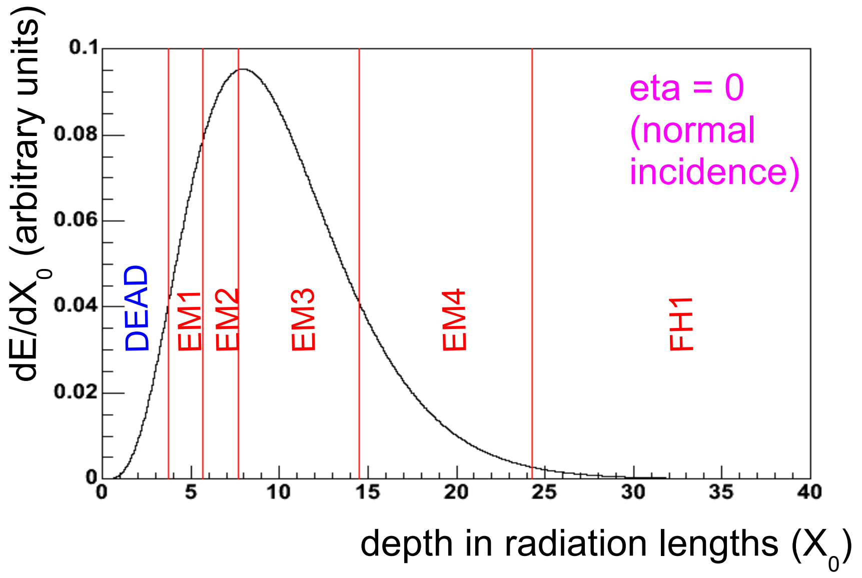


DØ: the CAL is not alone !



DØ: how we sample EM showers in Run II

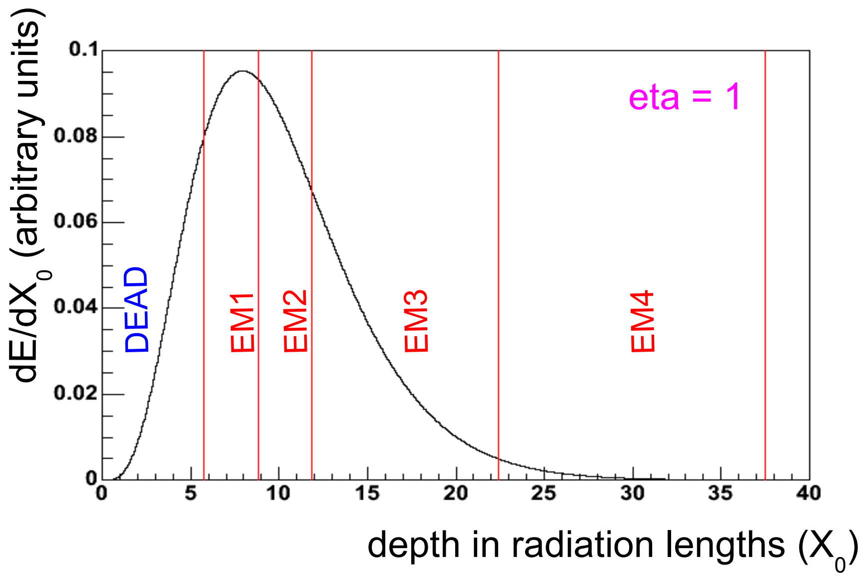
The plot on the right shows the average longitudinal profile of a shower with E = 45 GeV. Assuming normal incidence, the position of the active parts of the CC are also indicated.



In the reconstruction, we apply artificially high weights to the early layers (especially EM1) in an attempt to partially compensate the losses in the dead material:

Layer	depth (X_0)	weight (a.u.)	weight/X_0
EM1	2.0	31.199	15.6
EM2	2.0	9.399	4.7
EM3	6.8	25.716	3.8
EM4	9.1	28.033	3.1
FH1	≈ 40	24.885	≈ 0.6

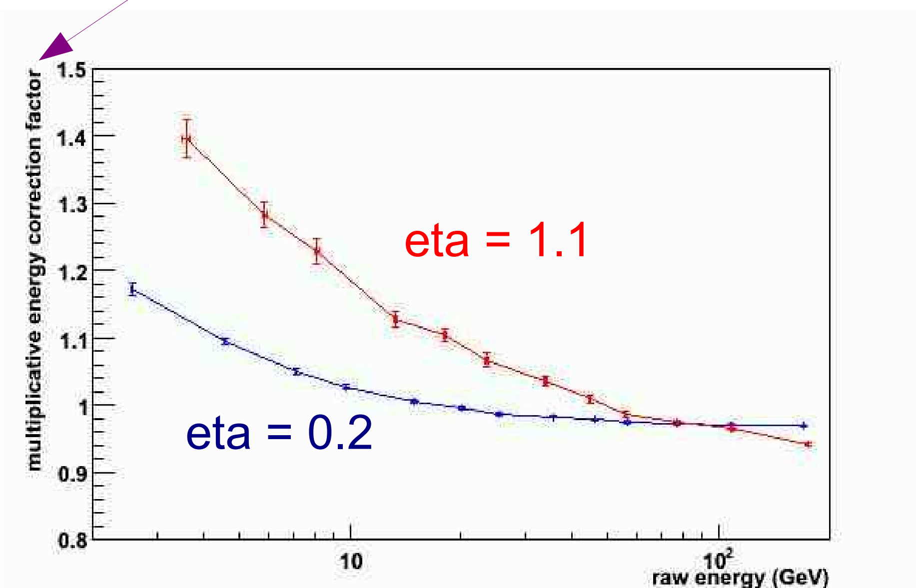
The lower plot illustrates the situation for the same average shower, but this time under a more extreme angle of incidence (physics eta = 1). The shower maximum is now in EM1 !



DØ: impact of dead material

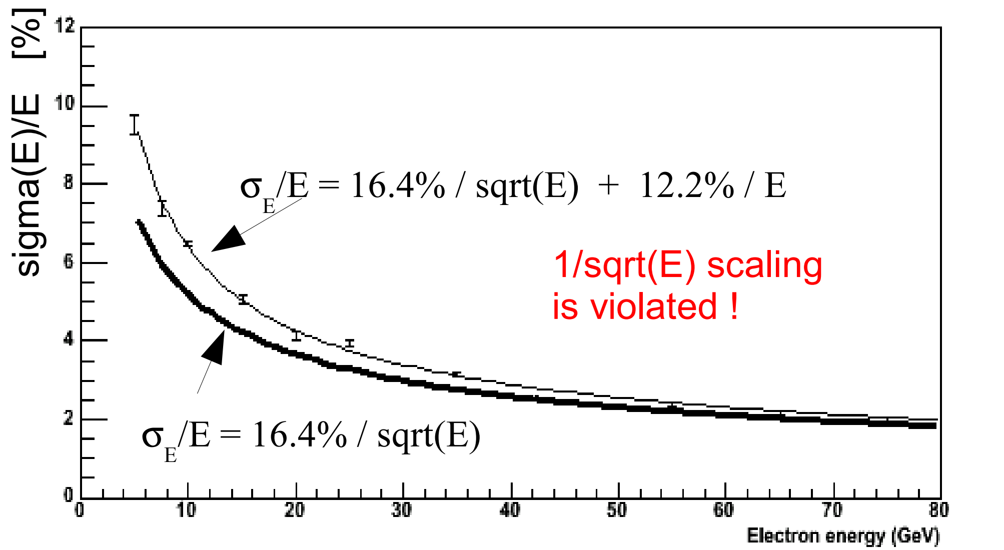
So we need to apply an energy-loss correction (from simulation) to our reconstructed electron energies to account for the energy lost in front of the calorimeter.

This is the energy correction factor that gets us back to the energy of the incident electron.



This is the energy as reconstructed in the CAL.

Resolution at normal incidence, as a function of electron energy:



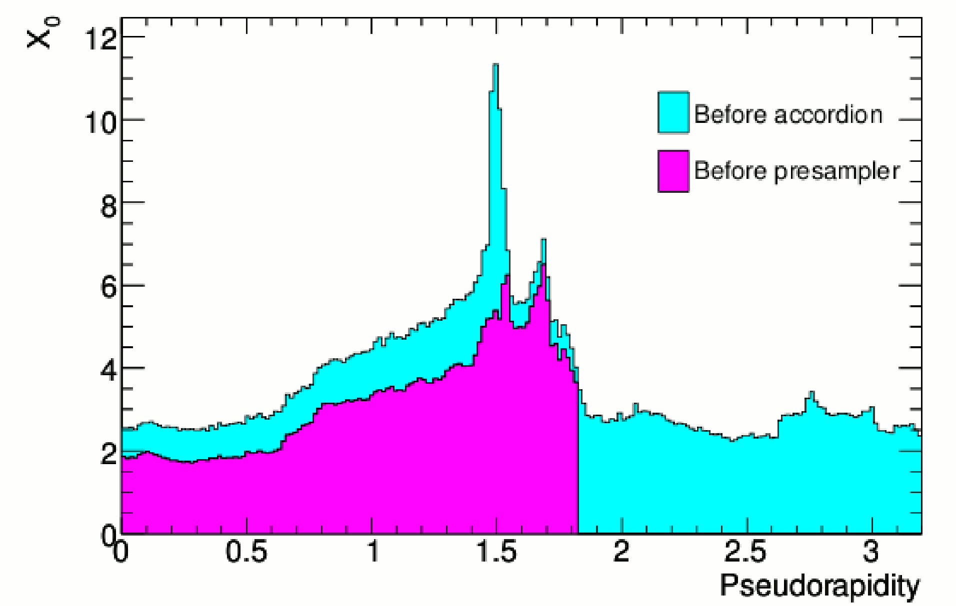
for an ideal sampling calorimeter (no dead material) one would expect this to scale as 1/sqrt(E)

For more details see:
Wine & Cheese seminar on the D0 Run IIa
W boson mass measurement (March 20^{th}, 2009)

Aside: dead material in ATLAS

Large amounts of dead material are not uncommon in modern experiments; here is one example.

From ATLAS detector paper:



Amount of passive material in front of the EM calorimeters.

From ATLAS CSC book:

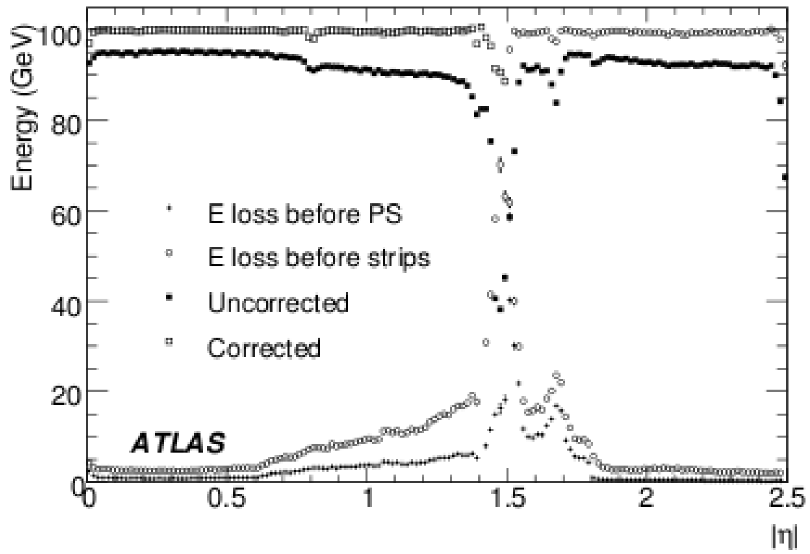
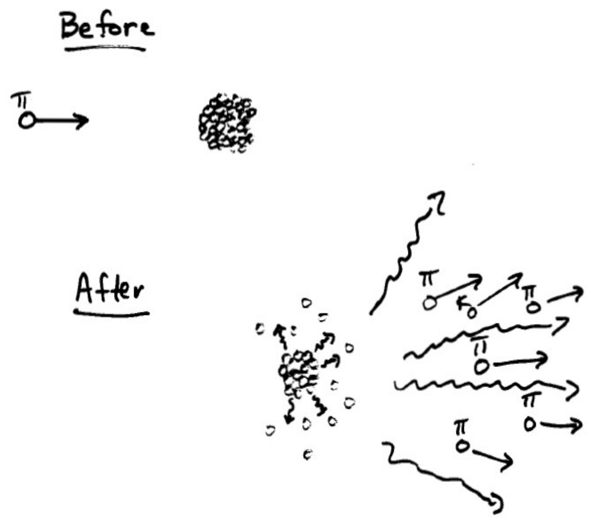
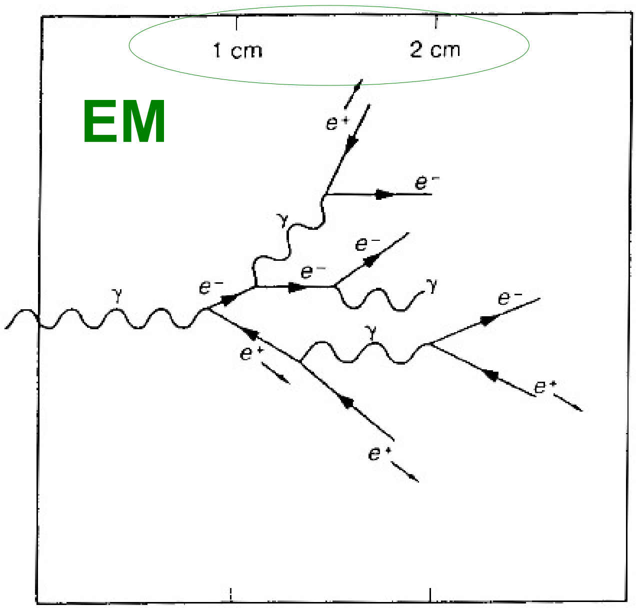


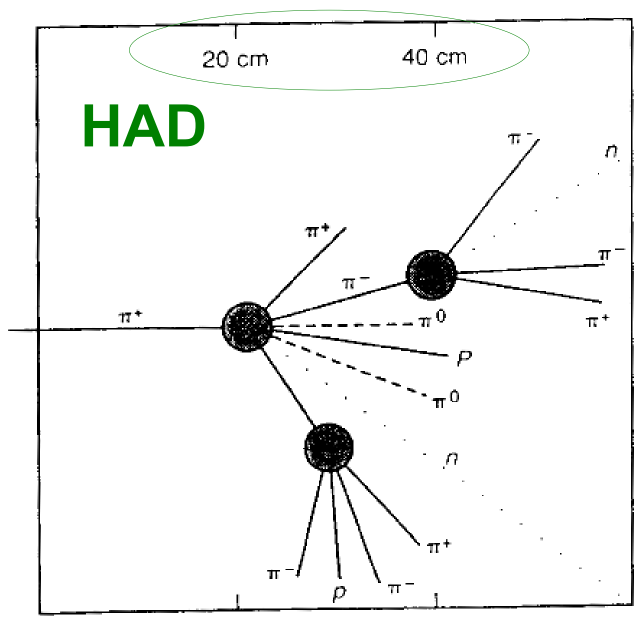
Figure 1: Average energy loss vs. $|\eta|$ for $E =$ 100 GeV electrons before the presampler/strips (crosses/open circles), and reconstructed energies before/after (solid/open boxes) corrections.

Hadronic processes

Hadrons with kin. energy above a few GeV can initiate nuclear interactions:







In final state:

- lots of debris (energetic pions, neutrons, ...),
- the nucleus is transformed (change A,Z)...
  ... and some kinetic energy is lost (for our CAL) in the reaction

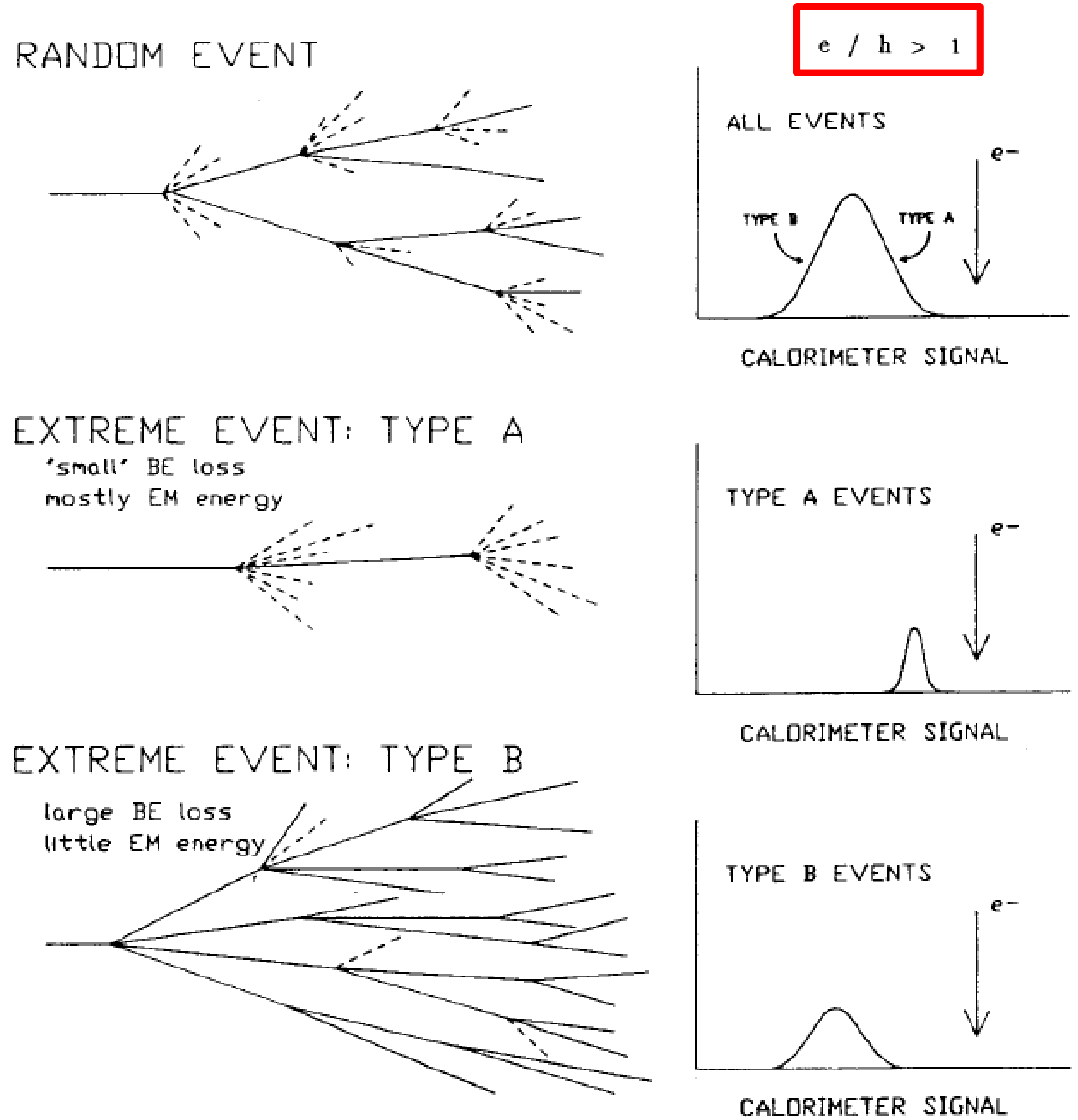
The nuclear interaction length is typically large compared to EM processes

=> on average, hadronic showers are larger (spatially) than EM showers (illustrated on the right);
hadronic showers often include “islands” of small energy deposits far away from the shower barycentre.

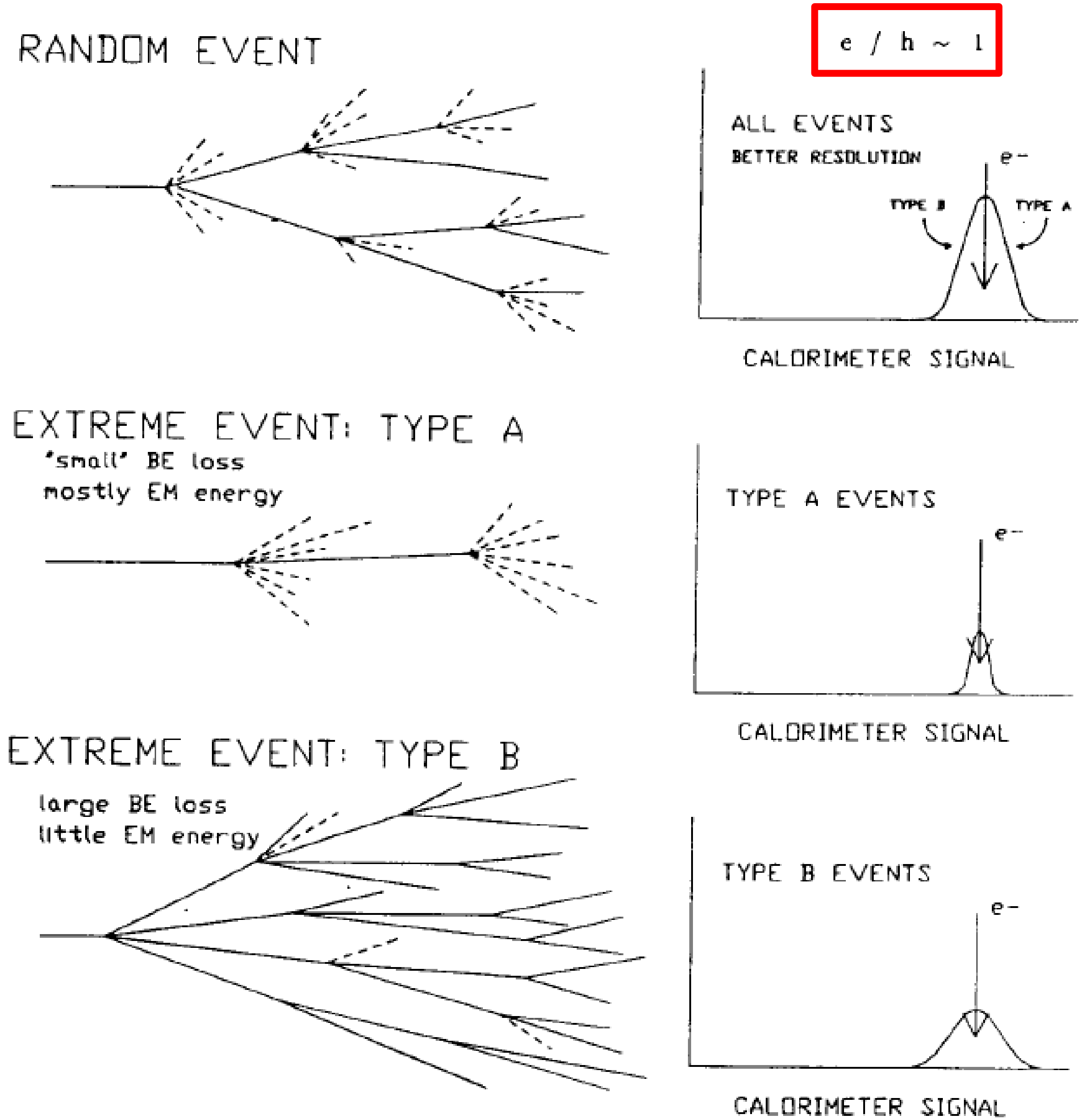
Hadronic showers: energy resolution

Two big problems in hadronic showers:

- large fluctuations in binding energy losses
- large fluctuations in EM-like component of shower ($\pi^0 \rightarrow \gamma\gamma$)



Hadronic showers: energy resolution



Effects of non-compensation

In addition to the degradation of the energy resolution, non-compensation also leads to problems with the mean energy response for hadrons:

h: response for hadronic shower component
e: response for EM shower component

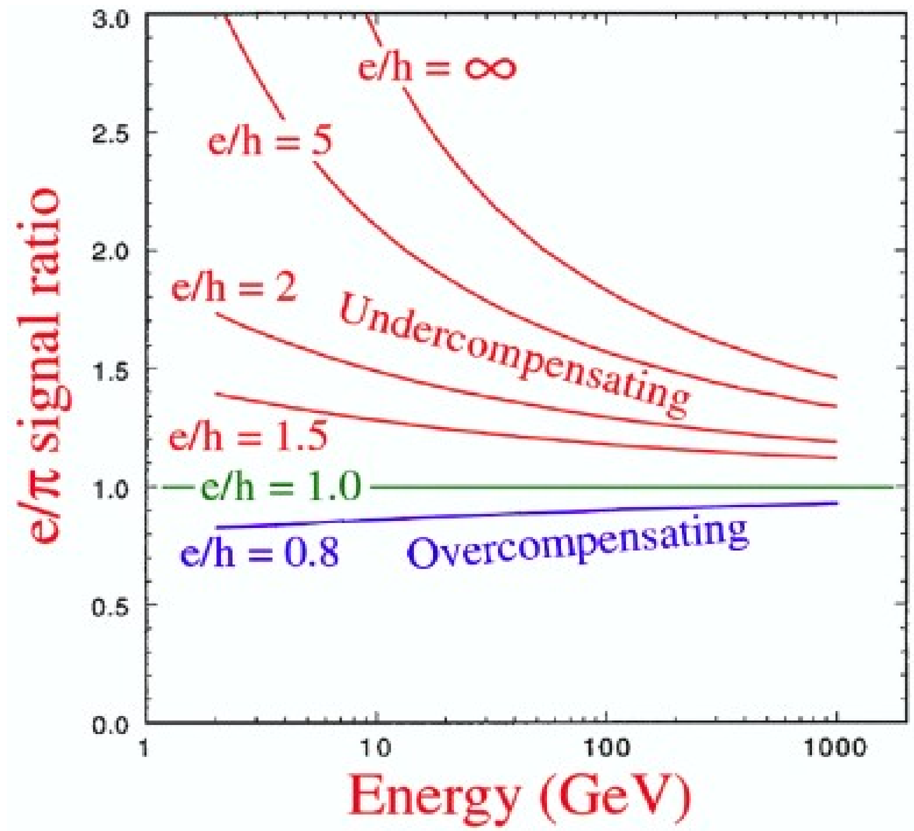
π: response for charged pions

$$\pi = f_{em} \cdot e + (1 - f_{em}) \cdot h$$

$$\pi / e = f_{em} + (1 - f_{em}) \cdot h/e$$

$$e/\pi = \frac{e/h}{1 - f_{em}[1 - e/h]}$$

f_{em} function of energy



Methods to achieve compensation

The electromagnetic and non-electromagnetic components of the hadronic shower can be equalised in response with a variety of techniques:

- Amplify the nuclear signal
  - amplify the nuclear energy itself
  - favour the nuclear signal in sampling
- Attenuate the EM signal
- Measure the hadronic and EM components separately
  (e.g. dual readout calorimeters with two readouts sensitive to different signal processes)

idea behind the depleted uranium ("nuclear weapon")

like in ZEUS calorimeter:
plastic scintillator plus 'right' timing

On "off-line compensation" ("H1 weighting"):

Simple idea: use fine segmentation of CAL readout to recognise, event-by-event, cells that are rich in EM deposits and cells that are rich in HAD deposits and weight their energy accordingly.

Comment from Wigmans' book: "Neither WA1 nor H1 have demonstrated any beneficial effects of these 'off-line compensation' methods for jets, or more generally for a situation in which energy is deposited in the calorimeter system by a collection of particles with unknown composition and energies".

Efforts to improve jet resolution using such techniques in D0 were also fruitless.

Timing; ZEUS vs. DØ

The plot on the right is for the ZEUS calorimeter (uranium/plastic scintillators); it is limited to neutron-induced processes

The recoil protons (neutrons "playing pool" with hydrogen nuclei in the plastic) are fast.

Neutron capture is slow, because it only works for neutrons of thermal energies (and thermalisation takes time).

ZEUS can change *h* by adjusting time integration window of the readout.

In the D0 version of this plot, the red component is much smaller (no plastic) compared to the blue one.
The green line illustrates the cut-off of the Run II readout. In Run I the integration time was longer.

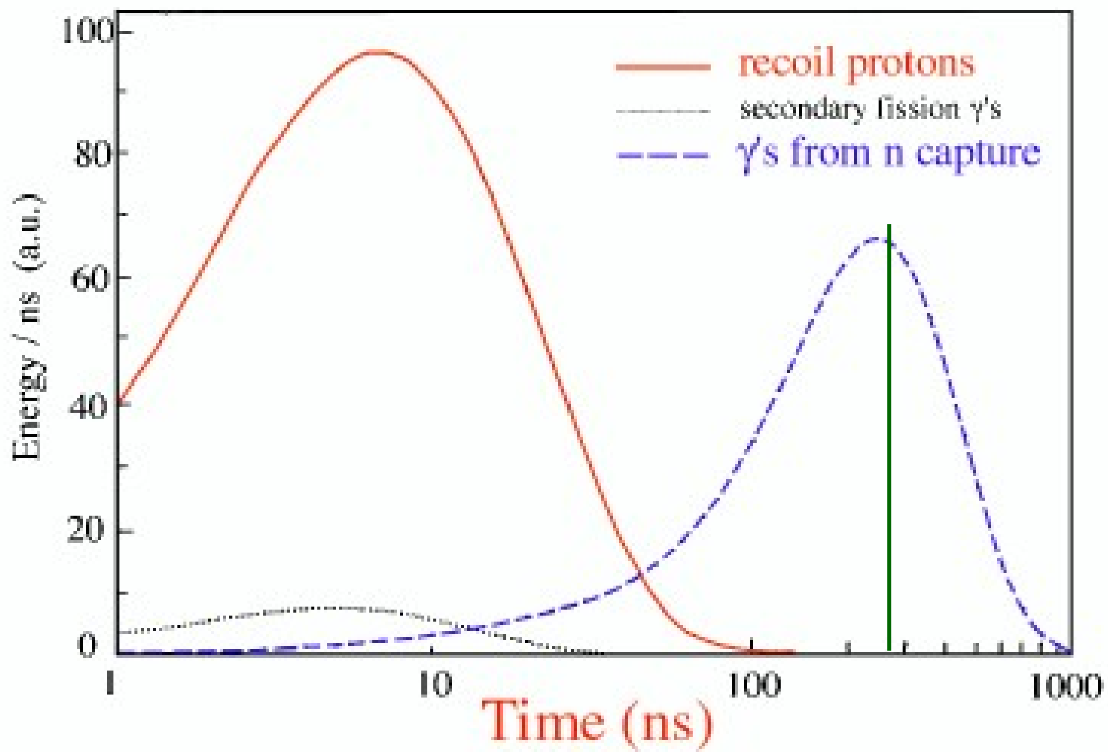


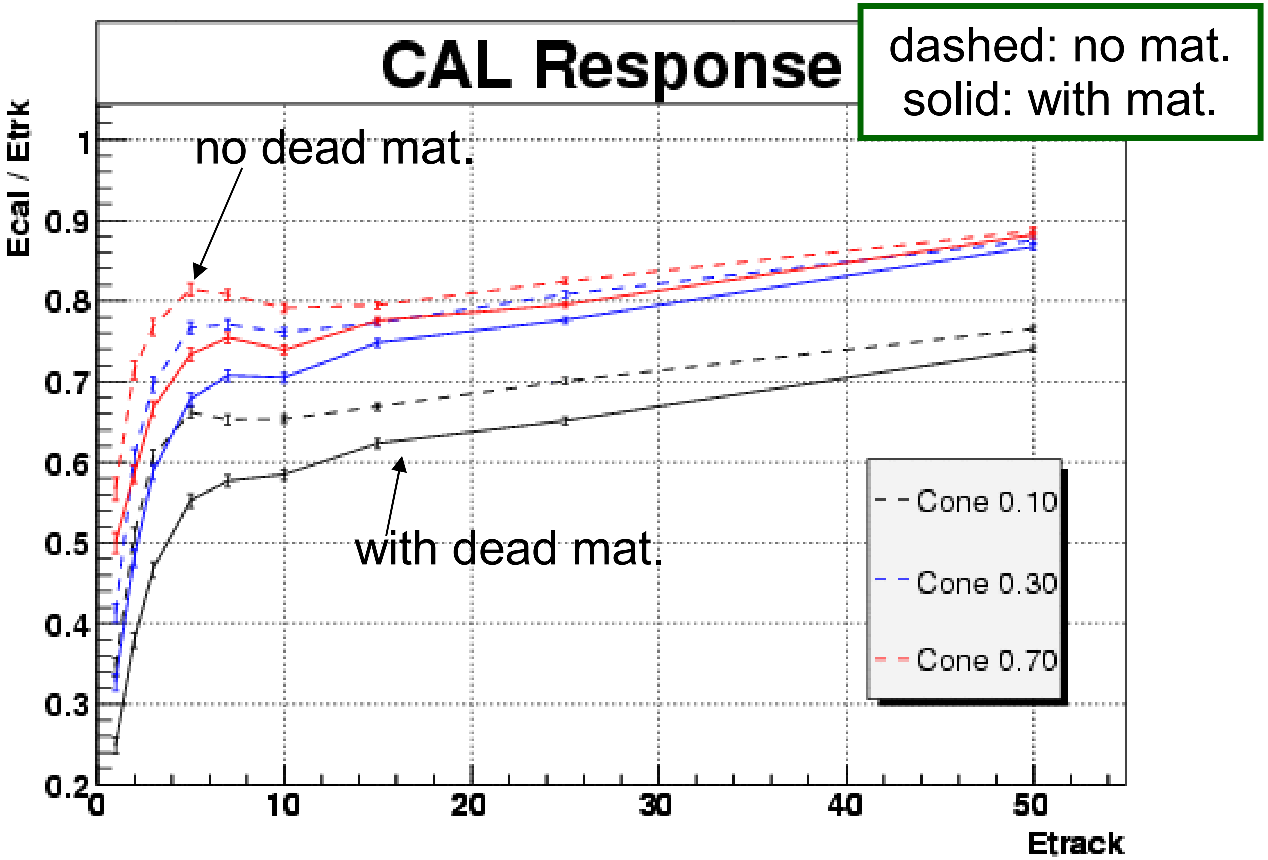
FIG. 3.22. Time structure of various contributions from neutron-induced processes to the hadronic signals of the ZEUS uranium/plastic-scintillator calorimeter [Bru 88].

DØ: pion response in Run II

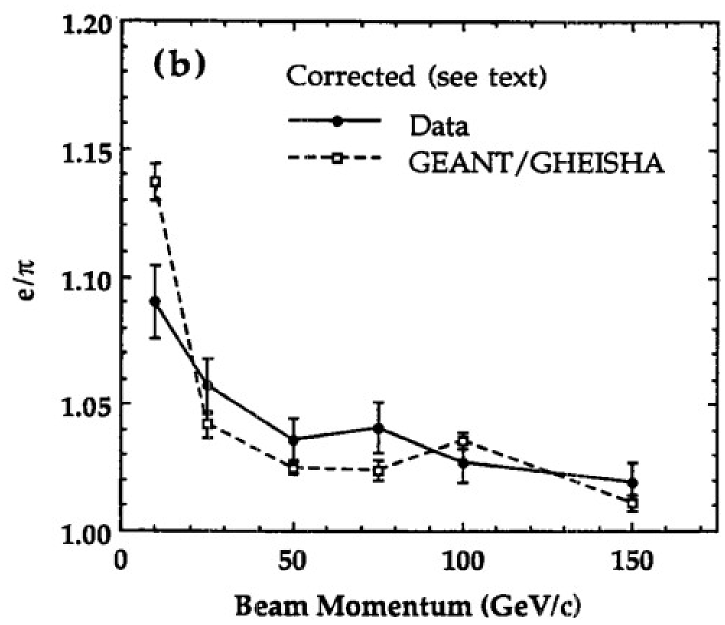
For details on charged pion response see:
K. Peters, P. Haefner, J.S., Calgo meeting, March 8th, 2006
K. Peters, Calgo meeting, Feb. 13th, 2007

Shown below is a plot of the charged pion energy response as a function of true pion energy (from MC simulation).

We can clearly see the impact of the degraded compensation (compared to Run I).



For comparison, from Run I test beam paper:



A few words on energy reconstruction in DØ

As discussed in this talk, different objects have very different energy responses in our CAL:

- the electron energy response strongly depends on angle of incidence and on energy,
- same for charged pions, and pions are very different from electrons,
- hadronics taus,
- jets,
- ...

To deal with this, the D0 energy reconstruction works in two majors steps:

- cell-level calibration (using a set of layer weights that is a compromise [*i.e.* not really good for any object]),
  cell energies are then input to clustering and object identification,
- an object-level calibration that takes into account the specifics
    - electron scale corrections,
    - tau energy scale,
    - JES,
    - ...

Selected conclusions

Calorimeters are a key ingredient in modern multi-purpose detectors.

To have a shot at understanding calorimetry, one has to understand the fundamental interactions of particles with matter.

EM processes are very well understood (but not always well implemented in all MC simulations). Hadronic processes are much less well known.

Dead material is a headache, but it is common and abundant in many modern detectors.

Compensation is a very desirable feature in hadron calorimetry.

We use depleted uranium as absorber because:
- it is a dense high-Z material (=> excellent shower containment with compact CAL)
- it can help achieve compensation

Uranium is neither a prerequisite nor a guarantee to achieve compensation.

In Run I, the D0 CAL was “almost” compensating.

In contrast to what is written in many Run II PhD theses, the D0 CAL is pretty non-compensating in Run II (due to the changes in integration time and zero suppression).

No software trick can replace true compensation.

References

An excellent (and sort of fat) text-book on calorimetry:

R. Wigmans, "*Calorimetry: energy measurement in particle physics*", Oxford University Press (2000).

Many excellent lectures on calorimetry are available on the web:

J. Brau, in the SLUO Lecture Series, January 7th and 14th, 1999.

M. Barbi, at the TRIUMF Summer Institute, July 2007.

G. Gaudio and M. Livan at the International School of Physics 'Enrico Fermi', July 2009.

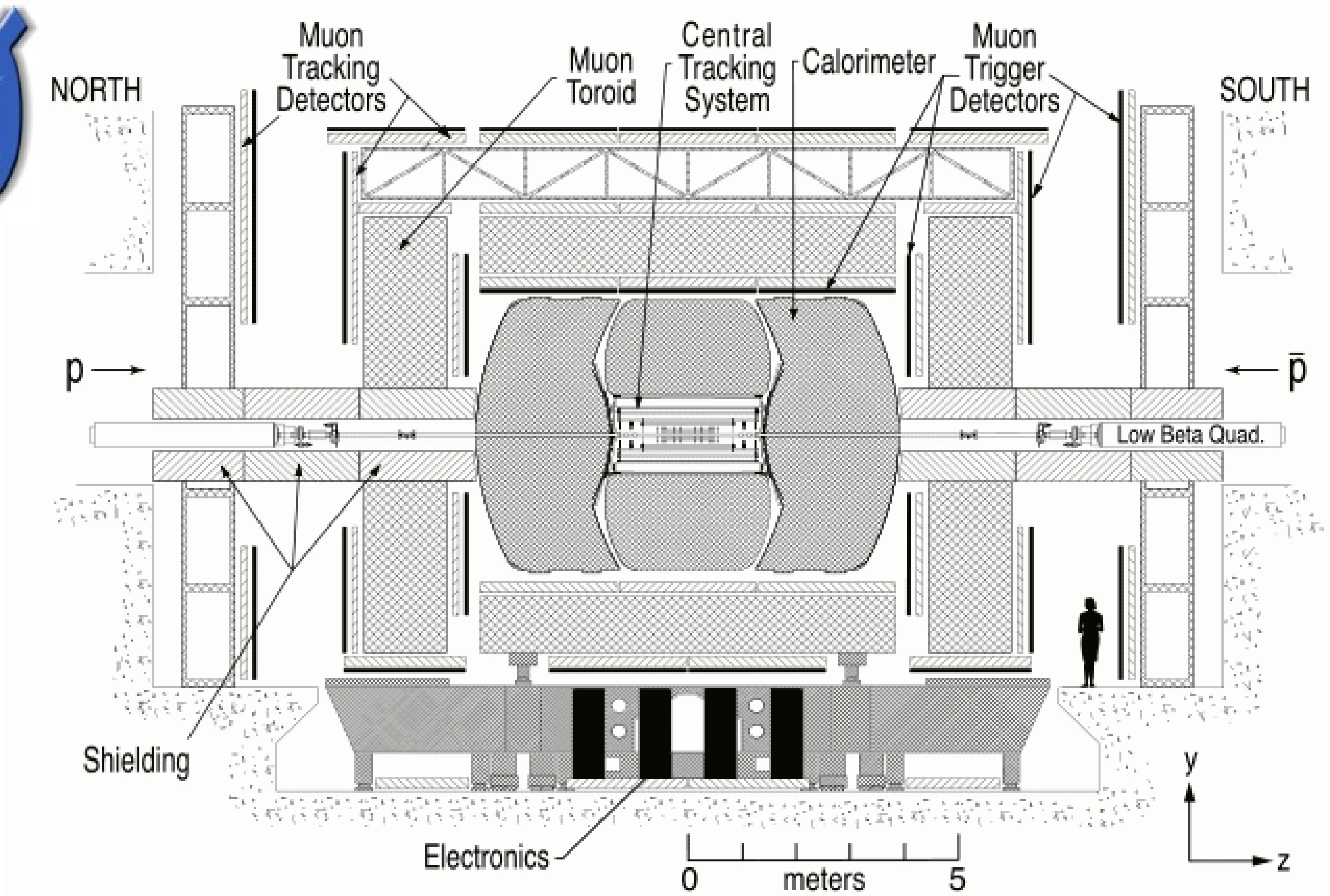
R. Erbacher, lectures at the UC Davis

...

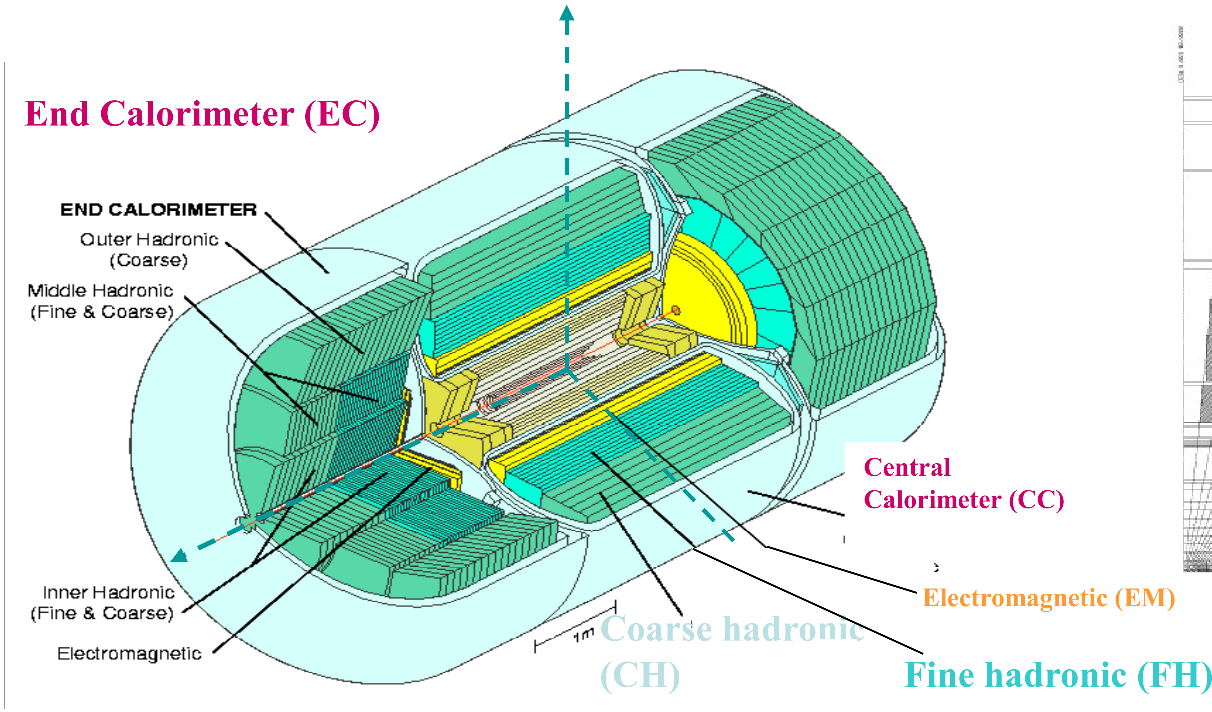
For the present lecture, we have drawn freely from these wonderful resources.

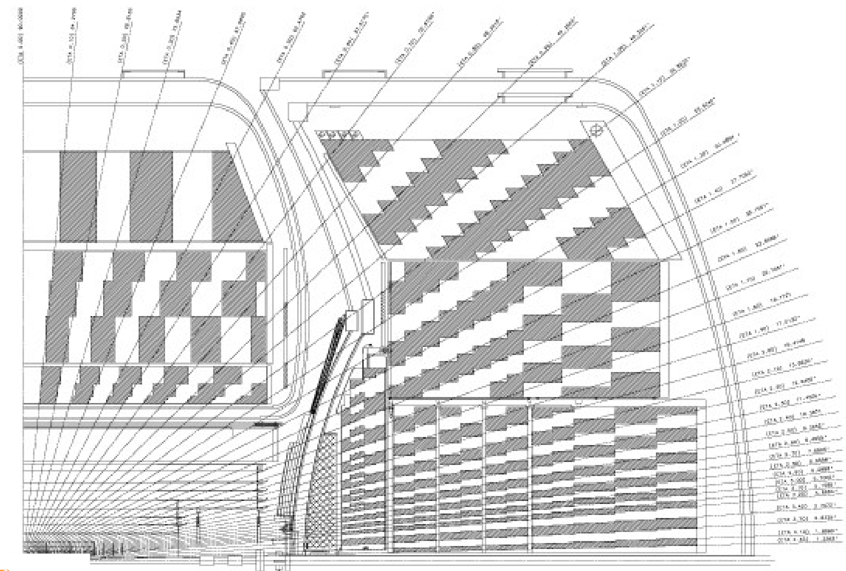
Backup slides

The upgraded DØ detector



Overview of the calorimeter





46000 cells

50 dead channels

- Liquid argon active medium and (mostly) uranium absorber
- Hermetic with full coverage :$|\eta| < 4.2$
- Segmentation (towers): $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$

  (0.05x0.05 in third EM layer, near shower maximum)

Particle identification