On the limits of the hadronic energy resolution of calorimeters

Richard WIGMANS
Texas Tech University

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The physics of hadronic shower development

- A hadronic shower consists of two components
  - **Electromagnetic component**
    - electrons, photons
    - neutral pions $\rightarrow 2 \gamma$
  - **Hadronic (non-em) component**
    - charged hadrons $\pi^\pm, K^\pm$ (20%)
    - nuclear fragments, p (25%)
    - neutrons, soft $\gamma$’s (15%)
    - break-up of nuclei (“invisible”) (40%)

- **Important characteristics for hadron calorimetry:**
  - Large, non-Gaussian fluctuations in **energy sharing em/non-em**
  - Large, non-Gaussian fluctuations in “invisible” energy losses
    (e.g. 100 GeV $\pi$: energy resolution ZEUS 3.5%, D0 7%)
The calorimeter response to the two shower components is NOT the same.

This effect is quantified by the $e/h$ ratio. For example, in crystal calorimeters, $e/h \sim 2$, i.e. 50% of the non-em energy deposit is invisible.
(Fluctuations in) the electromagnetic shower fraction, \( f_{em} \)

i.e. the fraction of the shower energy deposited by \( \pi^0 \)s

The em fraction is, on average, large and energy dependent

\( \pi^0 \) production is a “one-way street”
Consequences of $e/h \neq 1$

Hadronic response non-linearity
Example: CMS

Deviations from $E^{-1/2}$ scaling in $\sigma/E$
Example: ATLAS

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(a) $E_{\text{reconstructed}} / E_{\text{available}}$

(b) Energy resolution, $\sigma/E$ vs. $1/\sqrt{E}$
Why is $e/h \neq 1$?

**Dominant effect:**

*Nuclear binding energy losses*

**Secondary effects:**

*Escaping muons and neutrinos (meson decay)*
What to do about this?

*Use a measurable quantity that is correlated to these losses*

1) *The total kinetic energy of neutrons produced in the shower development*

2) *The electromagnetic shower fraction*

*Which of these offers the best correlation?*
Compensation

Achieved by boosting the relative contribution of neutrons to the signals by means of the sampling fraction, to the point where e/h = 1

SPACAL 1989

Pb - plastic fibers (4:1 volume ratio)
Hadronic signal distributions in a compensating calorimeter

from: NIM A308 (1991) 481
Hadronic signal (non-)linearity: Dependence on $e/h$

Fig. 3.14. The response to pions as a function of energy for three calorimeters with different $e/h$ values: the WA1 calorimeter ($e/h > 1$, [Abr 81]), the HELIOS calorimeter ($e/h \approx 1$, [Ake 87]) and the WA78 calorimeter ($e/h < 1$, [Dev 86, Cat 87]). All data are normalized to the results for 10 GeV.
Hadron calorimetry in practice

Energy resolution in a compensating calorimeter

\[
\frac{\Delta m}{m} = 0.13
\]

\[
\frac{\Delta m}{m} \sim 0.11
\]

from:
NIM A279 (1989) 503

W/Z separation:

Energy (ADC channels)

The WA80 calorimeter as high-resolution spectrometer. Total energy measured with the calorimeter for minimum-bias events revealed the composition of the momentum-selected CERN heavy-ion beam.
Dual-readout Method (DREAM):

Simultaneous measurement of scintillation light \((dE/dx)\) and Čerenkov light produced in shower development makes it possible to measure the em fraction of hadron showers event by event.

The effects of fluctuations in this fraction can thus be eliminated.

In this way, the same advantages are obtained as for intrinsically compensating calorimeters \((e/h = 1)\), WITHOUT the limitations (sampling fraction, integration volume, time):

- Correct hadronic energy reconstruction, in an instrument calibrated with electrons
- Linearity + excellent energy resolution for hadrons & jets
- Gaussian response functions
The dual-readout procedure

\[ S = E \left[ f_{em} + \frac{1}{(e/h)_S} (1 - f_{em}) \right] \]

\[ C = E \left[ f_{em} + \frac{1}{(e/h)_C} (1 - f_{em}) \right] \]

→ \( C/S \) signal ratio determines \( f_{em} \)

\[ \cot \theta = \frac{1 - (h/e)_S}{1 - (h/e)_C} = \chi \quad \text{(independent of } E!\text{)} \]

\[ E = \frac{S - \chi C}{1 - \chi} \]

From: NIM A866 (2017) 76
Hadron results obtained with a dual-readout fiber calorimeter

From:
NIM A866 (2017) 76
Comparison of performance results obtained with compensation and dual-readout

Energy (GeV)

$\frac{\sigma}{E} (%)$

$a)$ Electrons

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

$b)$ Hadrons
Monte Carlo simulations of hadron showers

Version GEANT4.10.3 patch-02
FTFP_BERT physics list

10, 20, 50, 100 GeV \( \pi^- \) in Cu and Pb
10,000 events per point

Extracted information for each event:
- The em shower fraction
- The total nuclear binding energy loss
- The total kinetic energy of the (non-reinteracting) neutrons
Correlation between binding energy loss and quantities measured in dual-readout (a) or compensation (b).

Results are for 100 GeV π- in lead absorber.
Correlation between nuclear binding energy loss and quantities measured with dual-readout (a) or compensation (b)

Results are for 50 GeV $\pi^-$ in copper
Energy dependence

Average binding energy loss

Correlations

![Graph showing energy dependence and correlations]

- **Energy (GeV)**
- **Average binding energy loss (fraction of $E_n$)**
- **Correlation with binding energy loss (%)**

- **Copper**
- **Lead**

- **$E_{\text{kin}}(n)$ Cu**
- **$f_{\text{em}}$ Cu**
- **$E_{\text{kin}}(n)$ Pb**
- **$f_{\text{em}}$ Pb**
Limit on the hadronic energy resolution

**Energy (GeV)**

Limit on the hadronic energy resolution (%)

- **Cu absorber**
  - 20%/\sqrt{E}
  - 10%/\sqrt{E}

- **Pb absorber**
  - 20%/\sqrt{E}
  - 10%/\sqrt{E}

**Dual readout**

**Compensation**

(a)

(b)
A hadronic signal distribution is a superposition of signal distributions for events with the same em fraction.
Conclusions

- Both dual-readout and compensation provide a great way to mitigate the problems of traditional hadron calorimeters.

- They offer signal linearity, Gaussian response functions, the same response (i.e. average signal/GeV) to electrons, pions and protons as well as very good energy resolution.

- Dual-readout is somewhat better than compensation, as evidenced by experimental data and confirmed by GEANT4 simulations.

- Hadronic energy resolutions of $20\%/\sqrt{E}$ are within reach.

- Efforts to develop a practical instrument for a 4π collider experiment have started (see R. Ferrari’s talk).