Compensating Calorimeters

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Idea of compensation

- Smaller calorimeter response to non-em components of hadron showers than to em components
  - Reason: invisible energy → no contribution to calorimeter signal
  - Main source: energy used to release nucleons from nuclei + myons + neutrinos (escape the detector)
- Consequences of non-compensation:
  - Non-linearity of hadronic calorimeter response
  - Degradation of the energy resolution
  - Effects on the line shape of the hadronic calorimeter

=> Need to compensate for the invisible energy

Important definitions

- $Calorimeter\ response = \frac{average\ calorimeter\ signal}{energy\ of\ the\ particle}$
- Linear calorimeter:
  - average signal proportional to particle energy

  → response = constant as a function of energy (benchmark particles = mips)
- What does X/mip < 1 mean?
  - on average, smaller signal for particles "X" of a given energy than for mips of the same energy
- $Sampling\ fraction = \frac{energy\ deposited\ by\ mips\ in\ the\ active\ calorimeter\ layer}{total\ energy\ deposited\ in\ the\ calorimeter}$

The e/h value

- e/h value = degree of non-compensation in calorimeters
- Definition (as derived from e/π - measurements):

$$\frac{e}{h} = \frac{1 - f_{em}(E)}{{}^{\pi}/_{e}\,(E) - f_{em}(E)}$$

- With different shower particles that contribute to em and non-em components:

$$\frac{e}{h} = \frac{{}^{e}/_{mip}}{f_{rel} \cdot {}^{rel}/_{mip} + f_{p} \cdot {}^{p}/_{mip} + f_{n} \cdot {}^{n}/_{mip}}$$

- Compensation ⇔ e/h = 1
  - Undercompensation ⇔ e/h > 1
  - Overcompensation ⇔ e/h < 1

The e/h value (2)

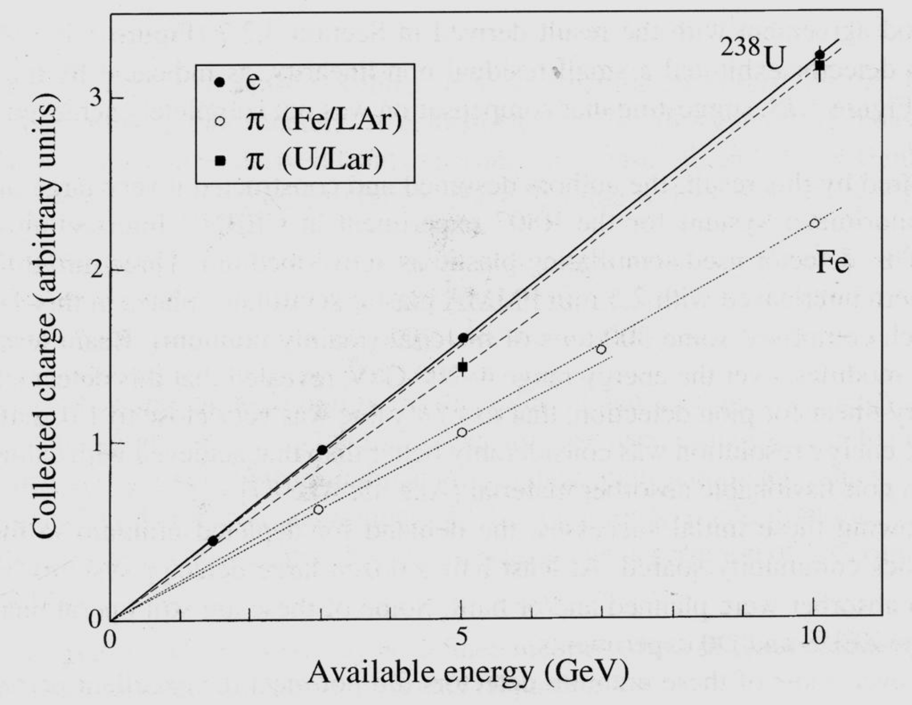
- In homogeneous calorimeters:
  - Always undercompensation, e/h > 1, since $f_{rel} + f_p + f_n < 1$ due to the invisible energy
- In sampling calorimeters:
  - Tuning of parameters until e/h = 1 is achieved.
  - Once active and passive materials have been chosen → values of f_{rel}, f_p, f_n are fixed
  - rel/mip = 1

=> Only tuning of e/mip, p/mip and n/mip possible

  - Usually: undercompensation, e/h > 1 => reduction

The first compensating calorimeter

- First uranium calorimeter by Fabjan and Willis
- 250 ^{238}U plates (1.7mm thick) in liquid argon (20mm gaps between plates)
- Compensation almost achieved → e/h ~ 1.1-1.2



- Electron measurements as normalization
- Small non-linearities

Experimental insights from first experiments

- Non-linearities:
  - Undercompensating calorimeters:
    Increase of hadronic response with increasing energy
  - Overcompensating calorimeters:
    Decrease of hadronic response with increasing energy
- Material choices:
  - For a certain passive material: For compensation, need the right active material in the right proportion.
- 3 different methods to achieve compensation:
  - Reduction of the em response
  - Boosting the non-em response
  - Off-line compensation

Reducing the em response

- Choose high-Z absorber material, e.g. lead, uranium → e/mip = 0.6-0.7

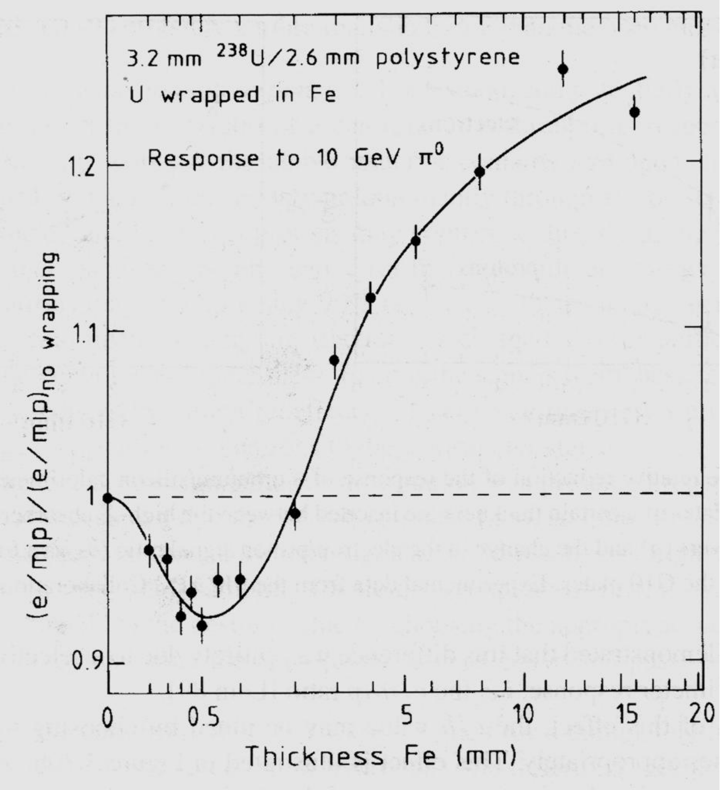
  => Ideally compensate 30-40% of invisible energy

- Reason for suppression of em response in sampling calorimeters with high-Z absorber material:
  - Dominating contribution of photoelectric effect to cross section
  - Contribution of created photoelectron to calorimeter signal <=> interaction takes place very close to the boundary layer

  => Photoelectron can escape into the active material => signal

Reducing the em response (2)

- Further suppression of e/mip:
  shielding the active layers with thin sheets of passive low-Z material (e.g. iron foil)
- e/mip → function of thickness of these foils
- ZEUS experiment: uranium plates wrapped in stainless steel



- Minimum: ~500µm iron foil ≈ range of electron with ~700keV (= energy where photoeffect starts dominating)

Boosting the non-em response

- Mechanism: nuclear fission
  - Fission processes in non-em part of the shower development

  => extra energy → nuclear γs and soft evaporation neutrons

  => Use depleted uranium ^{238}U
- Compensate to some extent for invisible energy (≈1/3)
- Nuclear fission neutrons increase f_n.

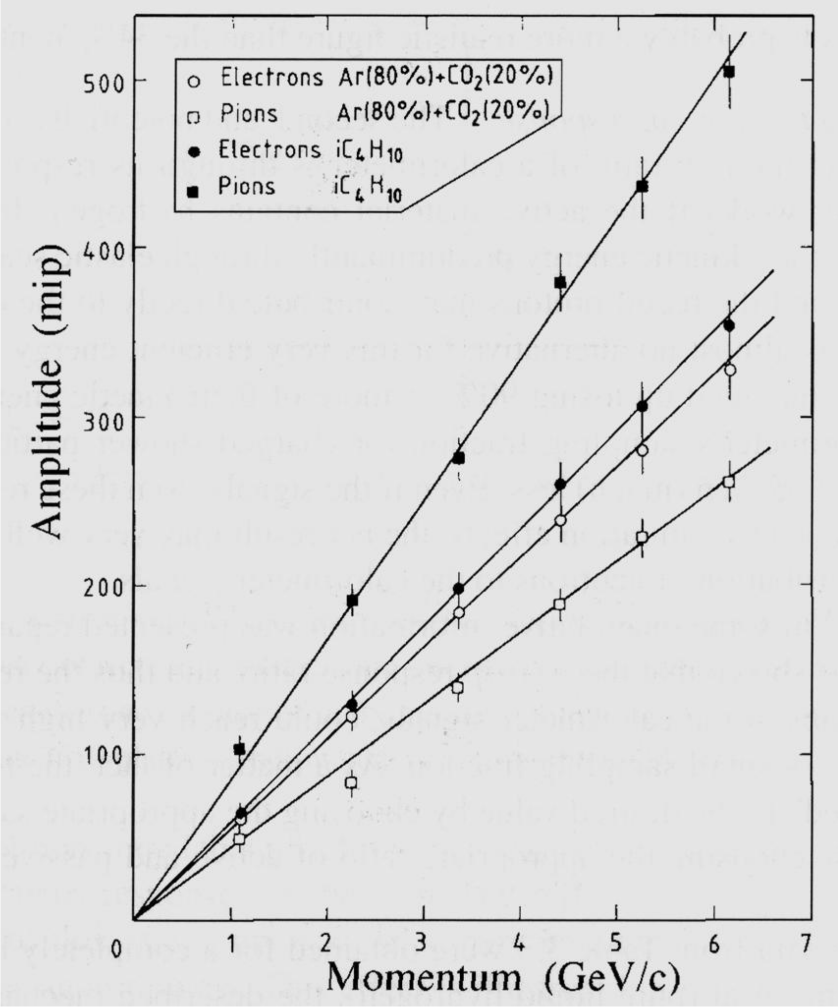
  => n/mip value required for compensation is smaller than in the absence of fission neutrons.

Boosting the non-em response (2)

- Manipulating the response to neutrons → active material has to contain hydrogen
  - Loss of kinetic energy of soft neutrons through elastic scattering with the hydrogen nuclei
  - Recoil protons → direct contribution to calorimeter signal.
  - Very efficient process → large contribution of neutrons to signal though possible saturation effect
- Rule: The smaller the sampling fraction for charged particles, the larger the relative contribution of neutrons to the calorimeter signal.

⇒ Tuning of n/mip by choosing the appropriate sampling fraction for mips

Boosting the non-em response (3)



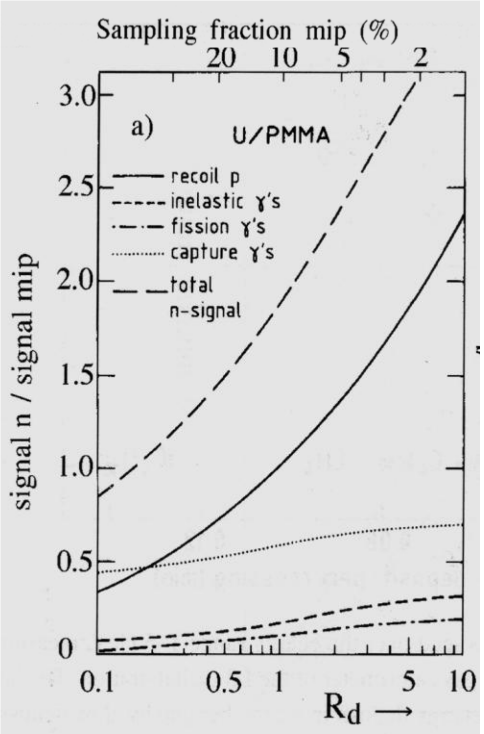
- L3 Collaboration (LEP, CERN)
  - 2 gas mixtures: Ar/CO_2 and isobutane (iC_4H_{10})
  - Electron signals barely affected by gas change
  - Pion signal increased by almost factor 2.
  - Ar/CO_2: undercompensation (e/h~1.3)
  - Isobutane: Overcompensation (e/h~0.6)
- For compensation: Choose right gas mixture

Boosting the non-em response (4)

- In dense hydrogenous materials (plastic scintillators), e.g. ^{238}U/PMMA
  → Saturation effects and higher densities
- Parameter R_d:

$$R_d = \frac{thickness\ of\ passive\ material}{thickness\ of\ active\ material}$$

- Monte Carlo Simulations: n/mip and e/h as function of R_d



- Dominant contribution: recoil protons
  → strongly dependent on sampling fraction

Sampling fractions in different materials

- Uranium/plastic scintillator calorimeters:
  - Sampling fraction for compensation: 10%
- Lead calorimeter Pb/PMMA:
  - Sampling fraction for compensation: 3%
  - Differences to uranium:
    no fission processes → no neutron induced fission γs and less neutrons → smaller value of f_n
    larger e/mip value due to Z dependence of e/mip
- Low-Z absorber materials (copper, iron):
  - Even smaller sampling fraction for compensation
- Saturation: If saturation was absent, compensation would be achieved for much larger sampling fractions.

Off-line compensation

- Determine energy sharing between em and non-em components of hadron showers on an event-to-event basis
- Apply weight factor e/h to the portion of the signal generated by the non-em components
- 2 methods:
  - Different spatial developments of em and non-em showers, especially in high-Z absorber materials → disentangle contributions of the 2 types of components
  - em showers → electrons and positrons → relativistic;
    non-em shower component → spallation protons, recoil protons (not relativistic)
    => Comparison of Čerenkov and scintillation light produced in optical calorimeters

Thanks for your attention

Literature:

Wigmans, R., *Calorimetry*, Oxford 2000, chap. 3.3

Figures:

Wigmans, R., *Calorimetry*, Oxford 2000, chap. 3.3

e/h value in dependence of sampling fraction

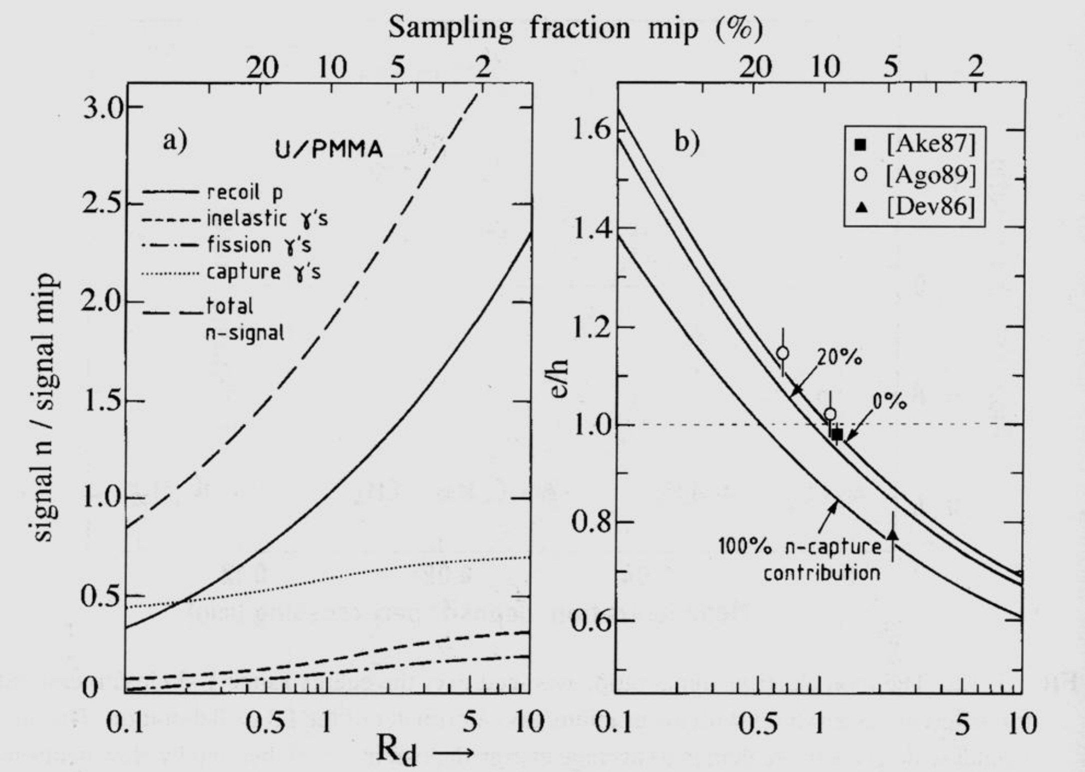


FIG. 3.33. The n/mip response ratio, split up into its components, for ^{238}U/PMMA calorimeters, as a function of R_d, the ratio of the thicknesses of the passive and active calorimeter layers (a). The e/h ratio as a function of R_d, assuming that 0%, 20% or 100% of the γs released in thermal neutron capture contribute to the calorimeter signals (b). The top axis of both graphs indicates the sampling fraction for mips. From [Wig 88].