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 $\rightarrow$ 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** = \( \frac{\text{average calorimeter signal}}{\text{energy of the particle}} \)

- **Linear calorimeter**:  
  - average signal proportional to particle energy  
  - \( \rightarrow \) response = constant as a function of energy (benchmark particles = mips)

- **What does \( X/\text{mip} < 1 \) mean?**  
  - on average, smaller signal for particles “\( X \)” of a given energy than for mips of the same energy

- **Sampling fraction** = \( \frac{\text{energy deposited by mips in the active calorimeter layer}}{\text{total energy deposited in the calorimeter}} \)
The e/h value

- e/h value = degree of non-compensation in calorimeters
- Definition (as derived from e/π - measurements):
  \[ \frac{e}{h} = \frac{1 - f_{em}(E)}{\frac{e}{\pi}(E) - f_{em}(E)} \]
- With different shower particles that contribute to em and non-em components:
  \[ \frac{e}{h} = \frac{\frac{e}{mip}}{f_{rel} \cdot rel/mip + f_p \cdot p/mip + f_n \cdot n/mip} \]
- 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 $\rightarrow$ values of $f_{rel}$, $f_p$, $f_n$ are fixed
  - $rel/mip = 1$

$\Rightarrow$ Only tuning of $e/mip$, $p/mip$ and $n/mip$ possible
  - Usually: undercompensation, $e/h > 1 \Rightarrow$ reduction
The first compensating calorimeter

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

- 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 $\rightarrow$ function of thickness of these foils

- ZEUS experiment: uranium plates wrapped in stainless steel

- Minimum: $\sim 500\mu$m iron foil $\approx$ range of electron with $\sim 700\text{keV}$ ($=\text{energy where photoeffect starts dominating}$)
Boosting the non-em response

- **Mechanism:** nuclear fission
  - Fission processes in non-em part of the shower development
    => extra energy \( \rightarrow \) nuclear \( \gamma \)S and soft evaporation neutrons
    => Use depleted uranium \( ^{238}\text{U} \)

- **Compensate to some extent for invisible energy (\( \approx 1/3 \))**

- **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\(_4\)H\(_{10}\))
  - 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 $R_d$:
  \[ R_d = \frac{\text{thickness of passive material}}{\text{thickness of active material}} \]

- 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 $n/m_{ip}$ response ratio, split up into its components, for $^{238}\text{U}/\text{PMMA}$ 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 $\gamma$s 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].