Calorimetry: 
Present trends and technology progress

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Disclaimer

- This presentation covers *mostly* HEP. Apologies to the Astro and NP community
- It is assumed that calorimetry at cryogenic temperature will be covered by the next speaker

Outlook

- Introduction
- Calorimetry for hadrons and jets
  - The problem..
  - The solutions ?
    - Compensating calorimeters
    - Dual readout calorimeters
    - Particle flow and high granularity calorimeters (Silicon, scintillator tiles)
  - Fast timing and 5D calorimetry
  - One slide about electronics
Calorimetry

• Need to measure the energy of all particles in a reaction, in particular neutral ones (photons, $K_L$, neutrons) which cannot be detected in a charged particles Tracker.

• Need to use a detection method whose size does not increase dramatically with the energy of the particles.
  – calorimeters length $\propto \ln(E)$ and resolution $\propto 1/\sqrt{E}$

• The word “calorimetry” is misleading: usually we do not measure the temperature increase of the detection media but a quantity proportional to the incoming energy.
  – Measurement of heat deposition in cryogenic detectors (Dark Matter ..) will be covered in the next talk.
Depending on the technique, the signal $S$ is detected:
- optically (light in crystal, scintillator, Cerenkov...)
- electrically (signal in semiconductor, ionization in liquid)
- thermally (bolometers at mK temperature)

**Depicts a particle shower with detected signal $S$.**

**Equation:**

$S \propto E$

**Text:**

Big European Bubble Chamber filled with Ne:He = 70%:30%, 3T Field, $L=3.5$ m, $X_0=34$ cm, 50 GeV incident electron

**Image:**

A liquid-scintillator total-absorption hadron calorimeter for the study of neutrino interactions.

Received 5 February 1975

NIM 125(1975) 447

JENAS conference 15/10/19
Electromagnetic calorimetry

Electromagnetic showers result from electrons and photons undergoing bremsstrahlung and pair creation until they reach the critical energy $E_c$

$E > E_c$

$E < E_c$

Longitudinal development governed by radiation length $X_0$

$$X_0 \approx \frac{180 \cdot A}{Z^2} \cdot g \cdot cm^{-2}, \ 5.5 \ mm \ in \ Pb$$

Lateral development governed by Moliere Radius

$$R_M = \frac{21 MeV \cdot X_0}{E_c} \approx \frac{7 \cdot A}{Z} \cdot g \cdot cm^{-2}, \ 14 \ mm \ in \ Pb$$

Electromagnetic showers are short and compact and linear, The emphasis is usually on resolution.

The resolution is given by the statistical fluctuations of the detection method (stochastic term) + all kind of experimental factors like noise, calibration -> (noise & constant term)
Semiconductor based detectors for Nuclear Physics

High Purity Germanium Detectors
34000 e-h pairs @ 100 KeV

Figure 1.1. Nuclear γ-ray spectrum of decaying uranium nuclei, measured with a bismuth germanium oxide scintillation counter (upper curve) and with a high-purity germanium crystal (lower curve). Courtesy of G. Roubad, CERN.

Few % at 100 KeV
Actually better than purely statistical (Fano factor)

Unfortunately very expensive!

AGATA n-type HPGe
Legnaro, GANIL, GSI

NIMA 668 (2012) 26–58
Homogeneous electromagnetic calorimeters HEP

CsI(Tl) calorimeter (scintillation light, slow) Belle(2), Babar, …

CMS calorimeter PbWO$_4$ (scintillation light, fast)

CMS ECAL PbWO$_4$

KOTO CHEF2013

Other examples
CALET TASC PbWO$_4$
Meg2 LXe

NA48/62 Liquid Krypton ionisation

$\sigma_E / \sqrt{E} = 1.9 \% / \sqrt{E}$

$\sigma_E / \sqrt{E} = 3.5 \% / \sqrt{E}$

ArXiv hep-ex/0012011

3x3 resolution
3.5 \% / \sqrt{E} (GeV)
0.128 \% / \sqrt{E} (GeV)
0.3 \% / \sqrt{E} (GeV)

Central impact
Uniform impact

Inorganic crystals

Inorganic crystals are still planned for many future HEP experiments where high precision is a must

- CsI undoped for Mu2e@ FNAL
- PWO for Panda @ FAIR
- LYSO for COMET @ JPARC
- PbF2 for g-2 @ FNAL
- LHCb Phase 2@ HL-LHC

but are unlikely (in my opinion) to be used in future large collider experiments (as it was for CMS) due to their high cost

Space future examples: AMEGO (FERMI-LAT successor), HERD (China s.s., LYSO)

“impossible energy range” where Compton and pair production compete

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Inorganic crystals (2)

The field is extremely active in two domains

- **Medical applications** (PET).
  
  Novel routes towards ultra-fast timing performance (sub-ns) are explored. A fast timing detector for CMS Upgrade is based on LYSO

- **Homeland security** (luggage control, search for explosive or radioactive material). High light output, high resolution <2% at 662keV

S/N can be improved by factor 5.2 (16.4) by timing at 100 (resp.10) ps

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The atmosphere is an inhomogeneous calorimeter offering about 26 $X_0$. $Ec = 86$ MeV

Detection methods
- Cerenkov radiation
- For $E \gg 10 \times 10^{17}$ eV
  - Fluorescence of nitrogen
  - Coherent Radio emission

Good timing is important
Sampling electromagnetic calorimeters

The resolution depends on:

1) **the sampling fraction**
   - The more you sample, the better

2) **the active layer thickness**
   - The thinner the active medium, the better.
   - Mainly due to the ability to capture low energy electrons (even \(< E_c\)) from the absorber

\( d \) is thickness of active layer

\( f_{\text{samp}} \) is sampling fraction
Measurement of hadrons and jets

Much more complex!

Electromagnetic and hadronic components have a different response ("e/h")

\[ \lambda_{int} = \frac{A}{N_A \times \sigma_{int}} \propto A^{2/3} \]

Electrons, photons \( \pi^0 \rightarrow 2\gamma \)

\( \Rightarrow \) em sub-shower

Ionizing particles
Neutrons

[58-72%]
[9-5%]
[33-23%]

Either not detected or too slow to be within detector time window \( \Rightarrow \) invisible energy

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Electromagnetic fraction $f_{em}$

- Varies with energy -> non linearity
- Fluctuates event by event -> poor resolution

Parameterization:
$$f_{em} = 1 - \left[ \frac{E}{E_0} \right]^{(k-1)}$$

Graph showing the average electromagnetic shower fraction vs. pion energy (GeV) for different energies (20 GeV, 200 GeV). The graph includes data points for different materials and experiments.
How to improve?
1- Compensating calorimeter e/h ~1

Boost non-e.m. response
- by using depleted uranium ($^{238}$U), extra energy contribution to the hadronic component from fission of nuclei. Used by L3, D0, ZEUS.
  drawback: natural radioactivity, nuclear waste!
- and/or by boosting the response to low energy neutrons (high hydrogen content in active medium, longer measurement gate). $n+H \rightarrow n+p$

and/or suppress the e.m. response
- thin layers of plastic scintillator in a calorimeter with high Z absorber (for example W)
  $\sigma_{\text{photo electrique}} \propto Z^4 \rightarrow \gamma < 1\text{MeV captured in absorber}$
  poorer e.m. energy resolution
  expensive
  Example: CALiCE AHCAL with W absorber

R.Wigmans [2] p.175

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How to improve?
2-Dual Readout calorimeter

DREAM: Dual REAdout Method – CERN RD52 project

measuring $f_{em}$ on an event by event basis

Simultaneous measurement of scintillation light ($dE/dx$) and Cerenkov light produced in showers:

- **Cerenkov** light only produced by relativistic particles: em component
- **Scintillation** light produced by relativistic and non-relativistic: em + hadronic component
Dual Readout Calorimeter (2)

Scintillator signals

\[ \langle S \rangle = 149.8 \pm 38.5 \text{ f}_{\text{em}} \]

Cerenkov signals

\[ \langle \tilde{C} \rangle = 40 \pm 148 \text{ f}_{\text{em}} \]

Cerenkov signal proportional to e.m. fraction

Uncorrected

Corrected using Č/S

Čerenkov signal (GeV)

Energy resolution

\[ \frac{\sigma}{E} = \frac{11\%}{\sqrt{E}} + 1\% \]

Energy (GeV)

Hence 15/10.
Growing interest for Dual Readout Calorimeter for FCC-ee or CepC detector

Still many developments needed
- projective geometry
- longitudinal segmentation (fibres starting at different depths, extended use of timing information, …)
- rad-hardness (quartz fibres YAG, but expensive)
- use of SiPMs to get rid of fibres forest
- industrial production of grooved absorber
- (Possibility to mix with homogeneous (crystal) calorimeter)

IDEA D.R. calorimeter
For FCC-ee
How to improve?
3- Particle Flow Approach for Jets measurement (PFA)

Principle: use the hadron calorimeter as little as possible!
• Charged tracks from tracker measurement
• e/g from e.m. calorimeter
• Only n and K_L are measured in the hadron calorimeter (10%)

Particle flow was
• pioneered by ALEPH
• extensively developed and studied in the past 15 years for Linear Collider Detectors (e.g. CALICE) => shown that jet energy resolution goals (3%-4% for energies from 45 GeV to 500 GeV) can be met
• routinely used by CMS (whose hadron calorimeter has a rather poor energy resolution 90%/\sqrt{E})
Example: performance in actual CMS

- Improve energy resolution
- Improve angular resolution
- Recover linearity

Particle Flow requires to separate spatially the showers from different particles.

The limitation of the method is the confusion between nearby objects.

For a Particle-Flow Calorimeter, granularity is more important than energy resolution!

\[ \text{High Granularity calorimeters} \]
High granularity calorimeters

Inspired by PFA approach, several High Granularity calorimeters are under design for collider experiments most notably for ILC detectors (CALICE collaboration) and for CMS HL-LHC upgrade Components:

- Silicon
- Scintillators tiles readout by SiPMs
- (option gaseous detector CALICE)

**Key Parameters**
- HGCAL covers $1.5 < \eta < 3.0$
- Full system maintained at $-30^\circ C$
- $\sim 640 \text{ m}^2$ of silicon sensors
- $\sim 370 \text{ m}^2$ of scintillators
- $6.1 \text{M}$ Si channels, 0.5 or 1.1 cm$^2$ cell size ($6M$)
  - 240k scint-tile channels ($\eta-\phi$)
- $\sim 31000$ Si modules (incl. spares)

**Active Elements:**
- Si sensors (full and partial hexagons) in CE-E and high-radiation region of CE-H.
- SiPM-on-Scintillating tiles in low-radiation region of CE-H
Silicon calorimetry

- Pioneered in the 80’s (P.G. Rancoita), revisited for LHC (RD35), applied at small scale in 2005 for CMS Preshower (20m²)
- Decisive momentum by ILC detectors R&D, following strong reduction of Si wafers cost and progress in low feature-size/power VFE electronics
- Adopted by CMS for its HL-LHC upgrade (Endcaps) and ALICE for forward rapidities (FoCal)

Silicon advantages:
- Fast response ~ 5ns
- Small transverse granularity (cm² or less) easy
- Longitudinal granularity (independent layers, thin active medium)
- Good S/N at MIP
- Radiation tolerance > 10x¹⁶ n/cm² (leakage current counteracted by low T). Can vary the silicon thickness to optimise this aspect
- Low power FE electronics (20 mW/channel CMS, ~100 times less @ILC with power pulsing). Good S/N.
- Large wafers (6”, 8”) available
- Automated module assembly
Silicon calorimetry CALICE

CALICE: 18x18 cm², 5x5mm² pixels (HPK)

CALICE technological prototype arXiv 1810.05133

JENAS confer

NIM A608(2009) 372

16.6 %/√E ± 1.1%
Silicon calorimetry CMS Endcap

CMS HGCAL: 8” silicon wafer with 1cm² cells (HPK)

CMS HGCAL: gantry for 8” automated module assembly (base plate, Kapton, sensor and readout PCB gluing (UCSB))

Tiling of an em layer

Table:
- Plane: Plane 10
- InnerRadius (mm): 289.0
- OuterRadius (mm): 1571.7
- Z (cm): 336.9
- Num. of Full sensors: 264
- Num. of Fives sensors: 12
- Num. of Choptwos sensors: 6
- Num. of Halves sensors: 18
- Num. of Semis sensors: 6
- Num. of Threes sensors: 12

Lowest fully covered eta and radius: 1.544 1507.0 mm
Highest fully covered eta and radius: 3.108 301.8 mm

Missing Area outside: 3901 cm²

Rmax silicon: 1555.8 mm
Rmin silicon: 290.0 mm
Silicon calorimetry

CMS test beam Nov 2018: 300 µm silicon 28 layers, 26X₀, W-Co/Pb absorber

CMS test beam 2018: event with a bremsstrahlung photon close to an electron (~2.5 cm)

Expected two showers separation in ILD
With 5x5 mm² cells CALICE-CAN-2017-001
The development of SiPMs has paved the way to high granularity hadron calorimeters with scintillator tiles. Pioneered by the CALICE AHCAL group:

- Tiles 3x3 cm$^2$ with dimple to uniformize the light collection and wrapped in ESR foil
- Large 22K channels prototype constructed
- Assembled with pick and place machine

arXiv:1808.09281v2
Large progress on SiPMs by various firms: FBK, HPK,…
also pushed by possible automotive applications (like LIDAR)

- Very fine pitch (10um or 15um)
- Trenches to avoid cross talk, while keeping high Photon Detection Efficiency (PDE)
  - Excess noise factor ~1
- Lower quench resistor for faster response
- Tested up to $2 \times 10^{14}$ n/cm$^2$. Requires operation at low T (-30°C in CMS upgrade) to keep low dark count
- Need for good T/voltage stabilisation (breakdown voltage is T dependent)
Data under analysis…
High granularity enables some (software) compensation

Correlation between total reconstructed energy and a factor linked to the number of hits with deposit < limit (5 MIP)

CALICE AHCAL: Fe absorber, 48 layers, scintillator tiles 3x3 cm²

Improvement of resolution using this correlation

\[
\frac{\sigma}{E} = \frac{57\%}{\sqrt{E}} \oplus 1.6\% \\
\frac{\sigma}{E} = \frac{45\%}{\sqrt{E}} \oplus 1.8\%
\]
Strong recent effort to exploit fast timing in calorimeters
- PET (already mentioned)
- High energy: reduce pileup at high rate (HL-LHC, CLIC,...)

**HL-LHC: bunch crossing collision $\Delta t$ (rms) $\sim 150$ ps**
A resolution $O(30\text{ps})$ could allow reducing the pileup by factor 5, bringing the HL-LHC pileup situation (up to 200 simultaneous events) similar as today ($\sim 50$ simultaneous events @ $L=2\times10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)

Can be obtained with calorimeters!
Fast timing in calorimeters

Silicon diodes
- 20 ps resolution
- Irradiation does not deteriorate performance
- ~ 40 such cells in a high-energy (100 GeV) electromagnetic shower
- Several such cells in a hadronic shower
- (CMS TB 2018 under analysis)

\( \text{PbWO}_4\): 25 crystals matrix
CMS Test beam 2018 with new (Phase2) electronics @160 MHz

Q: could it be useful for Air Showers detectors?
A word on electronics

None of the steps I have mentioned could have been done without tremendous progress
- in Front-End electronics, using low feature-size (and radiation tolerant) CMOS technology and fast optical data transmission
- In Back-End electronics, using new generations of FPGAs

Since we are in Paris…

HGCROC for CMS HGCAL
- 130nm CMOS
- 20ns peaking time
- 40 MHz sampling
- 17 bits dynamic with ADC + ToT
- 20 ps resolution with ToA
- 78 channels
- Low power (< 15 mW/channel)
- Trigger primitive formations
Calorimeters are an essential component of our detectors

New lines of developments are going on, enabled by the progress in active media (new crystals, semi-conductors), in sensors (large silicon wafers, SiPMs), in electronics (low power allowing millions of channels).

Precise measurement of hadron showers remains difficult. Alternative approaches are being pursued, in particular in view of future collider experiments.

5D (energy-position-time) calorimetry is also emerging.
Backup
**Figure 1:** Relative energy resolution for the standard (blue circles) and SC (red circles) reconstruction in the combined setup [8]. The curves are plotted using the fit parameters from the legend. The overall uncertainties are shown.

**Figure 2:** Relative energy resolution for the standard (black circles) and SC (red squares) reconstruction in the W-AHCAL [9]. The error bars (bands) show the statistical (systematic) uncertainties.

CALICE AHCAL: Fe absorber (left) $e/h \sim 1.2$

W absorber (right) $e/h \sim 1$