Lectures on calorimetry

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Lecture 3

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Plan of lectures

Lecture 1
Why/what calorimeters?
Physics of EM & HAD showers
Calorimeter Energy Resolution

Lecture 2
Example of Calorimeter
Calorimeter Objects & Triggering
Exercises

Lecture 3
Future of calorimetry

Lecture 4
Example of calorimeters (suite)
Exercises
“Future” of calorimetry

DREAM fibers

Si/W CALICE prototype
“Short” term: HL-LHC (2025-2035)
- Upgrade of ATLAS, CMS… (see later)

Longer term (30-50 years)
- Lots of on-going discussions on what will be the “best” machine
- Possible new e+e- colliders
  - Linear (ILC, CLIC)
  - Circular (FCC_{ee}, CEPC,…)
- Possible new hadron colliders: FCC_{hh}
- μ-colliders, …

Physics Goals:
- Higgs
  - high precision measurement on couplings to fundamental fields,
  - Tri- and quadri-linear couplings (HH, HHH production)
- Search / Study of new physics
  - SUSY, extra-dimensions, …
    - => High mass resonances (d-ijet, γγ, ee,…), jets+MET, multi-leptons, …

Require high precision for calorimetry, in particular for jets!
+ timing capabilities
+ radiation hardness…
Worst than (or at most as good as) single hadron resolution

- **How to improve on jet resolution?**
  - i.e., how to get rid / mitigate the inherent fluctuations (in particular on \( fEM \)) ??

**Two approaches:**

- Minimize influence of calorimeter: use combination of all detectors
  => “particle flow” (software and hardware)

- Measure the shower components in each event: access the source of the fluctuations
  => Dual readout (mostly hardware + software)
Hadronic/Jet Resolution

- **Hadron Calorimeter Resolution limited by fluctuations** (sampling, $f_{EM}$, quantum, leakage, …)
  - Non-compensation degrades resolution.

- Excellent hadron resolution already achieved by several experiments (~30%/$\sqrt{E}$):
  - Absorber/scintillating fibers compensated calorimeters: ZEUS (Ur), SpaCAL (Pb)
    - Resolution ultimately limited by sampling fluctuations

- **How to improve resolution**, ie:
  - Reduce contribution from sampling fluctuations
  - Elimate/Reduce effect of fluctuations in $f_{EM}$
  - Elimate/Reduce effect of fluctuation in invisible energy

… **WITHOUT the inherent problems** of “standard” compensation?
(time integration, volume, sampling fraction)

**Dual readout calorimeter!**
(one possible solution)
Dual REAdout Method (DREAM): concept

- **Estimate $f_{EM}$ event-by-event [1]:**
  - “hardware” identification
  - comparing light from Cerenkov light and light from scintillation ($dE/dx$)

- **Note:** ideally, one wants to measure also $f_n$ (proportional to binding energy) to remove fluctuations in invisible energy
  - Using time structure of showers

- **Why Cerenkov light?**
  - almost exclusively produced by EM component
  - 80% of non-em energy deposited by non-relativistic particles
    (mainly spallation protons with $E$~few hundred of MeV => no Cerenkov light)

- **Same medium read by 2 different fibers**
  - $2 \; e/h$ for the same event

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DREAM Prototype

Basic structure:
4x4 mm² Cu rods
2.5 mm radius hole
7 fibers
3 scintillating
4 Čerenkov

DREAM prototype:
5580 rods, 35910 fibers, 2 m long (10 λ_{int})
16.2 cm effective radius (0.81 λ_{int}, 8.0 ρ₂)
1030 Kg
X₀ = 20.10 mm, ρ₂ = 20.35 mm
19 towers, 270 rods each
hexagonal shape, 80 mm apex to apex
Tower radius 37.10 mm (1.82 ρ₂)
Each tower read-out by 2 PMs (1 for Q and 1 for S fibers)
1 central tower + two rings
How to determine $E$ and $f_{EM}$?

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

E.g. If $e/h = 1.3$ (S), 4.7 (Q)

\[ \frac{Q}{S} = \frac{f_{em} + 0.21 (1 - f_{em})}{f_{em} + 0.77 (1 - f_{em})} \]

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

with $\chi = \frac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$

Q: Cerenkov
S: Scintillation
Figure 2: Čerenkov signal distributions for 200 GeV multi-particle events. Shown are the raw data (a), and the signal distributions obtained after application of the corrections based on the measured em shower content, with (c) or without (b) using knowledge about the total “jet” energy [5].
**DREAM prototype results (2)**

**Linearity of response!**

Ultimately expect ~20%/\(\sqrt{E}\)

Prototype Resolution Limited by (lateral) leakage

- Many other tests done (with Pb instead of Cu, with crystals, …)
- Would need to see what it gives in a real experiment…
Jet Resolution improvement: another path
Two ways to deal with fluctuations:

- Adjust the hardware to response to equalize the e & h ("hardware” compensation)
- Identify the various components (EM, non-EM) and weight them adequately ("software” compensation)

Software weighting was deployed at H1 detector (LAr, SpaCal calorimeters) in the 90’s.

- Reconstruct 3D-cluster (group of “connected” cells of calorimeter)
- Energy of every cells is corrected by a weighting factor, depending on:
  - energy density of cell \( \frac{E_{\text{cell}}}{V_{\text{cell}}} \)
  - dense EM deposits vs mip from hadronic
  - total energy of the cell cluster

=> less tail in energy distribution, more Gaussian shape, and 15% improved resolution
Energy Flow, Particle Flow (2)

Going a step forward…

- Typically, the jet energy fraction can be split on average:
  - ~65% charged hadrons
  - ~25% photons
  - ~10% neutral hadrons

- “Default” way to reconstruct/identify particles.
  - Neutrinos: via missing energy
  - $e/\gamma$: mainly ECAL (+tracker)
  - Charged hadrons: calorimeters
    (but tracking system can be used as well)
  - Important to understand if prompt or non-prompt (decay of $V^0$'s,…)
  - Neutral hadrons: calorimeters (mainly HCAL)
  - Muons: muon station + tracker

- But no attempt to reconstruct individual particles
  and/or avoid double counting (tracker/calorimeter)
  - Jets are “clusters” of calorimeter deposits/towers/…

Can we combine measurement of tracker and calorimeter?
Pioneered in ALEPH at LEP (90’s)

**Tracking:**
- Large number of hits $O(20)$,
- redundancy of measurements
- Very High precision

**ECAL (Pb/wire chambers):**
- 3x3cm transverse segmentation
- 3 longitudinal compartments
- Multiple readout
- $\sigma \sim 20\%/\sqrt{E}$

**HCAL (Fe/readout tubes):**
- Coarse granularity
- $\sigma \sim 100\%/\sqrt{E}$
- AFTER the coil...

**“simple design” !**
(simplified) Overview of the algorithm

- Reconstruct charged tracks and clusters in calorimeters
  - Including cleaning (noisy channels, …)
- Extrapolate tracks to calorimeters and form “calo objects”
- For each calo object:
  - for identified electrons, muons, γ, π0, remove energy from calorimeters
  - Only charged hadrons (mostly pions) and neutral hadrons should remain
  - Neutral are built as clusters not linked to tracks or with incompatible E/p
“Energy Flow” in ALEPH: (some) results

\[ e^+e^- \rightarrow Z \rightarrow qq \]

- 6 GeV resolution vs 13 GeV for calorimeter only

- Also: better angular resolution, b-tagger improved by a factor 2…

- **BUT**: ultimately limited by HCAL resolution… and loss of information due to interaction in the coil before reaching the HCAL.
Beyond Calorimetry: The Particle Flow paradigm

**Particle Flow:**
- Reconstruct and identify every stable particle in the event
  - Combining Optimally all information from all sub-detectors

- Charged particles measured by tracker (~perfect)
- Photons by ECAL ($\sigma E/E \sim 10-20\%$)
- Neutral hadrons (ONLY) by HCAL ($\sigma E/E \sim 50-100\%$)

⇒ Much improved resolution on jets,
  wrt calorimeter measurement only
  (vs ~70\% of particles measured with HCAL in traditional approach)

- Not only:
  - Aim at having a “Global Event Description”
  - Use adapted calibration for each object
  - Natural mitigation of pile-up (at hadron colliders)
  - Improved angular resolution
  - Access to sub-structure of shower
  - etc….
Needed ingredients for a good Particle Flow

- **Good separation of charged and neutrals**
  - high field integral (BxR), “effective granularity”
  - Small granularity (to minimize overlapping showers)

- **“No” material before the calorimeters**
  - “light” tracker, calorimeters inside the coil

- **Small Moliere Radius**
  - to minimize shower overlap

- **Efficient Tracking**
CMS design meets several of the criteria for a good PF

- **Large Field Integral**: $B \times R = 4.9 \ T \cdot m$
  - CMS: $B = 3.8 \ T$, Ecal Radius $R = 1.29m$
  - ALEPH: $1.5 \times 1.8 = 2.7 \ T \cdot m$

- **ECAL** with excellent resolution ($\sigma_E/E \sim 3\%$), granularity and small $R_M$ (2.2 cm).
  - poor HCAL resolution (as ALEPH)

- **Excellent tracking** (high granularity, $\sigma_{p_T}/p_T \sim 1\% \ p_T$)

**BUT, considerable challenges!**

- Up to 2 $X_0$ of tracker material in front of ECAL
  - Nuclear & EM interactions in the tracker…
- pp collisions, pile-up and (very) high density of particles

First studies started in ~2004
Jet Response close to 1
BEFORE any jet correction
(use of calibrated particles!)

Large improvement in Jet Resolution, especially at low pT
PFLow @ CMS: Results

CMS Preliminary 2012

Several kinds of particle-flow MET:

- MET from all particles
- MET from pileup particles
- MET from primary vertex particles
- etc.

Multivariate MET estimation

Almost insensitive to pile-up
Not only for jets...

- **Jets**
  - energy resolution / 2
  - angular resolution / 3
  - Flavour dependence of response / 3
  - Systematic error on JES / 2
  - « electron in jet » b tagging
  - quark-gluon jet tagging

- **Electrons**
  - down to pT = 3 GeV
  - in jets

- **μ**
  - 4% more efficient ID @ same bgd rate
  - better momentum assignment at high pT

- **e, μ, τ, γ isolation**
  - pile-up control

- **τ**
  - jet fake rate / 3 @ same eff.
  - energy resolution / 4

- **MET:**
  - resolution / 3
  - smallest tails

- **Physics analyses**
  - Better trigger for jets, MET, taus (PF@HLT)
  - e.g:
    - FSR photon recovery in H→ZZ
    - embedding in H→ττ
    - jet substructure
The ILC case

- Study Higgs, Unitarity, top at e+e- linear colliders (ILC, CLIC, …)
  - Heavily involves W, Z and H in hadronic modes (high BR)

- Challenge: W/Z separation
  - Hadronic decay of W/Z
  - Need to separate W&Z
  - ie, measure the mass of di-jet pairs:
    $$\Delta M(W,Z) \approx 10 \text{ GeV}$$

- LEP-like, 60%/√E
  - Goal: 30%/√E

ex: WW scattering
A word on resolution...

- Forgetting the correlations, the jet resolution can be written as:

\[
\sigma_{\text{jet}}^2 = \sigma_{\text{h}_{\pm}}^2 + \sigma_{\gamma}^2 + \sigma_{\text{h}_{\circ}}^2 + \sigma_{\text{confusion}}^2 + \sigma_{\text{threshold}}^2 + \sigma_{\text{losses}}^2
\]

- \(\sigma_{\text{confusion}}\): mixing between neutral and hadron deposited energy
- \(\sigma_{\text{threshold}}\): threshold for each species (integrate fluctuations at low energy of jet fragmentation)
- \(\sigma_{\text{losses}}\): losses due to imperfect reconstruction

- Studies show the **confusion term play a major role**!

- Towards ultimate Pflow performance:
  - focus more on separating showers (ie, granularity) than single particle resolution
“Particle Flow Calorimeters”

Another step beyond: Design the detector for PFLOW

**Hardware:**
- Need to be able to resolve energy deposits from different particles
- Highly granular detectors (as studied in CALICE)

**Software:**
- Need to be able to identify energy deposits from each individual particle!
- Sophisticated reconstruction software

Particle Flow Calorimetry = HARDWARE + SOFTWARE

Initially thought for TESLA in 2000’s, then ILC.
“Particle Flow Calorimeters”… or “Imaging Calorimeters”!

Another step beyond: Design the detector for PFLOW
Lots of R&D since 15 years. TDR in 2013.

Lots of possible options. Ex:
- 3D-tracking:
  - High Precision vertex (Si) detector + TPC
- High Granular Calorimeters
  - ECAL with 30 longitudinal samples
  - HCAL (48 long. Samples)
- B-field: 3.5 T
- Iron yoke instrumented with Muons detection system (Gas or scintillators)
One possible option studied inside the CALICE collaboration: Si/W sampling calorimeter

- **R~1.8m**
- **W absorber**
  - Ensure compactness (~20 cm thickness),
  - small RM
- **Si as active medium**
  - for 30 layers: ~2600 m² of Si,
  - Large S/N
- **Extreme high granularity**
  - $10^8$ channels (vs $10^5$ at LHC !!!)
Carbon-fibre support contains every second W plate.

2 PCBs of embedded front end electronics with glued 16x16 sensors are on both sides of other W plates.
1 barrel module = 5 x 15 slabs
1 slab = 8...13 x Active Sensor Units,
1 ASU = 4 x Si sensors = 1024 chan.
HV, LV, signal cables, water cooling run in 3 cm ECAL - HCAL gap, exit between barrel - endcap.
Si/W prototypes

**Physics Prototype**
Proof of principle
2003 - 2011

**Technological Prototype**
Engineering challenges
2010 - ...

**LC detector**
DBD for ILC
CDR for CLIC

**ECAL:**
Channels: \(\sim 100 \times 10^6\)
Total Weight: \(\sim 130\) t

Number of channels: 9720
Weight: \(\sim 200\) Kg

Number of channels: 45360
Weight: \(\sim 700\) Kg

JINST 3, 2008

TDR EUDET-Report-2009-01
Si/W: physics prototype

• 30 layers of variable thickness Tungsten
• Active silicon layers interleaved
• Front end chip and readout on PCB board
• Analog signals sent to DAQ
• 10,000 channels

• PCB contains VFE electronics
• 14 layers, 2.1mm thick
• Analogue signals sent to DAQ

• 6x6 1x1cm² silicon pads
• Connected to PCB with conductive glue

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Si/W: physics prototype test beam results

Linearity of response

Resolution, ~16%/√E
One possible option studied inside the CALICE collaboration:

**Analogue HCAL Stainless Steel / Scintillators sampling calorimeter**

- 3x3 cm² scintillator tiles
- 8.10⁶ channels
  vs O(10k) for ATLAS/CMS!
~50%/$\sqrt{E}$ obtained in test beams (after software compensation)
Some other results

Linearity & Resolution of Semi-Digital HCAL

Resolution of A-HCAL with/without software compensation

Data/MC Track Length (Semi-Digital HCAL)
High Granular / Imaging Calorimeters need **powerful and innovative reconstruction algorithms** to be fully exploited

- Lots of R&D in parallel to detector developments.
- **Challenges:**
  - Avoid double counting of energy from same particles
  - Separate energy deposits from different particles

![Diagram showing three basic types of confusion:](image)

- Failure to resolve photons
- Failure to resolve neutral hadrons
- Reconstruct fragments as separate neutral hadrons
PANDORA Particle Flow Algorithms (PFA)

ConeClustering Algorithm
- Cone associations
- Back-scattered tracks
- Looping tracks

Topological Association Algorithms

Track-Cluster Association Algorithms
- 38 GeV
- 18 GeV
- 12 GeV
- 32 GeV
- 30 GeV Track

Reclustering Algorithms

Fragment Removal Algorithms

PFO Construction Algorithms
- Neutral hadron
- Photon
- Charged hadron

Layers in close contact
- 6 GeV
- 9 GeV

Fraction of energy in cone
- 6 GeV
- 9 GeV
- 3 GeV
- 3 GeV
PFA Results (examples)

W/Z separation (2-3 sigmas)

PFLow always “wins” against standard calorimetry

Optimization studies
(near) Future at LHC
LHC: from Run I to HL-LHC

```
\sqrt{s} = 13 \text{ TeV}
\int L \, dt = 300-500 \text{ fb}^{-1}
<\text{PU}> : \text{from } \sim 25 \text{ to } 60
\text{SUSY} \, ? \, 😊
```

--

```
\sqrt{s} = 13-14 \text{ TeV}
\int L \, dt = 3000 \text{ fb}^{-1}
<\text{PU}> : \sim 140-200
```

Well beyond design!
Challenges: Radiation damage

3000 fb-1 Absolute Dose map in [Gy] simulated with MARS and FLUKA

Pre-Shower + ECAL Endcap at $\eta \sim 3$: 1.5 MGy, $10^{16}$ n/cm$^2$

HCAL Endcap up to 30 kGy

Aging studies shows that Endcap Calorimetry (+Tracker) has to be replaced.
Challenges: Pile-Up (PU)

- HL-LHC Nominal Parameters:
  - 140 additional interactions per bunch crossing (every 25 ns) + out-of-time PU
    - Could go up to 200
  - Instantaneous Peak Luminosity: $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$,

- Challenges for Triggers (especially Level 1 !) & offline reco + computing (30xLHC)

> Need to preserve “low” energy physics (125 GeV Higgs) and explore TeV scale (e.g. SUSY) in a very harsh environment !
HGCAL: General Layout

CMS choice: **High Granular Sampling Si-based Calorimeter**
with 4D measurement of showers (energy, position)
(possibly 5D with timing)

Operation at -30°C via CO₂ Cooling
(to mitigate Si leakage current)

<table>
<thead>
<tr>
<th></th>
<th>CE-E</th>
<th></th>
<th>CE-H</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Si</strong></td>
<td>368</td>
<td>215</td>
<td>487</td>
</tr>
<tr>
<td><strong>Si</strong></td>
<td>3916</td>
<td>1939</td>
<td>389</td>
</tr>
<tr>
<td><strong>Scintillator</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area (m²)(*)</td>
<td>16008</td>
<td>8868 (3960)</td>
<td></td>
</tr>
<tr>
<td>Channels (k)</td>
<td>1008</td>
<td>1452</td>
<td></td>
</tr>
<tr>
<td>Partial modules</td>
<td>23</td>
<td>205</td>
<td></td>
</tr>
<tr>
<td>Weight (t) <strong>(</strong>)</td>
<td>28</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Si-only planes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed (Si+Scint) planes</td>
<td>16</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(*) 3x CMS tracker !
(**) one endcap:
~230 tonnes

**CE-E (26.3 X₀):** Electromagnetic Calorimeter: 28 layers Si – Pb (+Cu,Cu/W)
**CE-H (10.7 λ):** Hadronic Calorimeter. 24 layers Si/Scintillators - Steel
Si wafers & Modules

6” Si Module (for test-beam):
Cu/W baseplate (for CE-E),
Si wafer, “hexaboard” PCB…
[8” foreseen for the final detector]

Si active thickness and cell sizes varies with $\eta$.
(to cope with irradiation and Pile-Up)
HGCAL-ECAL: Cassettes

- Modules mounted on both side of 6mm Cu cooling plate (with embedded pipes).
- Pb (2.1mm)/SS (0.3mm) absorber on both sides
  ➞ **Cassette (60° wide in CE-E)**
- Cassettes connected in inner/outer periphery and then stacked to form the ECAL

<table>
<thead>
<tr>
<th>Cassette type</th>
<th>CE-E</th>
<th>CE-H (silicon)</th>
<th>CE-H (mixed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active sides</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Full Si modules</td>
<td>91–102</td>
<td>26–33</td>
<td>5–19</td>
</tr>
<tr>
<td>Partial Si modules</td>
<td>4–13</td>
<td>2–5</td>
<td>1–4</td>
</tr>
<tr>
<td>Scint. tile modules</td>
<td>-</td>
<td>-</td>
<td>3–12</td>
</tr>
<tr>
<td>Angular width (°)</td>
<td>60°</td>
<td>30°</td>
<td>30°</td>
</tr>
<tr>
<td>Linear width (m)</td>
<td>1.56–1.67</td>
<td>0.87–0.97</td>
<td>1.00–1.39</td>
</tr>
<tr>
<td>Radial length (m)</td>
<td>1.24–1.32</td>
<td>1.33–1.47</td>
<td>1.54–2.17</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>220–250</td>
<td>56–68</td>
<td>74–144</td>
</tr>
<tr>
<td>Total no. in CMS</td>
<td>168</td>
<td>192</td>
<td>384</td>
</tr>
</tbody>
</table>
In the hadronic part:
- **Cassettes are** 30° wide,
- modules only on 1 side
- 8 layers of full Si
- 16 layers of mixed scintillator-Si
- Cassettes inserted into Stainless Steel mechanical structure
Shower radius quite small in first layers.
Can use longitudinal segmentation for PU rejection, …

Stochastic term: ~20%
but low constant term (target: 1%)

Obtained with standalone G4 simulation. Benchmarked against CALICE test-beam results
High Granularity + longitudinal segmentation gives additional powerful handles for particle ID:

- shower start, shower length compatibility, restoration of projectivity, 3D shower profile fits, layer-by-layer PU subtraction, etc...

Combination of HGC and Tracker (with far from optimal PFlow algo)

- ~Recover Phase I 50 PU performance!
HGC: Test beams

- **Goals:**
  - Performance studies: S/N, timing, energy and positions resolutions
  - Validation of front-end electronics
  - Comparison with simulation

- **Several test beams campaign** (FNAL, CERN, DESY) with different number of layers / configurations and energy
  - FNAL: 120 GeV protons, 4-32 GeV electrons/pions
  - CERN: 125 GeV pions, 20-250 GeV electrons
  - DESY: 1-6 GeV electrons
HGCAL Test beams setup

“Cassette” (Cu+modules)

Full stack of 28 layers

- Recent Test beam at CERN (Oct’ 18):
  - 94 modules/40 layers for Si ECAL and HCAL
  - 40 scintillators layers (A-HCAL from CALICE)
HGC Test beams: (some) results

- FNAL: 32 GeV electron passing through 16 layers (15 $X_0$)

- CERN: 250 GeV electron passing through 8 layers (27 $X_0$)
CERN

Event display of 250 GeV π

FNAL

Total energy deposited in all layers vs e-beam energy

DATA/Sim agrees within 5%

Energy deposited in each layer

Shower max moves to higher depth as expected
HGCAL Timeline

- **HGCAL Schedule:**
  - -> 2020 : Prototyping
  - 2020 – 2014 : Pre-production et Production
  - 2024 – 2026 : Installation

First time a high-granularity 5D (x,y,z,E, t) calorimeter will be installed in an experiment taking data!
PHYSICS DRIVES the DETECTOR DESIGN

INSTRUMENTATION, DEVELOPMENTS PERMIT ADVANCE in PHYSICS

DETECTOR PERFORMANCE, IN HOSTILE ENVIRONMENT as LHC, REQUIRES THOROUGH DATA ANALYSIS

THESE LECTURES HAVE ONLY TOUCHED THE SURFACE of WHAT ALREADY EXISTS.
Calorimetry has been (and is still!) studied for decades

Calorimeters play a unique role in HEP experiments.
- Their usage have lead to major discovery in physics (W/Z bosons, top quark, Higgs boson,…)

Calorimetry has evolved from early energy measurement techniques, addressing the problem of the compensation of the intrinsic response to electromagnetic and hadronic showers, to arrive ultimately at "particle flow" (PFlow) techniques where the individual contributions of the particles are disentangled.
- This improves the measurement of jets and allows for a complete and coherent reconstruction of collision events.

Still, these developments will not kill other types of calorimeters
- "hardware" compensation is pursued (ex: dual readout calorimeters).
- "standard" calorimeters (crystals, Pb/scintillating fibers, …) will still be used (and their performance improved), depending on physics case/cost/…
  - Can PFLOW calorimeters play a role at 100 TeV pp colliders?
(fast) Timing
10-15% vertices merged in space…
… could be reduced to ~1% using the timing information (30 ps precision on time-of-flight needed)

Could now be achieved thanks (in particular) to the development of Ultra Fast Silicon Detectors (especially in high radiation field)

Ex: Low Gain Avalanche Diode (LGAD)

Usage of fast timing (both for charged and neutral particles):
• game changer (especially at hadron colliders)
• Will take more and more importance in the years to come (4D tracking, …)
MIPs Timing at HL-LHC

High Granular Timing Detector (HGTD)

- 2 layers of LGAD (2.4<|\eta|<4), in front Calo endcaps
  - 1.3 x 1.3 mm² pixels (3.5M channels)
  - 2 (3) hits per track for R>(<) 320mm (average)

- 2 layers of LGAD, 6 ARD and peripheral electronics

- Clock distribution: Need 10-15 ps in order not to spoil the performance of the detectors...

Resolution of 30-40 ps (after irradiation). LGAD Rad. Hard up to \(2 \times 10^{15}\) neq/cm² (10 times less for LYSO+SiPM)

Barrel (|\eta| < 1.5) LYSO:Ce crystal+SiPM
- Inside tracker volume

Endcaps (1.5<|\eta|<3) : 1 layer of LGAD
- 1x1.3 mm² pixels (1.8 M channels)
- In front of HGCAL
(picosecond) Timing… for showers!

Calorimeters can also provide precise timing for neutrals to determine γ’s origin in conjunction with vertex timing to mitigate PU in Jets-ID, MET resolution or Lepton Isolation

- CMS ECAL with PbWO₄ crystals + APDs + new FE can provide ≃ 30 ps for 30 GeV γ
- CMS HGCAL Sampling calorimeters benefit from large number of layers to provide 30 ps for few GeV Photons and good efficiency for hadrons above 2 GeV Pt.
  - Limitation in S/N is in electronics noise (pad size capacitance)

H→γγ vertex finding (4D Tracking+calo timing)

From D. Contardo
BACK UP SLIDES
2-PCB’s architecture:

- **Hexaboard** PCB for module & HGROC
- **Motherboard**: Group sensors (by 2, 3, …)
  - Contain all other components (LV, HV, trigger concentrator, services for clock, fast timing, slow control, …)
  - Contains optical fibers for Trigger and data transmission

![Diagram of 2-PCB's architecture](image)
CE-E: cassettes & mechanical structure (2)

- Cassettes connected at inner/outer periphery
  ⇒ Disks of cassettes

- Disks stacked in horizontal position

- In (final) vertical position, overall support by back disk + central Al cone.
Test Beams: set up

CERN (Similar at FNAL)

Mechanical design allows flexible insertion of modules and absorbers plates
DREAM prototypes

- **Some characteristics of the DREAM detector**
  - **Depth** 200 cm ($10.0 \, \lambda_{\text{int}}$)
  - **Effective radius** 16.2 cm ($0.81 \, \lambda_{\text{int}}, 8.0 \, \rho_M$)
  - **Mass** instrumented volume 1030 kg
  - **Number of fibers** 35910, diameter 0.8 mm, total length $\approx 90$ km
  - **Hexagonal towers** (19), each read out by 2 PMTs
DREAM prototype

DREAM readout
HGCAL is on the critical path towards physics discoveries & measurements in Phase II (HH, VBF jets for Higgs/SUSY/Dark Matter, Unitarity, … ) and has all ingredients for being rad-hard, mitigate PU, deal with high rates,…

Many major & excited challenges for the next decade :
- Engineering (includes cold/warm transition, services, …)
- FE electronics & L1 Trigger
- Software, computing
- …
One of the most challenging aspect of the project!  

**Need to have large dynamic range @ low power + low noise**

- **(stringent) Requirements:**
  - **Low Noise:** ~2000 e-  
    - including sensor $I_{\text{leak}}$ noise
  - **Shaping Time:** 10-20 ns  
    - Pulse Shape is 1-2 ns
  - **Dynamic Range:** up to ~10 pC  
    - ~3000 MIP in 300 $\mu$m Si
  - **Low Power:** ~10 mW / channel  
    - ($\Sigma = 100$ kW for 6M channels)
    - System on chip (digitization, processing…)

- **Baseline architecture: Charge + Time-over-Threshold (ToT) [**]**
  - Switch from charged readout to ToT at ~100 fC
  - ADC (10 bits) and TDC (12 bits) with existing designs
  - Potential for 50 ps timing per cell

[**] alternative: more classical readout (bi-gain) or switched feedback
One of the most challenging aspect of the project!

Need to have large dynamic range @ low power + low noise

- **SKIROC2_CMS** (not the final chip):
  - Includes some of the HGC features:
    - ~20ns shaping time and 40MHz sampling
    - ADC + TOA (~50ps) + TOT
    - P-on-N and N-on-P read-out options
  - Production launched in January, Available in ~June
  - Plan to use it for CERN test beams (Fall)
    - after tests on board (noise, stability, linearity, crosstalk, …)

- Also: test vehicles on blocks launched (TSMC 130nm)
- **First iteration of full chip expected by Spring 2017.**
  - with feedback from test vehicles & SKIROC2_CMS