Calibration Techniques and Strategies for the Present and Future LHC Electromagnetic Calorimeters

Martin Aleksa (CERN)

Introduction & Benchmarks
ATLAS & CMS EM Calibration
Comparing ATLAS & CMS Performance in Physics
Planned Calorimeter Upgrades for HL-LHC – CMS HGCAL Calibration
Timing Information for HL-LHC
INTRODUCTION: BENCHMARKS FOR EM-CALORIMETRY
EM calorimetry at the origin of many important ATLAS & CMS discoveries and measurements and of course essential ingredient for the full physics program!
LHC EM Calorimeters Requirements

→ LHC Calorimeters were actually designed for exactly these benchmark channels:
→ Here ATLAS requirements as an example (CMS very similar)

| Large dynamic range: 10 MeV – 3TeV (noise level up to highest energy deposits per cell) |
| → ≈16bit dynamic range (several gains necessary) |

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| Energy resol. \((e^\pm, \gamma)\): \(\sigma_E/E \approx 10%/\sqrt{E} \oplus 0.7\%\ (for H \rightarrow \gamma\gamma\ mass\ with\ 1\%\ resolution@120GeV) |
| → precise mechanics & electronics calibration |

| Linearity: 0.1 %, \(10^{-4}\) around the Z-peak (for W-mass measurement!) |
| → pre-sampler (correction for dead material), layer weighting, electronics calibration |

Time measurement: O(100 ps) for background rejection, bunch crossing, vertex...

Fast shaping to optimize signal/noise ratio:
→ 40 MHz sampling rate (LHC bunch crossing)
→ Digital filtering for signal reconstruction

Minimal coherent pickup noise (<5% of incoherent noise)

Minimal dead time at Level 1 (L1) 75 – 100 kHz trigger rate and storing of signals during the latency of the L1 trigger of up to 2.5\(\mu\)s (100 bunch crossings)
→ realized with switch capacitor array of 144 bunch crossings
Sampling calorimeter
- with Pb absorbers and active LAr gaps (2mm in barrel, 1.2 – 2.7mm in endcap)

Advantages of liquid argon (LAr) as active material
- linear behavior
- stability of the response over time
- radiation tolerance

Advantages of accordion geometry
- it allows a very high \(\eta-\phi\) granularity and longitudinal segmentation (PS, L1, L2, L3)
- it allows for very good hermeticity since HV and signal cables run only at the front and back faces of the detector
- it allows for a very high uniformity in \(\phi\)

Incident electrons create EM showers in Pb \((X_0=0.56\text{cm})\) and LAr gaps \((X_0=14.2\text{cm})\)

secondary \(e^+\) and \(e^-\) create \(e^-\)–ion pairs in LAr \((W=23.3\text{eV})\)

Ionized electrons and ions drift in electric field \((2\text{kV for 2mm gaps in barrel})\) and induce triangular signal \((\approx450\text{ns}e^-\text{drift time})\)

Design resolution:
\[
\frac{(E)}{E} = 10\% \oplus 0.2 \oplus 0.2\%
\]
Homogenous PbWO₄ (PWO) ECAL:

- **very low stochastic term**, excellent energy resolution, but response impacted by radiation (laser correction necessary)
- PbWO₄: 8.3g/cm³, X₀=8.9mm, Rₘ=22mm, Refr. index: 2.3, light yield: 100γ/MeV.
- Readout via Avalanche photodiodes (APD) in the barrel and Vacuum phototriodes (VPT) in the endcaps

**No longitudinal segmentation**

**Coverage:** |η|<3.0, Preshower (ES) 1.65<|η|<2.6

**Design resolution:**

\[
\frac{(E)}{E} = \frac{3\%}{\sqrt{E}} \oplus \frac{0.2}{E} \oplus 0.3\%
\]
**ATLAS**

- Sampling calorimeter (LAr-Pb), 3 longitudinal layers + presampler, 173000 channels), E range MIP – TeV
- High lateral granularity
  - $\Delta\eta=0.0031$, $\Delta\phi=0.025$
- Radiation resistance
- Good energy resolution
- Very stable response in time
  - rms in time $\approx 3 \times 10^{-4}$
- Outside solenoid field (behind the coil) $\rightarrow$ 3 – 6 $X_0$ in front
- Main correction: dead material correction using presampler
- Strength: background rejection (e.g. $\pi^0$), stability, photon vertex measurement (pointing)

**CMS**

- Homogeneous calorimeter (75000 PbWO$_4$ crystals + PS in forward direction), E range MIP – TeV
- High lateral granularity
  - $\Delta\eta=\Delta\phi=0.0175$
- Radiation resistance
- Excellent energy resolution
- Response impacted by radiation
  - after laser correction rms $\approx 2 \times 10^{-3}$
- Inside strong solenoid field $\rightarrow$ only 0.4 – 1.9 $X_0$ in front
- Main correction: Laser correction to compensate impact of radiation
- Strength: little material in front, energy resolution
ATLAS EM CALIBRATION
Cluster size: 3x0.025 ($\eta$) x 7x0.025 ($\phi$)

ATLAS EM Calibration on one slide 😊

LAr cell level

Cluster size: 3x0.025 ($\eta$) x 7x0.025 ($\phi$)
Concept of LAr calorimeter electronics calibration is to inject a well known exponential pulse as close as possible to the point where the ionization pulse is created and read it back with the normal front-end electronics (calibration resistor $R_{\text{cal}}$ known with 0.1% precision) → extract gain and pulse shapes, update DB every month.
The High Pile-Up Challenge – Baseline Correction

- **LAr** pulse-shapes have bi-polar shaping \((\text{CR}-(\text{RC})^2)\) → In infinite bunch trains the out-of-time pile-up would cancel the in-time pile-up in average. For finite bunch trains baseline shifts
  - → Correction implemented, relies on bunch-per-bunch luminosity measurement and exact knowledge of pulse-shapes
- **Precise LAr pulse-shapes from calibration runs** and recently extracted from special collision runs for each layer and \(\eta\) region (averaged over \(\phi\)).
- **BCID dependent baseline correction** compared to random triggers (zero bias data) – excellent performance of correction

Area of typical EM cluster:
\[3 \times 0.025 \times 7 \times 0.025 = 0.013\]
Between 5% and 15% of the particle energy is not reconstructed in the cluster and needs to be corrected for.

Several corrections are applied to the cluster before calibration (e.g. $S$-shape).

Then MVA based calibration (regression based on BDT):
- Target: $E_{\text{true}}/E_{\text{meas}}$
- Inputs: $E_{\text{accr}}, E_0, \eta, \phi$, shower-depth, shower-width (and extra variables for converted photons)
- Done separately for electrons, unconverted photons and converted photons.
Layer corrections needed in data to adjust residual effects not perfectly accounted for by the cell electronic calibration – data/MC comparison

- Material in front of calorimeter and layer response (L1/L2, L0) strongly correlated!
- Intercalibration between L1 and L2 performed with muons
  - Insensitive to the amount of passive material upstream of the EM calorimeter
- L0 (presampler) needs to be done with electrons (S/N!) → have to disentangle material effects from scale difference
  - Using simulations with different material in front of calo
  - Data from unconverted photons and electrons used to measure L0

~ 3 variables – 3 equations (one per particle type)
Data Driven Corrections

- After L1/L2 and L0 correction, EM showers used to measure amount of detector material upstream of calorimeter:
  - $e^\pm \rightarrow$ material up to L1,
  - unconverted $\gamma$ for material between PS(L0) and L1

- In addition: HV corrections and inter-module widening corrections.

Absolute scale calibration from comparison of the reconstructed invariant mass distributions (Z-peak) between data and MC (template method)

$\delta\alpha \sim 3 \times 10^{-4}$ (barrel), $\sim 5 \times 10^{-4}$ (endcap)
Achieved Resolution and Linearity

• Resolution measurement:
  – Assuming correct sampling term $a$ of 10% GeV$^{1/2}$ (validated with $J/\psi$ width)
  – Noise term $b \approx 200 – 300$ MeV per cluster (+ pile-up noise)
  – Template fit of constant term $c$ using $m_{ee}$ invariant mass (Z-peak)
• Linearity measurement with $J/\Psi$, Z-peak (and $E/p$)

$\sigma_{E}/E$ for $e^{\pm}$ from Z-decays: 1.7

- 1.9% for central barrel

$\rightarrow$ linearity $10^{-3}$ for 20-60 GeV
CMS EM Calibration on one slide 😊

Physics objects

Cluster size: 5x0.017 (η) x 5x0.017 (φ) + extension in φ

MVA
For Run-2 use out-of-time pile-up resistant multifit algorithm

- **Pulse shape** is modeled as a sum of one in-time pulse plus up to 9 out-of-time pulses
- **Minimize $\chi^2$ distribution** for best description of the in-time amplitude
- **Pulse shapes** (binned templates) extracted periodically from LHC isolated bunches
- Baseline and electronics noise from calibration runs
Response Monitoring – Radiation Damage

- Sources of response variations under irradiation:
  - crystal transparency (time dependent)
  - VPT conditioning in the endcaps
- Response monitored with a laser system injecting light in every ECAL crystal
- PbWO4 crystals partially recover during periods with no exposure
  - 1 calibration point / channel / 40min
  - corrections injected in (prompt) reconstruction (~48h latency)

1% signal loss in one fill rms = 1.9x10^-3 after corrections
rms = 1.5x10^-3 after corrections

E/p
Several methods used to **equalize the response of each single crystal** to the deposited energy.

### Methodology

<table>
<thead>
<tr>
<th>Method</th>
<th>Time Needed</th>
<th>Run I Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi$-symmetry</td>
<td><strong>few days</strong></td>
<td>1-3% in EB, 3-5% in EE</td>
</tr>
<tr>
<td>$\pi^0/\eta \rightarrow \gamma\gamma$</td>
<td>1 month</td>
<td>0.5% in EB, 3% in EE ($</td>
</tr>
<tr>
<td>Electron $E/p$</td>
<td>20 fb$^{-1}$</td>
<td>0.5% in EB, 2% in EE</td>
</tr>
<tr>
<td>$Z \rightarrow ee$ mass</td>
<td>20 fb$^{-1}$</td>
<td>equalise the scale vs $\eta$ in EE</td>
</tr>
</tbody>
</table>

**Endcap Preshower (ES) calibrated to ~5% accuracy using MIPs**
**Clustering and Corrections**

- **Dynamic clustering** to recover energy radiated upstream of ECAL via Bremsstrahlung or conversions
  - Super-clusters of clusters along $\phi$ (bending direction)
  - Soft conversion legs / brem may be not included in super-clusters
  - In the endcaps, add also pre-shower energy
  - Additional energy from pileup contaminates the shower

- **Algorithmic multivariate corrections** used to maximally exploit the information of the event.
  - Tuned on MC, validated on data.
  - Corrects also for material in front of the calorimeter
  - Relying on excellent agreement data/MC

- **The absolute scale** (as function of $\eta$) is calibrated using the $m_{ee}$ invariant mass (Z-peak)

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High tail due to high-material region $|\eta| > 1$.
Achieved Resolution and Linearity

- Derive electron energy resolution from $Z \rightarrow ee$ peak width
  - **Two categories** of electrons: low- and high-brem electrons
    - low-brem and unconverted photons: $R_9 = E_{3x3}/E_{SC} > 0.94$
    - Unconverted photon resolution similar to low-brem $e^\pm$
  - High-brem electrons 0.5% – 1% worse than low-brem $e^\pm$
- **Linearity** measured with $E/p$

$\sigma_{E}/E$ for $e^\pm$ from $Z$-decays: 1.5 – 2.1% for central barrel

(linearity $10^{-3}$ for 20-60 GeV)
COMPARING ATLAS AND CMS
**Comparison Higgs Mass**

- **Higgs discovery** in 2012 by ATLAS and CMS with basically **equal significance** – for both dominated by $H \rightarrow \gamma\gamma$ channel ($\rightarrow$ ECAL).
- **Higgs mass measurement** is a perfect benchmark measurement to compare the two experiments.

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![Graph showing Higgs mass measurement comparison between ATLAS and CMS](image.png)

- **ATLAS** and CMS
- **LHC Run 1**

- **ATLAS** $H \rightarrow \gamma\gamma$
- **CMS** $H \rightarrow \gamma\gamma$
- **ATLAS** $H \rightarrow ZZ \rightarrow 4l$
- **CMS** $H \rightarrow ZZ \rightarrow 4l$
- **ATLAS + CMS** $\gamma\gamma$
- **ATLAS + CMS** $4l$
- **ATLAS + CMS** $\gamma\gamma + 4l$

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Stat.</th>
<th>Syst.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATLAS</strong> $H \rightarrow \gamma\gamma$</td>
<td>126.02 ± 0.51 (± 0.43 ± 0.27) GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CMS</strong> $H \rightarrow \gamma\gamma$</td>
<td>124.70 ± 0.34 (± 0.31 ± 0.15) GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ATLAS</strong> $H \rightarrow ZZ \rightarrow 4l$</td>
<td>124.51 ± 0.52 (± 0.52 ± 0.04) GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CMS</strong> $H \rightarrow ZZ \rightarrow 4l$</td>
<td>125.59 ± 0.45 (± 0.42 ± 0.17) GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ATLAS + CMS</strong> $\gamma\gamma$</td>
<td>125.07 ± 0.29 (± 0.25 ± 0.14) GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ATLAS + CMS</strong> $4l$</td>
<td>125.15 ± 0.40 (± 0.37 ± 0.15) GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ATLAS + CMS</strong> $\gamma\gamma + 4l$</td>
<td>125.09 ± 0.24 (± 0.21 ± 0.11) GeV</td>
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</tr>
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</table>
**Systematic uncertainties** in both experiments dominated by energy and momentum scale terms.

- ATLAS has larger uncertainties for material, longitudinal response and lateral shower shape (data/MC agreement!)
  - ATLAS in general more conservative, but some differences can be explained
  - Material uncertainty: Due to more material in front of calorimeter 2x higher sensitivity on ID material

### Uncertainty in ATLAS results [GeV]:

<table>
<thead>
<tr>
<th>Source</th>
<th>$H \rightarrow \gamma\gamma$</th>
<th>$H \rightarrow ZZ \rightarrow 4\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material in front of ECAL</td>
<td>0.15 (0.13)</td>
<td>0.07 (0.07)</td>
</tr>
<tr>
<td>Material uncertainty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calorimetric material</td>
<td></td>
<td></td>
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<td>Integrated luminosity</td>
<td>0.01 (&lt;0.01)</td>
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</tr>
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<td>Additional experimental systematic uncertainties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Theory uncertainties</td>
<td>0.02 (&lt;0.01)</td>
<td>0.01 (&lt;0.01)</td>
</tr>
<tr>
<td>Systematic uncertainty (sum in quadrature)</td>
<td>0.27 (0.27)</td>
<td>0.15 (0.17)</td>
</tr>
<tr>
<td>Systematic uncertainty (nominal)</td>
<td>0.27 (0.27)</td>
<td>0.15 (0.17)</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>0.48 (0.45)</td>
<td>0.31 (0.32)</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>0.51 (0.52)</td>
<td>0.45 (0.59)</td>
</tr>
<tr>
<td>Analysis weights</td>
<td>19% (22%)</td>
<td>40% (46%)</td>
</tr>
</tbody>
</table>

### Uncertainty in CMS results [GeV]:

<table>
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<tr>
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<th>$H \rightarrow \gamma\gamma$</th>
<th>$H \rightarrow ZZ \rightarrow 4\ell$</th>
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<tr>
<td>Material in front of ECAL</td>
<td>0.12 (0.13)</td>
<td>0.02 (0.01)</td>
</tr>
<tr>
<td>Material uncertainty</td>
<td></td>
<td></td>
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<tr>
<td>Statistical uncertainty</td>
<td>0.43 (0.45)</td>
<td>0.42 (0.57)</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>0.51 (0.52)</td>
<td>0.45 (0.59)</td>
</tr>
<tr>
<td>Analysis weights</td>
<td>18% (14%)</td>
<td>23% (17%)</td>
</tr>
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**H→γγ Mass-Peak Resolution**

- **Statistical uncertainty bit better in CMS**
  - 0.43% ATLAS
  - 0.31% CMS
- Inclusive mass peak resolution slightly better in CMS, but higher tails

Statistical uncertainty driven by best photon categories – slight advantage of CMS → but ECAL resolution almost compensated by photon pointing in ATLAS

\( \sigma_{\text{eff}} = 1.2 \text{GeV} \)

\( \sigma_{\text{eff}} = 1.18 \text{GeV} \)
ATLAS published W-mass measurement in 2017
  – arXiv:1701.07240
    • \( m_W = 80370 \pm 7 \text{(stat.)} \pm 11 \text{(exp. syst.)} \pm 14 \text{(mod. syst.)} \text{MeV} = 80370 \pm 19 \text{MeV} \)
  – Measurement in \( e^\pm \) and \( \mu^\pm \) channel (equally contributing to result)

CMS: No measurement yet, working on measurement with \( \mu^\pm \)-channel only

→ Stability of the ATLAS EM calorimeter clearly an advantage. Could use full statistics to reduce systematic errors.
UPGRADES
The Challenges for HL-LHC

- $L = 5 \times 10^{34} \text{cm}^{-2}s^{-1}$ → in average $\langle \mu \rangle \approx 140$ pp collisions per bunch crossing.
  - → Pile-up mitigation by particle-flow techniques and timing information
- Radiation tolerance (e.g. $|\eta|=3$: $\sim 1.5 \text{MGy}$, $\sim 10^{16} \text{n/cm}^2$)
- New trigger concepts (higher hardware trigger rate, 750kHz in CMS, 1-(4)MHz in ATLAS), longer latency (10-12µs)

→ New trackers up to $|\eta| < 4$ and with higher granularity.

→ Changes in calorimeter trigger- and read-out electronics
  - Cooling of photodetectors in CMS barrel, new photodetectors for end-caps, new read-out electronics
  - Finer granularity HW trigger for ATLAS (Phase I) and CMS (Phase II), new read-out electronics, continuous read-out to reduce out-of-time pile-up contribution

→ New calorimeters / timing detectors:
  - HGCal in CMS
    - See talk by J.B. Sauvan on Tuesday
  - HGTD in ATLAS
    - See talk by D. Lacour and N. Makovec
→ Both exploit high granularity and timing information to suppress pile-up

See also talks by J.B Sauvan, D. Lacour, G. Mazza, B. Vachon, A. Lobanov, G. Aad, T. Quast, E. Pree, A. Massironi, N. Makovec this week
**CMS HGCal**

**Active Elements:**
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- “Cassettes”: multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H

**Key Parameters:**
- EC covers $1.5 < \eta < 3.0$
- Full system maintained at $-30^\circ$C
- ~600m$^2$ of silicon sensors
- ~500m$^2$ of scintillators
- 6M si channels, 0.5 or 1 cm$^2$ cell size
- ~22000 si modules
- Power at end of HL-LHC: ~60 kW per endcap

**Electromagnetic calorimeter (CE-E):** Si, Cu & CuW & Pb absorbers, 28 layers, 25 $X_0$ & ~1.3$\lambda$

**Hadronic calorimeter (CE-H):** Si & scintillator, steel absorbers, 24 layers, ~8.5$\lambda$

**Very challenging radiation environment:**
- e.g. at $|\eta| = 3$ at shower maximum: 1.5MGy, $10^{16}$n/cm$^2$.
- Extensive R&D in the past 20 years for Trackers and Pixels have led to development of Si-sensors which can sustain the high radiation levels

**High granularity and 3D imaging** help mitigate pileup effects

**Timing resolution of ~20ps for large enough signals** to associate showers with particular vertex

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**Calorimetry for the High Energy Frontier 2017 (Lyon) — M. Aleksa (CERN)**

October 2, 2017

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**Simulations**
• 6M Si channels (!)
• Aim to keep constant term below 1%
  – inter-calibration precision of <3% necessary to keep contribution to constant term below 0.5%
• Calibration using MIPs
• Simulation shows that 3% precision needs 1.5M events if noise < 0.3MIP signals
  – With MIP tracking algorithm can fit MIP peak even up to noise levels of 0.6MIPs (worst case sensor pad after 3ab⁻¹) – need higher statistics (up to factor 100)
  – → Achievable only with full Level-1 sample by histogramming in the HLT
• Independent monitoring and linearization using charge injection system.
• Depletion depth of all cells will be characterized by voltage/capacitance measurements with a precision of better than 1%.
• **Testbeam measurements** at CERN and FNAL confirm calibration strategy

• Landau convoluted with Gaussian fit to distribution per channel after tracking procedure (remove noise hits)

At least one calibration constant per ASIC necessary
MITIGATING PILE-UP WITH TIMING INFORMATION
### Timing Information in ATLAS: HGTD

- **Space between tracker and endcap calorimeter**
- **75 mm for Si sensors** (1.3 x 1.3 mm² LGADs), rad hard, <10% occupancy and + 50 mm moderator to protect ITk
- **Pile-up mitigation, track-to-vertex association, b-tagging, lepton isolation, jet/Etmiss**
- **Luminosity measurement**
- **Minbias trigger**
- **Goal:** Resolution of **30ps for MIP signals**

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**For comparison:**
**Legacy ATLAS LAr EM Calorimeter:**
Measured ~100ps timing resolution for cell energies > 20 GeV
Intrinsic limit due to shower fluctuations should be lower

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| Pseudorapidity coverage | $2.4 < |\eta| < 4.2$ |
|-------------------------|---------------------|
| Position in $z$ | $3420 < z < 3545$ mm including 50 mm of moderator |
| Radial extension (active area) | $3435 < z < 3485$ mm |
| Number of layers | 110–1100 mm (120 mm–640 mm) |
| Number of channels | 4 per side |
| Sensor size | 30 ps / mip (≤ 60 ps / mip / layer) |
| Number of Si modules (2 x 4 cm² each) | $1.3 \times 1.3$ mm² |
| Number of ASICs (2 x 2 cm² each) | 6.3M |
| Total active area (Si sensors) | 13952 |
| | 27904 |
| | 11.16 m² |
Timing Information in CMS: ECAL + HGCAL

- **ECAL:**
  - Timing precision in legacy ECAL ~ 140ps
  - **No pointing information from ECAL!** CMS relies on hadronic recoil balancing and conversion pointing to locate primary vertex in $H \rightarrow \gamma \gamma$ events
  - Becomes increasingly **difficult to locate the primary vertex at very high pileup:** Vertex selection efficiency drops from ~80% in current conditions to ~30% at 200 PU
  - **Shower timing:** Fundamental limit (due to crystal shower fluctuations and APD jitter) established in testbeam studies to be ~30ps for $E > ~30$ GeV (showers not MIPs)!
  - Depending on VFE option ~**40ps achieved for 50GeV**

- **HGCAL:**
  - Hybrid read-out: charge and ToT for larger signals (~50ps timing resolution each)
  - Testbeam measurements: Timing layer behind 6 $X_0$ tungsten absorber (1 mm distance). Time calculated as energy-weighted mean of all timing cells in the shower. $\sigma_t$ ~ 15ps measured, shower timing, not MIP timing!
  - **In addition:** Possible extension for MIP timing
    - Thin LYSO+SiPM layer between tracker and ECAL barrel calorimeter (reached ~30ps res. in TB)
    - Dedicated layer in endcap

30ps necessary for ~1cm vertex precision
Conclusions

• ATLAS and CMS chose two very different techniques for their EM calorimeters
• Nevertheless very similar performance observed
• State-of-the-art EM calorimeters in HEP environment have to rely on precise calibration and a multitude of corrections
  – Mix of MC-based calibration and data driven corrections
• Design parameters could be reached
• Next challenge (HL-LHC) will be pile-up
• High granularity and timing information will be used to mitigate pile-up impact
• Looking forward to many interesting physics results by LHC!
References:

- **ATLAS EM Calorimeter & HGTD**
  - W-mass pre-print: arXiv:1701.07240
  - LAr public plots:
    - [https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsLAr](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsLAr)
  - E-gamma public plots:
    - [https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ElectronGammaPublicCollisionResults#Public_PLOTS](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ElectronGammaPublicCollisionResults#Public_PLOTS)

- **CMS EM Calorimeter**
  - ECAL paper: CMS-PAS EGM-11-001
  - ECAL plots
    - [https://twiki.cern.ch/twiki/bin/view/CMSPublic/EcalDPGResults](https://twiki.cern.ch/twiki/bin/view/CMSPublic/EcalDPGResults)
  - Talk by E. Di Marco (Higgs Coupling 2016)
    - [https://indico.cern.ch/event/477407/contributions/2305075/attachments/1368970/2075215/hc16-edm.pdf](https://indico.cern.ch/event/477407/contributions/2305075/attachments/1368970/2075215/hc16-edm.pdf)
  - Talk by K. Chia Ming (TIPP 2017)
    - [http://indico.ihep.ac.cn/event/6387/session/50/contribution/131/material/slides/0.pdf](http://indico.ihep.ac.cn/event/6387/session/50/contribution/131/material/slides/0.pdf)

- **HGCal**
  - CMS Phase II Upgrade Technical Proposal: CERN-LHCC-2015-10
  - Talk by P. Block (ECFA 2016)
    - [https://indico.cern.ch/event/524795/contributions/2237279/attachments/1348498/2034530/Bloch_ECFA.pdf](https://indico.cern.ch/event/524795/contributions/2237279/attachments/1348498/2034530/Bloch_ECFA.pdf)
  - Private communications D. Barney and C. Seez
  - Talks at 2016 ECFA WS
    - [https://indico.cern.ch/event/524795/timetable/](https://indico.cern.ch/event/524795/timetable/)

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