First results from CMS SiPM-based hadronic endcap calorimeter

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Outline

• Overview and context
• Advantages deriving from the Phase1 HE upgrade
• SiPMs operational experience
• A look forward
Sampling scintillating calorimeter
Endcap coverage $1.3<|\eta|<3$
Brass absorber (~8 cm each layer)
4 mm SCSN81, 9 mm Bicron BC408 (for layer 0)
19 longitudinal layers
Light emission from tiles: $\lambda=410-425$ nm
Signal collected with wavelength shifting fibers ($\lambda=490$ nm)
Laser system to monitor scintillator response
The HE Phase1 upgrade: readout

- New photo-detector: HPDs $\rightarrow$ SiPMs
  - $x2.5$ higher PDE
  - $x400$ higher response
  - Reduced noise

- New front-end electronics: QIE8 $\rightarrow$ QIE11
  - 8-bit ADC with embedded TDC
  - Internal charge injection for in situ monitoring, programmable gain

- uTCA back-end
  - Supports larger data volumes, new trigger primitives
The HE Phase1 upgrade: layout

- In 2017 a **pilot system of 20°** in phi (**HEP17**) allowed deep understanding of physics performance, calibration, monitoring with no harm to data quality.

- Signal from depths was summed at software level to mimic the original layout.

**2016**
- Original configuration
- 2664 HPD channels
- Up to 3 depths

**2017**
- 1 wedge upgraded: **HEP17**
- **20°** of endcap
- 184 SiPMs channels
- Up to 7 depths

**2018**
- Full HE upgraded
- 184*36 SiPMs channels
- Up to 7 depths
The HE Phase1 upgrade: commissioning

- 36 readout boxes upgraded
  - 6624 channels
  - System burned in for 8 detector-months in 2016-17 prior installation

- Calibration with $^{60}$Co source
  - $^{60}$Co wire-source inserted into tubes embedded in HE megatiles
  - Verify end-to-end detector functioning and tile-by-tile mapping
  - Provides startup calibration
Immediate benefits deriving from the upgrade
Restore the symmetry of the response

• ... vs Time
  ○ Unpredictable degradation of the HPDs
  ○ Large spread between channels
  ○ High $\eta$ region is the most affected
  ○ SiPMs are behaving as the 'best HPD'

• ... vs Phi
  ○ RAW detector response is much more uniform

• Moreover the scintillator damage due to radiation is mitigated via 2.5x higher photon detection efficiency
A posteriori analysis of HPDs from HEP17

- Scan of a damaged HPD photocathodes using laser light
  - the response is reduced in a highly non-uniform way
  - localized damage spots corresponding to position of fibres from tiles
- Real structural damage: hard to model and predict

New

From HEP17

From high eta
Eliminate catastrophic noise

- Sources of catastrophic noise are eliminated
  - No noise associated to the readout box
  - No noise associated to the SiPMs

- Analysis of the hits in HE in a cosmosics run
  - Muon deposits are visible

- CMS Preliminary 2017

- 1 HPD = 18 channels
- 1 RBX = 4 HPD

- Events

- Number of rechits per RBX (E > 1.5 GeV)

- Muons

- HEP17 (SiPM)

- Other HE (HPD)
Operational experience and calibration
HEP17 experience

• All 184 channels corresponding to HEP17 were functional during the whole 2017 data taking
  ○ Smooth operations, negligible downtime related to the upgraded detector

• The HEP17 pilot system allowed to:
  ○ Measure the pulse shape for scintillator+fibre+SiPM+QIE11 from data
  ○ Project the reconstruction performance to the full scale HE
  ○ Fine-tune the simulation of the upgraded detector
  ○ Perform noise measurements
  ○ Gain experience in commissioning the trigger

More in Jay's talk
SiPMs dark current measurement

- SiPMs dark current has been monitored during data taking
  - Slope is proportional to the SiPM area
  - Deviation from linearity are due to recovery time in absence of beam and variation in instantaneous luminosity

- 110 MeV of noise are expected at the end of Run3 (500/fb, projecting linearly)
  - To further reduce the noise one handle is to operate the SiPMs at 0°C
SiPMs gain stability

- The gain of each channel is measured individually
  - Single fit function to the multi-peak charge spectrum in pedestal and low intensity LED runs

\[
f(x) = \sum_{i=0}^{N_{\text{peaks}}-1} A_i e^{-\frac{1}{2} \left( \frac{x-\mu_i}{\sigma_i} \right)^2}
\]

\[\mu_i = \mu_0 + iG\]

- The gain was found to be stable during the whole 2017 data taking at the 1% level
The HCAL calibration makes use of:
- $E/p$ from isolated tracks for the energy scale measurement vs pseudorapidity
- phi-symmetry for equalizing the response along phi

From 2018 the depth inter-calibration is also performed
- MIP deposits from muons are used to correct for depth dependent effects like ageing
- The improved sensitivity to MIPs (~5 pe/MIP/layer) is also exploited to extend the scale calibration beyond the tracker coverage
A look forward
HE in Run3

- Detector response assumed to follow an exponential loss for periods of constant dose rate:
  \[ L(d) = L_0 e^{-d/D} \]
  \[ D \text{ [Mrad]} = \text{dose constant} \]
  \[ d \text{ [Mrad]} = \text{total dose} \]

- Remaining light output in the front layers at high eta of HE after 500/fb:
  - As low as 5% (ieta 29) and 20% (ieta 28)
  - Light loss is recovered/exceeded by the higher PDE of SiPMs w.r.t. HPDs

- HE will survive to end of Run 3 with performance ~unaffected

\[ HE \text{ light yield} \times PDE \text{ relative to beginning of Run1} \]
In conclusion: will do the same to HB :) 

- Extremely positive experience from the operation of the upgraded HE in 2017 and 2018

- A look forward: the response loss (50-70%) of the front layers of the HCAL Barrel after 4500 fb\(^{-1}\) will be largely recovered by the higher SiPM photodetection efficiency
  - No impact on performance
Additional slides
Being explored

• Exploit the increased longitudinal segmentation to acquire information on the shower development:
  ○ Improve the pile-up suppression and improve the jet resolution

• Exploit the improved sensitivity to MIPs to develop a MIP/muon trigger beyond tracking acceptance
HE $^{60}$Co source calibration

Co60 outside tile and on tile
Response vs phi from HPDs in 2016

- Response for towers at ieta=28 at the end of the 2016 data taking, relative to the response at the beginning of the year from in-situ calibration. The response measured with collision events is compared to the one extracted from laser data. The response is plotted as a function of the azimuthal variable iphi.
What if we didn't upgrade HE?

- HE response loss will continue to progress
  - With largest contribution from HPD damage
  - Several channels at high eta will go below 10-20% of the new detector response

average signal loss in HE since 2012 (including 45 fb\(^{-1}\) of 2017 data)
HE readout module

- 1 readout module = 48 channels = 5° slice in φ
## SiPMs Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HE @ dVb=3V</th>
<th>HE @ dVb=1.7V</th>
</tr>
</thead>
<tbody>
<tr>
<td>(MIP S/N) / (MIP S/N HE dVb=3V)</td>
<td>1</td>
<td>~1</td>
</tr>
<tr>
<td>Non-linearity @ 300 GeV</td>
<td>21%</td>
<td>13%</td>
</tr>
<tr>
<td>Lost S/N for I\text{dark} $\rightarrow$ $\sim$I\text{dark}/4</td>
<td>~0%</td>
<td></td>
</tr>
<tr>
<td>Dark current [5C, 3.8/ab]</td>
<td>400μA</td>
<td>120μA</td>
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<tr>
<td>PDE</td>
<td>25%</td>
<td>17%</td>
</tr>
<tr>
<td>Power [mW, 5C, 3.8/ab]</td>
<td>27</td>
<td>8</td>
</tr>
</tbody>
</table>
Calibration of the SiPMs

Single fit function for the entire spectrum down to three orders of magnitude drop of the peak.

\[ f(x) = \sum_{i=0}^{N_{\text{peaks}}-1} A_i e^{-\frac{(x-\mu_i)^2}{2\sigma_i^2}} \]

\[ \mu_i = \mu_0 + iG \]

- \( A_i \): amplitude of the \( i \)th peak
- \( \sigma_i \): width of the \( i \)th peak
- \( \mu_i \): mean of the \( i \)th peak
- \( G \): gain

SiPM gain is a direct parameter of the fit.

Measured SiPM gain when bias voltage for all SiPMs were set for:

- a nominal gain of 50 fC
- a nominal gain of 40 fC

Note: Gains have not been leveled in this plot.
Dose-Rate plots from HEP17

- Dose constant (Mrad) vs. dose rate (krad/hr). The data points show the values of dose constants derived from the scintillator signal loss in the HE sector read out by SiPMs using 48.3 fb$^{-1}$ delivered to CMS in 2017. Red points correspond to layer 1 (L1) scintillators, and blue points correspond to layer 7 (L7) scintillators. The black line represents the best fit of the 2017 data using a parametrization $D = a \times R_b$, where $D$ is the dose donstant (Mrad) and $R$ is the dose rate (krad/hr).
Fractional jet $p_T$ resolution vs eta

Improvement with SiPMs relative to HPDs:
- 53% by 500 fb$^{-1}$
- 19% by 150/fb