Hadron calorimetry at the FCC-hh experiment

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01.06.2017
FCC Week, Berlin

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FCC-hh Hadron Calorimeter – physics requirements

- Jet rapidity of WBF
  \[ \rightarrow \eta \text{ coverage up to 6} \]

- Highly collimated final states (boosted decay products of heavy objects)
  \[ \rightarrow \text{High granularity} \] to resolve jet sub-structure and background rejection (e.g. pile-up jets, \( \pi^0 \))

- High \( p_T \) jets at \( \eta = 0 \)
  \[ \rightarrow \text{containment} \geq 11 \lambda \]
FCC-hh Hadronic Calorimeter – Scintillator/Steel I

1. Current reference for FCC-hh

ATLAS type Scintillator tile - Steel in Barrel and Extended Barrel

- kept Steel/Sci ratio 4.7
- 4 times higher granularity $\Delta \phi \times \Delta \eta = 0.025 \times 0.025$
- 10 instead of 3 longitudinal layers
- Steel → stainless Steel absorber (Calos in magnetic field)
- SiPM readout → faster, less noise, less space

$\sim 11 \lambda$ FCC-hh HCAL, pion resolution:

$$\sigma_E / E = 43\% / \sqrt{E} \pm 2.7\%$$
FCC-hh Hadronic Calorimeter – mechanics

128 modules in $2\phi$ feasible

mechanical structure fits within foreseen space

support outer radius

$85 \times 85$ mm in $dz = 9(2 \times 3)$ m space within mechanical support for SiPMs and electronics
FCC-hh full detector simulations
of the Sci-tile/stainless Steel HCAL

HCAL B
10 longitudinal layers
  2 \times 10 \text{ cm}
  + 4 \times 15 \text{ cm}
  + 4 \times 25 \text{ cm}
  \Delta \eta \times \Delta \Phi
  0.025 \times 0.025
HCAL B performance for $\text{e}^-$ and $\pi^-$

10,000 events per energy,
FTFP_BERT physics list,
$\eta = 0.36 \rightarrow 9.3 \# \lambda$

\[
e/h = \frac{e/h}{1 - \left(1 - \left(\frac{E_{\text{beam}}}{E_0}\right)^{1-k}\right) (1 - e/h)}
\]

- $E_0$, $k$ energy threshold/ multiplicity of $\pi^0$ production
- increasing EM fraction with increasing energy
How can we achieve compensation?

1. Increase response to neutrons by increased fraction of hydrogen in Scintillator

2. Suppression of EM response by higher Z absorber
   \[ \lambda_{\text{eff}} \text{ of HCAL Barrel increases to 20.87 from 20.59 cm (} \eta = 0.36) \]

Idea: replace spacers/masters

- Steel:Sci (4.7:1)
- Steel:Pb:Sci (3.3:1.3:1)
- Pb:Sci (4.7:1)

Expected compensation

- Fe:Sci \( \approx 20:1 \)
- Pb:Sci \( \approx 4-5:1 \)
Material budget of the HCAL B + EB

Steel:Pb:Sci (3.3:1.3:1)
$X_0$ increases by $\sim 50\%$, minor decrease in $\#\lambda$

Pb:Sci (4.7:1)
$X_0$ increases by $\sim 150\%$, still little change in $\#\lambda$

$\rightarrow$ first hints for Pb:Sci (4.7:1) to cause too much multiple scattering for muons
HCAL B performance with Pb spacers for $\text{e}^-$ and $\pi^-$

10,000 events per energy, FTFP_BERT physics list, $\eta = 0.36 \rightarrow 9.1 \lambda$

\[
E_{\text{reco}} = \sum_{i=1}^{\text{hits}} E_i / a
\]  \hspace{1cm} (2)

- $a_{EM,\text{hadron}} = 3.2\%$, $2.7\%$
- $e/h = 1.1$
- constant term decreased from 3.3 to 2.5\%

$\rightarrow$ need test performance in combined system

Arguments pro Pb

- Pb structures constructible!
- higher Z material not an issue for timing (50 ns in SPACAL)
- steel structure not needed as return yoke
FCC-hh Hadronic Calorimeter – Scintillator/Steel II

2. High Granularity (HGCAL) option

- Phase II upgrade of CMS Endcaps
- 3 × 3 cm² Sci tiles
- integrated SiPM readout
- active prototyping within CALICE collaboration

Plans for FCC-hh:

- combined with Silicon - Lead ECAL
- granularity used for pile-up rejection
- radiation hardness to be tested

→ Sergej will show jet reconstruction using this High Granularity HCAL
FCC-hh full detector simulations

**ECAL B, EC**
- LAr/Pb
- 3(-5.6)mm/2mm
- 8, 6 layers
- $\Delta \eta \times \Delta \phi$
- $0.01 \times 0.01$

**HCAL EC**
- LAr/Cu
- 3mm/2cm
- 6 layers
- $\Delta \eta \times \Delta \phi$
- $0.025 \times 0.025$

**HCAL B, EB**
- Sci-tile/stainless Steel
- 1/4.7
- 10, 8 layers
- $\Delta \eta \times \Delta \phi$
- $0.025 \times 0.025$
**Material budget of FCC-hh full B+EB+EC**

- **ECAL thickness**: $30 \#X_0$
- **E+HCAL thickness**: $115 - 150 - 300 \#X_0$
  
  $\rightarrow$ needs study of muons
- **E+HCAL thickness**: $\sim 11 \#\lambda$
  
  $- $ for all Pb options
- **approx. 1.5 $\#X_0$ in front of ECal**
- **good $\eta$ coverage, dip in $\#\lambda$ at $\eta = 1.7$**
  
  requires optimisation (longer HCAL EB?)

![Graph 1](image1)

![Graph 2](image2)

![Graph 3](image3)
EM showers are contained in ECAL (30 $\#X_0$)

Not included in the simulation yet:

- electronics noise
- pile-up noise
E+HCal Resolution and Linearity

10,000 $\pi^-$ events per energy, FTFP_BERT, $\eta = 0.36 \rightarrow 11 \# \lambda$

- Degraded resolution compared to HCal only: impact different sampling, EM scale ($e/h \neq 1$)
- 0.25 $\# \lambda / 1.5 \# X_0$ passive material between E and HCal
- Comparable to ATLAS results: $
\alpha = 52.1 \pm 5.5\%$, $\beta = 1.9 \pm 0.3\%$
- Pb spacers no effect on resolution, but linearity improves

Next steps:
1. Correction for lost energy needed
2. Clustering algorithm for jet reconstruction
Summary & Outlook

FCC-hh hadron calorimeters have to
- survive harsh radiation environment $\sim 5 \times 10^{14} \text{ neq}$
- perform precise jet reconstruction of boosted objects

First (reference) calorimeter system tested in simulations
- containment of 10 TeV hadron showers ensured
- combined hadron reconstruction need further corrections

Next steps
- implementation of other calorimeter options in FCCSW
- tests including pile-up
- jet reconstruction with particle flow algorithms
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Thank You!
Backup!
FCC-hh detector
baseline FCC week Berlin May 2017
total length $\sim 47$ m, height $\sim 18$ m

<table>
<thead>
<tr>
<th>NAME</th>
<th>Technology</th>
<th>$\eta$ coverage</th>
<th># long.layers</th>
<th>$\Delta\eta \times \Delta\varphi$</th>
<th># channels ($\times 10^8$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECAL B</td>
<td>LAr / Pb</td>
<td>&lt; 1.7</td>
<td>8</td>
<td>0.01 x 0.012</td>
<td>1.3</td>
</tr>
<tr>
<td>ECAL EC</td>
<td>LAr / Pb</td>
<td>1.5 – 2.5</td>
<td>6</td>
<td>0.01 x 0.012</td>
<td>0.6</td>
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<tr>
<td>HCAL EC</td>
<td>LAr / Cu</td>
<td>1.7 – 2.5</td>
<td>6</td>
<td>0.025 x 0.025</td>
<td>0.1</td>
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<tr>
<td>EFCAL</td>
<td>LAr / Pb</td>
<td>2.3 – 6.0</td>
<td>6</td>
<td>0.05 x 0.05</td>
<td>0.1</td>
</tr>
<tr>
<td>HFCAL</td>
<td>LAr / Cu</td>
<td>2.3 – 6.0</td>
<td>6</td>
<td>0.05 x 0.05</td>
<td>0.1</td>
</tr>
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