The Performance & potential of an ATLAS-like HCAL Tile with si-PMs for FCC-hh Detector

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On behalf of the FCC-hh Detector study group (convener: W. Riegler)


CALOR 2016 May 2016
Outline

- The FCC-hh collider and detector concept
- The potential of an ATLAS-like Tile hadronic calorimeter with si-PMs readout for the barrel HCAL
- HCAL requirements at 100TeV
- Summary and next steps
**FCC-hh collider**

- FCC-hh at CERN (CERN strong support)
- \( \sqrt{S} = 100 \text{ TeV} \) (x 7 LHC)
- 100 Km tunnel
- \( e^+e^- \) (FCC-ee) as intermediate step
- \( p-e \) (FCC-he) option
- Similar project in China (SPPC)

### FCC-hh

<table>
<thead>
<tr>
<th></th>
<th>Phase 1 (10 yrs)</th>
<th>Phase 2 (15 yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.M. Energy (TeV)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Luminosity (cm(^{-2})s(^{-1}))</td>
<td>5\times10(^{34})</td>
<td>30\times10(^{34})</td>
</tr>
<tr>
<td>Int. Luminosity (ab(^{-1})) *</td>
<td>2.5</td>
<td>15</td>
</tr>
<tr>
<td>Bunch spacing (ns)</td>
<td>25</td>
<td>25 (5)</td>
</tr>
<tr>
<td>Pile-up (per BX)</td>
<td>170</td>
<td>1024 (204)</td>
</tr>
</tbody>
</table>

* 5yrs cycles (3.5 years operation + 1.5 years shutdown)
• HL-LHC operation until ~2035
• Now developing FCC collider and detector concepts to be ready after HL-LHC (~2036)
FCC-hh Detector

Barrel HCAL: $\sigma_E/E \sim 50%/\sqrt{E} \pm 3\%$ better granularity than ATLAS/CMS

Barrel ECAL: $\sigma_E/E \sim 10%/\sqrt{E} \pm 1\%$ better granularity than ATLAS/CMS

Muon Chambers: inside twin solenoid

Tracker: $\sigma_{pt}/pt \sim 10\%$ at 10 TeV (2.5m radius)

Magnets: Twin Solenoid 6T, 12m bore radius

Magnets: fwd dipoles 10Tm

~ 62m
The role of HCAL & requirements at FCC-hh

• **Expect large energy of decay products**
  - Large jet $p_T$
  - Missing ET signatures
  - High-mass, long-lived particles
  - Tau decays
  - Veto on photons / electrons / jets

• **Requirements for HCAL**
  - Containment
  - Resolution
  - Segmentation
  - Dynamic range
  - $\eta$ Coverage
  - .....
Effect of HCAL energy resolution on dijet resonances

Jet resolution $\sim$2-3% needed for multi TeV dijet resonances
- Extend $Z'\rightarrow jj$ discovery potential by 10 TeV between $\sigma_m=10\%$ to 1%
- Constant term will dominate at TeV energies ($\sigma/E=a/\sqrt{E} \oplus c$)
- Good shower containment is mandatory!
Effect of HCAL transversal segmentation on jet sub-structure

S. Chekanov

- Improve $\sigma_m$ of sub-jettiness variables compared to $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ for high $p_T$ jets by:
  - 80% for $\Delta \eta \times \Delta \phi = 0.05 \times 0.05$
  - 120% for $\Delta \eta \times \Delta \phi = 0.025 \times 0.025$

Need at least 2-4 times better granularity than ATLAS/CMS $\Delta \eta \times \Delta \phi = 0.1 \times 0.1 \rightarrow 0.025 \times 0.025$
η coverage needs for calorimetry and tracking

- Coverage up to η~6 for vector boson fusion (VBF) production and WW scattering physics.

H production in gluon gluon fusion (ggF)
The potential of an ATLAS-like Tile hadronic calorimeter with si-PMs readout for the FCC-hh barrel HCAL
ATLAS Tile Calorimeter ($|\eta|<1.7$)

- Scint. Tiles; fibres parallel to incoming particles at $\eta=0$
  - Steel/Tiles: $= 4.7 : 1$ (\(\lambda = 20.7\) cm)
  - \~620k fibres; \~400k Tiles; \~10k channels
    - optics granularity 50 times better than readout!
  - 7.7 \(\lambda\) at $|\eta|=0$; (9.7 \(\lambda\) with the ECAL)
  - $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
  - 3 longitudinal layers (11 were possible...)
  - $e/h = 1.33$

Pion resolution (test beam):
- $\sigma_E/E \sim 52%/\sqrt{E} \oplus 5.7\%$ (7.9 \(\lambda\))
- $\sigma_E/E \sim 45%/\sqrt{E} \oplus 2\%$ (9.2 \(\lambda\))

Target at ATLAS (with EMCAL):
- Jet $\sigma_E/E \sim 50-60%/\sqrt{E} \oplus 3\%$
- Containment $\sim 98\%$ TeV hadrons, jets
ATLAS TileCal optics/granularity

- Minimal changes in optics/mechanics to exploit full granularity at FCC-hh

- ATLAS reading out all tiles
- $\Delta \eta$: 3mm tiles every 9-18mm in Z
  - $\Delta \eta$ (optics) $\sim 0.1/(50\text{-}100)$
- $\Delta R$: 11 tiles and 8 fibres in R
  - 8-11 layers with $1\lambda < \Delta R < 0.5\lambda$
- $\Delta \Phi$: 20 cm tiles
  - $\Delta \phi = 0.1$ (dual fibre readout)

Fibres start at different R and go radially out =>
- No $\phi$ cracks
- R segmentation
- PMTS at outer Radius
Si-PMs (CMS upgrades, ILC, CLIC,...)  
P. De Bararo; P. Rumerio; A. Heering, T. Tabarelli

8 ch Array package w/ 4 fiber/ch readout

18 ch Array package for single fiber readout

Advantages for FCC-hh:
• < space at $R_{\text{out}}$ (no fibre bundles needed)
• insensitive to B field
• Can read each fibre
• Faster response
• Radiation levels ok at outer radius

18 diodes per Array

Diode spacing of 1.4 mm

Fibre bundles in ATLAS Tilecal at $R_{\text{out}}$

$R_{\text{out}} \sim 30\text{cm} ($$\sim 1.5 \lambda$)
R&D needed vs. ATLAS

- Stainless Steel (non magnetic for solenoid), faster hadronic showers, less $\mu$ tails then Wi, Pb,...

- Redesign outer support:
  - Reduce thickness (ATLAS $\sim$30 cm; 1.5$\lambda$)
  - Optimize electronics location/space (no need to shield Si-PMT)
  - Optimize fibres to Si-PMTs coupling

- Improve $\phi$ granularity to $\Delta \phi = 0.025$
  - $\sim$ 120 modules in $\phi$
  - half trapezoidal tiles with single WLS fibre readout

- Increase HCAL to 10$\lambda$ (ECAL+HCAL = 12$\lambda$)

- Cesium calibration already sees each Tile ($\sim$ 20km pipes in ATLAS, 0.3% precision).
Ongoing mechanics studies

- 120 modules in $\phi$,
  ~2 times better than ATLAS
- Shorter outer mechanics supports
- Depth HCAL active cells
  ~$10\lambda$ -> ~2m (+29% than ATLAS)
- ~10 000 tons (in ~ 4 cylinders of 6m in $Z$)
In barrel HCAL max levels:

- $4$ KGy ($=400$ krad)
- $10^{14}$ ($10^{10}$-$10^{13}$ at electronics location)
- W/ ATLAS optics $=>$ -25% max. (still ok!)

Today’s materials more radiation hard

Organic scintillators in HCAL barrel is safe, even if tracker shortened by 1m.

More rad. hard technologies needed in HCAL end-cap and fwd (0.4MGy in EndCap; 4 GGy in fwd HCAL...)

FCC-hh HCAL (30 ab$^{-1}$)
Performance requirements at 100TeV

submitted in May to JINST:
Single hadron content in multi-TeV jets

- For jets $p_T > 30$ TeV, $\sim 10\%$ of hadrons with $E > 1$ TeV ($\sim 9$ hadrons/jet)
- What is the depth needed to contain at 98% few TeV single hadrons?
Non compensating calorimeter ($e/h \sim 1.33$)
- Implies non linearity for pions over energy

Leakage enhances low energy tails and non-linearity
- Response of 2 TeV pion: $8\lambda/12\lambda = 96\%$, $10\lambda/12\lambda = 98\%$
- Percent of events below 3 sigma for $8\lambda = 11\%$, $12\lambda = 3\%$

C. Solans
Single Pion Containment

π parameterization 98% containment:
\[ \lambda_{98\%} = a \cdot \ln(E) + b \]

\[ \begin{array}{|c|c|c|c|}
\hline
\text{Method} & \text{Data} & \text{Simulation} \\
\hline
\text{Mean} & a (\lambda/\text{GeV}) \quad b (\lambda) & a (\lambda/\text{GeV}) \quad b (\lambda) \\
\text{Peak} & 0.95 \quad 4.7 & 0.64 \quad 5.4 \\
\hline
\end{array} \]

- ~12 \lambda to contain few TeV single hadrons
- MC showers are ~ 5-10 % shorter than data

Jet Containment

Jet containment at 98%:
\[ \lambda_{98} = a \cdot \ln(p_T) + b \]

<table>
<thead>
<tr>
<th>Method</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a (\lambda/\text{GeV})</td>
</tr>
<tr>
<td>Mean</td>
<td>0.495</td>
</tr>
<tr>
<td>Peak</td>
<td>0.615</td>
</tr>
</tbody>
</table>

- Fixed \( p_T \) parton hadronized in Pythia8
  - Simulated \( Z' \rightarrow qq \) at rest (back to back)
- Reconstruct jets with antiKT jets \( R=0.5 \) with different depths
  - Truth matching \( \Delta R \) (truth, reco) < 0.2
  - Truth jet \( p_T \) within 10% of parton jet \( p_T \)
- \( \sim 12 \lambda \) needed to contain 20-40 TeV \( p_T \) jet
**Single Pion E resolution**

- MC more optimistic than data (in MC no noise, optics fluctuations, shorter showers)
- Improvement in data and MC at high E by increasing the calo depth
  - \( \Rightarrow \) reduce the constant term
- Energy resolution achievable
  - at 12 \( \lambda \): \( \sigma_E / E \sim 43\% / \sqrt{E} \pm 2.4\%

\[
\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \pm C
\]

<table>
<thead>
<tr>
<th>Depth (( \lambda ))</th>
<th>Simulation</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sigma</td>
<td>RMS</td>
</tr>
<tr>
<td></td>
<td>a (%GeV^{1/2})</td>
<td>c (%)</td>
</tr>
<tr>
<td>8</td>
<td>41</td>
<td>5.0</td>
</tr>
<tr>
<td>9</td>
<td>43</td>
<td>4.0</td>
</tr>
<tr>
<td>9.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>43</td>
<td>3.1</td>
</tr>
<tr>
<td>11</td>
<td>43</td>
<td>2.7</td>
</tr>
<tr>
<td>12</td>
<td>43</td>
<td>2.4</td>
</tr>
</tbody>
</table>
Can get better hadron resolution at TeV range with calorimeters optimized for particle flow (PFA)?

Software SiD (ILC) → Si FCC

Solenoid: 5T outside HCAL
Tracker: R=2m; 20-50 μm pixels
ECAL (Si/W): 2x2 cm. 32 layers
HCAL (Scint. / Fe):
- 5x5 cm cells
- 64 layers, 11.3 λ
- 3.1% sampling fraction (as Tilecal)

> 150 million cells, non-projective

- Resolution of charged tracks & PFA gets worse with energy
- Resolution of Calo Clusters better than PFA/tracks > ~1 TeV
- ~2% constant term for calorimeter clusters (as ATLAS-Tilecal)
- For jets PFA need to add neutral component and confusion term.

https://indico.cern.ch/event/438866/contributions/1085149/

A. Kotwal, N. Tran, S. Chekanov, ...
Summary

• FCC-hh is a discovery machine and exciting project for HEP and CERN future

• Need to mature the physics potential, accelerator and detectors design/feasibility.

• HCAL requirements:
  • Depth of ~12 λ (ECAL+HCAL)
  • Energy resolution constant term ~2-3% is needed
  • $\Delta \eta \times \Delta \phi \leq 0.025 \times 0.025$
  • Extended coverage up to $\eta \sim 6$ (with other/more radiation hard technologies)

• Tile Calorimeter + Si-PMs
  • Good for the barrel HCAL (45%/VE$\oplus$3%)
  • Flexibility to improve granularity in $\eta$, $\phi$, depth
  • Implemented in the FCC-hh software as baseline for central HCAL
  • Relatively cheap
Next steps

- More compact HCAL-Tile approach(s) to reduce solenoid radius
- Combined performance with different ECAL options +tracker
- HCAL longitudinal segmentation requirements
- Participate in the conceptual design in FCC-hh software framework
- ..... 

You are welcome to join!

Mailing list: fcc-experiments-hadron@cern.ch
To subscribe: http://cern.ch/simba3/SelfSubscription.aspx?groupName=fcc-experiments-hadron
And a lot of information at at the April 2016 Workshop in Rome: https://indico.cern.ch/event/438866/
Back-up
\[ \ln l = 0.35 \text{ (depth=7.9}\lambda) \]

\[ \sigma = \frac{(52.9\pm0.9)%}{\sqrt{E_{\text{beam}}}} \oplus (5.7\pm0.2)\% \]

Tile standalone

\[ \sigma_{E/E} = 52.05\% \sqrt{E} \oplus 3.02\% \oplus 1.59/E \]

Cell weighting

testbeam data

Tile+em Lar (depth~10 \(\lambda\))

Good performance thanks to >10 years R&D, test-beams, MC tuning, cosmics

Jet resolution close to design:
- constant term \(\sim\)3%
- Pile-up worsen low \(p_t\) resolution
- Improvements after pile-up corrections for in-time/out-time bunches/noise threshold tuning, etc.
SiPM Cell size vs Radiation Damage

LED vs. Flux ($R_L = 3$ kOhm, no bias correction, non-annealed)

- NDL SiPM, 0.25 mm$^2$, 2500 cells
- MPPC, 1 mm$^2$, 4489 cells
- MPPC, 1 mm$^2$, 2500 cells
- MPPC, 1 mm$^2$, 1600 cells
- MPPC, 1 mm$^2$, 400 cells

Neutron flux [n/cm$^2$]
| Characteristics                                    | ATLAS $|\eta|<1.7$                                      |
|--------------------------------------------------|---------------------------------------------|
| Absorber                                         | Steel                                       |
| Absorber/scintillator ratio                       | 4.7:1                                       |
| Geometry                                         | $\eta$ to pp beam axis                      |
| Tiles-Fe periodicity in $Z$                       | 18 mm (3mm Tiles+14mm Fe)                   |
| Tiles characteristics:                           | Polystyrene+1.5%PTP+0.04%POPOP by injection molding, no grooves; ~ 70 tons |
| - Tile dimensions ($\eta$ x $\phi$ x $R$)        | 11 trapezoidal sizes in depth/R; ~ 40105 tiles |
| - Inner radius                                    | 3 mm x ~22 cm x ~10 cm                      |
| - Outer radius                                    | 3 mm x ~35 cm x ~19 cm                      |
| - WLS Fibres                                     | Kurary Y11; 1mm diameter; ~1062 Km; ~620 000 fibres |
| 3 cylinders (Barrel+2 Ext B):                     | 12m                                          |
| Length in $Z$                                     | 4.2 m                                        |
| Outer radius(w/supports+elect.)                  | 3.9 m                                        |
| Outer active radius                               | 2.3 m                                        |
| Inner active radius                               | 1.6m; 7.7 $\lambda$                         |
| Active depth $\Delta R$ at $\eta=0$              | 372m3                                        |
| Volume (inner-outer active $R$)                   | 2900 T                                       |
| Weight                                           |                                              |
| Longitudinal Segmentation                         | 3 layers                                     |
| Transversal granularity ($\Delta \eta \times \Delta \phi$) | 0.1x0.1 inner and middle layers; 0.2x0.1 outer layer |
| # channels/PMTs                                   | 10 000 channels                              |
| Gain-dynamic range                                | $10^5$; 2 gain 10 bits ADCs                  |
| $X_0$ ; $\lambda_p$ ; Moliere Radius              | 22.4 mm ; 20.7 cm ; 20.5 mm                   |
## ATLAS Tile calorimeter Performance

| Characteristics                                      | ATLAS |η|<1.7 |
|------------------------------------------------------|-------|-----|
| Light yield                                          | 70 phe/GeV |
| $\sigma_E/E$ (tbeam standalone)                      | 52%/VE+ 5.7% (7.7 $\lambda$)  
                                      45%/VE+2 % ( if 9.2 $\lambda$) |
| Jet resolution target                                 | ~50-60%/VE ± 3% |
| e/h                                                   | 1.33 |
| em sampling fraction                                 | 3% |
| Max dose at HL LHC (3000 fb-1)                       | 0.2 Mard |
| Max light reduction due to irradiation in run1       | -2%  
                                      -15% |
| Max. light reduction expected at HL LHC              |       |
## Machine parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>c.m. energy [TeV]</td>
<td>14</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>dipole magnet field [T]</td>
<td>8.33</td>
<td></td>
<td>16 (20)</td>
</tr>
<tr>
<td>circumference [km]</td>
<td>26.7</td>
<td></td>
<td>100 (83)</td>
</tr>
<tr>
<td>luminosity $[10^{34} \text{cm}^{-2}\text{s}^{-1}]$</td>
<td>1</td>
<td>5</td>
<td>5 $\rightarrow 20$? (*)</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td></td>
<td>25 {5}</td>
</tr>
<tr>
<td>events / bunch crossing</td>
<td>27</td>
<td>135</td>
<td>170 {34}</td>
</tr>
<tr>
<td>bunch population $[10^{11}]$</td>
<td>1.15</td>
<td>2.2</td>
<td>1 {0.2}</td>
</tr>
<tr>
<td>norm. transverse emitt. [µm]</td>
<td>3.75</td>
<td>2.5</td>
<td>2.2 {0.44}</td>
</tr>
<tr>
<td>IP beta-function [m]</td>
<td>0.55</td>
<td>0.15</td>
<td>1.1</td>
</tr>
<tr>
<td>IP beam size [µm]</td>
<td>16.7</td>
<td>7.1</td>
<td>6.8 {3}</td>
</tr>
<tr>
<td>synchrotron rad. [W/m/aperture]</td>
<td>0.17</td>
<td>0.33</td>
<td>28 (44)</td>
</tr>
<tr>
<td>critical energy [keV]</td>
<td></td>
<td>0.044</td>
<td>4.3 (5.5)</td>
</tr>
<tr>
<td>total syn.rad. power [MW]</td>
<td>0.0072</td>
<td>0.0146</td>
<td>4.8 (5.8)</td>
</tr>
<tr>
<td>longitudinal damping time [h]</td>
<td>12.9</td>
<td></td>
<td>0.54 (0.32)</td>
</tr>
</tbody>
</table>

(* Inst. Luminosity $5 \times 10^{34} \rightarrow \sim 20$-$30 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ in a second phase)
Baseline Geometry used up to now, Twin Solenoid, 6T, 12m bore, 10Tm dipole

**Barrel:**

Tracker available space:
R=2.1cm to R=2.5m, L=8m

EMCAL available space:
R=2.5m to R=3.6m → dR=1.1m

HCAL available space:
R=3.6m to R=6.0m → dR=2.4m

Coil+Cryostat:
R=6m to R=7.825 → dR = 1.575m, L=10.1m

Muon available space:
R=7.825m to R=13m → dR = 5.175m
Revision of outer radius is ongoing.

**Endcap:**

EMCAL available space:
z=8m to z=9.1m → dz=1.1m

HCAL available space:
z=9.1m to z=11.5m → dz=2.4m

Muon available space:
z=11.5m to z=14.8m → dz = 3.3m

**Forward:**

Dipole:
z=14.8m to z=21m → dz=6.2m

FTracker available space:
z=21m to R=24m, L=3m

FEMCAL available space:
Z=24m to z=25.1m → dz=1.1m

FHCAL available space:
Z=25.1m to z=27.5m → dz=2.4m

FMuon available space:
z=27.5m to z=31.5m → dz=4m
Tracking Resolution for Dipole and Solenoid

Simulated $p_T$:
- 10 GeV
- 100 GeV
- 1 TeV
- 10 TeV

- solenoid
- dipole
Aim of the Software Project is to support all of hh/ee/eh studies
  - Need to support multiple detectors in simulation and reconstruction
  - Need to support simulation in different levels of details
Since FCC Week 2015 plenty of work finished
  - Most of the progress up to our highly motivated students!
Simulation
  - Delphes integrated and ready to use
  - Technical infrastructure for combined fast/full simulation with Geant4 in place
Reconstruction
  - Joint project with ATLAS to apply their track reconstruction software (ACTS)
  - PAPAS for fast simulation and particle-flow reconstruction
Analysis
  - Standalone reader for FCC data model
  - Heppy as python-based analysis framework
  - Both can be installed on your laptop!
For details see other presentations in this session
FCC Software in the HEP SW Landscape

- We do not have resources to do everything by ourselves
  - Whenever there is something (almost) ready to use ⇒ take advantage of the work others do!
- Our software is based on the following external software
  - Gaudi as underlying framework
  - Delphes for parameterized simulation
  - Geant4 for simulation
  - DD4hep for detector description
- Collaborating with
  - ATLAS on tracking
  - CMS on analysis interface
  - LHCb on simulation framework and infrastructure
  - CLIC on grid processing (planned)
  - Surprisingly successful cooperation within HEP SW community
- We are as well contributing to the HEP Software with our additions
  - Heppy and PAPAS as integrated Python-solution
  - PODIO for data models