Centre-of-mass collision energy

\[ \sqrt{s} = 100 \text{ TeV} \]

Consequences

- more particles produced
- higher average and maximum \( p_T \)

Requirements for EM calorimetry

- depth \( \geq 30 \times 0 \)
- precision tracking and calorimetry for \( |\eta| < 4 \)
- efficient jet tagging for \( |\eta| < 6 \)
Centre-of-mass collision energy

$\sqrt{s} = 100 \text{ TeV}$

**Consequences**

- more particles produced
- higher average and maximum $p_T$

**Requirements for EM calorimetry**

- depth $\geq 30 X_0$
Centre-of-mass collision energy

√s = 100 TeV

Consequences
- more particles produced
- higher average and maximum \( p_T \)
- particles into forward region

Requirements for EM calorimetry
- depth \( \geq 30 \) \( X_0 \)
- precision tracking and calorimetry for \(|\eta| < 4\)

\begin{figure}
\centering
\includegraphics[width=\textwidth]{FCC-hh_Simulation}
\caption{\( gg \to H \to 4\ell \)}
\end{figure}
Centre-of-mass collision energy

\[ \sqrt{s} = 100 \text{ TeV} \]

Consequences
- more particles produced
- higher average and maximum \( p_T \)
- particles into forward region
- Vector Boson Fusion jets into very forward region

Requirements for EM calorimetry
- depth \( \geq 30 X_0 \)
- precision tracking and calorimetry for \( |\eta| < 4 \)
- efficient jet tagging for \( |\eta| < 6 \)

**FCC-hh Simulation**

\[ p_T > 3 \text{ GeV} \]

\[ gg \rightarrow H \rightarrow 4\ell \]

**FCC-hh Simulation**

\[ p_T^{\text{jet}} > 25 \text{ GeV} \]

\[ VBF Higgs \]
Luminosity

peak: $30 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
integrated: $20 \text{ ab}^{-1}$ for 25 y.

Consequences
- huge pile-up
  ($\langle \mu \rangle \approx 1000$ in ultimate scenario)

Requirements for EM calorimetry
- high granularity for pile-up rejection
- use of timing information
- combination with tracker information
  (particle flow technique)
Luminosity

peak: \(30 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}\)
integrated: \(20 \text{ab}^{-1}\) for 25 y.

Consequences

• huge pile-up
  \((\langle \mu \rangle \approx 1000\) in ultimate scenario\)

• strong requirements on radiation hardness

<table>
<thead>
<tr>
<th></th>
<th>1 MeV neutron equivalent fluence ((n_{eq}\text{cm}^{-2}))</th>
<th>Dose ((\text{MGy}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>barrel</td>
<td>(4 \times 10^{15})</td>
<td>(\mathcal{O}(0.1))</td>
</tr>
<tr>
<td>endcap</td>
<td>(3 \times 10^{16})</td>
<td>(\mathcal{O}(1))</td>
</tr>
<tr>
<td>forward</td>
<td>(5 \times 10^{18})</td>
<td>(5 \times 10^{3})</td>
</tr>
</tbody>
</table>

Requirements for EM calorimetry

• high granularity for pile-up rejection

• use of timing information

• combination with tracker information
  (particle flow technique)

• choice of radiation hard materials, especially for high-\(\eta\) regions
Requirements for EM calorimeter performance

- good energy resolution \( \frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \)

  design goal: \( a = 10\% \), \( c = 1\% \)

- vertex identification
  - tracker for \( e^- \), \( e^+ \)
  - good pointing resolution for \( \gamma \)

- linearity of calorimeter response

- large detector acceptance

- fine granularity
  - combination with tracker information
  - 3D imaging
  - pileup mitigation
  - \( \pi^0 \) rejection
  - separation of boosted particles

\( \frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus c \)

- \( a = 6\% \), \( c = 0.7\% \)
- \( a = 10\% \), \( c = 1\% \)
- \( a = 20\% \), \( c = 2\% \)
FCC-hh detector

Electromagnetic calorimeter for FCC-hh

Anna Zaborowska

Electromagnetic calorimetry for FCC-hh

April 12, 2018
Electromagnetic calorimeter

**Barrel:**
- $|\eta| < 1.5$
FCC-hh detector

Electromagnetic calorimeter

Barrel:
- $|\eta| < 1.5$

Endcap:
- $1.4 < |\eta| < 2.5$
Electromagnetic calorimeter

**Barrel:**
- $|\eta| < 1.5$

**Endcap:**
- $1.4 < |\eta| < 2.5$

**Forward:**
- $2.3 < |\eta| < 6$
Electromagnetic calorimeter

- Reference detector: based on liquid argon
  - Used for barrel, endcap, and forward detector (radiation hard)
  - Endcap and forward detector ($1.4 < |\eta| < 6$) of hadronic calorimeter also based on liquid argon
“Reference” detector: based on liquid argon

- used for barrel, endcap and forward detector (radiation hard)
- endcap and forward detector \((1.4 < |\eta| < 6)\) of hadronic calorimeter also based on liquid argon
EM calorimeter barrel

- Liquid argon
- Plates inclined in transverse plane
- Absorber (lead, glue and steel)
- Printed circuit board (PCB)

- Much more granular than ATLAS calorimeter (×10)
- High longitudinal and lateral segmentation possible with straight, multilayer electrodes

+ Easier construction (inaccuracies enlarge the constant term)

− Sampling fraction changes with calorimeter depth

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Electromagnetic calorimetry for FCC-hh
April 12, 2018
EM calorimeter barrel

- much more granular than ATLAS calorimeter ($\times 10$)
- high longitudinal and lateral segmentation possible with straight, multilayer electrodes
• proposed layout:
  ○ liquid argon
  ○ plates inclined in transverse plane
  ○ absorber (lead, glue and steel)
  ○ printed circuit board (PCB)

• much more granular than ATLAS calorimeter (×10)
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EM calorimeter barrel

- much more granular than ATLAS calorimeter (×10)
- high longitudinal and lateral segmentation possible with straight, multilayer electrodes
  + easier construction (inaccuracies enlarge the constant term)
  - sampling fraction changes with calorimeter depth

proposed layout:
- liquid argon
- plates inclined in transverse plane
- absorber (lead, glue and steal)
- printed circuit board (PCB)
- 2 mm absorber plates inclined by $50^\circ$ angle
- LAr gap increases with radius 1.15 mm–3.09 mm
- 8 longitudinal layers
- $\Delta \eta = 0.01$ (0.0025 in 2nd layer), $\Delta \varphi = 0.009$
Calibration to EM scale

- sampling fraction changes with calorimeter radius
- calibration to EM scale done per layer

![Sampling fraction vs radial depth](image)

FCC-hh simulation
Calibration to EM scale

- sampling fraction changes with calorimeter radius
- calibration to EM scale done per layer

- significant improvement for 8 layers
Correction for material upstream

\[
E_{\text{corr}}^{\text{clu}} = \sum_{\text{cells}} f_{\text{layer}} \cdot \sum_{\text{sample}} E_{\text{deposit}} + E_{\text{upstream}}
\]

\[
E_{\text{upstream}} = P_00 + P_{01} \cdot E_{\text{clu}} + (P_{01} + P_{11}) \sqrt{E_{\text{clu}}} \cdot E_{1\text{stLayer}}
\]
Correction for material upstream

- Linear correlation between energy deposited upstream and in the first layer

\[
E_{\text{corr}}^{\text{clus}} = \sum_{\text{cells}} f_{\text{layer}} \times \sum_{\text{sample}} E_{\text{deposit}} + E_{\text{upstream}}
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Correction for material upstream

- linear correlation between energy deposited upstream and in the first layer

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E_{corr}^{clus} = \sum_{cells} f_{layer} \cdot E_{deposit} + E_{upstream}
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Correction for material upstream

- linear correlation between energy deposited upstream and in the first layer

\[ E_{\text{corr}} = \sum_{\text{cells}} f_{\text{layer sample}} E_{\text{deposit}} + E_{\text{upstream}} \]

\[ E_{\text{upstream}} = P_{00} + P_{01} \cdot E_{\text{clu}} + \left( P_{01} + P_{11} \right) \cdot E_{\text{1stLayer}} \]
Correction for material upstream

- linear correlation between energy deposited upstream and in the first layer

\[ E_{\text{corr}}^{\text{clus}} = \sum_{\text{cells}} f_{\text{sample}}^\text{layer} E_{\text{deposit}} + E_{\text{upstream}} \]

\[ E_{\text{upstream}} = P_0 + P_01 \cdot E_{\text{clus}} + \left( P_01 + \frac{P_{11}}{\sqrt{E_{\text{clus}}}} \right) \cdot E_{1\text{stLayer}} \]
Performance for single particles

- simulation of single electrons
- no electronic or pile-up noise in detector
- reconstruction with sliding window algorithm $\Delta \eta \times \Delta \varphi = 0.07 \times 0.17$
Endcaps layout

- both electromagnetic and hadronic calorimeters within same cryostat

- electromagnetic calorimeter
  - 1.5 mm lead discs
  - 0.5 mm LAr gap

- hadronic calorimeter
  - 2 cm copper discs in H
  - 2 mm LAr gap

- forward calorimeter simulated with same layout
  - 0.1 mm LAr gap
  - 1 cm copper discs in EM
  - 4 cm copper discs in H
Performance for single particles

- simulation of single electrons
- no electronic or pile-up noise in detector
- reconstruction with sliding window algorithm $\Delta \eta \times \Delta \varphi = 0.07 \times 0.17$
- no constant term due to constant and ideal ratio LAr/absorber

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Electronic noise

Preliminary estimations

- extrapolation from ATLAS electronics
- electronic noise estimated for PCB readout (additional capacitance)
- plot presents noise per one cell $\Delta \eta \times \Delta \varphi = 0.01 \times 0.009$ for each detector layer
- noise in cluster of size $\Delta \eta \times \Delta \varphi = 0.07 \times 0.17$ approx. 300 MeV
Pileup noise

- estimation from minimum bias events’ simulation
- noise calculated for clusters
- additional contribution from out-of-time pile-up as correction factor ($\sim 1.5$) - not included in the plots as like for HL-LHC it is planned to suppress the out-of-time pile-up contribution to a large extent.

The (enormous) in-time pile-up will need to be suppressed by rejecting energy deposits from pile-up vertices tagged by the inner tracker (to be studied).
Performance for single particles

- simulation of single electrons
- electronic and pileup noise included
- reconstruction with sliding window algorithm $\Delta \eta \times \Delta \varphi = 0.07 \times 0.17$

Size of clusters needs still to be optimised to contain a large fraction of the shower and the smaller amount of pile-up (optimised sliding window cluster or topo-cluster).
Di-photon invariant mass

- simulation of $H \rightarrow \gamma\gamma$
- pile-up scenarios $\langle \mu \rangle = 0$, $\langle \mu \rangle = 200$ and $\langle \mu \rangle = 1000$
- reconstruction with sliding window algorithm $\Delta \eta \times \Delta \phi = 0.07 \times 0.17$

It is obvious that efficient in-time pile-up suppression will be crucial.

This pile-up contribution is basically independent of the chosen active material of the EM calorimeter. A small reduction of in-time pile-up is expected for W absorbers.
Summary

• LAr detector studied as a reference for FCC-hh experiments
  ◦ electromagnetic calorimeter in $|\eta| < 6$
  ◦ hadronic calorimeter in $1.4 < |\eta| < 6$

• with optimised layout achieved the goal resolution
  ◦ sampling term $\sim 8\%$
  ◦ constant term $< 0.2\%$
  ◦ noise term highly depends on the pile-up

• pile-up the main challenge for any calorimeter

• tackle the pile-up with:
  ◦ readout system (out-of-time)
  ◦ optimised reconstruction algorithms (in-time)
  ◦ tagging pile-up in tracker (in-time)
Reconstruction

Sliding window algorithm

- Reconstruction of electrons in photons
- Based on https://cds.cern.ch/record/1099735

1. Calorimeter towers with fixed $\Delta \eta \times \Delta \varphi$ size
2. Seeding
   - Scanning the $\Delta \eta \times \Delta \varphi$ tower map with a fixed size window for local maxima
   - If energy inside window is above threshold → mark as pre-cluster
3. Barycentre position calculation
   - Energy-weighted position for each pre-cluster
4. Duplicates removal
   - If two pre-clusters are next to each other, the pre-cluster with lower energy is removed
5. Cluster building
   - Each step (1-4) can use window of different size (centred around the tower seed)