Calorimeter Simulation

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CEPC PFA Calorimeter Options

A highly segmented and full-contained calorimeter system is required

Absorber:
- ECAL: Tungsten
- HCAL: Steel

Readout:
- ECAL: analog
- HCAL: analog, digital

Active:
- Silicon
- Scintillator
- Scintillator
- RPC
- GEM/THGEM

More details are shown in CDR.
CEPC Full Simulation Software

http://cepcsoft.ihep.ac.cn/
Full Simulation Geometries

CEPC_v4

Baseline Geometry for CDR

Simplified Geometry

- calorimeter only
- ideal geometry (cylindrical barrel and two plate endcaps).
- easily modified for Arbor parameters
- no geometry defects
Critical performance requirements for ECAL

• Good photon energy resolution. A clear Higgs boson mass distribution should be reconstructed from the Higgs-$\rightarrow\gamma\gamma$ events.

• Good jet energy response. The boson mass resolution should be better than 4% at Higgs-$\rightarrow$di-jets events.

• Separation performance, which is crucial for the jet energy resolution and for physics with taus($\pi0$).

• Particle Identification

Critical performance requirements for HCAL

- Good Jet Energy Resolution
  - Neutral Hadron Energy Resolution
  - Confusion (Shower Separation)

- Particle Identification
EM-Shower Separation

Lots of nearby EM-showers exist in jets, the separation and reconstruction of them are important for some physics objects.

The reconstruction efficiency of two parallel 5 GeV photons was studied. The distance between these two photons ranges from 1mm to 80mm.

\[(E_{\text{blue cluster}} \approx \frac{1}{6}E_{\text{orange cluster}})\]

\[
\frac{1}{3}E_{\text{All}} < E_{\text{photon1}} < \frac{2}{3}E_{\text{All}} \quad \text{&} \quad \frac{1}{3}E_{\text{All}} < E_{\text{photon2}} < \frac{2}{3}E_{\text{All}} : \text{succeeded}
\]
Nearby EM-Shower Separation

Efficiency with different cell size was checked:
At large distance, the reconstruction efficiency converges to 100%.
At very close by distance, the reconstruction efficiency drops significantly.

The critical separation distance is defined as the distance with which the successful reconstruction efficiency is 50%.
Nearby Photon Showers in Physics Objects

Z→ττ (at Z-pole Energy)

Table 2. Percentages of photons that would be polluted by neighbor particles

<table>
<thead>
<tr>
<th>Cell Size</th>
<th>Critical Separation Distance with Arbor</th>
<th>Percentage of $Z \rightarrow \tau^+\tau^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mm</td>
<td>4 mm</td>
<td>0.07%</td>
</tr>
<tr>
<td>5 mm</td>
<td>8 mm</td>
<td>0.30%</td>
</tr>
<tr>
<td>10 mm</td>
<td>16 mm</td>
<td>1.70%</td>
</tr>
<tr>
<td>20 mm</td>
<td>38 mm</td>
<td>19.6%</td>
</tr>
</tbody>
</table>

At least ~10mm × 10mm effective cell size
Separation Eff VS. ECAL Layer Number

Cell Size = 5mm*5mm

Cell Size = 10mm*10mm
Separation at Strip Readout

5*45mm Cell -> 5*5mm Cell

Energies of Neighbor Layer Strips (2*9) are used to calculate the splitting weights

Next: further study at jet reconstruction
Photon Energy Resolution

0.5mm thick silicon in each layer

less layer gets worse photon energy resolution, due to the less sensor/absorber ratio

thicker sensor can compensate photon energy resolution

30 layers 0.5mm silicon
25 layers 1mm silicon
20 layers 1.5mm silicon
New ECAL Option: Segmented crystal ECAL

from Prof. Junguang LV's talk at Topical Workshop on the CEPC Calorimetry (https://indico.ihep.ac.cn/event/9195/), March 2019

Readout unit:
- **PbWO4 crystal**: 10mmx10mmx22mm
- **SiPM**: 6mmx6mm, 5µm pitch, PDE > 10%
- **10 layers**

The linear range of SiPM: \(4.8 \times 10^5\) pe
d\(E/dX\) of MIPs in \(\approx 22.4\) MeV \(\sim 150\) pe?
Dynamic range of is 1-3.2\(\times 10^3\) MIPs

Reference: CMS PbWO4 ECAL

**Expected energy resolution:**
\[
\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E(\text{GeV})}} \oplus \frac{12\%}{E(\text{GeV})} \oplus 0.3\%
\]

Cost
- **Crystal**: $5/\text{cc?} \times 1.46\times 10^7\text{cc} \sim 0.51\text{ billion ¥}
- **Electronics**: 6.6M ch \sim 0.66\text{ billion ¥}
- **Total**: \sim 1.2\text{ billion ¥}

Need detailed MC study
EM-Shower Separation for Crystal Option

The neutron hits make the EM shower to be “fat” at transverse direction. The separation performance is limited if only use position information for clustering.

But the energy information helps significantly for normal injection case.

Most of the “hot” hits are at the transverse center of the shower.

Transverse position distribution of the hits from two nearby showers, without hit energy weight (left) and with hit energy weight (right). Two 5GeV Photons with 20mm distance.
Good shower separation performance can be achieved for this simplified nearby photon shower cases at 10-layer crystal ECAL, with the help of hit energy information. Same level performance at 5-layer option.

Less than 10 layer crystal ECAL option is probably worth considering. More thorough study with other physics objects is necessary.
Photon Identification at CEPC_v4

Keep the photon identification efficiency above 99%.

Sample: single neutrons

TMVA method
Timing information helps the low Energy photon/neutron identification.

from Yuqiao Shen
Energy deposited in ECAL depends on the $\phi$ and $\theta$. Need corrections with $(\phi, \theta, E)$

**Only Considering the unconverted Photon in the Barrel case at the hit level**
ECAL Corrections and Calibrations at CEPCv4

Before correction

After correction

From Yuqiao Shen
Digitization: SiPM Dynamic Range for ScECAL

Compare between 10000, 4500 and 1600 pixel SiPM
Use Higgs mass resolution at H→γγ events as benchmark

<table>
<thead>
<tr>
<th>Pixel</th>
<th>10000</th>
<th>4500</th>
<th>1600</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIP LY / p.e.</td>
<td>20</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>PDE / %</td>
<td>10</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Mean / GeV</td>
<td>124.79</td>
<td>124.88</td>
<td>111.45</td>
</tr>
<tr>
<td>σ/Mean</td>
<td>1.57%</td>
<td>1.58%</td>
<td>2.62%</td>
</tr>
</tbody>
</table>

From Yazhou Niu
Software compensation for Energy reconstruction at AHCAL

Local Compensation
- Fit by $\omega_j = p_0 + p_1 e^{p_2 e_j}$
- Using least square method

Global Compensation

Local Compensation improves by ~18%
Global Compensation improves by ~15%

from Jiechen Jiang

Local Compensation

$$E_{\text{rec}} = \sum_i (E_{\text{HCAL},i} \times C_{\text{global}})$$

$C_{\text{global}} = \frac{n_{e<e_{\text{lim}}}}{N_{e<e_{\text{mean}}}}$
AHCAL layer num optimization

global software compensation has been used

Energy resolution

~40 layers for AHCAL is reasonable

from Jiechen Jiang
AHCAL scintillator thickness optimization

Simplify Geometry (Only AHCAL)

Incident particle: $k_L$
Direction: Z
Position (mm): 1000 400 2000

ACHAL structure
Fe: 20mm, 40 layers
PCB: 2mm

- Energy resolution is worse with 2mm thick sensor, but the degradation is limited.
- For 3mm thick option, the energy resolution remains the same level with 4mm thick option.

from Jiechen Jiang
AHCAL scintillator thickness optimization
software compensation has been used.

Energy resolution and residual

The differences of energy resolution caused by scintillator thickness can be further reduced.
Summary

- More progresses on the study of the calorimeter design optimization, on the foundation of the CEPC CDR. Try to specify the geometry parameters (transverse cell size, layer num, sensor thickness, etc.) and device selections (e.g. SiPM for ScECAL), directly based on the physics requirements.

- Improve the reconstruction performances (AHCAL software compensation, photon energy correction). Considering more supplementation and new idea.

- Start to study the performances at New calorimeter options. Preliminary results show that <10 layer crystal ECAL is worth considering, and more thorough study is necessary.

Thanks!
Back up
$\pi_0 \rightarrow \gamma\gamma$

Critical energy to separate an evenly decay $\pi_0$: 30 GeV

Z-$\rightarrow$ tau tau
(at Zpole Energy)
vvHiggs→diphoton Reconstruction

The reconstruction accuracy is mainly decided by the photon energy resolution because the spatial resolution is negligible.

30 layers ECAL with 2.8mmW+0.5mmSi in each layer

Resolution (σ/mean) with different total tungsten thickness
CEPC Detector Model Results

Table 1. Resolution of reconstructed Higgs boson mass through $vvHiggs, Higgs \rightarrow gluons$ events using different longitudinal structures at CEPC_v1 geometry.

<table>
<thead>
<tr>
<th>Layer number</th>
<th>Silicon sensor thickness</th>
<th>Higgs boson mass resolution (Statistic error only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.5 mm</td>
<td>3.74 ± 0.02 %</td>
</tr>
<tr>
<td>25</td>
<td>1 mm</td>
<td>3.71 ± 0.02 %</td>
</tr>
<tr>
<td>20</td>
<td>1.5 mm</td>
<td>3.78 ± 0.02 %</td>
</tr>
</tbody>
</table>
CEPC Detector Model Results
vvHiggs->gluon gluon

0.5mm Si, 30 layers
5mm*5mm

1mm Si, 25 layers
10mm*10mm

1.5mm Si, 20 layers
20mm*20mm

<table>
<thead>
<tr>
<th>Cell Size (mm²)</th>
<th>5×5</th>
<th>10×10</th>
<th>20×20</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMR</td>
<td>3.74 ± 0.02 %</td>
<td>3.75 ± 0.02 %</td>
<td>3.93 ± 0.02 %</td>
</tr>
</tbody>
</table>
The energy resolution of SDHCAL with different number of layers versus simulated pion energy ranging from 10 GeV to 80 GeV.

SDHCAL with 40-layer yields decent energy resolution, about 15% and 10% with pion energy of 20 GeV and 80 GeV, respectively.
HCAL Thickness & B Field

- HCAL: outer layers unused
- Smaller B Field needed

by Dan Yu
Separation Eff VS. ECAL Layer Number

![Graph showing separation efficiency vs. ECAL layer number. The graph compares 10 Layer and 5 Layer data points, with clear separation at certain distances.](image)
Photon Conversion Rate

The material in the unit of radiation length in the tracker

The photon conversion rate of 10GeV at different polar angles
Photon Conversion Rate of Different Energies
Decrease the SiPM pixels

<table>
<thead>
<tr>
<th>Pixel</th>
<th>infinite</th>
<th>10000</th>
<th>4800</th>
<th>2600</th>
<th>1600</th>
<th>800</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIP LY / p.e.</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Mass / GeV</td>
<td>124.83</td>
<td>124.82</td>
<td>124.83</td>
<td>124.87</td>
<td>125.03</td>
<td>118.91</td>
</tr>
<tr>
<td>$\sigma$/Mean</td>
<td>1.55%</td>
<td>1.56%</td>
<td>1.57%</td>
<td>1.58%</td>
<td>1.63%</td>
<td>2.26%</td>
</tr>
</tbody>
</table>
SiPM saturation effect on AHCAL dynamic range

Scintillator: $30 \times 30 \times 3\text{mm}^3$
SiPM: $1\text{mm}^2$ with 1600 Pixels

- SiPM Saturation will influence the AHCAL energy reconstruction.
- The digitization method has combined the simulation hits (deposit energy) and test results to calculate the fired pixel number for each SiPM by Monte Calo.

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Corrected by $N_{\text{fire}} = N_{\text{pix}}(1 - e^{-\varepsilon N_{\text{in}}/N_{\text{pix}}})$

After correction, the dynamic range of 1600 pixels SiPM is enough!
Local SC for AHCAL layer optimization

Energy resolution

Energy linearity and residual

- The result is the same as Global SC.
The tendency of energy resolution is similar for different absorber by SC. The differences of different absorbers can be reduced by SC.