Optimisation of the ECAL-P readout configuration

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Outline

Outline

Signal reconstruction

We assume that the calorimeter response is calculated as a weighted sum of signals from individual calorimeter layers:

$$S = \sum_i c_i \cdot s_i$$

where $i = 1 \ldots N = 20$ numbers the calorimeter layers.

For the averaged signal values we can write: $i, j = 1 \ldots N$

$$\langle S \rangle = \sum_i c_i \cdot \langle s_i \rangle$$

$$\langle S^2 \rangle = \sum_{i,j} c_i \cdot c_j \cdot \langle s_i s_j \rangle$$

Expected performance

For sampling calorimeter, assuming statistical fluctuations dominate:

$$\sigma_S \sim \sqrt{E} \qquad \Rightarrow \qquad \frac{\sigma_S}{\bar{S}} = \frac{a}{\sqrt{E}}$$

where a is a resolution parameter; simulation indicates $a \approx 0.2\sqrt{\mathrm{GeV}}$ for ECAL-P.

Normalized response parameters

To compare detector response at different energies, we can use scaled quantities:

- relative response shift:

$$\delta_S = \frac{\bar{S} - E}{a\sqrt{E}} \qquad \rightarrow 0 \quad \text{for perfect calibration}$$

- relative resolution:

$$\delta_\sigma = \frac{\sigma_S}{\bar{S}} \cdot \frac{\sqrt{E}}{a} \qquad \rightarrow 1 \quad \text{for expected resolution}$$

Figure of merit

Two goals, when optimizing calibration factors for sensor layers:

- best linearity:

$$F_L = \sum_E w_E \, \delta_S^2(E)$$

- best resolution:

$$F_R = \sum_E w_E \, \delta_\sigma^2(E)$$

where weights w_E can be added to take the expected energy distribution into account.

Final optimization goal can be then defined as:

$$F = f_l \cdot F_L + f_r \cdot F_R$$

where f_l and f_r define the relative weights of linearity vs resolution in the optimization

Calibration framework

Analytic optimization

see backup slides for more details

Calibration factors for all layers, c_i, can be found by solving a set of linear equations.
One can write it in a symbolic form:

$$\mathbb{A} \cdot \vec{c} \;=\; \vec{B}$$

where matrix $\mathbb{A}$ and vector $\vec{B}$ can be calculated from single layer averages, $\langle s_i^E \rangle$ and $\langle s_i^E s_j^E \rangle$.

These averages can be calculated only once (from MC event samples)
and then use to test different optimization strategies $\Rightarrow$ extremely fast!

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When only resolution is considered (for $f_l = 0$), additional constraint has to be added:
implemented using Lagrange multiplier

$$\sum_E \left(\sum_i c_i \langle s_i^E \rangle \; - \; E \right) \;=\; 0$$

Outline

Performance tests

Test samples

/nfs/dust/luxe/group/MCProduction/SinglePositron/elaser_positron

Samples produced in Nov 2021:

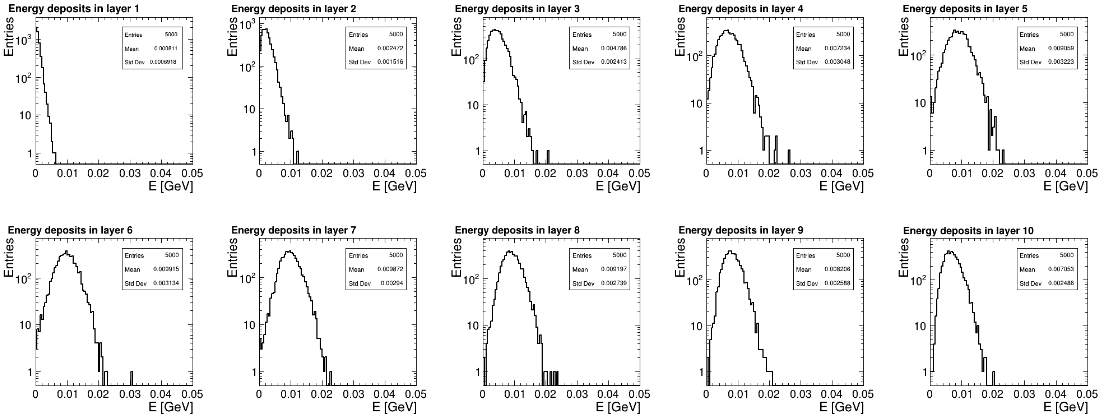
- files: mc21.singlePositron_*.G4gun.SIM.se0002.root
- e-laser configuration, positron gun at $z = -7.4$ m
- positron energy range: from 2.0 GeV to 15.0 GeV, with 0.5 GeV step
- 5000 events per file

Samples produced in 2023:

- files: mc21.singlePositron_*_ECALP_run2.G4gun.SIM.se0003.root
- e-laser configuration, positron gun at calorimeter face
- positron energy range: from 2.5 GeV to 15.0 GeV, with 2.5 GeV step
- 20 000 events per file

Monte Carlo sample analysis

example distributions for 8 GeV sample

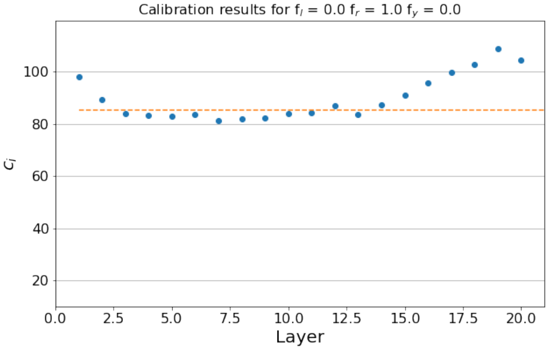


Performance tests

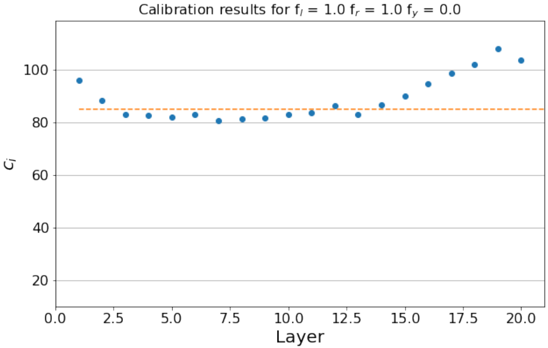
Full calorimeter calibration old samples

Calibration factors from optimization in the positron energy range from 2 to 8 GeV

Resolution only



Resolution + linearity

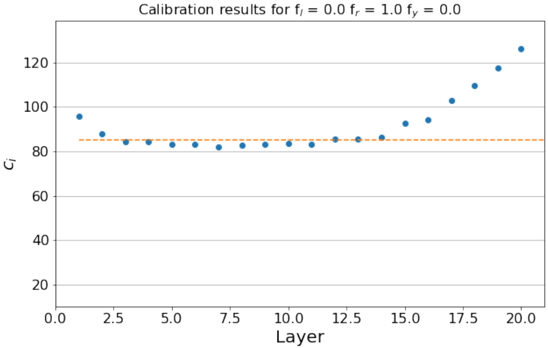


Performance tests

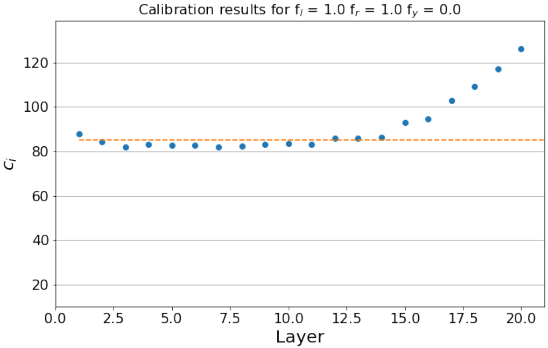
Full calorimeter calibration old samples

Calibration factors from optimization in the positron energy range from 2 to 15 GeV

Resolution only



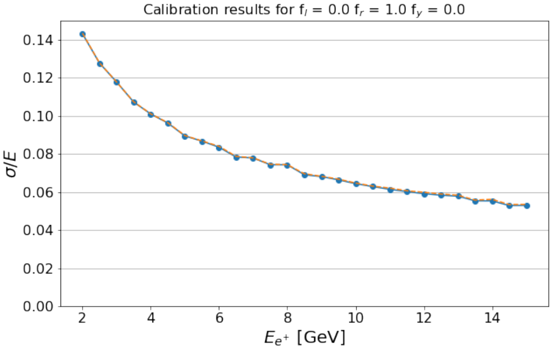
Resolution + linearity



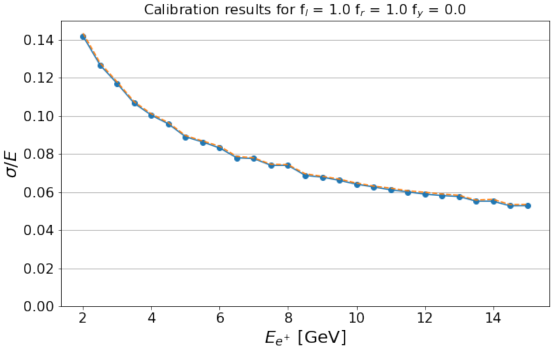
Full calorimeter calibration   old samples

Resolution from optimization in the positron energy range from 2 to 15 GeV

Resolution only



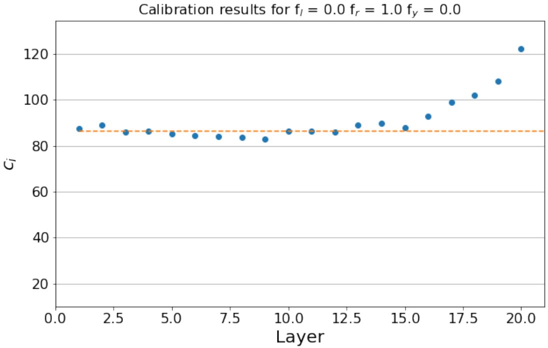
Resolution + linearity



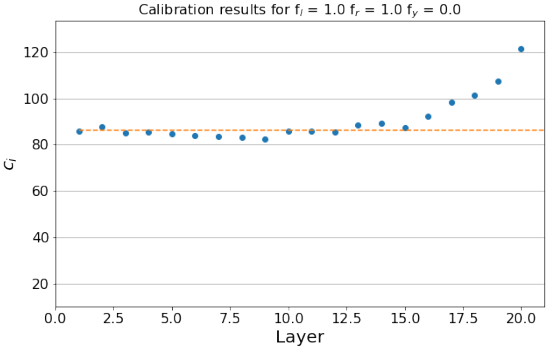
Full calorimeter calibration   new samples

Calibration factors from optimization in the positron energy range from 2.5 to 7.5 GeV

Resolution only



Resolution + linearity

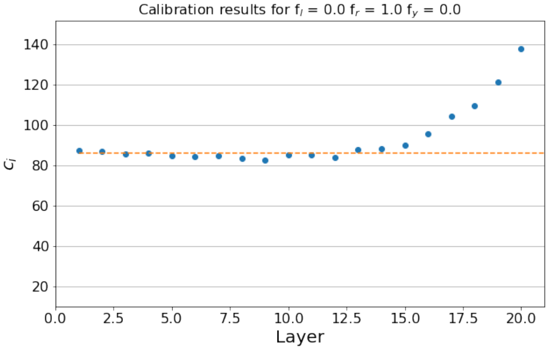


Performance tests

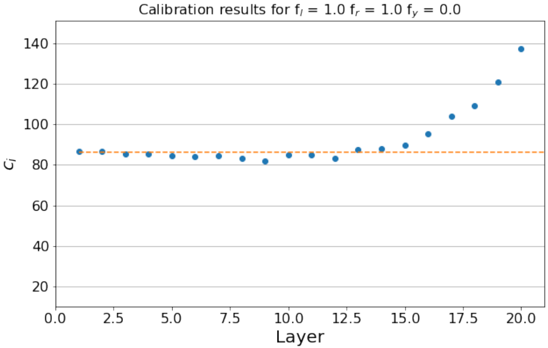
Full calorimeter calibration new samples

Calibration factors from optimization in the positron energy range from 2.5 to 15 GeV

Resolution only



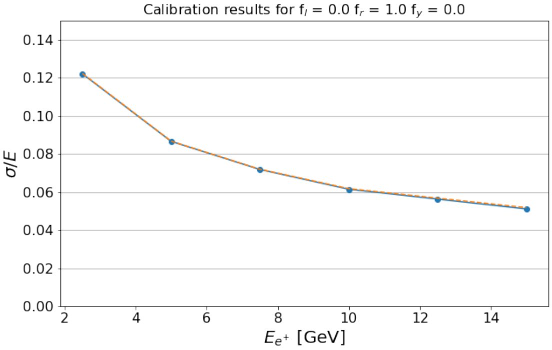
Resolution + linearity



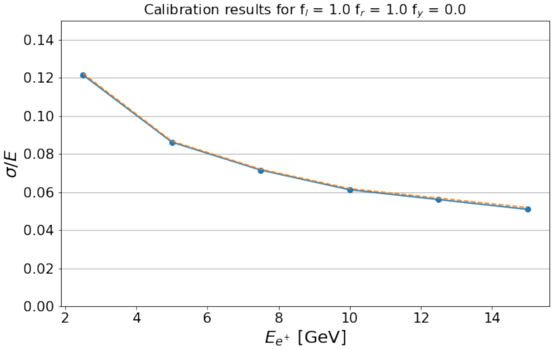
Full calorimeter calibration new samples

Resolution from optimization in the positron energy range from 2.5 to 15 GeV

Resolution only



Resolution + linearity



Outline

Configuration optimization

Approach

Optimization procedure can be considered also for not-fully-instrumented calorimeter

Layers can be easily "deactivated" by forcing their calibration factors to zero.

As the calibration procedure is very fast, it can be easily repeated for multiple configurations...
With $N = 20$ gaps we have total of

$$N_{\mathrm{comb}} = 2^{20} - 1 = 1'048'575$$

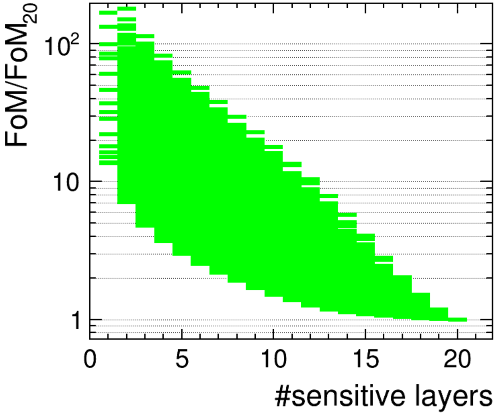
possible layer configurations, which can be checked in $\mathcal{O}(1\mathrm{h})$ (for single energy).

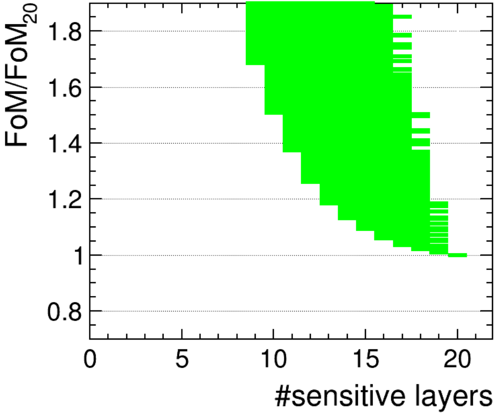
We can then look for the optimal configuration for given number of instrumented layers...

Results shown are obtained when optimizing for resolution only...

Configuration scan

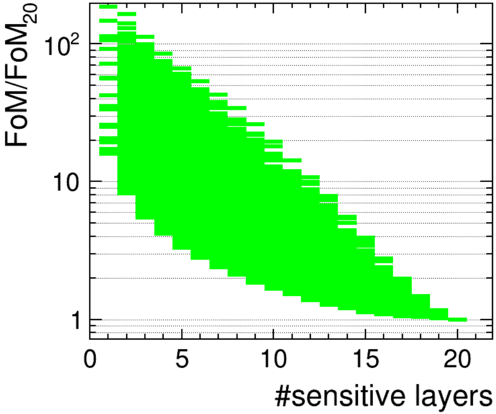
Figure of merit ($\sim \sigma_E^2$) change as a function of the number of active layers, for E = 2.5 GeV

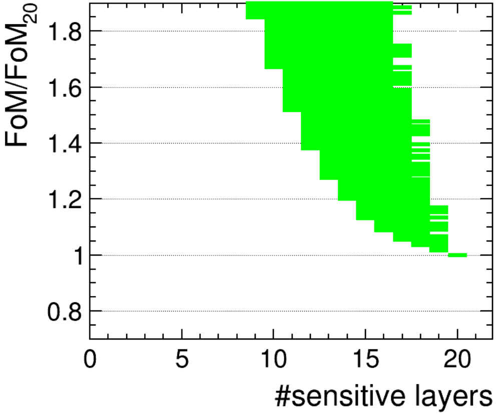




Configuration scan

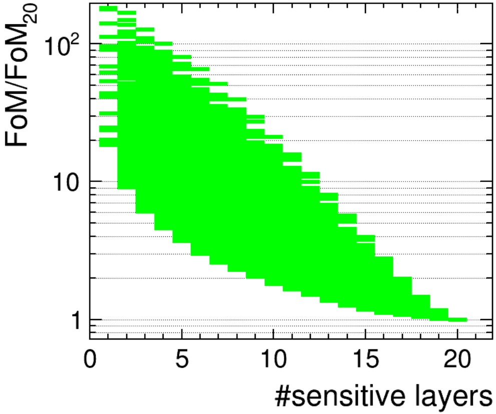
Figure of merit $(\sim \sigma_E^2)$ change as a function of the number of active layers, for $E = 5$ GeV

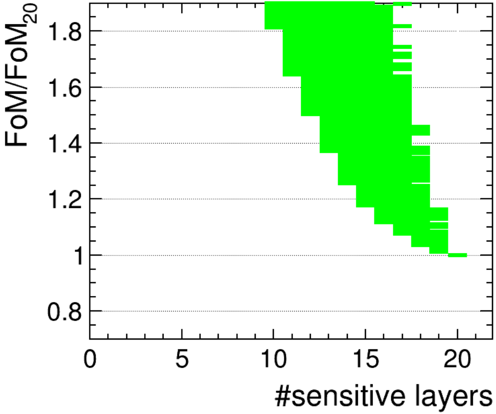




Configuration scan

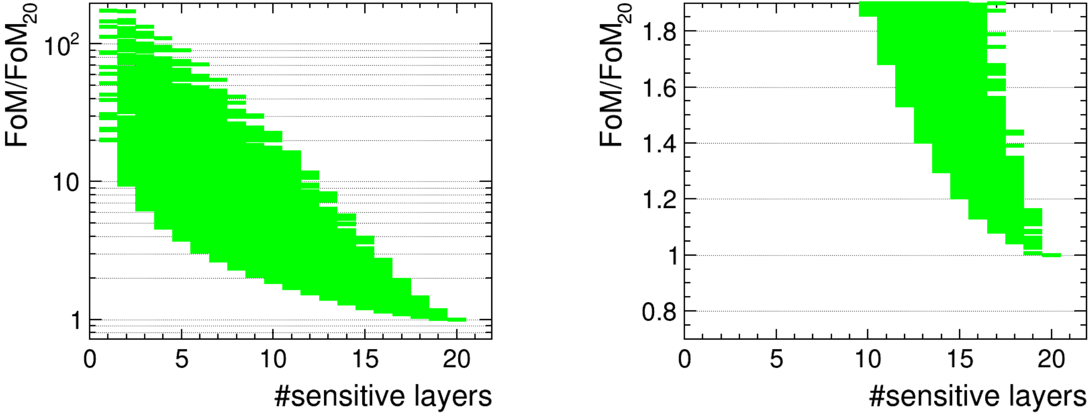
Figure of merit ($\sim \sigma_E^2$) change as a function of the number of active layers, for E = 10 GeV





Configuration scan

Figure of merit $(\sim \sigma_E^2)$ change as a function of the number of active layers, for $E = 15$ GeV



Configuration optimization

Results

Optimal configurations
for the decreasing number of active sensor layers

E = 2.5 GeV

| - active layer
. - empty slot

```
N_L   Best option
20    | | | | | | | | | | | | | | | | | | | |
19    | | | | | | | | | | | | | | | | | | | .
18    | | | | | | | | | | | | | | | | | | . .
17    | | | | | | | | | | | | | | | | | . . .
16    | | | | | | | | | | | | | | | . | . . .
15    . | | | | | | | | | | | | | | . | . . .
14    . | | | | | | | | | | | | | | . . . . .
13    . | | | | | | | | | | | | | . . . . . .
12    . | | | | | | | | | | | | . . . . . . .
11    . | | | | | | | | | | . | . . . . . . .
10    . . | | | | | | | | | . | . . . . . . .
9     . . | | | | | | | . | . | . . . . . . .
8     . . | | | . | | | | . . | . . . . . . .
7     . . | | . | | . | | | . . . . . . . . .
6     . . | | . | | . | . | . . . . . . . . .
5     . . | . | . | . | | . . . . . . . . . .
4     . . . | . | . | . | . . . . . . . . . .
3     . . . | . . | . | . . . . . . . . . . .
2     . . . . | . . | . . . . . . . . . . . .
1     . . . . . | . . . . . . . . . . . . . .
```

Results

Optimal configurations
for the decreasing number of active sensor layers

E = 5 GeV

| - active layer
. - empty slot

```
N_L | Best option
 20 | | | | | | | | | | | | | | | | | | | | |
 19 | | | | | | | | | | | | | | | | | | | . |
 18 | . | | | | | | | | | | | | | | | | | . |
 17 | . | | | | | | | | | | | | | | | | | . .
 16 | . | | | | | | | | | | | | | | | . | . .
 15 | . | | | | | | | | | | | | | | | . . . .
 14 | . | | | | | | | | | | | | | . | . . . .
 13 | . . | | | | | | | | | | | | . | . . . .
 12 | . . | | | | | | | | | . | | . | . . . .
 11 | . . | | | | | | . | | | | | . . . . . .
 10 | . . | | | | | | . | | . | | . . . . . .
  9 | . . | . | | | | . | | . | | . . . . . .
  8 | . . | . | | | | . | . | . | . . . . . .
  7 | . . | . | . | | . | | . | . . . . . . .
  6 | . . | . | . | . | . | . | . . . . . . .
  5 | . . . | . | . | . | . . | . . . . . . .
  4 | . . . | . . | . | . . | . . . . . . . .
  3 | . . . . | . . | . . | . . . . . . . . .
  2 | . . . . | . . . | . . . . . . . . . . .
  1 | . . . . . . | . . . . . . . . . . . . .
```

Configuration optimization

Results

Optimal configurations
for the decreasing number of active sensor layers

E = 10 GeV

| - active layer
. - empty slot

```
N_L | Best option
 20 | | | | | | | | | | | | | | | | | | | | |
 19 | . | | | | | | | | | | | | | | | | | | |
 18 | . | | | | | | | | | | | | | | | | | . |
 17 | . | | | | | | | | | | | | | | | | . . |
 16 | . . | | | | | | | | | | | | | | | . . |
 15 | . . | | | | | | | | | | | | | | | . . .
 14 | . . | | | | | | | | | | | | . | | . . . .
 13 | . . | | | | | | | | . | | | . | | . . . .
 12 | . . | . | | | | | | . | | | . | | . . . .
 11 | . . | | . | | | | | . | | . | | . . . . .
 10 | . . | | . | | | . | | . | . | | . . . . .
  9 | . . | . | | . | | . | . | . | | . . . . .
  8 | . . . | . | | | . | . | | . . | . . . . .
  7 | . . . | . | . | . | | . | . | . . . . . .
  6 | . . . | . | . | . | . . | . | . . . . . .
  5 | . . . | . | . | . . | . | . . . . . . . .
  4 | . . . | . . | . . | . . | . . . . . . . .
  3 | . . . . | . . | . . . . | . . . . . . . .
  2 | . . . . . | . . . . | . . . . . . . . . .
  1 | . . . . . . . | . . . . . . . . . . . . .
```

Results

Optimal configurations
for the decreasing number of active sensor layers

E = 15 GeV

| - active layer
. - empty slot

<table>
<tr><th>N_L</th><th>Best option</th></tr>
<tr><td>20</td><td>| | | | | | | | | | | | | | | | | | | |</td></tr>
<tr><td>19</td><td>. | | | | | | | | | | | | | | | | | | |</td></tr>
<tr><td>18</td><td>. | | | | | | | | | | | | | | | | | | .</td></tr>
<tr><td>17</td><td>. . | | | | | | | | | | | | | | | | | .</td></tr>
<tr><td>16</td><td>. . | | | | | | | | | | | | | . | | | .</td></tr>
<tr><td>15</td><td>. . | | | | | | | | | | | | . | | . | .</td></tr>
<tr><td>14</td><td>. . | | | | | | | | | . | | | . | . | .</td></tr>
<tr><td>13</td><td>. . | . | | | | | | | . | | | . | . | .</td></tr>
<tr><td>12</td><td>. . | . | | | | | | | . | . | . | . | .</td></tr>
<tr><td>11</td><td>. . | . | | | . | | | . | . | . | . | .</td></tr>
<tr><td>10</td><td>. . | . | | | . | | | . | . | . | . . .</td></tr>
<tr><td>9</td><td>. . . | | . | | . | | . | . | . | . . .</td></tr>
<tr><td>8</td><td>. . . | . | | . | . | . | . | . | . . .</td></tr>
<tr><td>7</td><td>. . . | . | . | . | | . . | . | . . . .</td></tr>
<tr><td>6</td><td>. . . | . | . | . . | . | . . | . . . .</td></tr>
<tr><td>5</td><td>. . . . | . | . . | . . | . | . . . . .</td></tr>
<tr><td>4</td><td>. . . . | . . | . . | . . . | . . . . .</td></tr>
<tr><td>3</td><td>. . . . | . . . | . . . | . . . .</td></tr>
<tr><td>2</td><td>. . . . . | . . . . | . . . .</td></tr>
<tr><td>1</td><td>. . . . . | . . . .</td></tr>
</table>

Results

Optimal configurations
for the decreasing number of active sensor layers

E = 2.5 – 7.5 GeV

| - active layer
. - empty slot

<table>
<tr><th>N_L</th><th>Best option</th></tr>
<tr><td>20</td><td>| | | | | | | | | | | | | | | | | | | |</td></tr>
<tr><td>19</td><td>| | | | | | | | | | | | | | | | | | | .</td></tr>
<tr><td>18</td><td>. | | | | | | | | | | | | | | | | | . |</td></tr>
<tr><td>17</td><td>. | | | | | | | | | | | | | | | | | . .</td></tr>
<tr><td>16</td><td>. | | | | | | | | | | | | | | | | . . .</td></tr>
<tr><td>15</td><td>. | | | | | | | | | | | | | | | . . . .</td></tr>
<tr><td>14</td><td>. | | | | | | | | | | | | | . | . . . .</td></tr>
<tr><td>13</td><td>. . | | | | | | | | | | | | . | . . . .</td></tr>
<tr><td>12</td><td>. . | | | | | | | | | . | | . | . . . .</td></tr>
<tr><td>11</td><td>. . | | | | | | | | | . | | . . . . . .</td></tr>
<tr><td>10</td><td>. . | | | | | | . | | . | | . . . . . .</td></tr>
<tr><td>9</td><td>. . | . | | | | . | | . | | . . . . . .</td></tr>
<tr><td>8</td><td>. . | . | | | . | | . | . | . . . . . .</td></tr>
<tr><td>7</td><td>. . | . | | . | . | | . | . . . .</td></tr>
<tr><td>6</td><td>. . . | | . | . | . | . | . . . .</td></tr>
<tr><td>5</td><td>. . . | . | . | . | . . | . . . .</td></tr>
<tr><td>4</td><td>. . . | . . | . | . . | . . . .</td></tr>
<tr><td>3</td><td>. . . . | . . | . . | . . . .</td></tr>
<tr><td>2</td><td>. . . . | . . . . | . . . .</td></tr>
<tr><td>1</td><td>. . . . . . | . . . .</td></tr>
</table>

Configuration optimization

Results

Optimal configurations
for the decreasing number of active sensor layers

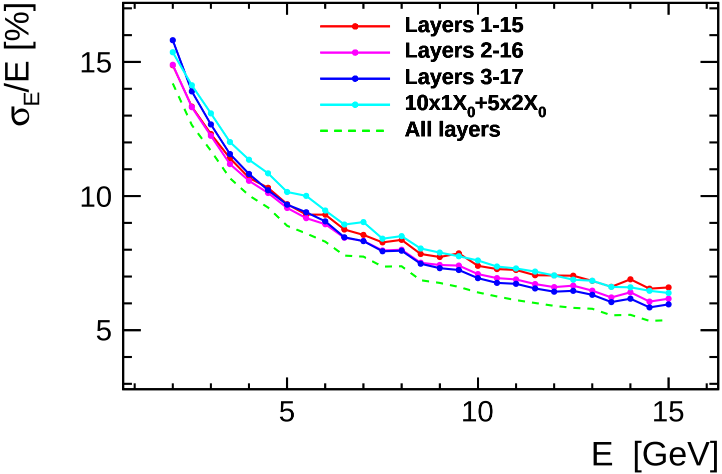
$E = 2.5 - 15$ GeV

| - active layer
. - empty slot

```
N_L | Best option
 20 | | | | | | | | | | | | | | | | | | | | |
 19 | . | | | | | | | | | | | | | | | | | | |
 18 | . | | | | | | | | | | | | | | | | | | .
 17 | . | | | | | | | | | | | | | | | | . | .
 16 | . | | | | | | | | | | | | | | . | | . .
 15 | . . | | | | | | | | | | | | | | | . . .
 14 | . . | | | | | | | | | | | | . | | . . .
 13 | . . | | | | | | | | | . | | . | | . . .
 12 | . . | | | | | | | | | . | . | | . . . .
 11 | . . | | . | | | | | | . | . | . | . . .
 10 | . . | . | | | | . | | . | | . | . . . .
  9 | . . | . | | | . | | . | . | . | . . . .
  8 | . . . | | . | | . | | . | . . | . . . .
  7 | . . . | . | | . | . | . | . | . . . . .
  6 | . . . | . | . | . | . . | . | . . . . .
  5 | . . . | . | . | . . | . | . . . . . . .
  4 | . . . | . . | . . | . . | . . . . . . .
  3 | . . . . | . . . | . . . | . . . . . . .
  2 | . . . . . | . . . . | . . . . . . . . .
  1 | . . . . . . . | . . . . . . . . . . . .
```

Result summary

calibration optimized for best energy resolution in 2–15 GeV range

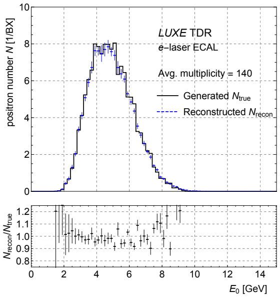


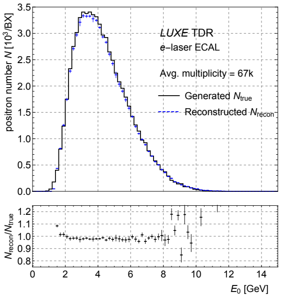
Outline

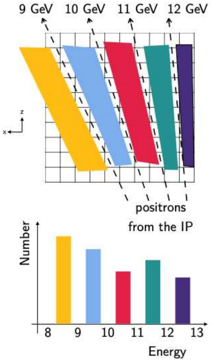
Secondary optimization goal

For single showers, we want to verify position–energy relation with ECAL only.

When running in high intensity conditions photon energy is given by shower position (!) and the energy measurement is used to extract the photon flux at given energy.







⇒ we need precise position determination as well!

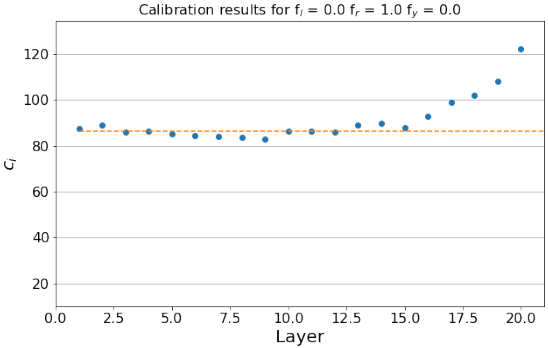
from Shan's presentation in plenary session

Position reconstruction

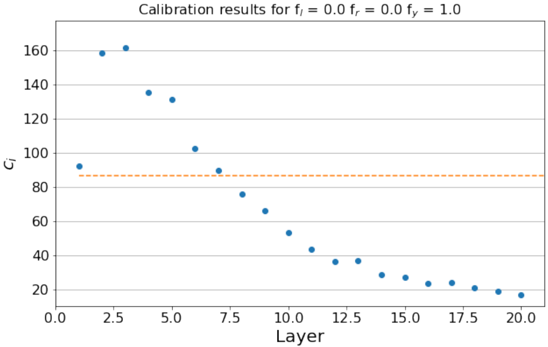
Optimization

Optimal calibration factors for full calorimeter, calibration for 2.5 to 7.5 GeV

Energy reconstruction



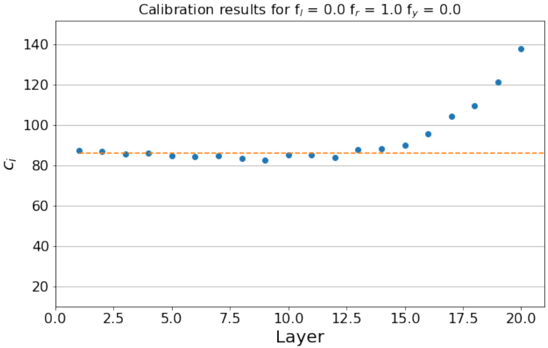
Position reconstruction (weighted average)



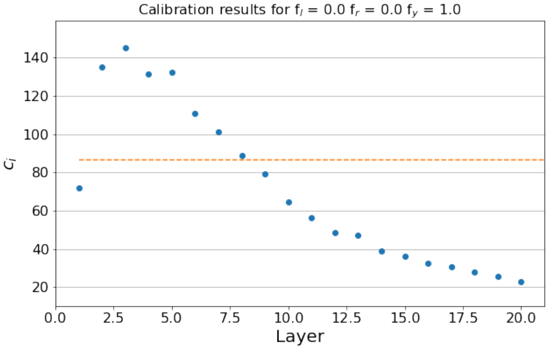
Optimization

Optimal calibration factors for full calorimeter, calibration for 2.5 to 15 GeV

Energy reconstruction



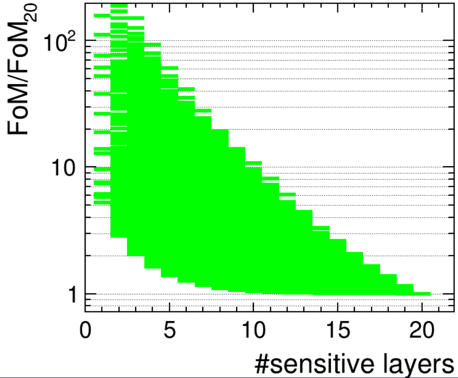
Position reconstruction (weighted average)



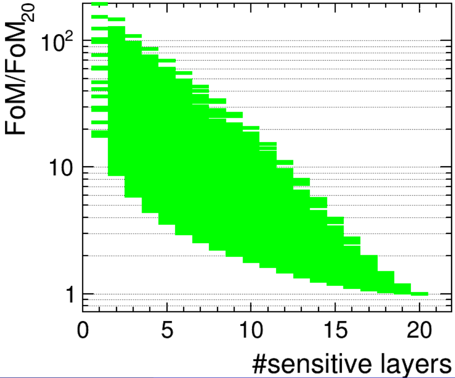
Configuration scan

Figure of merit change as a function of the number of active layers, for $E = 2.5 - 15$ GeV

Position resolution optimization



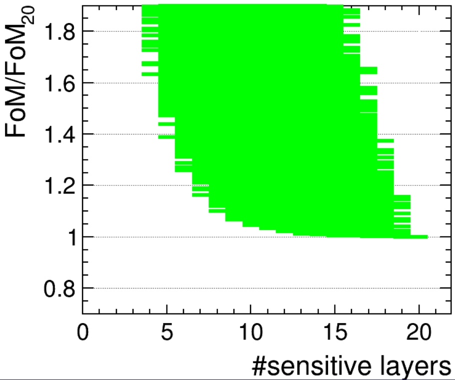
Energy resolution optimization



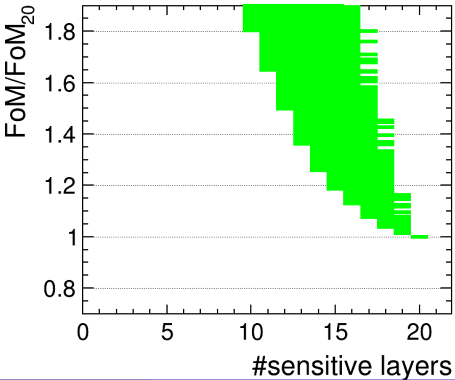
Configuration scan

Figure of merit change as a function of the number of active layers, for $E = 2.5 - 15$ GeV

Position resolution optimization



Energy resolution optimization



Configuration scan

Optimal configurations
looking at the Y position spread only
position calculated as weighted average

$E = 2.5 - 15$ GeV

| - active layer
. - empty slot

```
N_L | Best option
 20 | | | | | | | | | | | | | | | | | | | | |
 19 | | | | | | | | | | | | | | | | | | | | .
 18 | | | | | | | | | | | | | | | | | | | . .
 17 | | | | | | | | | | | | | | | | | | . . .
 16 | | | | | | | | | | | | | | | | | . . . .
 15 | | | | | | | | | | | | | | | | . . . . .
 14 | | | | | | | | | | | | | | | . . . . . .
 13 | | | | | | | | | | | | | | . . . . . . .
 12 | | | | | | | | | | | | | . . . . . . . .
 11 | | | | | | | | | | | | . . . . . . . . .
 10 | . | | | | | | | | | | . . . . . . . . .
  9 | . | | | | | | | | | . . . . . . . . . .
  8 | . | | | | | | | | . . . . . . . . . . .
  7 | . | | | | | | | . . . . . . . . . . . .
  6 | . . | | | | | | . . . . . . . . . . . .
  5 | . . | | | | | . . . . . . . . . . . . .
  4 | . . | | | | . . . . . . . . . . . . . .
  3 | . . . | | | . . . . . . . . . . . . . .
  2 | . . . | | . . . . . . . . . . . . . . .
  1 | . . . . | . . . . . . . . . . . . . . .
```

Position reconstruction

Optimization

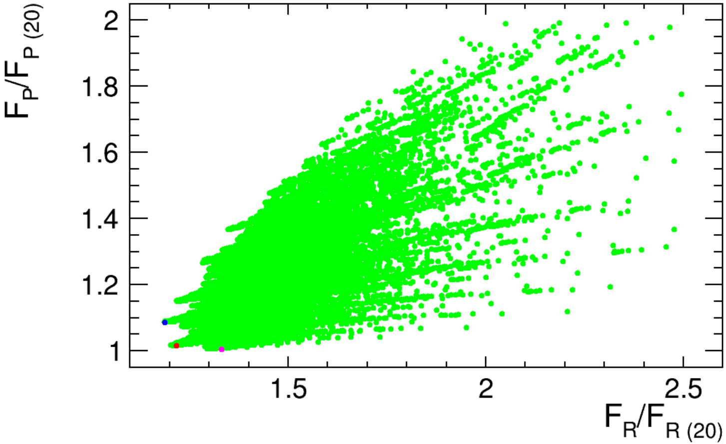
Position vs resolution optimization results for N=15 hardware configurations 2.5–15 GeV

Indicated configurations:

. . | | | | | | | | | | | | | | . . .

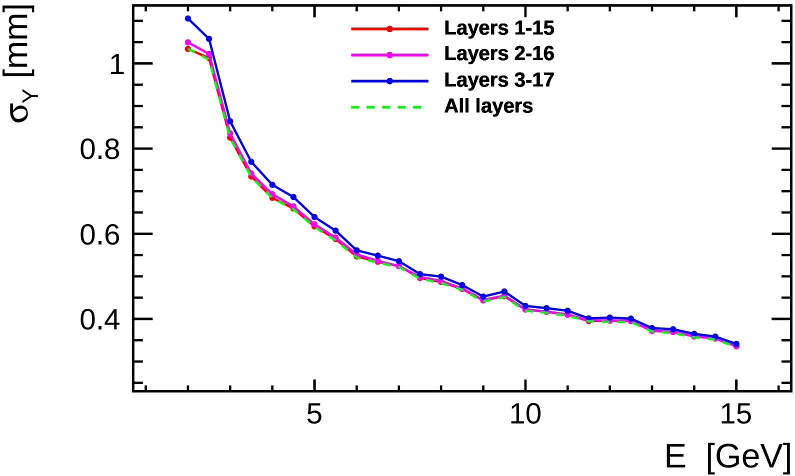
. | | | | | | | | | | | | | | . . . .

| | | | | | | | | | | | | | . . . . .



Result summary

calibration optimized for best position resolution in 2–15 GeV range



Outline

Conclusions

General framework for calorimeter response optimization.
Including response linearity, energy resolution and position resolution goals.

Different calorimeter configurations can be very efficiently compared.

The framework was used to look for the optimal ECAL-P readout configuration when running with the reduced number of sensitive layers.

When only the energy resolution is taken into account, instrumenting layers 3–17 seems to be the best choice.

However, considering also the position measurement precision, and that the spectra is dominated by low energy positrons, instrumenting layers 2–16 looks like a better/safer solution.

Backup slides

Linearity

Relative response shift:

$$\delta_S(E) = \frac{\bar{S} - E}{a\sqrt{E}} = \frac{1}{a\sqrt{E}} \left[\left(\sum_i c_i \cdot \langle s_i^E \rangle \right) - E \right]$$

Figure of merit for linearity:

$$F_L = \sum_E w_E \, \delta_S^2(E) = \sum_E \frac{w_E}{a^2 E} \left[\left(\sum_i c_i \cdot \langle s_i^E \rangle \right) - E \right] \cdot \left[\left(\sum_j c_j \cdot \langle s_j^E \rangle \right) - E \right]$$

Minimum is found by calculating derivatives: $i, k = 1 \ldots N$

$$\frac{\partial F_L}{\partial c_k} = \sum_E 2 w_E \, \delta_S(E) \frac{\partial \delta_S(E)}{\partial c_k} = \sum_i c_i \left(\sum_E \frac{2\, w_E}{a^2 E} \langle s_i^E \rangle \langle s_k^E \rangle \right) - \sum_E \frac{2\, w_E}{a^2} \langle s_k^E \rangle$$

$\Rightarrow$ set of linear equations for extracting values of c_i...

Resolution

Expected resolution:

$$\begin{aligned}
\sigma_S^2 &= \langle S^2 \rangle - \langle S \rangle^2 \\
&= \sum_{i,j} c_i \; c_j \; \langle s_i s_j \rangle - \left(\sum_i c_i \langle s_i \rangle \right) \cdot \left(\sum_j c_j \langle s_j \rangle \right) \\
&= \sum_{i,j} c_i \; c_j \; \left(\langle s_i s_j \rangle - \langle s_i \rangle \langle s_j \rangle \right)
\end{aligned}$$

Relative resolution modified to obtain a linear problem:

$$\delta_\sigma^2 = \frac{\sigma_S^2}{\bar{S}^2} \cdot \frac{E}{a^2} \quad \approx \quad \frac{\sigma_S^2}{a^2 E} \qquad \text{for proper calibration: } \bar{S} \rightarrow E$$

Resolution

Figure of merit for resolution:

$$F_R = \sum_E w_E \, \delta_\sigma^2(E) = \sum_E \frac{w_E}{a^2 E} \sum_{i,j} c_i \, c_j \left(\langle s_i^E s_j^E \rangle - \langle s_i^E \rangle \langle s_j^E \rangle \right)$$

Partial derivatives:

$$\frac{\partial F_R}{\partial c_k} = \sum_E 2 w_E \, \delta_\sigma(E) \, \frac{\partial \delta_\sigma(E)}{\partial c_k} = \sum_i c_i \left[\sum_E \frac{2\, w_E}{a^2 E} \left(\langle s_i^E s_k^E \rangle - \langle s_i^E \rangle \langle s_k^E \rangle \right) \right]$$

Minimum condition for the total FoM:

$$\frac{\partial F}{\partial c_k} = f_l \cdot \frac{\partial F_L}{\partial c_k} + f_r \cdot \frac{\partial F_R}{\partial c_k} = 0$$

$f_l, \; f_r$ – relative weights of linearity and resolution

$$\Rightarrow \sum_i c_i \sum_E \frac{2\, w_E}{a^2 E} \left[f_r \langle s_i^E s_k^E \rangle + (f_l - f_r) \langle s_i^E \rangle \langle s_k^E \rangle \right] = \sum_E \frac{2\, w_E}{a^2} \, f_l \, \langle s_k^E \rangle$$