Dual-readout calorimetry
An integrated high-resolution solution for energy measurements at future electron-positron colliders

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Calorimetry Requirements

at future leptonic colliders

The jet energy resolution is the fundamental quantity for event reconstruction and tagging in multi-jet final states.

Example: $HZ \rightarrow 4\text{jet}$

At an energy resolution of: 

$$\frac{\sigma}{E} \simeq \frac{30\%}{\sqrt{E}}$$

the detector resolution is comparable to the natural widths of $W$ and $Z$ bosons.

Two Proposed Solutions:
Dual-readout calorimetry and Particle Flow with Highly granular calorimeters.
Calorimetry at future leptonic colliders

Highly granular calorimeters

CLIC detector

Highly granular calorimeters

ILC SiD detector

CepC detector

Highly granular calorimeters

Dual-readout calorimeter

FCCee & CepC IDEA detector

FCC CDR: https://cds.cern.ch/record/2653669
CEPC CDR: https://arxiv.org/abs/1811.10545
Non compensation
or why hadronic calorimetry is so hard...

Electromagnetic component: electrons, positrons and photons

Non-electromagnetic component: charged hadrons, nuclear fragments, neutrons, invisible energy

The calorimeter response is different for the two components:

$$\frac{h}{e} \neq 1$$
Non compensation problems

Event-by-event fluctuations of the electromagnetic component are non symmetrical, with an average value increasing with the energy.

All non compensating calorimeters, in hadron detection, exhibit:

- An asymmetrical reconstructed energy
- A non linear reconstructed energy
- An energy resolution much broader than $30\%/\sqrt{E}$

**Dual-readout method**

The only way to overcome the limits due to lack of compensation is to measure the electromagnetic fraction event-by-event and correcting for its value.

Scintillation signal from scintillating fibers: every ionizing particle passing through them releases a light signal.

\[ S = E[fem + \left( \frac{h}{e} \right)_s (1 - fem)] \]

Cherenkov signal from clear-plastic fibers: every relativistic charged particle (almost exclusively electrons) passing through them releases a light signal.

\[ C = E[fem + \left( \frac{h}{e} \right)_c (1 - fem)] \]

\[
\frac{S}{C} = \frac{\text{fem} + \left( \frac{h}{e} \right)_s (1 - \text{fem})}{\text{fem} + \left( \frac{h}{e} \right)_c (1 - \text{fem})}
\]

It is possible to estimate \( fem \) by measuring the ratio of the two signals event-by-event.
Why is it better than the past?

Usually, h/e < 1: the main source of this is the *invisible energy* affecting only the non-electromagnetic component.

The most precise calorimeter is likely the one that exploits the quantity better correlated to the invisible energy.

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**Dual-readout calorimeters**

- *Electromagnetic shower fraction*

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**Neutron boosting calorimeters:**

- SPACAL, ZEUS Calorimeter, …

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**Neutron boosting calorimeters:**

- *Kinetic neutron energy (GeV)*

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Why is it better than the past?

Hints of this better correlation were already present in data!

Dual-readout calorimeters

Number of entries per bin

Neutron boosting calorimeters:
SPACAL, ZEUS Calorimeter, …
How to apply it?

After a calibration with electrons, the S and C reconstructed energy must be combined with:

\[
E = \frac{S - \chi C}{1 - \chi}
\]

\[
\chi = \frac{1 - (h/e)_s}{1 - (h/e)_c}
\]

This equation correctly reproduces both the electron and the hadron energies: *everything is calibrated at the electromagnetic scale, i.e. with electrons.*

From the RD52 lead calorimeter
Absorber Materials

The $\chi$ factor is universal: it does not depend on energy or particle type! It does only depend on the materials and geometry.

$$\chi = \frac{1 - \frac{h}{e}_s}{1 - \frac{h}{e}_c}$$

Keep it high

Keep it low

Hadronic resolution at 1 GeV

Iron

Brass

Lead

$\sigma_E$ vs $E$
The sampling fraction can be raised up as much as possible (not possible with calorimeters compensating by neutron boosting).

The scintillation and Cherenkov signals represent for electrons two independent signals.

A dual-readout calorimeter can reach an excellent electromagnetic and hadronic performance in a single package.
A new machine learning inspired technique is a promising solution to also exploit calibrations with hadrons. The single event under reconstruction is compared to only pre stored events with approximately the same electromagnetic fraction.

The correct hadron energy is then given by

\[ E = \frac{1}{2n} \sum_{i}^{n} \frac{E_{i}}{s_{i}} \times s + \frac{1}{2n} \sum_{i}^{n} \frac{E_{i}}{c_{i}} \times c \]
Lead based calorimeter - 40 GeV π⁻
Simplified jet structure

The same machine learning algorithm could be calibrated and used to reconstruct energy of jets.

Simplified jet model assuming:

fragmentation function

\[ D(z) = (\alpha + 1) \frac{(1 - z)^\alpha}{z} \]

\[ \alpha = 3 \]

\[ z = \text{jet energy fraction} \]

jet composition

90% pion 10% kaon

30% neutral 70% charged

Does it reconstruct the correct energy for all the particles?

Electrons and gammas  Yes

Hard hadrons
(undergoing nuclear interactions)  Yes

Soft hadrons
(behaving like mips)  ? usually  \( \frac{e}{mip} \neq 1 \)
When detecting hadrons the calorimeter deals with a constant number of hard hadrons plus an increasing number of soft hadrons.
Jet energy reconstruction

**DR method**

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<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Entries</td>
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<tr>
<td>Mean</td>
<td>4.253e+04</td>
</tr>
<tr>
<td>Std Dev</td>
<td>1964</td>
</tr>
<tr>
<td>$\chi^2 / \text{ndf}$</td>
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<td>Constant</td>
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<tr>
<td>Sigma</td>
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</table>

**Machine Learning**

<table>
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<th>Value</th>
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</thead>
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<tr>
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</tr>
<tr>
<td>Sigma</td>
<td>1863 ± 14.6</td>
</tr>
</tbody>
</table>

With the classical approach, the average reconstructed energy is slightly overestimated due to:

$$\frac{e}{\text{mip}} < 1$$

With machine learning, the energy is on average correctly reproduced:

Soft hadrons are present also in the trained database.

A dual-readout calorimeter can reach an excellent electromagnetic, hadronic and jet performance in a single package.

Lead based calorimeter - 40 GeV jet
Four different particle identification techniques have been studied with data reaching, for isolated particles, a **99.8%** electron identification efficiency with a rejection factor of 500 for pions.

**At VCI 2019:** A SiPM-based dual-readout calorimeter for future leptonic colliders

Particle Identification

granularity helps

$50 \text{ GeV } e^- \quad 100 \text{ GeV } \pi^0$
The IDEA 2019 Test Beam

To deal with particle identification with multi particle environment a longitudinal segmentation given by an electromagnetic and a hadronic section might be needed.

A possible solution is investigated with a 9x9x250 cm$^3$ lead module with half fibers staggered of 25 cm from the front face.

20 GeV $\text{e}^-$ in long fibers

Signal
Compatible with pedestal

20 GeV $\text{e}^-$ in short fibers
Staggered module results

But... how is it possible to calibrate the short fibers with electrons if electrons do not reach short fibers?

**Scintillating fibers**

60 GeV π⁻ long fibers

60 GeV π⁻ short fibers

Peak induced by hadrons that start showering late in the short section: mean value can be used to scale calibration constants of long fibers to obtain the short fiber ones.
Staggered module results

And for the Cherenkov signal?

**Cherenkov fibers**

**60 GeV π⁻ long fibers**

**60 GeV π⁻ short fibers**

Peak mean value can be used to scale calibration constants of long fibers to obtain the short fiber ones, even for the Cherenkov signal.
The IDEA calorimeter is placed after the magnet. What is the effect of the budget material on the electromagnetic performance?

**RD52 lead calorimeter with lead absorbers in front and a GEM Detector as preshower**

Weighted radius of the em showers given by:

$$R_w = \frac{\sum_{ch} E_{ch} \sqrt{x_{ch}^2 + y_{ch}^2}}{\sum_{ch} E_{ch}}$$

Correlation between radius of shower and number of cluster in GEM preshower.
Conclusions

- The excellent electromagnetic and hadronic resolution of a dual readout calorimeter, as well as its high transverse granularity, make it a great candidate for a detector at future e+e- colliders.

- The RD_FA Collaboration is developing a SiPM based readout, a machine learning based energy calibration/reconstruction and is studying some longitudinal segmentation options. As alternative to the longitudinal segmentation, the extraction of timing information will also be addressed.

More at VCI 2019:
*A SiPM-based dual-readout calorimeter for future leptonic colliders*,
M. Antonello, 19/02 El9
*IDEA Test Beam Results*,
L. Borgonovi, Poster Session A