Dual Readout Calorimetry
For future $e^+e^-$ colliders

Iacopo Vivarelli
University of Sussex
Particle physics in stalemate?

- Did not checkmate fundamental laws of nature
- ... but maybe there is no next move that can be done?
Not really...

• Next move of experimentalists is obvious

Put the Higgs under the microscope (a $e^+e^-$ Higgs factory)
Not really...

• Next move of experimentalists is obvious

Put the Higgs under the microscope (a $e^+ e^-$ Higgs factory)

...while looking for BSM elsewhere
**e^+e^- Higgs factories on the table**

<table>
<thead>
<tr>
<th>Circular</th>
<th>Linear</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN</td>
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</tr>
<tr>
<td><img src="image" alt="CEPC" /></td>
<td><img src="image" alt="CERN" /></td>
</tr>
<tr>
<td>$\sqrt{s} = 90 - 240 \text{ GeV}$</td>
<td>$\sqrt{s} = 380 - 3000 \text{ GeV}$</td>
</tr>
<tr>
<td><img src="image" alt="FCC" /></td>
<td><img src="image" alt="Japan" /></td>
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<tr>
<td>$\sqrt{s} = 90 - 375 \text{ GeV}$</td>
<td>$\sqrt{s} = 250 \text{ GeV}$</td>
</tr>
</tbody>
</table>
Far future?

**CEPC Project Timeline**

- **Pre-Studies (2013-2015)**
  - 2013.9 Project kick-off meeting
  - 2015.1 R&D funded by IHEP
  - 2015.3 Release of Pre-CDR

- **Key Tech. R&D Engineering Design (2016-2021)**
  - 2016.6 R&D funded by MOST
  - 2018.5 1st Workshop outside of China
  - 2018.11 Release of CDR

- **Construction (2022-2030)**
  - 2018.2 1st 10 T SC dipole magnet built
  - 15 T SC dipole magnet & HTS cable R&D

- **Government Approval**
  - 2019-2021 Big Science cultivation
  - Site selection, geological surveys and civil engineering design
  - Key technology demonstration & system verification
  - 2021 Release of Acc. TDR

- **Data Taking (2030-2040)**
  - Higgs
  - Z
  - W

- **SPPC Alternatives: ep/eA**

- **Operation**
  - 2022 MoU, international collaboration
  - 2023-2027 Tunnel & infrastructure construction
  - 2022-2027 Acc. components mass production; 2028-2030 installation, alignment & calibration, followed by commissioning
  - 2023 Decision on detectors and release of detector TDRs; 2024-2030 detector construction, installation and commissioning

- **HTS Magnet R&D Program**
  - 20 T dipole magnet R&D with Nb₃Sn+HTS or HTS
e^+e^- at ZH threshold

- For CEPC (but similar number and performance for FCC):
  - 5.6 ab\(^{-1}\) translate in a million ZH events
e^+e^- at ZH threshold

• For CEPC (but similar number and performance for FCC):
  • **5.6 ab\(^{-1}\) translate in a million ZH events**
  • Higgs boson tagging gives unique access to e^+e^-→ZH production cross section
e^{+}e^{-} at ZH threshold

• For CEPC (but similar number and performance for FCC):
  • **5.6 ab^{-1} translate in a million ZH events**
  • Higgs boson tagging gives unique access to e^{+}e^{-}→ZH production cross section

• **3% model-independent** Higgs boson width measurement from

\[
\Gamma_H = \frac{\Gamma(H \to ZZ^*)}{\text{BR}(H \to ZZ^*)} \propto \frac{\sigma(ZH)}{\text{BR}(H \to Z Z^*)}
\]

\[
\Gamma_H = \frac{\Gamma(H \to b\bar{b})}{\text{BR}(H \to b\bar{b})} = \frac{\Gamma(H \to WW^*)}{\text{BR}(H \to WW^*)} \propto \frac{\sigma(\nu\bar{\nu}H)}{\text{BR}(H \to WW^*)}
\]
Higgs boson sensitivity

![Precision of Higgs coupling measurement (7-parameter Fit)]

- LHC 300/3000 fb^{-1}
- CEPC 240 GeV at 5.6 ab^{-1} wi/wo HL-LHC
Higgs boson sensitivity

Precision of Higgs coupling measurement (10-parameter Fit)

- CEPC 240 GeV at 5.6 ab\(^{-1}\)
- Combined with HL-LHC
Physics requirements for calorimetry

• **Precision physics** at $e^+e^-$ collider calls for **high-resolution hadronic calorimetry**

<table>
<thead>
<tr>
<th>Physics Process</th>
<th>Measured Quantity</th>
<th>Critical Detector</th>
<th>Required Performance</th>
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<tr>
<td>$ZH \rightarrow \ell^+\ell^- X$</td>
<td>Higgs mass, cross section</td>
<td>Tracker</td>
<td>$\Delta(1/p_T) \sim 2 \times 10^{-5}$</td>
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<tr>
<td>$H \rightarrow \mu^+\mu^-$</td>
<td>BR($H \rightarrow \mu^+\mu^-$)</td>
<td>Tracker</td>
<td>$\oplus 1 \times 10^{-3}/(p_T \sin \theta)$</td>
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<tr>
<td>$H \rightarrow b\bar{b}, c\bar{c}, gg$</td>
<td>BR($H \rightarrow b\bar{b}, c\bar{c}, gg$)</td>
<td>Vertex</td>
<td>$\sigma_{\phi} \sim 5 \oplus 10/(p \sin^{3/2} \theta)$ $\mu$m</td>
</tr>
<tr>
<td>$H \rightarrow q\bar{q}, VV$</td>
<td>BR($H \rightarrow q\bar{q}, VV$)</td>
<td>ECAL, HCAL</td>
<td>$\sigma_{E_{\text{int}}}/E \sim 3 - 4%$</td>
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<tr>
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![Graphs showing M_{134} vs. M_{12} for different jet energy resolutions (JER)]
Particle flow approach

- Basic idea: tracking wins at low particle energy
- Use tracks to measure charged particles in the shower

From arXiv:1706.04965


From https://warwick.ac.uk/fac/sci/physics/staff/academic/boyd/warwick_week/detector_physics/warwick_lecture_calorimetry.pdf
A different approach

- Attacking the problem from **two sides** always gives opportunities to learn

- Dual readout calorimetry:
  - Excellent **native electromagnetic and hadronic** calorimeter resolution
  - Excellent lateral granularity

Mate in 2
Hadronic Calorimetry - primer
Hadronic Calorimetry - primer

• Hadronic shower:
  
  • **Driven by a relatively small number** of strong interactions with nuclei
  
  • **Strong** intrinsic interaction intensity, but **small targets** (scale to bear in mind 1 fm = 10^{-15} m)
  
  • \( \pi^0, \eta^0 \) production leads to **EM component within hadronic shower**
Hadronic showers

• Lots of different physics processes at work in a hadronic shower:
  • EM component: large fluctuations in number and energy of $\pi^0, \eta^0$
  • HAD component:
    • Ionisation from charged hadrons
    • Nuclear remnants (fission, knock-off)
    • Delayed photons
    • Invisible component (nuclei breakup)
Hadronic showers

- Large **event-by-event** fluctuations in shape (and energy) deposit
- **Charged hadrons propagate the shower** on large scale \( \lambda_l \), **local** EM showers from \( \pi^0, \eta^0 \).
Why is hadronic calorimetry challenging?

Typically* the calorimeter response to the electromagnetic (e) and hadronic (h) components is different (because of invisible energy)

*This is actually true for non-compensating calorimeter (the vast majority of those in use nowadays)
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The fraction of energy in EM component and HAD component is energy dependent with large fluctuations.
Why is hadronic calorimetry challenging?

Typically*, the calorimeter response to the electromagnetic (e) and hadronic (h) components is different (because of invisible energy)

*This is actually true for non-compensating calorimeter (the vast majority of those in use nowadays)

The fraction of energy in EM component and HAD component is energy dependent with large fluctuations

The calorimeter response to hadrons is energy dependent and fluctuates a lot
Calorimeter response to hadrons

• Typically calorimeters are calibrated to the **EM scale**

  • For example: you shoot 20 GeV electrons and want to read 20 GeV

  • Say \( r \) is the energy deposit in active material in the calorimeter. Then you choose \( k \) such that

\[
E_e = ker
\]

• Then the response to a hadron is

\[
E_h = k(ef_{em} + h(1 - f_{em}))r
\]

• and with respect to that of an electron of the same energy

\[
E_h = E_e(f_{em} + \frac{h}{e}(1 - f_{em}))
\]
**f_{em} energy dependence**

- Simple model: **only pions** are produced at each interaction, **respecting isospin symmetry**

- Then the math is:
  \[
  \pi^\pm, E = E_0
  \]
**f_{em} energy dependence**

- Simple model: **only pions** are produced at each interaction, **respecting isospin symmetry**
- Then the math is:

\[
\sum E_{\pi^\pm} \sim \frac{2}{3} E_0 \\
\sum E_{\pi^0} \sim 1 - \sum E_{\pi^\pm} = 1 - \frac{2}{3} E_0
\]
**f_{em} energy dependence**

- Simple model: **only pions** are produced at each interaction, **respecting** isospin symmetry

- Then the math is:

\[
\begin{align*}
\sum E_{\pi^\pm} &\sim \frac{2}{3}E_0 \\
\sum E_{\pi^0} &\sim 1 - \sum E_{\pi^\pm} = 1 - \frac{2}{3}E_0 \\
\sum E_{\pi^0} &\sim 1 - \frac{4}{3}E_0 \\
\sum E_{\pi^0} &\sim 1 - \frac{2}{3}E_0
\end{align*}
\]
**f_{em} energy dependence**

- Simple model: **only pions** are produced at each interaction, respecting isospin symmetry.

- Then the math is:

\[
\frac{f_{em}}{E} = \frac{E_{em}}{E} = 1 - \left( \frac{2}{3} \right)^n \\
\left( \frac{2}{3} \right)^n E = E_{th} \quad \text{(Condition to stop shower)}
\]

\[
n = p \ln \frac{E}{E_{th}} \quad \text{(for some number p)}
\]

\[
f_{em} = 1 - \left( \frac{2}{3} \right)^n = 1 - \left( \frac{E}{E_{th}} \right)^{k-1} \quad \text{(for some number k)}
\]
**$f_{em}$ energy dependence**

- $f_{em}$ depends on the **incoming particle energy**
- Fluctuations in $f_{em}$ are **large and non-poissonian**

$$f_{em} = 1 - \left( \frac{E}{E_0} \right)^{k-1}$$
The curse of hadronic calorimetry

- Non-compensating calorimeters: response to em part different from that to non-em part. $h/e < 1$

- $\langle f_{em} \rangle$ energy dependent $\Rightarrow$ Non-linear calorimeter response to hadrons

\[ E_{\text{meas}} = E \left( f_{em} + \frac{h}{e} (1 - f_{em}) \right) \]
The curse of hadron calorimetry (2)

- Event-by-event $f_{\text{em}}$ fluctuations dominate the hadronic calorimeter resolution

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Detector</th>
<th>Absorber material</th>
<th>$e/h$</th>
<th>Energy resolution (E in GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UA1 C-Modul</td>
<td>Scintillator</td>
<td>Fe</td>
<td>$\approx 1.4$</td>
<td>$80%/\sqrt{E}$</td>
</tr>
<tr>
<td>ZEUS</td>
<td>Scintillator</td>
<td>Pb</td>
<td>$\approx 1.0$</td>
<td>$34%/\sqrt{E}$</td>
</tr>
<tr>
<td>WA78</td>
<td>Scintillator</td>
<td>U</td>
<td>0.8</td>
<td>$52%/\sqrt{E} \pm 2.6%$*</td>
</tr>
<tr>
<td>D0</td>
<td>liquid Ar</td>
<td>U</td>
<td>1.11</td>
<td>$48%/\sqrt{E} \pm 5%$*</td>
</tr>
<tr>
<td>H1</td>
<td>liquid Ar</td>
<td>Pb/Cu</td>
<td>$\leq 1.025^*$</td>
<td>$45%/\sqrt{E} \pm 1.6%$</td>
</tr>
<tr>
<td>CMS</td>
<td>Scintillator</td>
<td>Brass (70% Cu / 30% Zn)</td>
<td>$\approx 1$</td>
<td>$100%/\sqrt{E} \pm 5%$</td>
</tr>
<tr>
<td>ATLAS (Barrel)</td>
<td>Scintillator</td>
<td>Fe</td>
<td>$\approx 1$</td>
<td>$50%/\sqrt{E} \pm 3%$</td>
</tr>
<tr>
<td>ATLAS (Endcap)</td>
<td>liquid Ar</td>
<td>Brass</td>
<td>$\approx 1$</td>
<td>$60%/\sqrt{E} \pm 3%$</td>
</tr>
</tbody>
</table>

Dual readout
Dual readout - the principle

• Suppose I read out two signals, S and C, with different h/e. Then:

\[ E_S = E \left( f_{em} + \left( \frac{h}{e} \right)_S (1 - f_{em}) \right) \]
\[ E_C = E \left( f_{em} + \left( \frac{h}{e} \right)_C (1 - f_{em}) \right) \]

\[ f_{em} = \frac{\left( \frac{h}{e} \right)_C - \left( \frac{h}{e} \right)_S \left( \frac{E_C}{E_S} \right)}{\left( \frac{E_C}{E_S} \right) \left( 1 - \left( \frac{h}{e} \right)_S \right) - \left( 1 - \left( \frac{h}{e} \right)_C \right)} \]

\[ E = \frac{(E_S - \chi E_C)}{1 - \chi} \]

\[ \chi = \frac{1 - \left( \frac{h}{e} \right)_S}{1 - \left( \frac{h}{e} \right)_C} \]

Depends only on the detector, it can be determined in test beam for example.
Dual readout - the signals

In practice, this is realised with:

- **S**: scintillating fiber signal measuring dE/dx of particles. Sensitive to **all shower components** - h/e < 1

- **C**: undoped fibres sensitive to **Cherenkov** signal from relativistic particles in the shower (essentially only EM component) - h/e ~ 0.2

\[
\frac{S}{E} = \left( f_{em} + \left( \frac{h}{e} \right)_S (1 - f_{em}) \right)
\]

\[
\frac{C}{E} = \left( f_{em} + \left( \frac{h}{e} \right)_C (1 - f_{em}) \right)
\]

\[\chi = \frac{1 - \left( \frac{h}{e} \right)_S}{1 - \left( \frac{h}{e} \right)_C} = \cot \theta\]
Dual readout calorimeters (PMT readouts)

2003 DREAM
Cu: 19 towers, 2 PMT each
2m long, 16.2 cm wide
Sampling fraction: 2%

2012 RD52
Cu, 2 modules
Each module: $9.2 \times 9.2 \times 250$ cm$^3$
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~4.6%
Depth: ~10 $\lambda_{\text{int}}$

2012 RD52
Pb, 9 modules
Each module: $9.2 \times 9.2 \times 250$ cm$^3$
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~5.3%
Depth: ~10 $\lambda_{\text{int}}$
Dual readout calorimeter at work

Leakage counters

RD52 (Pb)

Ancillary detectors
Electron response

\[ \frac{\sigma}{E} = \frac{11\%}{\sqrt{E \text{ (GeV)}}} + 1\% \]

- **Scintillation**
- **Čerenkov**
- **S + Č**

### 40 GeV electrons

**Scintillator**
- Entries: 739
- \( \chi^2 / \text{ndf} \): 280.3 / 19
- Mean: 40.8 ± 0.8
- Sigma: 1.337 ± 0.01

- **Čerenkov**
- Entries: 739
- \( \chi^2 / \text{ndf} \): 305.5 / 223
- Mean: 39.94 ± 0.10
- Sigma: 1.609 ± 0.015

### Cu (low-energy measurements)

- **Scintillation**
- **Čerenkov**

### Pb (high-energy measurements)

- **Scintillation**
- **Čerenkov**
Single hadron response - linearity

• Dual readout signal largely recovers linearity while vastly improving resolution

20 GeV pions

- Entries 28570
  - Mean 7.994
  - RMS 3.032

- Entries 28570
  - Mean 11.71
  - RMS 2.373

- Entries 28570
  - \( \chi^2 / \text{ndf} \) 552.3 / 292
  - Mean 18.28 ± 0.02
  - Sigma 2.896 ± 0.013
Single hadron response - resolution

- Curse of calorimeter R&D: a fully containing calorimeter is expensive

No signal in leakage counters

![Graphs showing single hadron response resolution](image)
Performance of Dual Readout

- **Hadronic resolution comparable to compensating calorimeters.**

- Resolution at TB (dominated by leakage). G4 estimate with full containment $\frac{\sigma}{E} = 34\% \sqrt{E}$

See [https://doi.org/10.1016/j.ppnp.2018.07.003](https://doi.org/10.1016/j.ppnp.2018.07.003)
Recent results
A practical implementation: IDEA

See here for additional information
IDEA slice on beam (2018)

- A full **combined test** of IDEA:
  - Drift chamber prototype
  - GEM as preshower + µRWell for µ detection
  - Several calorimeter options tested on beam
From PMTs to SiPM

SiPM pros:
- Compact readout
- Resilience to magnetic field
- Large light yields
- High readout granularity (particle flow “friendly”)
- Photon counting (calibration)
- High timing resolution

SiPM cons:
- Signal saturation/dynamic range
- Cross talk between C and S signals
- Instrumental effects
SiPM dual readout

- Single fibre readout with HAMAMATSU SiPM
- Readout for Cherenkov and Scintillation light separated to minimise cross talk (the latter expected to be ~ 50 times larger if not attenuated)
SiPM dual readout

Operating with $5.5 \ V_{OV}$ - PDE ~ 22%

Cherenkov light yield (70 Spe/GeV) ~ a factor 2 larger than what measured with PMT

(Filtered) scintillation light yield under control (~95 Spe/GeV).

EM stochastic term ~ 10% is achievable

**No saturation effects:**
Hottest fibre: 9.8 Spe/GeV linear within 1%

Hottest fiber
SiPM dual readout (shower shape)

• Readout of single fibre gives unprecedented lateral segmentation

• Em lateral shower shape measured with ~ 1 mm precision.

\[
\begin{align*}
\bar{x} &= \frac{\sum_i x_i E_i}{\sum_i E_i}; \quad \bar{y} = \frac{\sum_i y_i E_i}{\sum_i E_i} \\
r &= \sqrt{(x_i - \bar{x})^2 + (y_i - \bar{y})^2}
\end{align*}
\]

Doi:10.1016/j.nima.2018.05.016

![Graph](image)
Combined measurements (RD52)

- RD52 performance studied in detail elsewhere
  - Focus on DAQ combination and combined runs with GEM-based preshower

\[
R_{\text{shower}} = \frac{\sum_{ch} E_{\text{ch}} \cdot \sqrt{x_{\text{ch}}^2 + y_{\text{ch}}^2}}{\sum_{ch} E_{\text{ch}}}
\]

Shower width from 5 mm Pb + additional material correlates with number of clusters in GEM preshower
Longitudinal segmentation (standalone test)

- Particle identification (e.g. hadronic tau decay) may benefit from **longitudinal segmentation**.
- “Staggered” option tested on beam

  “HAD” section: \( E(\text{short fibres}) \)
  “EM” section: \( E(\text{long fibres}) - E(\text{short fibres}) \)

- Challenge: calibration of the short section.
Longitudinal segmentation

• Problem: how do we calibrate short section?

• Idea: propagate calibration from long section using hadrons.

Long section 60 GeV π signal

Short section 60 GeV π signal

Scintillation fibers

Ratio

Longitudinal segmentation

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Long section 60 GeV π signal

Short section 60 GeV π signal

Scintillation fibers
Longitudinal segmentation

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![Long section 60 GeV π signal](image1)

![Short section 60 GeV π signal](image2)

![Ratio](image3)

Scintillation fibers
Longitudinal segmentation

• Problem: how do we calibrate short section?

• Idea: **propagate calibration** from long section **using hadrons**.

Long section 60 GeV π signal

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Short section 60 GeV π signal

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Ratio

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Scintillation fibers
Open questions
Simulation

- Final choices need **reasonably well understood G4 simulation**
- Existing fast sim + **full G4 sim projective geometry**

**Barrel (right):** 40 towers  
Inner length 2.5m  
Tower height 2.0m

**Endcap (right):** 39 towers  
Inner length 2.25m  
Tower height 2.0m

- **Open points:**
  - Reliability of G4 to reproduce $\chi$ value.
  - More structured software effort for full IDEA project
Absorber and layout

- Copper/brass calorimeter would avoid problems with e/mip
  - But lead more cost-effective
  - Options to be finalised with G4 simulation

- Readout with longitudinally distributed fibres is the baseline:
  - Excellent lateral segmentation and electronics all outside the calorimeter
  - But large number of fibres/SiPM readout channels needed

- Other options being investigated:
  - Tiles
  - More creative options

Courtesy of L. Pezzotti
Longitudinal segmentation - use timing?

• Profit from **excellent SiPM time resolution** - derive **energy deposit longitudinal position** with time

• More studies with simulation needed

SiPM readout (2):

- digitiser (ASIC) & feature extraction (FPGA)
  - started investigating
  - time stamps w/ O(100 ps res)
    - get shower longitudinal development

\[
\Delta x \approx 5 \text{ cm} \Rightarrow \Delta t \approx 100 \text{ ps}
\]

- started looking at neural network implementation
Costs

- Total foreseen cost at the moment ~ 150 M€.
  - Dominated by optical elements (fibre + SiPM)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Quantity</th>
<th>Total (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibres</td>
<td>0.25 €/m</td>
<td>57.4</td>
</tr>
<tr>
<td>SiPM</td>
<td>0.25 € each</td>
<td>47.7</td>
</tr>
<tr>
<td>Absorber</td>
<td>2000 €/ton</td>
<td>6.7</td>
</tr>
<tr>
<td>Front-end</td>
<td>-</td>
<td>17.9</td>
</tr>
</tbody>
</table>

- Actively looking at ways of reducing these costs
Summary

- Dual readout:
  - **Complementary** principles w.r.t. particle flow.
  - Excellent EM and HAD native resolution.
  - Could be combined with pFlow approach if need be.

- Towards a prototype. Help welcome on each of the open questions
Backup
EM performance

- Excellent $e$ and $\gamma$ calorimeter performance thanks to high sampling fraction.
  - EM and HAD calorimetry in one device.
Results from 2017 test beam

- Detector operated at 0.5V over breakdown (PDE ≈ 2%)
- Temperature stability correction:
  - < 0.5°C during a single run (negligible)
  - < 2°C during the full scan (considered)
- PDE correction for temperature variation

\[ N_{\text{fired}} = N_{\text{total}} \times \left[ 1 - e^{-\frac{N_{\text{photons}} \times \text{PDE}}{N_{\text{total}}}} \right] \]

Even if the SiPMs are not saturated with this setting, they are working in a strongly non-linear regime: a correction is required.

Valid as a first approximation: the light uniformly illuminate the SiPMs, all photons come at the same time and spurious effects are negligible.

Scintillation light

Results from 2017 test beam

- Detector operated at 0.5V over breakdown (PDE ≈ 2%)
- Temperature stability correction:
  - < 0.5°C during a single run (negligible)
  - < 2°C during the full scan (considered)
- PDE correction for temperature variation

Once the correction is applied, the linearity is improved even if it is not fully recovered (i.e. signal from the seed)

To reduce this effect we decided to attenuate the scintillating light using a yellow filter
Cherenkov light

*Cherenkov light yield:*

\[ V_{\text{Bias}} = 5.5 \ V_{\text{ov}} (57.5 \ V) \text{ and } PDE \approx 25\%. \]

\[ \sim 28.6 \ \text{Cpe/GeV}, \ 2\% \text{ linear from 6 to 125 GeV}. \]

Correcting for 36\% e.m. energy containment: \( 69 \pm 5 \ \text{Cpe/GeV}. \)

More than *2 times larger* than what measured with the previous* PMT-based modules.

*Example:*

Stochastic term of RD-52 e.m. resolution could be improved from \( \sim 14\%/\sqrt{E} \)

up to \( \sim 12.5\%/\sqrt{E} \).

(sampling fluctuations: \( \sim 9%/\sqrt{E} \)).
Grouping channels

In a full scale module, the number of *readout channels* will be of the order of $10^8$.

The possibility to **sum up the analog output** is under study:

- Number of SiPM that can be grouped guarantying the *Multi-Photon spectrum*.
- SiPM *dynamic range*: sensors have to operate in a *linear regime*.

![Graph showing Multi-Photon spectrum and readout granularity]

**Multi-Photon spectrum preserved also with 9 grouped SiPM.**

![Diagram showing SiPM and space granularity]

**Readout granularity can be reduced: 2x2, 2x3, 3x3...**

<table>
<thead>
<tr>
<th>SiPM number</th>
<th>1</th>
<th>4</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space granularity (mm²)</td>
<td>4.5</td>
<td>18</td>
<td>36</td>
</tr>
</tbody>
</table>
Outline

- Why dual readout?
- Towards a combined detector: IDEA test beam
  - Combined data taking with old prototypes
  - SiPM readout
  - Longitudinal segmentation
- Summary
**EM showers: relevant numbers**

- **Radiation length** $X_0$: typical scale of longitudinal shower development
  \[
  X_0 \sim 1433 \frac{A}{Z(Z + 1)(11.32 - \ln Z)} \left( \frac{\text{g}}{\text{cm}^2} \right) \Rightarrow \sim \frac{1}{Z}
  \]

- **Critical energy** $E_C$ (below which ionisation takes over bremsstrahlung)
  \[
  E_C \sim \frac{160 \text{ MeV}}{Z + 1.24} \Rightarrow \sim \frac{1}{Z}
  \]

- **Molière radius** $R_M$ (typical scale of lateral shower development)
  \[
  R_M \sim \frac{X_0 \times 21.2 \text{ MeV}}{E_C} \Rightarrow \sim \text{const}
  \]

- **Shower depth** (shower maximum), where the multiplication process stops
  \[
  X_{\text{max}} = X_0 \frac{\ln \left( \frac{E}{E_C} \right)}{\ln 2} \Rightarrow \sim \frac{1}{Z}, \sim \ln E
  \]
Reminder: why dual readout?

- Precision physics at e+e- collider calls for high-resolution hadronic calorimetry

\[
\frac{\sigma}{E} = \frac{60\%}{\sqrt{E}}
\]

\[
\frac{\sigma}{E} = \frac{22\%}{\sqrt{E}}
\]

ideal resolution
EM shower

- Large number of particles involved
- Regular shape
- Small event-by-event fluctuations
**f_{em} energy dependence**

- **Simple model**: only pions are produced at each interaction, respecting isospin symmetry

- Then the math is:

\[
f_{em} = \frac{E_{em}}{E} = 1 - \left(\frac{2}{3}\right)^n
\]

\[
\left(\frac{2}{3}\right)^n E = E_0
\]

\[
n = p \ln \frac{E}{E_0} \quad \text{(for some number } p)\]

\[
f_{em} = 1 - \left(\frac{2}{3} \ln \frac{E}{E_0}\right)^p = 1 - \left(\frac{E}{E_0}\right)^{k-1} \quad \text{(for some number } k)\]
Calorimetry - a primer

• Electromagnetic shower:
  • Driven by **EM interactions with atom EM field**
  • **Moderate** intrinsic interaction intensity, but **big targets** (scale to bear in mind ~ 10^{-10} m)
  • Main mechanisms at work: **bremsstrahlung, pair production, ionisation.**
  • Lots of particles involved
Measuring hadronic showers

• Definitions:
  
  • e is the efficiency of the measurement of the **EM component**
  
  • h is the efficiency of the measurement of the **HAD component**
  
  • e/h is a characteristic number **of the calorimeter**

  • Normally e/h > 1 (mostly because of invisible component), and the calorimeter is said to be **non-compensating**.
SiPM readout - results (test beam 2017)

- Cherenkov light yield linear with beam energy over a wide range.
- Light yield 28 Spe/GeV:
  - After correcting for containment ~ 55 Spe/GeV.

- Scintillation response showing evidence of saturation (addressed in 2018 test).
Calorimeter options used during TB

• **RD52 module** (combined data taking with other sub detectors)

• **SiPM-based** readout (standalone)

• **“Staggered” module** (standalone)