Near Detector ECAL: Software and Results.

DUNE Collaboration Meeting

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DESY/Manchester
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Outline.

1. Motivation
2. Optimisation study results
3. Software Status
4. Outlook and Conclusion
Motivation.
A case for a highly granular calorimeter

Near detector design

- Revolves around a Liquid Argon TPC and a HPgTPC surrounded by an ECAL, a magnet and a muon detector
- HPgTPC does not have the capabilities to track converted π0
  - Very high granular ECAL needed!
  - Reconstruction of the π0 vertex
- **Challenge**: Very low photon energies ~ few 10 to few 100 MeV

[Plot of photon spectrum from π0 decays courtesy of C. Marshall]
The concept.

A geometrical concept for the ECAL

- Electromagnetic calorimeter with **highly segmented** active material
- *Very limited space* → cannot fit the full ECAL inside the **pressure vessel**
- Split the calorimeter into two parts separated by the pressure vessel
The concept.

A geometrical concept for the ECAL

- Concept based on the **CALICE AHCAL**
- *Individual tiles* of scintillator readout by **SiPMs**
- Granularity is one of the variable to **optimise**
  - Especially *backing layers* may not need a very high granularity
The concept.
A geometrical concept for the ECAL

- **First design:**
  - using *Cu absorber* and scintillator tiles of between 2x2 and 3x3 cm²
  - **80 layers** - 30 (inner) + 50 (outer)
  - **Pressure Vessel** of ~1-2 cm thickness made of steel or tungsten

*Optimisation of the detector design needed*

Simulation studies
Where to improve?

- Several optimisation studies
  - Influence of the **pressure vessel**
  - **Granularity** of the inner and outer ECAL
  - **Absorber** material and thickness
- Observables
  - Influence on **energy resolution** and **angular resolution**
  - $\pi_0$ reconstruction
  - Neutron detection efficiency
- Preliminary simulations by **Lorenz Emberger (MPI Munich)**
  - Standalone G4 simulation
  - Simple digitisation / reconstruction
- Other efforts ongoing
  - Study of **different absorber thicknesses** in the ECAL
Some Results and Studies ongoing (MPI).

ECAL energy resolution and angular resolution

- Various variables driving the energy and angular resolution
  - Use of these two observables to compare the calorimeter performance
  - Below: 2x2 cm² with 2 mm Cu absorber

\[
\frac{\sigma}{E_{\text{mean}}} = \sqrt{\left(\frac{A}{\sqrt{E}}\right)^2 + \left(\frac{B}{E}\right)^2 + (C)^2}
\]

\[
\text{Resolution} = \sqrt{\left(\frac{A}{\sqrt{E}}\right)^2 + \left(\frac{B}{E}\right)^2 + (C)^2}
\]

A \ 0.0486 \pm 0.0002
C \ 0.0288 \pm 0.0007

A \ 0.0439 \pm 0.0003
B \ 0.0194 \pm 0.0007
Some Results and Studies ongoing (MPI).

Influence of the pressure vessel

- **Driving factors:** thickness, material, sampling fraction
- Pressure vessel → thinner is better for energy and less for angular resolution
- **No** pressure vessel gives the **best** energy resolution

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**Graphs:**

1. **Normalized angular resolution**
   - No vessel
   - 14mm titanium vessel (~0.4X0)
   - 20mm steel vessel (~1X0)

2. **Normalized energy resolution**
   - No vessel
   - 14mm titanium vessel (~0.4X0)
   - 20mm steel vessel (~1X0)
Some Results and Studies ongoing (MPI).

Neutron detection

- HPgTPC does not have the capabilities for **neutron detection**
- → **ECAL** can provide sensitivity to neutrons
- Need to determine the **neutron performance** (detection efficiency and hadronic energy resolution)
  - **Efficiency** above 50-60% for neutron energies above 50 MeV
  - **Energy resolution** around 50-60% (for energies between 10 - 600 MeV)
Some Results and Studies ongoing (MPI).

**ECAL optimisation**

- **Pion reconstruction**
  - Use of the calorimeter geometrical information
  - Kinetic information (invariant mass)
- Use of a $\chi^2$ minimisation to optimise the vertex estimate
- Vertex reconstruction improves with pion energy
- Vertex reconstruction gets worse at larger distance to the ECAL front face
- Potential for improvements
Some Results and Studies ongoing (U. Mainz).

**ECAL optimisation**

- Ongoing study influence of the **absorber thickness**
- Work from **Jan Schäffer** (janschae@students.uni-mainz.de)

- Based on the SHiP experiment software
- Low energy photons of high interest
- Optimize for energies of 10 to 250 MeV

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>New Setup</th>
</tr>
</thead>
<tbody>
<tr>
<td>N layers</td>
<td>80</td>
<td>70</td>
</tr>
<tr>
<td>Passive</td>
<td>Copper</td>
<td>Copper</td>
</tr>
<tr>
<td>Active</td>
<td>0.5 cm</td>
<td>0.75 cm</td>
</tr>
<tr>
<td>Passive</td>
<td>0.2 cm</td>
<td>50x 0.1 cm</td>
</tr>
<tr>
<td></td>
<td>10x 0.2 cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10x 0.35 cm</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>56 cm</td>
<td>63 cm</td>
</tr>
<tr>
<td>A [√GeV]</td>
<td>5.1 \times 10^{-2}</td>
<td>3.3 \times 10^{-2}</td>
</tr>
<tr>
<td>B [GeV]</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>2.6 \times 10^{-2}</td>
<td>8.8 \times 10^{-2}</td>
</tr>
</tbody>
</table>

\[
\frac{\sigma}{E_{\text{mean}}} \pm 8.8 \%
\]

\[
\frac{3.3 \%}{\sqrt{E[\text{GeV}]}}
\]

Study increase of absorber thickness with increasing depth

⇒ Energy resolution improved for \( E_{\gamma} \leq 250 \text{MeV} \)
Some Results and Studies ongoing.

Optimisation overview

- Overview of the current optimisation efforts
- **Summary:**
  - **PV material** and **thickness** impact the **energy resolution** mainly
  - **Absorber type** → **Pb** **improves** energy resolution but **degrades** angular resolution
  - **Granularity** → small granularity favoured in the **inner ECAL**
  - **Real-world considerations:** Channel count… (80 layers)
    - 2x2 cm$^2$ → ~200k channels / m$^2$
    - 3x3 cm$^2$ → ~88k channels / m$^2$
  - → Need to know the **granularity requirements** to optimise the detector design
  - → **Clever solutions** to reduce the channel count

<table>
<thead>
<tr>
<th></th>
<th>Angular Resolution</th>
<th>Energy Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>No vessel</td>
<td>Default</td>
<td>Default</td>
</tr>
<tr>
<td>Copper absorber</td>
<td>Default</td>
<td>Default</td>
</tr>
<tr>
<td>Titanium vessel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel vessel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead absorber</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Higher granularity in</td>
<td></td>
<td></td>
</tr>
<tr>
<td>inner calorimeter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Higher granularity in</td>
<td></td>
<td></td>
</tr>
<tr>
<td>outer calorimeter</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Angular Resolution**
- Negative
- Positive
- Neutral
ECAL Geometry

- **Geometry:**
  - Redesign of the ECAL -> **cylindrical shape** around the TPC
  - New geometry code -> courtesy of M. Kordosky with gegede

- **Optimisation** of the geometry code
  - Remove the *explicit description* of each tile
    - → **Simplify** geometry layout
    - → **Faster loading** with G4 and ROOT

- Baseline design (for now)
  - 2 mm Cu absorber
  - 5 mm Scintillator
  - 1 mm FR4 (electronics)

- Plan to **integrate other sub-detectors** later on (ArgonCube + 3DST)
Software Status (DESY).

Integration into GArSoft

- Initially **simple** ECAL described into GArSoft
- Implementation of the **new ECAL design** into the framework
  - Full chain to implement: **Simulation → Digitisation → Reconstruction → Event Display**
- Current status
  - Mostly **full chain has been implemented** and is working
  - New **data products** created in GArSoft for ECAL hits (CaloDeposits, CaloRawDigits and CaloHits)
- Ongoing
  - **Segmentation** of the Endcap and Barrel, try to keep it **flexible** for optimisation studies
Outlook & Conclusion.
Towards a high granular ECAL for a neutrino experiment

• ECAL for the ND is a challenge
  • **High granularity** is important to help in photon reconstruction and pointing.
  • Help to **locate** the primary vertex of $\pi_0$
  • **Space constrains** in the HPgTPC impose a two-part ECAL:
    • → Inner ECAL with **high granularity** to provide good angular resolution
    • → Outer ECAL to **contain showers** and achieve a good energy resolution

• ECAL Optimisation
  • **Angular resolution** depends mainly on the **granularity**
  • **Energy resolution** depends mainly on absorber type, thickness and pressure vessel
  • *More studies still ongoing* (mix of absorber thicknesses, study within GArSoft…)

• Software
  • **New ECAL design** is implemented into art with **GArSoft (few things left to be ironed out)**
  • → **Optimisation studies can continue using the foreseen framework**
Backup Slides.
Simulation with Geant4

Creation of a new simulation data product called CaloDeposits for ECAL hits

- Contains all simhits with the time, energy, position and ID (Inner/Outer Barrel or Endcap)

Works for single particles, need to check with GENIE but should be in principle fine
Readout simulation

Simple simulation of the readout of the ECAL

- Similar to the AHCAL
- Some assumptions on the light yield (25 px/MIP), SiPM Gain (20 ADC/px), effective pixels (3000 px), dynamic range of the ADC (4096 ADC) and 1 ns time resolution
- Can be changed easily in the fcl configuration (used to configure art at runtime)

Creation of a raw data product (CaloRawDigits) containing the time, position, ID and energy in ADC

What is to be done (ongoing)

- Segmentation of the cells (after change of the geometry file, see later slides)
- Allow for flexible granularity (maybe per layer)
Hit reconstruction

Very simple and basic hit reconstruction

- Creation of a CaloHitFinder_module
- Calibration to the MIP scale
- Desaturation of the SiPM
- Calibration to the MeV scale (only visible energy)

What to do else?

- Simple hit clustering?
- Integration with PandoraPFA? Like LArSoft?
- \( \pi^0 \) reconstruction?
Neutrons are generated in neutrino interactions with the argon nucleons

The detection and energy measurement is vital for:

- The determination of the energy spectrum of the neutrino beam
- The reduction of systematic errors in the energy spectrum
- The determination of cross-sections of neutrino-nucleus interactions

**Challenge:** Neutron energies of a few 100MeV
No clear signature in the calorimeter

→ Study detection efficiency and hadronic energy resolution in this region
Inner Granularity

- 20mm to Ly30; 20mm to Ly80: A: 0.044, B: 0.019
- 10mm to Ly30; 40mm to Ly80: A: 0.042, B: 0.017
- 20mm to Ly30; 40mm to Ly80: A: 0.045, B: 0.019
- 30mm to Ly30; 40mm to Ly80: A: 0.046, B: 0.021
- 10mm to Ly10; 30mm to Ly30: A: 0.043, B: 0.020
Influence of the Absorber

Inner granularity: 20mm, outer granularity: 20mm, no vessel

Conclusion: Copper yields better angular resolution, but 1mm copper is leaking very much energy
Shower Profile - Vessel

- 14mm titanium vessel
- 20mm steel vessel
- No vessel
Shower Profile - Copper

Layer index

$E_{\text{vis}} / \text{layer / event [MeV]}$

2mm copper absorber
1mm copper absorber
Shower Profile - Copper/Lead

Layerindex

E_{\text{vis}} / \text{layer / event [MeV]}

2mm copper absorber
1mm lead absorber