A high-performance electromagnetic calorimeter for neutrino physics in the DUNE Near Detector complex

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on behalf of the DUNE collaboration

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Overview

• The KLOE electromagnetic calorimeter
  - general description
  - achieved performance

• The DUNE experiment and the Near detector complex
  - the role of the electromagnetic calorimeter in SAND
  - the expected performance
  - DUNE sensitivity
Some history

- **KLOE** was designed for high precision Kaon and hadron physics at DAFNE Φ factory of the Laboratori Nazionali di Frascati (Italy)

- Data taking:

- A lot of **very important results** based on K and η decay observation:
  - **CPT symmetry test:** by measuring the $K_S \rightarrow \pi e \nu$ decay charge asymmetry
    \[
    \text{BR}(K_S \rightarrow \pi e \nu) = (6.91 \pm 0.37) \times 10^{-4}
    \]
  - **CP violation:**
    - by the experimental limit on the $K_S \rightarrow \pi^0 \pi^0 \pi^0$ decay
      \[
      JHEP12(2006)011
      \]
    - by measuring the branching ratio of the $K_L \rightarrow \pi^+ \pi^-$ decay
      \[
      PLB 723 (2013) 54
      \]
    - by searching for the decay $\eta \rightarrow \pi^+ \pi^-$
      \[
      JHEP10(2020)047
      \]
  - High precision (0.1%) test of **unitarity of CKM matrix**
    \[
    1 - |V_{ud}|^2 - |V_{us}|^2 = 0.0004 \pm 0.0007
    \]
    \[
    JHEP04(2008)059
    \]

L=8 fb^{-1} => 2.4 \times 10^{10} \Phi \text{ decays} 
O(8 \times 10^9) K_S K_L \text{ pairs}
The KLOE ecal

- **Structure**: made by an optimized composite of scintillating fibers ($\varnothing$ 1.0 mm, $\lambda_{\text{Peak}} \approx 460$ nm) immersed in 200 grooved lead foils 0.5 mm thick. Volumetric ratio: lead: fiber:glue = 42:48:10

- **Dimensions**: $\varnothing 4 m$, L=3.4 m
  - 4 $\pi$ coverage
  - Total thickness: 23 cm
  - Barrel: 24 modules
    - 60 cells each
    - 5 planes
    - H:4.4-5.3 cm – W:4.4 cm – L:4.3 m
  - Endcap: 32 modules
    - 10-15-30 cells each

Average density: 5 g/cm$^3$
Radiation length: 1.5 cm
Total width $\approx$ 15 radiation lengths

The readout

- 2 PMTs (1.5 inch) for each cell on both sides
  - 2880 channels for barrel
  - 2000 channels for endcaps
- ADC for charge signals and TDC for time signals
- Energy threshold: (100 keV)

Light guides for matching with cylindrical PMTs

4880 Photomultipliers very stable in low magnetic field

- Reconstructed time
- Reconstructed position

\[
t (\text{ns}) = \frac{t^A + t^B}{2} - \frac{t^A_0 + t^B_0}{2} - \frac{L}{2v}
\]

\[
s (\text{cm}) = \frac{v}{2}(t^A - t^B - t^A_0 + t^B_0)
\]

\[v \text{ and } t_0 \text{ precisely calibrated with muons}\]
Demonstrated performances in KLOE

- high efficiency for gamma detection
- high resolution for shower vertex identification (due to the high granularity)
- excellent time resolution
- excellent energy resolution (25 p.e./MeV for MIP)

\[
\frac{\sigma(E)}{E} = 5.7\% / \sqrt{E(\text{GeV})}
\]

\[
\sigma_t = 54 \text{ ps} / \sqrt{E(\text{GeV})} + 140 \text{ ps}
\]

NIM A482, 364 (2002)
**Demonstrated performances in KLOE**

\[ K_S \text{ mass from photon energy} \]
\[ K_S \rightarrow \pi^0 \pi^0 \text{ events} \]

- **\( \beta \) spectrum of \( K_L \) interacting in the ecal**
- (by time-of-flight)

\[ \beta = 0.2133 \]
\[ \sigma(\beta) = 0.0039 \]
\[ \delta W_{DAΦNE} = 1 \text{ MeV} \]
\[ \delta \beta = 0.004 \]

**NIM A482, 364 (2002)**

A high-performance calorimeter for neutrino physics

L. Di Noto
Neutron detection efficiency

- Tested with neutrons in 20-200 MeV energy range

- huge inelastic production of neutrons on the lead planes

- secondary neutrons, protons and photons that contribute to the visible energy thanks to the fine granularity structure

NIM A 598 (2009) 244–247
DUNE: Deep Underground Neutrino Experiment

- **Main goals:**
  - Precisely measurement of the $\nu_\mu/\bar{\nu}_\mu$ oscillation probability to discover CP violation in neutrino sector, mass hierarchy, $\theta_{23}$ angle octant
  - Observation of supernovae neutrinos
  - Observation of proton decay

- **Experimental apparatus:**
  - Long-baseline Neutrino Facility at Fermilab:
    - high intense neutrino beam 1.2 MW – $1.1 \times 10^{21}$ POT/year (upgrade to 2.4 MW) with wideband spectrum (energy peak at 2.6 GeV)
  - Far Detector at 1300 km from Near Detector: to uniquely identify the different effects (mass hierarchy and CP violation) in the oscillations
The experimental apparatus

→ **4 modules**: liquid Argon time projection chamber, 17 kton mass each (15 m X 15 m x 64 m)
→ They will be installed at **Sanford Underground Facility** in South Dakota, 1.5 km underground
→ EVENTS: 3000 $\nu_\mu$ CC/year, 250 $\nu_e$ CC/year

→ Near Detector complex at **Fermilab** (600 m far from the beam target).
→ 3 detectors:
  → ND-LAr, ND-GAr movable out of axis
  → SAND permanently on-axis
→ EVENTS: $O(10^8)$ CC events/year in ND-LAr, $O(10^6)$ CC events/year in ND-GAr/SAND

The KLOE calorimeter and magnet will be re-used in the SAND detector
**SAND geometry: GRAIN+ECAL+STT**

**GRAIN:** GRanular Argon for Interactions of Neutrinos

- 1 ton LAr cryostat in the upstream volume

**ECAL + MAGNET**

- Superconducting coil $B = 0.6$ T
- Mass: 475 tons

**STT (Straw Tube Tracker)**

- 5 mm diameter
- 90 modules interleaved by carbon target or $\text{CH}_2$ target (5 ton) + transition radiator detector

**Carbon target module**

**$\text{CH}_2$ target + radiator module**

Instrumented with:

- SiPMs only
- Or with SiPM matrix coupled to an optical focusing system (R&D under development)
The role of the ecal in SAND

**SAND main goals:**

- Monitor for beam parameter changes on a weekly basis
- Collect interactions on Carbon and on CH\(_2\) target in STT
- Collect interactions on Argon
- For cross-section studies on different targets (C, H, Ar)
- For \(\nu_\mu\), \(\nu_e\), \(\bar{\nu}_\mu\), \(\bar{\nu}_e\) on-axis flux measurement

**by using interactions in ecal (23 ton) in the upstream part**

**ecal fundamental for:**
- Neutral particles detection (neutrons, gamma),
- For particle identification
- For time information for background reduction

<table>
<thead>
<tr>
<th>Target</th>
<th>CP optimized FHC (1.2MW, 2y)</th>
<th>CP optimized RHC (1.2MW, 2y)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\nu_\mu) CC</td>
<td>(\nu_\mu) CC</td>
</tr>
<tr>
<td>CH(_2)</td>
<td>13,010,337</td>
<td>624,330</td>
</tr>
<tr>
<td>H</td>
<td>1,222,576</td>
<td>111,574</td>
</tr>
<tr>
<td>C</td>
<td>1,547,011</td>
<td>67,294</td>
</tr>
<tr>
<td>Ar</td>
<td>3,114,331</td>
<td>121,506</td>
</tr>
<tr>
<td>Pb</td>
<td>62,127,600</td>
<td>2,507,940</td>
</tr>
</tbody>
</table>
The ecal as a target for beam monitoring

- Interactions on front-ECAL + STT + GRAIN
  → for beam monitoring on a weekly basis
  → by studying the neutrino spectrum variations

<table>
<thead>
<tr>
<th>Proton beam parameter</th>
<th>1σ deviation as given by beam group</th>
<th>New $\sqrt{\Delta \chi^2(E_{\nu})}$</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horn current</td>
<td>+3 kA</td>
<td>12.57 9.44</td>
<td></td>
</tr>
<tr>
<td>Water layer thickness</td>
<td>+0.5 mm</td>
<td>4.69 3.58</td>
<td></td>
</tr>
<tr>
<td>Proton target density</td>
<td>+2%</td>
<td>5.28 4.07</td>
<td></td>
</tr>
<tr>
<td>Beam sigma</td>
<td>+0.1 mm</td>
<td>4.41 3.53</td>
<td></td>
</tr>
<tr>
<td>Beam off set X</td>
<td>+0.45 mm</td>
<td>5.11 3.54</td>
<td></td>
</tr>
<tr>
<td>Beam theta phi</td>
<td>$0.07$ mrad $\theta$, $1.57$ $\phi$</td>
<td>0.62 0.28</td>
<td></td>
</tr>
<tr>
<td>Beam theta</td>
<td>$0.070$ mrad</td>
<td>0.91 0.58</td>
<td></td>
</tr>
<tr>
<td>horn 1 X shift</td>
<td>+0.5 mm</td>
<td>4.70 3.42</td>
<td></td>
</tr>
<tr>
<td>horn 1 Y shift</td>
<td>+0.5 mm</td>
<td>5.27 3.87</td>
<td></td>
</tr>
<tr>
<td>horn 2 X shift</td>
<td>+0.5 mm</td>
<td>1.18 0.69</td>
<td></td>
</tr>
<tr>
<td>horn 2 Y shift</td>
<td>+0.5 mm</td>
<td>1.31 0.77</td>
<td></td>
</tr>
</tbody>
</table>

SAND is also sensitive to 0.13 mrad changes in neutrino beam direction

DUNE DocDB:13262-v7
SAND expected performances
an interplay between ecal and STT

- Good detection efficiency for neutrons in the ecal and STT:
  - energy evaluation by time of flight measurement
- Good \( p/\pi/K \) identification capability by \( dE/dx \) and range in ecal and STT
- High \( \pi^0 \) detection efficiency from gammas detection in ecal and STT
- High detection efficiency for charged particle tracks in the bending plane by STT \( \Delta p/p \leq 3\% \), \( \Delta \theta/\theta \leq 1.5 \% \) mrad
- Good \( e/\pi \) identification capability thanks to the transition radiation detector \( (e/\pi \sim 10^{-3}) \)

Neutron detection efficiency

<table>
<thead>
<tr>
<th>Target</th>
<th>QE</th>
<th>RES</th>
<th>DIS</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>64.8%</td>
<td>76.5%</td>
<td>80.1%</td>
<td>73.6%</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>80.5%</td>
<td>85.0%</td>
<td>87.4%</td>
<td>82.3%</td>
</tr>
</tbody>
</table>

A high-performance calorimeter for neutrino physics

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Background rejection and event time identification

$\nu/\bar{\nu}$ interactions induced by the beam in the materials result in:

- random particles (mainly neutrons) overlapping with a (anti)neutrino interaction in SAND within a single beam spill (10 \text{ us})
- external neutrino interactions misidentified as internal interactions

<table>
<thead>
<tr>
<th>Detector element</th>
<th>Mass</th>
<th>FHC</th>
<th>RHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet</td>
<td>511 t</td>
<td>68.9</td>
<td>36.6</td>
</tr>
<tr>
<td>ECAL</td>
<td>100 t</td>
<td>13.5</td>
<td>7.2</td>
</tr>
<tr>
<td>LAr+STT</td>
<td>8.2 t</td>
<td>1.1</td>
<td>0.59</td>
</tr>
<tr>
<td>STT fiducial volume</td>
<td>5.5 t</td>
<td>0.74</td>
<td>0.39</td>
</tr>
<tr>
<td>Total</td>
<td>619.2</td>
<td>83.5</td>
<td>44.39</td>
</tr>
</tbody>
</table>

but the events are well separated in time! the \textit{ecal} is fundamental to identify external tracks!

In KLOE

Outgoing $\mu$  
Incoming $\mu$

$T_{1}-T_{5}$ (ns)

distribution of the first hits in the ecal layers for interactions in ecal, yoke, rock [from simulations]
Expected DUNE sensitivity

The Near Detector Complex is designed to provide robust and complementary measurements of flux and spectrum of all neutrino flavour for constraining nuclear effect and tune neutrino interaction model at GeV energy.

in order to reduce systematics to few % level for a data driven long-baseline oscillation analysis for measuring $\delta_{CP}$ in 7-10 years of data taking.
Conclusions

• The KLOE electromagnetic calorimeter has shown high performance in term of:
  - energy resolution
  - time resolution
  - neutral particle detection
• all of these are fundamental properties for neutrino interaction detection in SAND

• Currently the SAND consortium is planning to dismounting the apparatus and to refurbish the magnet and the electromagnetic calorimeter
• for preparing the future installation within the SAND detector in the DUNE Near Detector complex
backup
KLOE stability during the years


\[
\sigma_E/E \approx 5.6\% /\sqrt{E(\text{GeV})} \\
\sigma_t \approx 58\text{ ps} /\sqrt{E(\text{GeV})} \oplus 135\text{ ps}
\]

E. Diociaiuti et al. KLOE-2 note
DUNE-PRISM

• Method:
  - 50% data taken with ND-LAr+ND-GAr off-axis at various position (8 steps 12 day each)+ horn variation

• Goal:
  - create a ND data sets with flux spectra very similar to the oscillated FD fluxes,
    • minimizing errors arising from the near-to-far flux difference,
    • minimizing errors related to the neutrino interaction model