Solar neutrinos in DUNE and SoLAr

Activities in Milano-Bicocca

DUNE Italia Meeting - October 30, 2024

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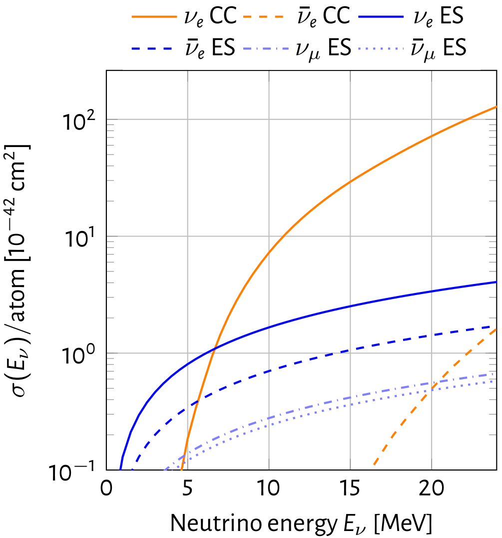
Opportunities at low-energy

Dominant interaction channel:
CC interaction $\nu_e(^{40}\text{Ar}, ^{40}\text{K}^*)e^-$ (eff. thrs. $\approx$ 5 MeV)
$\hookrightarrow$ final state: $e^- +$ few γ

- Supernova neutrinos
- ^{8}B + *hep* solar neutrinos
  - **^{8}B**: Complementary measurement of θ_{12} and Δm^2_{12} + Solar core temperature
  - ***hep***: Only component of the solar neutrino flux still undetected

LArTPC can probe this energy region without charge multiplication
Complementary to LS/Cherenkov experiment

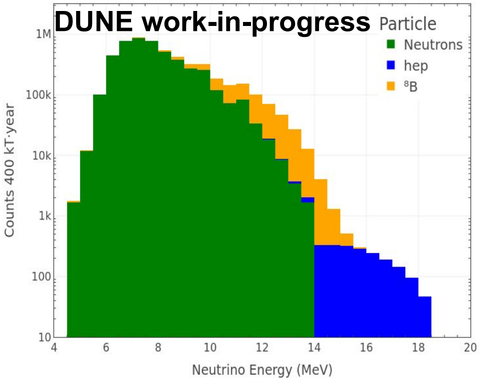
MicroBooNE, arXiv:2410.18419
MicroBooNE, *Phys.Rev.D* 109 (2024), arXiv:2307.03102

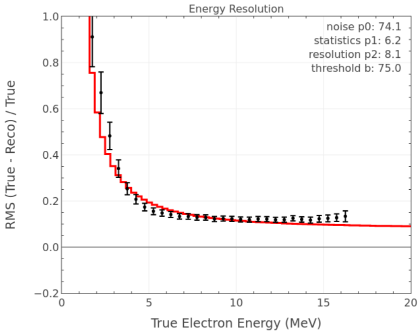


Solar neutrinos in DUNE

Courtesy of Sergio Manthey-Corchado

- Reconstruction for low energy events using a hit-clustering scheme based on channel and time proximity (3 channels, 12.5 μs window).
- Electron energy resolution ≈ 10% (ideal drift reconstruction).





Challenges:

- High background level
- Difficult matching between PDS and TPC clusters
  - Flash-matching proposal
- Energy resolution can be improved
  - Charge+Light calorimetry at low-energy

PDS simulation...

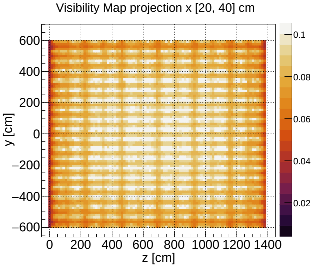
- **Production** phenomenological model modifying the Birks' charge recombination model and reproducing light/charge anticorrelation and its dependence with dE/dx and E_{field} [F. Marinho et al., 2022 *JINST* 17 C07009]
- **Propagation** photons ray-tracing unbearable in G4

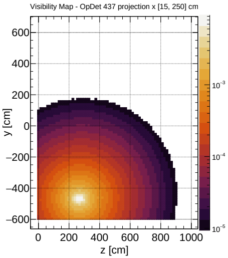
  $\hookrightarrow$ **Semi-analytical** light propagation model

$$N_{\text{ph hit}}^{\text{opdet } i} = N_{\text{ph}} \cdot \boxed{Q_{\text{abs}} \cdot Q_{\text{trans}} \cdot G(d,\theta) \cdot T(d,\theta)} \cdot \text{QE}_{\text{eff}}$$

[D. Garcia-Gamez et al, *Eur.Phys.J.C* 81 (2021) 4, 349]

> PhotonVisibilityExport_module for producing 3D **visiblity maps** (full detector and single opdets)
> [duneopet PR#64]





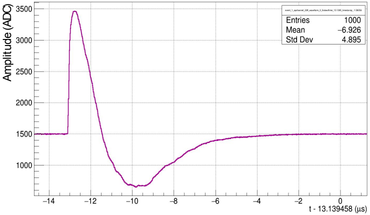
- **Digitization** produce a digitized waveform for each PDS channel

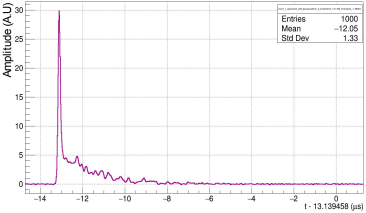
> OpDetDigitizerDUNE_module uses a **testbench model**
> for the SiPM's single p.e. response

…and reconstruction [reco1]

- **Waveform filtering** for restoring the "true" photon hit's time profile removing the SiPM impulse response

`Deconvolution_module` implements two digital filters (Wiener, SBND) for removing the possible undershoot in the SiPM response
Now used in ProdoDUNE-HD LArSoft analysis





PDS simulation and reconstruction - automatic validation

Motivation

Automatize the production of high statistics datasets and the comparison of selected distributions with a reference sample

Originally focused on PANDORA reconstruction, now including much more (gen, sim, hit level) + **PDS**

Workflow

Simulation workflow follows the "standard" adopted for PDS studies within the low-energy WG

- 100k events simulated by MARLEY with flat energy spectrum
- sim and reco stages for light only
- $\approx 5\,\text{h}$ run time

General structure

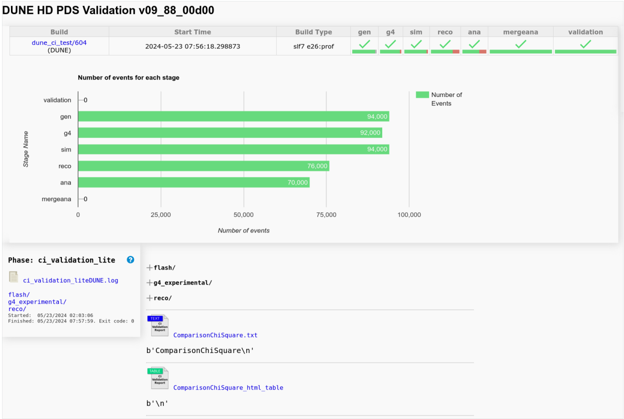
- Process run using the `lar_ci` framework
- Define a **workflow** specifying the nr of jobs + number of events + progress of simulation & reconstruction stages [gen, g4, sim, reco]
- Produce distributions for different variables and compare them with a reference

Validation

Prepare histograms and compare with reference

- FD-specific list of histograms keys to be compared
- Compatibility quantified using a simple χ^2 as "test-statistics"
- Compute residuals between validation and reference distributions

PDS simulation and reconstruction - automatic validation



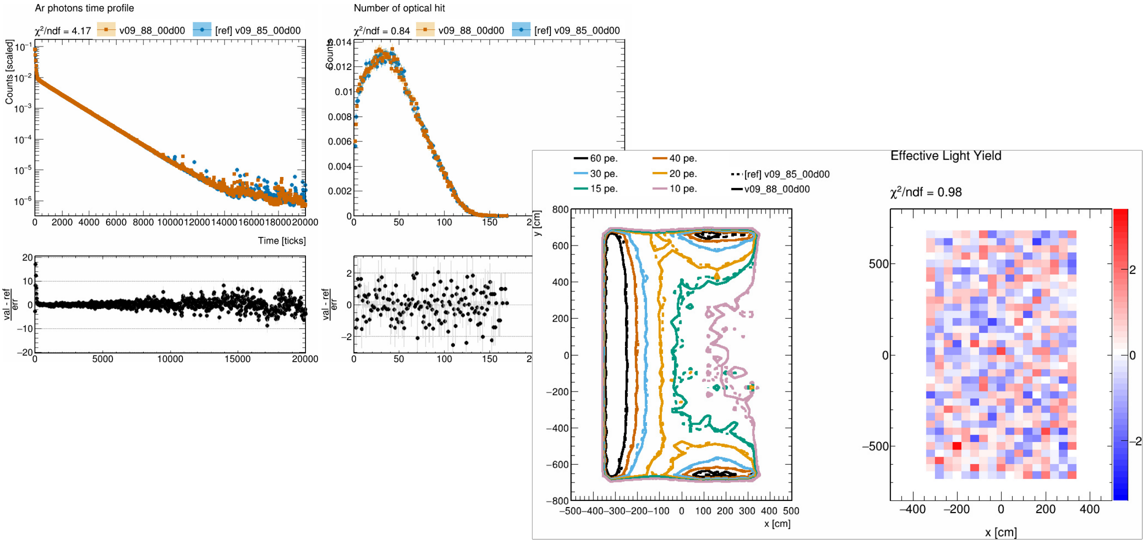
DUNE Release	Parameter	Chi2
v09_85_00d00 vs v09_88_00d00	reco/effLY_map	1.036374
v09_85_00d00 vs v09_88_00d00	reco/ophit_distr	0.875366
v09_85_00d00 vs v09_88_00d00	reco/recope_vs_distance	1.413047
v09_85_00d00 vs v09_88_00d00	reco/recope_vs_opDet	0.874868
v09_85_00d00 vs v09_88_00d00	reco/opdet_avg_pe	0.874868
v09_85_00d00 vs v09_88_00d00	flash/n_opflash	1.616197
v09_85_00d00 vs v09_88_00d00	flash/flash_pe	0.835508
v09_85_00d00 vs v09_88_00d00	flash/flash_pe_event	0.846874
v09_85_00d00 vs v09_88_00d00	flash/flash_purity	454.048895
v09_85_00d00 vs v09_88_00d00	g4_experimental/opdet_avg_qe	1.010757
v09_85_00d00 vs v09_88_00d00	g4_experimental/opdet_avg_trueph_direct	0.876648
v09_85_00d00 vs v09_88_00d00	g4_experimental/opdet_avg_trueph_reflected	0.779359
v09_85_00d00 vs v09_88_00d00	g4_experimental/trueph_time_profile_direct	2.099404
v09_85_00d00 vs v09_88_00d00	g4_experimental/trueph_time_profile_reflected	3.649947
v09_85_00d00 vs v09_88_00d00	g4_experimental/direct_trueph_vs_distance	1.663674
v09_85_00d00 vs v09_88_00d00	g4_experimental/reflected_trueph_vs_distance	2.407212
v09_85_00d00 vs v09_88_00d00	g4_experimental/total_recope_vs_trueph_prf	0.965064
v09_85_00d00 vs v09_88_00d00	g4_experimental/opdet_recope_vs_trueph_prf	0.959080

g4
Monte Carlo Truth

Reco
Reconstructed variables

Flash
Flash variables

PDS simulation and reconstruction - automatic validation



Next steps at low-energy

- Combined charge+light calorimetry requires correct matching of PDS and TPC signals
- Low energy challenge: $\mathcal{O}(100)/(1000)$ flash candidates per TPC cluster in FD HD/VD
- Idea: make use of the light propagation model to select the most compatible match
  Low-energy events $\sim$ point-like $\to$ described by 5 parameters $\boldsymbol{\theta} = \{\mathbf{x} = \{x, y, z\}, t, E\}$

TPC hits constrain E + position on the anode (y, z)	PDS flash constrains E + time $\to$ position along drift (x)

For each flash candidate evaluate a likelihood function like [Patterson et al, *Nucl.Instrum.Meth.A* 608,2009]

$$\mathcal{L}(\{\text{opHit}\}|\boldsymbol{\theta}) = \prod_{i}^{\text{unhit XA}} (1 - P(i\,\text{hit}|\boldsymbol{\theta})) \cdot \prod_{i}^{\text{hit XA}} P(i\,\text{hit}|\boldsymbol{\theta}) f_q(q_i|\boldsymbol{\theta}) f_t(t_i|\boldsymbol{\theta})$$

where each term can be evaluated from the detector response and light propagation model (e.g., opDet visibility maps built with `PhotonVisibilityExport_module`)

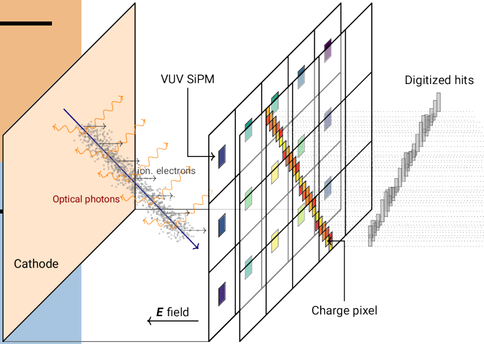
Towards DUNE Phase II: SoLAr

Improved background suppression

Passive shielding, material selection, pulse-shape discrimination, event topology

Pixelated readout:

Pixel readout plane will enhance event reconstruction, while replacing TPC wires is expected to simplify construction and installation



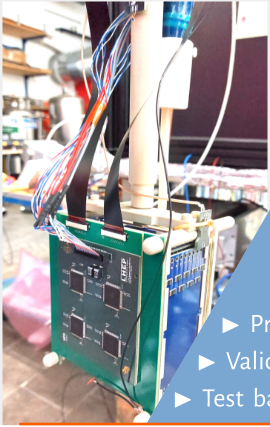
Improved light sensors:

Arapuca-style modules + **VUV SiPMs integrated on the anode**
Exploit the light signal in LAr to perform **combined Q + L calorimetry**: Target $\Delta E/E \approx 7\%$

SoLAr Roadmap

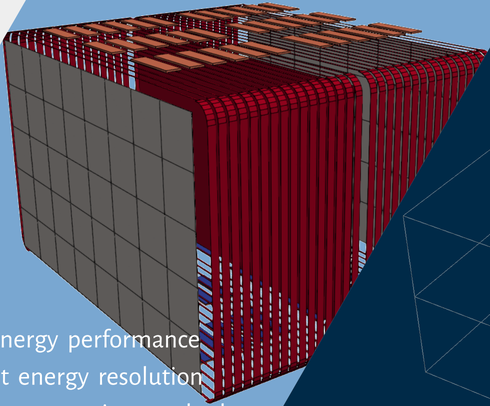
Phase I: Prototyping

Development of integrated charge+light readout



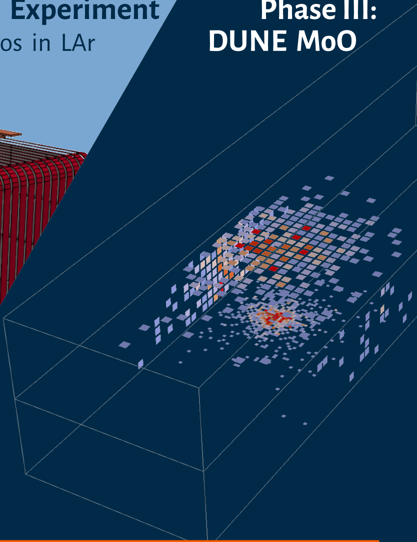
Phase II: Medium Scale Experiment

First detection of solar neutrinos in LAr



- Prove low-energy performance
- Validate target energy resolution
- Test background suppression methods

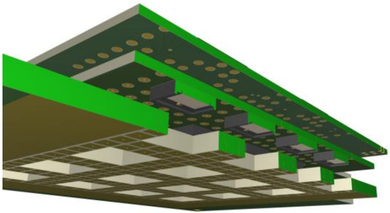
Phase III: DUNE MoO

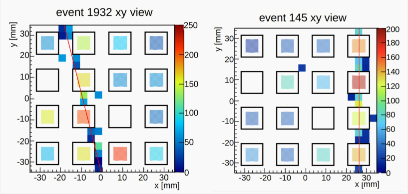


SoLAr prototyping activities: SoLAr_v1

SoLAr Collaboration, arXiv:2406.14121

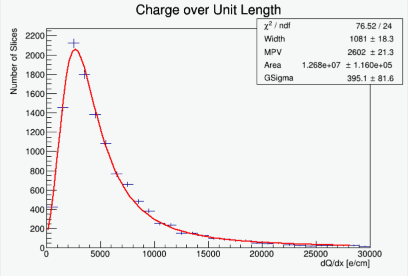
- **Charge readout:**
  256, $3 \times 3\,\text{mm}^2$ pads, readout by 4 LArPix v2a ASIC + PACMAN
- **Light readout:**
  16 Hamamatsu S13370-6050CN ($6 \times 6\,\text{mm}^2$) + Cold pre-amp + Warm amp + 62.5 MS/s digitizer
- **Anode assembly:**
  Three stacked PCB layers to accommodate SiPMs packaging
  SiPM floating bias to enhance charge collection





Test outcome

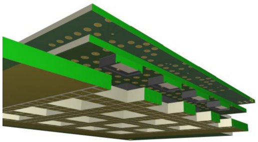
- combined operation of charge+light sensors
- calorimetric response ok



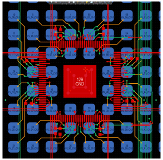
SoLAr prototyping activities: SoLAr_v2

- Tile dimension: 32×32 cm^2 (active area 25.6×25.6 cm^2)
- Divided into 8×8 regions (64 — 4 pixel, 1 SiPM)
- 20 LArPix (room for 64)
- 64 Hamamatsu VUV MPPC with independent readout
- Complete re-design of the PCB

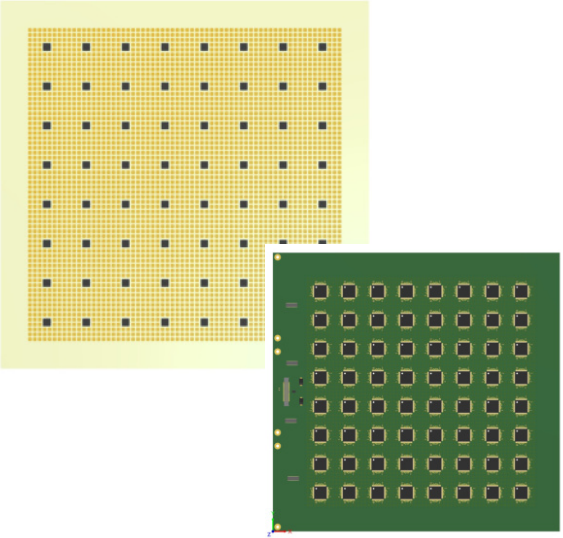
SoLAr tile V1 → SoLAr tile V2



Three PCB stacked

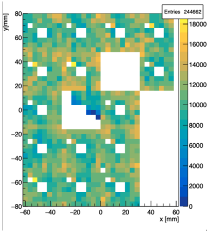


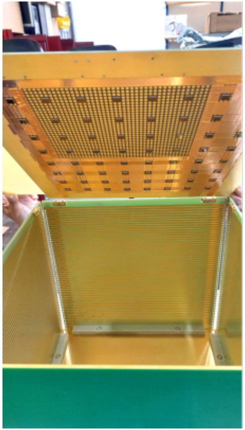
Single multilayer PCB

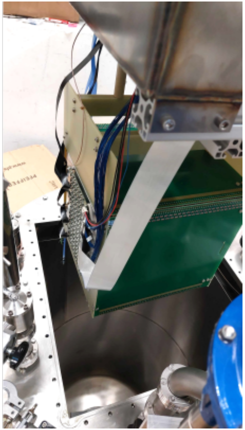


SoLAr_v2: Operations

- 30 cm drift length
- Un-routed pads grounded with copper tape
- 2 days of cosmic data taking with nominal HV 15 kV
  + special runs at 7.5 and 3.75 kV
- Additional run with ^{60}Co source
- Good LAr purity
- Low charge hit threshold $\approx$ 3.8 ke
- few dead areas on the anode



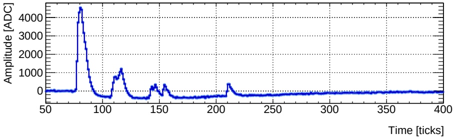


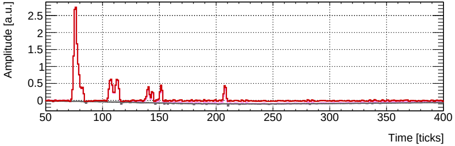


SoLAr_v2: Preliminary results

SiPM waveform analysis

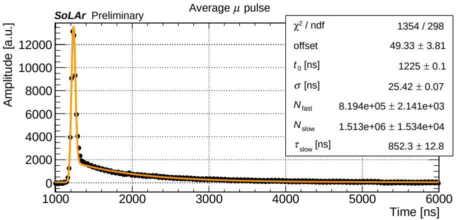
- SiPM waveform show a characteristic undershoot due to electronics coupling
- SiPM impulse response studies with dedicated LED runs
- Various waveform filtering strategies (Wiener filter, ...)
- Residual baseline modulation corrected applying a SNIP algorithm





Preliminary results

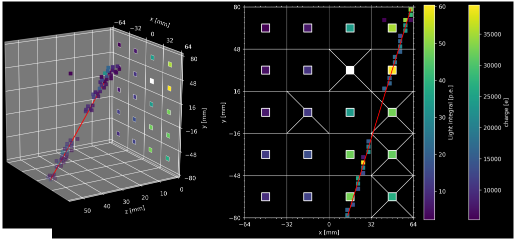
- Scintillation time profile obtained averaging filtered waveforms from $\approx$ 80 min cosmic run
- Slow time constant and relative weight of fast/slow component show a small discrepancy with expected values

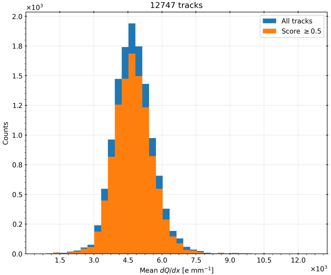


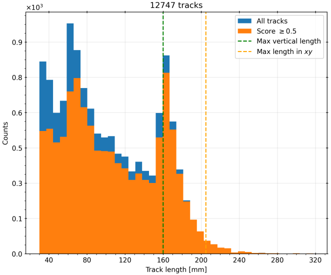
SoLAr v2: Preliminary results

Charge hit analysis

- **Clustering**
  Solving ambiguities due to dead areas using simulated data
- **Track fit**
  Identify outliers and secondary tracks







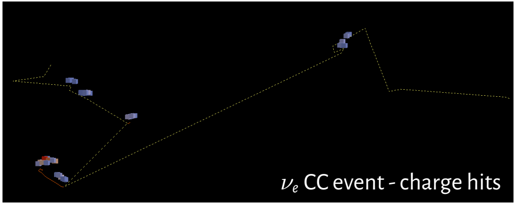
Preliminary results

- Track length distribution influenced by dead areas on the anode tile
- dQ/dx distribution compatible with similar experiments

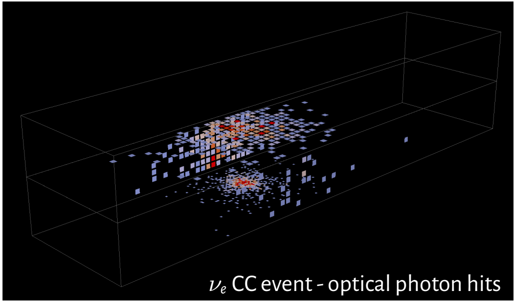
SoLAr simulation

solar-sim Geant4-based simulation package

- **Geometry** description in external configuration file (including cavern, cryostat)
- **Physics**
  - Multiple generators integration:
    MARLEY, BxDecay0, CRY, RadSrc, Externals, ...
  - HP Physics for n and low-energy ions
  - Currently integrating G4Cascade for (n, γ) cascades
  - Includes charge-light anticorrelation (LArQL)
  - Geant4 ray-tracing for optical photons
- Include charge diffusion and pixel **readout effects** (in progress)
- **Ongoing studies**:
  - SoLAr_v2 run
  - end-to-end simulation of neutron background
  - oscillation parameters sensitivity



ν_e CC event - charge hits



ν_e CC event - optical photon hits

Outlooks

PDS Simulation and Reconstruction

- MiB activities in PDS simulation and reconstruction covers a significant part of the workflow (Digitizer, Deconvolution, Production of visibility maps)
- Develop automatic validation of PDS simulation and reconstruction based on Low-Energy WG studies
- Ready use our expertise on PDS for flash-matching with high background level
  $\hookrightarrow$ key step towards combined calorimetry at low-energy

SoLAr

- Two prototyping runs demonstrated the technological concept
  Track reconstruction, matching light flash, analysis ongoing
- Developed a simulation package to establish the detector requirements and guide the design