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on behalf of the **SoLAr Collaboration**

CADMO

Developing the potential of Boosted Dark Matter searches in Liquid Argon TPCs

Dark Matter with a boost

While the search for WIMPs narrows down the parameter space, alternative DM scenarios are gaining interest.

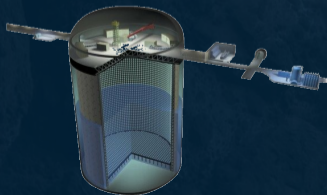
Assuming a more complex **Dark sector**, lighter DM components can exist and become relativistic

- produced in the annihilation of heavier DM particles [\[Agashe et al, 1405.7370\]](#)
- accelerated by cosmic rays [\[Ema, Sala, Sato, 1811.00520, 2011.01939\]](#)
[\[Bringmann & Pospelov, 1811.00520\]](#)

These scenarios predict a flux of **Boosted Dark Matter (BDM)** particles, with energies in the 10 MeV to 1000 MeV range, that can be detected in large, underground experiments.

- [\[Super-Kamiokande, 1711.05278\]](#)
- [\[Super-Kamiokande, 2209.14968\]](#)
- [\[LZ, 2503.18158\]](#)
- [\[PandaX, 2112.08957, 2403.08361, 2412.19970\]](#)

...

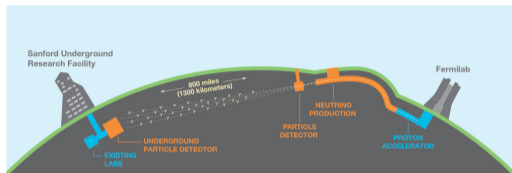


The Deep Underground Neutrino Experiment (DUNE)

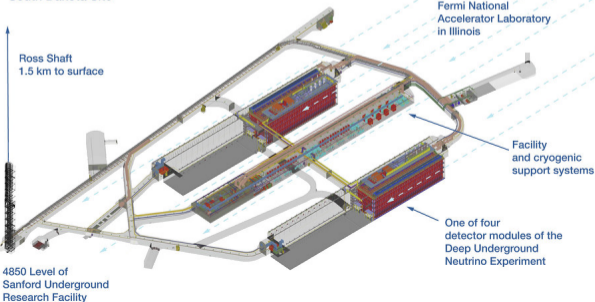
Open questions in neutrino physics (oscillations):

- › Mass ordering
- › CP violation
- › Octant of θ_{23}

Test the 3-flavor paradigm with unprecedented precision in a single experiment



Long-Baseline Neutrino Facility South Dakota Site

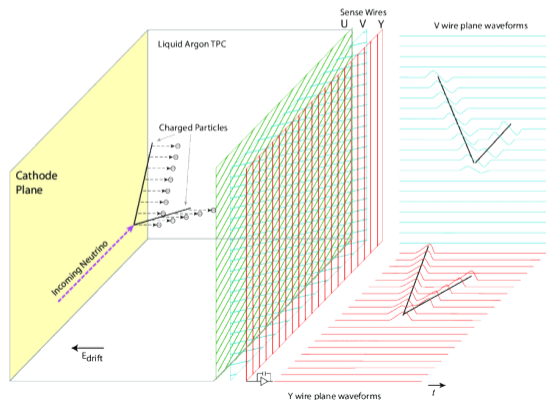


The huge DUNE Far Detector complex, 1.5 km underground at the Sanford Underground Research Facility (SURF), offers unique opportunities for non-beam neutrino physics

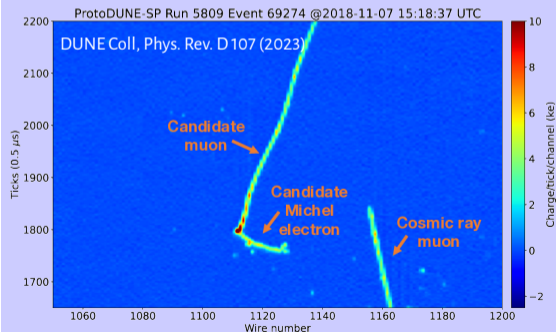
- › Atmospheric neutrinos
- › supernova neutrinos
- › solar neutrinos
- › **BSM physics**

Liquid Argon Time Projection Chambers

- Strong electric field (~ 500 V/cm) \rightarrow ionization electrons collected on readout planes
- Long absorption length for LAr VUV scintillation light \rightarrow self-triggering capability



- 3D tracking with mm-scale resolution
- Excellent calorimetric performance
- Topological reconstruction



The DUNE Far Detector Complex (Phase I)

Horizontal Drift (HD) module:

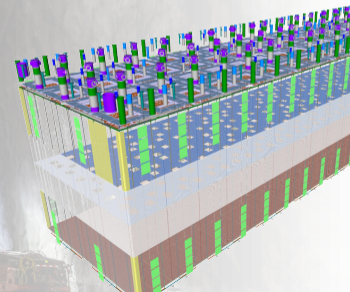
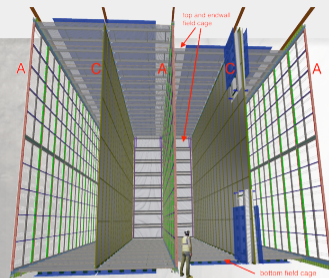
JINST 15 (2020) 08

- › 17.5 kt LAr
- › 4 drift volumes, 3.6 m drift
- › Wire charge readout (APA)
- › X-ARAPUCA light detectors integrated in APA

Vertical Drift (VD) module:

JINST 19 (2024) 08

- › 17.5 kt LAr
- › 2 drift volumes, 6 m drift
- › Strip charge readout (CRP)
- › LAr + Xe doping for enhanced light yield
- › X-ARAPUCA light detectors on the cathode plane + cryostat membrane



DBM opportunities and challenges in LArTPCs

- › The classical signature of boosted dark matter are multi-MeV interactions of an invisible (**neutrino-like**) particle pointing toward the galaxy center.
- › In the same low-energy region also **supernova** and **solar neutrinos**, significant interest in the community to improve the performance of LArTPCs in this energy range for DUNE Phase II

 DUNE Coll
JINST 19 (2024)

› **Challenges:**

- › Radiological background
- › Limited efficiency in flash-matching
- › Limited energy resolution

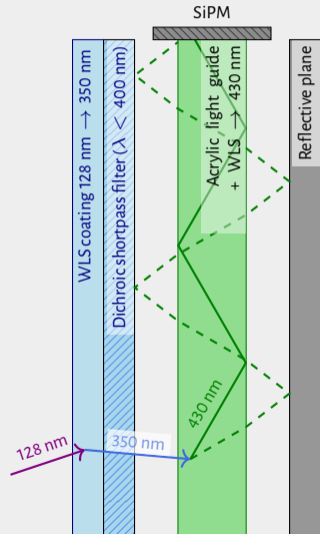
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 DUNE Coll
JINST 19 (2024)

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- > Limited efficiency in flash-matching
- > Limited energy resolution
- > A path forward: **improved light detection system**
 - > State of the art: X-ARAPUCA light traps



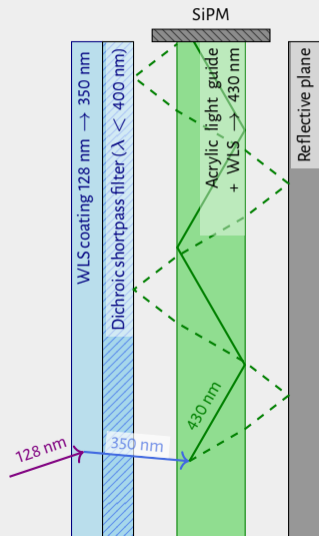
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 DUNE Coll
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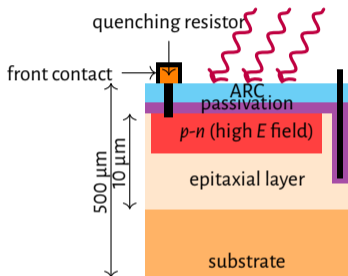
> Challenges:

- > Radiological background
- > Limited efficiency in flash-matching
- > Limited energy resolution
- > A path forward: **improved light detection system**
 - > State of the art: X-ARAPUCA light traps
 - > More efficient sensors
 - > Better integration with the charge readout

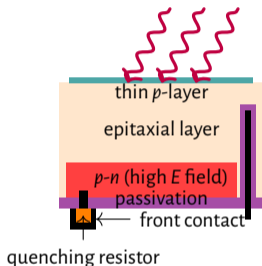


New sensor technologies for LAr scintillation light

Front-side-illuminated



Back-side-illuminated



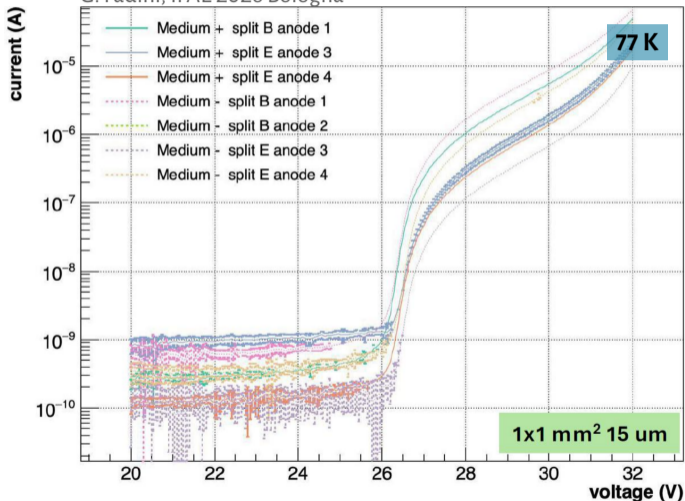
- LAr scint light peaks at 128 nm
- NUV SiPMs use anti-reflective coating (ARC) that **absorbs VUV** light in < 10 nm
- HPK replaced SiO_2 -based ARC with proprietary micro-layer partially transparent to VUV light + metal-in-trench for optical insulation

➤ Partnership **FBK-INFN** (IBIS, IBIS_NEXT), **development of backside-illuminated devices**

- Almost 100% fill-factor
- Smaller SPAD size → higher dynamic range
- Free entrance window → ARC w/ surface treatments specific for VUV light
- Higher radiation tolerance (smaller high field region)

First Characterization of NUV-BSI SiPM (frontside processed wafers)

G. Fadini, IFAE 2026 Bologna



First characterization of new cell structure with frontside-processed wafers

- ✓ Single photon detection
- ✓ DCR under control
- ⚙️ First tests on fully processed BSI devices underway

Integrated Charge+Light anode: the SoLAR Project

Goal:

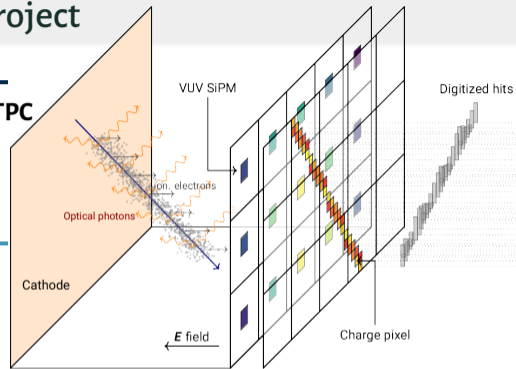
Expand the physics reach of DUNE with a **multipurpose LArTPC** improving the performance at low-energy.

Readout system innovation:

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

Arapuca-style modules + **VUV SiPMs** integrated on the anode
Exploit the light signal in LAr to perform

- Enhance effective **light yield**
- Improved **light uniformity**
- **combined Q + L calorimetry**: Target $\Delta E/E \approx 7\%$



The SoLAR V1 Prototype (2022)

Detector specs

› Charge readout:

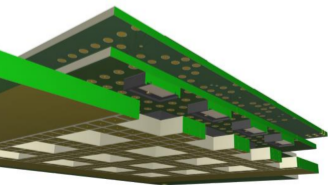
256, $3 \times 3 \text{ mm}^2$ pads, readout by 4 LArPix v2a ASIC + PACMAN

› Light readout:

16 Hamamatsu VUV4 S13370-6050CN ($6 \times 6 \text{ mm}^2$, $\approx 15\%$ PDE)
+ Cold pre-amp + Warm amp + 62.5 MS/s digitizer

› Anode assembly:

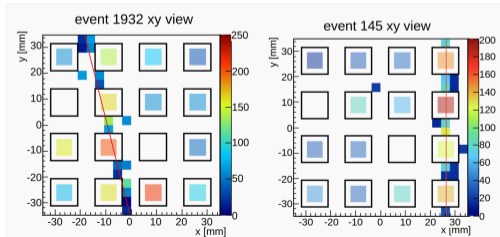
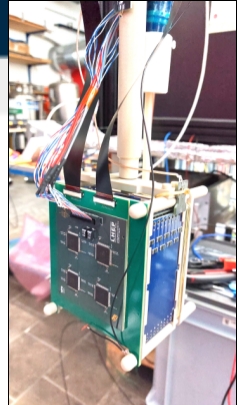
Three stacked PCB layers to accommodate SiPMs packaging
SiPM floating bias to enhance charge collection



Test outcome

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

SoLAR Coll., JINST 19 (2024) 11



The SoLAR V2 Prototype (2023)

Motivations:

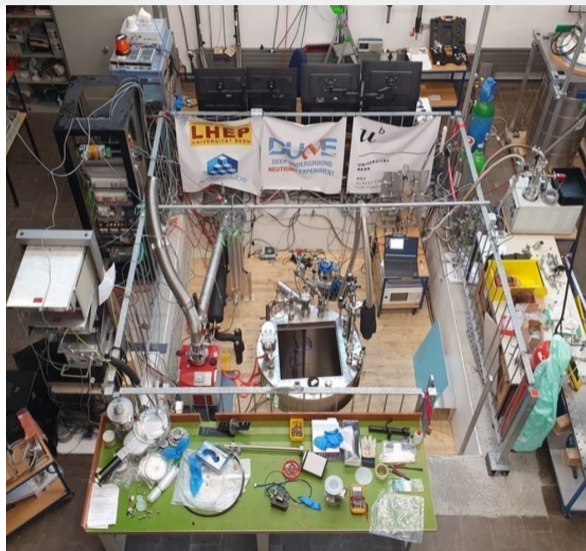
- More pixels and more SiPMs
- Better assessment of readout performance
- First test of combined charge+light analysis

Run plan:

- LED calibration run
- Cosmic-ray run
- ^{60}Co source run

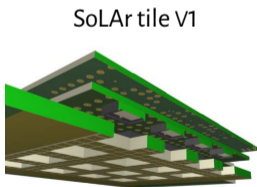
Results:

- 📄 Paper out 📄 SoLAR Coll, *JINST* 21 (2026)



The SoLAR V2 Prototype

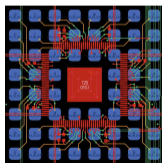
- Tile dimension: $32 \times 32 \text{ cm}^2$
(active area $25.6 \times 25.6 \text{ cm}^2$)
- Divided into 8×8 regions (64 — 4 pixel, 1 SiPM)
- 20 LArPix v2b (room for 64)
- 64 Hamamatsu VUV4 SiPM
- Complete re-design of the PCB



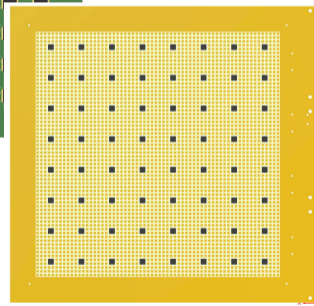
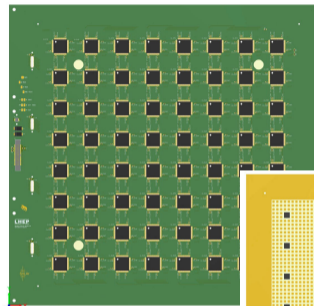
SoLAR tile V1



SoLAR tile V2



Single multilayer PCB



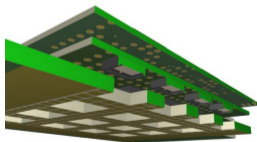
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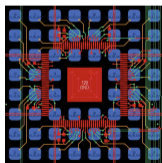
SoLAR tile V1



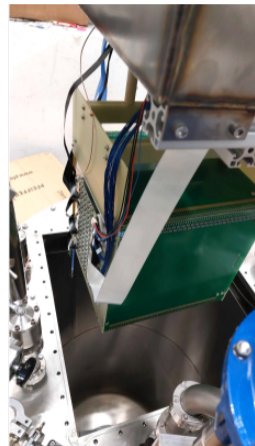
SoLAR tile V2



Three PCB stacked



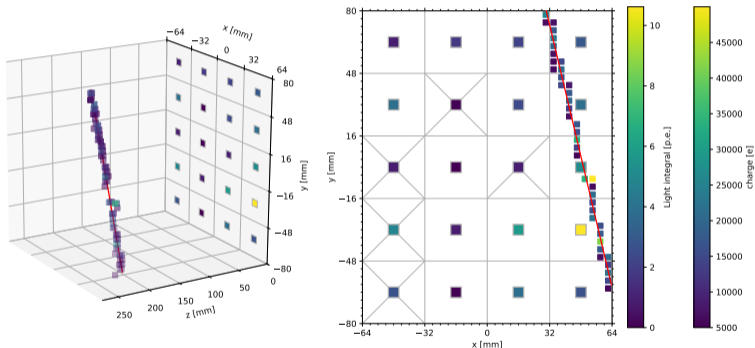
Single multilayer PCB



Operated in a $33 \times 33 \times 30 \text{ cm}^3$ LArTPC

Cosmic-ray run

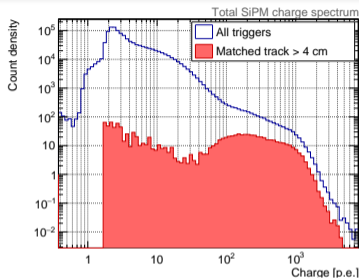
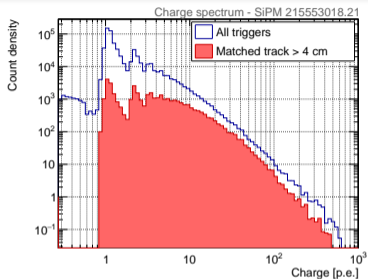
Event 81 - Charge = $6.74\text{E}+05$ e - Light = $5.60\text{E}+01$ p.e.



≈ 80 min of cosmic-ray data
(≈ 50 k tracks)

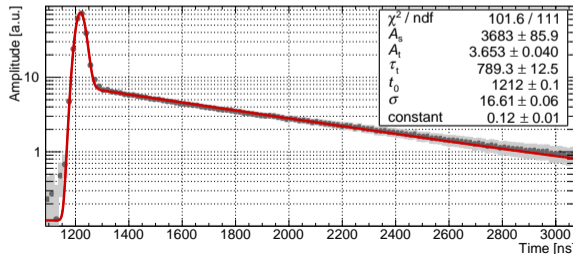
- Test integration of charge and light readout systems on the same PCB
- Verify charge readout system reconstruction performance
- Test the potential of granular light readout

SiPM system performance



- Charge on single SiPMs goes from few to $\mathcal{O}(10^2)$ p.e.
- Total charge on all SiPMs for reconstructed tracks (length > 4 cm) goes from $\mathcal{O}(50)$ to $\mathcal{O}(10^3)$ p.e.

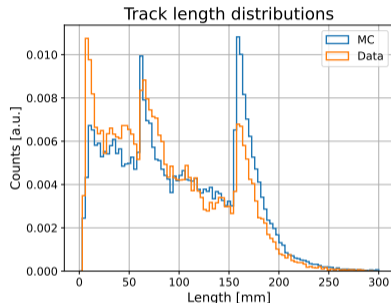
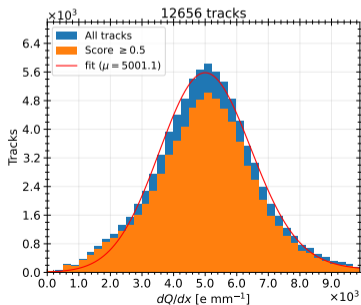
- Average μ pulse shape fitted with a double-exponential model
- Short $\tau_t = (789 \pm 13)$ ns indicates contamination
- Light yield correction factor $f_{\text{purity}} = 0.61$



Charge readout system performance - track reconstruction

Track reconstruction:

- Reconstruction of cosmic- μ tracks must deal with inactive areas (SiPMs, inactive ASICs, bad channels)
- Custom track reconstruction algorithm based on DBSCAN clustering + RANSAC regression
- Track length distribution features due to inactive areas



Energy deposition measurement:

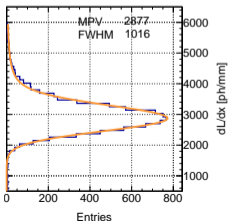
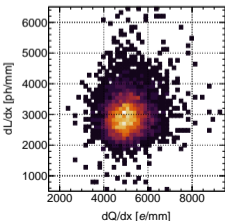
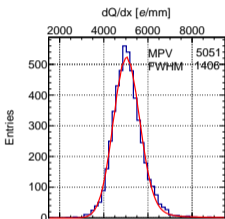
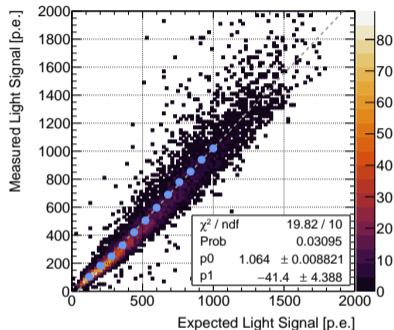
- Electron lifetime 1.87(18) ms
- COMSOL-based estimate a 6% loss of collected charge due to field distortions around the SiPMs
- Measured dQ/dx distribution consistent with ND-LAr results 5.30 ke $^{-}$ /mm most probable value [DUNE, Instruments 8 (2024) 3, 41]

Combined charge+light energy reconstruction

Uses track topology and MC-based visibility model of the TPC to predict light signal L_{exp} for each track. Good agreement L_{data}/L_{exp}

Use the model to extract scintillation light emission per unit length

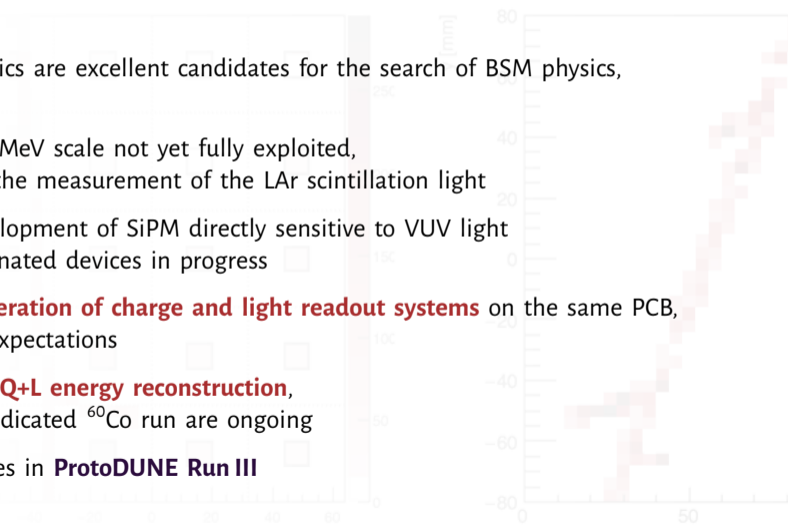
$$\frac{dL}{dx} = \left. \frac{dE}{dx} \right|_{mip} \cdot (LY \cdot f_{purity}) = \frac{L_{data}}{\ell_{track}^{TPC} \cdot PDE \cdot \sum_{i=1}^{N_{SiPM}} \overline{\Omega}_i}$$



Cosmic- μ are not the ideal sample for Q+L calorimetry studies
 Dedicated run with a ^{60}Co source was collected during the same test and the analysis is ongoing

Conclusions and outlooks

- Large LArTPCs for neutrino physics are excellent candidates for the search of BSM physics, including boosted dark matter
- Full potential of LArTPCs at 100 MeV scale not yet fully exploited, one way forward is to improve the measurement of the LAr scintillation light
- Partnership w/ FBK for the development of SiPM directly sensitive to VUV light first tests of the backside illuminated devices in progress
- Demonstration of **combined operation of charge and light readout systems** on the same PCB, with performance in line with expectations
- First steps towards a **combined Q+L energy reconstruction**, more detailed studies with a dedicated ^{60}Co run are ongoing
- **Next steps:** deploying SoLAr tiles in **ProtoDUNE Run III**



Backup material

DAQ System

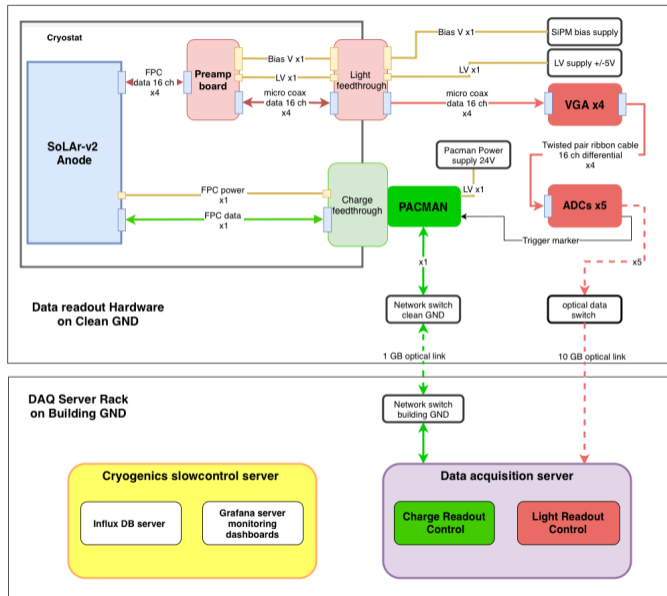
> Charge readout system:

LArPix ASICs read out via a **single** cable to a **PACMAN** unit outside the cryostat

> Light readout system:

Cold pre-amplifiers + warm amplifiers + 14-bit 62.5 MS/s digitizer boards

> Light readout system gives a trigger marker to PACMAN when signal goes above threshold (2 p.e.)



SiPM waveform processing

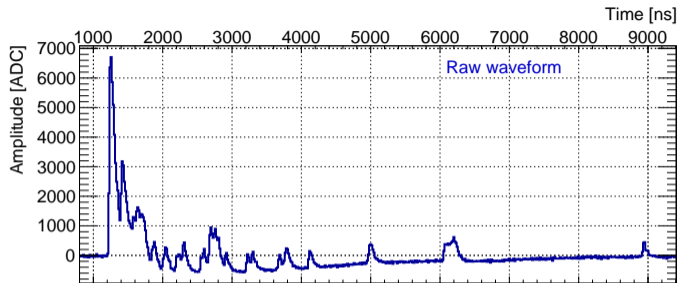
Inversion + Baseline subtraction



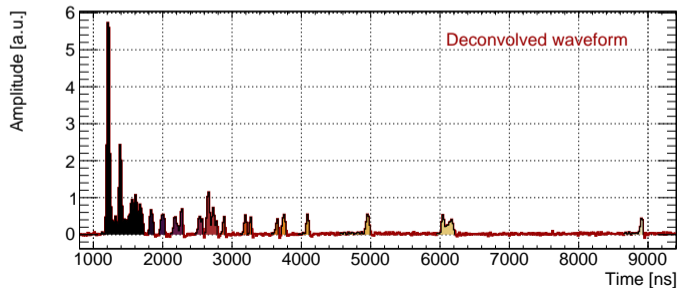
Deconvolution



Hit finding



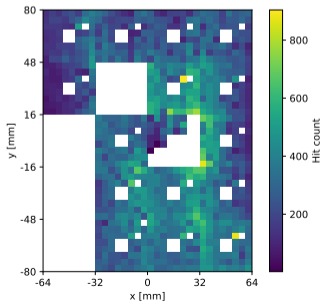
SoLAR-V2 run: 2023-07-06 19:16:44
event: 12930 - ts [ns]: 629760
SiPM board 215537201 - ch 38



Calibration

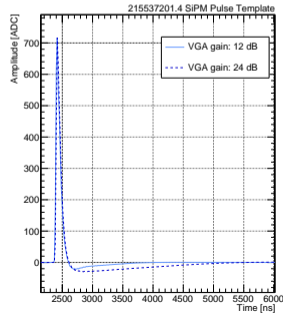
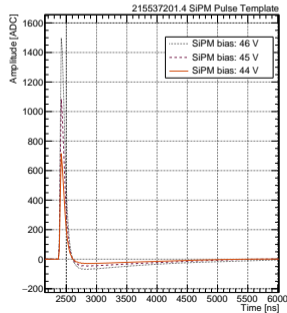
Charge readout system:

- Forced triggers on all channels of each single ASIC to measure relative pedestal offsets
- Issues with one inactive ASIC limited the readout of the full tile (reconfiguring the readout network still possible)
- Trigger threshold set at $\approx 3.8 \text{ ke}^-$



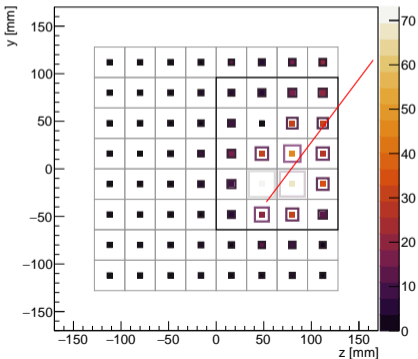
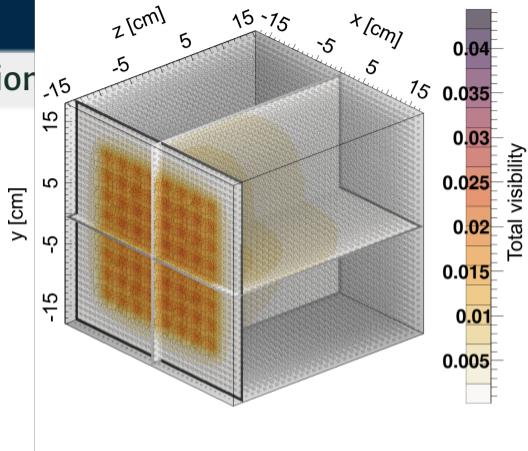
Light readout system:

- Anode flashed with a LED
- Study the SiPM response at different bias (44–46 V) and gain settings (12, 24 dB)
- Channel-wise response model for pulse deconvolution



Combined charge+light energy reconstruction

- Sample of through-going μ (single track, len > 4 cm, score > 0.5)
- Spatial effects on light collection estimated integrating a MC-based light-map over the reconstructed track



- Given the **track topology** reconstructed with the charge readout, one can estimate the **expected light** collected by each SiPM
- Good agreement with the data in the relative SiPM signal intensities

Combined charge+light energy reconstruction

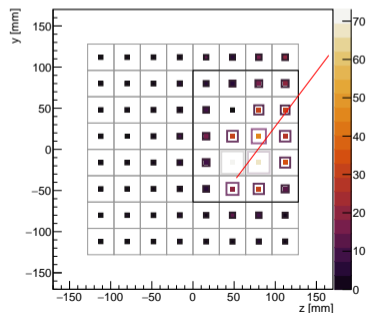
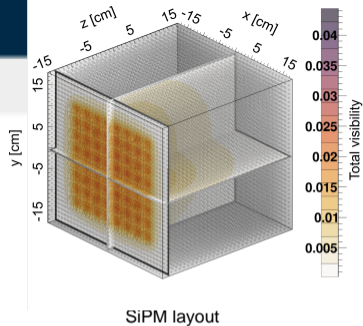
- Select a “golden sample” of through-going muons (single track, length > 5 cm, score > 0.5)
- Extrapolate the track inside the TPC volume (\mathbf{x}_{in} , \mathbf{x}_{out} , \hat{u}_{track})
- Compute the expected light signal on the SiPM i as

$$q_i = \sum_{k=1}^N \left. \frac{dE}{dx} \right|_{mip} \cdot \delta x \cdot (LY(\mathcal{E}) \cdot f_{purity}) \cdot PDE \cdot \Omega_i(\mathbf{x}_{in} + k \delta x \hat{u}_{track})$$

with $\Omega_i(\mathbf{x})$ the **visibility** of SiPM i from point \mathbf{x} (obtained from interpolating a MC-based visibility map)

- The total expected light signal is then

$$L_{exp} = \left. \frac{dE}{dx} \right|_{mip} \cdot \ell_{track}^{TPC} \cdot (LY(\mathcal{E}) \cdot f_{purity}) \cdot PDE \cdot \sum_{i=1}^{N_{SiPM}} \bar{\Omega}_i(\mathbf{x}_{in}, \hat{u}_{track})$$



Next steps: SoLAr towards ProtoDUNE Run III

- **Large scale** engineering **prototype** for mass production, installation, and integration of Phase II components at full Far Detector dimensions
- Proposal for a **Optical and Charge Hybrid Run** at NP02 submitted to the CERN SPSC
- Proposed operation in **2028–2029** during SPS LS3

(SoLAr and Pixels) Goals:

- Test pixel charge readout with m-scale drift
- Assess the optical gain from the SoLAr SiPMs vs depth
- Validate integration for large anode planes

SoLAr R&D:

- Redesign of the SoLAr tile PCB for easier integration into a pixelated anode plane
- Test new readout options for SiPMs (LightPix)

