Towards DUNE Phase II

Experimental validation of the SoLAr anode concept and plans for ProtoDUNE Run III

DUNE-Italia Collaboration Meeting, 10 November 2025

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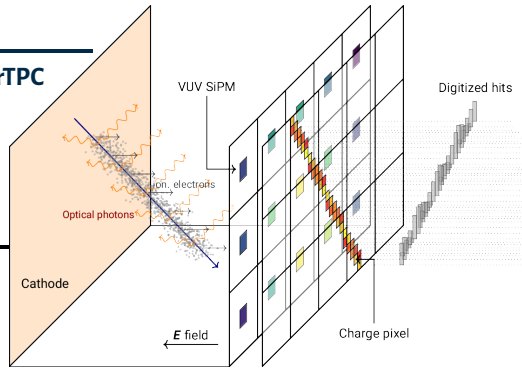
The SoLAr Project

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

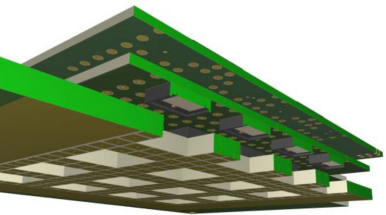
Arapuca-style modules + **VUV SiPMs integrated on the anode**
Exploit the light signal in LAr to perform

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

The SoLAr V1 Prototype

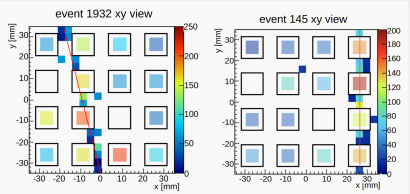
SoLAr, JINST 19 (2024) 11, arXiv:2406.14121

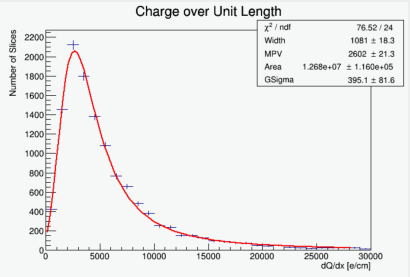
- **Charge readout:**
  256, $3 \times 3\,\mathrm{mm}^2$ pads, readout by 4 LArPix v2a ASIC + PACMAN
- **Light readout:**
  16 Hamamatsu S13370-6050CN ($6 \times 6\,\mathrm{mm}^2$) + Cold pre-amp + Warm amp + 62.5 MS/s digitizer
- **Anode assembly:**
  Three stacked PCB layers to accommodate SiPMs packaging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



Test outcome

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

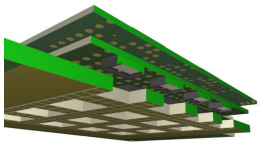




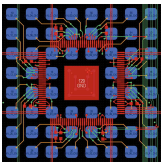
The SoLAr V2 Prototype

- 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 v2b (room for 64)
- 64 Hamamatsu VUV4 SiPM
- Complete re-design of the PCB

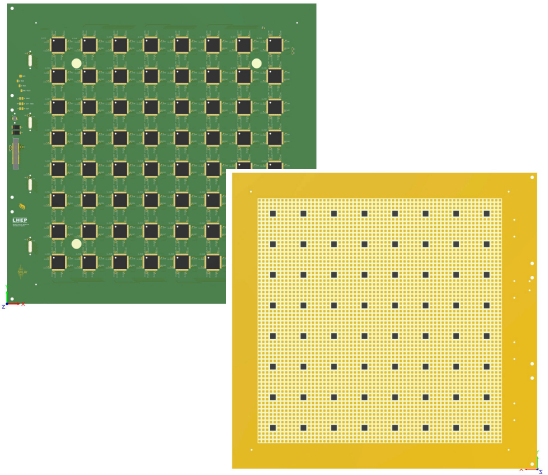
SoLAr tile V1 → SoLAr tile V2



Three PCB stacked



Single multilayer PCB



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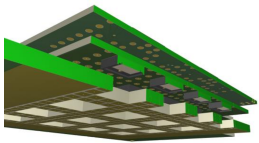

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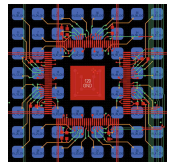

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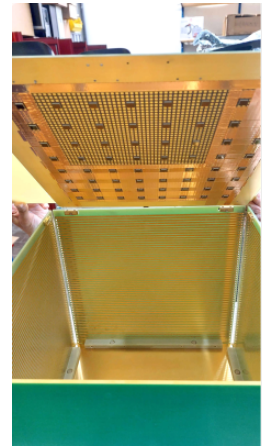
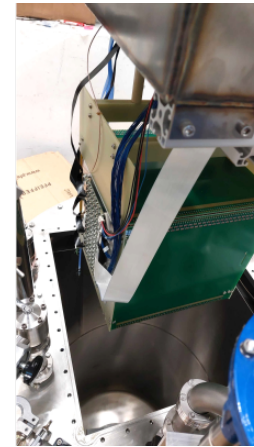
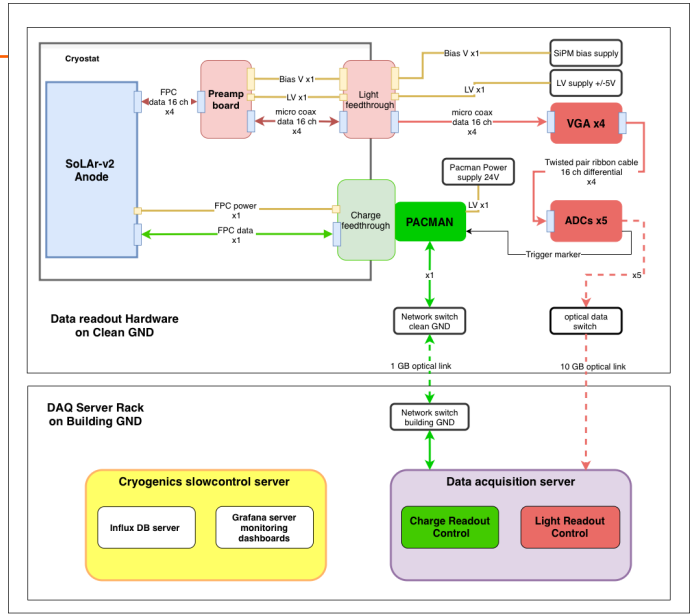




Operated in a $33 \times 33 \times 30\ \text{cm}^3$ LArTPC at University of Bern

DAQ System

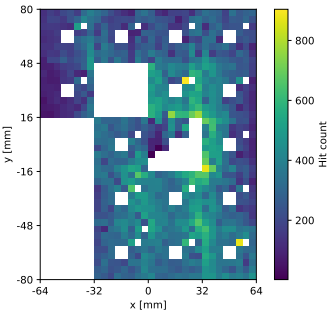
- **Charge readout system:**
  LArPix ASICs read out via a **single** cable to a **PACMAN** unit outside the cryostat
- **Light readout system:**
  Cold pre-amplifiers mounted on the tile, warm amplifiers and 14-bit 62.5 MS/s digitizers outside the cryostat
- Light readout system gives a trigger marker to PACMAN when signal goes above threshold (2 p.e.)



Calibration

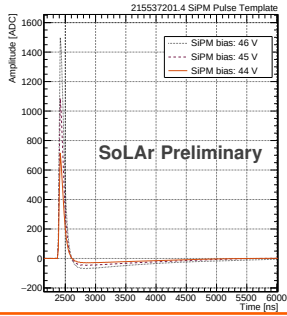
Charge readout system:

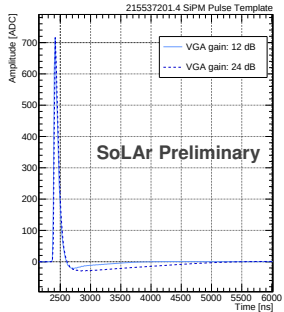
- Forced triggers on all channels of each single ASIC to measure relative pedestal offsets
- Issues with one inactive ASIC limited the readout of the full tile (reconfiguring the readout network still possible)
- Trigger threshold set at $\approx 3.8\,\mathrm{ke}^-$



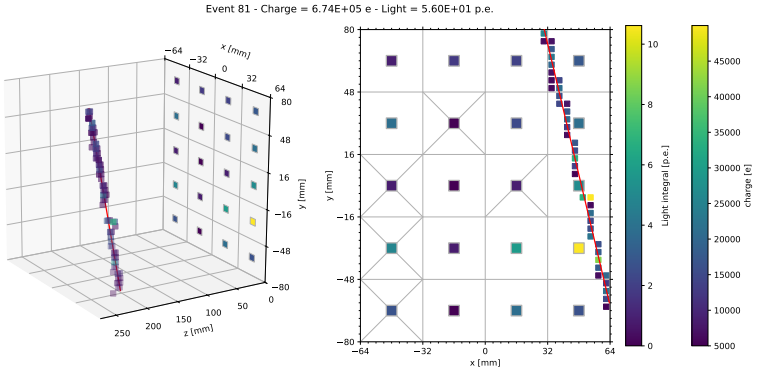
Light readout system:

- Anode flashed with a LED
- Study the SiPM response at different bias (44, 45, 46 V) and gain settings (12, 24 dB)
- Channel-wise response model for pulse deconvolution



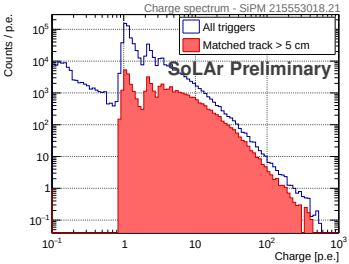


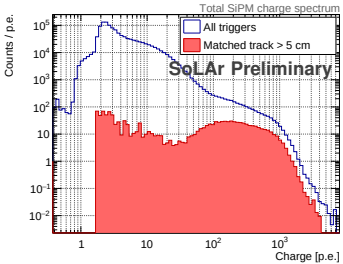
Cosmic-ray run



- ≈ 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

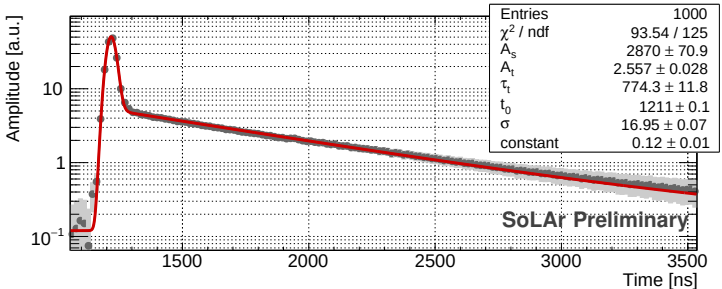
SiPM system performance





- Charge on single SiPMs goes from few to $\mathcal{O}(10^2)$ p.e.
- Total charge on all SiPMs for reconstructed tracks (length > 5 cm) goes from $\mathcal{O}(50)$ to $\mathcal{O}(10^3)$ p.e.

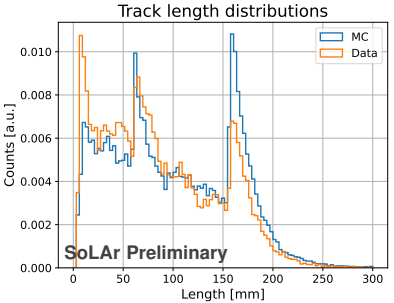
- Average μ pulse shape fitted with a double-exponential model
- Short $\tau_t = (774 \pm 12)$ ns indicates contamination
- Light yield correction factor $f_{\text{purity}} = 0.60$

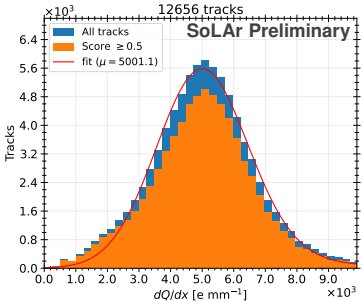


Charge readout system performance - track reconstruction

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 (confirmed with MC)





Energy deposition measurement:

- Electron lifetime (1.87 ± 0.18) 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]

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Combined charge+light energy reconstruction

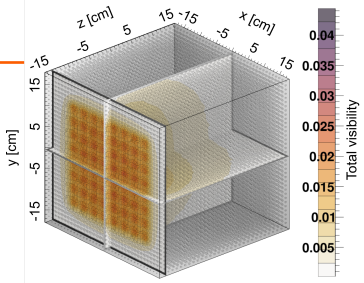
- Select a "golden sample" of through-going muons (single track, length $> 5\,\text{cm}$, score > 0.5)
- Extrapolate the track inside the TPC volume ($\boldsymbol{x}_{\text{in}}$, $\boldsymbol{x}_{\text{out}}$, $\hat{u}_{\text{track}}$)
- Compute the expected light signal on the SiPM i as

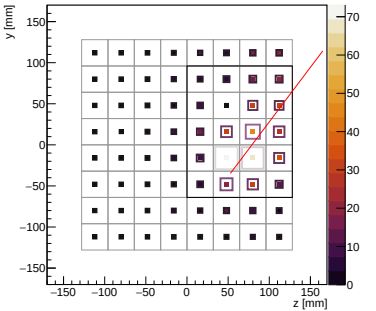
$$q_i = \sum_{k=1}^{N} \left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\text{mip}} \cdot \delta x \cdot \left(\text{LY}(\mathcal{E}) \cdot f_{\text{purity}}\right) \cdot \text{PDE} \cdot \Omega_i\left(\boldsymbol{x}_{\text{in}} + k\,\delta x\,\hat{u}_{\text{track}}\right)$$

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

- The total expected light signal is then

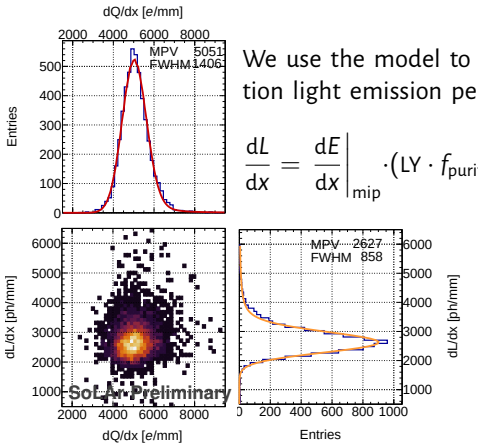
$$L_{\text{exp}} = \left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\text{mip}} \cdot \ell^{\text{TPC}}_{\text{track}} \cdot \left(\text{LY}(\mathcal{E}) \cdot f_{\text{purity}}\right) \cdot \text{PDE} \cdot \sum_{i=1}^{N_{\text{SiPM}}} \overline{\Omega}_i\left(\boldsymbol{x}_{\text{in}}, \hat{u}_{\text{track}}\right)$$





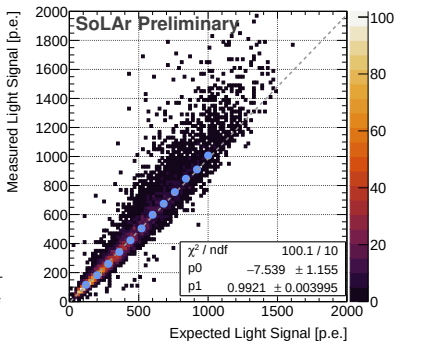
Combined charge+light energy reconstruction

Slope of L_{exp} vs L_{data} indicates that the model describes scintillation light propagation and detection with good accuracy.



We use the model to extract the scintillation light emission per unit length

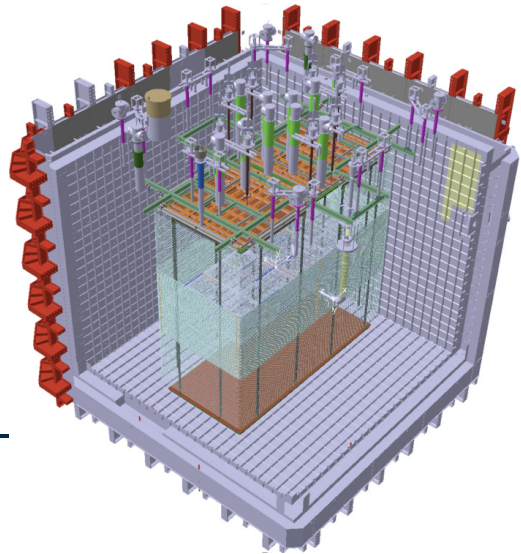
$$\frac{dL}{dx} = \frac{dE}{dx}\bigg|_{mip} \cdot (LY \cdot f_{purity}) = \frac{L_{data}}{\ell^{TPC}_{track} \cdot PDE \cdot \sum_{i=1}^{N_{SiPM}} \overline{\Omega}_i}$$



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

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
  - ARIADNE (dual-phase) readout for top anode
  - **Pixel** + strip readout for bottom anode
  - APEX light readout on field cage walls
- Proposed operation in 2028–2029 during SPS LS3

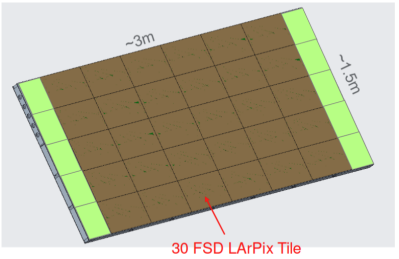


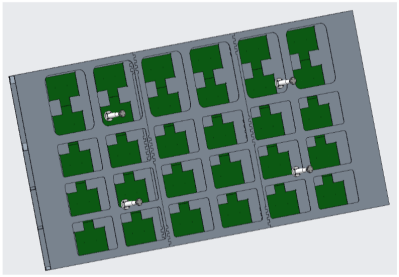
(SoLAr and Pixels) Goals:

- 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 @ ProtoDUNE Run III

- Plan to integrate one or more SoLAr tiles in the pixel sector of the bottom anode plane.
- Same charge readout system as surrounding pixel tiles (LArPix), straightforward integration.
- Redesign of the PCB to match standard LArPix tile form factor $30 \times 48\,\mathrm{cm}^2$, 160 LArPix, 160 SiPMs.
- Two possible readout strategies for SiPMs:
  - **LightPix**: LArPix-derived cryogenic ASIC for SiPM readout
    - 64 channels per ASIC
    - No waveform digitization, on-chip pulse integration
    - TDC with sub-ns resolution
    - Same architecture as charge readout
      ↪ shared power and I/O lines
  - "Classic" SoLAr approach
    cold preamp + warm electronics + digitizer

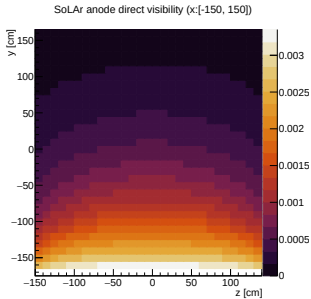


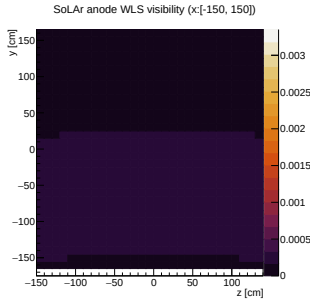


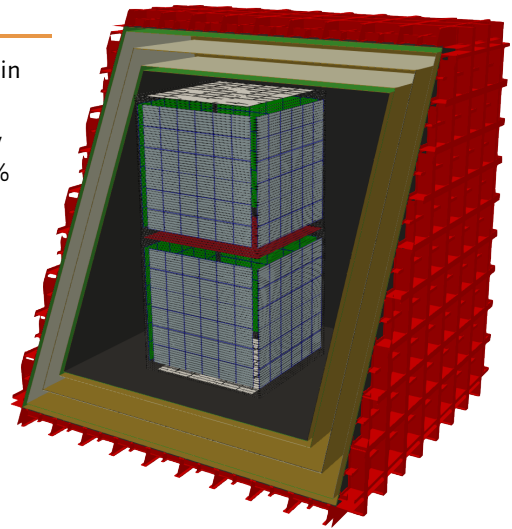
SoLAr @ ProtoDUNE Run III

Light readout system requirements:

- What is the required dynamic range per SiPM to operate in ProtoDUNE Run III?
- Ongoing MC production to produce LUTs of SiPM visibility including visible light emission from APEX modules (100% coverage)







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Conclusions and outlooks

- Analysis of **SoLAr V2 cosmic-ray** run has been **finalized** and is ready for final review
- The test demonstrated the **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 step**: deploying SoLAr tiles in **ProtoDUNE Run III**
  - UniBe is working on the redesign of the PCB
  - Ongoing studies to define the light readout system requirements
  - Planning to test LightPix and test if it can match the ProtoDUNE Run III requirements
- Starting from the SoLAr collaboration, **MiB electronics group** is working with the **LBNL LArPix team** to develop a **digital multiplexer for the LArPix ASICs**