University of Sheffield

STEEL - The University of Sheffield LArTPC Test Stand for Development of Next Generation Charge Readout Technologies

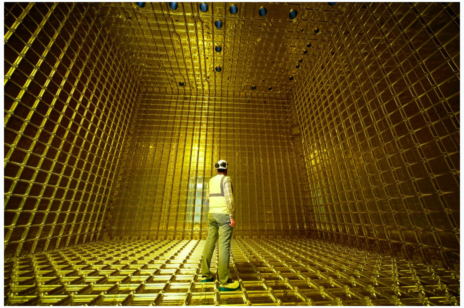
2024 IOP Joint APP, HEPP and NP Conference

Harry Scott (They/Them) 10/04/2024

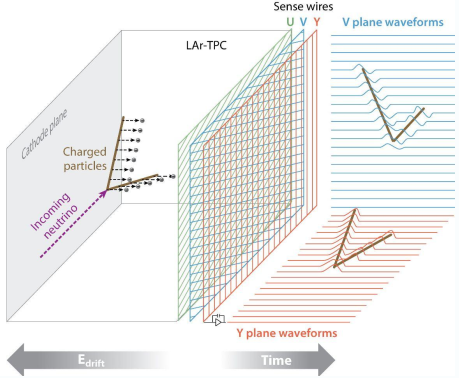
Liquid Argon Time Projection Chambers (LArTPCs)

- The LArTPC is a particle imaging apparatus, containing liquid argon at 87 K in a uniform E-field, drifting ionisation electrons to a charge readout plane, allowing for complete 3D imaging and reconstruction of particle tracks.

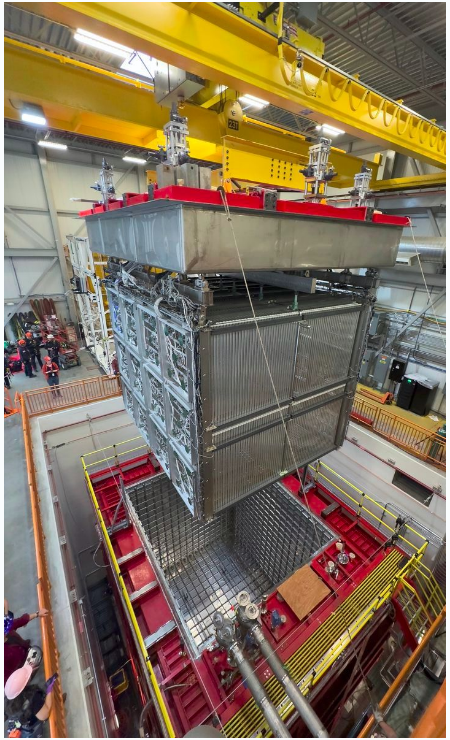
- LArTPC technology is utilised by state-of-the-art neutrino detector experiments such as ProtoDUNE, ICARUS, MicroBooNE and SBND to perform world-leading physics analysis and measure high precision ν_μ-Ar cross-sections.



Internal TPC of a ProtoDUNE detector.
Image: Max Brice, CERN.



Schematic of a LArTPC.



SBND TPC lowered into the cryostat.
Image: Ryan Postel, Fermilab.

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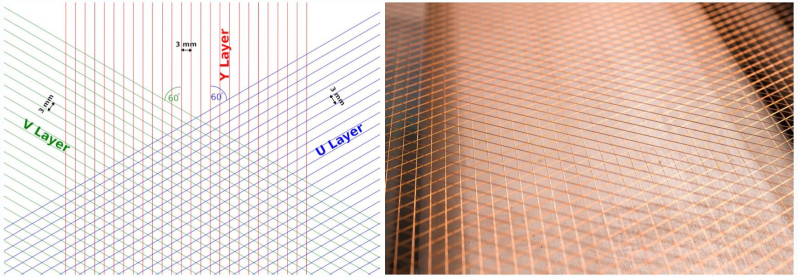
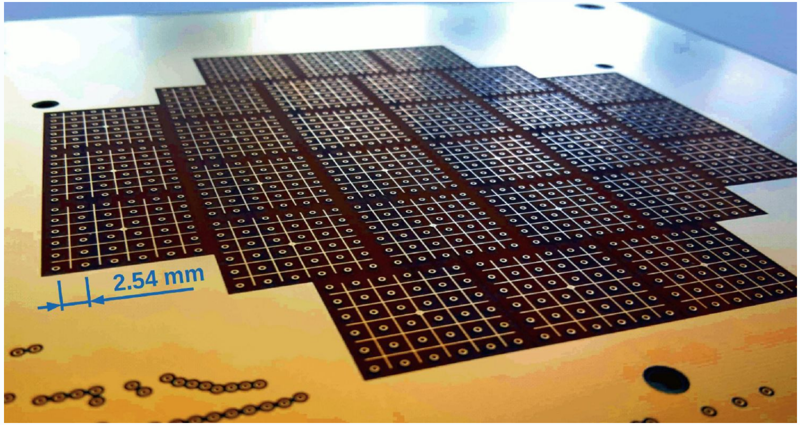
LArTPC Charge Readout Technologies

- **Wire Planes:** Ionisation charges induce signals on two wire planes before collection on a third wire plane; allows for 3D imaging of the initial particle. Utilised by ICARUS, MicroBooNE and SBND.

- **Pixel Readout:** Plane of pixels collecting ionisation charges, focused by voltage-biased ROIs (Regions of interest). Pixels are motivated by wire planes exhibiting ambiguities in event reconstruction, as well as detector pile-up [2]. Pixels will be used to readout charge in the DUNE near detector [3].



Schematic (left) and photo (right) of the SBND first induction (U), 2nd induction (V) and collection (Y) wire planes [1].



The University of Bern pixelated anode PCB (Printed Circuit Board) [2].

[1] R. Acciarri et al., Journal of Instrumentation 15, P06033–P06033 (2020).
[2] J. Asaadi et al., Instruments 4 (2020).
[3] A. A. Abud et al., Instruments 5 (2021).

STEEL - Sheffield TEst-stand Experiment with Liquid argon

- STEEL is a University of Sheffield-based LArTPC experiment, purpose-built for the development and optimisation of pixelated charge readout technology, for use in future large-scale LArTPC neutrino detector experiments such as DUNE.

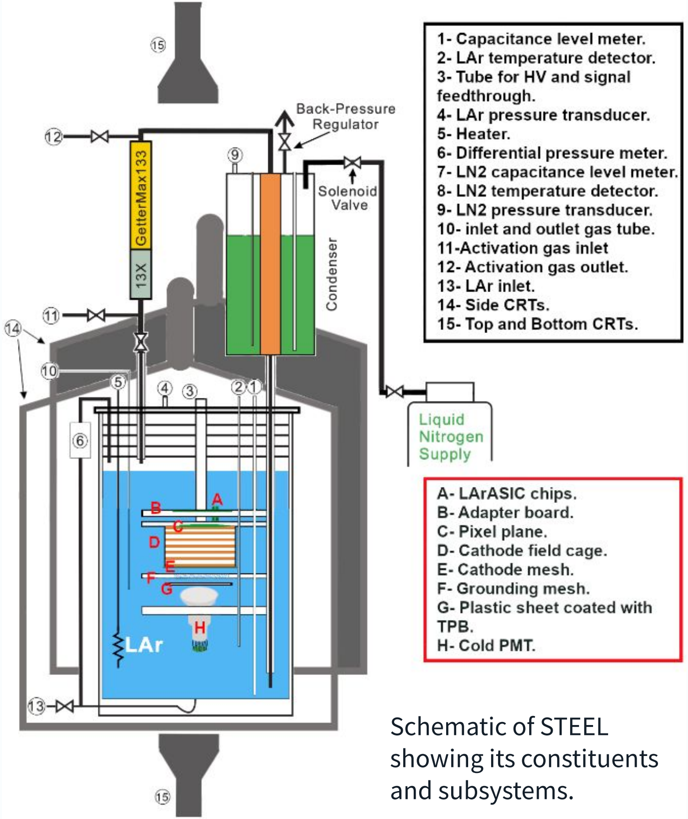
- Development of hit-finding and event reconstruction algorithms will potentially provide the groundwork for the DUNE Phase-II near detector.

Photos of STEEL with the dewar open (left) and closed (right).

STEEL Detector Setup

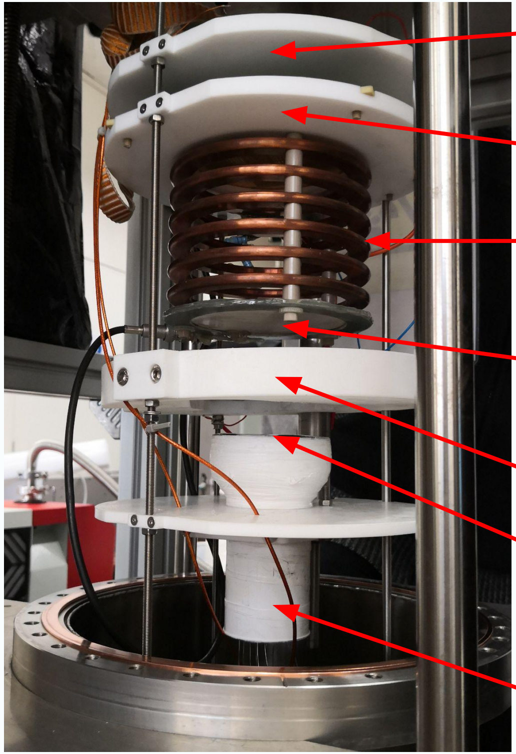
- STEEL consists of a 20 l steel dewar filled with argon, an internal PhotoMultiplier Tube (PMT), four external Cosmic-Ray Taggers (CRTs), and a cylindrical field cage with 10 cm drift distance, allowing for the detection of ionisation charges and cosmic-ray event tagging.

- LAr evaporates into GAr, flowing through a purification system that filters out electronegative impurities (such as water and oxygen molecules), before passing through a condenser system, where circulating 78 K liquid nitrogen cools the argon back to liquid at 87 K, falling back to the bottom of the dewar.



Schematic of STEEL showing its constituents and subsystems.

Internal STEEL Detector System



Inside the STEEL dewar showing the field cage, pixelated anode PCB and cold PMT.

Adapter board plane with two LArASIC chips - Amplifies and shapes raw charge information into processed signals.

Anode pixel plane - PCB-based charge readout plane.

TPC Field Cage - Field strength varies from 0 - 600 V/cm, directed downwards, drifting ionisation electrons upwards.

Cathode mesh - Wire mesh transparent to scintillation light, negatively voltage-biased to induce a potential difference.

Grounding mesh - Protects the PMT from E-field interference.

TPB-coated plastic sheet - Shifts 128 nm argon scintillation light to the visible range so the PMT can read out photons.

Cold PMT - Amplifies the photon energy to a measurable readout signal, operates optimally at 1700 V.

STEEL Pixelated Anode Readout

- The pixel anode plane consists of 1008 pixels, 2.54 mm apart, divided into a 6x6 grid, each surrounded by an ROI.

- Each ROI is voltage-biased to induce a signal and concentrate charges to be collected by the individual 900 μm wide pixels.

- The pixel DAQ has a total of 64 readout channels: 28 ROIs and 36 pixels, where multiplexing allows for each pixel in the same relative 6x6 grid position to share one readout channel.

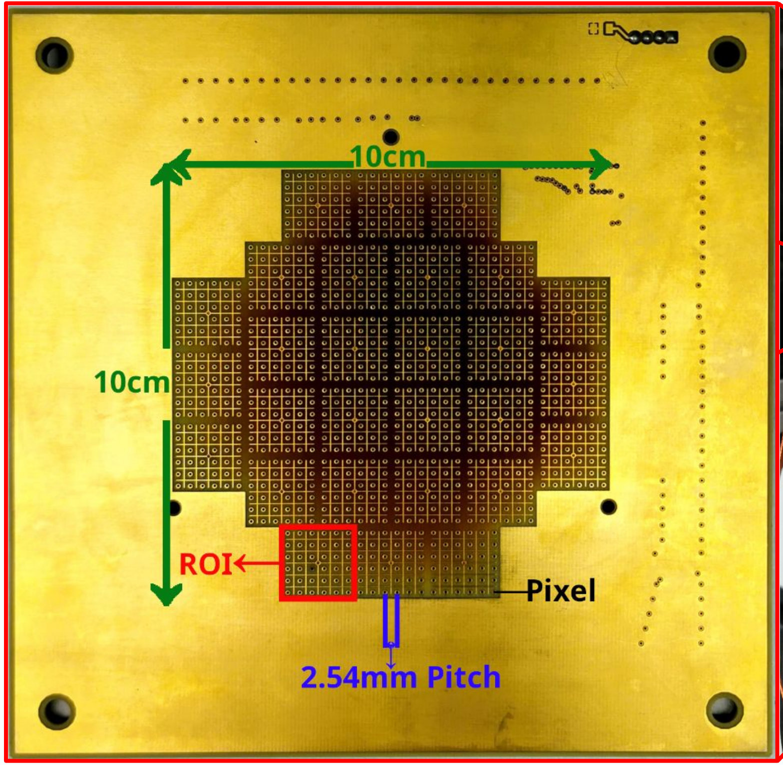
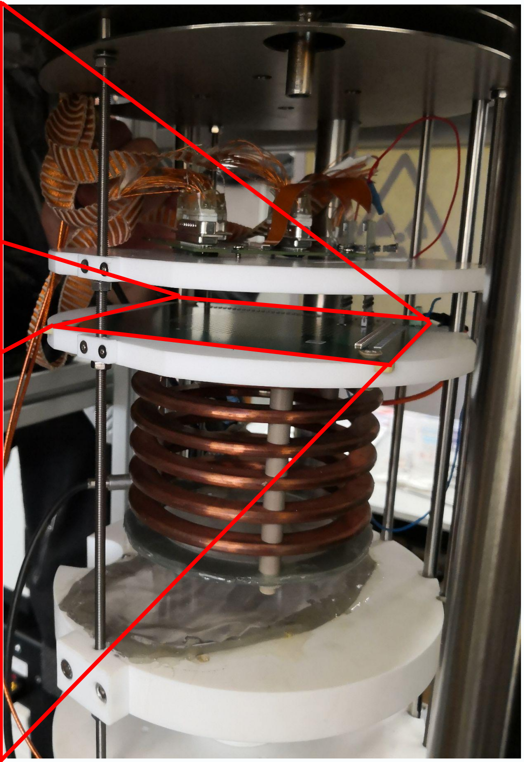


Photo of the University of Bern-designed pixelated anode PCB.



STEEL TPC detector showing the field cage and the anode pixel plane inside the dewar.

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STEEL Detector Commissioning and Operation

- After verifying that the experiment (TPC and subsystems) is fit for data-taking, the dewar is continually pumped full of GAr to purge it of air.
- LN is circulated through the condenser until > 90% of the argon is liquid. The argon liquid level, LAr pressure and LAr/LN temperature are tracked live.
- When LAr temperature is maintained at < 87 K, LN temperature < 86 K, LAr pressure < 0.5 bar and impurity ~ 1 ppm, the experiment is ready for data-taking.

Live LAr pressure and LAr/LN temperature monitors above STEEL. LAr pressure is calculated using a partial differential pressure monitor.

Above the STEEL dewar; the steel coil acts as a nucleation point for frost build-up

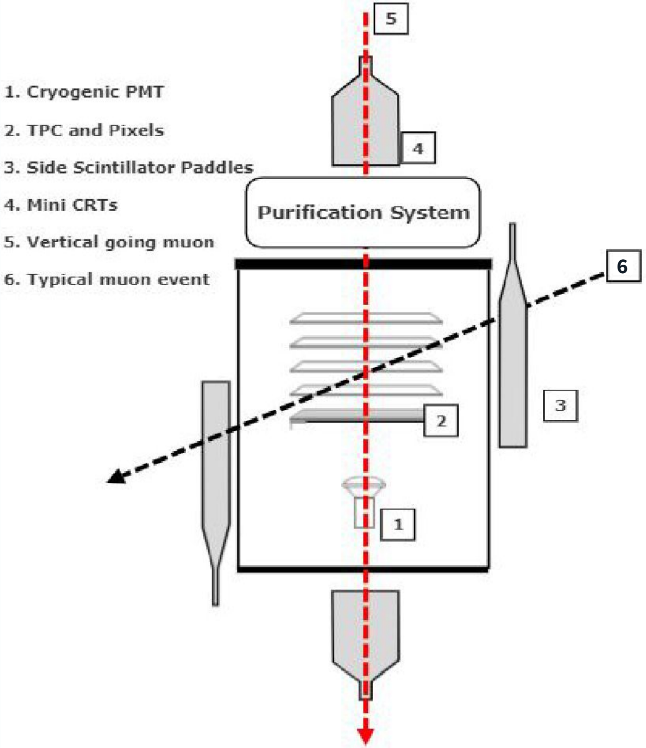
40 l LN (left) and LAr (right) cryogenic containers, filling the STEEL condenser and dewar respectively.

STEEL Operations and Data-Taking

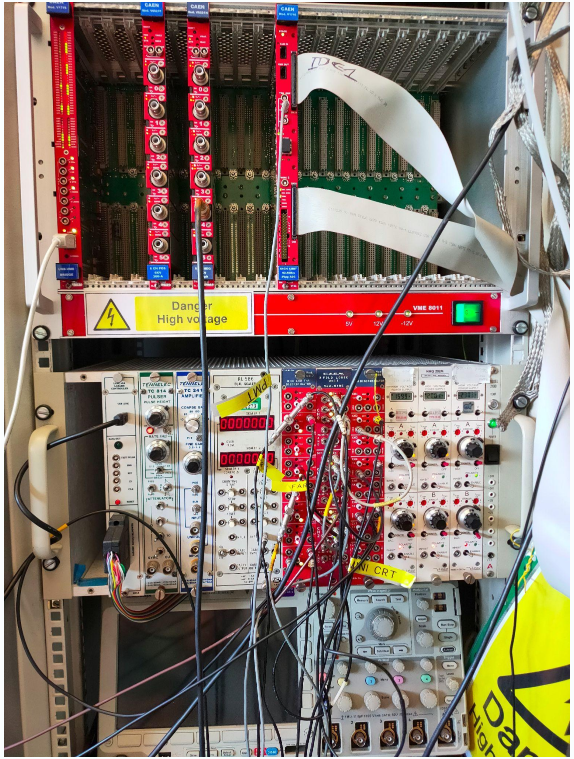
- STEEL collects cosmic-ray muon data, reading out an event when a muon simultaneously triggers the side/top CRTs, cold PMT and pixels.

- Two DAQ systems process the raw data into root files: CAEN1730 for the pixels, and KeySight DAQ for the CRTs, cold PMT and logic trigger.

- In summer 2023, STEEL collected 22 continuous days of cosmic-ray muon data, maintaining consistently low impurity levels for the entire run.



Schematic of the coincidence trigger system of STEEL. Dotted lines represent cosmic-ray muon paths.



STEEL rack: CAEN-V6521 voltage supply (top), logic trigger system (middle), oscilloscope (bottom).

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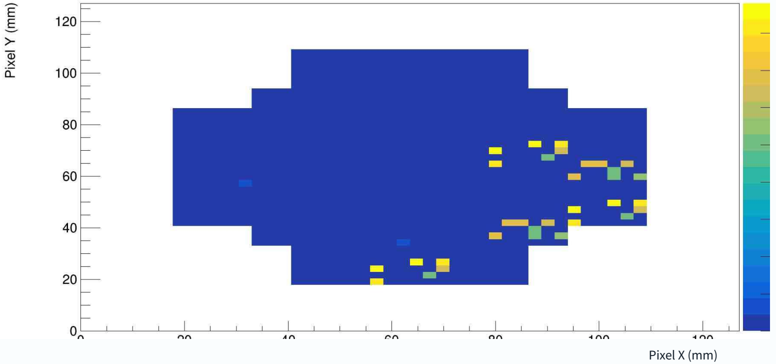
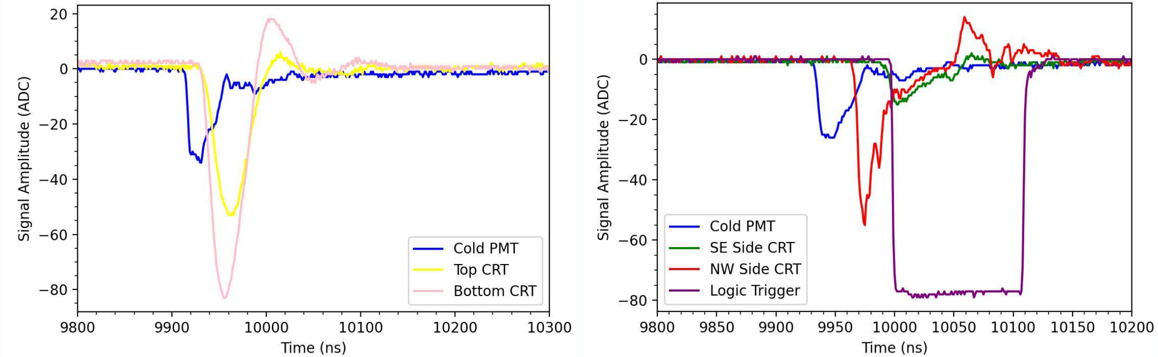
STEEL Event Displays

- The events were run through a noise filter, hit-finding algorithms were developed and employed to identify signal peaks in the pixel readout channels.

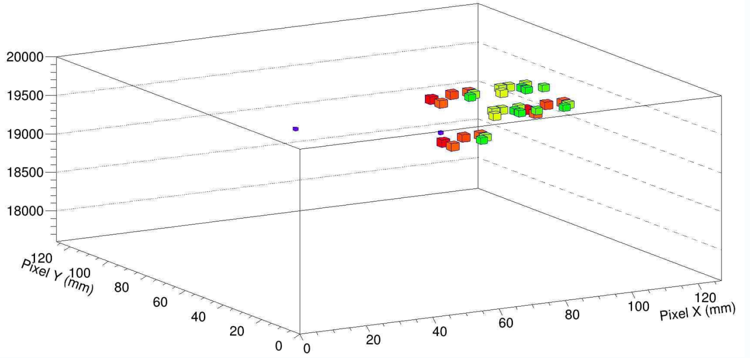
- 2D and 3D event displays were developed to visualise hits on the pixel plane, with an additional time axis for the 3D event display.

- Signal waveforms from cosmic-muon events tagged by the CRTs and cold PMT in coincidence are plotted for noise filtering and time-of-flight studies.





Signal waveforms outputted from a vertical (left) and diagonal (right) cosmic-ray muon, with the respective CRTs in coincidence with the cold PMT.



2D (top) and 3D event displays showing the energy deposited on each pixel, with the colour representing ADC amplitude.

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Tracking LAr Purity Using Scintillation Pulses

- ElectroNegative Impurities (ENI), such as O_2 or N_2, quenches electron lifetime and scintillation light yield [4]. Argon de-excitation with impurities (X_2) occurs through the triplet state:

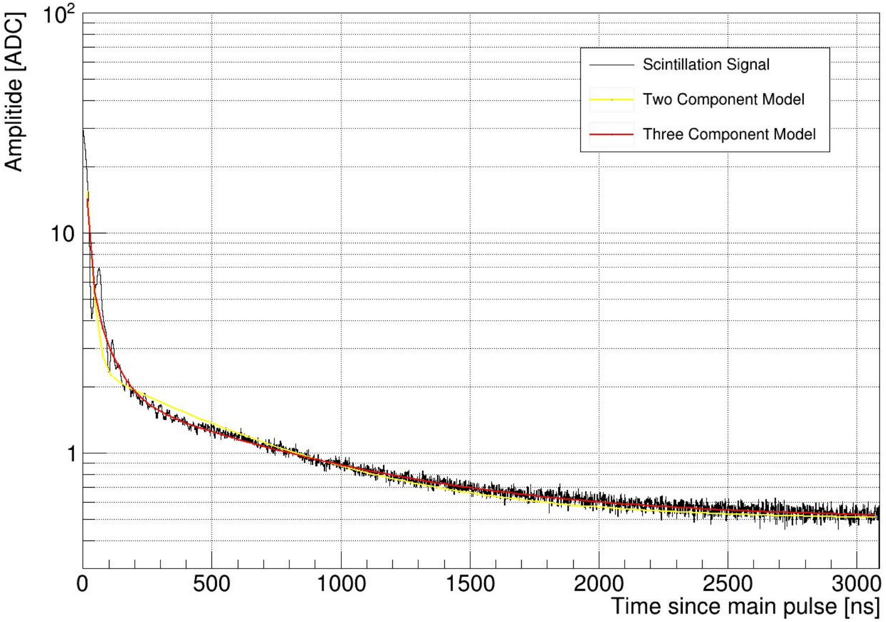
$$\mathrm{Ar}_2^* + \mathrm{X}_2 \rightarrow 2\mathrm{Ar} + \mathrm{X}_2$$

- The triplet time constant τ_3 increases with ENI density. This can be modelled using a two (including the singlet decay constant τ_1, unaffected by ENI) or three (with a theoretical intermediate decay constant τ_i [5]) component exponential decay:

$$f = Ae^{-\frac{t}{\tau_1'}} + Be^{-\frac{t}{\tau_3'}} + Ce^{-\frac{t}{\tau_i'}}$$

- ENI density is then calculated using the measured triplet decay constant τ_3', theoretical minimum triplet decay constant $\tau_3 = 1.6 \pm 0.1$ µs [6] and quenching factor $k_X = 1.9$ ppm^{-1} for O_2 [7]:

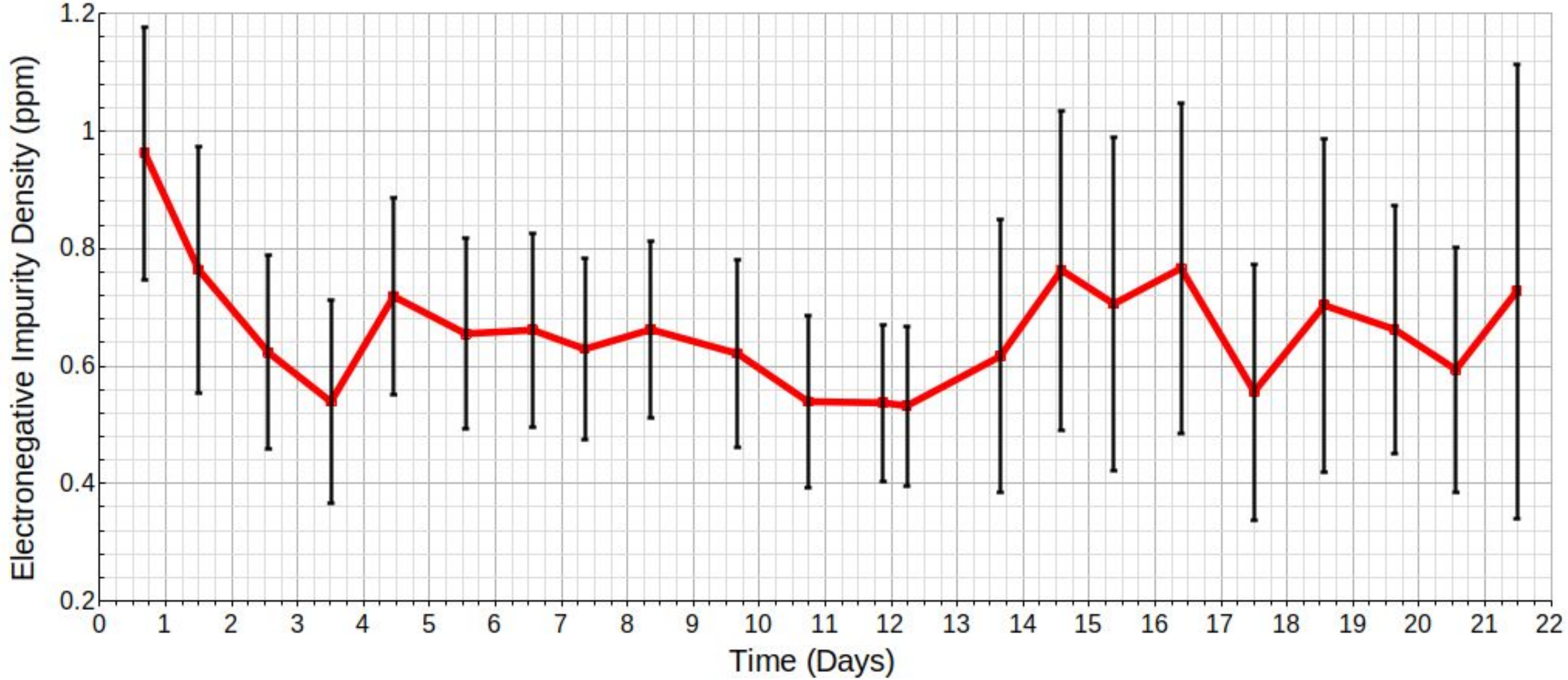
$$[X] = \frac{\tau_3 - \tau_3'}{\tau_3' k_X}$$



Scintillation pulse from the first peak, averaging STEEL cold PMT signals from 200 events, showing the fitted two and three component exponentials.

[4] S. Amoruso et al., Nuclear Instruments and Methods in Physics Research 516, 68 (2004).
[5] C. Lastoria, Journal of Instrumentation 15, C06029 (2020).
[6] A. Hitachi et al., Phys. Rev. B 27, 5279 (1983).
[7] G. Bakale, U. Sowada, and W. F. Schmidt, The Journal of Physical Chemistry 80, 2556 (1976).

Averaged LAr Purity in STEEL Over Three Week Run



Electronegative impurity density (parts per million) as a function of time (days), averaging LAr purity values for each day. Data was taken starting from 3:30pm 22nd June 2023 until 4:30pm 13th July 2023: 21 days almost continuously.

STEEL Conclusions and Future Work

- STEEL's state-of-the-art LAr recirculation and purification system capabilities allowed for continuous collection of cosmic-ray muon data with consistently low impurity levels.

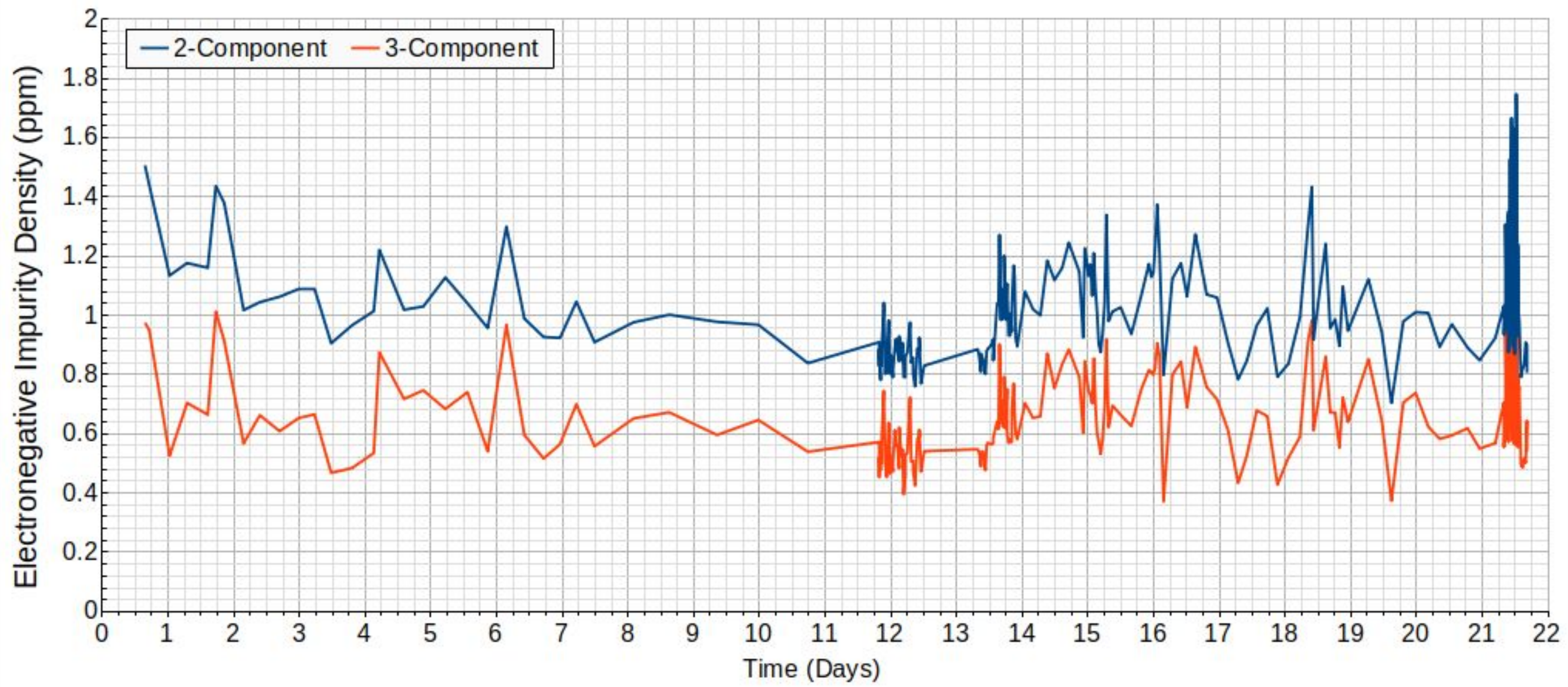
- Developments in hit-finding and track reconstruction algorithms have led to high precision particle identification and event displays.

- ENI density measurements through scintillation decay pulses allows for live purity monitoring, with current work ongoing on measuring purity levels using charge attenuation in the pixels, increasing the accuracy and precision of purity measurements.

- A paper will be out within the next few months in JINST detailing the experimental setup and operations, with more papers planned this year as more data analysis is conducted.

Thanks for listening. Any questions?

2-Component vs. 3-Component Fits



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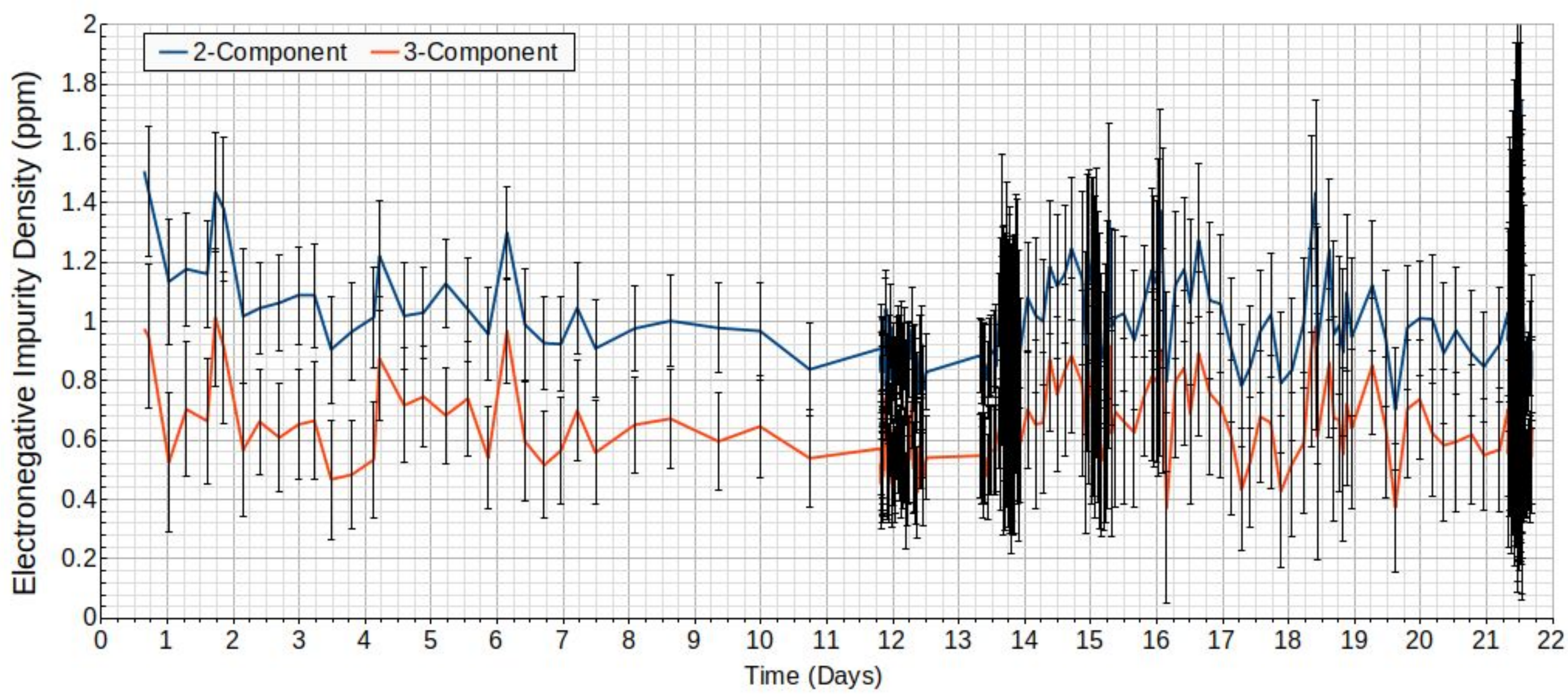
2-Component vs. 3-Component w/ Error Bars



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