SoLAr detector prototyping

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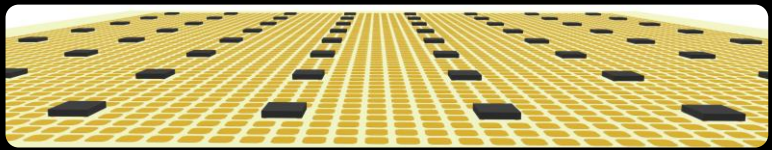
On behalf of the SoLAr collaboration

IOP, 08-11 Apr 2024

The SoLAr detector

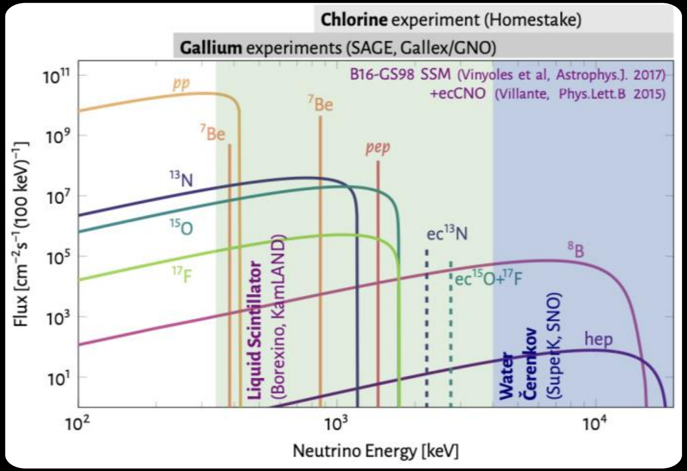
Novel detector concept

- Pixelated readout providing true 3D reconstruction from both charge and light
- Integrated array of VUV SiPMs on anode plane
- Easily scalable for a kiloton-scale LAr-TPC
- Online localized triggering for dealing with high data rates



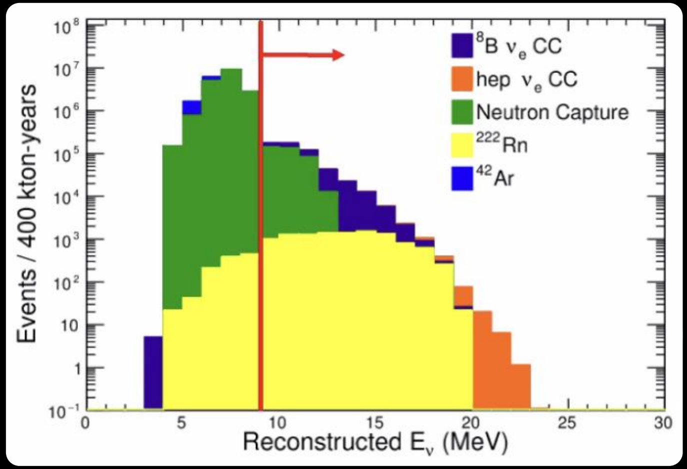
Physics motivation

- Detecting the Solar ^{8}B and hep neutrino fluxes via both CC and ES reactions
- Detecting Supernova neutrino bursts
- Detecting other processes in the MeV scale

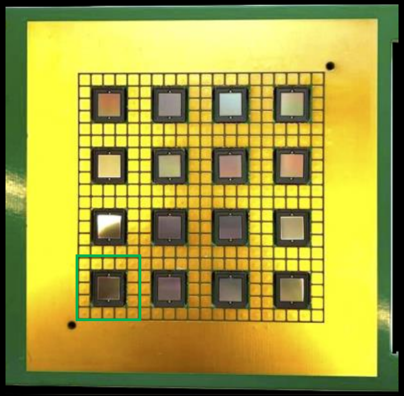


Challenges

- Achieve an excellent energy resolution
- Low-energy background mitigation strategy
- Neutrino flavour tagging
- Identify neutrino direction (angular resolution)
- Calibration at MeV energies across the detector
- An efficient event reconstruction for online triggering

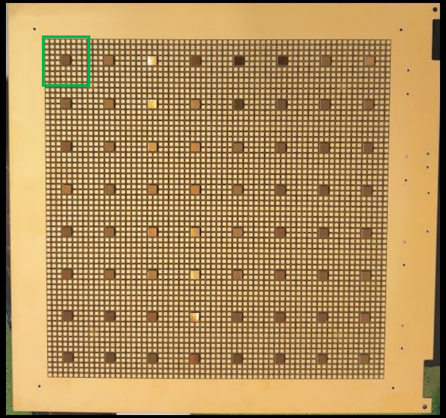


Existing SoLAr prototypes



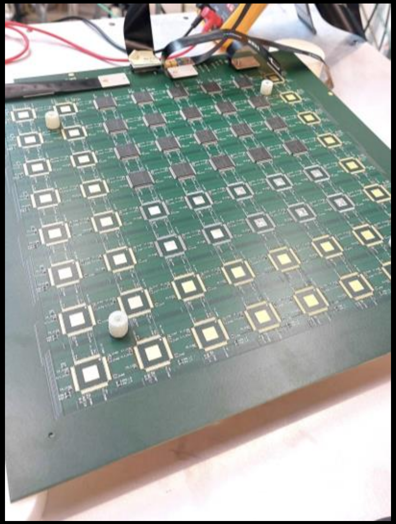
1) Small scale v1 - October 2022 @ The University of Bern

- $7x7$ cm^2 anode plane, 5 cm drift – 3 stacked PCBs
- 16 Hamamatsu ceramic packaged VUV SiPMs with connector pins
- 4 LArPix v2a chips
- Observed cosmic muon tracks



2) Small scale v2 - July 2023 @ The University of Bern

- $30x30$ cm^2 anode plane, 30 cm drift – single PCB
- 64 Hamamatsu SMD packaged VUV SiPMs
- 20 LArPix v2b chips – slots for 64 chips
- Observed cosmic muon tracks and ^{60}Co gamma source



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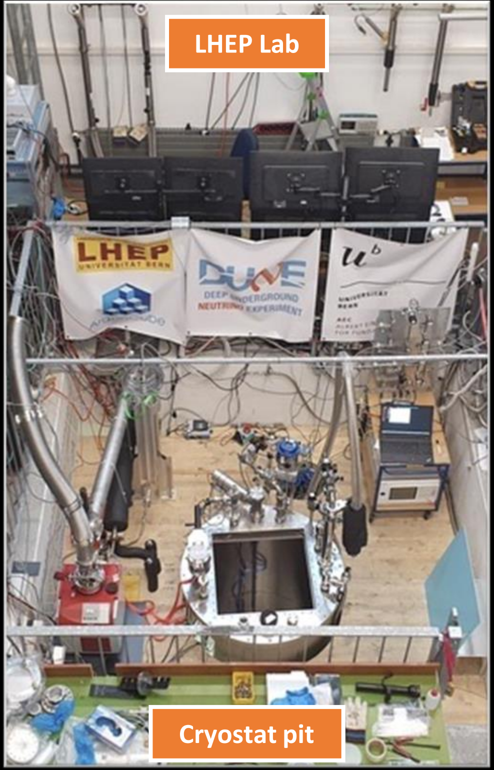
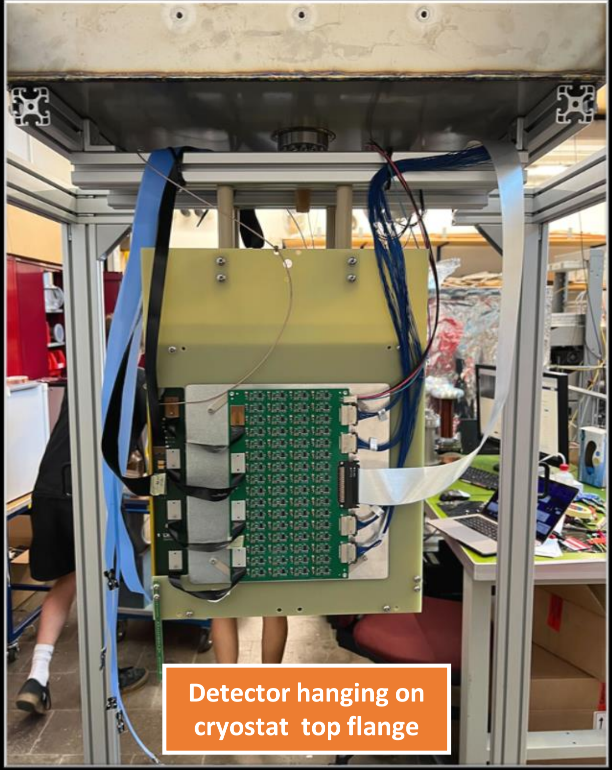
SoLAr V2 prototype

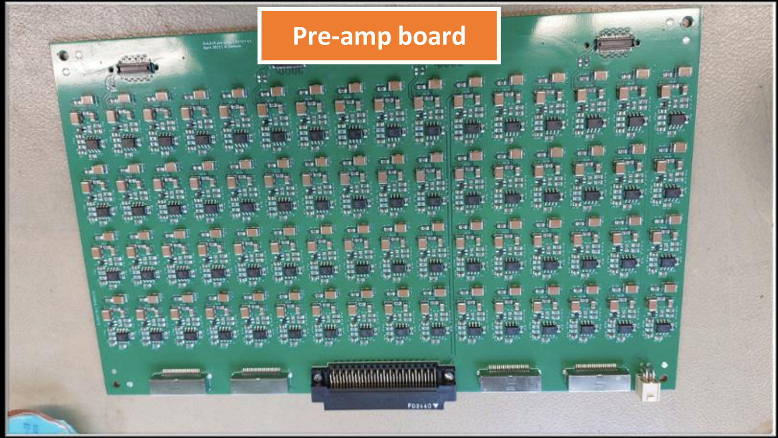
- $30x30$ cm^2 anode plane
- 64 SMD packaged VUV SiPMs
- 6840 $3x3$ mm^2 pixels
- 500 V/cm electric field

SMD SiPMs are V2's biggest advantage over V1

- ➢ No need for stacked PCBs to fit connector pins
- ➢ No ceramic mount distorting electric field lines and taking up pixel space







Anode divided in 64 pixel quadrants

- ➢ 1 quadrant = 60 pixels + 1 SiPM

Only 20 LArPix chips installed

- ➢ 20 quadrants

SoLAr

SoLAr V2 run

Readout diagram

Charge

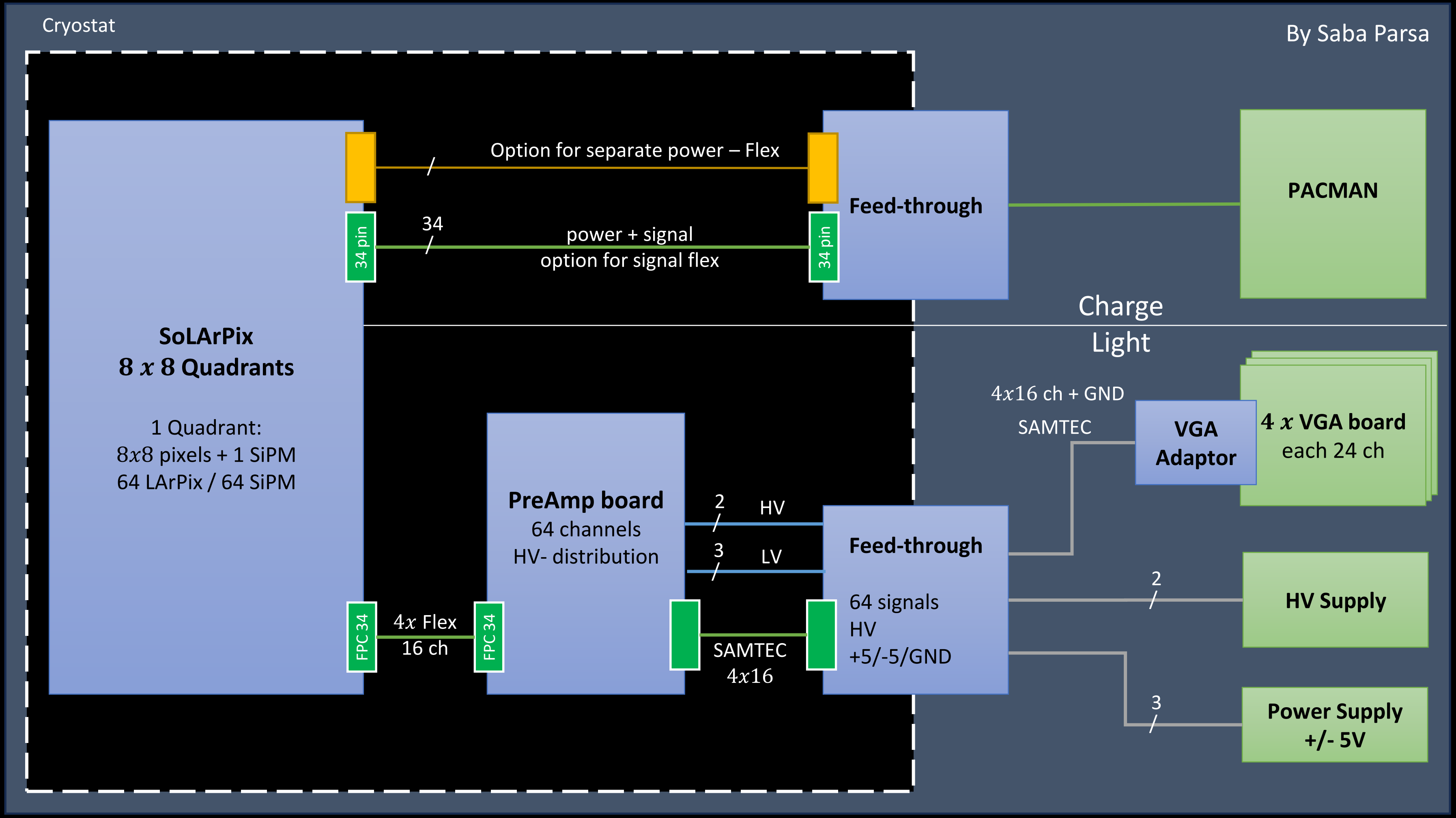
LArPix-v2b chips + PACMAN

- Continuous Self-triggering
- Low power Low noise
- Channel threshold ~ 100 keV

Light

SiPM + Pre-Amp + VGA + ADC

- 62.5MHz sampling frequency
- 10µs digitized window
- Trigger on the Sum of up to 6 SiPMs



SoLAr V2 run

Overview

1. Achieved good LAr purity
2. Achieved very low charge hit threshold $\sim 3.8\ \mathrm{k}e^{-}$ → 100 keV
3. 85.7% of the charge events found a corresponding light event match within a search window of 10 µs

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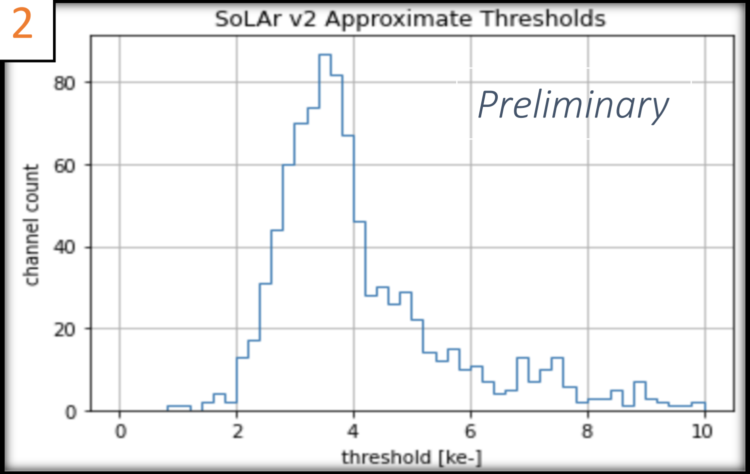
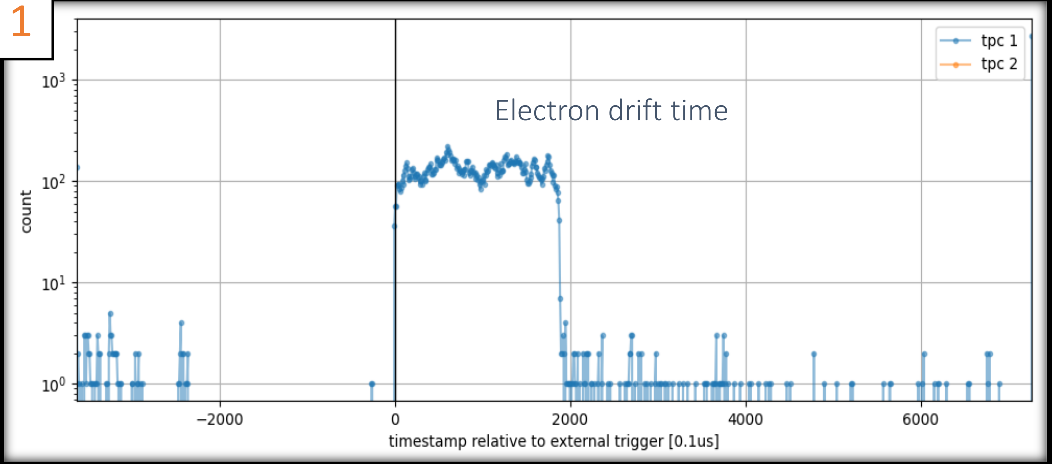
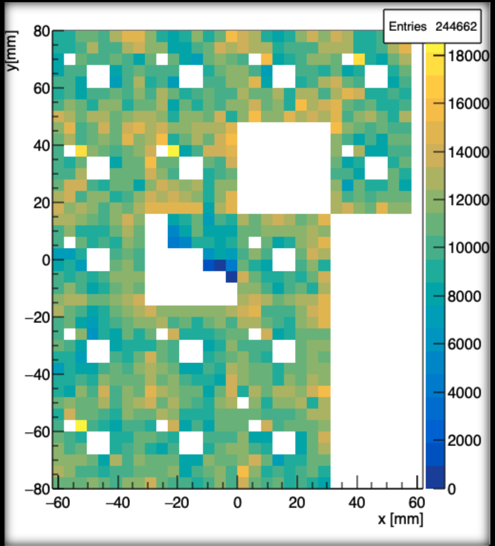
- Two days of cosmic run with nominal 15 kV HV
- Special ^{60}Co source run
- Special runs with 7.5 kV and 3.75 kV HV
- Special runs with varied SiPM bias over voltage

2



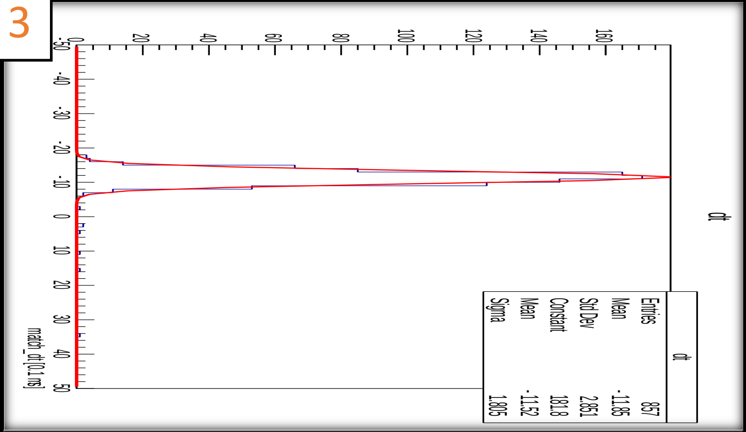
1





Hit map shows location of disabled charge pixels

3



dt = charge timestamp – light timestamp

Data Processing

Reconstruction methods

Charge tracks fitting

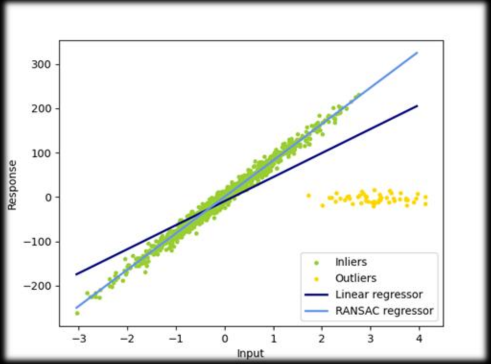
1. DBSCAN clustering

1) Cluster hits in the xy-plane
2) Determine the intervals in z between clusters
3) Generate fake data filling dead areas withing the z intervals
4) Cluster hits + fake data in the xy-plane
5) Cluster hit labels from first stage with hit z-coordinates
6) Remove fake data

Handling dead areas due to disabled pixels (steps 3–6)

2. RANSAC regression

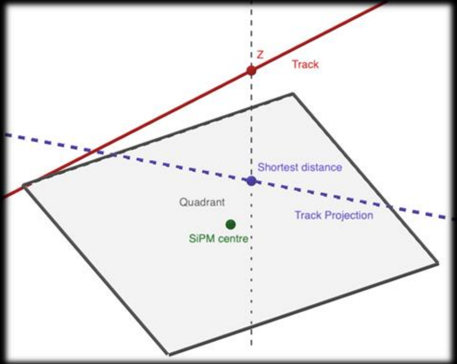
- Fit line to clustered hits
- Use hit charge as weight for line fit
- Optionally re-cluster and fit outliers to find secondary tracks



dQ/dx is obtained by defining same sized stacked cylinders along the fitted tracks

Light "track" fitting

1. **Obtain light signal xy-coordinates**
   - Select top 5 SiPMs with largest light signal
   - Minimum of 3 SiPMs with non-zero signal
   - x and y are determined by SiPM's coordinates
2. **Estimate light signal z-coordinate**
   - Average the z-coordinate of the charge hits within the SiPM's quadrant
   - Use total average z-coordinate if no hits in the SiPM's quadrant
   - Average is weighted by hits charge
3. **RANSAC regression**
   - Fit line to light coordinates
   - Fit quality depends strongly on angle of incidence to anode

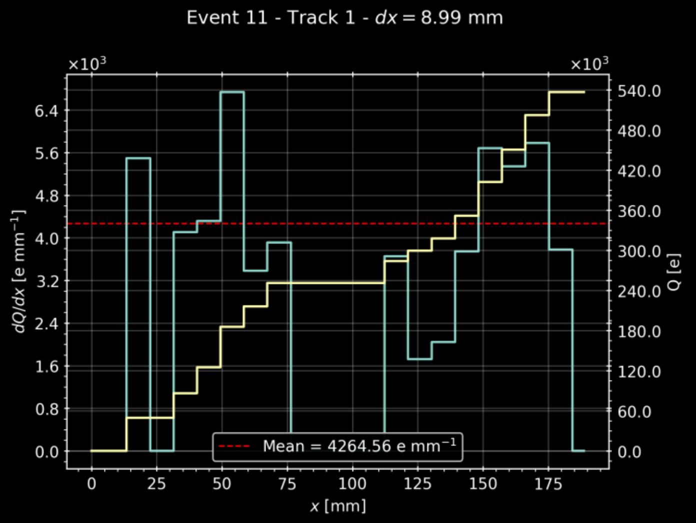


Light fit is a coarse approximation to the charge track and is expected to be approximately parallel to it

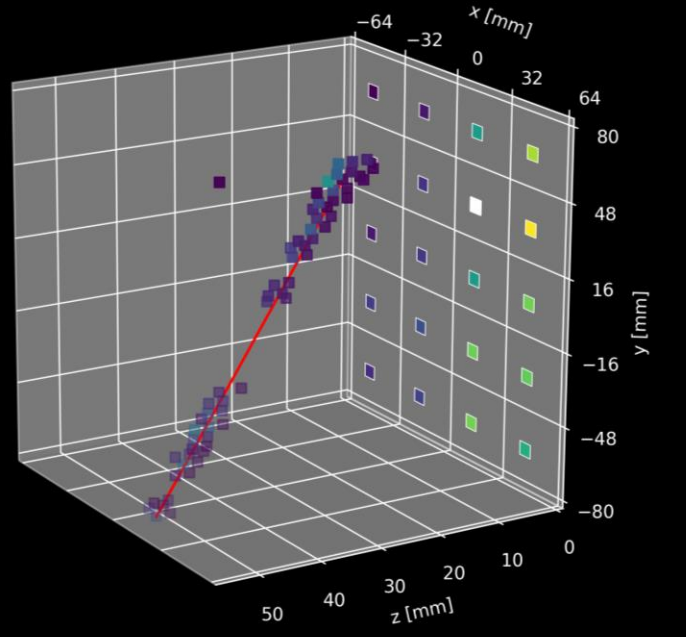
Data Processing

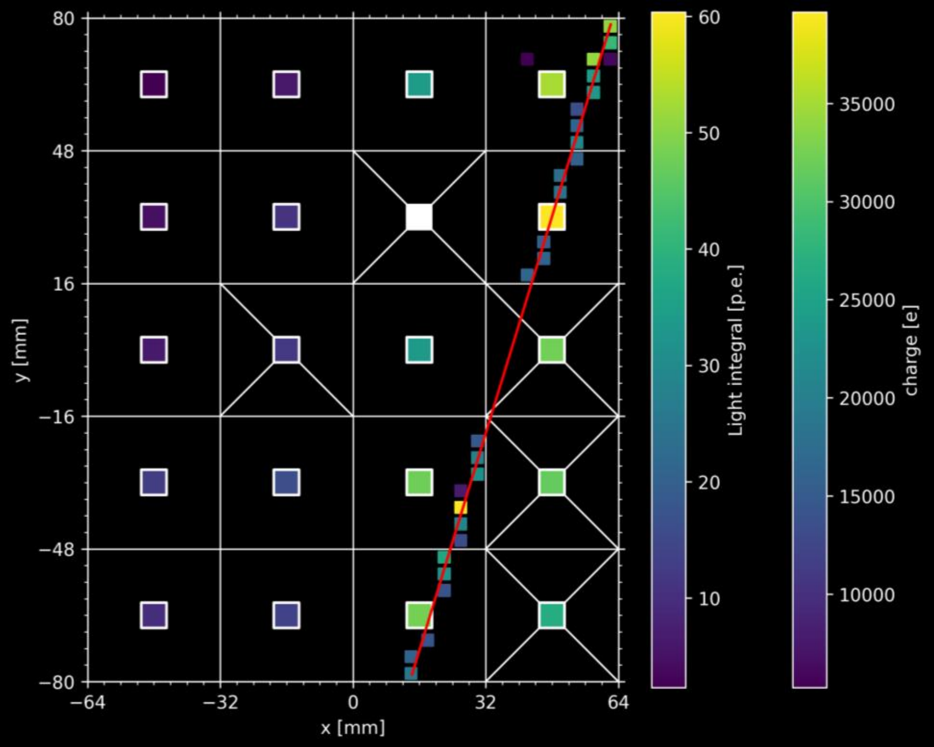
Single cosmic ray event

Integrated charge and light event display



Single track dQ/dx plot showing gap in dead area





Crosses indicate quadrants with dead chips. 1 chip = 1 quadrant with 60 pixels

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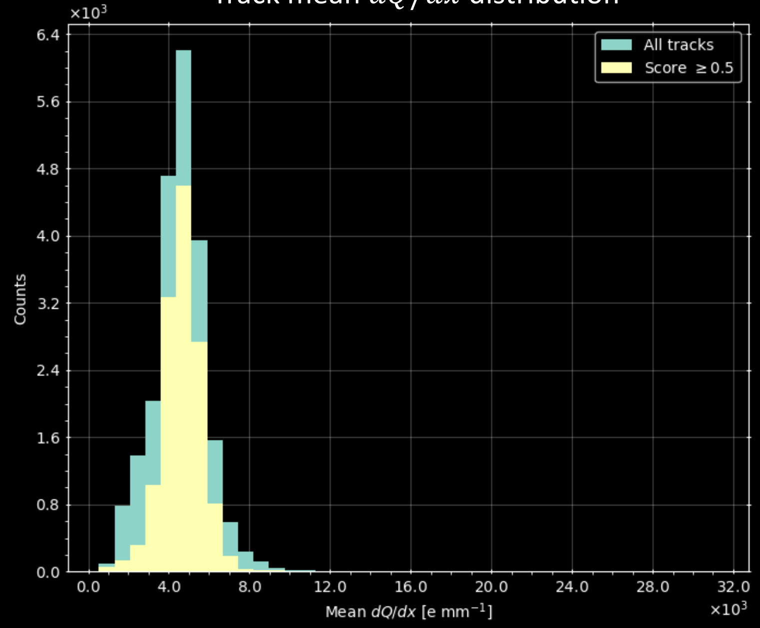
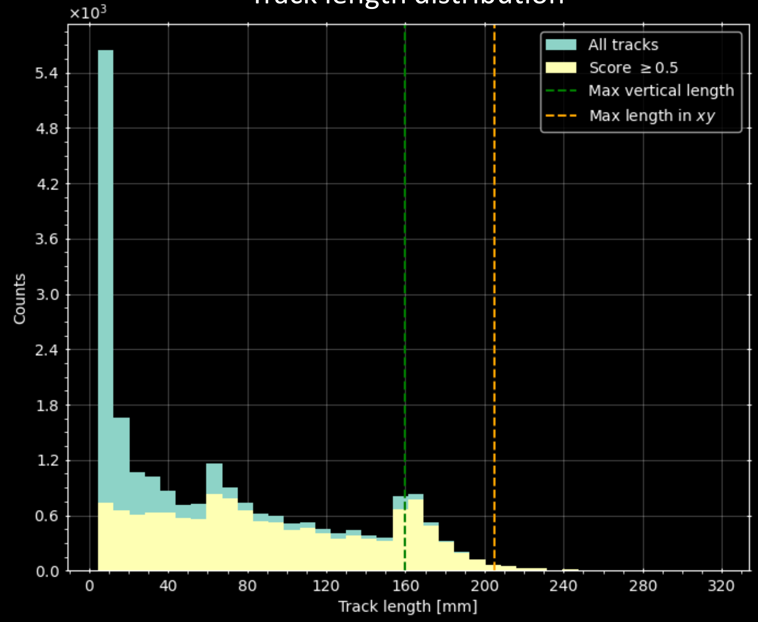
Analysis

~80 minutes of cosmics – all single-track events

Track mean dQ/dx distribution

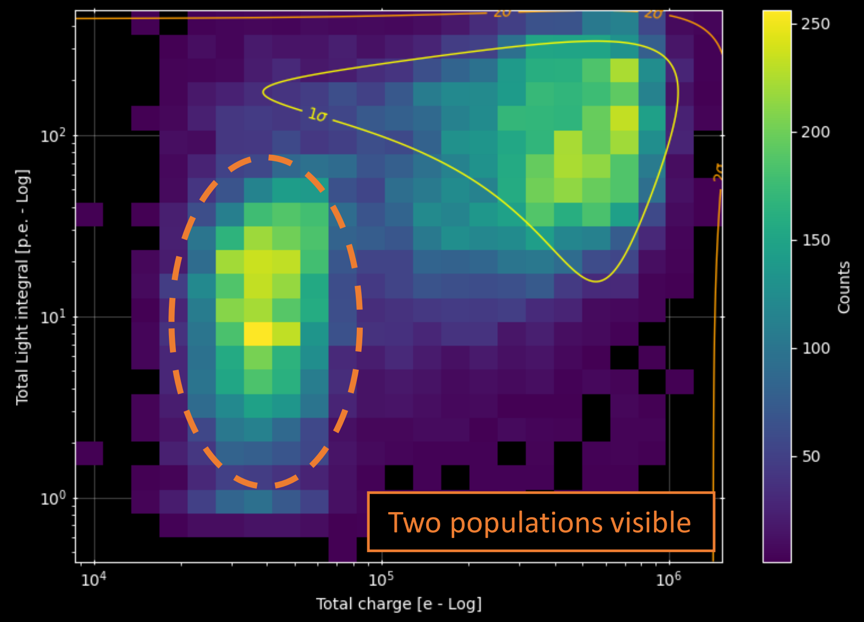


Track length distribution

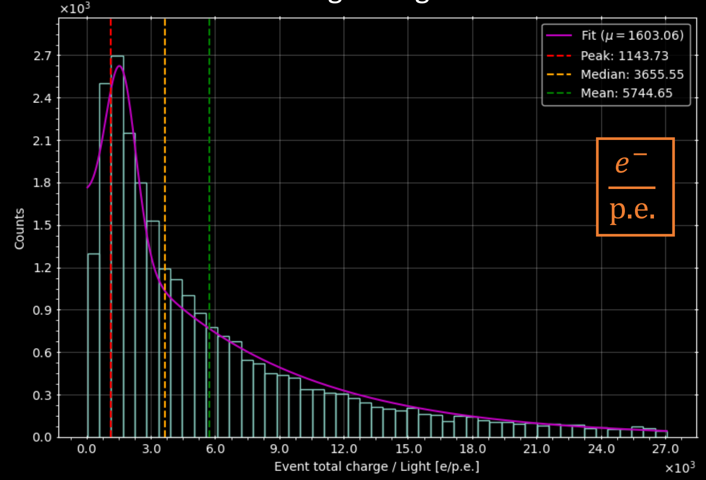


2D event charge vs. light

Both axis in log scale



Event charge to light ratio



- Score indicates "goodness of fit". Shorter tracks are not well fit
- Fit quality doesn't affect total event light and charge

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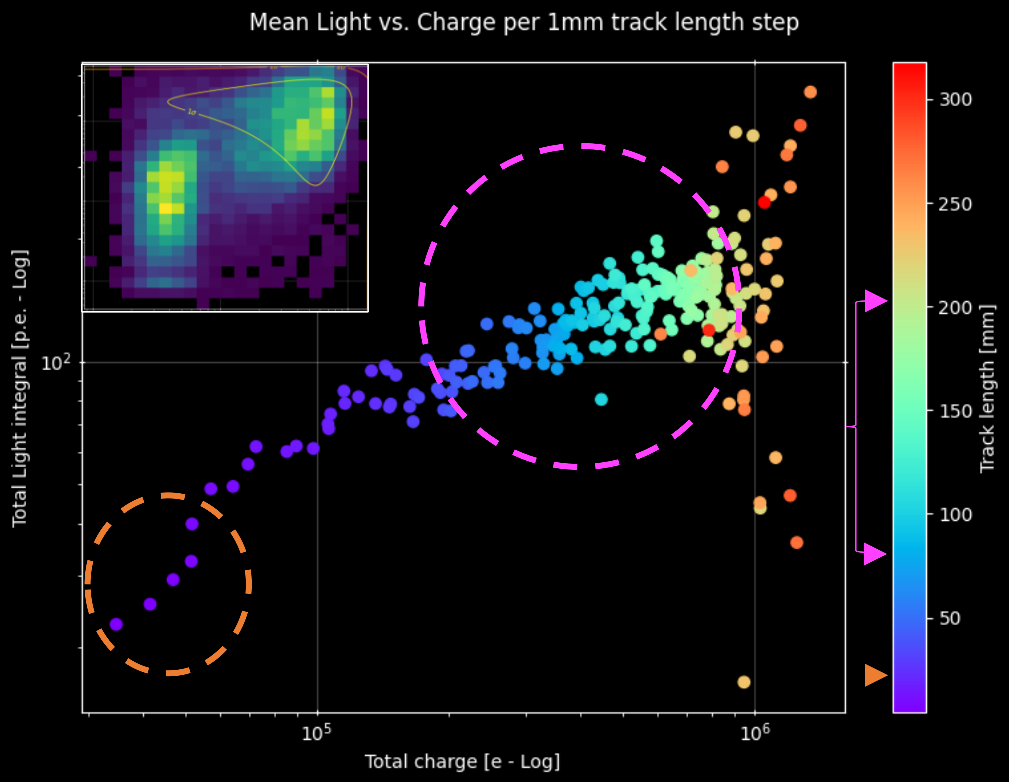
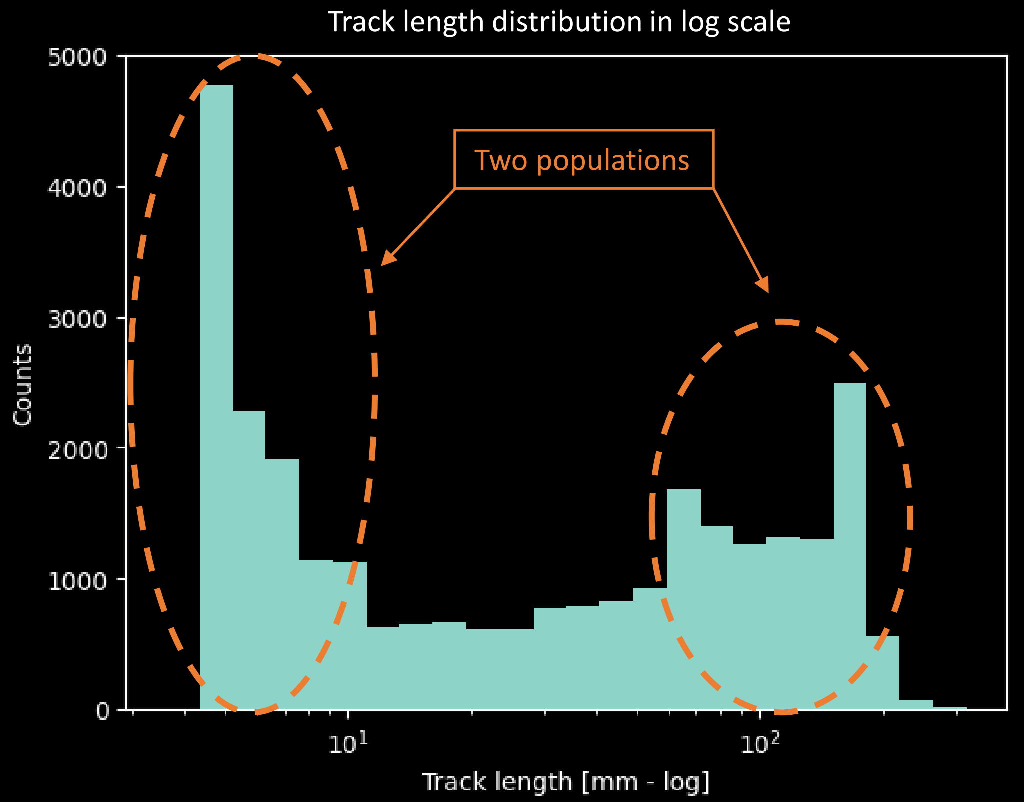
Analysis

~80 minutes of cosmics – all single-track events



For every 1mm step in track length, plot mean light vs. charge

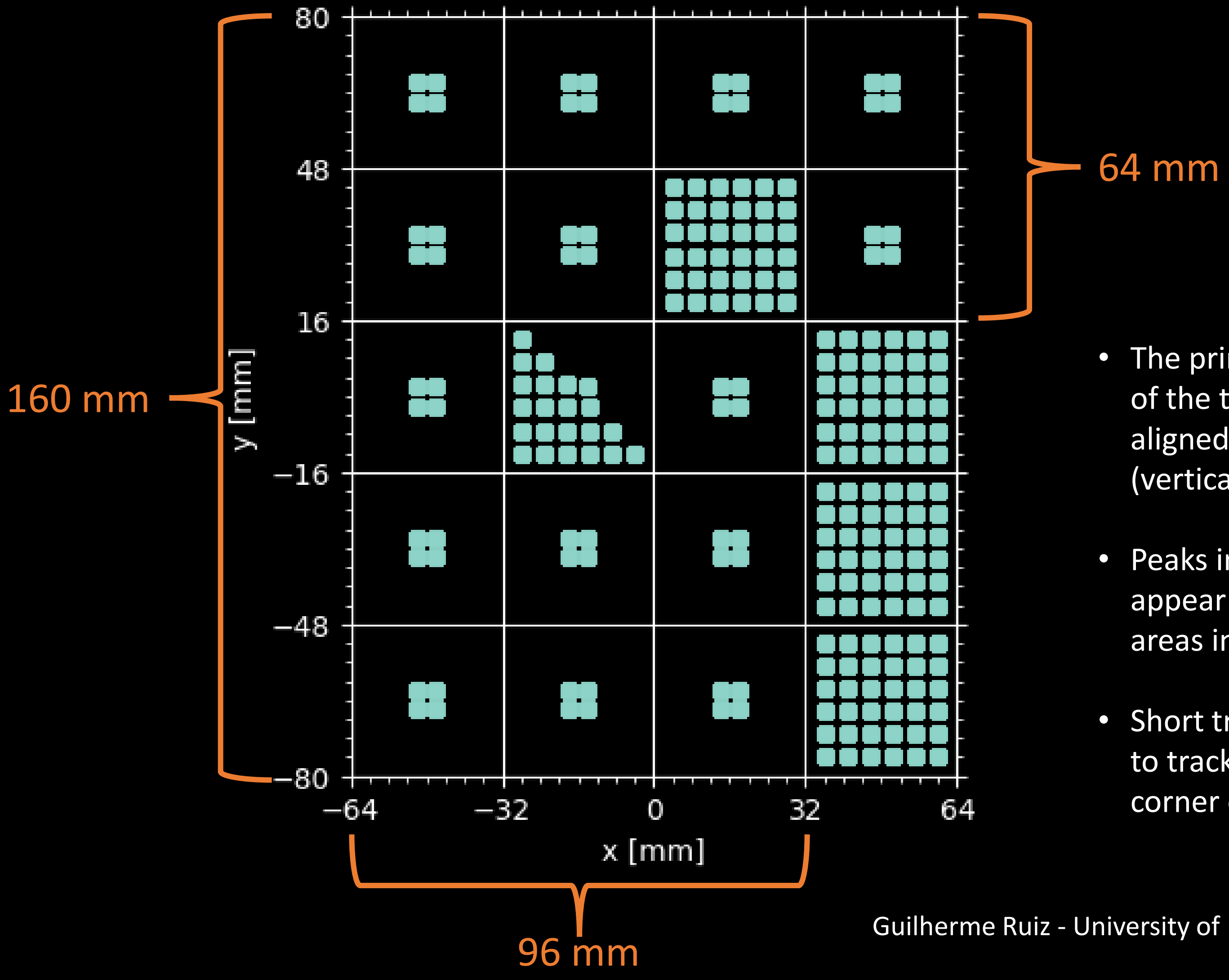
- Scattering on large tracks due to low statistics



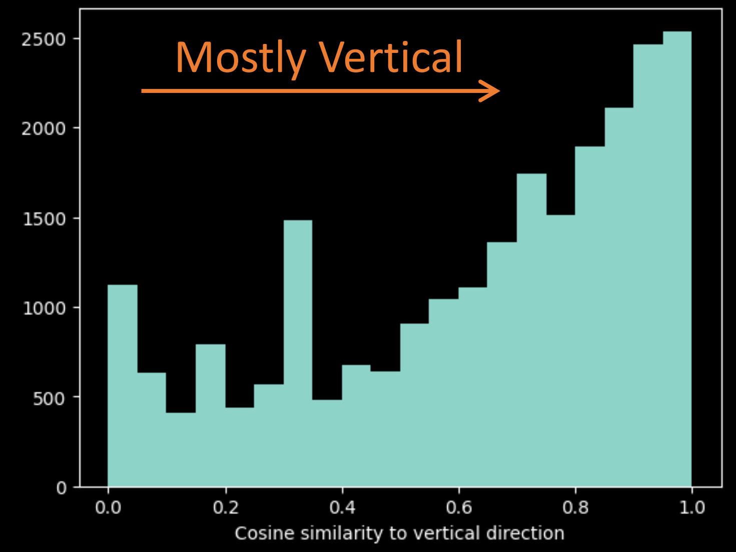
Peaks in track length correspond to peaks in light vs. charge

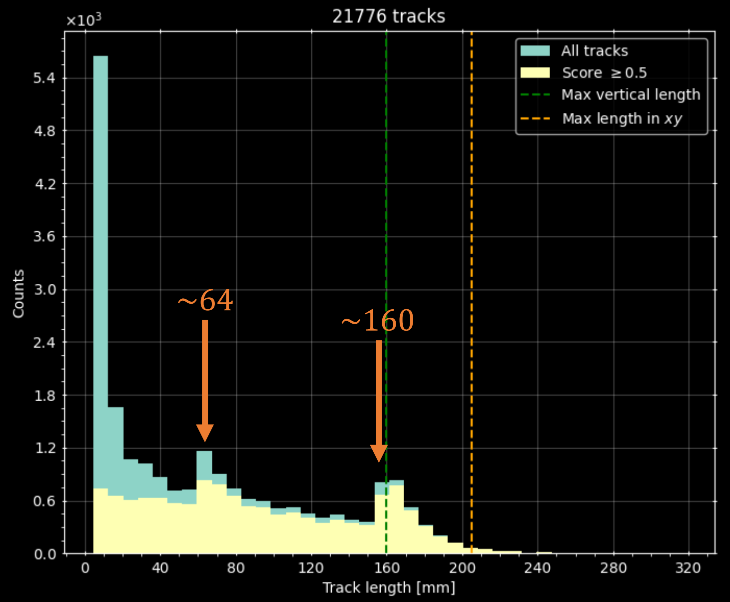
Analysis

Dead area map and angle of incidence



- The principal component of the tracks are mostly aligned with the y-axis (vertical)
- Peaks in track length appear to be due to dead areas in the anode plane
- Short tracks could be due to tracks that cross only a corner of the live area





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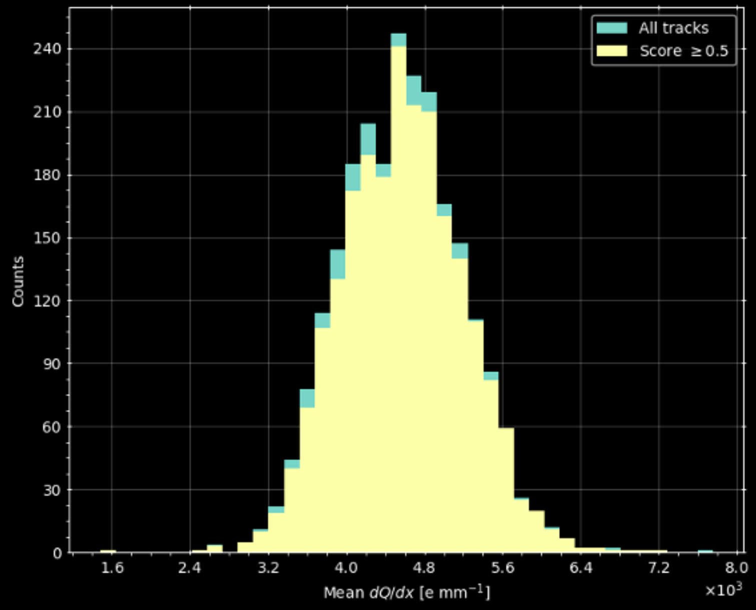
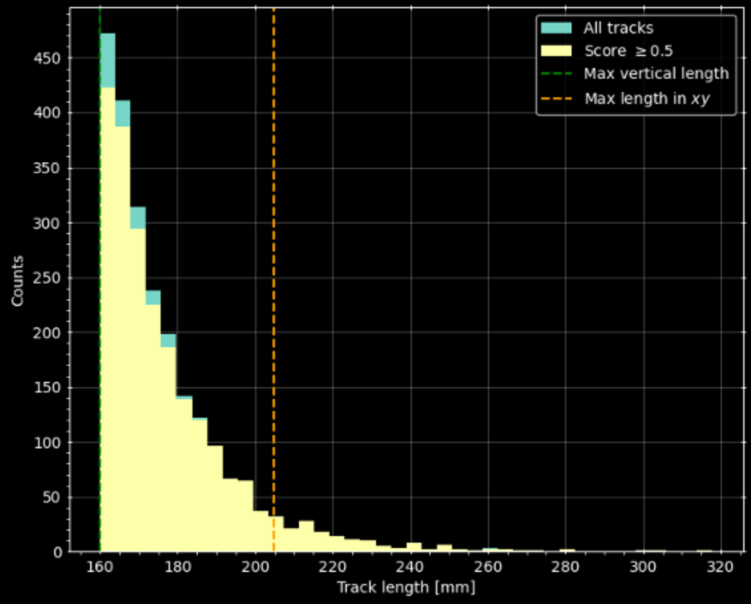
Analysis

Single tracks fully crossing the TPC

Track mean dQ/dx distribution

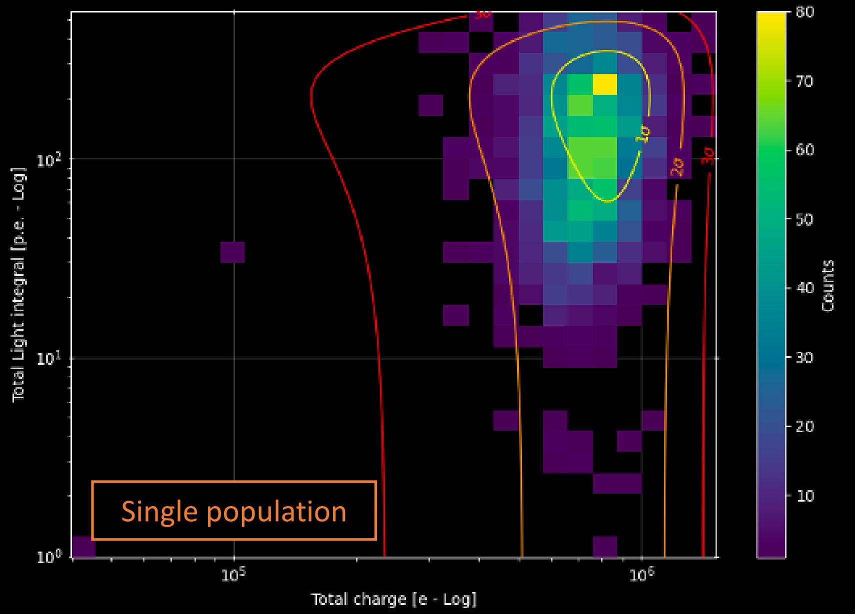


Track length distribution

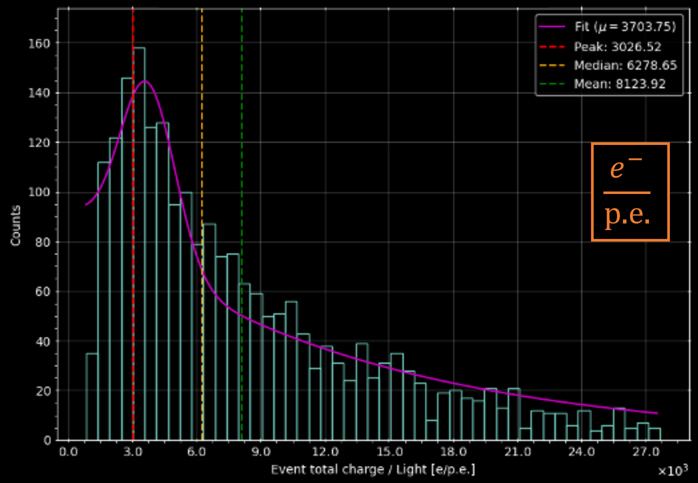


2D event charge vs. light

Both axis in log scale



Event charge to light ratio

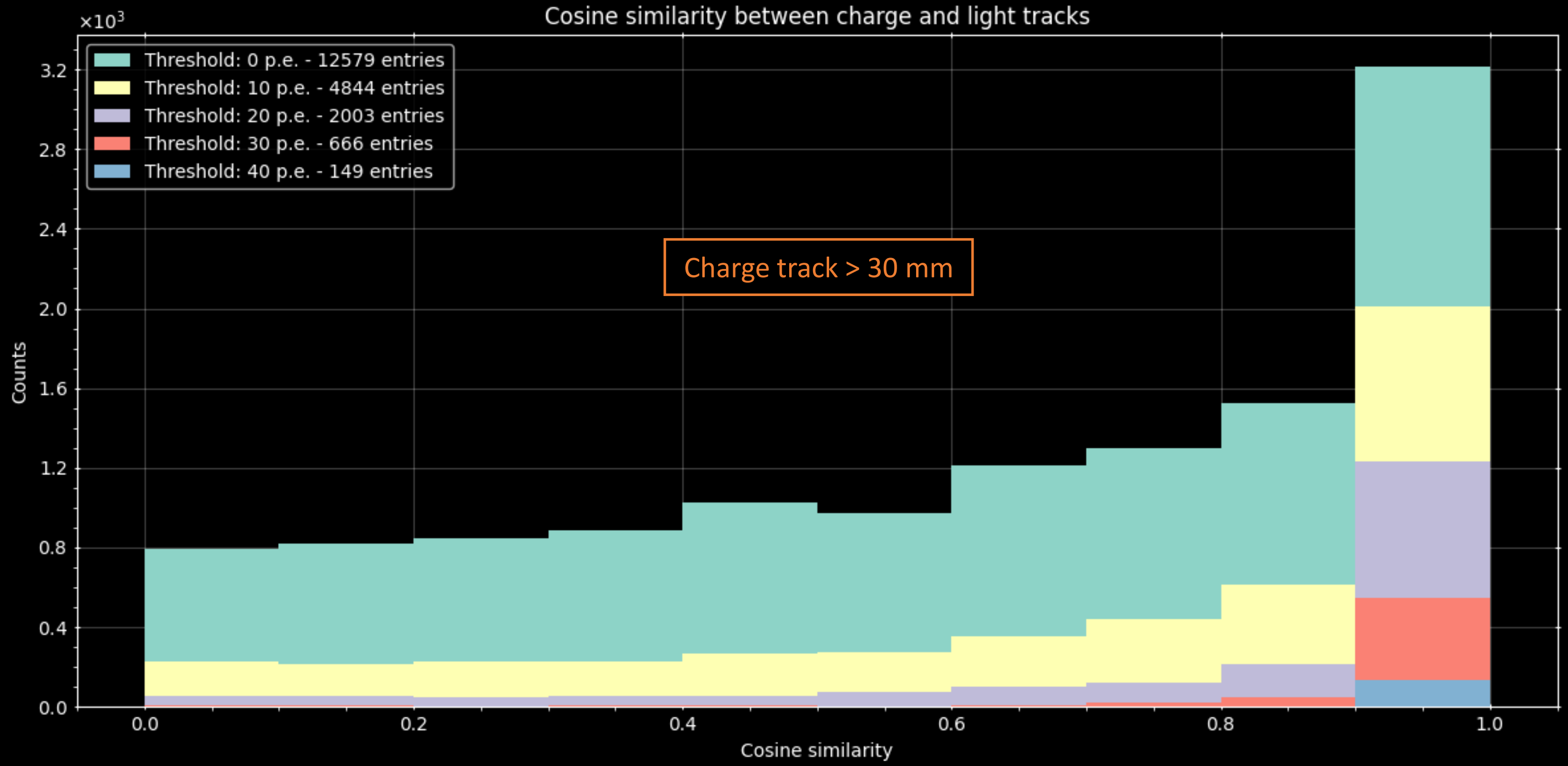


- Mean $dQ/dx \approx 4.6\ ke/mm$
- Measured electron lifetime from cathode/anode crossers: 1.828ms

Analysis

Track reconstruction from light

- A cut at 30 mm eliminates short tracks, likely confined to a single SiPM quadrant.
- The light fit depends strongly on the angle of incidence of the track to the anode.
    - Luckily most tracks have a shallow angle to the anode
- Light “tracks” have lower granularity than charge tracks but result in a similar direction
- Increasing the light threshold removes events without improving the cosine distribution

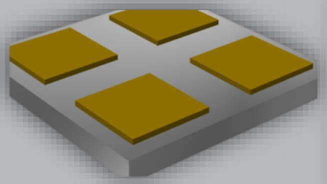


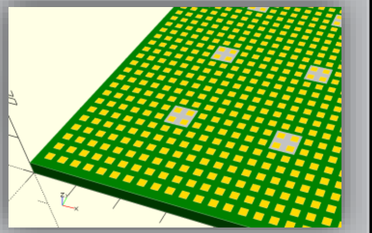
The direction of the light fits align well with their charge track counterparts!

Proposed SoLAr prototypes

Small scale prototype

- Custom-made SiPMs with charge pads mounted on top of photosensitive cell



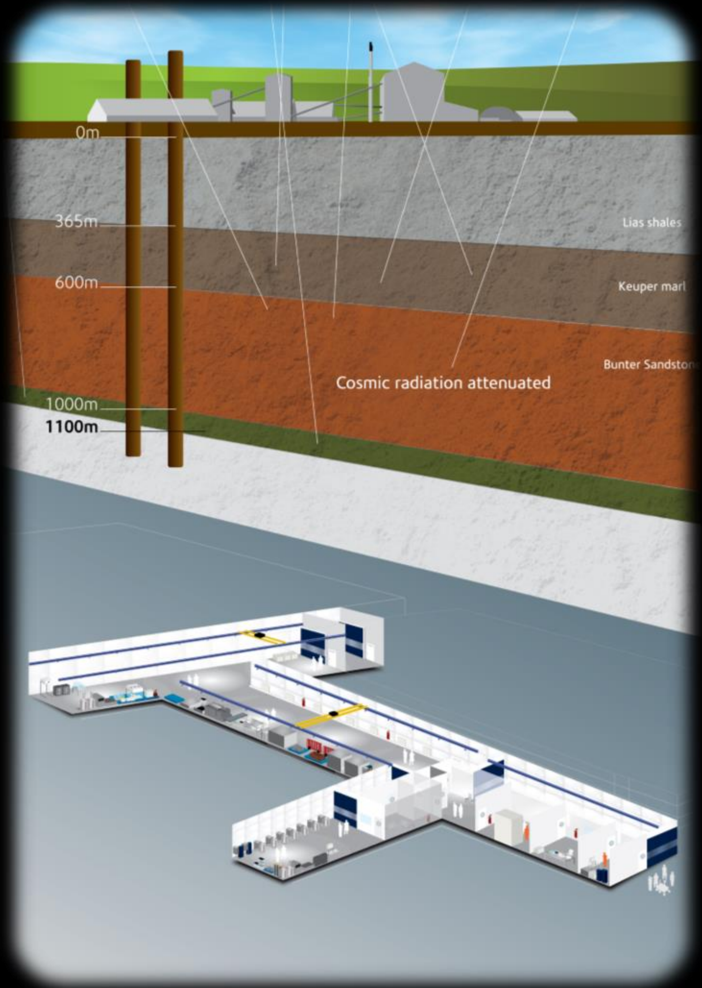


- Test of alternative readout chips when available, i.e.
  - LightPix
  - Q-Pix

Mid scale Demonstrator

- 2025-2028 prospect at Boulby Underground Laboratory
- Few-ton scale LAr detector underground
  - 1100 m overburden
- $1.6\ x\ 2.6\ x\ 2\ \mathrm{m}^3$
  - 1 m drift distance
- $30x30\ \mathrm{cm}^2$ readout anode tiles
  - ≈ 6400 pixels per tile
- First measurement of flavor tagged solar neutrinos in LAr

Boulby Underground Laboratory



Summary

Scan Me

- SoLAr is the first integrated light and charge detector
- V2 prototype produced essential data to support the concept
- V2 data analysis is still ongoing but progressing fast
  - Most charge events are correctly matched to their light counterparts
  - Reconstructing events required refined methods due to large areas without charge pixel coverage
  - Track reconstruction from charge is performing remarkably well
  - Light “tracks” are in reasonable agreement with their respective charge counterparts
- SoLAr is a rapidly growing project with much more to come!

For more, access https://solar-project.web.cern.ch

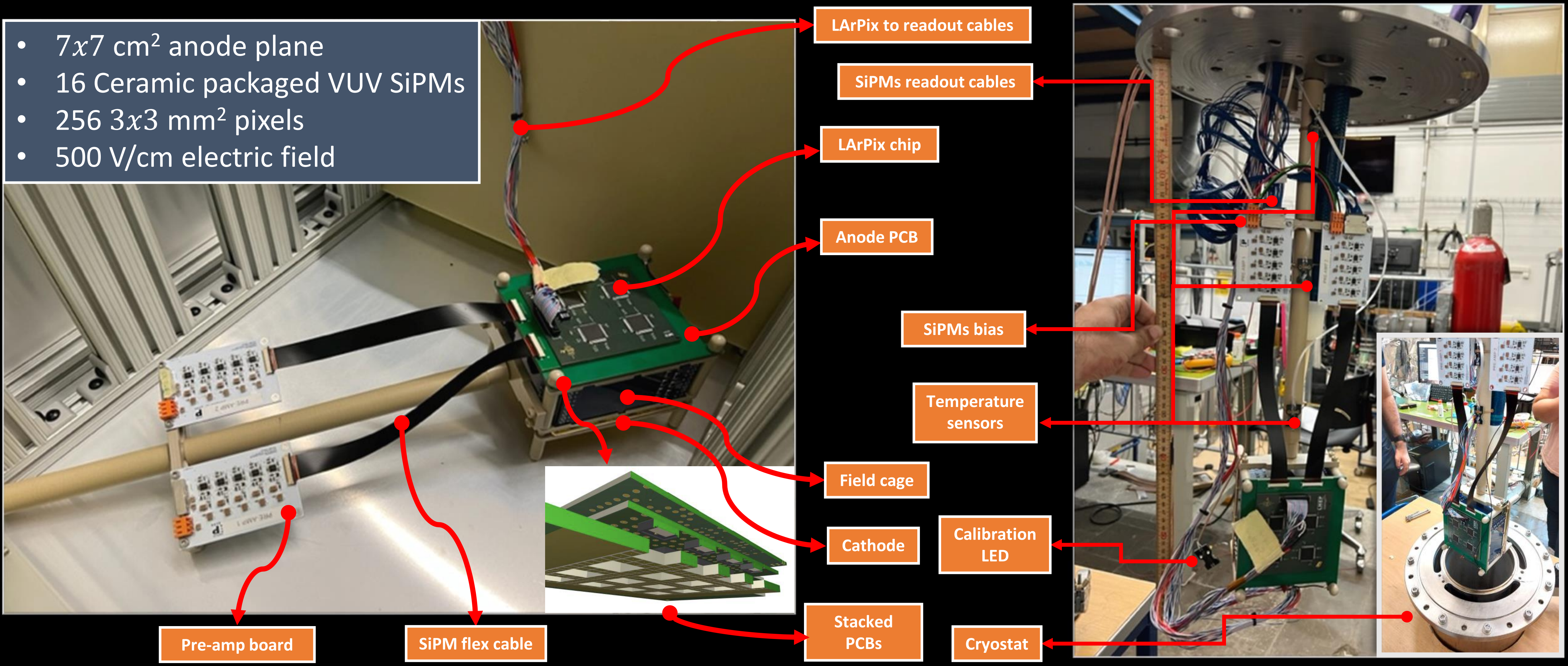
Thank you!

SOLAr

Backup Slides

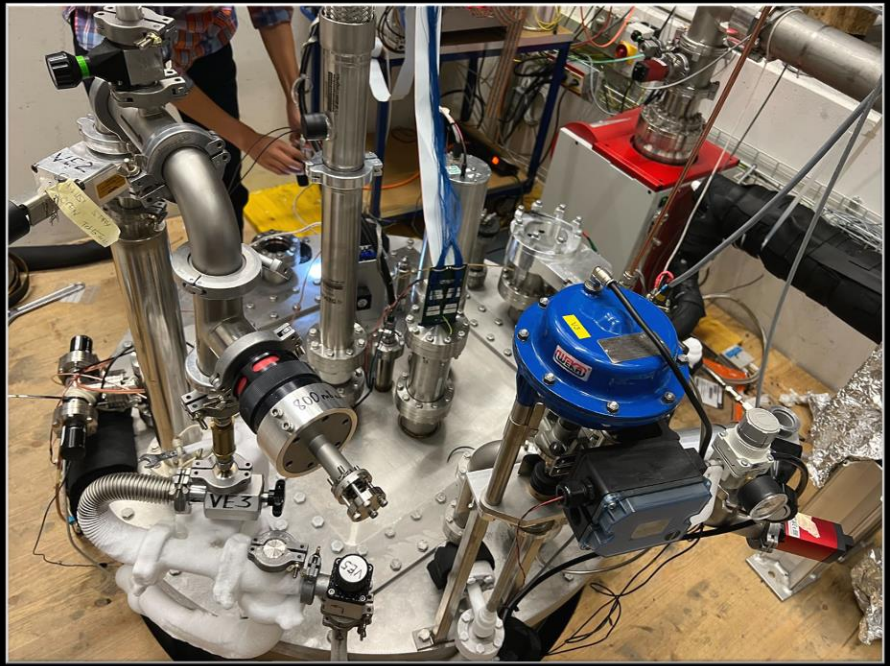
SoLAr V1 prototype

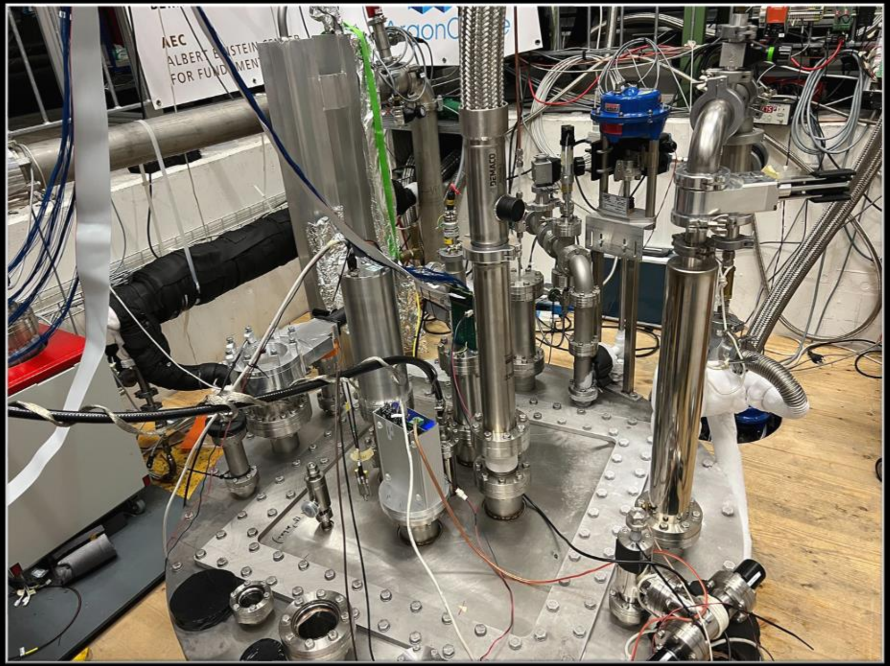
- $7x7$ cm^2 anode plane
- 16 Ceramic packaged VUV SiPMs
- 256 $3x3$ mm^2 pixels
- 500 V/cm electric field



ArgonCube cryostat

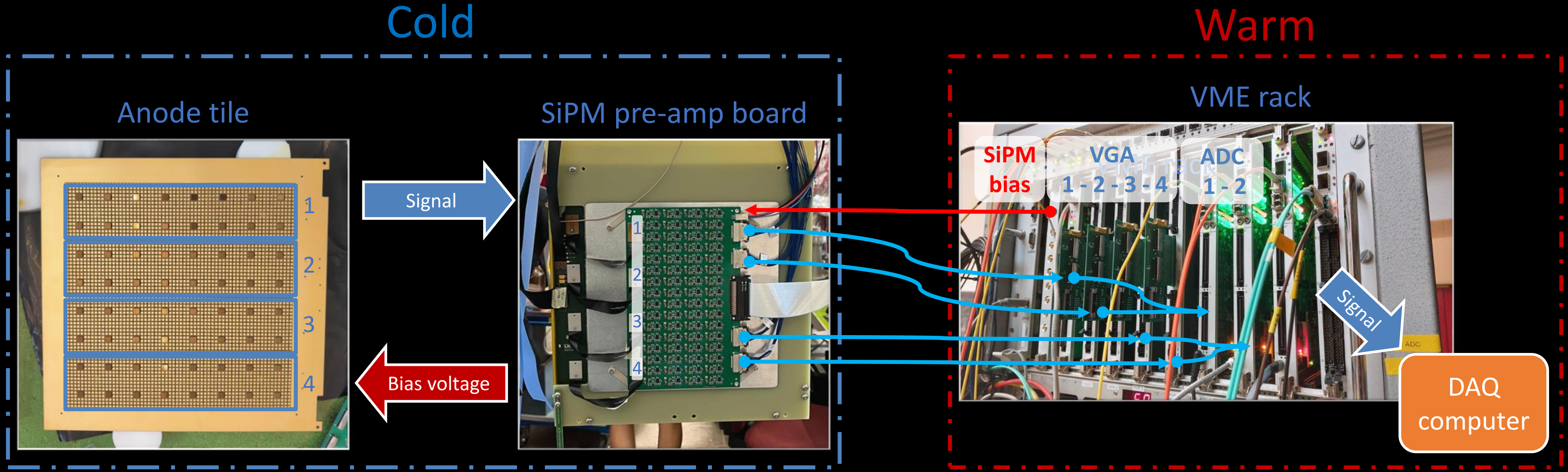
@LHEP – University of Bern





V2 run used the fully instrumented and automated ArgonCube cryostat, which can cool and filter the Argon!

Light readout diagram



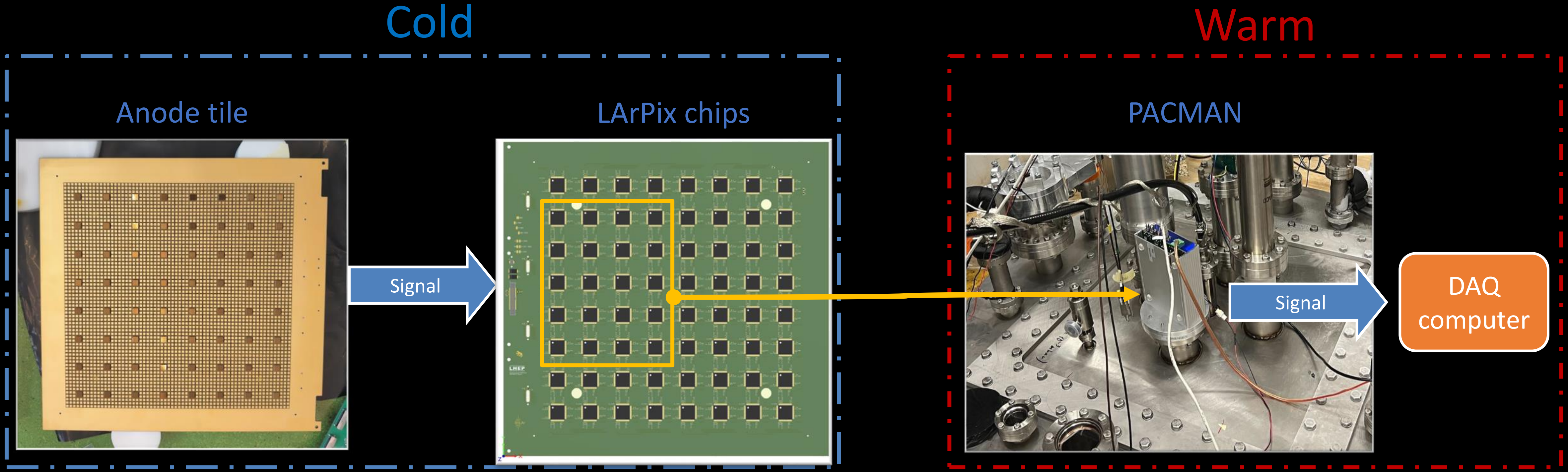
64 SiPMs in 4 groups of 16

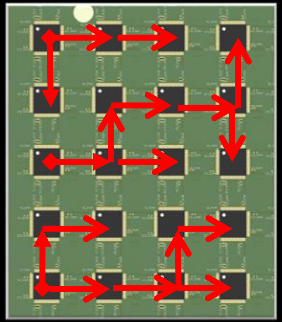
Each group goes to corresponding pre-amp sector

Each pre-amp sector has its own VGA

Each pair of VGAs go to one ADC

Charge readout diagram





LArPix chips form a "Hydra" network

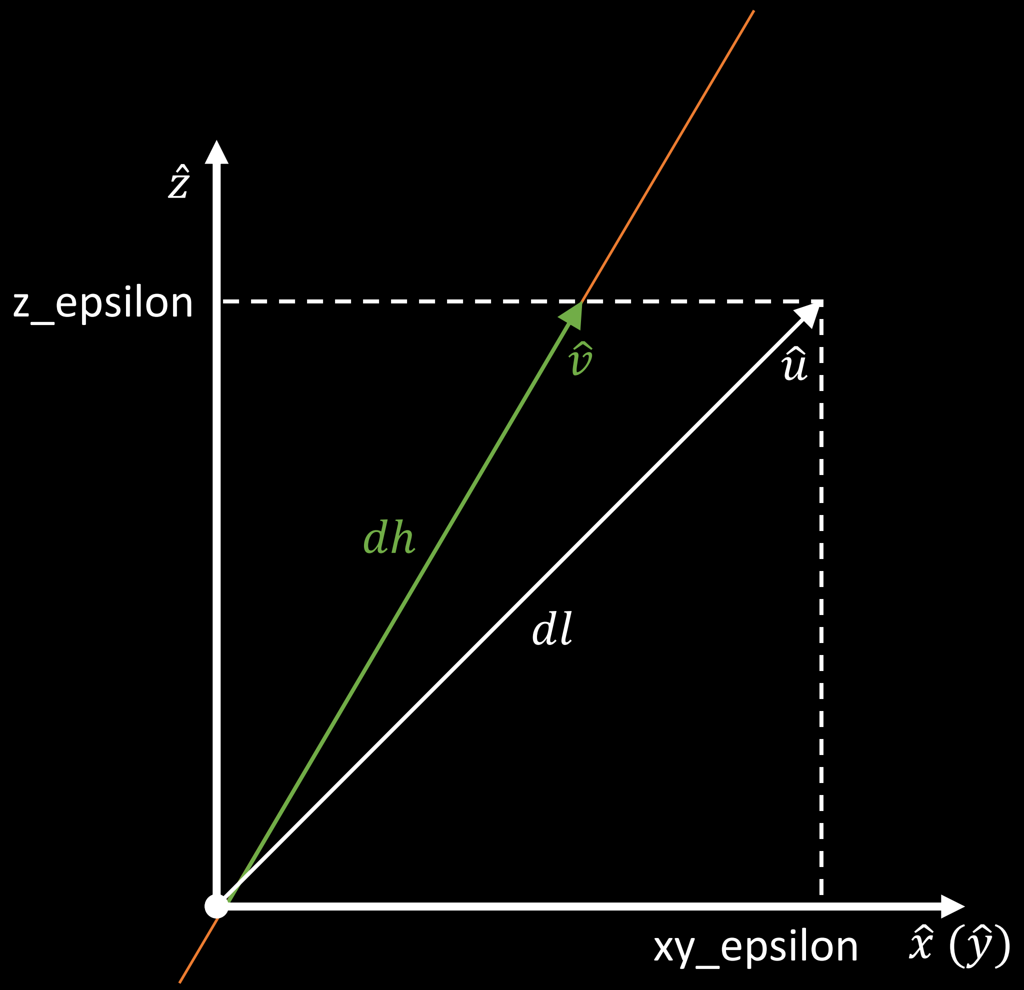
- Only root chips communicate with PACMAN
- Root chips must not be neighbors
- Remaining chips connect through one or more neighbor chips
- All connected chips have a single root chip

FAQ

- DBSCAN parameters:
    - xy_epsilon = 8 mm (2 pixels)
    - Z_epsilon = 8 mm
- RANSAC parameters:
    - Residual_threshold = 6
    - Max_trials = 1000
- RANSAC has random component and may not always return the same fit
- Cylinder parameters are determined dynamically but bound by DBSCAN parameters

Cylinder parameters

dh estimation

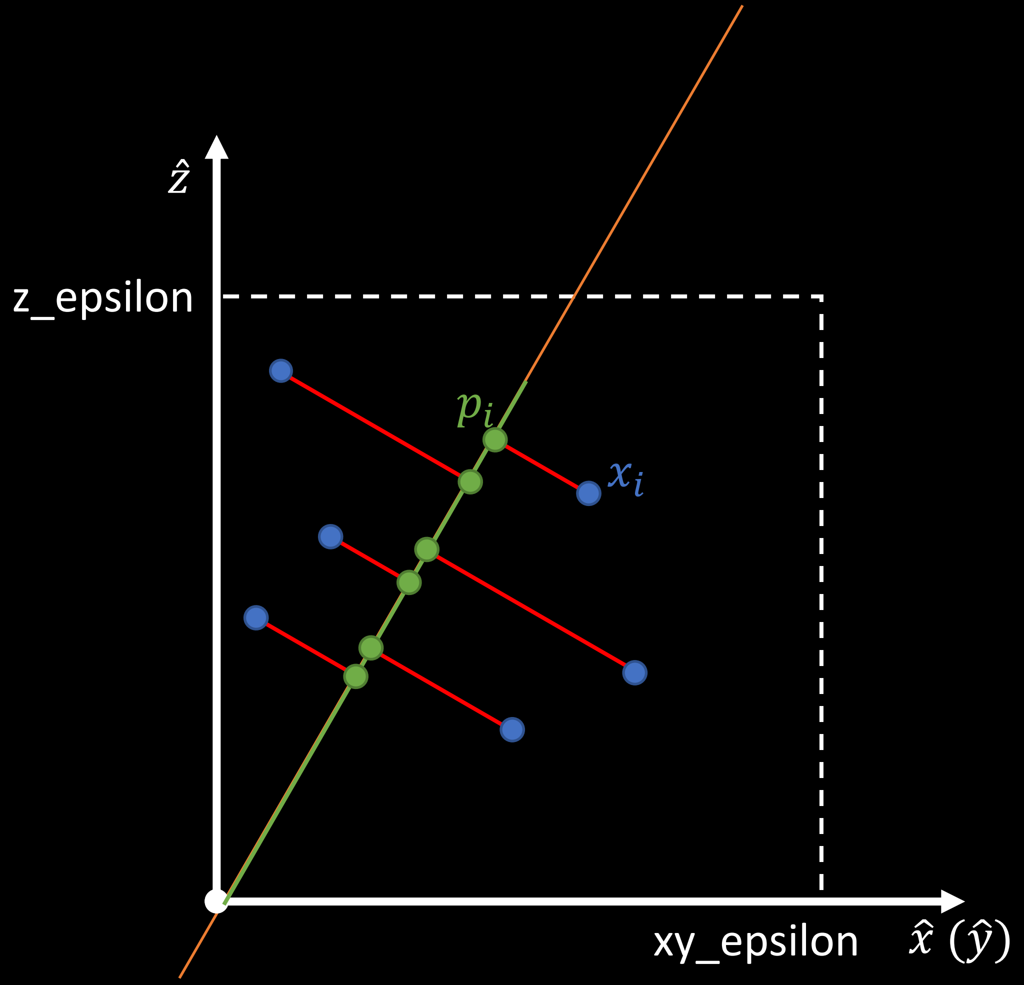


$$dl\ \hat{u} = [\ \text{xy\_epsilon}\ (\hat{x} + \hat{y}) + \text{z\_epsilon}\ \hat{z}\ ]$$

$$dh = dl\ (\hat{u} \cdot \hat{v})$$

Cylinder parameters

dr estimation



$$dr = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - p_i)^2}$$

Minimum dr is bound to $\frac{dl}{4}$

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Light to charge z-coordinate estimation