ARIADNE+: Large scale demonstration of fast optical readout for dual-phase LArTPCs at the CERN Neutrino Platform

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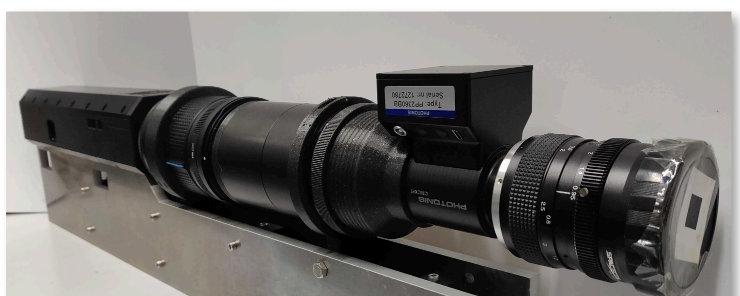
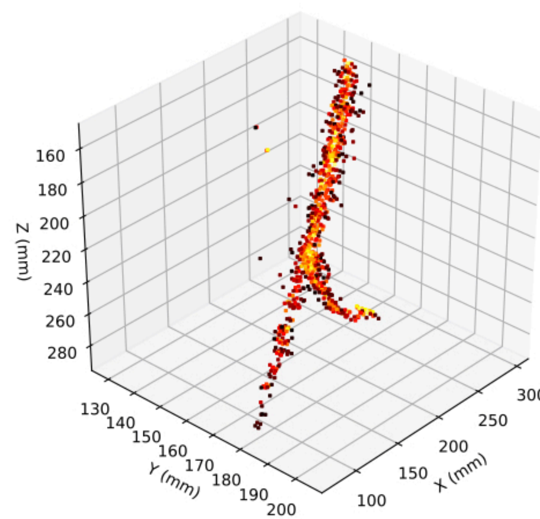
IoP HEPP, AP & NP

April 2024





https://hep.ph.liv.ac.uk/ariadne

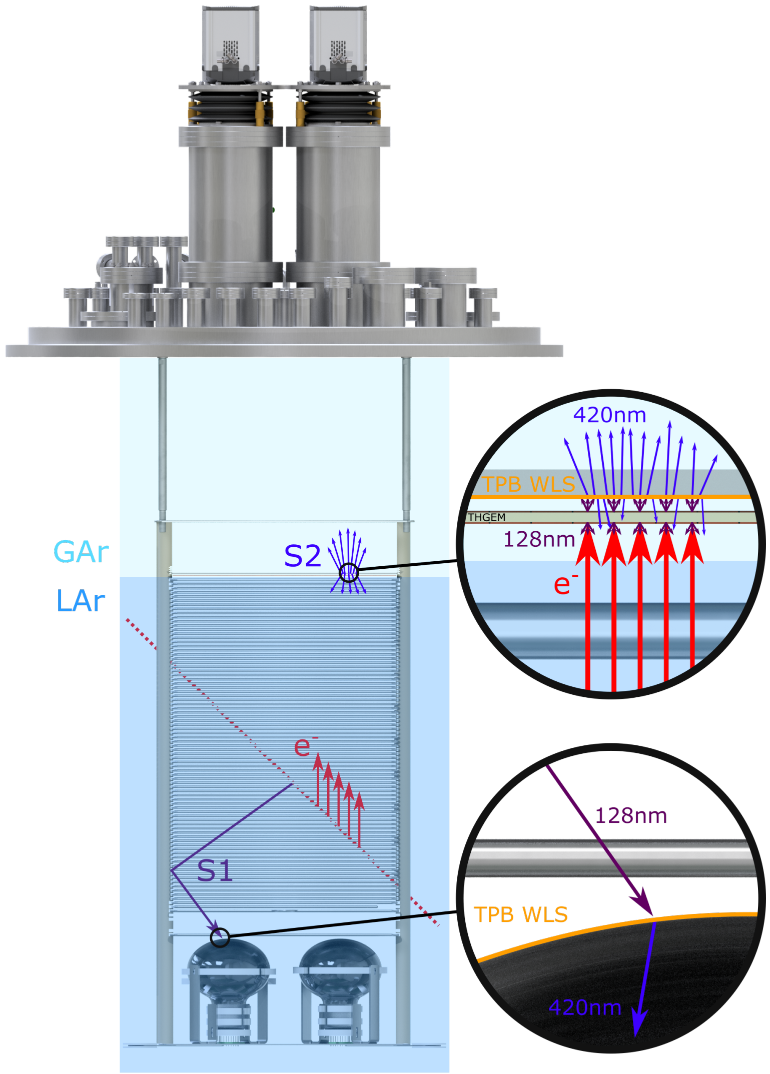
Talk Outline

- Background to the ARIADNE Program
- The ARIADNE+ detector at the CERN Neutrino Platform
    - Analysis using cosmic data over a 3 week run
- Upgrades to the 1 tonne ARIADNE detector
- Outlook

ARIADNE Detection Principle

ARIADNE aims to demonstrate light readout as a viable alternative to charge in dual-phase TPC neutrino experiments

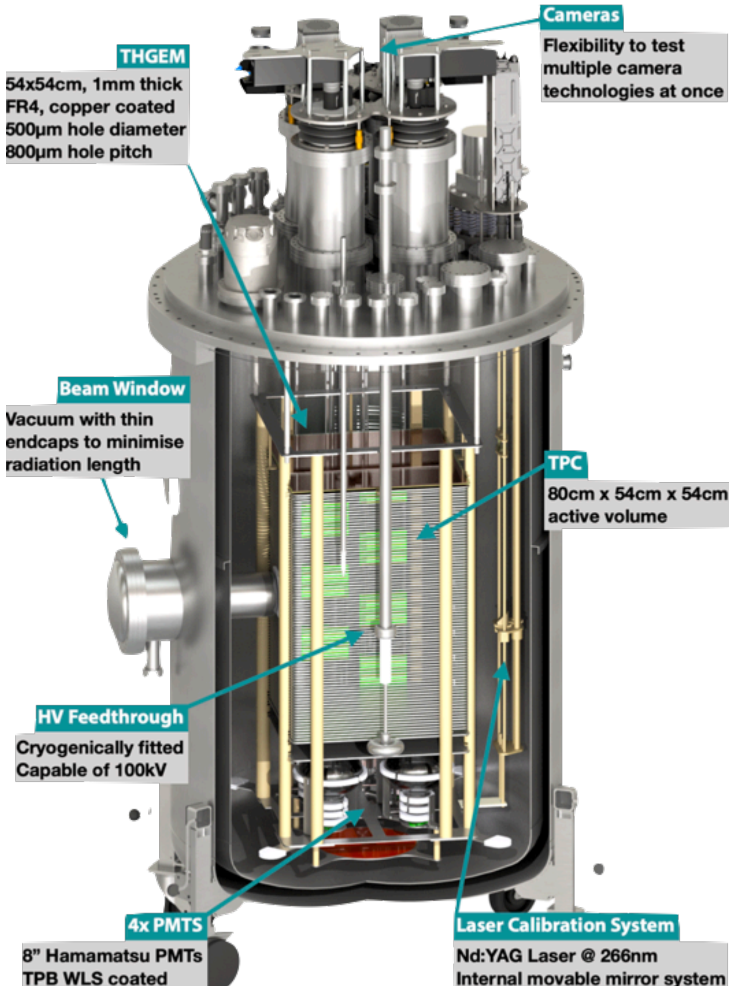
- Incoming particles ionise LAr and create **prompt scintillation** light (**S1**)
- Electrons drift towards the **extraction grid** situated below the liquid level
- A **THGEM** (THick-Gaseous Electron Multiplier) amplifies drift charge (capable of >30 kV/cm in LAr) generating **secondary scintillation** light (**S2**)
- **WLS** (Wavelength Shifting) for an intensifier stage before imaging with Timepix3 camera



***ARIADNE** (**AR**gon **I**m**A**ging **D**etectio**N** chamb**E**r)*

The ARIADNE Advantage - Optical TPCs

- Benefits over previous charge readout methods:
  - **High Resolution:** For e.g. TPX3 camera has 256 x 256 pixels, imaging 35 x 35 cm area, as on ARIADNE, gives ≈1 mm resolution
  - **Sensitivity to low energies:** Gain is generated by the THGEM; a THGEM accelerated electron can generate upwards of 100 photons, cameras can be sensitive to single photons
  - **Very low Noise:** Sensors are decoupled from TPC electronics
  - **Ease of Access:** Technology can be swapped in and out even with TPC operating
  - **Cost Efficient:** No need for thousands of internal charge TPC readout channels, pre-amps etc.

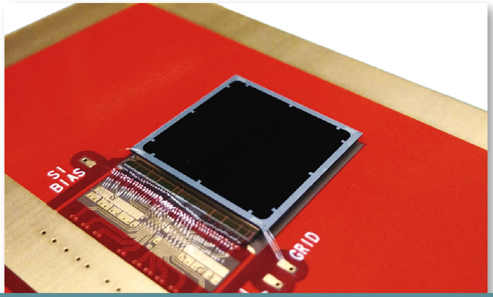


ARIADNE 1-tonne detector

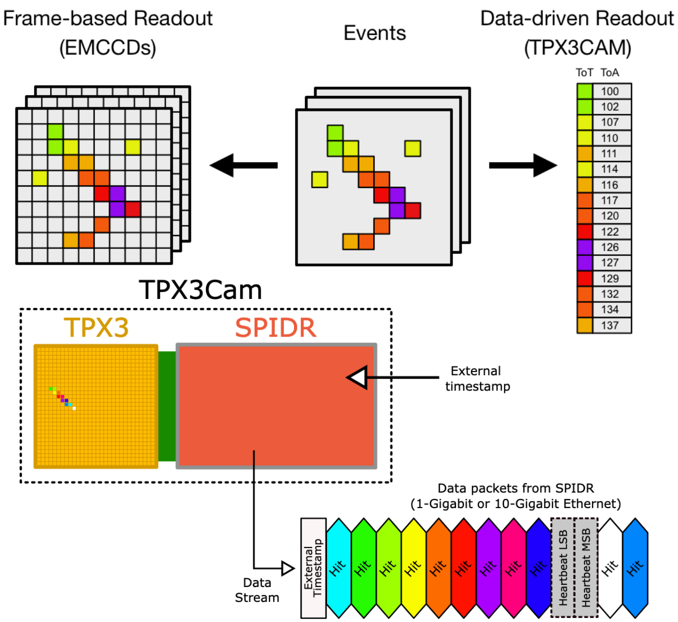
The ARIADNE Advantage - Full 3D optical readout with Timepix3

- Well established technology by the **CERN** Medipix collaboration:
  - **Natively 3D:** Timepix chip gives X and Y position, Time of Arrival (ToA) (which is equivalent to z position) and Time over Threshold (ToT) (equivalent to intensity)
  - **Background Suppression:** Data driven readout based on hits rather than frame
  - **Efficient data storage:** Continuous streaming, trigerless operation - few kBytes per event
  - Technology ready for deployment **now**!

Sensor resolution	256x256 pixels
Pixel size	55μm x 55μm
Max readout rate	80Mhits•sec^{-1}
Time resolution	1.6 ns
Time over Threshold Resolution	10 bit



TPX3 ASIC Chip bump bonded to an optical sensor



ARIADNE: Optical Readout for kilo-tonne scale LAr TPCs

- Proven scalable technology
- Cost efficient, comparable performance to other readout methods
- Considered an option for one of the phase 2 modules

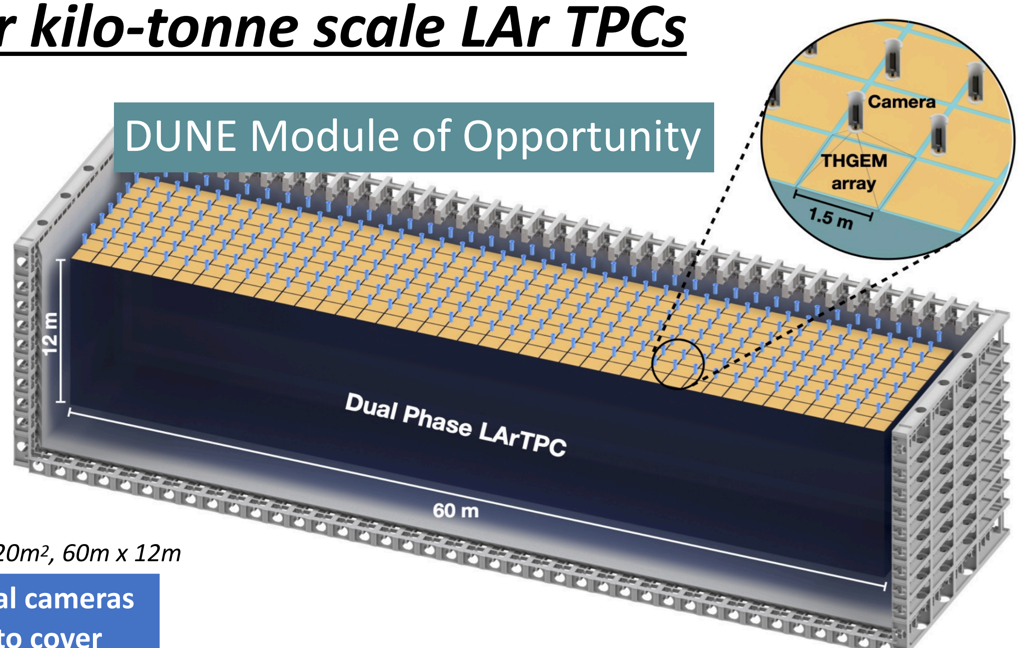
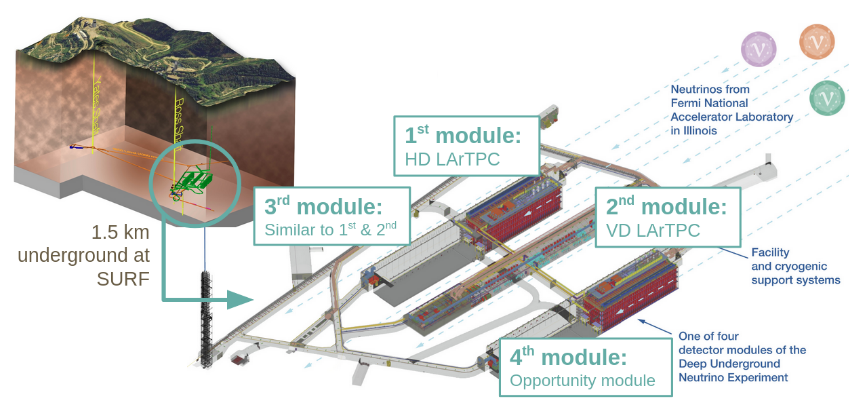
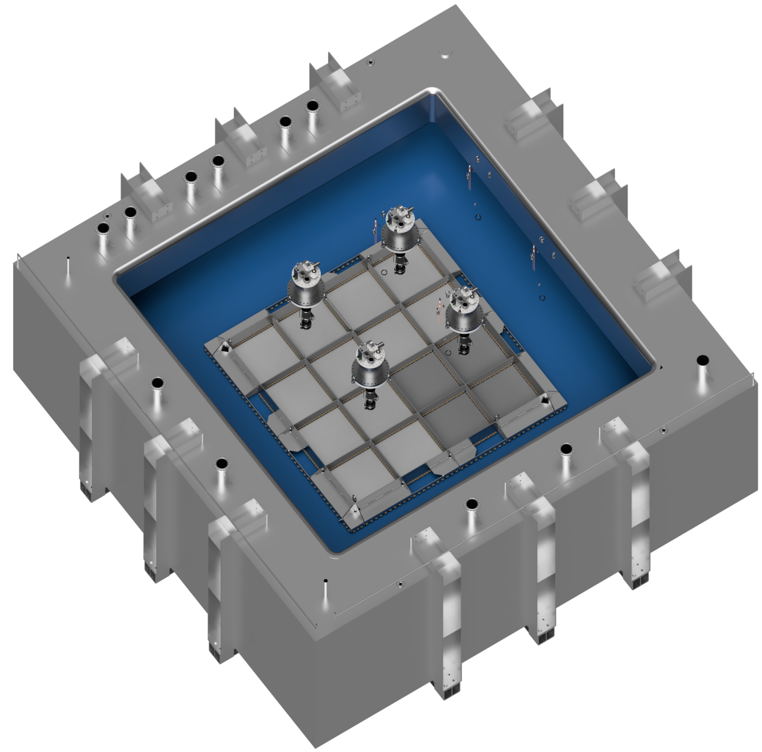


Table: As an example, demonstration figures for use of TimePix within Dune - 720m^2, 60m x 12m

Camera type	Sen. Size (pixels)	Cameras to cover 1m^2	Resolution (mm/pix)	Total cameras (to cover 720m^2)
TPX3	256x256	9	1.3 (~ARIADNE)	6480
TPX3	256x256	4	2	2880
TPX3	256x256	1	4 (~ARIADNE+)	720
TPX4	512x448	4	1	2880
TPX4	512x448	1	2	720
TPX4	**512x448**	**0.66 (1.5m/cam)**	**3**	**320**



Large-scale demonstration of the ARIADNE LArTPC optical readout system at the CERN Neutrino Platform



Testing optical readout on a scale relevant for DUNE using the existing Proto-DUNE cold box

15 Tonne Cryogenic Vessel filled from Proto-DUNE dual-phase cryostat

Carried out between February and April 2022

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[2] *European Organization for Particle Physics (CERN), Geneva, Switzerland*
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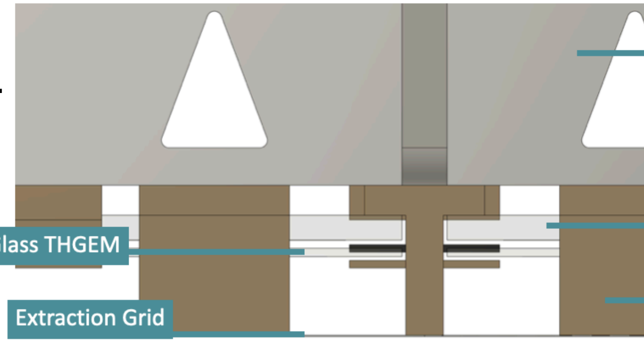
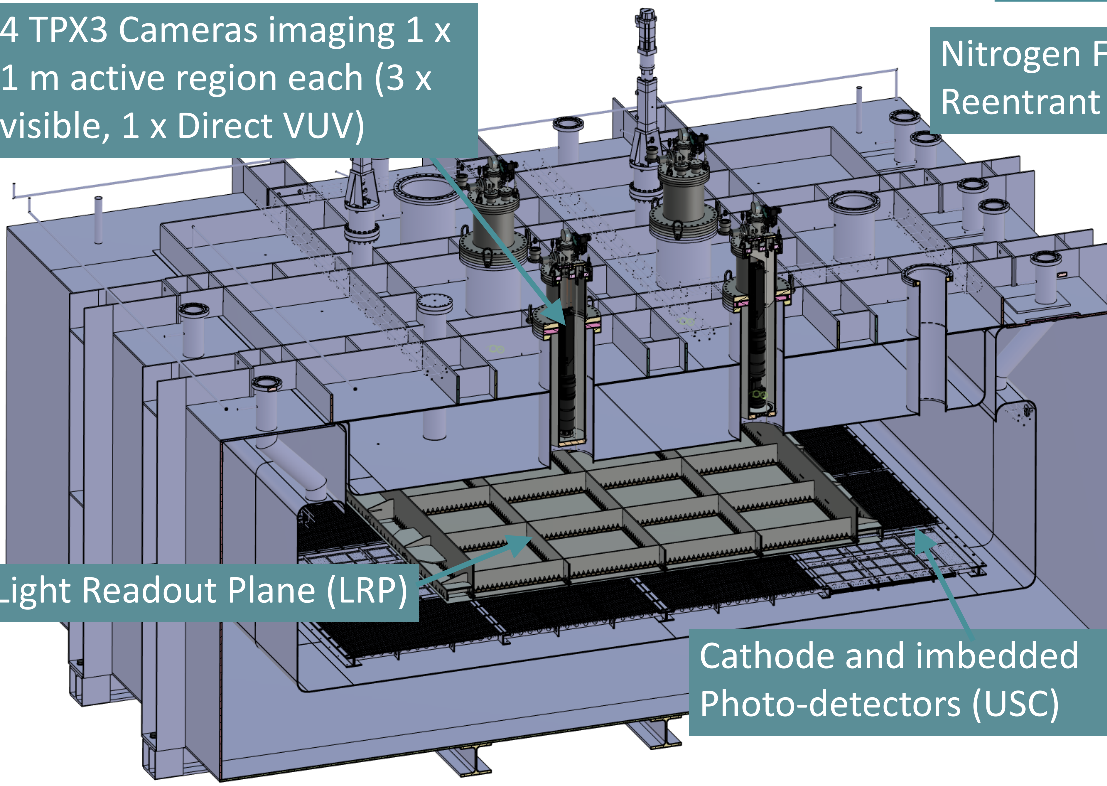
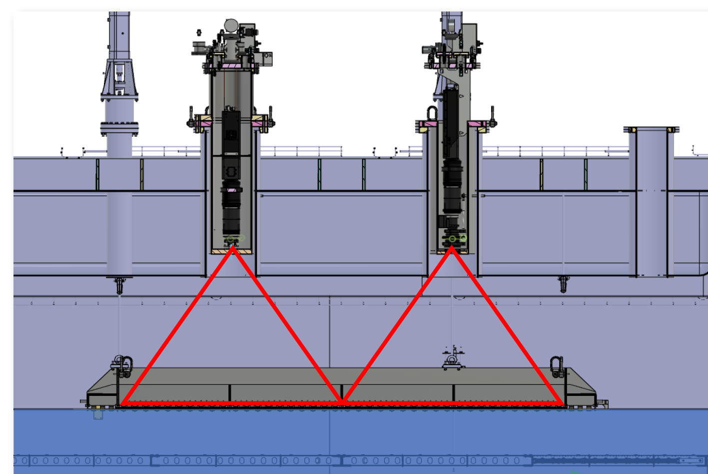
CERN LOI: https://cds.cern.ch/record/2739360

ARIADNE+: Cryostat Configuration

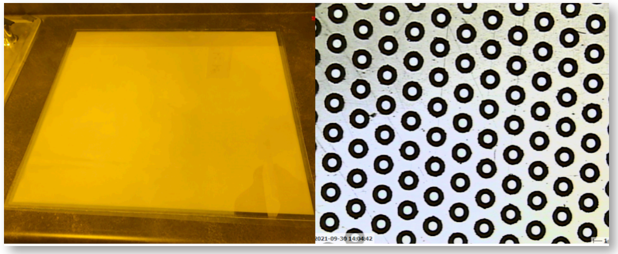






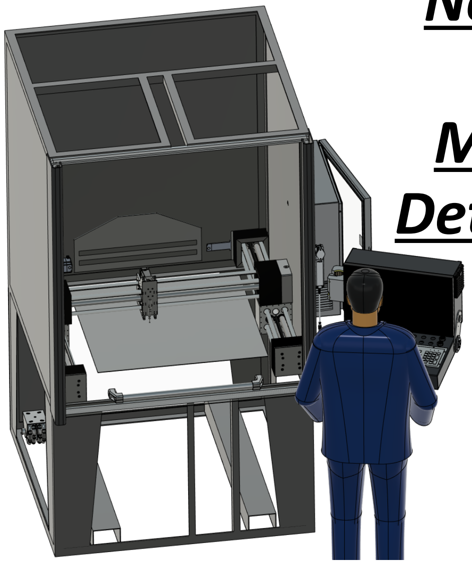
ARIADNE+ Detector - Glass THGEMs

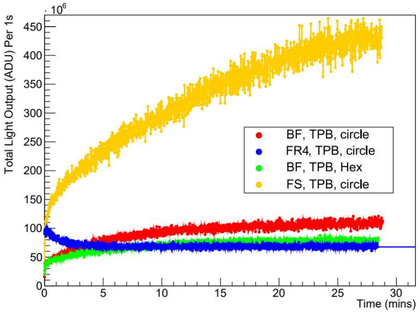
Glass THGEMs - Liverpool development into glass as a dielectric for THGEMs



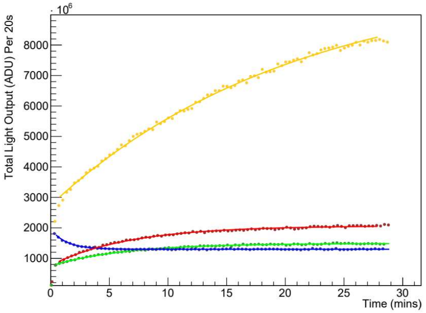
New for 2024: Liverpool Micropattern Detector Facility

- Tolerant to sparking and discharges as it does not carbonise like FR4
- Abrasive machining creates bi-conical holes that store charge over time
- Less prone to sagging compared to FR4 at larger surface areas





(a) 1 s binning.



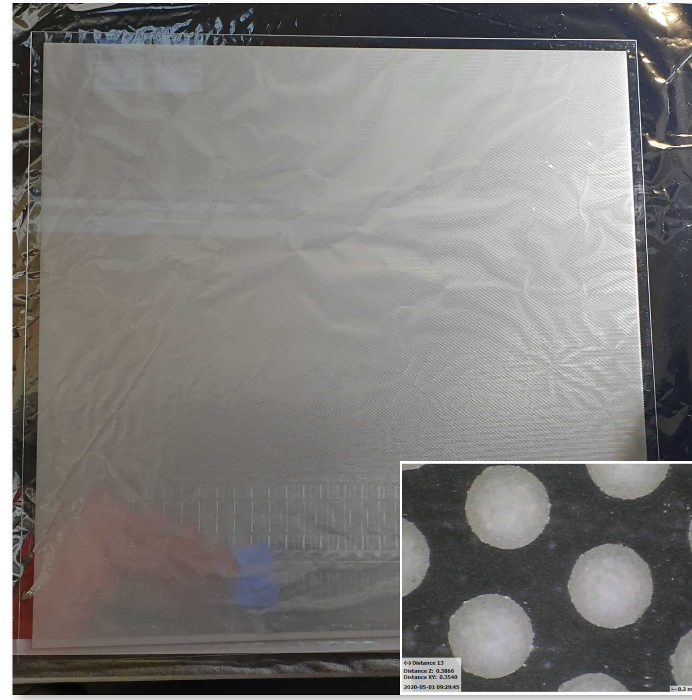
(b) 20 s binning with fit.

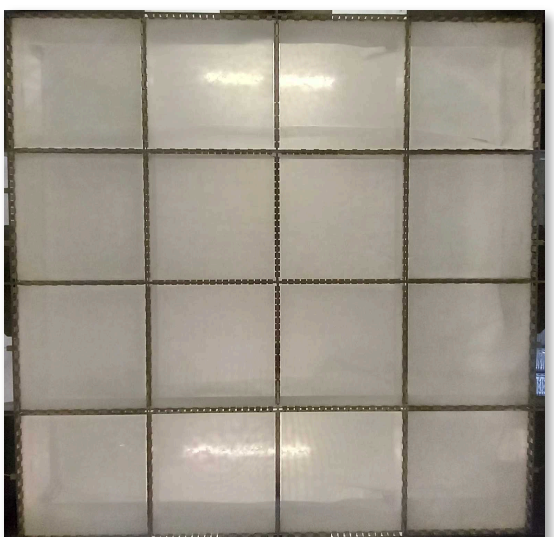
Abrasive machining facility in the University of Liverpool physics building - producing ARIADNE glass THGEMs and capable of much more

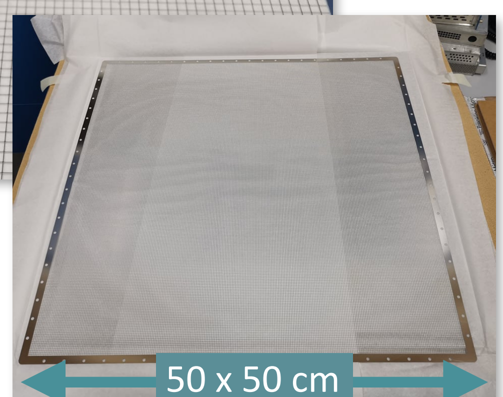
(https://www.mdpi.com/2076-3417/11/20/9450)

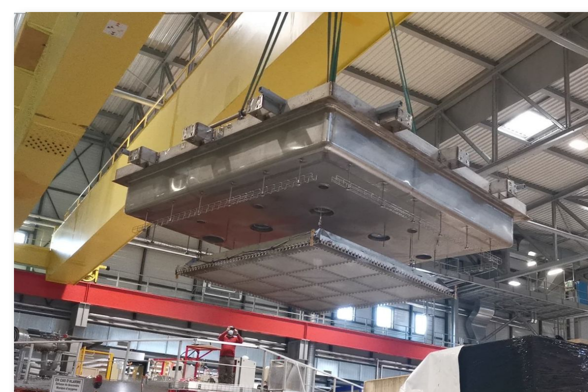
Light Readout Plane (LRP)

- Largest Glass THGEM array made to date
- 16 50 x 50 cm Glass THGEMs, developed by Liverpool Patent (Patent GB2019563.2)
- 1.1 mm thick, 500 µm ID holes, ~500k holes per THGEM, 800 µm pitch hexagonal array
- 12 50 x 50 cm PEN coated WLS glass
- Photochemically etched modular extraction grid
- 2.3 x 2.3 m frame mounted underneath cold box lid

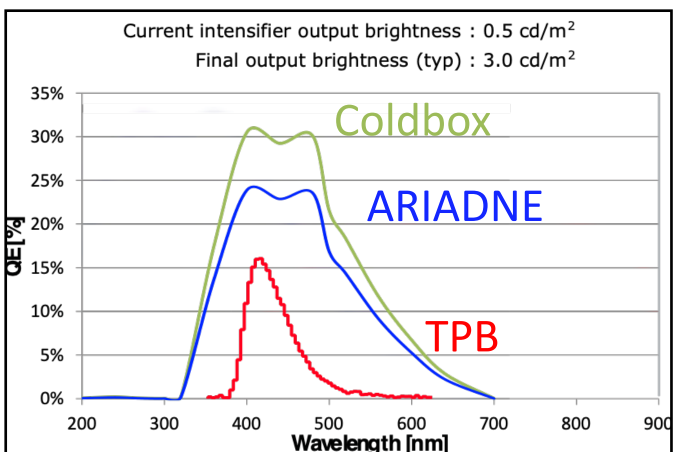


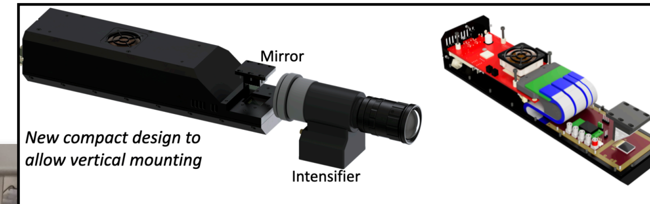






TPX3 Camera Setup



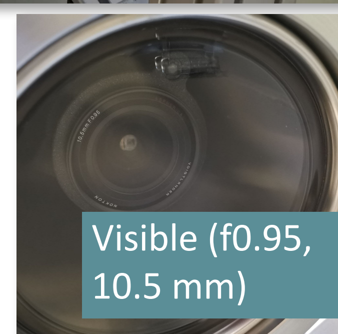


Timepix 3 Camera

Relay optics

Image intensifier

Objective lens

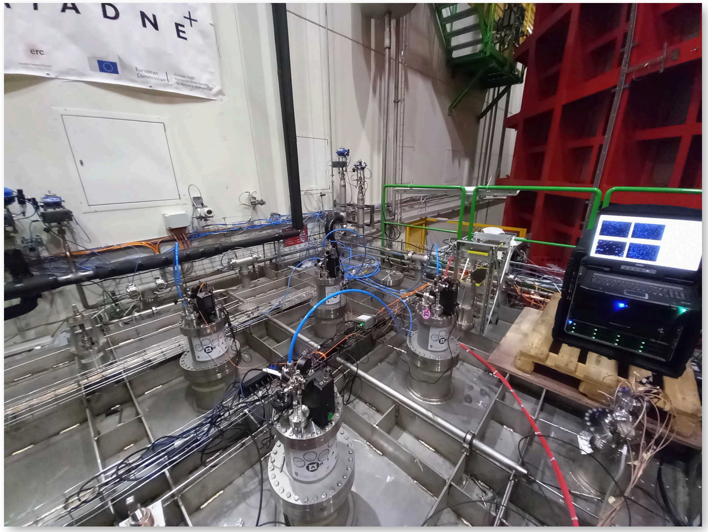


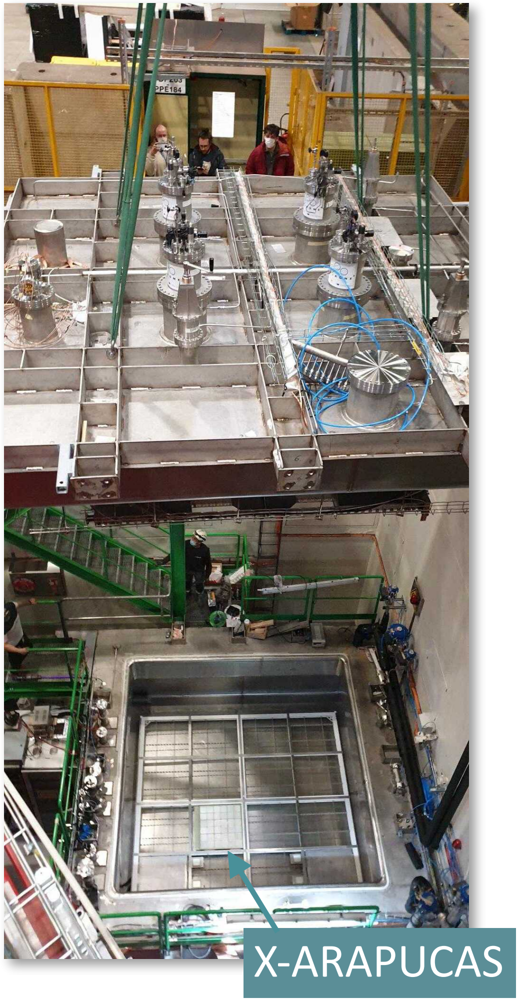
Visible (f0.95, 10.5 mm)

Custom made VUV MgF_2 Lens (f3, 11mm, 5mm diameter)

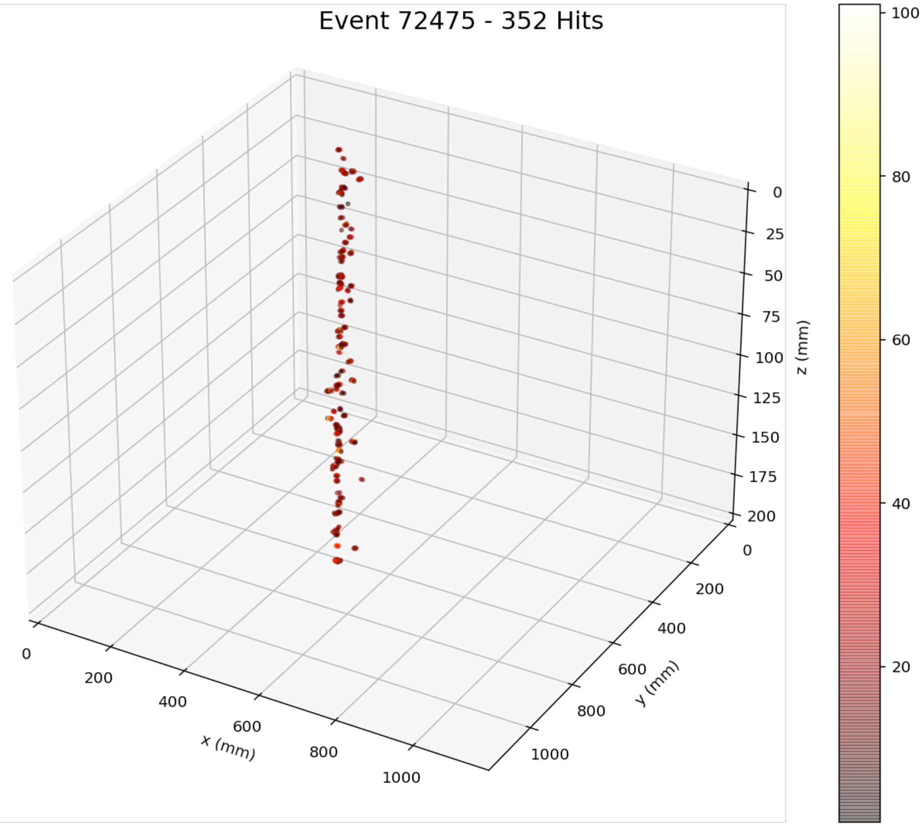
Data Collection

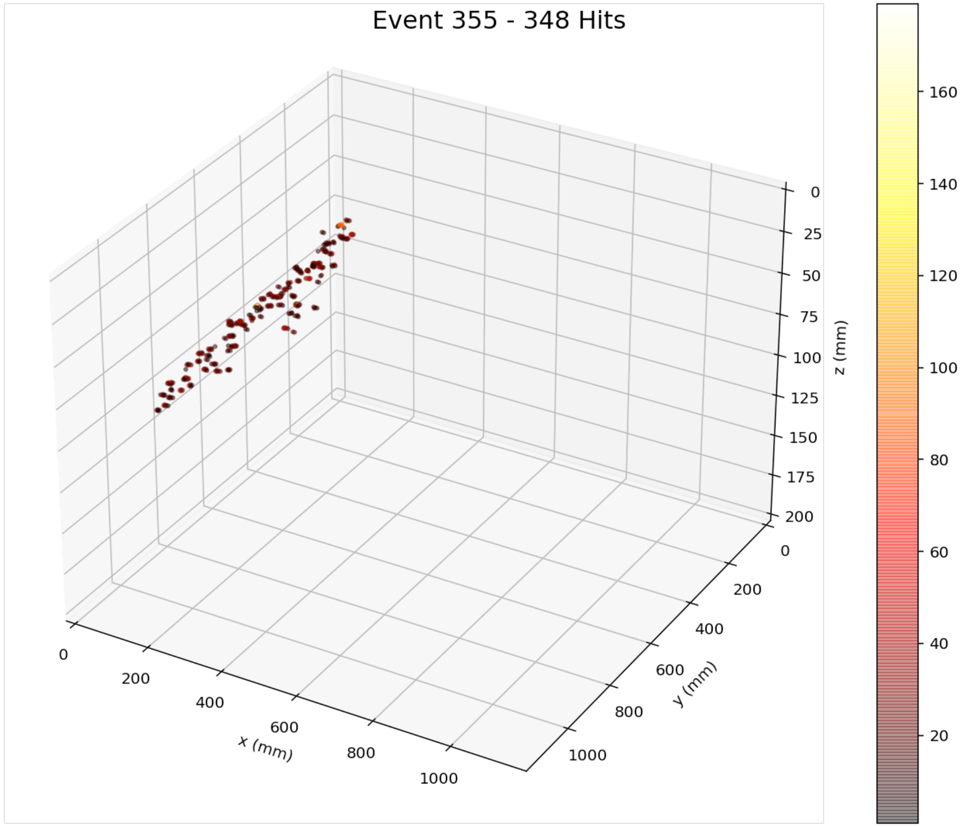
- Very stable cryogenic conditions thanks to the great CERN team
- Argon purity was approximately 0.5 msec
- Three weeks of data collection, refilled twice
- USC collected S1 data using X-ARAPUCAS embedded within the cathode





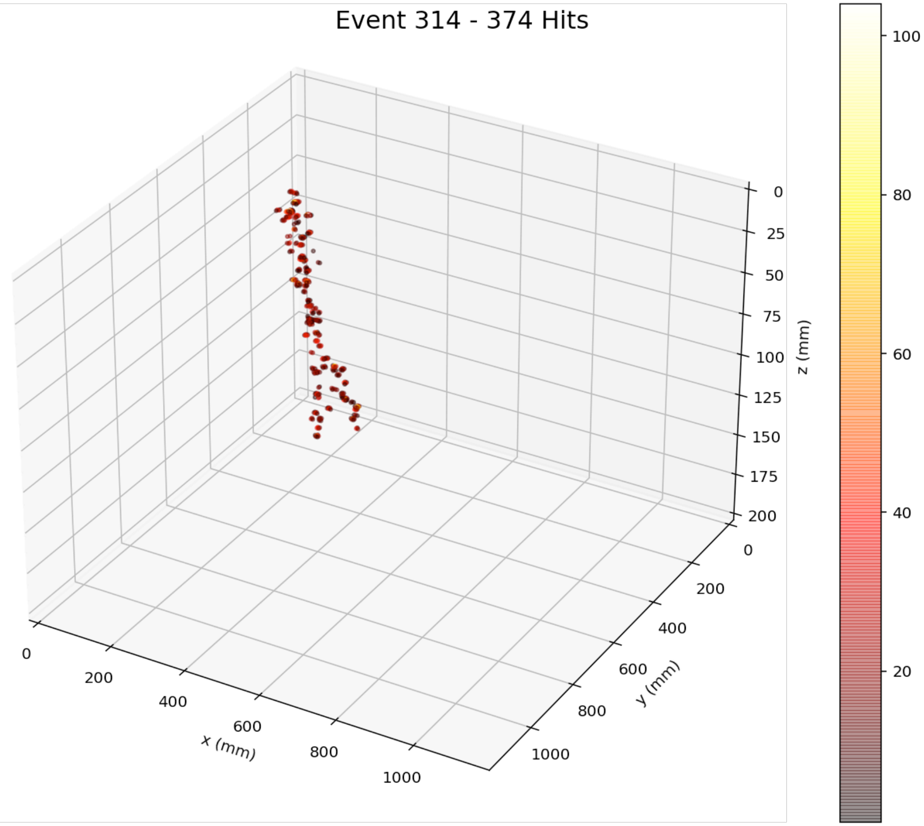
Gallery of Events - Visible Light

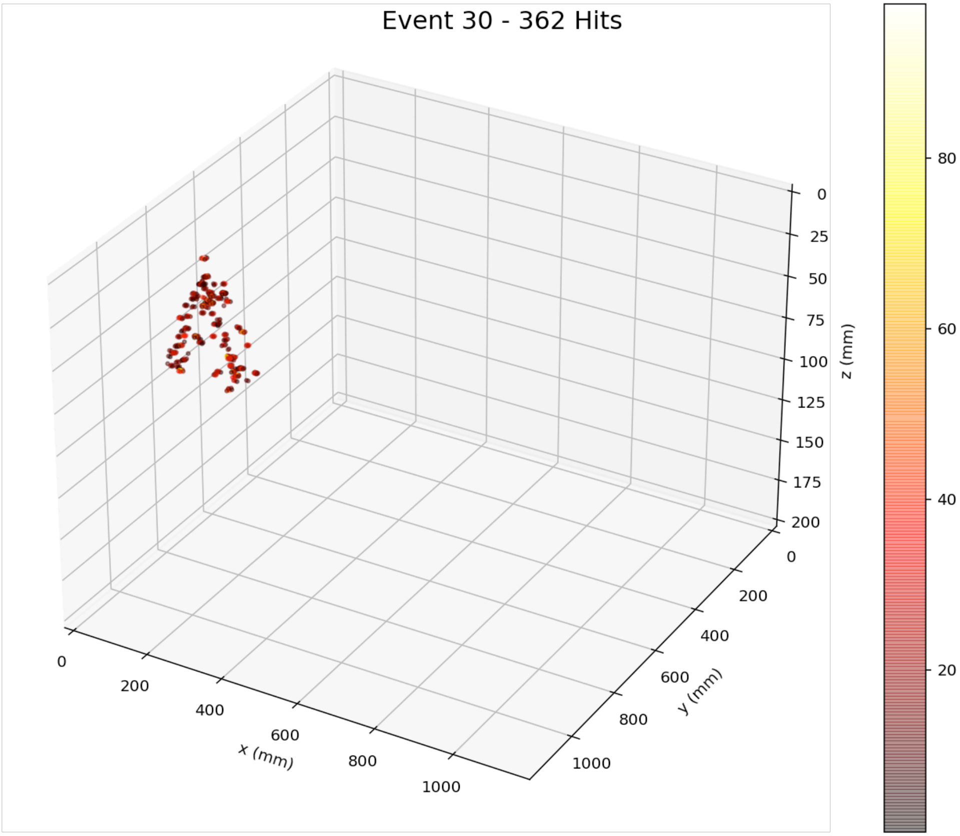




~4 mm Resolution

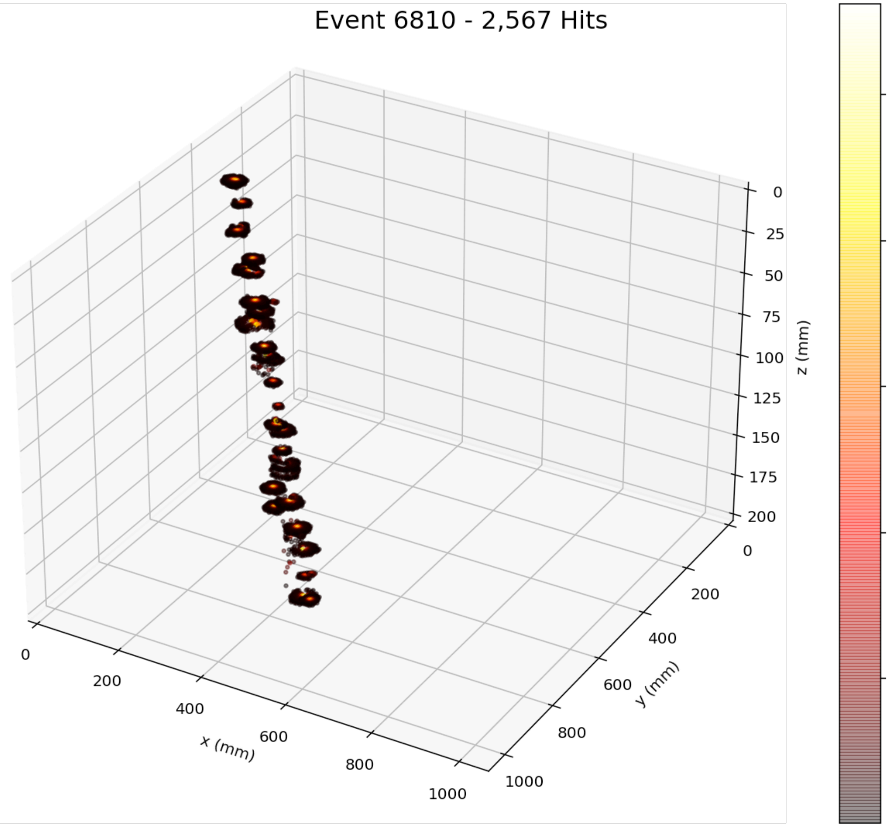
Gallery of Events - Visible Light

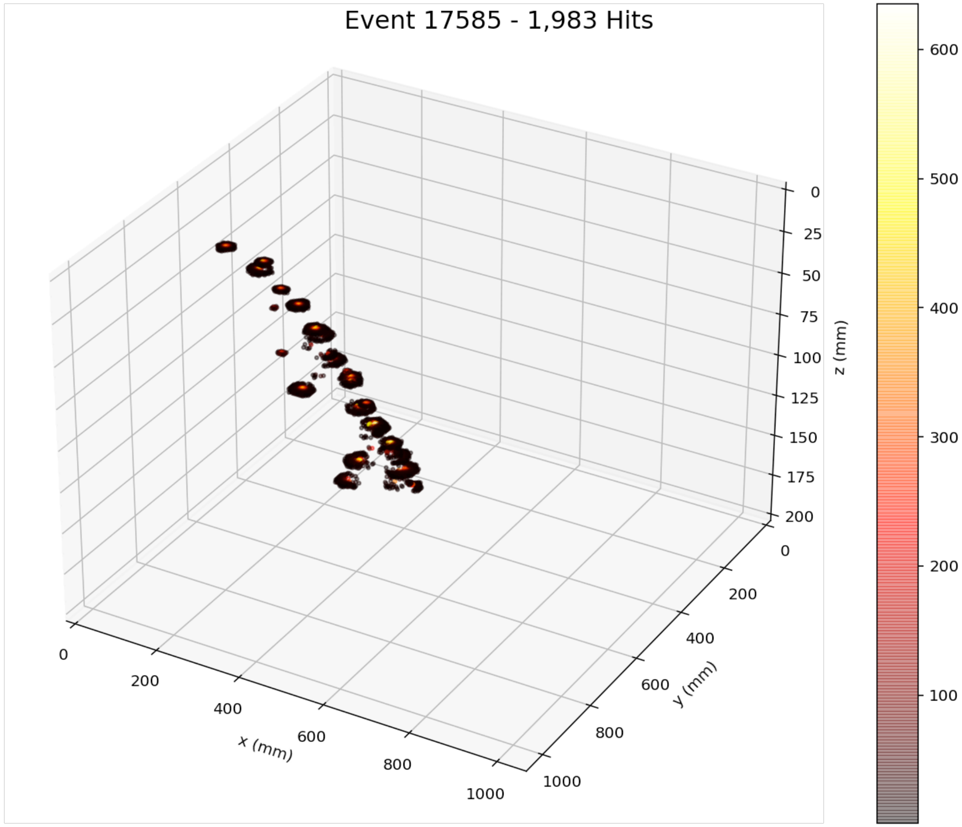




~4 mm Resolution

Gallery of Events - VUV

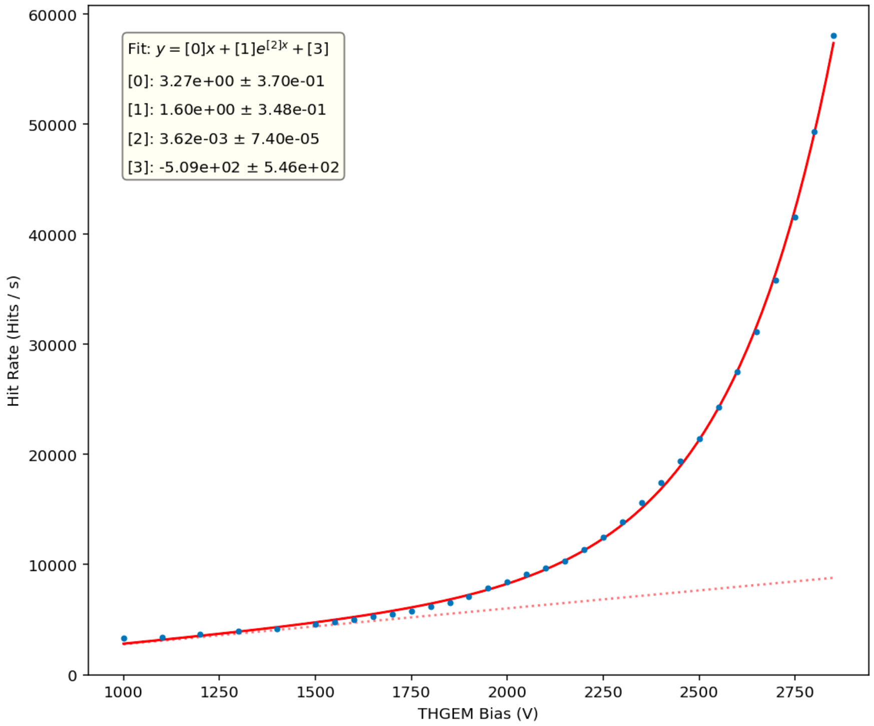




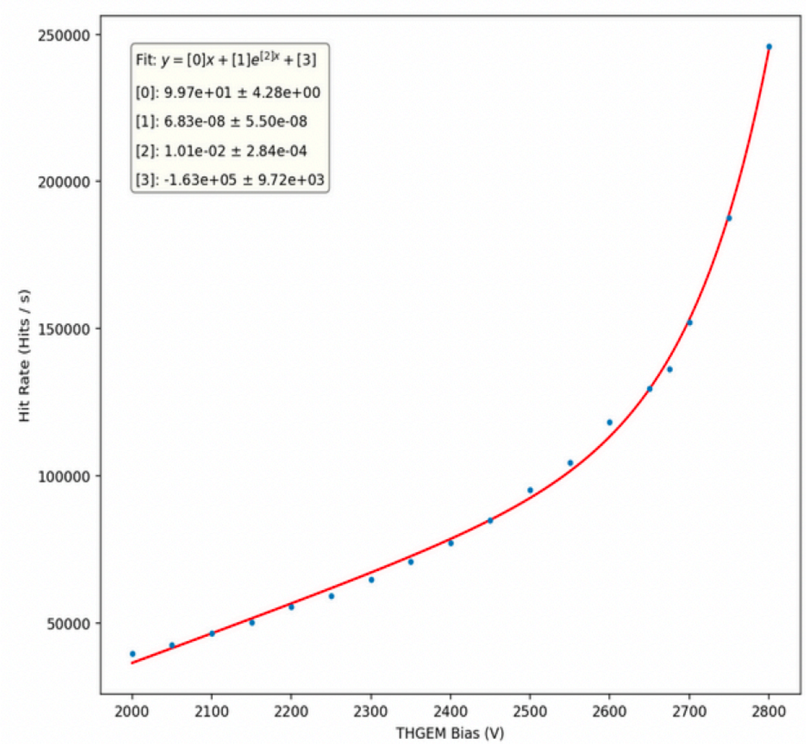
~4 mm Resolution

Glass THGEM Light Study

Visible Light

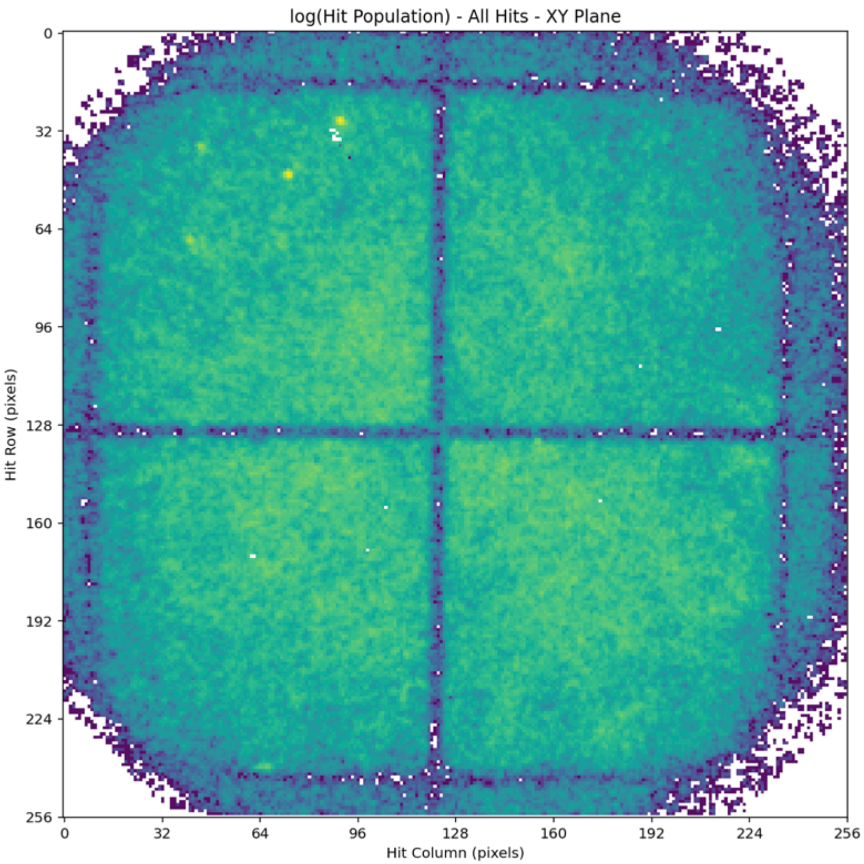


VUV Light

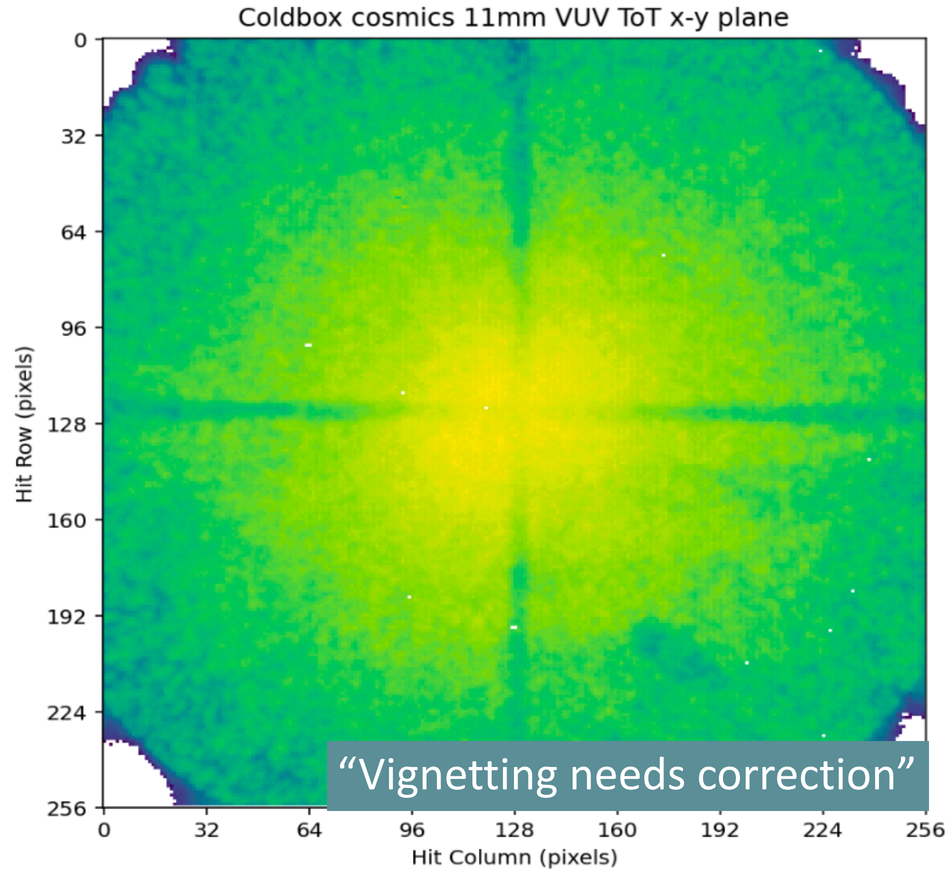


30 Second Exposure Cosmics

Visible Light



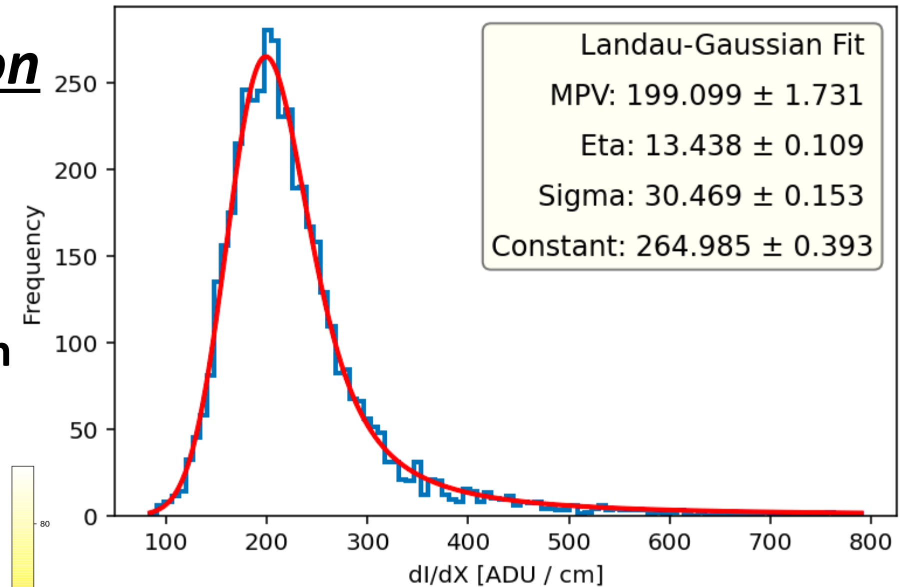
VUV Light

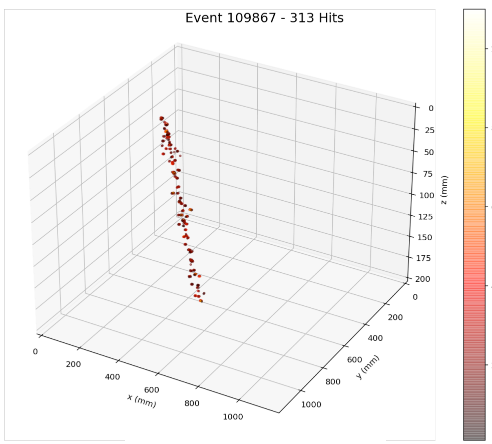


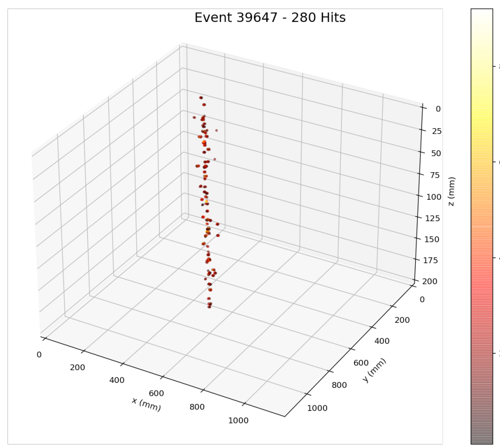
"Vignetting needs correction"

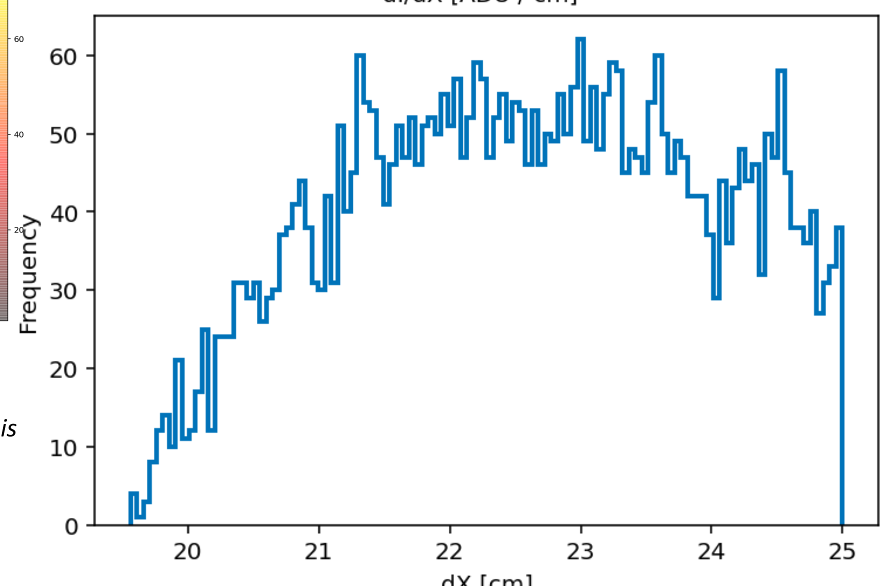
Energy Calibration and Resolution

- Track fitting to through going muons (Through THGEM and greater than 19 cm depth)
- Energy conversion : **199.10 ± 1.73 ADU / cm**
- Energy resolution : **16.73 ± 0.16 %**





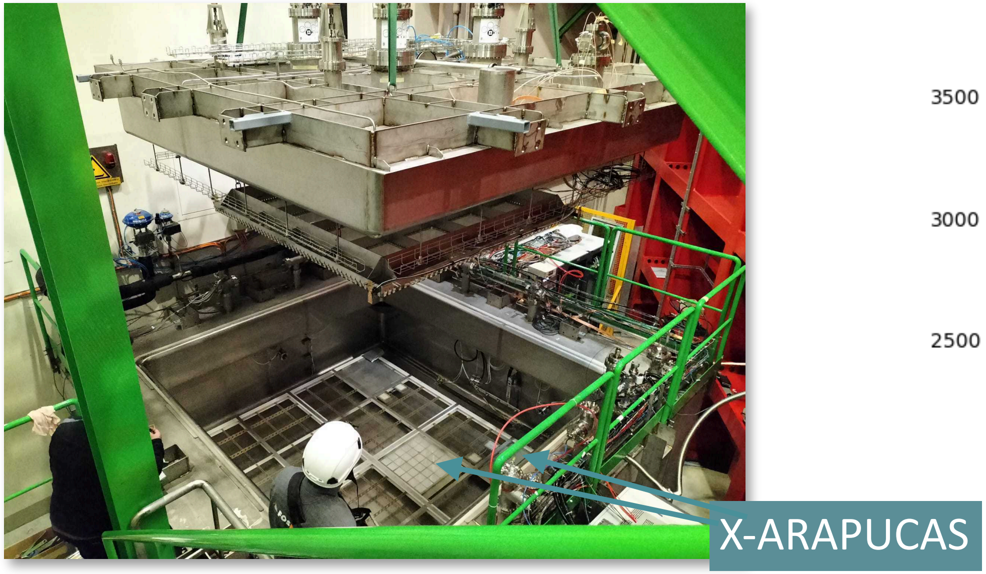


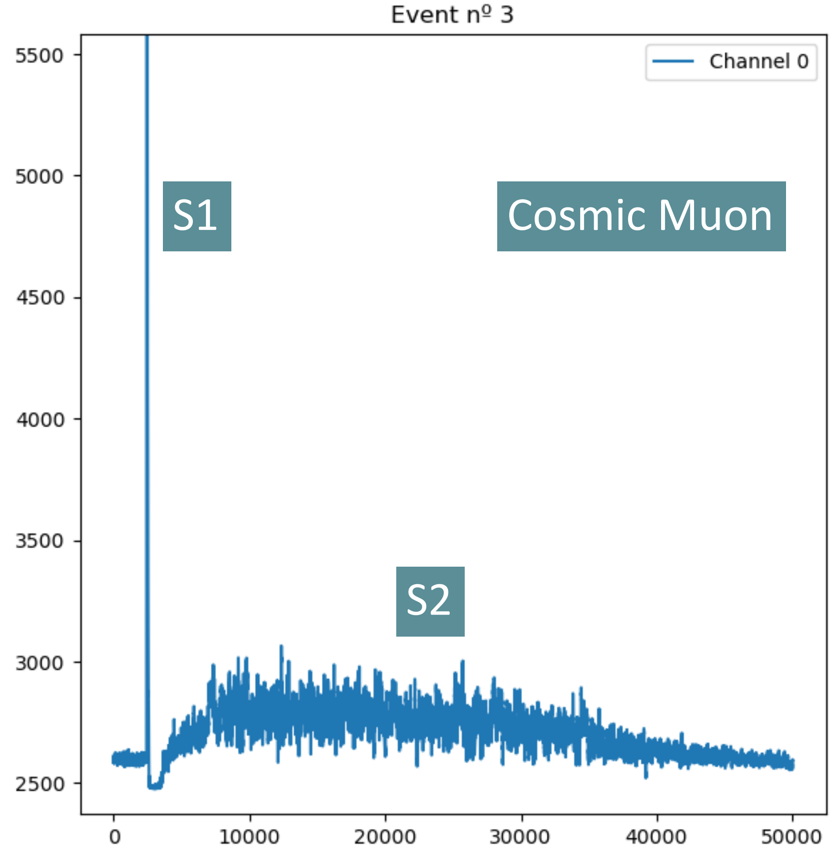


Further detail on the run and analysis can be found in this paper.

S1 Light Collection Studies

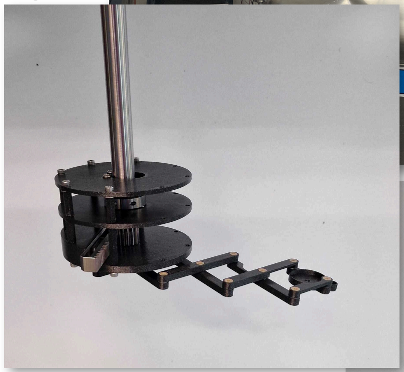
- USC collected data using the X-ARAPUCAS embedded within the cathode of the cold box
- Studies into discriminating between S1 and S2 signals
- Analysis is ongoing - correlation between X-ARAPUCA signal and ARIADNE+ data

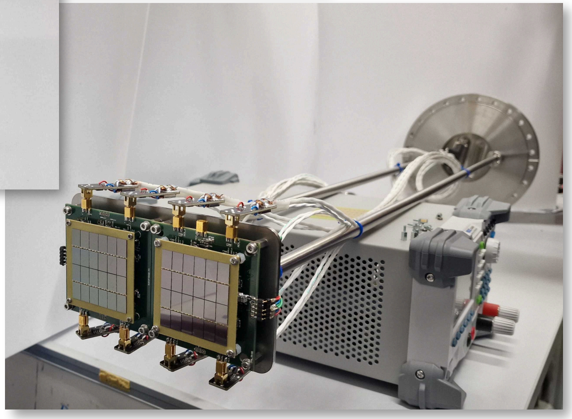




ARIADNE Upgrade

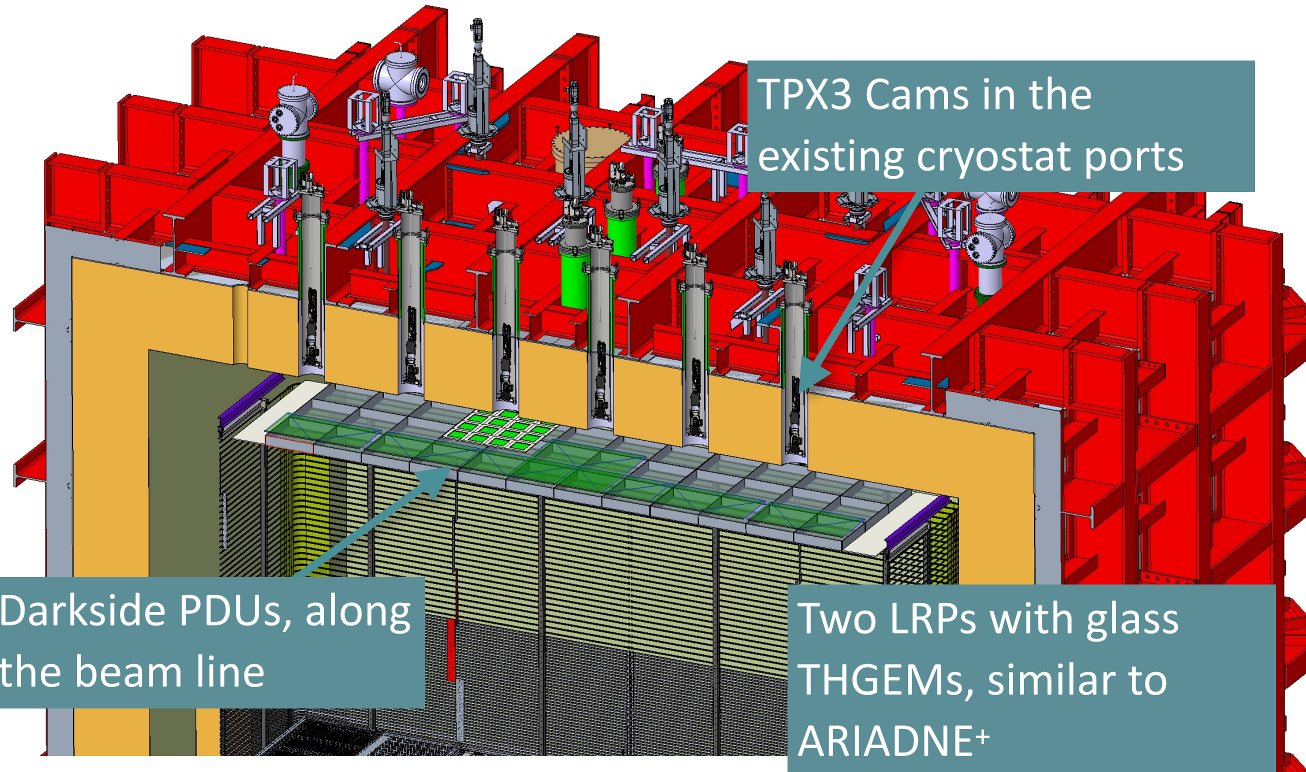
- First time running multiple Timepix3 cameras on ARIADNE
- Swapping the existing FR4 GEM with a glass THGEM
- Introduction of a calibration source for probing the low-energy threshold of the detector
- Two different types of intensifier - one previously used on ARIADNE and the new intensifier on ARIADNE+
- Addition of a Darkside PDU for investigating Dark Matter detection feasibility (light saturation etc.) - Neutrino & DM …

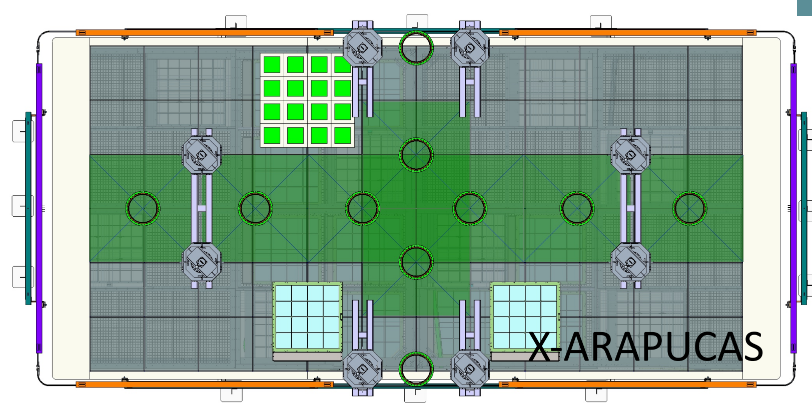




Outlook: Proposed Proto-DUNE Instrumentation

- Using Proto-DUNE dual-phase to test optical readouts for Neutrinos <u>and</u> DM; TPX3Cams, DarkSide PDUs & X-ARAPUCAS
- TPX3 cam superb 3D tracking capability with energy sensitivity down to ~100keV
- DarkSide-20k type Photo Detection Modules (single keV energy threshold)





In dark green shade is the FoV of the TPX cameras(1mx1m) using the current cryostat ports

Conclusions

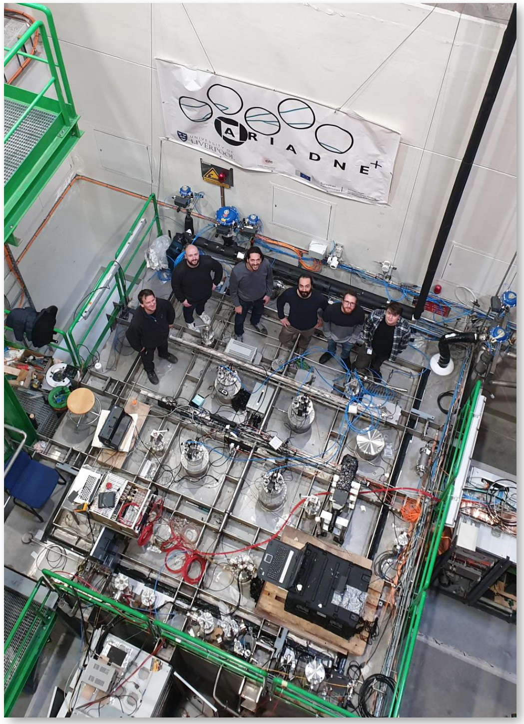
TPX3Cam TPC Benefits

- Raw data is natively 3D
- Huge readout rates possible (80 MHits/s)
- Zero suppressed readout (approx. few kbytes per event)
- High resolution with approx. 1 mm per pixel
- Easy access for swapping in/out technologies
- Same readout is possible for dual-phase or gas TPCs
- Comparatively low cost to other readout methods

- Optical readout achieved with stable detector conditions has been demonstrated at the same scales as that for vertical drift tests (CERN Neutrino Platform Cold Box)
- Dual phase extraction region very stable at large scale
- TPX3 and Glass THGEM technology is ready for deployment **now**
- Considered an option for **DUNE LAr Far Detector.** An option for DUNE **GAr Near Detector?** (if enough light is produced in pressurised gas Argon. Tests are in preparation in collaboration with USC)

Thank You for Listening!

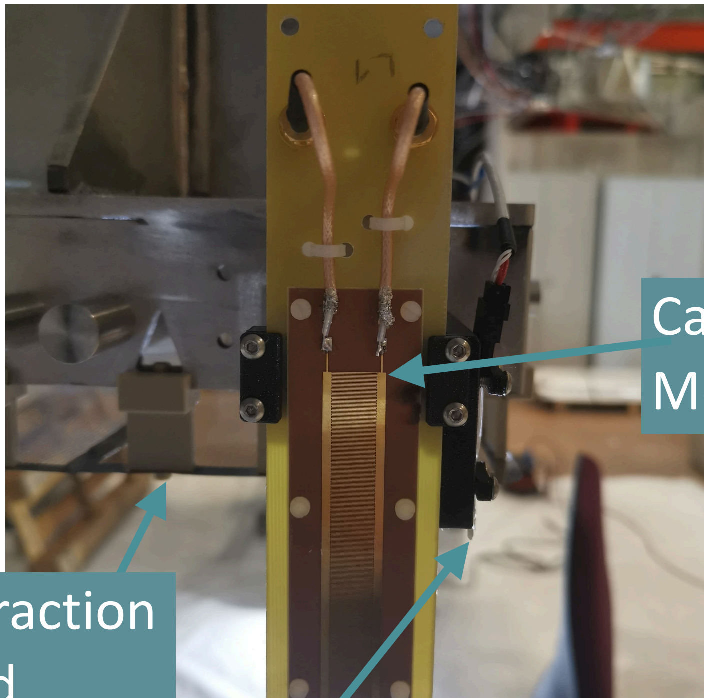
Any questions?



Once again thank you to the amazing CERN team for hosting ARIADNE+ and all their help getting the detector up and running!

Extra Slides

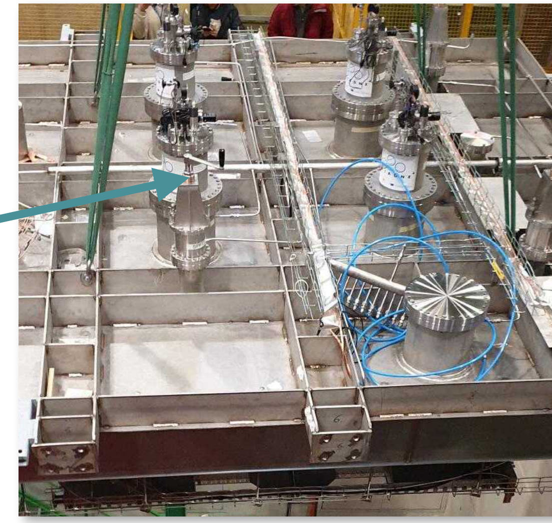
Detector Levelling



Capacitive Level Meter

Extraction Grid

PT100 Temperature Sensor



Height Adjustment

TPX3 to TPX4

			Timepix3 (2013)	Timepix4 (2019)	
Technology			130nm – 8 metal	65nm – 10 metal	
Pixel Size			55 x 55 µm	55 x 55 µm	
Pixel arrangement			3-side buttable 256 x 256	4-side buttable 512 x 448	**3.5x**
Sensitive area			1.98 cm^2	6.94 cm^2	
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA		
		Event Packet	48-bit	64-bit	**33%**
		Max rate	0.43×10^6 hits/mm^2/s	**3.58×10^6 hits/mm^2/s**	**8x**
		Max Pix rate	1.3 KHz/pixel	**10.8 KHz/pixel**	
	Frame based (Imaging)	Mode	PC (10-bit) and iTOT (14-bit)	CRW: PC (8 or 16-bit)	
		Frame	Zero-suppressed (with pixel addr)	Full Frame (without pixel addr)	
		Max count rate	~0.82 x 10^9 hits/mm^2/s	~5 x 10^9 hits/mm^2/s	**6x**
TOT energy resolution			< 2KeV	**< 1Kev**	**2x**
Time resolution			1.56ns	**195.3125ps**	**8x**
Readout bandwidth			≤5.12Gb (8x SLVS@640 Mbps)	≤163.84 Gbps (16x @10.24 Gbps)	**32x**
Target global minimum threshold			<500 e^-	<500 e^-	

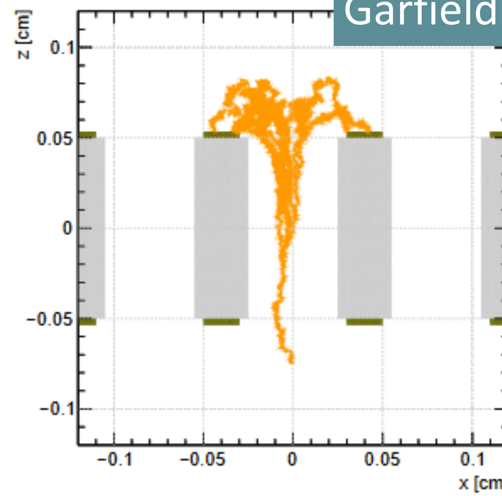
THGEM S2 Light Production

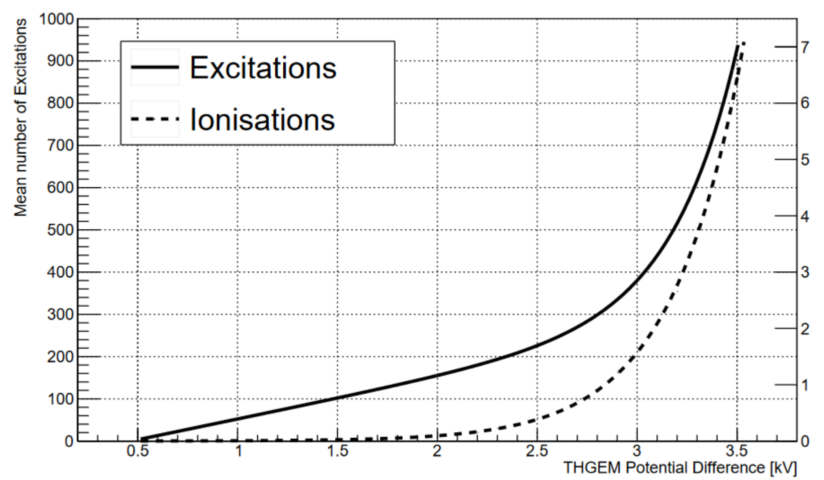
VUV (126nm) light produced through de-excitation of Argon gas.
TPB Wavelength shifter above THGEM converts to 430nm.

At low field (<2kV/cm), S2 light production is linearly proportional to THGEM field. No charge gain. Very stable operation without discharges. No ion production.

At higher fields, electron multiplication occurs (Townsend avalanche).
Exponentially increasing S2 light production -> Improved sensitivity/threshold

Garfield Simulation

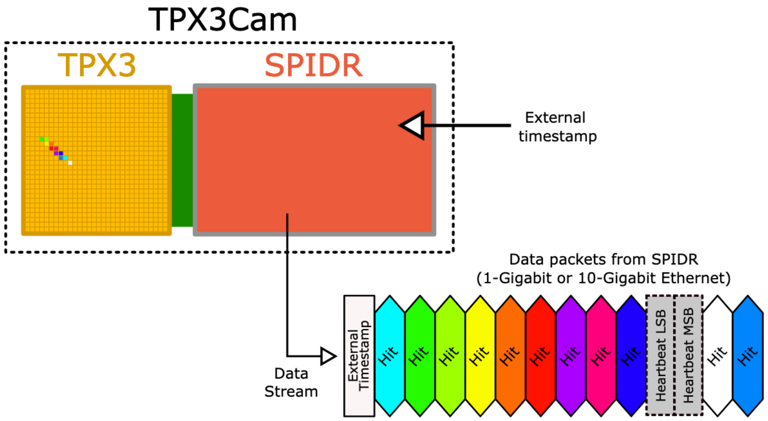




TPX3 Data Packets

Each Hit (Min 500 electrons):

- X Position
- Y Position
- Time of Arrival (ToA)
- Time over Threshold (ToT)



THGEM Characterisation

Mean TPX3Cam ToT rate (calculated as the summed ToT of all hits in a run divided by the total duration of the run and measured in ADU per second) as a function of the electric field across the THGEM. A single function—comprising a combination of linear and exponential functions is fitted to the data

Energy Calibration and Resolution

Simply the conversion between the incident light intensity in ADU and the corresponding physical energy in MeV

Through-going muons are ideal for calculating this calibration, they are minimum-ionising particles (“MIPs”) with a well-known mean energy deposition rate, dE/dX , of 2.12 MeV/cm

The summed ToT is calculated across all hits which comprise each event, and this summation is divided by the 3D track length of the through-going track.

The energy resolution, defined as the Landau (eta) and Gaussian (sigma) widths combined in quadrature and expressed as a fraction of the MPV