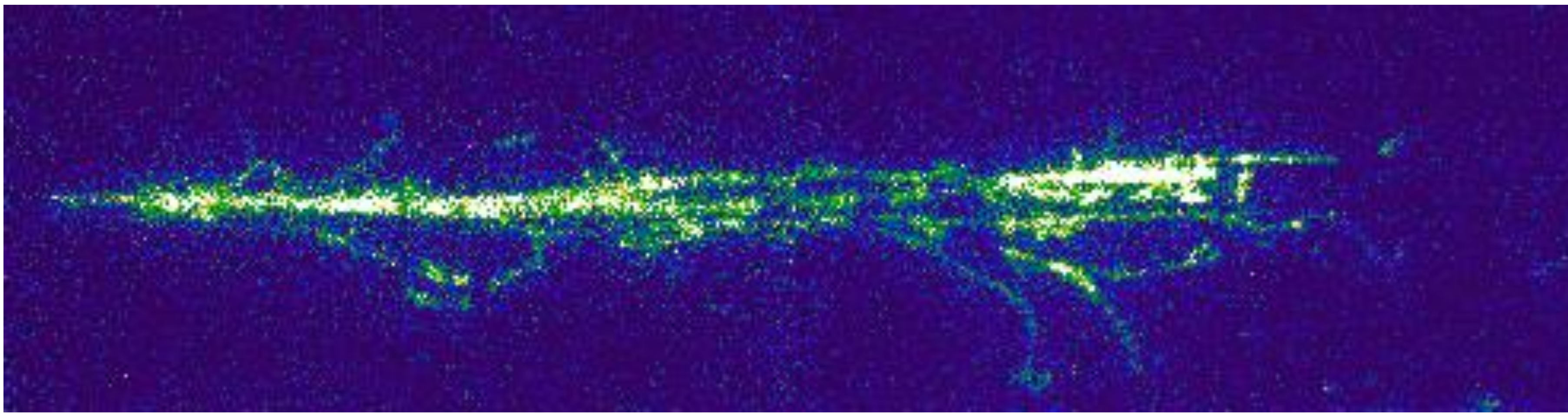
ARIADNE: bringing a game changing optical readout to two phase LAr TPCs



Kostas Mavrokoridis
k.mavrokoridis@liv.ac.uk

NNN 2019,
Medellin, Colombia, November 2019

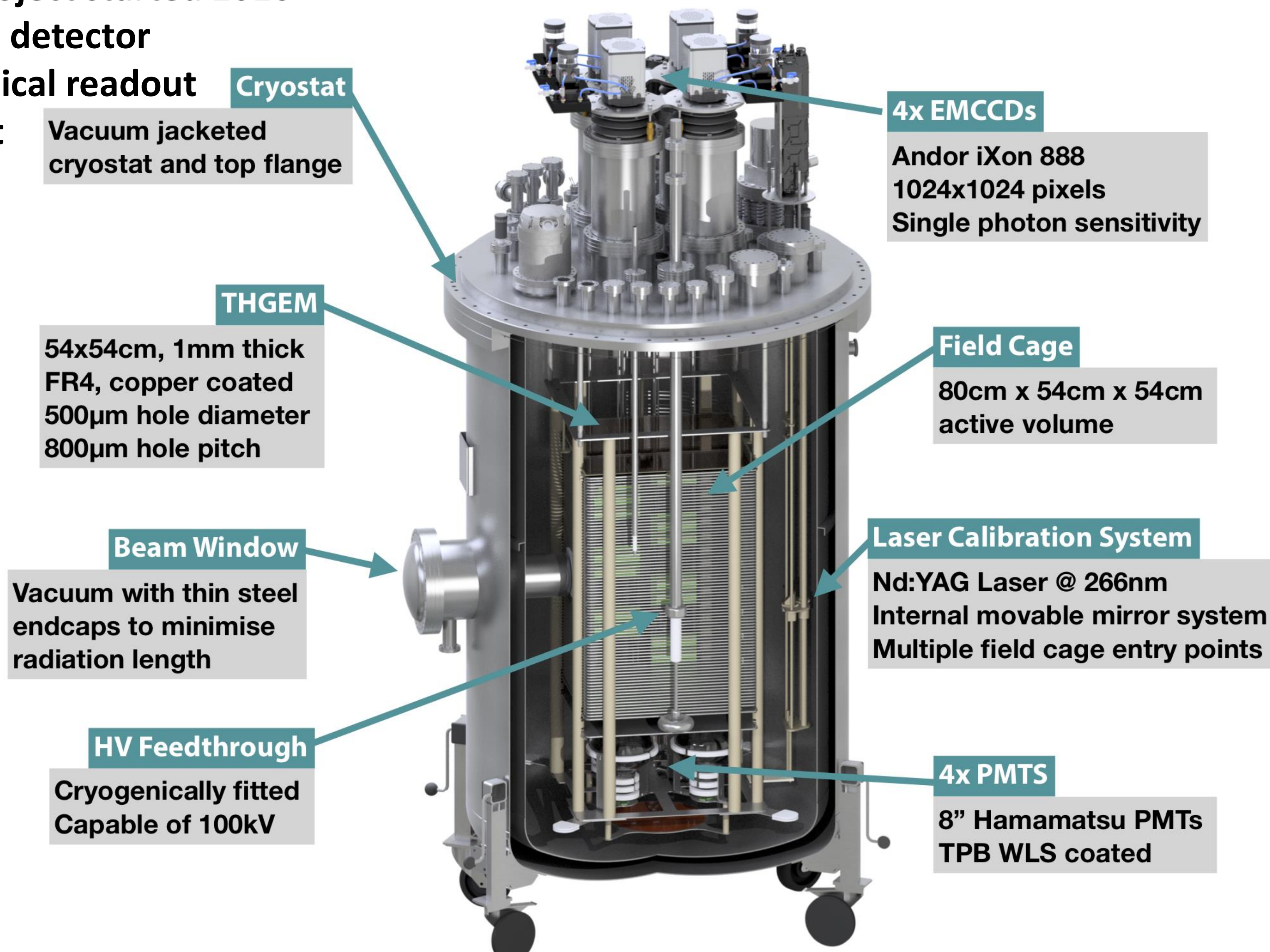
http://hep.ph.liv.ac.uk/ariadne

Outline

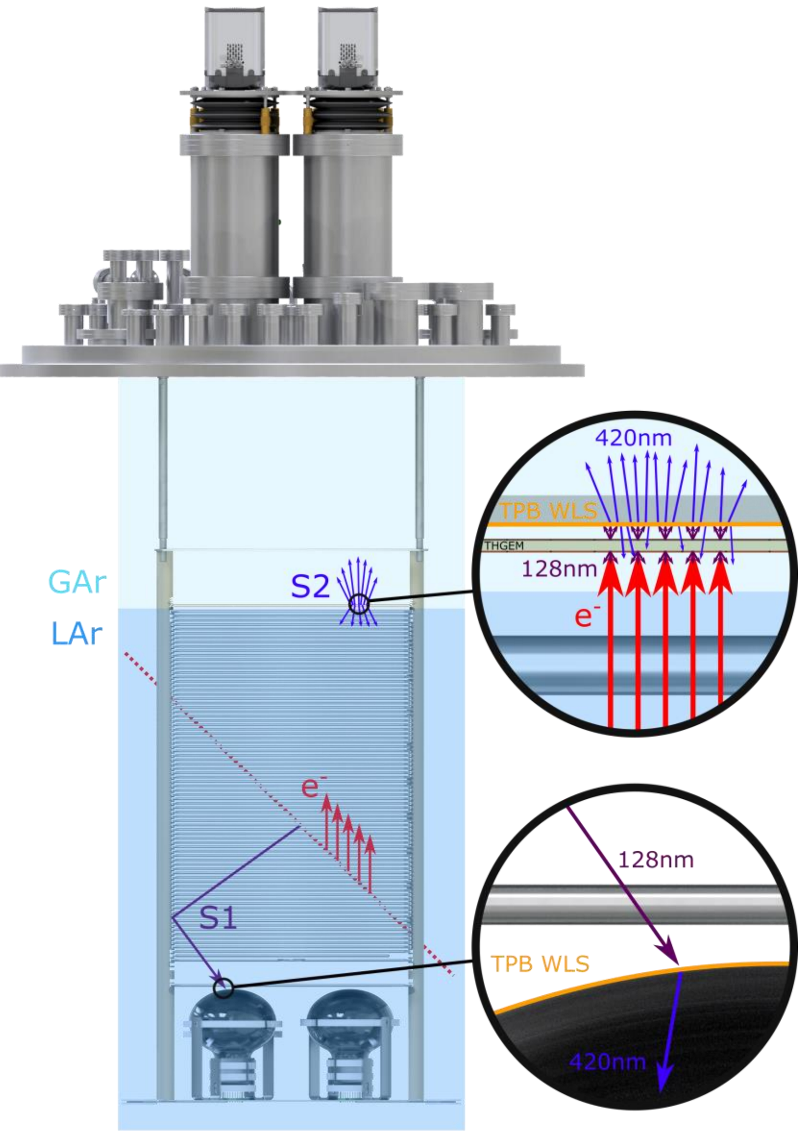
- The ARIADNE Detector
  - Construction at Liverpool
- Operation at CERN T9 beamline with EMCCDs & first results
- ARIADNE upgrade at Liverpool
  - 3D imaging with TPX3 camera on ARIADNE
- Future directions

ARIADNE

- ERC funded project started 2016
- Two phase LAr detector innovating optical readout
- 1500L Cryostat



Operation & Benefits



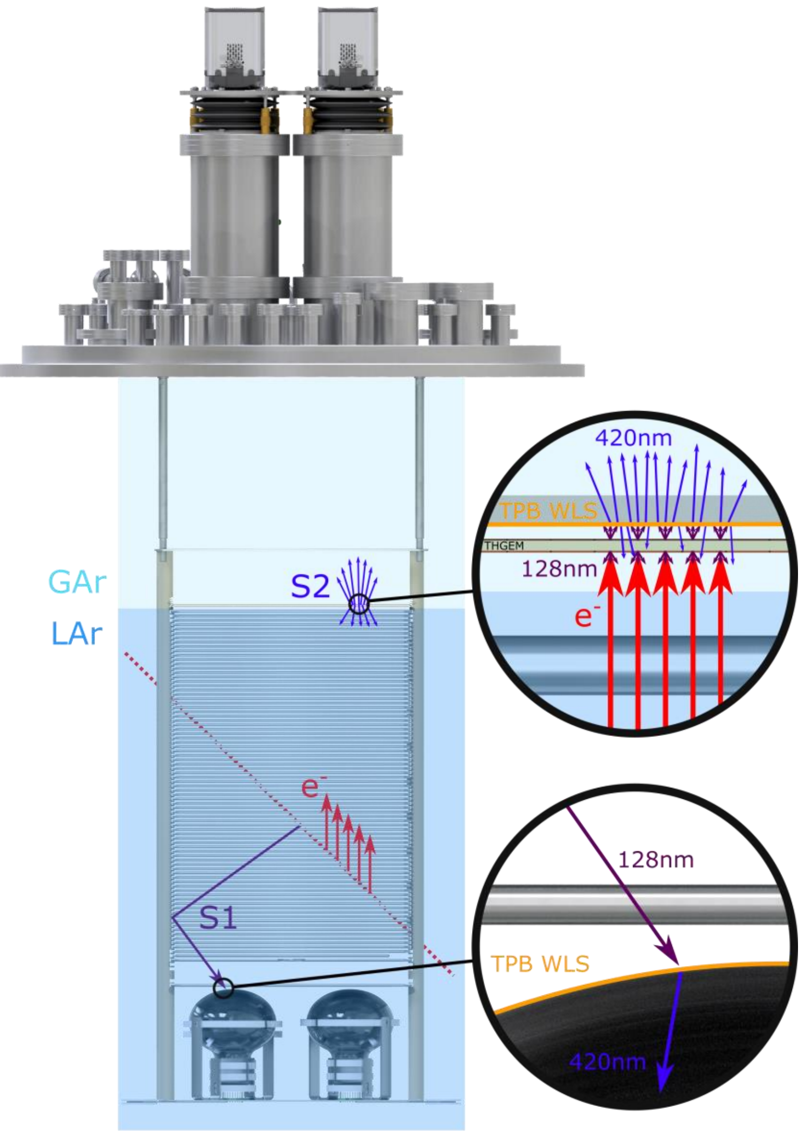
ARIADNE - developing optical readout, as an alternative to charge.

- **Two-phases**, Liquid and Gas Argon
- Particles interact with argon creating detectable scintillation light and ionization (charge)

<u>Innovation of ARIADNE:</u>

- **THGEM** in gas phase amplifies drifted charge by up to 100 times
- This creates secondary scintillation light (S2) that we photograph with high sensitivity cameras (EMCCDs or now TPX3)

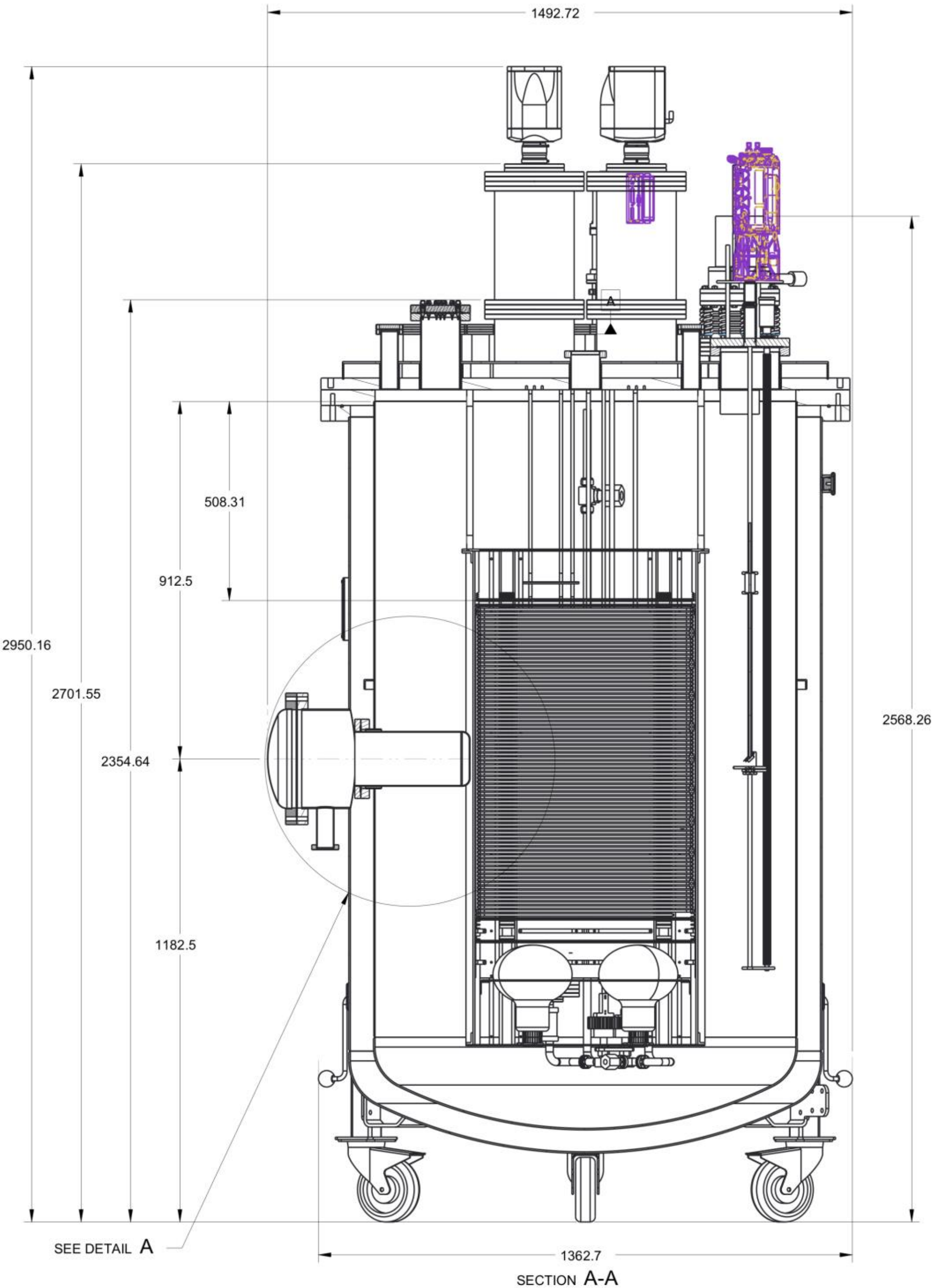
Operation & Benefits



ARIADNE - developing optical readout, as an alternative to charge.

Benefits over previous charge readout techniques:

- **High resolution** — For e.g. an EMCCD sensor is 1024x1024 pixels (run with 4x4 binning ≈ 1mm resolution).
- **Sensitivity to low energies** — gain is generated in the THGEM (~100s of photons per accelerated e^-); cameras can be sensitive to single photons.
- **Very low noise** — Externally mounted cameras are decoupled from TPC electronic noise sources.
- **Ease of access** — Cameras can easily be replaced or upgraded - particularly useful during long-term cryogenic running.
- **Cost efficient** (No need for thousands charge channels used in previous charge readout technology)



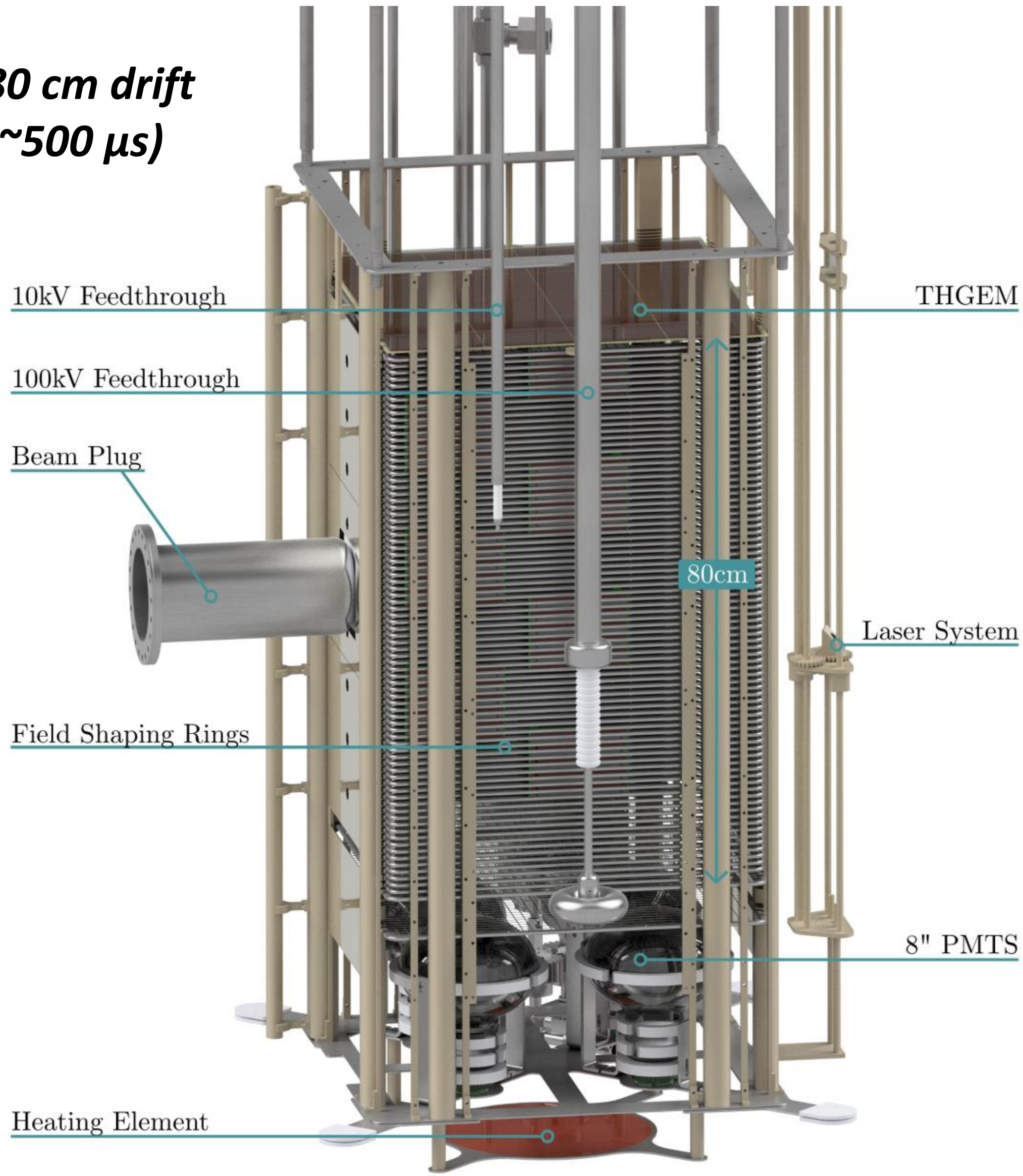
ARIADNE
Design & Construction

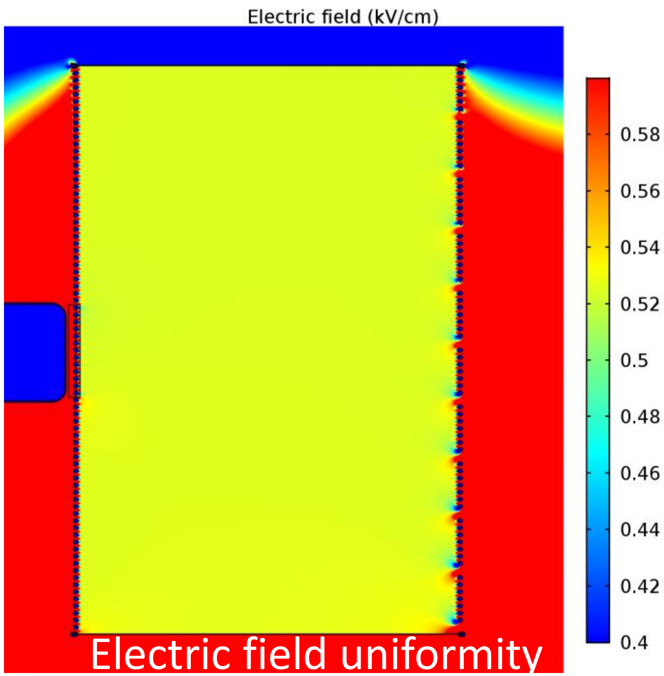
ARIADNE TDR:

http://arxiv.org/abs/1910.03406

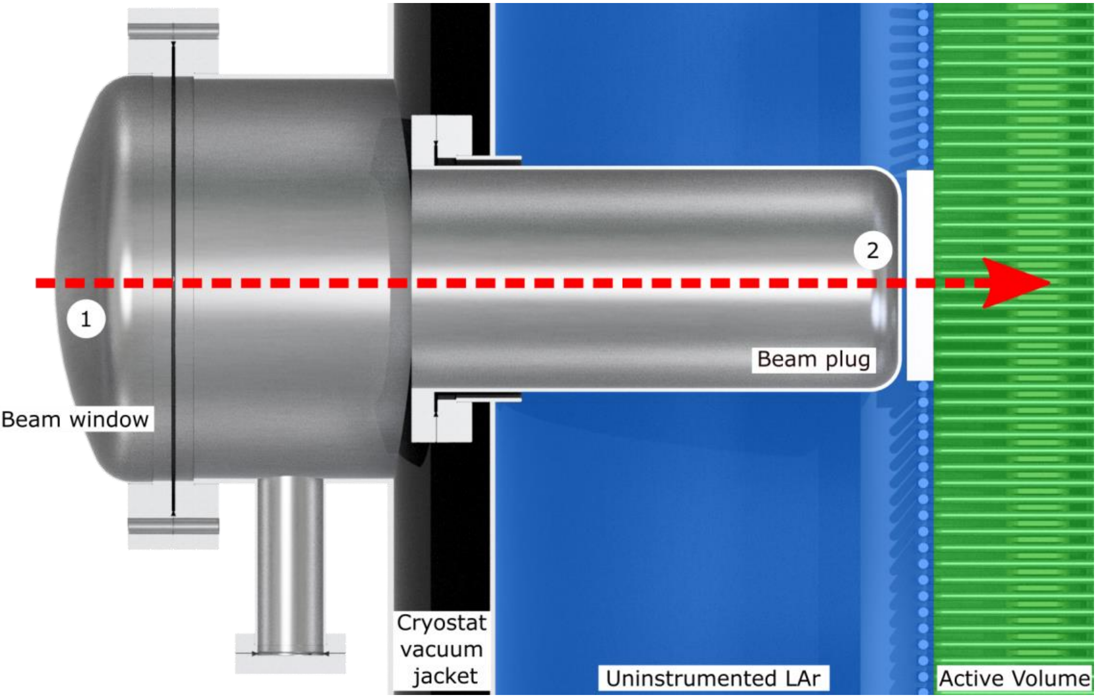
ARIADNE TPC

80 cm drift
(~500 µs)



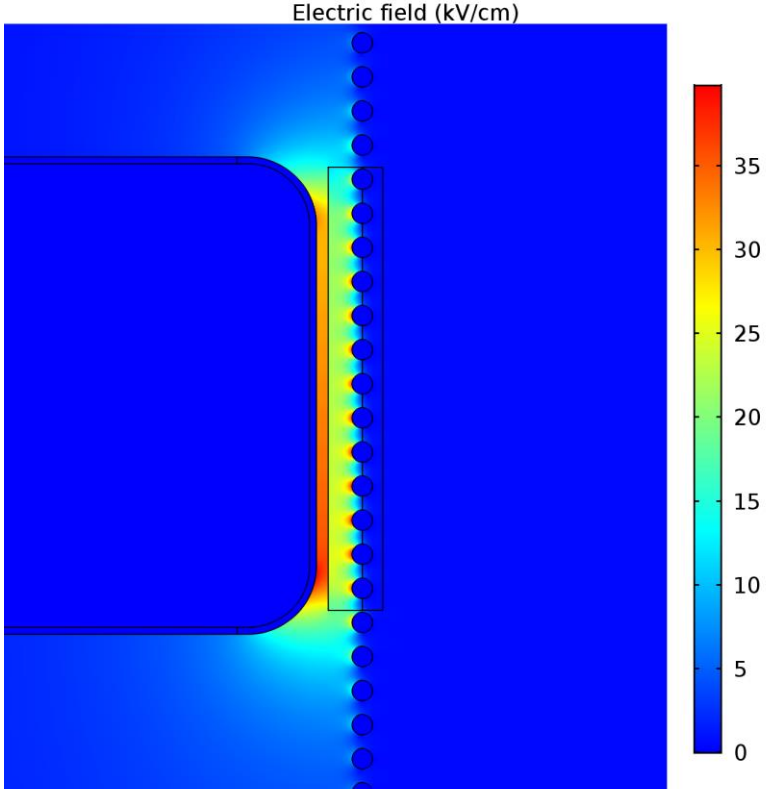


Beam window/plug



Beam transport through the ARIADNE beam window, plug and UHMWPE element.

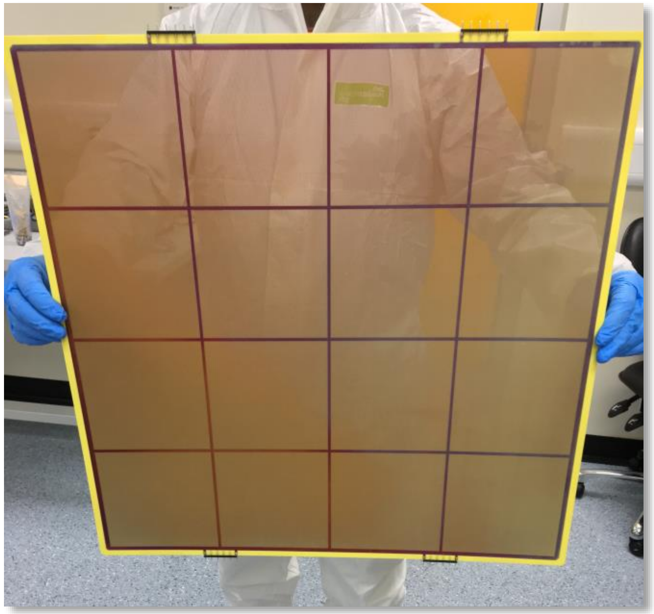
- The total material budget for this design is **0.22 X_0**
- Unmodified cryostat would give 2.34 X_0



COMSOL simulation of the electric field in the region near the end of the beam plug.

ARIADNE THGEM

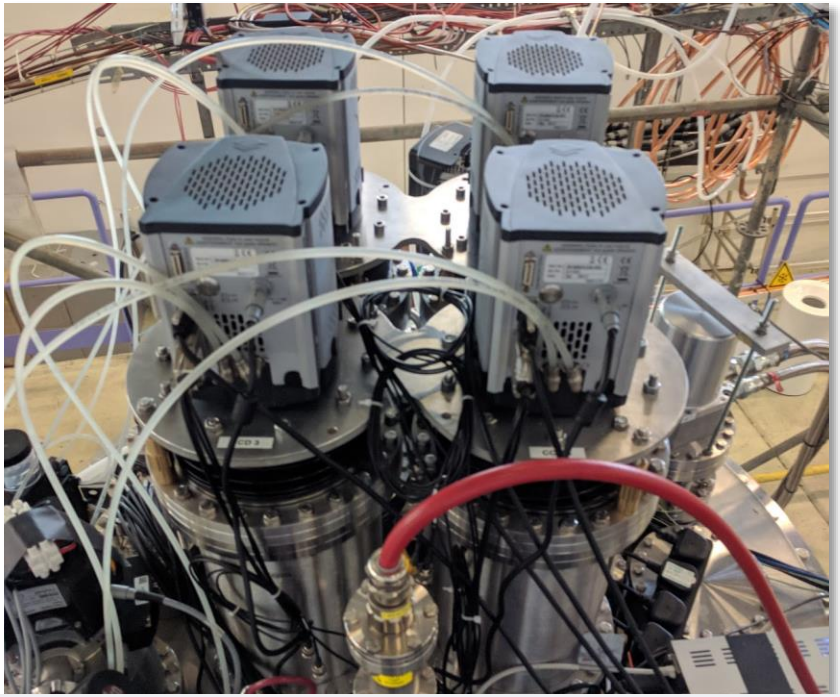
- 54cm x 54cm x 1mm FR4 board
- Copper coating on both faces
- 500µm hole diameter; 800µm hole pitch
- Very strong E-Fields - generally 25-36kV/cm

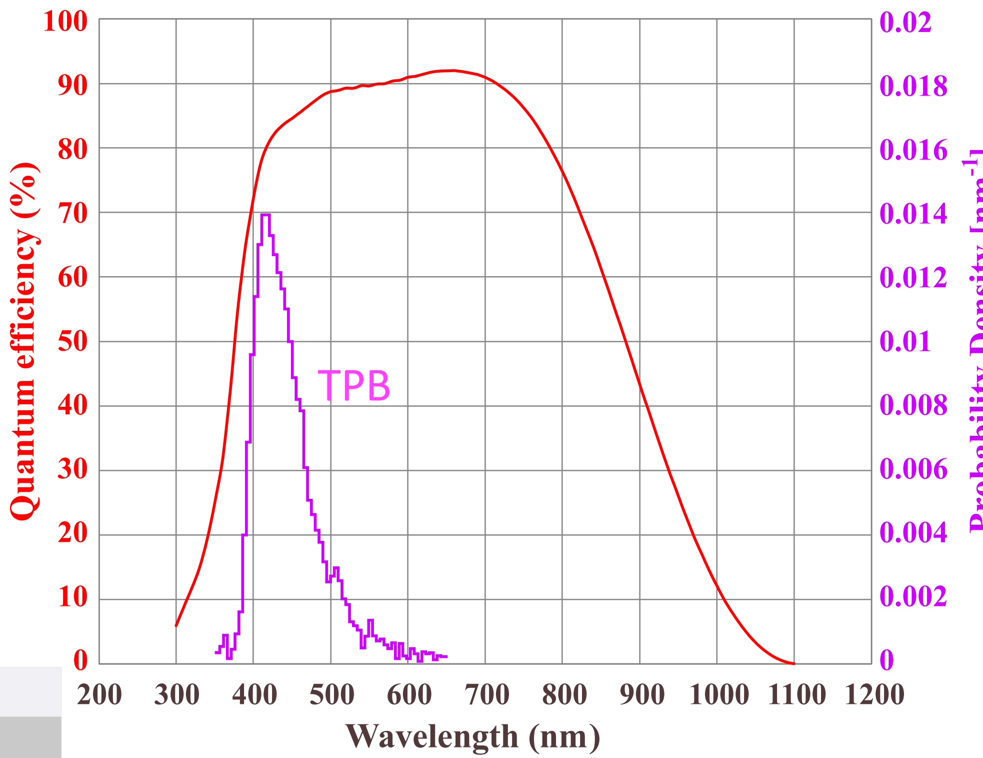


16 pad segmented (originally used)

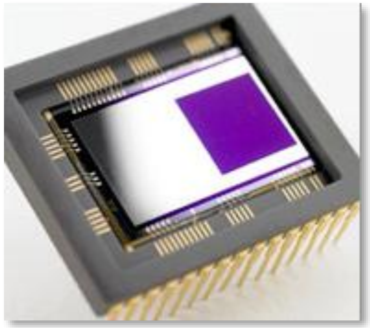
Monolithic (current)

EMCCD Specs



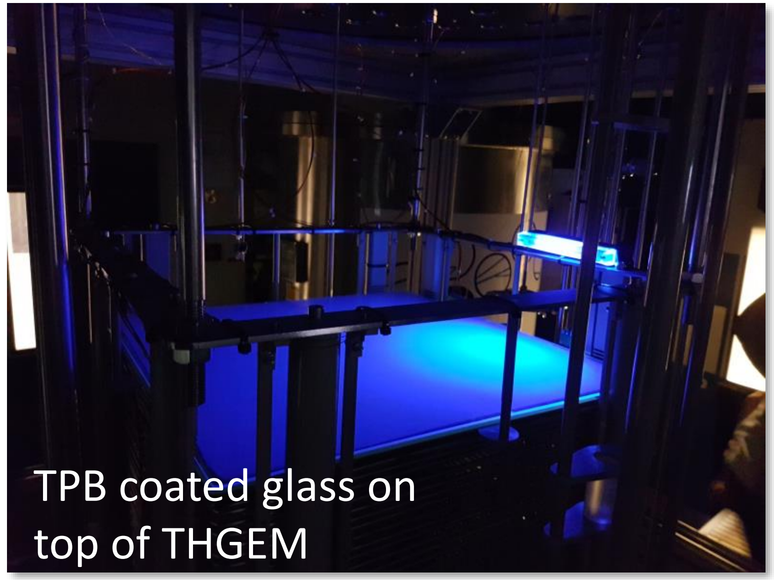


Models	iXon 888
Core attributes	Field of view, sensitivity and speed
Sensor format	1024 x 1024
Sensor diagonal	18.8 mm
QE Options	BV (Life) or BV, EX2, UVB (Ultra)
Pixel Size	13 µm
Frame Rate	26 fps (670 fps with 128 x 128 Crop Mode)
Read Noise	< 1 e- with EM Gain
Pixel well depth	80,000 e-
Interface	USB 3.0



TPB Vacuum Evaporation

Vacuum evaporation chamber capable of coating 55cm x 55cm area



TPB coated glass on top of THGEM

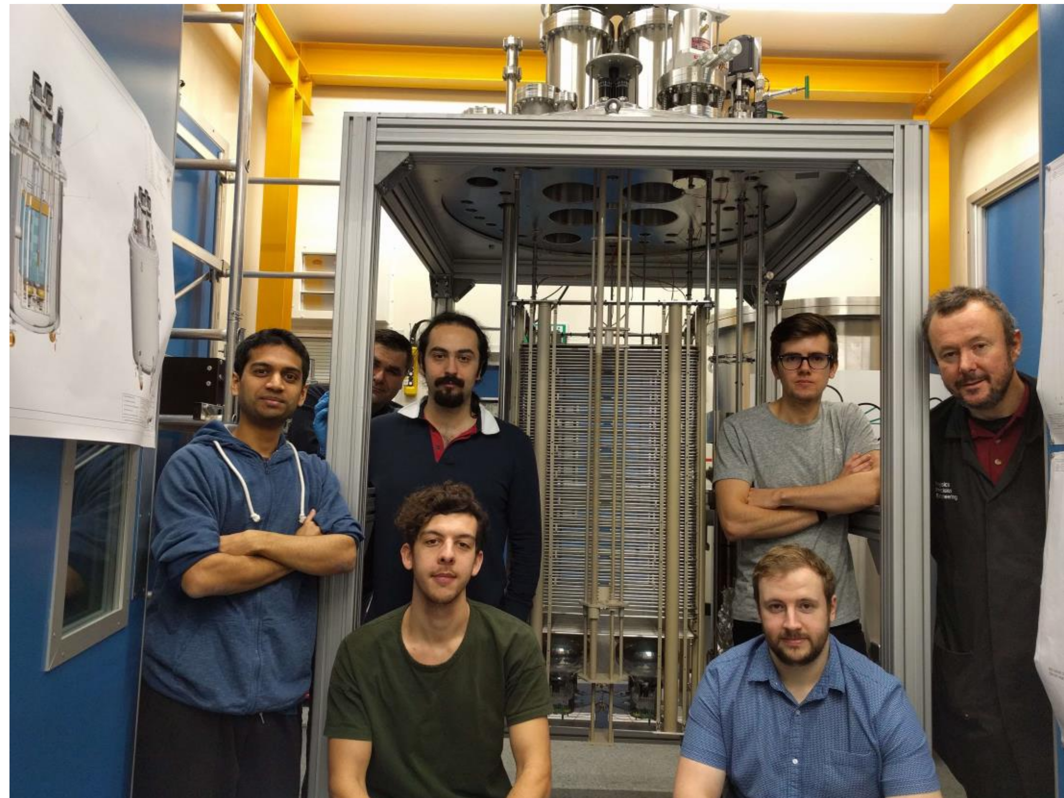
PMTs

Reflectors

The VUV (128nm) light is shifted to 420nm using TPB

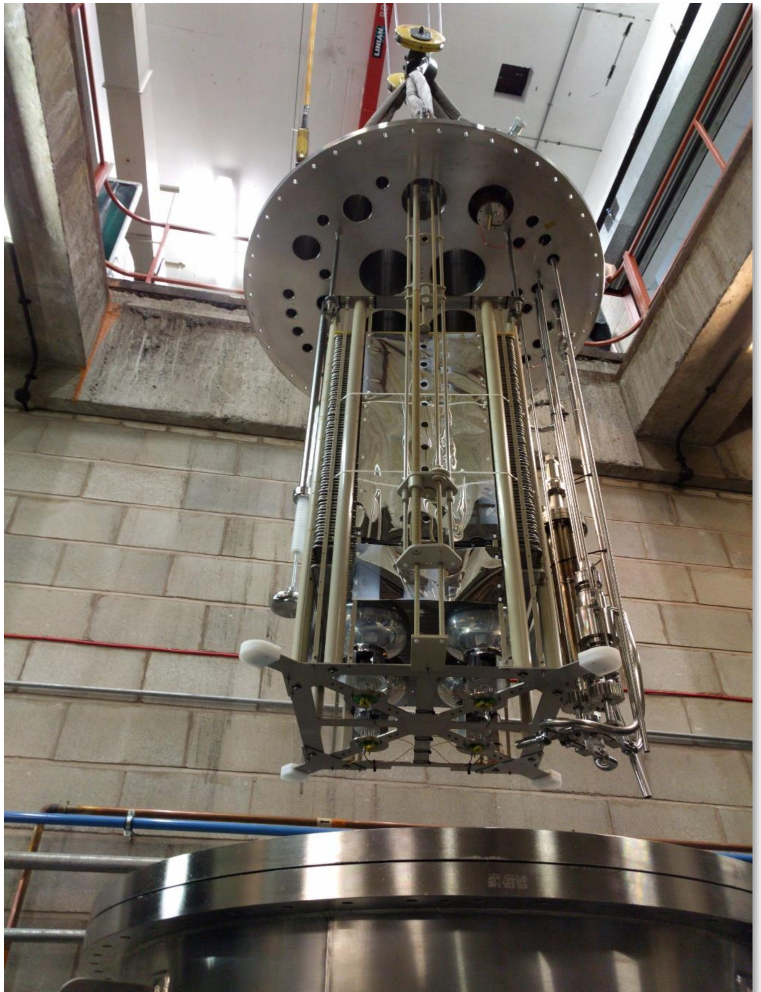
Construction at Liverpool

TPC



First Detector assembly in the Liverpool Liquid Argon facility, November 2017

Construction at Liverpool



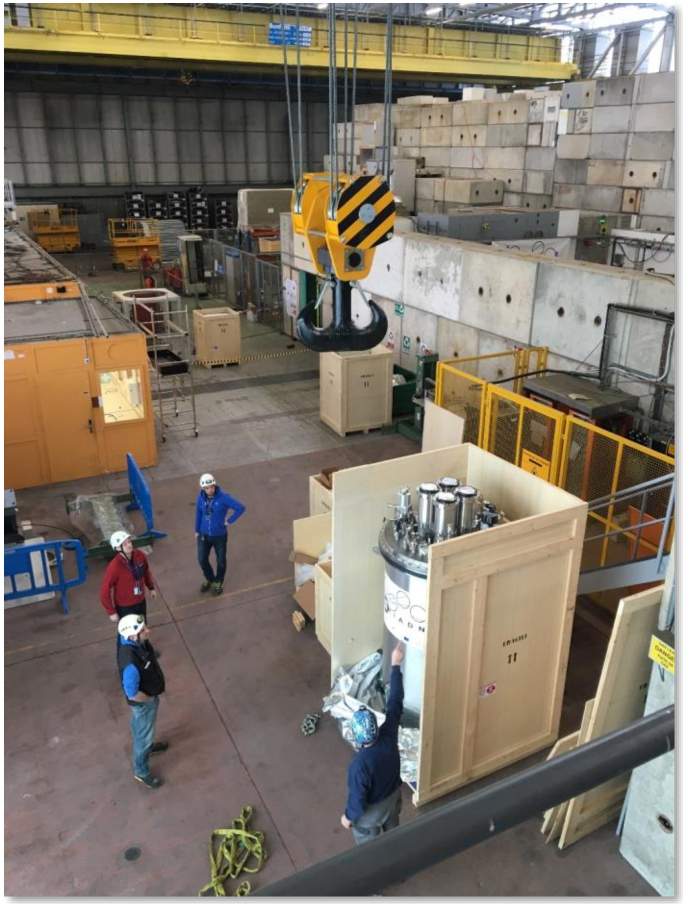
- ○ Closing the Detector at Liverpool end 2017
- ✓ Ready to ship to CERN T9 beam early 2018

ARIADNE at T9 Beamline, **CERN**

ARIADNE at CERN

ARIADNE detector arrived from Liverpool to CERN March 8th 2018

Commissioning and data collection in March/April

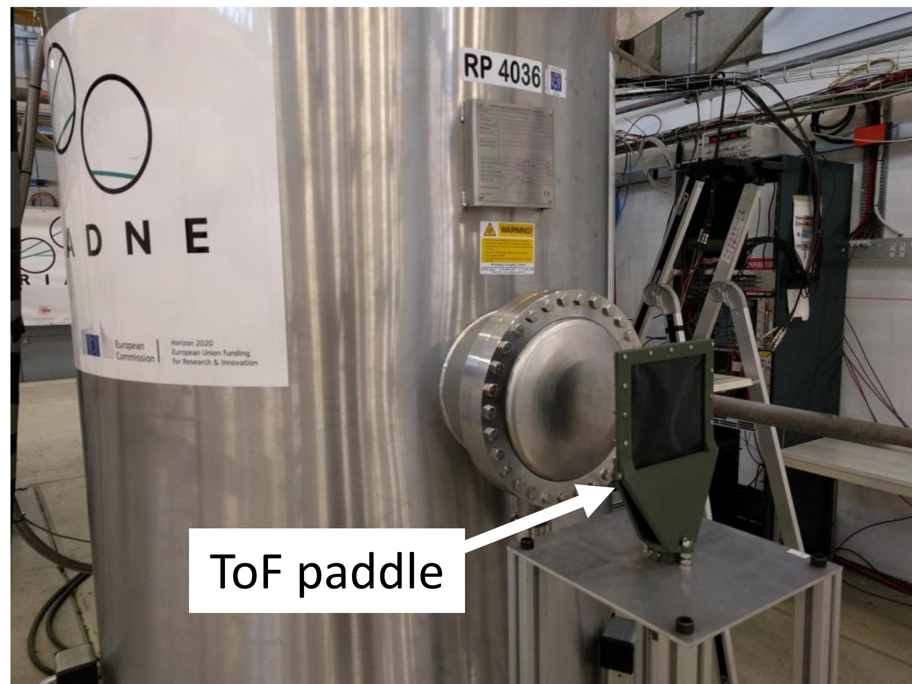


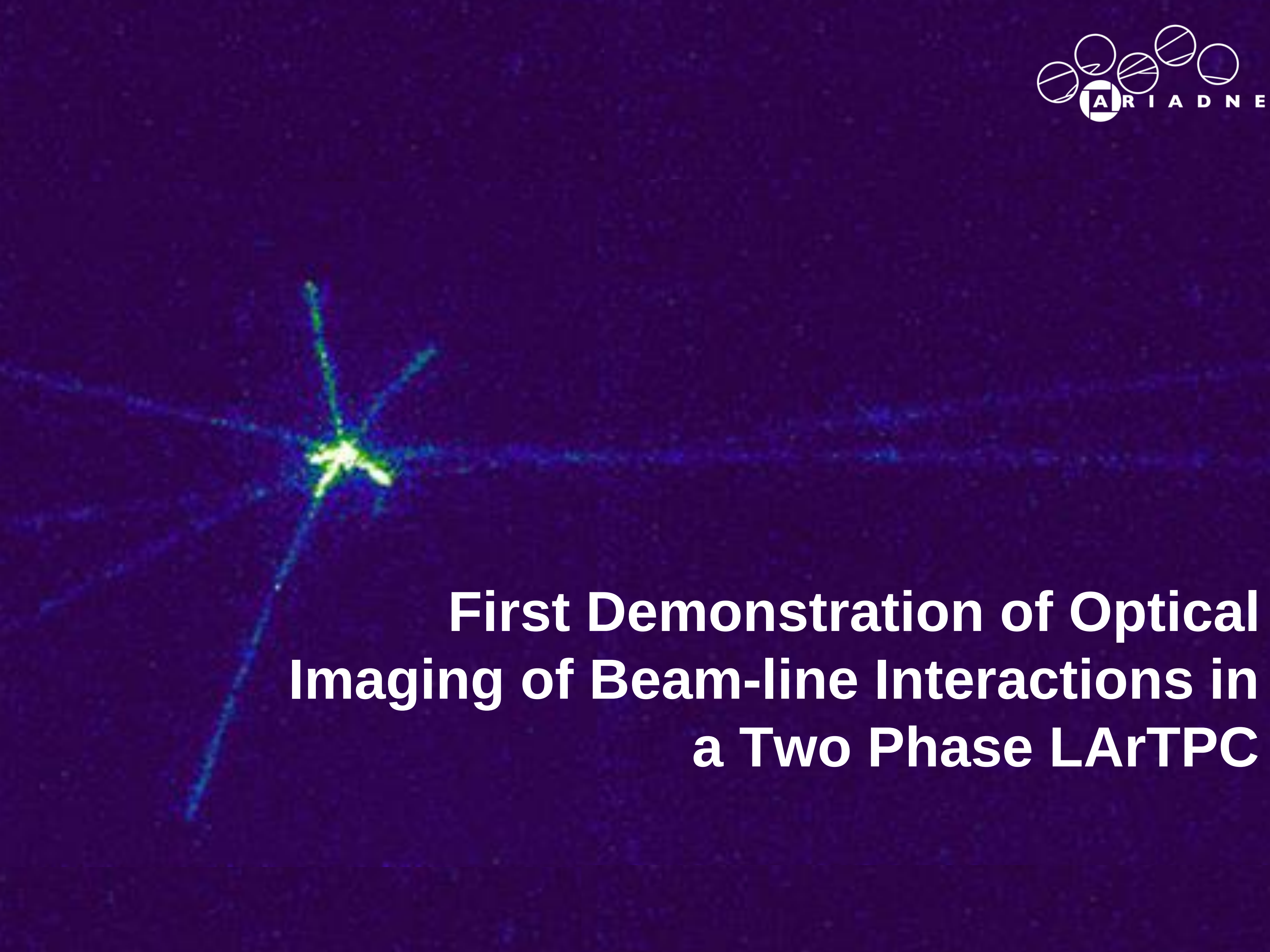
T9 Beam-line at CERN

ARIADNE at CERN

Run March/April 2018
Data collected: **0.5 GeV – 8 GeV:**
Mix of **$e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $p^{\pm}$**

400,000 events Negative Polarity
400,000 events Positive Polarity

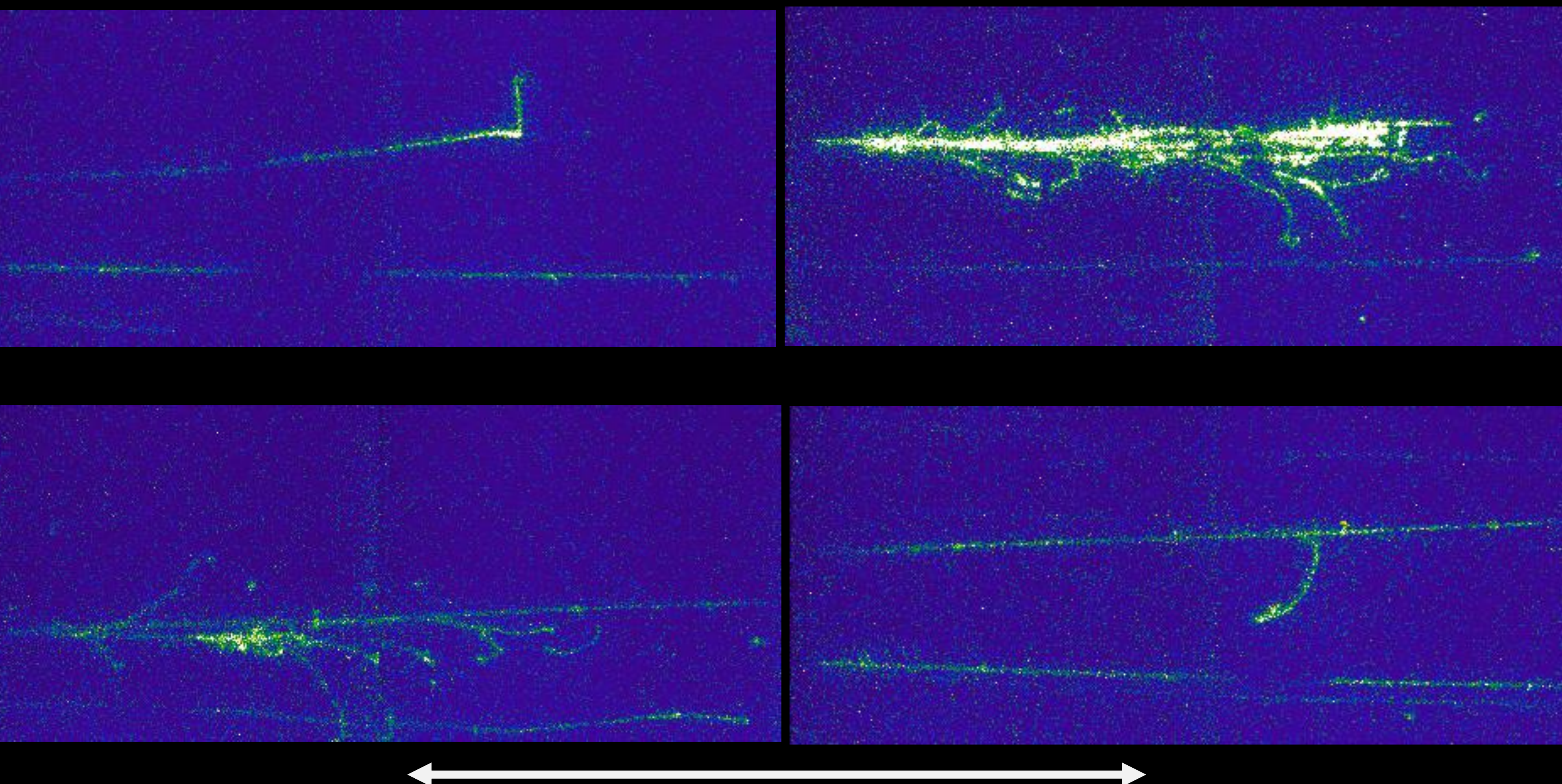




First Demonstration of Optical Imaging of Beam-line Interactions in a Two Phase LArTPC

Beamline Events

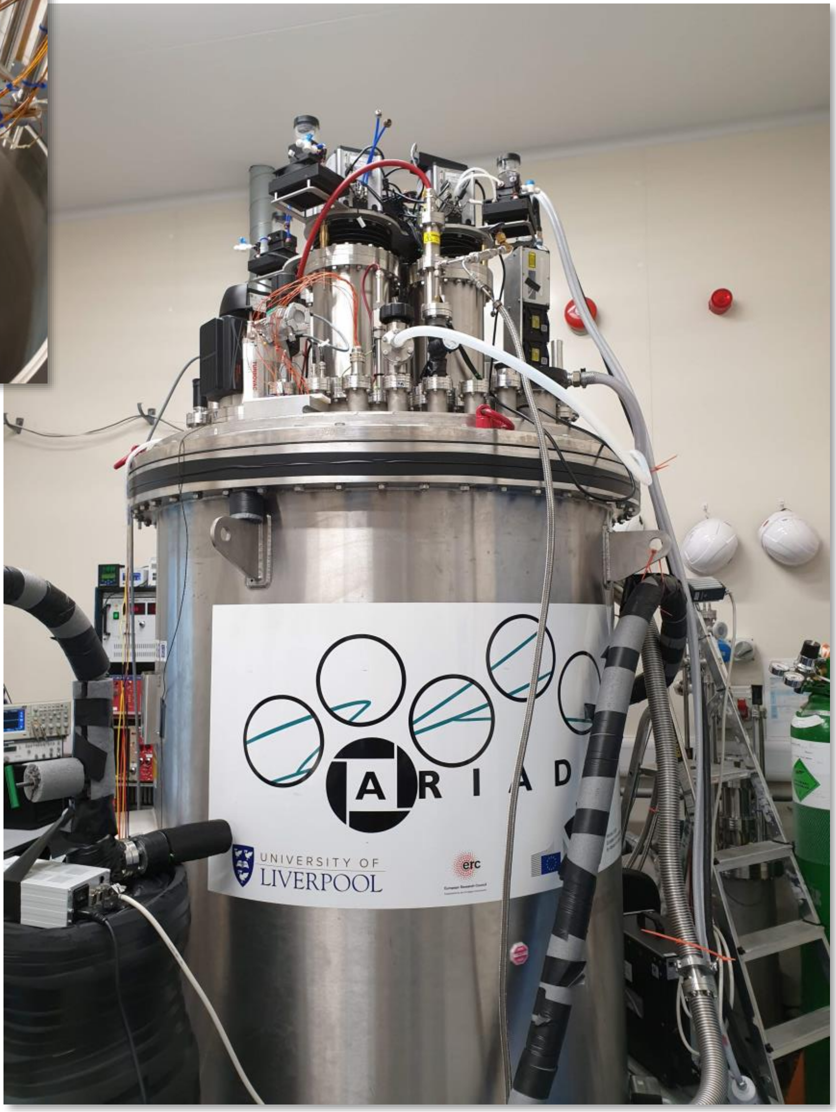
1.1mm / pixel resolution (4x4 bin)
(@Low THGEM gain 27 kV/cm)



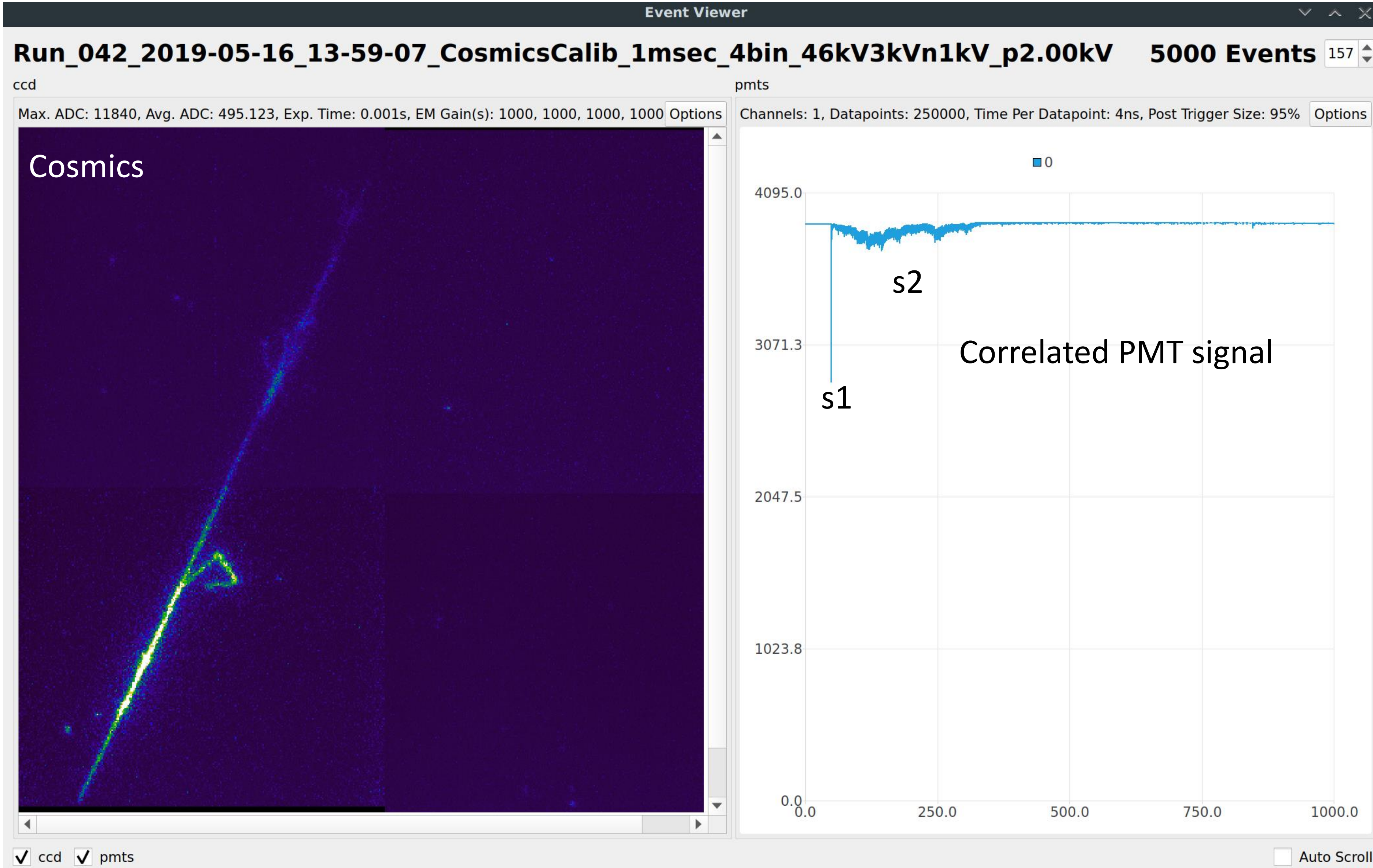
0.4m

ARIADNE upgrades at Liverpool

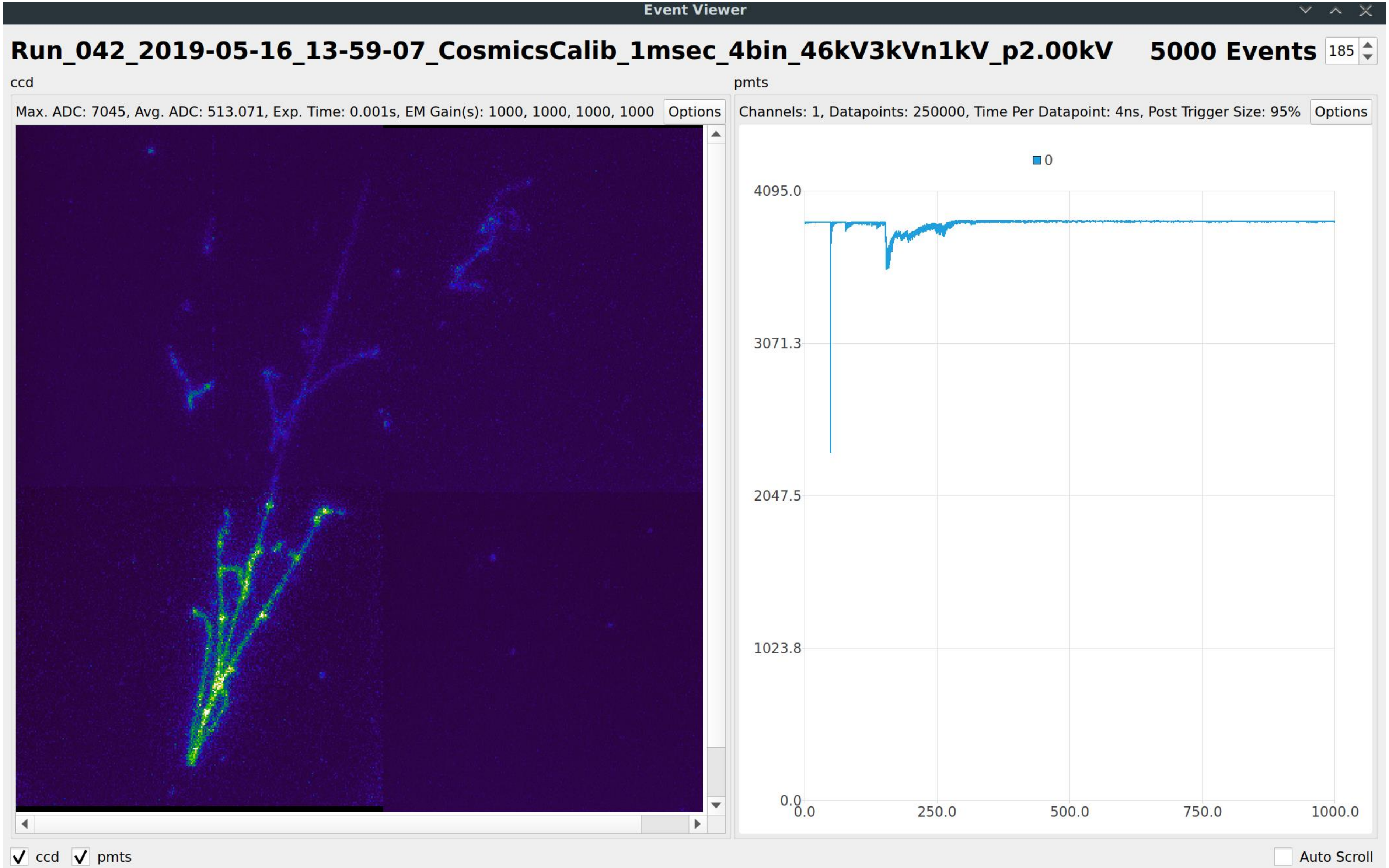
Back to Liverpool - New THGEM



EMCCD LAr run New Results

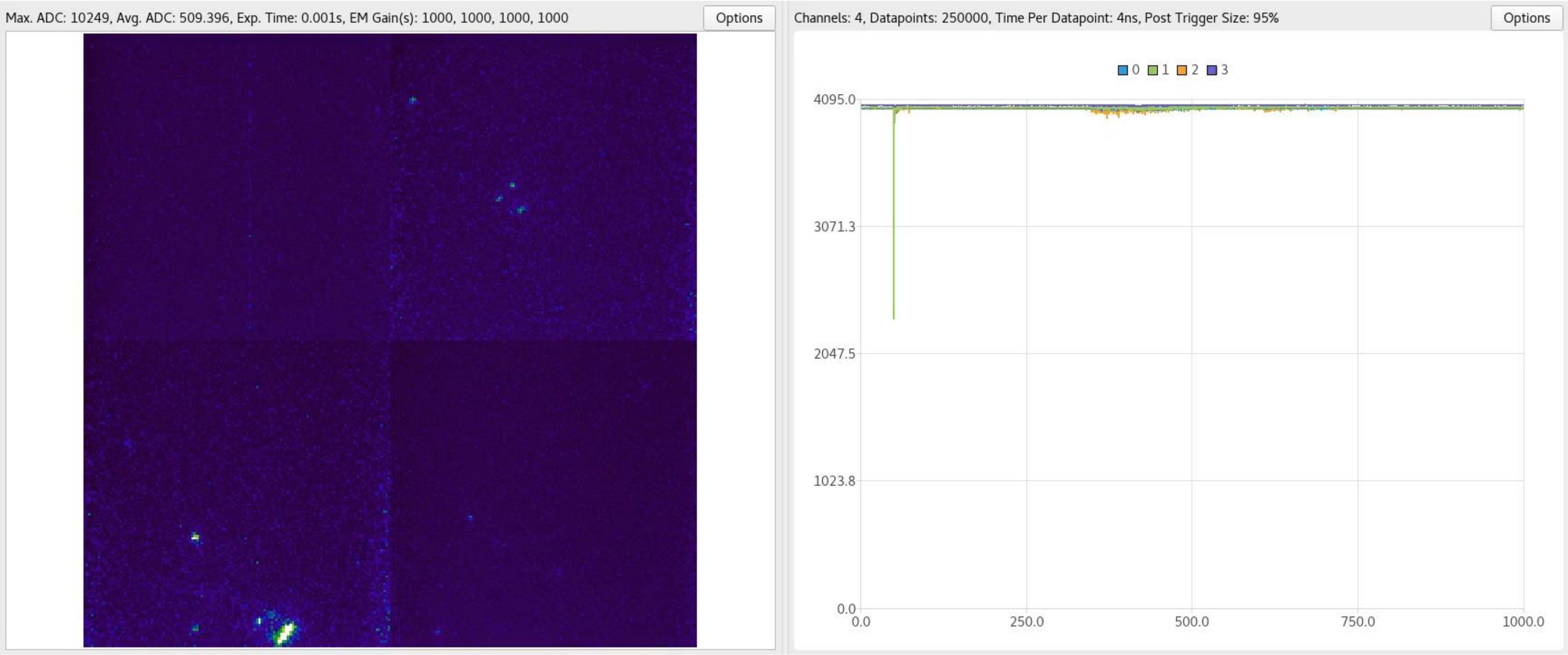


EMCCD LAr run New Results

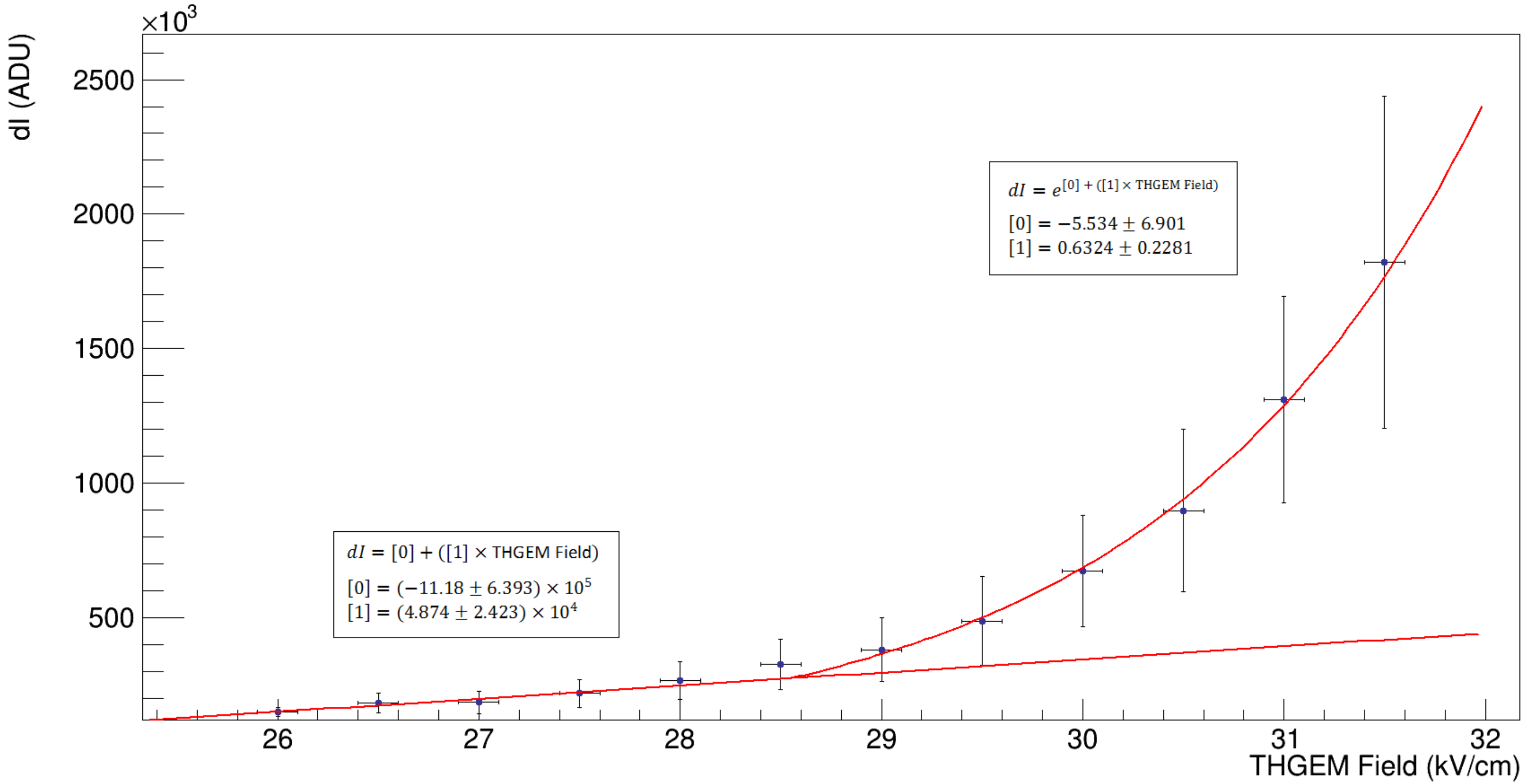


EMCCD LAr run New Results

Video: 1 msec exposure (raw data), 4x4 binning, PMT correlation

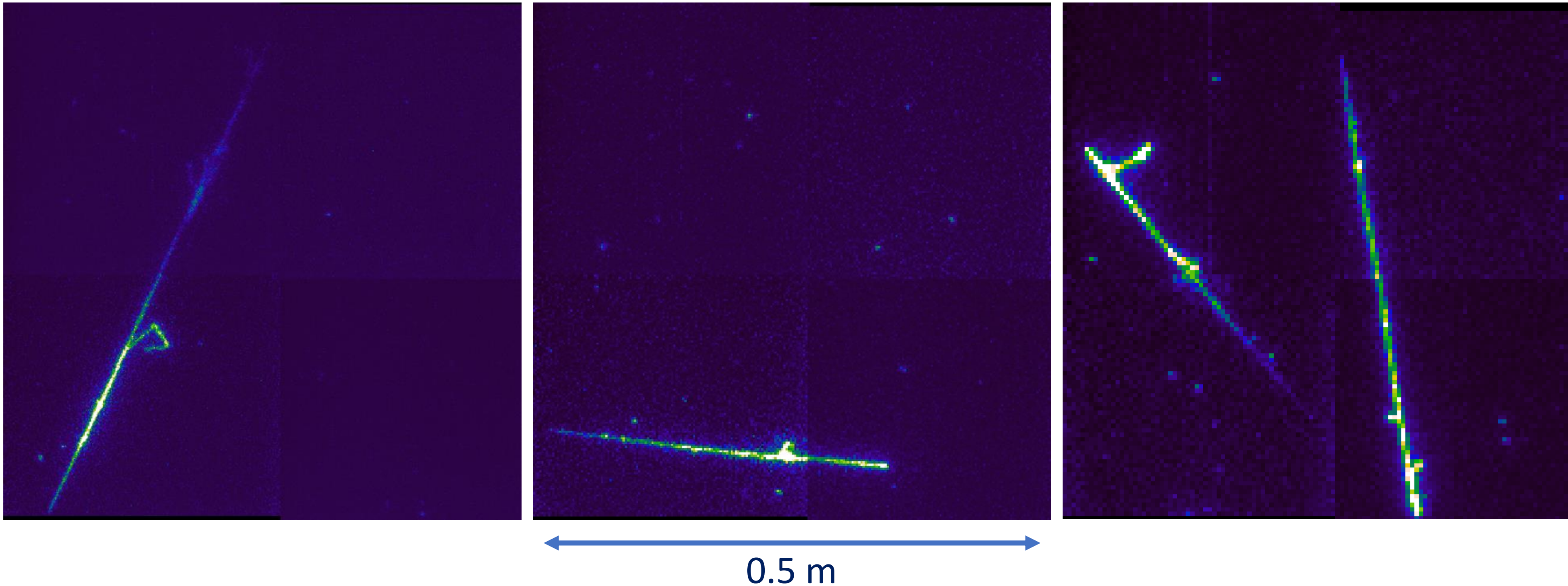


EMCCD Intensity vs THGEM Bias



Scanning THGEM bias -light sensitive at low THGEM bias

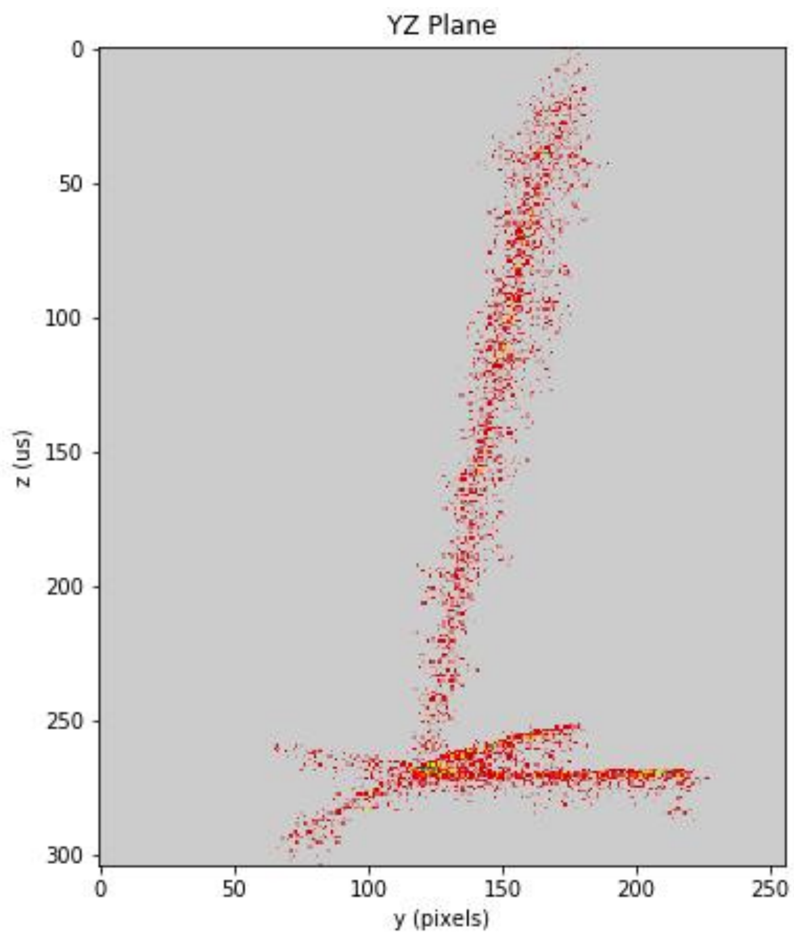
EMCCD Binning



4x4 (1.1mm/pix) **8x8** (2.2 mm/pix) **16x16** (4.4mm/pix)

- 16x16 binning = 4.4mm/pixel, for **kton scale** LArTPC detectors **resolution** will be limited by **electron diffusion** (~4.2mm over 12m drift).

(TPX3 currently collecting data)



ARIADNE: now a dream 3D optical TPC with TPX3 Camera

Demonstration of technology in CF_4 using prototype → **First demonstration of 3D optical readout of a TPC using a single photon sensitive Timepix3 based camera.** https://arxiv.org/abs/1810.09955

2D -> Full 3D Readout

EMCCD Limitations

- Great resolution and sensitivity, however acquisition rate of EMCCD sensors (~50Hz) is slow compared to the drift speed of LAr TPCs (~2mm/μs)
- Can only provide flattened 2D representation of event geometries
- Z-axis can be calculated from timing information from S1 and S2 signals from PMTs - however only possible for simple track geometries and in low-pile up situations as correlation is challenging

The MUCH faster TPX3 readout can give full 3D readout!

(whilst still having the sensitivity of EMCCDs)

First demonstration of 3D optical readout of a TPC using a single photon sensitive Timepix3 based camera (https://arxiv.org/abs/1810.09955)

2D -> Full 3D Readout

Silicon pixel readout chip developed by the Medipix collaboration. **Very well established** technology at CERN.

Simultaneous 10 bit Time over Threshold (ToT) and 18 bit Time of Arrival (ToA).

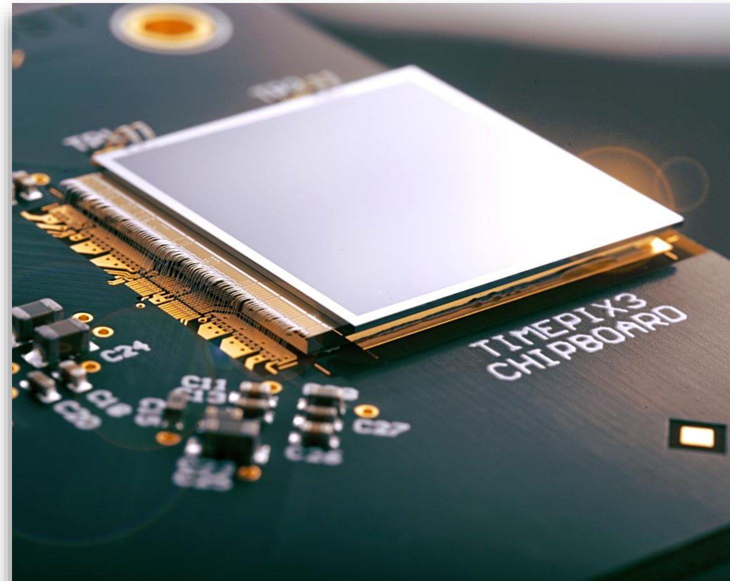
ToT allows accurate calorimetry measurements.

ToA accurate timing and 3D reconstruction.

"Data driven readout": pixels read out asynchronously, allows very efficient sparse readout.

Possible to have continuous trigger-free readout.

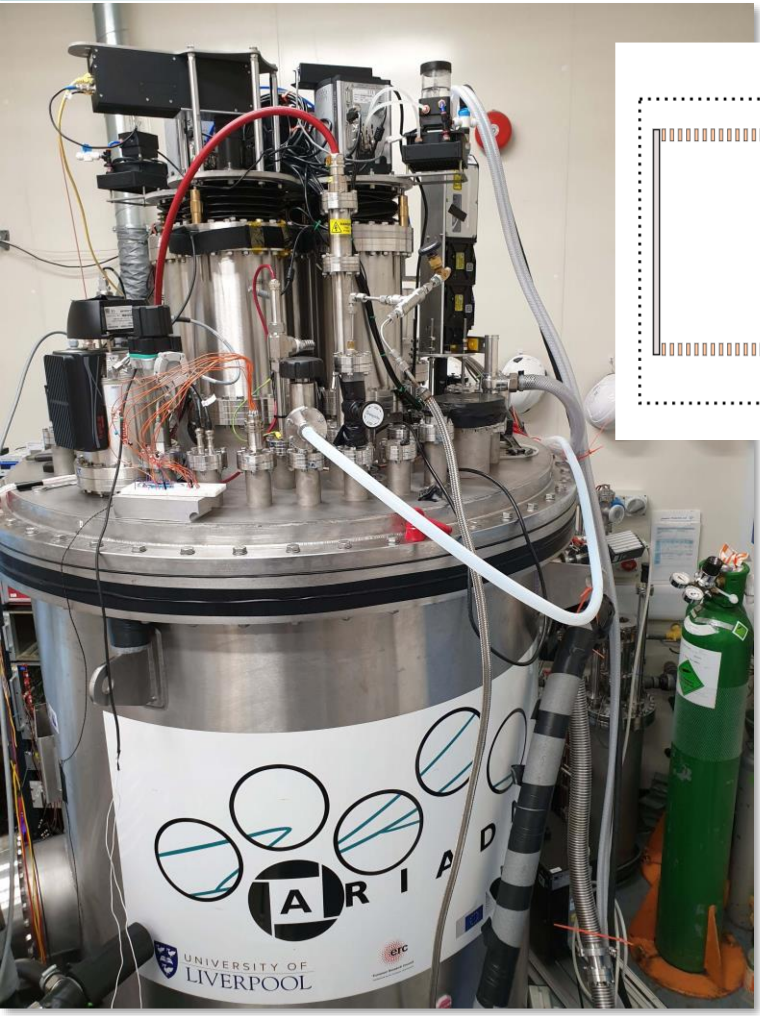
Until recently only used to measure deposited charge, now also light [1].



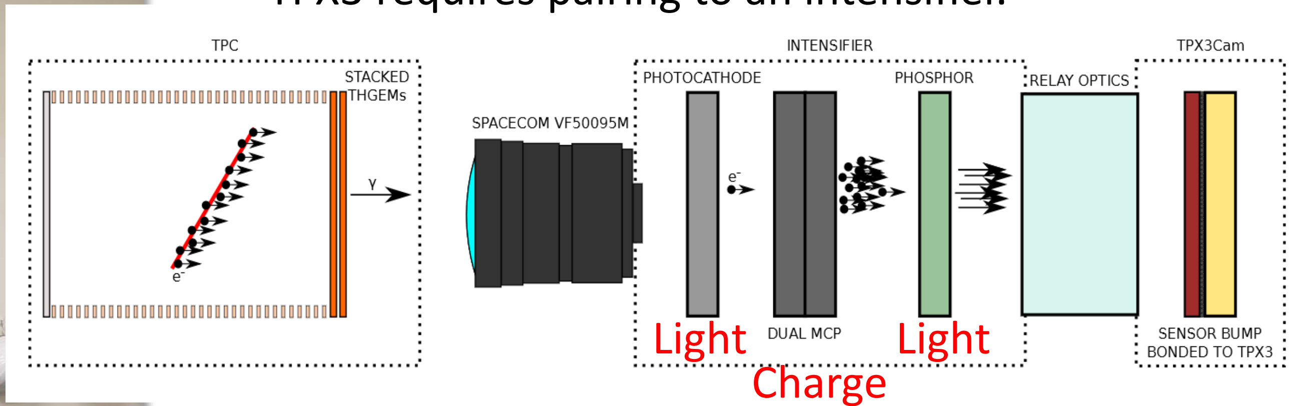
Sensor resolution	256x256 pixels
Pixel size	55µm x 55µm
Max readout rate	40Mhits•cm^{-2} •sec^{-1}
Time resolution	1.6 ns

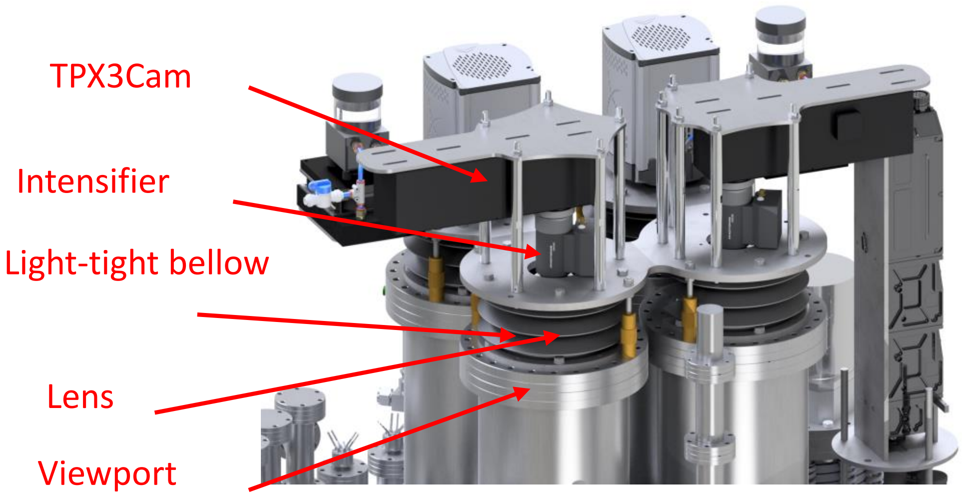
[1] M. Fisher-Levine, A. Nomerotski, Timepixcam: *a fast optical imager with time-stamping*, Journal of Instrumentation 11 (03) (2016) C03016.

TPX3Cam on ARIADNE



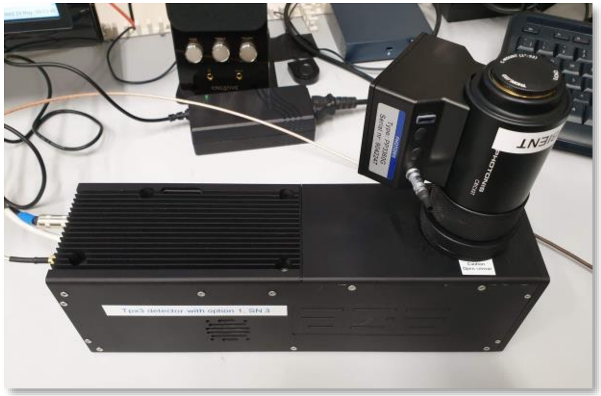
- TPX3 requires pairing to an intensifier.





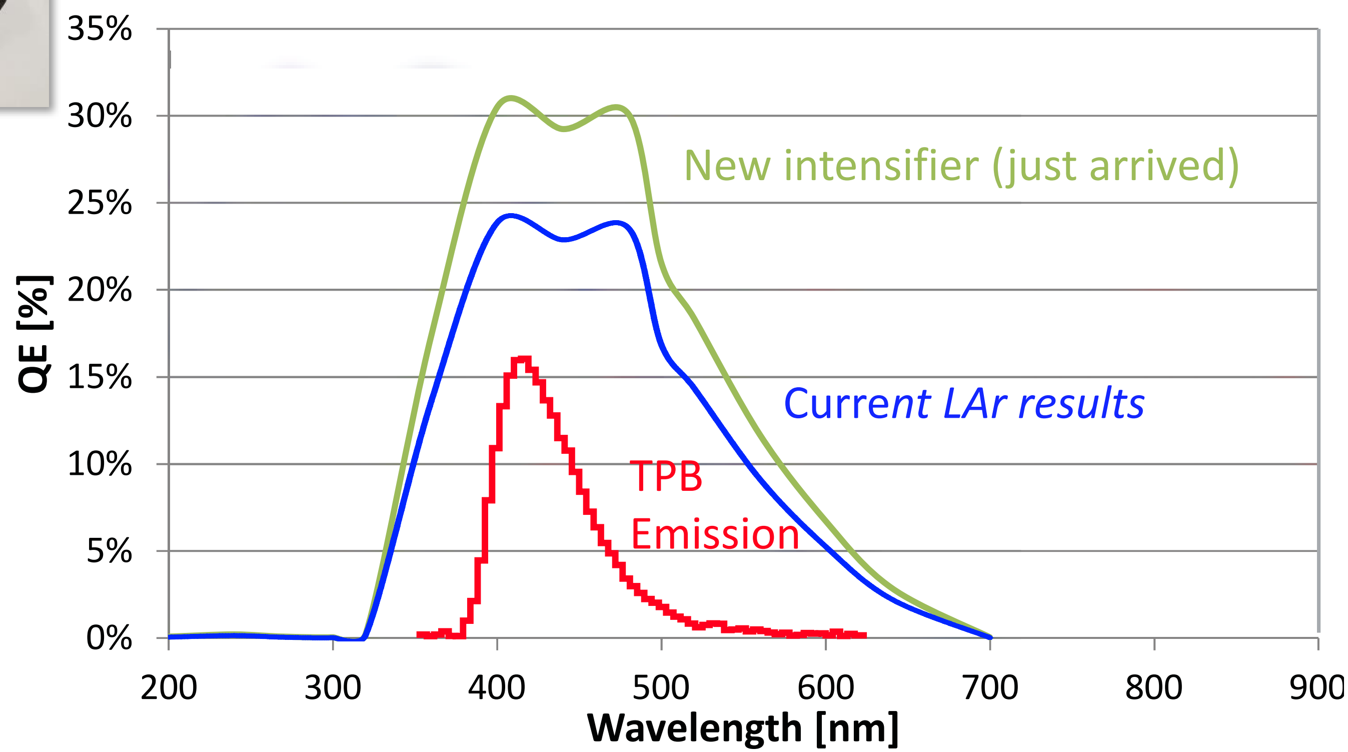
- One EMCCD replaced with TPX3Cam
- Second intensifier to arrive soon

Intensifier Specs



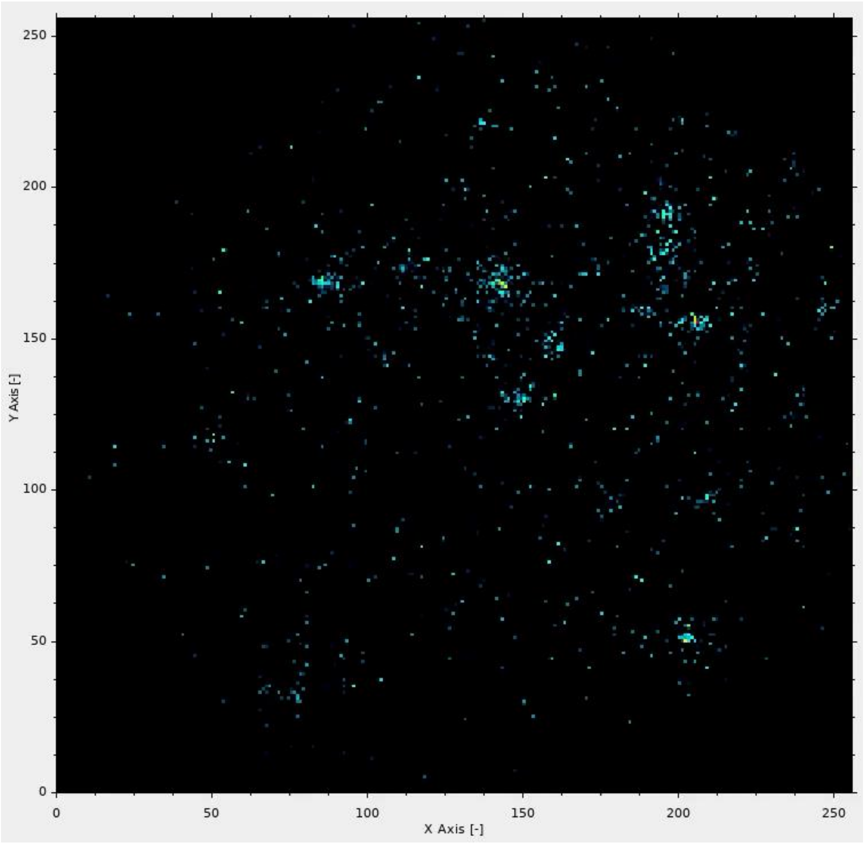
Collaborating with DESY for TPX3Cams (Jochen Kuepper et. al)

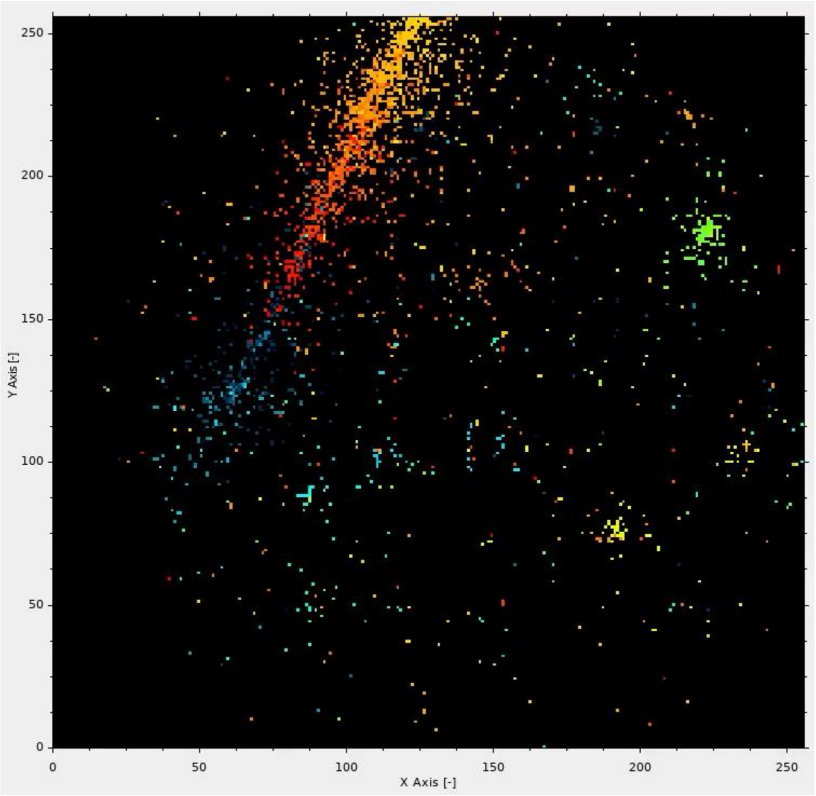
Current intensifier output brightness : 0.5 cd/m^2
Final output brightness (typ) : 3.0 cd/m^2



https://arxiv.org/abs/1104.3259

TPX3Cam LAr Results



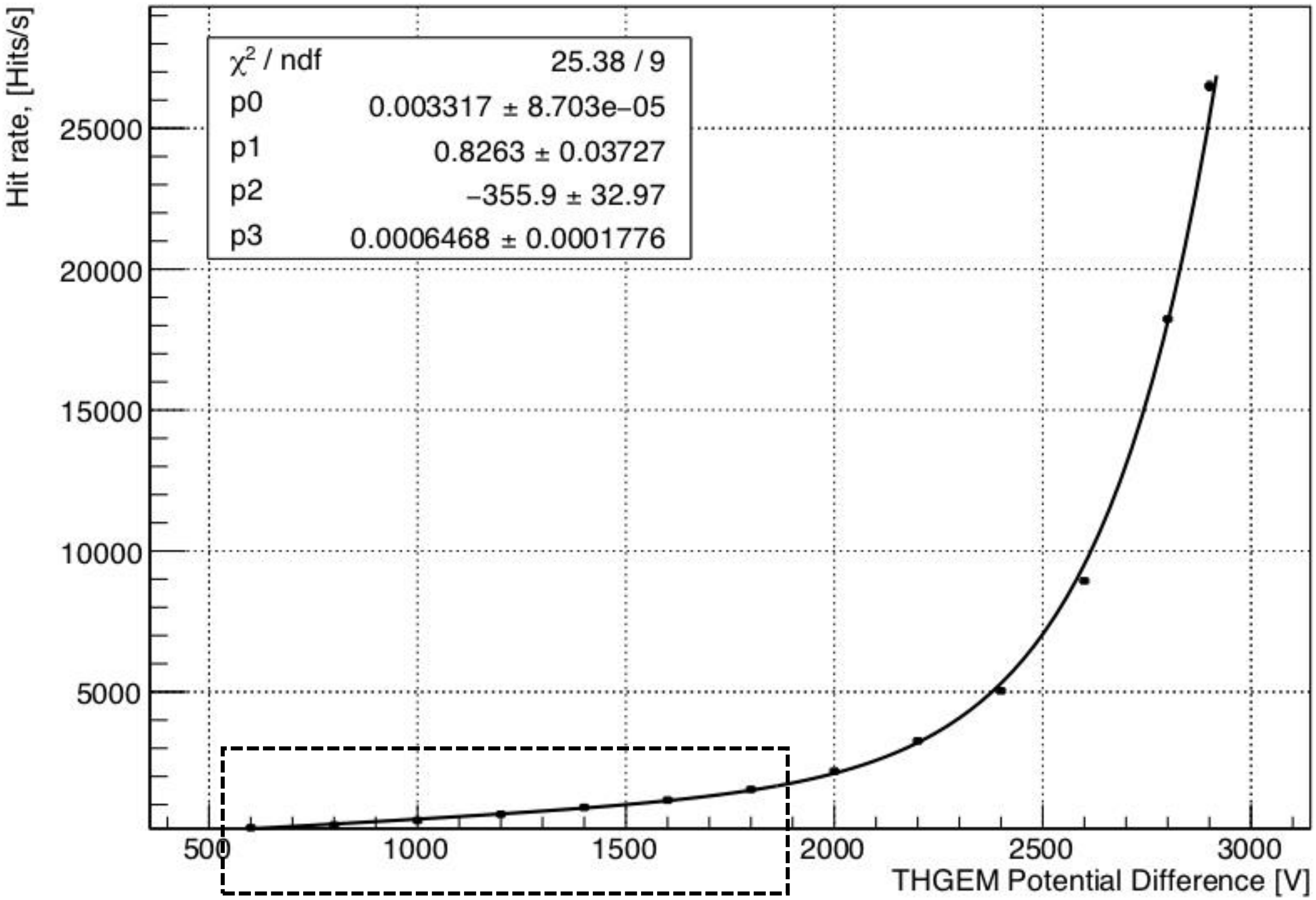


Video: ToT 100 msec

Video: ToA 50 msec

- **Lower energy background gammas are also visible**
- **This low energy threshold is very useful for supernova studies**
- **Resolution is similar to 4x4 binning on the EMCCD ie 1.1mm/pixel**

TPX3Cam LAr Results

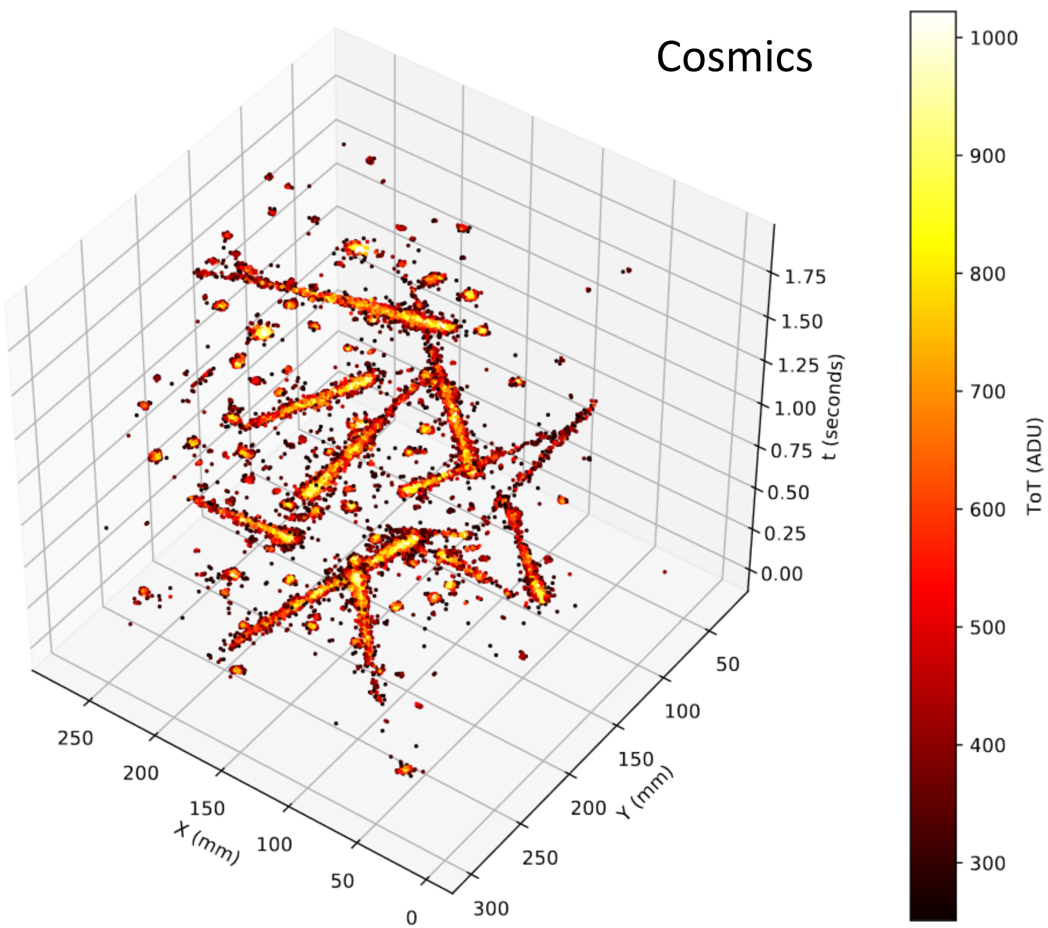


Sensitive to electroluminescence light -ie no charge multiplication in THGEM, solving issues with good performance that was necessary before in order to amplify enough the signal

TPX3Cam LAr Results

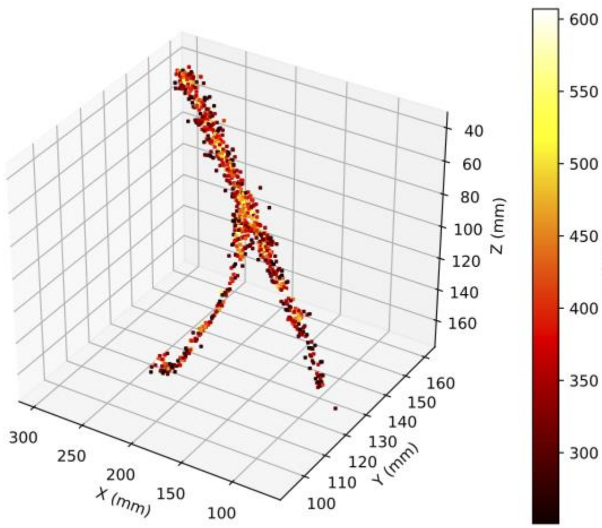
- 1.75 sec streaming (ie equivalent to 3km drift)

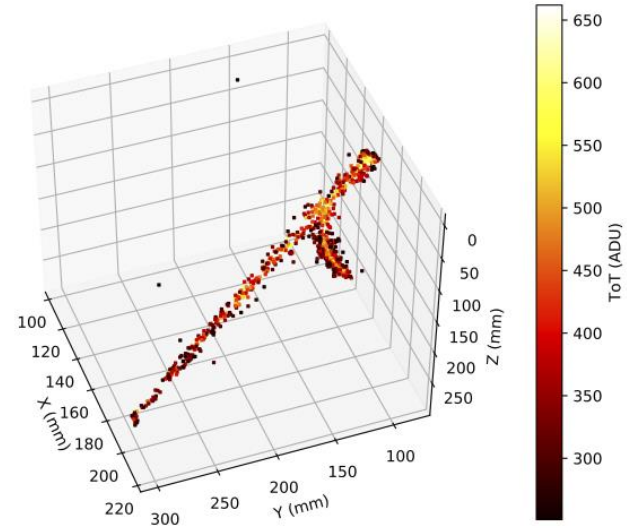
[Nominal drift velocity is 0.16 cm/µsec for 0.5kV/cm]

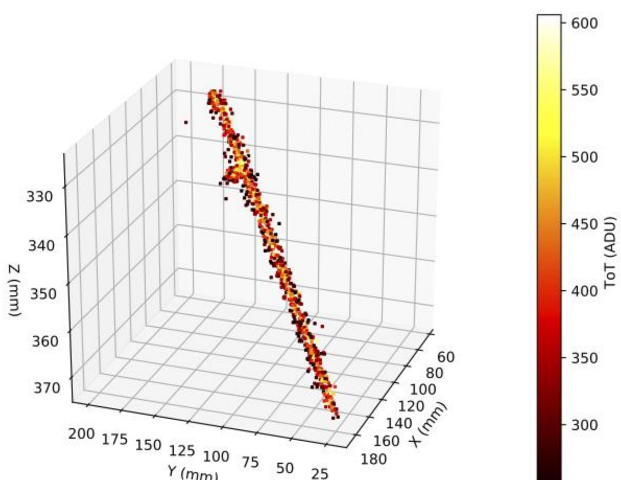


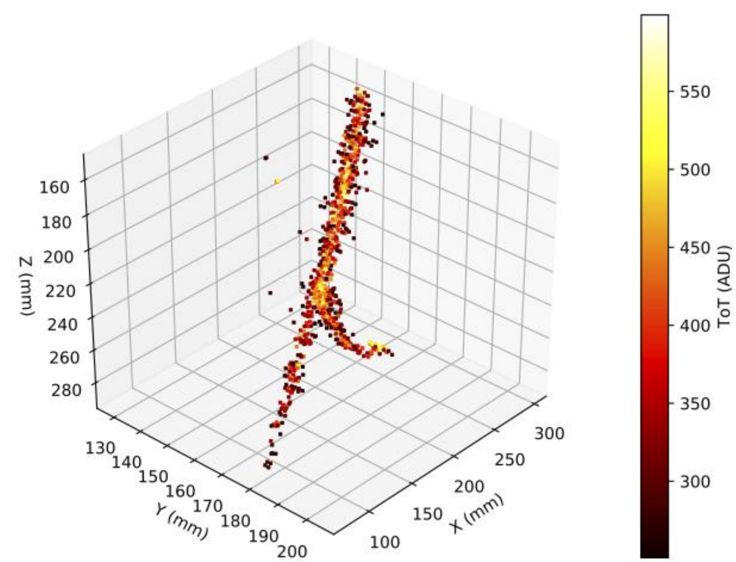
TPX3Cam 3D Cosmics LAr

~100µsec drift window, about 20cm tracks





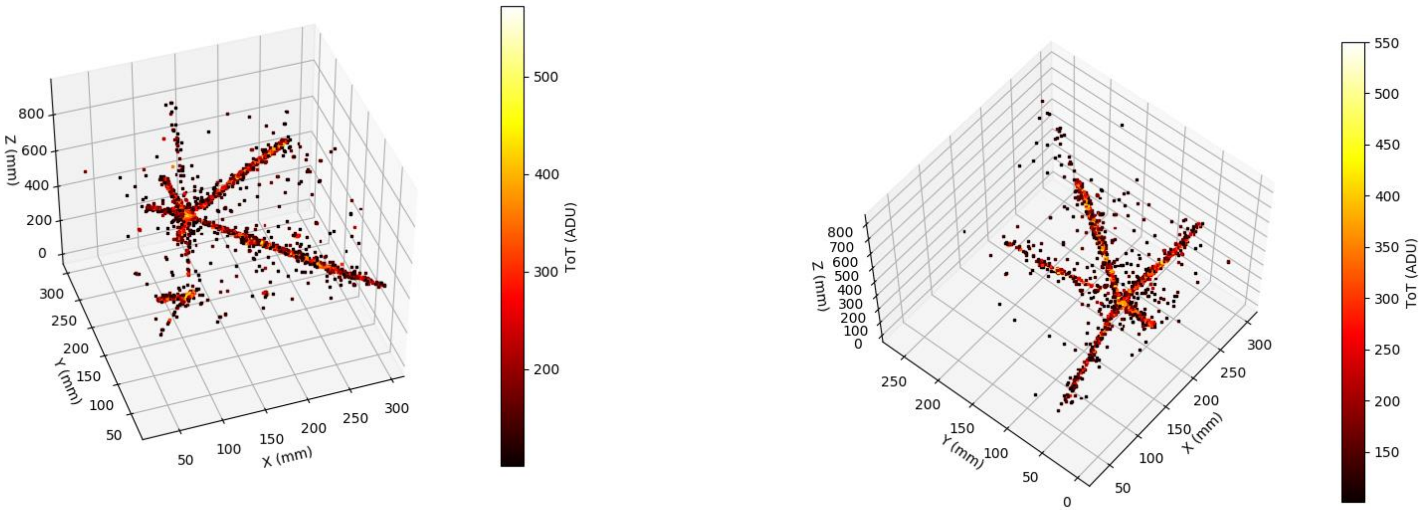




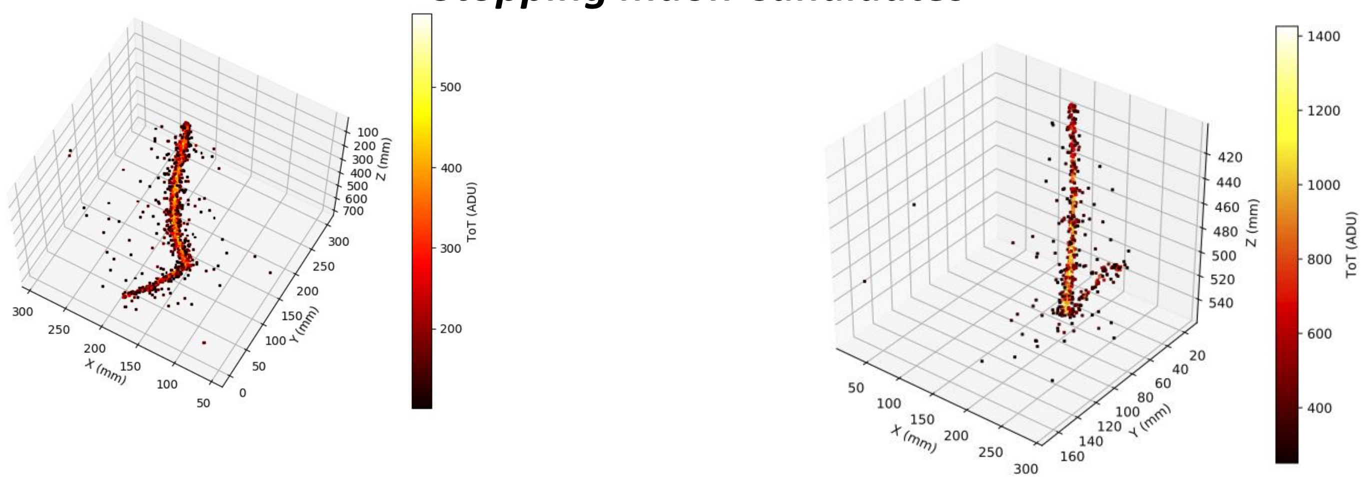
TPX3Cam 3D Cosmics LAr

~100µsec drift window, about 20cm tracks

Antiproton Candidates



Stopping muon Candidates

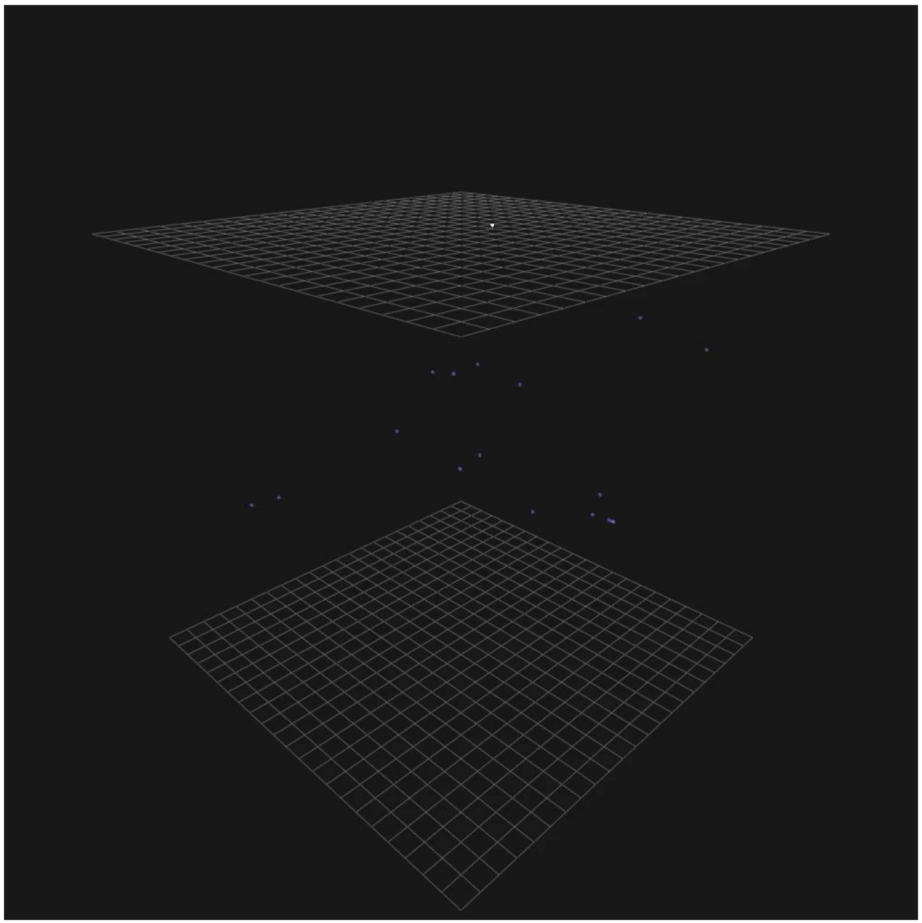


TPX3Cam 3D Cosmics LAr

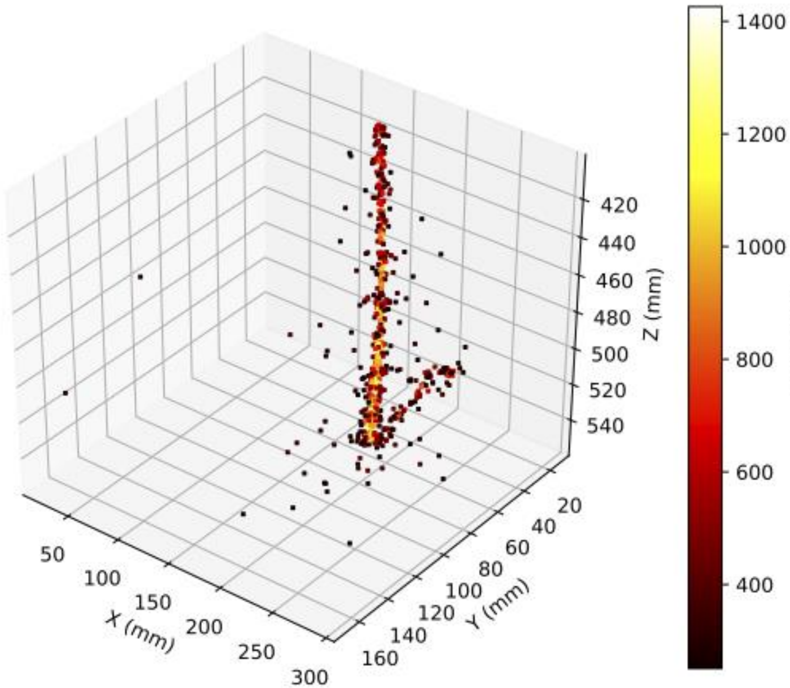
Continuous streaming, 10 msec slice (playing 1ms jump per frame**)**

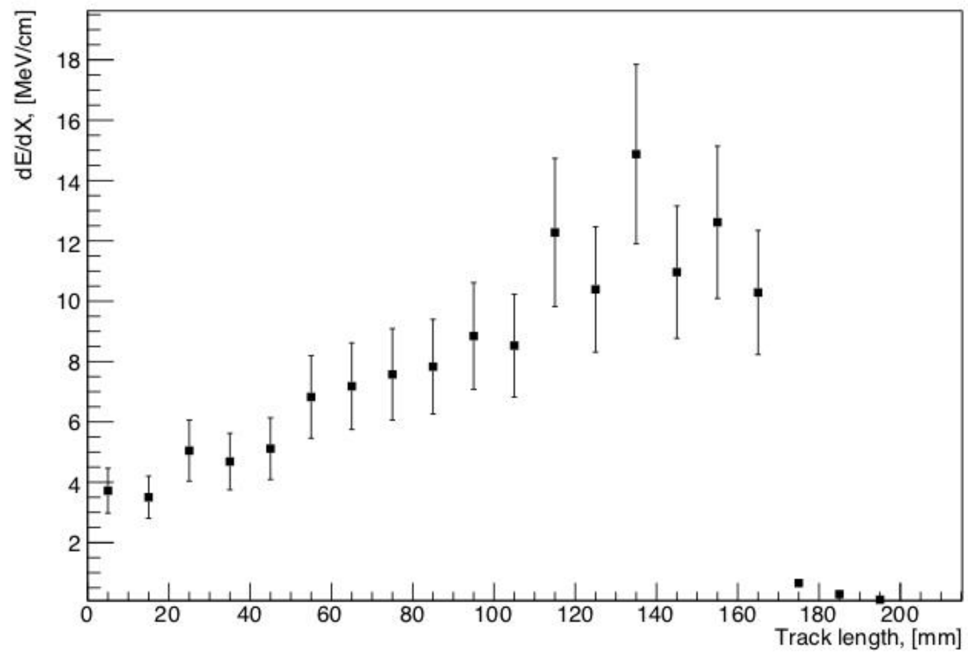
Top View

Side View



Stopping Muon & dE/dx





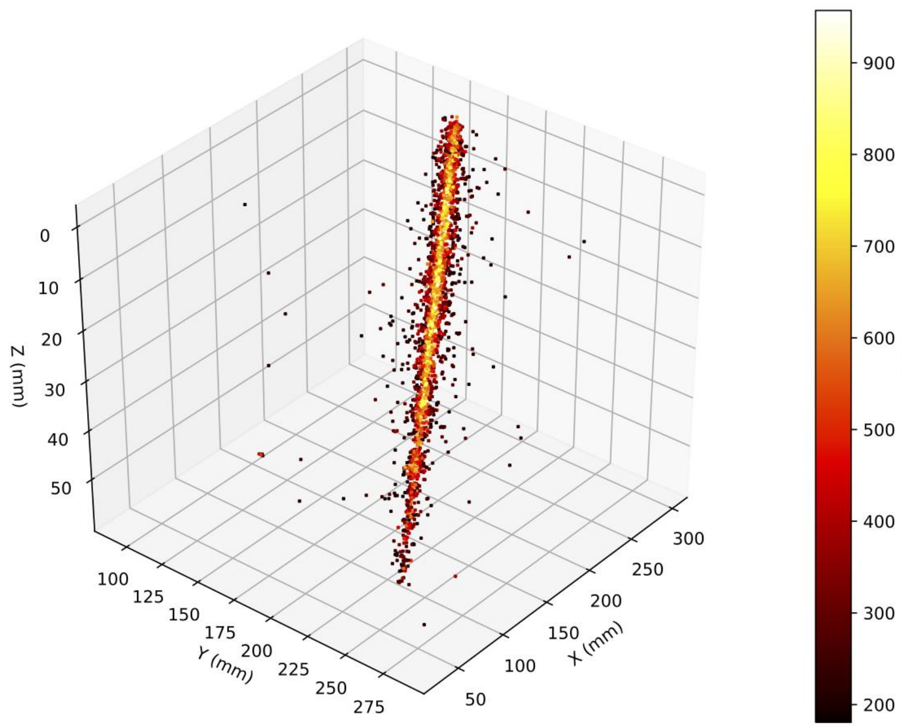
Stopping muon candidate

Energy profile of the left stopping muon even

- Ongoing analysis with more statistics

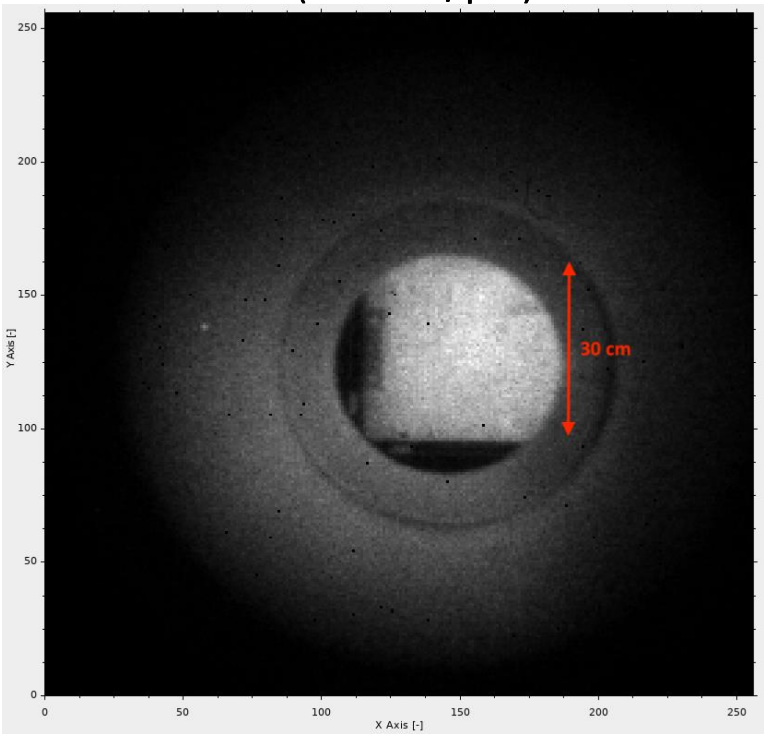
TPX3Cam TPC Benefits

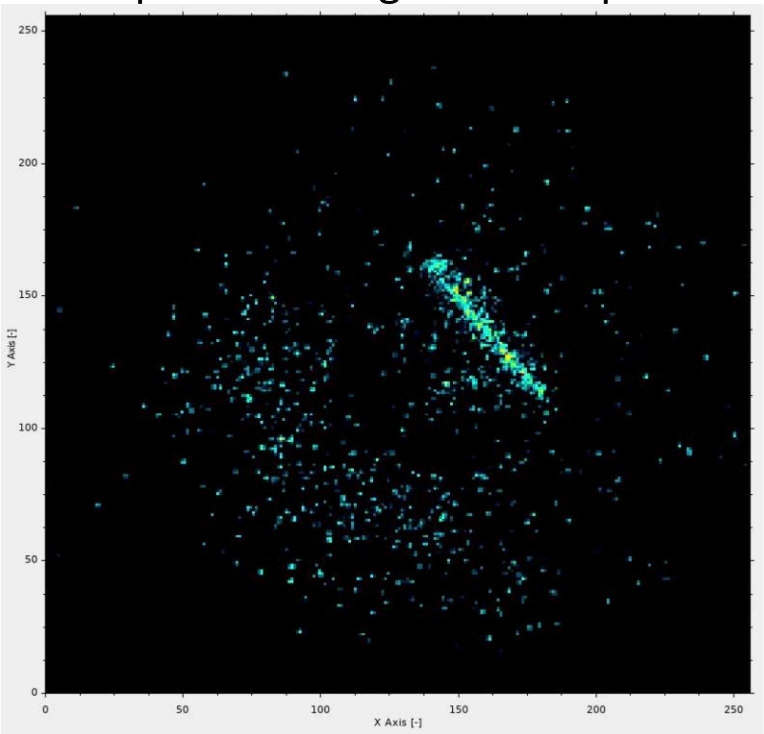
- Raw data is natively 3D. Just need to convert ToA to z position using known drift velocity in the TPC (drift velocity in LAr is 0.0016 mm/ns). x,y pixel number to mm using the know field of view of the lens.
- Huge readout rates are possible (80MHits/s)
- Zero suppressed readout comes for free
- Physics sensor (Timepix) being used for a Physics application
- Lower cost than other readout methods is possible with some R&D
- Same readout is possible for two phase or gas TPCs



Determining max field of view/sensitivity for one TPX3cam

For sacrificed resol. (4.5mm/pix) the camera was capable to image 1.2m^2 equivalent area on ARIAD





Left: Field of view seen when using the 11.5mm focal length lens (F/1.4). The 30cm x 30cm area that is visible of the THGEM only takes up roughly 1/4 of the total sensor area. The total field of view is approximately 1.2mx1.2m. The resolution is 4.5mm per pixel in x and y.

Right: A single cosmic muon seen in Time over threshold mode. The muon passes across most of the 30 cm length of the THGEM that is visible.

TPX3Cam at Larger Scale

Technology/performance is superb, Cost is of course important.

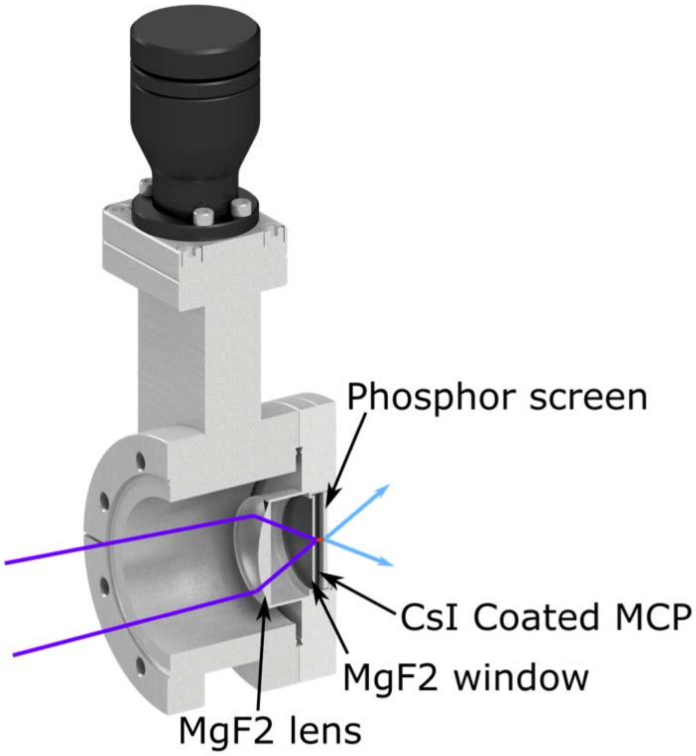
Table: As an example, demonstration figures for use of TimePix within Dune - 720m^2, 60m x 12m

Camera type	Sen. Size (pixels)	Cameras to cover 1m^2	Resolution (mm/pix)	Total cameras (to cover 720m^2)	Total cost (assuming €5k /camera*)
TPX3	256x256	9	1.3 (~ARIADNE)	6480	32.4M
TPX3	256x256	4	2	2880	14.4M
TPX3	256x256	1	4	720	3.6M
TPX4	512x512	4	1	2880	14.4M
TPX4	512x512	1	2	720	3.6M
TPX4	512x512	<1	3	530	2.65M

* Cost is a place holder assumes large production and optimized optics

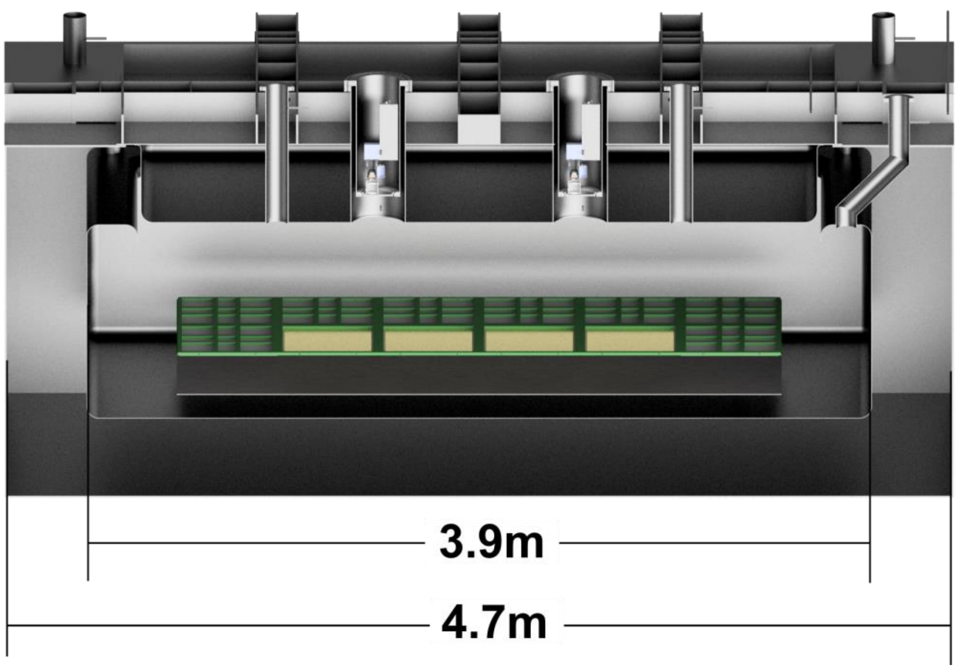
ARIADNE – Next steps

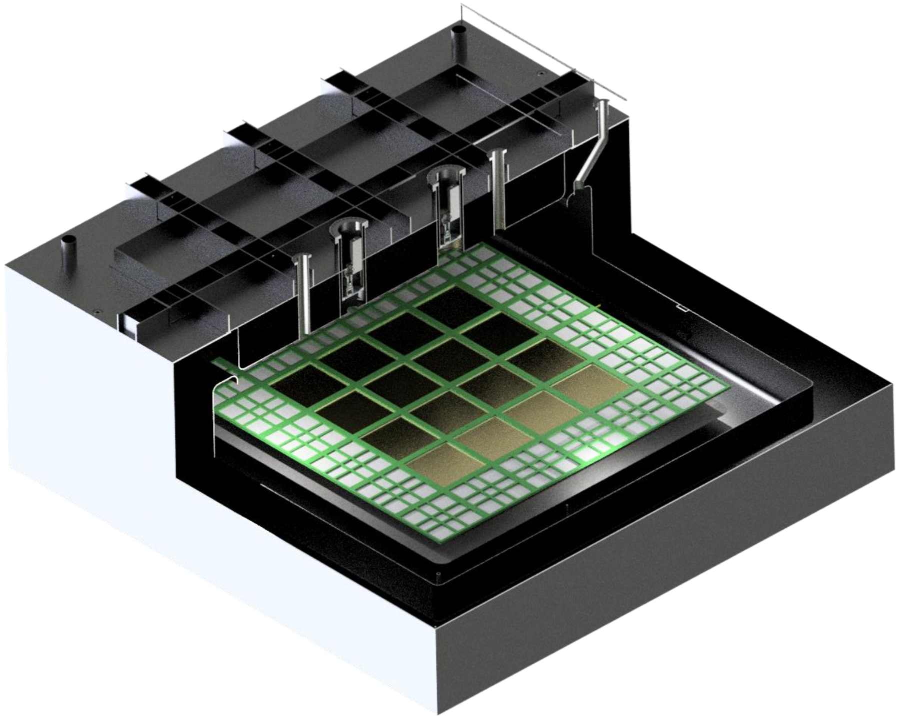
- Further optimisations ongoing/planned,
  - Plans to test a VUV sensitive intensifier to remove the need of TPB
  - Further in the future bring the cost even lower by alternatives to intensifiers



ARIADNE – Next steps

- Collaboration within the Neutrino platform framework to use this technology on a bigger system and take it further
  - If you want to get involved we are open to collaboration





The A.-Team

Thank you!

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

Extra Slides

TPX3 Specifications

	Timepix3
Pixel matrix	256 x 256
Pixel size	55 x 55 μm^2
Technology	CMOS 130 nm
Measurement modes	• Simultaneous 10 bit TOT and 14 + 4 bit TOA • 14 + 4 bit TOA only • 10 bit PC and 14 bit integral TOT
Readout type	• Data driven • Frame based (both modes with zero suppression)
Dead time (pixel, data driven)	>475 ns (pulse processing + packet transfer)
Output bandwidth	40 Mbits/s – 5.12 Gbits/s
Maximum count rate	0.4 Mhits/mm²/s (data driven mode)
TOA Precision *	1.56 ns
Front end noise	60e- RMS
Minimum threshold	~500 e-

≈ 1mm in LAr

TPX3 Specifications

Timepix3 → Timepix4

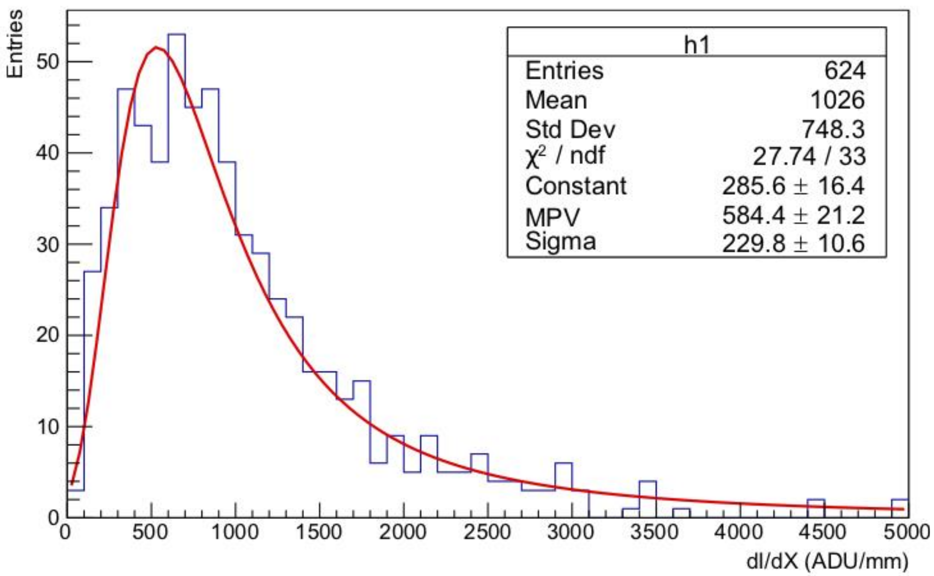
		Timepix3	Timepix4
Technology		IBM 130nm	TSMC 65nm
Pixel Size		55 x 55 μm	≤ 55 x 55 μm
Pixel arrangement		3-side buttable 256 x 256	4-side buttable 256 x 256 or bigger
Operating Modes	Data driven	PC (10-bit) and TOT (14-bit)	CRW: PC and iTOT (12...16-bit)
	Frame based	TOT and TOA	
Zero-Suppressed Readout	Data driven	< 80 MHits/s	< 500 MHits/s
	Frame based	YES	YES
TOT energy resolution		< 2KeV	< **1Kev**
Time resolution		1.56ns	**~200ps**
Readout bandwidth		5.12Gb (8x SLVS@640 Gbps)	20.48 Gbps (4x 5.12 Gbps)
Front-end		"with" Volcano	No volcano → Dynamic gain But supply only 1.2V

Higher x,y resolution (or cover more area with one camera)

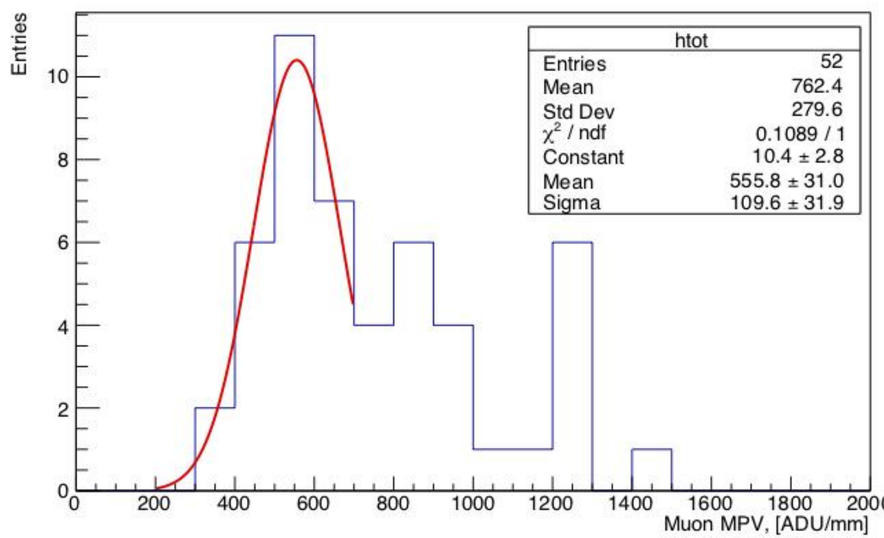
Faster readout rates

Improved calorimetry

Energy Calibration



Sample distribution of summed hit intensities for 1 mm slices of a cosmic muon track.

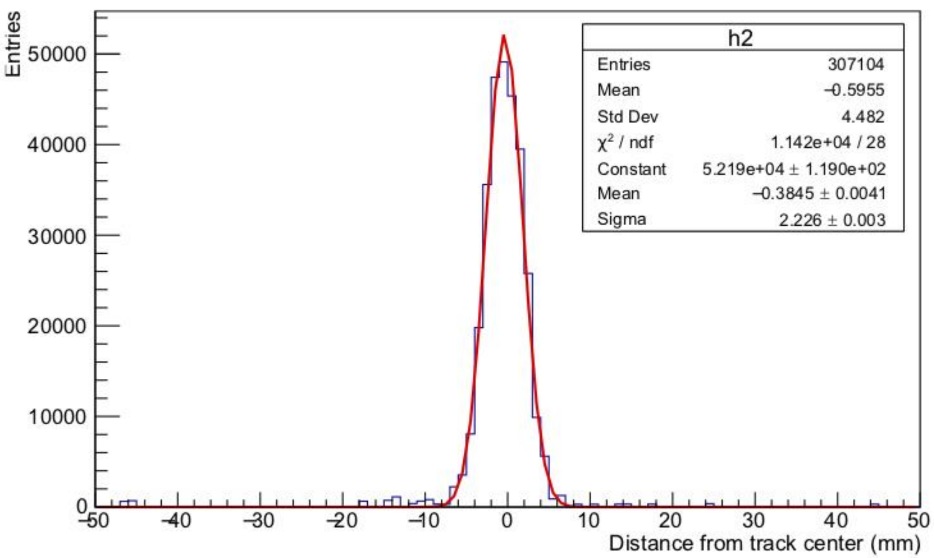


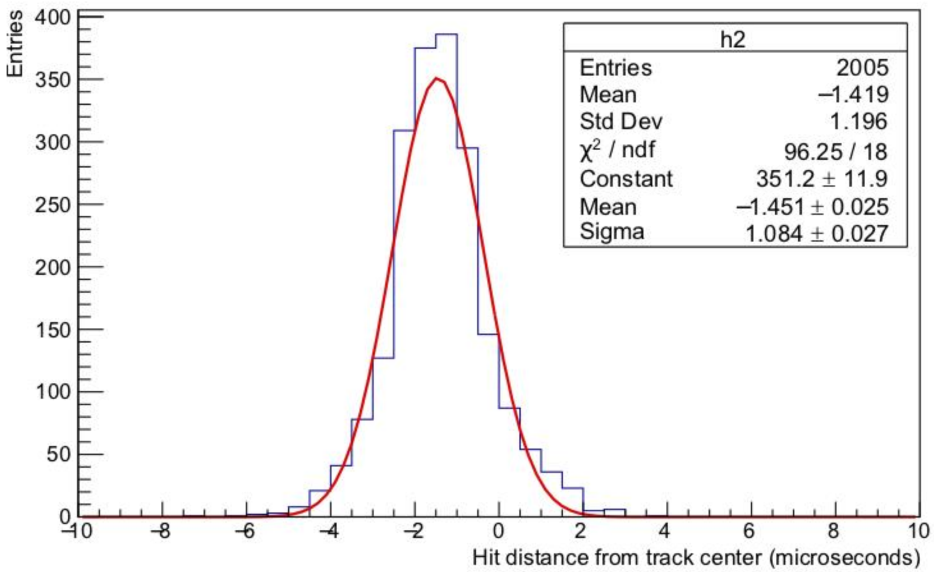
Distribution of MPV values for well fitted cosmic muon samples. Gaussian peak corresponds to the expected muon MPV energy loss of 1.6 MeV/cm.

Track position resolution

x - y pixel hits from the track centre (>300 ADU)

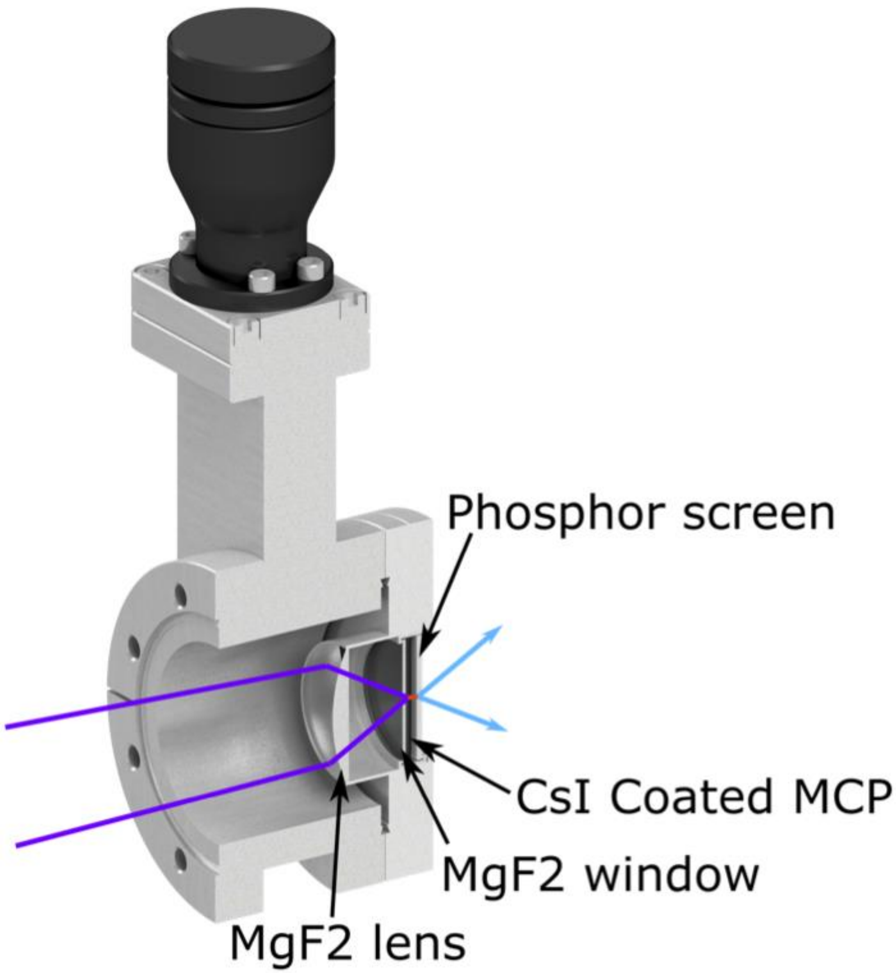
Hit timings in the z axis, relative to the centre of the fitted track.





TPX3Cam Next R&D Steps

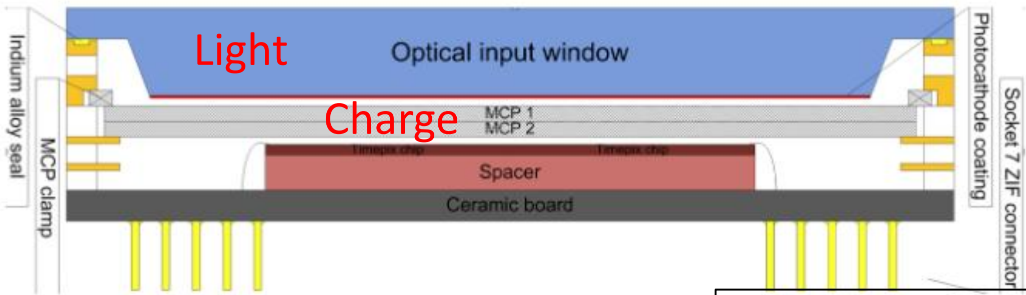
Eliminating TPB, conceptual direct VUV imaging setup



TPX3Cam Next R&D Steps

Future optical TPX R&D and bringing the cost down...

- Need to move away from intensifier (~16k euro)
- Integrate TPX3/4 into a Photonis Planacon 1 inch tube



1 inch Planacon

Something similar has already been made with TPX2 (quad) and It worked beautifully [2]

Not yet been done with TPX3 or TPX4 so we never had simultaneous ToA & ToT in such a device

Many physics applications, similar devices used for RICH (LHCb)

Quad Planacon:

[2] http://iopscience.iop.org/article/10.1088/1748-0221/9/05/C05055/pdf

Benefits of direct integration into Planacon:

- No longer need a Phosphor screen – phosphor screen degrades timing performance and adds cost/complexity
- Compact – Entire TPX + intensifier package fits in the palm of your hand (1 inch x 1 inch tube)
- Lower cost – eliminated phosphor and entire device can be manufactured in a proven / already existing factory.

Extra – Geant4 Energy Containment