High Pressure Time Projection Chambers for Neutrino Physics

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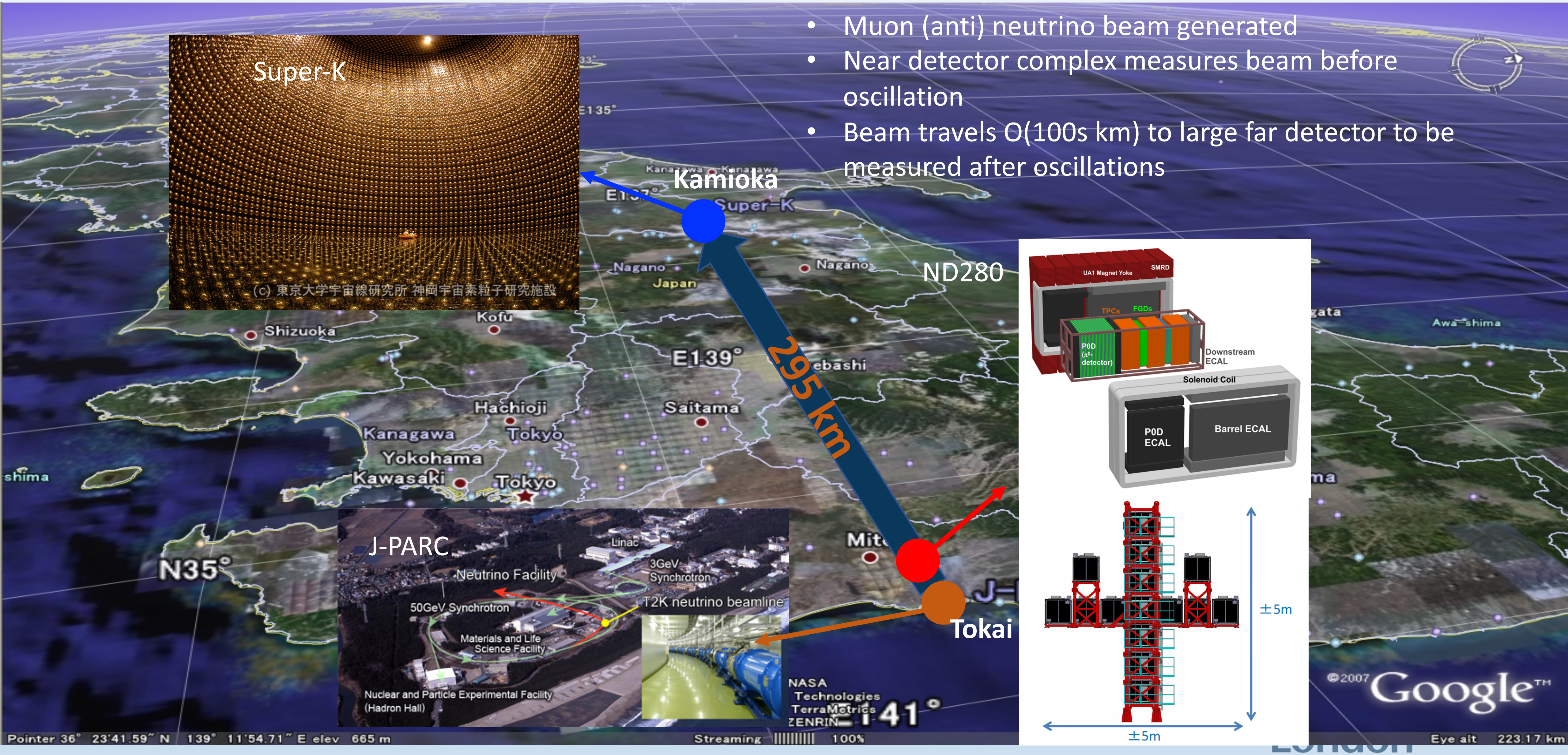
Introduction

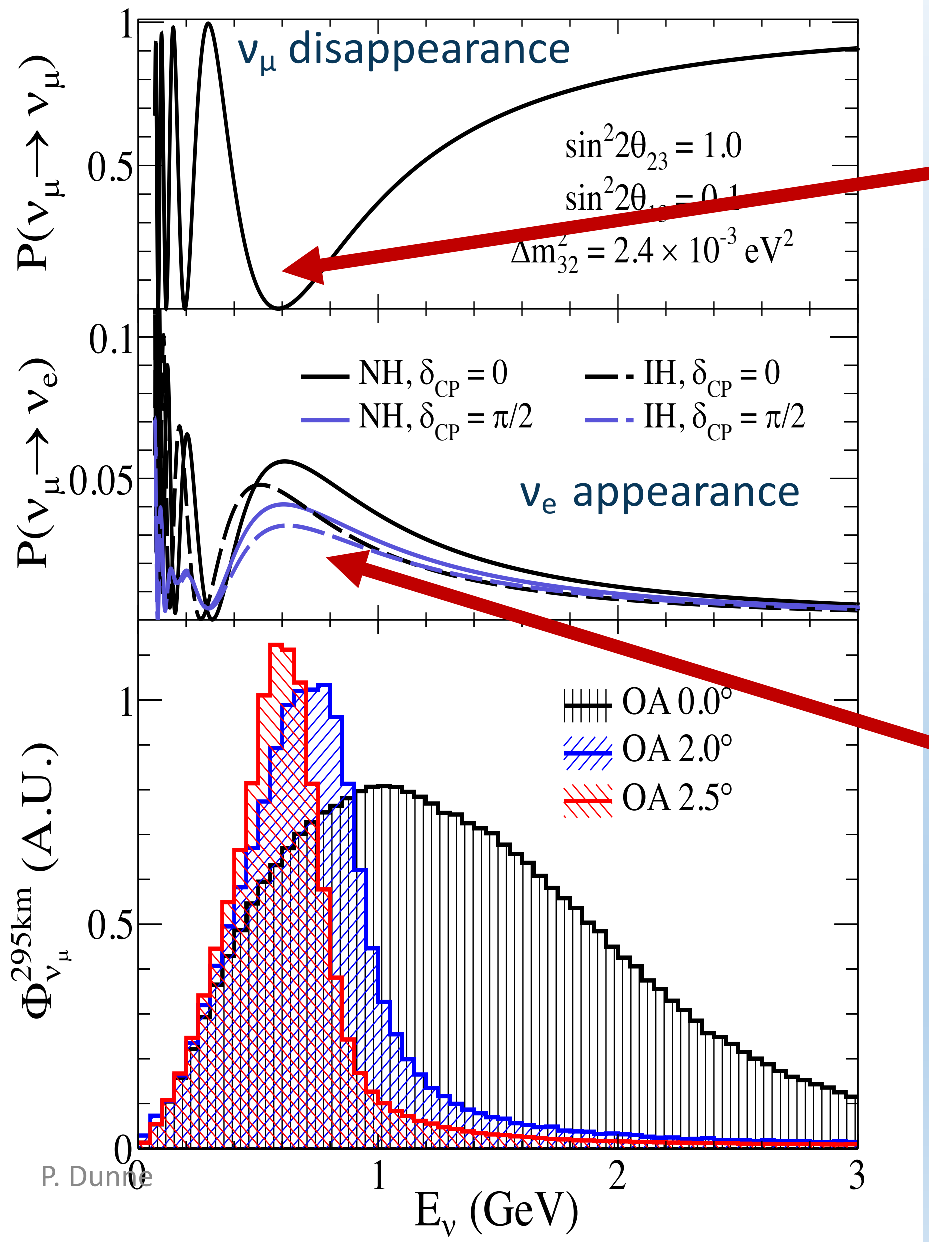
- How do you do a long baseline neutrino experiment?
- Why does the next generation of experiments need an HPTPC?
- The UK HPTPC prototype
- Beam test at CERN
- Future prospects

Long baseline neutrino experiments

- Muon (anti) neutrino beam generated
- Near detector complex measures beam before oscillation
- Beam travels O(100s km) to large far detector to be measured after oscillations



Neutrino oscillations at T2K



- Muon (anti)neutrino disappearance
  - Location of dip determined by Δm^2_{23}
  - Depth of dip determined by $\sin^2(2\theta_{23})$
- Electron (anti)neutrino appearance
  - Leading term depends on $\sin^2(\theta_{23})$, $\sin^2(\theta_{13})$ and Δm^2_{23}
  - Sub-leading dependance on δ_{CP}
    - $\delta_{CP} = \pi/2$: fewer neutrinos, more anti-neutrinos
    - $\delta_{CP} = -\pi/2$: more neutrinos, fewer anti-neutrinos
  - Matter effects give dependence on mass hierarchy
  - Sensitivity dominated by how well you can place the peaks/dips

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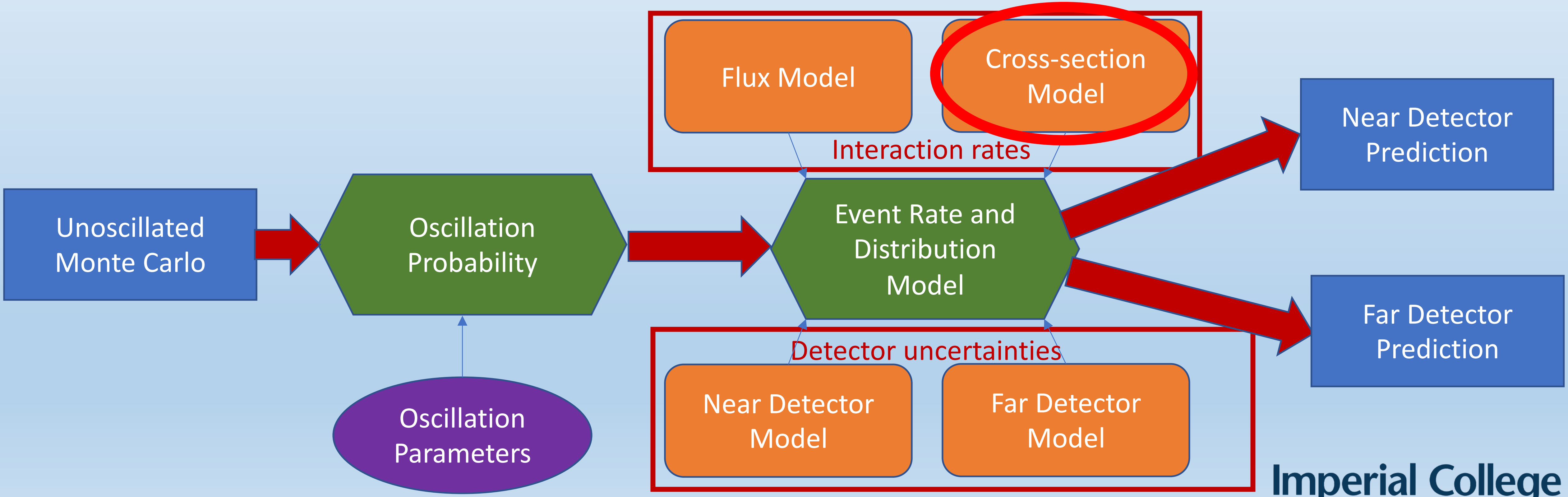
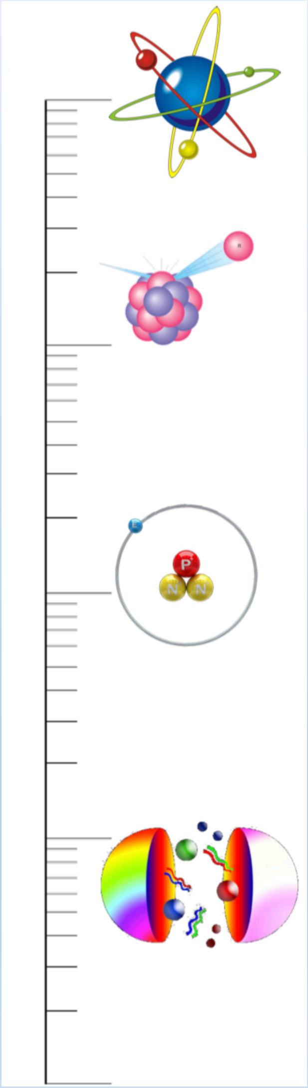
How do we measure neutrino oscillations?

- Apply oscillation effects to Monte Carlo as a function of true E_ν
- Construct model to predict event rates and distributions at near and far detectors
- Need to ensure experiment can constrain non-oscillation elements of model
  - Cross-section model highly dependent on nuclear effects and has large uncertainties
  - Important to allow enough uncertainty to mitigate bias in case of incorrect model choice



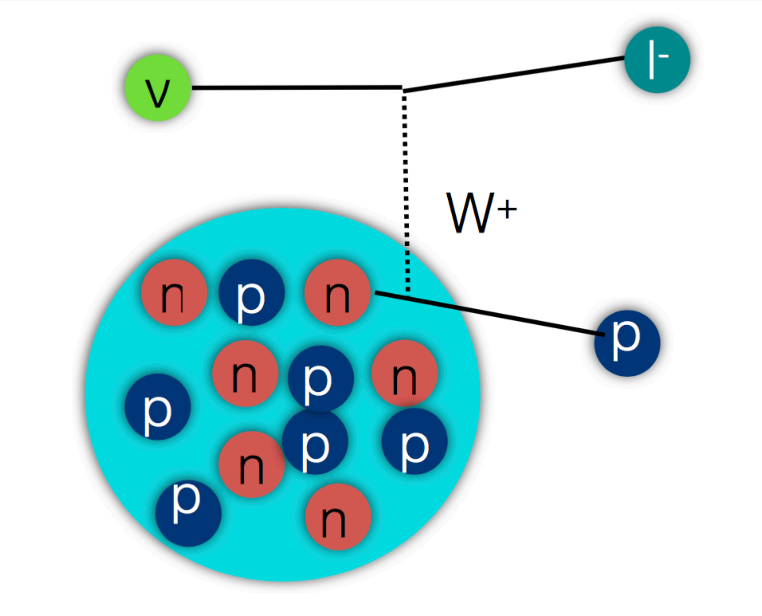
Why are neutrino-nucleus interactions hard?



- Neutrino energies of interest are O(0.5-10 GeV)
- Depending on momentum transfer (Q^2) this energy range covers anything from coherent interaction with nucleus to deep inelastic scattering
- Typical ordering is:
  - Coherent: Interact with whole nucleus
  - Quasi-elastic: Interact with a single nucleon ($\nu + n \rightarrow \ell^- + p$)
  - 2p2h: Interact with a correlated pair of nucleons quasi-elastically
  - Resonant: Excite a nucleon into a resonance which then decays
  - DIS: Interact with quarks inside the nucleon
- Reality is a continuous shift between these processes

Cross-section modelling

- Generators model interactions differently for each interaction type
- Factorisation:
  1. Nuclear initial state
  2. Screening of target by rest of nucleus
  3. **Neutrino-nucleon interaction**
  4. Final state interactions leaving the nucleus
- Problem: for each type of neutrino-nucleon interaction need differing other elements, not all of which are consistently described by theory
- Relying on model for $E_{\nu,true} \rightarrow E_{\nu,reco}$ mapping
  - Need to allow enough uncertainty so as not to add bias from incorrect model choice



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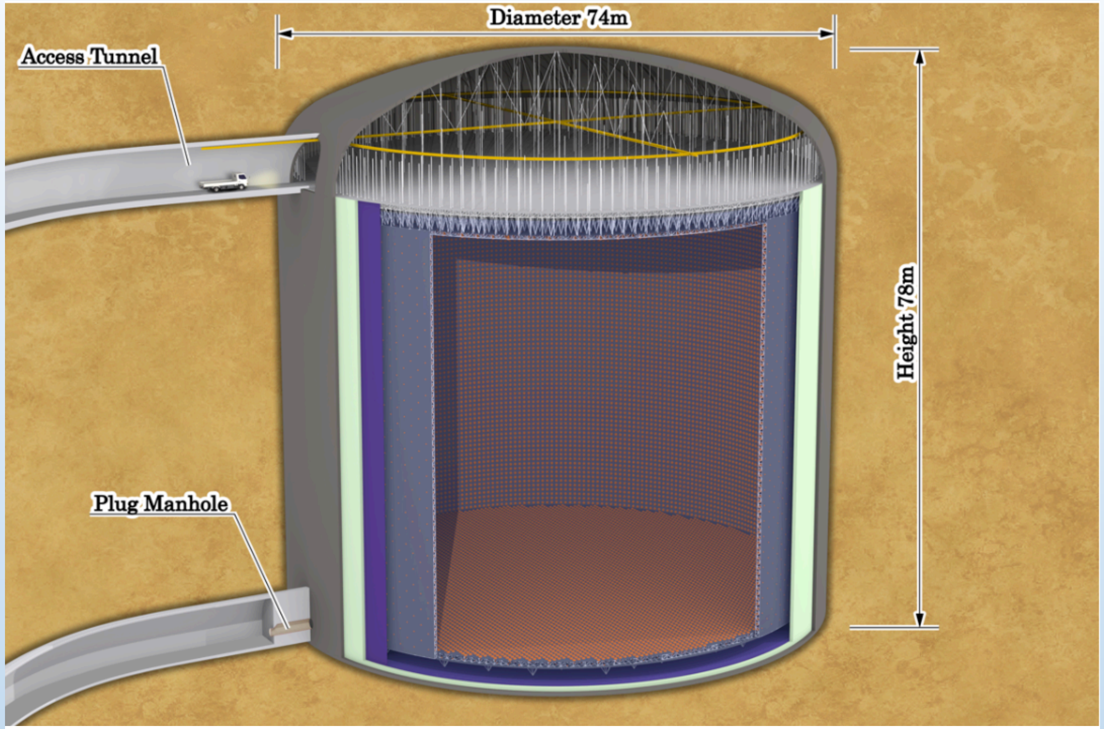
Where are we now?

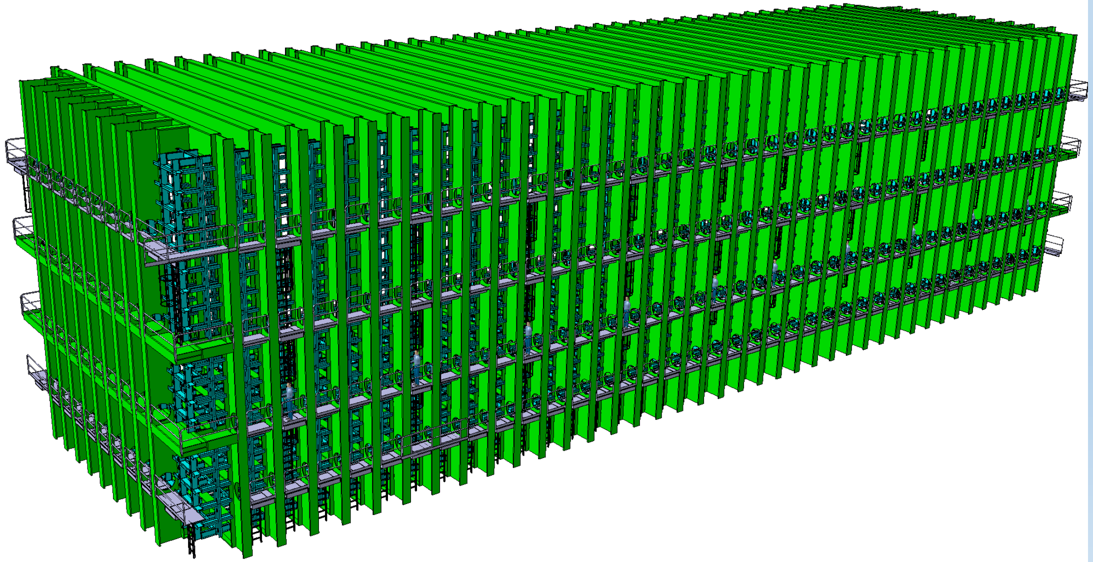
- Current T2K errors are O(6%) largely from cross-section

	% Errors on predicted event rates, Osc. Parameters as for rates					
	1R μ-like		1R e-like			
Error Source	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode CC1π	ν-mode/$\bar{\nu}$-mode
SK Detector	2.40	2.01	2.83	3.80	13.15	1.47
SK FSI+SI+PN	2.21	1.98	3.00	2.31	11.43	1.57
ND280 const. flux & xsec	3.27	2.94	3.24	3.10	4.09	2.67
Eb	2.38	1.72	7.13	3.66	2.95	3.62
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.61	3.03
NC1γ	0.00	0.00	1.09	2.60	0.33	1.50
NC Other	0.25	0.25	0.15	0.33	0.99	0.18
Total Systematic Error	5.12	4.45	8.81	7.13	18.38	5.96

What do we need for future?

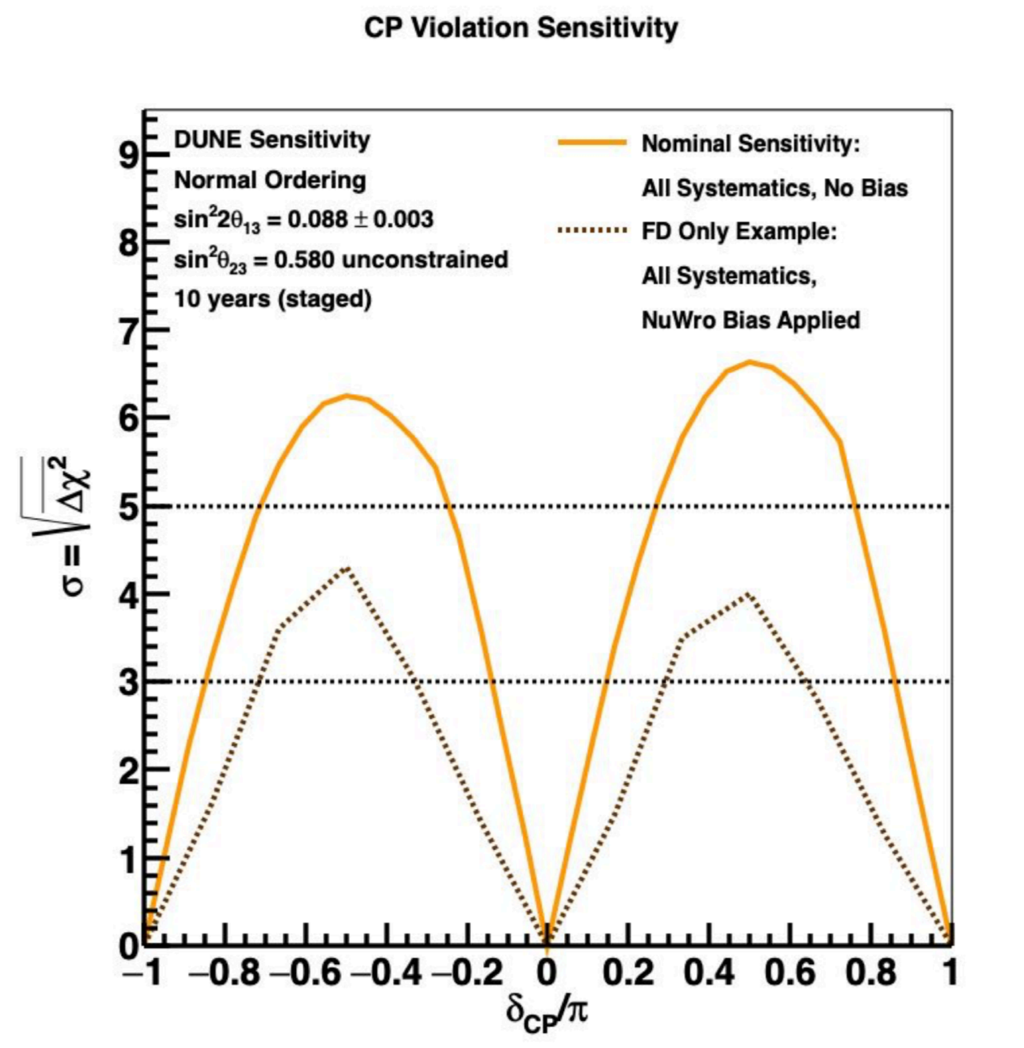
- Larger successor experiments to T2K/NOvA
  - HK: Water Cerenkov detector ~9xSK
  - DUNE: 40 kton fiducial volume LAr far detector
- >1 MW beam power (2x T2K/NOvA design)
- Starting data taking in mid/late 2020s
- Aiming for 5σ δ_{CP} observation unless value is unfavourable
- UK involved in both projects





What uncertainties do we need for DUNE/HK

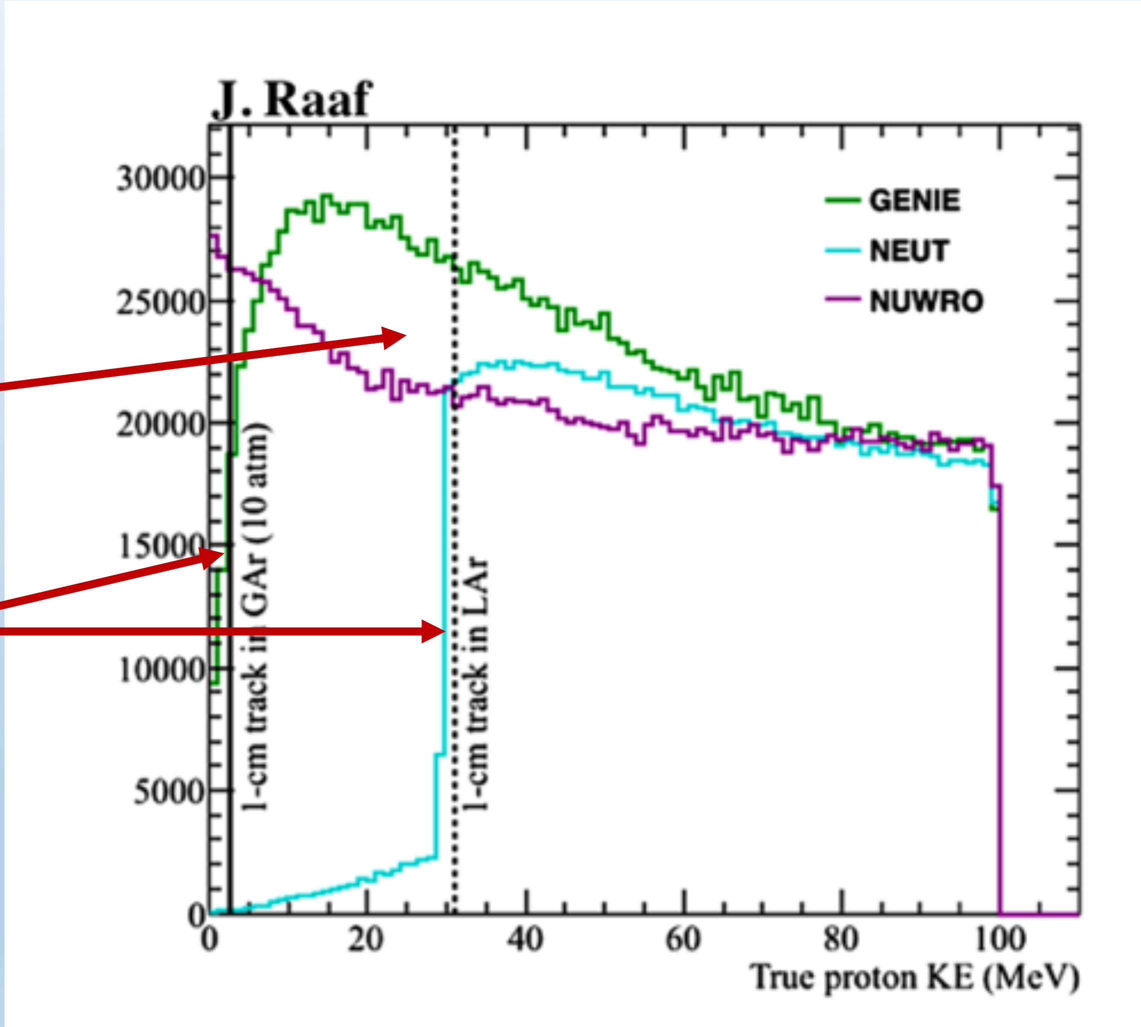
- Sensitivity studies assume ~2% total normalisation uncertainty for ν_e events
- Implies ~1% error on each of flux, cross-section, detector effects



Why a High Pressure Gas TPC?

Why a High Pressure Gas TPC: Thresholds

- Neutrino cross-section models are tuned in the regions where we have data
- Outside these regions there are large uncertainties
- Low energy hadrons travel further from the interaction point in gas than in denser detectors giving a lower threshold
- High pressure plus Mega-Watt beams gives enough events to do interesting physics with a gas target



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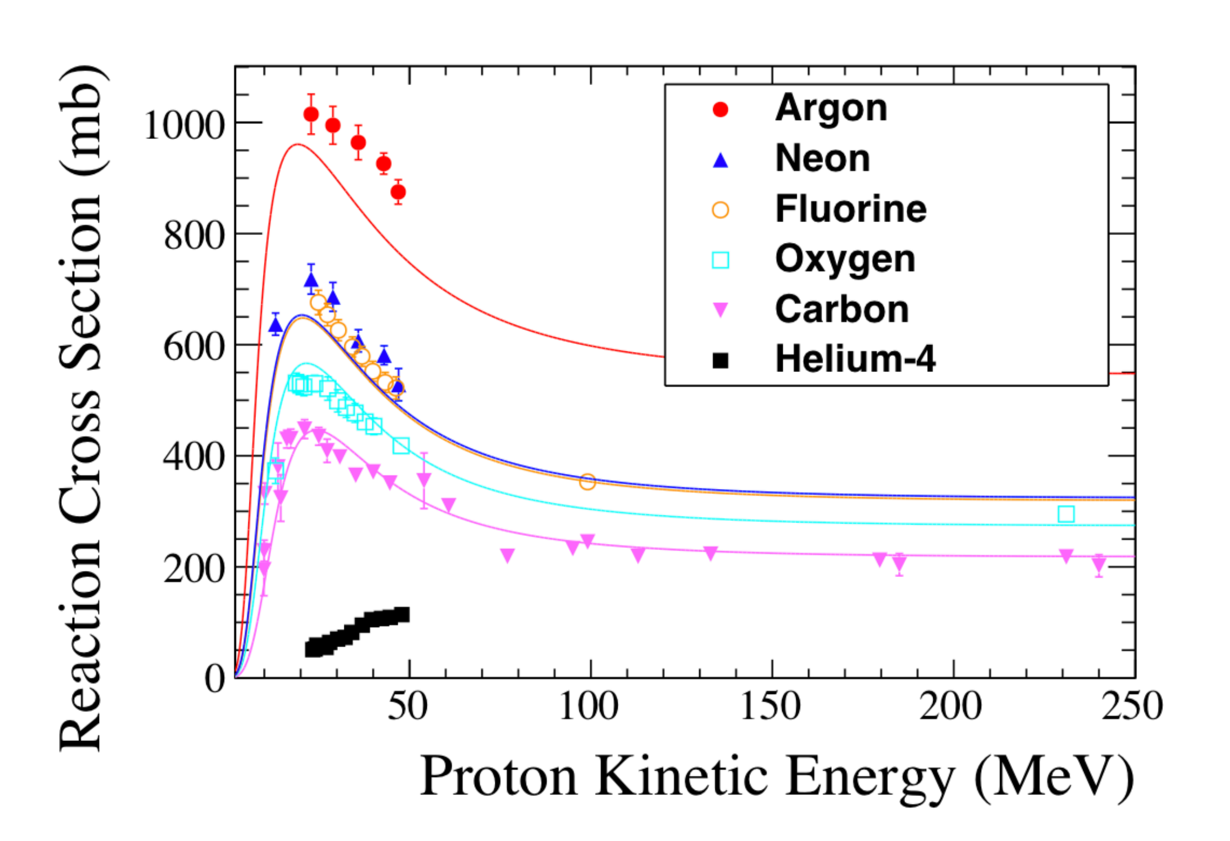
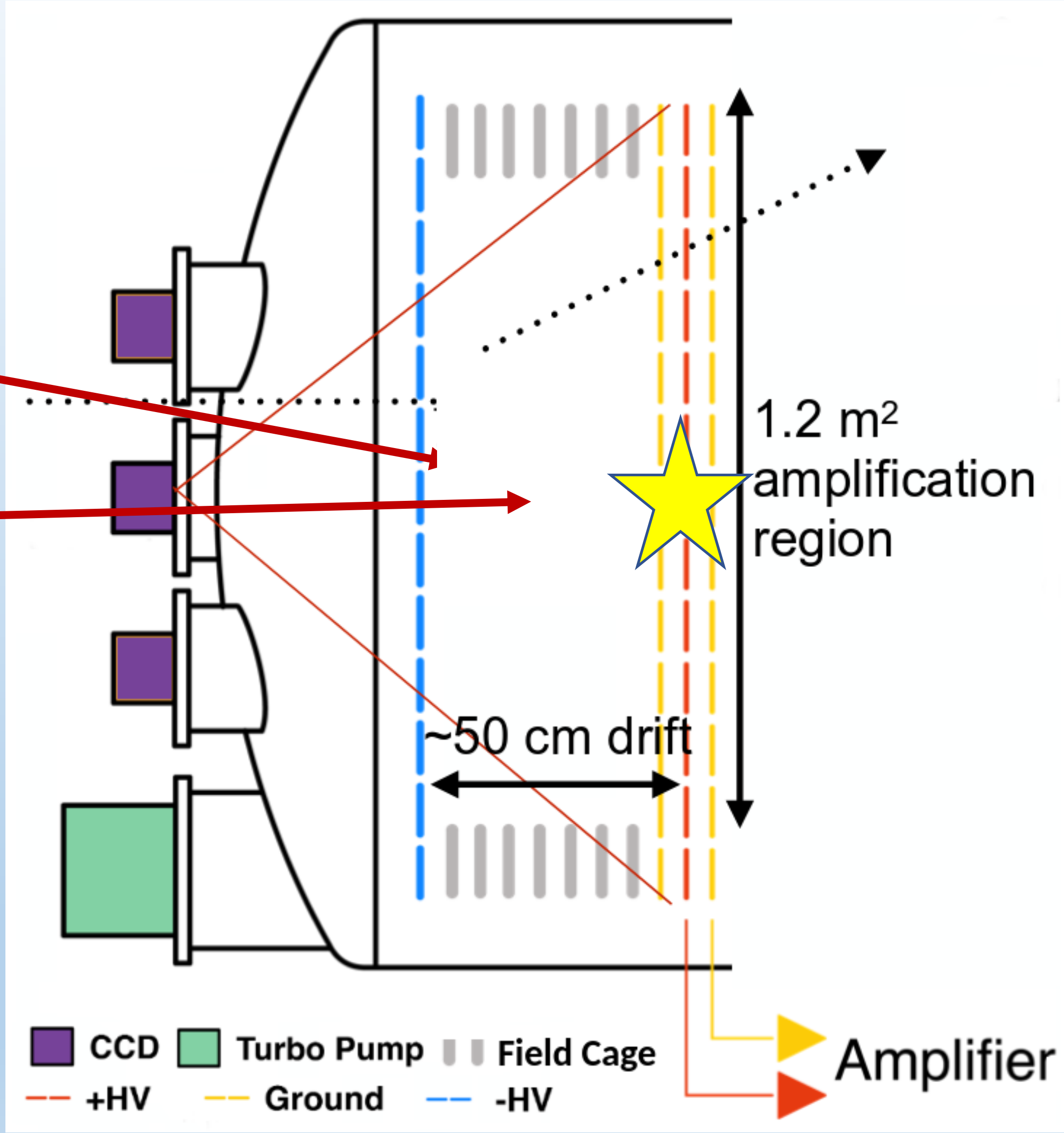
Why a High Pressure Gas TPC: Target Swapping

- Significant theoretical difficulties in scaling measurements from one nucleus to another
- Gaseous detector can swap out target gas straightforwardly
- Gives data on different targets in identical beam at energies of interest for oscillation experiments



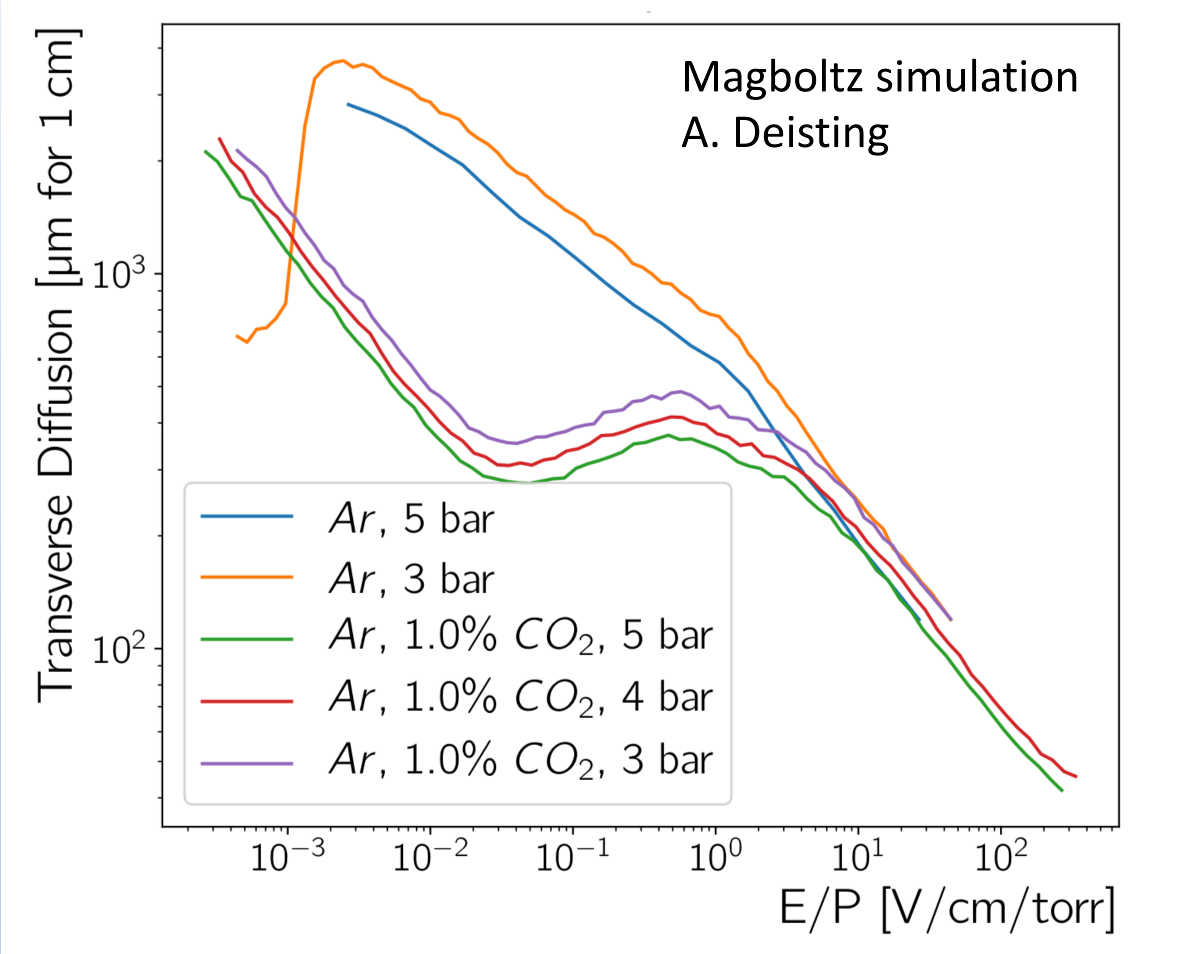
Traditional TPC Reminder

- Particles ionize gas as they travel through
- Ionisation electrons drift through field cage to an amplification region
- Avalanche in amplification region is read out by charge readout system



High Pressure: Operating voltages

- Limiting factor on track imaging is transverse diffusion
  - Too much diffusion leads to signal<detector noise
- Diffusion is a function of E/P
  - Higher pressure means higher Voltage



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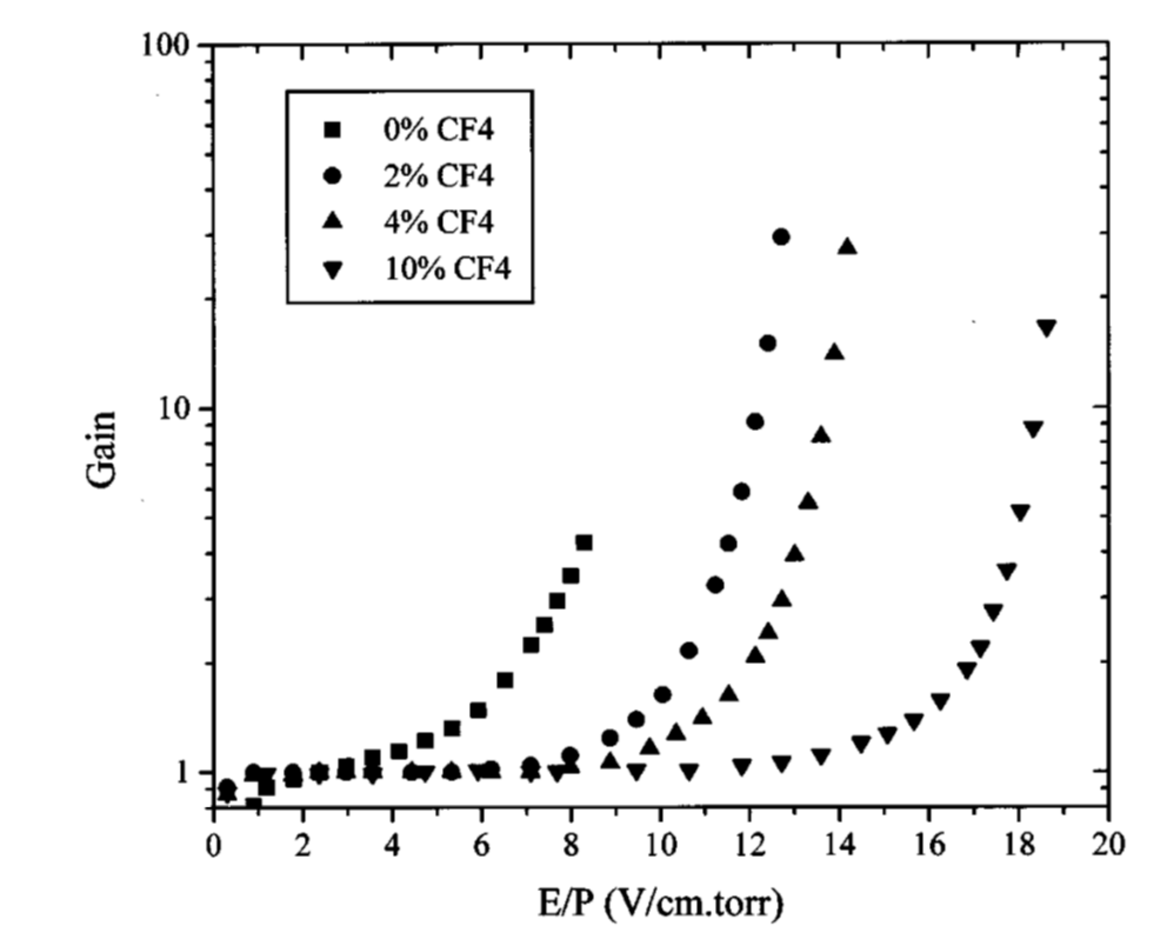

Fraga et al, IEEE trans. Nucl. Sci. Vol 48 no 3 June 2001

High Pressure: Operating voltages

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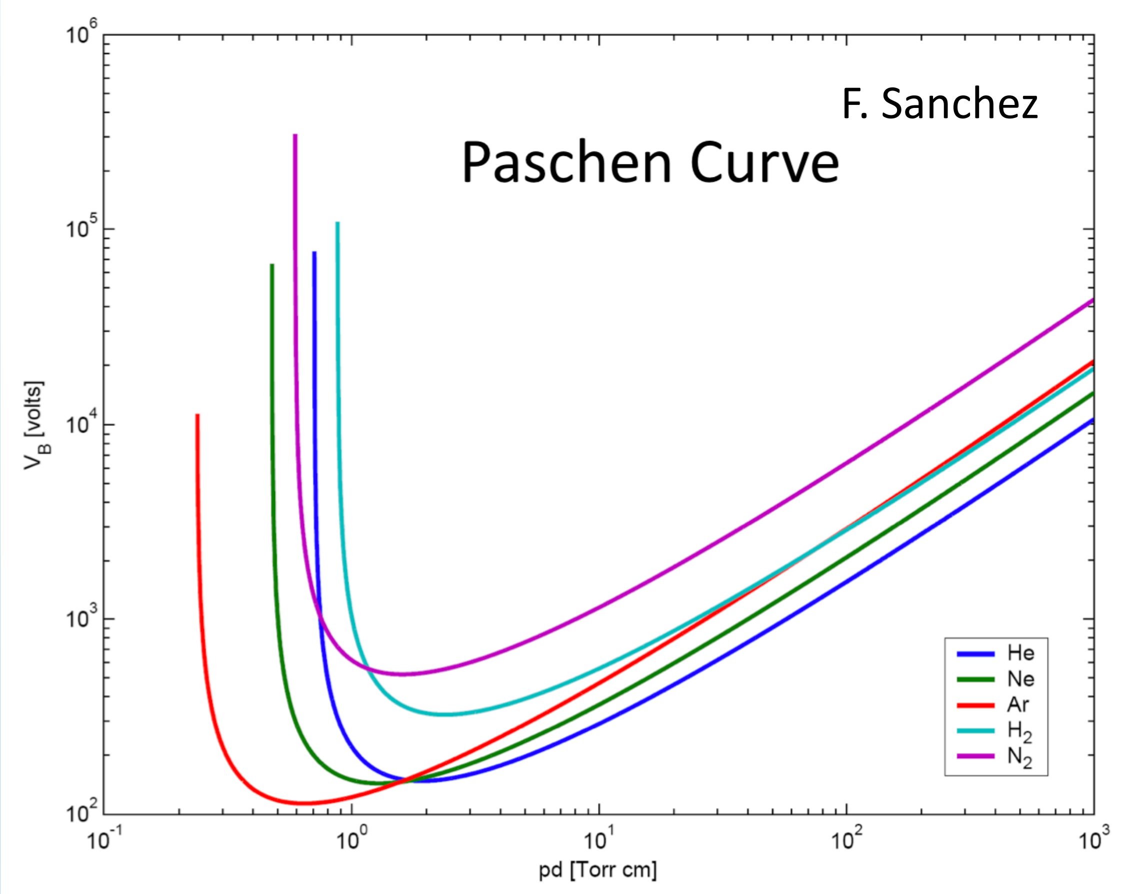
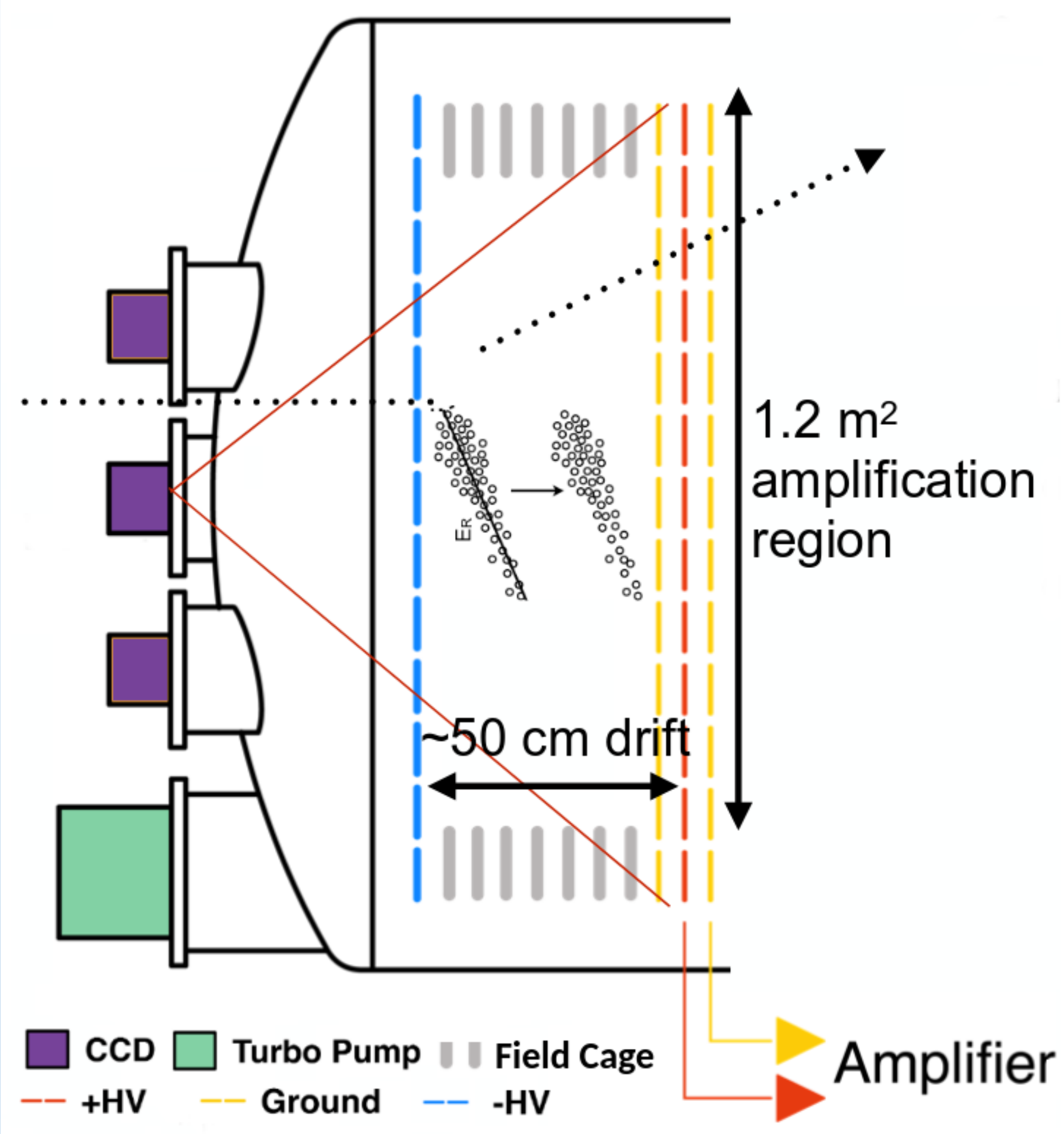
  - Gain in amplification stage is also a function of E/P
- Breakdown voltage increases linearly with pressure at high pressures



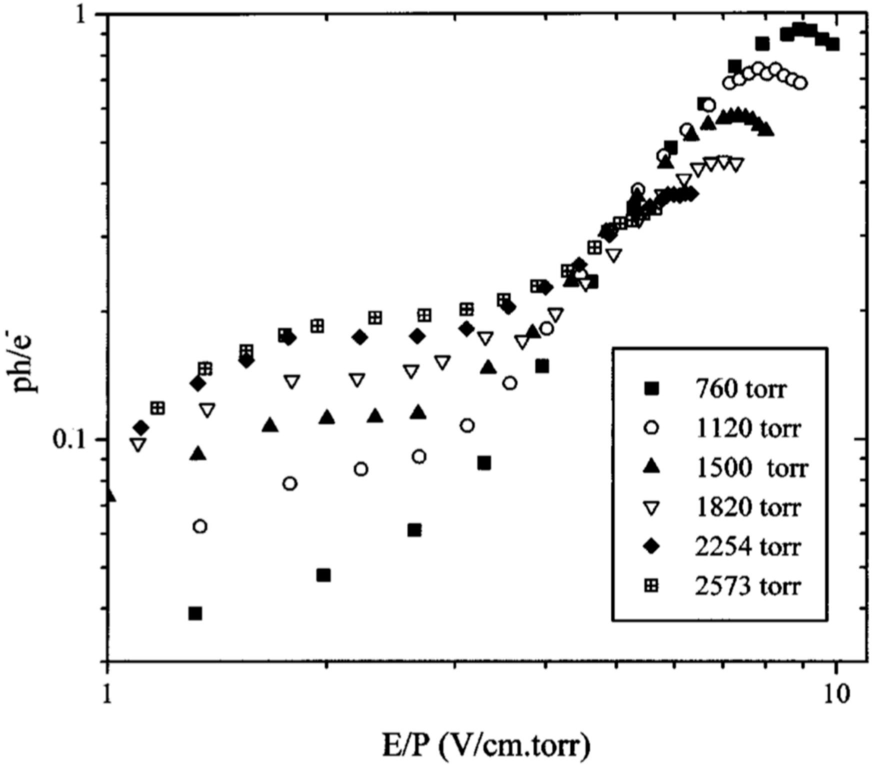
UK Prototype: CCD Readout

- Avalanche amplification causes scintillation light to be given off as well as charge signal
- We use CCD cameras to image amplification region
- High granularity readout for much less cost than pixelated charge readout
- Important to choose gas mix to give enough visible light



CCD Readout: Getting enough light

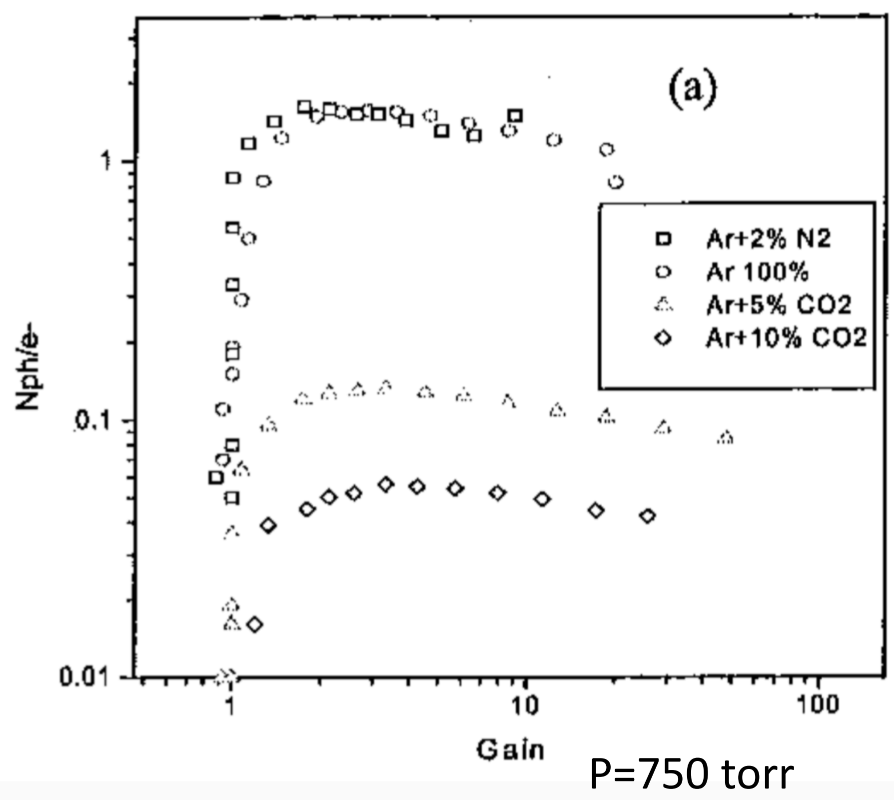
- Photons per avalanche electron flattens off at high voltage
- Some evidence that higher pressures have less light at high voltage



IEEE, VOL. 48, NO. 3, JUNE 2001

CCD Readout: Getting enough light

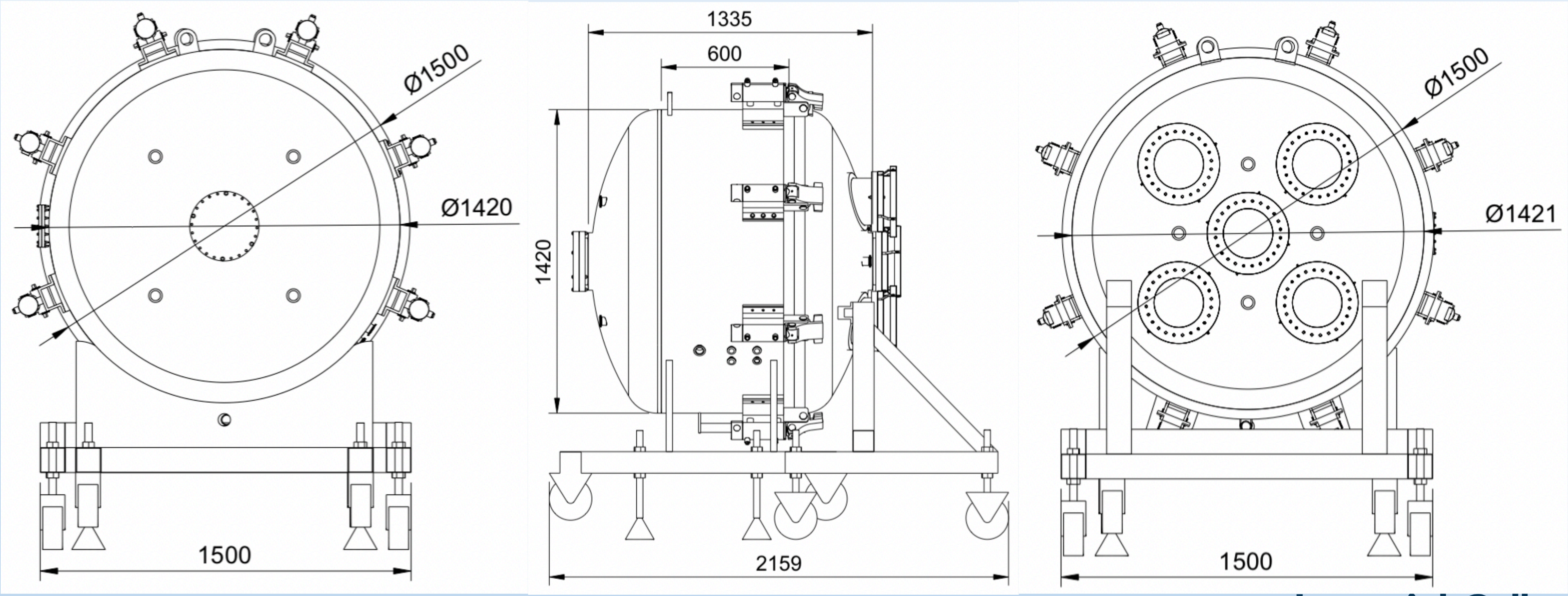
- Photons per avalanche electron flattens off at high voltage
- Some evidence that higher pressures have less light at high voltage
- Adding other gases to improve operational stability (fewer sparks) can reduce light yield
- Need to find a balance in terms of gas mix and working voltage



IEEE, VOL. 47, NO. 3, JUNE 2000

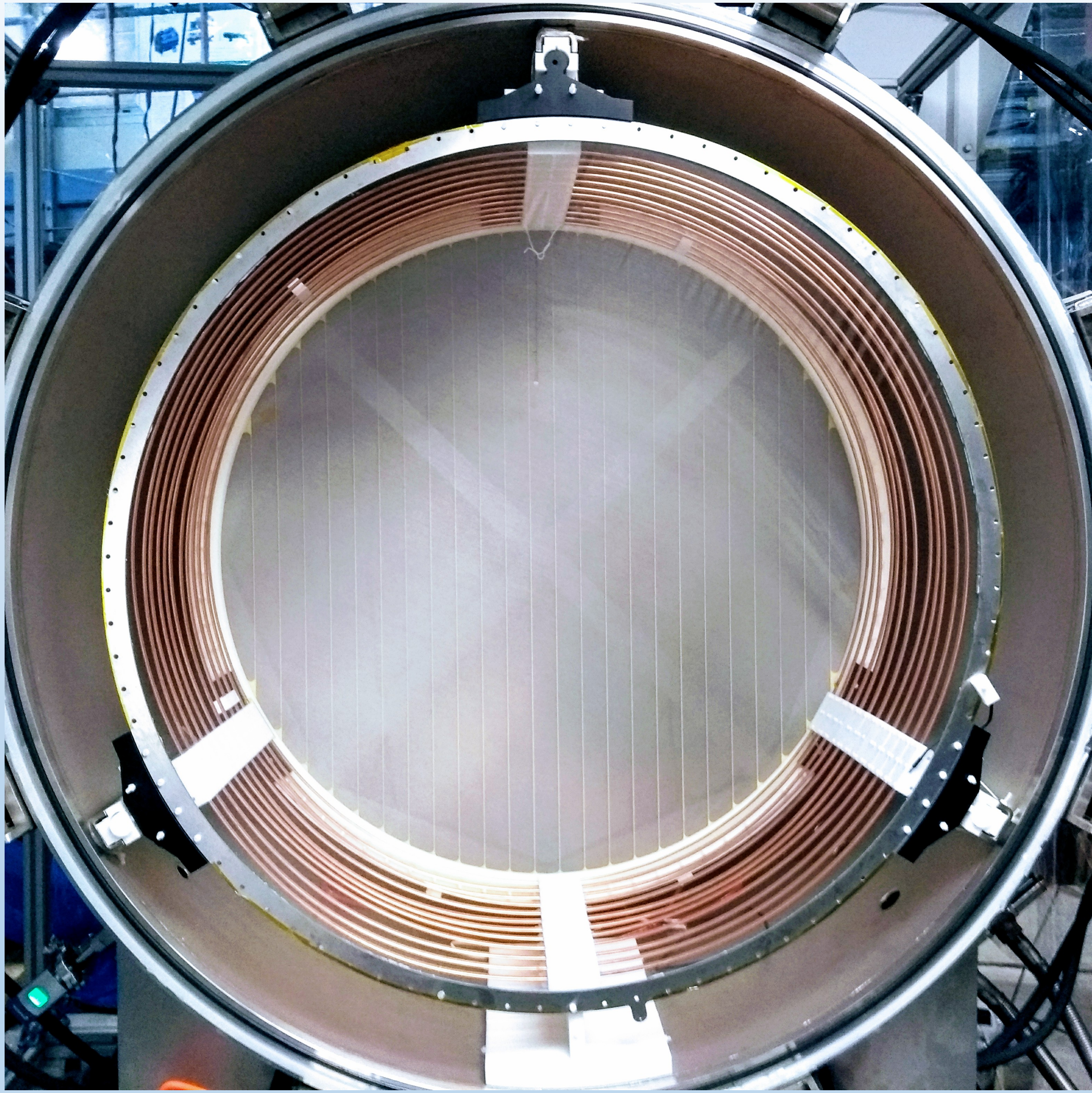
UK Prototype

- Cubic metre pressure vessel rated to 5 barG has been built



UK Prototype

- TPC formed from 1.2m diameter steel meshes and copper rings
- Very fine cathode mesh transparent to allow cameras to image through it
- Amplification region made up of three meshes with O(mm) spacing
- Copper rings form field cage for drift field uniformity
- Vessel received Autumn 2017 for Summer 2018 beam test



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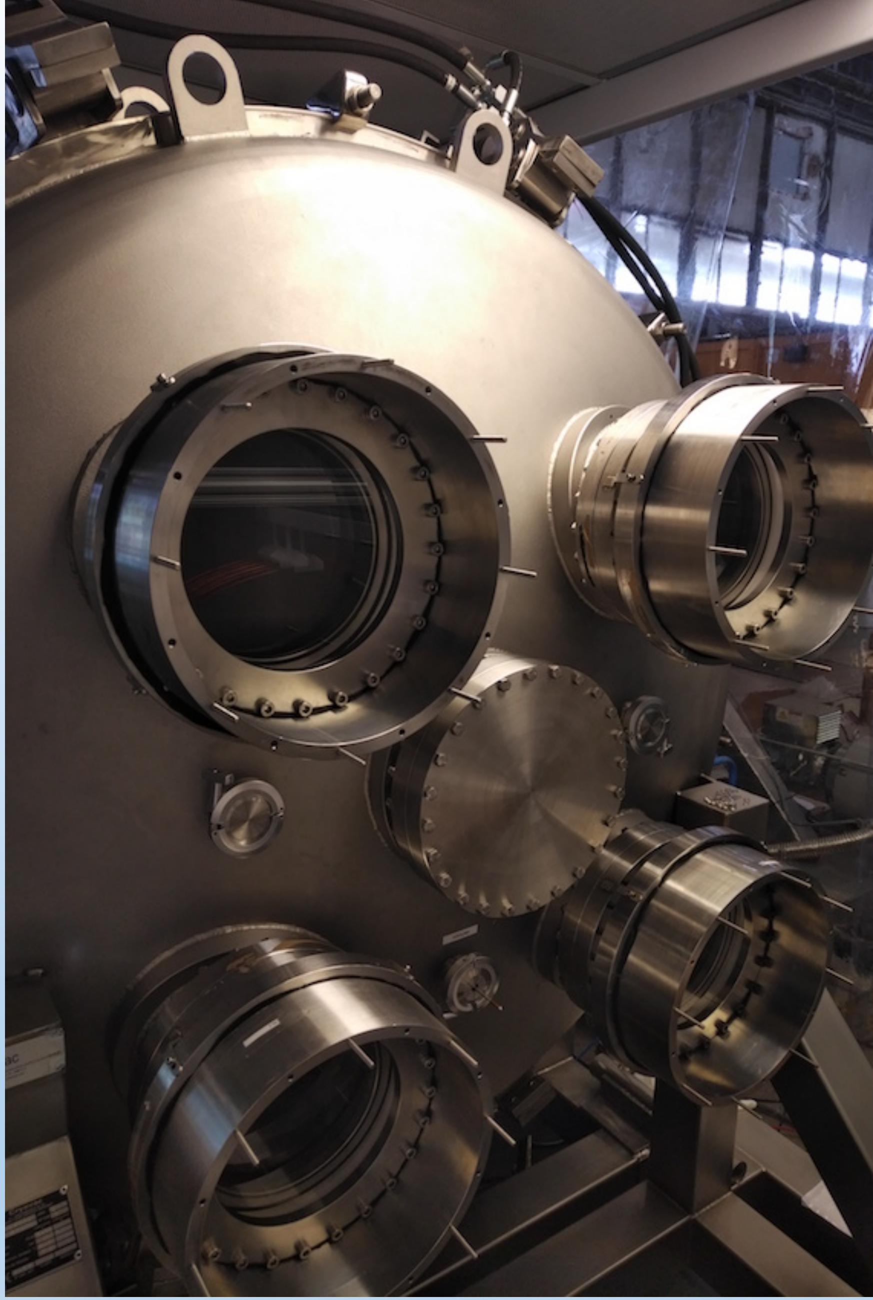
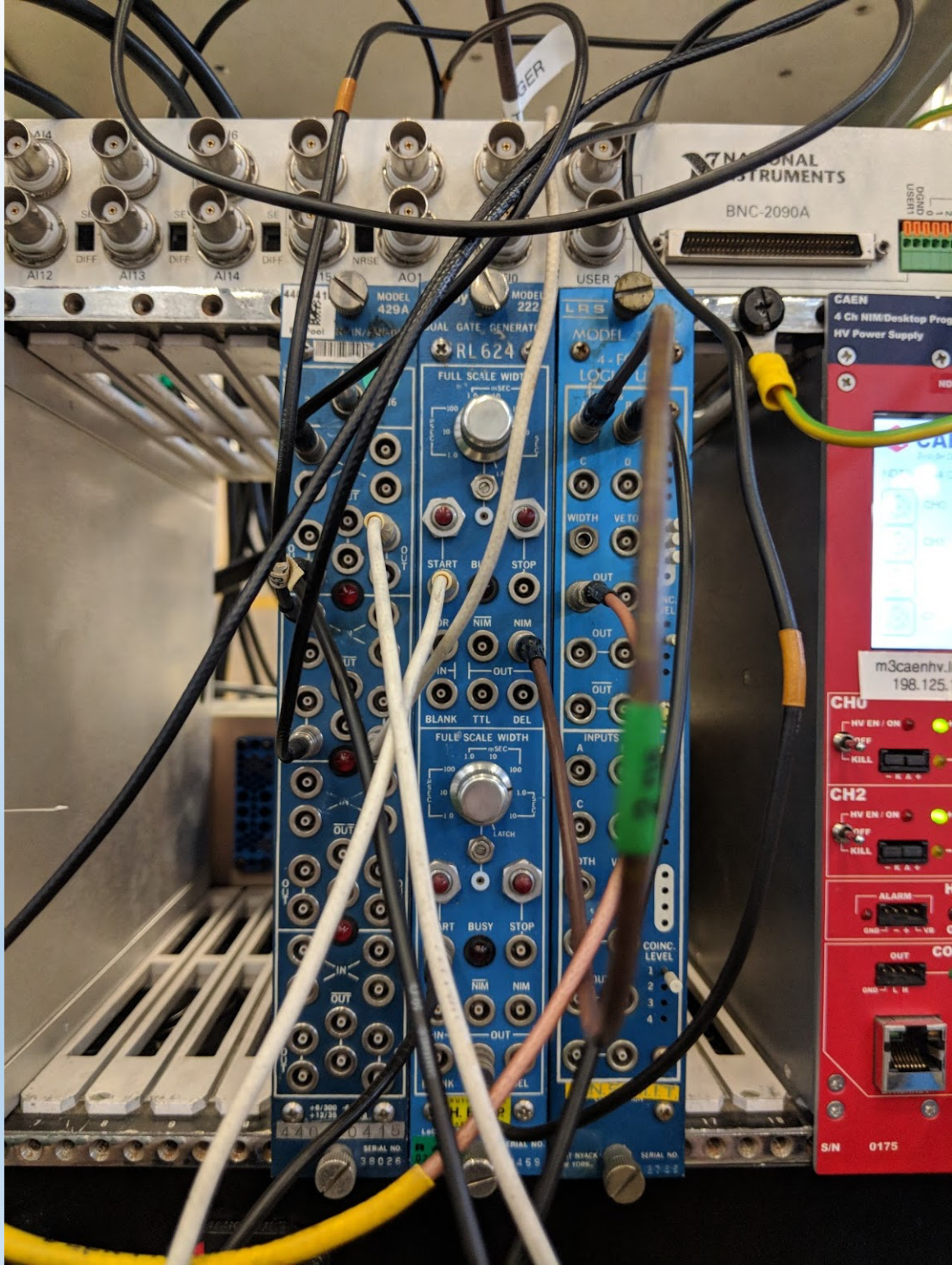
Cameras

- Four single photon accurate cameras each image one quadrant of amplification region
- 9 MP resolution gives sub-mm readout pitch at amplification region
- Exposure and readout time is O(seconds)
  - Need charge readout to do time projection
- Optical feedthrough to pressurized region through quartz windows
  - Cameras don’t have to be in pressurized region



Data Acquisition (DAQ)

- NIM logic trigger system set up to take an external beam trigger
- Cameras record the entire beam spill window
- Each anode mesh read out through a separate charge integrating pre-amplifier into a DAQ PC
  - Pulses are collected whenever a signal is detected coincident with the beam spill signal



DAQ experting ☹

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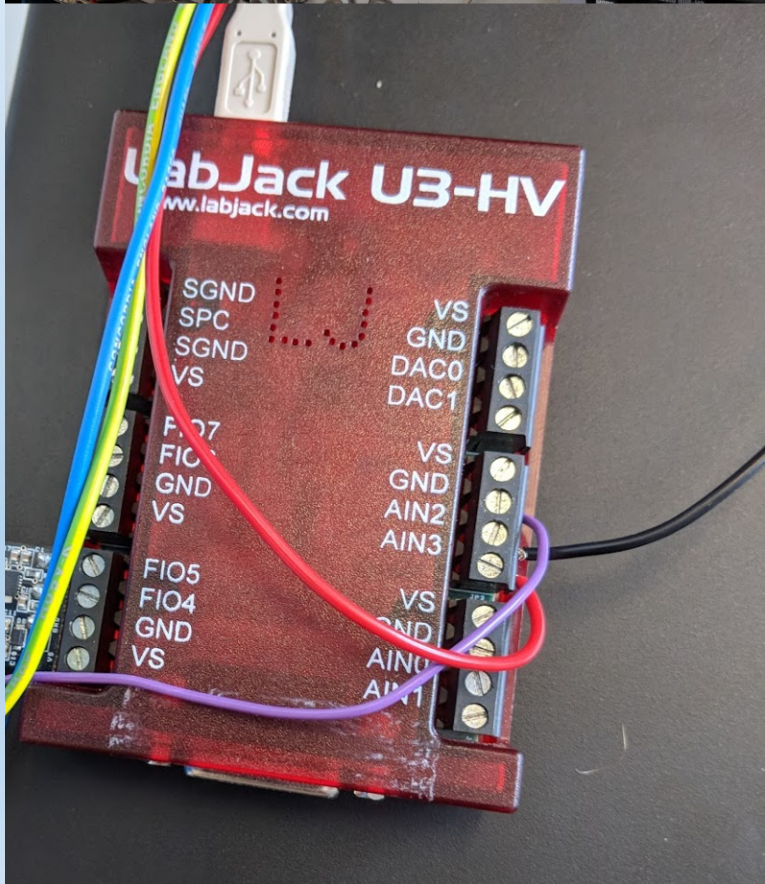
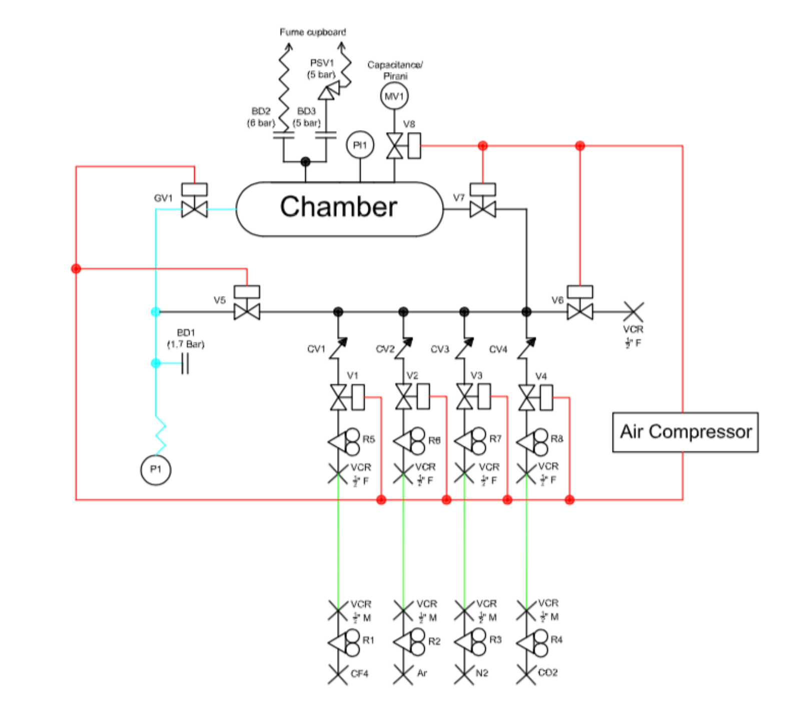
Pressure and voltage control

- Slow control system based on DMTPC detector
- New higher voltage cathode supply required significant modifications



Pressure and voltage control

- Slow control system based on DMTPC detector
- New higher voltage cathode supply required significant modifications
- Automated pressure control added to system
  - Remote actuated valves controlled using networked power supply
  - Able to fill from four separate gases automatically
  - Mix controlled by sequential filling to partial pressure



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Beam test

- Tested last August to September at T10 facility at CERN
- T10 beam's lowest setting is 800 MeV where it's mostly made up of pions
- We mainly want to see protons of low energy O(100 MeV)…

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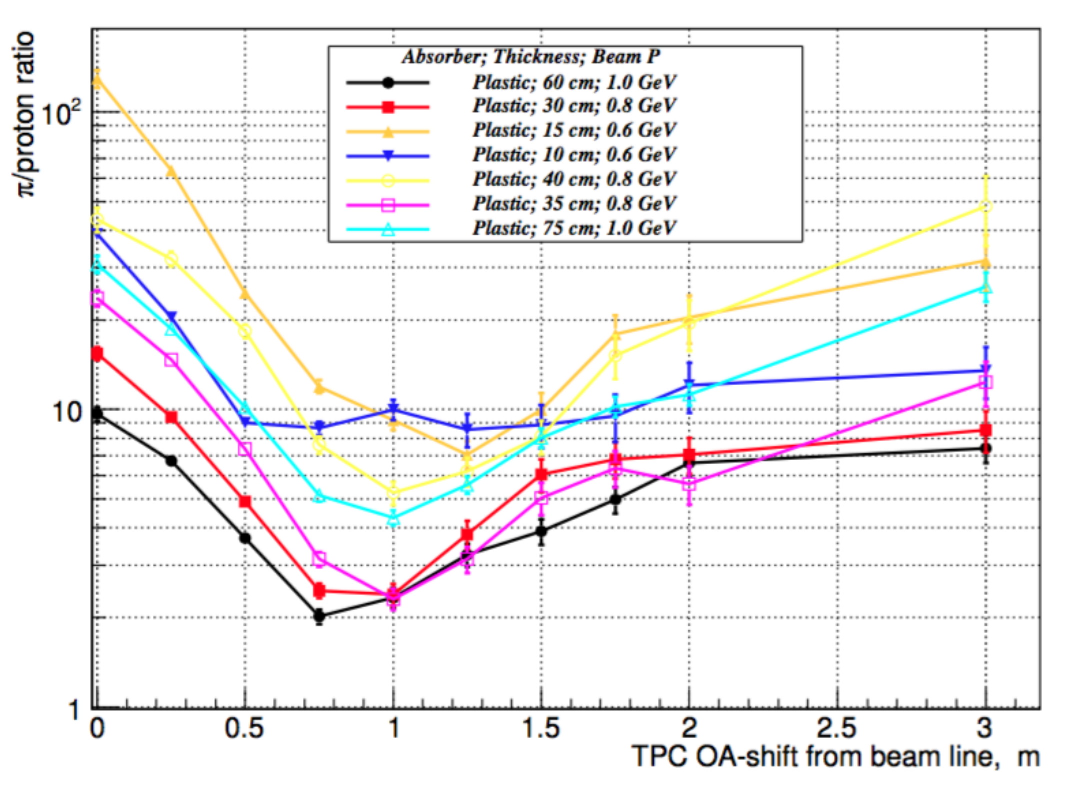
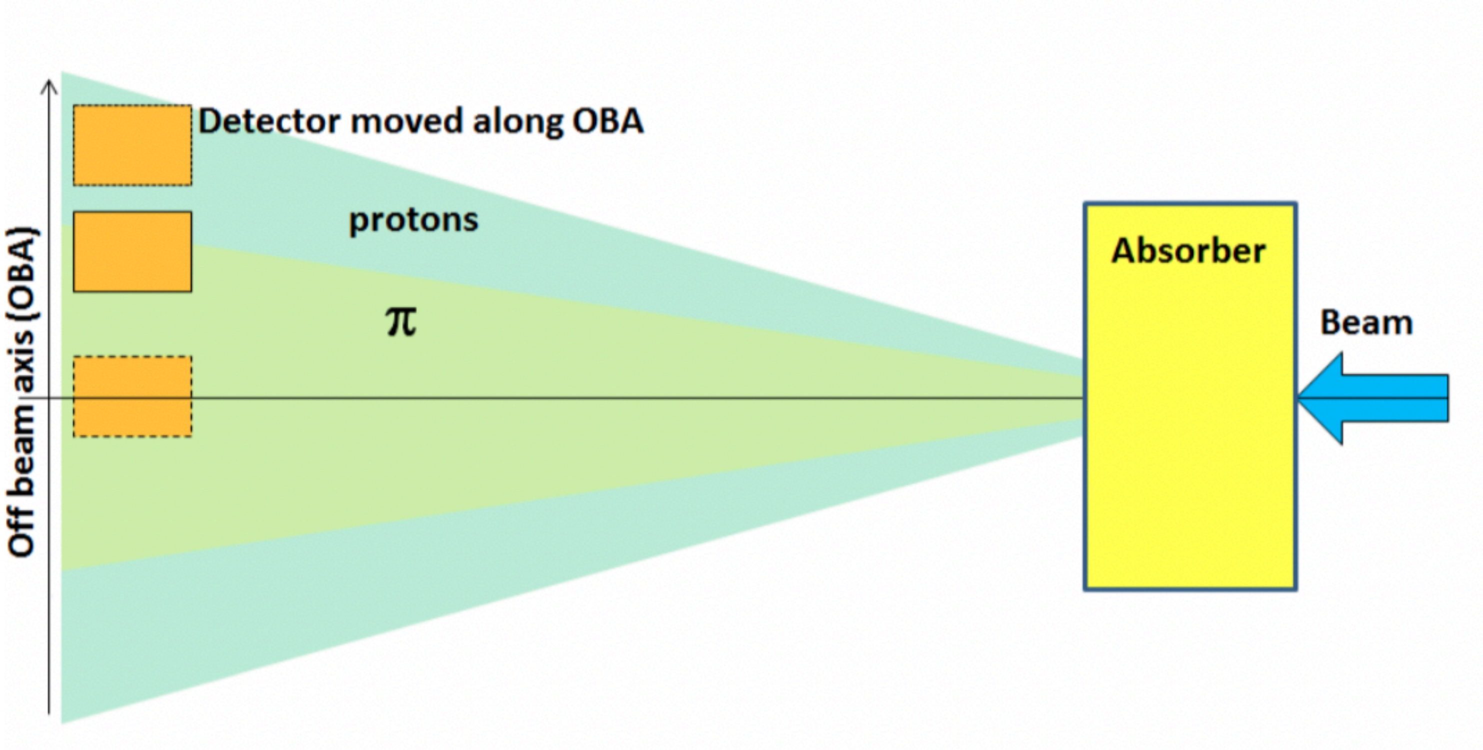
Moderate and go off axis





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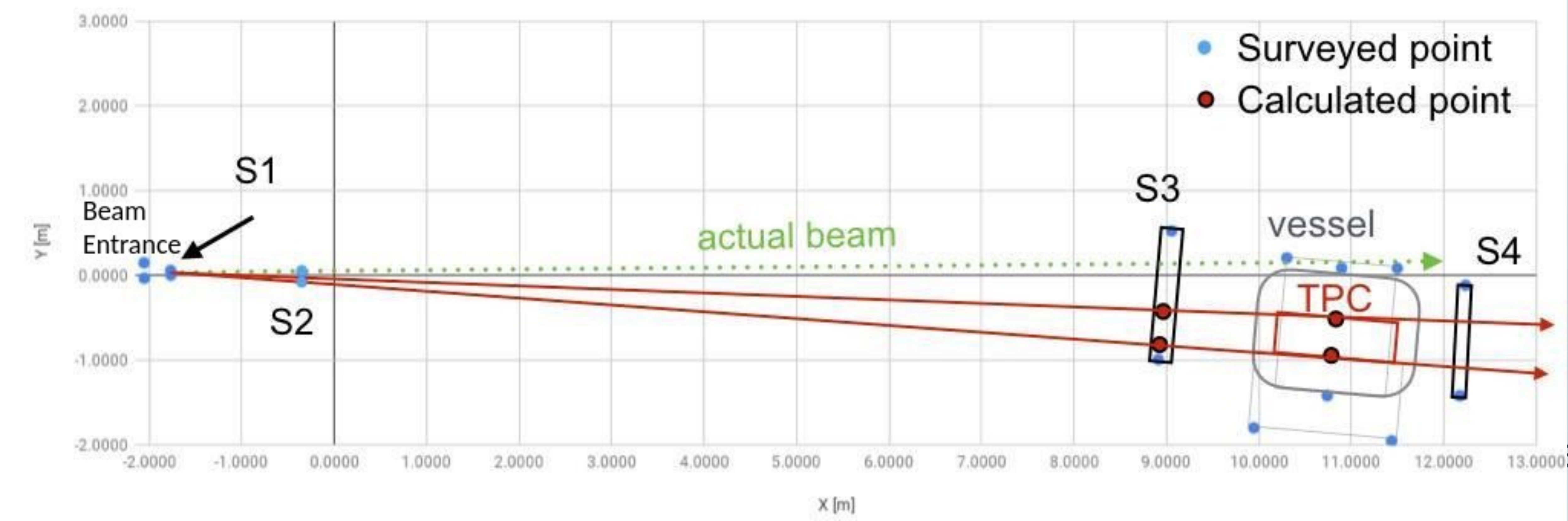
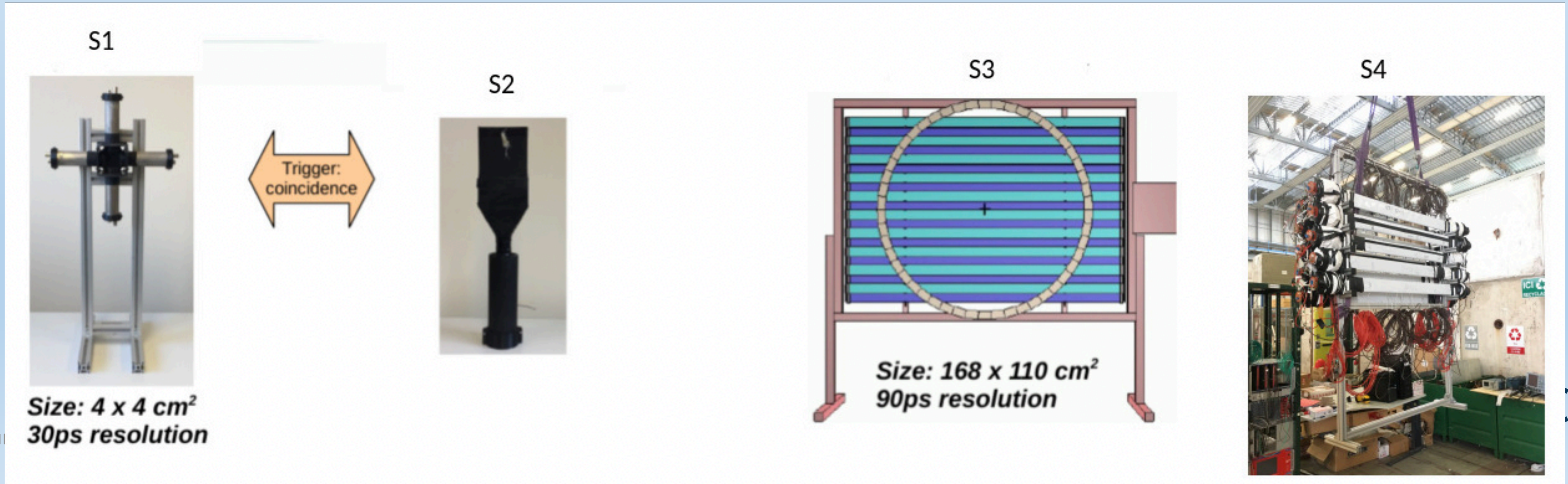
Time of Flight Energy Measurement

- Particle species tagging and momentum measurement performed using time of flight (ToF) system
- Ideal system for testing the moderator plus off-axis method



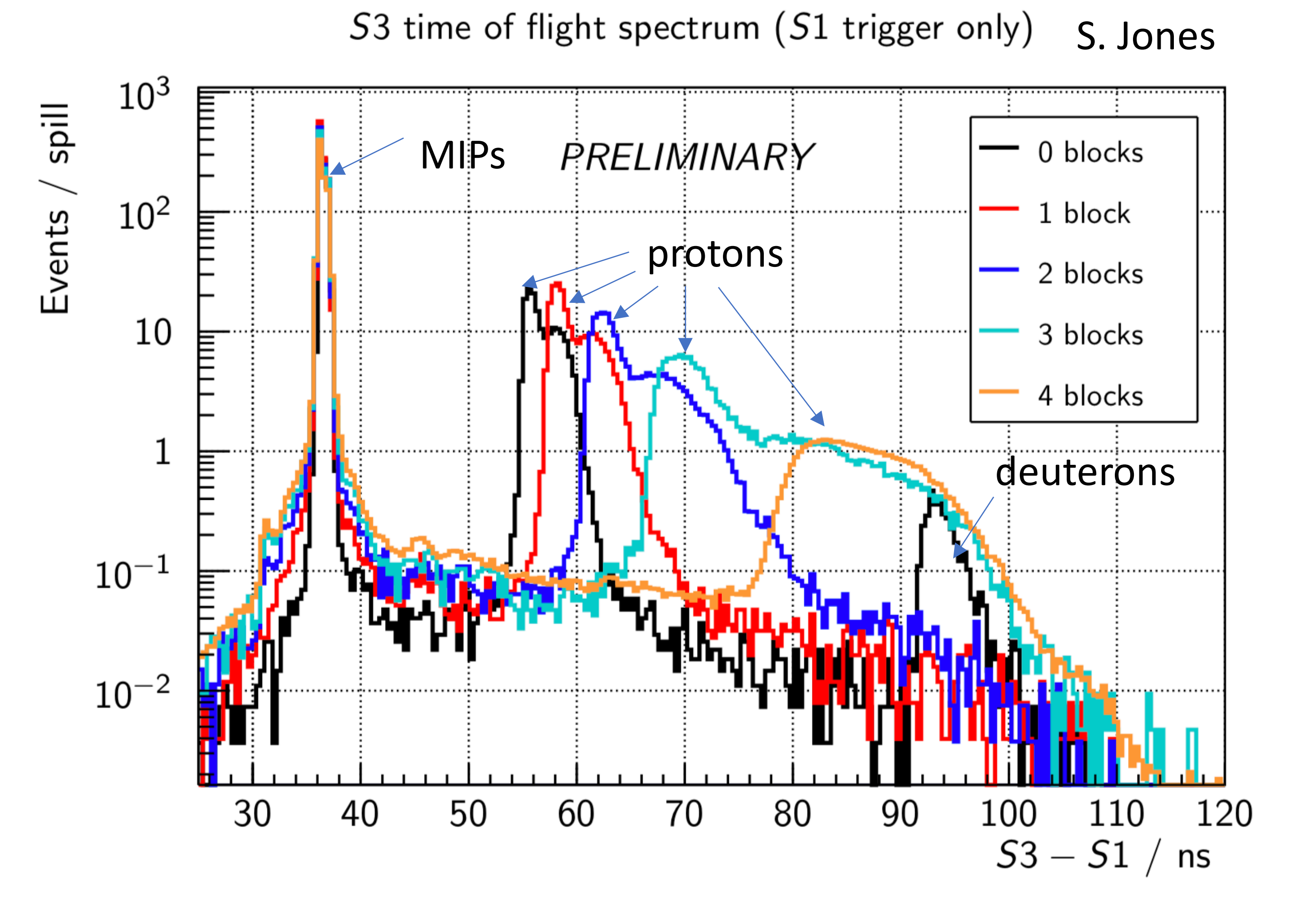
ToF components

- 3 upstream components provided by University of Geneva
  - S1 and S2 single pixel fast trigger counters, S1 with 30 ps resolution
  - S3 wall with 20 bars of plastic scintillator with 90 ps resolution, prototype for the SHiP detector
- 1 downstream UCL wall S4 made up of 10 scintillator bars with 1ns resolution



Early results from Time of Flight: Energy

- MIPs, protons and deuteron peaks all visible in data
- Increase in number of moderator blocks increases MIP/proton separation
  - Proton energy is being reduced



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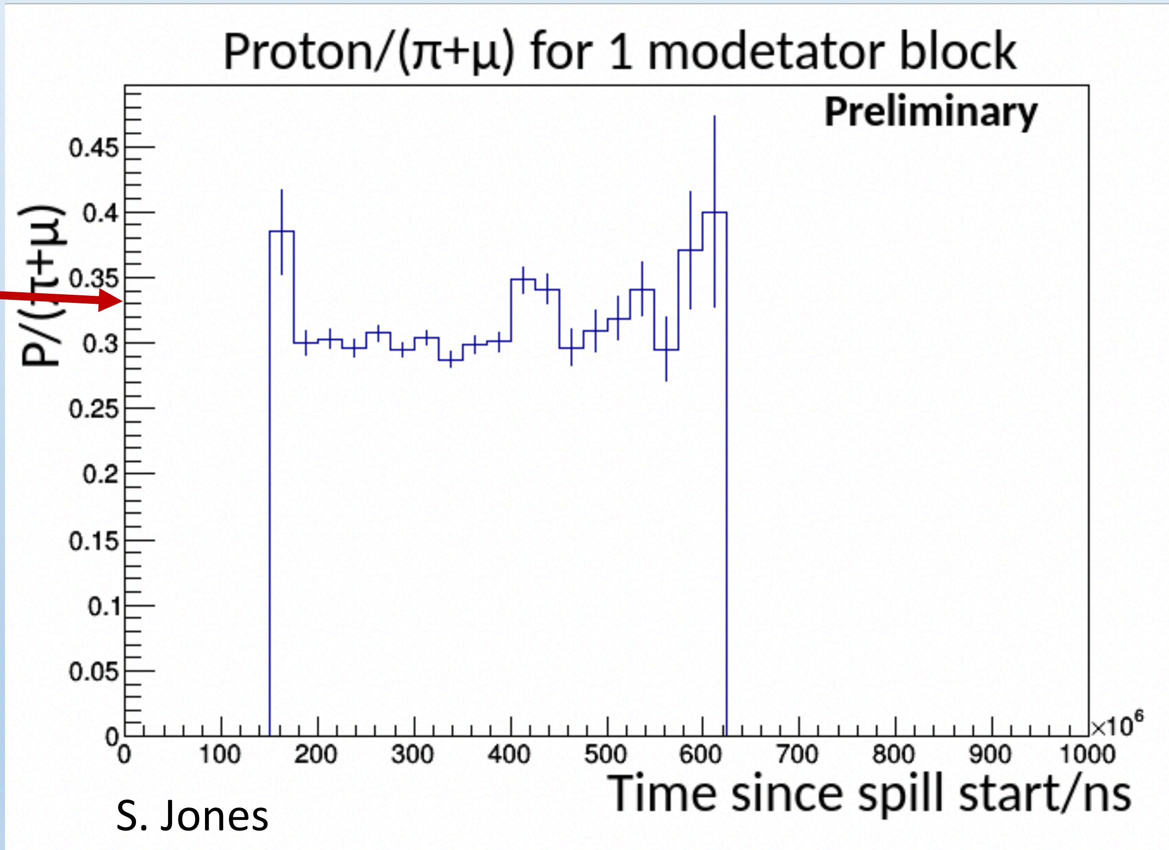
P-pi ratio

- On-axis no moderator p:MIP ratio is less than 1:10
- After moderation and 3.5° off axis, ratio of 1:3 is achieved



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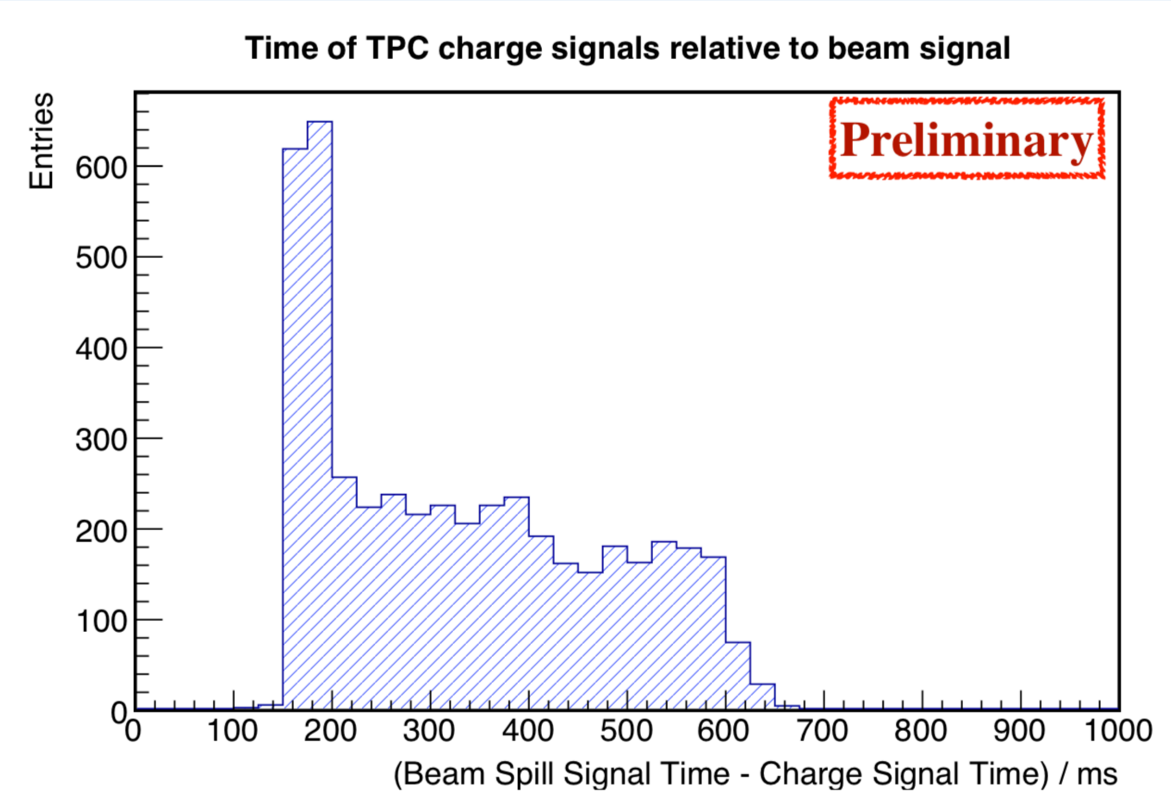
Charge readout

- Beam spill structure is seen in the charge readout system trigger times
- Signal amplitude in process of being calibrated against deposited energy
- Matching TPC charge and ToF signals across different DAQ systems to get species/momentum tagged events



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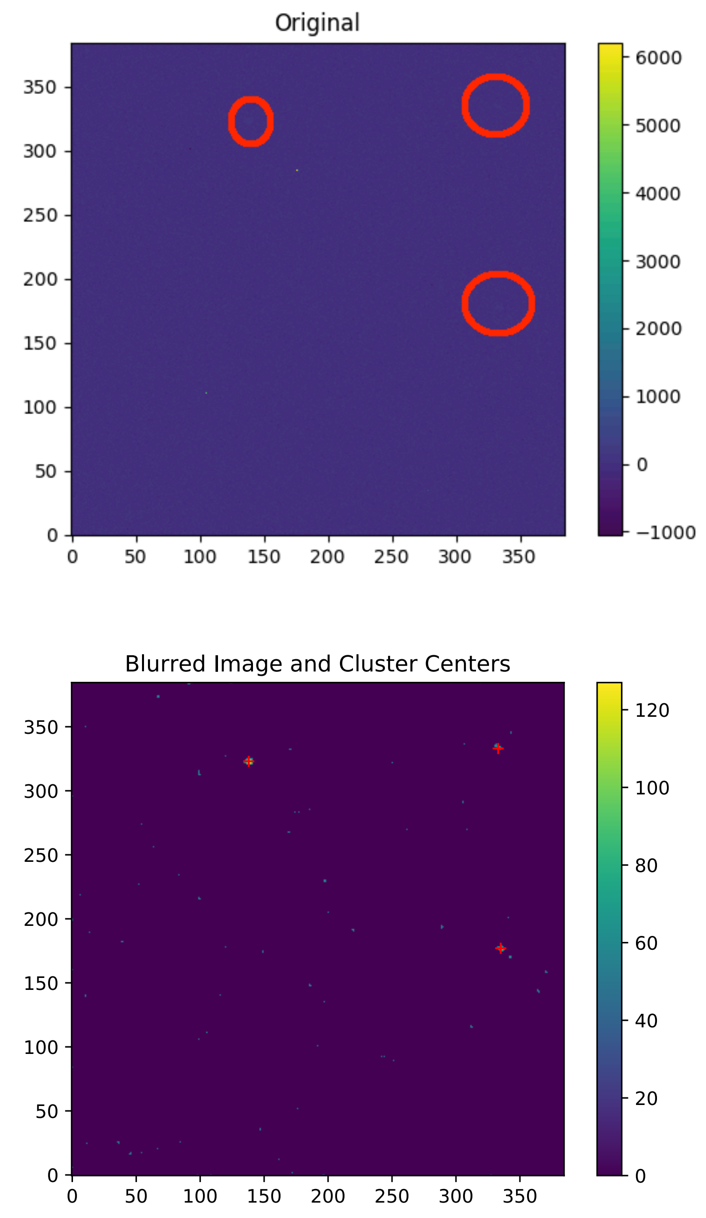
Light yield

- Detector had 4 Am-241 calibration sources at known locations inside
- Our clustering algorithm can detect these sources
- Working on producing light yield vs gas mix and voltage using size of clusters



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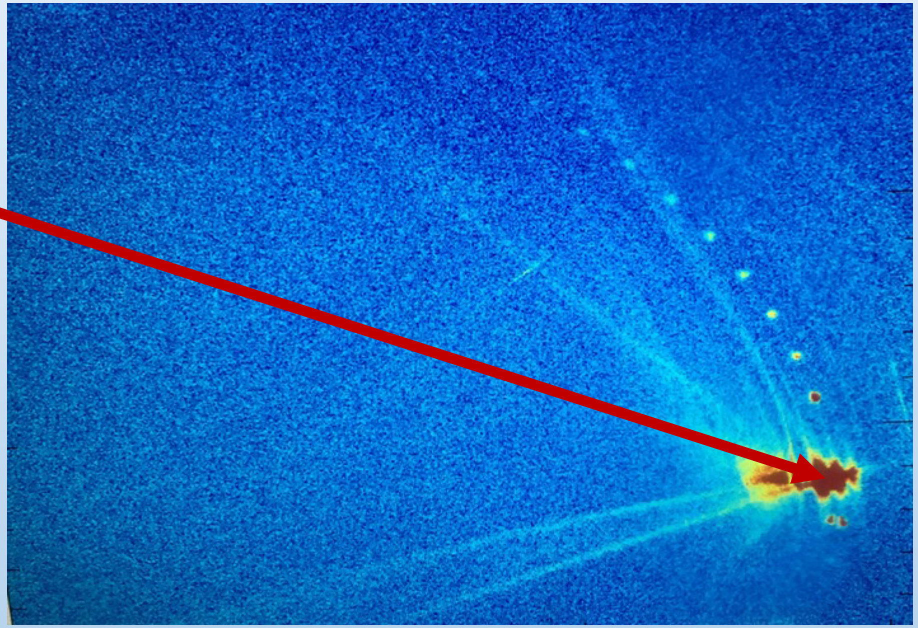
Sparking

- Major limitation so far has been sparking
- Voltage achieved was limited by sparking along nylon bolts holding amplification region together
- Tolerance on bolt hole drilling not sufficient to prevent bare conductors being close
- At high voltages nylon can have conducting tracks etched into it
- DUNE HPgTPC will not use this design



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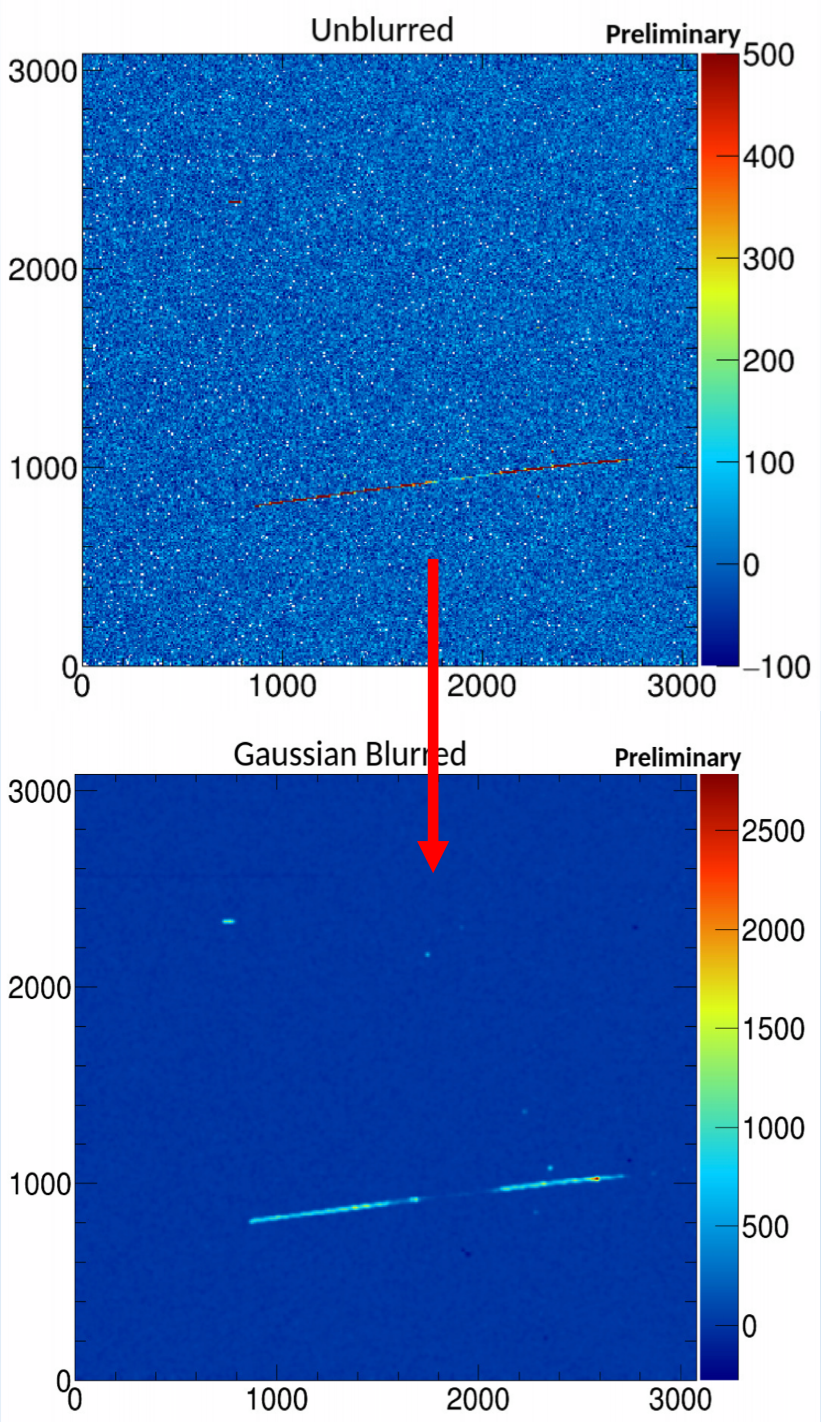
Track Reconstruction

- Some tracks seen by eye in CCD images
- Due to lower than expected voltages most tracks not passing close to amplification region hard to pick out by hand
- Image processing techniques are being used to try to make them more obvious (e.g. Gaussian convolution, Hough transforms)



HPTPC for DUNE

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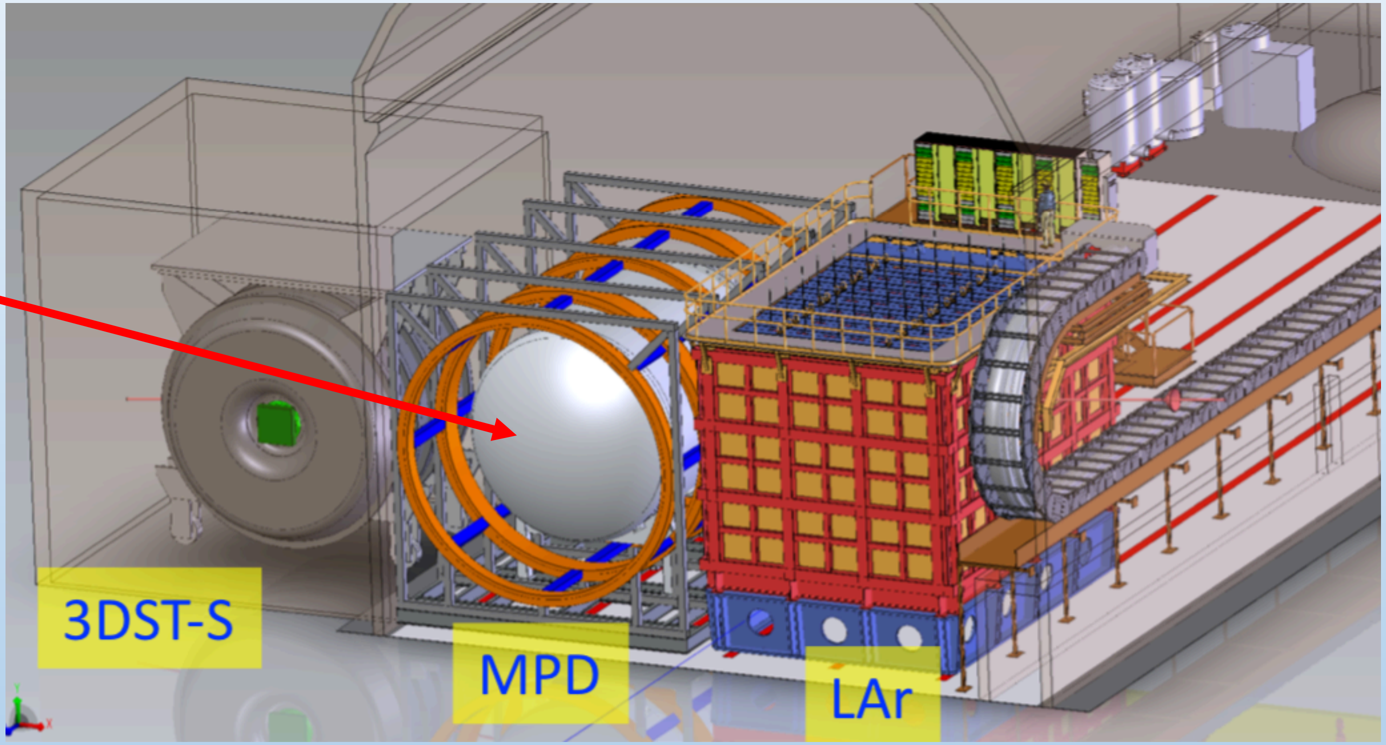
DUNE

- HPgTPC is part of the baseline near detector complex for DUNE
- UK prototype can contribute significantly in preparations for this detector
- Proposal for UK involvement in near detector DAQ as well



DUNE Near Detector HPTPC

- ALICE experiment is upgrading their TPC during LS2
- DUNE detector will use readout chambers (ROCs) from ALICE as their amplification stage
  - Two types of ROCs, small inner (IROCs) and larger outer (OROCs)
- ROCs use wire chamber design which gives better amplification for same voltage

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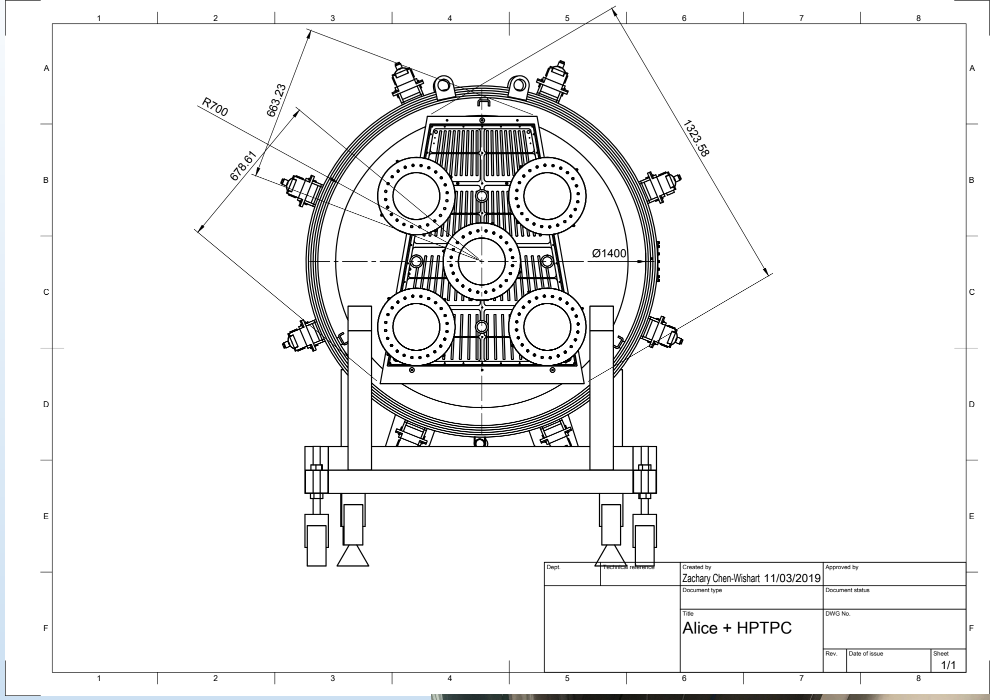
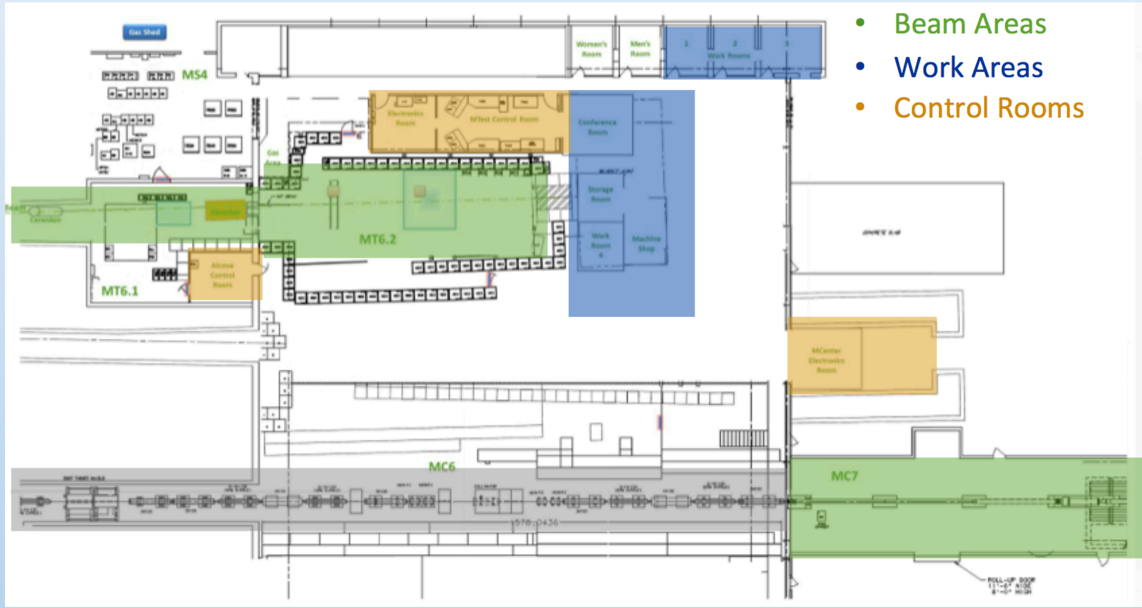
UK Prototype tests for DUNE

- UK HPTPC prototype is only vessel plus field cage available large enough to test OROCs
- Detector now back at Royal Holloway in larger lab ready for upgrade
- Working with DUNE HPgTPC group, one of the OROCs is being tested in London



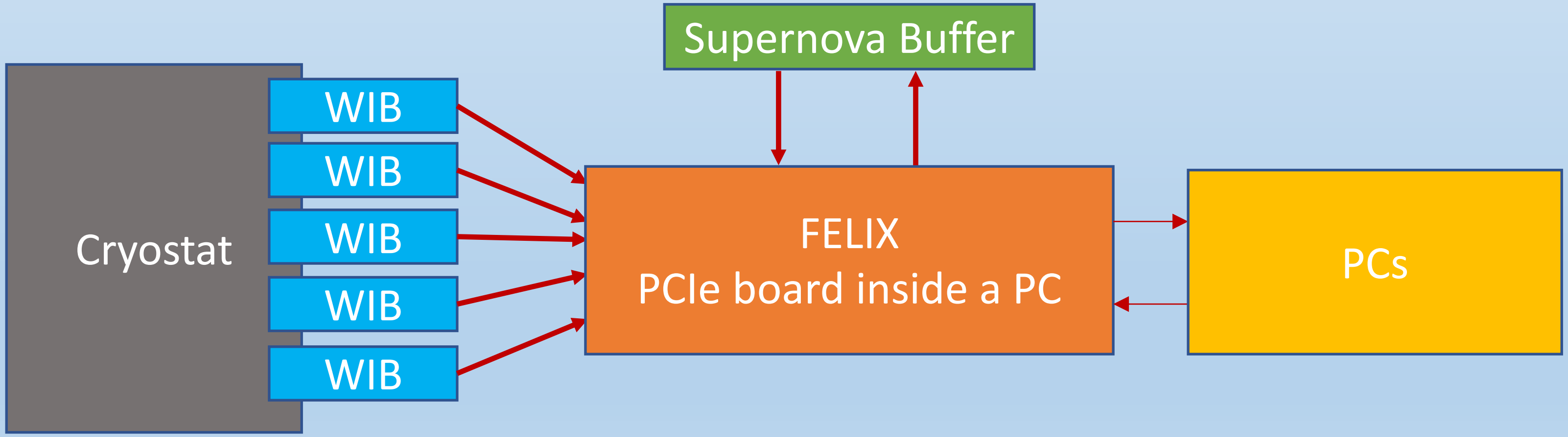
OROC+FNAL beam test

- Test beam facility at Fermilab has beamlines suitable for several month run
- Beam energy is lower than T10 O(200 MeV) so complicated techniques to reduce energy will not be necessary
- UK OROC test stand will be transported to FNAL for beam test in Summer/Autumn 2020



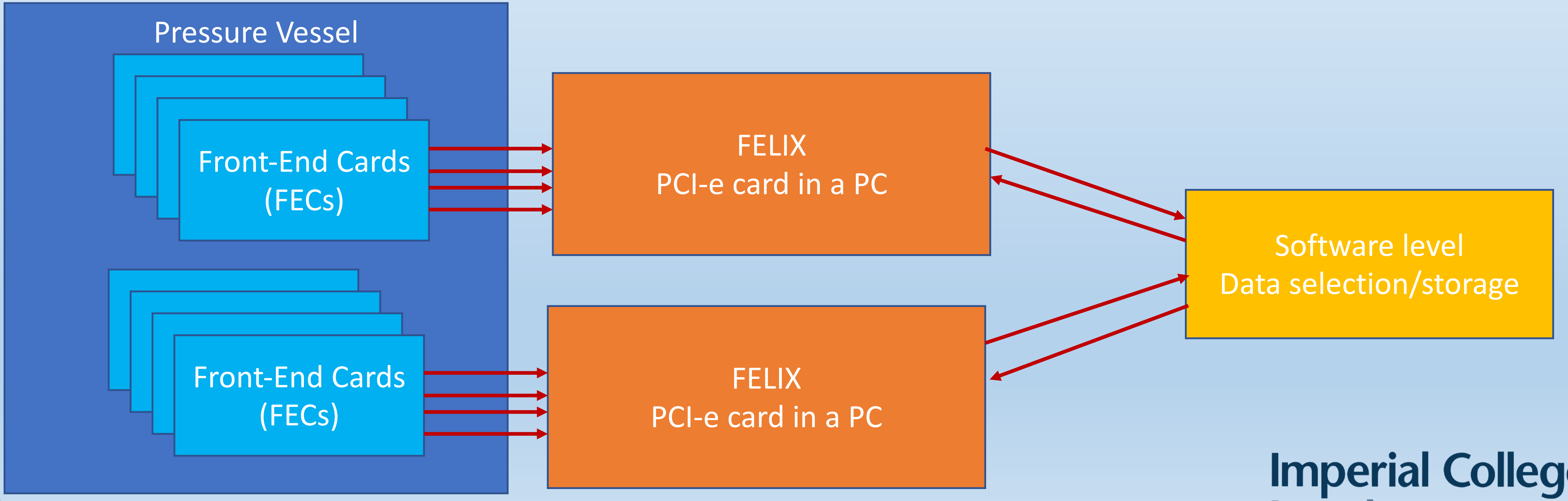
DUNE DAQ

- UK already involved in building DUNE far detector DAQ



DUNE DAQ

- UK already involved in building DUNE far detector DAQ
- Unified near/far detector DAQ has many advantages (expertise/spares etc.)
- Involvement in both DAQ and HPTPC should allow us to make this happen



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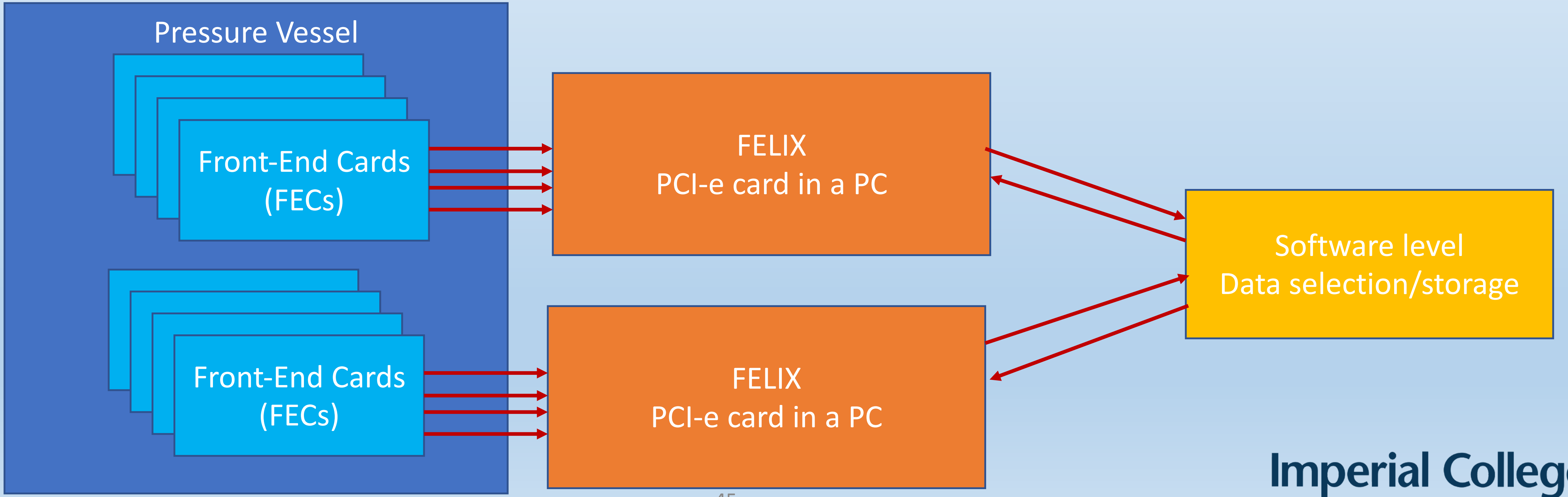
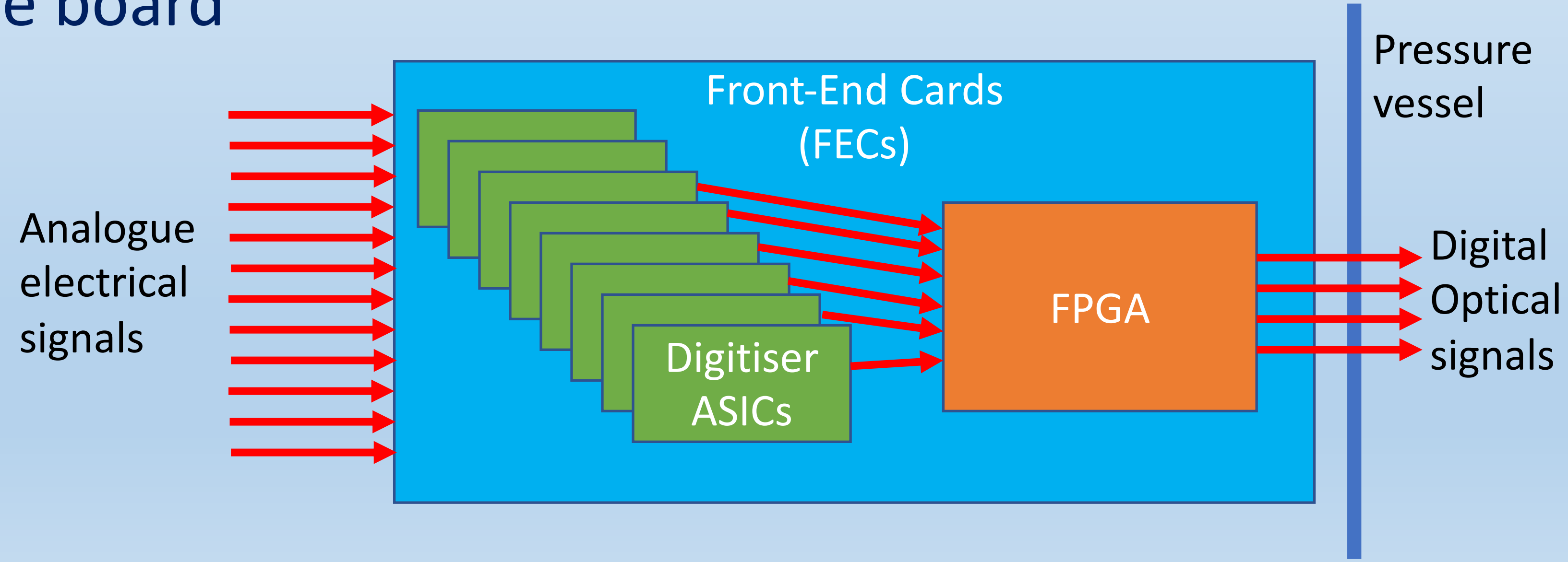
What hardware do we need to develop?

- FELIX's are an already existing board also used for DUNE far detector and ATLAS that can be mounted in off-the-shelf PCs
- FECs don't exist so far and are specific to an HPgTPC
  - I am proposing to design and build them in the UK



Front-end cards (FECs)

- Input is analogue electrical signals from detector
- Primary role is digitization of signals and zero-suppression
- Data then aggregated and converted to optical signal in an FPGA
- Possibility for buffering/low-level processing as will have an FPGA on the board



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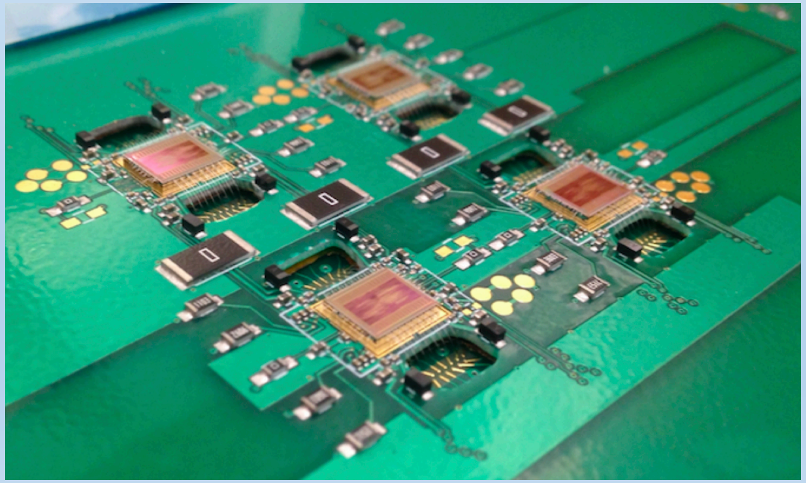
Digitiser ASIC options

- Investigating several options for digitizer ASIC on FECs
- High sampling frequency needed for good longitudinal resolution

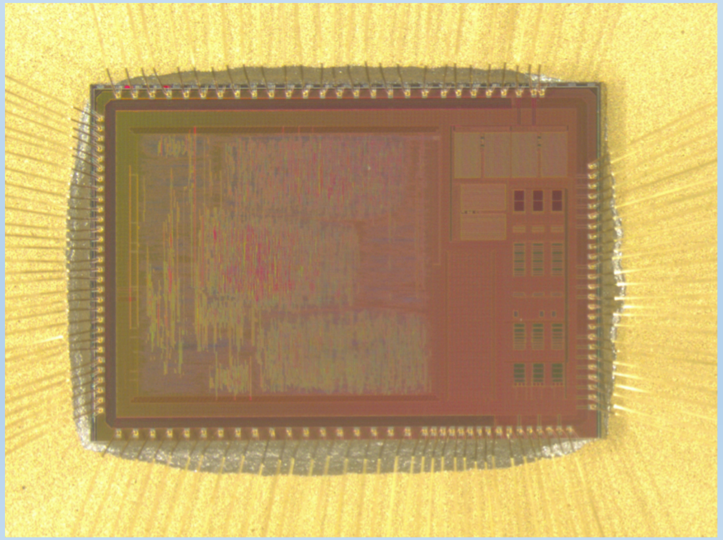
LArPix chip for Argon Cube

- 64 channels at 500 kHz (can be upgraded
- ~100 uW/channel



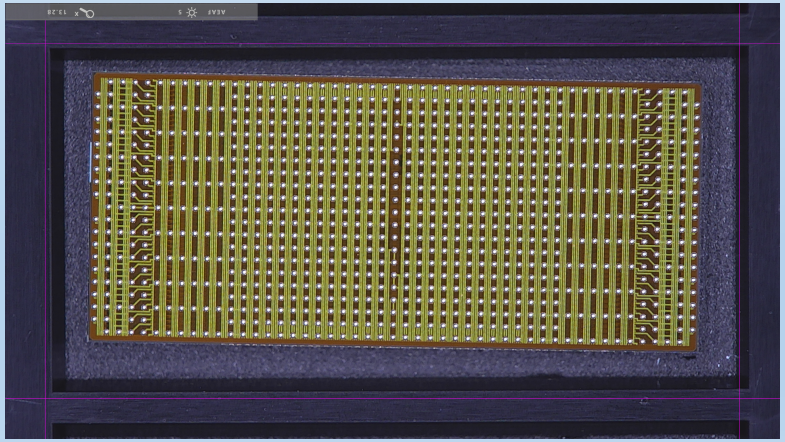
SAMPA chip develop for ALICE TPC upgrage

- 32 channels at 5 or 10 MHz
- ~35 mW/channel



HGROC chip developed for CMS HGCAL

- 72 channels at 40 MHz
- ~15 mW/channel



Summary

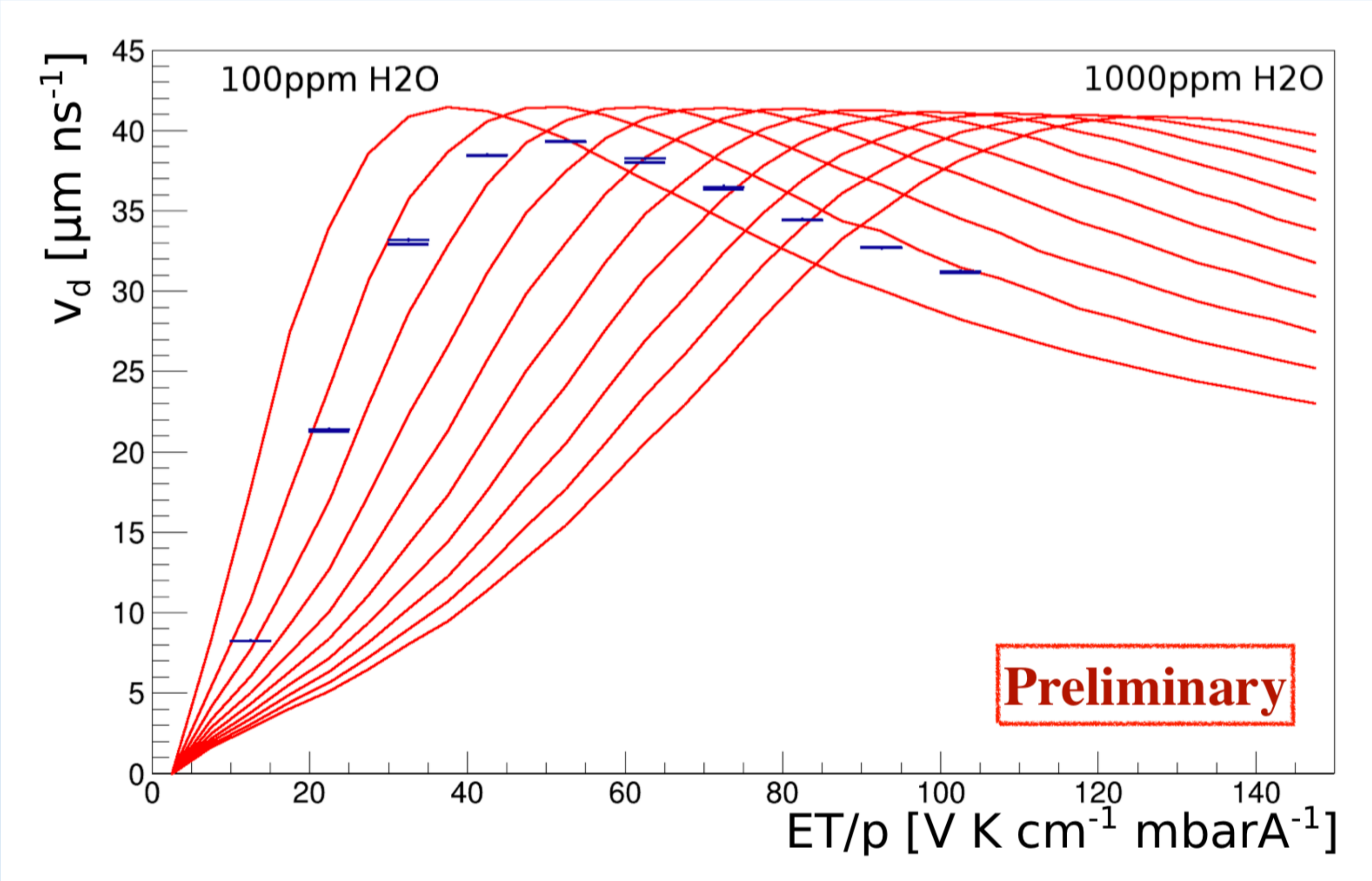
- Prototype HPTPC has been constructed and operated in a beam at CERN
- Analysis of data from CERN underway
  - Tracks have been reconstructed
  - ToF system has demonstrated that beam manipulation techniques worked
- UK HPgTPC group is merging with DUNE ND group
  - Will test DUNE ND readout chambers in beam at FNAL in 2020
  - Proposing to build DAQ for DUNE ND HPgTPC including front-end cards

CERN, RWTH Aachen University, Imperial College, University College London, Lancaster University, University of Geneva, Royal Holloway University of London, University of Warwick

Backup

Gas purity monitoring

- Aachen group tested a gas purity monitor during beam test
- Two radioactive sources at known positions are measured using a wire amplification system
- Scanning electric field allows drift velocity to be measured
- Simulated drift velocity as a function of field shown



Imperial College London

Gaussian Convolution

- Most noise is randomly distributed
  - No pixel to pixel correlation
- Signal is strongly correlated between neighbouring pixels
- Convoluting neighbouring pixels into one another using a Gaussian kernel will therefore reduce background by more than signal increasing significance
- Analysis underway