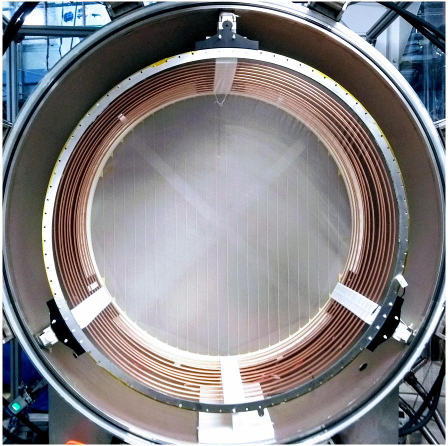
Taking a Time Projection Chamber to high pressure

Alexander Deisting

Royal Holloway, University London

HEP Seminar, University College London
14$^{\text{th}}$ of December, 2018



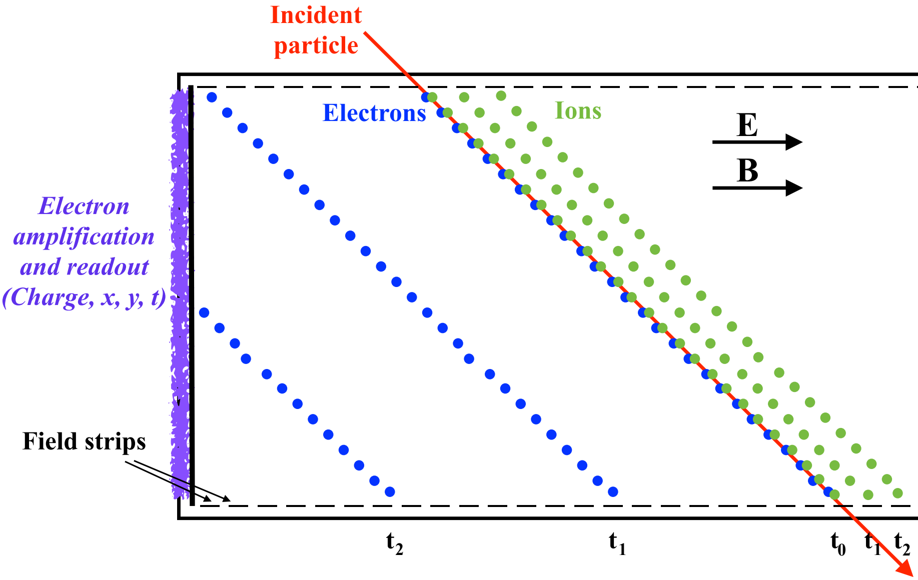
Outline

- Introduction: Time Projection Chambers (TPCs)
- TPCs for neutrino (ν) measurements – Or: Why it is interesting to operate TPCs at High Pressure
  - Implications of operating at $P >$ atmospheric pressure
- The HPTPC prototype and beam test
- Future plans

On the High Pressure Time Projection Chamber the following groups are collaborating:

RWTH Aachen, Universitè de Genéve, Imperial College London, Lancaster University, Royal Holloway University London, University College London, University of Warwick

Time projection chambers



Incident
particle
Electrons
Ions
E
B
Electron
amplification
and readout
(Charge, x, y, t)
Drift
cathode
Gas
volume
Field strips
t_2
t_1
t_0
t_1
t_2

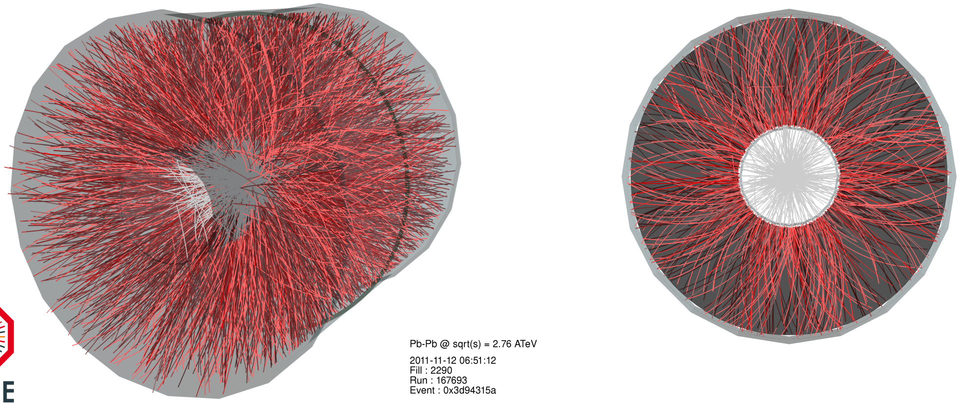
Time Projection Chambers in HEP

Advantages:

- Continuous and low density detection medium $\rightarrow 4\,\pi$ coverage
  - Ideal for particle tracking, 3D reconstruction of a particle's trajectory possible
  - Tracking in high multiplicity events possible
- Low momentum threshold for particle detection
- Particle identification capabilities
- The gas or liquid can be used as target in addition to it being the detection medium

Disadvantages:

- The readout time for each event is at minimum a full drift time: Order of 100 µs
- TPCs can be considered as rate limited at high event rates

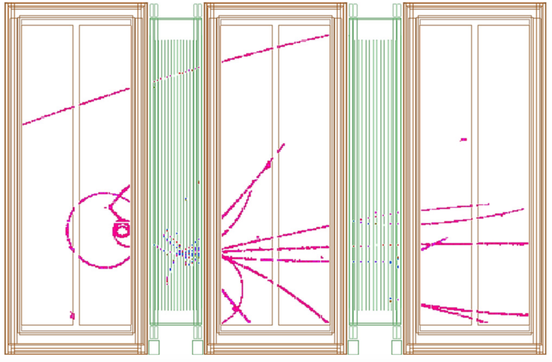


ALICE
A JOURNEY OF DISCOVERY

Time projection chambers for ν measurements

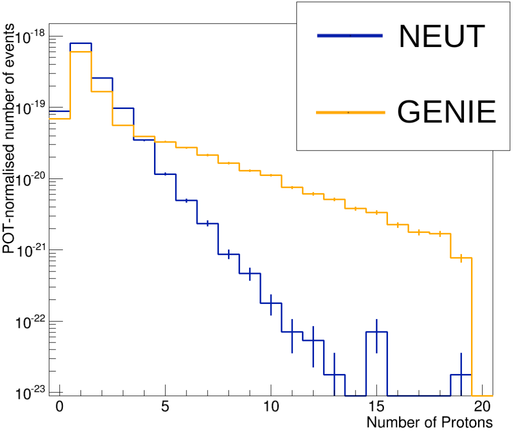
T2K near detector time projection chambers

- T2K examines ν oscillations of ν sent from J-PARC to the Super-Kamiokande detector in 295 km
- 280 m downstream of the production target, the *near detector* is located, including three TPCs
- The near detector measures pre-oscillation charged current neutrino interaction rates
- These are used to reduce uncertainties in the oscillation measurements by the far detector
- Operated at about 750 torr with the *T2K gas mixture:* $\mathrm{Ar}\text{-}\mathrm{CF}_4\text{-}i\mathrm{C}_4\mathrm{H}_{10}$ (95-3-2)



From: NIM A 637 (2011) 25–46

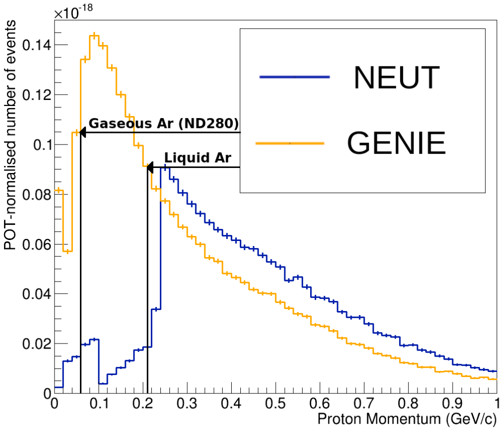
A High Pressure TPC for ν oscillation measurements – 1/2



ν_μ CC interactions on Ar

- T2K's systematic uncertainties on neutrino interactions are currently in the range of 5-7 %
- Future experiments, *i.e.* Dune and Hyper-Kamiokande aim at systematic uncertainties on the level of 1-2 %
- In order to achieve this goal the uncertainties of the nuclear-models used in neutrino Monte Carlo generators (NEUT and GENIE) need to be reduced
- There are currently discrepancy for these models at low hadron momentum are very large and additional experimental input is needed

A High Pressure TPC for ν oscillation measurements – 1/2



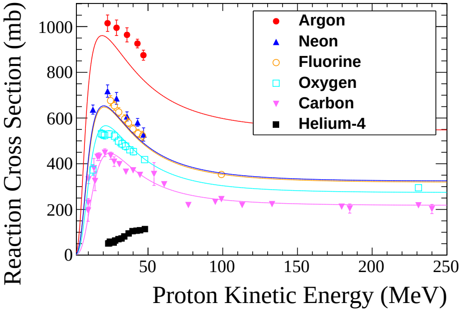
ν_μ CC interactions on Ar

- T2K's systematic uncertainties on neutrino interactions are currently in the range of 5-7 %
- Future experiments, *i.e.* Dune and Hyper-Kamiokande aim at systematic uncertainties on the level of 1-2 %
- In order to achieve this goal the uncertainties of the nuclear-models used in neutrino Monte Carlo generators (NEUT and GENIE) need to be reduced
- There are currently discrepancy for these models at low hadron momentum are very large and additional experimental input is needed

A High Pressure TPC for ν oscillation measurements – 2/2

- I An HPTPC can potentially provide a precise measurement of the multiplicity and momentum distribution of final-state particles, after a ν-nucleus interaction
- II Furthermore a HPTPC could measure hadron-nucleus scattering $\rightarrow$ results are used to tune the way the Monte Carlo generators simulate final state interactions

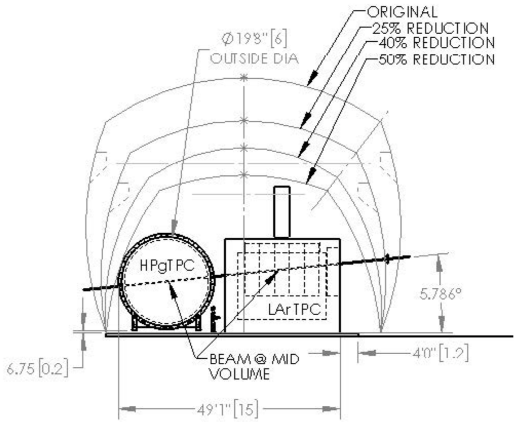
While **I** would be the use of a HPTPC in future experiments, **II** could already be done during the R&D phase



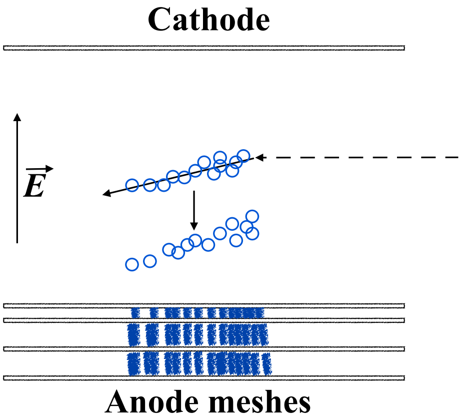
Existing data for proton-nucleus interactions at low proton momentum

DUNE HPgTPC

- Deep Underground Neutrino Experiment (DUNE) decided to have a HPTPC as part of their near detector
- The particular cylindrical shape is driven by the fact that they intend to buy the ALICE TPC readout chambers

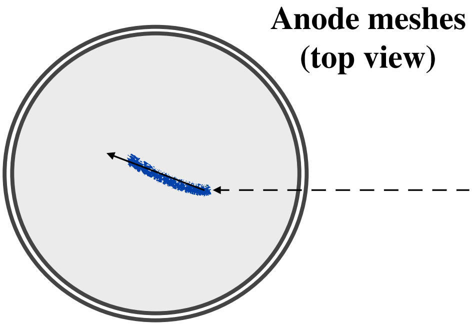


Working principle of the HPTPC



- Primary ionisations in the drift region are guided to the amplification region by an electric field
- A high electric field amplifies the charge, producing electrons and photons during the process
- Cameras image the amplification region and record a 2D projection of the charge $\Rightarrow$ Highly segmented readout at low cost per pixel possible
- Read-out of the induced charge provides additional charge information and the time coordinate

Working principle of the HPTPC

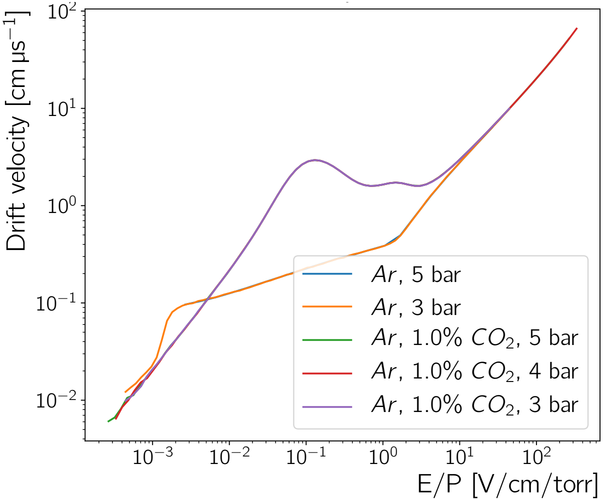


- Primary ionisations in the drift region are guided to the amplification region by an electric field
- A high electric field amplifies the charge, producing electrons and photons during the process
- Cameras image the amplification region and record a 2D projection of the charge $\Rightarrow$ Highly segmented readout at low cost per pixel possible
- Read-out of the induced charge provides additional charge information and the time coordinate

Changing from atmospheric to higher pressure

Operating at higher than atmospheric pressure – Implications:

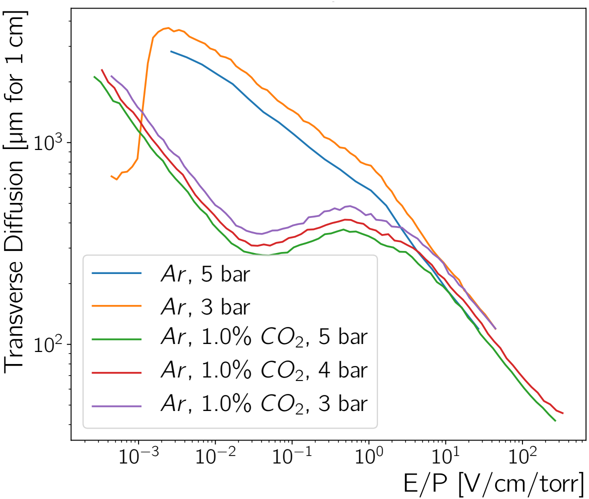
- Higher interaction probability *i.e.* more ν interactions in the detector volume
- Larger primary ionisation density
- Need for a high pressure vessel
- A high voltage power supply is needed to compensate for the E/P scaling
- High voltage feed-throughs which can isolate the necessary high voltage from other nearby conductors



Magboltz simulations

Operating at higher than atmospheric pressure – Implications:

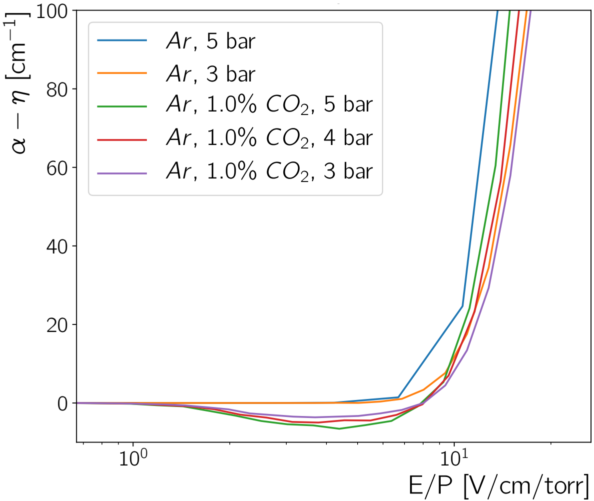
- Higher interaction probability *i.e.* more ν interactions in the detector volume
- Larger primary ionisation density
- Need for a high pressure vessel
- A high voltage power supply is needed to compensate for the E/P scaling
- High voltage feed-throughs which can isolate the necessary high voltage from other nearby conductors



Magboltz simulations

Operating at higher than atmospheric pressure – Implications:

- Higher interaction probability *i.e.* more ν interactions in the detector volume
- Larger primary ionisation density
- Need for a high pressure vessel
- A high voltage power supply is needed to compensate for the E/P scaling
- High voltage feed-throughs which can isolate the necessary high voltage from other nearby conductors



Magboltz simulations

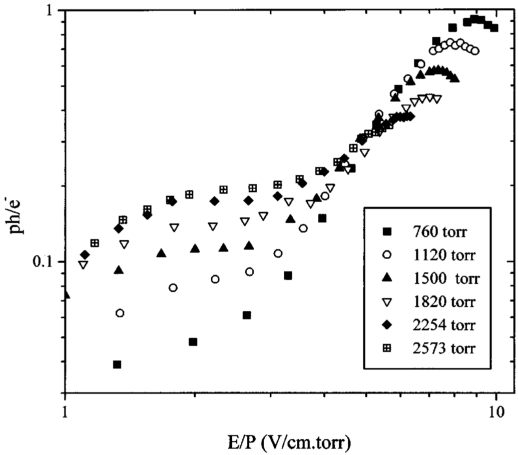
Operating at higher than atmospheric pressure – Implications:

- Higher interaction probability *i.e.* more ν interactions in the detector volume
- Larger primary ionisation density
- Need for a high pressure vessel
- A high voltage power supply is needed to compensate for the E/P scaling
- High voltage feed-throughs which can isolate the necessary high voltage from other nearby conductors

Gas amplification

$$N_e = N_0 \exp\left(\int_{x_0}^{x_1} \alpha - \eta\left(\frac{E(x)}{N}\right) \mathrm{d}x\right)$$

Light yield for different gas mixtures

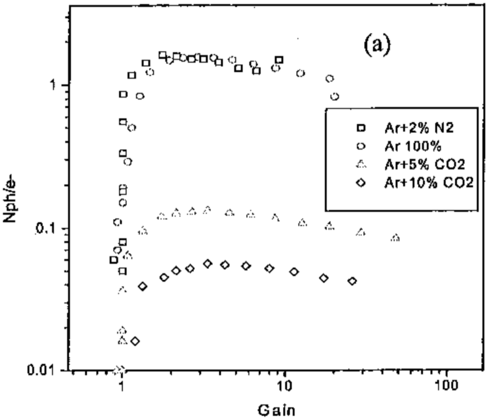


IEEE, VOL. 48, NO. 3, JUNE 2001

- Measurements of the photon-to-electron ration in pure Argon and various mixtures with Argon pre-dominance in the near infra-red region 400 nm to 1000 nm
- At high electric fields the light emission levels off $\rightarrow$ transition to a purely ionising regime
- While a quencher like $\mathrm{CO_2}$ improves operational stability (*i.e.* less sparks), it decreases the light yield

Figure: Pure Ar, various P

Light yield for different gas mixtures

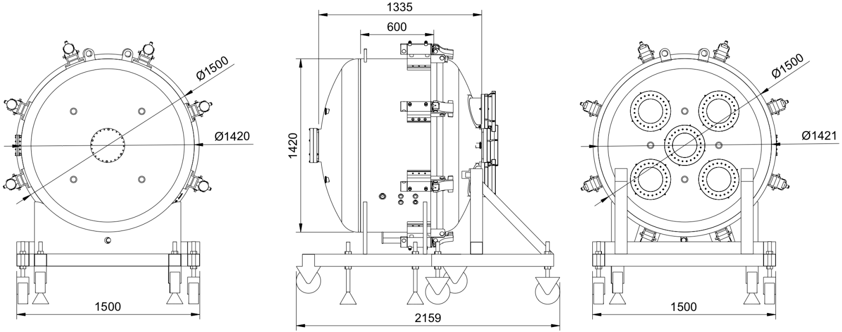


IEEE, VOL. 47, NO. 3, JUNE 2000

- Measurements of the photon-to-electron ration in pure Argon and various mixtures with Argon pre-dominance in the near infra-red region 400 nm to 1000 nm
- At high electric fields the light emission levels off → transition to a purely ionising regime
- While a quencher like CO_2 improves operational stability (*i.e.* less sparks), it decreases the light yield

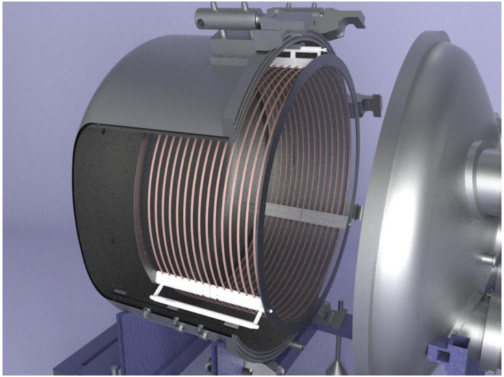
Figure: $P \sim 750$ torr

The HPTPC prototype



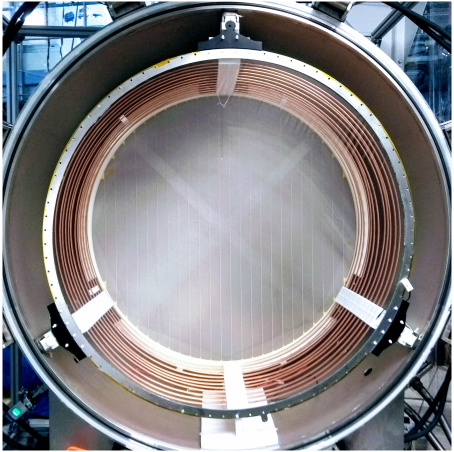
High pressure TPC prototype

- 44.7 cm drift length, enclosed by a field cage with 12 field strips
- One high transparency mesh serves as cathode
- Three meshes serve as amplification region (distances: 0.5 mm, 1 mm)
- The voltages on the meshes in the cascade and on the cathode can be set independently
- Charge read-out of the last three anode meshes
- The TPC is embedded in a pressure vessel allowing gas pressures of up to 5 barG



High pressure TPC prototype

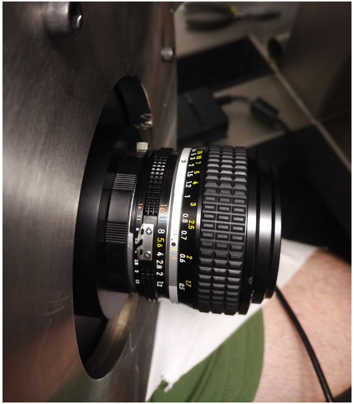
- 44.7 cm drift length, enclosed by a field cage with 12 field strips
- One high transparency mesh serves as cathode
- Three meshes serve as amplification region (distances: 0.5 mm, 1 mm)
- The voltages on the meshes in the cascade and on the cathode can be set independently
- Charge read-out of the last three anode meshes
- The TPC is embedded in a pressure vessel allowing gas pressures of up to 5 barG



High pressure TPC prototype

- 44.7 cm drift length, enclosed by a field cage with 12 field strips
- One high transparency mesh serves as cathode
- Three meshes serve as amplification region (distances: 0.5 mm, 1 mm)
- The voltages on the meshes in the cascade and on the cathode can be set independently
- Charge read-out of the last three anode meshes
- The TPC is embedded in a pressure vessel allowing gas pressures of up to 5 barG

Optical readout



- Four FLI Proline PL09000 CCD cameras are mounted on the TPC, each is centred on one quadrant of the readout area
- The cameras have 3056×3056 pixel, $15\,\mu m$ pixel length
- Each pixel images a square on the amplification plane with $230\,\mu m$ side length $\Rightarrow$ In total a region of $71 \times 71\,cm$ per camera
- The internal Peltier cooler, together with an external chiller for water cooling are capable of cooling the cameras down to $-30\,^{\circ}C$
- They are each coupled to a Nikon f/1.2 50mm focal length lens and focused onto the amplification region

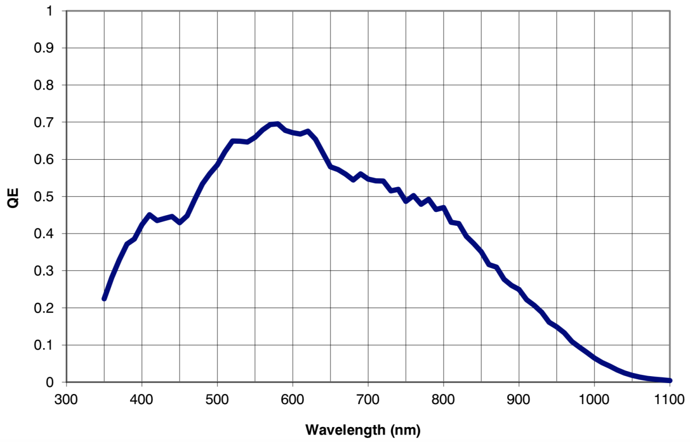
Optical readout

- Four FLI Proline PL09000 CCD cameras are mounted on the TPC, each is centred on one quadrant of the readout area
- The cameras have 3056×3056 pixel, 15 µm pixel length
- Each pixel images a square on the amplification plane with 230 µm side length $\Rightarrow$ In total a region of 71×71 cm per camera
- The internal Peltier cooler, together with an external chiller for water cooling are capable of cooling the cameras down to $-30\,^{\circ}\mathrm{C}$
- They are each coupled to a Nikon f/1.2 50mm focal length lens and focused onto the amplification region

Optical readout

- Four FLI Proline PL09000 CCD cameras are mounted on the TPC, each is centred on one quadrant of the readout area
- The cameras have 3056×3056 pixel, $15\,\mu m$ pixel length
- Each pixel images a square on the amplification plane with $230\,\mu m$ side length $\Rightarrow$ In total a region of $71 \times 71\,cm$ per camera
- The internal Peltier cooler, together with an external chiller for water cooling are capable of cooling the cameras down to $-30\,^{\circ}C$
- They are each coupled to a Nikon f/1.2 50mm focal length lens and focused onto the amplification region

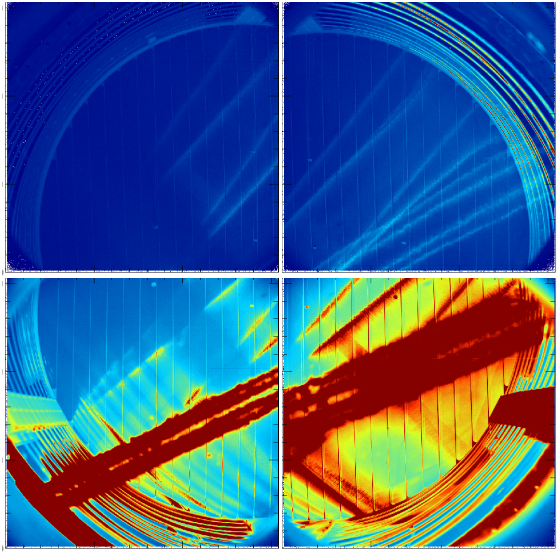
CCD & optical path efficiency



- The cameras are sensitive in a similar wavelength range as probed by the afore presented measurements
- Considering the full optical path including quartz window and lens, we expect up to 1×10^{-4} acceptance
- This factor has to be compensated for with a higher light gain in the gas amplification stage

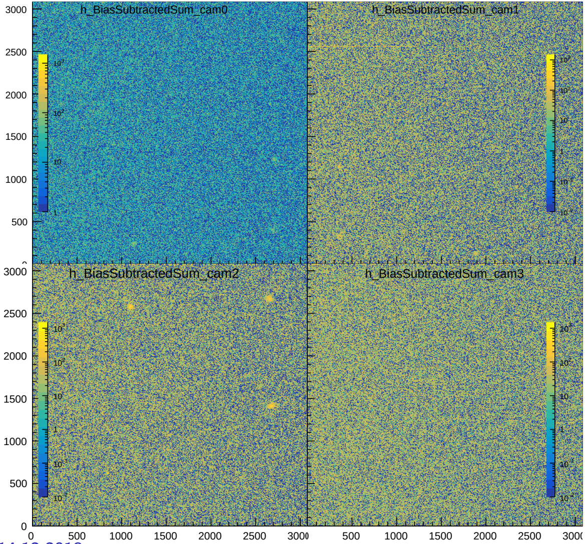
Camera image of a spark

- In case of sparking inside the TPC, the whole detector is illuminated
- Permanent sparking inside the detector can be potentially harmful
- Occasional sparks can however be used to gain position information
- In the spark picture here, the calibration source positions can be clearly identified

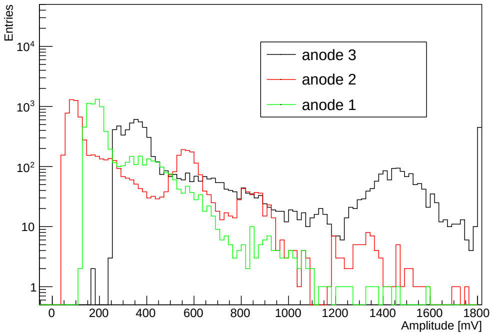


Calibration sources

- Five α sources are installed in the overlap regions between the cameras in a distance of about 5 cm from the anode meshes
- The measurement has been done in 100 % Ar at 3 barA with $V_1 = 1500\,\mathrm{V}$, $V_2 = 2900\,\mathrm{V}$, $V_3 = 3750\,\mathrm{V}$, $V_\mathrm{C} = -8500\,\mathrm{V}$
- The light from these sources can be used to calibrate the light gain
- All sources are moveable in z, hence a rough diffusion measurement can be done



Charge readout



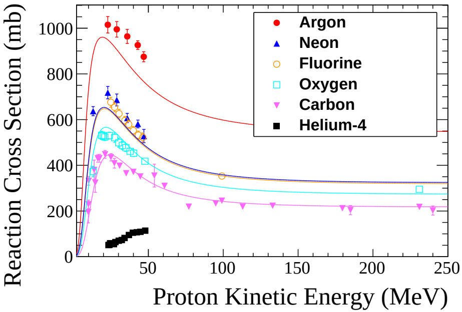
- Having the 2D projection from the camera, the third coordinate will be reconstructed from the time information of the induced charge on the meshes
- During one camera exposure a certain number of charge signals are recorded $\rightarrow$ these have to be matched with events in the camera exposures
- Charge signals are decoupled from the high voltage supply line, amplified with CREMAT CR113 pre-amplifiers ($1.2\,\mathrm{mV\,pC^{-1}}$) and fed into a digitiser

HPTPC beam time at CERN's PS

Beam test in T10 from 15^{th} of August to 17^{th} of September

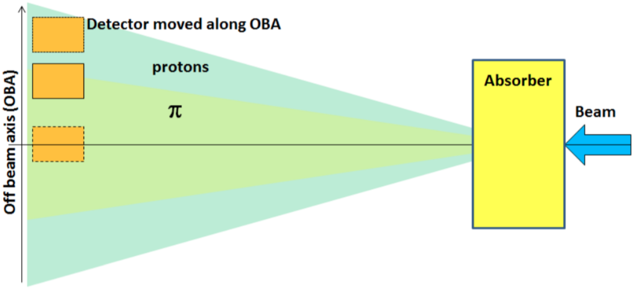
T10 beam time: Dates and goals

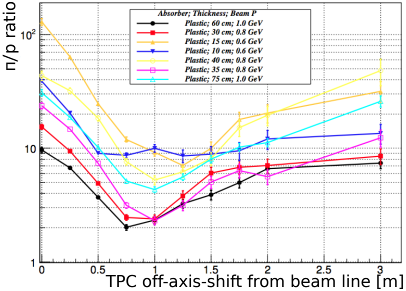
- Goal: Measuring proton-Argon (pAr) cross section with low momentum protons ($p_{\mathrm{p}} \lesssim 0.5\,\mathrm{GeV/c}$)
- 2 Time Of Flight (TOF) systems used for beam characterisation, one of which uses SiPMs coupled to the scintillator bars instead of PMTs.
- High Pressure Gas Monitoring Chamber (HPGMC) to monitor the gas quality



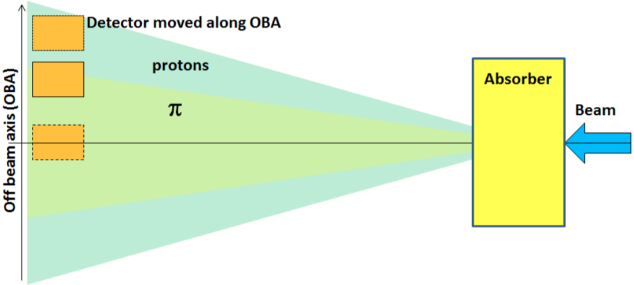
Reminder: Existing data for proton-nucleus interactions at low proton momentum

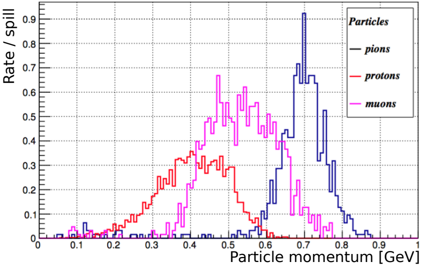
Off axis technique: enhancing the proton to pion ratio





Off axis technique: enhancing the proton to pion ratio



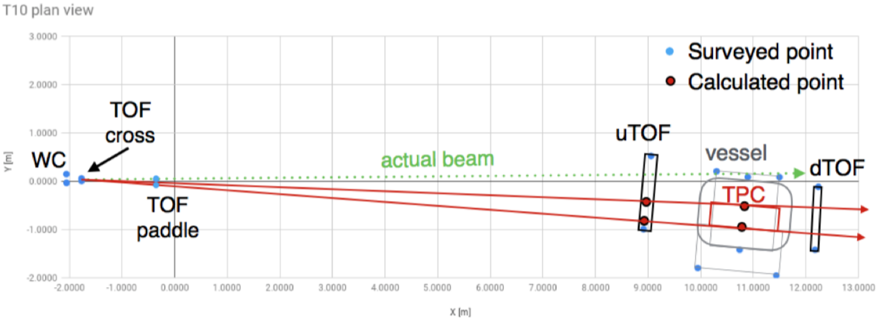


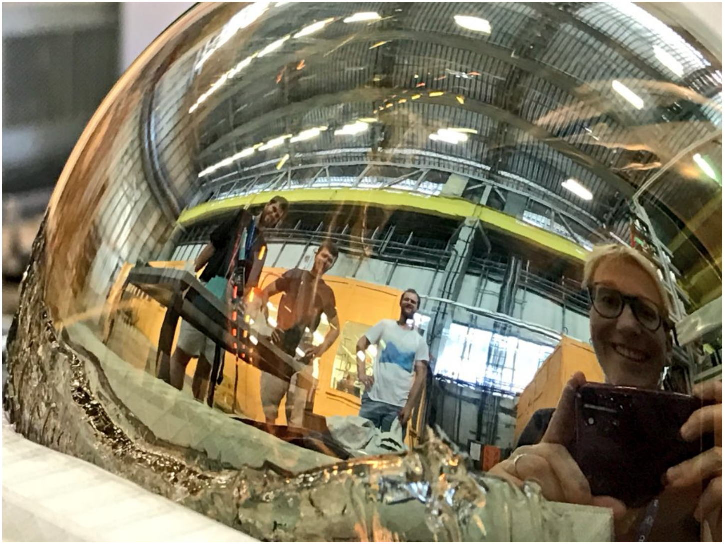
GEANT4 simulations – Optimised settings with respect to low proton momentum and low π/p ratio and the proton momentum distribution are achieved for:

- $\sim 35\,\mathrm{cm}$ long plastic absorber
- $0.6\,\mathrm{GeV/c}$ to $0.8\,\mathrm{GeV/c}$ beam energy (hadron beam)

HPTPC beam test in T10

- Beam impinges on a plastic absorber
- TPC active area is displaced by 3.5° with respect to the beam axis
- TOF systems are placed upstream- (uTOF) and downstream (dTOF) of the TPC
- HPGMC is placed as well in T10, close to the TPC






ARRET D'URGENCE
GENERAL

Data taking conditions

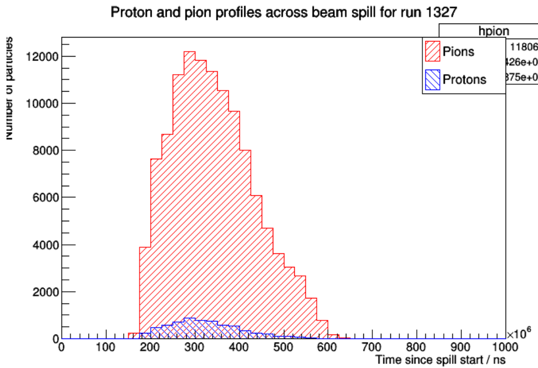
HPTPC

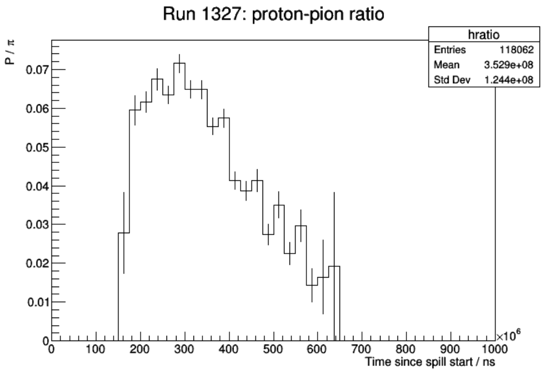
- Data taking at different pressures from 1 barA to 5 barA
- Different gas mixtures were employed: Pure Ar, $\mathrm{Ar\text{-}CF_4}$, $\mathrm{Ar\text{-}CO_2}$, $\mathrm{Ar\text{-}N_2}$ and $\mathrm{Ar\text{-}CO_2\text{-}N_2}$ – quencher content in the 0.5 % to 3 % range
- Beam triggered data as well as *gain data*, dedicated to image the calibration sources
- Data without high voltage to check for beam interactions within the camera silicon
- Off-axis as well as on-axis measurements

TOF Systems

- Beam energy scans
- Off-axis and on-axis measurements
- Absorber tests

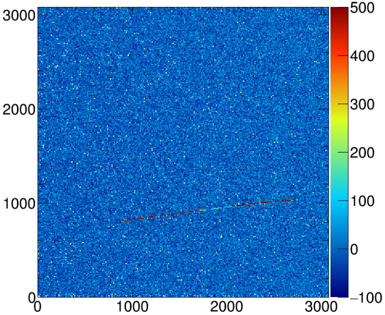
Downstream TOF measurement example





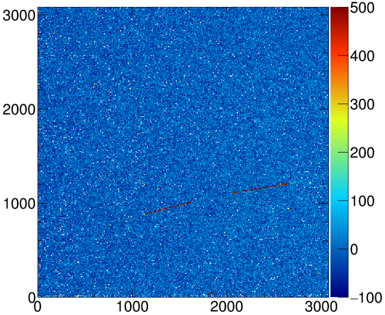
- Beam momentum 0.8 GeV/c
- 4 moderator blocks inside
- 260 spills

Tracks in the HPTPC



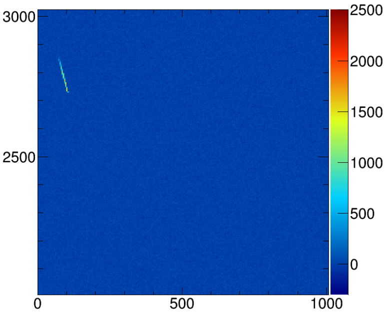
- In general: The HPTPC gas gain was limited by sparks of the amplification region
- Calibration (α) sources were visible in the raw data
- Only the tracks with the lowest diffusion were visible in the raw data
  - Tracks crossing /close to the amplification region
- Most tracks have a length on the order of a cm or less
- High level tracking algorithm under development $\rightarrow$ recover the tracks with large diffusion
- The maximal diffusion over the whole drift length can amount to several mm – a reconstruction challenge

Tracks in the HPTPC



- In general: The HPTPC gas gain was limited by sparks of the amplification region
- Calibration (α) sources were visible in the raw data
- Only the tracks with the lowest diffusion were visible in the raw data
  - Tracks crossing /close to the amplification region
- Most tracks have a length on the order of a cm or less
- High level tracking algorithm under development $\rightarrow$ recover the tracks with large diffusion
- The maximal diffusion over the whole drift length can amount to several mm – a reconstruction challenge

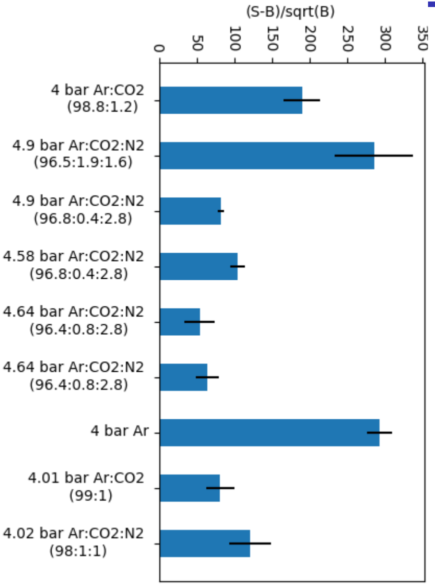
Tracks in the HPTPC



- In general: The HPTPC gas gain was limited by sparks of the amplification region
- Calibration (α) sources were visible in the raw data
- Only the tracks with the lowest diffusion were visible in the raw data
  - Tracks crossing /close to the amplification region
- Most tracks have a length on the order of a cm or less
- High level tracking algorithm under development $\rightarrow$ recover the tracks with large diffusion
- The maximal diffusion over the whole drift length can amount to several mm – a reconstruction challenge

High Pressure TPC light yield measurements

- One of the α source mounted inside the TPC was consistently visible in the raw data at CERN
- Using the brightness of this source, we made a preliminary light yield measurement for different gas mixtures
- The measurements were performed at the highest voltages at which the amplification region could be stably operated
- The source brightness in a square region containing the 3.5 MeV α source is integrated and bias subtracted, then normalised with respect to the exposure time
- After pure Ar, Ar-CO_2-N_2 (96.5-1.9-1.6) performs best in terms of light yield



CERN beam time summary

- The HPTPC has been tested with a 0.8 GeV/c hadron beam at T10/PS
- During this test the gas gain was limited by sparking in the amplification region
- A wealth of data (camera exposures / waveforms from the mesh read-out) has been recorded to disk

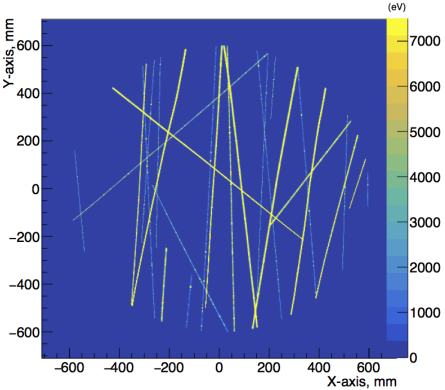
Work in progress

- Calibration measurement campaign at RHUL
- Analysis of the calibration data taken right now at RHUL
- Analyse the beam test data with optimized reconstruction algorithms
- Development of a new analysis framework, *Response in Argon to Protons at pressures of 3750 torr* rapTorr
- Adopting the TREX reconstruction from T2K for track-finding to our data
  - This includes the introduction of a cluster finding algorithm, allowing to identify tracks with large diffusion

Future developments

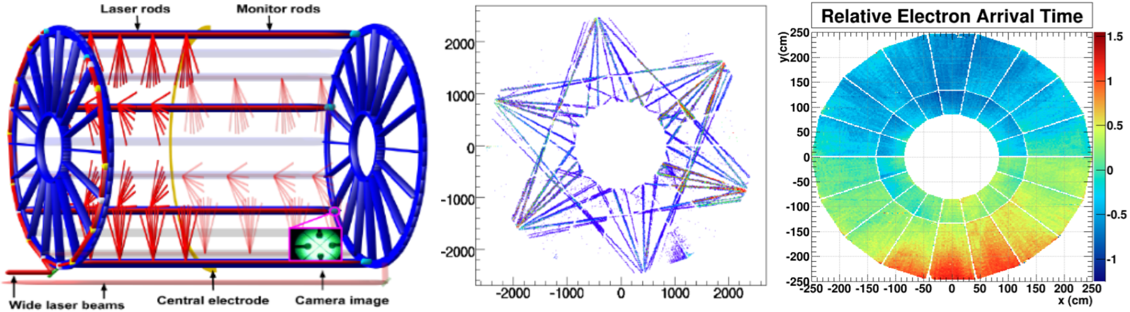
Future work

- Tune detector Monte Carlo simulation using the large data set acquired
- Determine the $\mathrm{d}\varepsilon/\mathrm{d}x$ of the measured tracks, Extracting the scattering cross section
- Technical paper on the HPTPC
- Continue to further develop the detector and coordinate wider HPTPC R&D efforts
  - Improve the gas amplification stage: New meshes or Gas Electron Multipliers
  - Explore the feasibility of a laser calibration system



HPTPC MC simulation, pre-test beam

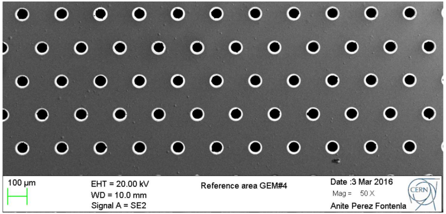
Example: The ALICE TPC laser calibration system



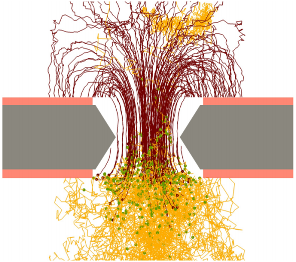
- An ultra-violet laser (266 nm) is guided into the TPC, split and produces tracks at defined positions
- Stray-light hits the cathode and ejects photo electrons which drift the full drift distance

Gas Electron Multiplier foils

- 50 µm polyimide foils with a 5 µm copper cladding on both sides
- Hexagonal hole pattern with a standard pitch of 140 µm



GEM cross section with simulation:



For tests at RHUL we just received:

- Four thick GEMs: 400 µm thick, hole diameter of 350 µm, and a pitch of 600 µm
- Two standard GEMs

Summary

- A High Pressure TPC prototype has been commissioned, which can be operated at up 5 barA
- The prototype is still in the test phase – we are learning still a lot
- In the last 4.5 months the project moved at quite a high speed
- During that time HPTPC has been successfully employed at CERN PS
- Currently we are about to conclude the calibration campaign at RHUL phase
- The next steps are already planned
- Test beam data under-way... **Stay tuned!**