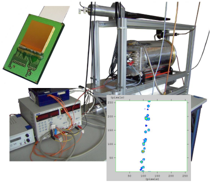
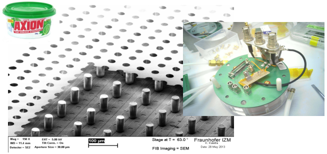
Lessons learned from recent gas TPCs

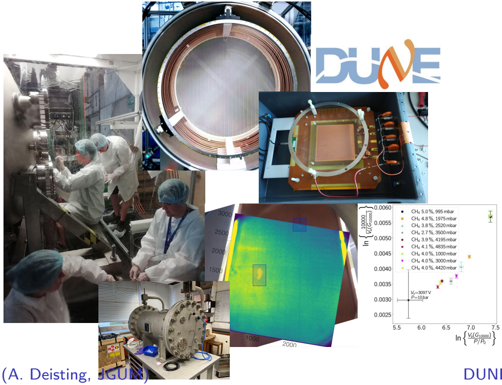
A. Deisting – deisting@uni-mainz.de

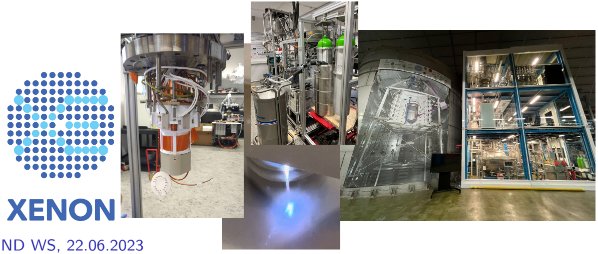
DUNE Phase II Near Detector Workshop, 22th June 2023




AXION
Fraunhofer IZM
FIB Imaging = SEM
100 µm


ALICE


DUNE


XENON

Some lessons learned from some (recent) gas TPCs...

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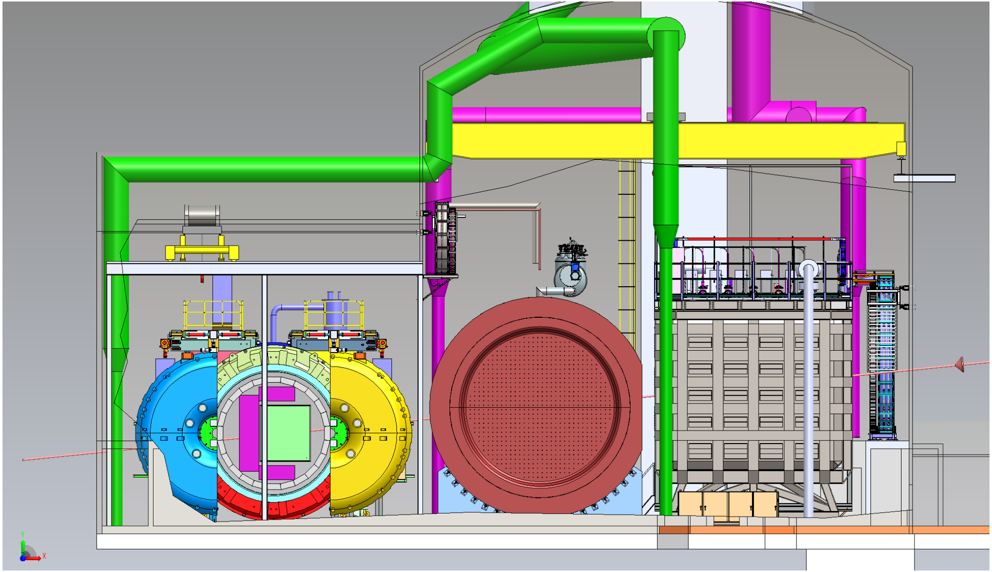
From Mary's slides on Tuesday: "*Identify candidate Phase II ND designs and assess their maturity and R&D needs: For e.g. ND-GAr, SAND upgrades for scattering physics..*"

These slides: Some comments on the gas filled TPC as a candidate technology

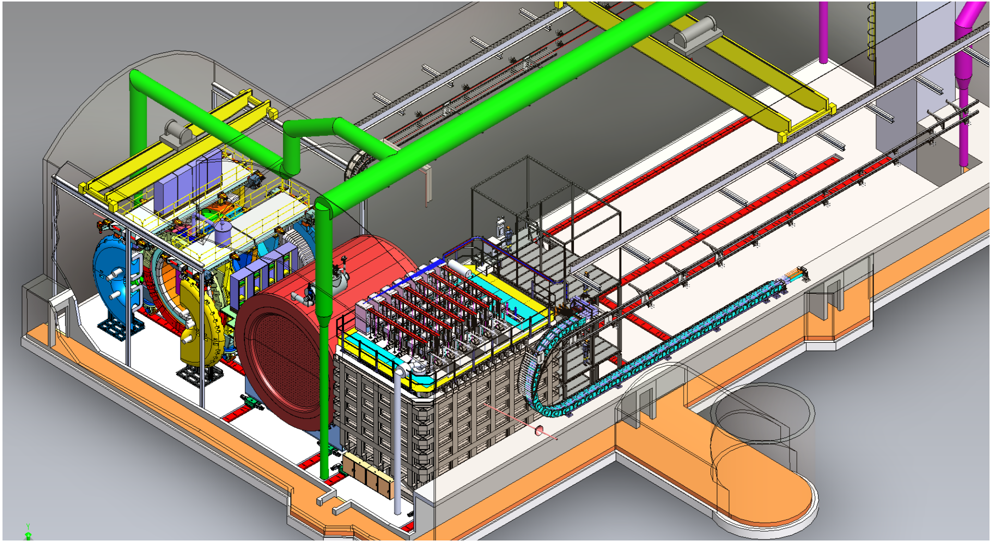
Outline

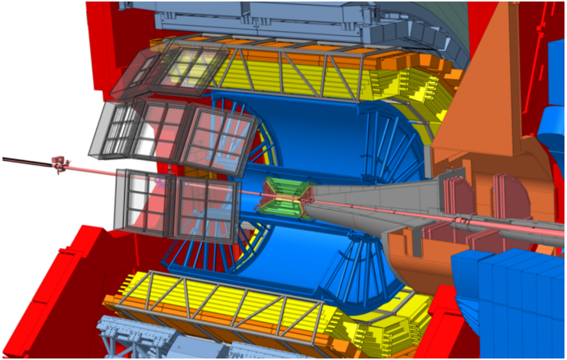
- The white paper ND-GAr (and the ALICE TPC)
- Comments on TPC performance
- How to amplify and readout the signals of the primary ionisations
- The counting gas
- TPC calibration
- Summary

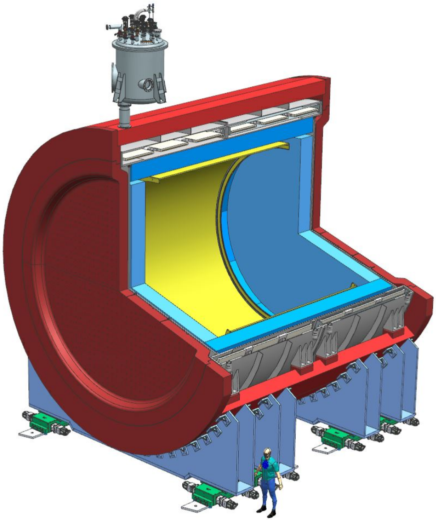
TPC designs



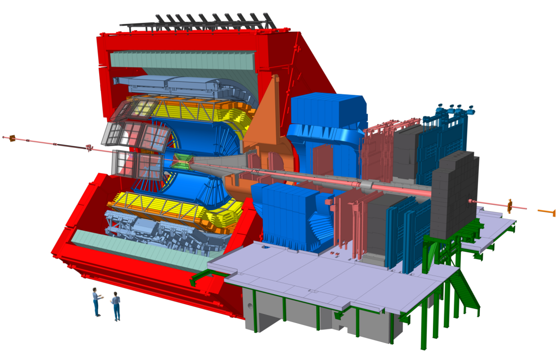
Y
X

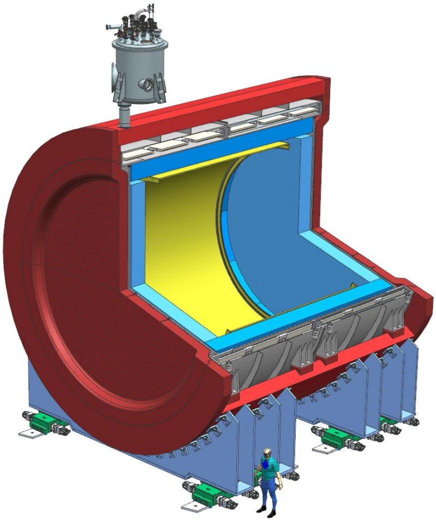






- Readout chambers (ROCs) of pre-Run3 ALICE TPC were/are considered for ND-GAr
- ND-GAr shape influenced by the ALICE TPC design ($\rightarrow$ collider TPC)





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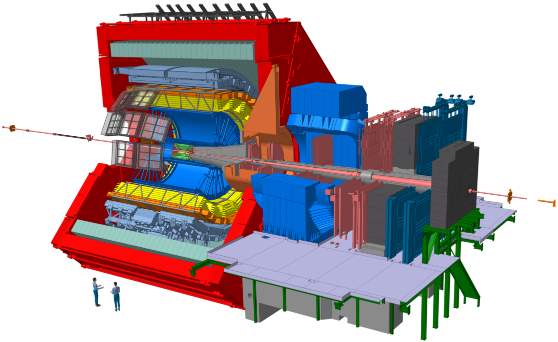

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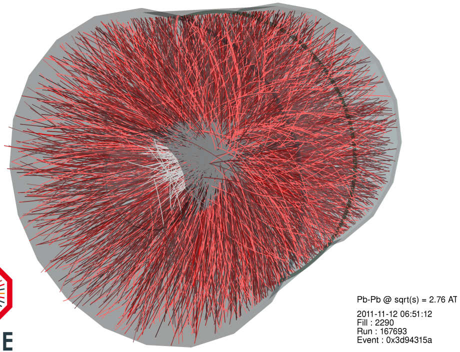
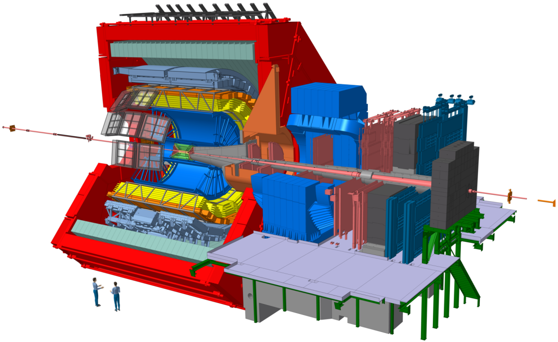
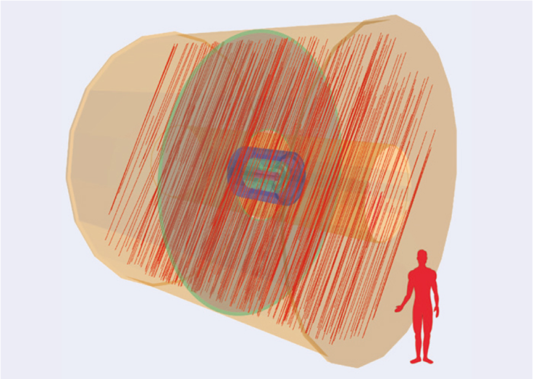
ALICE
A JOURNEY OF DISCOVERY







(ALICE looks to the skies (part II))

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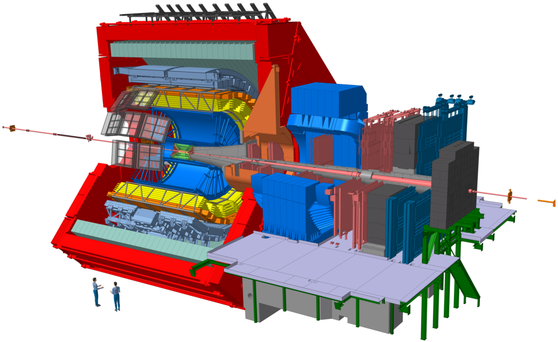

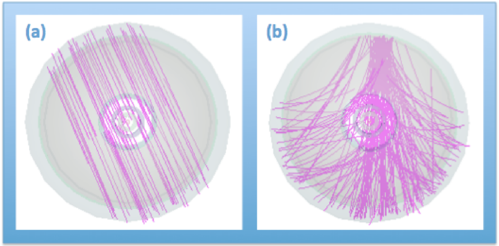

(Study of muon bundles from extensive air showers with ALICE detector at the LHC, Katherin Shtejer Diaz)

- Readout chambers (ROCs) of pre-Run3 ALICE TPC were/are considered for ND-GAr
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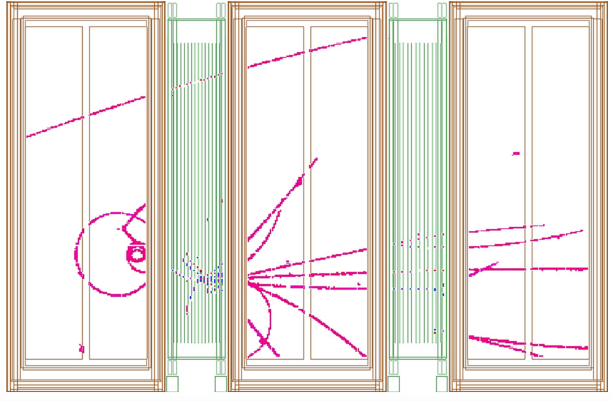
Other shapes are available



T2K ND280 TPCs

NIM A 637 (2011) 25–46

TPC performances and DUNE ND needs

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- Performance comments: Next slides

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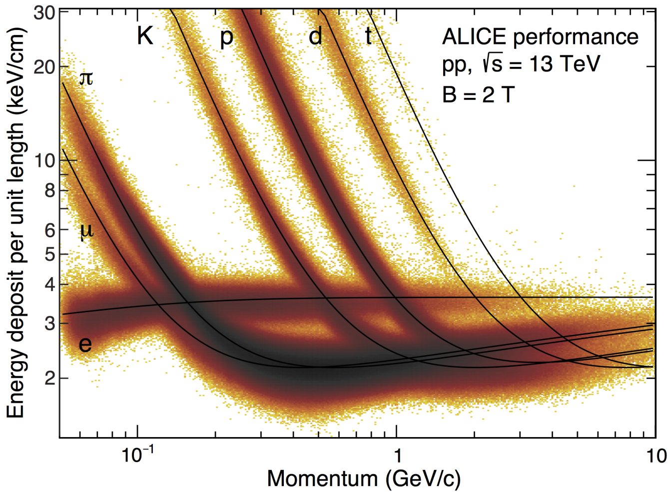
- Requirements for the DUNE ND: Not yet precisely defined, **but**:
- Needs to track μons from ND-LAr
- Measure ν-nucleus scattering cross sections $\rightarrow$ charged πons, Kons, protons

TPC performances and DUNE ND needs

- Performance comments: Next slides
- Requirements for the DUNE ND: Not yet precisely defined, **but**
- Needs to track μons from ND-LAr
- Measure ν-nucleus scattering cross sections $\rightarrow$ charged πons, Kons, protons
- ... also measure neutrons, γs

ALICE TPC: Particle identification and tracking resolution



The ALICE TPC at atmospheric pressure:

$d\varepsilon/dx$:

- 5.2 % in pp collisions
- 6.5 % in PbPb collisions, *i.e.* high track densities

Transverse momentum:

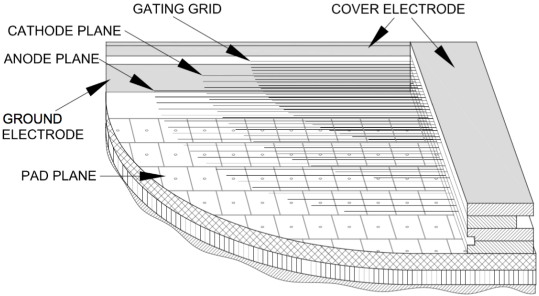
- $\sim 6\,\%$ for particles with $p \sim 10\,\mathrm{GeV/c}$
- $< 1\,\%$ for particles with $p \sim 1\,\mathrm{GeV/c}$

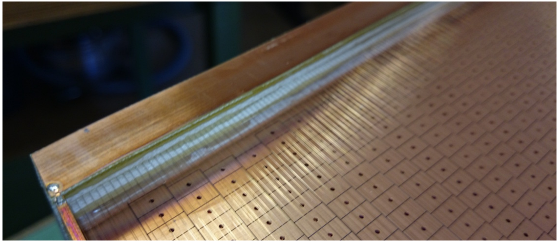
PID for neutrino nucleus scattering cross section measurements

- Pressure $\gg 1\,\mathrm{atm} \rightarrow$ width of the $\mathrm{d}\varepsilon/\mathrm{d}x$ will significantly reduce. (The reason PEP4 is still up on the top considering PID)
- PID for low momentum $\mathrm{K}^{\pm}$, $\pi^{\pm}$, p can be expected to be excellent
- μon and πion separation may still be challenging
- μons from the ND-LAr should be not a problem
- The limiting factor will likely be the number of points recorded along a low momentum track $\rightarrow$ requirements on the readout granularity, diffusion inside the gas mixture

Readout chambers

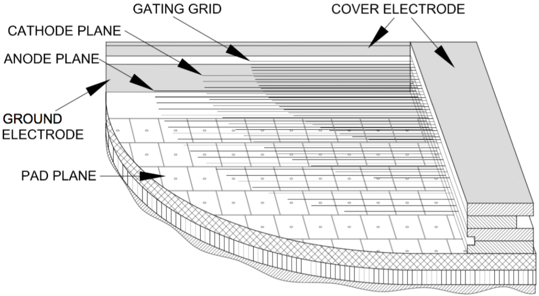
ALICE TPC multi wire proportional chambers

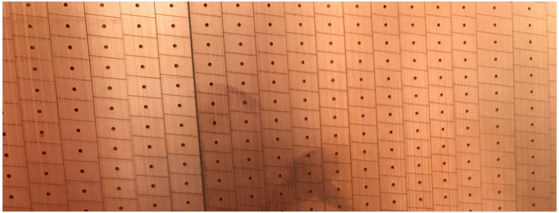




- 18 Inner and Outer ReadOut Chambers (IROCs/OROCs) per side
- Each has three wire planes: Anode wires, cathode wires and gating grid wires
- Pad sizes: $4 \times 7.5\,\text{mm}^2$, $6 \times 10\,\text{mm}^2$ and $6 \times 15\,\text{mm}^2$, in total 160 pad rows

ALICE TPC multi wire proportional chambers





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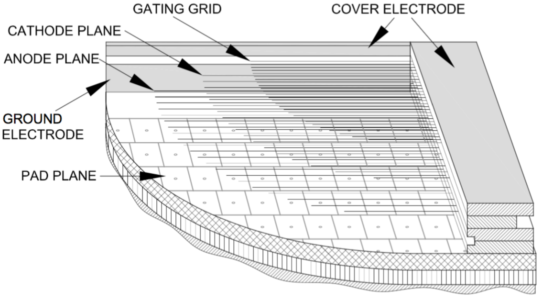

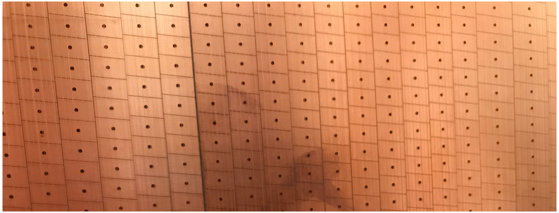

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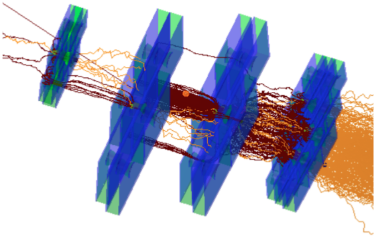
- **Ion back-flow expectation for a DUNE ND TPC?** Will the corresponding distortions still allow for the TPC to meet its requirement?

New ALICE TPC ROCs: A continuously read-out TPC



- Quadruple GEM stacks
- Position 1 & 4: Standard GEMs
- Position 2 & 3: Large pitch (280 μm) GEMs
- Each GEM mask rotated by 90 °
- Gain 2000, gas mixture: $Ne\text{-}CO_2\text{-}N_2$ (90-10-5) at atm

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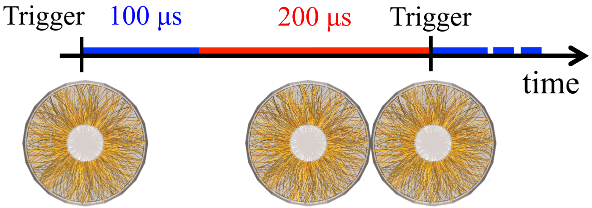
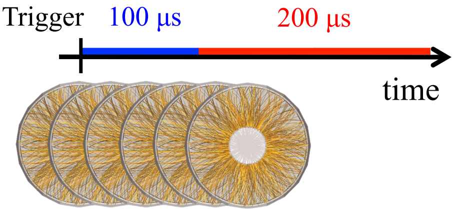
Old read-out schema at low rate:



At 50 kHz:



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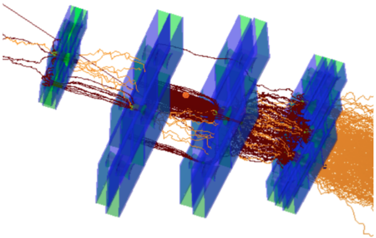

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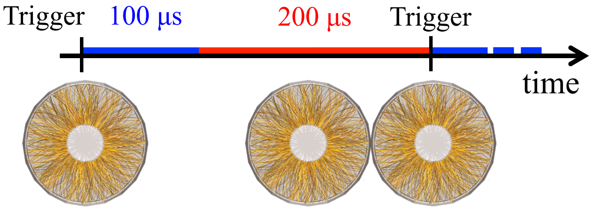
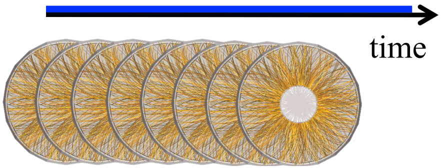
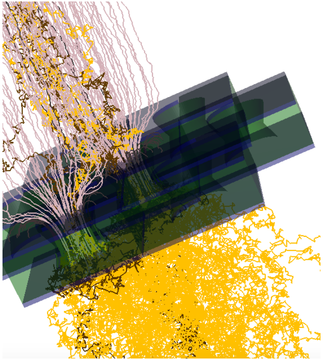


Continuous readout:



Lessons already learned (and to learn) with GEMs:

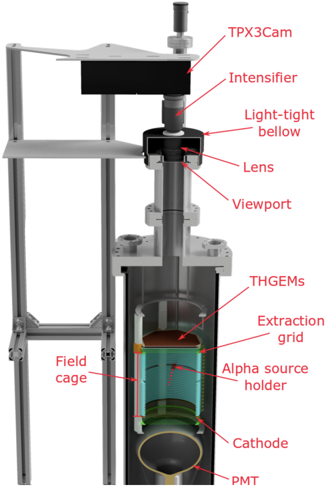
- Standard GEMs at atmospheric pressure very mature, mass production capabilities exist
- There is a large variety in GEMs – another already trained example could be seen in Kosta's talk
- GEMs operation in 10 bar operation will need some R&D (people are on it; *e.g.* Tanaz slides, Diego's slides, work in Liverpool and Warwick, ...)
- Operation stability over the expected run time will need thorough R&D



(Deisting)

Optical and hybrid read-out

- Cameras: Integrated devices, high readout granularity; a window replaces many feed-throughs
- Optical readout: *E.g.* Kosta's and Diego's slides
- Demonstration of 3D tracking with a TimePix in 100 mbar CF_4 (Liverpool)
- Hybrid readout: high granularity camera- and low granularity charge readout (*e.g.* DMTPC):
  - "Slow" camera readout and fast charge readout $\rightarrow$ 3D information
  - Likely one would just use a TimePix à la Ariadne
- Still some lessons to be learned before a large high pressure gas TPC can be build (Large interest to do that: IGFAE, Liverpool, Warwick, ...)



(A. Roberts et al 2019 JINST 14 P06001)

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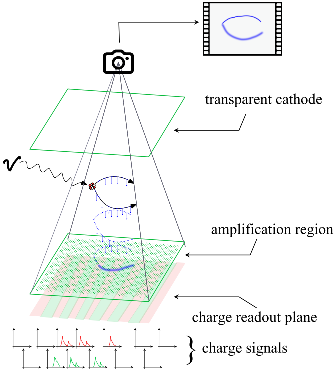
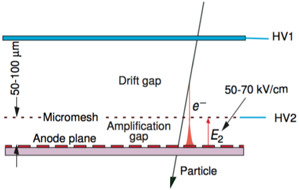
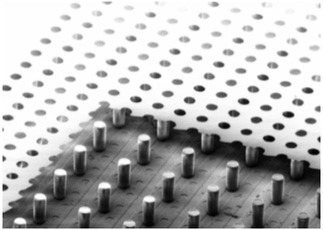
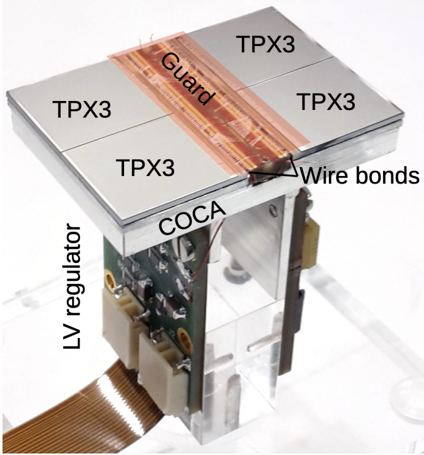


(A. Deisting 2022 J. Phys.: Conf. Ser. 2374 012145)

R&D for the ILC TPC: Micromegas like, read-out with TimePix chips







(Nucl.Instrum.Meth.A 956 (2020) 163331)

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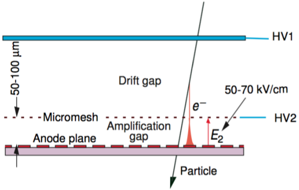

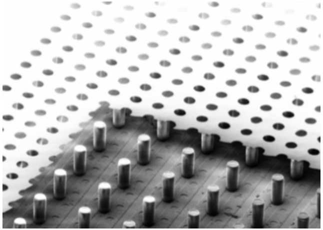

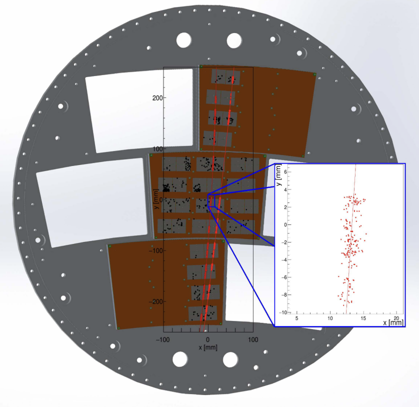

(IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 64, NO. 5, MAY 2017, M. Lupberger *et al.*)

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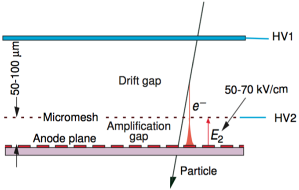
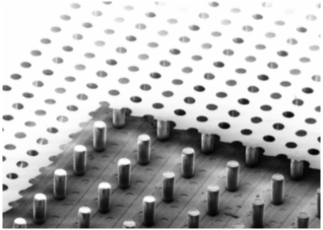
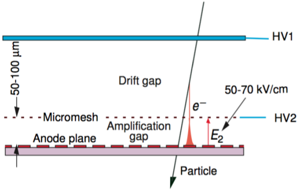
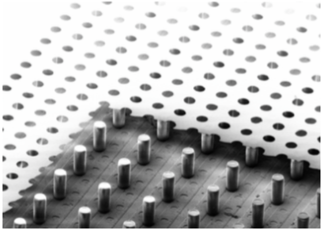


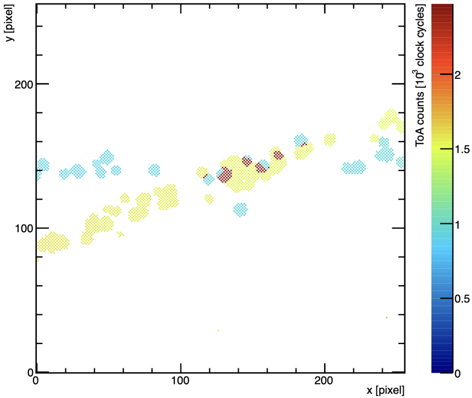


- Pad plane: The 256 × 256 bonding pads of a Time-Pix chip, 55 µm × 55 µm
- Mesh added with electrochemical processes
- For the ILC's ILD this technology has been tested on a larger scale, even in a magnetic field
- Excellent resolution
- Questions about cost and discharge stability remain

R&D for the ILC TPC: Micromegas like, read-out with TimePix chips







(A GEM BASED TIME PROJECTION CHAMBER WITH PIXEL READOUT, C. Brezina)

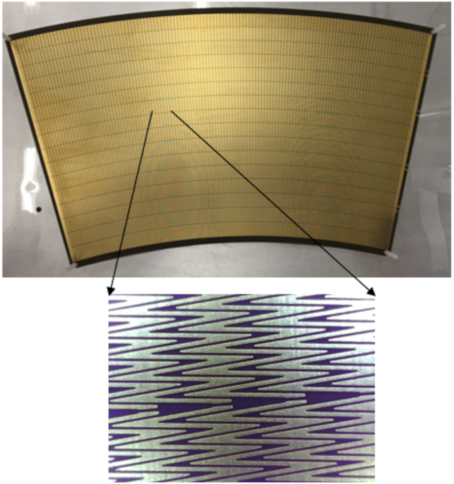
Lessons to be learned with micro-pattern gaseous detectors:

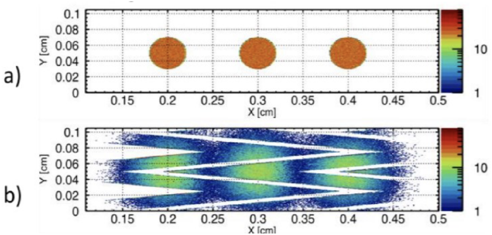
- Micro-pattern gaseous detectors (MPGDs) still lack thorough testing at the operating point a ND-GAr TPC will operate at
- When these are Requirements™ are defined, there is a zoo of MPGDs to chose from
- At atmospheric pressure, the largest TPCs using MPGDs these days are T2K (Micromegas) and the ALICE TPC (GEMs)
- Most experience at different conditions has been made by the dual-phase community and high pressure gaseous Xenon detectors
- Wires, in contrast, have already a history of working well at high pressure

Another word on pad planes

- Transversal diffusion in the gas, and the pad size will need tuning to THE REQUIREMENTS
- Examples already mentioned throughout this talk:
  - ALICE: $4 \times 7.5\,\mathrm{mm}^2$, $6 \times 10\,\mathrm{mm}^2$ and $6 \times 15\,\mathrm{mm}^2$
  - T2K: $9.8 \times 7.0\,\mathrm{mm}^2$
  - GridPix for ILD: $0.055 \times 0.055\,\mathrm{mm}^2$ (at $\sim$50 % occupancy)

sPEHNIX zig-zag pads



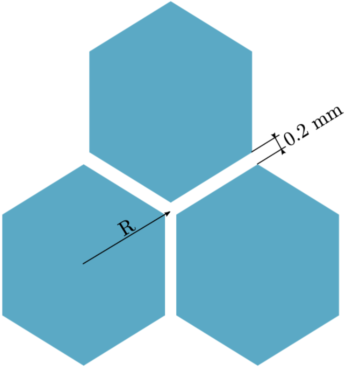


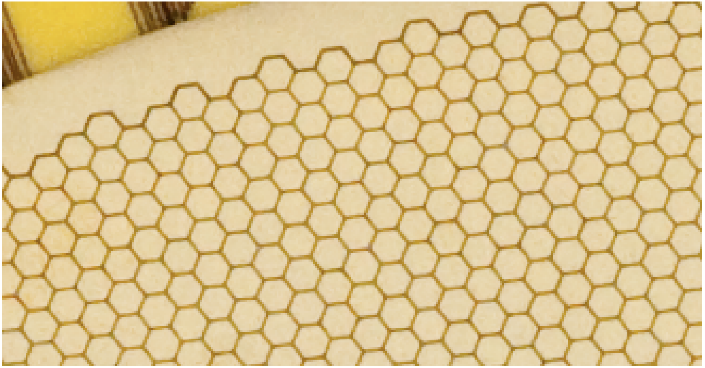
- Goal: Improve the resolution over the "standard" pitch/$\sqrt{12}$
- Increase the charge sharing by pads "overlapping"

(J.Phys.Conf.Ser. 2374 (2022) 1, 012147) and (H Klest 2020 J. Phys.: Conf. Ser. 1498 012025)

Hexagonal pads

- Example: "A Large Ungated TPC with GEM Amplification"
- May be a good fit to detectors, where the vertex originates in the gas volume





(Nucl.Instrum.Meth.A 869 (2017) 180-204)

The counting gas

Table 11.4 Some TPCs built around colliders

Blum, Riegler, Rolandi

Name of experiment	PEP 4	TOPAZ	ALEPH	DELPHI	CDF(1)
Reference	[LYN 87] [AVE 89]	[KAM 86] [SHI 88]	[DEC 90] [ATW 91]	[BRA 89] [AAR 90] [SIE 90]	[SNI 88]
Geometry					
Outer/inner radius (cm)	100/20	127/30	180/31	116/32	21/7
Drift length (cm)	2×100	2×122	2×220	2×134	2×15
Number of sense wires	2196	2800	6336	1152	384
Sense-wire spacing (mm)	4	4	4	4	6.3
Number of pads	13824	8192	41004	20160	384
Pad dimensions ($r \times r\varphi$) (mm^2)	7×7.5	12×10 (4)	30×6	8×7	41×14
Max. no. of measured points per outgoing track					
On pads	15	10	21	16	3
On wires	183	175	338	192	24
Gas and fields					
Gas (percentage fractions)	Ar(80) + CH_4(20)	Ar(90) + CH_4(10)	Ar(90) + CH_4(10)	Ar (80) + CH_4(20)	Ar(50) + C_2H_6(50)
Gas pressure (bar)	8.5	3.5	1	1	1
Electric drift field (kV/cm)	0.55	0.35	0.12	0.15	0.25
Magnetic field (T)	1.32	1.0	1.5	1.2	1.5
Drift velocity (cm/µs)	5	5.3	5.0	6.7	4.3
Approx. value of $\omega\tau$	1.5	4.9	7	5.4	3.5

Table 11.4 Some TPCs built around colliders

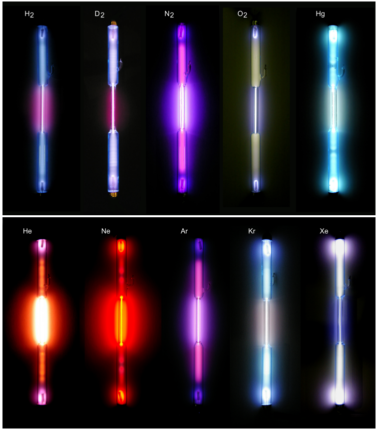
Blum, Riegler, Rolandi

Name of experiment	PEP 4	TOPAZ	ALEPH	DELPHI	CDF(1)
Reference	[LYN 87] [AVE 89]	[KAM 86] [SHI 88]	[DEC 90] [ATW 91]	[BRA 89] [AAR 90] [SIE 90]	[SNI 88]
Geometry					
Outer/inner radius (cm)	100/20	127/30	180/31	116/32	21/7
Drift length (cm)	2×100	2×122	2×220	2×134	2×15
Number of sense wires	2196	2800	6336	1152	384
Sense-wire spacing (mm)	4	4	4	4	6.3
Number of pads	13824	8192	41004	20160	384
Pad dimensions ($r \times r\varphi$) (mm^2)	7×7.5	12×10 (4)	30×6	8×7	41×14
Max. no. of measured points per outgoing track					
On pads	15	10	21	16	3
On wires	183	175	338	192	24
Gas and fields					
Gas (percentage fractions)	Ar(80) $+ CH_4(20)$	Ar(90) $+ CH_4(10)$	Ar(90) $+ CH_4(10)$	Ar (80) $+ CH_4(20)$	Ar(50) $+ C_2H_6(50)$
Gas pressure (bar)	8.5	3.5	1	1	1
Electric drift field (kV/cm)	0.55	0.35	0.12	0.15	0.25
Magnetic field (T)	1.32	1.0	1.5	1.2	1.5
Drift velocity (cm/µs)	5	5.3	5.0	6.7	4.3
Approx. value of $\omega\tau$	1.5	4.9	7	5.4	3.5

Some TPCs built

Name of experiment	T2K ND280	ALICE TPC
Reference	[NIM A 637 (2011) 25–46]	[NIM A 622 (2010) 316–367]
Geometry		
Outer/inner radius (cm)	It is a box	84.8/258.0
Drift length (cm)	89.7	2x 249.7
Number of sense wires	bulk micromegas	MWPC pad readout
Sense-wire spacing (mm)		
Number of pads	1728 per module (72 modules)	15488 (5504 + 5952 + 4032) x 2 x 18
Pad dimensions ($r \times r\varphi$) (mm^2)	9.8 x 7.0	4.0 x 7.5, 6.0 x 10.0 and 6.0 x 15.0
Max. no. of measured points per outgoing track		159
On pads		
On wires		
Gas and fields		
Gas (percentage fractions)	Ar (95) +CF_4 (3) + iC_4H_{10} (2)	Ar (88) + CO_2 (12) or Ne (95) + CO_2 (10) + N_2 (5)
Gas pressure (bar)	1.0	1.0
Electric drift field (kV/cm)	0.275	0.4
Magnetic field (T)	0.2	2.0
Drift velocity (cm/μs)	7.5	2.65
Approx. value of $\omega\tau$		

Gas notes



(Heinrich Pniok License FAL [Free Art License 1.1])

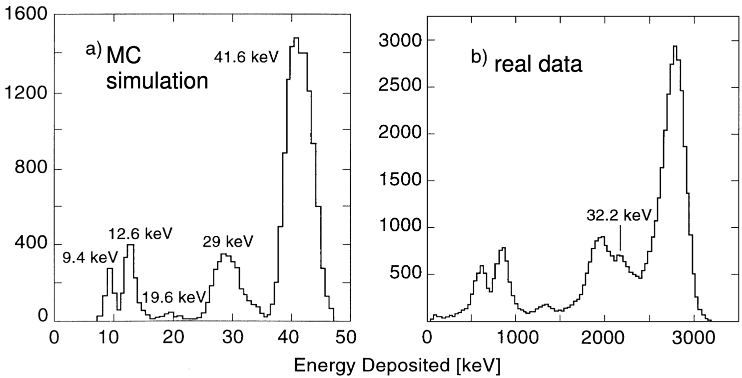
- Lessons already learned with gas-mixtures with Ar pre-dominance, also at high pressure
- Closed gas systems are widely used in the liquid or dual-phase Ar and the Xe community
- Since the war in the Ukraine, other TPCs caught up (*e.g.* ALICE)
- The push to not use green-house gases, may create challenges for using *e.g.* CF_4
- Exchanging the gas mixture/pressure: An idea floated for many physics reasons (*e.g* Phys. Rev. D 102, 033005 (2020))
  - ∗ The hardware of a ND-GAr TPC operating at 10 bar will be tightly tuned to its gas mixture

  → Changing will be harder as it sounds

TPC calibration

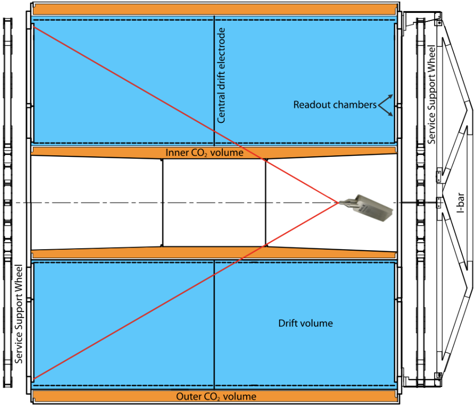
Gain calibration using Krypton

- ^{83m}Kr produces different energy deposits inside the detector, similar to the energy deposits along charge particle tracks
- The spectrum has a total of 4 peaks, which allow for a *gain* calibration, testing the full response of a ROC



NA49 TPCs

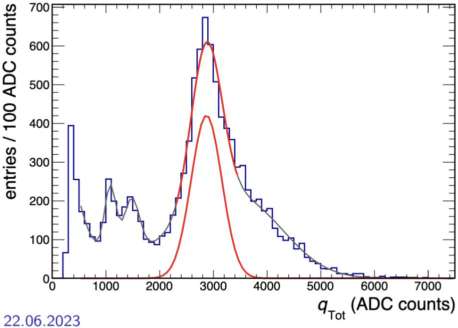
Gain calibration using x-rays



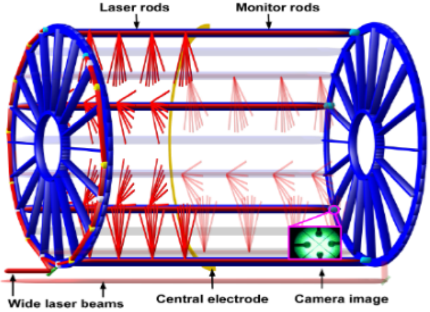
Upgraded ALICE TPC, commissioning withx-rays,

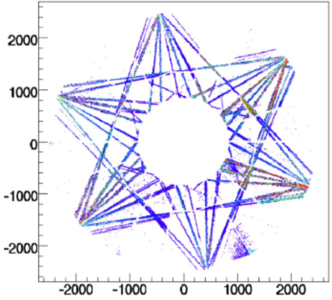
JINST 16 (2021) P03022

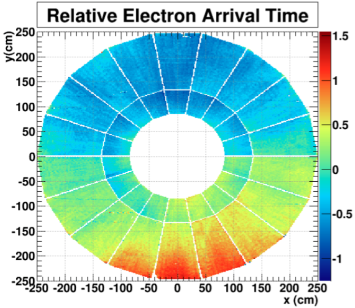
- Downside of ^{83m}Kr: It decays and a decent amount of decays is needed at every readout channel
- X-rays tubes can be a great alternative here



ALICE TPC laser calibration system

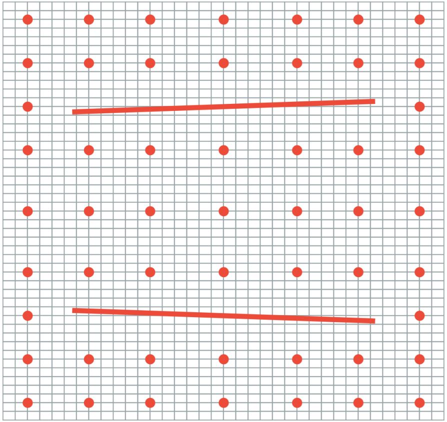






- 266 nm laser is guided into the TPC, split and produces tracks at defined positions
- A “laser run” consists of 100 laser triggers – the first block occurring 0.5 h in a data taking run and then hourly
- Stray-light hits the cathode and ejects photo electrons which drift the full drift distance

T2K: Aluminium laser targets



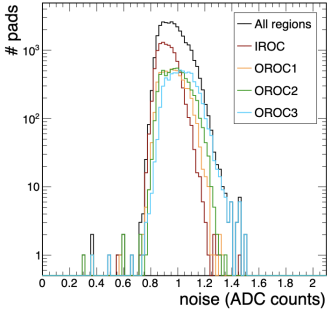
NIM A 637 (2011) 25–46

- Aluminium target on the cathode opposite to each bulk micromegas
- 266 nm laser light is brought into the TPC on fibres, defocused and hits the cathode
- The work function of the Al is lower than copper (cathode), hence the targets emit more electrons $\leftarrow$ measure on the micromegas
- The sPHENIX TPC is following a similar approach
- All laser / cathode based system only work if there is a “classical” cathode

Calibrating the electronic response: Pedestal and pulser runs

- **Pedestal runs:** Determine the pedestal and noise value for each readout channel
- **Pulser runs:** Verify the proper functioning of each readout channel & study the pulse-shaping properties of the electronics

⇒ **What happens if one notices a front-end card (FEC) is not working ?** In the ALICE TPC case this often meant an access during no-beam times and redundancy, allowing to live with a few "bad" FECs



Upgraded ALICE TPC, pedestals, JINST 16 (2021) P03022

Calibrating the electronic response: Pedestal and pulser runs

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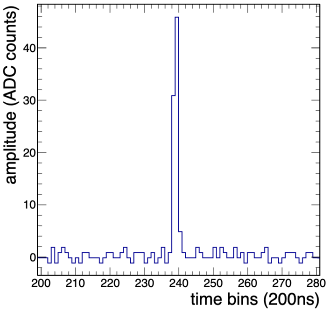

Upgraded ALICE TPC, pedestals, JINST 16 (2021) P03022

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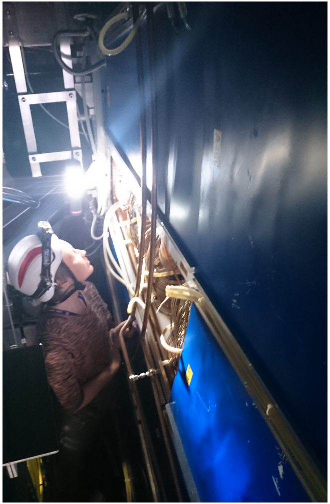
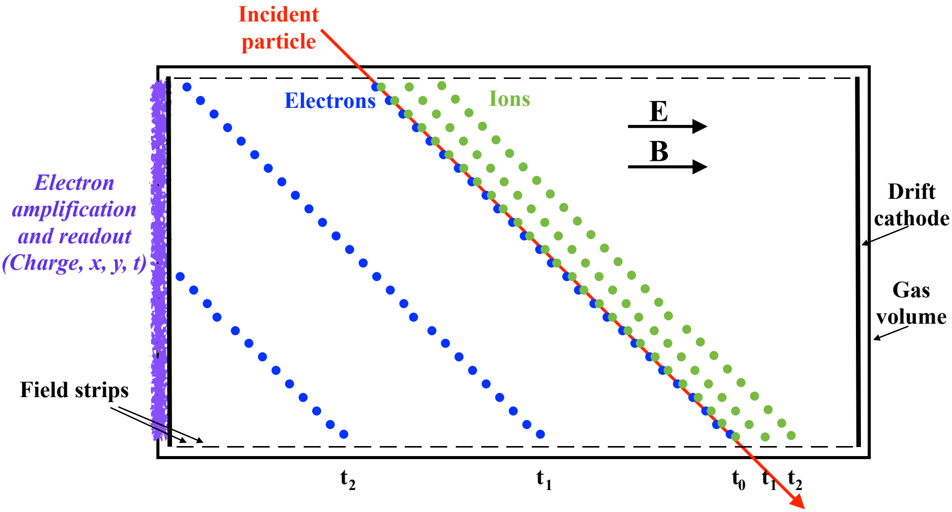


But wait ! There is more !

- I did not mention external system, as the gas property monitors used by T2K
- A similar approach has been developed for high pressure applications:

  Design of a Gas Monitoring Chamber for High Pressure Applications
  arXiv:1911.04846 [physics.ins-det]
- ... and there is likely even more



(DOI 10.11588/heidok.00024133)

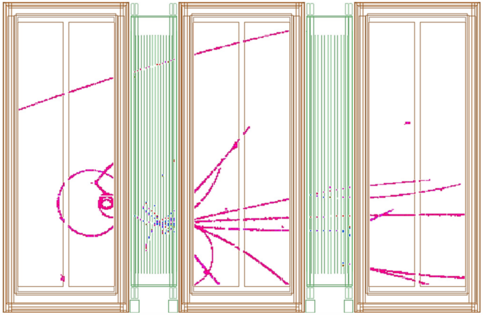
Lessons learned from recent gas TPCs

- Can one build a high pressure gas TPC with a gas mix, predominately argon? **Yes.**
- Can one build one such TPC large enough? **Yes.**
- Can one build THE ND-GAr TPC which
  - … tracks μons from ND-LAr? **Yes.**
  - … full-fills all other requirements for the long baseline and ND physics programme? **One would really need these requirements** *(The interest inside community suggests also this may be possible)*

Backup

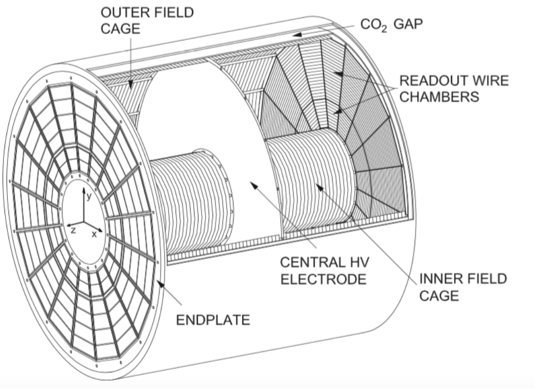
T2K near detector time projection chambers

- T2K examines ν oscillations of νs 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)



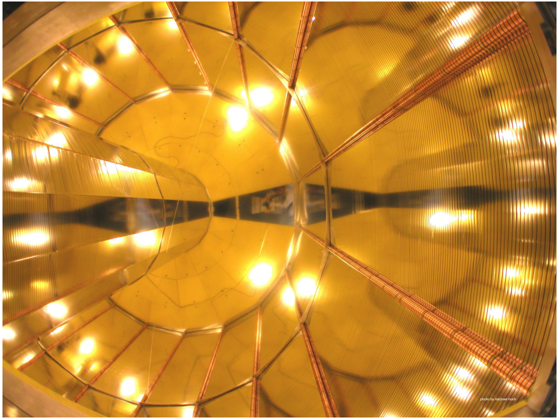
NIM A 637 (2011) 25–46

ALICE time projection chamber



- About $90\,\mathrm{m}^3$ gas volume filled with Ar-CO_2 (88-12) at atmospheric pressure
- Ne-CO_2-N_2 (90-10-5) and Ar-CO_2 (90-10) have been used as well
- Drift field of $400\,\mathrm{V\,cm}^{-1}$ ($\rightarrow$ central cathode at $100\,\mathrm{kV}$)
- Maximal electron drift time: $\lesssim 100\,\mu\mathrm{s}$
- Multi Wire Proportional Chambers (MWPCs) with gated read-out
- Operated successfully in LHC Run 1 and Run 2

ALICE time projection chamber



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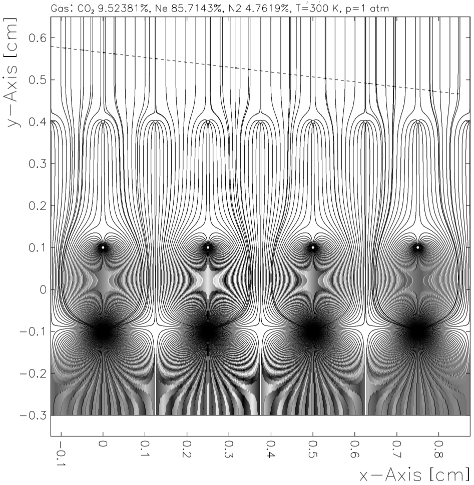
- Drift field of $400\,V\,cm^{-1}$ ($\rightarrow$ central cathode at 100 kV)
- Maximal electron drift time: $\leq 100\,\mu s$
- Multi Wire Proportional Chambers (MWPCs) with gated read-out
- Operated successfully in LHC Run 1 and Run 2

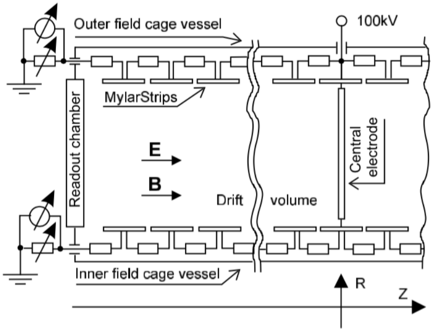
ALICE TPC MWPCs: Ion gating

Ion drift lines with open gating grid



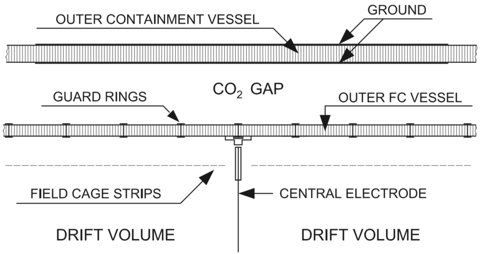
- An alternating potential is applied to switch the gating grid closed, *i.e.* $U_{\mathrm{GG}} = U_0 \pm \Delta U$
- In the closed configuration the gating grid is neither transparent to charge carriers from the drift volume nor from the readout chamber
- The grid is kept closed for 200 µs to efficiently block the ions from the gas amplification
- Together with the maximum drift time of $\sim$ 100 µs, the closing time of the grids limits the readout rate to $\sim$ 3 kHz

Field cage



- The ALICE TPC field cage is mounted on 18 rods on the inner and the outer side of the TPC
- $V_{\mathrm{cathode}} = 100\,\mathrm{kV}$ (Drift field: $400\,\mathrm{V\,cm^{-1}}$) is degraded by a voltage divider network, also supplying the 165 field strips
- The high voltage insulation is achieved by a set of guard rings and a CO_2 filled containment module
- The field cage rods are used to flush the TPC with gas, house the HV supply to the cathode and the laser system, and supply cooling to the voltage dividers for the field strips

Field cage



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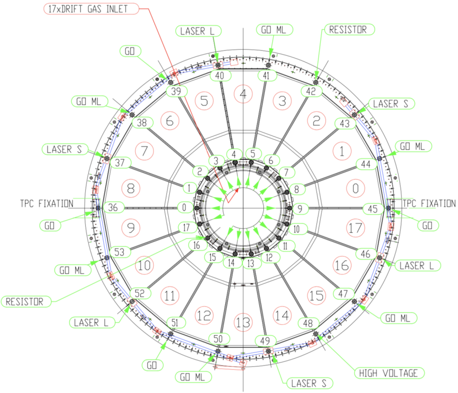
Field cage



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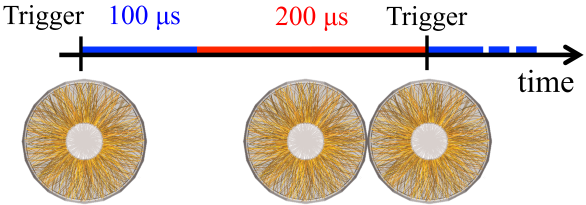
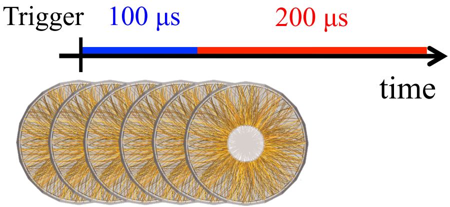
ALICE TPC upgrade: A continuously read-out TPC

Old read-out schema at low rate:



At 50 kHz:



- At 50 kHz there are on average 5 events piled up inside the drift volume
- The gated readout of the MWPCs is no longer feasible as is their un-gated operation
- New readout chambers are needed which allow for continuous read-out and preserve the current TPC's performance

ALICE TPC upgrade: A continuously read-out TPC

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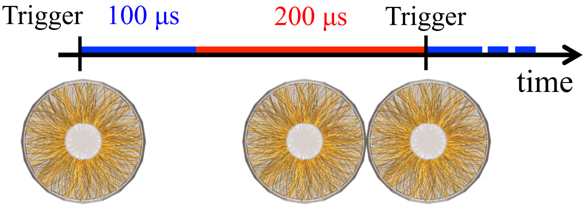
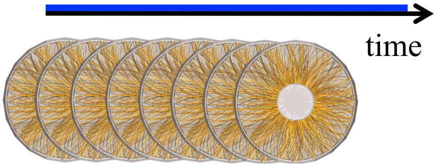


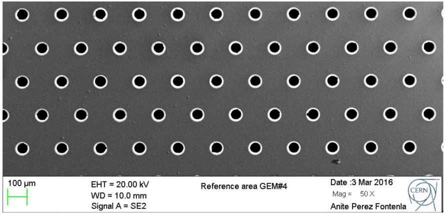
Continuous readout:



- At 50 kHz there are on average 5 events piled up inside the drift volume
- The gated readout of the MWPCs is no longer feasible as is their un-gated operation
- New readout chambers are needed which allow for continuous read-out and preserve the current TPC's performance

Gas Electron Multiplier foils

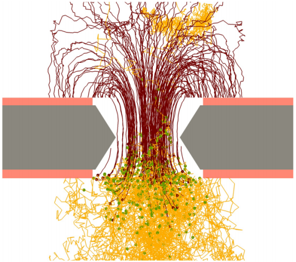
- 50 µm polyimide foils with a 5 µm copper cladding on both sides
- Hexagonal hole pattern with a standard pitch of 140 µm



Requirements on the ALICE TPC GEM stacks:

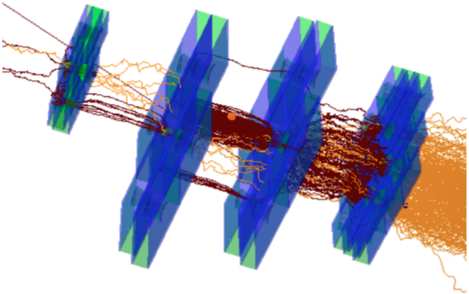
- Provide an Ion Back Flow (IBF) of less than 1 % in order to keep the space charges in the TPC at a tolerable level
- Preserve the momentum and $\mathrm{d}\varepsilon/\mathrm{d}x$ resolution of the old chambers ($\frac{\sigma_\varepsilon}{\varepsilon_{^{55}\mathrm{Fe}}} \leq 12\%$)
- Stable operation at LHC Run 3 conditions

GEM cross section with simulation:



ALICE TPC GEM stack settings

ΔU_{GEM1}	ΔU_{GEM2}	ΔU_{GEM3}	ΔU_{GEM4}	E_{D}	E_{T1}	E_{T2}	E_{T3}	E_{Ind}
270 V	230 V	288 V	359 V	$0.4\,\frac{\mathrm{kV}}{\mathrm{cm}}$	$4\,\frac{\mathrm{kV}}{\mathrm{cm}}$	$4\,\frac{\mathrm{kV}}{\mathrm{cm}}$	$0.1\,\frac{\mathrm{kV}}{\mathrm{cm}}$	$4\,\frac{\mathrm{kV}}{\mathrm{cm}}$



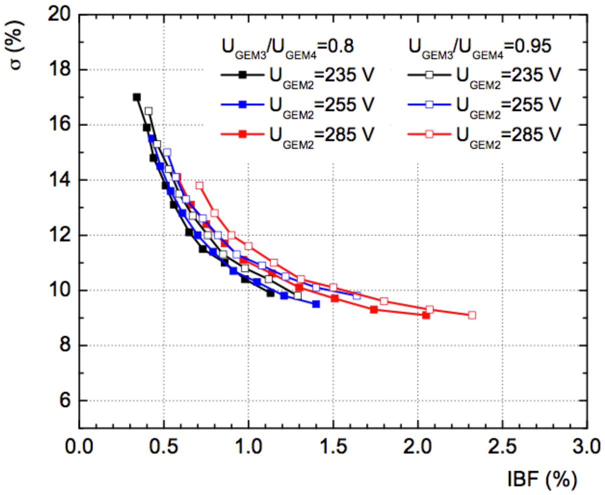
ALICE TPC GEM stacks:

- Quadruple GEM stacks
- Position 1 & 4: Standard GEMs
- Position 2 & 3: Large pitch (280 µm) GEMs
- Each GEM mask rotated by 90 °
- Gain 2000
- Gas mixture: $Ne\text{-}CO_2\text{-}N_2$

Performance: Energy resolution vs IBF

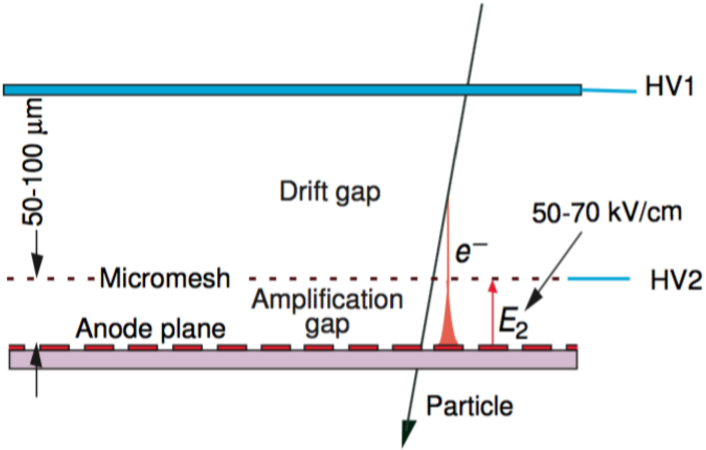
- Quadruple GEM stacks (S-LP-LP-S)
- Done with small prototypes ($10\,\mathrm{cm} \times 10\,\mathrm{cm}$ GEMs)
- $225\,\mathrm{V} \leq \Delta U_{\mathrm{GEM1}} \leq 315\,\mathrm{V}$, keeping the gain at 2000
- E_{T1} & $E_{\mathrm{Ind}} = 4\,\mathrm{kV\,cm^{-1}}$,
  $E_{\mathrm{T2}} = 2\,\mathrm{kV\,cm^{-1}}$,
  $E_{\mathrm{T3}} = 0.1\,\mathrm{kV\,cm^{-1}}$

$\Rightarrow$ **Optimisation of energy resolution and IBF are competing effects**

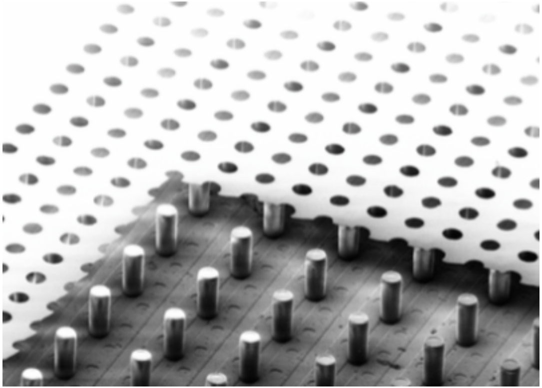


Micromegas

- A readout plane of pads or anode strips of a few 10 µm to a few 100 µm width
- A micro mesh is placed on top of the anode plane in a distance of 50 µm to 100 µm
- High(ish) voltage is applied to the mesh. Electrons passing through the mesh, are accelerated and ionise further electrons in the high electric field between mesh and anode.



InGrid: An example for micromegas



- Using photolithographic methods a micro mesh is constructed on top of a TimePix ASIC with 256×256 pixels with 55 µm pitch
- The mesh's holes are aligned exactly with the chip's pixels – the mesh chip distance is 50 µm
- Electrons are amplified between the pad of the pixel and the mesh

A GEM based TPC with pixel readout (ILC group @ Bonn)

Experimental set-up:

- TPC prototype with ~30 cm drift length
- Triple GEM stack
- Readout: A TimePix ASIC with 256×256 pixels with 55 µm pitch

$\Rightarrow$ In the limit of zero diffusion, the single-point resolution is limited by $140\,\mu\text{m}/\sqrt{12}$