TPC technologies using MPGDs

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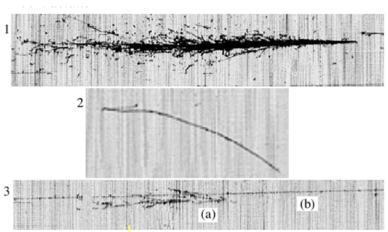
TPC - a versatile tracking detector

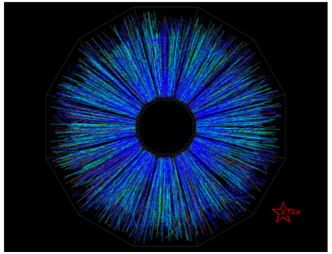
TPC – an (almost) ideal tracking detector

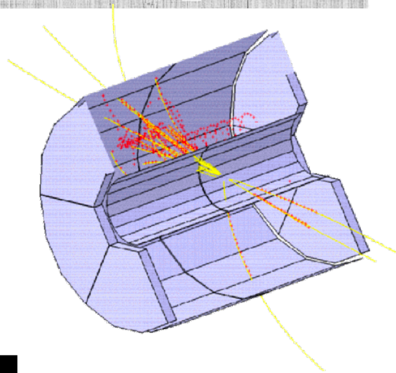
- large active volume and acceptance
- high particle densities
- 3D spatial information about hits
- good momentum, time and spatial resolution
- particle identification via measurement of $\langle dE/dx \rangle$

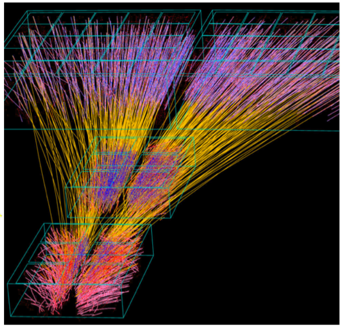
Wide range of applications

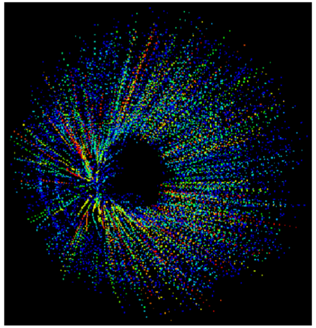
- low energy nuclear physics
- pp, e^+e^-, HIC
- neutrino physics
- BSM physics: DM, $\beta\beta 0\nu$
- … and more

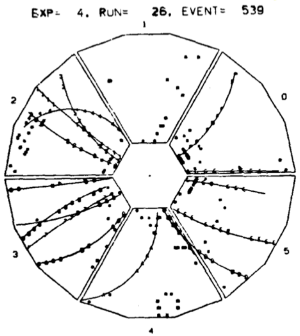


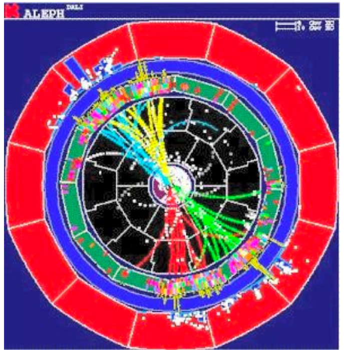






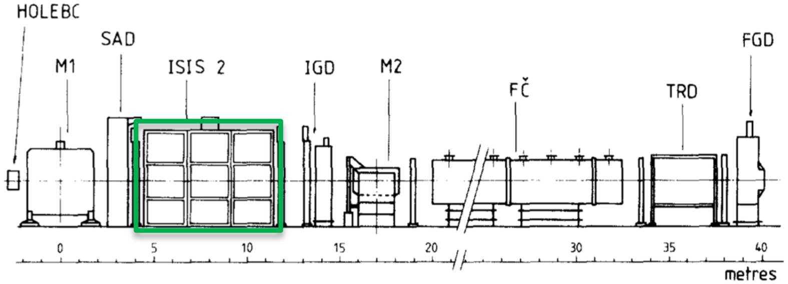






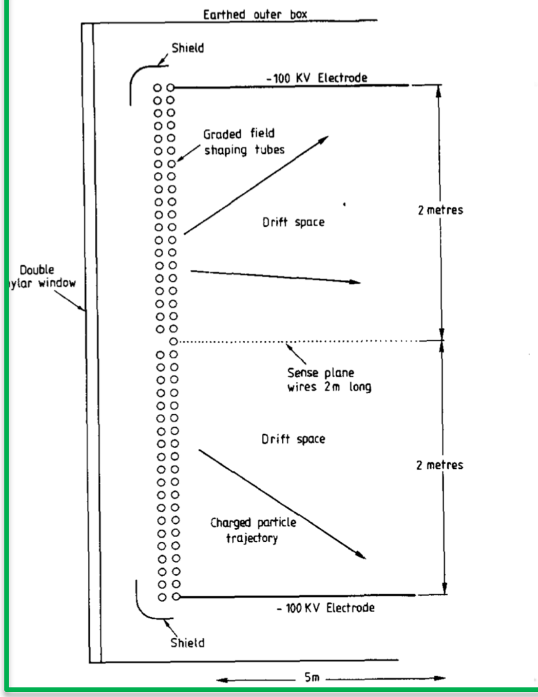
BRIEF TPC HISTORY

Predecessor in Oxford



THE IDENTIFICATION OF SECONDARY PARTICLES BY IONISATION SAMPLING (ISIS)

- First described in 1973/74 (J. Mulvey, W. Allison)
- **ISIS pictorial drift chamber** in the European Hybrid Spectrometer at the CERN SPS
  - **ISIS1** – 4 × 2 x 1.3 m^3
  - **ISIS2** – 4 × 2 x 5.1 m^3
- Large volume containing gas and ***E***
- Two drift spaces
- Wire plane (anode/cathode) in the middle. G ≈ 10^4
- Ar-CO_2 (80-20), E_d = 500 V/cm, ≈100 µs drift (ISIS2)
- Measurement of ionization density for PID
  - Spatial resolution poor due to diffusion, long drift
- Ionisation resolution: 3.5% r.m.s.
- 89% mass assignment efficiency



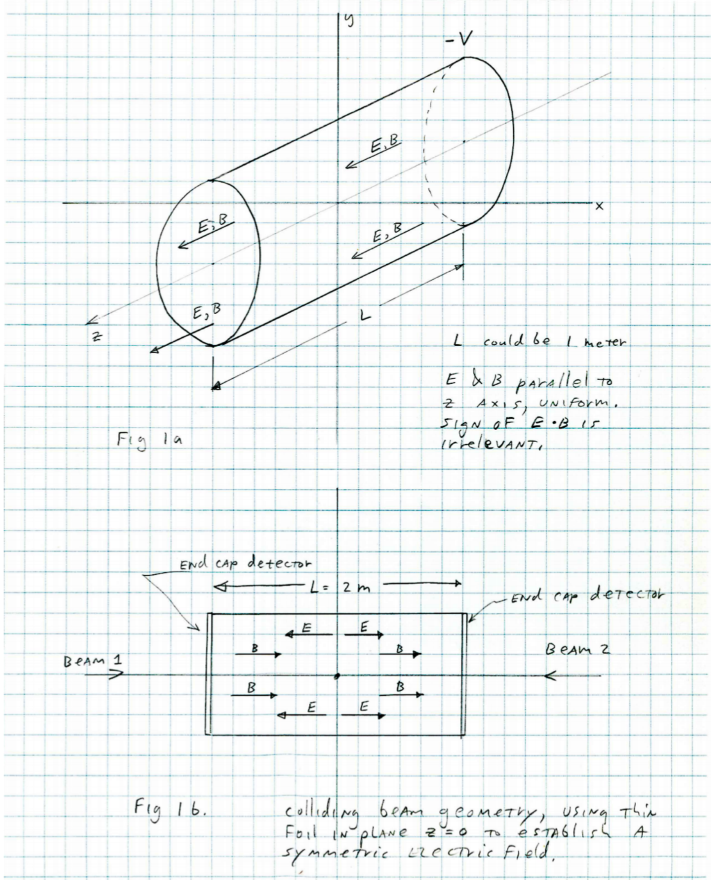
TPC - origins

THE AXIALLY-FOCUSED TIME-PROJECTOR DETECTOR

- Large, gas-filled cylindrical volume, ***E*** field between endplates
- Placed in a strong magnetic field ***B***, ***E*** × ***B*** = 0 everywhere
- Traversing particle bends in ***B*** ➛ momentum
- Ionisation trail drifts towards the endcaps ➛ consider electrons

- Drift in *z*: $\sigma_z = \sqrt{2DT}$, no effect from ***B*** (no Lorentz force along ***B***)
- In transverse direction: $\sigma_{xy} \rightarrow \frac{\sigma_{0xy}}{(1+\omega^2\tau^2)}$
  - $\omega = e\mathbf{B}/m$ – cyclotron freq. of electron
  - τ – mean time between electron-gas collisions (use Ramsauer minimum!)
  - E.g. Ar-CH_4 at **B** = 1.5 T, $\sigma_{xy} \approx \sigma_{0xy}/50$

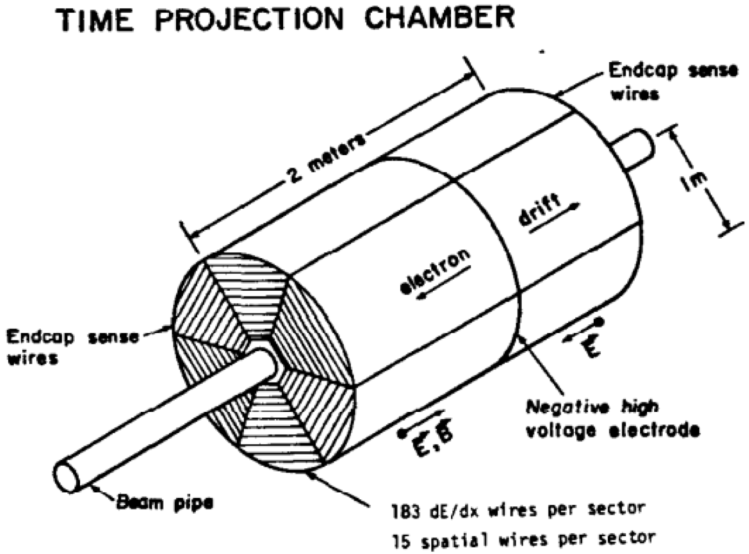
- Record r, ϕ, t at the endcaps, reconstruct 3D coordinates of primary ionization, w/o ambiguities

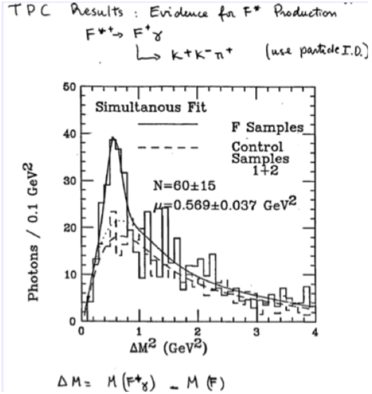


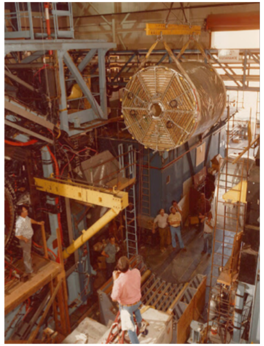
D. R. Nygren, "*Proposal to Investigate the feasibility of a Novel Concept in Particle Detection*", LBL internal report, February 1974.

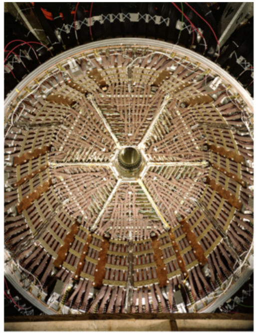
PEP-4 TPC

- First TPC, with many innovations
- SLAC e+e- collider
- Ar-CH4 (80-20) at 8.6 bar, B = 0.4 T
  - primary statistics, and therefore signal-to-noise, increase with p
  - If E scaled accordingly, diffusion decreases as ~1/p
  - High pressure also used in the TOPAZ TPC
- Great physics outcome, including discovery of F^* (now D_S) meson









End cap of the TPC (1981)

Nygren: A mixture of elation and dread

FROM A BALL-WIRE TO MPGD READOUT

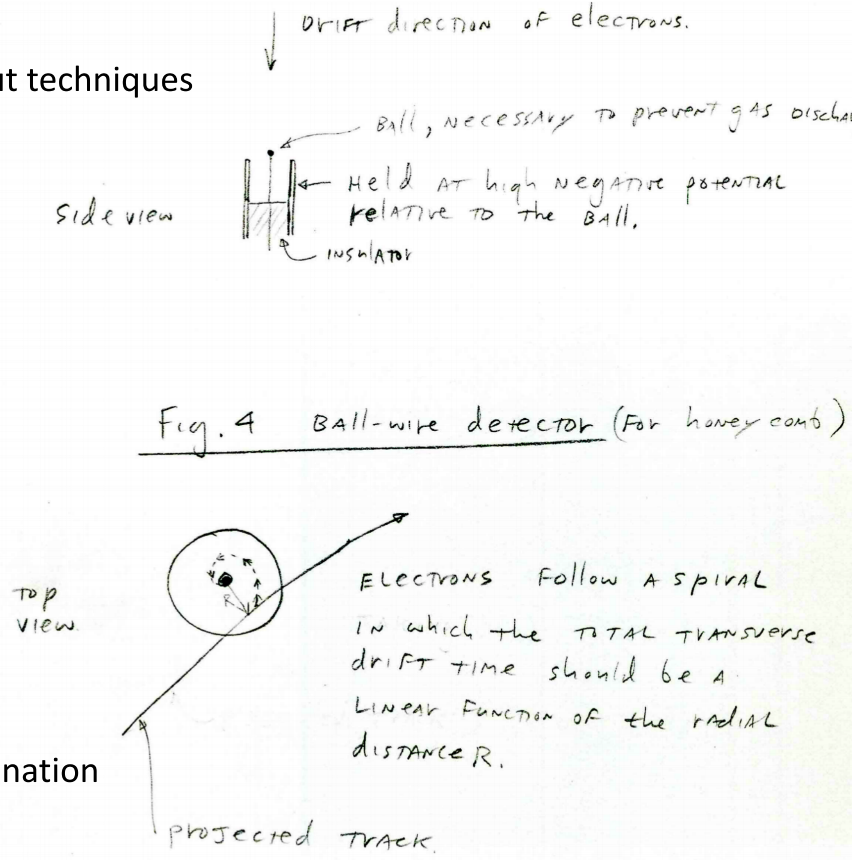
PEP-4 TPC readout

- In the first proposal by D. Nygren (LBKL, 1974), 2 readout techniques proposed
  - Ball-wire detector
  - MWPC readout

Ball-wire detector

- 0.25 inch diameter copper tubing
- 1 mil diameter platinum wire (ended with a ball)
- operated as a proportional counter or Geiger counter
- high sensitivity
- organized in a honeycomb structure
- precise measurement of *R* within each structure

- position measurement – tracking – momentum determination



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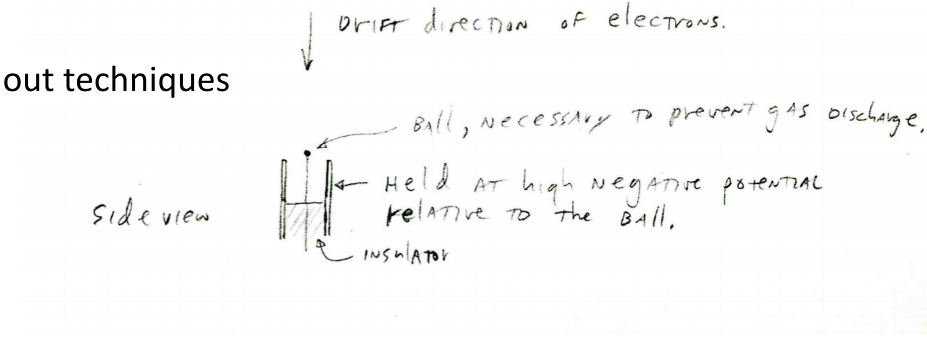

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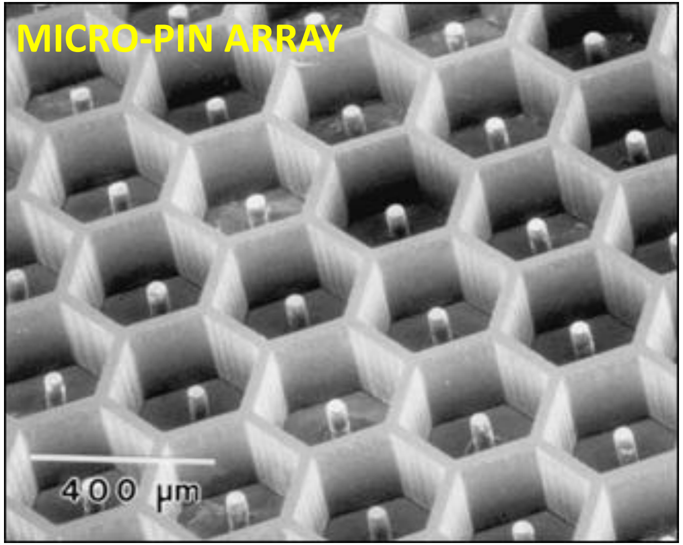
"Almost" an MPGD ☺



P. Rehak et al . IEEE TNS-47(2000)1426

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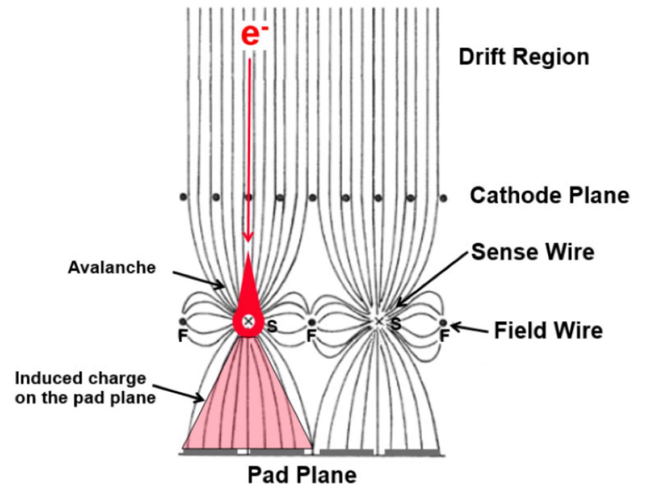
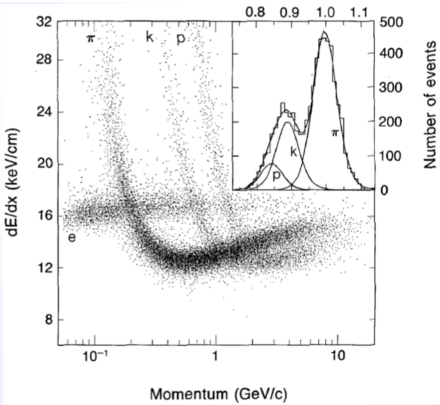


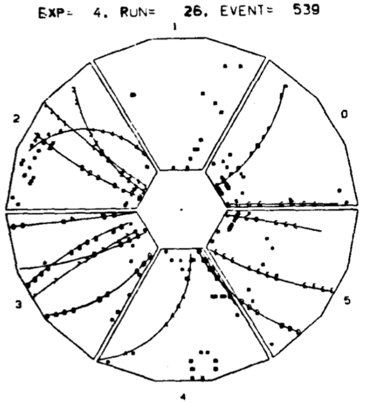
MWPC readout

- Sense wire readout for dE/dx measurement
- 15 pad rows (circular arrangement) for position measurement
- No gating grid yet

- $\sigma_{xy} \approx 300$ µm
- $\sigma_{dE/dx} \approx 4\%$

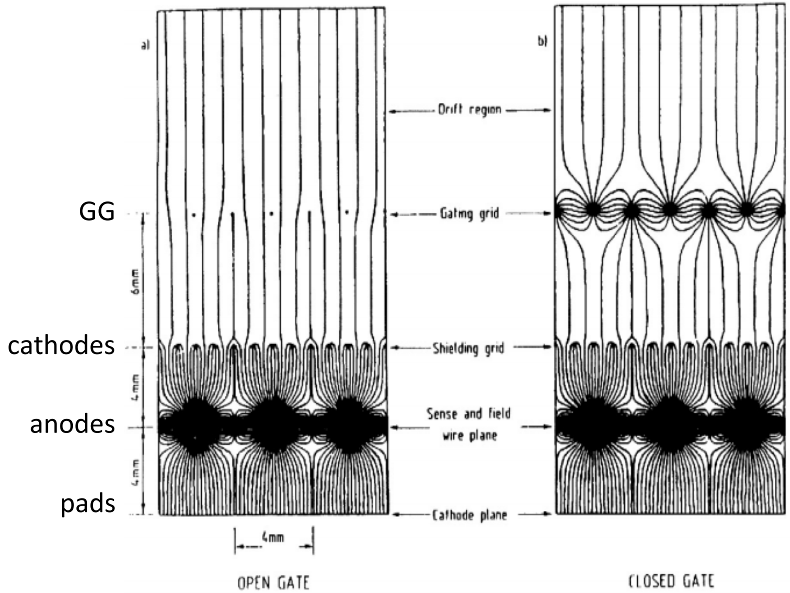
- Further improvements with magnet upgrade in ‘84

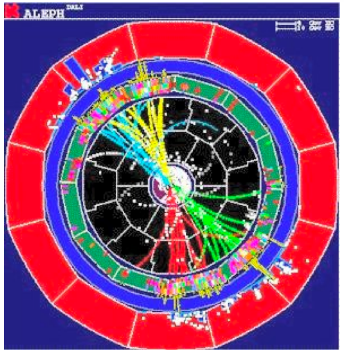




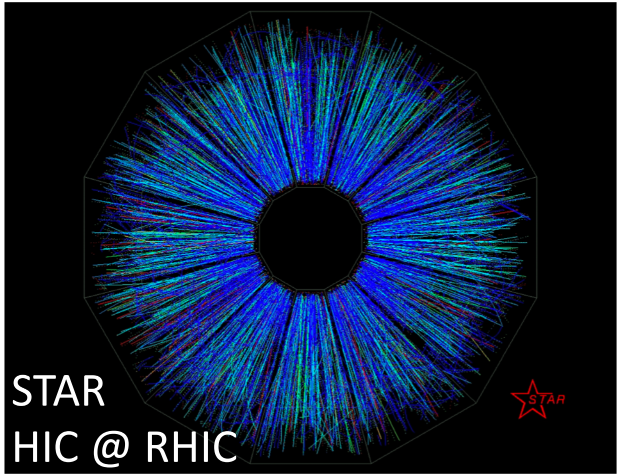
MWPC with Gating Grid

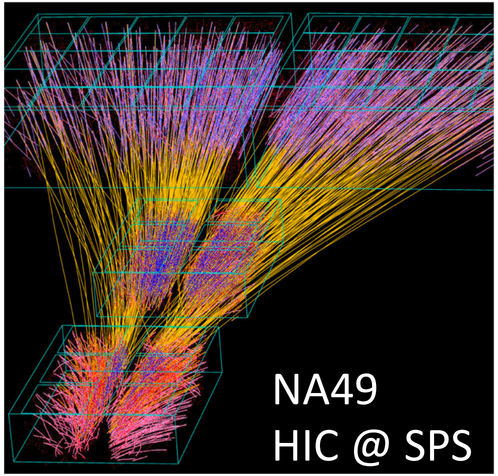
- GG introduced in Aleph TPC (also Delphi)
- Electrons reach the chambers and amplification occurs only when an event is triggered upon
- Gate is open during the maximum drift time only (t_e)
- Then the gate closes to prevent ions to invade drift volume (t_{ions})
- This technique opens the gate to higher rates and multiplicities without substantial space-charge distortions
- IBF suppression ≈10^{-5}

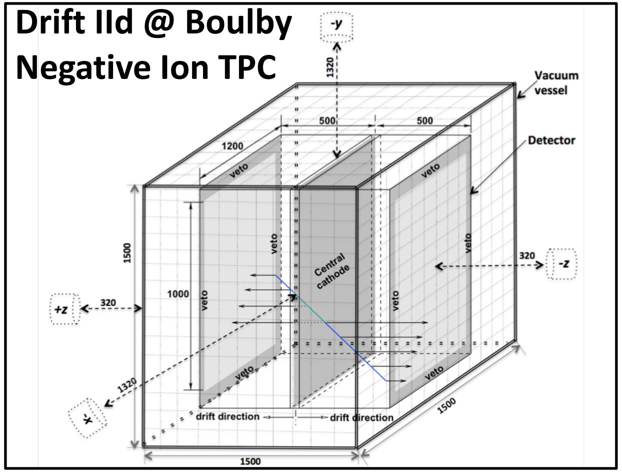


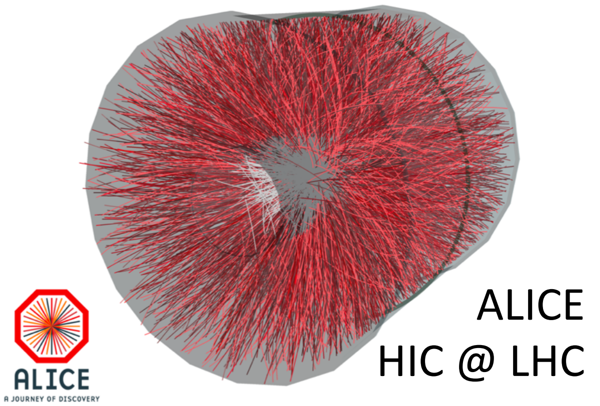


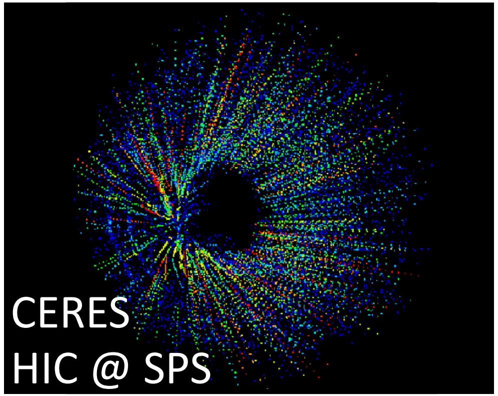
Some TPCs with MWPC readout

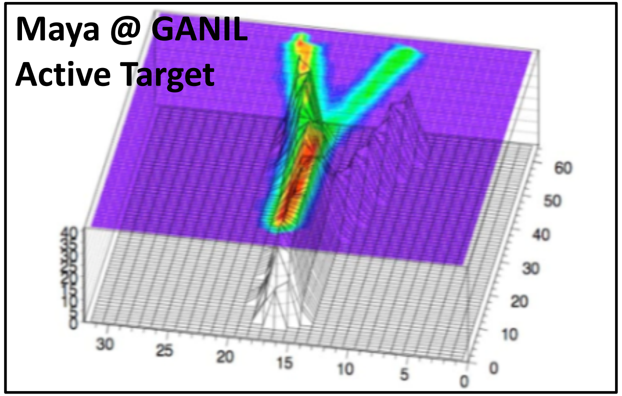












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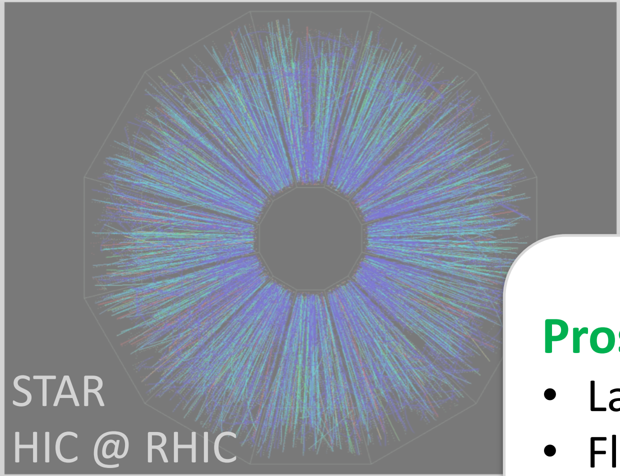
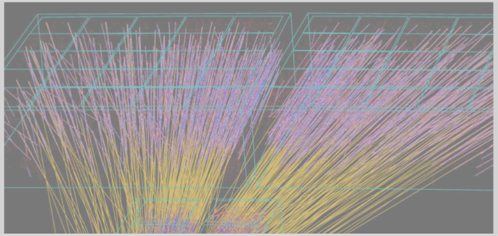
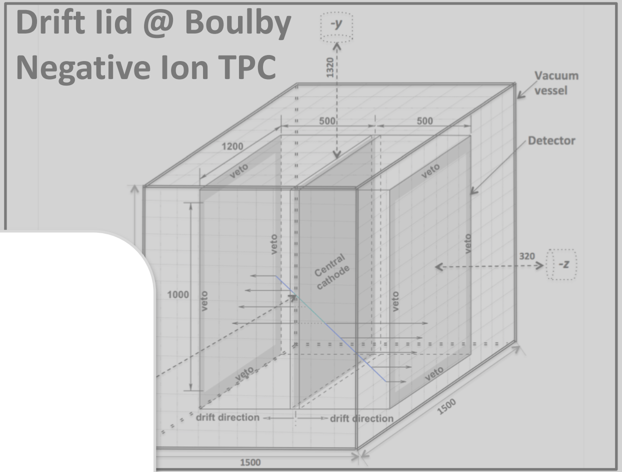
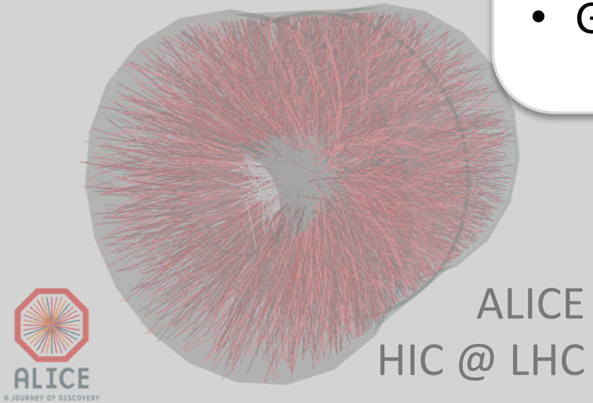
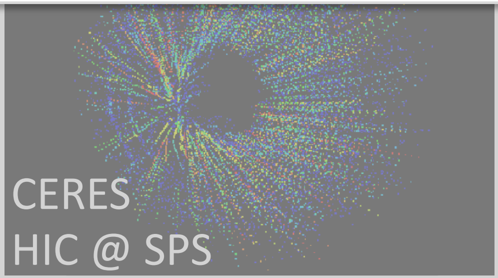


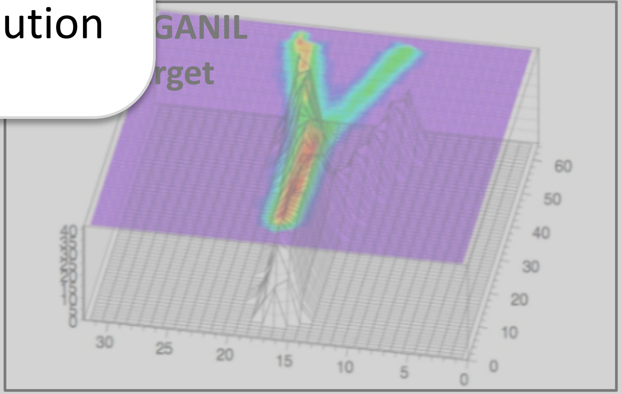




Pros:
- Large areas at low prices
- Flexible geometries
- Good spatial and energy resolution







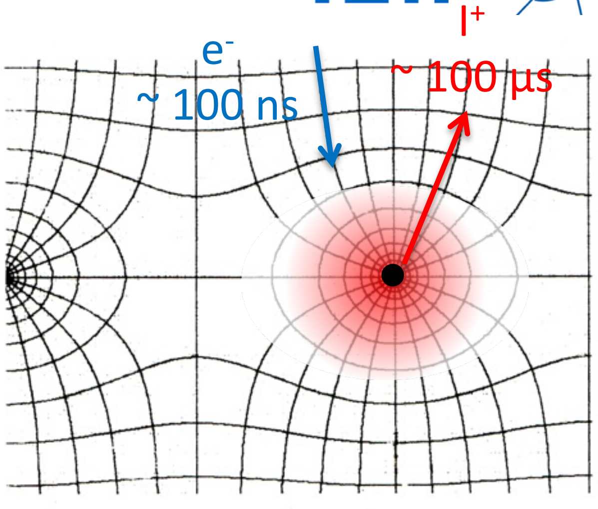
Limitations of wire readout

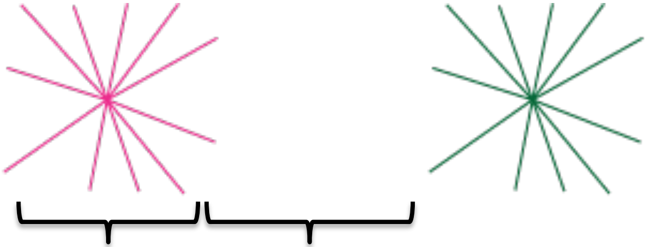
1) **Relatively long time to evacuate ions from the amplification regio**
   - Fast gain drop at high fluxes: (>10 kHz/cm^2)
   - Space charge accumulation, distortion of E field.
   - Screening effect for next event

2) **Limited multi-track separation** (~100 µm)
   - Minimum wire distance ~1mm
     (mechanical instabilities due to electrostatic repulsion)

3) **E×B effects** (Lorentz angle) around wires degrades *x-y* resolution

4) **MWPC with Gaiting Grid**
   - Introduces dead time (e.g. 200 µs in ALICE)
   - Continuous operation not possible
   - Reduces maximum readout rates to $\mathcal{O}$(1 kHz)
   - IBF = 10-20% without GG





5) **Aging - note gas and material dependency, also in MPGDs**
   - Permanent damage of anode structure after long term exposure to radiation.
   - Formation of solid deposits
   - Gain drops and instabilities

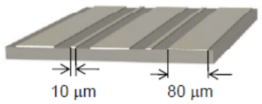
Overcoming the MWPC limitations

MPGD – Micro Pattern Gaseous Detectors

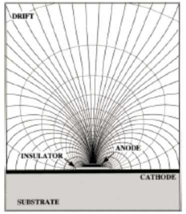
- Reduction of the size of the detecting cell (~ 100 um) using chemical etching techniques
- Same working principle as proportional wire chambers
  - Conversion region (low E drift field)
  - High E field in well localized regions where multiplication happens
- Rate capability goes up to few MHz/cm^2 thanks to the fast charge signal (<100 ns in MM)
- E×B effects negligible
- Simpler and more robust construction
- IBF can be significantly reduced to the <1 % level with optimized geometry and HV settings

- Electrical discharges – sparks
  - High field close to both electrodes
  - inter-electrode space is on micron scale, i.e. very sensitive to dust
  - thin electrodes can be seriously damaged
- Dielectric material
  - Movement of charges when HV is applied
  - Charging up

Microstrip Gas Chamber
[A. Oed, NIM A263, 351 (1988)]

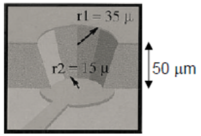


Microgap Chamber (MGC)
[F. Angelini et al., NIM A335, 69 (1993)]

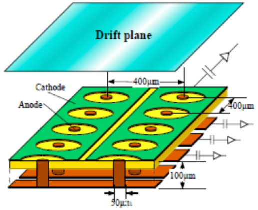


Compteur à Trous (CAT)
[F. Bartol et al., J. Phys. III 6, 337 (1996)]

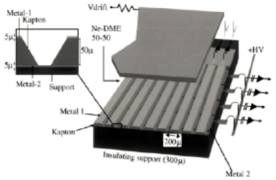
WELL Detector (µCAT)
[R. Bellazzini et al., NIM A423, 125 (1999)]



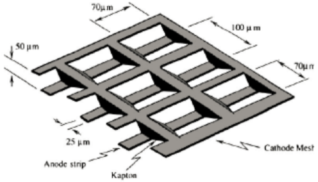
Microdot Chamber
[S.F. Biagi et al., NIM A361, 72 (1995)]



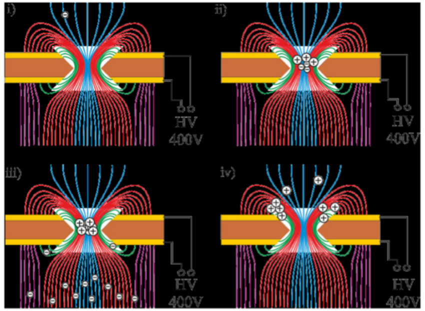
Micro Groove Counter
[Bellazzini et al., NIM A424, 444 (1999)]



Micro Wire Detector
[B. Adeva et al., NIM A435, 402 (1999)]



GEM and Micromegas



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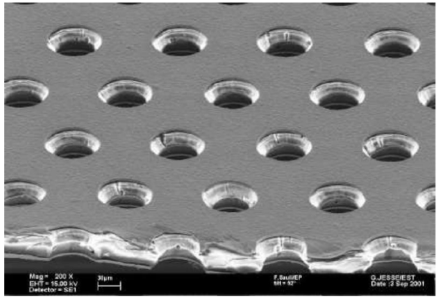

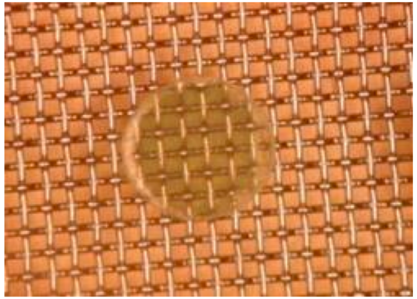

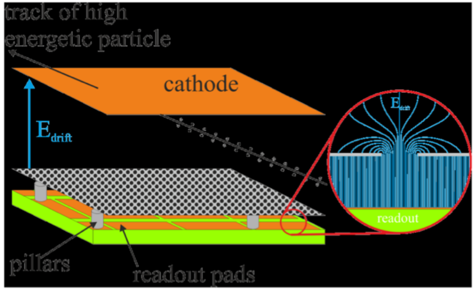

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GEM (Gas Electron Multiplier)

F. Sauli, Nucl. NIM A **386** (1997) 531

- high E-field inside 50 µm holes ➛ amplification
- no issue with rate capability
- lower (effective) gain since signal is produced by (fast) electrons
- ion backflow $\mathcal{O}$(10%) for a single GEM
- operated in a stack
  (stability against discharges, IBF reduction)

Micromegas (Micro-Mesh Gaseous Structure)

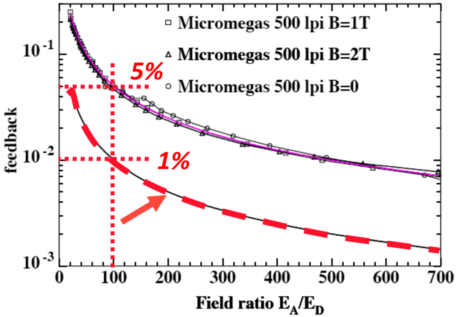
Y. Giomataris *et al.*, NIM A **376** (1996) 29

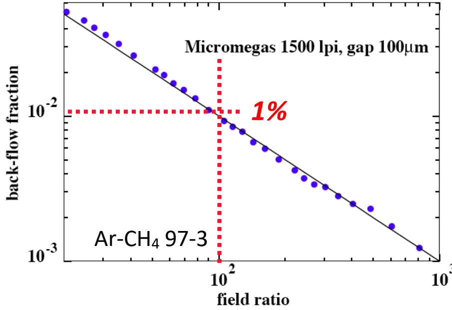
- high/low electric field regions separated by a mesh
- gap (50-100 µm) uniformity by spacers and pillars
- great intrinsic ion backflow suppression
- stability against discharges
  (**but:** resistive MM, floating strip MM, segmented MM, …)

* from P. Colas (CEA), IAS HEP@HKUST workshop, Honk-Kong, 18/01/19 (link)

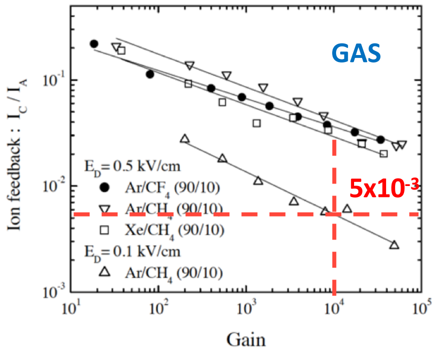
IBF

- **Micromegas**
  - Great IBF capabilities
  - depends on avalanche spread but cannot be smaller than the field ratio
  - further reduction: MM with offset meshes of $\mathcal{O}(10^{-5})$
    (F. Jeanneau *et al.*, NIM A **623** (2010) 94)
- **GEM stacks**
  - complex interplay of **geometry, fields, diffusion**
  - charge density and B-field dependency must be considered
  - hole alignment

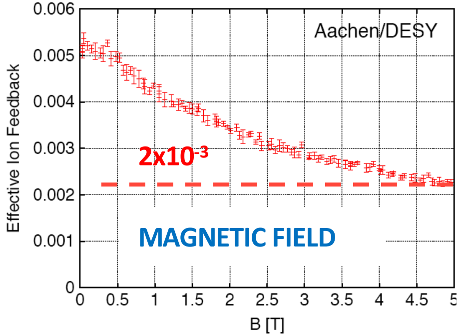




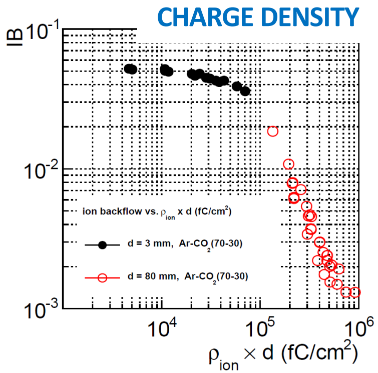
P. Colas *et al.*, Nucl. Instr. and Meth. A **535** (2004) 226.



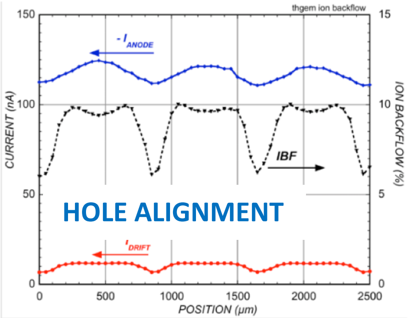
A. Bondar *et al.*, NIM A **496** (2003) 325



M. Killenberg *et al*, NIM A **530** (2004) 251.



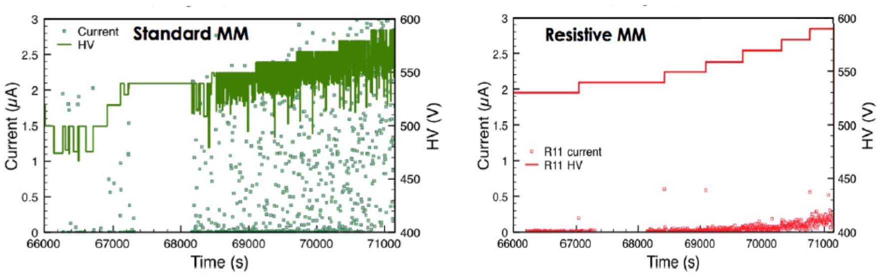
M. Ball *et al*, JINST 9 (2014) C04025



F. Sauli *et al.*,NIM A **560** (2006) 269.

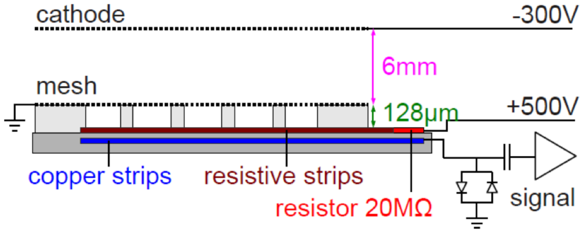
Discharge stability

T. Alexopolous *et al.*, NIM A **640** (2011) 110.



Micromegas

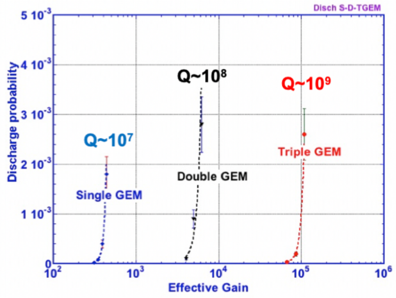
- working principle as parallel plate detector, $Q_{crit} \approx 10^7$-10^8 e$^-$
- complete discharge of mesh; recovery time t_{dead} > 1 ms
- harmful for FEE but not for mesh (robustness!)
- **REMEDY:** resistive MM, floating strip/pad MM



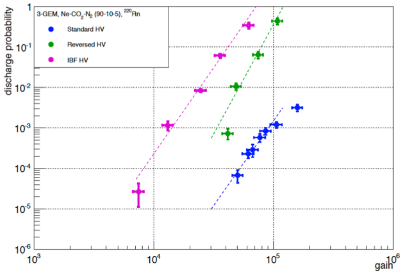
© J. Bortfeldt, Ph.D. Thesis, LMU, 2015.

GEMs

- $Q_{crit} \approx 10^6$-10^7 e$^-$ for single GEM hole ➛ build stacks
- optimized HV settings (lower amplification towards bottom of a stack)
- primary and secondary discharges (in the gaps) may be harmful to GEMs



S. Bachmann *et al.*, NIM A **479** (2002) 294.



© ALICE, CERN-LHCC-2015-002, 2015.

TPCs WITH MPGD READOUT

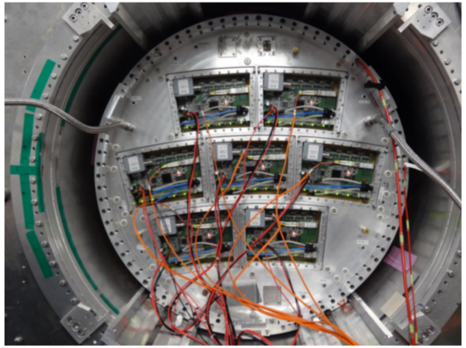
High rate trackers

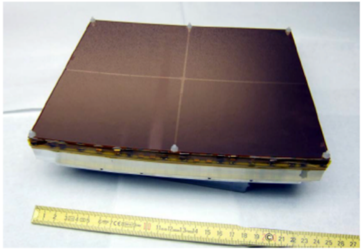
pp, e^+e^- and heavy-ion collisions

A Time Projection Chamber for a Future Linear Collider

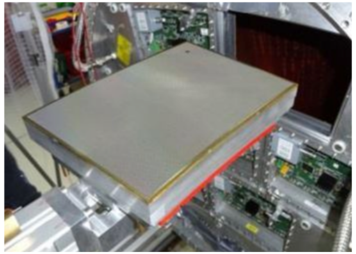
Development of a high-performance TPC for the physics up to $\sqrt{s}$ = 1 TeV energy at the planned International Linear Collider

- Need to support high density of tracks and/or final states with 6+ jets
  - high granularity 3D tracking (σ_{pt} < 100µm (rϕ) and ≈ 500µm (rz)
  - good two tracks separation (2-hit resolution <2 mm (rϕ) and <6 mm (rz))
  - track identification (dE/dx resolution ≈ 5%)
- Extensive R&D with large-scale prototypes to choose the best readout technology
- Gating still optional (1 ms long bunch trains every 200 ms)

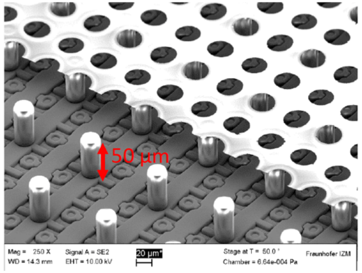




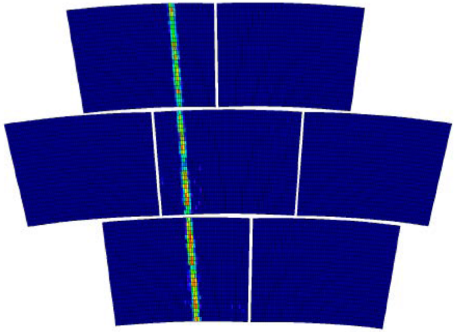
- 3GEM
- 95% active area
- $\sigma_{dE/dx}$ = 4.1% (220 pts)



- Encapsulated Resistive Anode MMG
- $\sigma_{dE/dx}$ = 4.5-4.8% (170 pts)



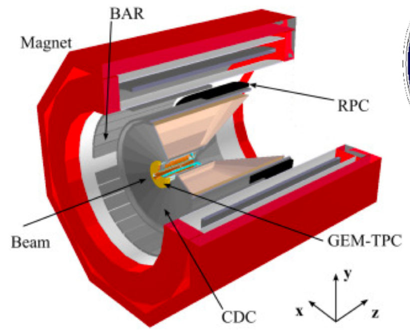
- Gridpix - "Digital TPC"
- QUAD: 4x TimePix3 chips
- $\sigma_{dE/dx}$ = 2.7%

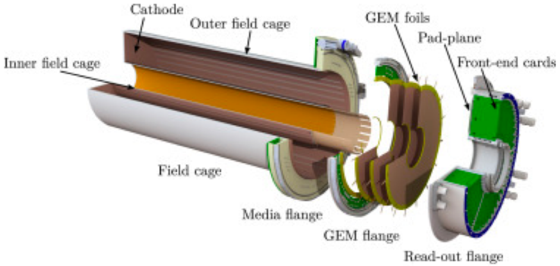


FOPI GEM-TPC (aka PANDA Prototype)

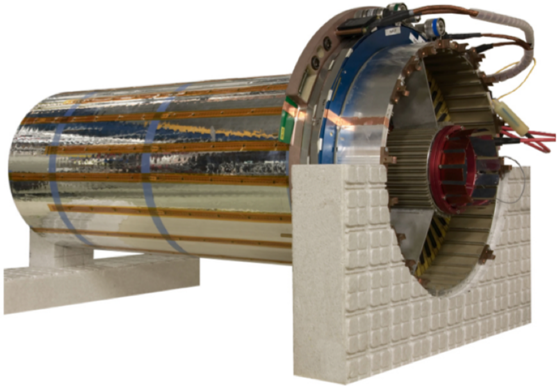
M. Berger et al. NIM A 869 (2017) 180
F. Böhmer et al. NIM A 719 (2013) 101

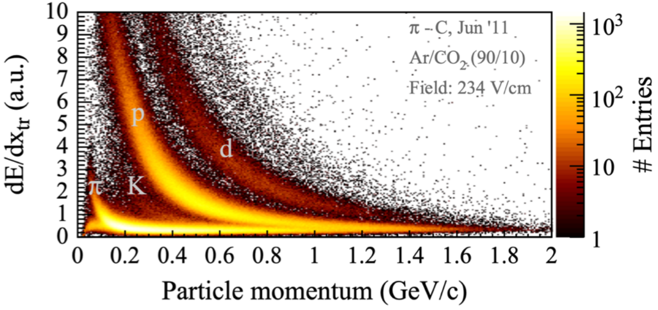
- A prove of the concept of an ungated TPC with GEM amplification
- Successfully operated within the FOPI spectrometer (GSI) in π+A run
- Currently in Bonn, to be used at CB-ELSA

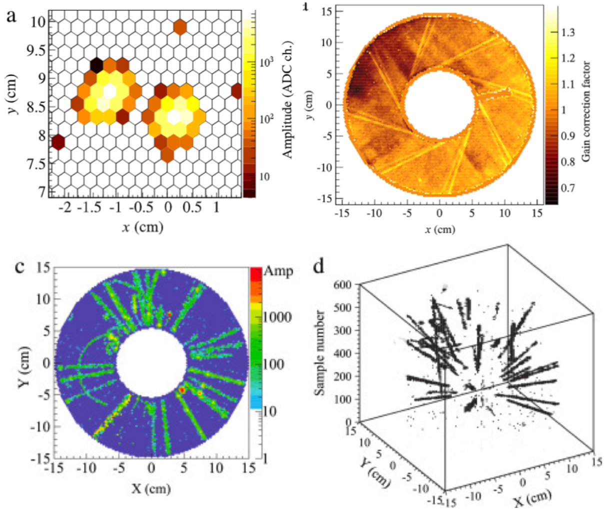




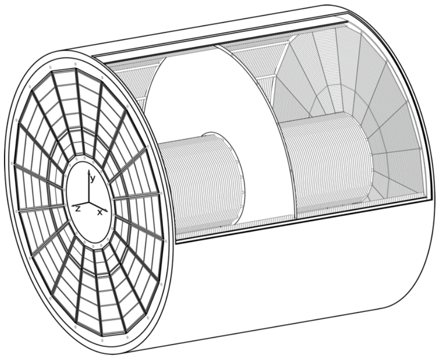
- 3-GEM stack (Ar-CO_2)
- light-weight field-cage
- Readout with AFTER chip (T2K)
- ^{83m}Kr calibration
- first dE/dx measurement with GEM-based TPC





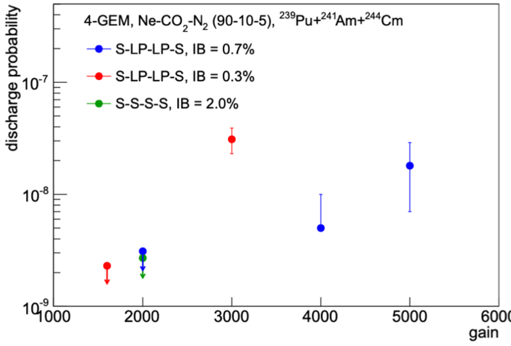


First continuously operated TPC – ALICE TPC upgrade



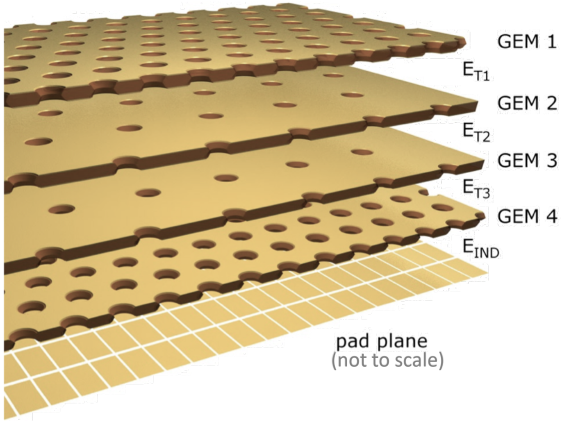
ALICE TPC

- Diameter: 5 m, length: 5 m
- Gas: Ne-CO2-N2, Ar-CO2
- Max. drift time: ~100 µs
- 18 sectors on each side, MWPC with GG
- 72 Inner and outer read out chambers: IROC, OROC



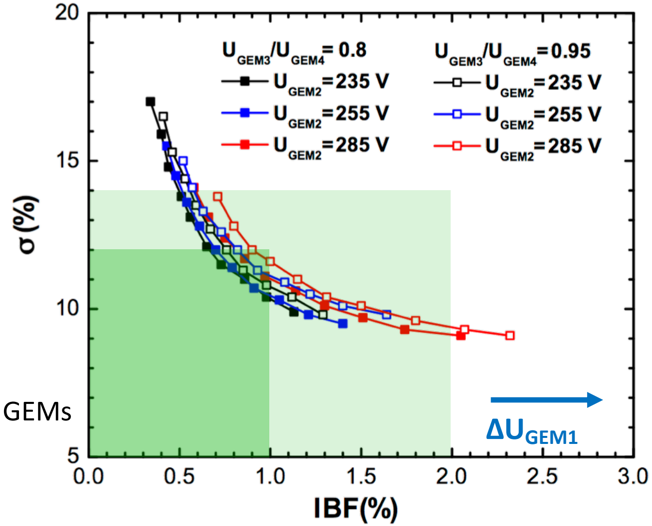
TPC Upgrade requirements:

- Continuous operation at 50 kHz Pb-Pb
- Nominal gain = 2000 in Ne-CO_2-N_2 (90-10-5)
- IBF < 1% (ε = 20), σ_E/E < 12% for ^{55}Fe
- Stable operation under LHC Run 3 conditions
- Unprecedented challenges in terms of loads and performance



Baseline solution: 4-GEM stack

- Combination of standard (S) and large pitch (LP) GEMs
- Highly optimized HV configuration
- Result of intensive R&D

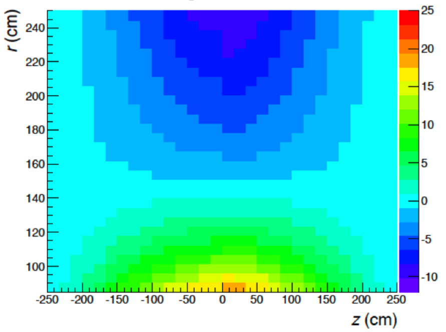


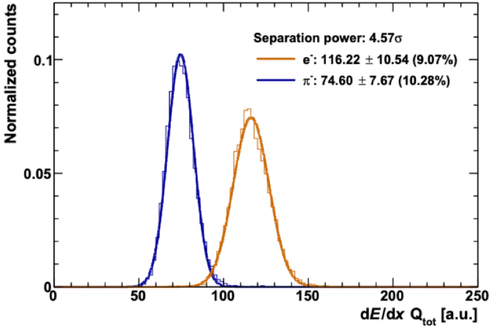
Upgraded ALICE TPC

ALICE, CERN-LHCC-2013-020, 2013.
ALICE, CERN-LHCC-2015-002, 2015.
ALICE TPC, NIM A 903 (2018) 215.

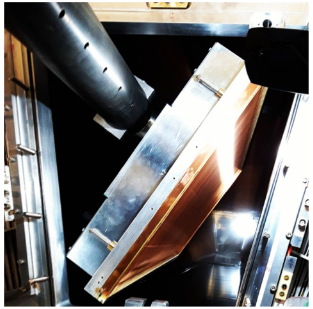
- Ions from 8000 events pile up in the drift volume at 50 kHz Pb-Pb
  - Distortions up to *dr* ≈ 20 cm at an *IB* of 1 % (!!!)
  - Corrections to $\mathcal{O}(10^{-3})$ are required for final calibration
    - Space charge maps + external detectors (ITS, TRD)
  - Limits of calibration procedure tested up IB = 2 %

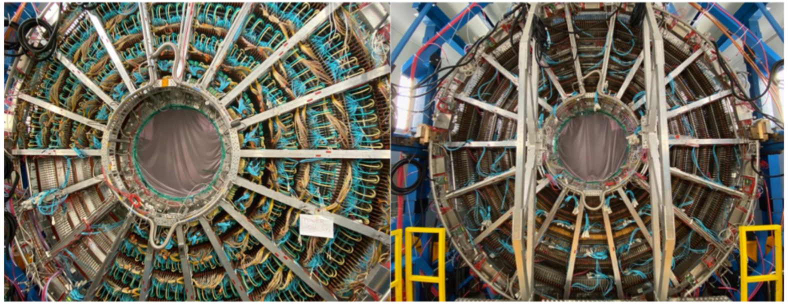
- dE/dx performance as with the MWPC readout
  - Confirmed with several test beams
  - Last one (2017) with new SAMPA -based FEE

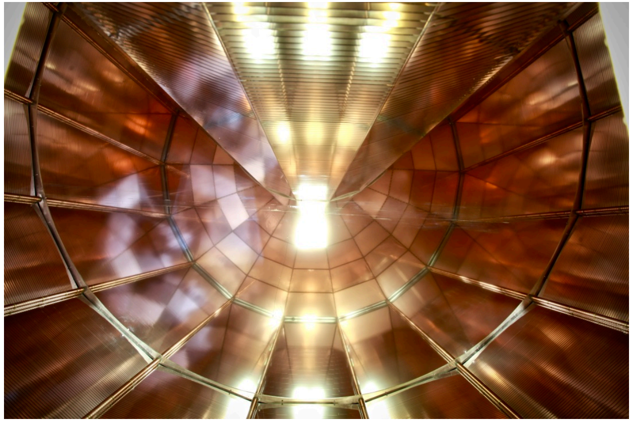




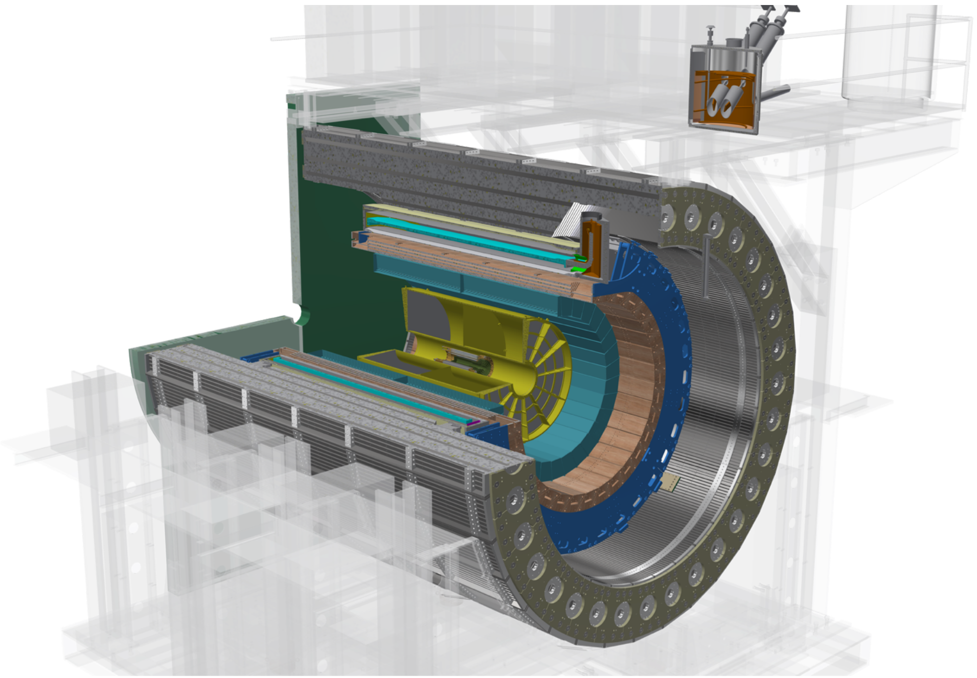
- The TPC Upgrade is taking place **NOW**
  - GEM chambers installed, FECs installed. First tracks this week!
  - GEM TPC ready for installation and commissioning in ALICE in 03.2020



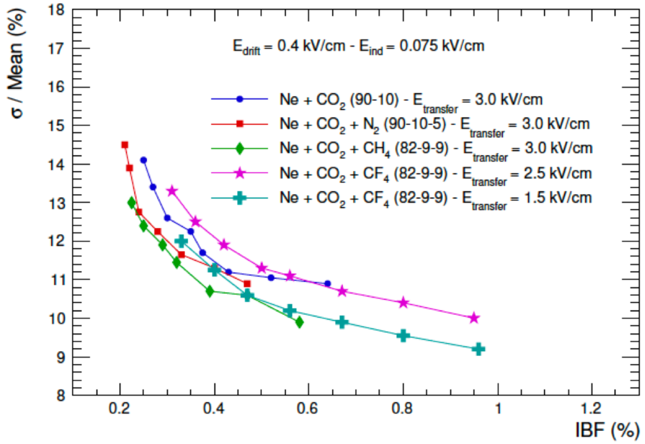




sPHENIX TPC



- State-of-the art jet detector at RHIC
- Probe the inner workings of QGP
- 15 kHz readout in Au+Au
- Tracker + Calorimeter stack
- **Continuous readout TPC**
  - A'la ALICE GEM TPC, 4-GEM readout considered
  - No external detector (TRD) for space-charge corrections
  - Further reduction of IBF?
  - Hybrid 2GEM + MM options?



S. Aiola et al. NIM A 834 (2016) 149

LOW ENERGY NUCLEAR PHYSICS

Active target TPCs

- Experiments with secondary radioactive beams ➛ low intensities (0.1-100 kHz)

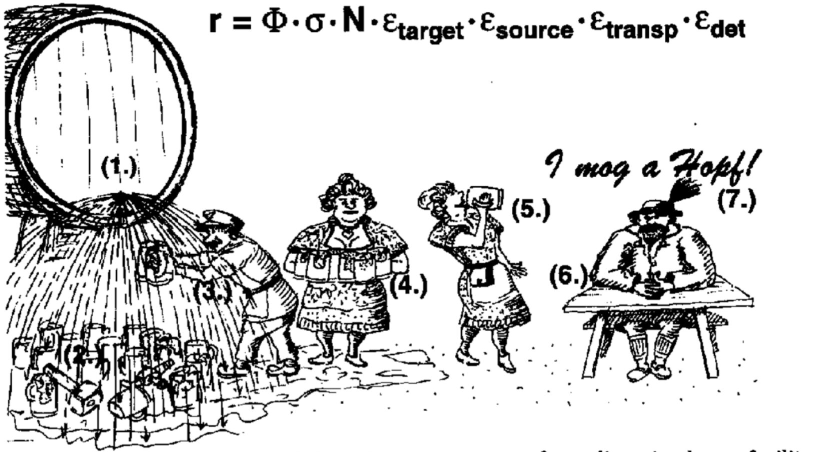


Fig. 1: Schematic representation of the subsequent stages of a radioactive beam facility.

U. Köster, Prog. Part. Nucl. Phys. 46 (2001) 411

- To compensate ➛ thick targets and high detection efficiencies needed
- Target ➛ light particles (p, d, ^{3,4}He) ➛ change from direct to inverse kinematics
- Active target TPC ➛ gas serves as target and tracking medium
- Gas contained in the TPC not only as the ionization medium but also as a low-mass active target.
- Charged nuclear reaction products can be tracked and identified inside the target
- Active target TPC overview ➛ Y. Ayyad *et al*. Eur. Phys. J. A **54** (2018) 181

Challenges of Active Target TPCs

Active Target TPCs – relatively new development

- Current focus on the MPGD readout
- Still many challenges to address
- Recent review: Y. Ayyad *et al*. Eur. Phys. J. A **54** (2018) 181

High pile-up, space charge (fluctuations)

- Low intensity bunched beams may reach very high instantaneous rates (>10 MHz); bunch microstructure
- Beam contaminants (isobars) produced with orders of magnitude higher intensities than the ions of interest

Final resolution of the reaction characteristic

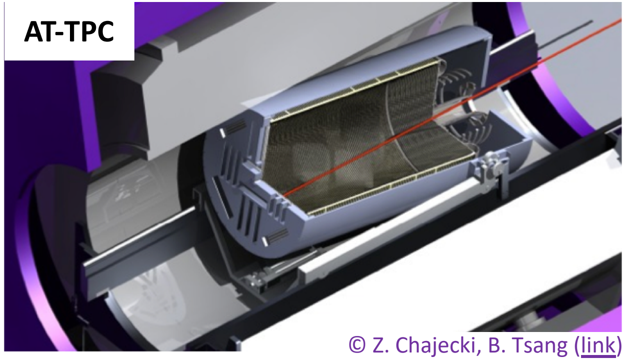
- Beam quality – large emittance

Dynamic range, discharge stability

- Detection of light recoil particles in presence of heavy beam particles
- E.g. ^{132}Sn + p ➛ ^{132}Sn + p $(\langle dE/dx\rangle_{Sn} = 2500\times \langle dE/dx\rangle_{p})$

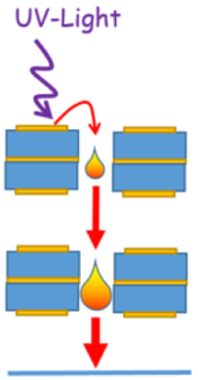
Name	Lab	Gas ampl.	Volume [liter]	Volume [cm^3]	Pressure [atm]	Energy [MeV/n]	Electronics	No. of chan.	Status^a
Ikar	GSI	NA	75	$60 \cdot 20^2\pi$	10	$\gtrsim 700$	FADC	$6 * 3$	O
Maya	GANIL	wire	7.5	$30 \cdot 28.3^2$	0.02–2	2–60	gassiplex	1024	O
ACTAR TPC	GANIL	μmegas	8	20^3	0.01–3	2–60	GET	16000	C, P
MSTPC^b	CNS	wires	21	$70 \cdot 15 \cdot 20$	< 0.3	0.5–5	FADC	128	O
			^{c}						
CAT	CNS	GEM	2.5	$10 \cdot 10 \cdot 25$	0.2–1	100–200	FADC	400	T
MAIKo	RNCP	μ-PIC	2.7	14^3	0.4–1	10–100	FADC	2×256	T
pAT-TPC	MSU	μmegas	47	$50 \cdot 12.5^2\pi$	0.01–1	1–10	GET	256	T, O
AT-TPC	FRIB	μmegas	200	$100 \cdot 25^2\pi$	0.01–1	1–100	GET	10240	O
TACTIC	TRIUMF	GEM	7.5	$24 \cdot 10^2\pi$	0.25–1	1–10	FADC	48	T
ANASEN	FSU/ LSU	wires	13	$43 \cdot 10^2\pi$	0.1–1	1–10	ASIC	512	O
MINOS	IRFU	μmegas	6	6000	1	> 120	feminos	5000	O
O-TPC	TUNL	grid	19	$21 \cdot 30^2$	0.1	~ 10 CCD	optical	$2048\times$ 2048	O
SpecMAT	Leuvan	μmegas					GET		T
TexAT	Texas AM	μmegas	5	$(22.4)^2 \cdot 10.15$			GET	1024	T
ACTAF	FAIR	wires	200	$100 \cdot 25^2\pi$	20	1000	FADC	288	T
IRIS ATTPC	TRIUMF	μmegas + TGEM			1–10		GET		P

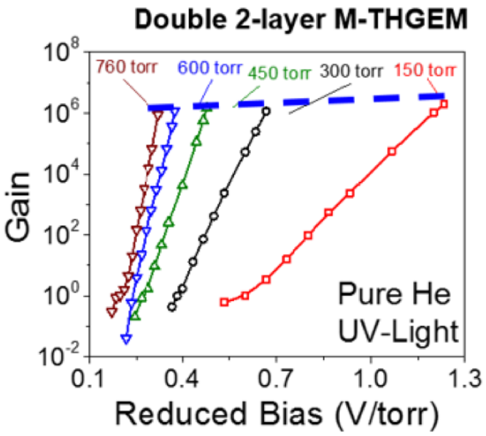
Y. Ayyad *et al*. Eur. Phys. J. A **54** (2018) 181

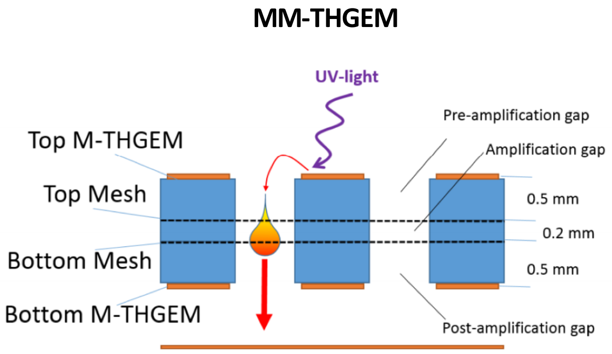


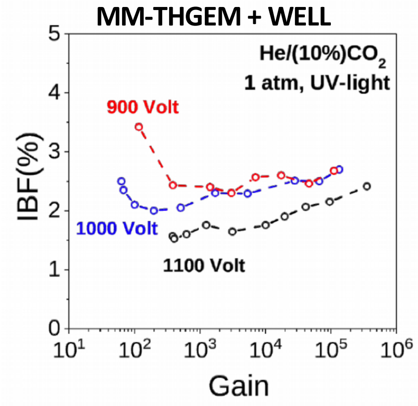
New (exotic) structures

- Development of Active Target TPCs may pave the road for more exotic structures and/or configurations
  - Further IBF suppression
  - Discharge stability in elemental gases w/o quenchers (H_2, D_2, He, …)
- M-THGEM ➢ Multi-Layer Thick GEM (M. Cortesi et al. Rev. Sci. Instrum. 88, 013303 (2017))
- MM-THGEM ➢ Multi-Mesh Thick GEM (R. de Oliveira and M. Cortesi, JINST 13 (2018) P06019)
- And many more…

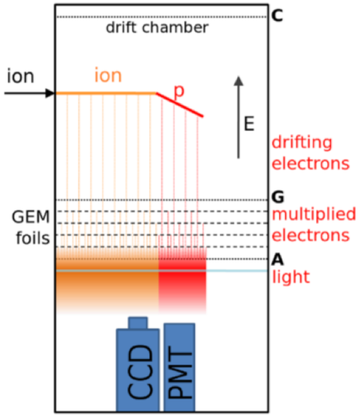


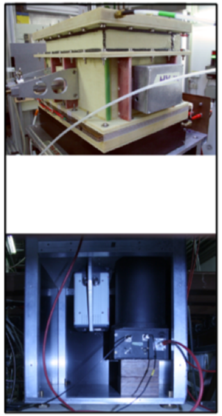




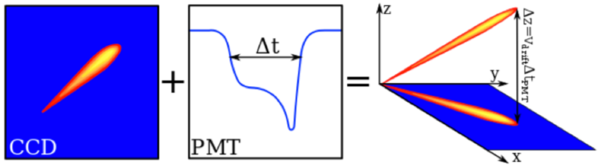


New readout concepts: Warsaw OTPC



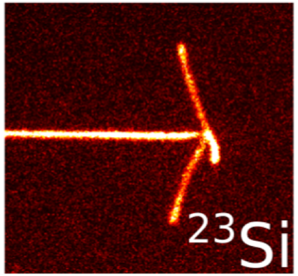


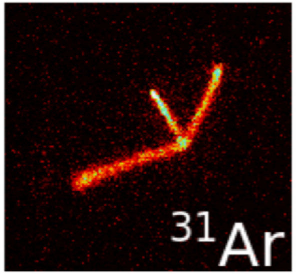
OTPC - details: A.A. C. et al., Eur. Phys. J. A 52, 89, 2016



© A. Ciemny (Uni Warsaw) Bormio 2019 (link)

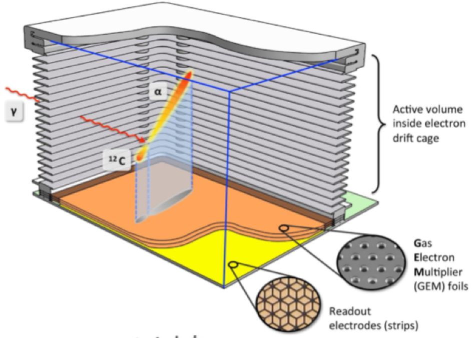
- General purpose Optical TPC (OTPC) for decay studies
- XY (CCD camera) + Z (PMT) readout
- $He/Ar/CF_4$ 69:29:2 (exemplary mixture)
- Multiplication (scintillation generation) with quadruple GEM stack
- Crucial studies for understanding nuclear structure:
  ß decays with delayed (multi-) particle emission





- A.A. C. et al., Prog. in Research (01.04.2017-31.03.2018), Cyclotron Institute, Texas A&M University, College Station, TX, USA, p. IV-67 (2018)
- A.A. L. et al., Phys. Rev. C 91, 064309 (2015)

- Further development ➛ ELITPC for nuclear disintegration using high energy γ beam
  (M. Ćwiok et al. Acta Physica Polonica B 49 (2018) 509)

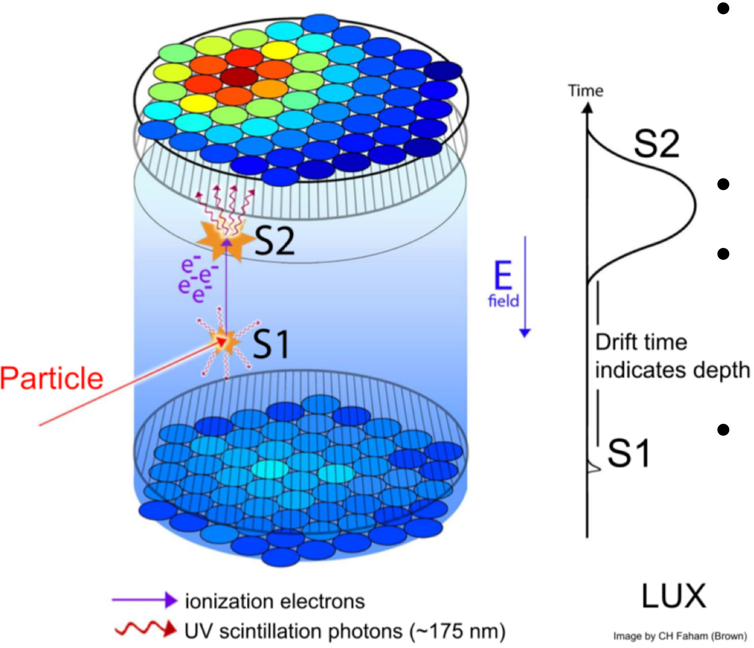


- See more on optically read-out GEMs in F.M. Brunbauer et al. JINST 13 (2018) T02006

RARE EVENTS, BSM PHYSICS

Rare events TPC review

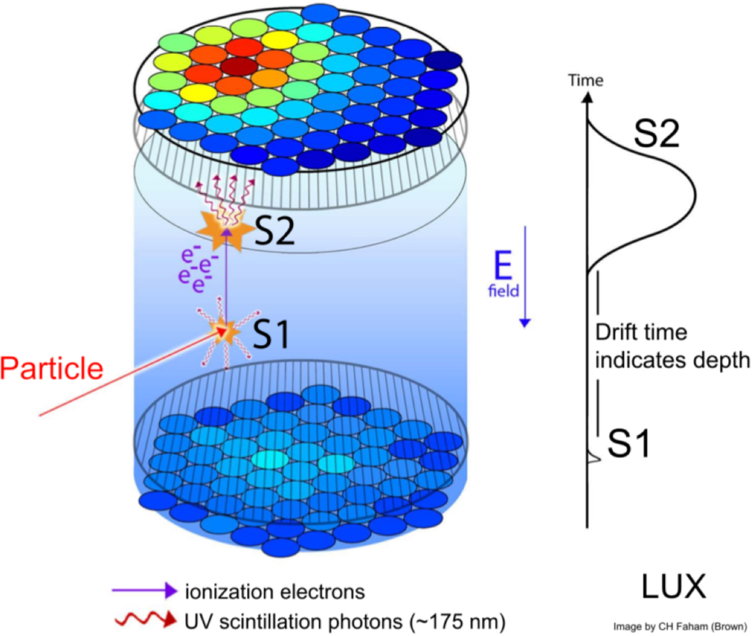
- Recent review by D. Gonzalez-Diaz and collaborators
  - NIM A 878 (2018) 200 (link)



- **Register complex topologies with high accuracy**
  - reconstruct the energy loss path (usually full tracks confined)
  - low track multiplicities
- **Primarily: register light**
  - Primary scintillation
  - Electroluminescence (secondary scintillation)
- **But also charge (with MPGDs ?)**
- **Low rates**
  - No IBF, no space-charge
  - No aging, however…
- **… only certified construction materials (radiopurity)**
  - Low background
  - See e.g. https://arxiv.org/pdf/0709.4524.pdf (EXO-200)

Rare events TPC review

- Recent review by D. Gonzalez-Diaz and collaborators
  - NIM A 878 (2018) 200 (link)



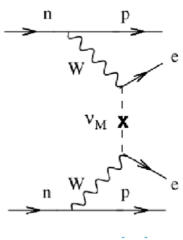
	TPC	E_d [V/cm]	B [T]	$H(\times S)$ [m × m^2]	P [bar]	image plane	layout	medium	Ref
gaseous	ACTAR	flexible	-	$0.25\,(\times\,0.25^2)$	0.1-3	MM (bulk)	3D	generic (H_2, He, Ar...)	[16]
	AT-TPC	flexible	up to 2	$1\,(\times\pi\,0.3^2)$	0.05-1	MM (microbulk)	3D	generic (H_2, He, Ar, CO_2...)	[78]
	Warsaw	flexible	-	$0.21\,(\times\,0.18\times 31)$	1	4-GEM + PMT + CCD	2D+1D	Ar/He/CH_4/N_2-based	[76]
	TUNL	flexible	-	$0.21\,(\times\,0.3\times 0.3)$	0.13-0.18	MSAC + PMTs + CCD	2D+1D	CO_2/N_2	[15]
	NEXT-NEW	200-600	-	$0.53\,(\times\pi\,0.21^2)$	5-15	mesh + SiPMs + PMTs	3D	^{136}Xe-enriched xenon	-
	PandaX-III	up to 1000	-	$(2\times)\,1\,(\times\pi\,0.75^2)$	10	MM (microbulk)	2D+2D	^{136}Xe-enriched Xe/TMA	[287]
	DRIFT	600-700	-	$(2\times)\,0.5\,(\times\,1\times 1)$	0.055	MWPC	2D+2D	CS_2,O_2-based	[39]
	DMTPC	150-250	-	$(4\times)\,0.275\,(\times\,1\times 1)$	0.04-0.1	mesh + PMTs + CCDs	2D+1D	CF_4	[53,51]
	NEWAGE	80-300	-	$0.41\,(\times\,0.3\times 0.3)$	0.2	μ-PIC + GEM	2D+2D	CF_4	[52]
	MIMAC	100	-	$(2\times)\,0.25\,(\times\,0.1\times 0.1)$	0.05	MM (bulk)	2D+2D	CF_4/CHF_3/i-C_4H_{10}	[288,51]
	TREX-DM	flexible	-	$(2\times)\,0.25\,(\times\,0.25\times 0.25)$	1-10	MM (microbulk)	2D+2D	Ne, Ar -based	[21]
	T2K-ND	200-300	0.18	$(2\times)\,1.25\,(\times\,1\times 2.55)$	1	MM (bulk)	3D	Ar/CF_4/i-C_4H_{10}	[161]
	CAST	~100	-	$0.03\,(\times\,0.06\times 0.06)$	1.4	MM (microbulk), INGRID	2D+2D	Ar/i-C_4H_{10}	[21,289]
	MuCap	2000	-	$0.12\,(\times\,0.15\times 0.3)$	10	MWPC	2D+2D	D-depleted H_2	[290]
dual-phase	DUNE-FD	1000	-	$(\times 4)\,12\,(\times 60\times 12)$	1	LEMs + PMTs	2D+2D	argon	[155]
	LUX	181	-	$0.48\,(\times\pi\,0.235^2)$	1-2	mesh + 2 PMT planes	3D	xenon	[291]
	XENON1T	120	-	$1\,(\times\pi\,0.5^2)$	1-2	mesh + 2 PMT planes	3D	xenon	[66]
	PandaX-II	393.5	-	$0.6\,(\times\pi\,0.32^2)$	1-2	mesh + 2 PMT planes	3D	xenon	[292]
	DarkSide-50	200	-	$0.35\,(\times\pi\,0.178^2)$	1	mesh + 2 PMT planes	3D	^{39}Ar-depleted argon	[43]
	WARP(1001)	90-330	-	$0.6\,(\times\pi\,0.25^2)$	1	mesh + PMTs	3D	argon	[293]
	ALICE	400	0.5	$(2\times)\,2.5\,(\times 18)$	1	MWPC (GEMs)^{*a} + pads	3D	Ne/CO_2/N_2	[61]
	STAR	135	0-0.5	$(2\times)\,2.1\,(\times 18)$	1	MWPC + pads	3D	Ar/CH_4	[286]

Table 5
Some technical parameters of the most representative TPCs used in the search of rare processes, both in gas (top block) and dual (middle block) phase. For reference, the lowest block includes two paradigmatic collider TPCs. The size of the active dimension along the electric field is dubbed H and S is the active area. For dual-phase, the electric field is given for the liquid phase and the pressure for the gas phase. The compilation is illustrative since several of the collaborations are already heading towards an upgrade, e.g., NEXT [182], MIMAC [51], T2K-ND [294], DarkSide [295] or LUX [23].

^{*a} the ALICE TPC will replace its MWPC plane by a 4-GEM one.

0νββ

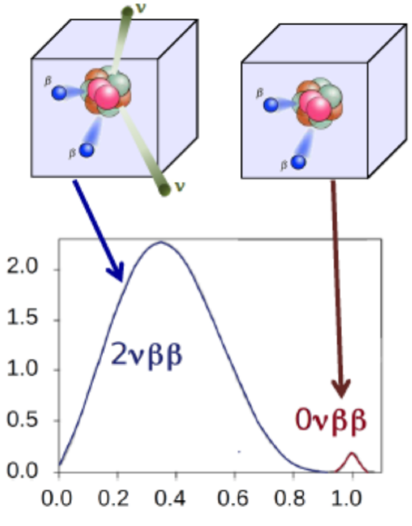
- NOT allowed by SM: **0νßß**, $T_{1/2} > 10^{25}$ y (expectation), (A,Z) ➛ (A,Z+2) + $2e^-$
  - Lepton number violation
  - Neutrinos are Majorana fermions
- Experimental method: source = detector
  - Peak over 2νßß Q spectrum
  - Width – detector resolution - make use of electroluminescence (near-intrinsic energy resolution)!

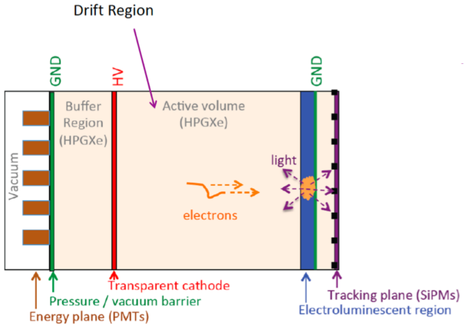


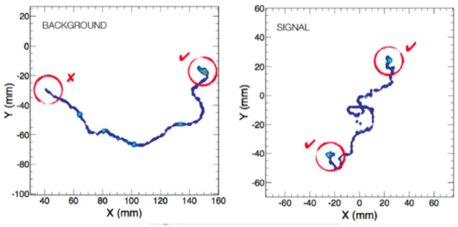
Isotope	ββ(0ν) Half-life limit (years)	Natural Abundance [%]	Q-value (MeV)
^{48}Ca	>1.4 × 10^{22} [31]	0.187	4.2737
^{76}Ge	>3.0 × 10^{25} [32]	7.8	2.0391
^{82}Se	>1.0 × 10^{23} [33]	9.2	2.9551
^{100}Mo	>1.1 × 10^{24} [34]	9.6	3.0350
^{130}Te	>4.0 × 10^{24} [35]	34.5	2.5303
^{136}Xe	>1.1 × 10^{25} [36]	8.9	2.4578
^{150}Nd	>1.8 × 10^{22} [37]	5.6	3.3673

R.Henning, Reviews in Physics 1 (2016) 29–35

from: C. Brofferio, VCI2019, Wien 18-22.02.19 (link)







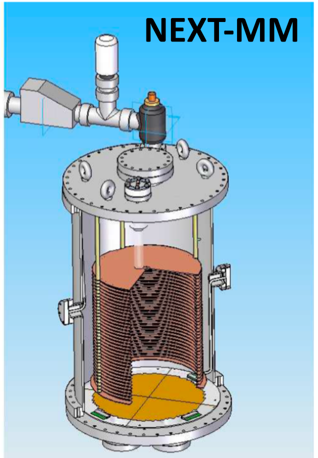
© L. Rogers, RD51 MW, CERN 12.2018 (link)

NEXT TPC

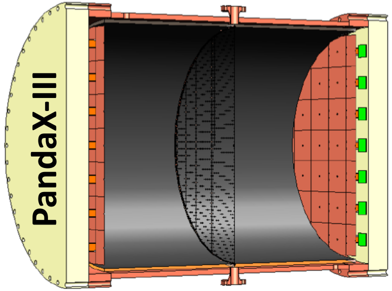
- 10-15 bars, gaseous ^{136}Xe
  (clear topological reconstruction – spaghetti with two meatballs)
- Detection of secondary light multiplication
- PMT and SiPM readout
- Energy resolution of <0.5 % FWGM at Q_{bb}

- NEXT-NEW (5-10 kg) currently operated
- NEXT-100 under construction

$0\nu\beta\beta$ – NEXT-MM & PANDAX-III



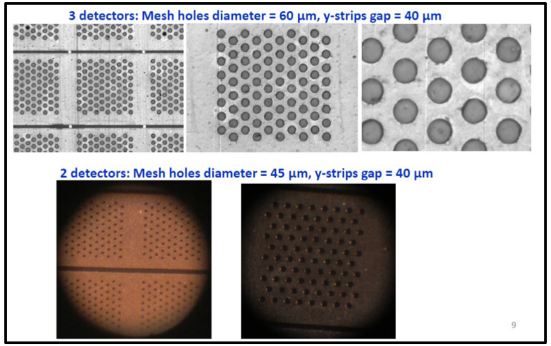
V. Álvarez et al., JINST 9 (2014) P03010



S. Wang, VCI 2019, Vienna (link)

- Alternative option based on charge readout with MPGD: NEXT-MM prototype (1kg, ~25 l active volume)
- Microbulk Micromegas
  - Gain uniformity over 50 µm gap
  - Radiopurity (Cu and Kapton, <0.1Bq/cm^2)
  - Good energy resolution
- Xe/TMA 99:1 mixture (reduce *D* coeff.)
- Energy resolution:
  - 10.6 % FWHM @ 30 keV
  - 3-4 % at Q_{bb} in ^{136}Xe (extrapolation)
- Concept followed by PandaX-III Collaboration
  - China JinPing underground Lab (2.4 km underground + clean water shielding)
  - Phase 1: 2 m long, 1.5 m diameter module (200 kg HPGXe136, 10 bars)
  - Phase 2: 5x Phase 1 modules
  - TPC: symmetric, double-end charge readout
  - 82 20x20 cm^2 Microbulk MM modules, 2D strip readout
  - Sensitivity expected: 10^{26} y $T_{1/2}$ limit
  - 20-kg scale prototype TPC (5 bar) with 7 MM has been built and operational (https://arxiv.org/abs/1804.02863)

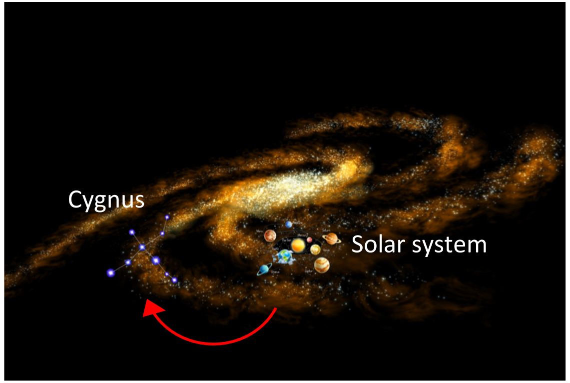
Microbulk MM



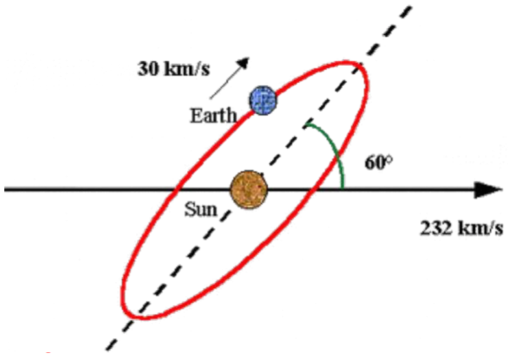
T. Geralis et al., PoS (TIPP2014) 055

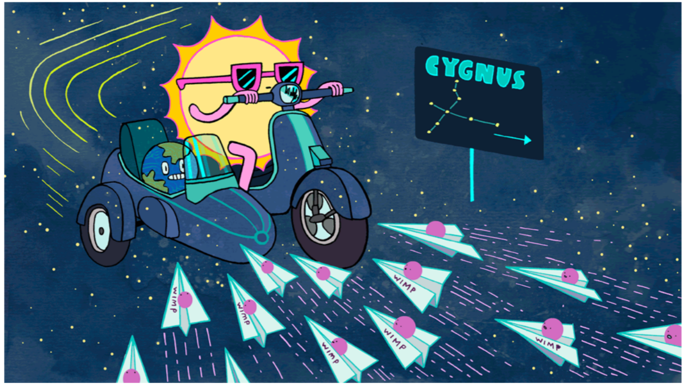
S. Wang, VCI 2019, Vienna (link)

Directional Dark Matter searches



from G. Cavoto (Sapienza Univ. Roma & INFN), VCI 2019 (link)

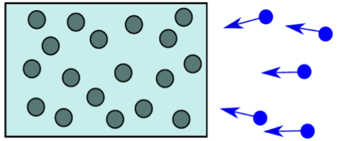




Artwork by Sandbox Studio, Chicago with Corinne Mucha

- We are all immersed in a halo of dark matter particles (0.3 GeV/cm³)
- Our Solar System moves through the halo (towards Cygnus) with v_{sun} = 232 km/s
- Dark matter particles are appearing as coming from the Cygnus constellation – WIMP wind
- Yearly modulation (~10 %) of the DM wind, depending on the v_{earth} wrt. v_{sun}
- Look for interactions of DM particles from the halo with nuclei in a detector - measure E_{recoil}
  - Expect low event rate ➛ build large detectors
  - Expect low energy events $\mathcal{O}$(keV) ➛ low thresholds
  - Expect lots of backgrounds ➛ underground, radiopure materials, background discrimination
  - Build a TPC ➛ measure shape of the recoil (bkg. rejection) and its direction (WIMP wind)

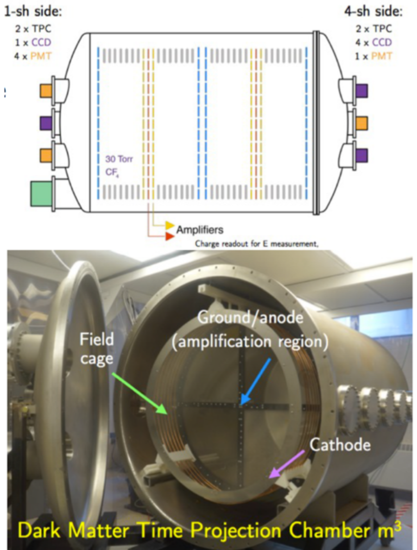
from B. Kavanagh (CEA Saclay), link



DMTPC & CYGNUS-TPC

DMTPC – a family of detectors

- Most recent DMTPC m^3
- Low pressure (30 Torr) gas TPC (CF_4)
- Record F nucleus recoils after WIMP scattering
- Record CF_4 scintillation using CCD cameras
- PMT and charge readout
- Determine the direction form the dE/dx profile



CYGNUS-TPC

- CYGNUS-TPC project aims at building a multi-ton gas target for DM as various TPC detectors distributed in underground labs. Possibility of achieving great angular resolution by combining:
- MPGD (GEM) + Optical readout
    - ORANGE prototype
    - He/CF_4 60:40 mixture
    - Time structure from PMT and GEM3_bot measurements
- Negative Ion TPC technique:
    - add small amount of highly electronegative component (SF_6, CS_2)
    - create negative ions with ionization electrons
    - drift with negligible diffusion
    - amplification stage: exceeding electrons are released and an avalanche can develop
    - Different arrival times (different v_{dirft}) allow to evaluate depth of the event
    - Demonstrator (5×3×3 cm^3) operated at close-to-atm pressure with He/CF_4/SF_6 59:39.4:1.6

DMTPC & CYGNUS-TPC

DMTPC – a family of detectors

- Most recent DMTPC m^3
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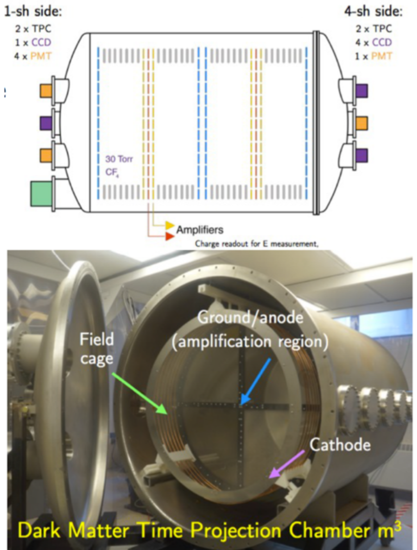

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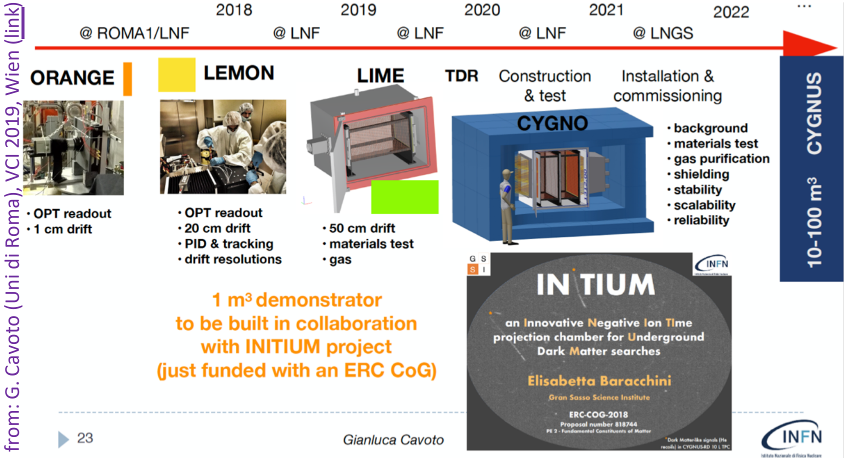


NEUTRINOS

Neutrino experiments

- Big questions of neutrino physics

- *how much do neutrinos weigh?*
- *what is the nature of the ν?*

β decay and 0νββ decay

- *which neutrino is the heaviest and which is the lightest (MH)?*
- *do neutrinos violate CP?*

long-baseline neutrinos

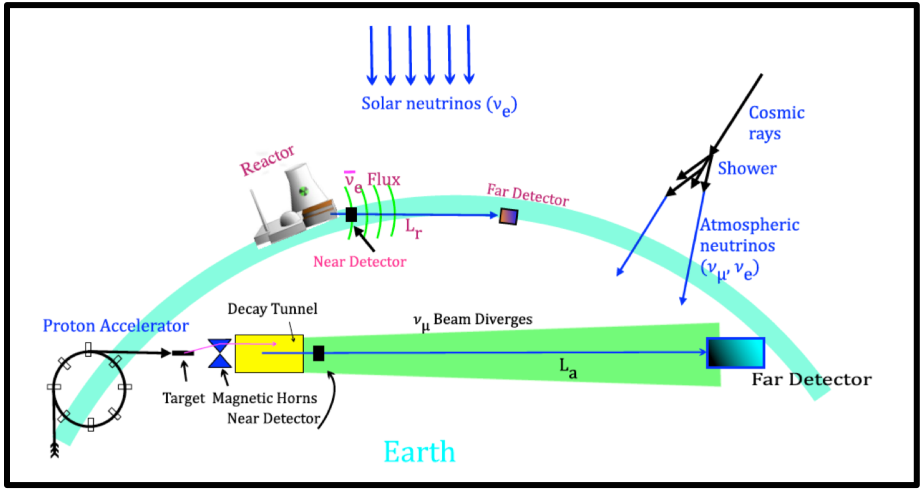
- *is our picture correct?*

- *are there more than 3 kinds of neutrinos?*

short-baseline neutrinos

from: S. Zeller, NygrenFest, BNL 2014 (link)

- Neutrino sources for ν-oscillation exp.

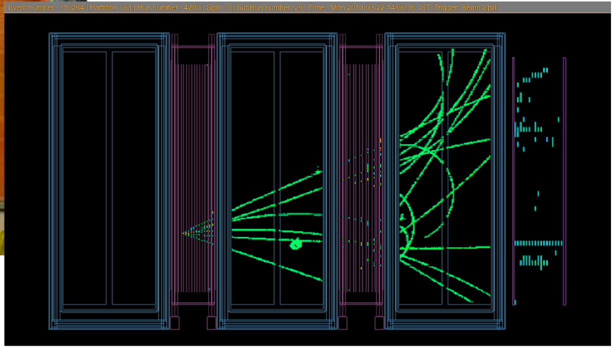


M. Diwan et al. Annu. Rev. Nucl. Par. Sci. 66, 47-71 (2016)

TPCs in neutrino physics

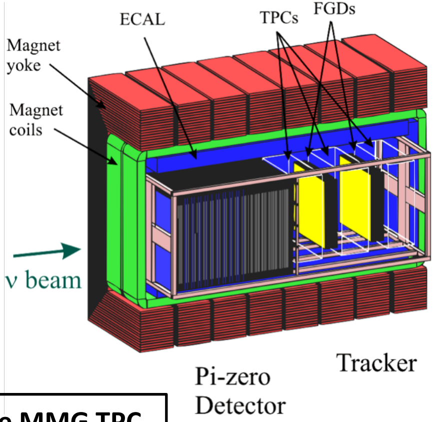
- **Gaseous TPCs**
  - **T2K** (long-base, near detector) ➛ first large-scale implementation of MMG
  - Hadro-production experiments for constraining ν fluxes (HARP, **NA61/SHINE**, MIPP)
    e.g. M. Posiadala-Zezula, J.Phys.Conf.Ser. 888 (2017) 012064
  - Spherical TPCs (low energy ν) I. Giomataris, J.D. Vergados, NIMA 530 (2004) 330

NIM A 637 (2011) 25-46



T2K TPC

- check initial beam composition
- pre-oscillation charged current neutrino interaction rates (5-7% sys. uncertainties)
- reduce uncertainties in the oscillation measurements
- **includes 3 large MM TPCs, AFTER chip readout**
- **operated at about 750 torr with Ar/CF4/iC4H10 (95:3:2)**

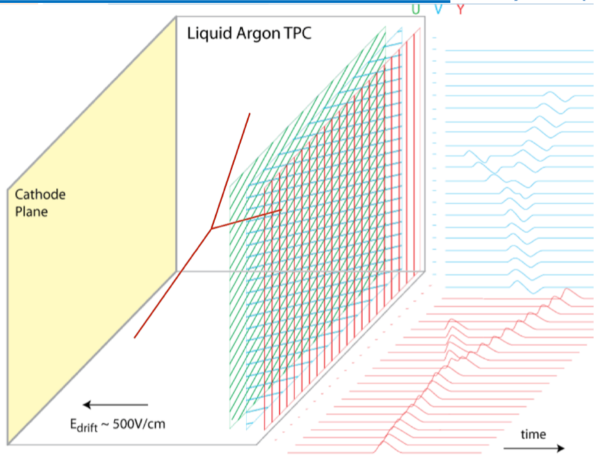


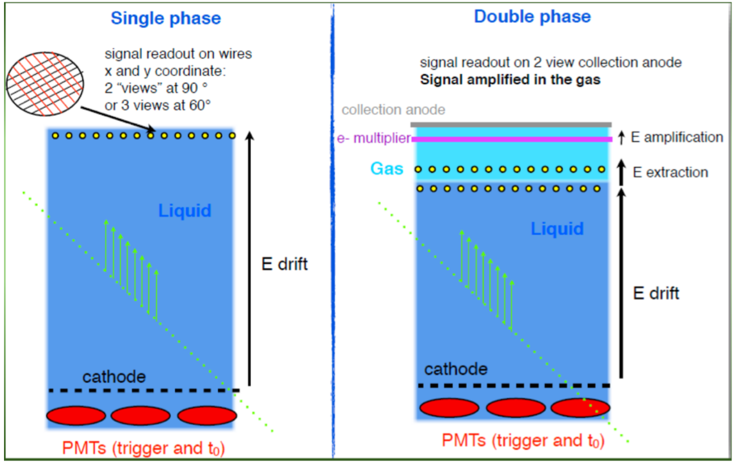
© T2K Near Detector

Note: T2K upgrade with Resistive MMG TPC
© D. Attié et al. arXiv:1907.07060v2

TPCs in neutrino physics

- **LAr TPCs***
  - First proposed by C. Rubbia in 1977, CERN-EP/77-08 (1977)
  - ICARUS, ArgoNeuT, MicroBooNE, future short- and long-base exp.
  - **dense medium, more ν interactions, many ionization electrons**
  - **high electron lifetime, high light yield (40 kγ/MeV), cheap (!)**
  - **self triggering: primary Ar scintillation (PM readout)**





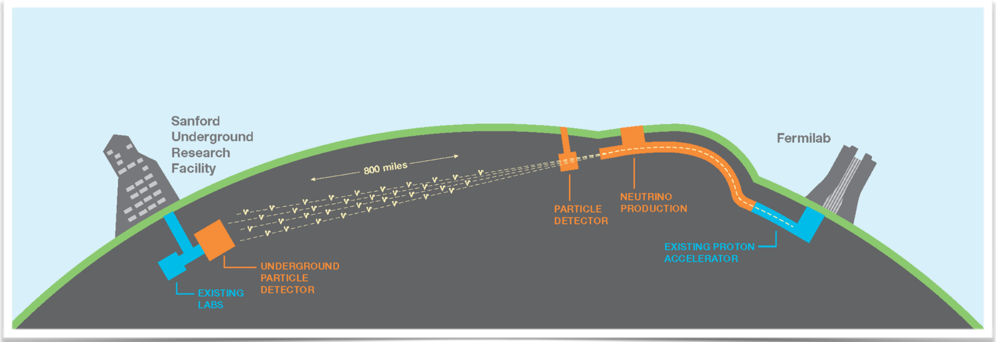
Dual Phase TPC **

- Extraction of the ionization electrons to the gas phase
- Amplification of the signal by charge avalanche in the gas phase

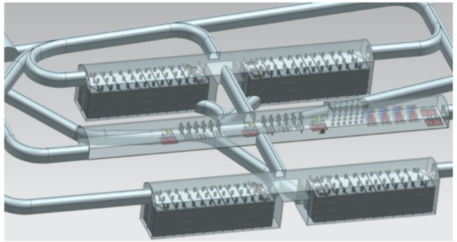
- Larger signal/noise ratio, better image quality
- Allows constructing detectors with longer drift distances
- Long drifts ➛ charge attenuation (high purity required)
- Compensate attenuation with charge multiplication

based on:
* S. Zeller, Nygren Fest, BNL 2014 and ref. therein (link)
** G. Brunetti, Fermilab, 16.03.2017 (link)

Deep Underground Neutrino Experiment

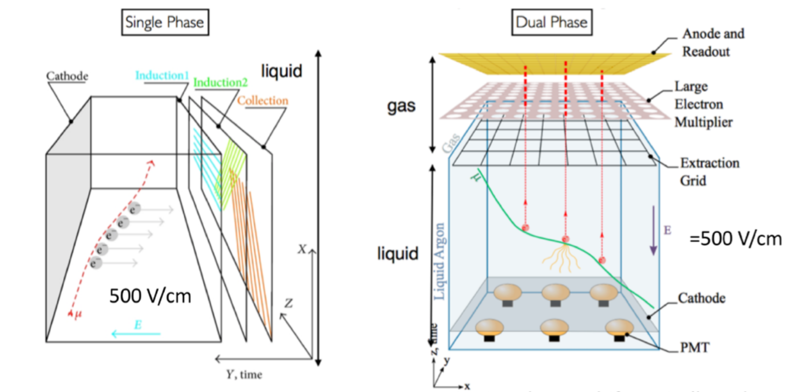


Physics Program:
- ν oscillations
- ν cross-sections (1-2% sys. uncertainties)
- Proton decay
- Supernova and low energy ν
- BSM



DUNE Far Detector
- 1300 km from Fermilab
- 1500 m underground

4 modules, each one:
- 17 kton total
- **10 kton fiducial**
  (scale ICARUS by factor >10)
- Two technology options: single- and dual-phase Lar TPCs



- Ionization charges drift horizontally and are read out with wires
- No signal amplification in liquid
- 3.6 m maximum drift
- Read out by APAs

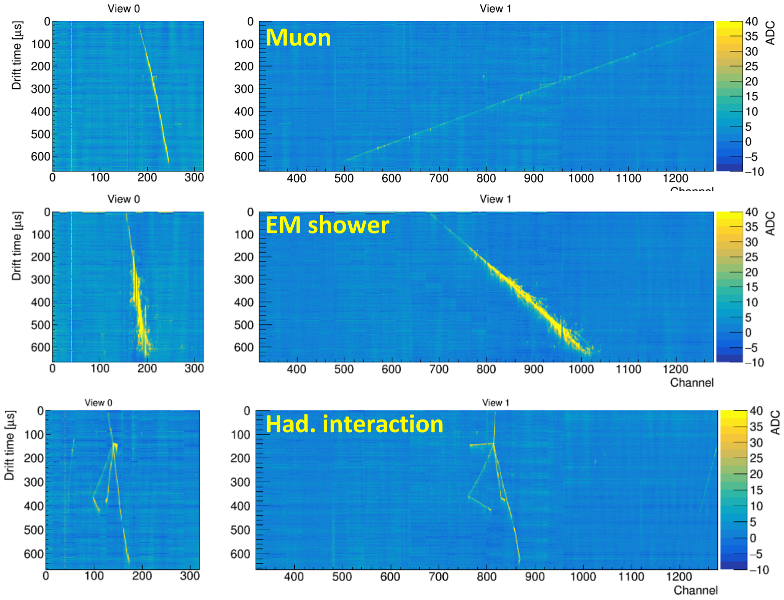
- Ionization charges drift vertically and are read out on PCB anode
- Amplification of signal in gas phase by LEM
- 12 m maximum drift
- Access through chimneys on top

DUNE is committed to deploying both technologies – staging depends on funding and ProtoDUNE results

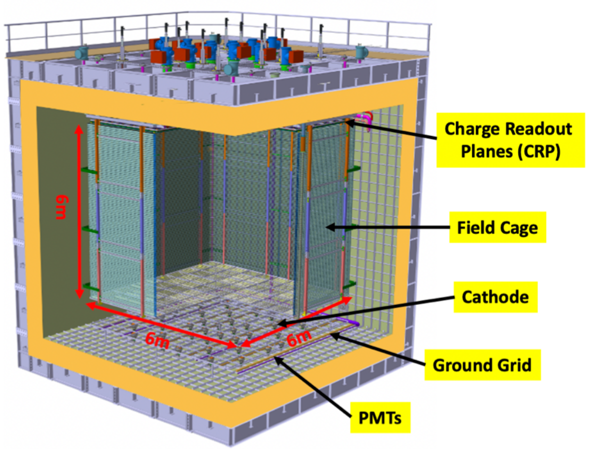
C. Touramanis (Uni of Liverpool), VCI2019 (link)

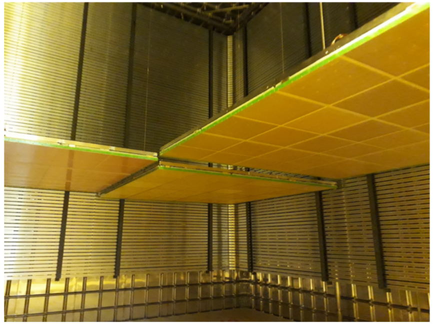
WA105 and ProtoDUNE DP

- E. Mazzucato (CEA, Irfu, DPhP), RD51 Collaboration meeting, CERN Feb. 2019 (link)
- E. Mazzucato, RD51 Collab. Meeting, CERN Oct. 2019 (link)

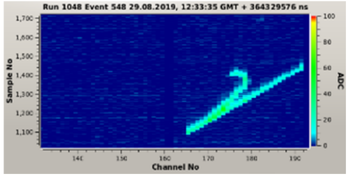


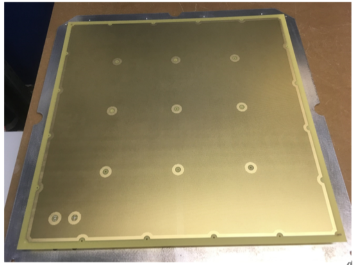
- **3×3×1 m^3 prototype** operated 06-11. 2017
- Proportional scintillation (S2) observed
- Extraction of electrons over 3 m^2 area achieved
- Amplification through LEMs measured





- **1 CRP = 36 Anodes + 36 LEMs (50×50 cm^2) + 3×3 m^2 Extraction Grid**
- Constructed at CERN NA (Neutrino Platform)
- Filled with Lar in Jul/Aug 2019
- Drift voltage 150 kV (nominal 300 kV)
- First tracks on August 29th

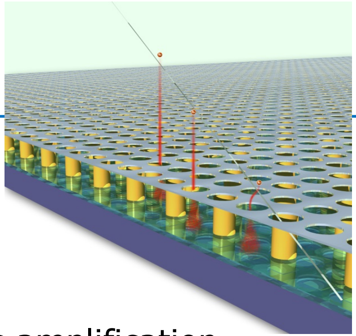


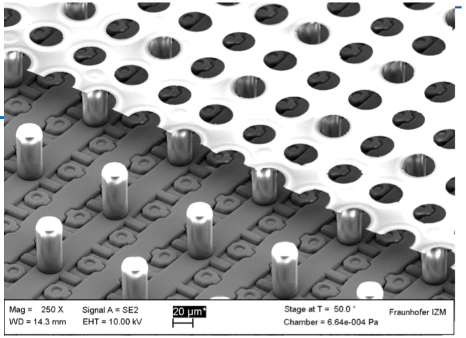


FUTURE

GridPix Technology

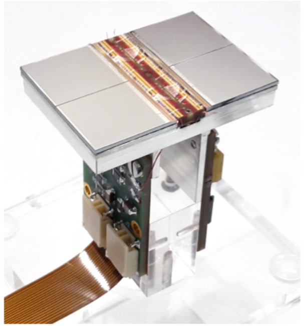
from: P. Kluit (NIKHEF), VCI 2019, Vienna (link)





- Pixel chip with integrated Grid (Micromegas-like)
- InGrid post-processed @ IZM
- Grid set at negative voltage (300–600 V) to provide gas amplification
- Very small pixel size, detecting individual electrons
- Aluminium grid (1 µm thick)
- 35 µm wide holes, 55 µm pitch, supported by SU8 pillars 50 µm high

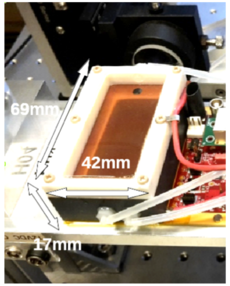
- Pixel chip: **TimePix3**
- 256×256 pixels, 55×55 µm pitch, 14.1×14.1 mm^2 active area
- TDC with **610 MHz clock** (1.64 ns)



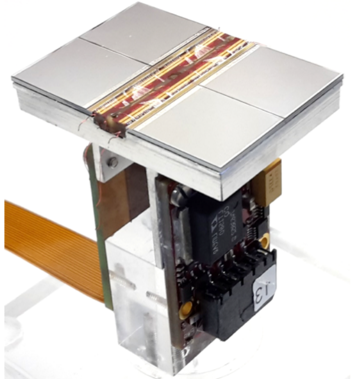
- QUAD module – four TimePix3 chips
- 39.6 × 28.38 mm^2, ~70% active area
- Next step: 8×QUAD module

Pixel TPC

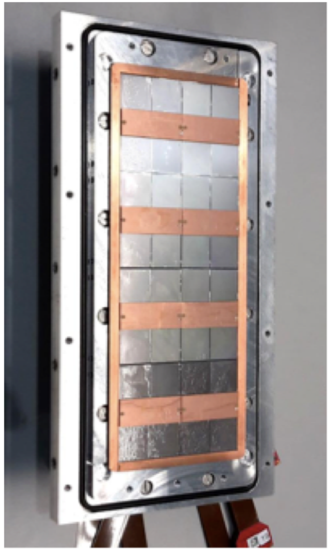
from: P. Kluit (NIKHEF), VCI 2019, Vienna (link)



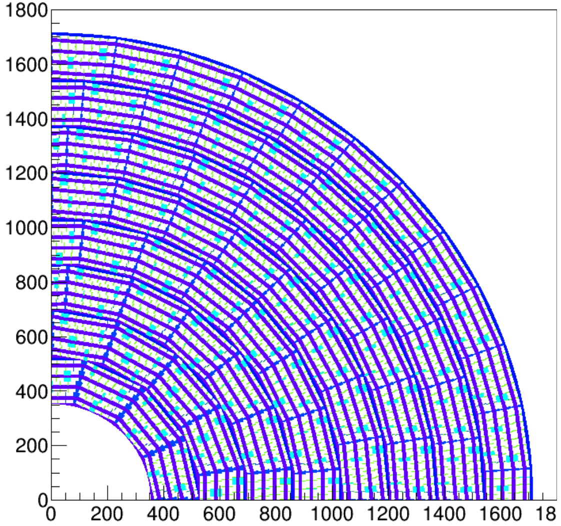
Single chip
2017



Quad
2018



Module
2019



TPC plane

- Reduced occupancy ➛ increased rate capabilities
- High granularity ➛ identify properties of the ionization
- Single electron counting ➛direct measurements of converted photons
- Uniform gap distance ➛ gain uniformity
- Measure complete collected charge for the particle energy deposition

M. Lupberger et al. PoS (TIPP2014) 225

SUMMARY

- TPC is a mature technology (45 y)
- Successfully used in many experiments
- Many new projects ongoing or being prepared

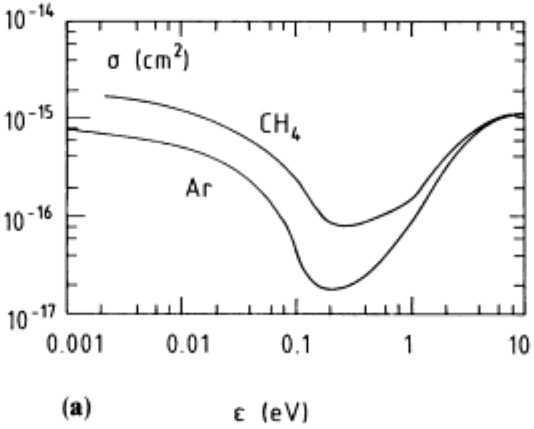
- For some applications (e.g. neutrinos, radioactive beams, …) there is no better solution
- MPGD – currently a default amplification structure

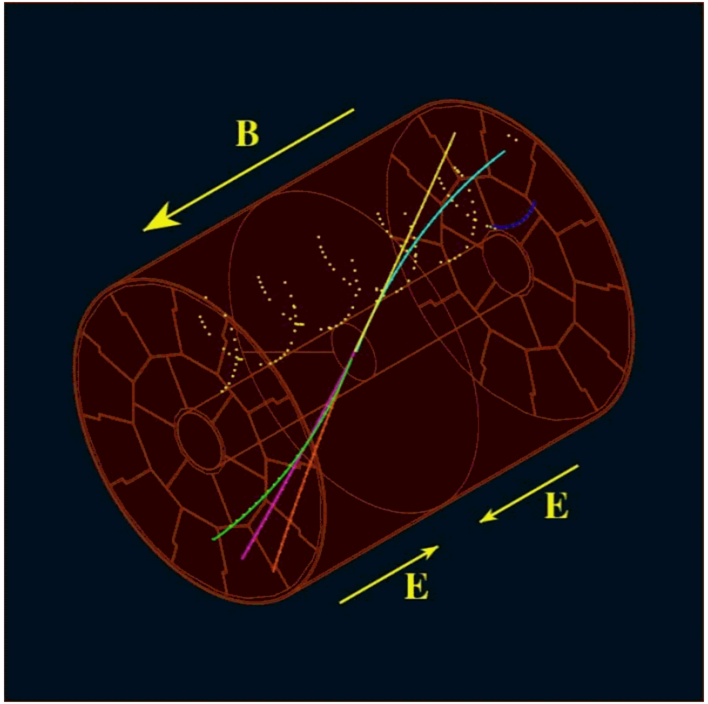
- We are not at our limits, still going bigger, faster, more precise…
- Still, many challenges ahead

BACKUP SLIDES

Ar-CH_4: Ramsauer dip and diffusion

- Chose the drift velocity such that the average electron energy falls in the Ramsauer dip: minimum elastic cross section
  - e.g. ~100 V/cm in Ar-CH_4 (90-10)
- The magnetic field then helps focusing the electrons
- High drift velocity achieved like this



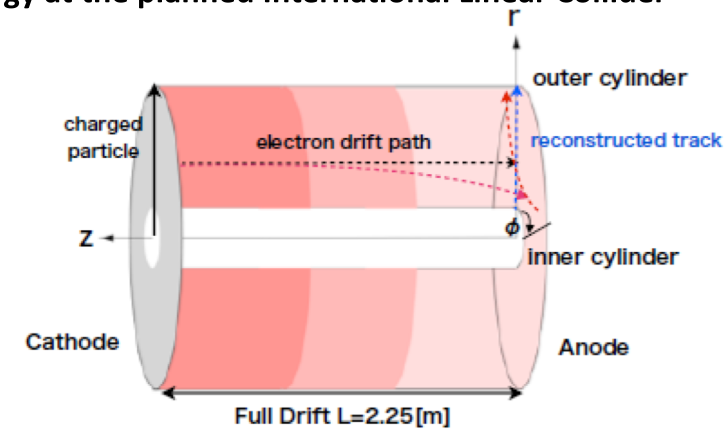


From: D. Attié (CEA Saclay), Novosibirsk, 1.03.2008

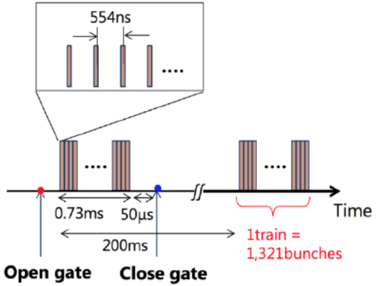
A Time Projection Chamber for a Future Linear Collider

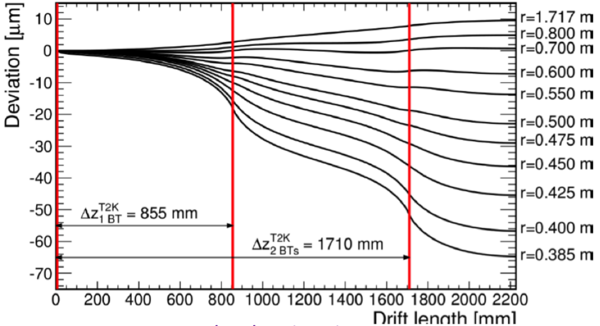
Development of a high-performance TPC for the physics up to √s = 1 TeV energy at the planned International Linear Collider

- Need to support high density of tracks and/or final states with 6+ jets
  - high granularity 3D tracking (σ_{pt} < 100µm (rϕ) and ≈ 500µm (rz)
  - good two tracks separation (2-hit resolution <2 mm (rϕ) and <6 mm (rz))
  - track identification (dE/dx resolution ≈ 5%)



- **To gate or not to gate?**
  - Space charge accumulation in the drift volume (**E**×**B** effects)
  - Distortions of e^- drift trajectory
  - Primary charge distortions $\mathcal{O}$(10 µm) 👍
  - Point resolution $\mathcal{O}$(100 µm)
  - Amplification charge distortions up to 60 µm 👎
  - Gating in LCTPC still possible as 1 ms long bunch trains will arrive every 200 ms
  - R&D ongoing



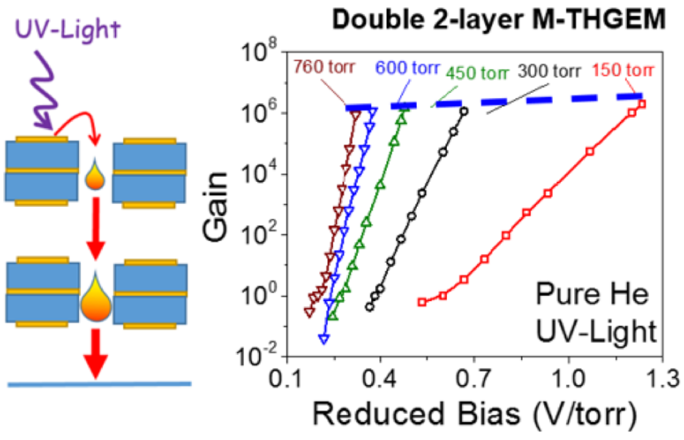


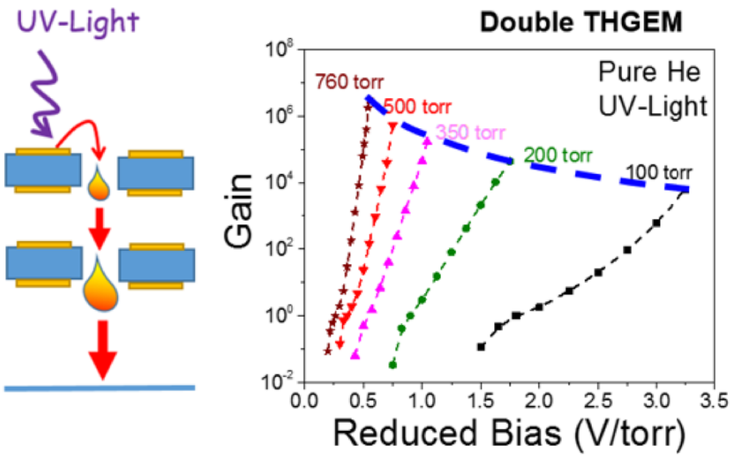
© P. Colas (CEA), IAS HEP@HKUST workshop, Honk-Kong, 18/01/19 (link)

New (exotic) structures

(See more in M. Cortesi, Monday 10:50, link)

- Development of Active Target TPCs may pave the road for more exotic structures and/or configurations
  - Further IBF suppression
  - Discharge stability in elemental gases w/o quenchers (H_2, D_2, He, …)
- M-THGEM ➛ Multi-Layer Thick GEM (M. Cortesi et al. Rev. Sci. Instrum. 88, 013303 (2017))
  - Higher max gain at low pressure (reduced secondary effects mitigated by photons, long avalanche region)
  - Higher effective gain (no charge losses in transfer gaps)

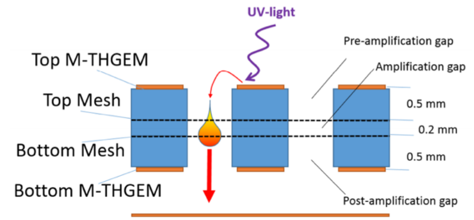


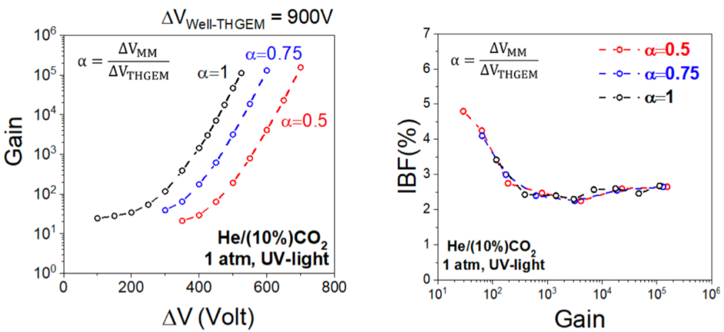


New (exotic) structures

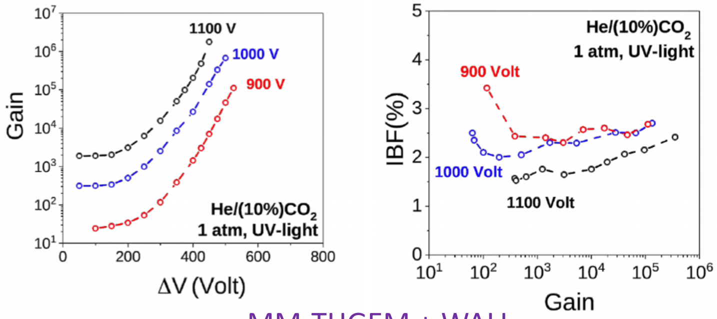
(See more in M. Cortesi, Monday 10:50)

- Development of Active Target TPCs may pave the road for more exotic structures and/or configurations
  - Further IBF suppression
  - Discharge stability in elemental gases w/o quenchers (H_2, D_2, He, …)
- MM-THGEM ➛ Multi-Mesh Thick GEM (R. de Oliveira and M. Cortesi, JINST 13 (2018) P06019)
  - Improved IBF figure (here with MM-THGEM + WELL configuration) of 1-2%
  - Several MM-THGEM layers operated in the TPC mode may result in <1% IBF
  - Can be mounted in WELL configuration (close-bottom) improving avalanche statistics.



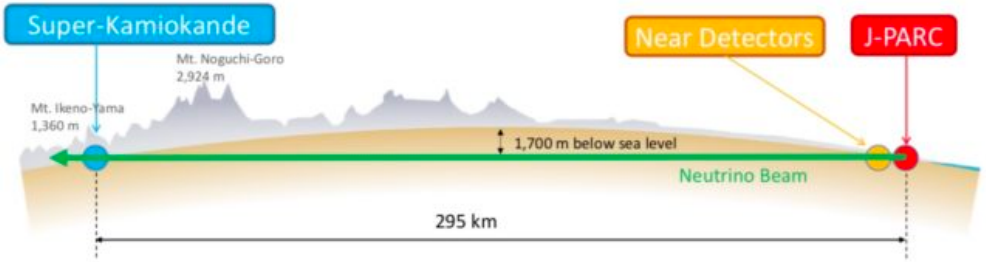


MM-THGEM

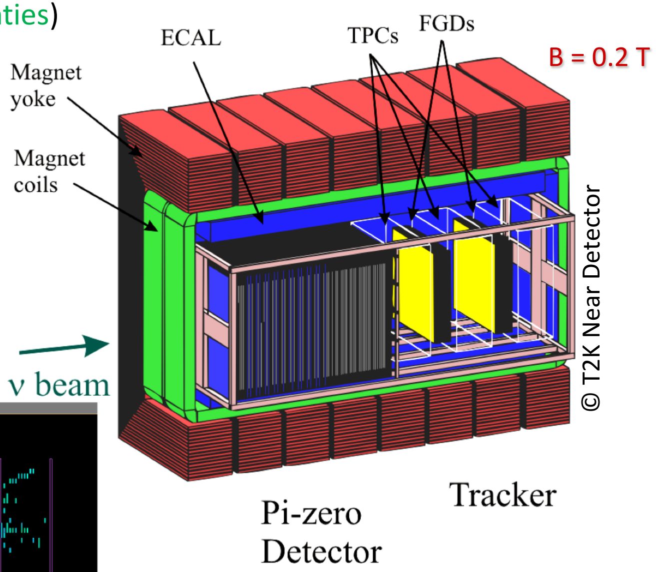


MM-THGEM + WALL

T2K : Tokai to Kamiokande

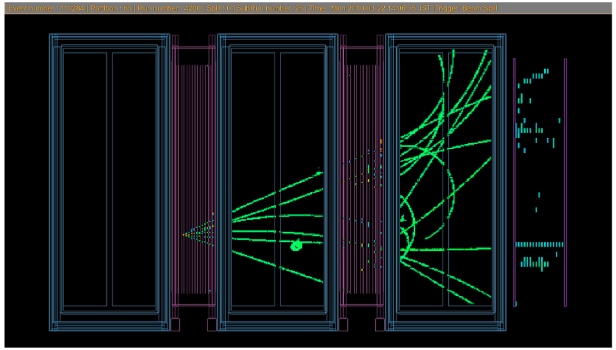


- Long baseline ν experiment in Japan
- Near Detector (280 m), J-PARC
  - Check initial beam composition
  - pre-oscillation charged current neutrino interaction rates (5-7% sys. uncertainties)
  - reduce uncertainties in the oscillation measurements
  - **Includes 3 large MM TPCs, AFTER chip readout**
  - **Operated at about 750 torr with Ar/CF4/iC4H10 (95:3:2)**



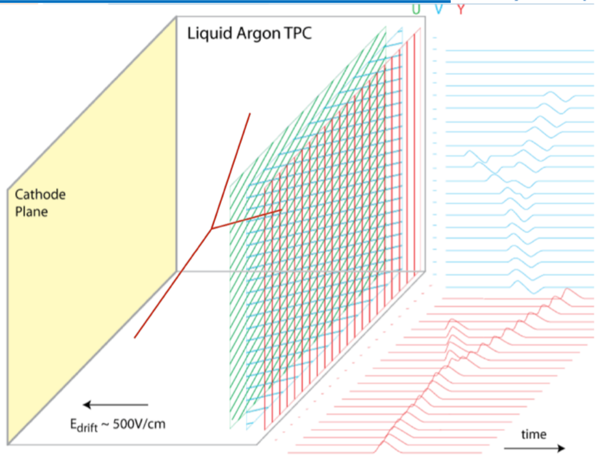
- Far Detector (295 km), Kamioka
  - Super Kamiokande

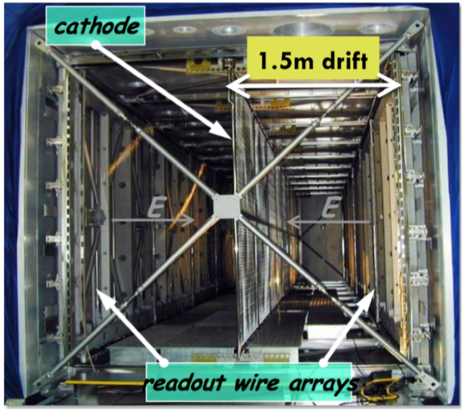
- Many great physics results
  - CC ν_μ interaction in the T2K ND
  - World leading ν x-sections
    Abe et al., PRD 87, 092003 (2013)
  - first definitive (7σ) observation of the appearance of ν_e in a ν_μ beam
    Abe et al., PRL 112, 061802 (2014)



TPCs in neutrino physics

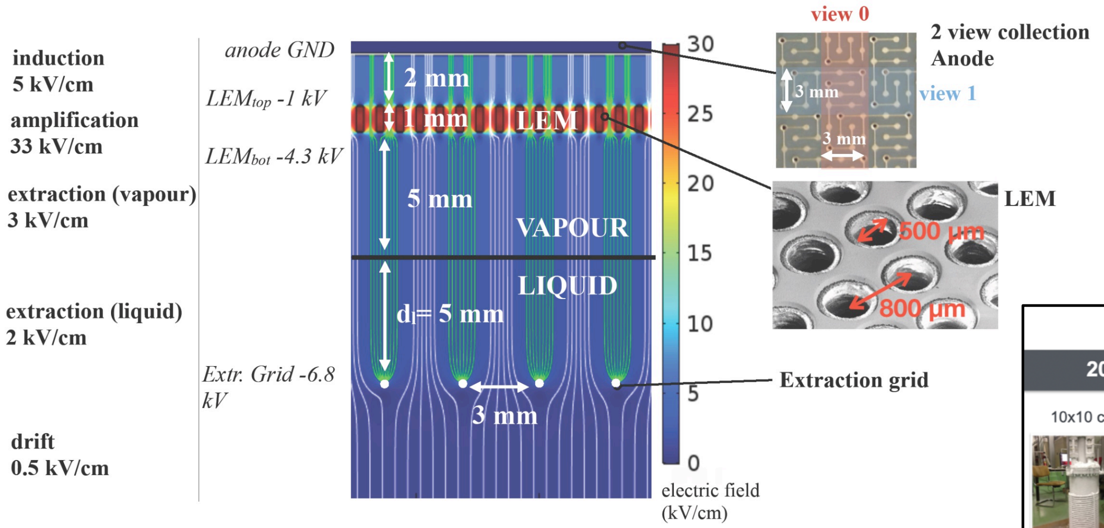
- **LAr TPCs** © S. Zeller, Nygren Fest, BNL 2014 and ref. Therein (link)
  - First proposed by C. Rubbia in 1977, CERN-EP/77-08 (1977)
  - ICARUS, ArgoNeuT, MicroBooNE, future short- and long-base exp.
  - **dense medium, more ν interactions, many ionization electrons**
  - **high electron lifetime, high light yield (40 kγ/MeV), cheap (!)**
  - **self triggering: primary Ar scintillation (PM readout)**





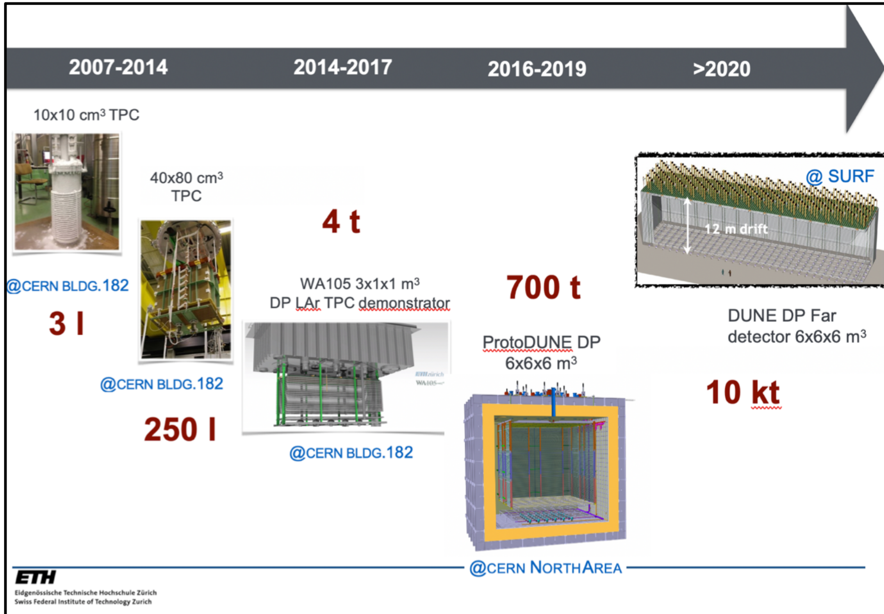
ICARUS T600 – the largest LAr TPC in the world (600 t)
- two 300 ton modules, each with 2 TPCs
- 3.6 × 3.9 × 19.9 m^3
- 75 kV nominal voltage; 53‘248 wires

DUNE FD – Dual Phase Lar TPC



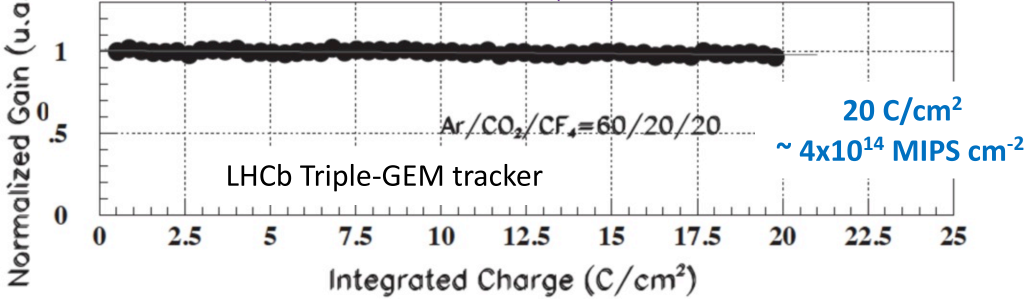
© E. Mazzucato (CEA, Irfu, DPhP), RD51 Collaboration meeting, CERN Feb. 2019 (link)

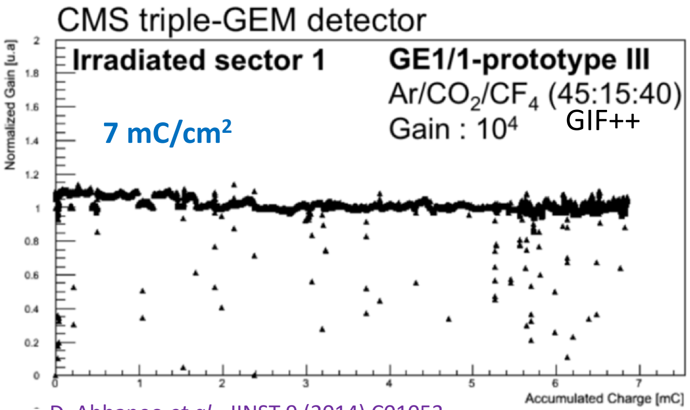
© L. Molina Bueno (ETH Zurich), ICHEP 2018, Seoul (link)



Aging

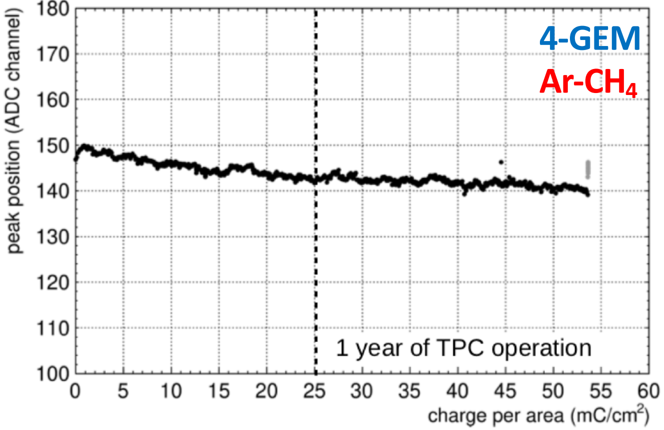
M. Alfonsi *et al.*, Nucl. Instr. and Meth. A **518** (2004) 106.





D. Abbaneo *et al.*, JINST 9 (2014) C01053.

M. Jung, C. Garabatos, R.A.N. de Oliveira, RD51 Meeting, Munich 2018



Aging - note gas and material dependency, also in MPGDs

- Positive results with Ar, Ne, CO_2, CF_4 mixtures
- Signs of degradation in methane

TPC review

PARAMETER / EXPERIMENT	PEP4	TRIUMF	TOPAZ	ALEPH	DELPHI	STAR	ALICE [1]
1. OPERATION	1982 / 1984	1982 / 1983	1987	1989	1989	2000	2009
INNER / OUTER RADIUS [m]	0.2 / 1.0	~0.15 / 0.50	0.38 / 1.1	0.35 / 1.8	0.35 / 1.4	0.5 / 2.0	0.85 / 2.5
MAX. DRIFTLENGTH (L/2) [m]	1	0.34	1.1	2.2	1.34	2.1	2.5
MAGNETIC FIELD [T]	0.4 / 1.325	0.9	1	1.5	1.23	0.25 / 0.5	0.5
GAS :	Ar / CH4	Ar / CH4	Ar / CH4	Ar / CH4	Ar / CH4	Ar / CH4	Ne /CO2/ N2
Mixture	80 / 20	80 / 20	90 / 10	91 / 9	80 / 20	90 / 10	90/ 10/ 5
Pressure [atm]	8.5	1	3.5	1	1	1	1
DRIFT FIELD [KV / cm / atm]	0.088	0.25	0.1	0.11	0.15	0.14	0.4
ELECTRON DRIFT VELOCITY [cm/μsec]	5	7	5.3	5	6.69	5.45	2.7
ωτ (see 2.2.1.3)	0.2 / 0.7	2	1.5	7	5	1.15 / 2.3	< 1
PADS: Size w•L [mm•mm]	7.5x7.5	(5.3-6.4)x19	(9-11)x12	6.2x30	~7x7	2.85x11.5	4x7.5
						6.2x19.5	6x10/15
Max. no. 3-D points	15 - straight	12	10 - linear	9+12 - circular	16 - circular	13+32 - straight	63+64+32
dE/dx: Max. no. samples/track	183	12	175	148+196	192	13+32	63+64+32
Sample size [mm atm]; w or p	4•8.5; wires	6.35; wires	4x3.5; wires	4 ; wires	4 ; wires	11.5 + 19.5;pads	7.5+10+15; pads
GAS AMPLIFICATION	1000	50 000		3000-5000	5000	3000/1100	20 000
GAP a-p; a-c; c-gate [2]	4; 4; 8	6	4; 4; 8	4; 4; 6	4; 4; 6	2; 2; 6 / 4; 4 ; 6	2; 2; 3 / 3; 3; 3
PITCH a-a; cathode; gate	4; 1; 1		4; 1; 1	4; 1; 2	4; 1; 1	4; 1; 1/ 4; 1; 1	2.5; 2.5; 1.5
PULSE SAMPLING [MHz/ no. samples]	10/455, CCD	only 1 digitiz., ADC	10/ 455, CCD	11/ 512, FADC	14/ 300, FADC	9.6 / 400	5-10/500-1000, ADC
GATING [3]	≥1984 o.on tr.	≥1983 o.on tr.	o. on tr.	synchr. cl.wo.tr	static	o.on tr.	o.on tr.
PADS, total number	15 000	7800	8200	41 000	20 000	137 000	560 000
PERFORMANCE							
Δx_T [μm]-best / typ.	130-200	200/	185/230	170/200-450	180/190-280	300-600	spec:800-1100
Δx_L [μm]-best / typ.	160-260	3000	335/900	500-1700	900	500-1200	spec:1100-1250
2-TRACK SEPARATION [mm], T / L	20		25	15	15	8 - 13 / 30	
$\partial p/p^2$ $[GeV/c]^{-1}$: TPC alone; high p	0.0065		0.015	0.0012	0.005	0.006	spec:0.005
dE/dx [%] SINGLE TRACKS/ IN JETS	2.7 / 4.0		4.4 /	4.4 /	5.7 / 7.4	7.4 / 7.6	spec:4.9 / 6.8
COMMENTS		a in single PCs	chevron pads	circular pad rows	circular pad rows	No field wires	No field wires
		strong ExB effect				> 3000 tracks	≤ 20 000 tracks

1) Expected performance
2) a = anode, p = pads, c = cathode grid
3) o. on tr.: gate opens on trigger; cl.wo.tr. : opens before collision and closes without trigger; static : closed for ions only (see text).

PARAMETER / EXPERIMENT cont.	NA35	EOS / HISS	NA49 VTX	NA49 MAIN	CERES/NA45	HARP	T2K[a]
1. OPERATION	1990	1992	1995	1995	1999	2001	2009/10
INNER / OUTER RADIUS or L / W [m]	2.4 / 1.25 (L / W)	1.5 / 0.96 (L / W)	2.5 / 1.5 (L/W) ; 2x	4 / 4 (L/W); 2x	0.6 / 1.3; L=2	0.1 / 0.41	2.2 / 0.7 (H/L); 3x
MAX. DRIFTLENGTH (L/2) [m]	1.12 vert.	0.75 (H)	0.67 vert.	1.1 vert.	0.7 rad.	1.6	0.9 W
MAGNETIC FIELD [T]	0	1.3	1.5	0	Bz < 0.7; Br < 0.3	0.7	0.2
GAS :	Ar / CH4	Ar / CH4	Ne / CO2	Ar / CH4 / CO2	Ne / CO2	Ar / CH4	Ar/CF4/i-C4H10
Mixture	91/ 9	90/ 10	90 / 10	90/ 5 / 5	80/ 20	91/ 9	95/ 3/ 2
Pressure [atm]	1	1	1	1	1	1	1
DRIFT FIELD [kV / cm / atm]	0.12	0.12	0.19	0.175	0.2-0.6	0.111	0.2
ELECTRON DRIFT VELOCITY [cm / μsec]	5	5.5	1.3	2.3	0.7-2.4	5.2	7
ωτ (see 2.2.1.3)	0	0.5	1	0		3.3	0.7
PADS: SIZE (w•L, mm•mm)	5.5x40	8x12	3.5x(16 , 28)	(3.6, 5.5)x40	10 chevron	6.5x15	6.9x9.7
Max. no. 3-D points	60+30	128	<150	90		20	72x3
dE/dx: MAX. NO. SAMPLES/TRACK	60	128	<150	90		20	72x3
Sample size [mm• atm]; w or p	40; pads	12	16, 28	40		15	9.7
GAS AMPLIFICATION		3000	20 000	5000	8000	20 000	~1000
Gap a-p; a-c; c-gate [2]		4; 4; 6	3 , 2;	2,3; 3; 6	3;3;6	5;5;6	0.128
PITCH a-a; cathode; gate	4; 1; 2	4; 1; 2	4; 1; 1	4; 1; 1	6; 2; 2	4; 2; 2 stagg.	
PULSE SAMPLING [MHz / no. samples]	12.5 /	10 / 256, SCA	/ 512	/ 512		10 / >300, FADC	/ 512 SCA
GATING [3]		o. on tr.	o. on tr.	o. on tr.	o. on tr.	o.on tr.	none
PADS, total number	11 000	15 000	74 000	108 000	78 000	4000	125 000
PERFORMANCE							
Δx_T [μm]-best / typ.	300-800	300	150	150	230/340	600-2400	600 (1m drift)
Δx_L [μm]-best / typ.	250-450				dr=400/ 640	3.5	
2-TRACK SEPARATION [mm]	18	25		10			
$\partial p/p^2$ $[GeV/c]^{-1}$: TPC alone; high p		1			1	0.2/0.45-0.50	spec: <10 ;
dE/dx [%] : single tracks / in jets	/ 6	/ 4	<4 : VTX + Main			16	spec: <10 /
COMMENTS	B=0	only pad r.o.	Kr^m calibration	up to 1200 tr.	Radial TPC	el. cross-talk	Micromegas r.o.
	only pad r.o.		only pad r.o.	only pad r.o.	No field wires		

H.J. Hilke, *"Time Projection Chambers"*, Rep. Prog. Phys. 73 (**2010**) 116201