

TPCs from low to high rate: challenges and trends

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- This is my own point of view;
 - I will not make a walk across many experiments, but try to outline some general considerations and the key interesting points where to invest efforts;
 - My arbitrary choices have no meaning about the merits of detectors I do not mention;
 - I have restricted the presentation to the *classical TPCs*, i.e. those **gaseous** (with one accidental exception) detectors capable of doing at the same time:
 - tracking
 - dP/p (where a magnet is present)
 - dE/dx
- and
- e^- drift (see Elisabetta's talk for ion drift!).

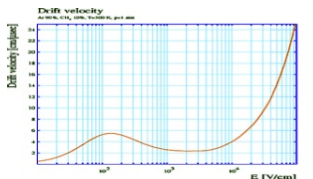
A few words on types of gasses and (ideal) momentum measurement

Grossly speaking, in my mind TPCs fall into two main categories regarding the choice of gas and operating parameters. Diffusion is one of the main limiting factors entering.

Cat 1 - Hot gasses

$$V_{drift} \propto E$$

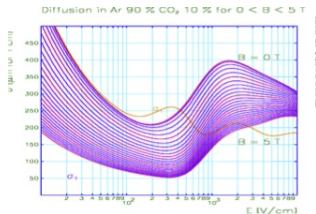
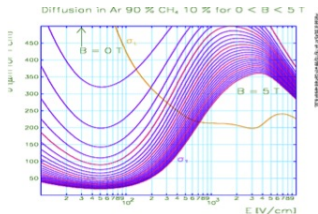
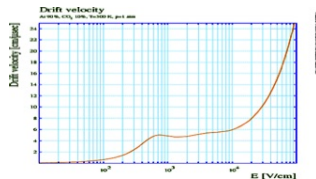
$$\sigma_T \propto \frac{1}{1+(\omega\tau)^2}$$



Cat 2 - Cold gasses

$$V_{drift} \propto E$$

$$\sigma_T \propto \frac{1}{\sqrt{E}}$$



A simple exercise to see the progress in amplification structures and magnets

Collider TPCs tend to fall in the first group. The ideal geometry for strong B fields allows to exploit $D_{\perp} = \frac{D_0}{1+(\omega\tau)^2}$, where $\omega = \frac{eB}{m}$.

In first approximation, the resolution follows the Gluckstern formula:

$$\left(\frac{\sigma_{p_T}}{p_T}\right)_{\text{meas}} = \sqrt{\frac{720}{N+4} \frac{\sigma_x}{L^2} \frac{p_T}{0.3 B}}.$$

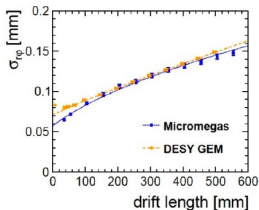
Parameter	PEP-4 TPC	ILC-like TPC
Track length L (m)	2.0	2.2
Magnetic field B (T)	1.325	3.5
Number of points N	180	200
Spatial resolution σ_x (μm)	200	100

Let's plug in the numbers in this (wildly) ideal case and see what could be the effect:

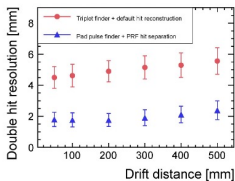
Detector	p_T (GeV/c)	σ_{p_T}/p_T	σ_{p_T}/p_T (%)
PEP-4	1	2.49×10^{-4}	0.0249
ILC-like	1	3.70×10^{-5}	0.0037

This is to make the point that technological progress allowed to gain one order of magnitude in momentum resolution, essentially without changing L. Actual numbers from measurements are different, but the jump in performance is real.

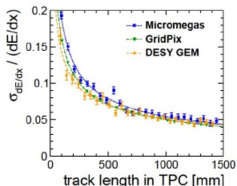
With 1mm x 6mm pads @ 3.5 T you can obtain:



- resolution clearly diffusion limited beyond 2m drift;
- the GridPix is not shown here, but the resolution of $55 \times 55 \mu m^2$ pixels makes the TPC diffusion-limited at any drift length.



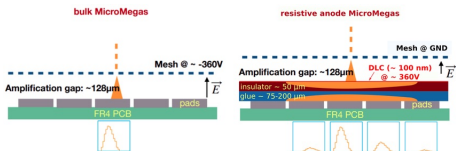
- Double hit resolution as good as $\approx 2mm$.



- Energy resolution does not really change whatever the readout, not even with a GridPix system.

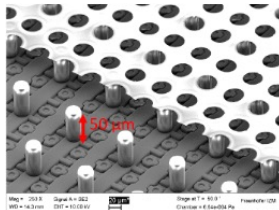
Where can we further play?

The resolution is driven by the convolution $\sigma_{D\perp} \otimes \sigma_P RF \otimes pad\ width$.
Approaching the diffusion limit is impossible without MPGDs, and maybe achievable with the GridPix.



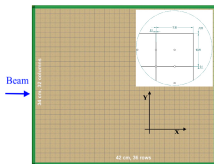
- adjusting the PRF
 - by re-arranging the GEM stacks w.r.t. the induction plane;
 - by manipulating the PRF of a MM by using resistive layers.

- by going fully to the highest granularity;
- then further squeeze the diffusion via $D_{\perp} = \frac{D_0}{1+(\omega\tau)^2}$ and higher B field;
- B=10T and $\sigma_{D\perp} \approx 30\mu m$ would bring real life dP/P down to the 10^{-5} level.

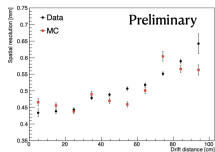


While we are on the resistive layers ...

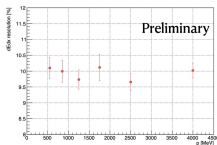
... let's open a short parenthesis: T2K and the ERAMs (Encapsulated Resistive Anode Micromegas).



The modification of the PRF by using resistive layers has wider interest than in the typical collider TPCs. The technique has been successfully used in a completely different environment: the near detector of the TPC experiment.

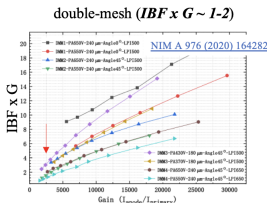
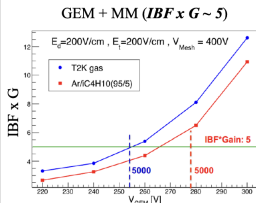
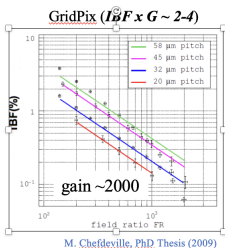
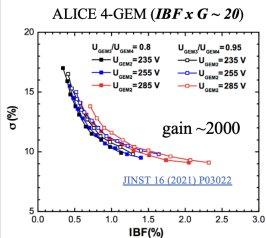


This an example of the freedom given by MPGDs: tracks of interest in the T2K near detector may have almost any direction, leading to squared pads for reduced pad-angle effect.



Squared (instead of slightly elongated) and less numerous pads w.r.t. the bulk-micromegas of the older chambers, and comparable performances nonetheless.

All TPCs at colliders and in general in high-rate situations do experience E field distortions due to inhomogeneous accumulation of positive charge, i.e. ions created in the amplification regions and re-entering the drift volume.



- ALICE is the present gold standard;
- the GridPix keeps being a surprising device even in this perspective.

Plot composition from Diego's talk at the last TPC workshop in Paris

For the purpose of what follows, I spare you (and myself) the typing of the complete Bethe-Block and PAI(R) models formulas, and go straight to the essential.

As usual in *sampling*

$$\sigma^2 \sim \sigma_0^2 + \sigma_{stat}^2$$

The motivation for the *truncated mean* approach is that we know, empirically, that for a certain interval of the cutoff parameter $0.35 < \eta < 0.75$ the quantity

$$\langle S \rangle_\eta = \frac{1}{n} \sum_1^n S_j$$

is approximately distributed as a Gaussian, so that we can write

$$\sigma_{stat} \sim \frac{1}{\sqrt{n}}.$$

In practical terms, taking into account also the sample length (in *cm bar*)

$$\sigma \sim n^{-0.46} (xP)^{-0.32}$$

Let's skip for the moment possible reasons why the second term has not been much regarded, with the exception of the very first time.

W. W. M. ALLISON et al.

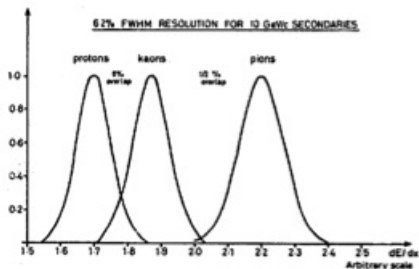


Fig. 13. The separation expected with a 5 m deep ISIS device at 10 GeV/c.

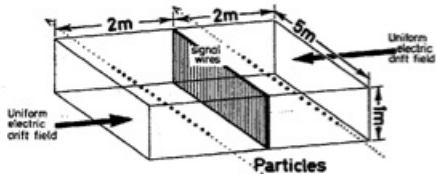


Fig. 14. The geometry of an ISIS behind an RCT.

Almost everything was already said in 1980: *Unfortunately, fluctuations in individual energy-loss measurement are very large. [...] Only by measuring many samples on each track may the required resolution of a few percent be achieved. In fact, considerably more than 100 samples [...] are required.*

The main experimental obstacles were already identified: diffusion, attenuation (i.e. attachment) and statistics.

Statistics is not simply a matter of n . It is also meaningful what your sampling is in terms of *thickness*.

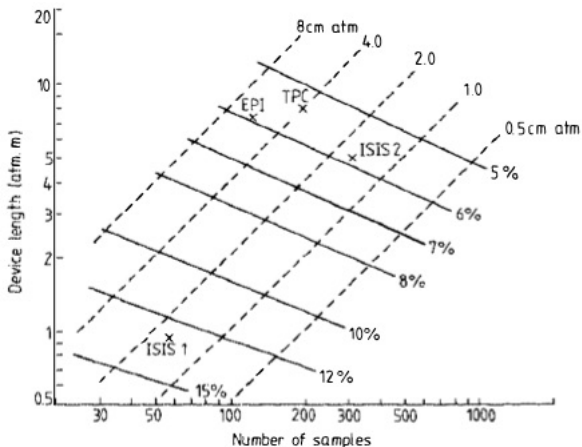


Figure 13 The ionization resolution (% FWHM) of a multisampling detector filled with pure argon calculated with the PAI model for $\beta\gamma = 100$. The dashed lines are loci of constant sample thickness. The devices EPI, ISIS1, ISIS2, and TPC are described in Table 2.

You may play on the chessboard and place your own existing or daydreaming TPC, and see how high you score. The board is nowadays blackened with points, but the one ahead is still there.

TPC here was ... well ... the only existing one. Only much later we had to specify *PEP-4*. The hunt for better dE/dx is still on.

Table 2 Relativistic energy-loss particle identifiers (May 1980)

Name	Gas	Samples (cm)	Acceptance	Physics objective ^f	Status
EPI ^a	Ar/5% CH ₄ 1 atm	128 × 6	2m × 1m	diffraction dissociation with BEBC (CERN)	Data 1978
ISIS1 ^b	Ar/20% CO ₂ 1 atm	80 × 1.6	4m × 2m	Strong interaction and charm physics with EHS (CERN)	{ Data early 1980 Construction
ISIS2 ^b	Ar/20% CO ₂ 1 atm	320 × 1.6	4m × 2m		
CRISIS ^c	Ar/20% CO ₂ 1 atm	192 × 1.6	1m × 1m	Hadron physics with FHS (FNAL)	Construction
JADE ^d	Ar/C ₂ H ₆ 4 atm	48 × 1	~4π	e ⁺ e ⁻ at PETRA	Data 1979
TPC ^e	Ar/20% CH ₄ 10 atm	192 × 0.4	~4π	e ⁺ e ⁻ at PEP	Construction
UA1 ^f	Ar/C ₂ H ₆ 1 atm	200 × 0.8	~4π	pp collider at CERN	Construction

^a Jeanne et al 1973, Lehraus et al 1978, and Figure 13.

^b Allison et al 1974, 1978b, 1978c, 1979, and Figure 13.

^c Wadsworth et al 1979.

^d Barber et al 1976, Farr et al 1978, Wagner et al 1980.

^e Nygren 1976, Fancher et al 1979, and Figure 13.

^f Astbury et al 1978.

^g BEBC = Big European Bubble Chamber; EHS = European Hybrid Spectrometer; FHS = Fermilab Hybrid Spectrometer.

- Curiously, in Allison's 1982 paper, one can read: *ISIS is a pictorial drift chamber similar to the more recent TPC [...] Its (ISIS) prime role is particle identification; tracking is a free but impressive by-product;*
- It was one step shy of the TPC, which made a big leap forward: dE/dx becomes inextricably linked to tracking, in a device defining a set of (almost) independent *voxels* in a volume of gas.

Anyway, I cannot invent a better summary than the following table from the BRR (Blum/Riegler/Rolandi ©) bible

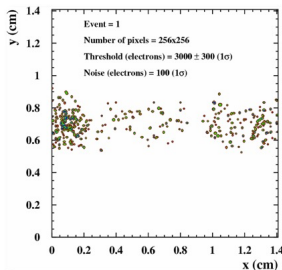
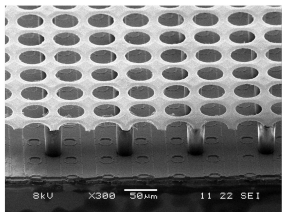
Table 10.4 Ionization-measuring capability of some universal drift chambers in collider experiments^a

Drift chamber Reference	OPAL Jet Chamber [BRE 87] [HAU 91]	PEP 4 TPC [COW 88]	ALEPH TPC [ATW 91]
Drift chamber type ^b	2	3	3
Max. no. of samples per track	159	183	340
Sample length (cm bar)	4	3.4	0.4
Max. drift length (cm)	3–25	100	220
Gas mixture	Ar(88) + CH ₄ (10) + i-C ₄ H ₁₀ (2)	Ar(80) + CH ₄ (20)	Ar(91) + CH ₄ (9)
Pressure (bar)	4	8.5	1
Gas amplification factor	10000	–	5000
Estimation method employed ^c	$\langle S \rangle_{70}$	$\langle S \rangle_{65}$	$\langle S \rangle_{60}$
Analysis of isolated tracks:			
Min. polar angle required (deg):	45	45	45
Observed resolution (FWHM, per cent)	7.3	6.9	10.3
Theoretical limit ^d (our (10.9))	6.0	5.9	8.8

The first TPC nailed almost everything ...

The elusive chimera: dE/dx by cluster counting

Still in the Townsend amplification regime, dN/dx may provide a better energy resolution than the truncated-mean dE/dx , and instruments capable of imaging clusters in TPC-mode do exist.



- there is a clear statistical advantage: $\sigma \propto \sqrt{N}$;
- potentially, a factor 2 better energy resolution.

However TPCs may hit intrinsic limitations, and not all TPCs may take advantage

- long drift lengths wash out the primary ionization. Technique difficult to apply to large e-drift TPCs;
- certain gasses (He, Ne) may be better than others (Ar) due to their primary ionization characteristics.

A word of caution regarding dN/dx

- What matters, in the end, is the PID separation power in the energy/momentum plot;
- dN/dx flattens the relativistic rise, and the effect on PID is not obvious ;
- Worth the effort? judgment is pending ... since long.

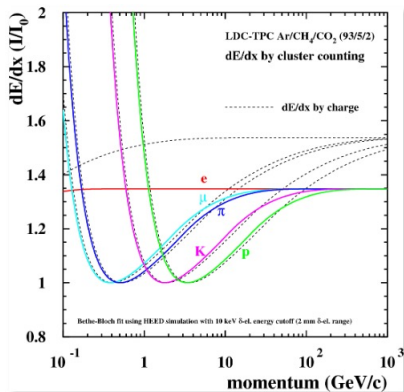


Figure: Argon

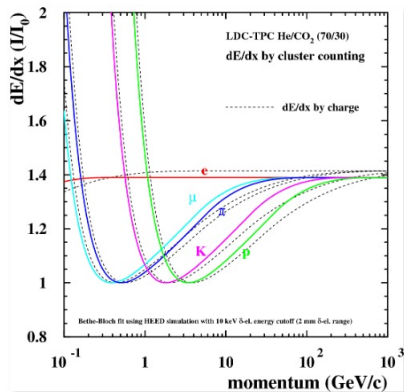


Figure: Helium

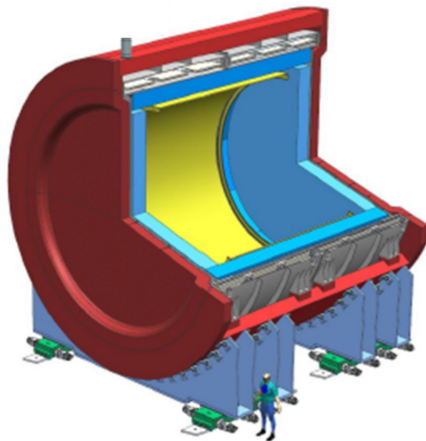
It is obvious that the HP path has been abandoned immediately. I can see a number of reasons. It is difficult to pin down a single one.

- HP field cages are more difficult and expensive;
- Not suitable where lightness is needed:
 - because you have interesting low energy secondaries for which you need additional detectors downstream;
 - because you have an inner tracker in front (and Si trackers are now ubiquitous in colliders);
- low- or no-hazard gas mixtures are now mandatory.

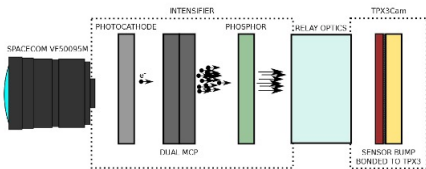
The use of TPCs as gas target and active medium is reviving the issue, propelled by the use as neutrino target or source.

One example of neutrino-target HP TPC

The most straightforward thinking is to use a gas Ar target to study neutrino cross-sections for DUNE: same material, same beam, much lower threshold



- operated at 10 bar
- $5 \times 5 \times 5 \text{ m}^3$
- 1t Ar - gas mix Ar $\geq 90\%$
- 5 MeV threshold, 4π acceptance
- 0.5 T magnet
- readout by refurbished ALICE MWPC; GEM/THGEM also under consideration



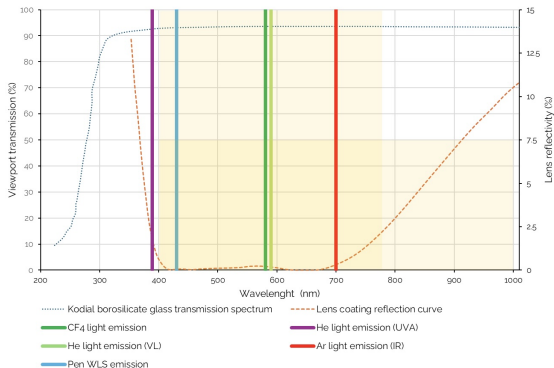
- Alternative: optical readout derived from ARIADNE, originally a dual-phase LAr readout. Being dual-phase it can also read out standard gaseous TPCs;
- The low momentum threshold in gas is of interest for any neutrino cross-section study. If the far detector is not made of the same material, a range of gasses (He, Ne, Ar) have to be used to establish an A-dependence;
- Prototyping a HP optical readout and perform a systematic study of several gas mixtures is the purpose of an AIDAInnova task 7.4 (Hybrid readout high pressure gas TPC for neutrino physics).

Issue with optical readouts: wavelength

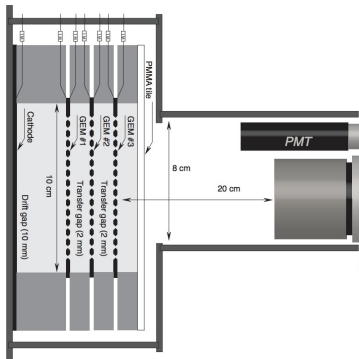
To obtain an effective optical readout system, one has to match optics and intensifier transmission and sensitivity to

- different wavelengths depending on the base noble gas of choice (He, Ne, Ar);
- possible admixture of wavelength shifters (e.g. CF₄);
- presence of physical wavelength shifters in front of the camera (PEN foils);
- variation of the above depending on the operational pressure.

A systematic study is indeed needed.



Why is it so imperative to quantify the light emission and maximize it in the optical region of interest? Geometry and camera sensitivity!

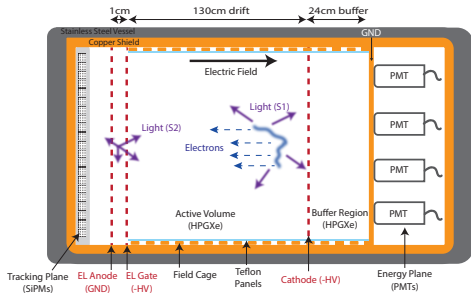


- The camera system is focussed on the light emission plane;
- The temptation is to go further away to image a larger area;
- The further away, the smaller the solid angle covered by the camera, the lower the detectable light yield.

The difficult task is to compromise between the needed effective granularity, the gas amplification and the light emission spectrum.

The alternative to cluster-counting: electroluminescence

The optical readout of S2 proportional scintillation avoids the statistical fluctuations of the avalanche multiplication, promising energy resolutions even better than cluster counting. A typical example is the NEXT $0\nu\beta\beta$ experiment based on a 10 to 15 bar ^{136}Xe gas TPC.



- Key points: energy + topological background rejection;
- Gas-phase Xe preserves long electron tracks (tens of cm), enabling topological discrimination between signal and background;
- EL readout gives excellent energy resolution - $\approx 1\%$ FWHM at $Q\beta\beta$ (2458 KeV)
- Scalability to ton-scale.

with NEXT we have entered a different field: not only trackers and targets, but also:

- self-sensitive decay detectors;
- light active target for low-energy events (typically dark matter) ;
- low threshold for directionality (dark matter & X=ray polarimetry).

These tend to be

- read out optically, in electroluminescence or not;
- present serious challenges in terms of external background control and radiopurity.

- The CYGNO TPC is a gaseous detector operated \sim atmospheric pressure, using a low-mass target gas mixture (He and CF₄) to boost sensitivity to WIMPs at the 1–10 GeV mass scale.
- Here recoil recoil visibility, including the angle, is primordial and leads to the choice of He as the base noble gas, highly enriched with CF₄ to keep the light emission spectrum in the visible.

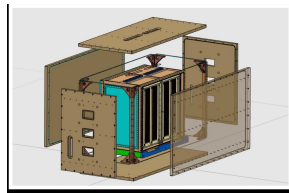
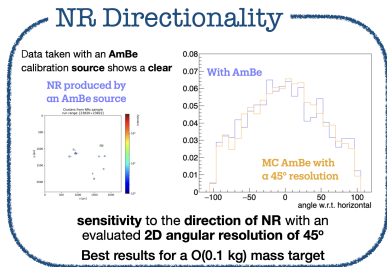


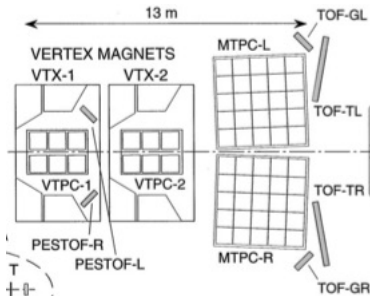
Figure: CYGNO 04 drawing, construction in 2026

Figure: Directional capability at the momentum of interest

- Momentum resolution much improved with passing time, MPGDs being an enabling technology. Further progress is possible;
- Excellent PID by dE/dx in TPCs is well established since the beginning, with yet to be surpassed performance - if ever;
- Cluster-counting in e^- drift TPCs is still an elusive technique;
- The use of EL amplification instead of avalanche is well established and has potential for additional applications;
- Systematic studies of emission spectra are key for several types optical readout systems;
- The resurgence of HP TPCs, even if with different motivations w.r.t. the beginning, is well under way;
- radiopurity screening and radioactive event background suppression has become key also in gaseous TPCs;
- Another, much neglected, *enabling technology* for the future of HP TPCs is the mechanical study and design of light field-cage and pressure vessel construction.

Thank you.

NA49 operates 4 TPCs: 2 *vertex* (VTPC) in the magnets, and 2 *main* (MTPC) ones outside.



- The MTPCs can do tracking and dE/dx , but no P measurement
- Specialized for particle ID
- They use the necessary *number of samples* along the track to reach the required resolution
- The function is similar to ISIS2

Being at $B=0$, NA49 MTPCs are forced to be in Cat 2, with a number of consequences.

- A *cold* gas has slower drift and, in general, larger attachment
- The track density imposes a small PRF and
- Amplification in this kind of gasses tends to be lower and therefore
- Signal amplitudes are critical
- Not on a plateau of V_{drift} so the calibration is more delicate

In this case exploiting the second term $(xP)^{-0.32}$ was not obvious

- HP would have slowed down the drift with potentially larger attachment (negating some of the advantages)
- would have required a sturdy field-cage, contrary to the goal of an almost transparent (literally) wall

Overall, NA49 MPTCs were in one of the most difficult corner of the TPC *phase space*.

It is the reason why I consider it a reference in this *Cat 2*, as much as the PEP-4 TPC is in *Cat 1*. Somehow, the first instance of both categories got everything right. Quite remarkable.

- optimization of the S/N.
 - event topology and PRF
 - gas choice
 - pressure, diffusion and attachment
 - amplification
 - electronics and cross-talk
- Calibration
 - purity and stability
 - specific measurements
- Statistics
 - pad size (cm bar)
 - size of the chamber (how many samples)

It is a long list of inter-related items. Gas choice influences diffusion, attachment and amplification, which in turn are related to PRF, which is determined by the event topology and drives and actual S/N of the signals on pads, ...

An often overlooked detail is the amplification. Electronics undershoot/overshoot phenomena, maybe added on top of channel-to-channel cross-talk, can seriously disrupt S/N in certain conditions or hit configurations.

A good protective measure is allow for a large gain, which unfortunately sometimes goes against the natural propensity of protecting the gas amplifiers (wires, MPGDs, ...) by keeping the HV as low as possible.

NA49 has an extensive system of control, monitoring and calibration

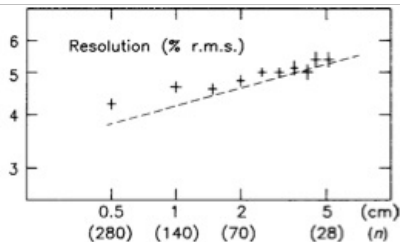
- Gas purity is very well controlled, down to 2-4 ppm oxygen. Gas mixing has to be stabilized to very high accuracy.
- The gas system is equipped with V_{drift} monitors, and gain monitors both on the input and exhaust lines. Gain is controlled to better than 0.5%, V_{drift} down to $5 \cdot 10^{-4}$
- Simultaneous calibration of electronics and gas gain can be achieved by releasing a known number of electrons into the TPC drift space (^{83}Kr)
- Complicated corrections of electronics cross-talk at high charge density
- Charge needs to be corrected for local track angle
- Correct for charge loss due to drift length, $\leq 2\%$ due to diffusion, plus effects due to zero-suppression thresholds (apparent charge loss $\sim 5\%$)

The longest tracks traverse all TPCs, both VTX and MTPC. The truncated mean is computed on the base of $(\langle S \rangle_{50})$.

Despite all the obstacles, the reported performance is $\sigma \sim \frac{38\%}{\sqrt{N}}$, giving $\sim 3\%$ (RMS) for the longest tracks, reaching identification abilities at the level of the best ones.

In addition to the overall dimensions (L) and number of pads (n), one can play with the pad size (x) - or more precisely: the sample length (at a give pressure). The gain with n is partly offset by the loss due to smaller x , but calculations seem to indicate that there is still a net gain with n while keeping L fixed. This seems to be supported by the following plot from ALEPH.

Fig. 10.7 Ionization resolution at constant track length as a function of the sample length. *Crosses:* measured in the ALEPH-TPC (average track length 140 cm, argon (91%) + methane (9%) at 1 bar, diffusion < 1.4 mm r.m.s.). *Line:* prediction of Allison and Cobb, our (10.9)



A pitch much smaller than 0.4 cm is not easy, but maybe the tiny PRF of MPGD amplification and the advances in multiplexed readout will allow to exploit this possibility.