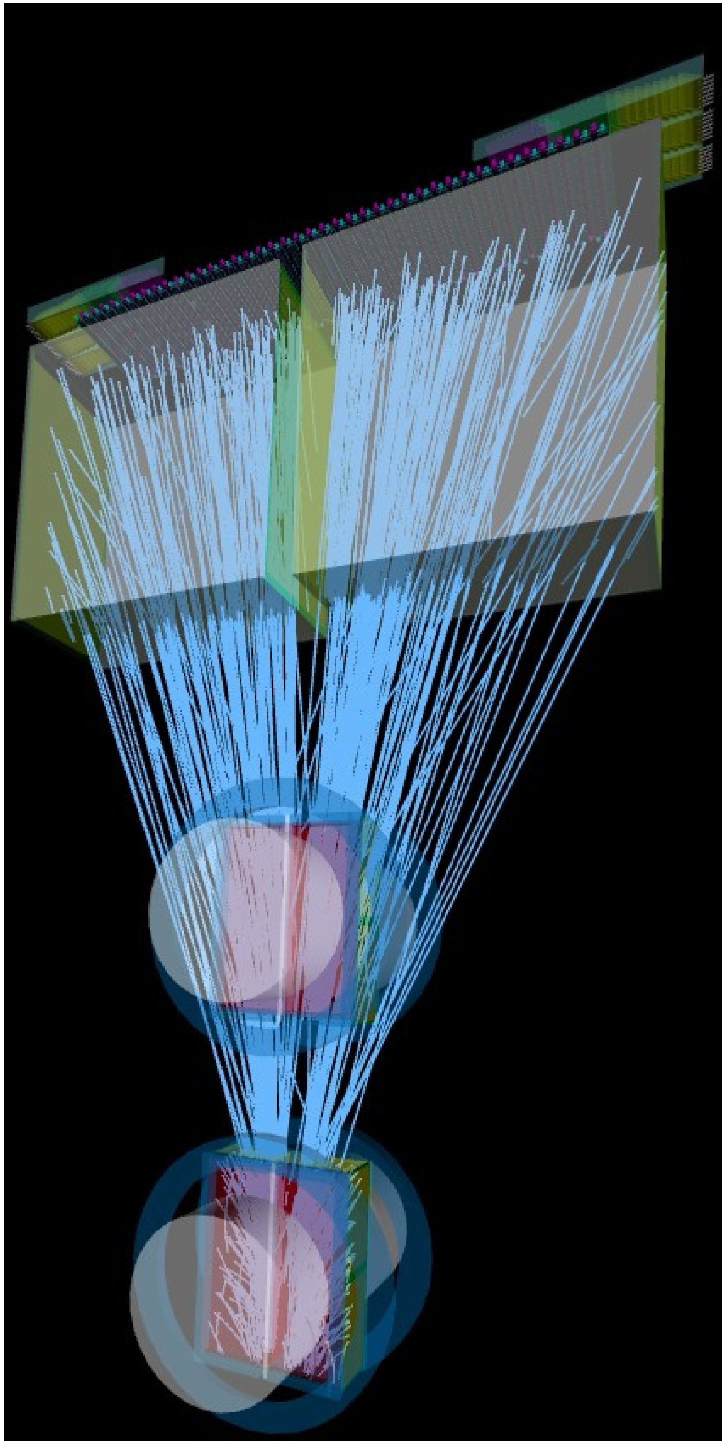
Introduction to TPCs



Overview:

- **History**
- **P**rinciple
- Mechanics
- Readout
- Position resolution
- Calibration
- Particle identification
- Corrections

A short history of TPCs

Invented 1974 by David R. Nygren (Lawrence Berkeley Lab) and used in the experiment PEP4 at SLAC (1981) — CCDs to store analog signals

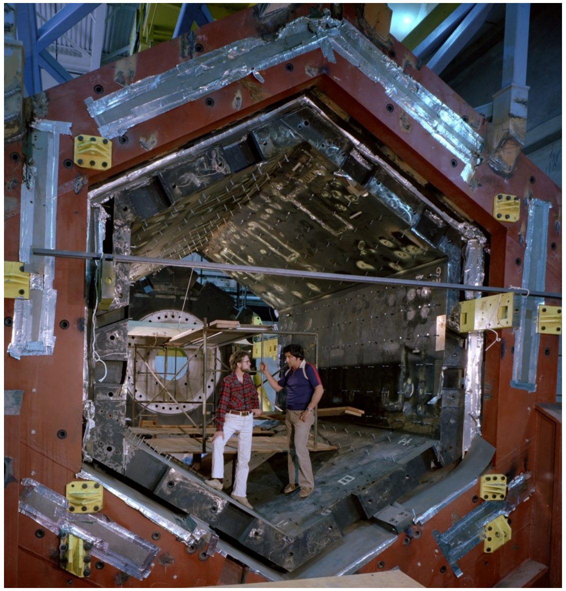
Other experiments with a TPC in **particle physics**:
TOPAZ experiment at TRISTAN (1987), KEK Tsukuba, Japan
Early CDF experiment at Fermilab: vertexing (1987)
LEP collider: ALEPH, DELPHI (1989) — flash ADCs

Almost identical
Wire geometry

Heavy ions:
EOS @ LBLN (1990) — switched capacitor array (SCA)
later at AGS, Brookhaven and Fermilab
NA35 (1988), NA36 @CERN — flash ADCs
CERES (NA45) @ CERN (1998) — radial drift
NA49 @ CERN (1992) — switched capacitor arrays
STAR @ RHIC, Brookhaven (1999) — no field wires — SCA, later low power CMOS ASICs

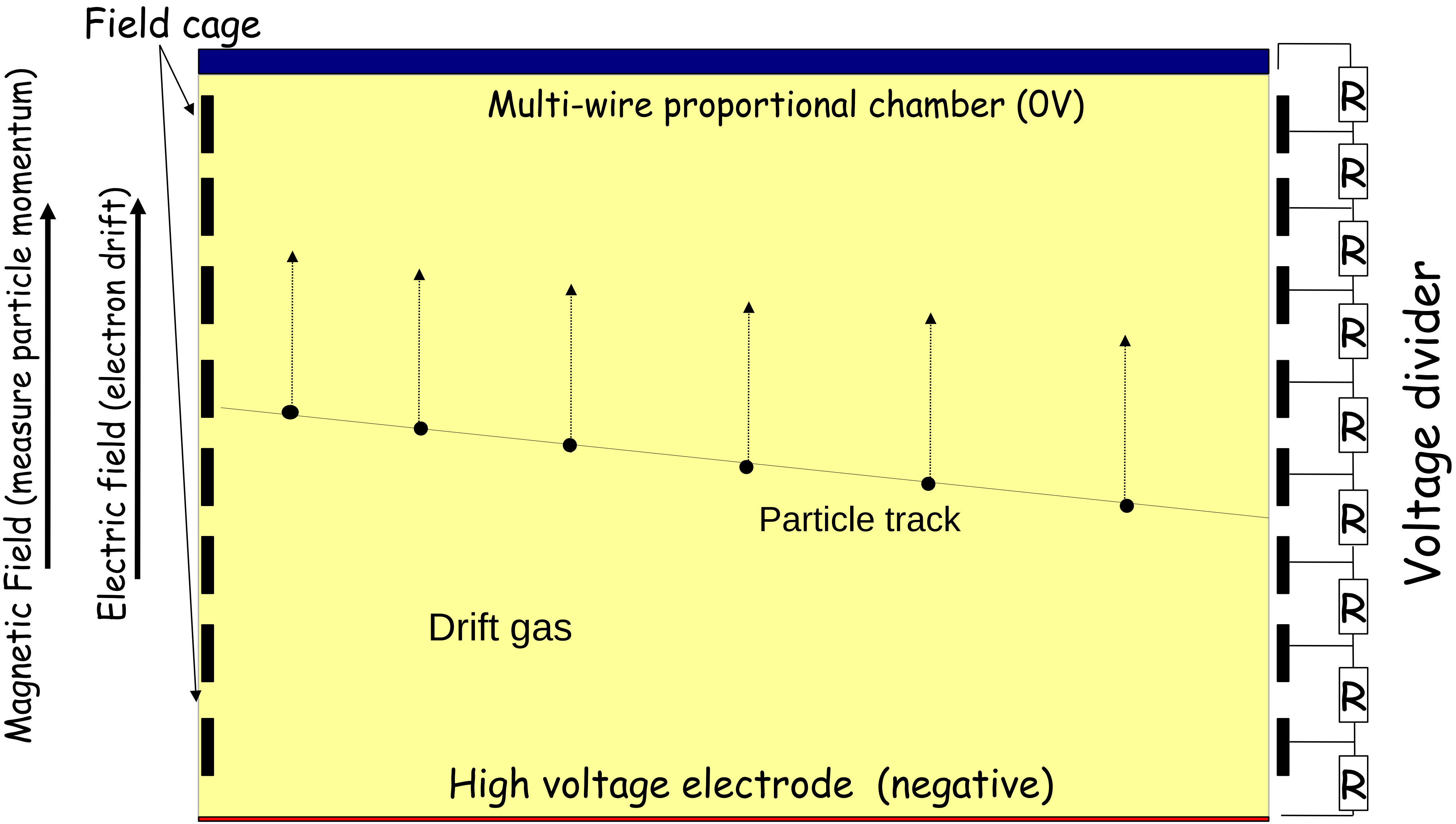
ALICE @ CERN (2000) — no field wires — low power CMOS ASICs

Neutrino physics:
T2K (2003)
Liquid Ar TPCs: ICARUS, MicroBooNE, DUNE

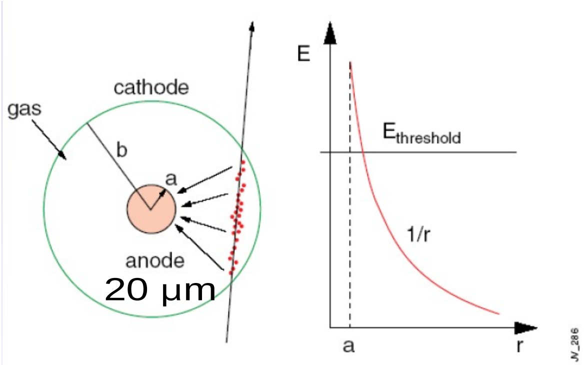


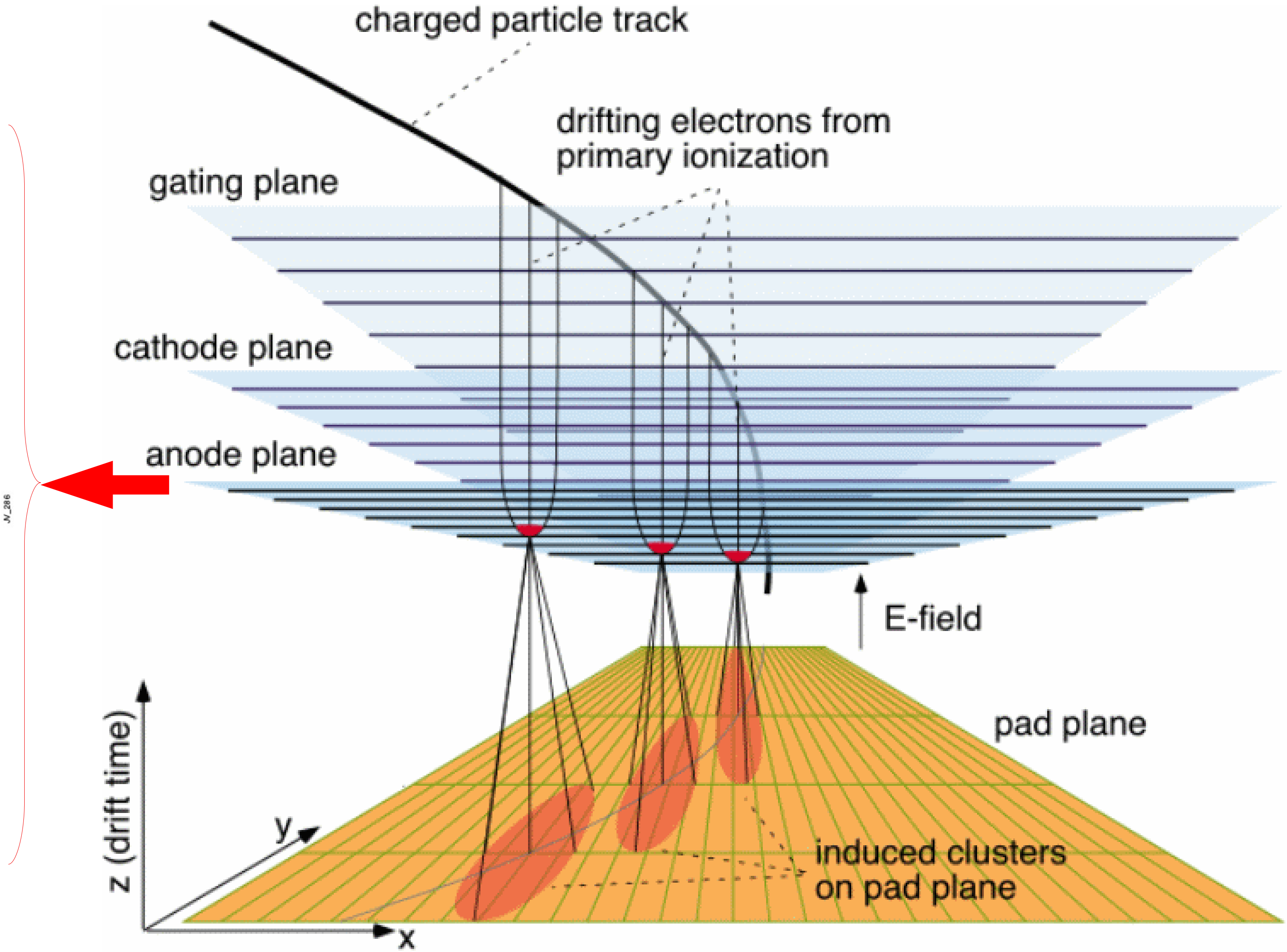
Dave Nygren (left) and PEP4

Working principle of a TPC



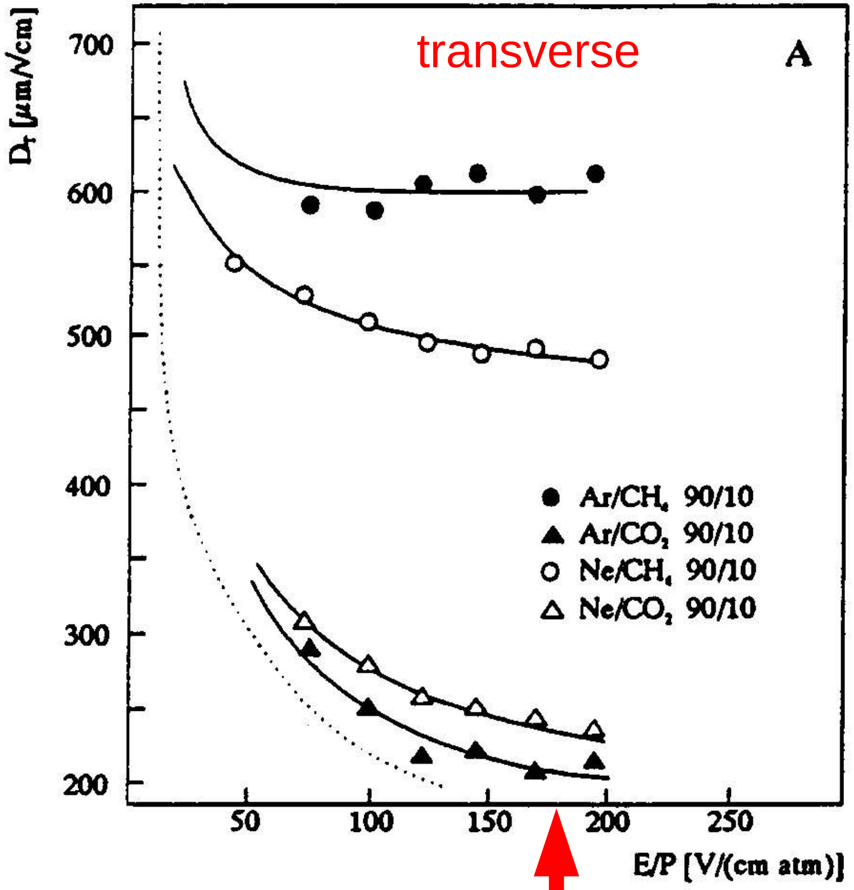
Signal generation in a multiwire proportional chamber with pad readout

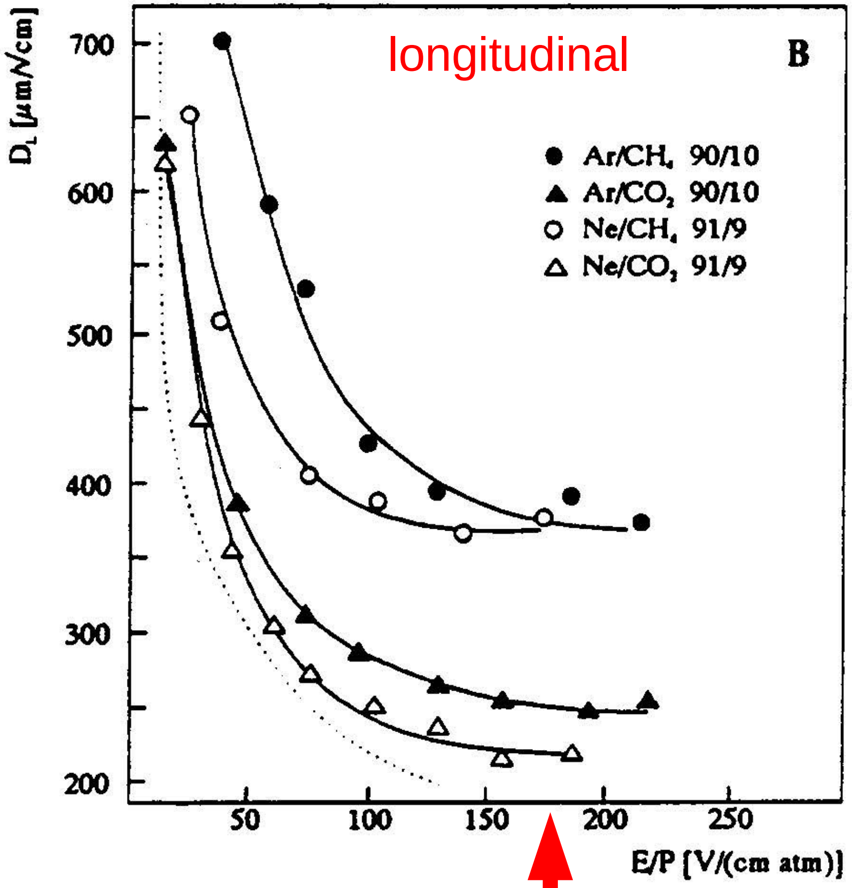




Signals induced on pad plane by back drifting positive ions (not electrons!!)

Drifting electrons: diffusion, Oxygen

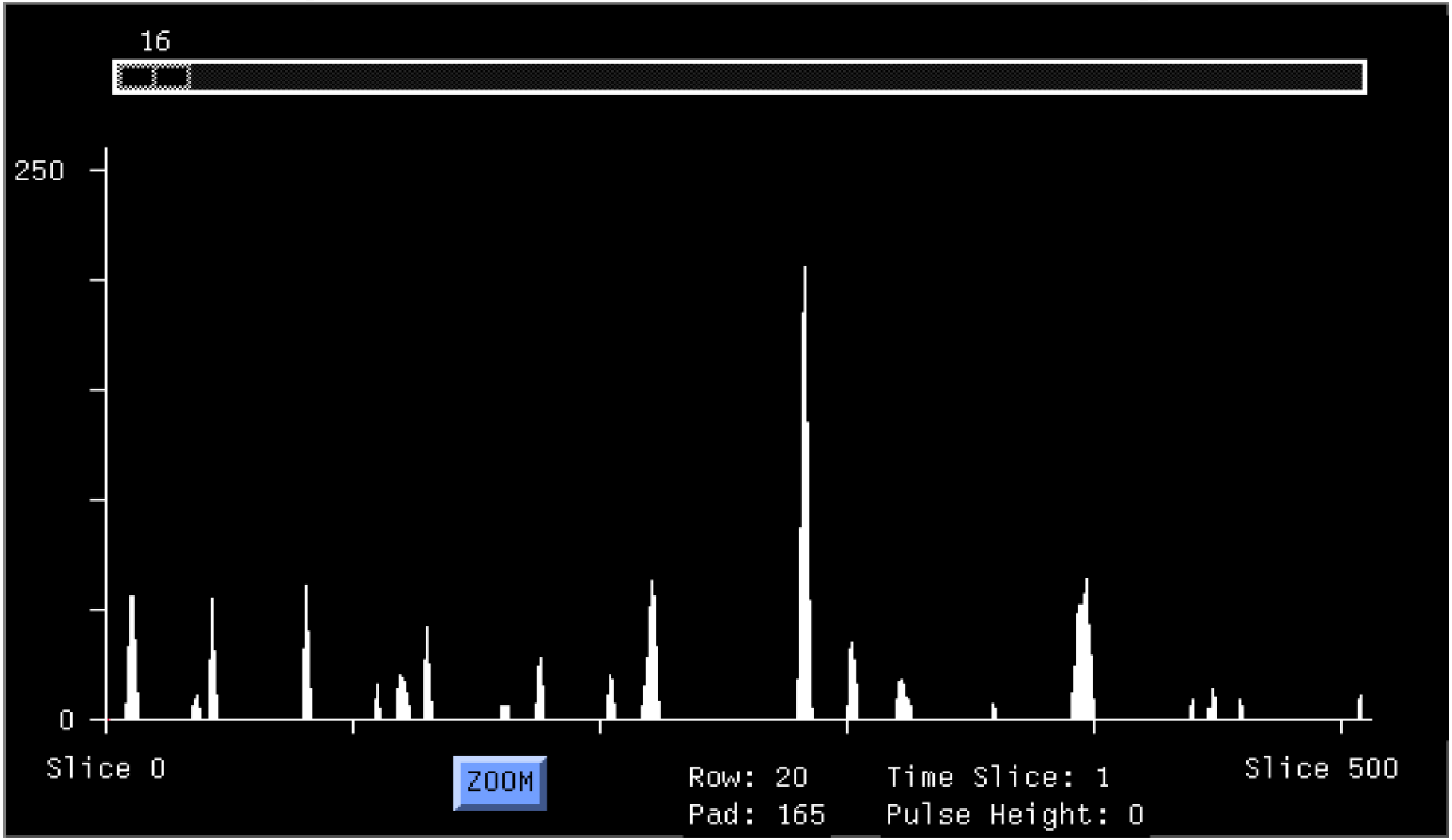




NA61 drift fields

Oxygen levels have to be low (< 5 ppm) to keep electron attachment to O_2 low, especially in the presence of CO_2

Signals of **one** pad after digitization and zero suppression (NA49 online monitor)

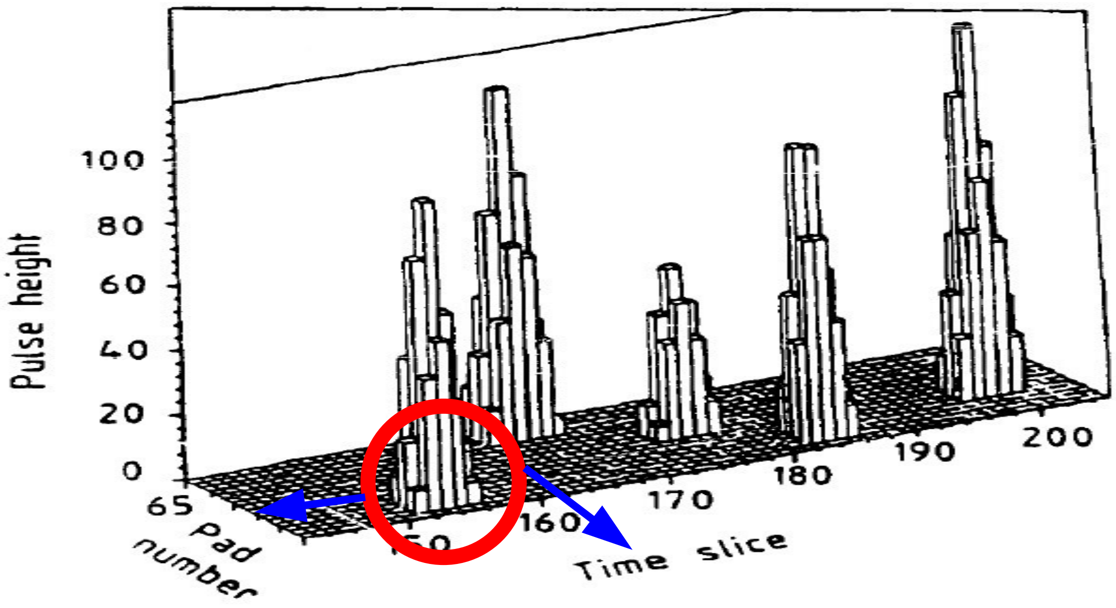


Row: 20
Pad: 165
Time Slice: 1
Pulse Height: 0

Amplitude (ADC counts)

Drift time of electron cloud

Calculation of position



For each pad-row:
1 Identification of clusters: signals close in time and space
2 Projection onto time axis
3 Projection onto pad axis
4 determination of centroids → x, z coordinates
(alternatively: 2-d Gauss fit)
5 y coordinate: center of pad-row

Main feature: very good position resolution (~150 u) even with relatively wide pads (~5 mm)

Calculation of position, tracking

Pad direction (x-direction):
Information from several pads is combined (summed over time bins) and the center Of gravity (weighted mean) is calculated.

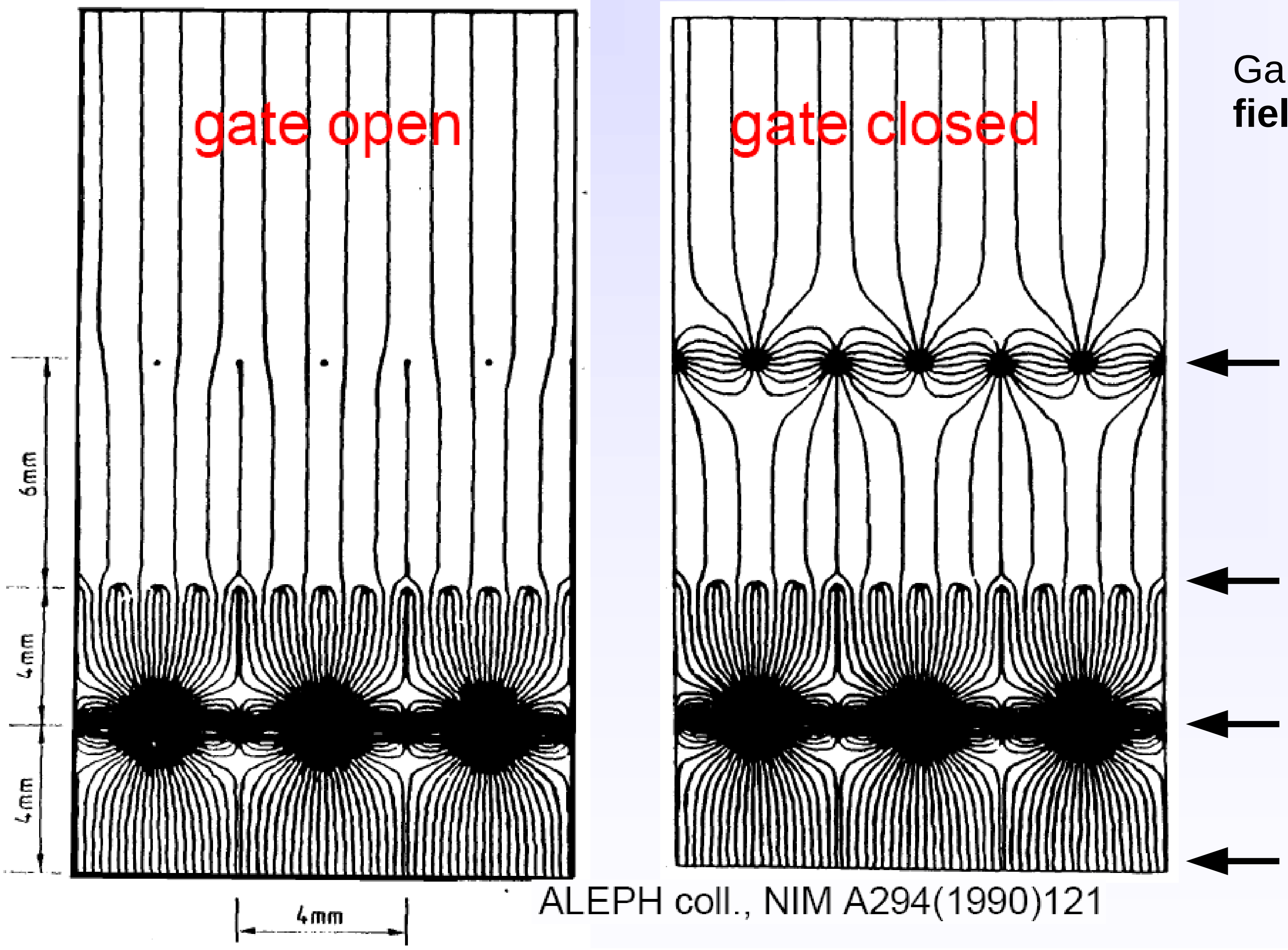
Time direction (y-direction):
Information from several pads is combined (summed over pads) and center of gravity Is calculated

The third coordinate (z-coordinate) is simply the center of the pad (in longitudinal Direction) equivalent to the position of the pad-row

The last step is then the to combine the track points to tracks. This is done starting from The low rack density region and searching for clusters in the direction towards the target In a reasonably defined cone.

The gating grid

- prevents positive ions from drifting back into drift volume: space charge distortions
- prevents electrons from entering the amplification region: aging



Garfield calculation of **field** lines

gating plane

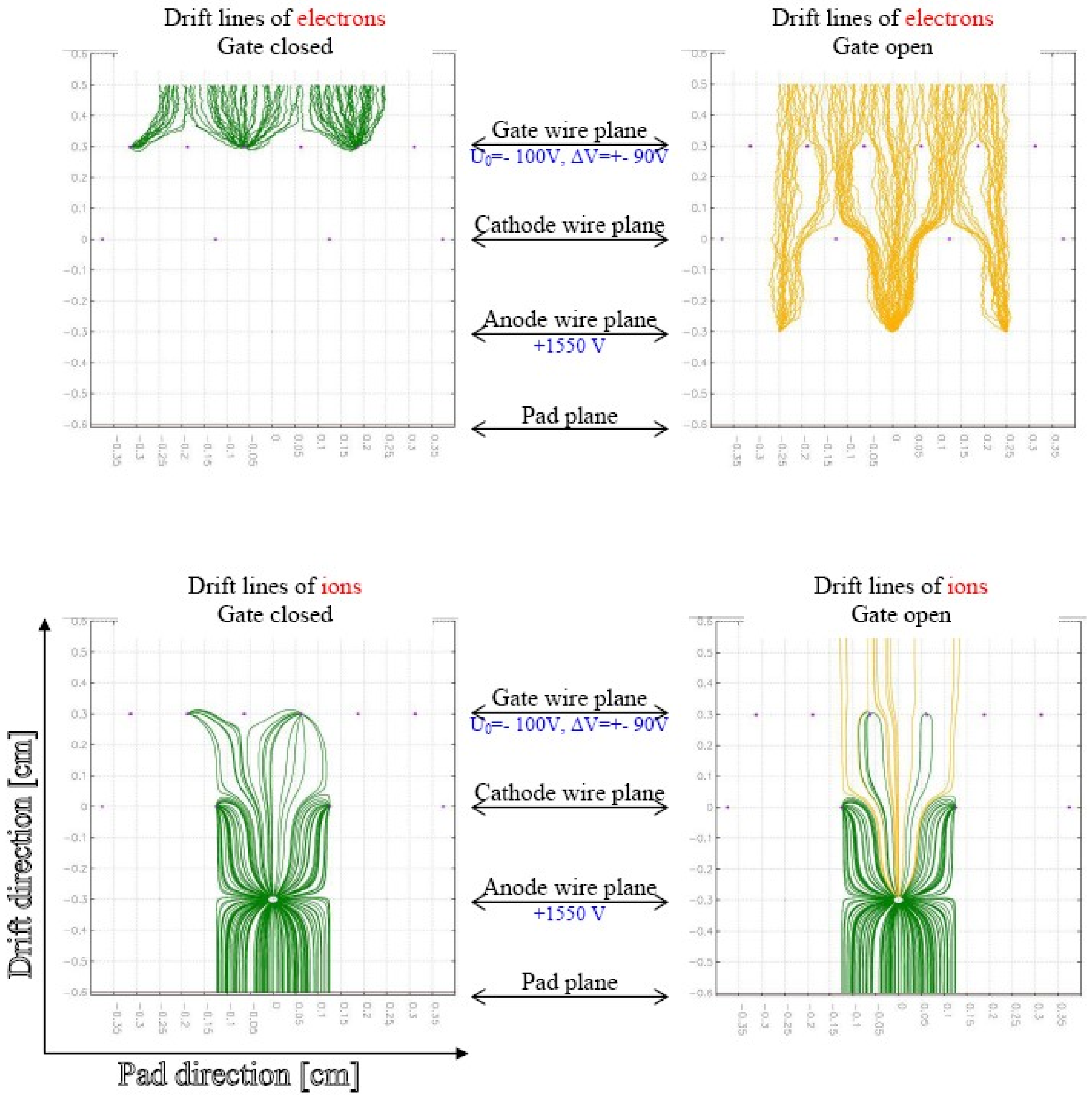
cathode plane

anode wires
field wires

readout pads

ALEPH coll., NIM A294(1990)121

The gating grid



Different way of presentation:
drift lines of electrons/ions

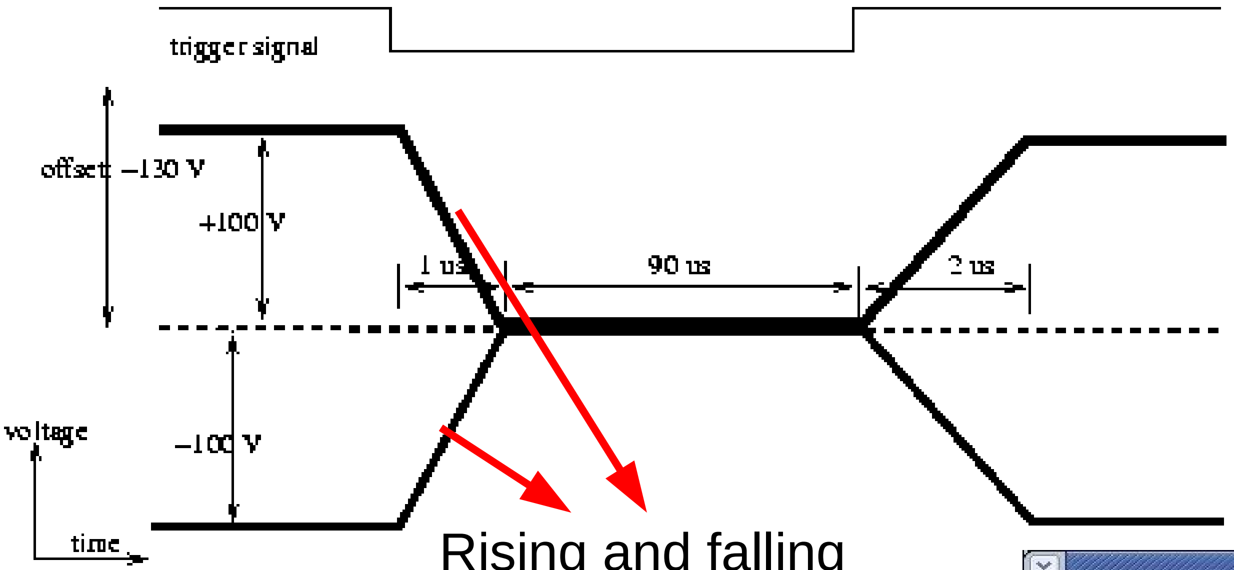
Garfield calculation for OROC chambers of ALICE (no field wires → larger signals on pads)

Ion blocking of gating grid: ~ 10^{-5}

Side remark:
for GEM readout it is ~5x10^{-3}

Gating grid pulser

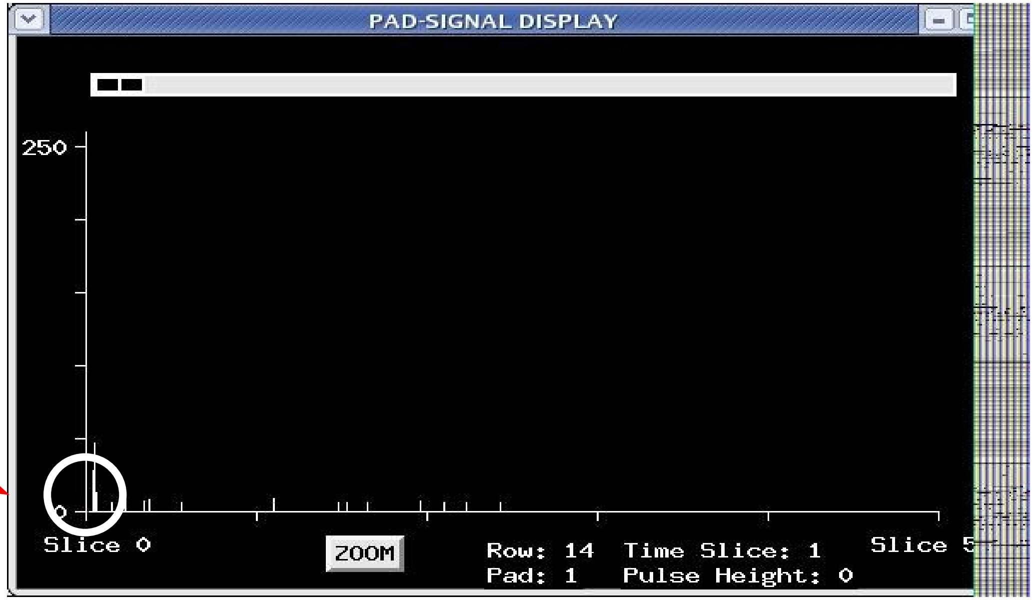
Principle of operation:



Rising and falling edge ideally should cancel

Badly tuned pulser causes noise in the first couple of time bins

ONE THING TO BE CHECKED BY SHIFT CREWS!



Row: 14 Time Slice: 1
Pad: 1 Pulse Height: 0

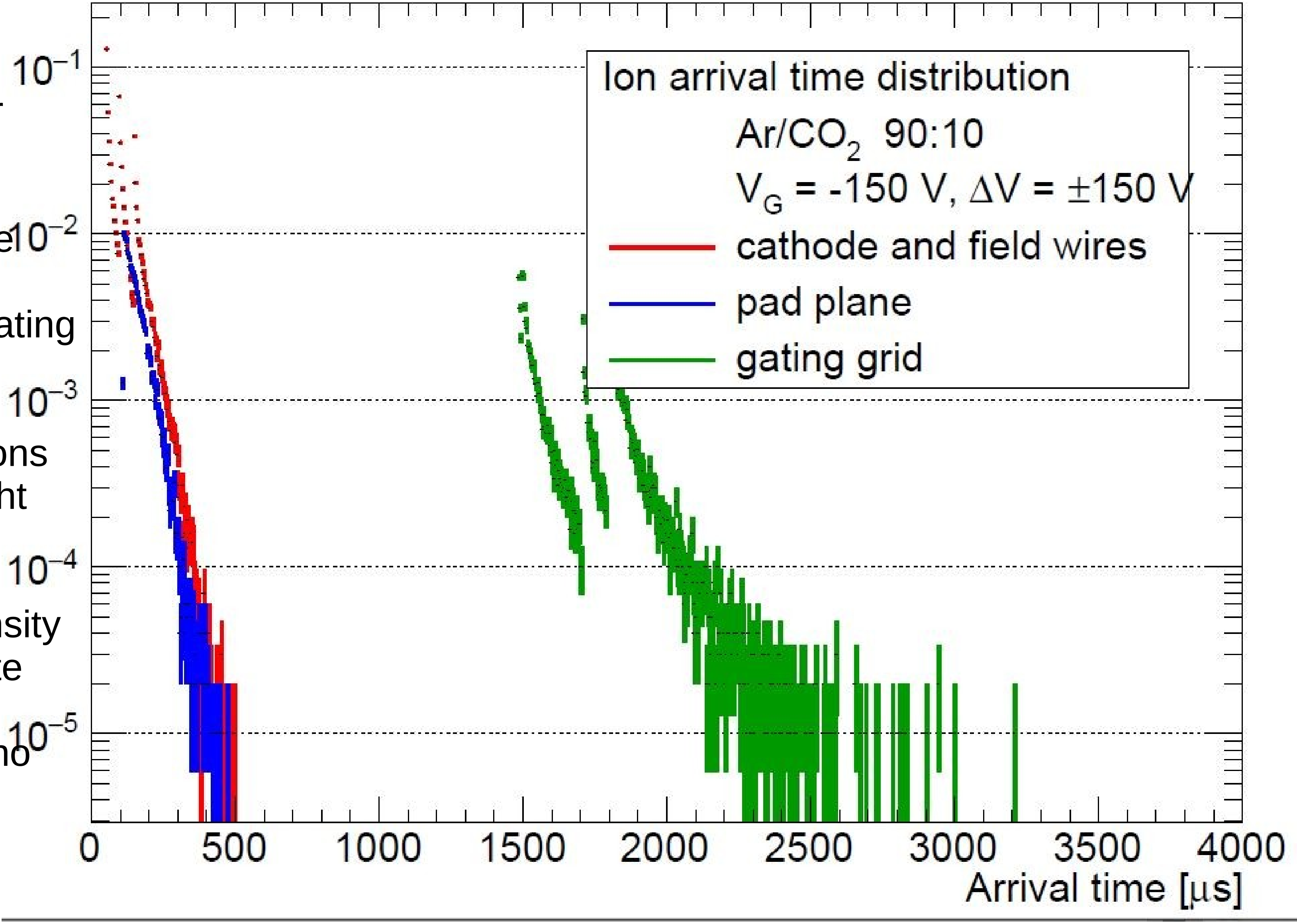
Dead time due to ion drift time to gating grid

NA61 aims at trigger rates up to 1 kHz

This requires that the Positive ions arrive Within 1 ms at the gating Grid

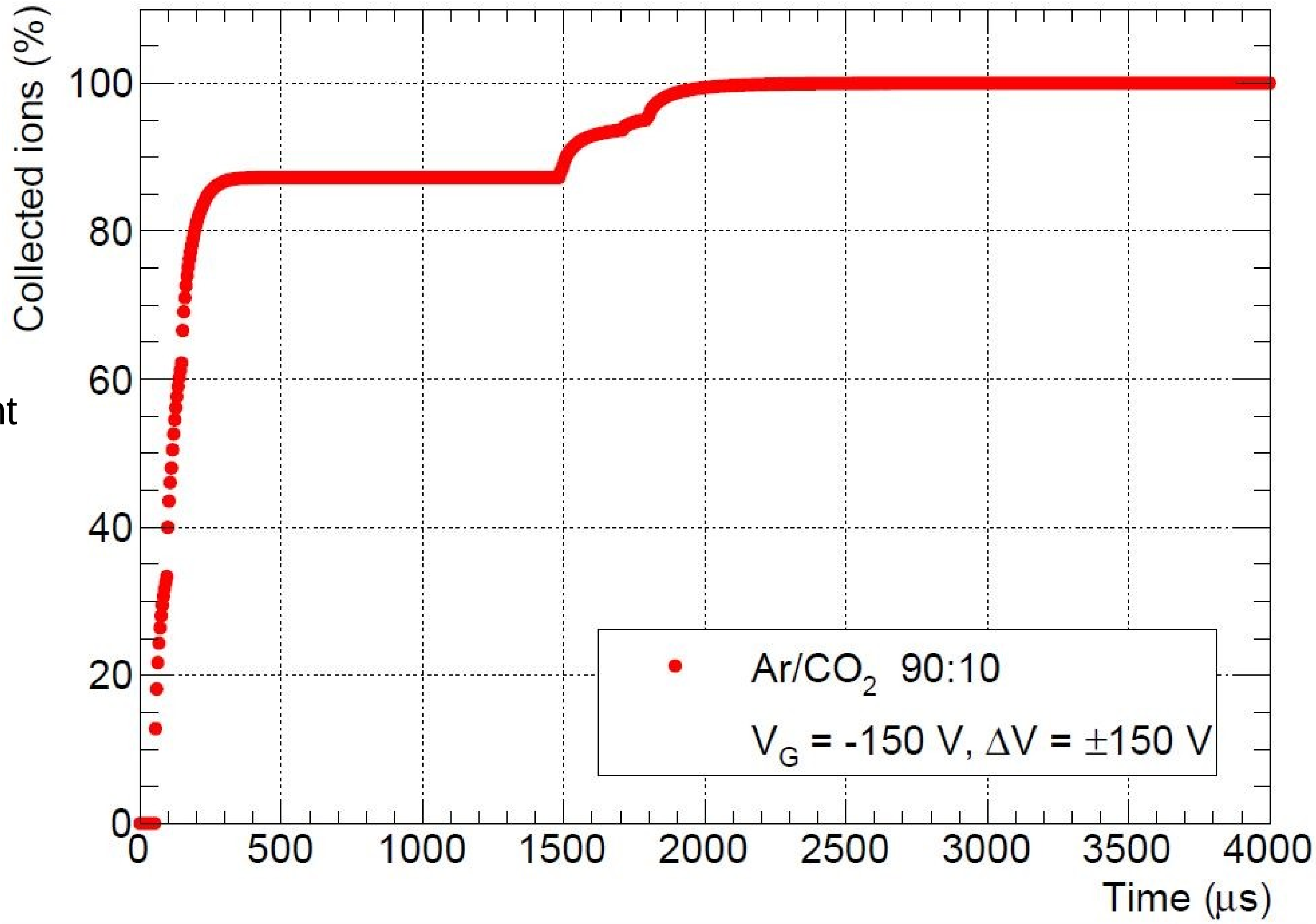
GARFIELD simulations Show that there might be a problem

Tests with high intensity Beam and 1 kHz gate opening/closing Frequency showed no problem

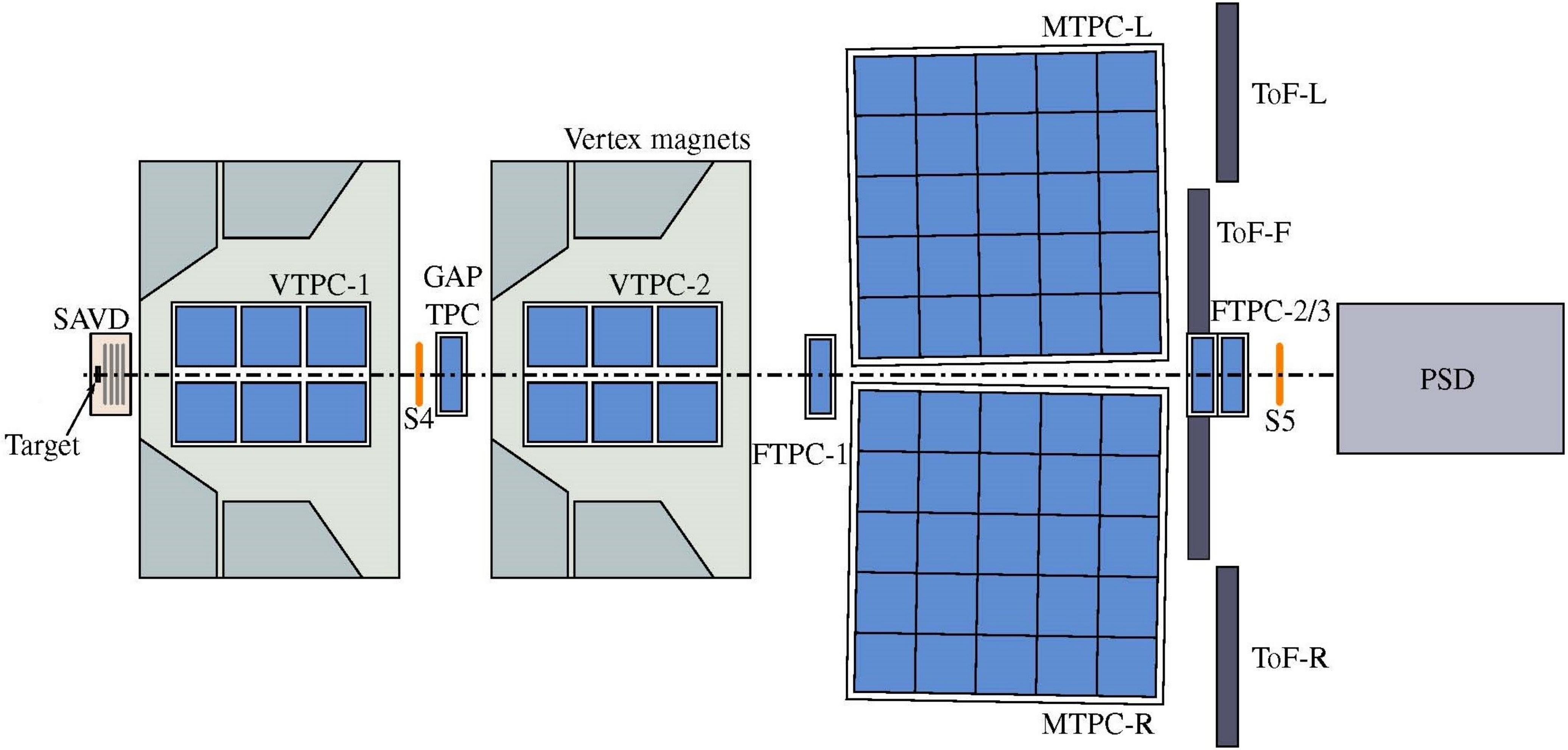


Dead time due to ion drift time to gating grid(2)

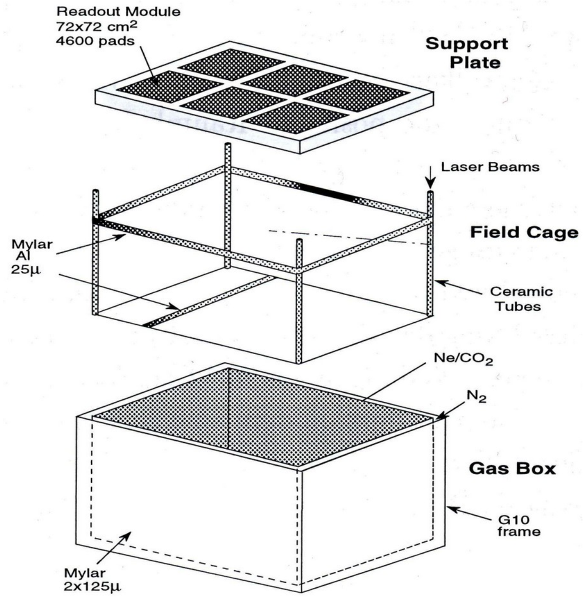
Another way to present
The potential problem

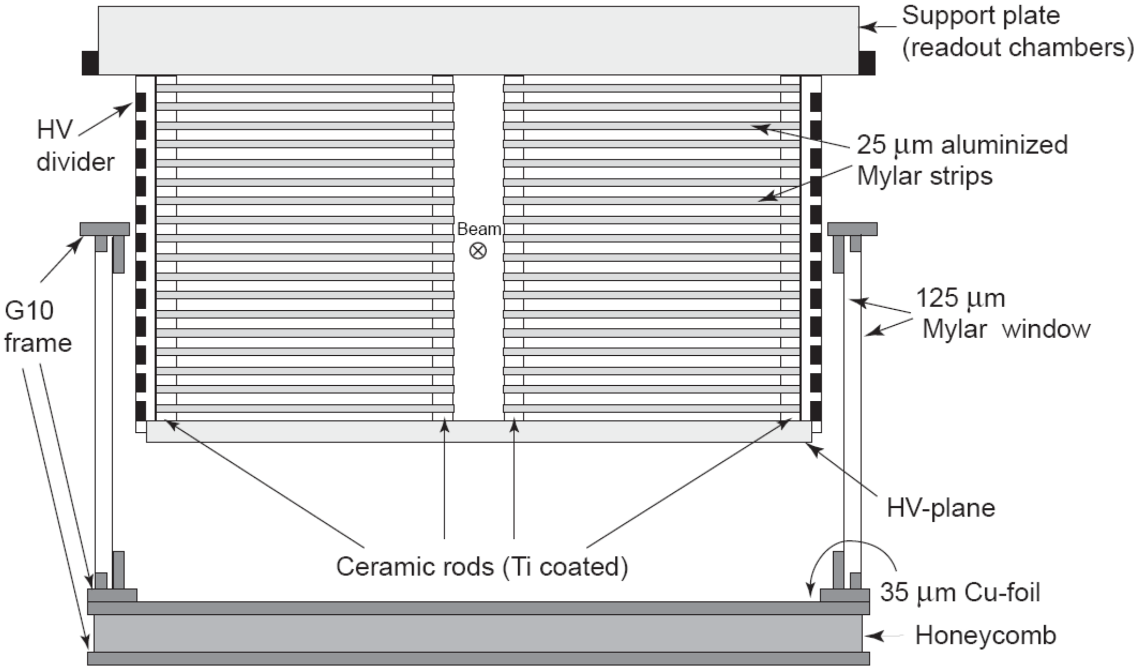


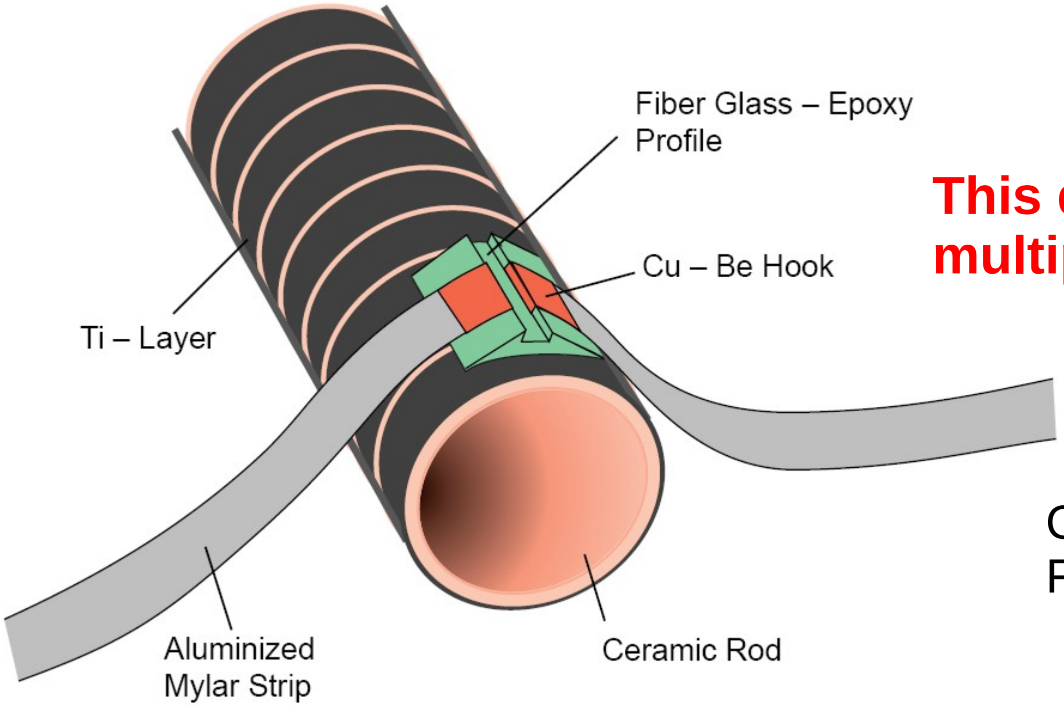
NA61 TPCs


MTPC-L
ToF-L
Vertex magnets
ToF-F
VTPC-1
GAP
TPC
VTPC-2
FTPC-2/3
SAVD
PSD
S4
S5
Target
FTPC-1
ToF-R
MTPC-R

Construction of the VTPCs







This design allows very light construction: multiple scattering is minimized

Optimized: strip width and strip distance: Field leakage and HV stability

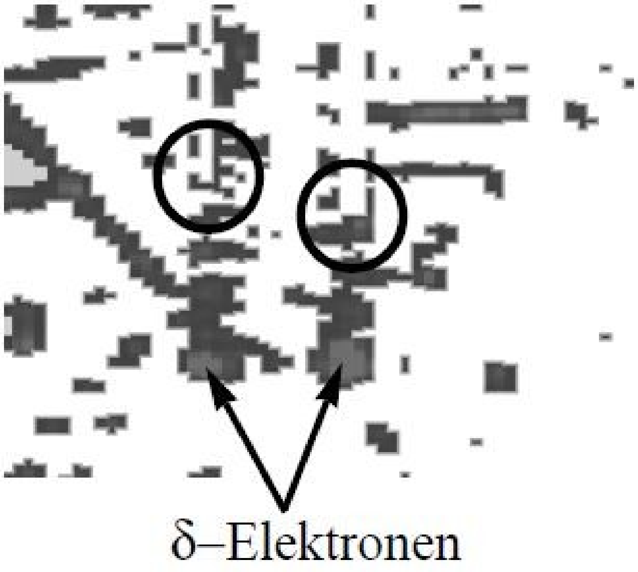
VTPC (before beam pipe):

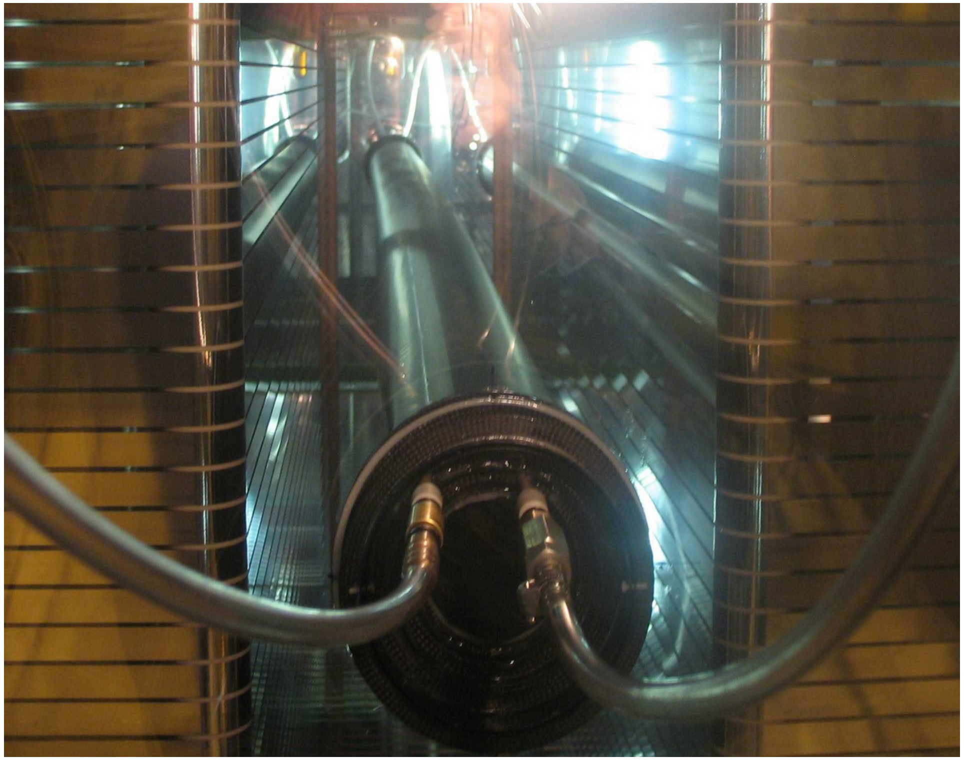
looking along the beam direction

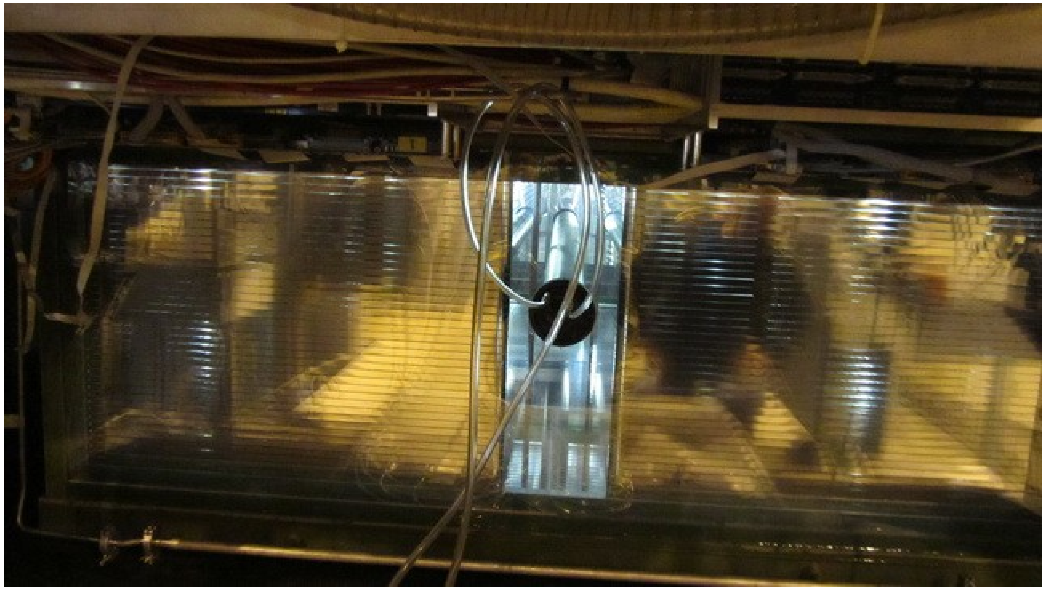
field cage is split into two halves, the beam area is outside the field cage

VTPC now with **He beam pipe**

→ to reduce interactions between beam and chamber gas
→ less delta electrons
→ double walled to avoid He leakage into VTPC
→ slight overpressure in insulating volume to keep the tube straight
→ no distortions by potential charge up since placed in between the field cage half's



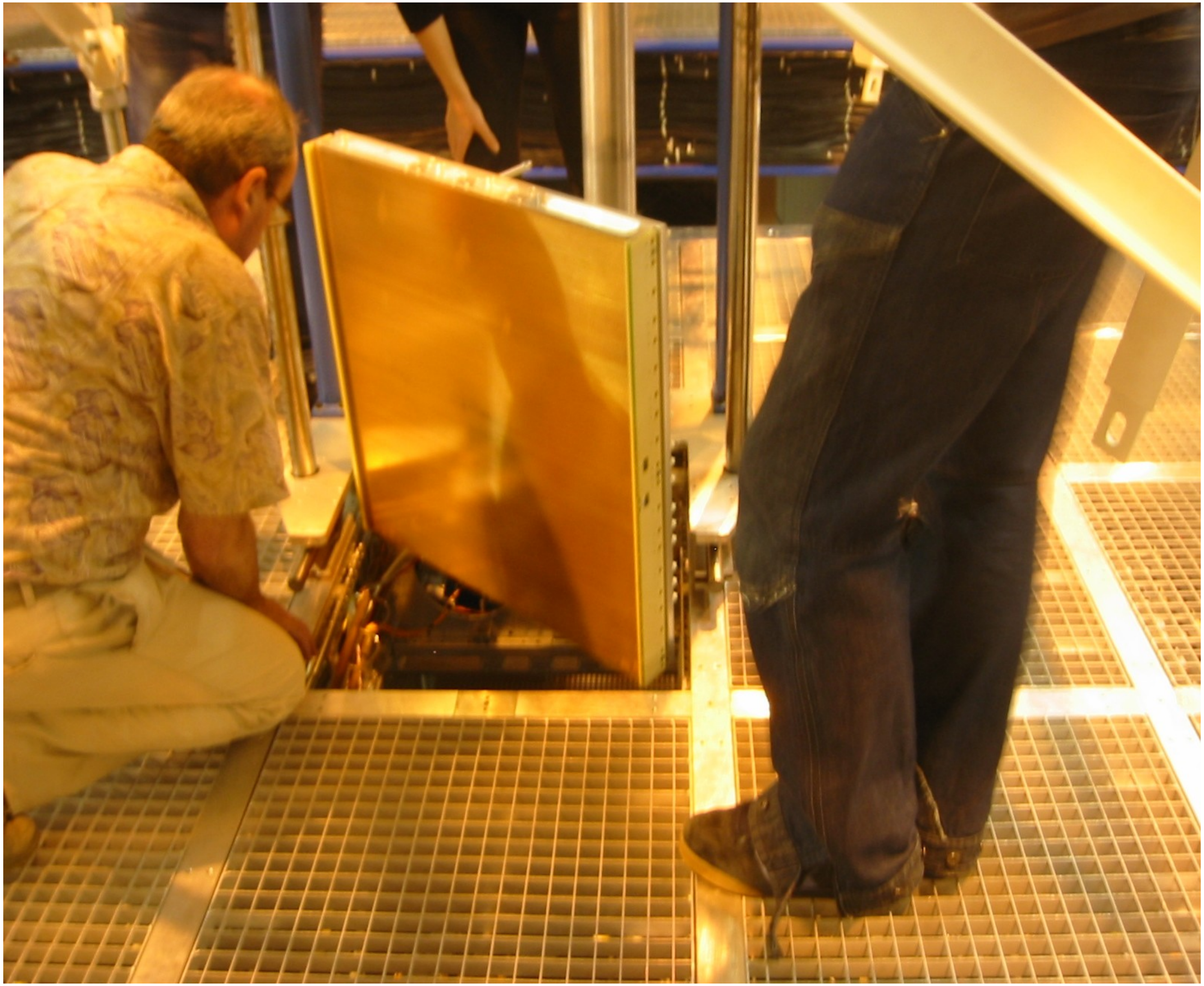




MTPC field cage

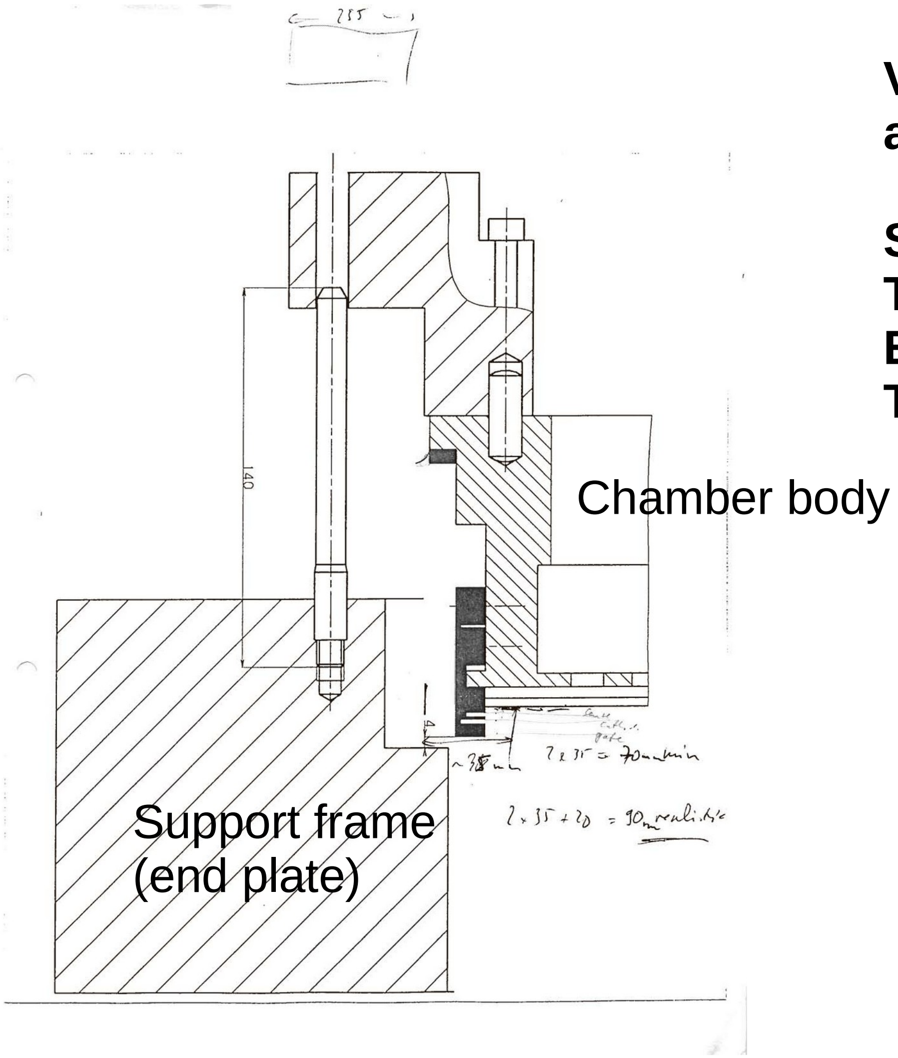
Inside the MTPC

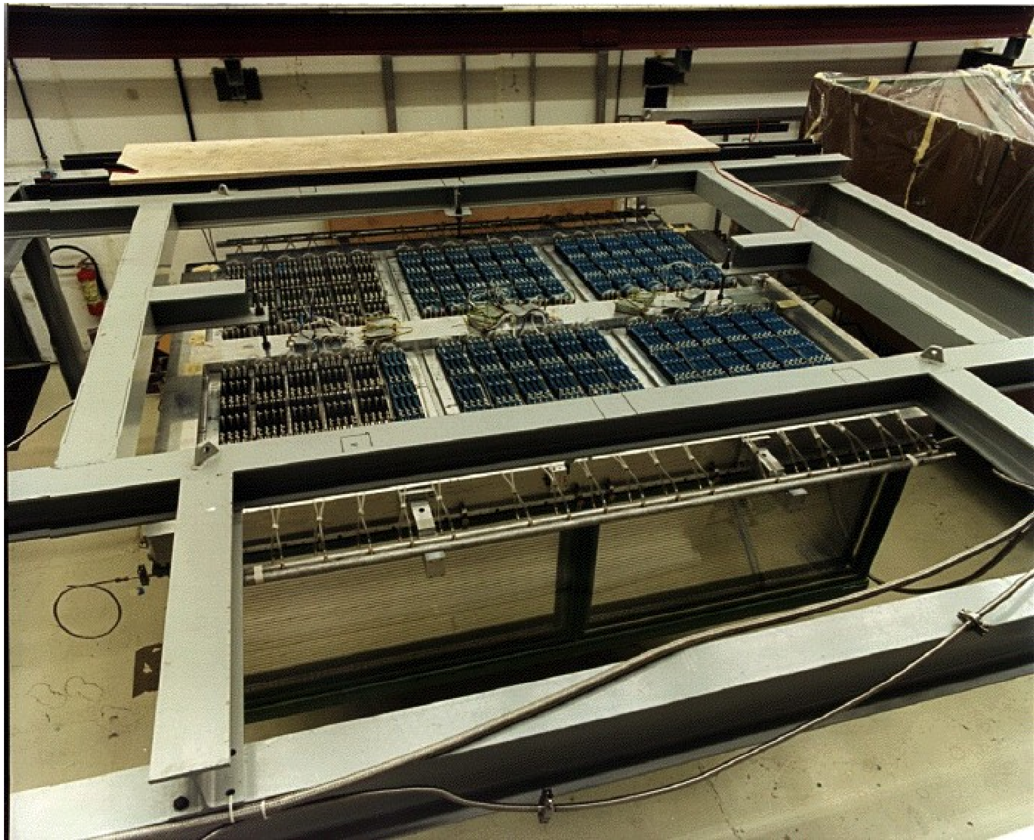
MTPC chambers are first inserted through the opening, turned and then pulled back. O-rings provide the sealing.



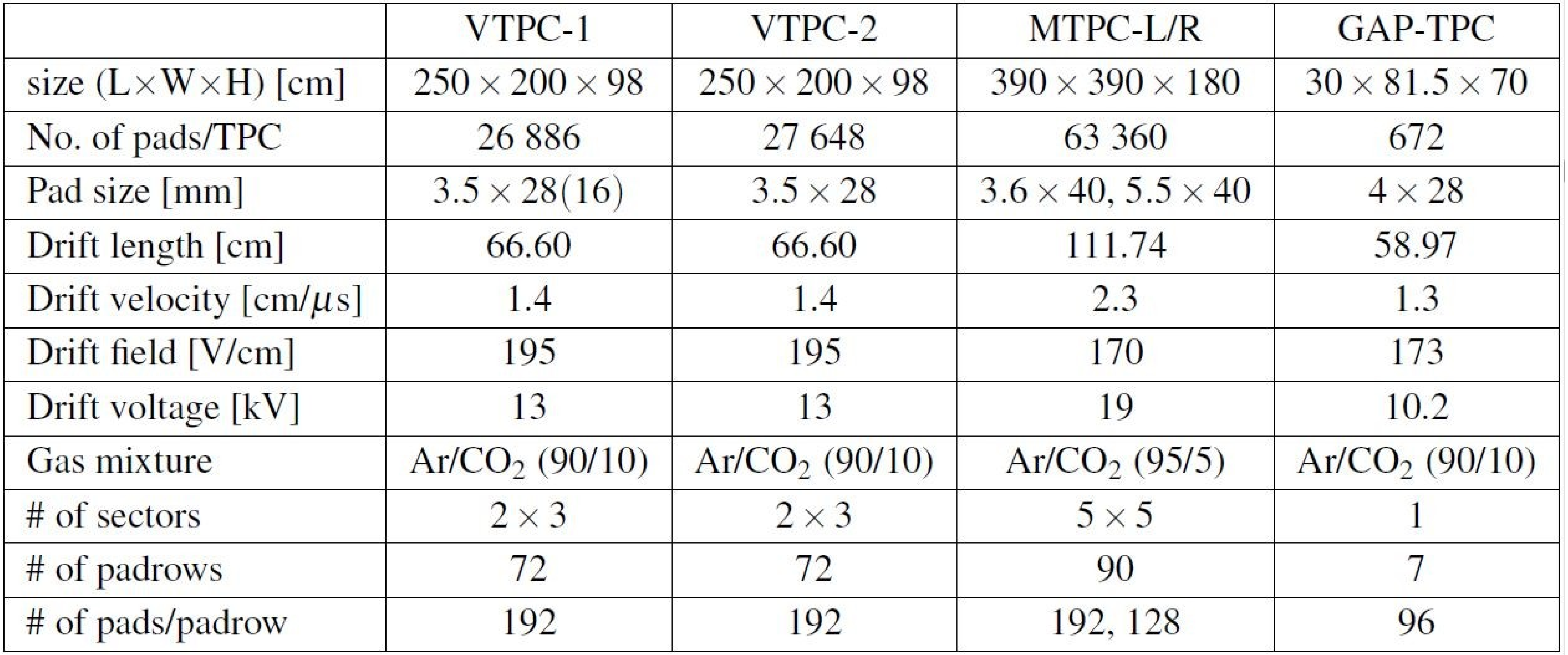
VTPC chambers are inserted from top and sealed with RTV (silicone)

Somewhat controversial in the community due To the potential danger of causing aging Extensively tested (H.G.Fischer) and proven To be no problem (for the RTV brand used!!!!)





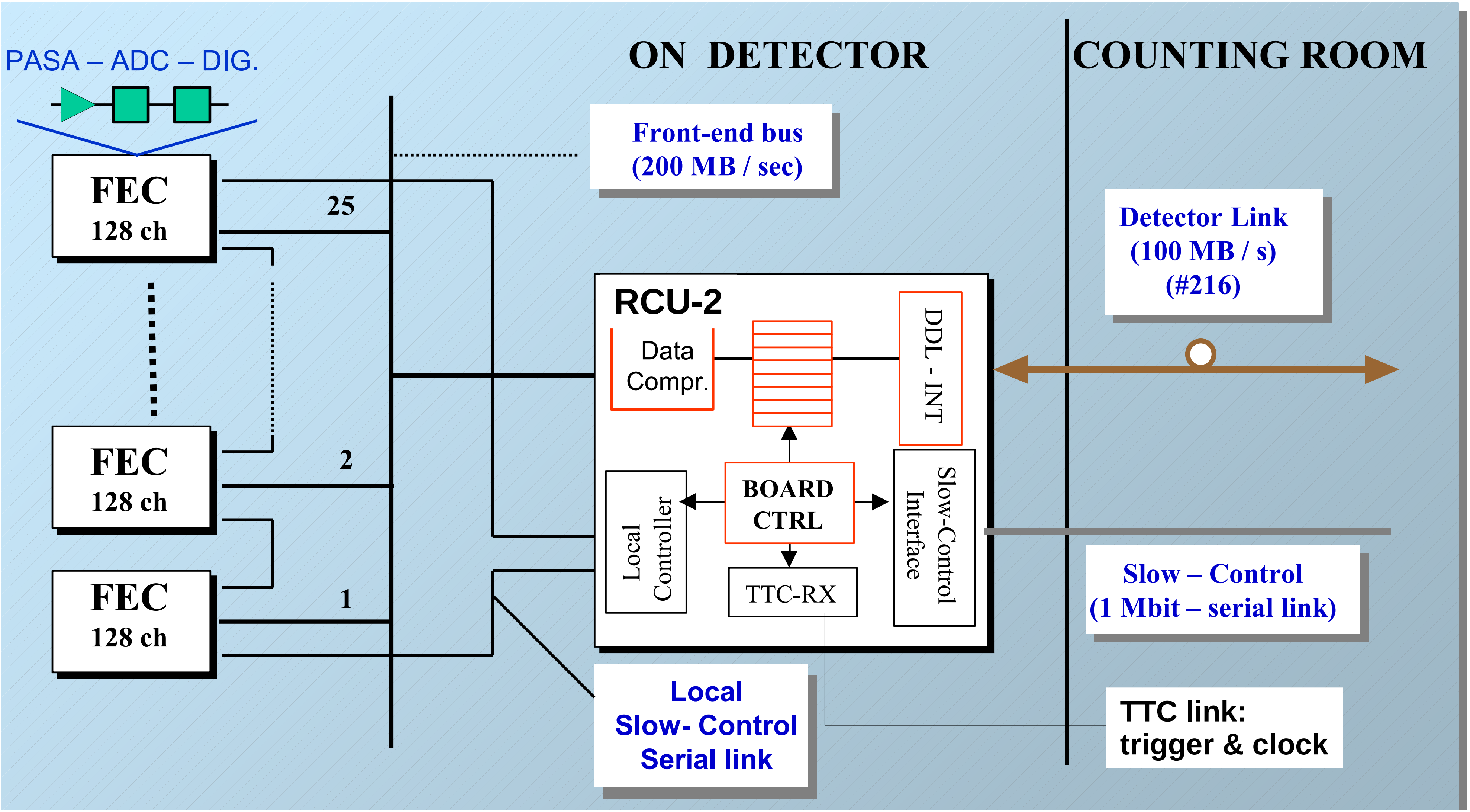
NA61 TPCs: overview



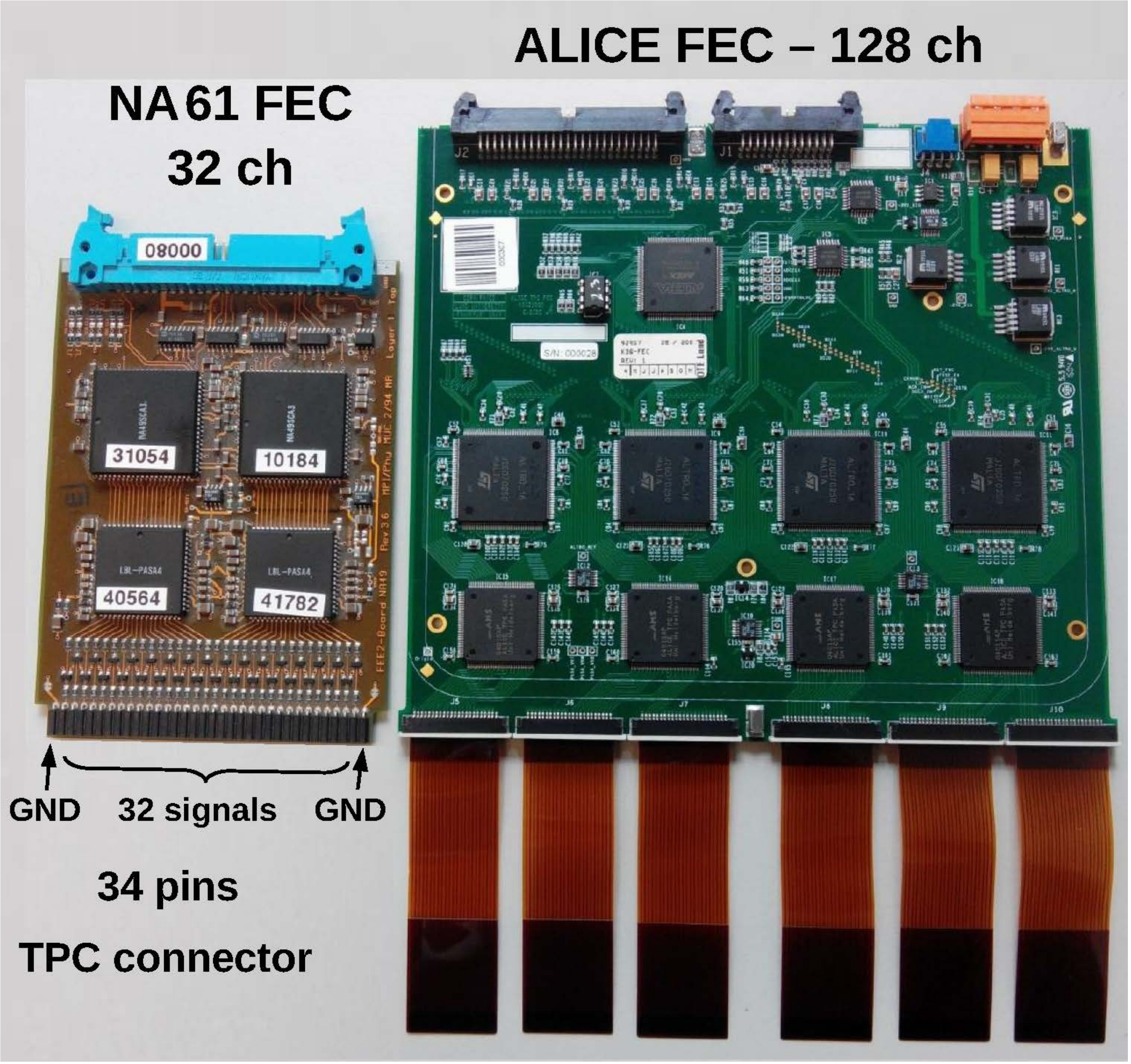
	VTPC-1	VTPC-2	MTPC-L/R	GAP-TPC
size (L×W×H) [cm]	$250 \times 200 \times 98$	$250 \times 200 \times 98$	$390 \times 390 \times 180$	$30 \times 81.5 \times 70$
No. of pads/TPC	26 886	27 648	63 360	672
Pad size [mm]	$3.5 \times 28(16)$	3.5×28	3.6×40, 5.5×40	4×28
Drift length [cm]	66.60	66.60	111.74	58.97
Drift velocity [cm/μs]	1.4	1.4	2.3	1.3
Drift field [V/cm]	195	195	170	173
Drift voltage [kV]	13	13	19	10.2
Gas mixture	Ar/CO_2 (90/10)	Ar/CO_2 (90/10)	Ar/CO_2 (95/5)	Ar/CO_2 (90/10)
# of sectors	2×3	2×3	5×5	1
# of padrows	72	72	90	7
# of pads/padrow	192	192	192, 128	96

TPC readout

Global readout architecture

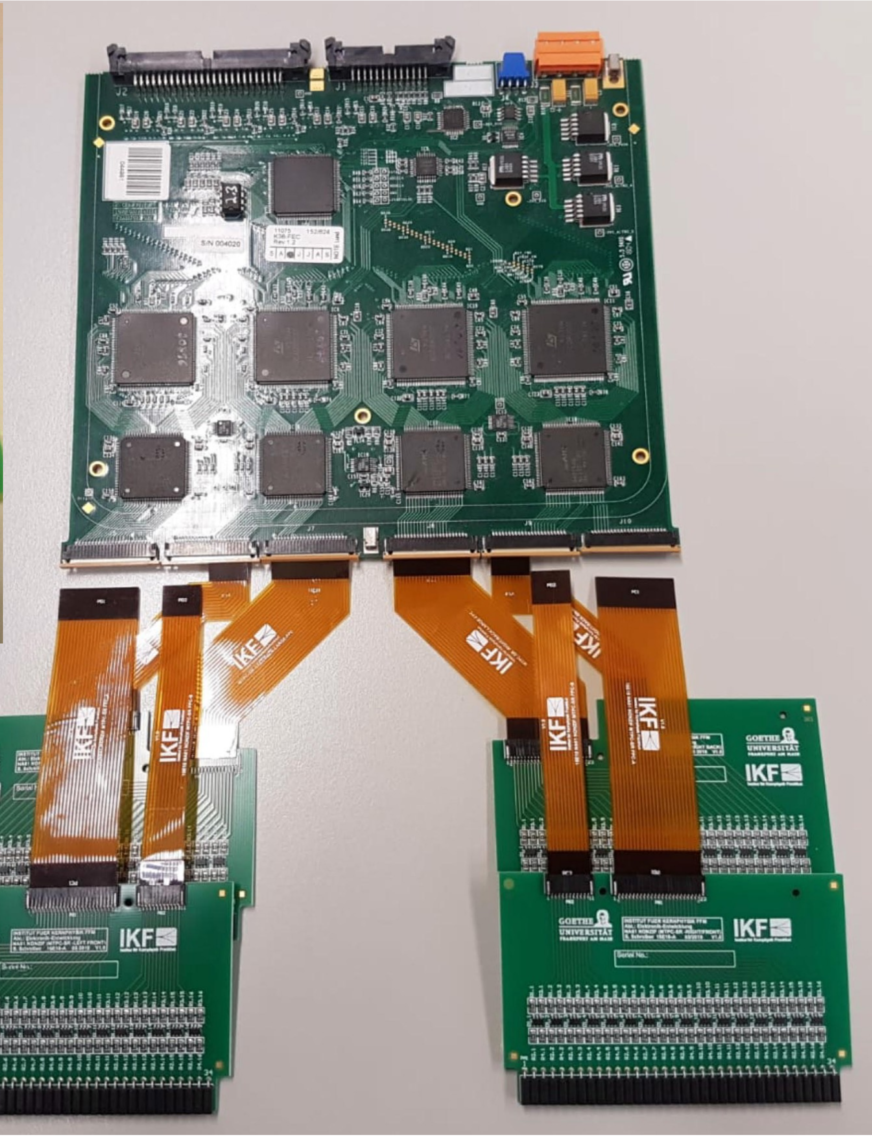


New readout: front-end-card (FEC)



Flexible Kapton Cables with 23 copper strips (traces)

Input adapters: final version

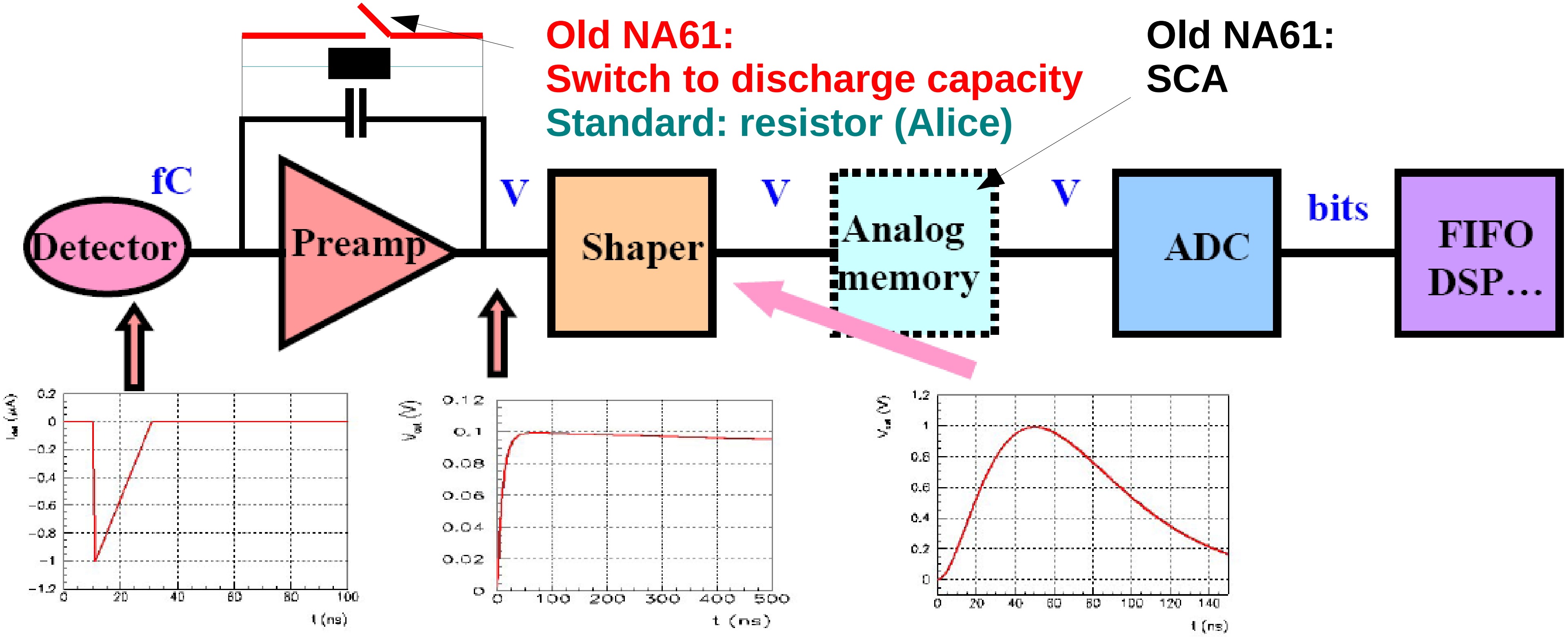


The introduction of rigid adapter boards allowed
The introduction of a new feature:
a strong input protection (ESD)

In ALICE a lot of preamp/shaper chips were damaged by discharges in the wire chambers. This happened even though there is ESD protection on the CMOS chip.

Overview of readout electronics

- Most front-ends follow a similar architecture



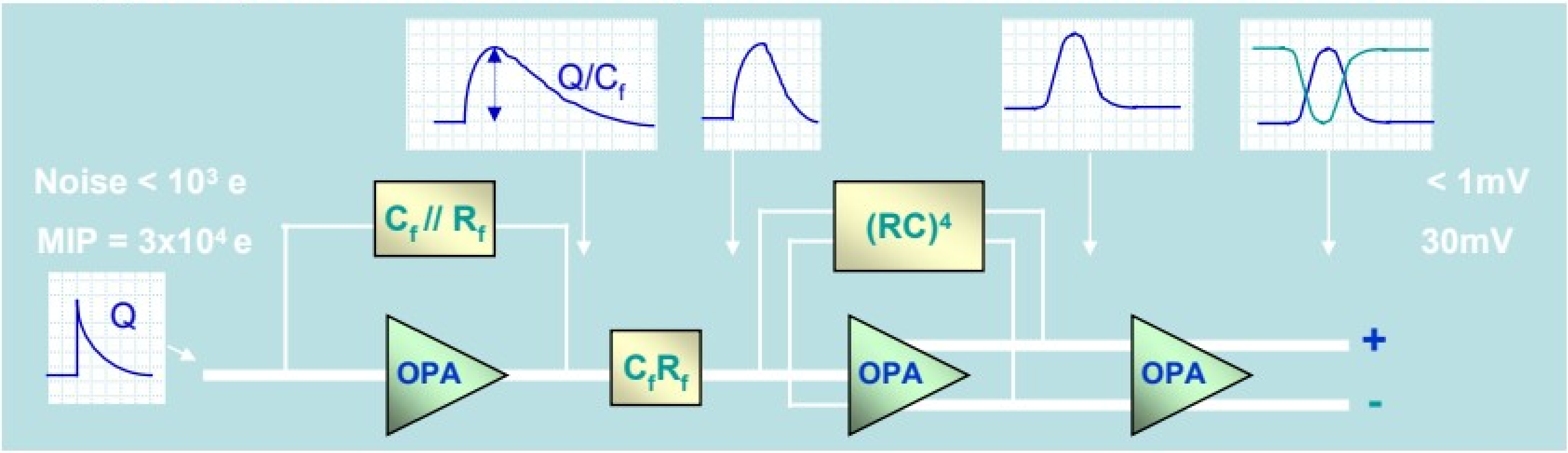
Old NA61:
Switch to discharge capacity
Standard: resistor (Alice)

Old NA61:
SCA

- Very small signals (fC) -> need amplification
- Measurement of amplitude and/or time (ADCs, discris, TDCs)
- Several thousands to millions of channels

preamplifier/pulse-shaper chip

PRE-AMPLIFIER SHAPING AMPLIFIER (PASA) MAIN FEATURES



16-ch Amplifier / Shaper (PASA)

CMOS 0.35 µm (AMS)

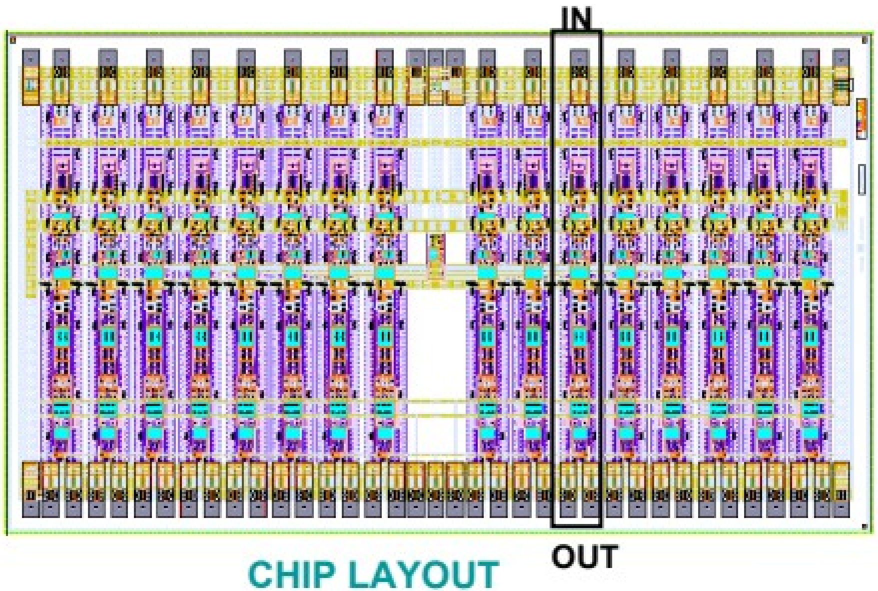
Area: 16.7 mm^2

Power: 12 mW / ch

Gain: 12mV / fC

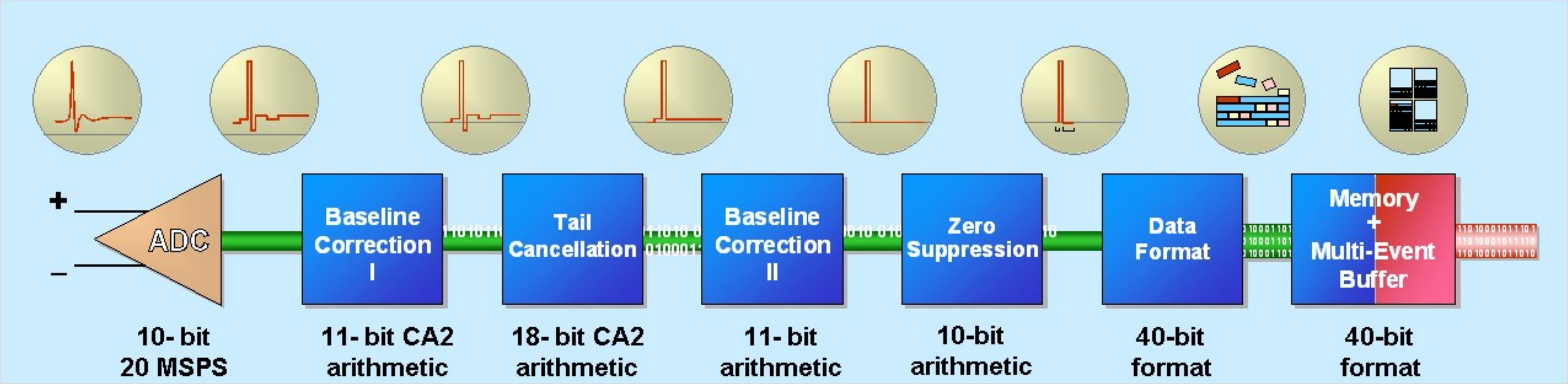
Noise: 400 e

Crosstalk:< 0.4%



CHIP LAYOUT

ADC/Filter Chip (ALTRO ALice Tpc ReadOut)

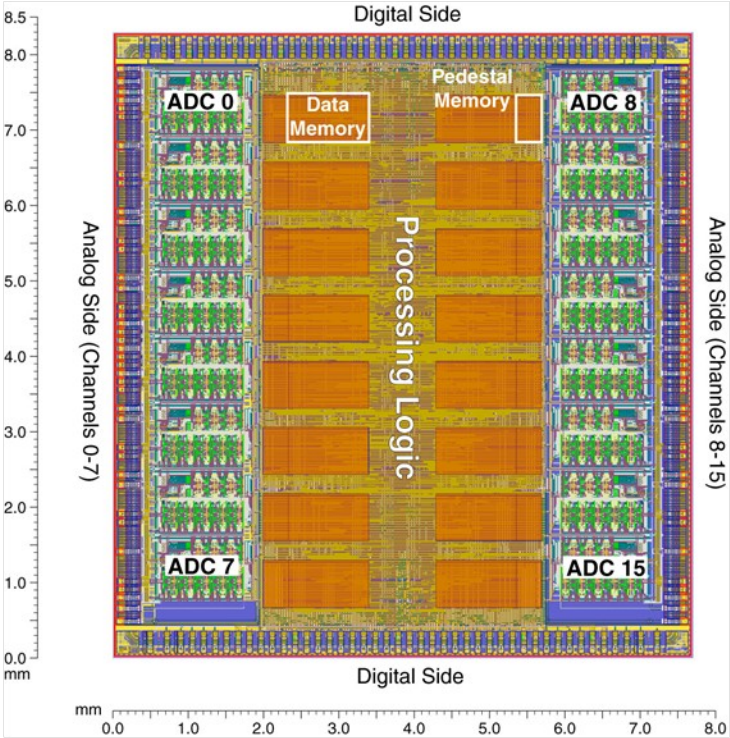


🟦 MAX SAMPLING CLOCK 40 MHz

🟩 MAX READOUT CLOCK 60 MHz

16-ch signal digitizer and processor

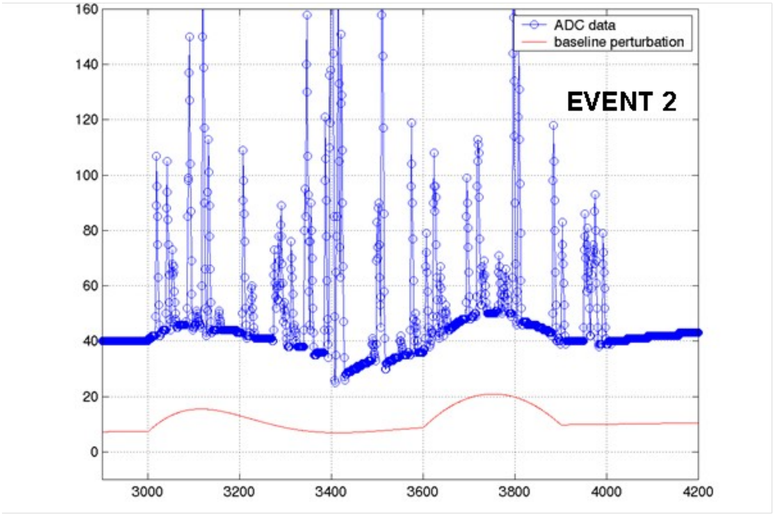
- HCMOS7 0.25 μm (ST)
- area: 64 mm^2
- power: 16 mW / ch
- prototype delivery: Feb ‘02
- 300 samples fully tested
- delivery of $4x10^4$ chips: Dec ‘02



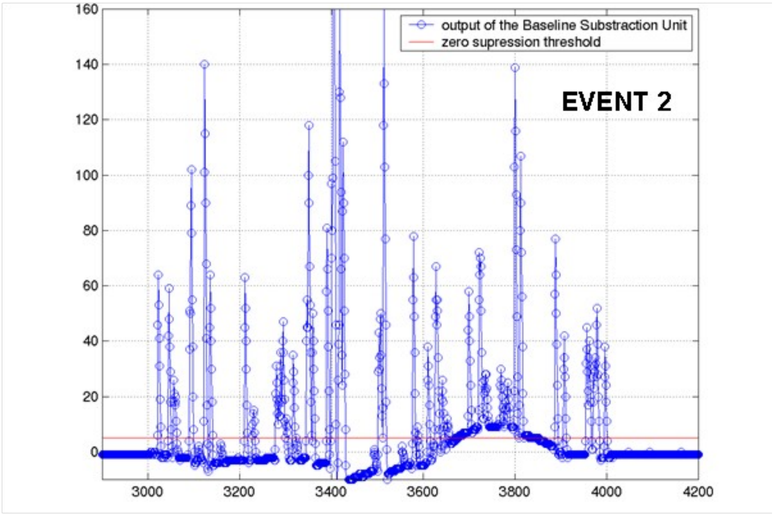
Filtering in the ALTRO chip

FRONT-END SIGNAL PROCESSING

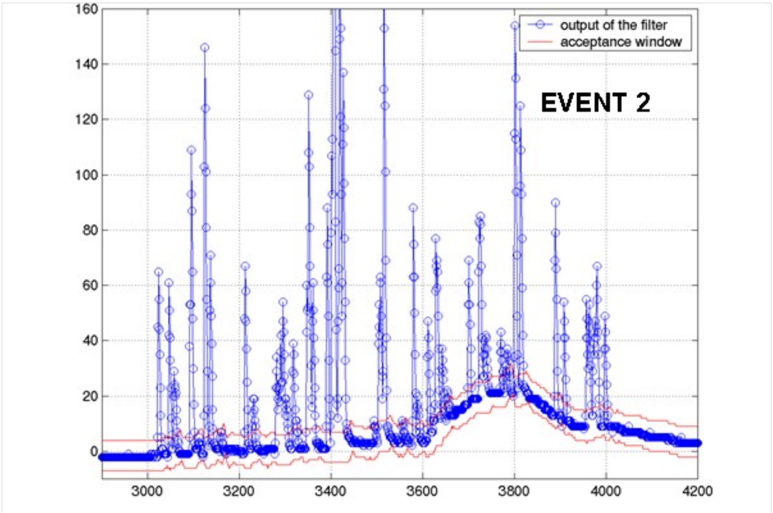
INPUT SIGNAL



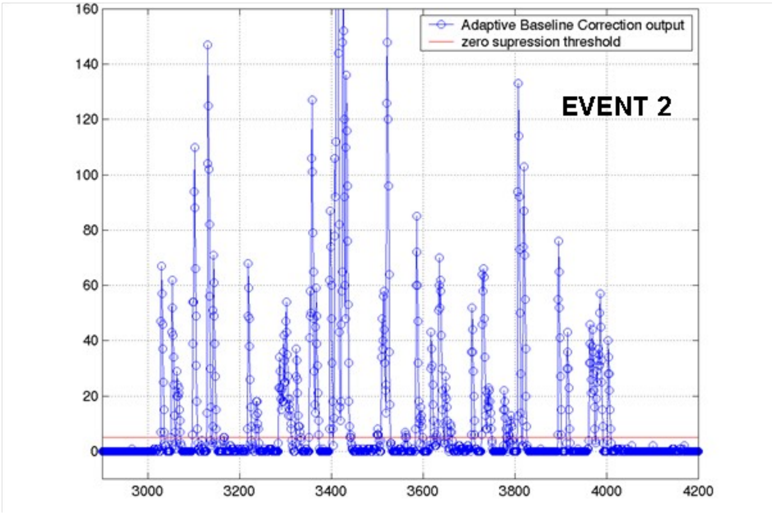
AFTER 1st BASELINE CORRECTION



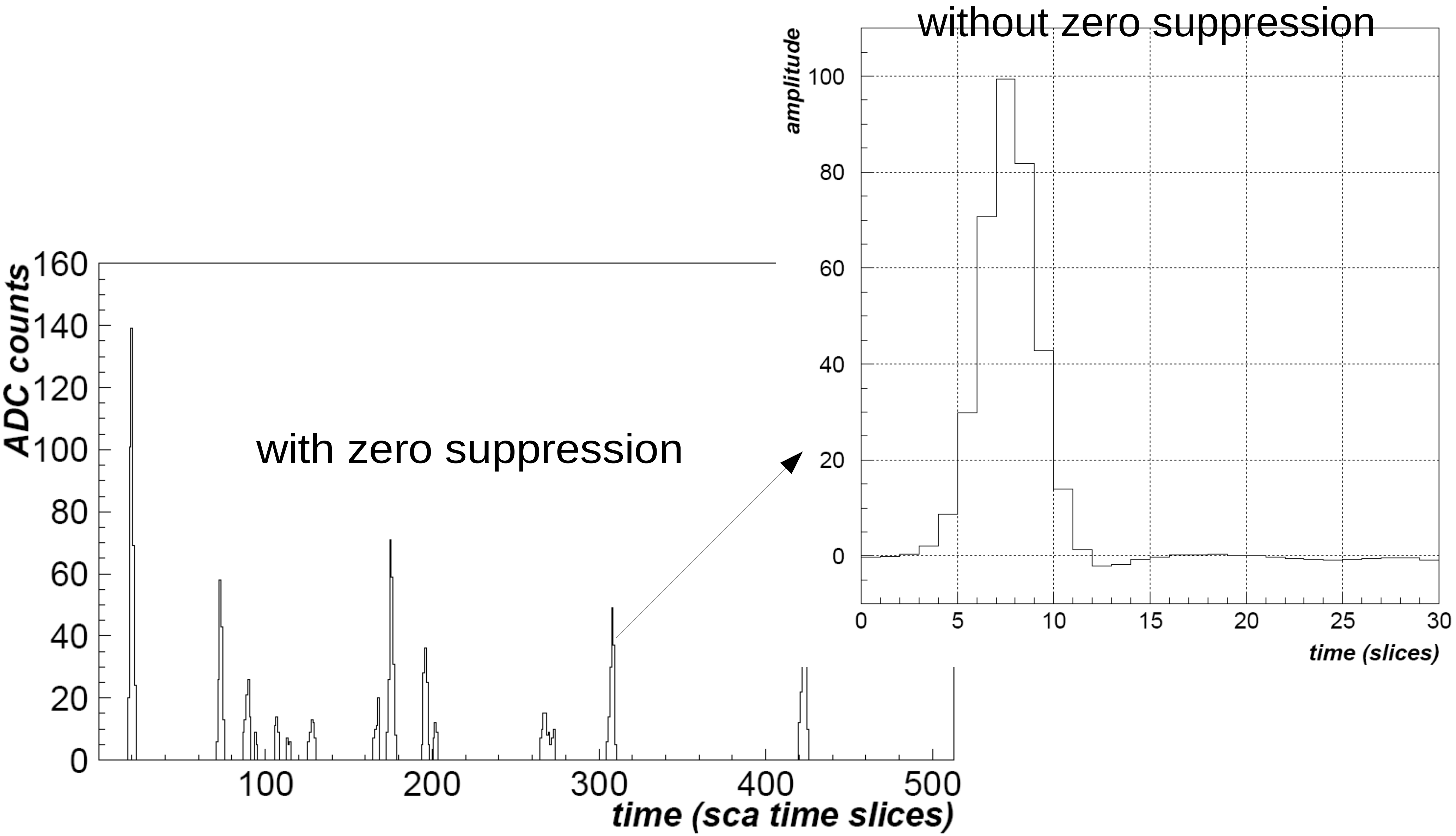
AFTER TAIL CANCELLATION



AFTER 2nd BASELINE CORRECTION



Digitized signal of one pad

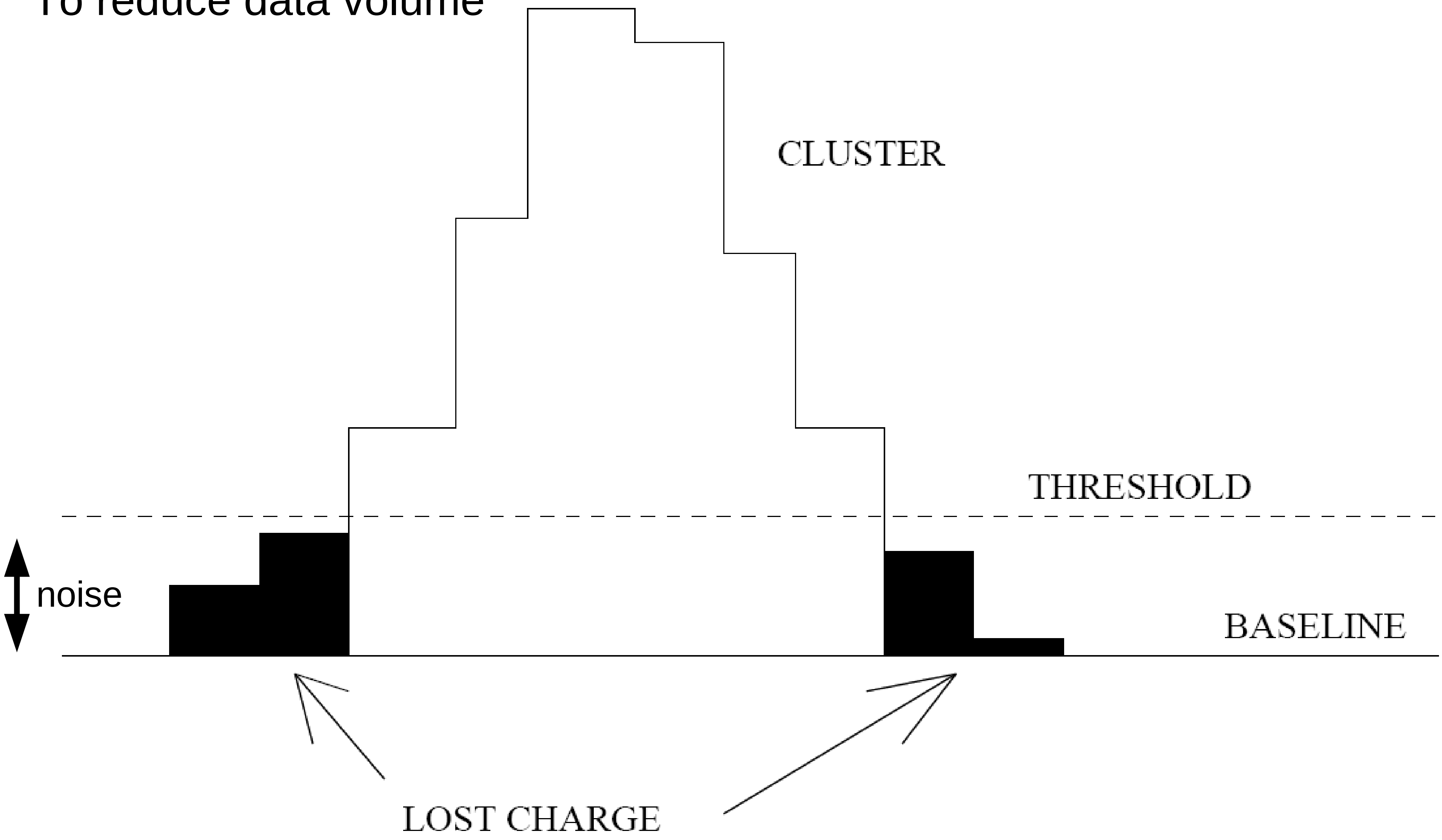


without zero suppression

with zero suppression

Threshold effect

To reduce data volume

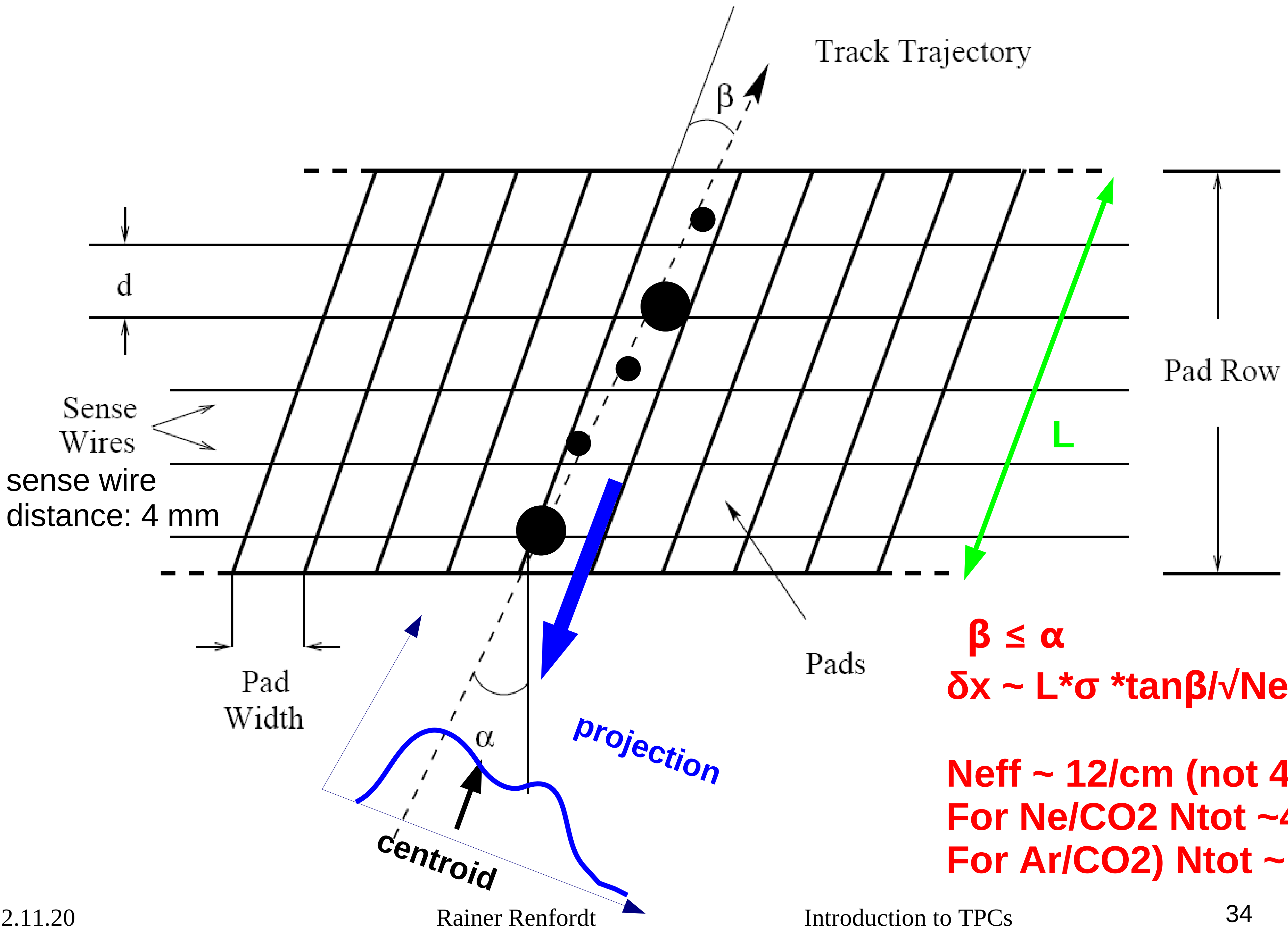


Important for dE/dx resolution → explained later

Resolution issues: position resolution

Important for momentum (vector) determination: - curvature in magnetic field
- emission angle

Effect of track angle



$\beta \le \alpha$

$\delta x \sim L*\sigma *\tan\beta/\sqrt{N_{eff}}$

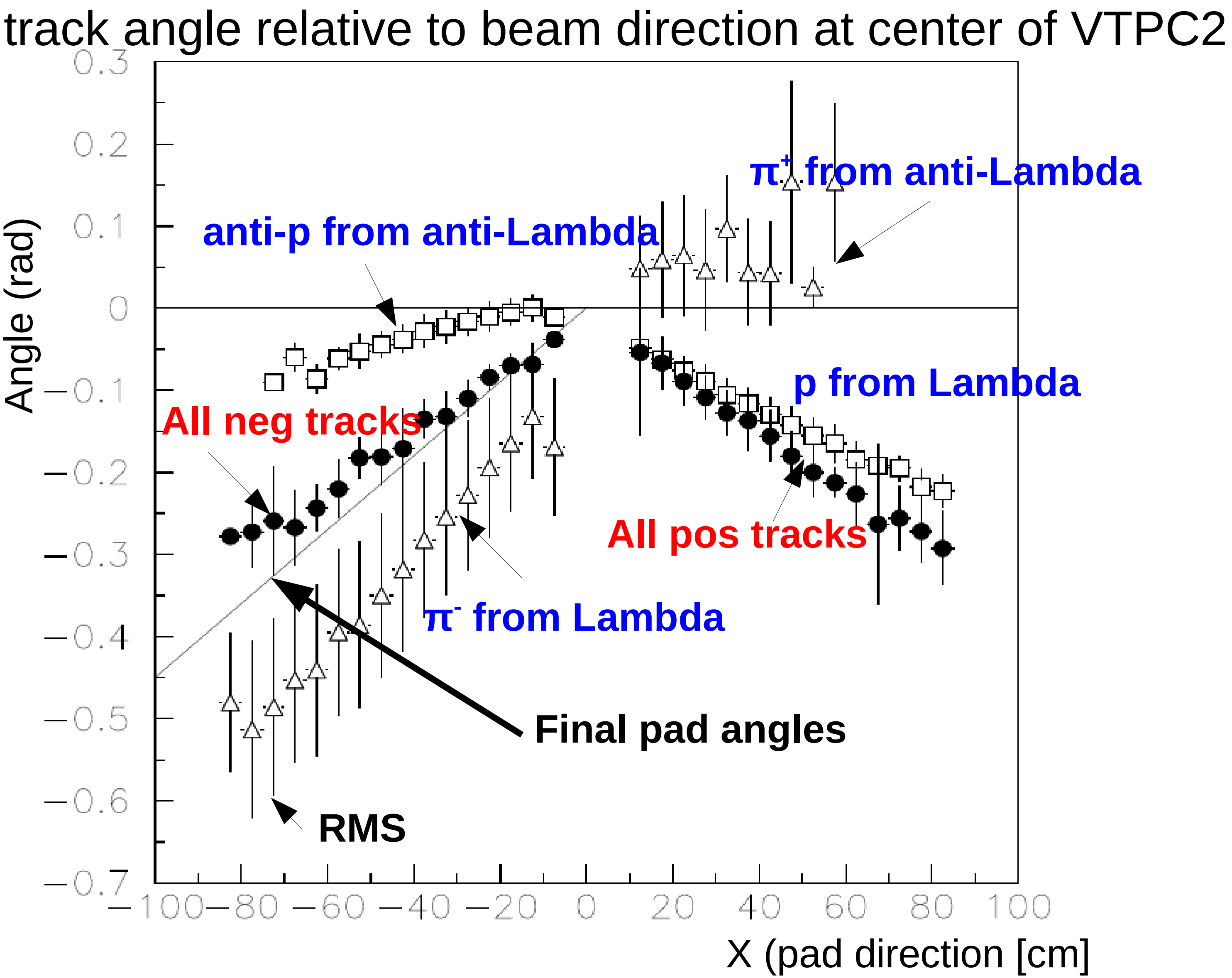
N_{eff} ~ 12/cm (not 40 !!)

For Ne/CO_2 N_{tot} ~45

For Ar/CO_2) N_{tot} ~100

Optimization of pad angles: should be as parallel as possible to track direction

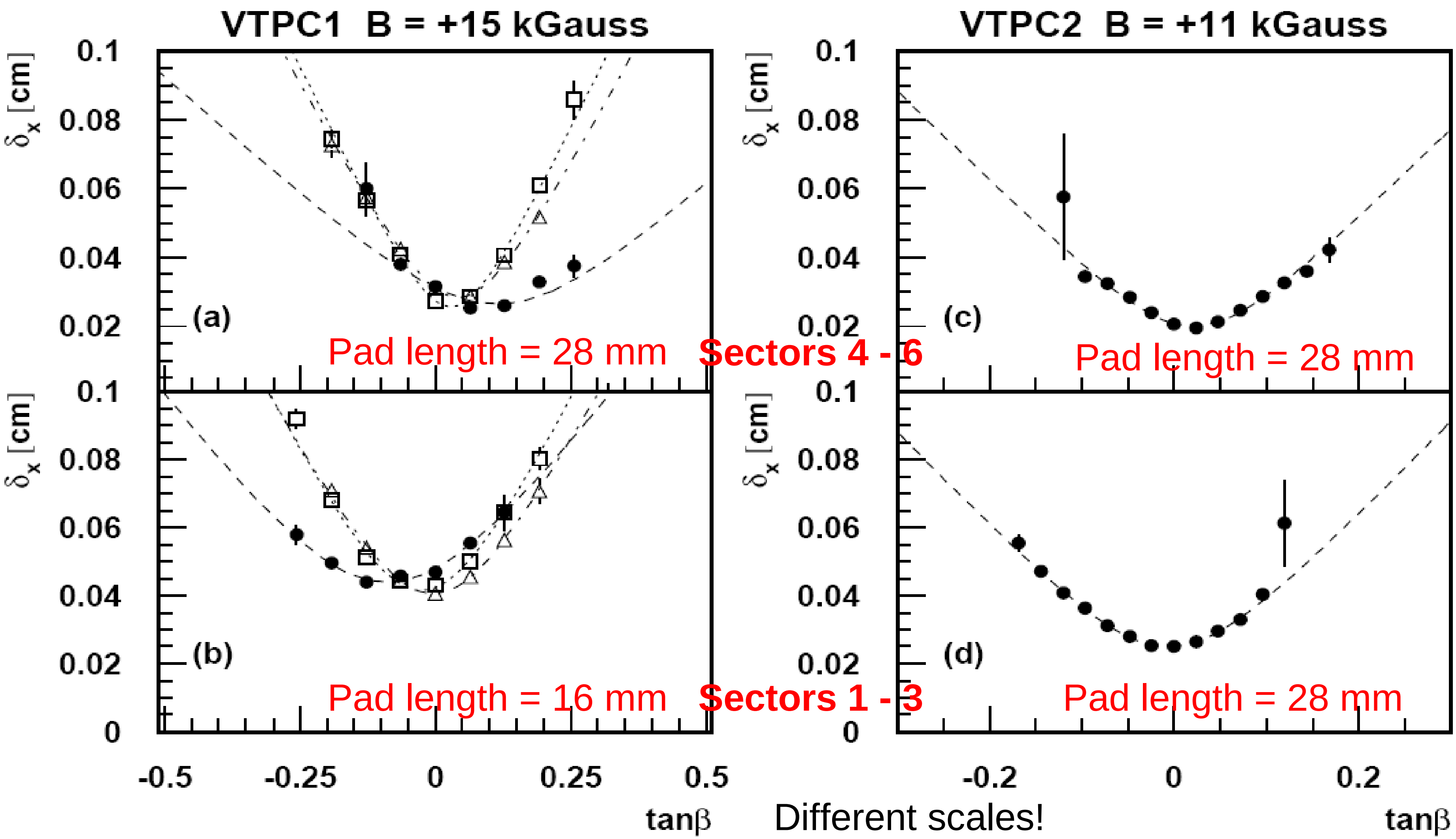
(Indico: https://edms.cern.c(in inh/file/812079/1/pad_geo_vtpc2.pdf)



The finally chosen angles of the pads are a compromise!

Position resolution as function of track angle

From Joerg Guenther's thesis:
https://edms.cern.ch/file/815933/1/guenther.pdf



Pad length = 28 mm

Sectors 4 - 6

Pad length = 28 mm

Pad length = 16 mm

Sectors 1 - 3

Pad length = 28 mm

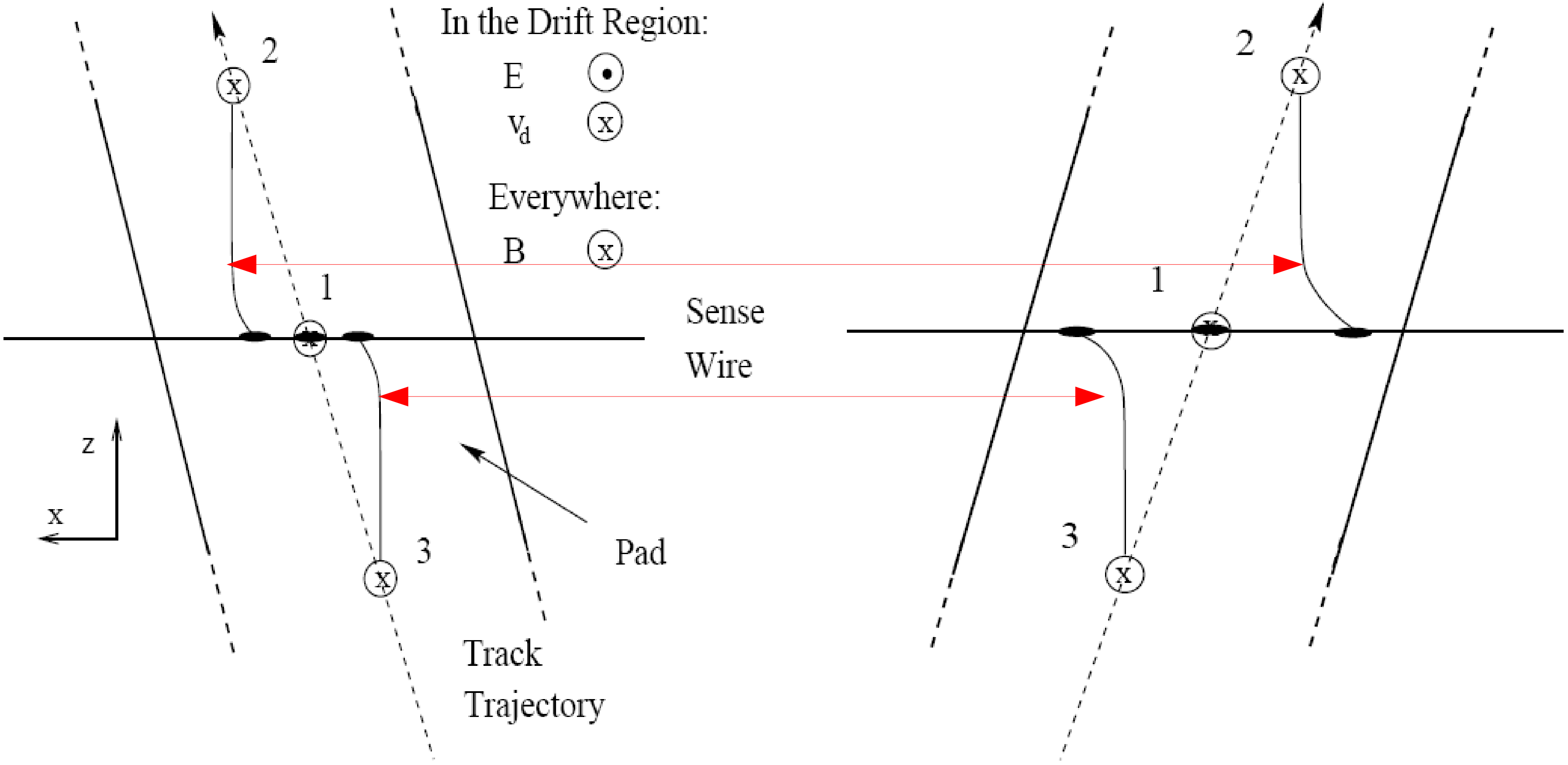
Different scales!

Look at full dots only!

β: crossing angle pad-track

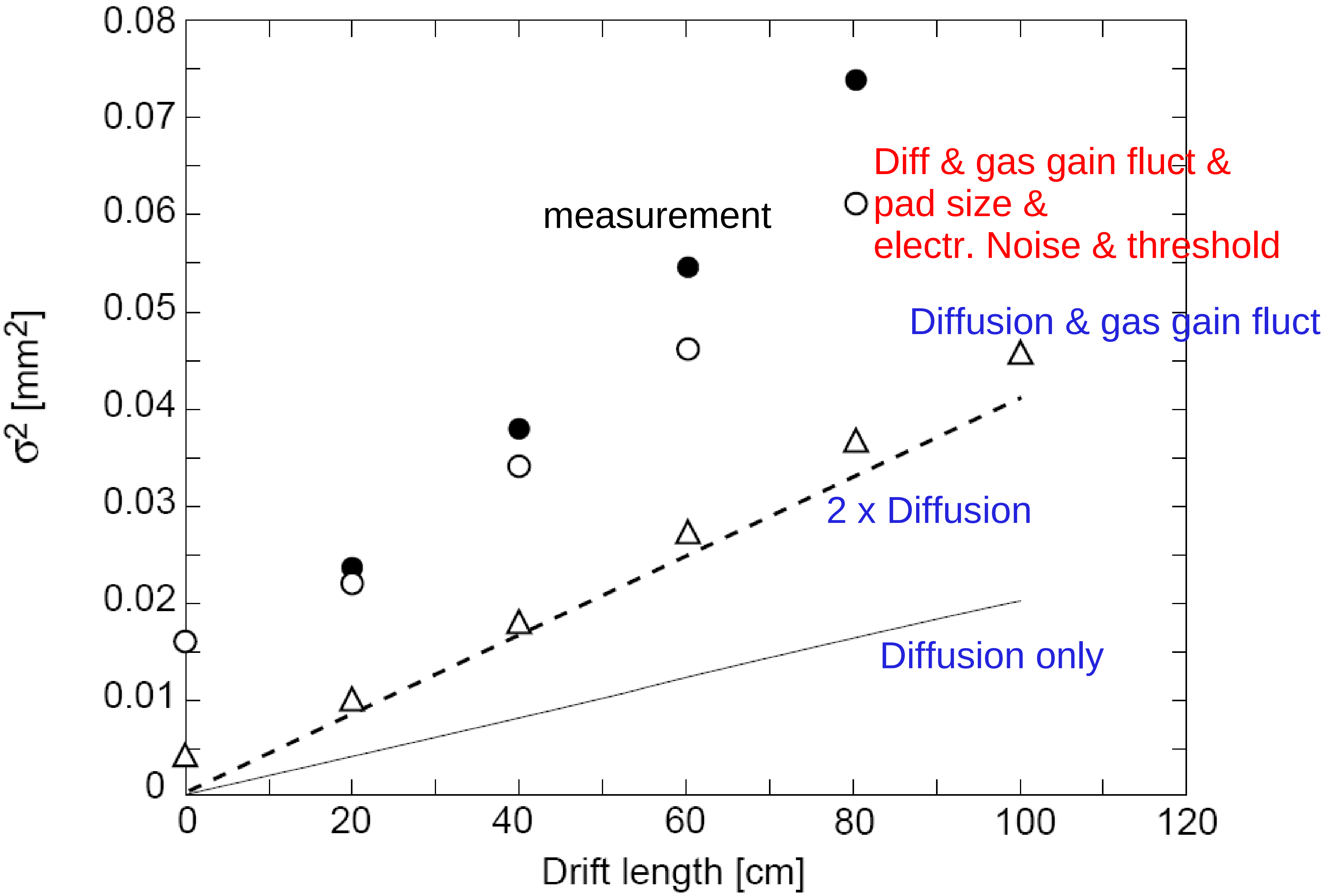
Effect of Lorentz angle at wire on cluster width and resolution

asymmetric relative to beam direction, i.e. positive and negative particles



Anode wire distance: 4 mm

Position resolution (pad direction) as function of drift length (MTPC)



Electronic gain calibration

Important for precise position determination: centroid calculation.

However, due to the fact that the spread of parameters is small within a chip (significantly larger from chip to chip and batch to batch) and in NA61 neighboring pads are connected to neighboring channels and there are 16 channels per chip there is a only a small improvement due to calibration.

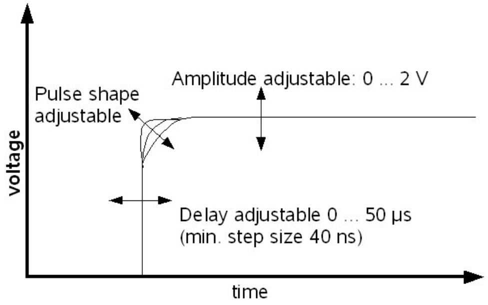
Not so important for dE/dx calibration: elementary observable has already large spread
(due to the Landau distribution of signal)
more important: systematic shifts due to mechanical tolerances leading to gas gain variations

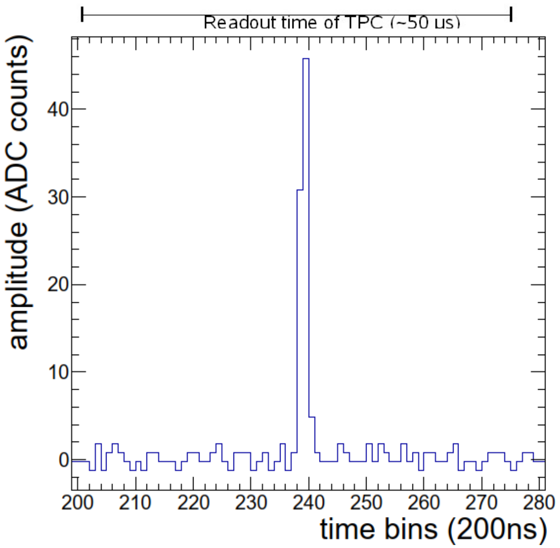
Calibration pulser

Even though the electronics gain calibration is not applied there is a **calibration pulser** in NA61.

A signal (fast rise time, flat top) is fed into the field wires (between the sense (anode) wires) of the multi-wire proportional chambers. This induces a narrow spike in the readout chain. The BNC cables to the sectors have to be of the same length for the time calibration.

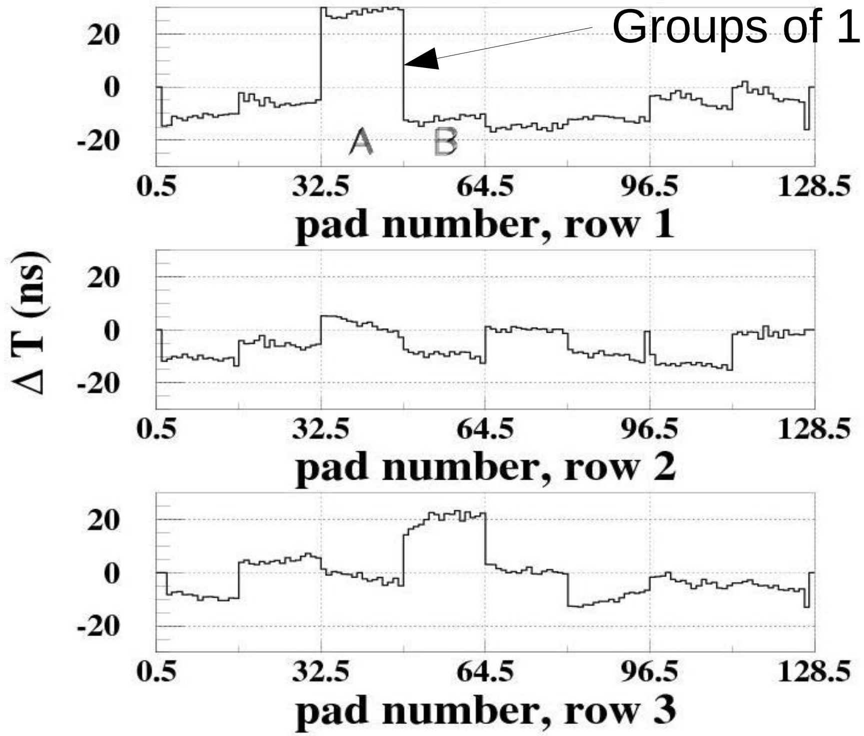
It's purpose is first **time calibration** and then **diagnostics**: find dead channels, dead chips (groups of 16 channels), problems of front-end-cards (128 channels), readout problems....





Time calibration

Time shifts due to:
- trigger cable length variations (large)
- shaping time variations: variations chip to chip (relatively small)



Groups of 16 channels from one chip

Figure 6: Time calibration of individual channels for three padrows of MTPCL, sector 2 . The additive correction is relative to the mean of a TPC.

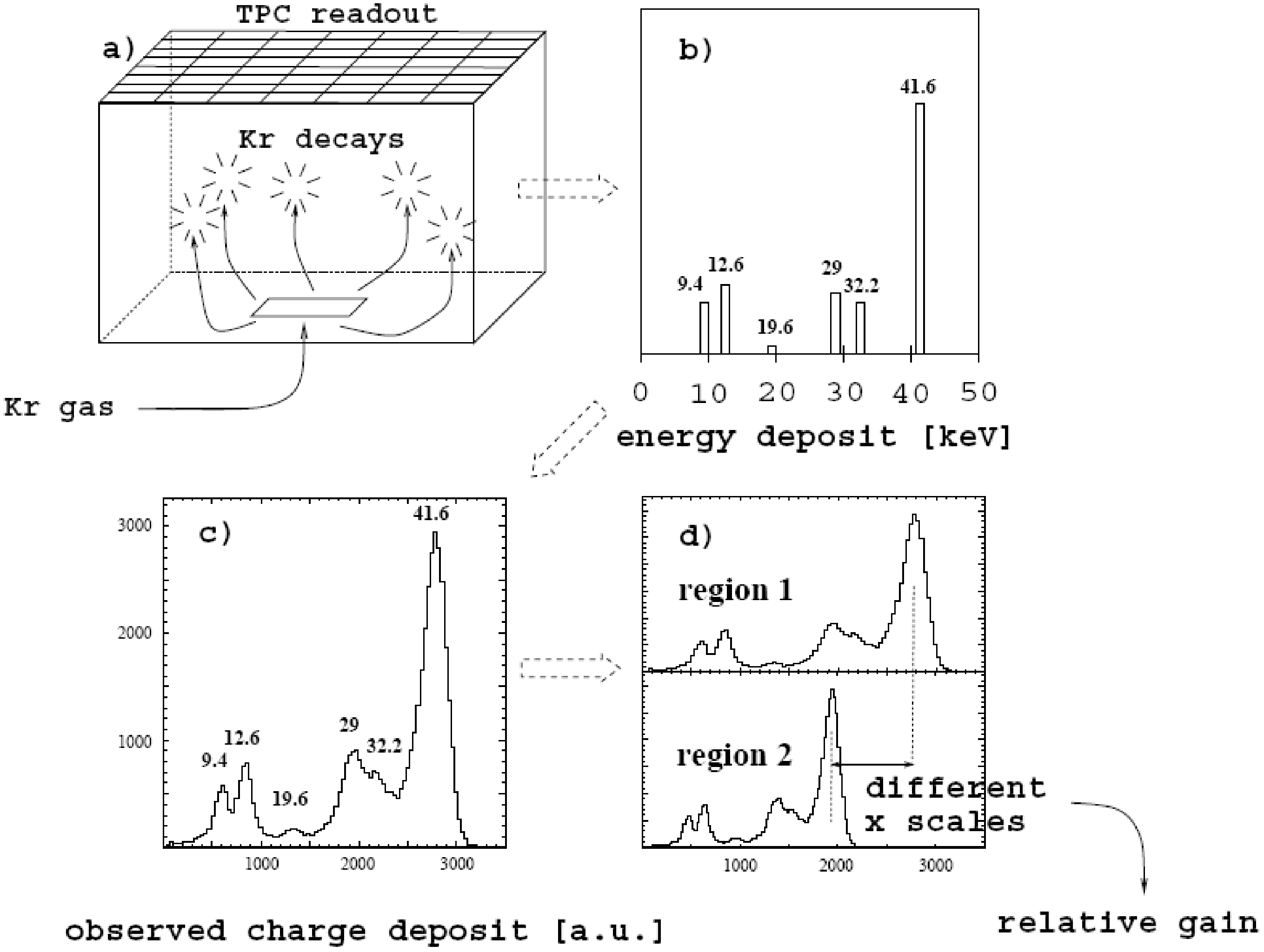
Full gain calibration

includes gas gain calibration

Krypton calibration

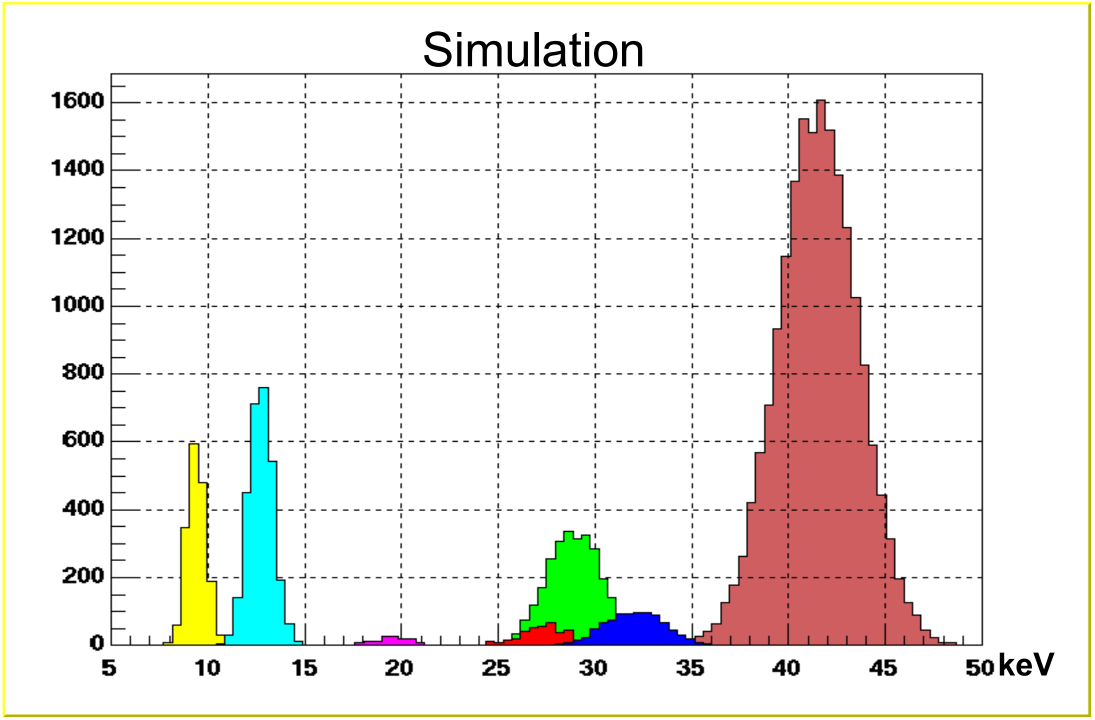
(the only gain calibration in NA61)

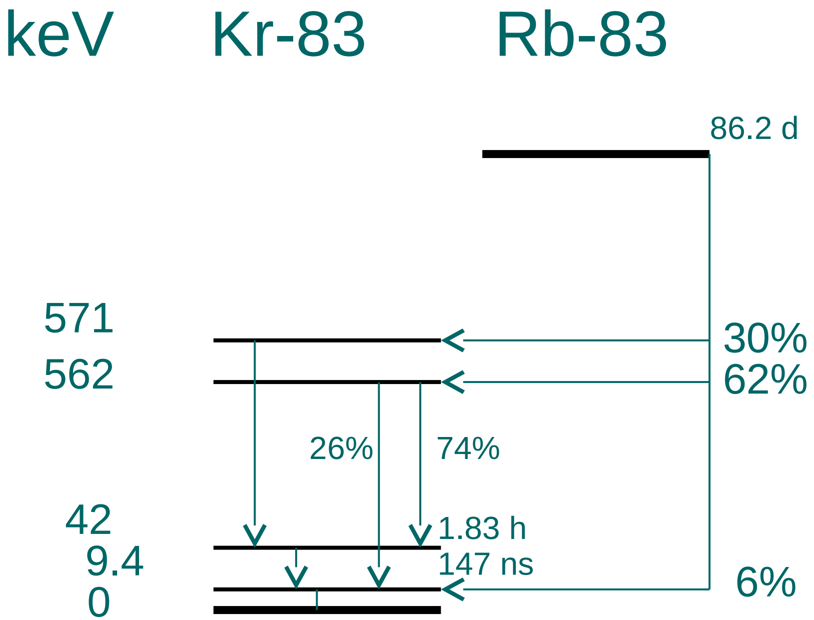
advantage: takes also gas gain variations into account due to mechanical variations across chamber surface



Slide
From Danilo Vranic

Response Simulation

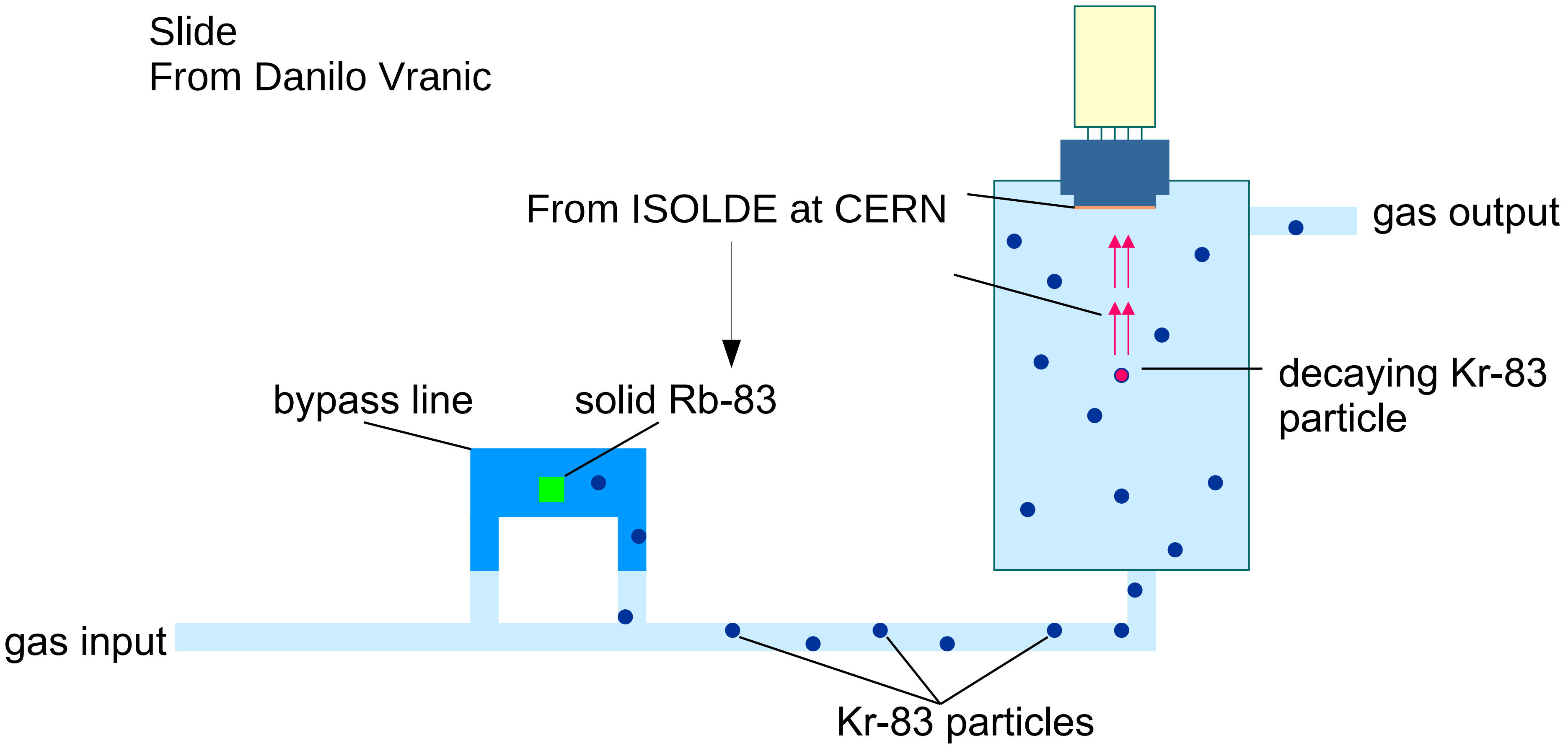




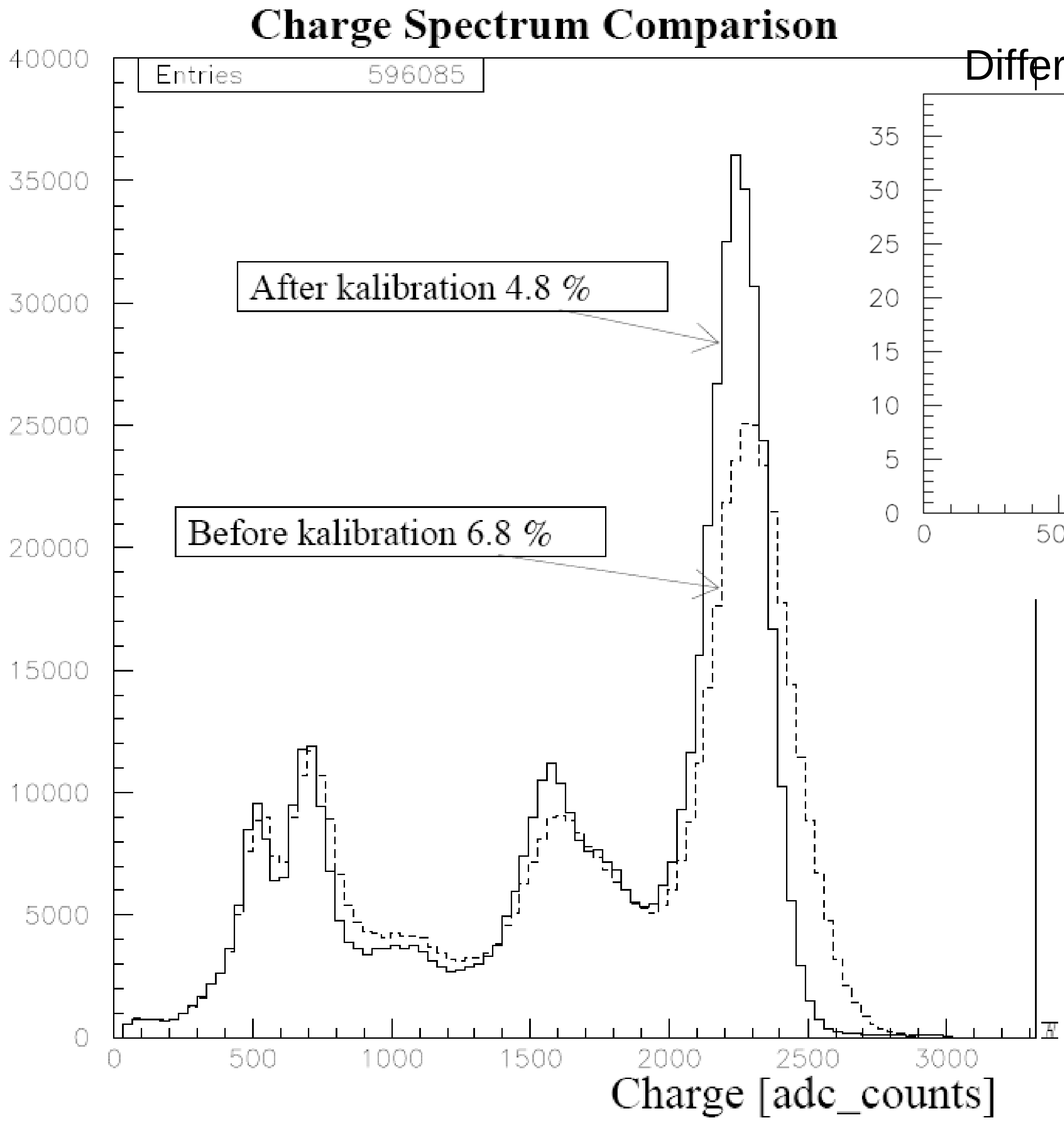
- Isomeric 41.5 keV level decays entirely to the 9.4 keV level by IC
- In addition, Auger electrons and X-rays are produced

Setup

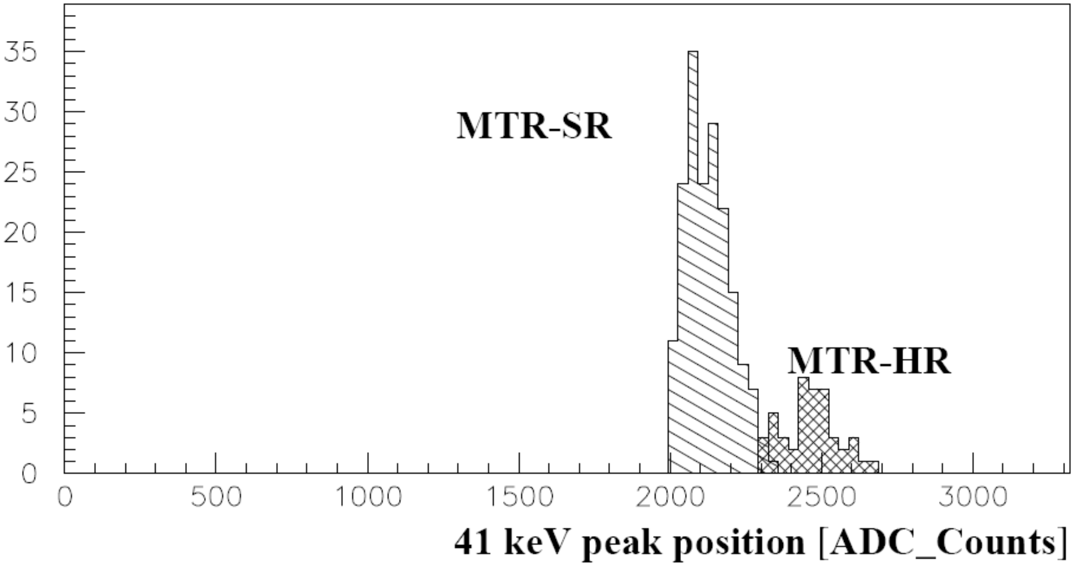
Slide
From Danilo Vranic



With and without calibration:

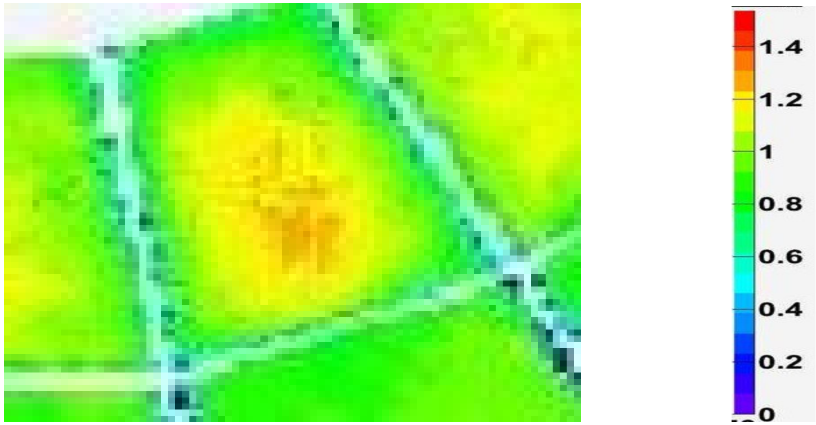


Difference between sector types of MTPC



Example for gain variation across the chamber surface

(this is from ALICE, I don't have an equivalent plot from NA49/NA61)



Needed for Krypton calibration:

^{83}Rb from ISOLDE, some Mbq (5 Mbq is the limit set by CERN safety)

and: lots of analysis work .....

As of today:

Kr calibration data taken with high statistics.

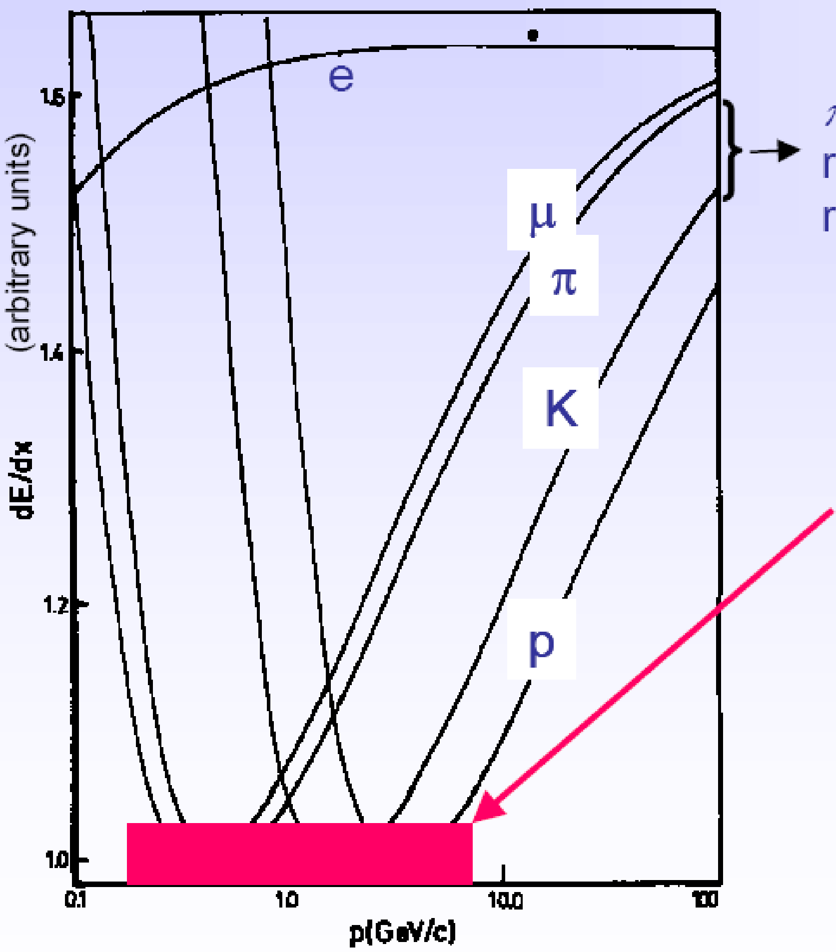
This allows gain calibration < 1% per pad!

Particle identification by dE/dx

Particle ID through dE/dx

$$\left.\begin{aligned} p &= m_0 \beta\gamma c \\ \frac{dE}{dx} &\propto \frac{1}{\beta^2}\ln\left(\beta^2\gamma^2\right) \end{aligned}\right\}$$

Simultaneous measurement of *p* and *dE/dx* defines mass m_0, hence the particle identity



π/K separation (2σ) requires a *dE/dx* resolution of < 5%

Not so easy to achive !

- dE/dx is very similar for minimum ionising particles.
- Energy loss fluctuates and shows Landau tails.

Average energy loss for e, μ, π, K, p in 80/20 Ar/CH_4 (NTP)
(J.N. Marx, Physics today, Oct.78)

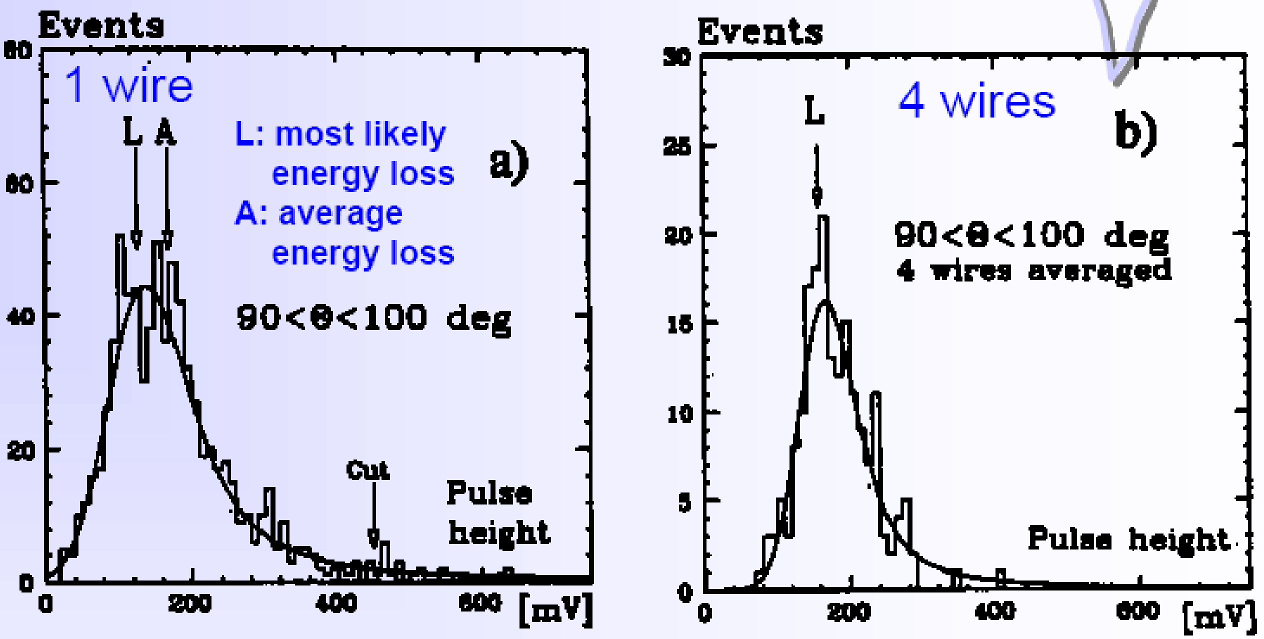
Particle ID through dE/dx

How to reduce fluctuations ?

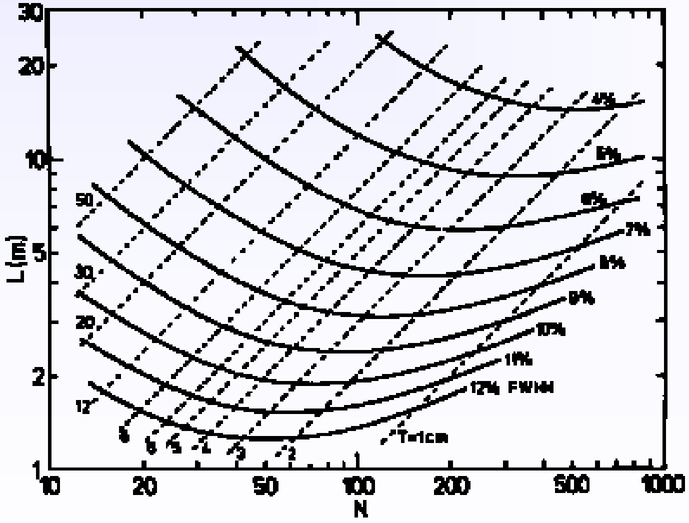
- subdivide track in several dE/dx samples
- calculate truncated mean, i.e. ignore samples with (e.g. 40%) highest values

- Also increased gas pressure can improve resolution (→ higher primary statistics), but it reduces the rel. rise due to density effect !

Don't cut the track into too many slices ! There is an optimum for a given track length L.

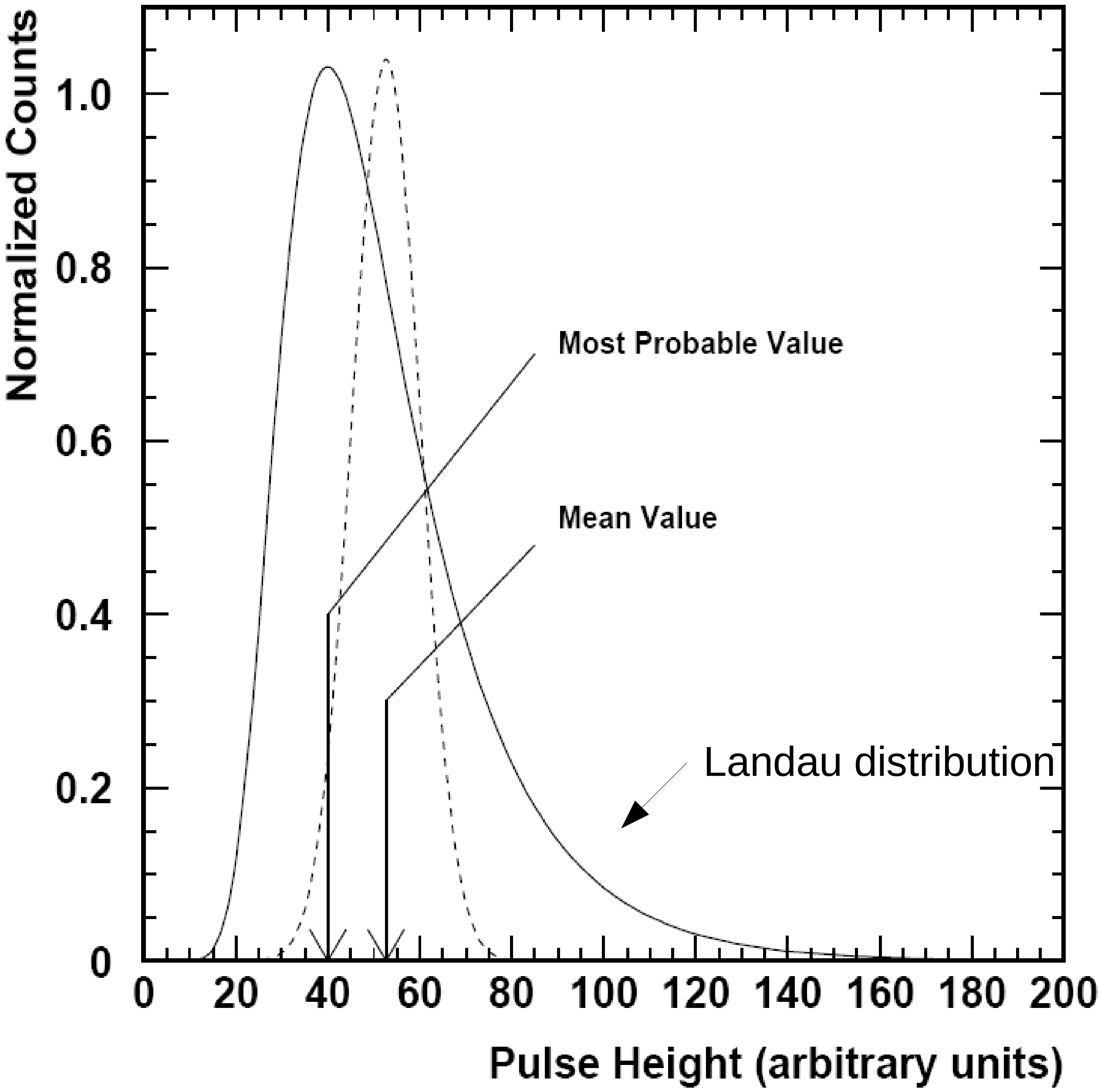


(B. Adeva et al., NIM A 290 (1990) 115)

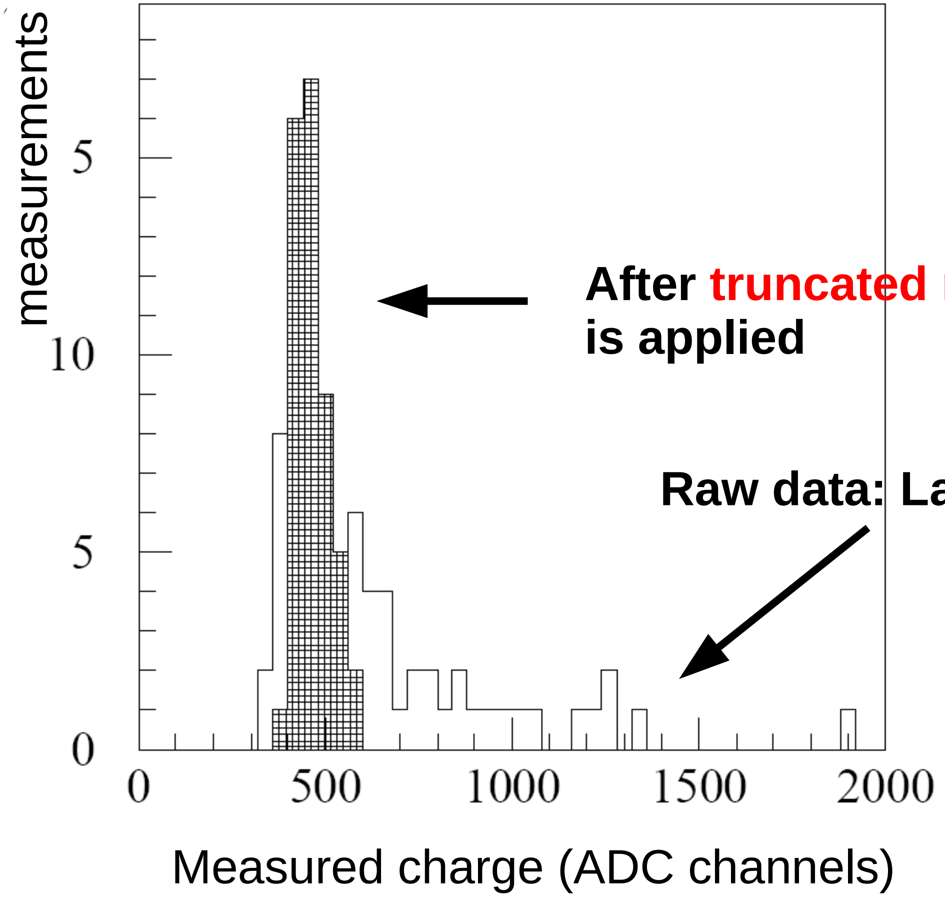


(M. Aderholz, NIM A 118 (1974), 419)

dE/dx signal amplitude distribution

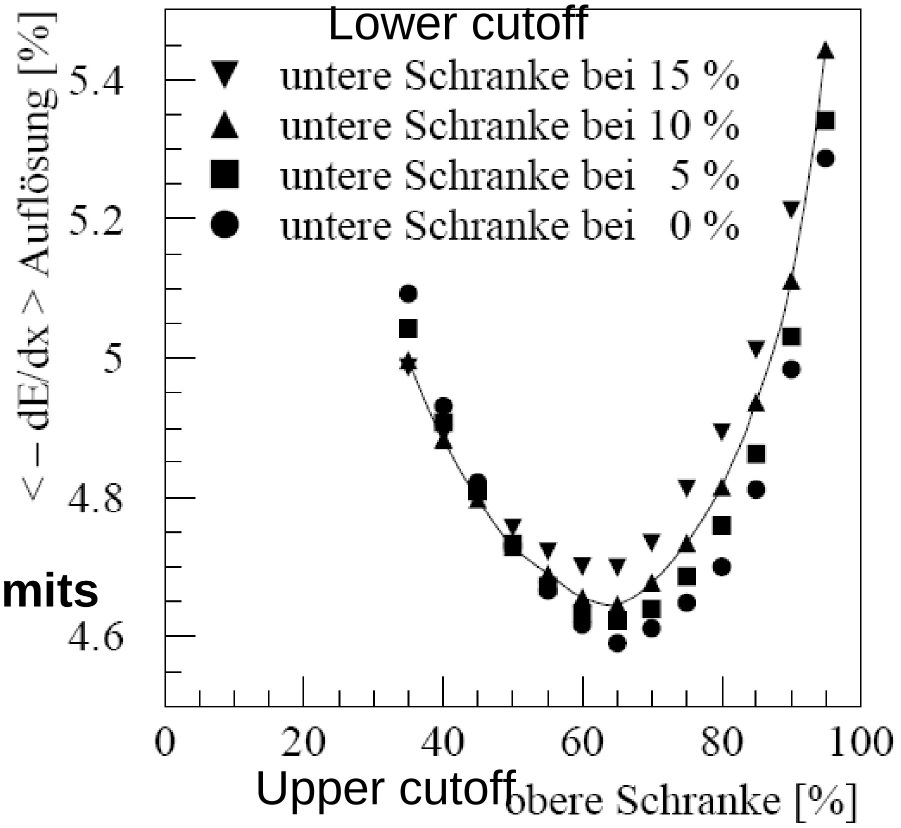


“Truncated mean” method



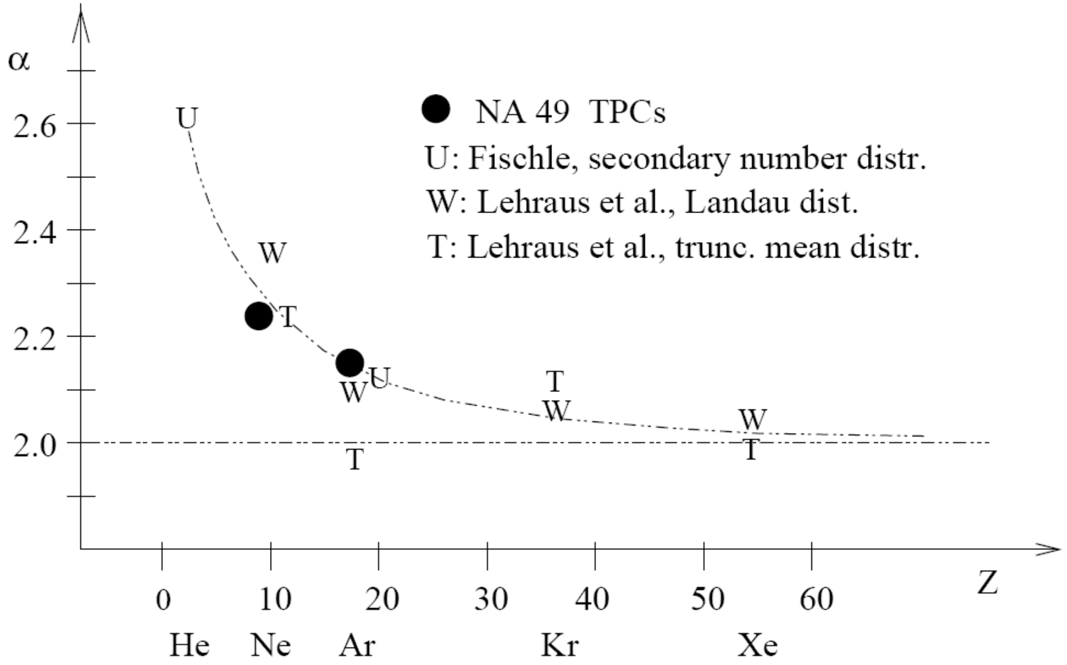
After truncated mean method is applied

Raw data: Landau distribution



Effect of different truncation limits

dE/dx resolution for different gases

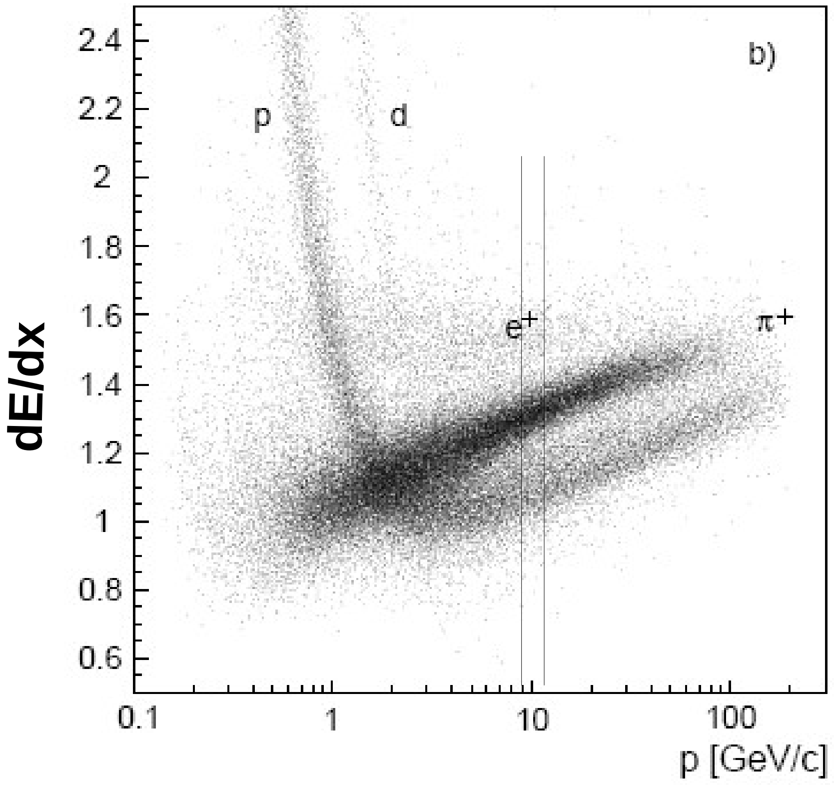


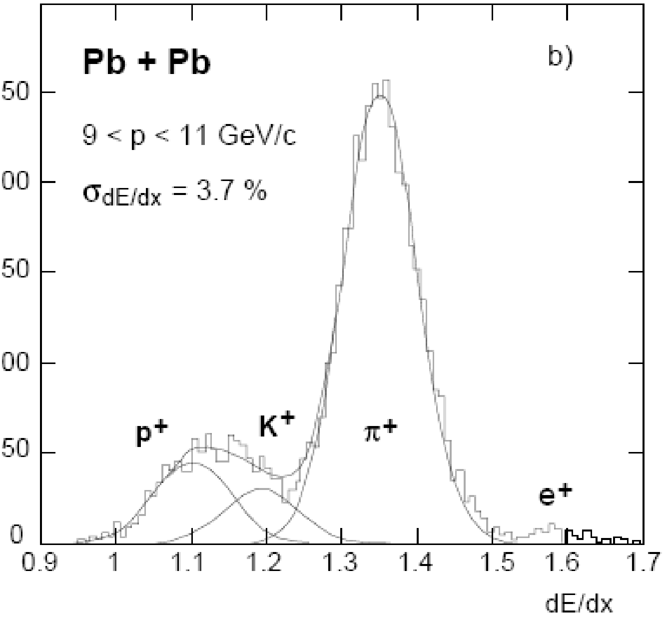
dN/E = $E^{-\alpha}$

α smaller for heavier gases **but** N overall larger for heavier gases --> compensating effect

dE/dx resolution about the same for Ne and Ar

From Pb + Pb interactions





For the extraction of particle yields:
Gauβ fits
one needs to know the exact form of the dE/dx curve (this parameter is kept fixed in minimization)

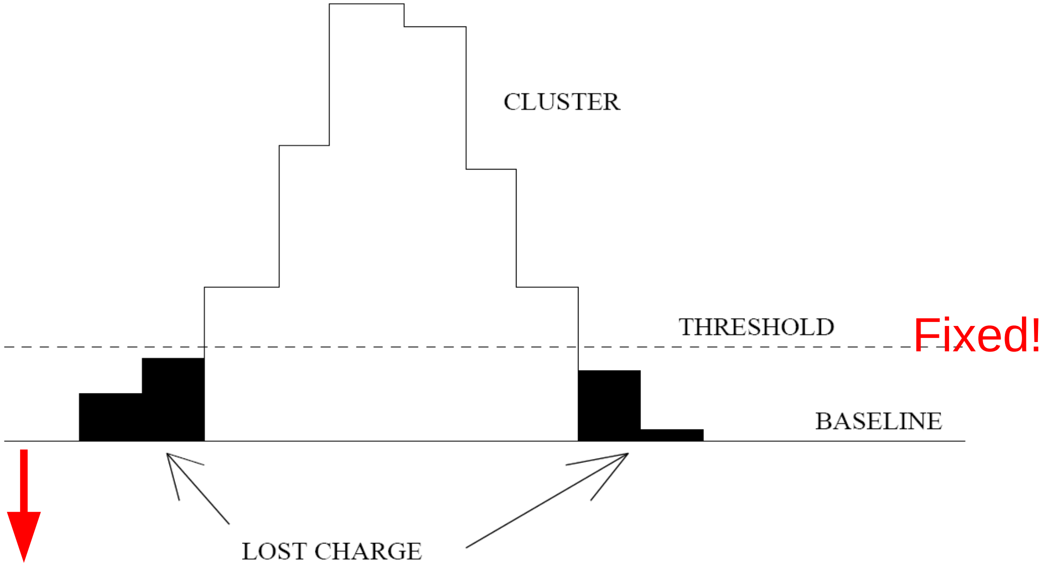
corrections

NA61 specific problems

dE/dx measured in different TPCs with different gas mixtures: relativistic rise different difficult to combine

Additional problem at high multiplicities, as in Pb-Pb at top SPS energy:

- Baseline shift
- Common mode effect



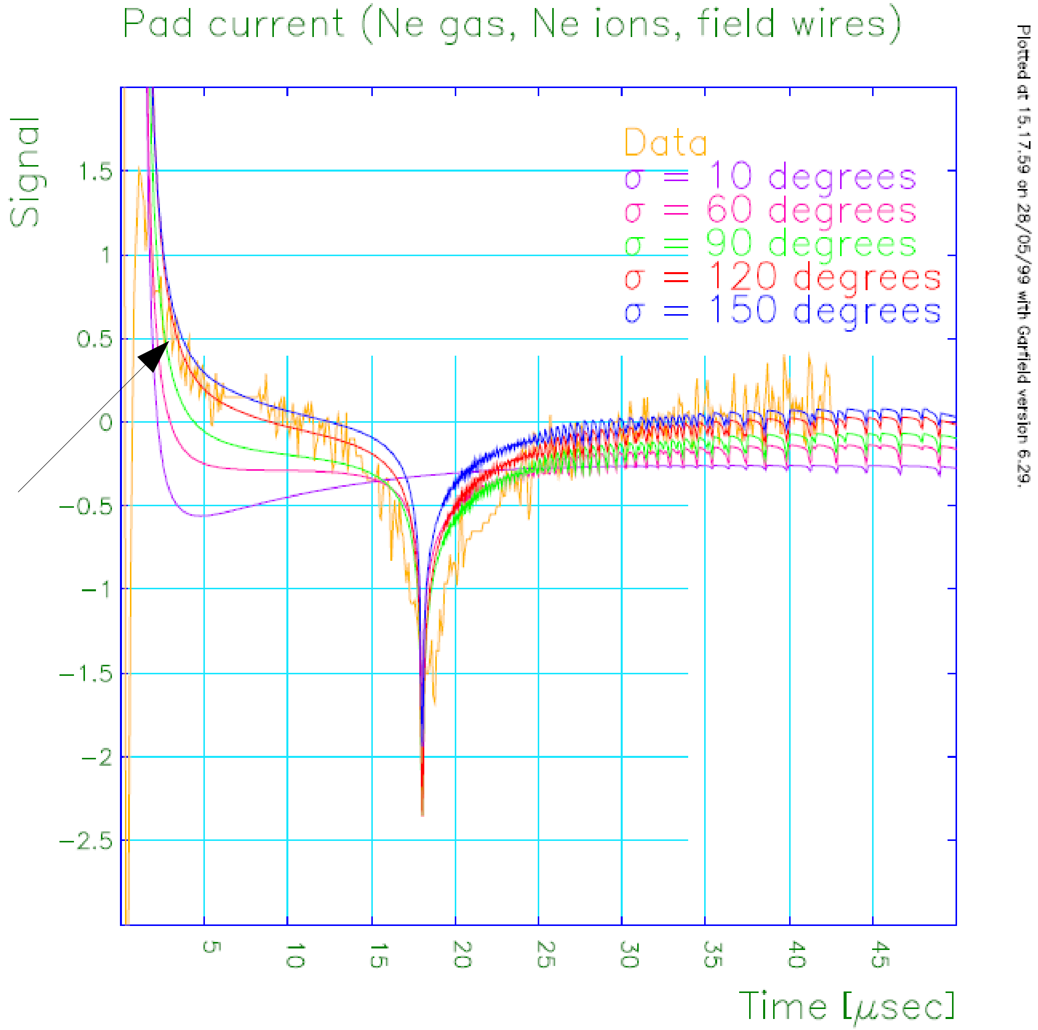
Fixed!

Baseline shift

Relevant for Pb-Pb collisions at the highest energies:
→ high track densities
→ systematic shifts of dE/dx as function of drift length

VTPC

NE/CO_2



NA49 laser signal

Simulation: Garfield,
Rob Veenhof

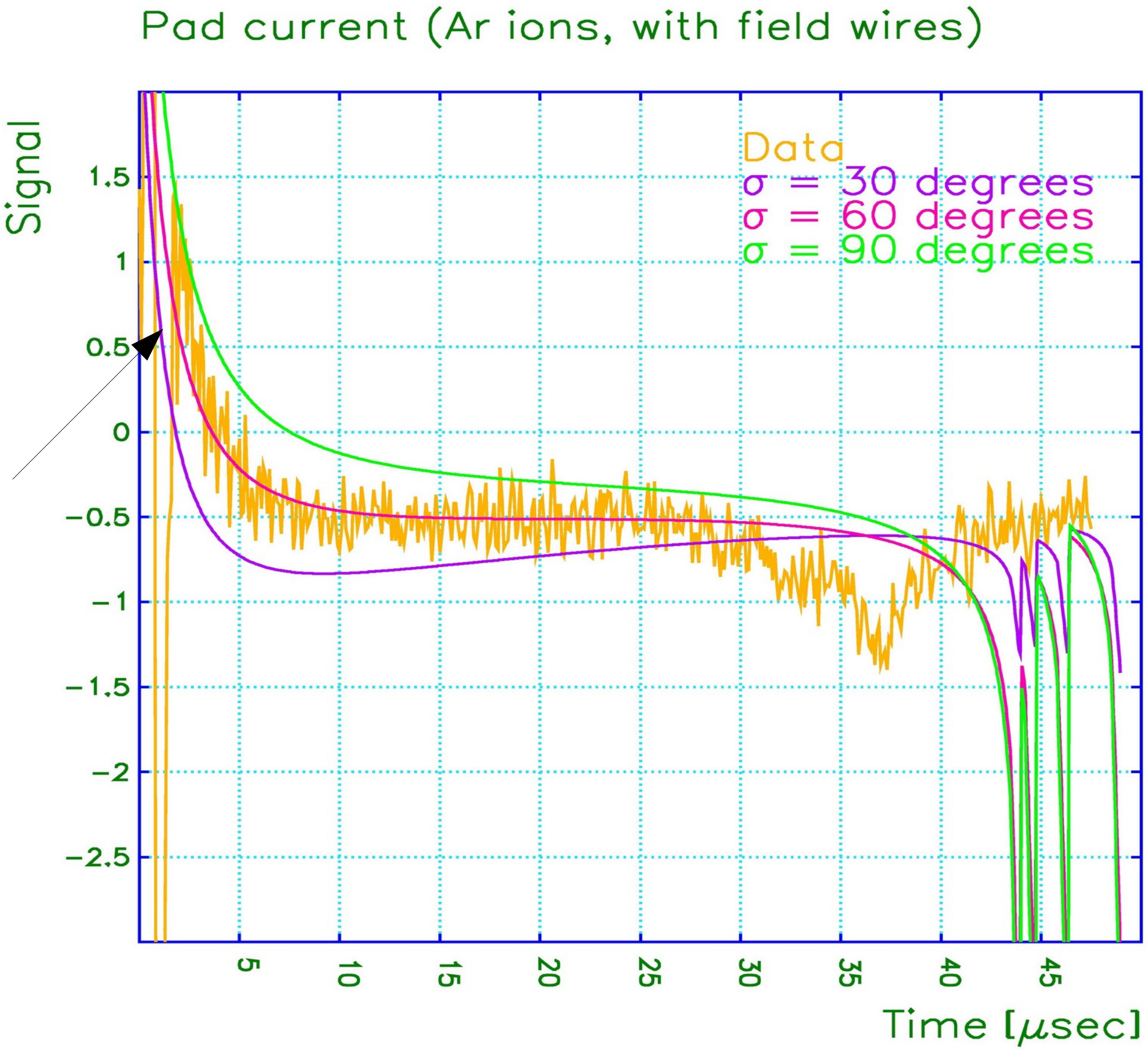
Figure 9: Comparison of observed baseline behaviour to simulation [9]. In the simulation it is assumed that Ne ions drift in Ne gas. Different assumptions are made about the extension of

Baseline shift

MTPC

(Ar/CO_2/CH_4)

NA49 laser signal



Simulation: Garfield, Rob Veenhof

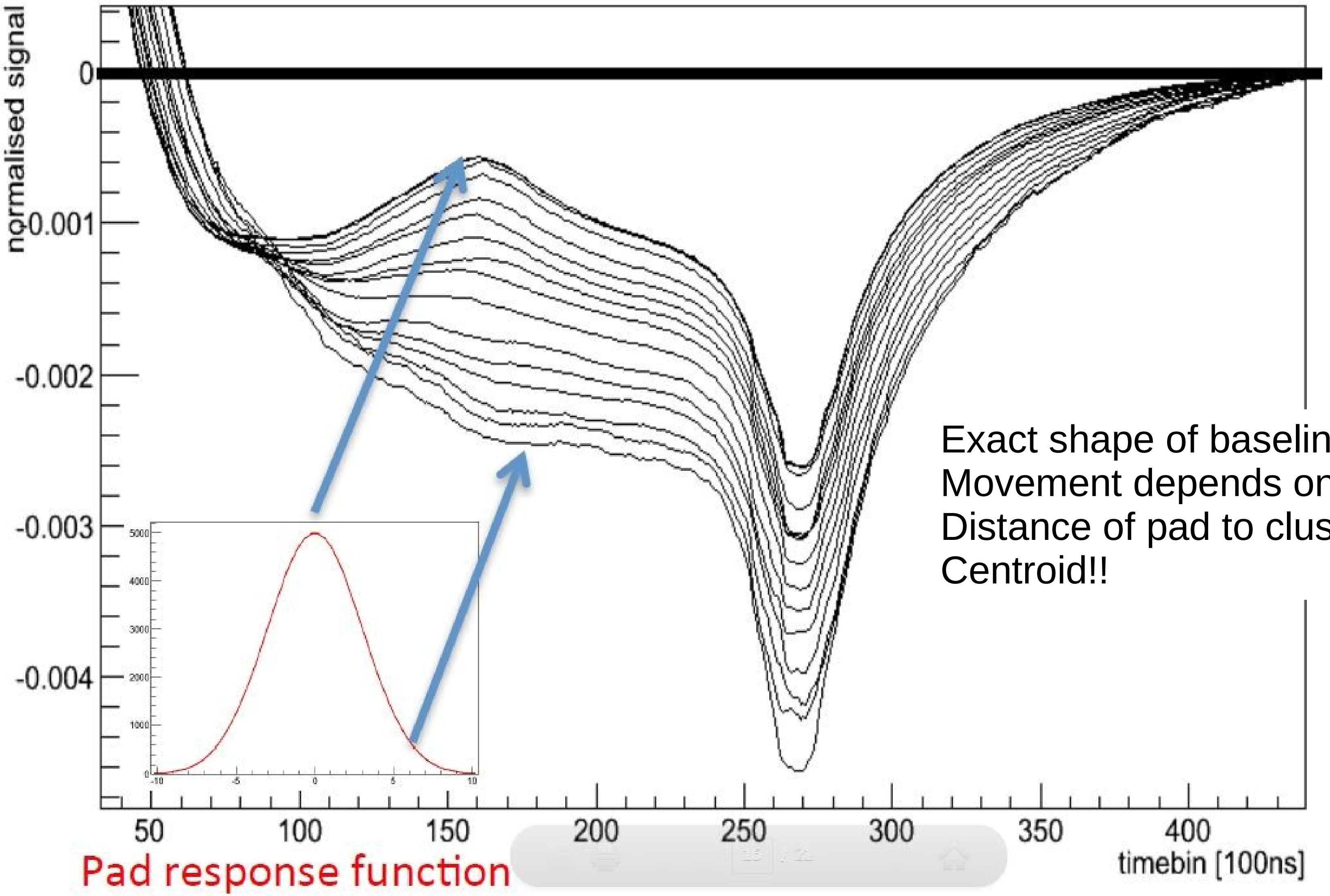
Drift velocity of ions not correct in simulation

Baseline shift

From Mesut Arslandok, Alice

Cluster ions in gas-based detectors
Y. Kalkan,[a,b,1] **M. Arslandok,**[c] **A.F.V. Cortez,**[d] **Y. Kaya,**[e] **˙I. Tapan**[a] **and R. Veenhof** [f,a]
2015 JINST 10 P07004

Alice: no field wires



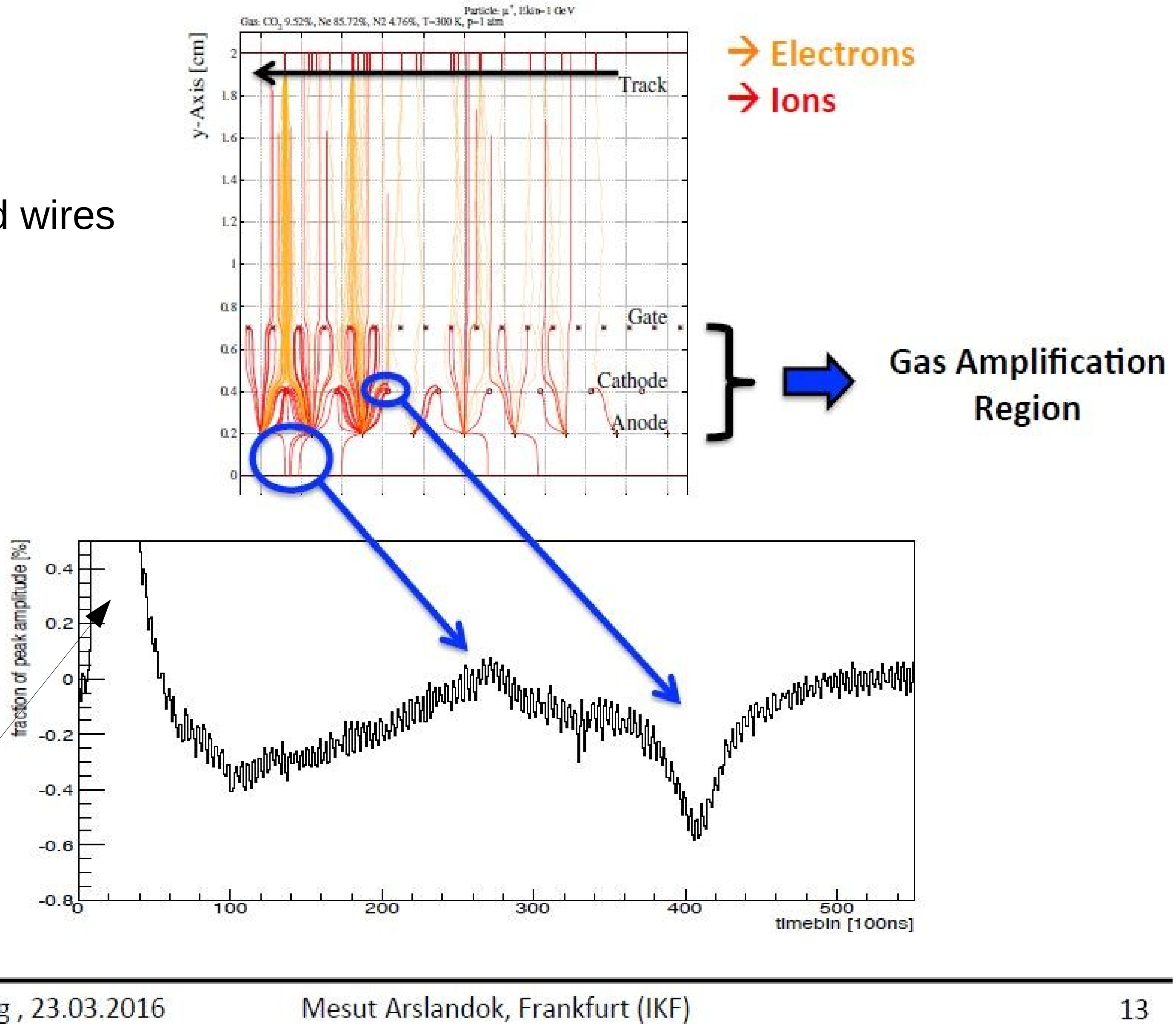
Pad response function

Exact shape of baseline
Movement depends on
Distance of pad to cluster
Centroid!!

From Mesut Arslandok, Alice

Baseline shift

Alice: no field wires



→ Electrons

→ Ions

Gas Amplification Region

TPC Weekly Meeting , 23.03.2016 Mesut Arslandok, Frankfurt (IKF) 13

Alice laser signal

Common mode effect

Common mode effect

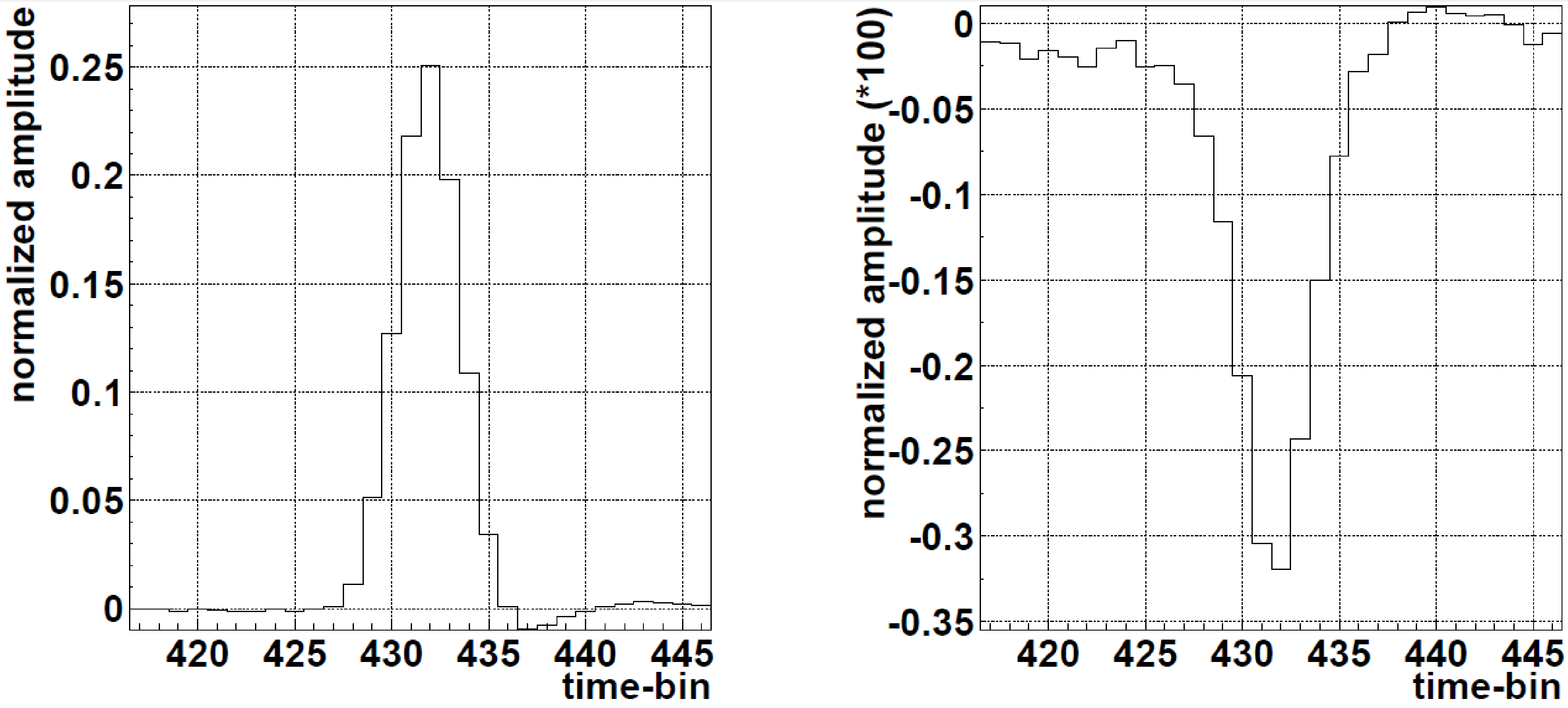
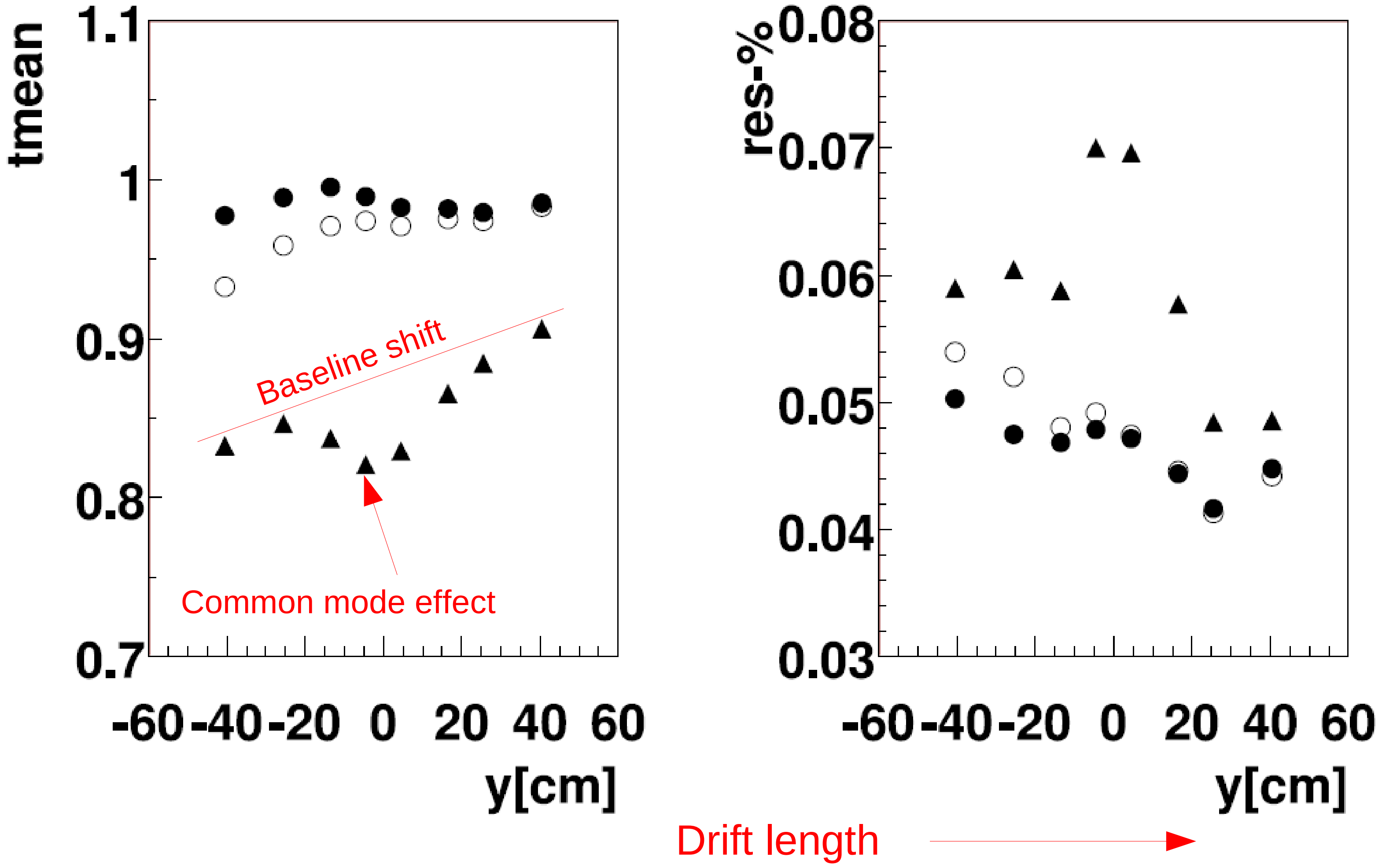


Figure 10: Left panel: Signal of a laser track crossing a randomly chasen padrow where the signals of the 6 contributing pads are summed and normalized to the integral charge. Right panel: signal on a single distant pad of the same padrow in the same time region using the same normalization (1 time bin = 100 ns).

Correction of baseline shift and Common mode effect in Pb-Pb



Baseline shift

Common mode effect

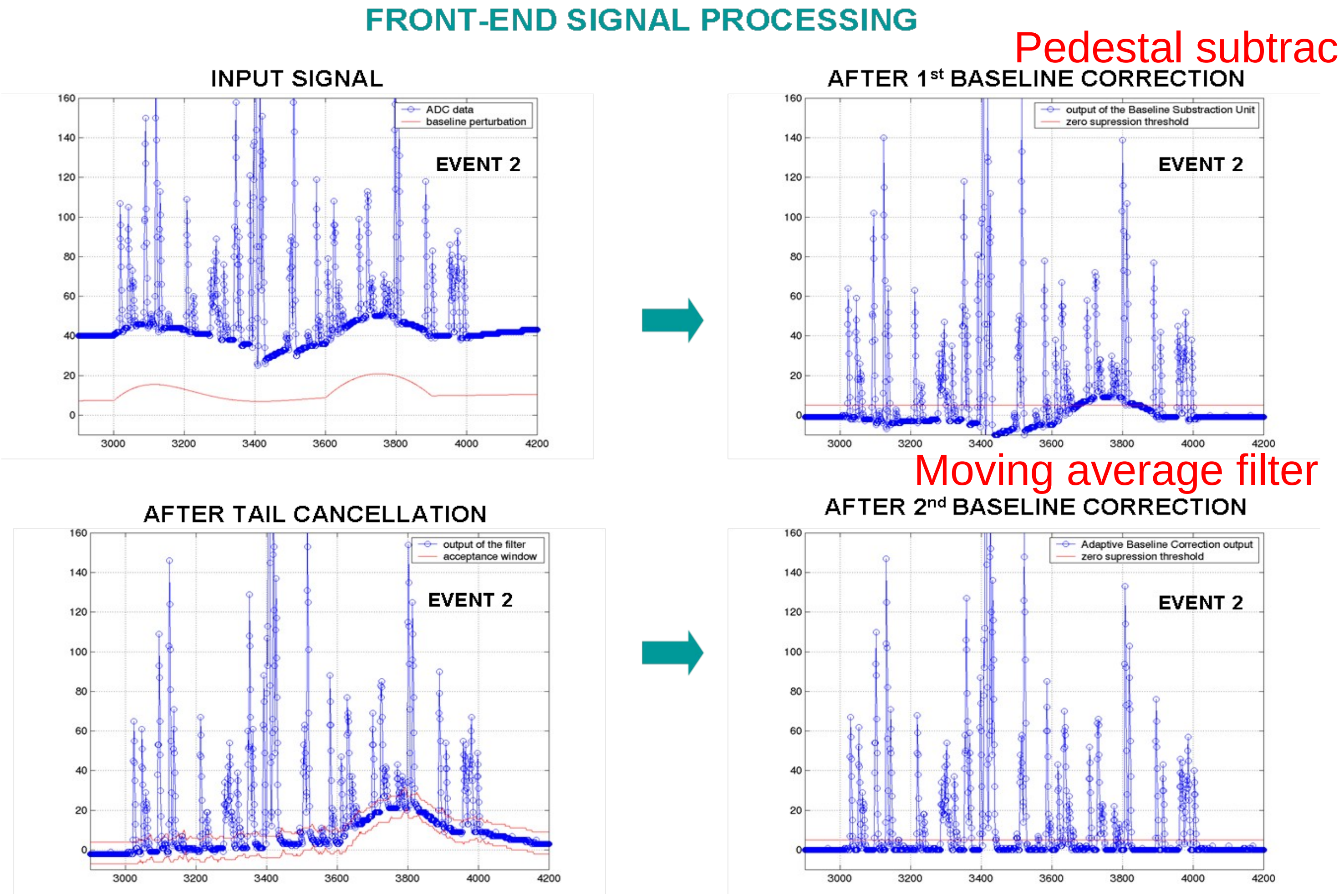
Drift length

Thesis Christof Roland (now CMS)

Figure 13: Left panel: normalized mean dE/dx as function of drift length without corrections (triangles), with lateral cross talk correction (open points) and and with baseline and lateral cross talk correction (full points). Richt pane: the same for the σ(dE/dx)/dE/dx as function of drift length.

Possible solution of baseline shift problem with Alice electronics

This what should happen in the Alice readout:

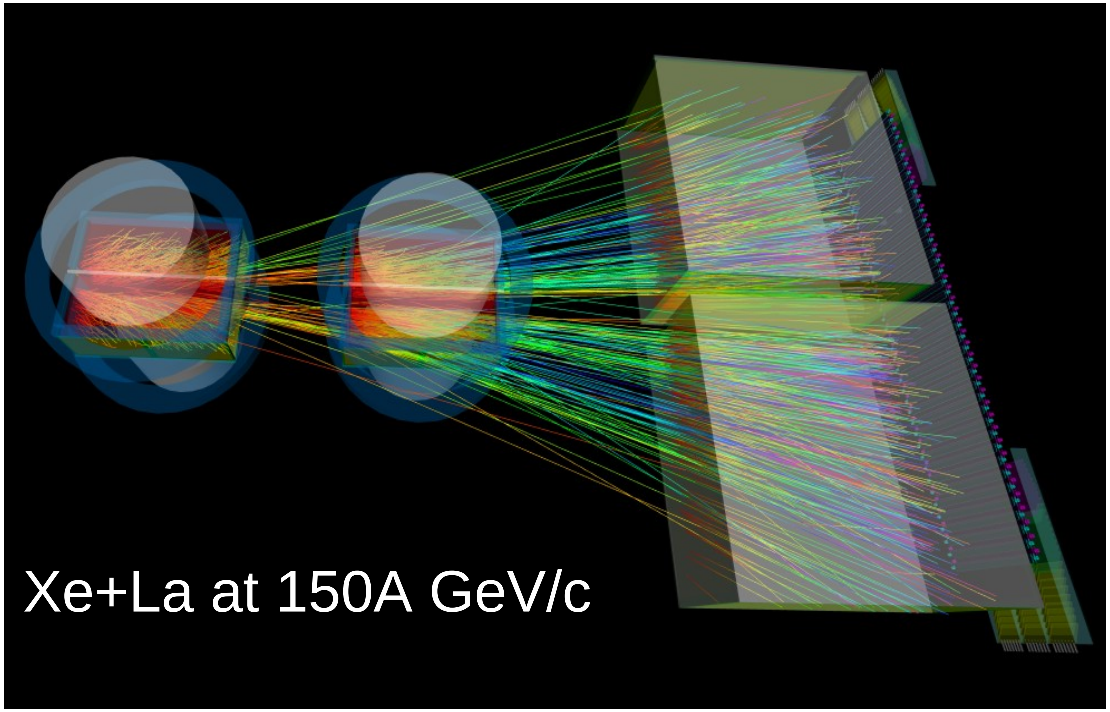


Pedestal subtraction

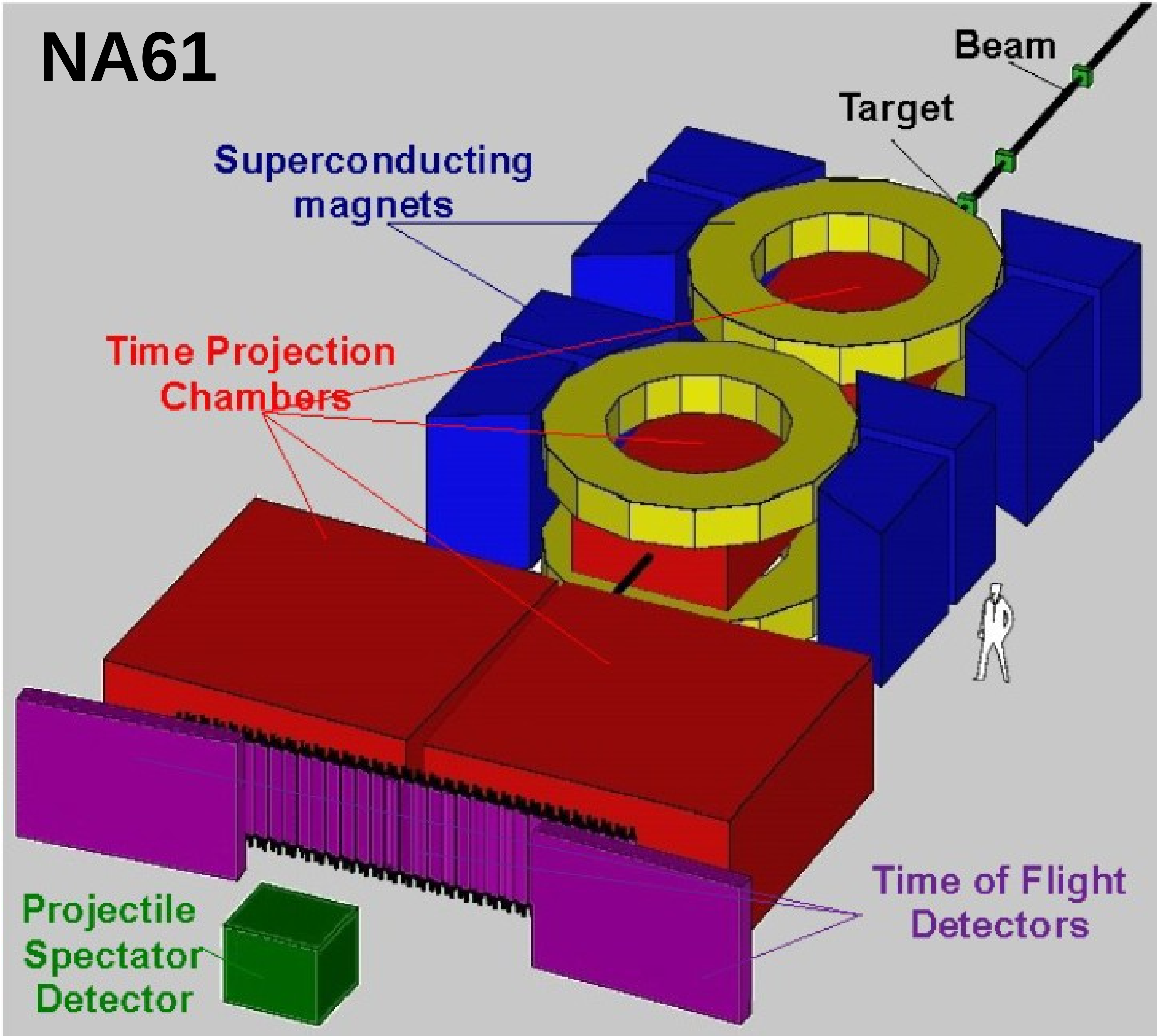
Moving average filter

This last step never worked in Alice up to now.
May be now experts found a trick in the firmware.

the end


Xe+La at 150A GeV/c

NA61


Beam
Target
Superconducting magnets
Time Projection Chambers
Time of Flight Detectors
Projectile Spectator Detector

Aging effects

Horror pictures