Charge dispersion MPGD Readout & ILC-TPC Prototype Test Beam Studies

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Motivation & overview

- ILC tracker goal $\Delta(1/p_T) \leq 5.10^{-5}$ (GeV/c)$^{-1}$

  => MPGD-TPC $\Delta(1/p_T) \leq 1.5 \times 10^{-4}$ (GeV/c)$^{-1}$
- TDR TPC: 200 pads; σ_{Tr} ~ 100 μm ($\approx$ 2 m drift), pad size 2 x 6 mm^2

  => Total TPC pad count ~1.5 x 10^6
- R&D shows 2 mm too wide for 100 μm resolution with normal readout.

  Ways to improve the MPGD-TPC resolution:

1) Under consideration - narrower 1 mm x 6 mm pads (3 x 10^6 total). R&D issues: High density electronics, increased heat load, TPC endcap mass etc.
2) Alternative: Disperse avalanche charge to improve resolution for wide pads. Development of TPC readout with charge dispersion in MPGDs with a resistive anode.
   - Charge dispersion demonstrated in cosmic ray TPC tests with no magnet.
   - The new TPC readout concept was tested in a beam test last October. 1 T superconducting magnet & 4 GeV/c hadron test beam at KEK PS.
   - Two TPCs: Multi Technology Test TPC - MT3 TPC (MPI Munich) + Carleton TPC with Micromegas (Saclay) & GEMs(Saga University).
   - Two weeks of beam data in October2005.
3) Magnetic field performance of MPGD-TPC with charge dispersion readout in a test beam.

Diffusion sets the limit on TPC momentum resolution

- The physics limit of TPC resolution comes from transverse diffusion: $\sigma_x{}^2 \approx \frac{D_{Tr}^2 \cdot z}{N_{eff}}$ N_{eff} = effective electron statistics.

- For best resolution, choose a gas with smallest diffusion

.

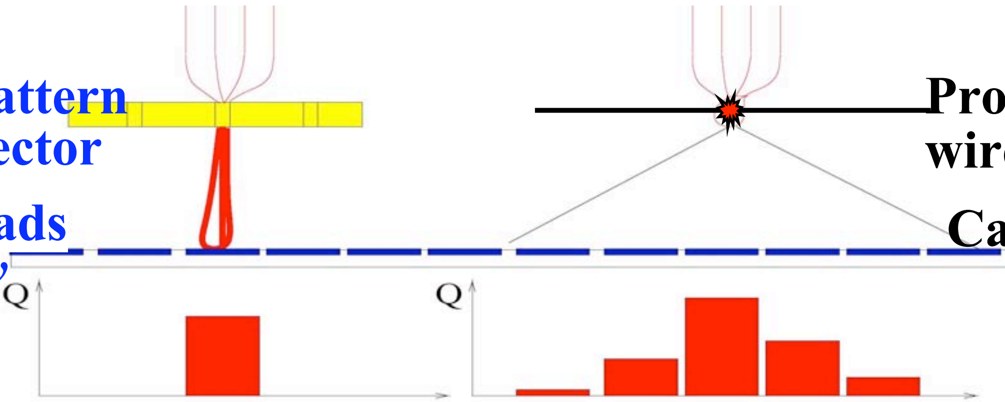
The rule applies to the wire TPCs which use induced cathode pad signals for position determination. But **ExB** & track angle systematic effects degrade wire TPC resolution.

ExB effect does not limit the MPGD-TPC. But there are no comparable induced cathode pad signals.

The MPGD-TPC resolution is limited by pad width ***w.*** The resolution gets worse for wide pads in absence of diffusion.

$$\sigma_x{}^2 \Rightarrow \frac{w^2}{12} \quad as\ z \Rightarrow 0$$

Pad width limits the MPGD-TPC resolution
ExB angle effects limit the wire/pad TPC resolution



Direct signal on the MPGD anode pad

For small diffusion, less precise centroid for wide pads

Induced cathode signal determined by geometry

Accurate centroid determination possible with wide pads

$$\sigma_x{}^2 \approx \sigma_0{}^2 + \frac{1}{N_{eff}}\left[D_{Tr}^2 z + w^2/12\right]$$

$$\sigma_x{}^2 \approx \sigma_0{}^2 + \frac{D_{Tr}^2 \cdot z}{N_{eff}}$$

Improving MPGD TPC resolution without resorting to narrower pads

- Disperse track charge after gas gain to improve centroid determination with wide pads.
- For the GEM, large transverse diffusion in the high E-field field in transfer and induction gaps provides a natural mechanism to disperse the cluster charge.
- Measurements with prototype GEM-TPCs indicate that ~ 1 mm wide pads may be needed for TPC operation in high magnetic fields.
- Explore other concepts to disperse the charge

Charge dispersion - a geometrical pad signal induction mechanism making position sensing insensitive to pad width.

Position sensing from charge dispersion in a MPGD with a resistive anode

Position sensing on a resistive anode proportional wire from charge division

Telegraph equation (1-D):

$$\frac{L}{R}\frac{\partial^2 Q}{\partial t^2} + \frac{\partial Q}{\partial t} = \frac{1}{RC}\frac{\partial^2 Q}{\partial x^2}$$

Deposit point charge at t=0

Solution for charge density (L ~ 0)

$$Q(x,t) = \sqrt{\frac{RC}{4\pi t}}\, e^{\frac{-x^2 RC}{4t}}$$

Generalize charge division on a resistive wire to 2 D

Position sensing from charge dispersion in MPGDs with a resistive anode

Equivalent to Telegraph equation in 2-D

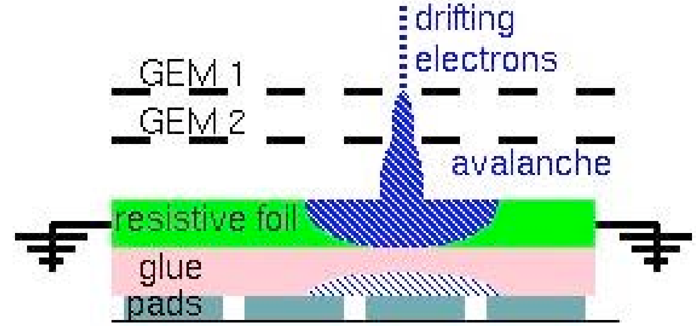
$$\frac{\partial Q}{\partial t} = \frac{1}{RC}\left[\frac{\partial^2 Q}{\partial r^2} + \frac{1}{r}\frac{\partial Q}{\partial r}\right]$$

Solution for charge density in 2-D

$$Q(r,t) = \frac{RC}{2t}\, e^{\frac{-r^2 RC}{4t}}$$

Charge dispersion in a MPGD with a resistive anode

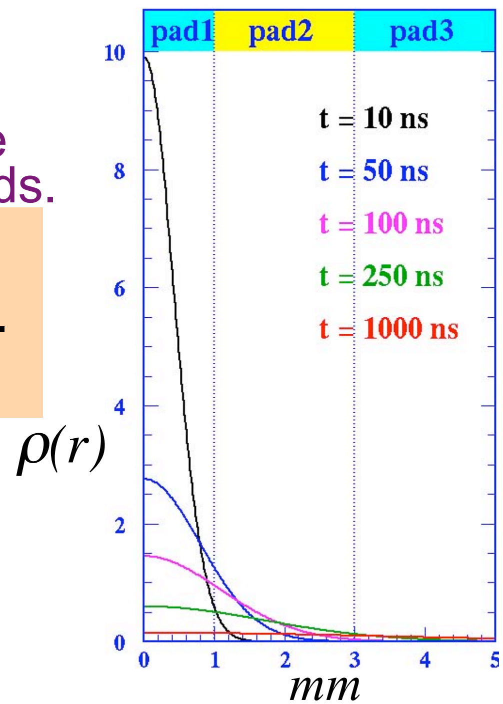
- Modified MPGD anode with a high resistivity film bonded to a readout plane with an insulating spacer.
- 2-dimensional continuous RC network defined by material properties & geometry.
- Point charge at *r = 0 & t = 0* disperses with time.
- Time dependent anode charge density sampled by readout pads.

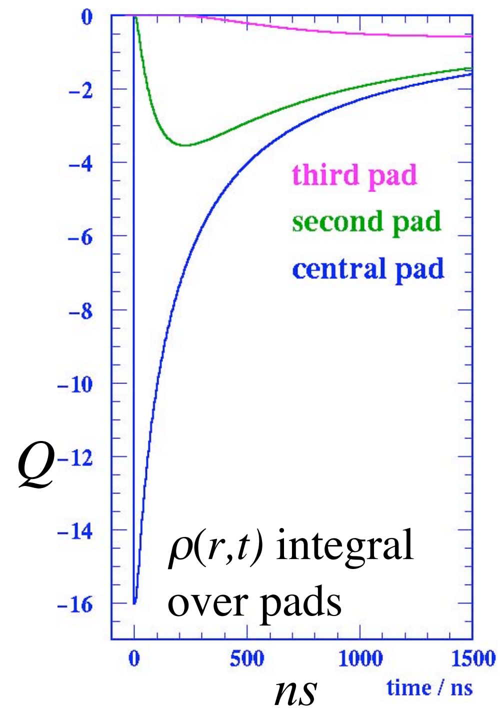


Equation for surface charge density function on the 2-dim. continuous RC network:

$$\frac{\partial \rho}{\partial t} = \frac{1}{RC}\left[\frac{\partial^2 \rho}{\partial r^2} + \frac{1}{r}\frac{\partial \rho}{\partial r}\right]$$

$$\Rightarrow \rho(r,t) = \frac{RC}{2t} e^{\frac{-r^2 RC}{4t}}$$





M.S.Dixit et.al., Nucl. Instrum. Methods A518 *(2004) 721.*

Simulation of charge dispersion phenomenon

- The charge dispersion equation describe the time evolution of a point like charge deposited on the MPGD resistive anode at $t = 0$.
- To compare to experiment, one needs to include the effects of:
  - Longitudinal & transverse diffusion in the gas.
  - Intrinsic rise time T_{rise} of the detector charge pulse.
  - The effect of preamplifier rise and fall times t_r & t_f.
  - And for particle tracks, the effects of primary ionization clustering.

The simulation for a single charge cluster

The charge density function for a point charge in Cartesian coordinates:

$$\rho\delta(x,y,t) = \frac{\tau}{4\pi t} exp\left[-\tau\left(x^2+y^2\right)/4t\right] \; where \; \tau = RC$$

Physics effects included in simulation in two parts: 1) as effects which depend on spatial coordinates x & y, or; 2) as effects which depend on time.

1) The spatial effects function includes charge dispersion phenomena & transverse size *w* of the charge cluster due to transverse diffusion.

$Q_{pad}(t)$ is the pad signal from charge dispersion when a charge Nq_e of size w is deposited on the anode at $t = 0$;

$$Q_{pad} = \frac{Nq_e}{4}\left[erf\left(\frac{x_{high}}{\sqrt{2}\sigma_{xy}}\right) - erf\left(\frac{x_{low}}{\sqrt{2}\sigma_{xy}}\right)\right]\left[erf\left(\frac{y_{high}}{\sqrt{2}\sigma_{xy}}\right) - erf\left(\frac{y_{low}}{\sqrt{2}\sigma_{xy}}\right)\right] \quad (1)$$

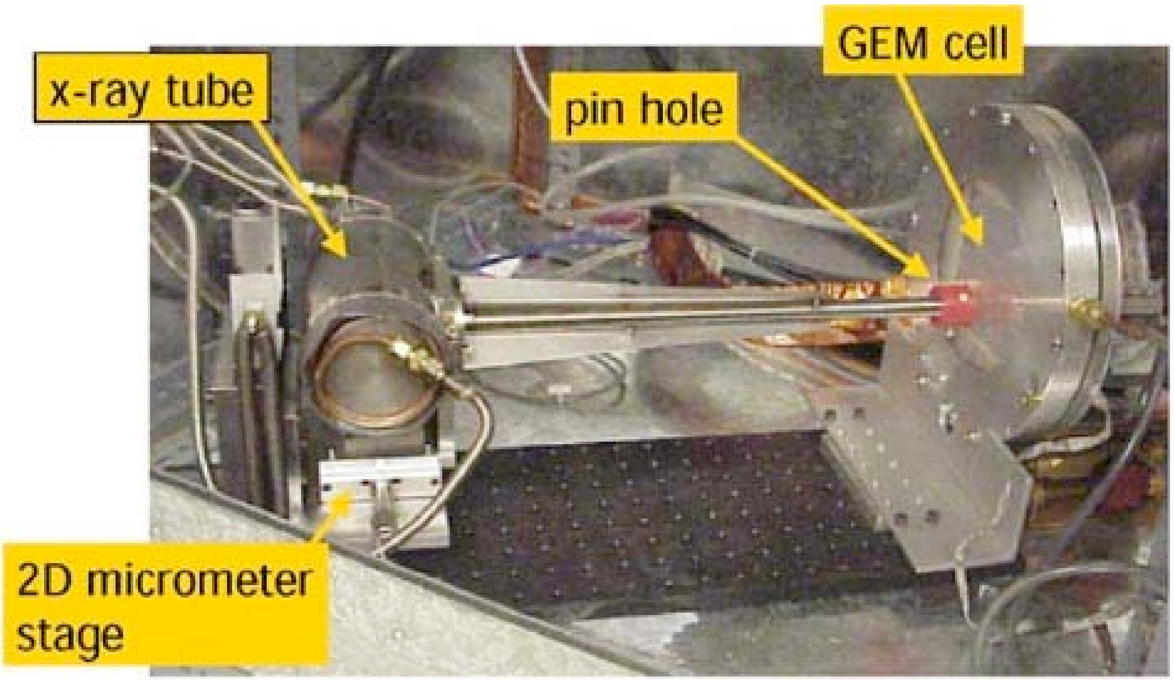
x_{high}, x_{low}, y_{high}, y_{low} define the pad boundaries & $\sigma_{xy} = \sqrt{2t/\tau + w^2}$

$$I(t)=\frac{1}{2T_{rise}}\left[\begin{array}{l} exp\left(\sigma^2a^2/2-at\right)\left[erf\left(\frac{t-T_{rise}-\sigma^2 a}{\sigma\sqrt{2}}\right)+1\right]- \\ exp\left(\sigma^2b^2/2-bt\right)\left[erf\left(\frac{t-T_{rise}-\sigma^2 b}{\sigma\sqrt{2}}\right)+1\right]+ \\ exp\left(\sigma^2a^2/2-a\left(t-T_{rise}\right)\right)\left[erf\left(\frac{t-2T_{rise}-\sigma^2 a}{\sigma\sqrt{2}}\right)+1\right]- \\ exp\left(\sigma^2b^2/2-b\left(t-T_{rise}\right)\right)\left[erf\left(\frac{t-2T_{rise}-\sigma^2 b}{\sigma\sqrt{2}}\right)+1\right]+ \\ exp\left(\sigma^2a^2/2-at\right)\left[erf\left(\frac{t-\sigma^2 a}{\sigma\sqrt{2}}\right)+erf\left(\frac{t-T_{rise}-\sigma^2 a}{\sigma\sqrt{2}}\right)\right]- \\ exp\left(\sigma^2b^2/2-bt\right)\left[erf\left(\frac{t-\sigma^2 b}{\sigma\sqrt{2}}\right)+erf\left(\frac{t-T_{rise}-\sigma^2 b}{\sigma\sqrt{2}}\right)\right] \end{array}\right] \quad (2)$$

I(t) incorporates intrinsic rise time, longitudinal diffusion & electronics shaping times as time dependent effects. $a = 1/t_f\,;\, b = 1/t_f + 1/t_r$

(1) and (2) are convoluted numerically for the model simulation.

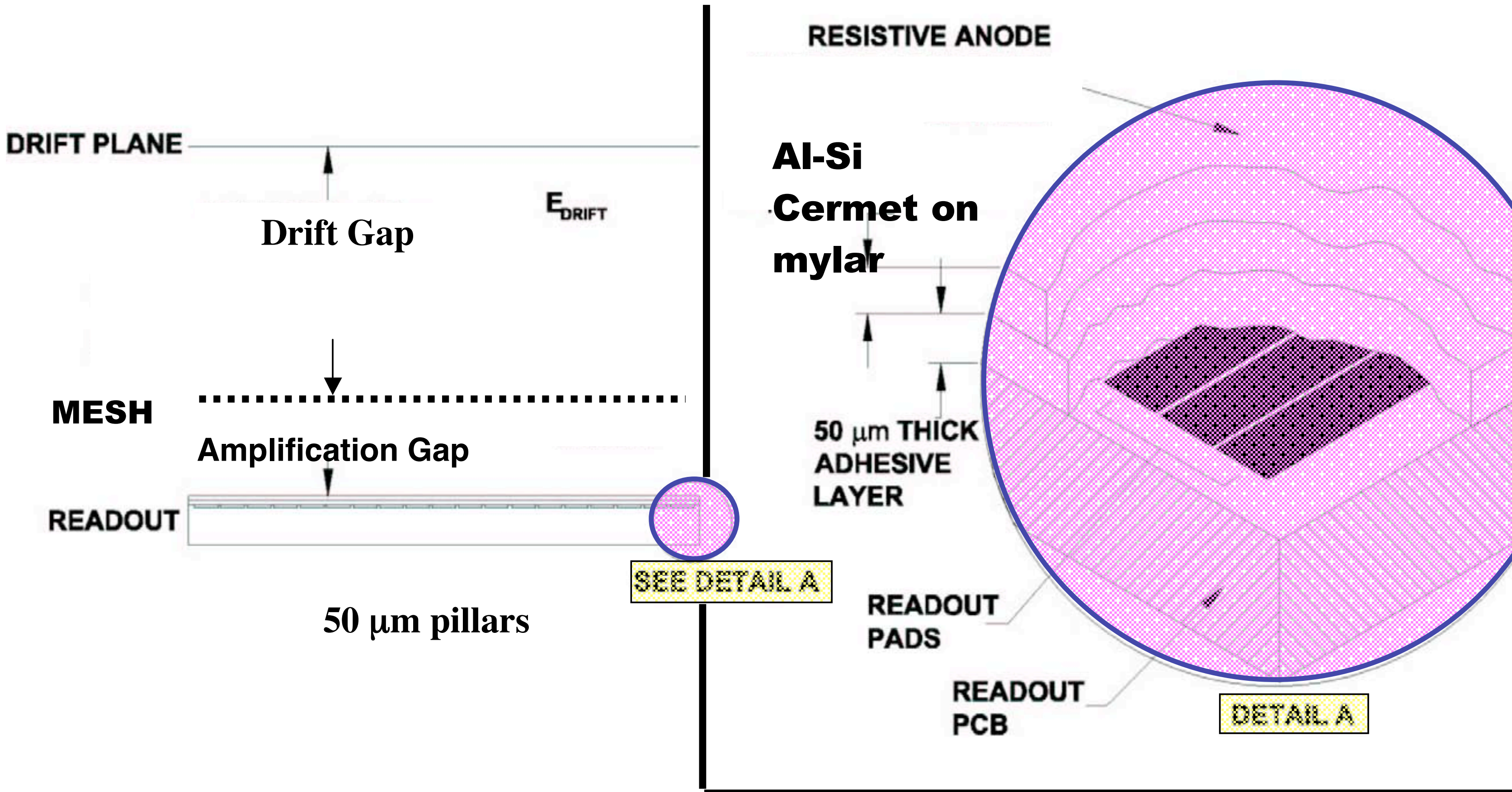
MPGD charge dispersion tests with a collimated point x ray source



•Point source ~ 50 µm collimated 4.5 keV x rays.
•Aleph TPC preamps. τ_{Rise}= 40 ns, τ_{Fall} = 2 µs.
•DAQ - 500 MHz Tektronix digital scope.

Resistive anode Micromegas

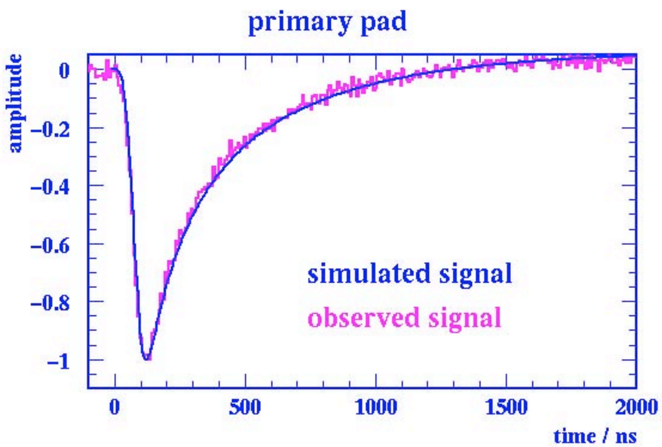
530 kΩ/□ Carbon loaded Kapton resistive anode was used with GEM. This was replaced with higher resistivity 1 MΩ/□ Cermet for tests with Micromegas.

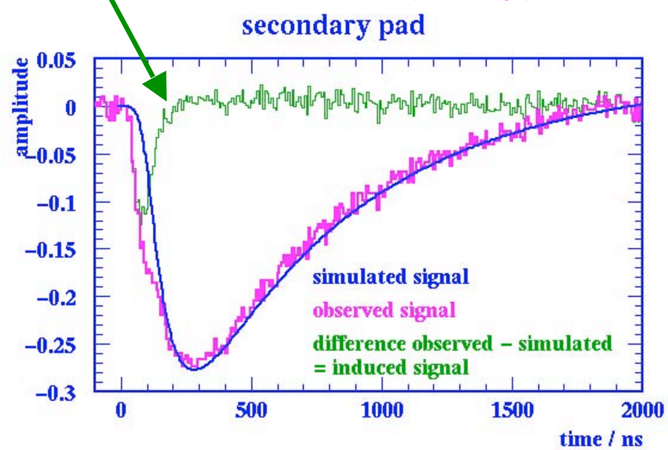


Charge dispersion signal for a GEM Simulation versus measurement (Ar+10%CO2)

(2 x 6 mm² pads) Collimated ~ 50 μm 4.5 keV x-ray spot on pad centre.

Difference = induced signal (not included in simulation) studied previously: MPGD '99 (Orsay), LCWS '00



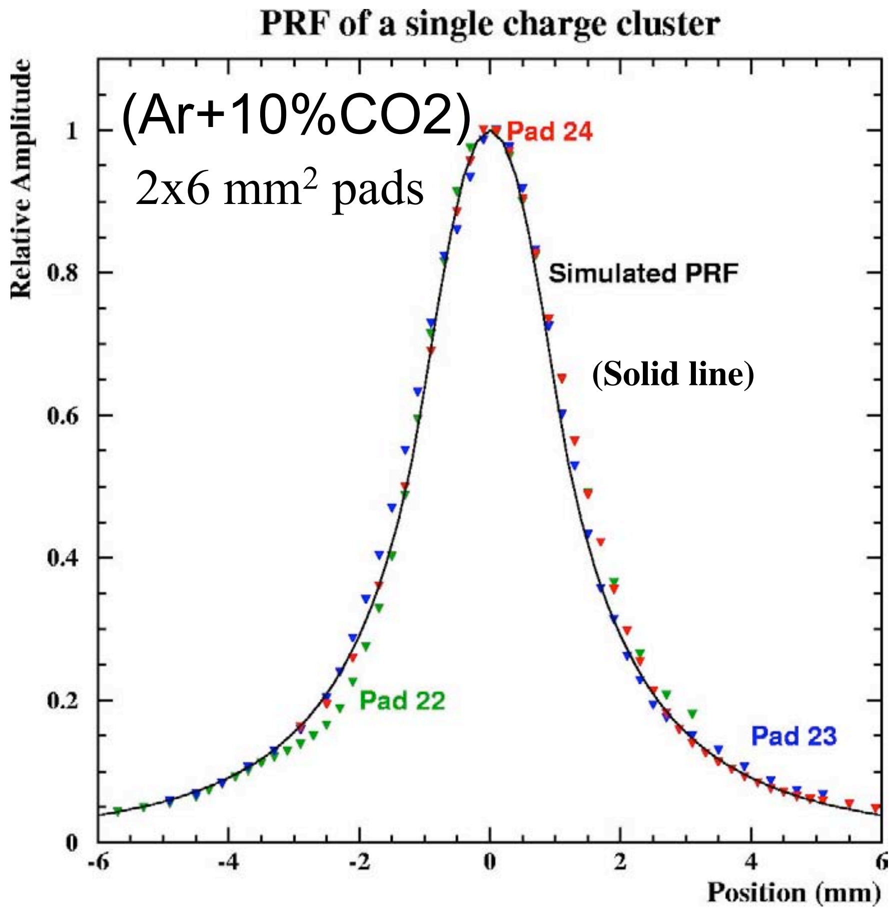


Simulated primary pulse is normalized to the data.

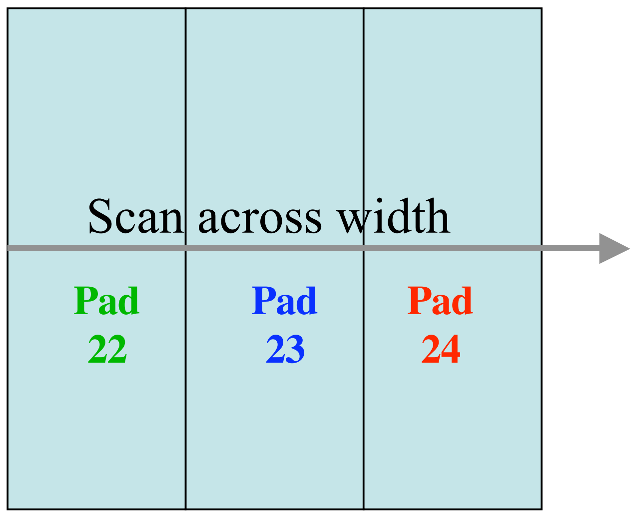
Primary pulse normalization used for the simulated secondary pulse

GEM pad response function (PRF) for a point source

Simulation compared to the measured PRF



Ionization from 50 μm collimated x-ray spot.

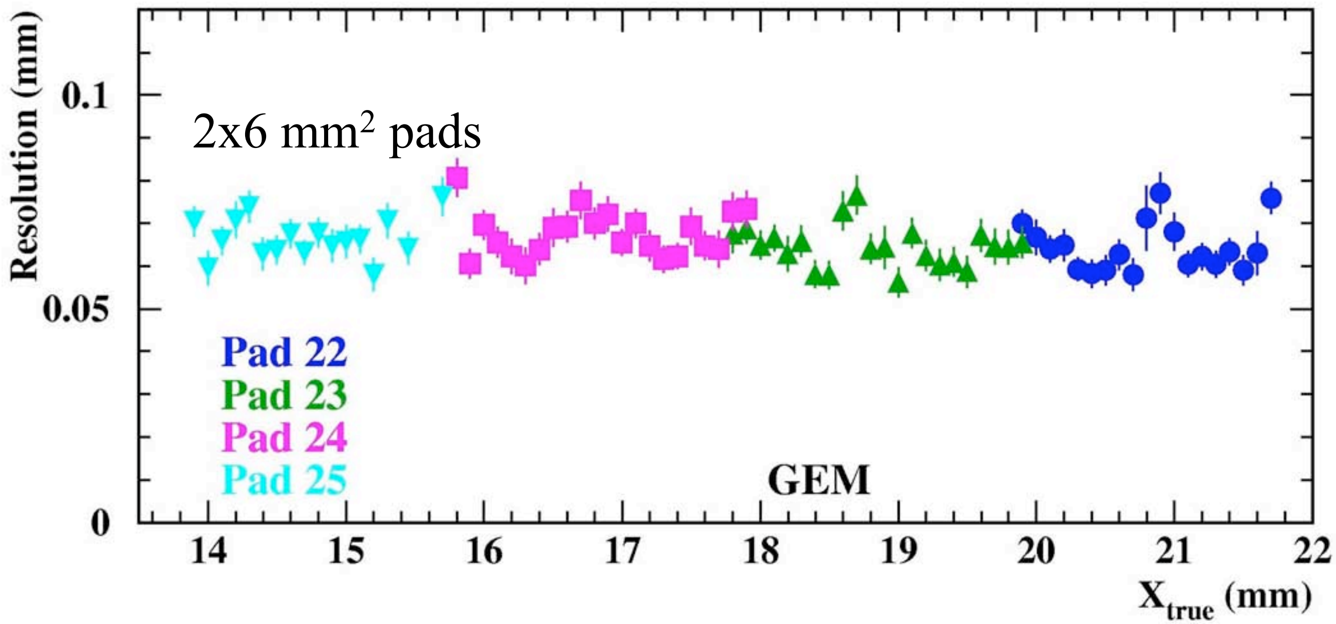


Measured PRF deviates from simulation due to anode RC nonuniformities.

PRF - a measure of signal amplitude as a function of cluster position.

Double-GEM space point resolution with charge dispersion readout (Ar+10%CO2)

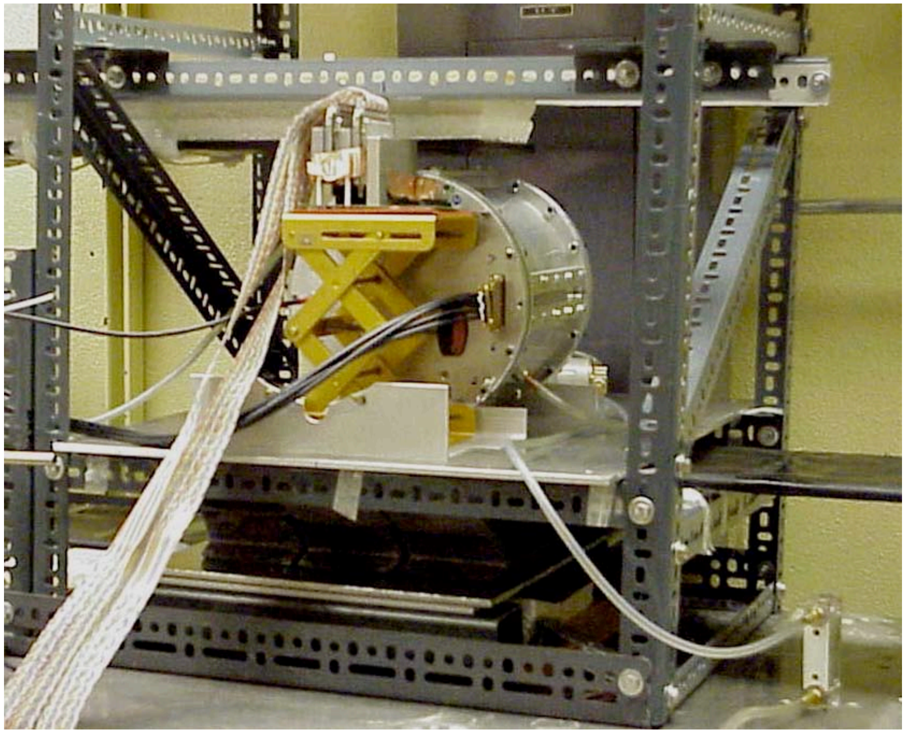
Collimated ~ 4.5 keV x rays, Spot size ~ 50 μm



- GEM resolution ~ 70 μm.
- Similar resolution measured for a Micromegas with a resistive anode readout using 2 mm x 6 mm pads

Cosmic ray TPC tests with charge dispersion

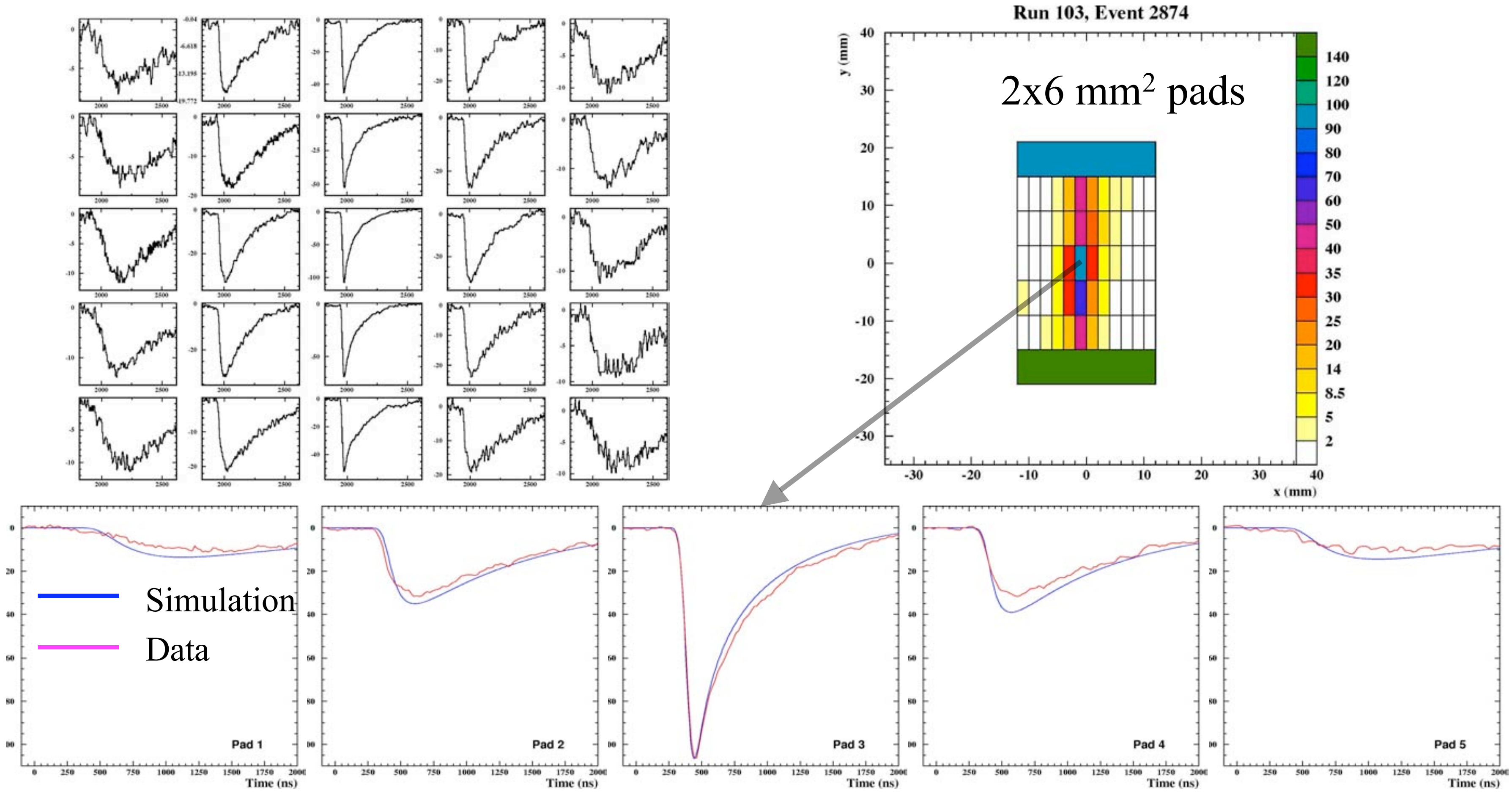
- 15 cm drift length with GEM or Micromegas readout
- B=0
- Ar+10% CO_2 chosen to simulate low transverse diffusion in a magnetic field.
- Aleph charge preamps.
  τ_{Rise}= 40 ns, τ_{Fall} = 2 μs.
- 200 MHz FADCs rebinned to digitization effectively at 25 MHz.
- 60 tracking pads (2 x 6 mm^2)
  + 2 trigger pads (24 x 6 mm^2).



The GEM-TPC resolution was first measured with conventional direct charge TPC readout.

The resolution was next measured with a charge dispersion resistive anode readout with a double-GEM & with a Micromegas endcap.

GEM TPC charge dispersion simulation (B=0)
Cosmic ray track, Z = 67 mm Ar+10%CO2



Centre pulse used for simulation normalization - no other free parameters.

The pad response function (PRF) for a track

- The PRF is a measure of signal size as a function of track position relative to the pad.
- Unusual highly variable charge dispersion pulse shape; both the rise time & pulse amplitude depend on track position.
- We use pulse shape information to optimize the PRF.
- The PRF can, in principle, be determined from simulation.
- However, system RC nonuniformities & geometrical effects introduce bias in absolute position determination.
- The position bias can be corrected by calibration.
- PRF and bias determined empirically using a subset of data which was used for calibration. The remaining data used for resolution studies.

Track PRFs with GEM & Micromegas readout

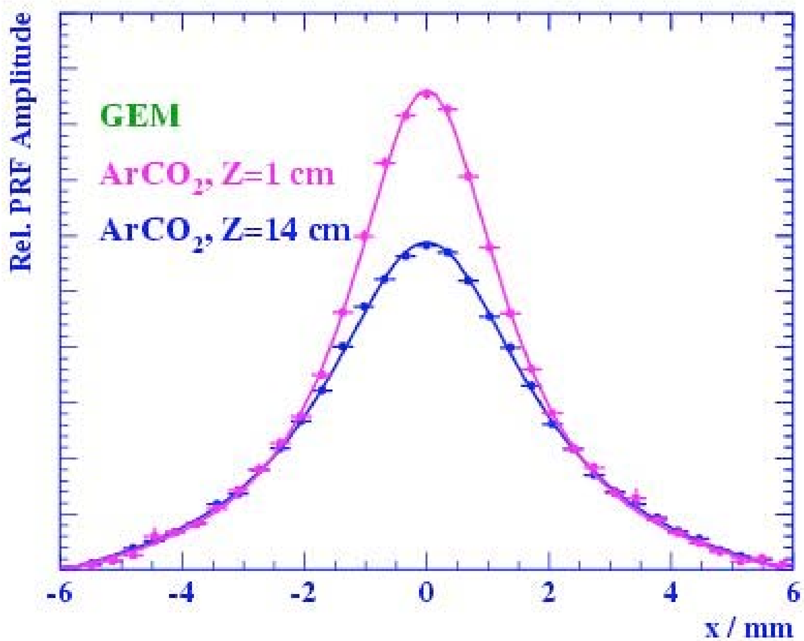
- The PRFs are not Gaussian.
- The PRF depends on track position relative to the pad.
- PRF = PRF(x,z)
- PRF can be characterized by its FWHM Γ(z) & base width Δ(z).
- PRFs determined from the data have been fitted to a functional form consisting of a ratio of two symmetric 4th order polynomials.

$$PRF[x,\Gamma(z),\Delta,a,b] = \frac{(1 + a_2 x^2 + a_4 x^4)}{(1 + b_2 x^2 + b_4 x^4)}$$

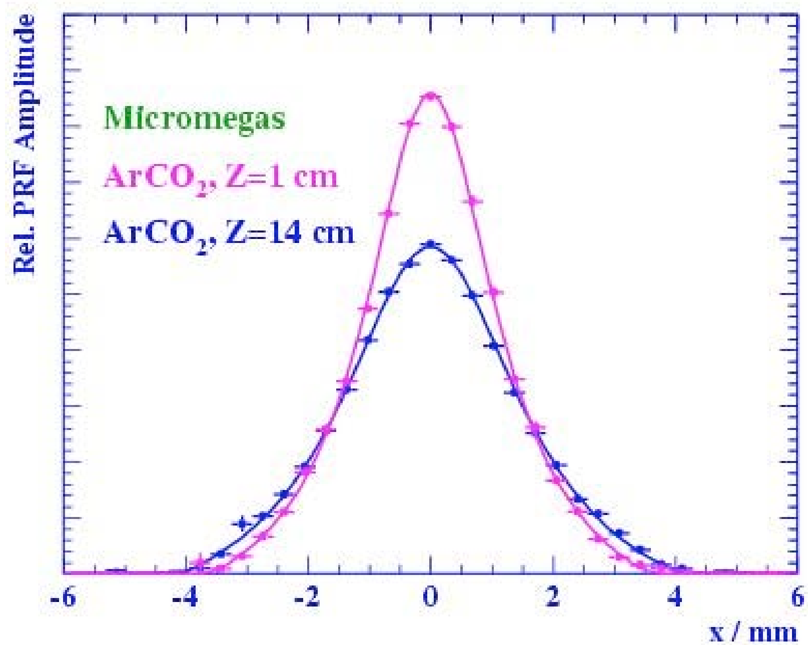
a_2 a_4 b_2 & b_4 can be written down in terms of Γ and Δ & two scale parameters a & b.

GEM & Micromegas PRFs for tracks
Ar+10%CO2 2x6 mm^2 pads

The pad response function amplitude for longer drift distances is lower due to Z dependent normalization.



GEM PRFs



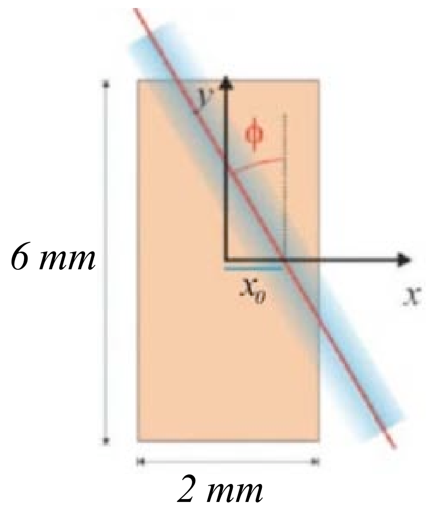
Micromegas PRFs

Micromegas PRF is narrower due to the use of higher resistivity anode & smaller diffusion than GEM after avalanche gain

Track fit using the the PRF

Track at: $x_{track} = x_0 + tan(\phi)\, y_{row}$

$$\chi^2 = \sum_{rows} \sum_{i=pads} [(A_i - PRF_i)/\partial A_i]^2$$



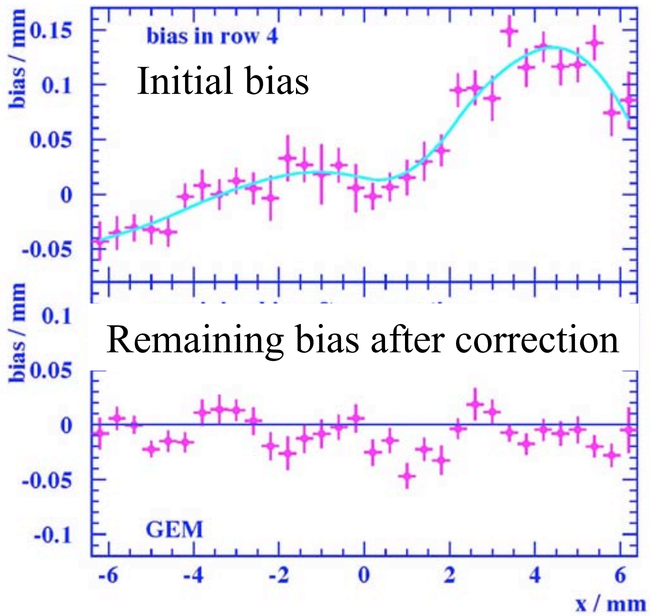
Determine x_0 & ϕ by minimizing χ^2 for the entire event

One parameter fit for x_{row} (track position for a given row) using ϕ

Bias = Mean of residuals (x_{row}-x_{track}) as a function of x_{track}

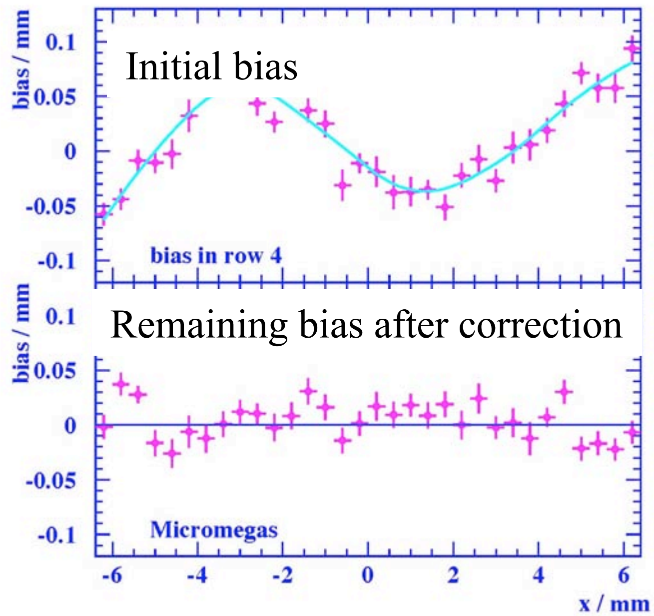
Resolution = σ of track residuals for tracks with $|\phi| < 5°$

Bias corrections for the GEM & for Micromegas



2x6 mm^2 pads

GEM

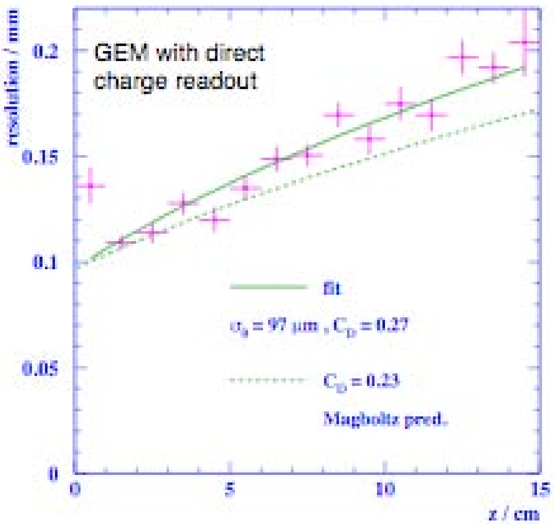


2x6 mm^2 pads

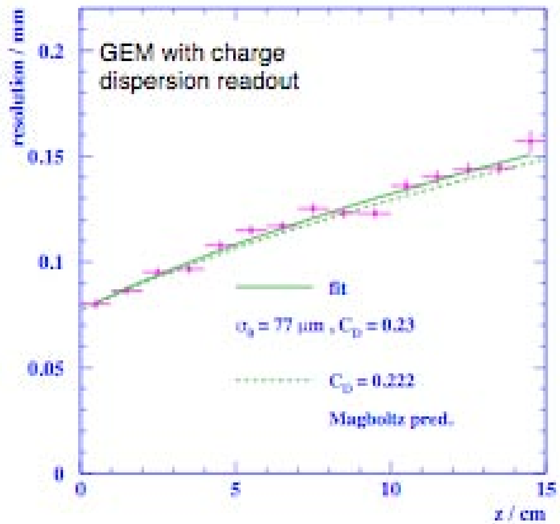
Micromegas

Transverse resolution for cosmic rays Ar+10%CO2 (B=0)

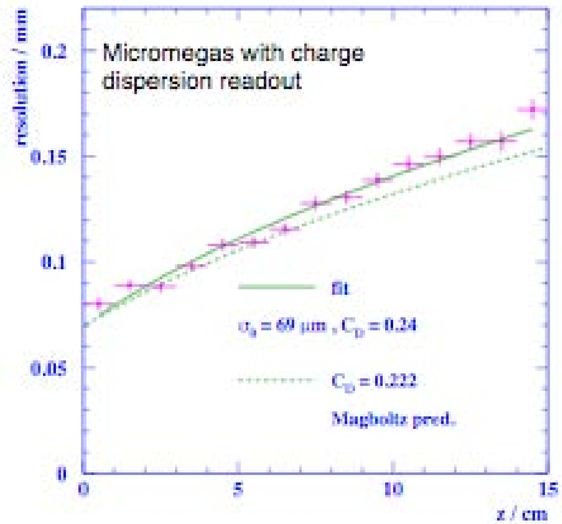
R.K.Carnegie et.al., NIM A538 (2005) 372



R.K.Carnegie et.al., to be published



To be published



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$$\sqrt{\sigma_0^{\ 2} + \frac{C_D^{\ 2}}{N_e} z}$$

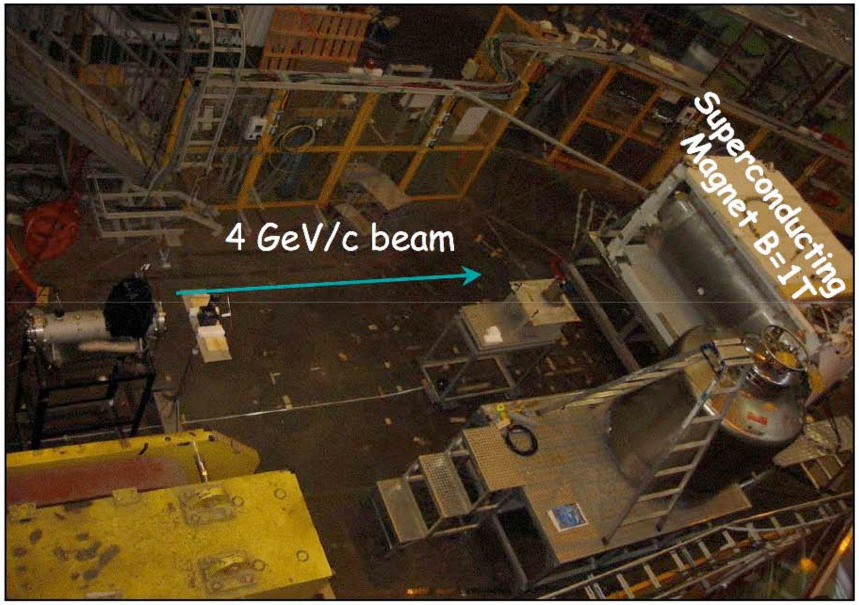
Compared to conventional readout, charge dispersion gives better resolution for the GEM and the Micromegas.

Charge dispersion TPC beam test in a magnet at KEK - October 2005

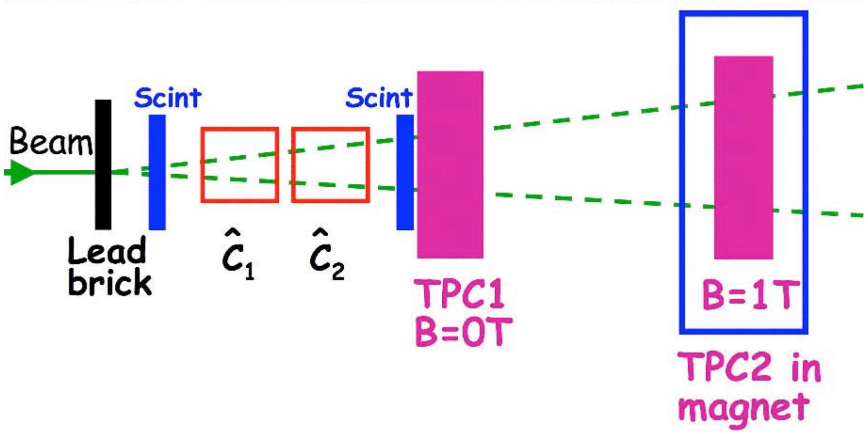
Canada	**A.Bellerive, K.Boudjemline, M.Dixit, J.Miyamato, E.Neuheimer, E.Rollin, K.Sachs &Y.Shin**	***Carleton University***
	J.-P. Martin	***University of Montreal***
France	**D.Burke, P.Colas, A.Giganon & I.Giomataris**	***DAPNIA CEA Saclay***
	V.Lepeltier & Th.Zerguerras	***LAL Orsay***
Germany	**R. Settles**	***MPI (Munich)***
Japan	**H.Kuroiwa & T.Takahashi**	***Hiroshima University***
	K.Fujii, M.Kobayashi, T.Matsuda & H.Yamaoka	***KEK/IPNS***
	Y.Kato	***Kinnki University***
	T.Watanabe	***Kogakuin University***
	T.Araki, H.Fujishima, T.Higashi, , K.Kodomatsu, A.Sugiyama, T.Yamamoto & Y.Tanaka	***Saga University***
	A.Yamaguchi	***Tsukuba University***
	M.Habu, S.Matsushita, K.Nakamura & O.Nito	***Tokyo University of Agriculture &Technology***

KEK PS π2 beam test of Carleton & MT3 TPCs

Beam data taken both in & outside the magnet for the two TPCs

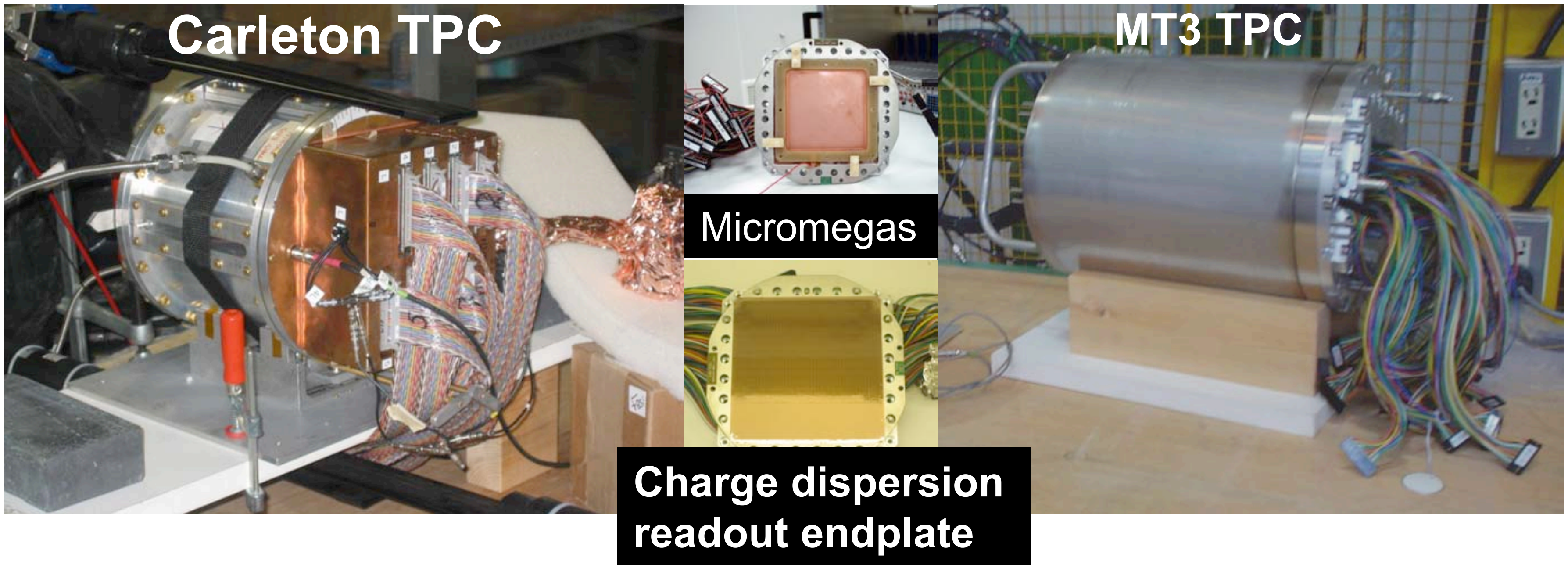


- 4 GeV/c hadrons (mostly π s)
- 0.5 & 1 GeV/c electrons
- Super conducting 1.2 T magnet without return yoke
- Inner diameter : 850 mm
- Effective length: 1 m



Carleton TPC in the beam outside the magnet

The two beam test TPCs



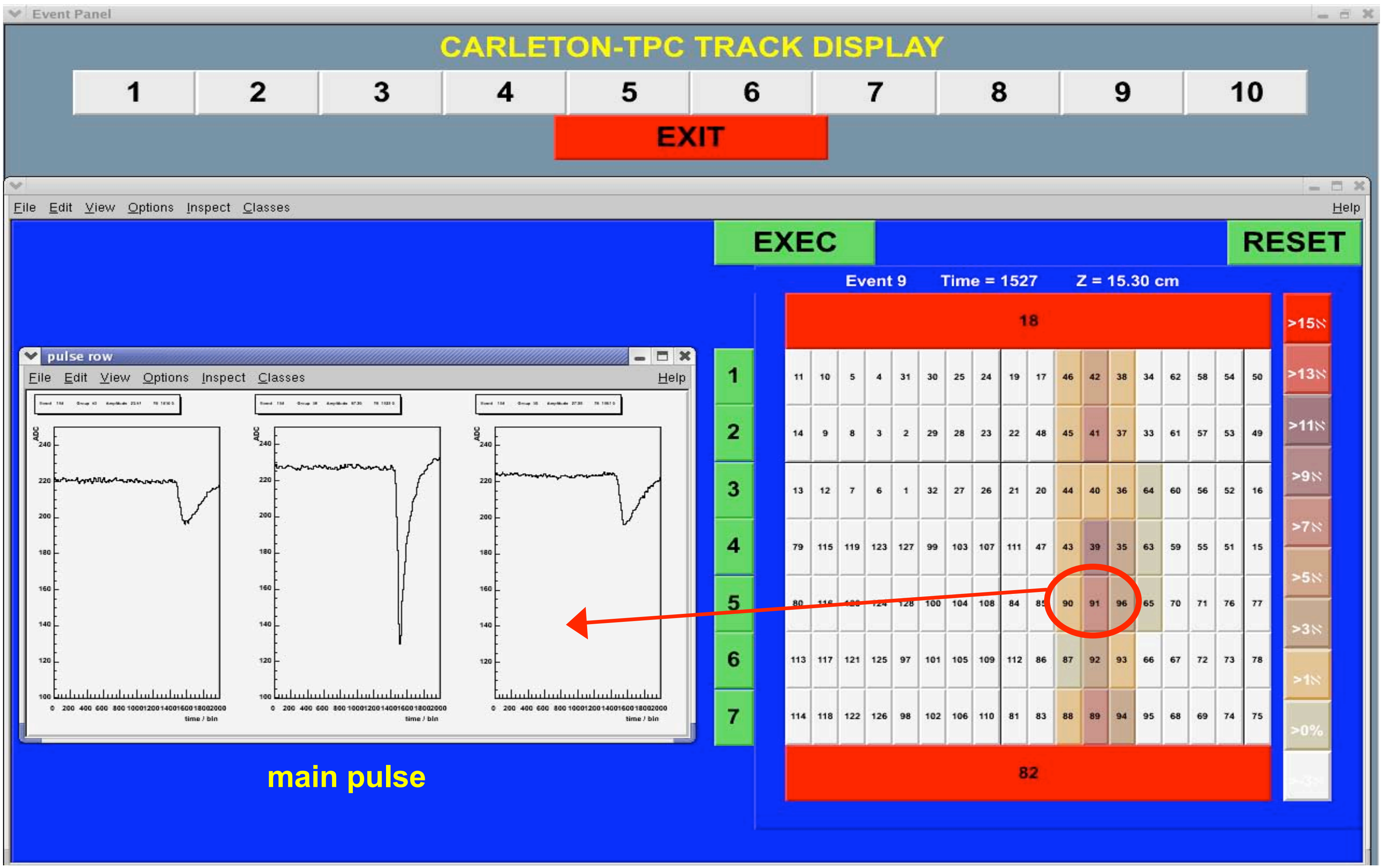
- Micromegas 10 x10 cm^2
- Drift distance: 16 cm
- 126 pads, 2 x 6 mm^2 each in 7 rows
-ALEPH preamps + 200 MHz FADCs rebinned to 25 MHz equivalent FADCs

-Micromegas & GEMs 10 x10 cm^2
-Drift distance 25.9 cm
- 384 pads 2.3 x 6.3 mm^2 each in 16 rows
-ALEPH preamps + 11 MHz Aleph Time Projection Digitizers

Track display - Ar+5%iC4H10

Micromegas 2 x 6 mm^2 pads B = 1 T

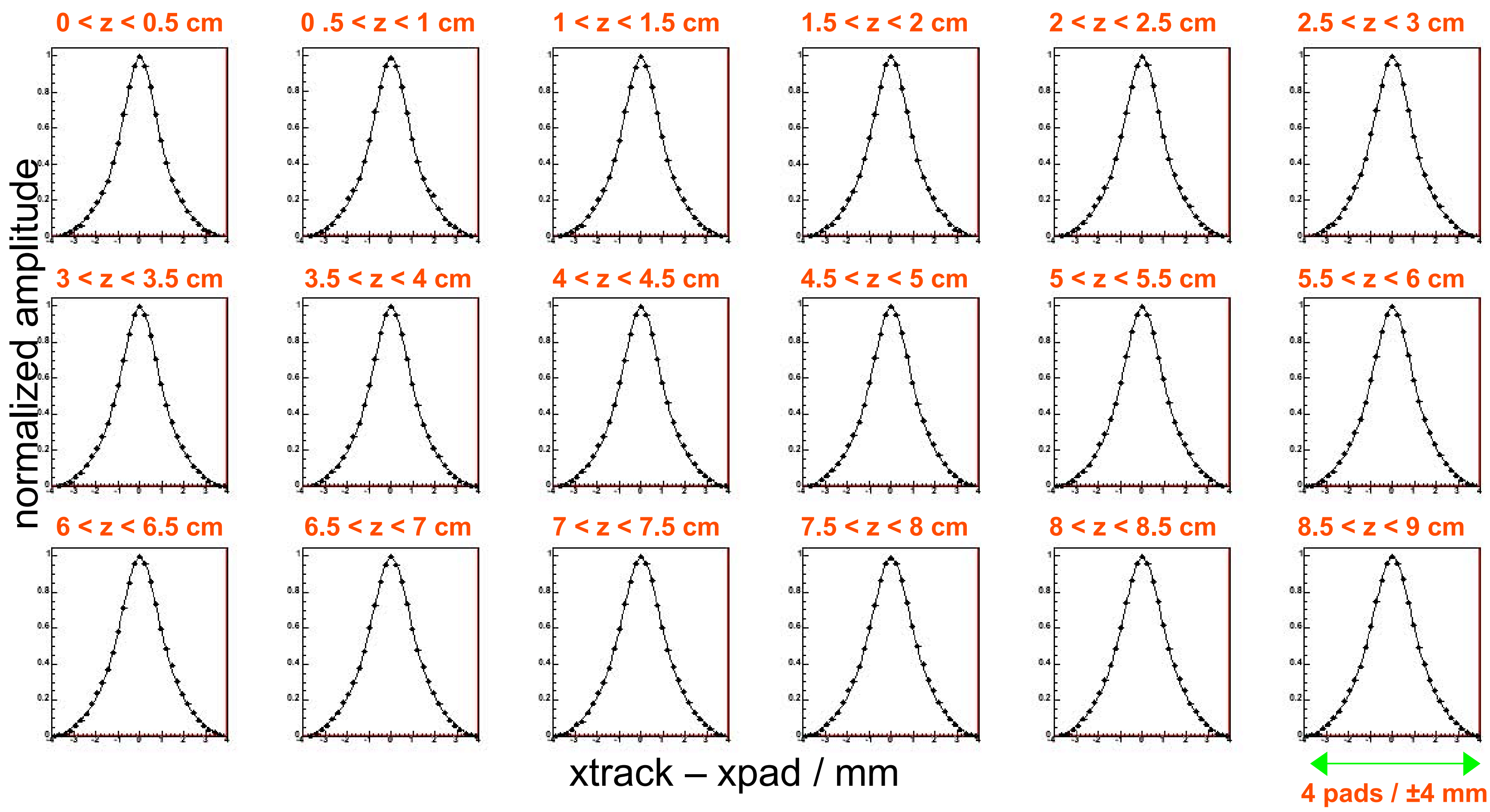
Z_{drift} = 15.3 cm



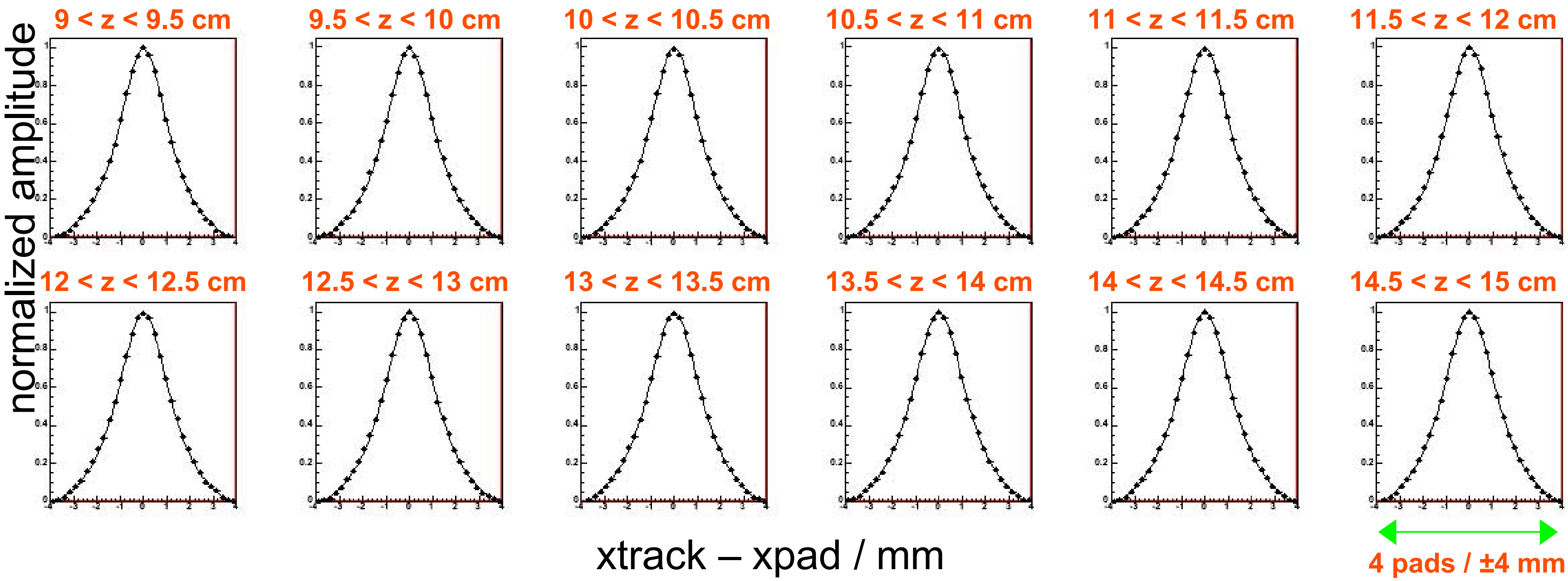
Pad Response Function / Ar+5%iC4H10

Micromegas+Carleton TPC 2 x 6 mm^2 pads, B = 1 T

30 z regions /
0.5 cm step

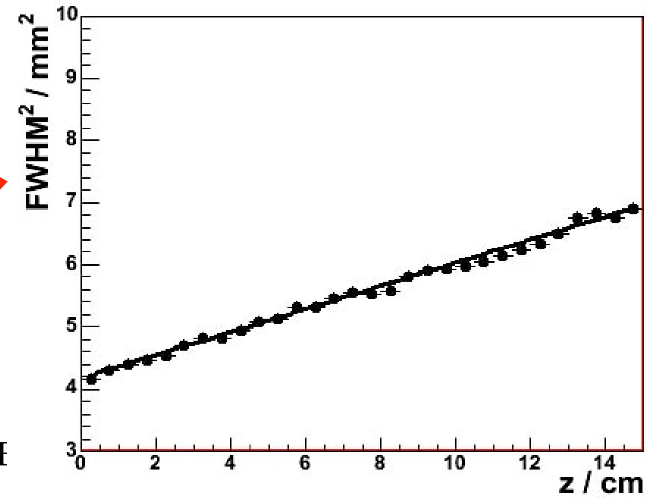


Pad Response Function / Ar+5%iC4H10



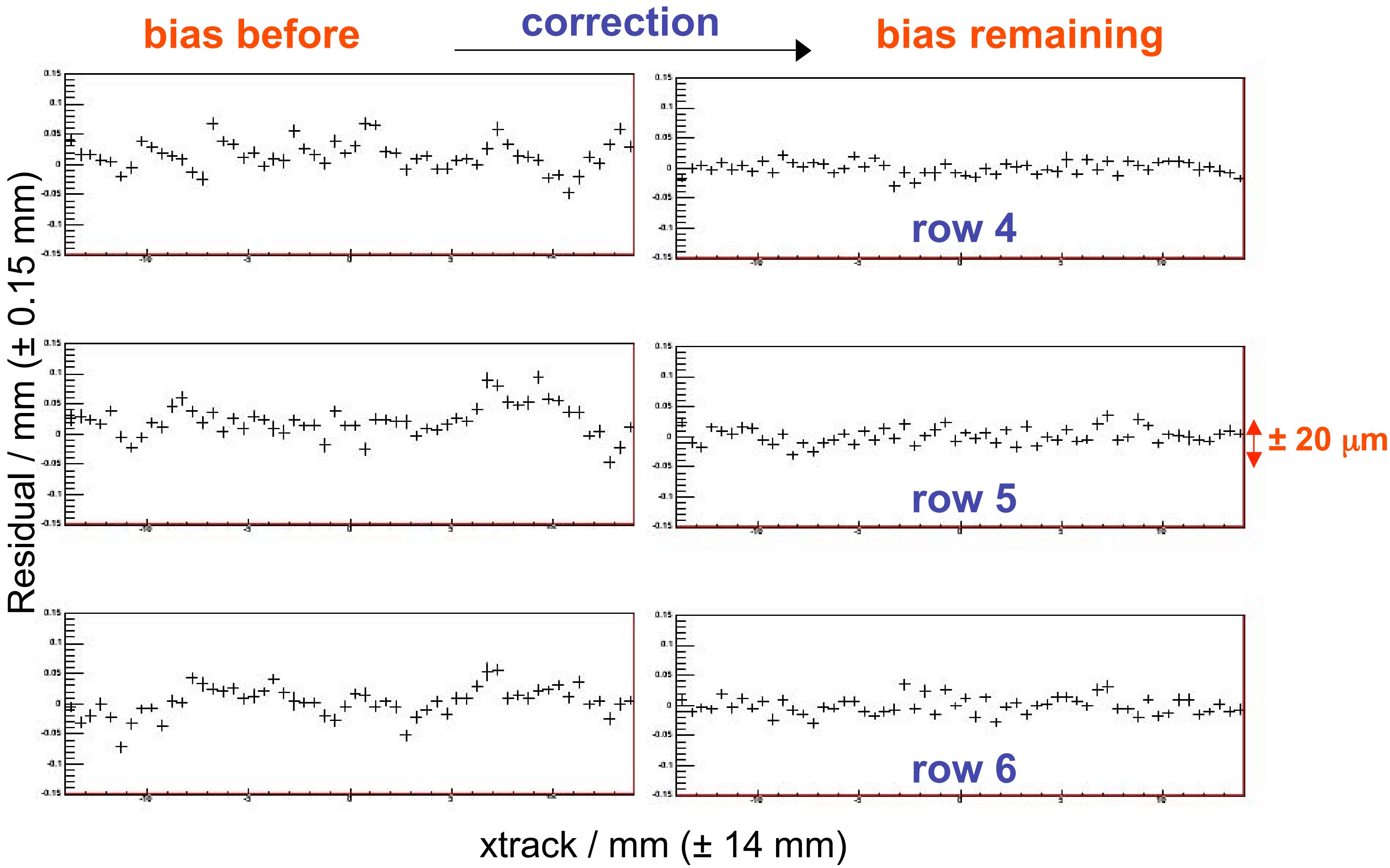
PRF parameters

- $a = b = 0$
- Δ = base width = 7.3 mm
- Γ = FWHM = f(z)

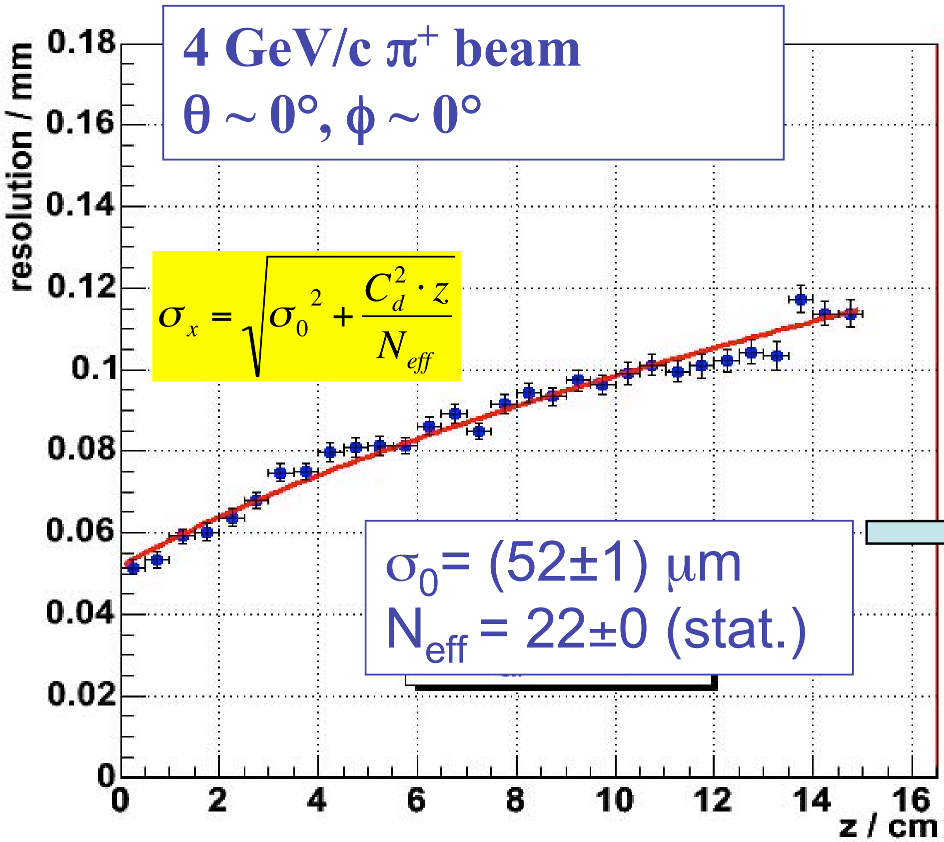


The parameters depend on TPC gas & operational details

Bias for central rows / Ar+5%iC4H10 B = 1 T



Transverse spatial resolution Ar+5%iC4H10
E=70V/cm D_{Tr} = 125 µm/√cm (Magboltz) @ B= 1T
Micromegas+Carleton TPC 2 x 6 mm² pads



•Strong suppression of transverse diffusion at 4 T.

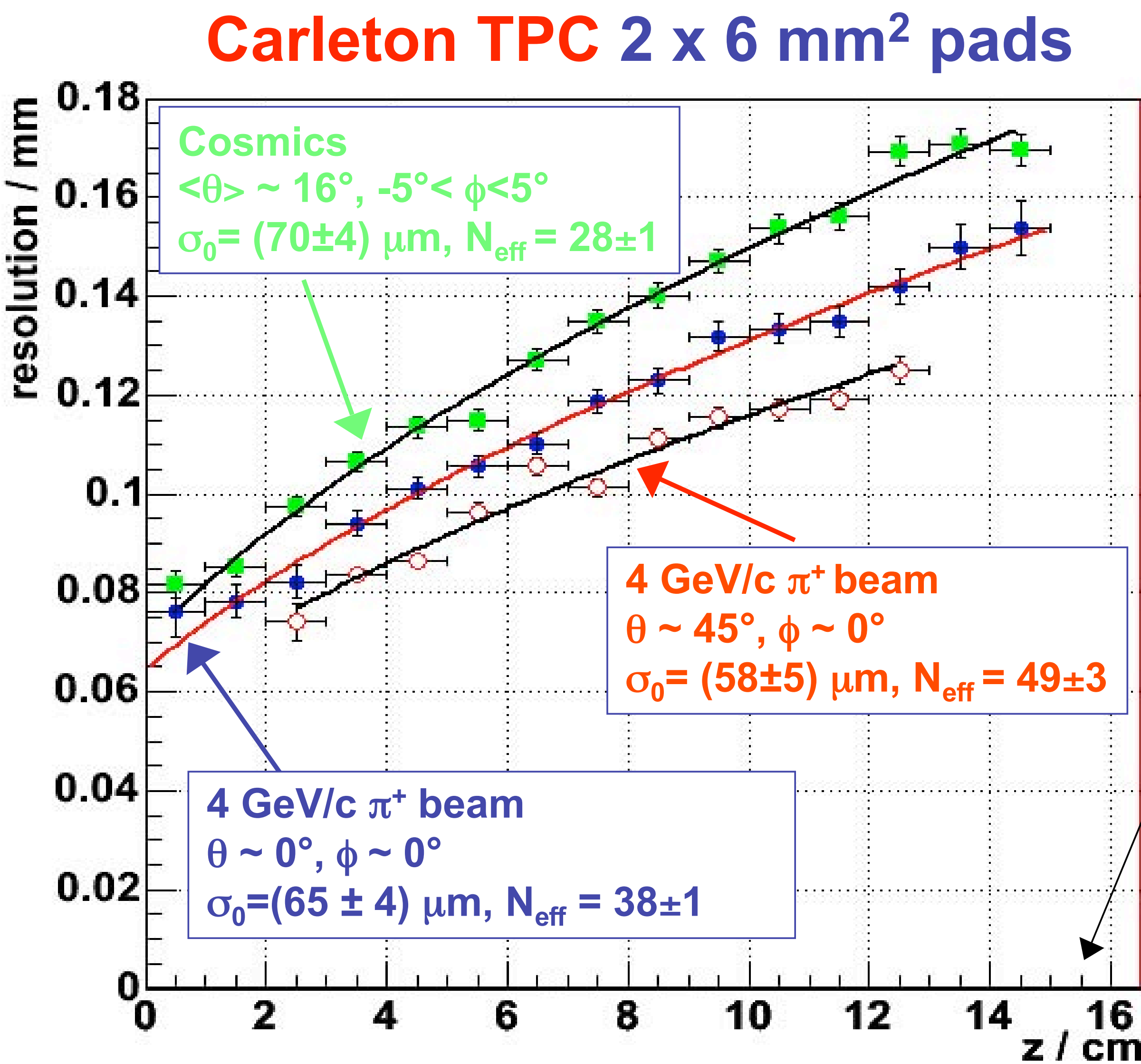
Examples:

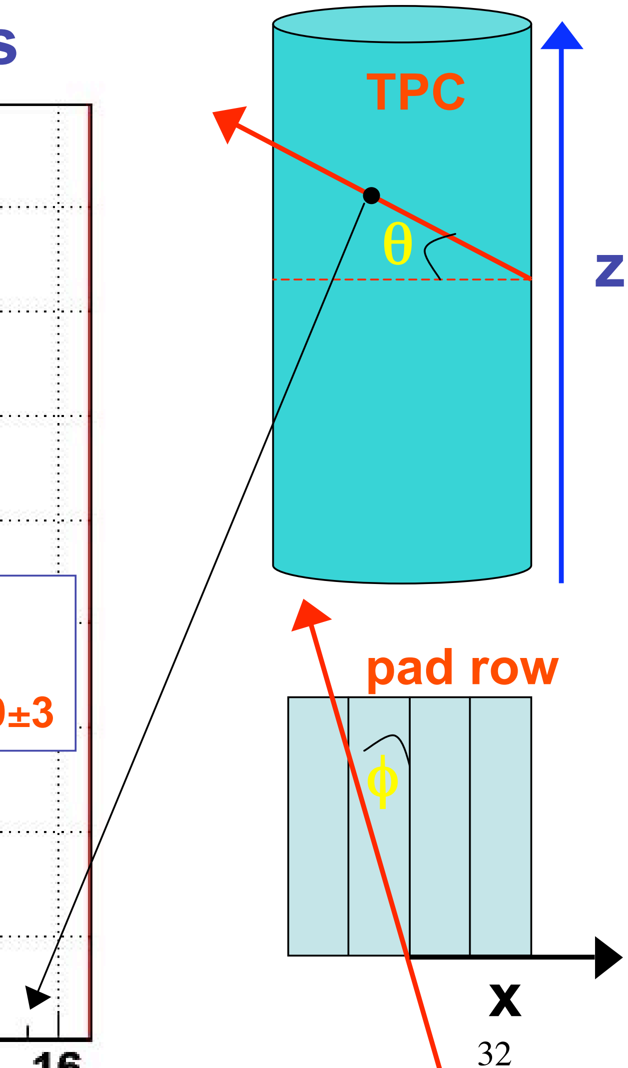
D_{Tr}~ 25 µm/√cm (Ar/CH4 91/9) Aleph TPC gas

~ 20 µm/√cm (Ar/CF4 97/3)

Extrapolate from present data to B = 4T
Use D_{Tr} = 25 µm/√cm
Resolution (2x6 mm² pads)
$\sigma_{Tr} \approx$ 100 µm (2.5 m drift)

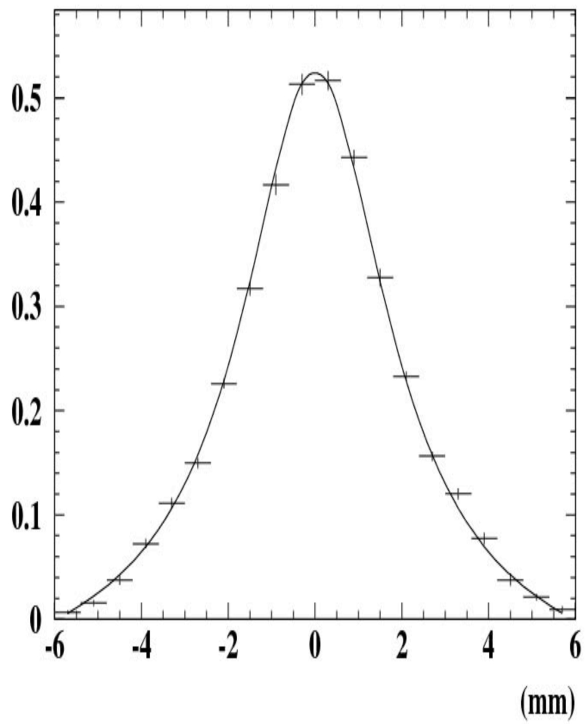
Transverse resolution with no magnet - Angle dependence
Ar+10% CO_2, D_{Tr} = 222 μ/√cm (Magboltz) E=300 V/cm



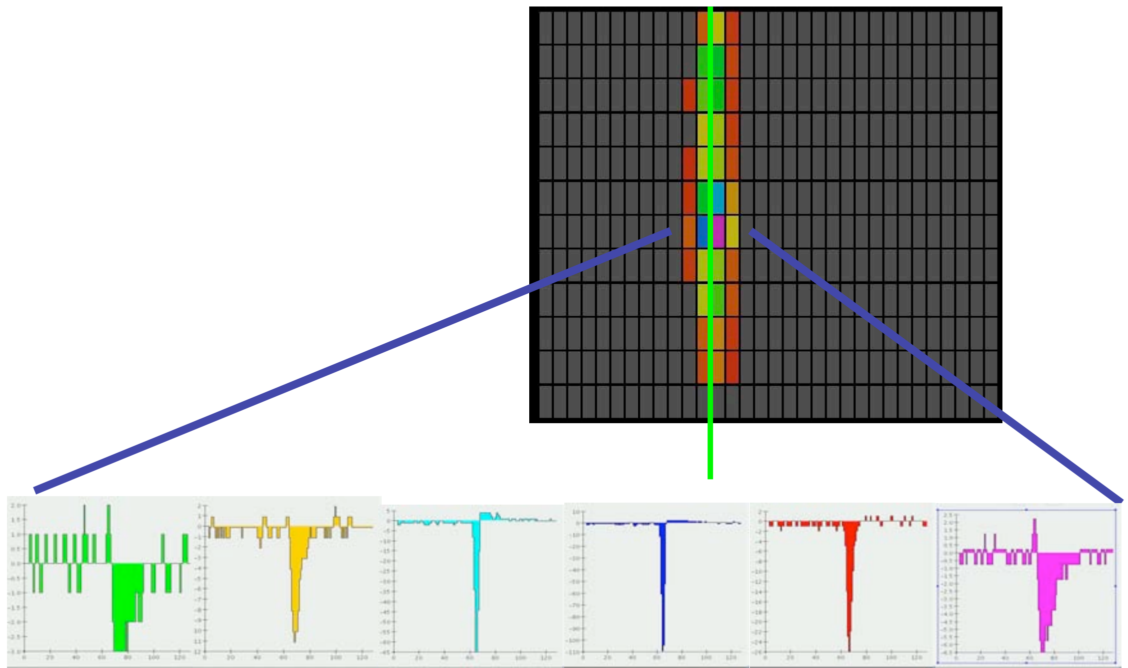


MT3 TPC event display + Micromegas read out with Aleph TPDs 2.3 x 6.3 mm^2 pads Ar+5%iC4H10

E=220V/cm D_{Tr}=193 µm/√cm @ B= 1T



Example pad response function

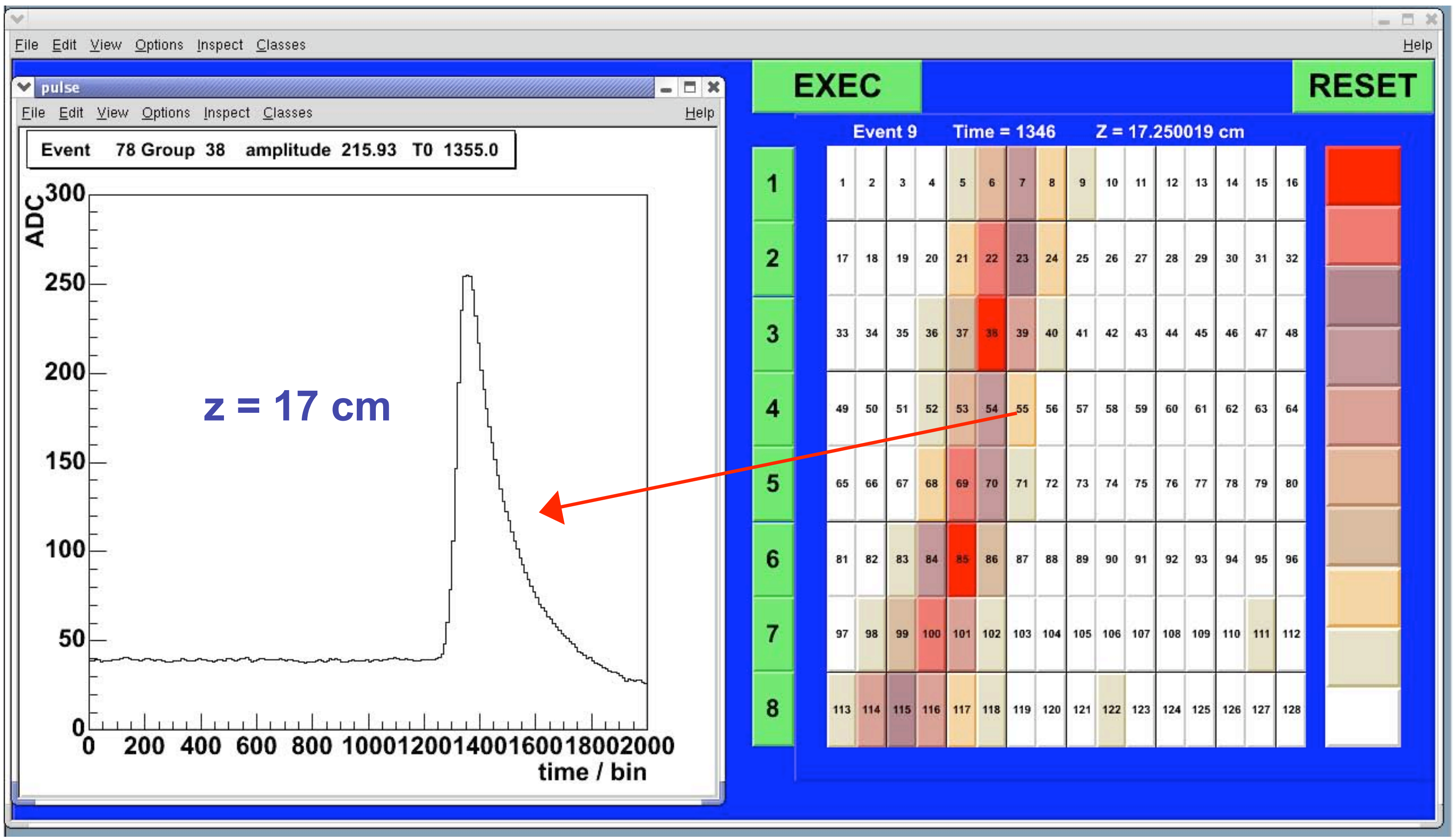


spreading of charge due to foil can be seen across six pads

Data analysis is in progress

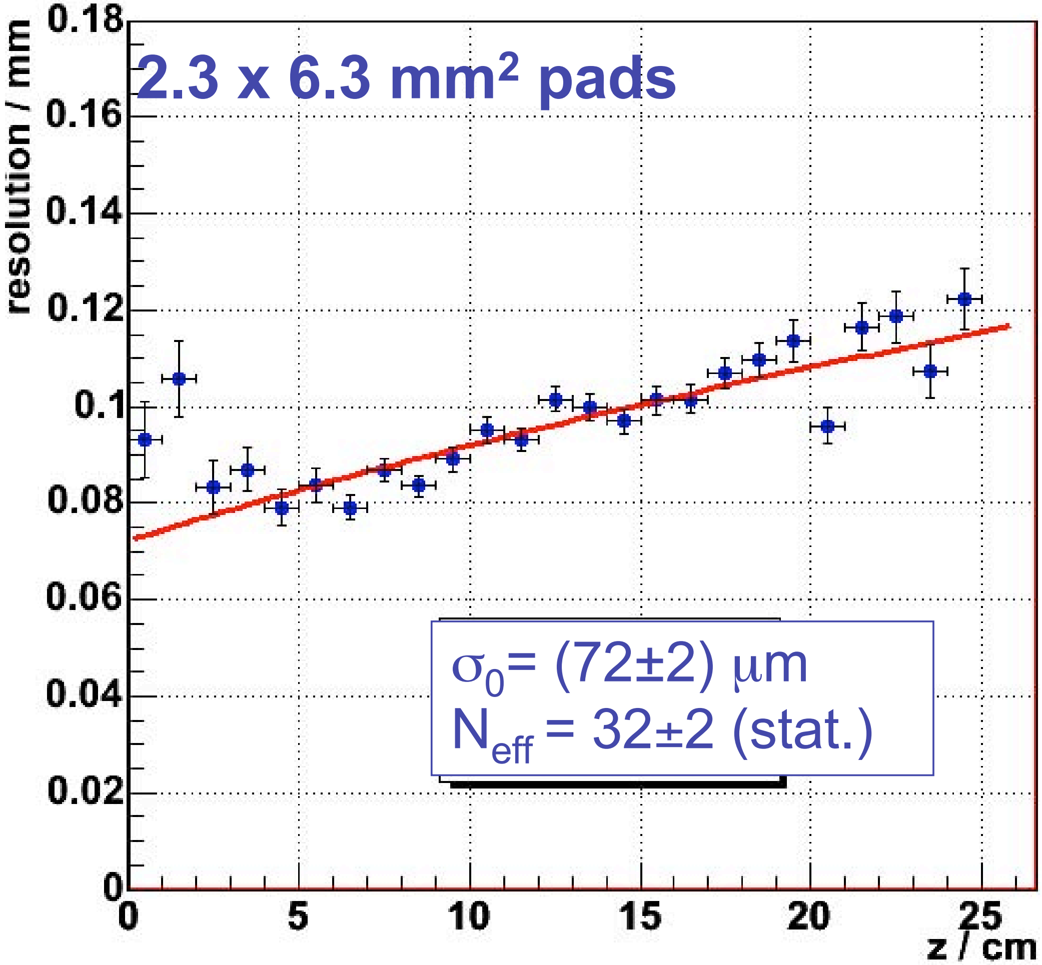
Track display MT3 TPC with triple GEM readout

Part of MT3-TPC read out with Carleton FADCs 4 GeV/c π+ beam
2.3 mm pitch x 6.3 mm pads 25 cm maximum drift distance
Ar/CH4 (95/5) E = 50 V/cm D_{Tr} = 102 µ/√cm (Magboltz) @ 1T



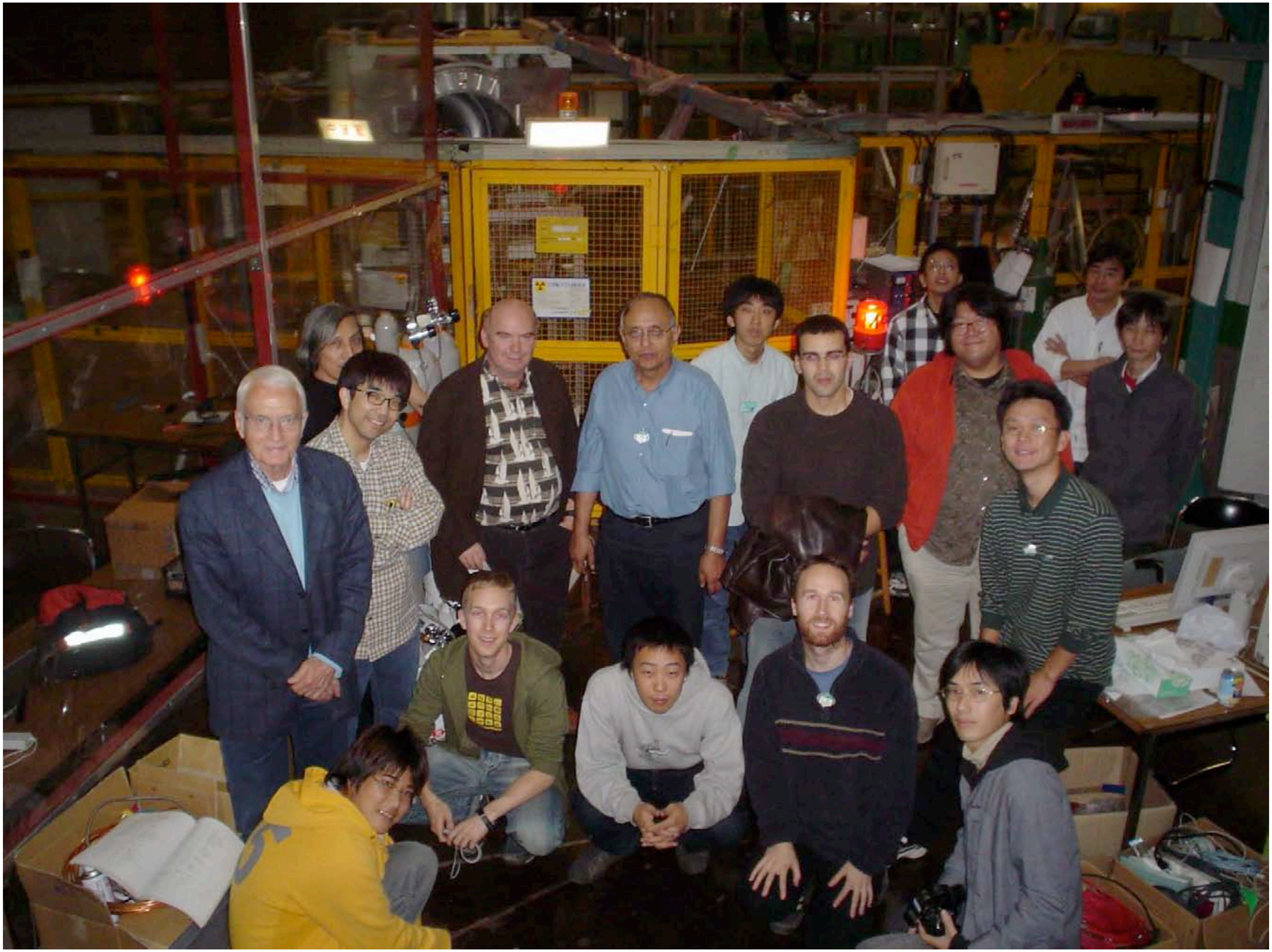
Transverse resolution - MT3-TPC with Triple GEM

Ar+5%CH4 E = 50 V/cm D_{Tr} = 102 μ/√cm (Magboltz) @ 1T



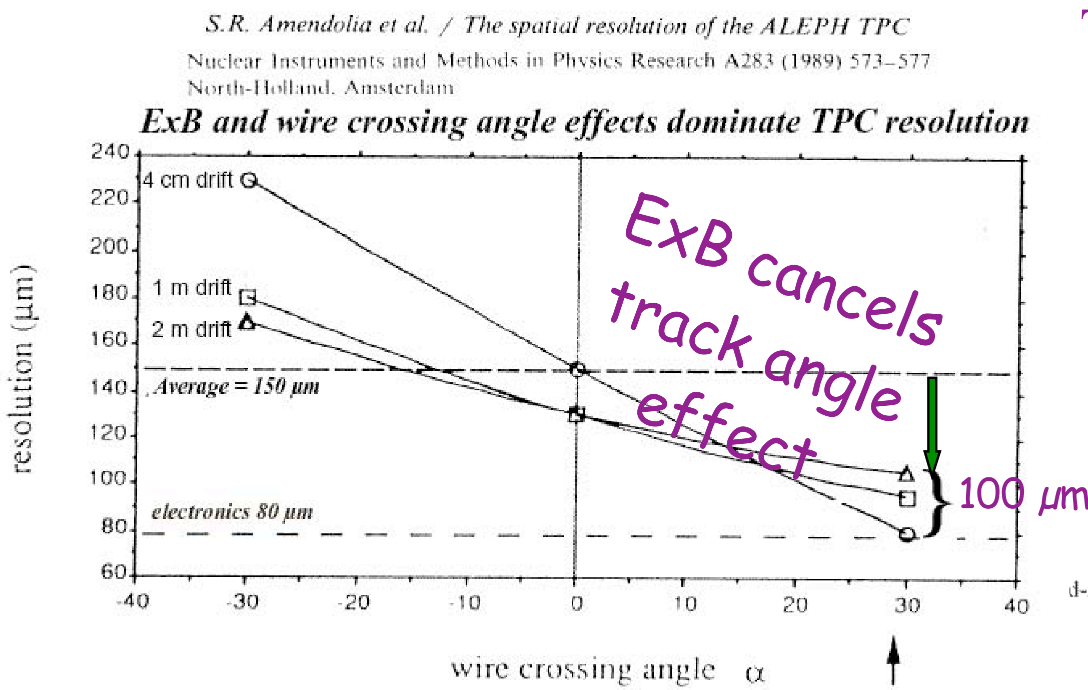
Summary

- Traditional MPGD-TPC readout has difficulty achieving good resolution if wide pads similar in width to conventional wire TPC pads are used.
- With charge dispersion, the cluster charge can be dispersed in a controlled way such that wide pads can be used without sacrificing resolution. With such a readout system, we have achieved excellent resolution with wide pads both for the GEM and the Micromegas.
- The ILC-TPC resolution goal, 100 μm for all tracks, should be feasible with 2 x 6 mm^2 pads with a good understanding of systematics.
- R&D plans - cosmic ray TPC tests at 4 T & two track resolution studies in a beam.
- R&D issues: New technology issues of fabrication & quality control, understanding/reducing bias. As charge dispersion pulses are slow, ~25 MHz digitizers could be used.

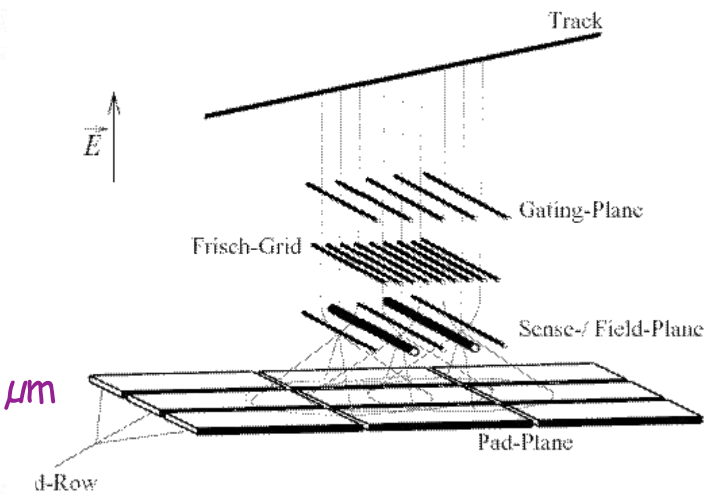


Conventional TPCs never achieve their potential!

Example:Systematic effects in Aleph TPC at LEP



TPC wire/pad readout



- Average Aleph resolution ~ 150 μm
- About 100 μm best for all drift distances
- Limit from diffusion σ (10 cm drift) ~ 20 μm; σ (2 m drift) ~ 90 μm