TPC Readout Development with Charge Dispersion Signal

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Outline

- Principle of Charge Dispersion Signal with MPGD
- Recent Results
- Applications: ILC & T2K
- Simulation Framework
- Summary

Motivation and Principle

Diffusion sets the fundamental limit on achievableTPC resolution

- The physics limit of TPC resolution comes from transverse diffusion:

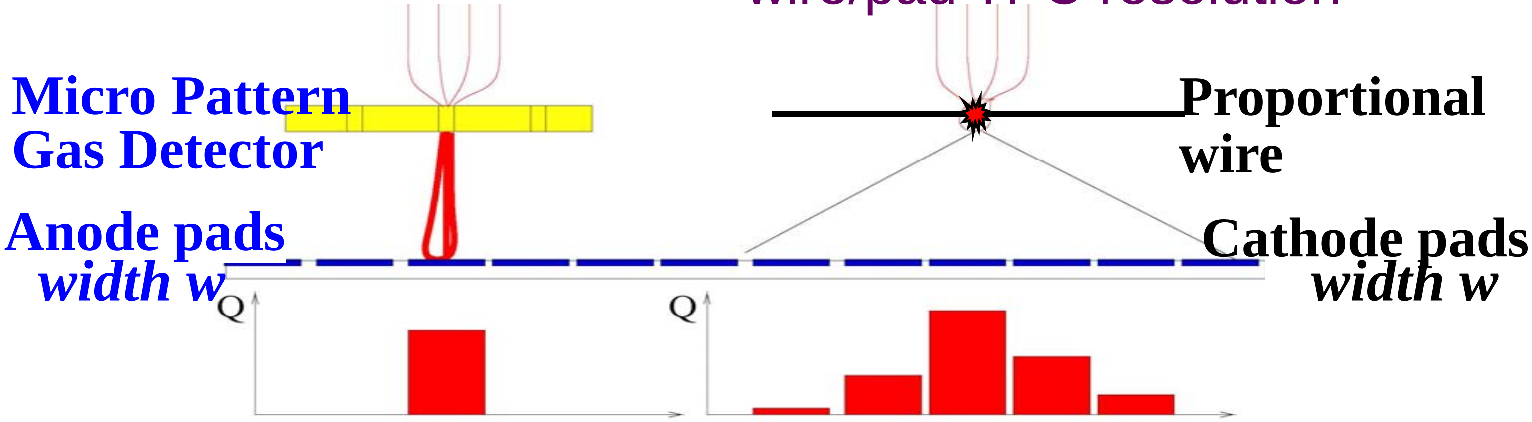
$$\sigma_x{}^2 \approx \frac{D_{Tr}^2 \cdot z}{N_{eff}}$$

N_{eff} = effective electron statistics.

- For best resolution, choose a gas with smallest diffusion in a high magnetic field

Pad width would limits MPGD TPC resolution

ExB systematics limits wire/pad TPC resolution



Direct signal on the MPGD anode pad

For small diffusion, less precise centroid for wide pads

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

Induced cathode signal determined by geometry

Accurate centroid determination possible with wide pads

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

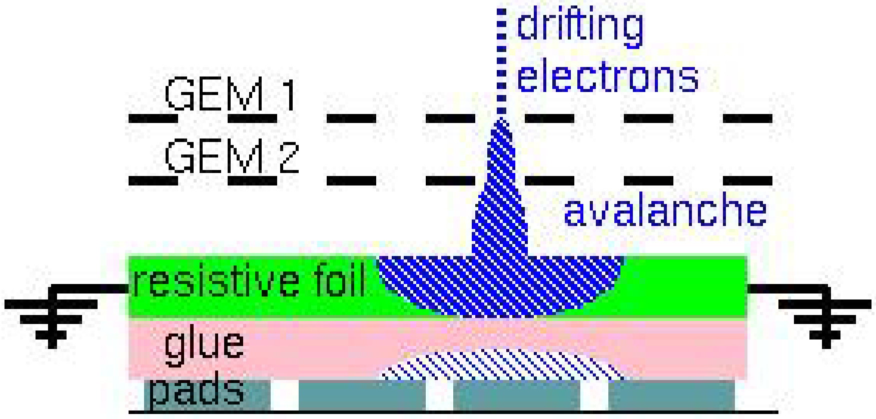
Charge dispersion in a MPGD with a resistive anode

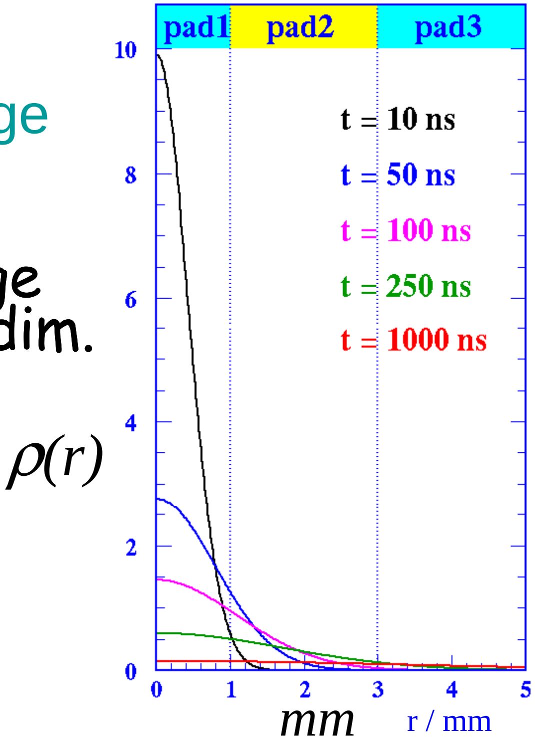
- Modified GEM anode with a high resistivity film bonded to a readout plane with an insulating spacer.
- 2-dimensional continuous RC network defined by material properties & geometry.
- Point charge at r = 0 & t = 0 disperses with time.
- Time dependent anode charge density sampled by readout pads.

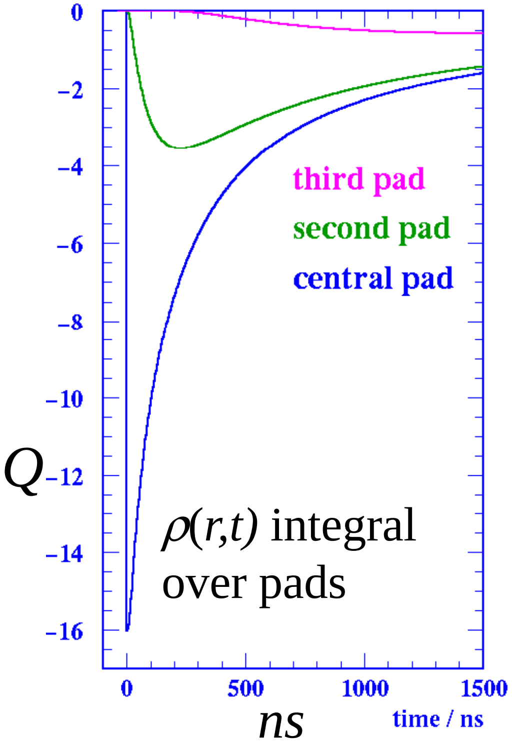
Equation for surface charge density function on the 2-dim. continuous RC network:

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

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

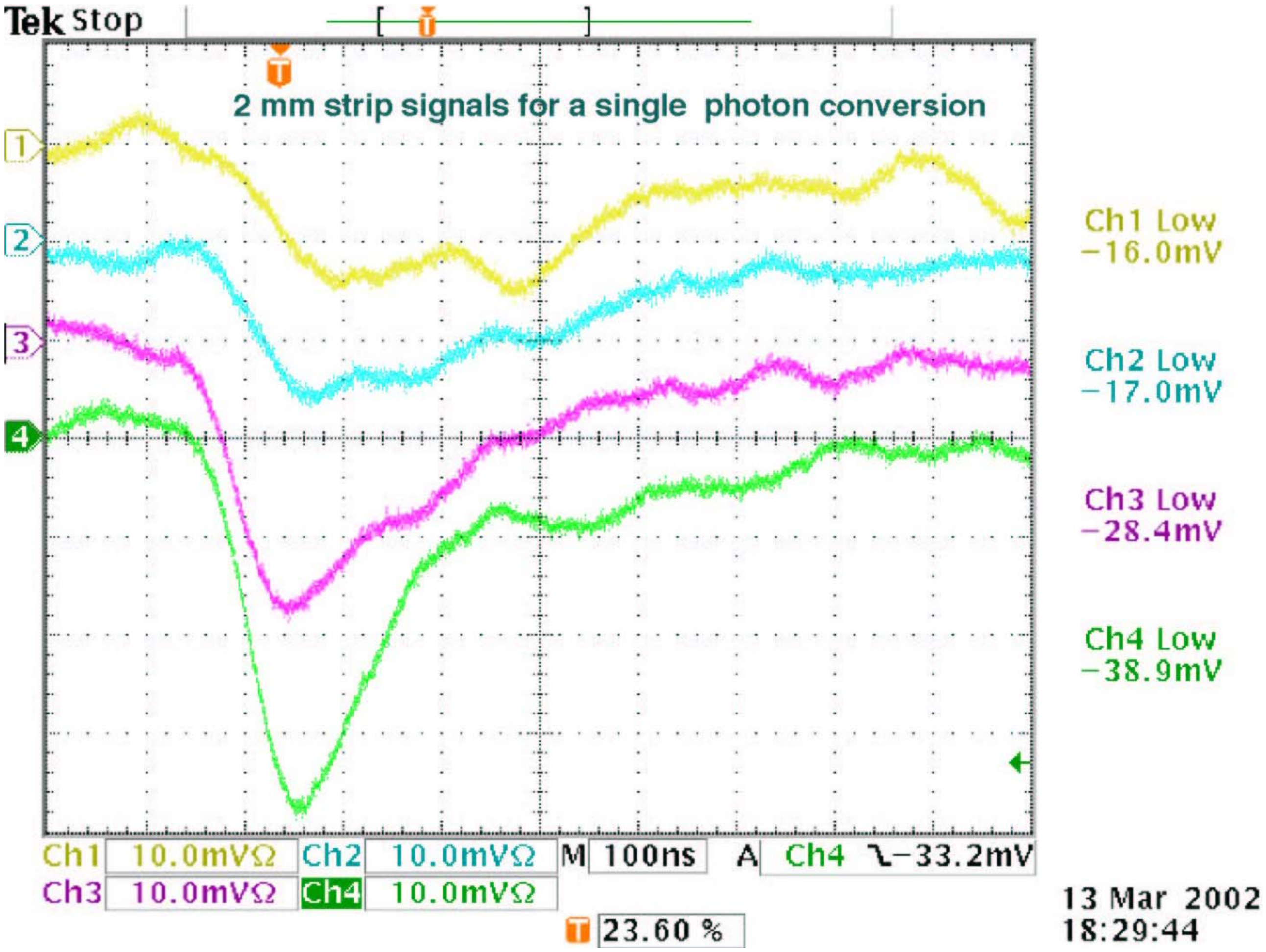


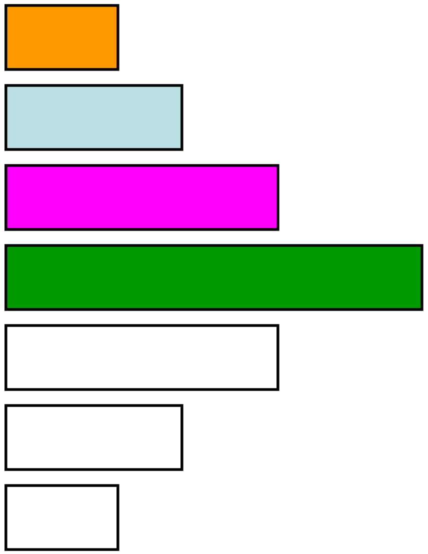




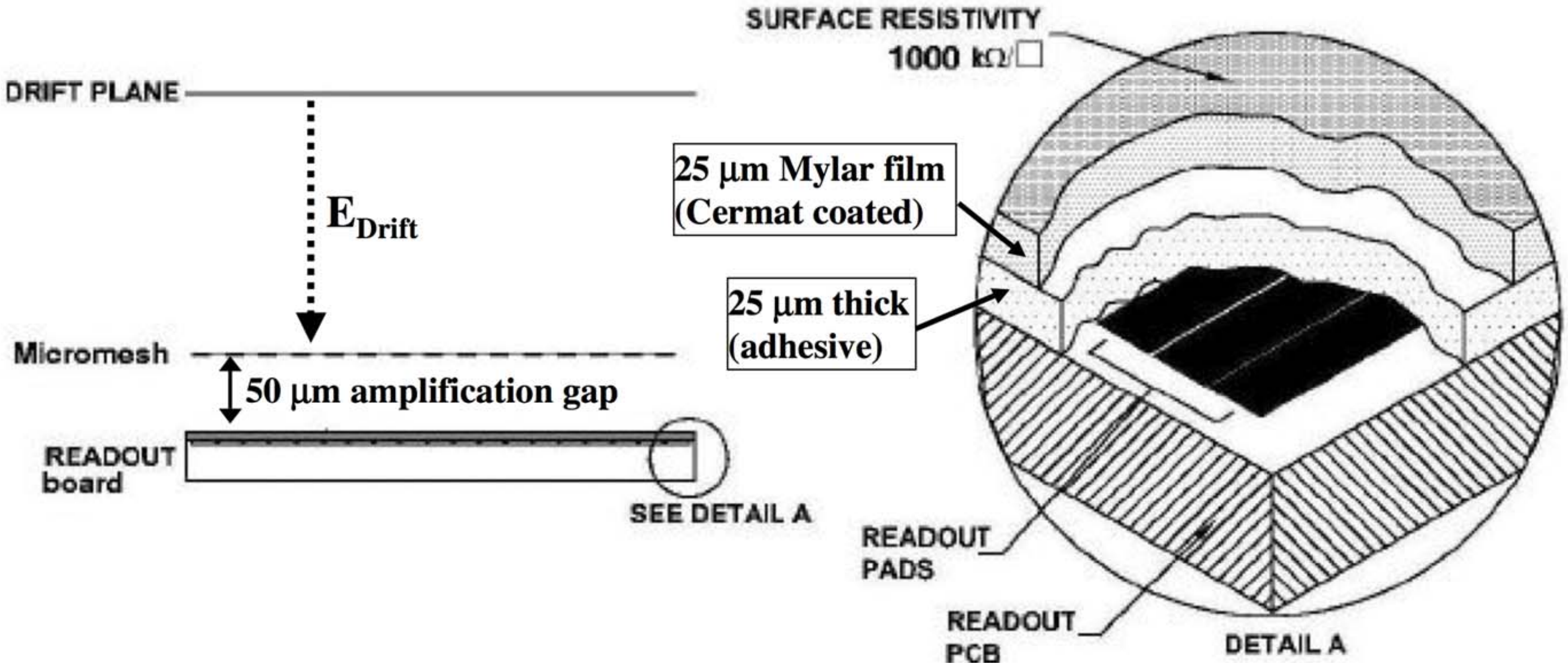
The proof - a 6 keV ^{55}Fe x-ray photon event as seen in our first GEM test cell with a resistive anode

Collimator size ~ 1 mm ; signal detected by ~7 anodes (2 mm width)





Micromegas with a resistive readout

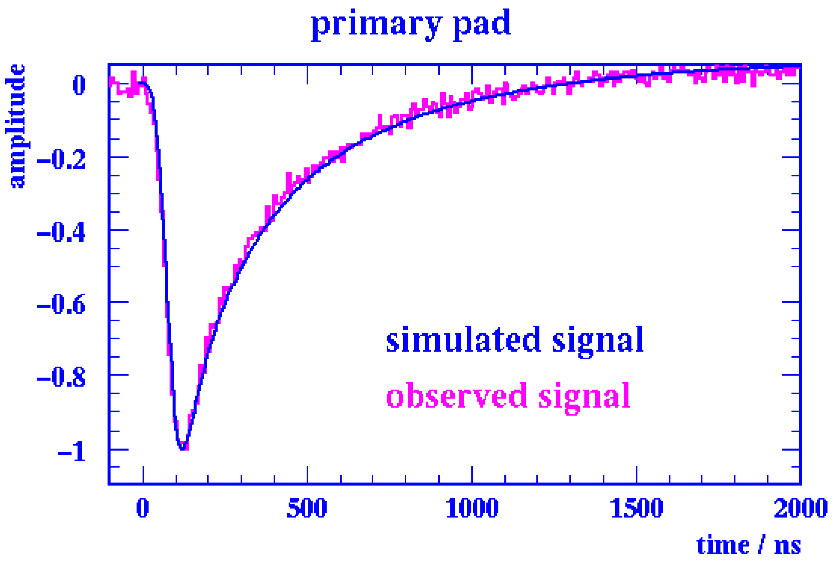


Charge dispersion signals for the GEM readout

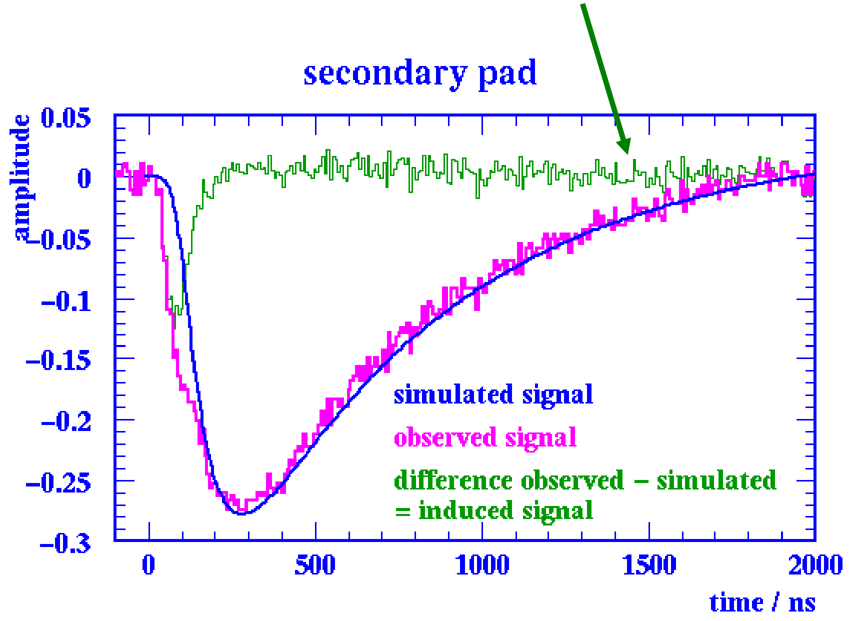
Simulation vs. measurement for Ar+10%CO$_2$ (2 x 6 mm^2 pads)

Collimated ~ 50 μm 4.5 keV x-ray spot on pad centre.

Difference = induced signals (MPGD '99, Orsay & LCWS 2000) were not included in simulation).



primary pad



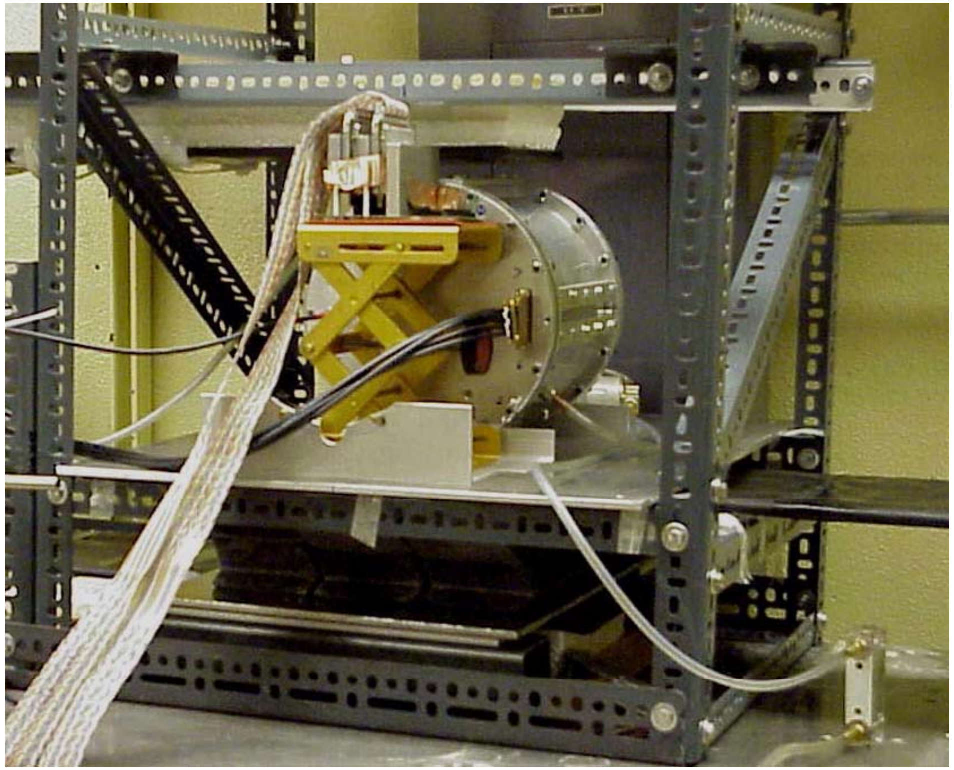
secondary pad

Simulated primary pulse is normalized to the data.

Primary pulse normalization used for the simulated secondary pulse

Initial B=0 Cosmic Ray Tests in Canada

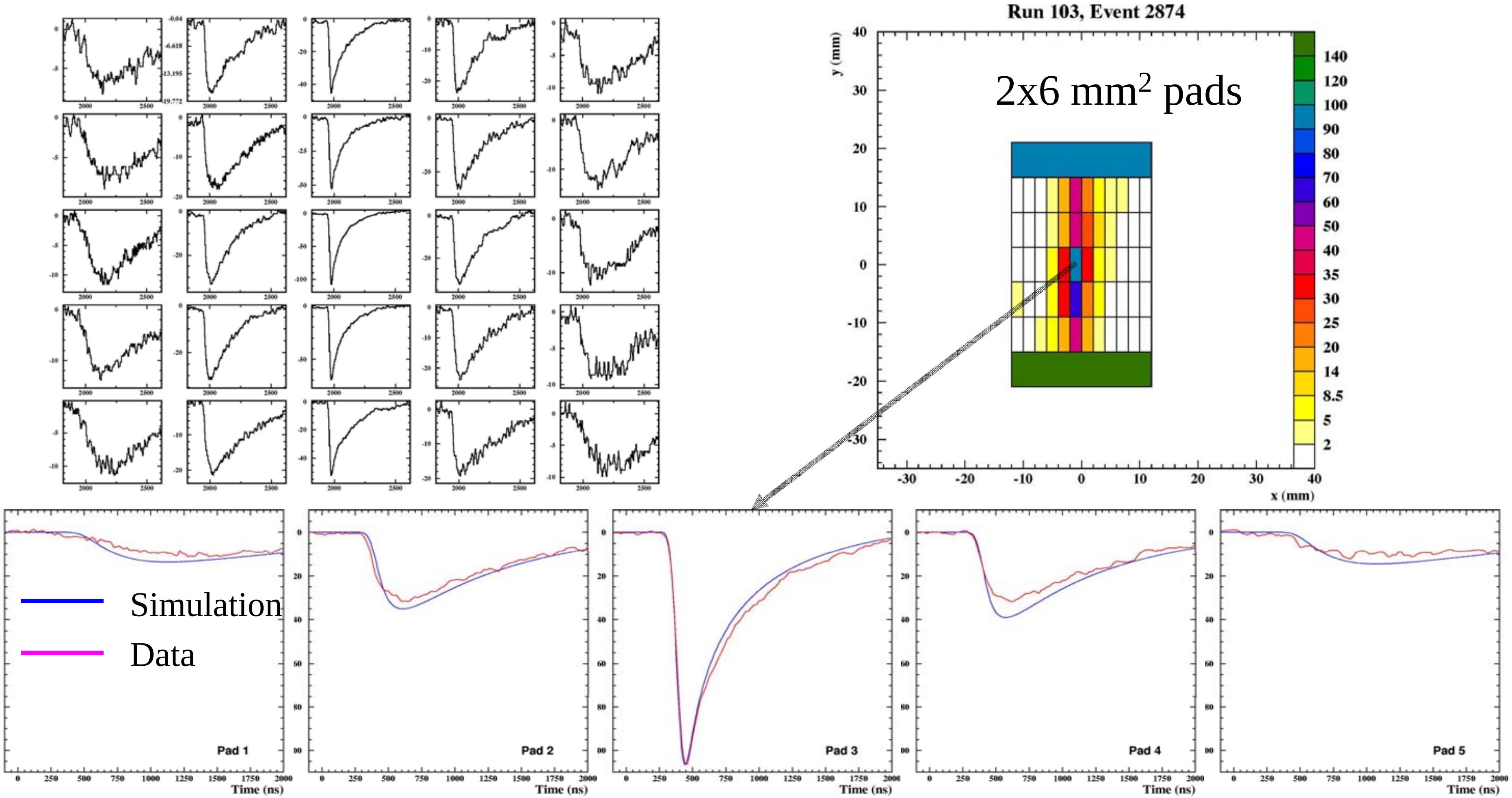
- 15 cm drift length with GEM or Micromegas readout
- Ar+10% CO_2 chosen to simulate low transverse diffusion in a magnetic field.
- Aleph charge preamps. $\tau_{Rise} = 40$ ns, $\tau_{Fall} = 2\ \mu s$,
- 200 MHz FADCs rebinned to digitization effectively at 25 MHz.
- In contrast to normal practice, we use digitized preamp pulse with no shaping so as not to lose electron statistics.



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.

GEM TPC charge dispersion simulation (B=0)
Cosmic ray track, Z = 67 mm Ar+10%CO_2



Centre pulse used for normalization - no other free parameters.

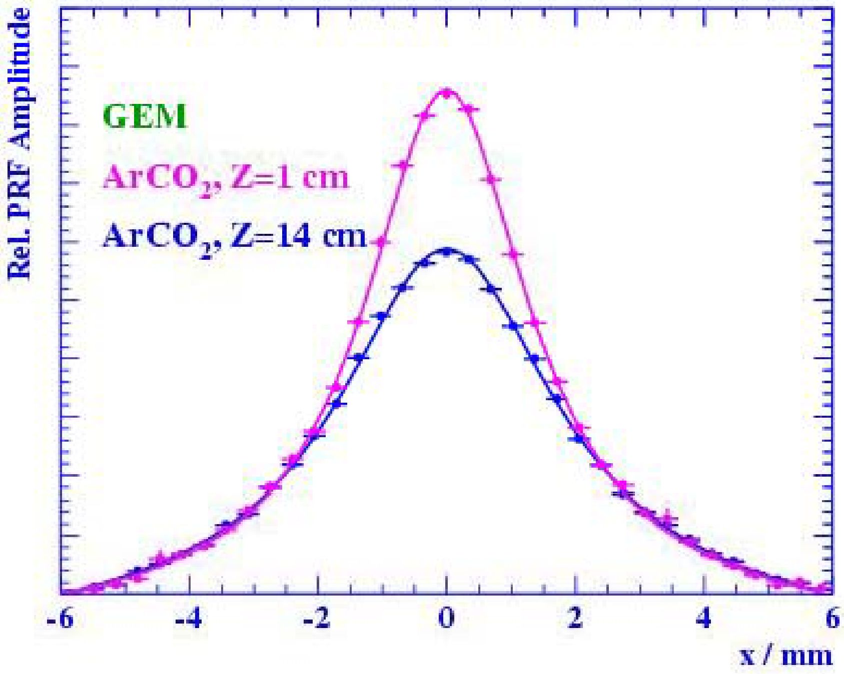
Charge dispersion pulses & pad response function (PRF)

- Non-standard variable pulse shape; both the rise time & pulse amplitude depend on track position.
- The PRF is a measure of signal size as a function of track position relative to the pad.
- We use pulse shape information to optimize the PRF.
- The PRF can, in principle, be determined from simulation.
- However, system RC non-uniformities & 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 used for calibration. Remaining data used for resolution studies.

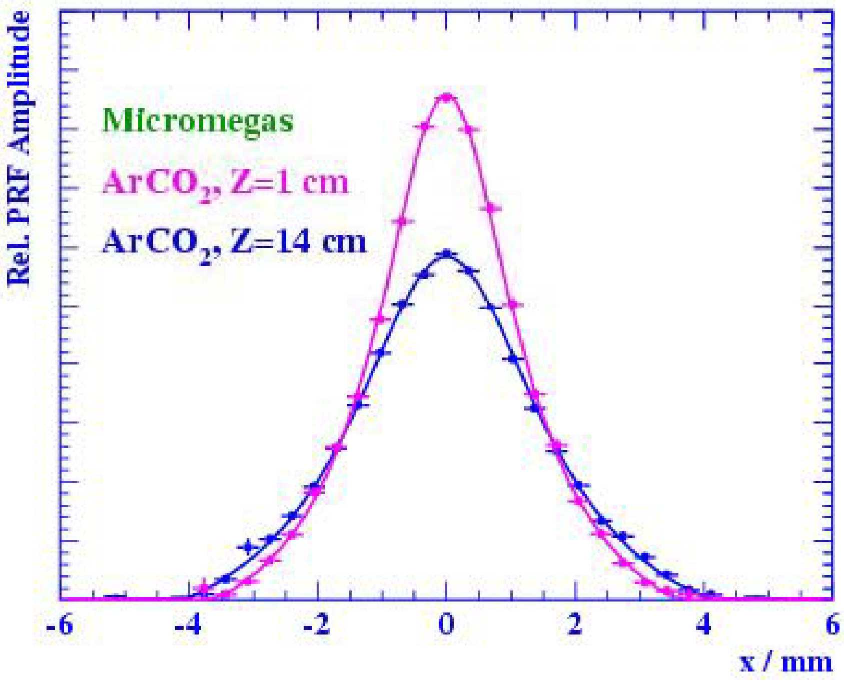
GEM & Micromegas PRFs for tracks

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



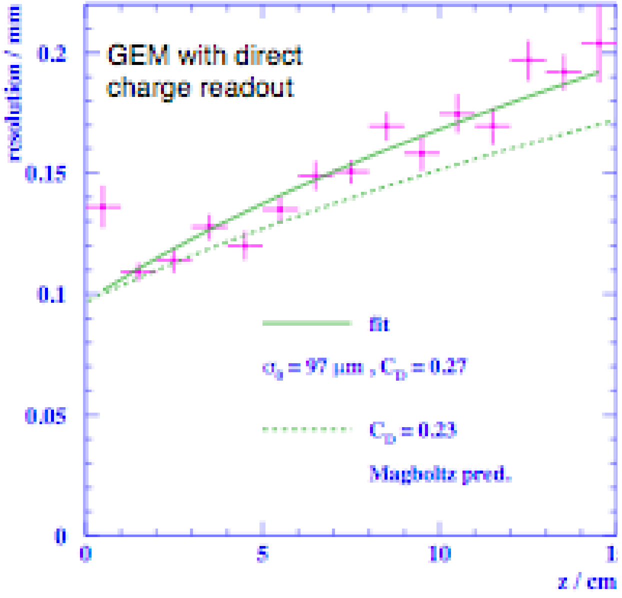
Micromegas PRFs

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

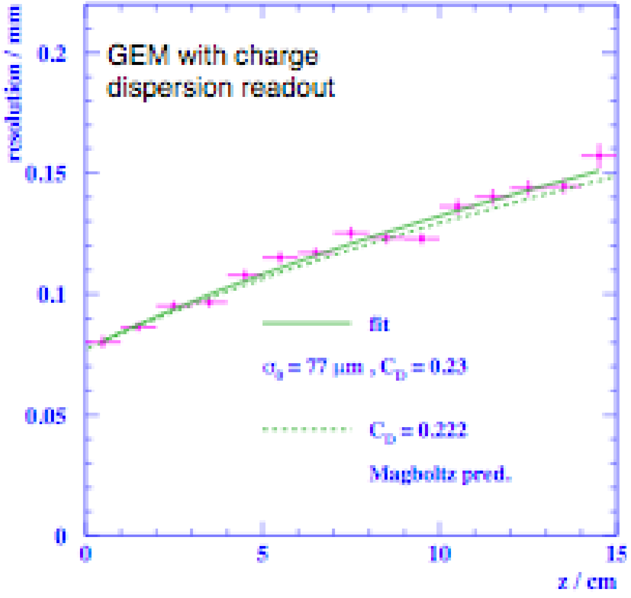
Results

B=0 Cosmic Ray Transverse Resolution $Ar+10\%CO_2$

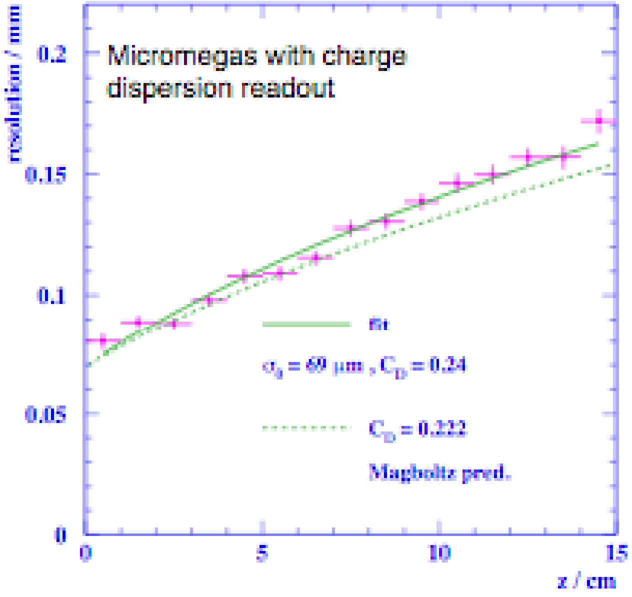
R.K.Carnegie et.al.,
NIM A538 (2005) 372



K. Boudjemline et.al.,
NIM A - in press



A. Bellerive et al,
LCWS 2005, Stanford



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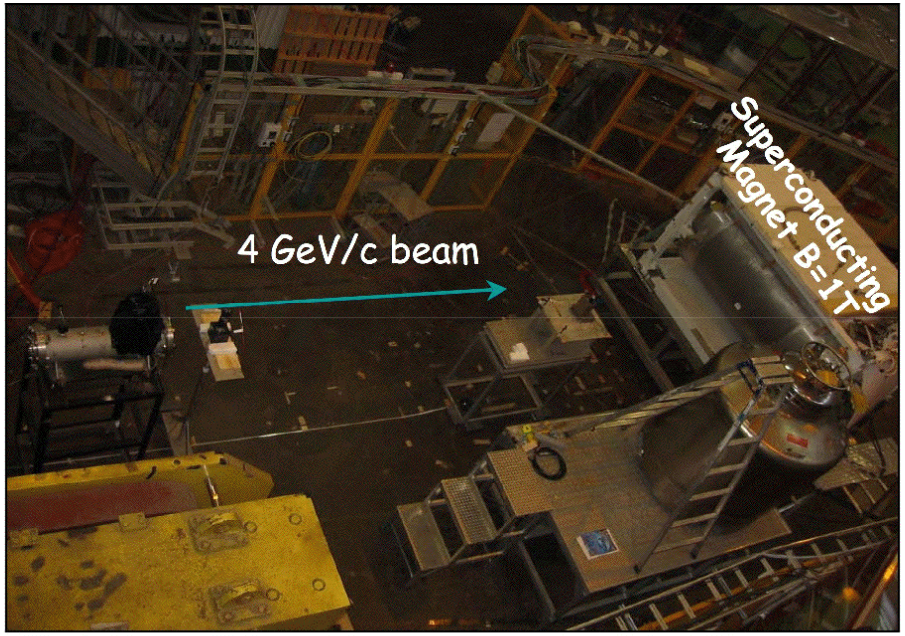
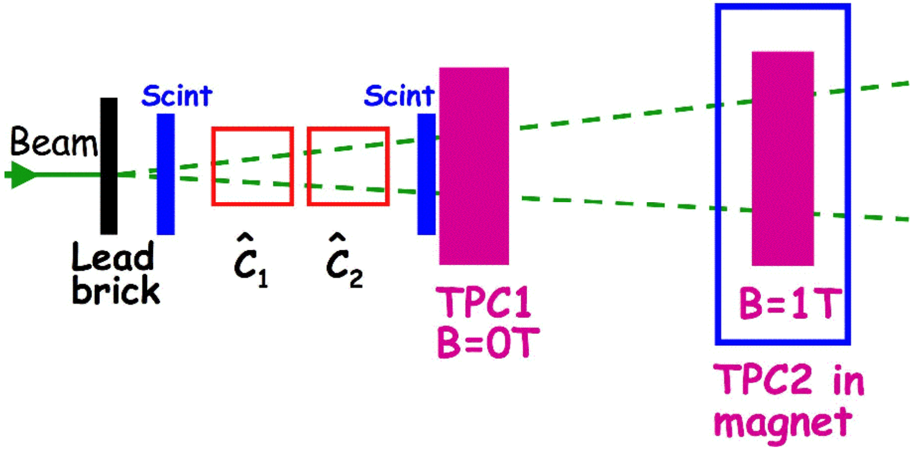
$$\sqrt{\sigma_0{}^2 + \frac{C_D{}^2}{N_e} z}$$

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

KEK beam test in a magnet at 1 T Canadian/French & Japan/German TPCs



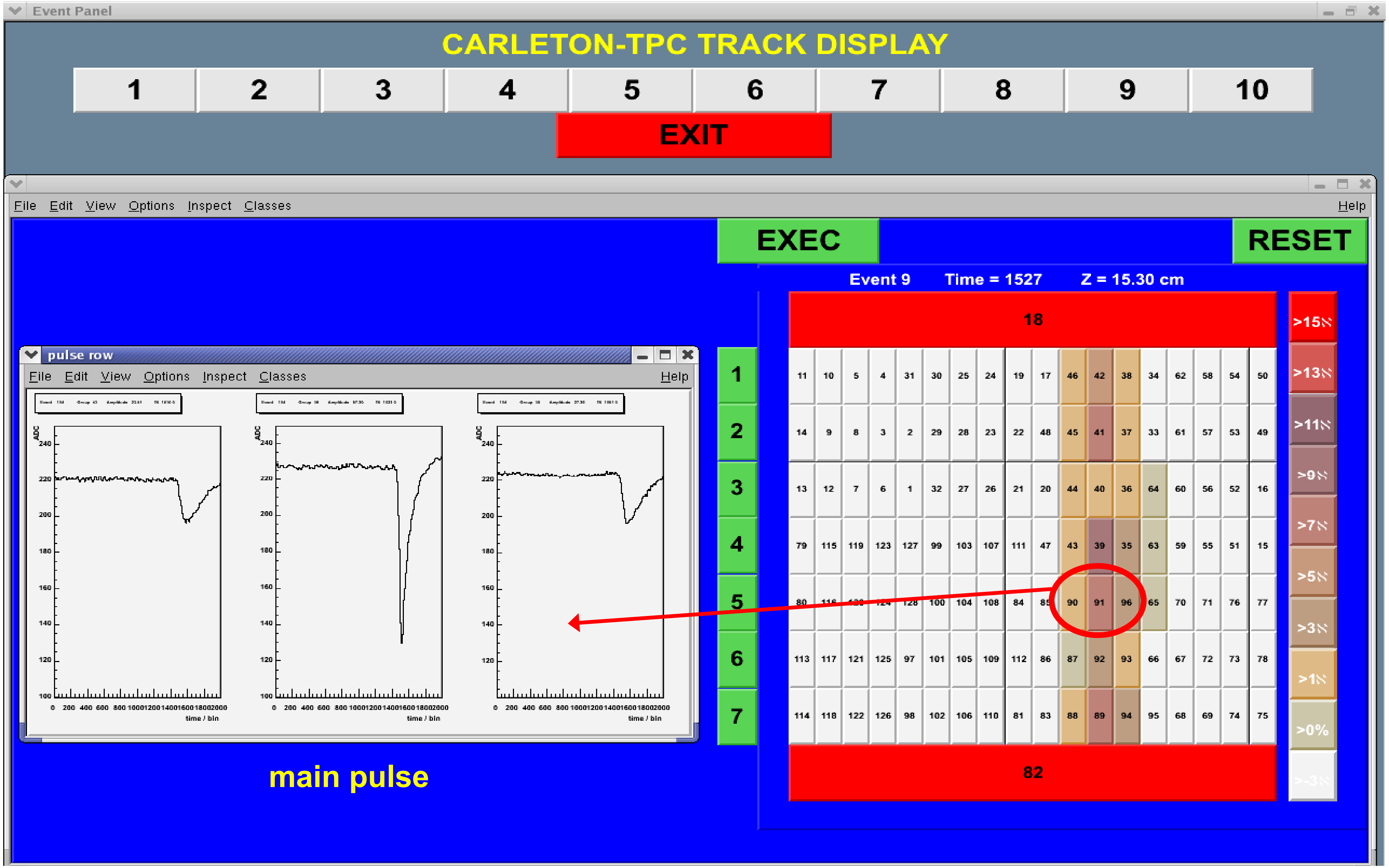
- 4 GeV/c hadrons (mostlyπs)
- 0.5 & 1 GeV/c electrons
- Super conducting 1.2 T magnet without return yoke
- Inner diameter : 850 mm
- Effective length: 1 m



Canadian TPC in the beam outside the magnet

Track display - Ar+5%iC4H10
Micromegas 2 x 6 mm^2 pads B = 1 T

Z_{drift} = 15.3 cm



Event 9 Time = 1527 Z = 15.30 cm

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1	11	10	5	4	31	30	25	24	19	17	46	42	38	34	62	58	54	50
2	14	9	8	3	2	29	28	23	22	48	45	41	37	33	61	57	53	49
3	13	12	7	6	1	32	27	26	21	20	44	40	36	64	60	56	52	16
4	79	115	119	123	127	99	103	107	111	47	43	39	35	63	59	55	51	15
5	80	116	120	124	128	100	104	108	84	85	90	91	96	65	70	71	76	77
6	113	117	121	125	97	101	105	109	112	86	87	92	93	66	67	72	73	78
7	114	118	122	126	98	102	106	110	81	83	88	89	94	95	68	69	74	75

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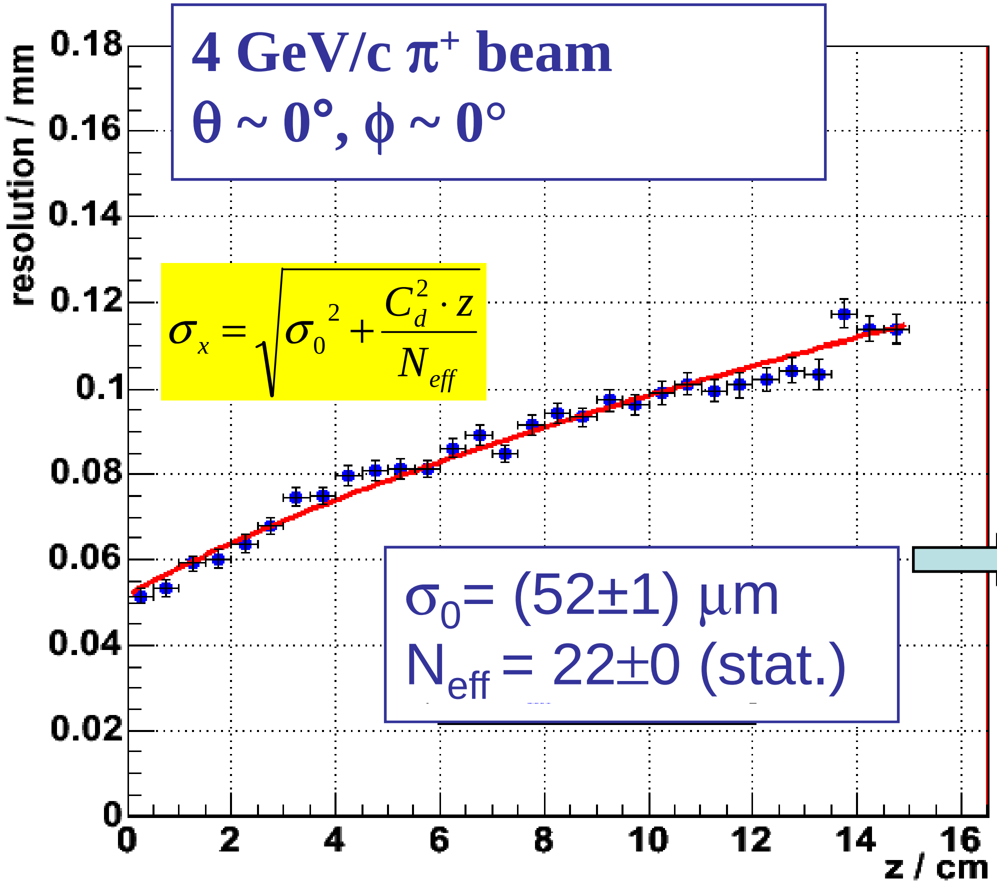
Transverse spatial resolution Ar+5%iC4H10 E=70V/cm D_{Tr} = 125 µm/√cm (Magboltz) @ B= 1T

Micromegas TPC 2 x 6 mm^2 pads - Charge dispersion readout



4 GeV/c π^+ beam
$\theta \sim 0°$, $\phi \sim 0°$

$$\sigma_x = \sqrt{\sigma_0^{\,2} + \frac{C_d^2 \cdot z}{N_{eff}}}$$

σ_0= (52±1) µm
N_{eff} = 22±0 (stat.)

- Strong suppression of transverse diffusion at 4 T.

Examples:

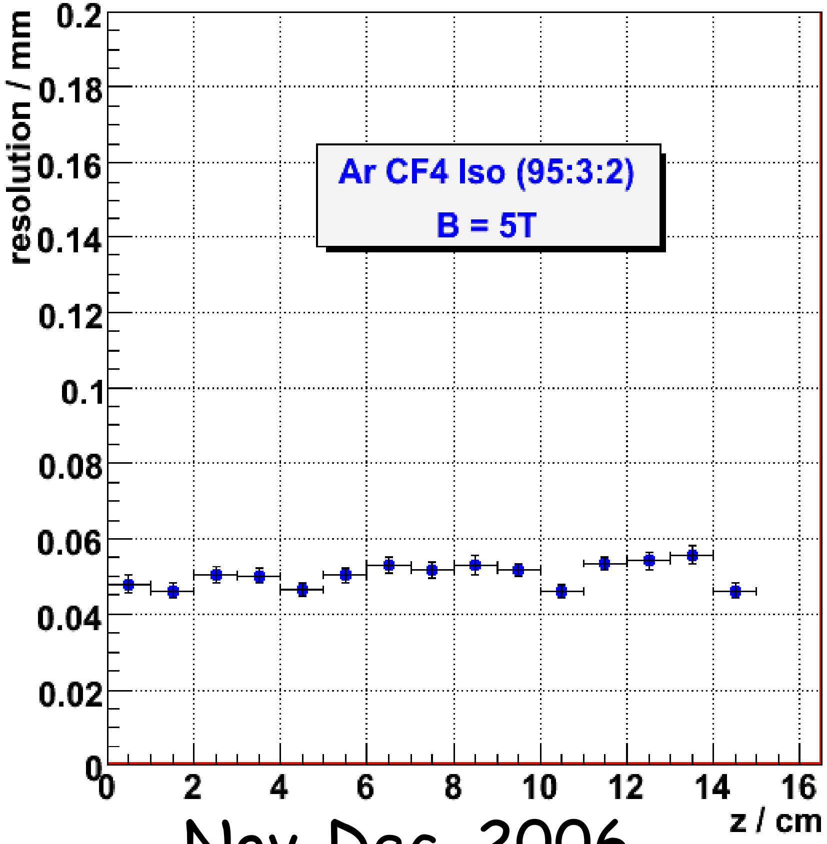
D_{Tr}~ 25 µm/√cm (Ar/CH4 91/9)
Aleph TPC gas
~ 20 µm/√cm (Ar/CF4 97/3)

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

Extrapolation confirmed in 5 T cosmic tests at DESY

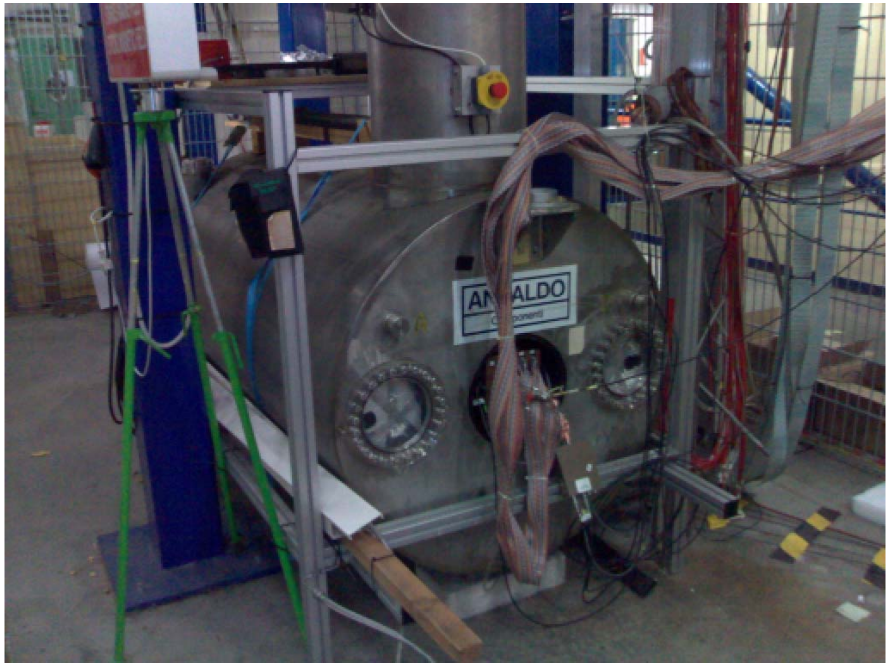
COSMo (Carleton, Orsay, Saclay, Montreal) Micromegas TPC

D_{Tr}= 19 μm/√cm, **2 x 6 mm² pads**



Nov-Dec, 2006

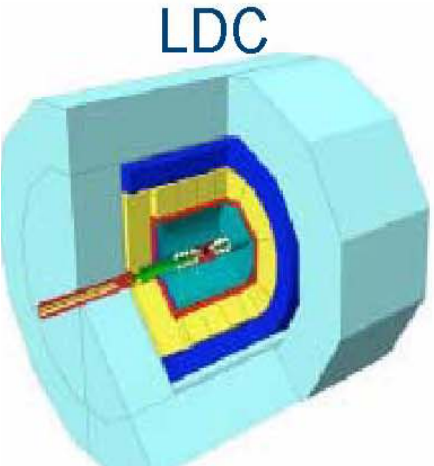
NEW



~ 50 μm av. resolution over 15 cm (diffusion negligible)
100 μm over 2 meters looks within reach!

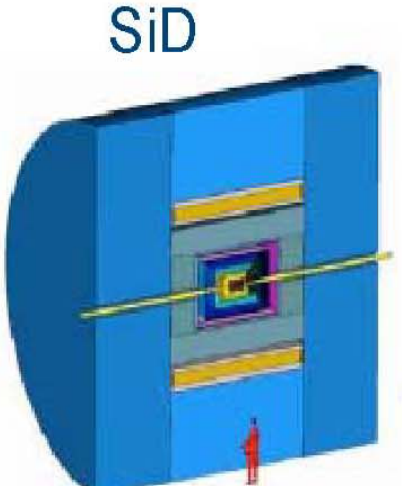
Applications

TPC tracker part of 3 present ILC detector concepts

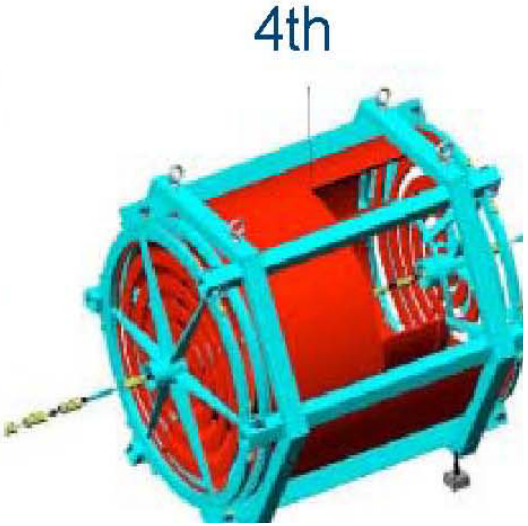


TPC (B=4T)

TPC (B=3T)



Silicon (B=5T)



TPC (B=3.5 T)

Demonstration phase ILC TPC R&D

- Canada has been involved from the beginning
- 2 mm x 6 mm pads (1,500,000 channels) for the readout with GEMs or Micromegas were proposed initially
- For the GEM, large transverse diffusion in the transfer & induction gaps provides a natural mechanism to disperse the charge and facilitate centroid determination.
  - The GEM will still need ~ 1 mm wide pads to achieve ~ 100 μm resolution goal with ~3,000,000 readout channels
  - Even narrower pads would be needed for the Micromegas

Development of the new concept of charge dispersion in a MPGD with a resistive anode makes position sensing insensitive to pad width

The technique works for both the GEM and the Micromegas

Charge dispersion concept to reduce #channels and hence cost

Preparing the detector for physics at ILC

- A formal Linear Collider TPC (LC-TPC) collaboration recently formed

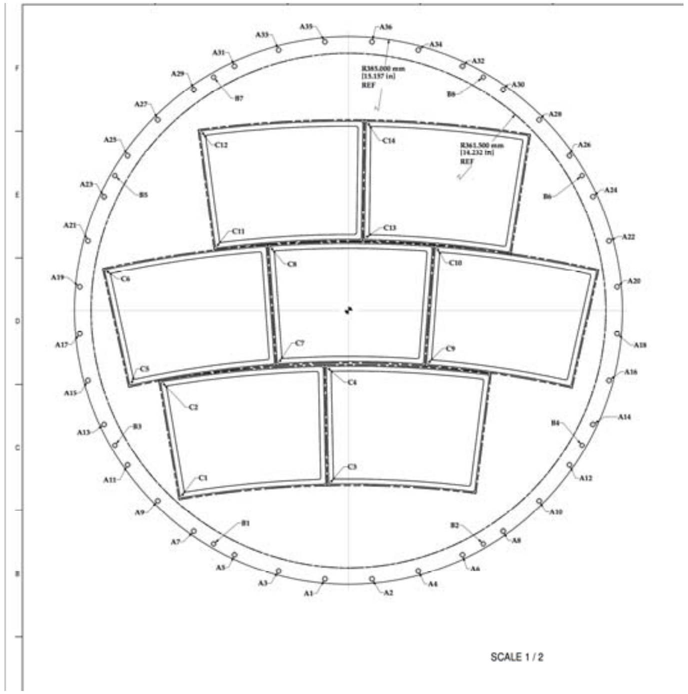
- Formal review of tracking systems at Beijing - First TPC assignment construct a 1 meter prototype & comprehensive beam tests in a 4 T magnet in a beam with ILC like time structure with **realistic electronics** by 2010 in time to write detector EDR.

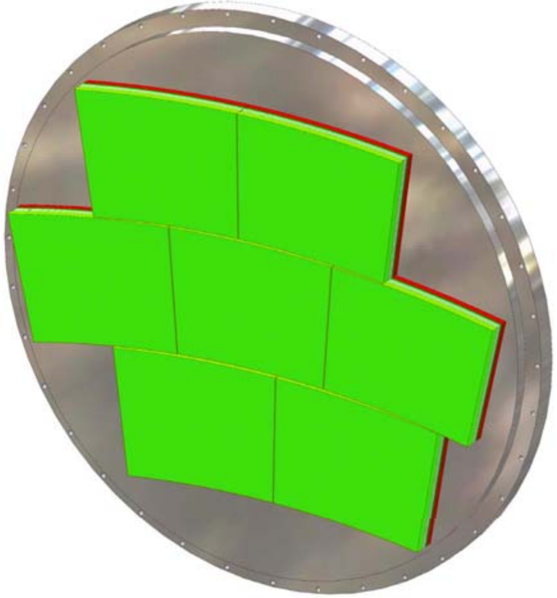
- Test two possible readout options being developed

  1) GEM with 1 mm pads

  2) Micromegas with 2 mm pads with charge dispersion readout

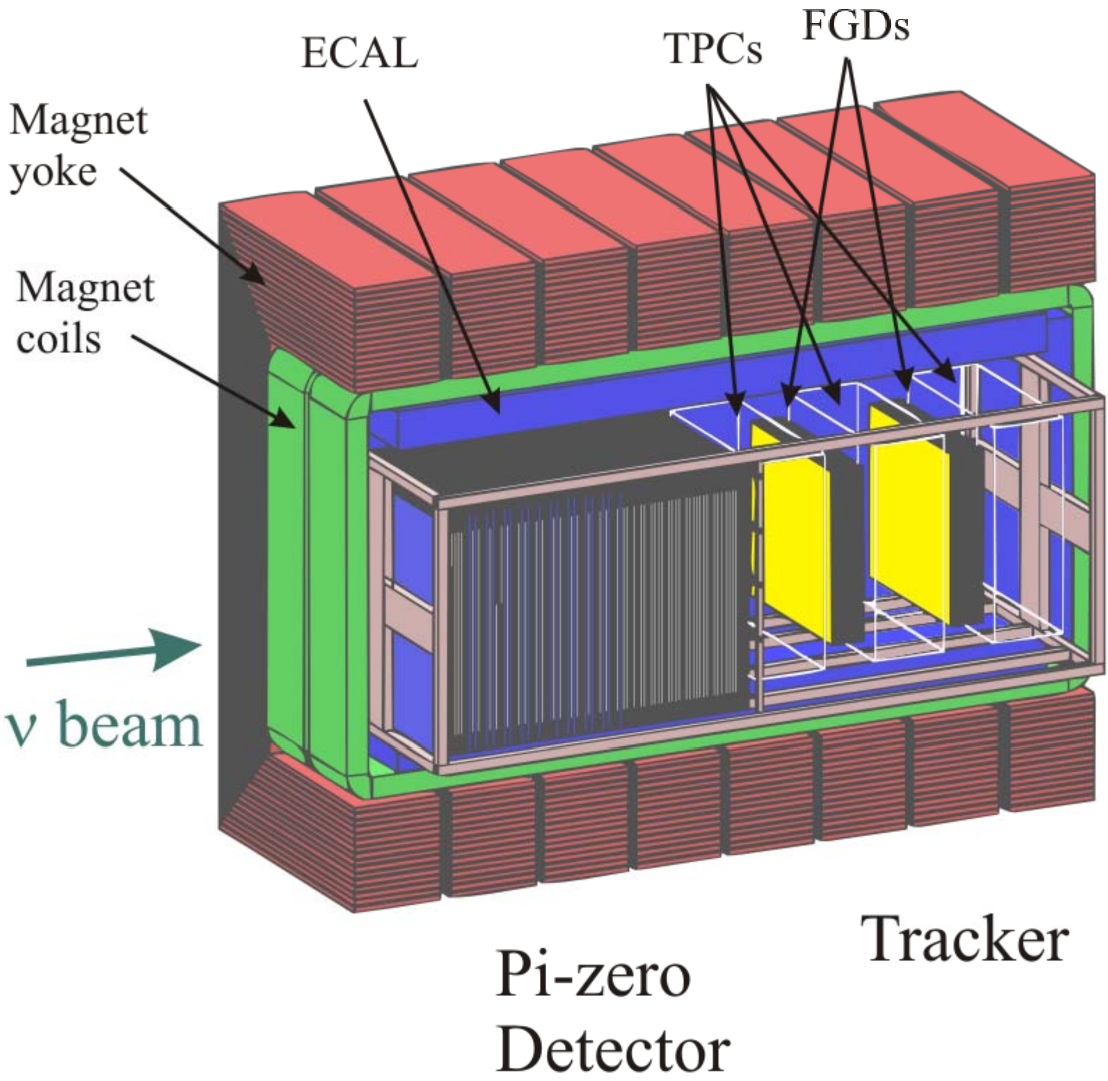
1 meter Large Prototype TPC being developed for 1 T tests at DESY (2008) & 4 T tests at Fermilab (2010)





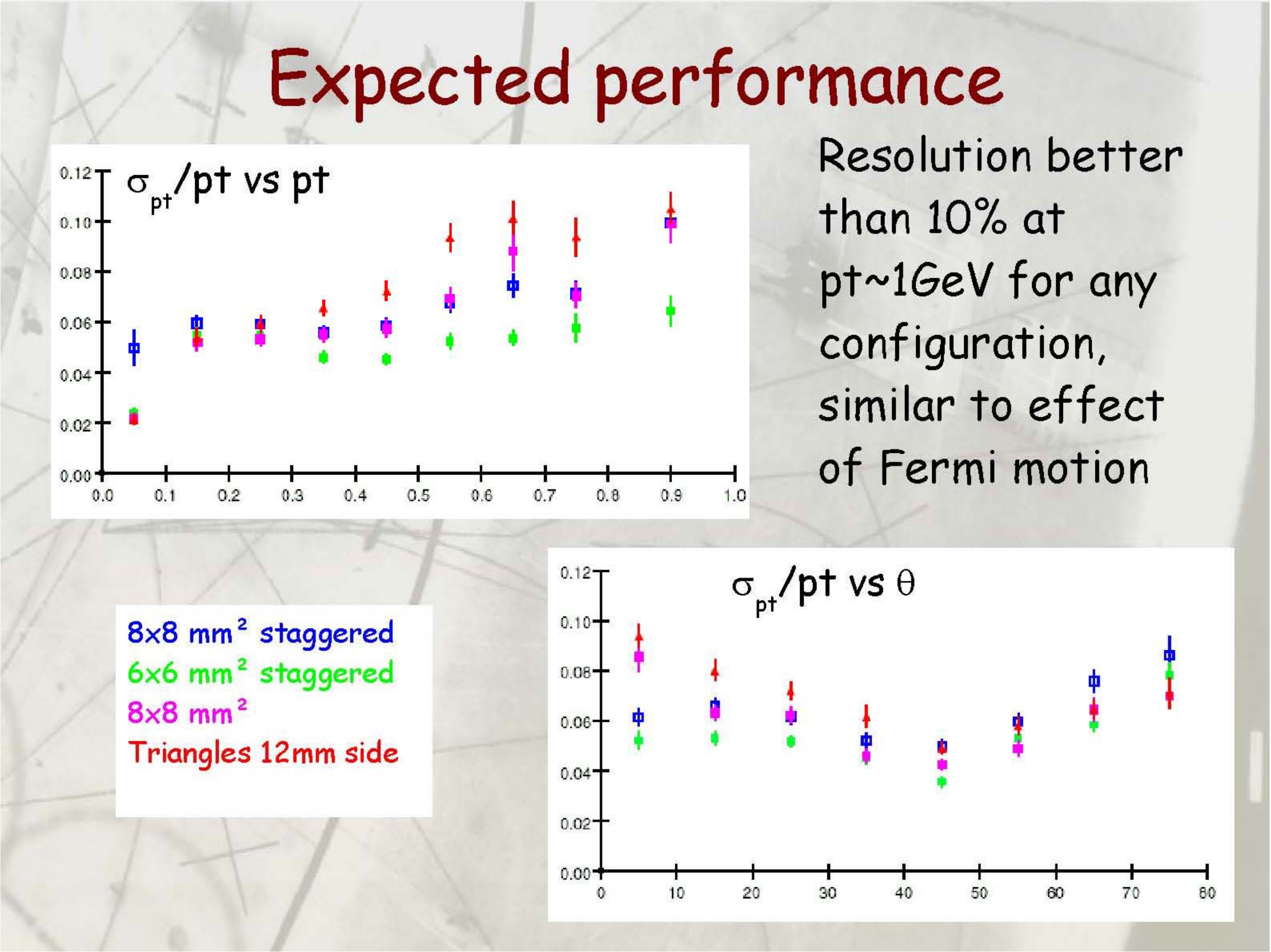
7 panels ~ GEMs with 1 mm pads and Micromegas with 2 mm wide pads
Up to 10,000 instrumented channels

T2K Near Detector - TPC



Building T2K TPC prototype at TRIUMF

Application to T2K TPC



Expected performance

Resolution better than 10% at pt~1GeV for any configuration, similar to effect of Fermi motion

8x8 mm² staggered
6x6 mm² staggered
8x8 mm²
Triangles 12mm side

- **7x9 mm^2 pads**
- **10% Δp/p (1 GeV/c)**
- **Good enough**
- **Requirement limited by Fermi motion**

Partnership
between
CARLETON
&
CEA/DAPHNIA

From a talk by F.Sánchez (Universitat Autònoma de Barcelona)

But better momentum resolution would be useful:

Better background rejection = More channels => $$?

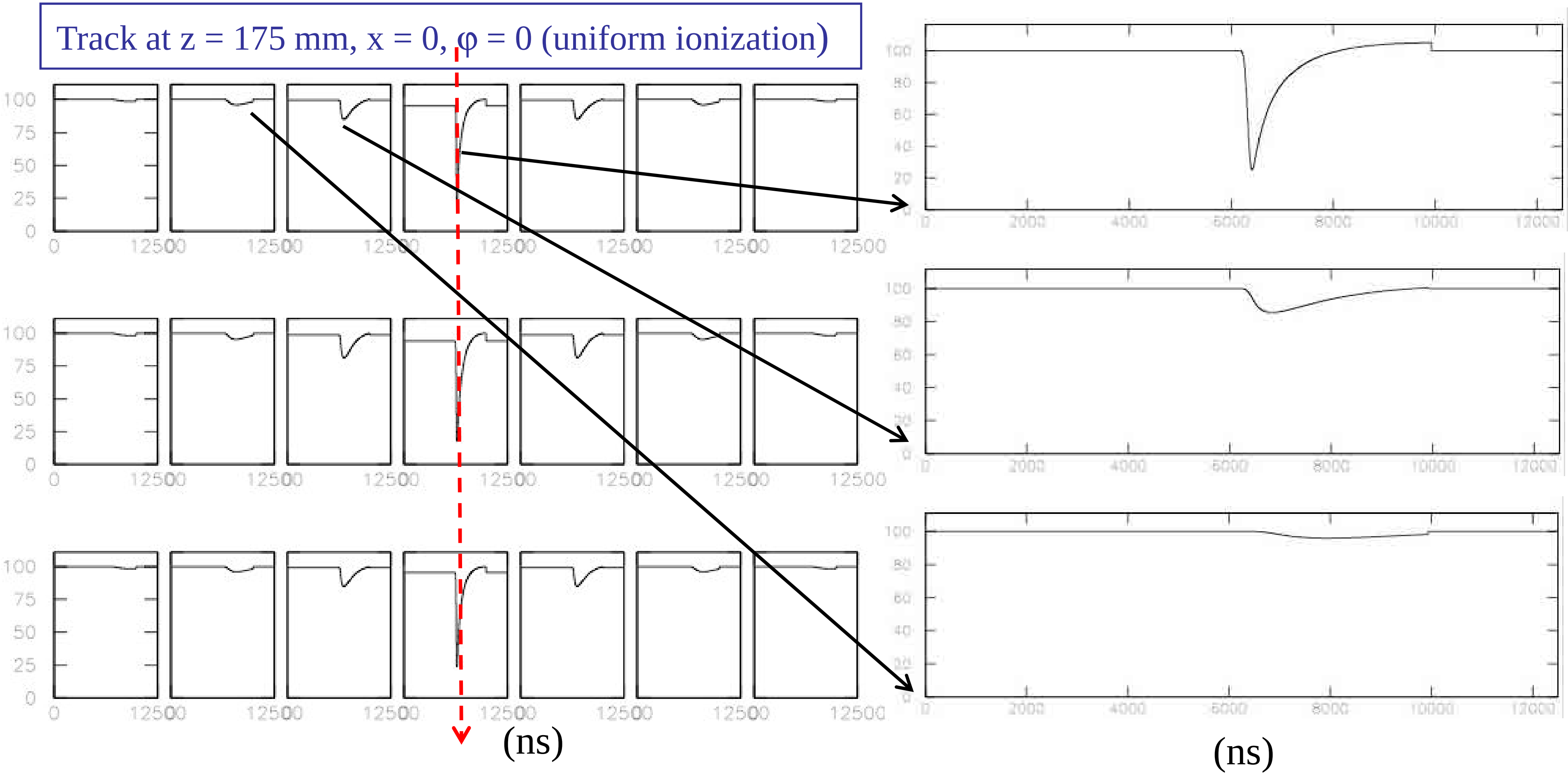
Can one do it with the presently chosen pad dimensions?

T2K simulation for 8 x 8 mm^2 pads

Track crosses no pad row or column boundaries

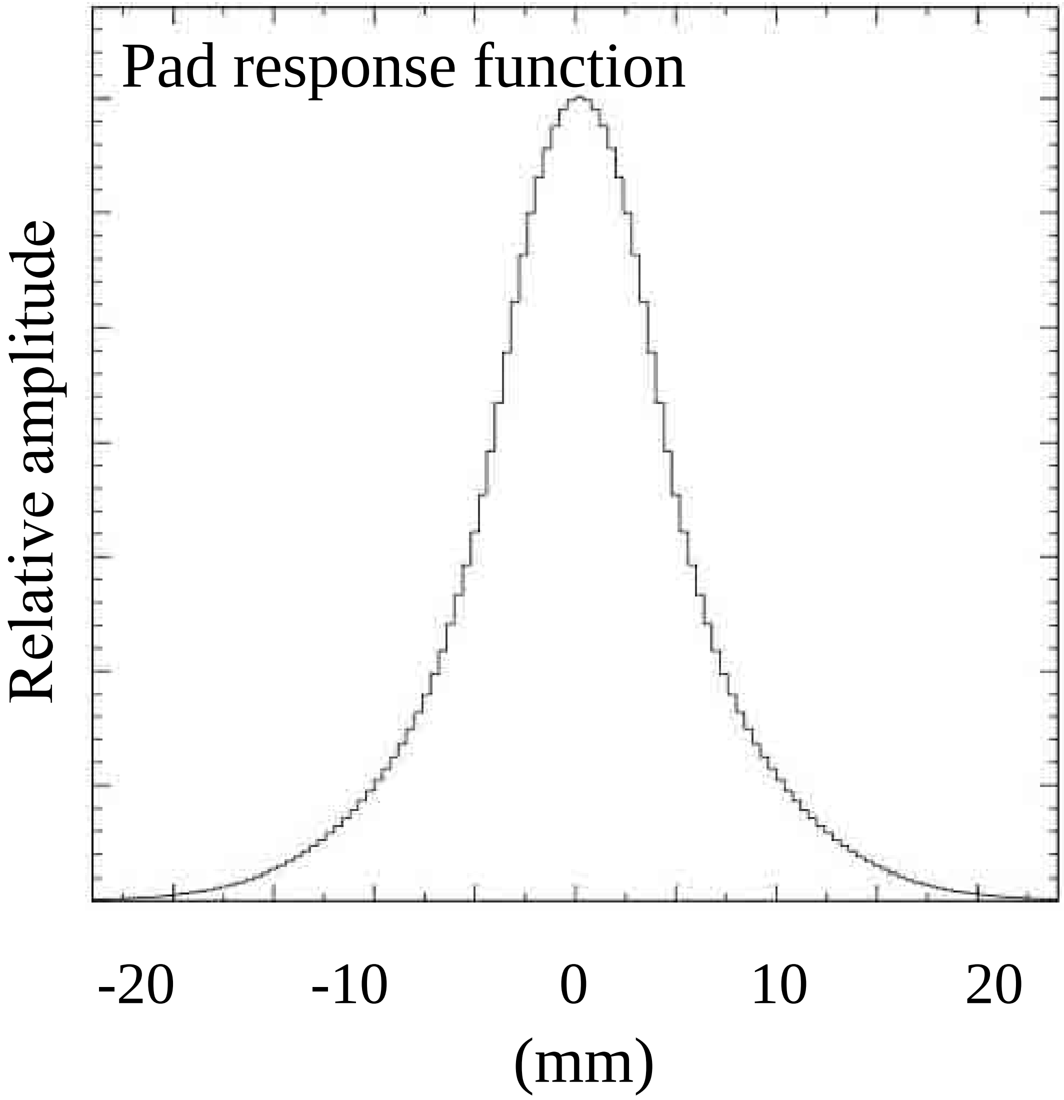
Ar+10% CO_2 , v_{Drift} = 28 μm/ns (E = 300 V/cm) Aleph preamp t_{Rise} = 40 ns, t_{Fall} = 2 μs

Anode surface resistivity 150 KΩ/☐, dielectric gap = 75 μm


Track at z = 175 mm, x = 0, φ = 0 (uniform ionization)

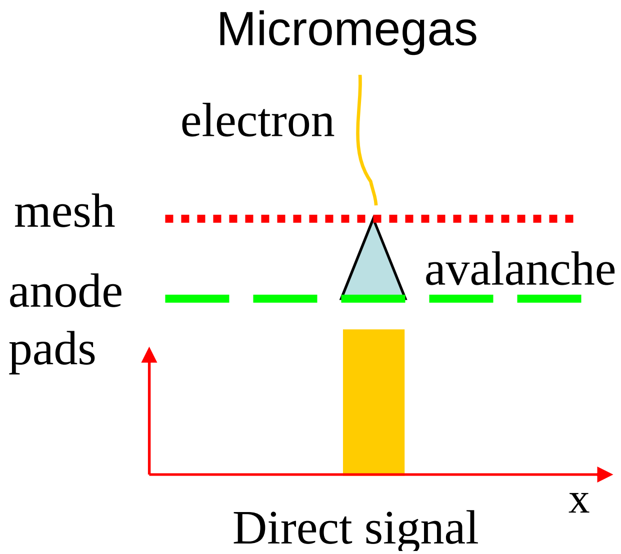
Micromegas TPC with resistive readout - Simulated PRF

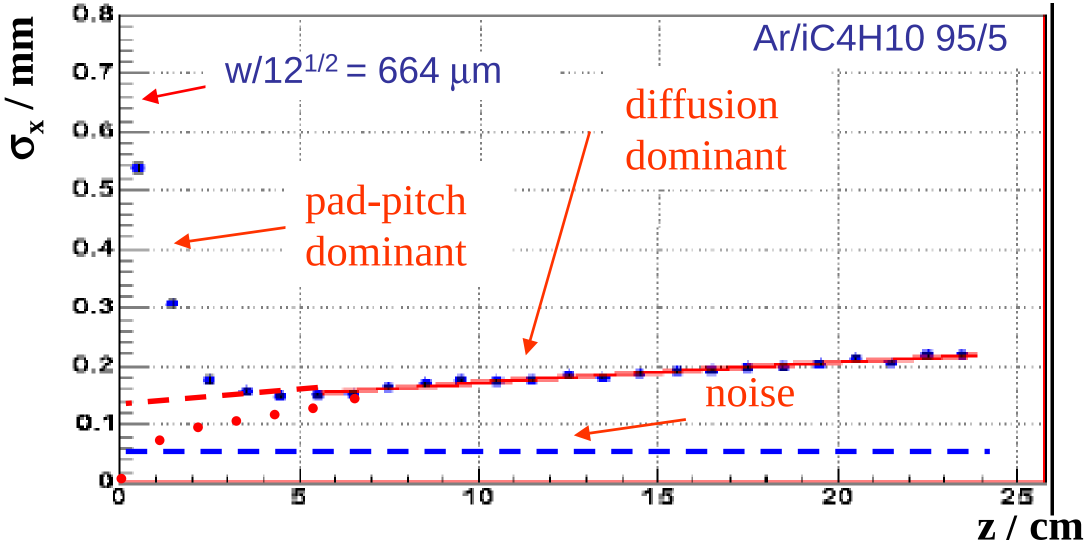
8 x 8 mm^2 pads, Ar+10% CO$_2$@ 300 V/cm, 175 mm drift distance

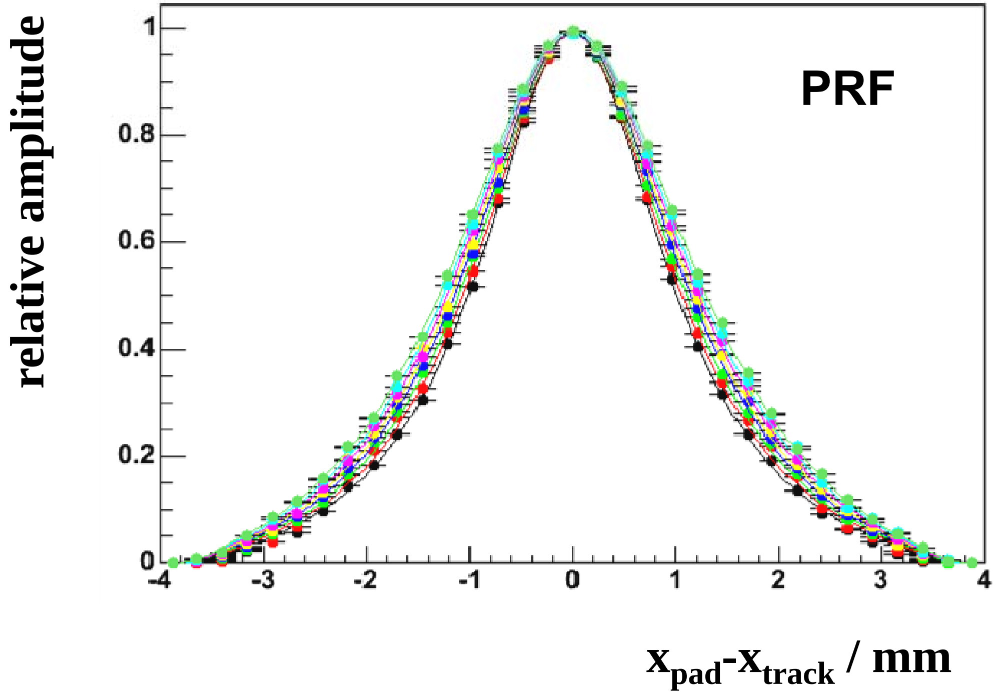


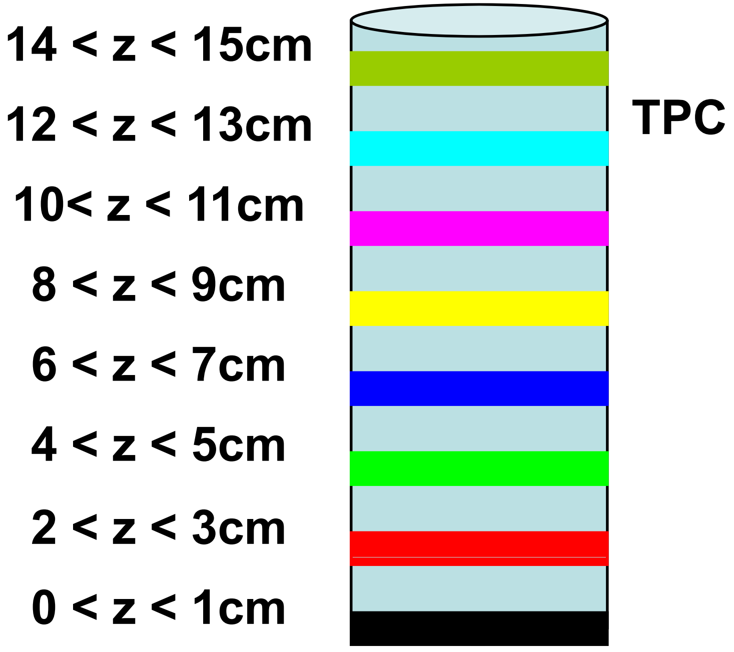
Simulation

MC Simulation – Resolution & PRF

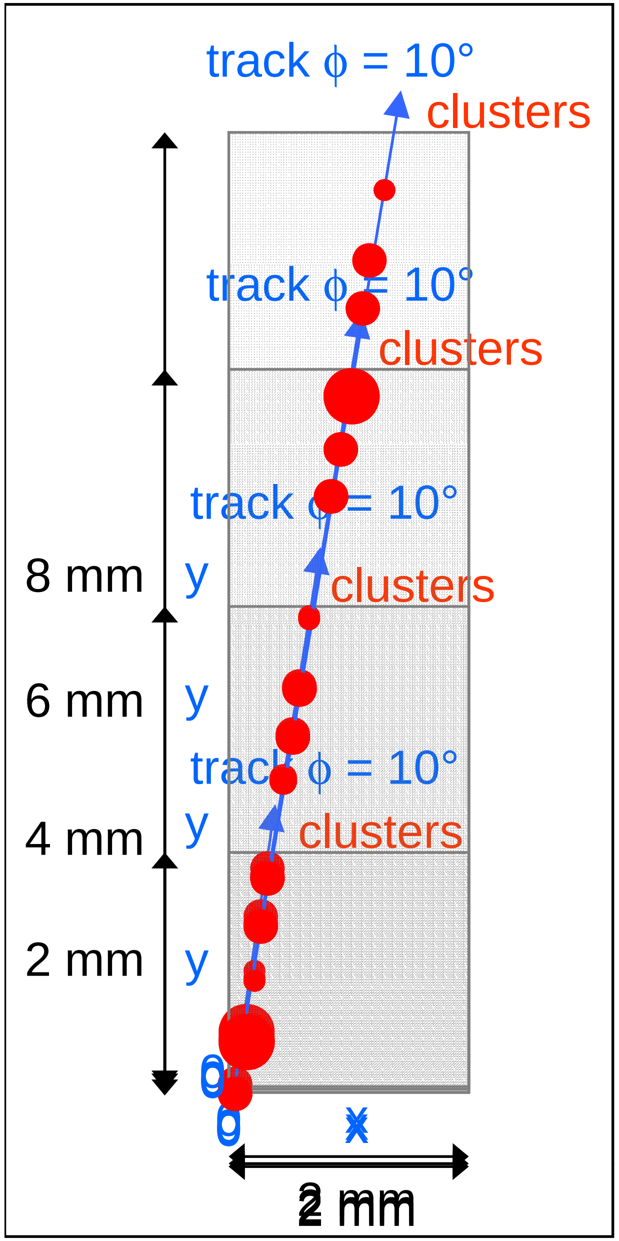






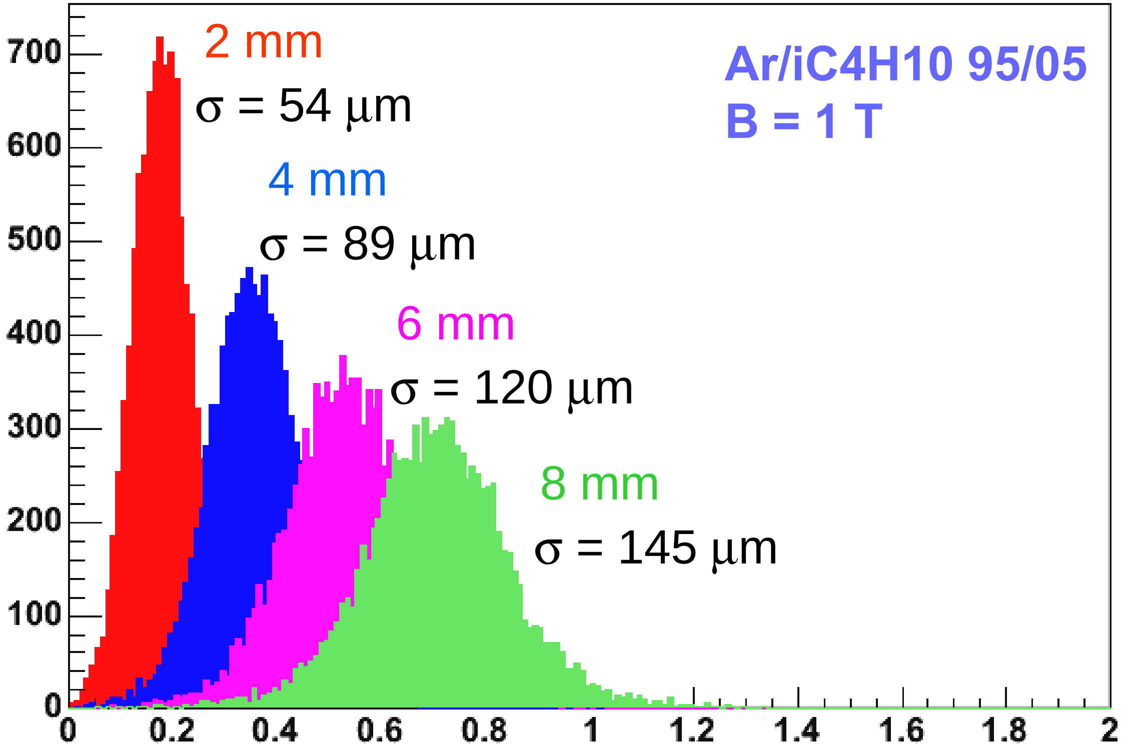


Transverse Spatial Resolution



Ionization Statistics & Angle Effect

Monte Carlo Simulation



$$x = \sum_{clusters} x_c \cdot Ne_c \,/\, \sum_{clusters} Ne_c$$

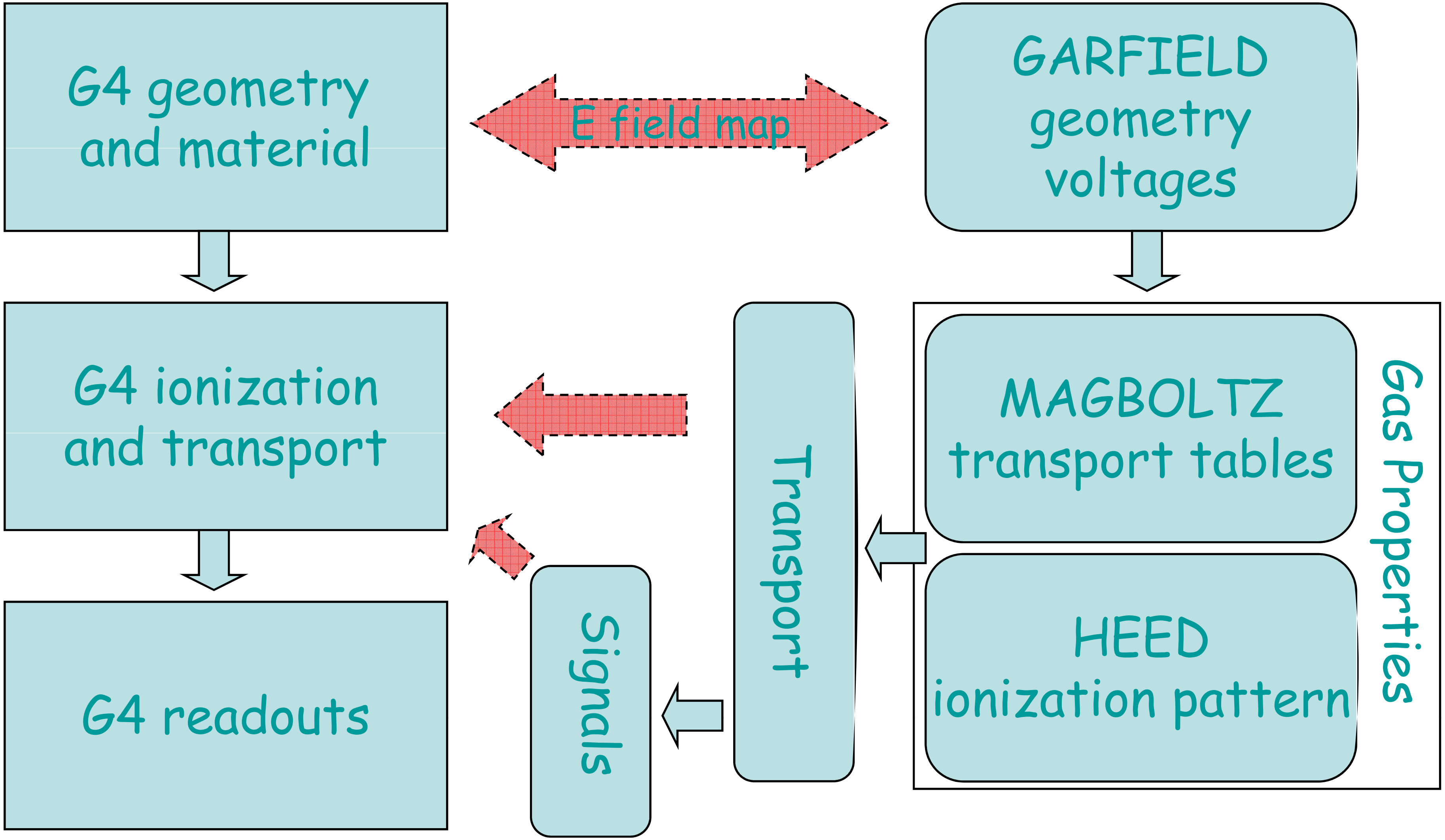
Simulation of TPC

- The standard is to use G4 for the definition of geometry and material
- Maps for **E** & **B** fields
- Use of the standard EM package
- Ionization at fixed intervals (~10 μm)
- Break out of G4 to drift clusters to readout pads
- Several groups uses different software packages: Alice, EXO, ILC/TPC, T2K, etc…

WHY NOT HAVING A COMMON FRAMEWORK EMBEDED WITHIN G4 ?!?

New Initiative

Incorporate 1) ionization statistics & transport in G4 based on GARFIELD
2) signal & avalanche in G4 based on GARFIELD
3) new cluster object in G4 (faster)



G4 geometry and material

E field map

GARFIELD geometry voltages

G4 ionization and transport

Transport

MAGBOLTZ transport tables

HEED ionization pattern

Gas Properties

G4 readouts

Signals

Conclusion

Summary

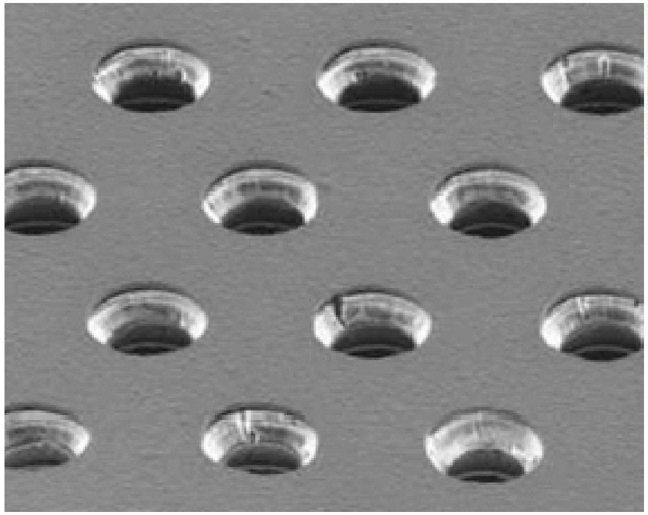
- A standard MPGD-TPC cannot get good resolution with wide pads
- With charge dispersion, wide pads can be used without sacrificing resolution. Charge dispersion works both for GEM and Micromegas.
- **At 5 T, an average ~ 50 μm resolution has been demonstrated with 2 x 6 mm^2 readout pads for drift distances up to 15 cm.**
- The ILC-TPC resolution goal ~100 μm for all tracks up to 2 m drift appears feasible.
- Canadian responsibilities for large 1 m prototype tests to 2010: Construct seven large Micromegas panels with charge dispersion shared with France (Carleton & Montréal)
- Application to T2K: R&D France/Canada
- **Development of common simulation framework for TPC**
- Ionization and transport in G4 [via Garfield capabilities]

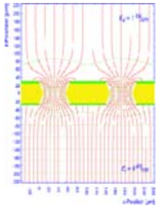
Extra Slides

No ExB effects in MicroPattern Gas Detectors (MPGD)

GEM a thin film proportional detector

Gas gain in narrow channels with high electric field





300-400V

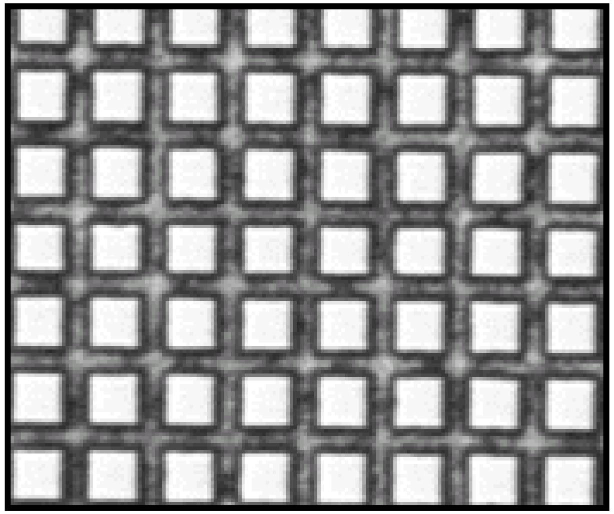
Thin ~ 50 μm double-sided copper clad Kapton foil

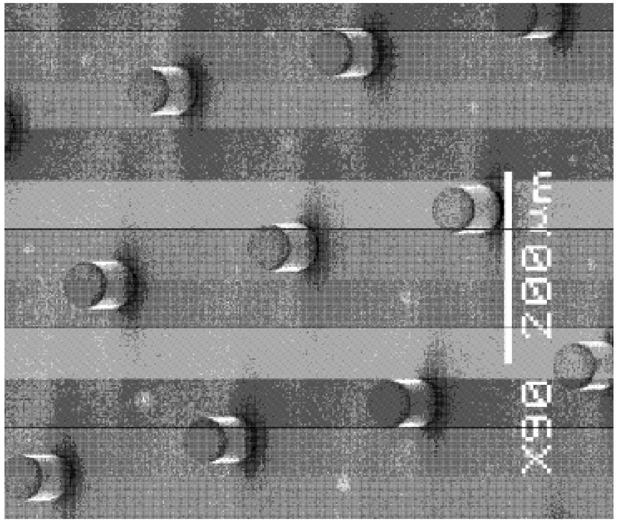
Matrix of 50-70 μm diameter channels ~ 140 μm pitch

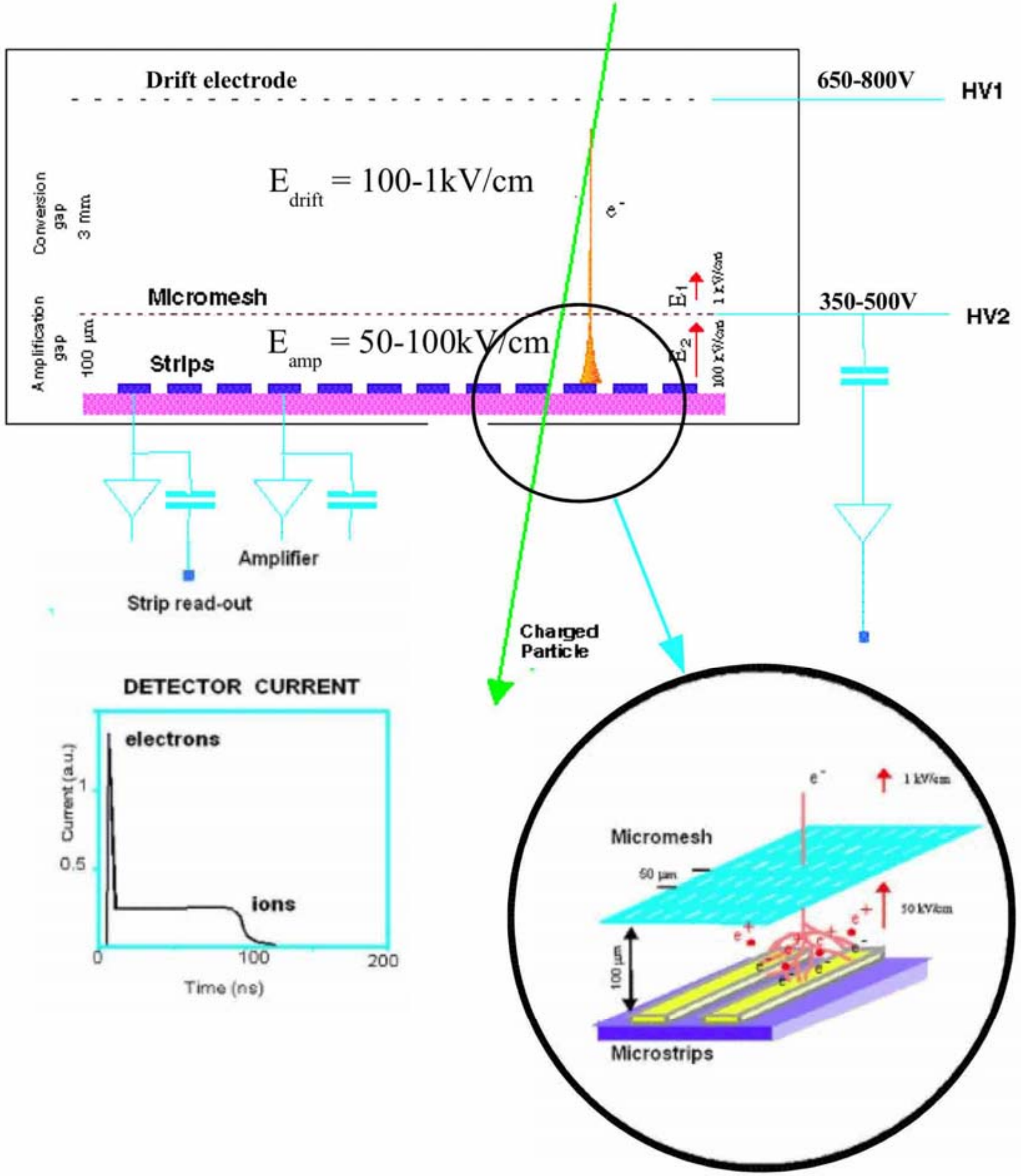
Up to 80 kV/cm electric field inside channels

Micromegas - A small gap parallel plate proportional detector

Micromesh supported by ~ 50 μm pillars above anode







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 FWHM $\Gamma(z)$ & base width $\Delta(z)$.

PRFs determined from the data parameterized by a ratio of two symmetric 4th order polynomials.

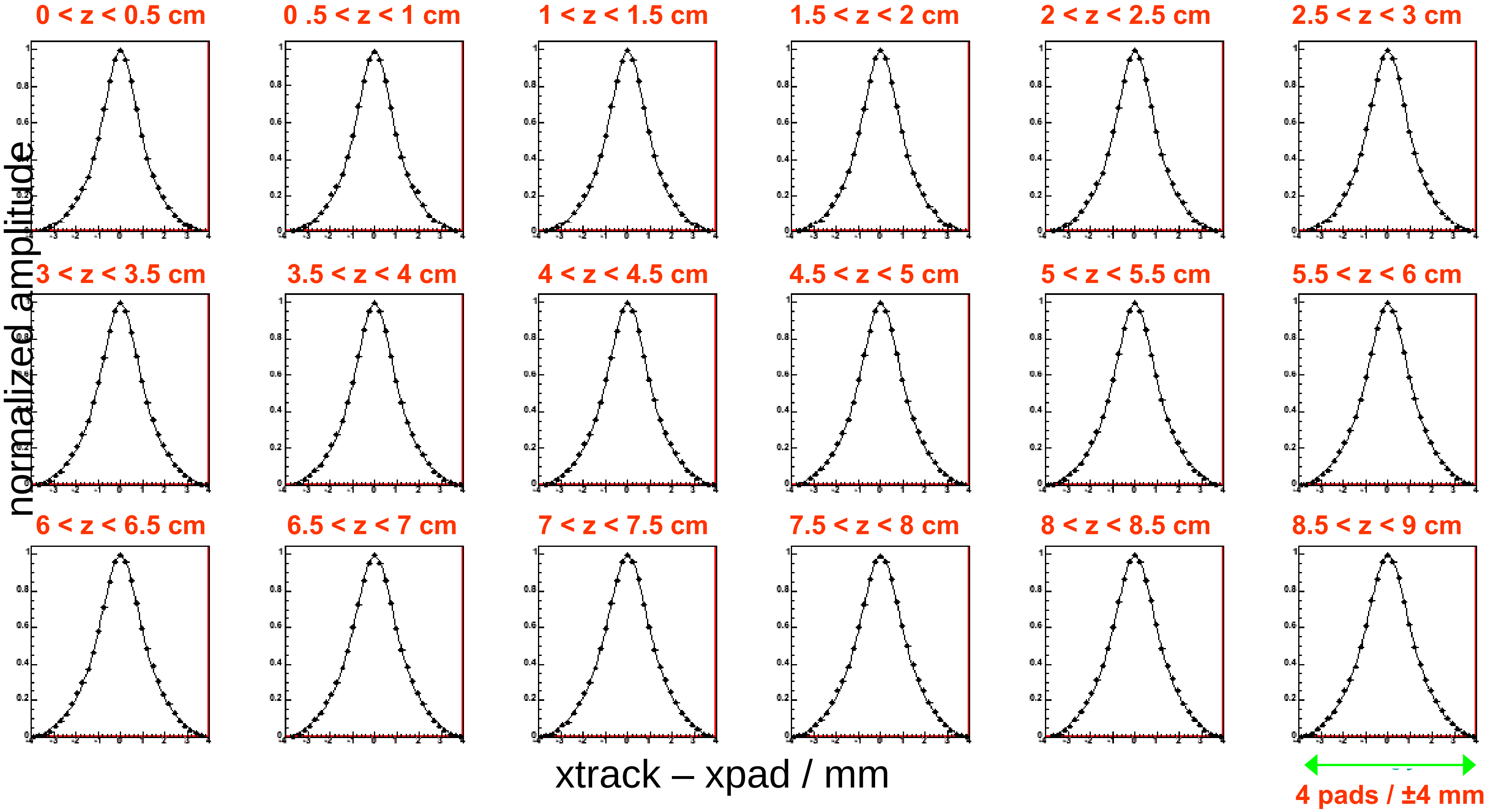
$$PRF[x,\Gamma(z),\Delta(z),a,b] = \frac{(1 + a_2 x^2 + a_4 x^4)}{(1 + b_2 x^2 + b_4 x^4)}$$

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

Pad Response Function / Ar+5%iC4H10

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

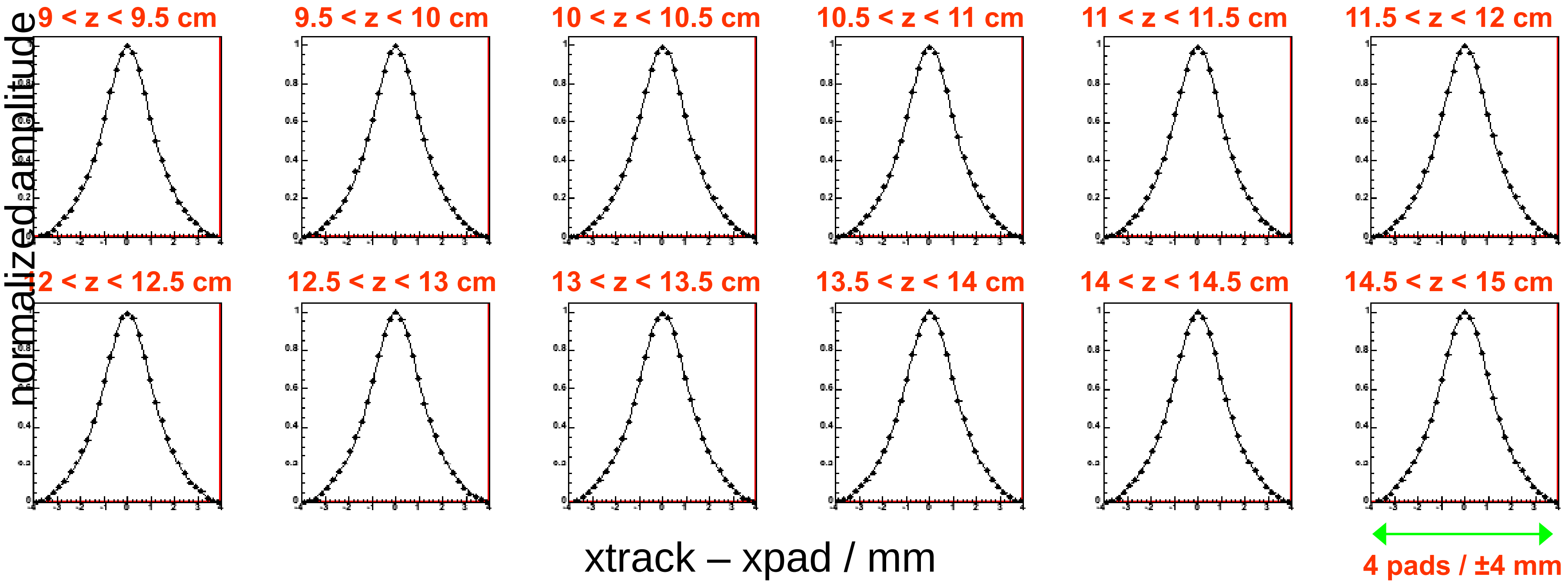
30 z regions /
0.5 cm step



0 < z < 0.5 cm
0 .5 < z < 1 cm
1 < z < 1.5 cm
1.5 < z < 2 cm
2 < z < 2.5 cm
2.5 < z < 3 cm
3 < z < 3.5 cm
3.5 < z < 4 cm
4 < z < 4.5 cm
4.5 < z < 5 cm
5 < z < 5.5 cm
5.5 < z < 6 cm
6 < z < 6.5 cm
6.5 < z < 7 cm
7 < z < 7.5 cm
7.5 < z < 8 cm
8 < z < 8.5 cm
8.5 < z < 9 cm

4 pads / ±4 mm

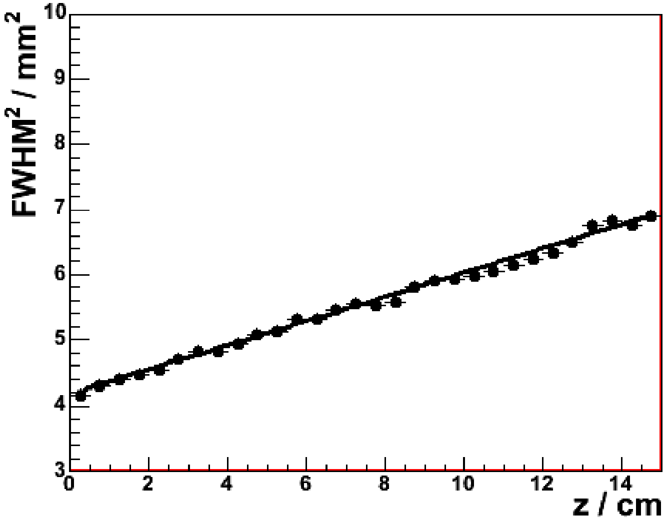
Pad Response Function / Ar+5%iC4H10



PRF parameters

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

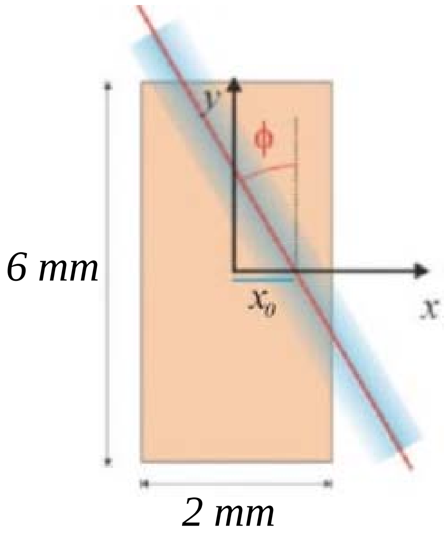
The parameters depend on TPC gas & operational details



Track fit using the the PRF

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

$$\chi^2 = \sum_{rows} \sum_{i=pads} \left(\frac{A_i - PRF_i}{\partial A_i} \right)^2$$

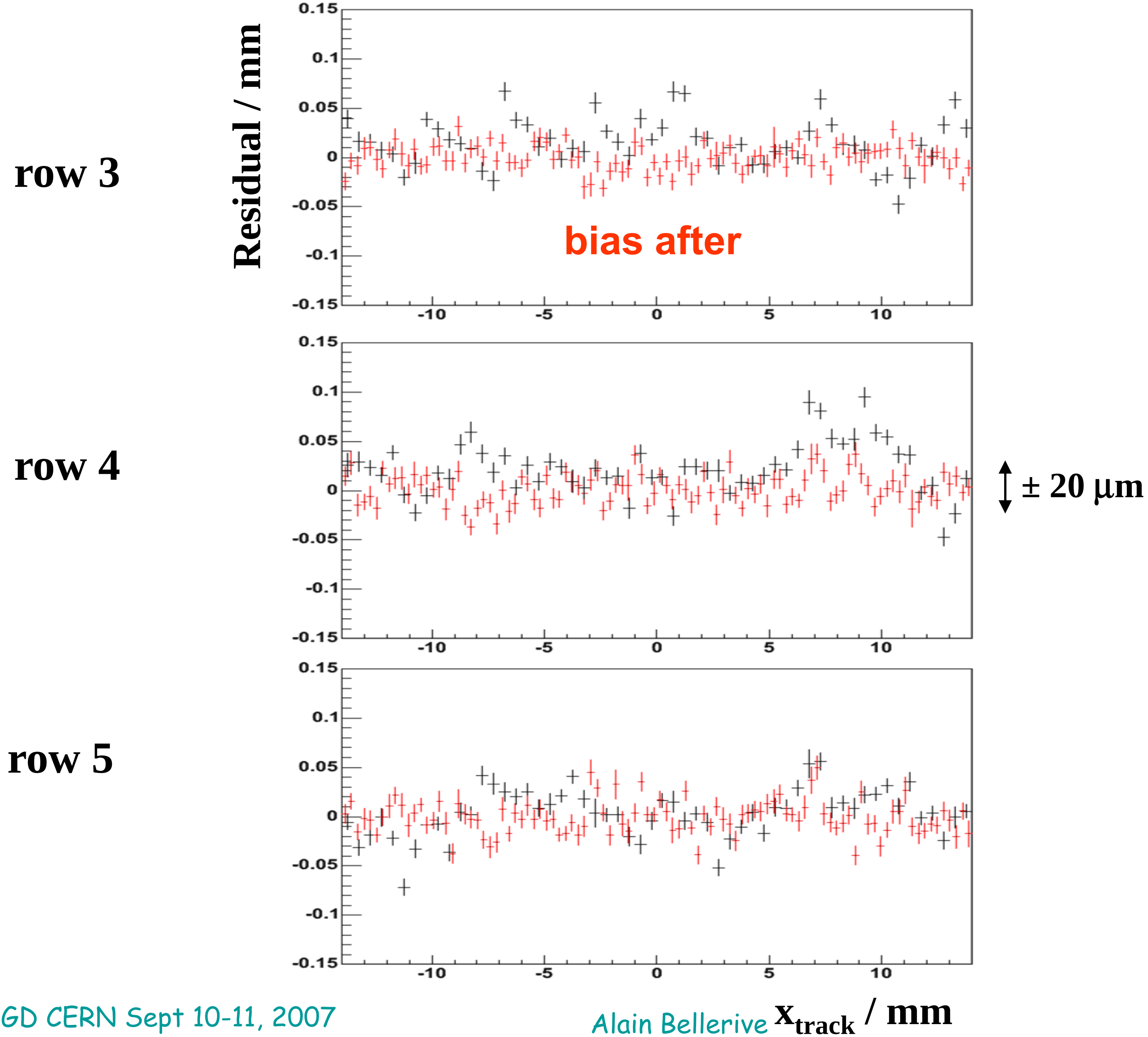


Determine x_0 & ϕ by minimizing χ^2 for the entire event

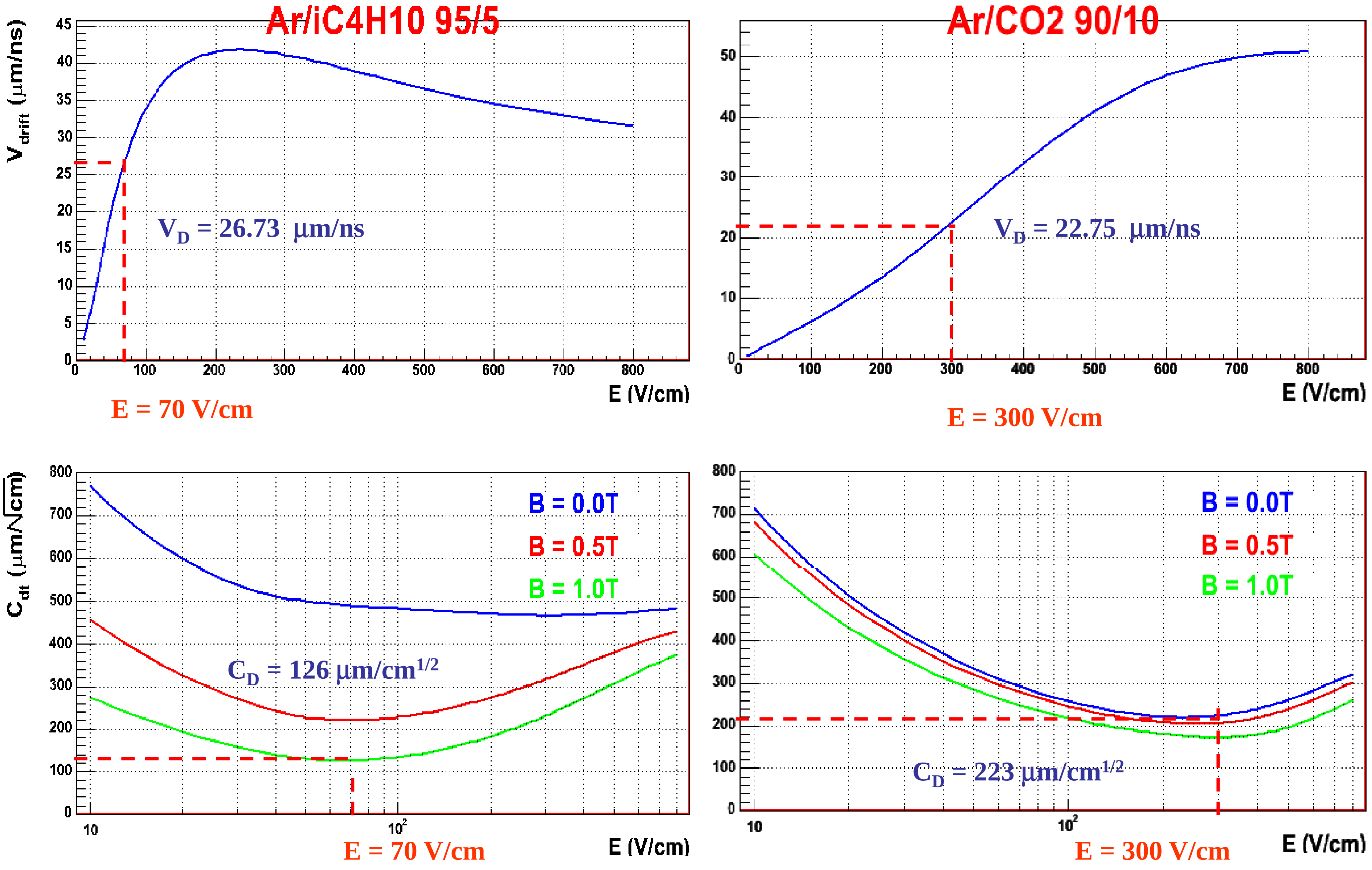
Definitions:

- residual: $x_{row} - x_{track}$
- bias: mean of $x_{row} - x_{track} = f(x_{track})$
- resolution: standard deviation of residuals

Bias for inner rows



Beam test motivations



V_D = 26.73 μm/ns

E = 70 V/cm

V_D = 22.75 μm/ns

E = 300 V/cm

C_D = 126 μm/cm$^{1/2}$

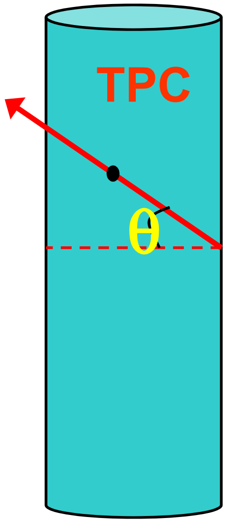
E = 70 V/cm

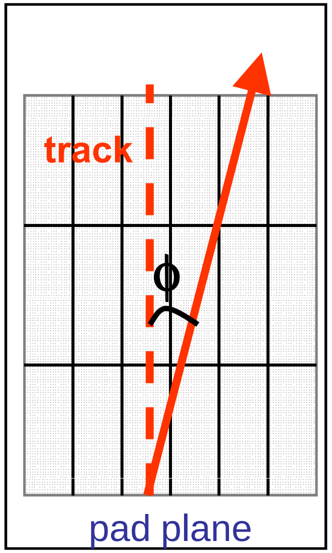
C_D = 223 μm/cm$^{1/2}$

E = 300 V/cm

Transverse Spatial Resolution

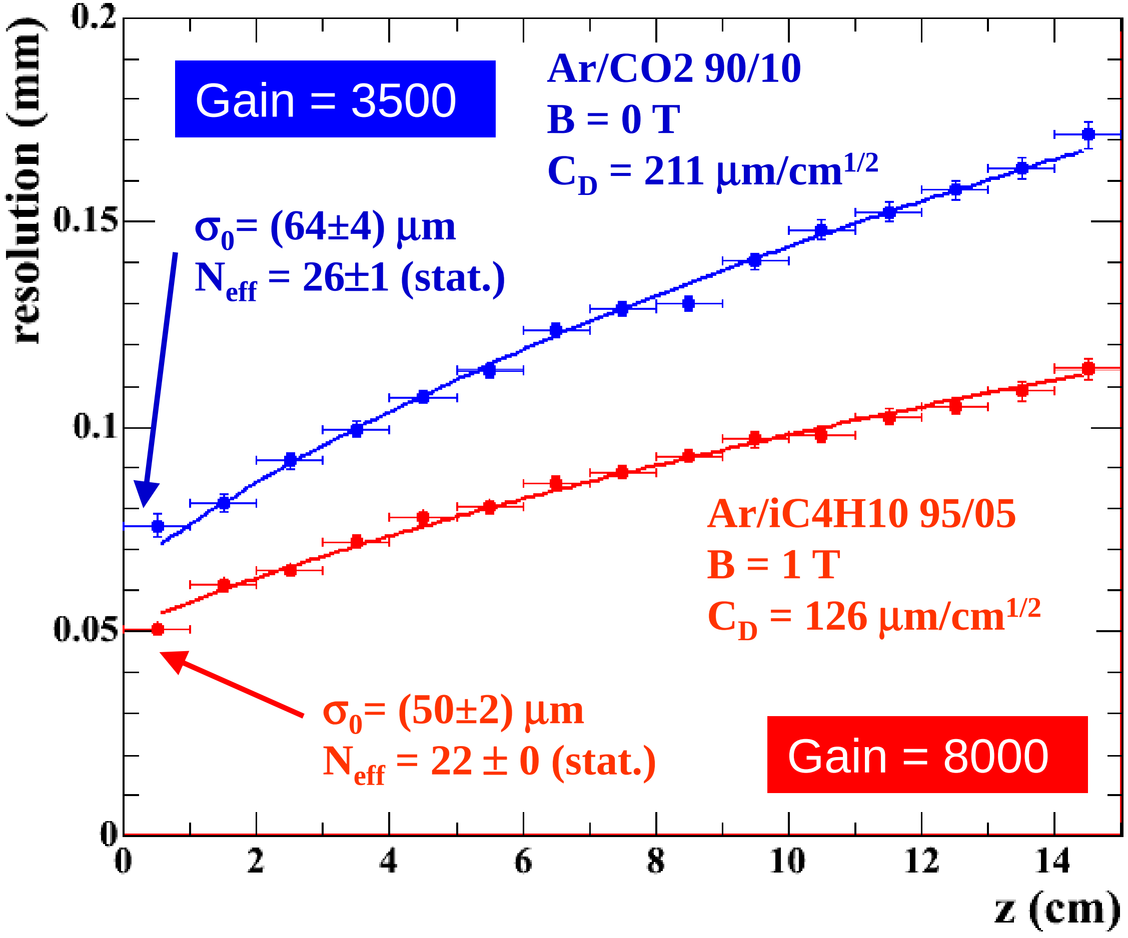
4 GeV/c π^+ beam
$\theta \sim 0°$, $\phi \sim 0°$





$$\sigma_x = \sqrt{\sigma_0^2 + \frac{C_D^2 z}{N_{eff}}}$$

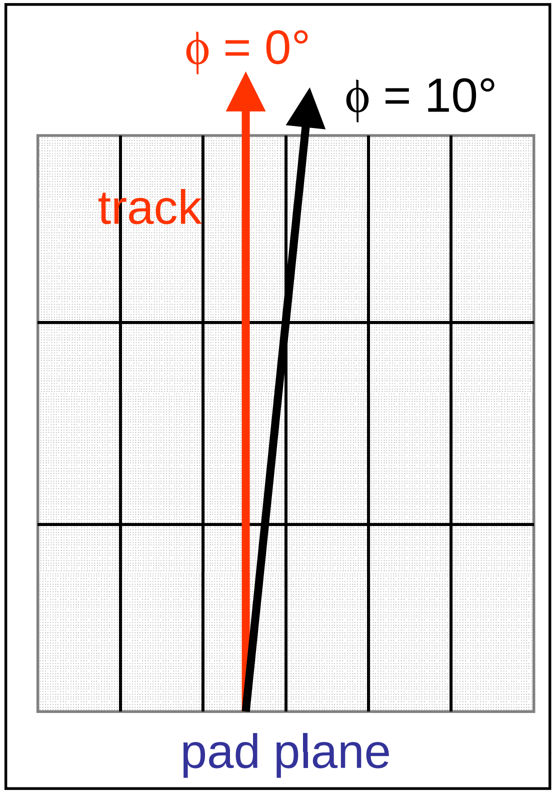
Carleton TPC (2 x 6 mm² pads)



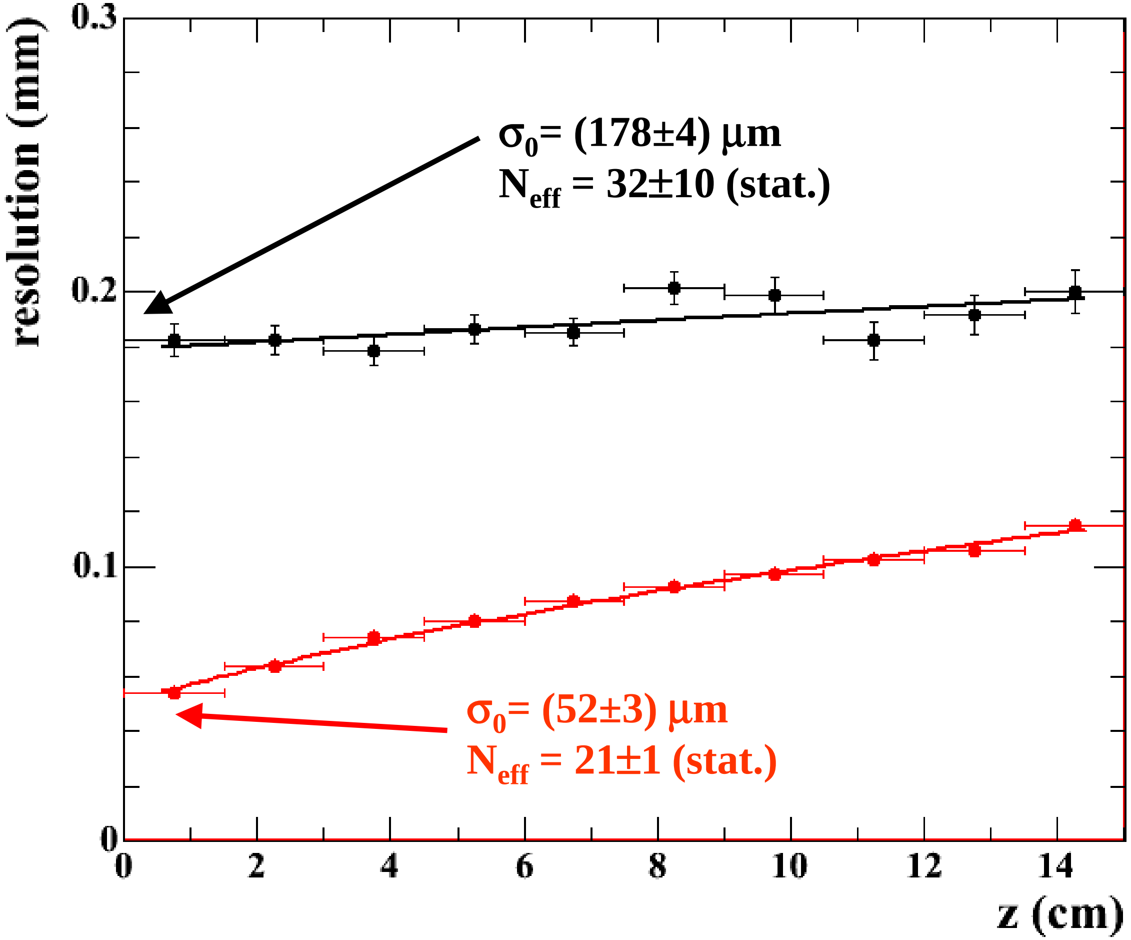
Transverse Spatial Resolution

Angle effect

Ar/iC4H10 95/05
4 GeV/c π^+ beam
$\theta \sim 0°$, B = 1 T,
C_D = 126 $\mu m/cm^{1/2}$



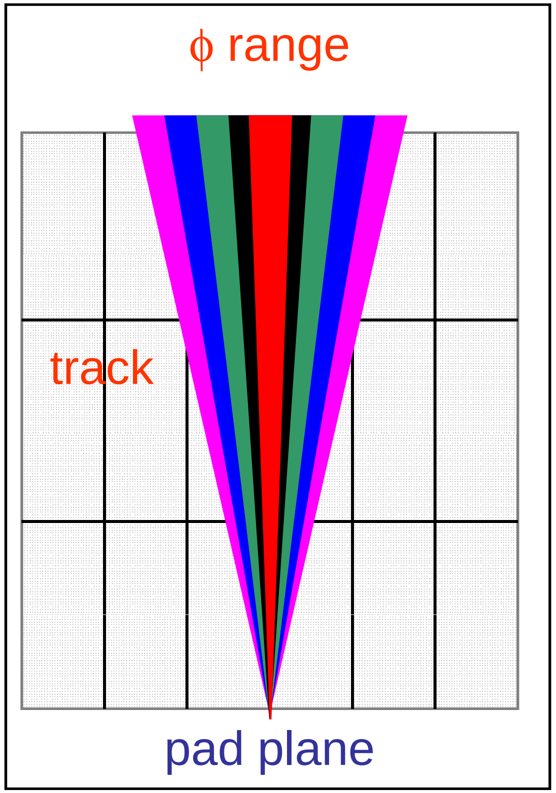
Carleton TPC (2 x 6 mm^2 pads)



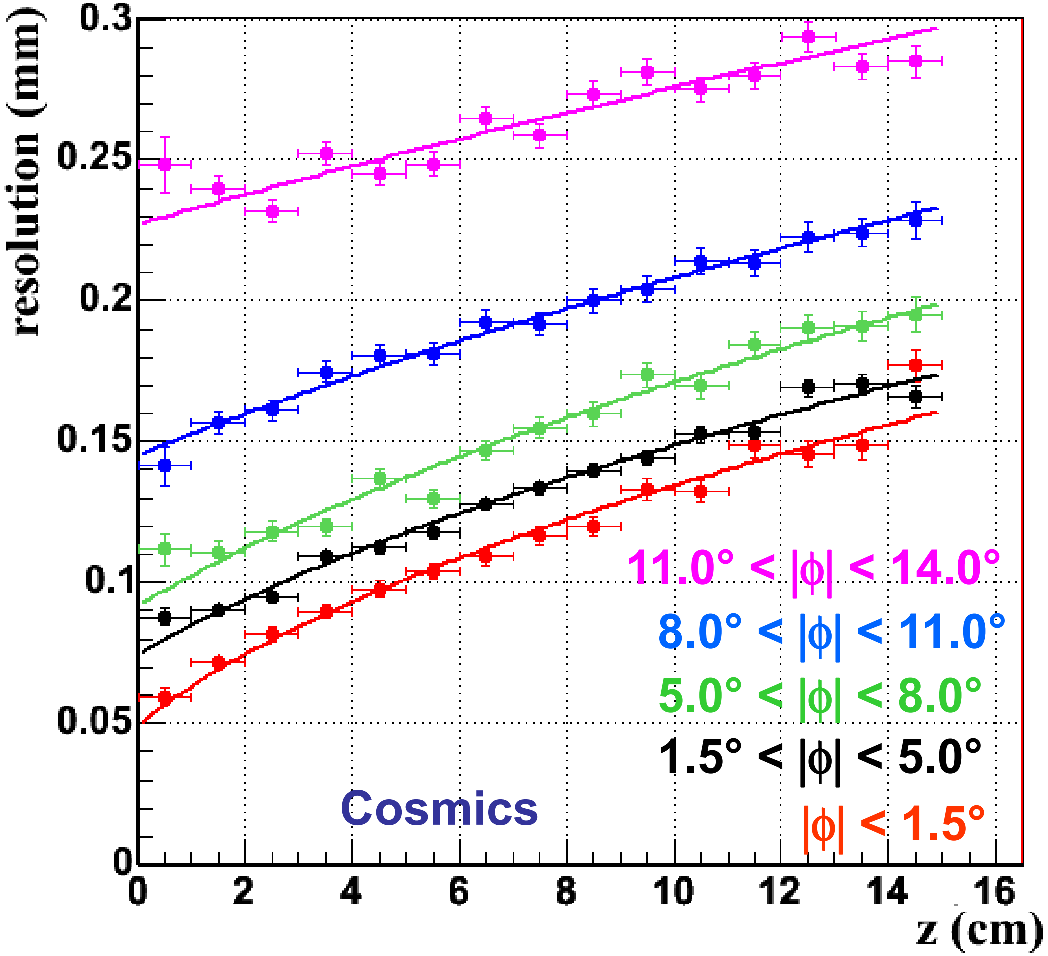
Transverse Spatial Resolution

Angle effect

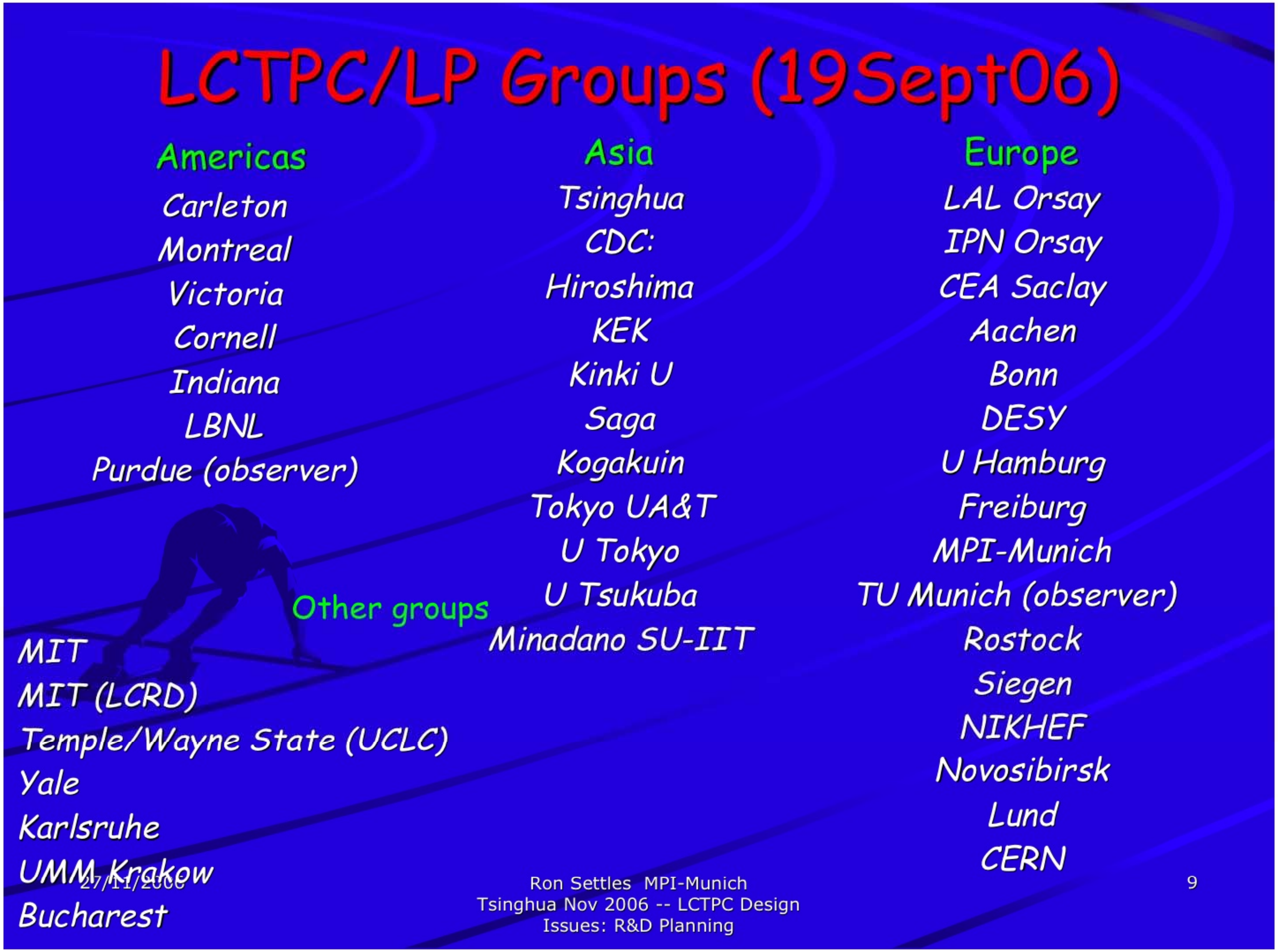
Ar/iC4H10 95/05
Cosmics
$\theta \sim 0°$, B = 0 T,
$C_D = 223\ \mu m/cm^{1/2}$



Carleton TPC (2 x 6 mm^2 pads)



TPC R&D for the ILC - a world wide effort



LCTPC/LP Groups (19Sept06)

Americas

Carleton
Montreal
Victoria
Cornell
Indiana
LBNL
Purdue (observer)

Asia

Tsinghua
CDC:
Hiroshima
KEK
Kinki U
Saga
Kogakuin
Tokyo UA&T
U Tokyo
U Tsukuba
Minadano SU-IIT

Europe

LAL Orsay
IPN Orsay
CEA Saclay
Aachen
Bonn
DESY
U Hamburg
Freiburg
MPI-Munich
TU Munich (observer)
Rostock
Siegen
NIKHEF
Novosibirsk
Lund
CERN

Other groups

MIT
MIT (LCRD)
Temple/Wayne State (UCLC)
Yale
Karlsruhe
UMM Krakow
Bucharest

R&D Planning

- 1) Demonstration phase
  - Continue work with small prototypes on mapping out parameter space, understanding resolution, etc, to prove feasibility of an MPGD TPC. For CMOS-based pixel TPC ideas this will include proof-of-principle tests.
- 2) Consolidation phase
  - Build and operate the Large Prototype (LP), Ø ~ 80cm, drift ~ 60cm, with EUDET infrastructure as basis, to test manufacturing techniques for MPGD endplates, fieldcage and electronics. LP design is starting → building and testing will take another ~ 3-4 years.
- 3) Design phase
  - During phase 2, the decision as to which endplate technology to use for the LC TPC would be taken and final design started.

What next in view of proposed ambitious timeline for ILC?

- Feb 2007 Global Design Effort (GDE) releases the accelerator Reference Design Report (RDR)
- 2010 end – Target date for the accelerator Engineering Design Report (EDR)
- Detector concepts - the 4 existing concepts are described in the ILC Detector RDR released recently.
- 2008 Summer - Detector Letters of Intent invited by World Wide Study (WWS)
- 2009 Summer Target date for formation of two Detector Collaborations
- 2010 Target date for detector EDRs
- Use ILC accelerator and detector EDRs as basis to get the project approved, select the site and secure international funding
- 2012 start construction
- 2019 ILC operational