Performance of Time Projection Chamber Prototypes for the Linear Collider Experiment

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on behalf of part of
the ILC-TPC Collaboration

KEK, Saclay, Orsay, Carleton, Montreal, MPI, DESY, MSU、
Tsukuba U, TUAT, Kogakuin U, Kinki U, Saga U, Hiroshima U.

Workshop on MPGDs
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ILC-TPC R&D Groups

Europe

RWTH Aachen
CERN
DESY
U Hamburg
U Freiburg
U Karlsruhe
UMM Krakow
Lund
MPI-Munich
NIKHEF
BINP Novosibirsk
LAL Orsay
IPN Orsay
U Rostock
CEA Saclay
PNPI StPetersburg

America

Carleton U
Cornell/Purdue
Indiana U
LBNL
MIT
U Montreal
U Victoria

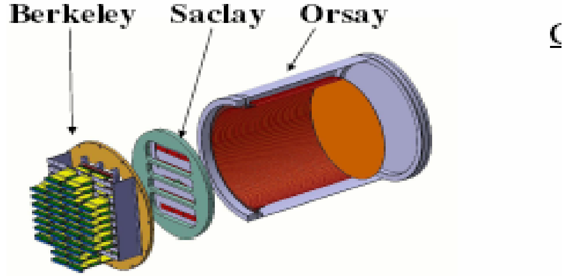
Asian ILC gaseous-tracking groups

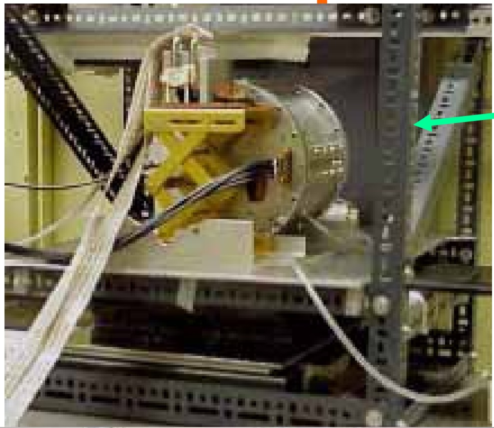
Chiba U
Hiroshima U
Minadamo SU-IIT
Kinki U
U Osaka
Saga U
Tokyo UAT
U Tokyo
NRICP Tokyo
Kogakuin U Tokyo
KEK Tsukuba
U Tsukuba
Tsinghua U

Other

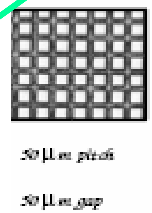
MIT (LCRD)
Temple/Wayne State (UCLC)
Yale

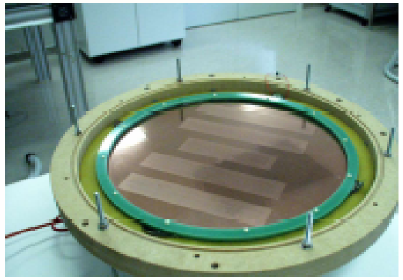
Examples of Prototype TPCs



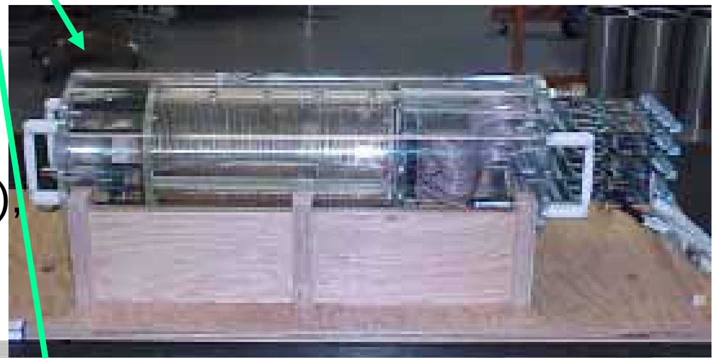


Carleton, Aachen,
Cornell/Purdue,Desy(n.s.)
for B=0or1T studies

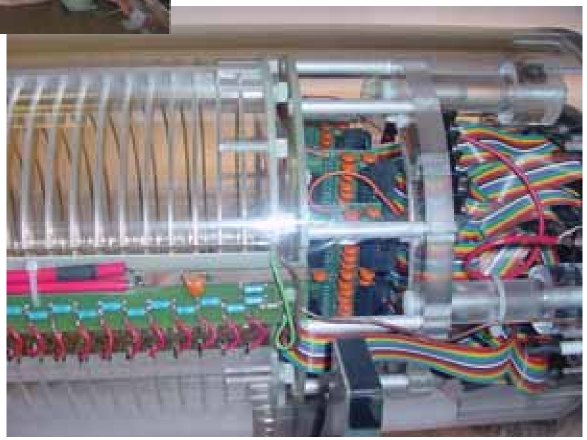


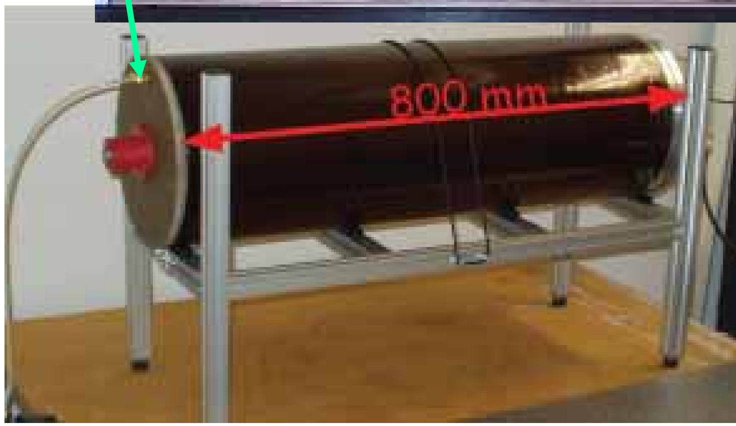


Saclay, Victoria, Desy
(fit in 2-5T magnets)



Karlsruhe, MPI/Asia,
Aachen built test TPCs
for magnets (not shown),
other groups built small
special-study chambers





ILC-TPC

A Large, High precision, High 3-D granularity Time Projection Chamber operated under a high magnetic field of 3 – 4 T

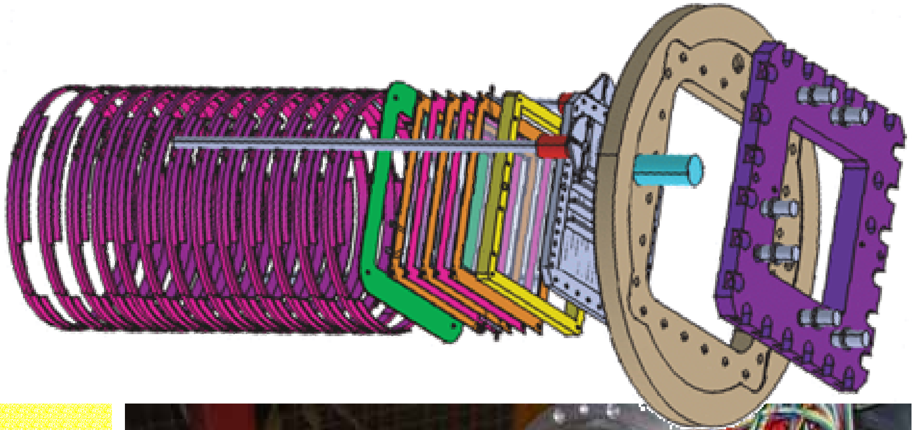
Size: Effective volume = 4.1 m (diameter) ×4.6 m (full length)
Spatial resolution r-ϕ : 100 – 200 μm z: ≲ 1 mm
Two-track resolving power r-ϕ : ≲ 2 mm z: ≲ 10 mm
Number of coordinate samples per track: ~ 250
Momentum resolution (TPC alone) $\delta Pt / Pt \sim 10^{-4}$ Pt [GeV/c] for high momentum tracks
Particle identification capability: dE/dx ~ 4%

Unprecedented requirements to TPC especially for granularity

→ use of micro pattern gas detector (MPGD) as a readout device

→ performance tests using prototypes

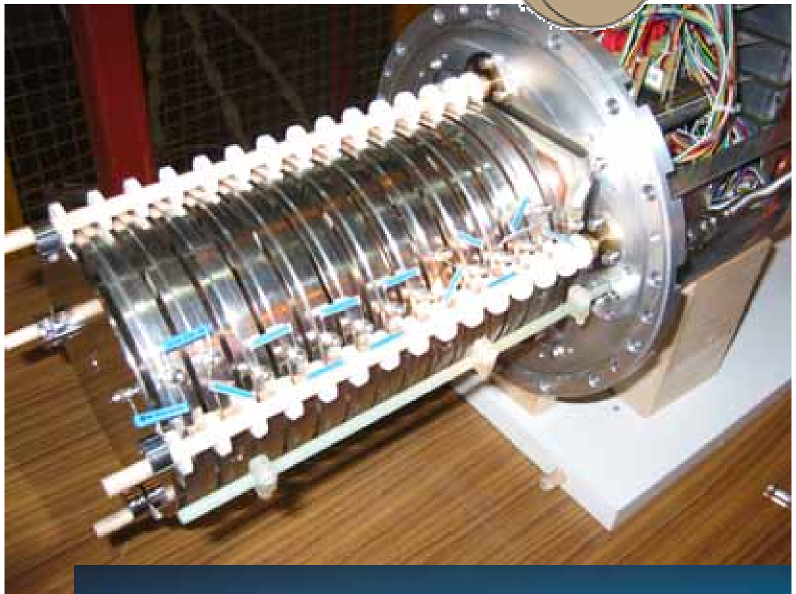
Prototype TPC



Field cage

maximum drift length: 260 mm

typical cathode H.V. :   - 6 kV



Readout plane

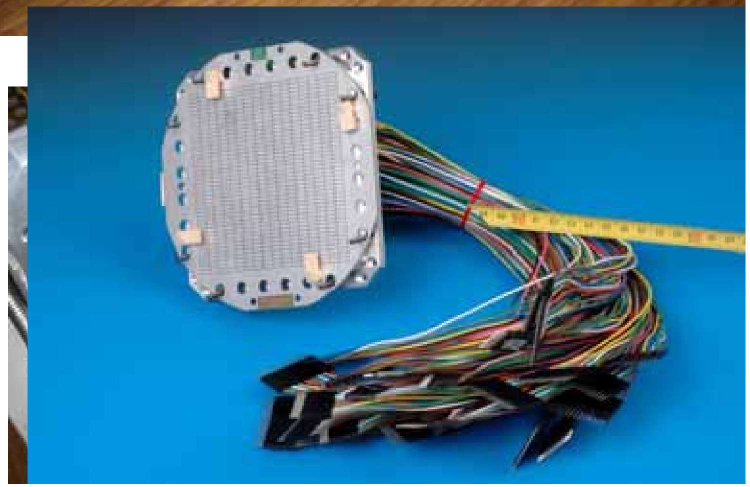
effective area: 100 mm×100 mm

MWPC

GEMs (3-stage)

or

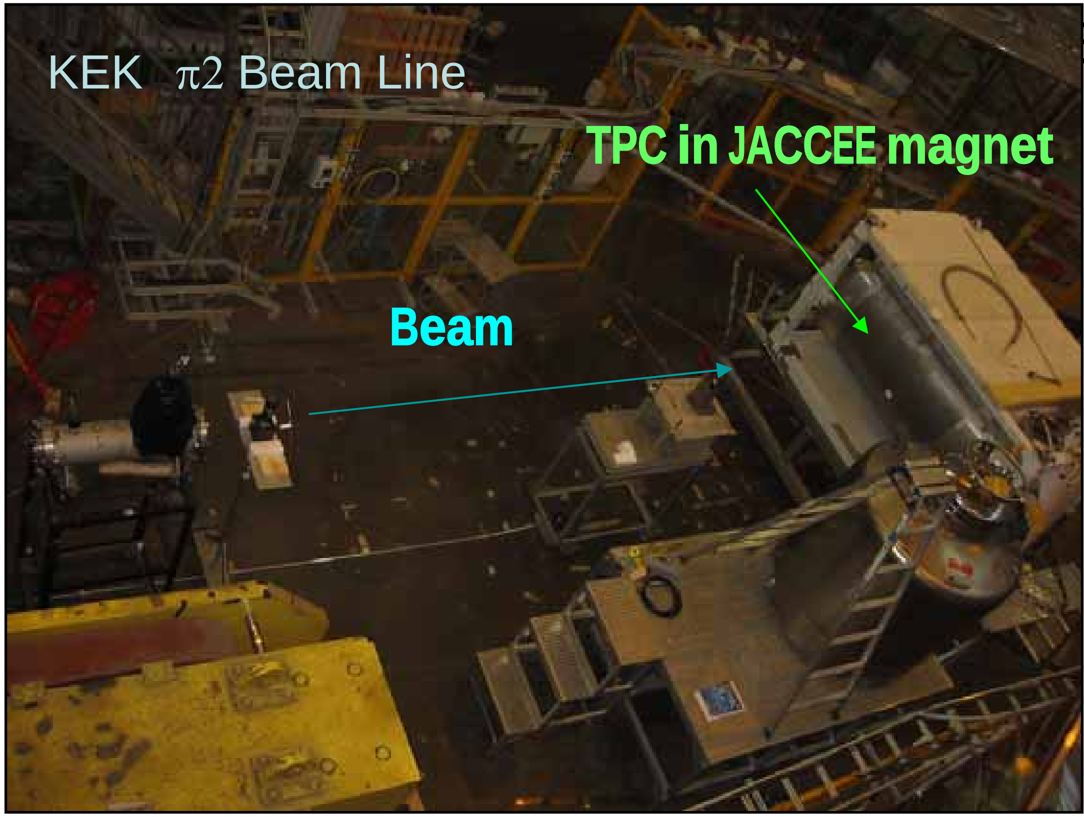
MicroMEGAS



Experimental setup

We have conducted a series of beam experiments at KEK PS.

- **Beam**: mostly 4 GeV/c pions (0.5-4 GeV/c hadrons & electrons)
- **Magnet**: super conducting solenoid



JECCEE
inner diameter : 850 mm
effective length: 1 m

Readout scheme and Gas

Readout Device	Pads: 32 pads ×12 pad rows Width (pitch)×Length (pitch)	Gas (1 atm.) Drift field
MWPC SW spacing 2 mm SW - Pads 1 mm	2 (2.3) mm×6 (6.3) mm	TDR [Ar-CH_4 (5%)-CO_2 (2%)] 220 V/cm
GEM (triple stage) CERN Standard transfer gaps 1.5 mm induction gap 1.0 mm	1.17 (1.27) mm×6 (6.3) mm staggered	TDR 220 V/cm Ar – methane (5%) 100 V/cm
MicroMEGAS 50-μ m mesh 50-μ m gap	2 (2.3) mm×6 (6.3) mm	Ar - isobutane (5%) 220 V/cm

ALEPH TPC Electronics:

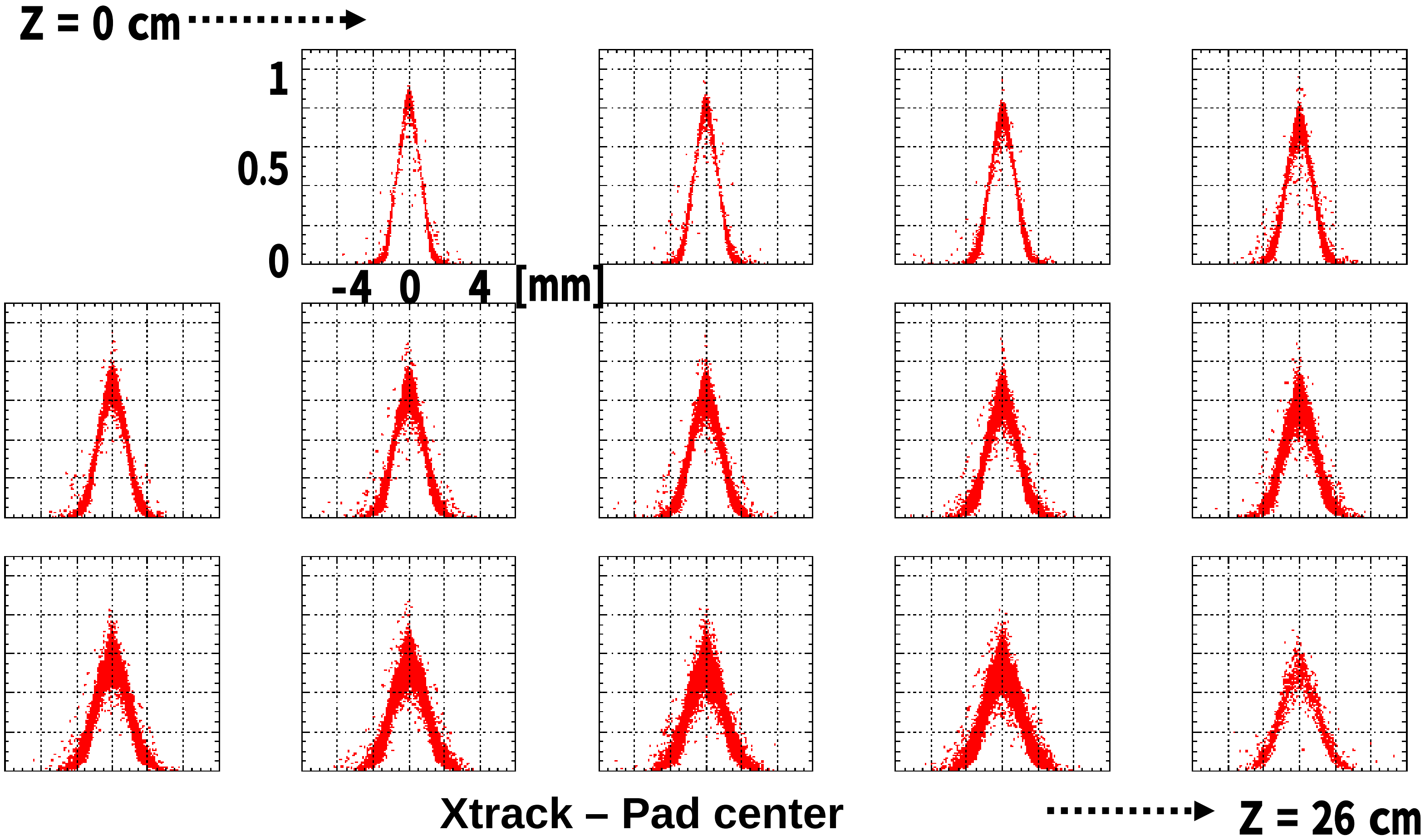
charge sensitive preamp. + shaper amp. (shaping time = 500 ns)

+ digitizer (time bucket = 80 nsec)

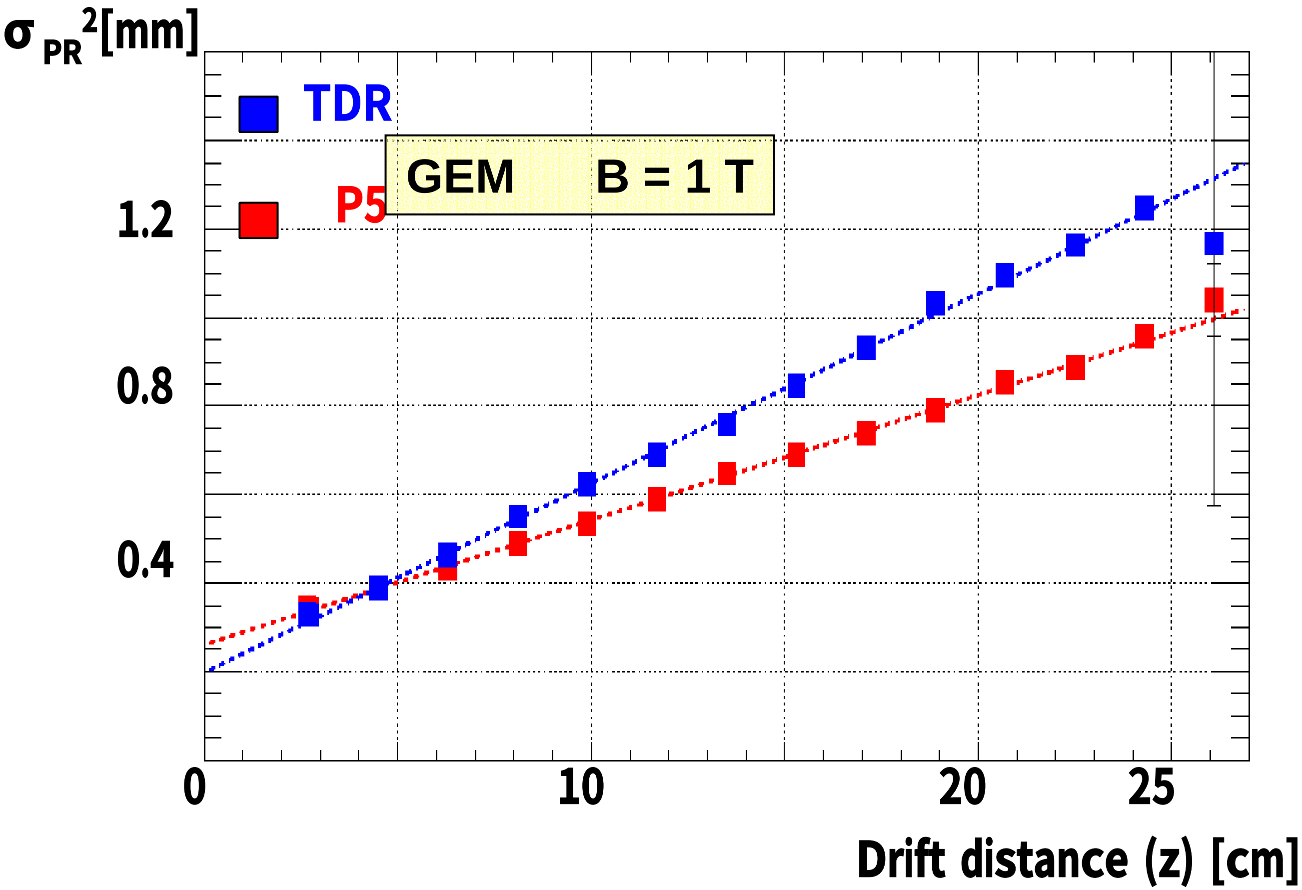
Examples of Experimental Data

Pad responses for different drift distances

GEM   Gas: P5, B = 1 T



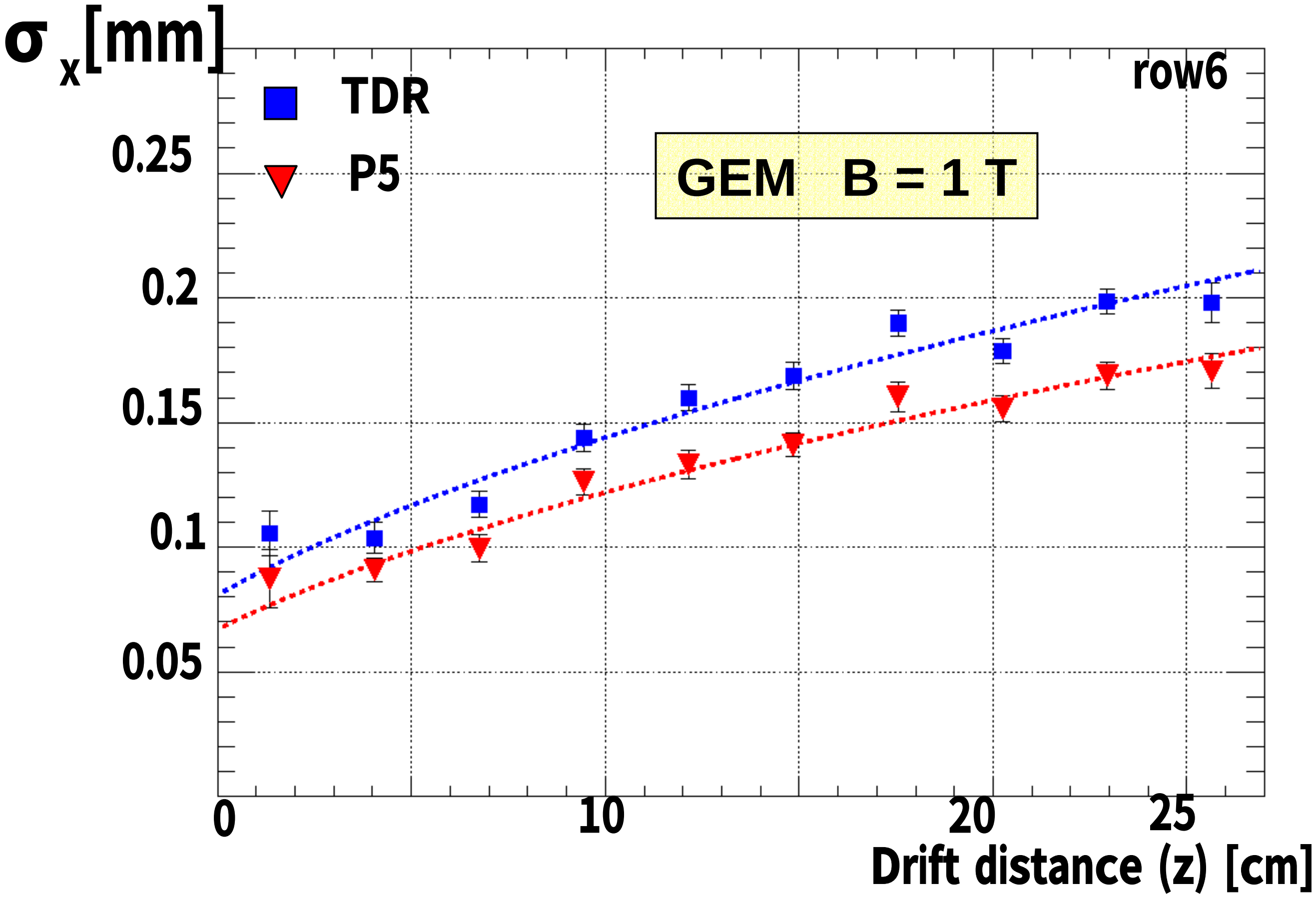
Pad response width vs. z



$$\sigma_{PR}^2 = \sigma_{PR0}^2 + D^2 z$$

	σ_{PR0} (μ m)	D (μ m / $\sqrt{\ }$cm)
TDR	443 $\pm$ 5	207 $\pm$ 1
P5	511 $\pm$ 2	168 $\pm$ 1

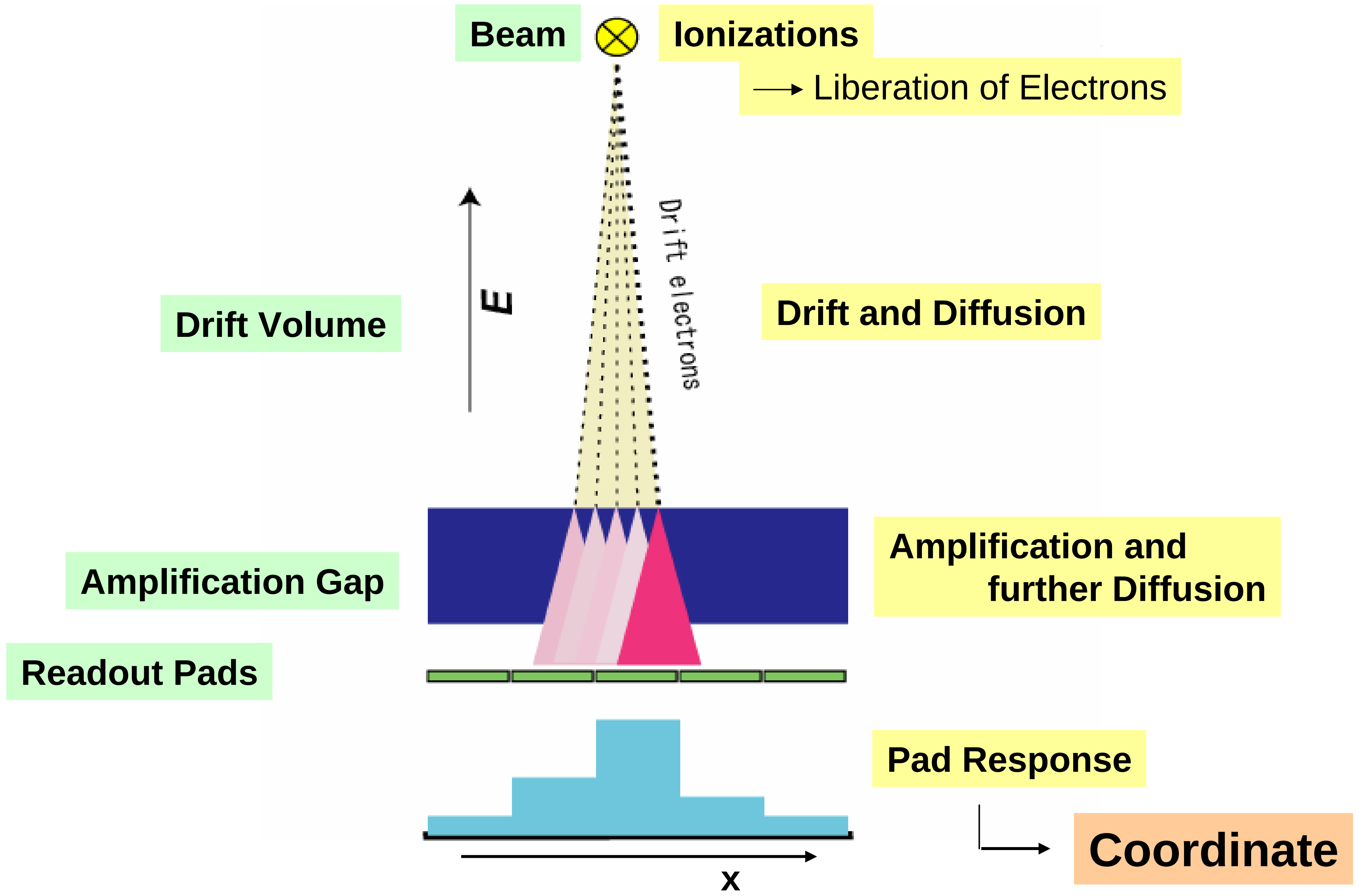
Spatial resolution vs. z



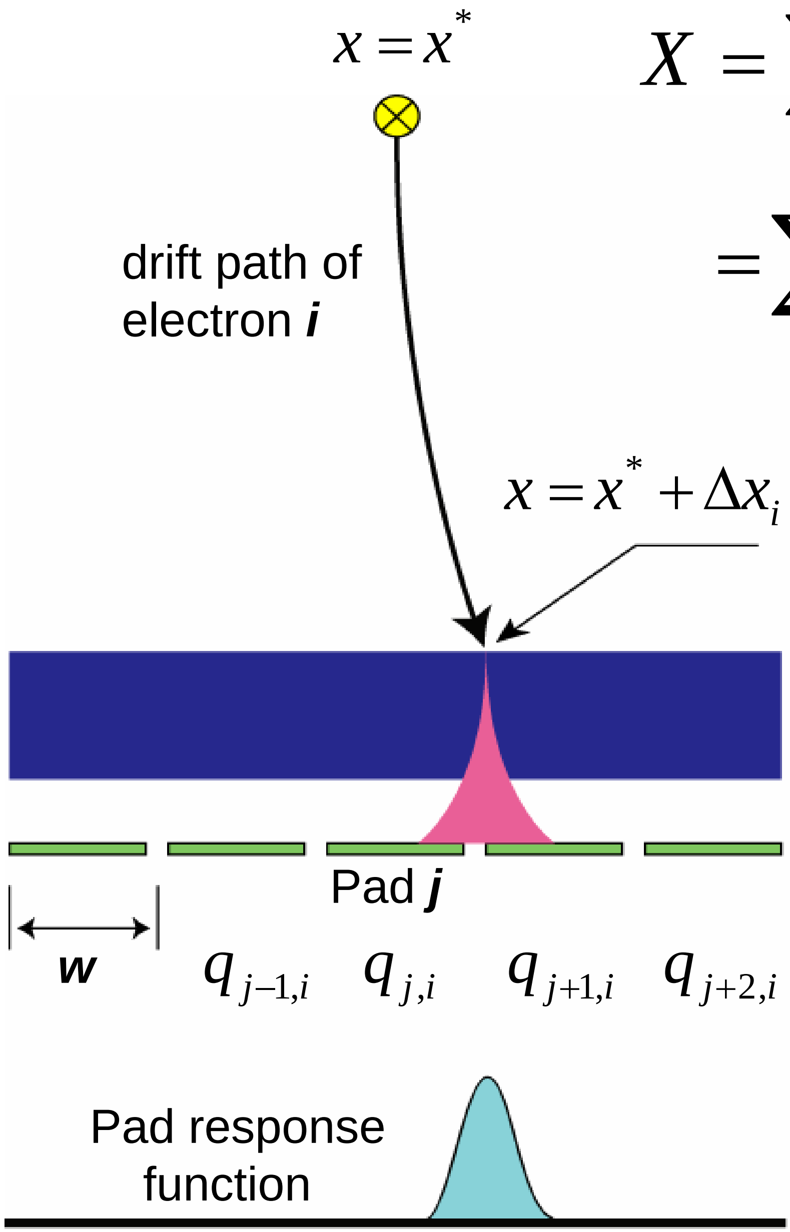
$$\sigma_X = \sqrt{\sigma_{X0}^2 + D^2 / N_{\mathrm{eff}}\, z}$$

	σ_{X0} (μm)	N_{eff}
TDR	81 ± 6	30 ± 2
P5	67 ± 6	27 ± 2

Track coordinate measurement



Charge Centroid X



$$X = \sum_j (jw)\left(\sum_i q_{ji} / \sum_i \sum_j q_{ji}\right)$$

$$= \sum_i Q_i \sum_j (jw) F_j(x^* + \Delta x_i) / \sum_i Q_i \,,$$

where $Q_i = \sum_j q_{ji} \,,$

$$F_j(x^* + \Delta x_i) \equiv q_{ji} / Q_i$$

w **: pad pitch**

j **: pad #**

$q_{j,i}$ is the charge on pad *j* created by electron *i* .

Δx_i is the displacement due to lateral diffusion and its variance is given by $< \Delta x^2 > = D^2 z$, where D is the diffusion constant and z is the drift distance.

i runs through 1 to N, where N is the total number of drift electrons (not a constant).

Formulation of Spatial Resolution

for tracks perpendicular to the pad row

$$\sigma_X^2 = \int_{-1/2}^{+1/2} d\left(\frac{x^*}{w}\right) \left\{ [\mathrm{i}] + \frac{1}{N_{\mathrm{eff}}} [\mathrm{ii}] \right\} + [\mathrm{III}]$$

$$[\mathrm{i}] \equiv \left\{ \sum_j (jw) \langle F_j(x^* + \Delta x) \rangle - x^* \right\}^2$$

$$[\mathrm{ii}] \equiv \sum_{j,k} jkw^2 \langle F_j(x^* + \Delta x) F_k(x^* + \Delta x) \rangle - \left(\sum_j jw \langle F_j(x^* + \Delta x) \rangle \right)^2$$

$$[\mathrm{III}] \equiv \frac{\langle (\Delta q)^2 \rangle}{\langle Q \rangle^2} \left\langle \frac{1}{N^2} \right\rangle \sum_j (jw)^2$$

(Δq: electric noise charge on a pad)

where $N_{\mathrm{eff}} \equiv \left\{ \left\langle \frac{1}{N} \right\rangle \frac{\langle Q^2 \rangle}{\langle Q \rangle^2} \right\}^{-1}$ **and**

$$\langle F_j(x^* + \Delta x) \rangle \equiv \int_{-\infty}^{+\infty} d(\Delta x) P_D F_j(x^* + \Delta x)$$

with $P_D \equiv \frac{1}{\sqrt{2\pi} D} \exp\left(-\frac{(\Delta x)^2}{2D^2} \right).$

The definition is similar for $< Fj \cdot Fk >$ *.*

Remarks on the Formulation

$$F_j(x) \equiv \int_{jw-w/2}^{jw+w/2} f(\xi - x)\, d\xi$$

with *f* (*x*) being the pad response function.

Therefore *Fj* can be evaluated once the pad response function is defined.

$$N_{\text{eff}} \equiv \left\{ \left\langle \frac{1}{N} \right\rangle \frac{\left\langle Q^2 \right\rangle}{\left\langle Q \right\rangle^2} \right\}^{-1} \equiv \frac{\left\langle N \right\rangle}{R},$$

where *R* is defined as $R \equiv (1+K) < N >< N^{-1} >$

with $K \equiv \sigma_Q^2 / < Q >^2 ,$

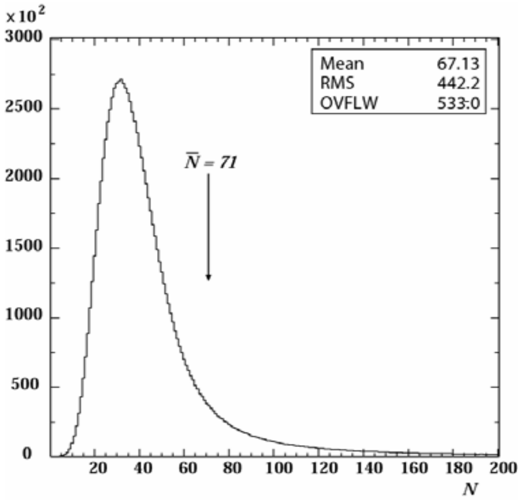
the relative variance of avalanche fluctuation for a single drift electron.

$< N >< N^{-1} >$ **is greater than 1 because of asymmetric distribution of N.**

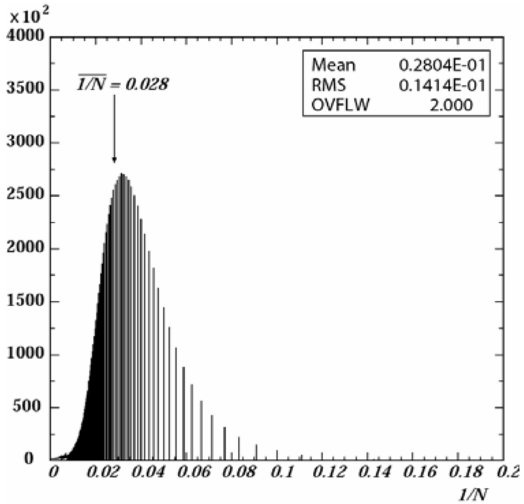
Therefore the effective number of electrons is smaller than the average number of drift electrons.

Remarks (cont'd)

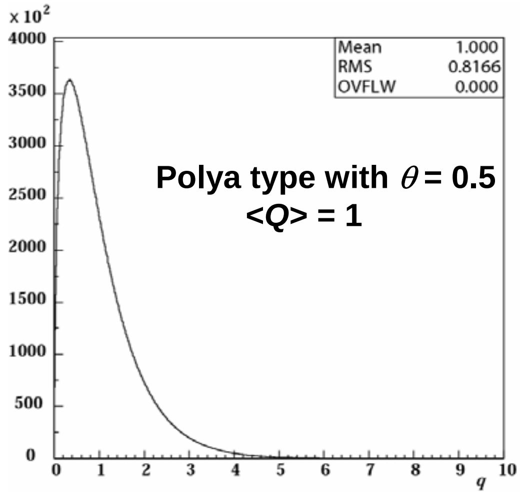
An example of estimation of *N*eff
for 4 GeV/c pions and pad row pitch of 6.3 mm
in pure argon



Distribution of *N*
(<*N*> = 71)



Distribution of 1/*N*
(<1/*N*> = 0.028)



Distribution of *Q*
(*K* = 0.67)

$$R \equiv (1+K) < N > < N^{-1} > \approx (1+0.67) \times 71 \times 0.028 \approx 3.32$$

$$N_{\text{eff}} = \frac{\langle N \rangle}{R} \approx 21$$

Origin and characteristic of each term

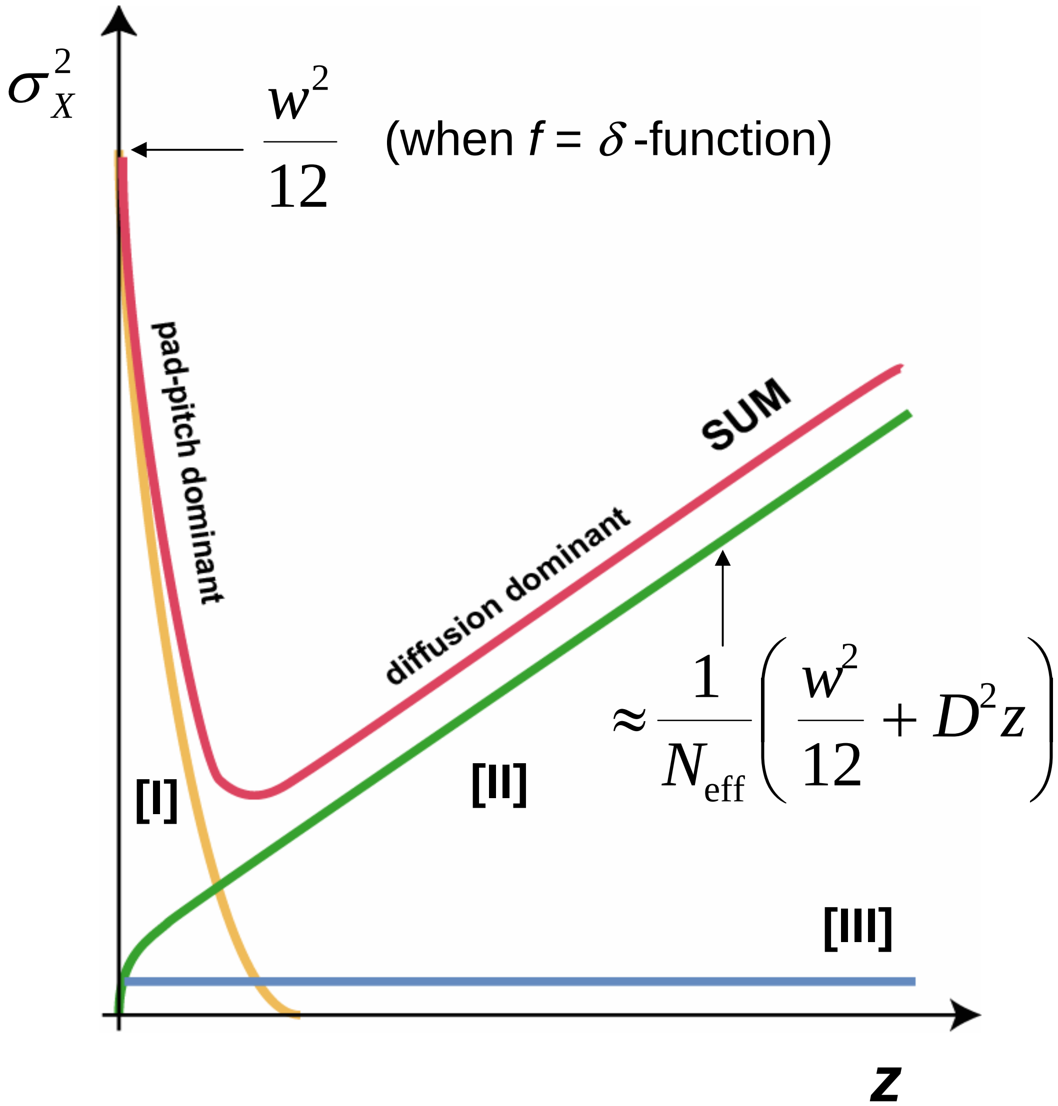
[I] Finite pad pitch ⟶ systematic biases due to charge centroid method.
Rapidly decreases with drift distance (*z*) because of diffusion. *N* independent. $w^2/12$ at $z = 0$ when $f = \delta$.

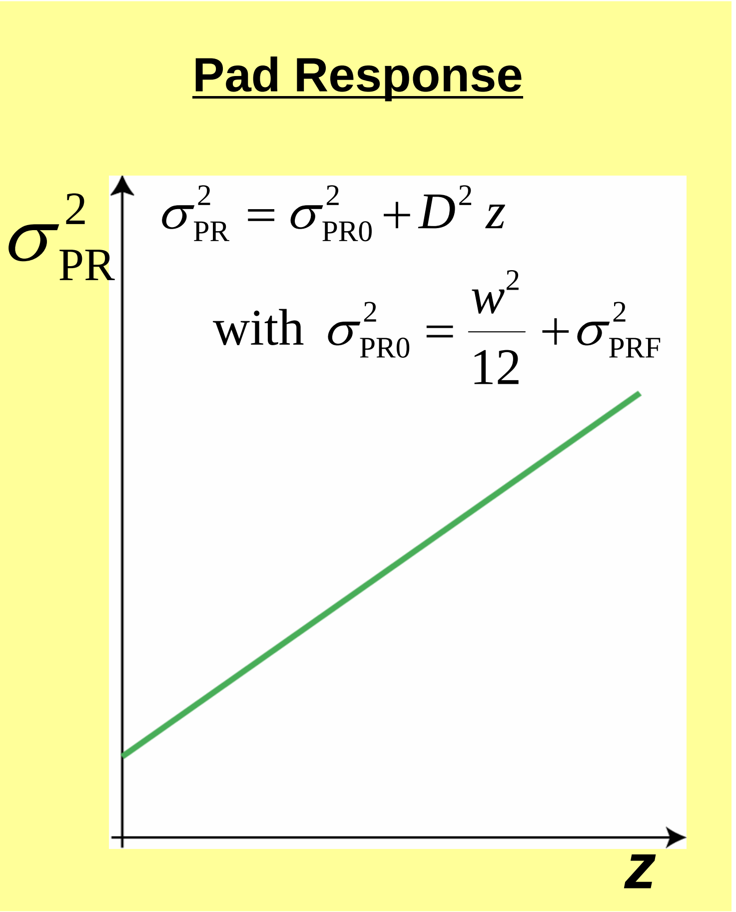
This term can be reduced by calibration if the signal charge is shared by two or more pads.
In reality, however, electronic noise significantly degrades the resolution when the charge sharing among the pads is not sufficient.

[II] Diffusion, gas-gain fluctuation, finite pad pitch combined.
Gradually increases with drift distance, asymptotically $1/N_{\mathrm{eff}}\left(w^2/12 + D^2 z\right)$.

[III] Random electronic noise. *z* independent.

Illustration of each contribution





Charge spread with respect to the centroid

$$\sum_{i=1}^{N} \frac{q_i}{\sum_k q_k} \left(x_i^\# - \frac{\sum_k x_k^\# q_k}{\sum_k q_k} \right)^2 = \sum_{i=1}^{N} \frac{q_i}{\sum_k q_k} \left\{ \left(x_i^\# - x^*\right) - \left(\frac{\sum_k x_k^\# q_k}{\sum_k q_k} - x^* \right) \right\}^2$$

$$= \sum_{i=1}^{N} \frac{q_i}{\sum_k q_k} \left\{ \left(x_i^\# - x^*\right)^2 + \left(\frac{\sum_k x_k^\# q_k}{\sum_k q_k} - x^* \right)^2 - 2\left(x_i^\# - x^*\right)\left(\frac{\sum_k x_k^\# q_k}{\sum_k q_k} - x^* \right) \right\}$$

$$= \sum_{i=1}^{N} \frac{q_i}{\sum_k q_k} \left\{ \left(x_i^\# - x^*\right)^2 + \left(\frac{\sum_k x_k^\# q_k}{\sum_k q_k} - x^* \right)^2 \right\} - 2 \cdot \left(\frac{\sum_k x_k^\# q_k}{\sum_k q_k} - x^* \right)^2$$

$$= \sum_{i=1}^{N} \frac{q_i}{\sum_k q_k} \left(x_i^\# - x^*\right)^2 - \left(\frac{\sum_k x_k^\# q_k}{\sum_k q_k} - x^* \right)^2$$

Averaging over x^*, x_i, q_i and N,

$$\left\langle \sum_{i=1}^{N} \frac{q_i}{\sum_k q_k} \left(x_i^\# - \frac{\sum_k x_k^\# q_k}{\sum_k q_k} \right)^2 \right\rangle = \left\langle \left(x^\# - x^*\right)^2 \right\rangle - \left\langle \left(X^\# - x^*\right)^2 \right\rangle, \quad \text{with} \quad X^\# \equiv \frac{\sum_k x_k^\# q_k}{\sum_k q_k}.$$

Notice that $\left\langle \left(x^\# - x^*\right)^2 \right\rangle = \frac{w^2}{12} + \sigma_{\mathrm{d}}^2$ and $\left\langle \left(X^\# - x^*\right)^2 \right\rangle$ is nothing but the spatial resolution (σ_X^2).

Notations

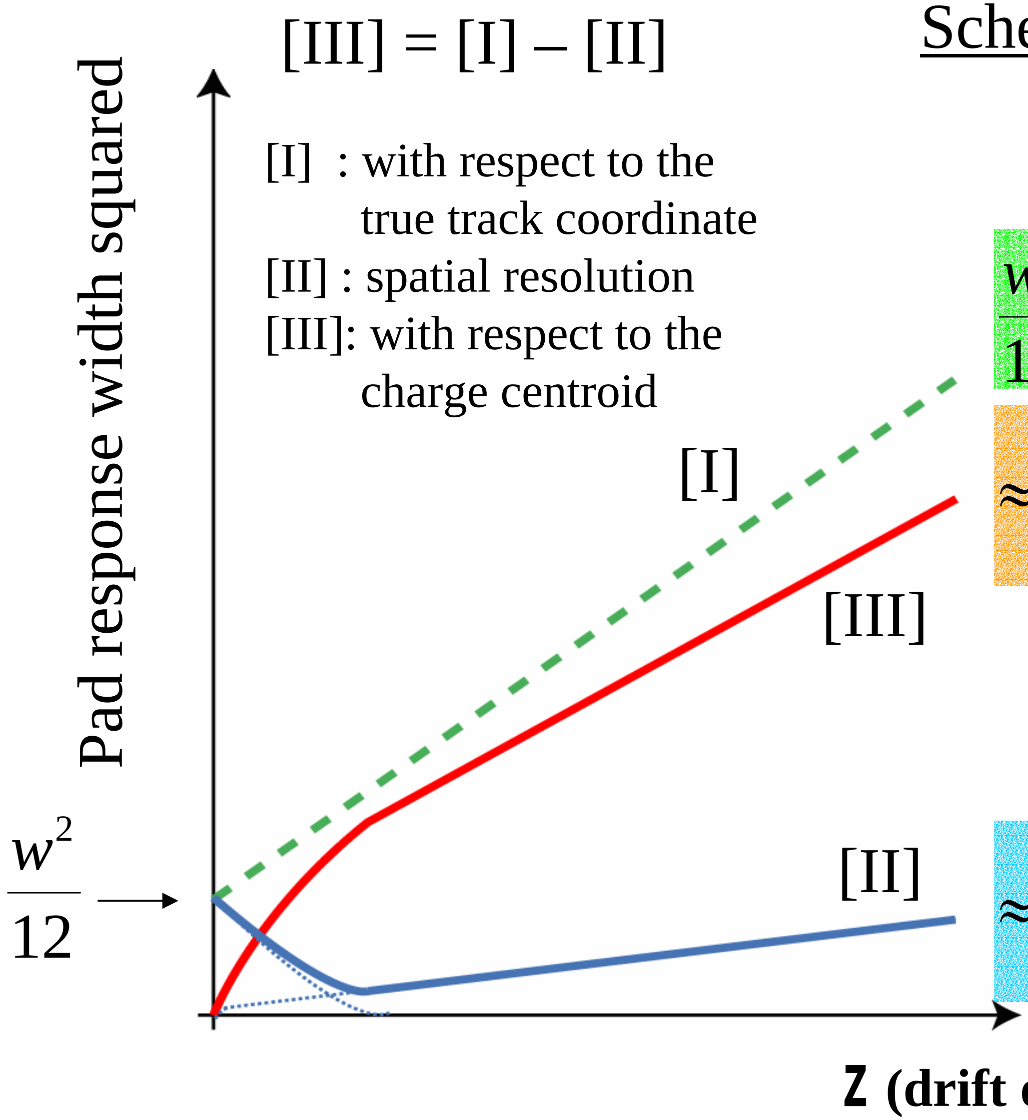
x^* : original (true) track coordinate

$x_i^\#$: arrival position of electron *i*, quantized by the pad pitch (*w*)

Width of Pad Response

pad response function: δ *- function*

Schematic: not to be scaled



$$\frac{w^2}{12} + D^2 \cdot z$$

$$\approx \left(1 - \frac{1}{N_{\text{eff}}}\right)\frac{w^2}{12} + D^2\left(1 - \frac{1}{N_{\text{eff}}}\right)\cdot z$$

$$\approx \frac{1}{N_{\text{eff}}}\left(\frac{w^2}{12} + D^2 \cdot z\right)$$

Brief Summary of Formulation

If *w*, *D*, *f* and *Neff* are known σ_X can readily be calculated for given *z*.

- ***w*: known**

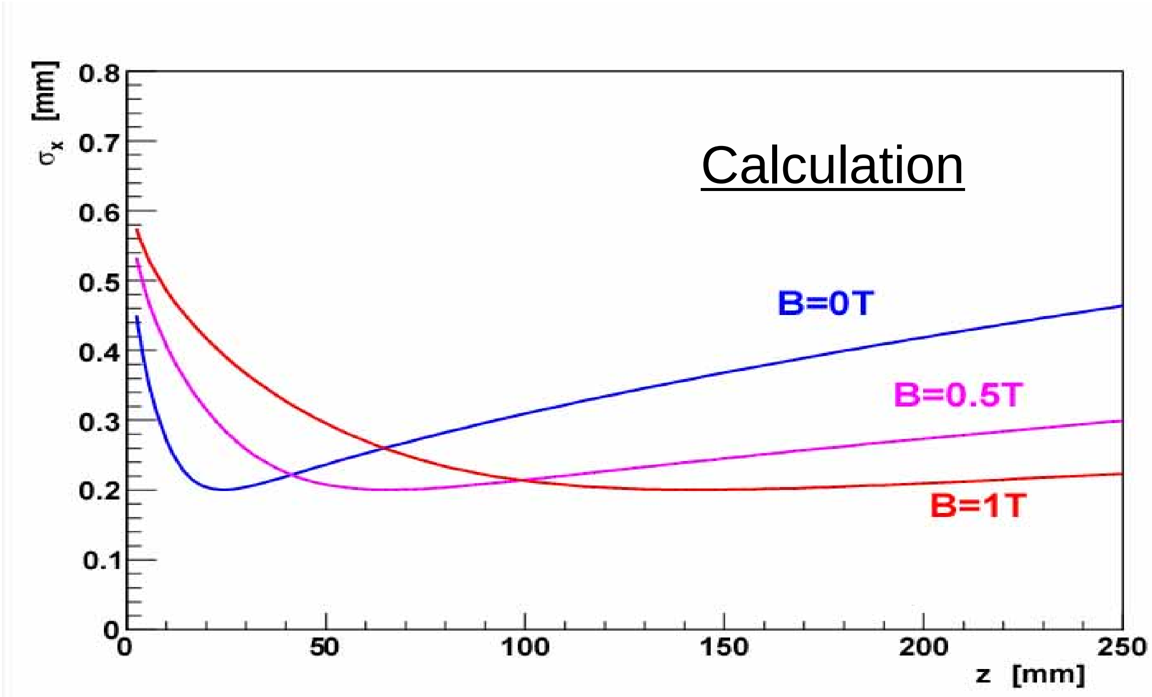
- ***D*: measured**: determined from z dependence of pad-response width
  (or given by Monte-Carlo simulation)

- ***Neff*: measured**: determined from ***D*** and z dependence of spatial resolution
  (or estimated with assumptions on ionization statistics and avalanche fluctuation)

- ***f*** (**pad response function**): **not known** (Monte-Carlo simulation?)
  → δ-function is assumed for ***f***.

- electronic noise (σ_{NOISE}): measurable and different from pad to pad
  → considered here as a constant term independent of ***z***

Examples of Calculated Resolution



w **= 2.3 mm**

D **= 469, 285 and 193** $\mu m/\sqrt{cm}$
respectively for
B **= 0, 0.5, and1.0 T**
(gas: Ar-isobutane (5%))

Neff **= 27.5**

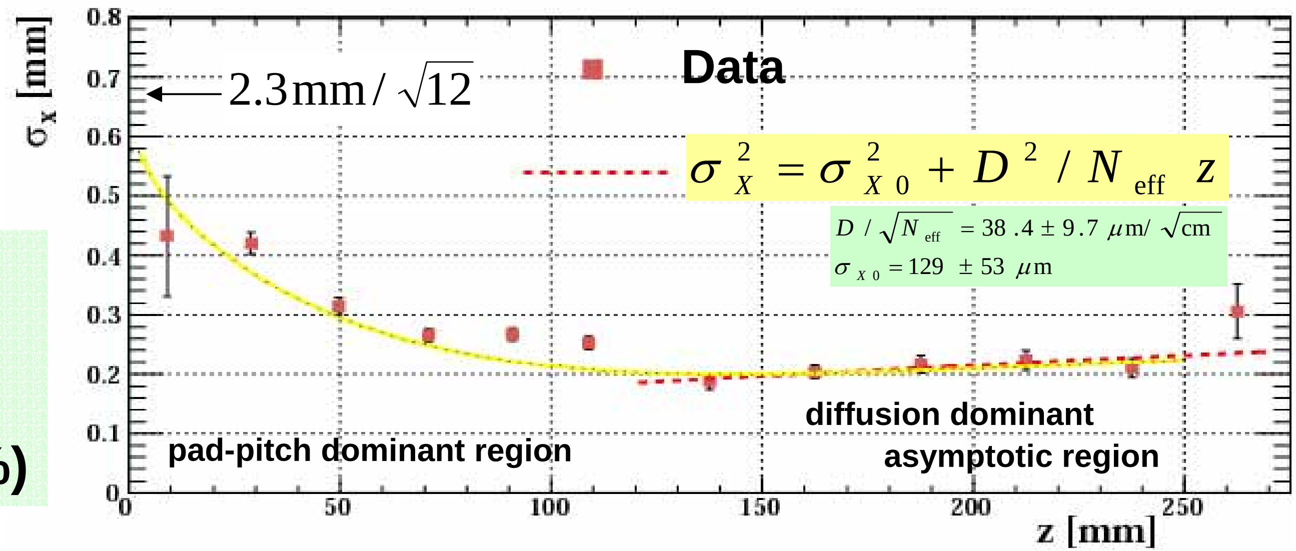
f **:** δ **function**

Electronic noise: absent

Comparison
with the real data

Data: MicroMEGAS

B = 1 T
Gas: Ar-isobutane (5%)



Asymptotic behavior at long drift distances

Expectation vs. Data

Pad Response (B = 1 T)

PRF dominant

	MWPC	GEM		MicroMEGAS
Gas	TDR	TDR	P5	Ar-isobutane (5%)
$\sigma_{PR0}(\mu m)$	1390	443±5	511±2	781±79
$w/\sqrt{12}\,(\mu m)$	663 (w = 2.3 mm)	367 (w = 1.27 mm)		663 (w = 2.3 mm)
$D\,(\mu m/\sqrt{cm})$	220	207±1	168±1	198±15
D [MAGBOLTZ]	200	200	166	193

$$\sigma_{PR}^2 \approx \sigma_{PR0}^2 + D^2 z \quad \text{with} \quad \sigma_{PR0}^2 = w^2/12 + \sigma_{PRF}^2$$

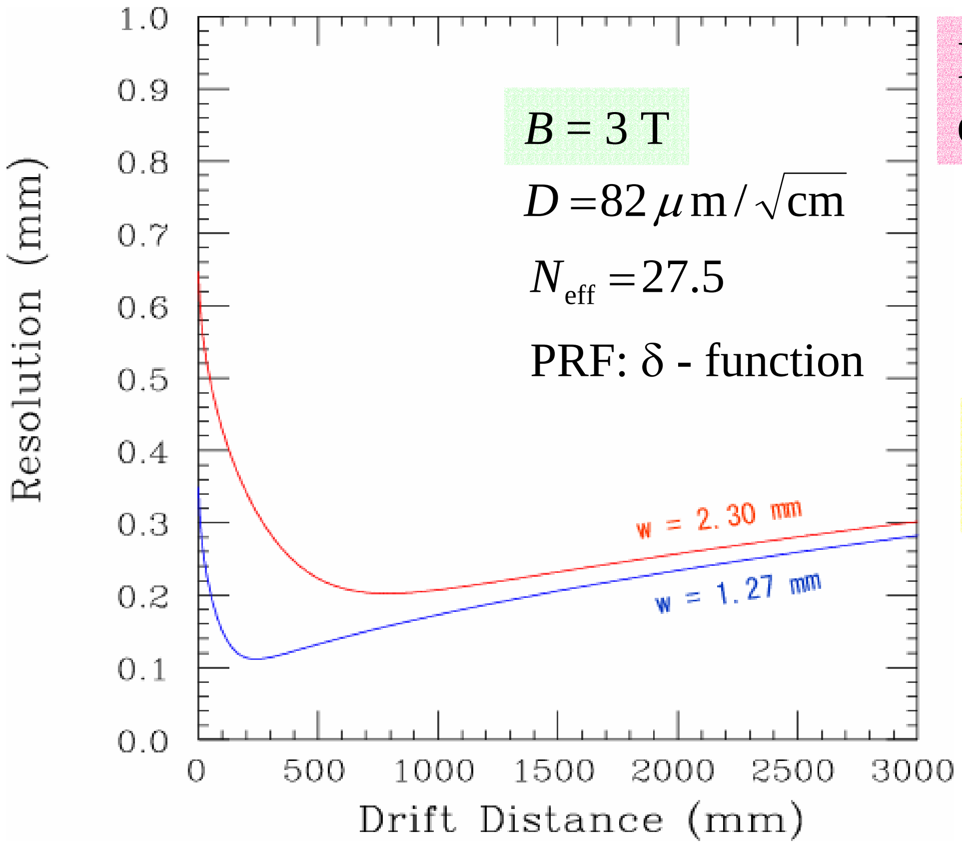
Spatial Resolution (B = 1 T)

small S/N ratio

	MWPC	GEM		MicroMEGAS
Gas	TDR	TDR	P5	Ar-isobutane (5%)
$\sigma_{X0}(\mu m)$	220	81±6	67±6	129±53
$\frac{1}{\sqrt{N_{eff}}}\frac{w}{\sqrt{12}}\,(\mu m)$	135	67	71	128
$\frac{D}{\sqrt{N_{eff}}}\,(\mu m/\sqrt{cm})$	45	38±1	32±1	38±10
N_{eff}	24	30±2	27±2	27±14

$$\sigma_X^2 \approx \sigma_{X0}^2 + \frac{1}{N_{eff}} D^2 z \quad \text{with} \quad \sigma_{X0}^2 = \frac{1}{N_{eff}}\frac{w^2}{12} + \sigma_{NOISE}^2$$

Calculated Resolution for LC TPC



It is important to reduce pad-pitch dominant region in Linear Collider TPC.

↓

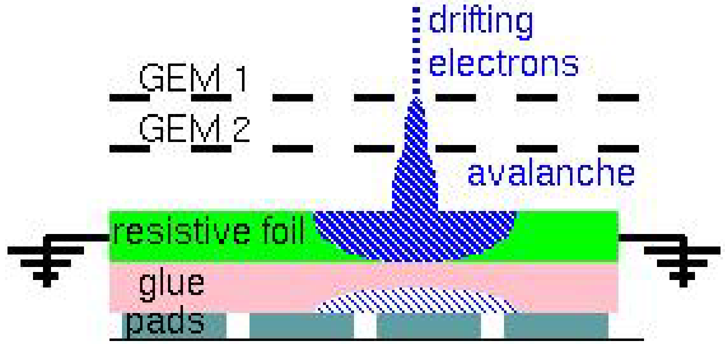
Reduced pad pitch with a larger number of readout channels

or

Use of resistive anode technique (see the next slide.)

Charge dispersion in a MPGD with a resistive anode

Concept & first results: M.S.Dixit et.al., Nucl. Instrum. Methods A518 (2004) 721

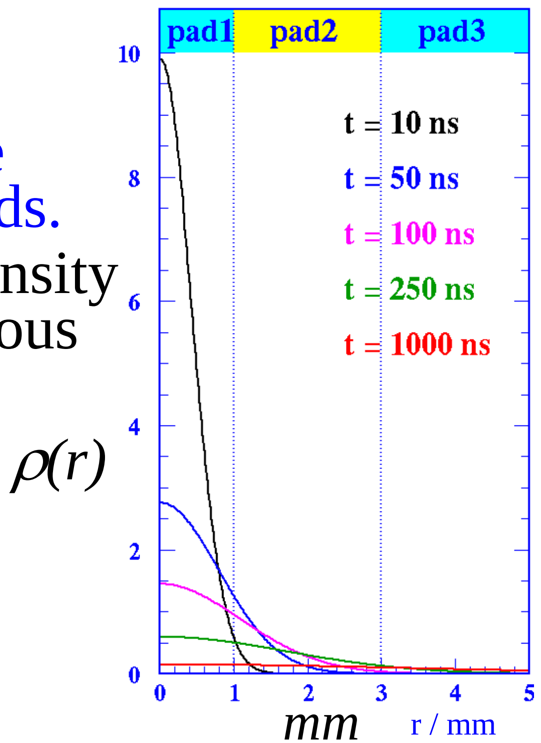


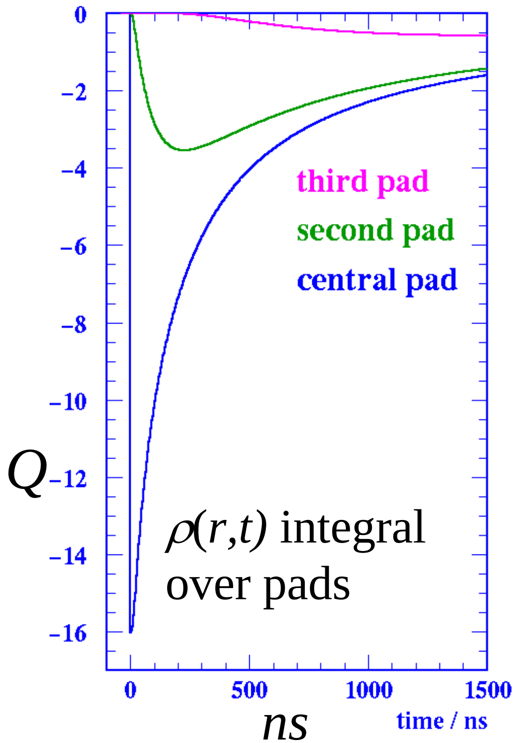
- Modified GEM anode with a high resistivity film bonded to a readout plane with an insulating spacer.
- 2-dimensional continuous RC network defined by material properties & geometry.
- Point charge at $r = 0$ & $t = 0$ disperses with time.
- Time dependent anode charge density sampled by readout pads.

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

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

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

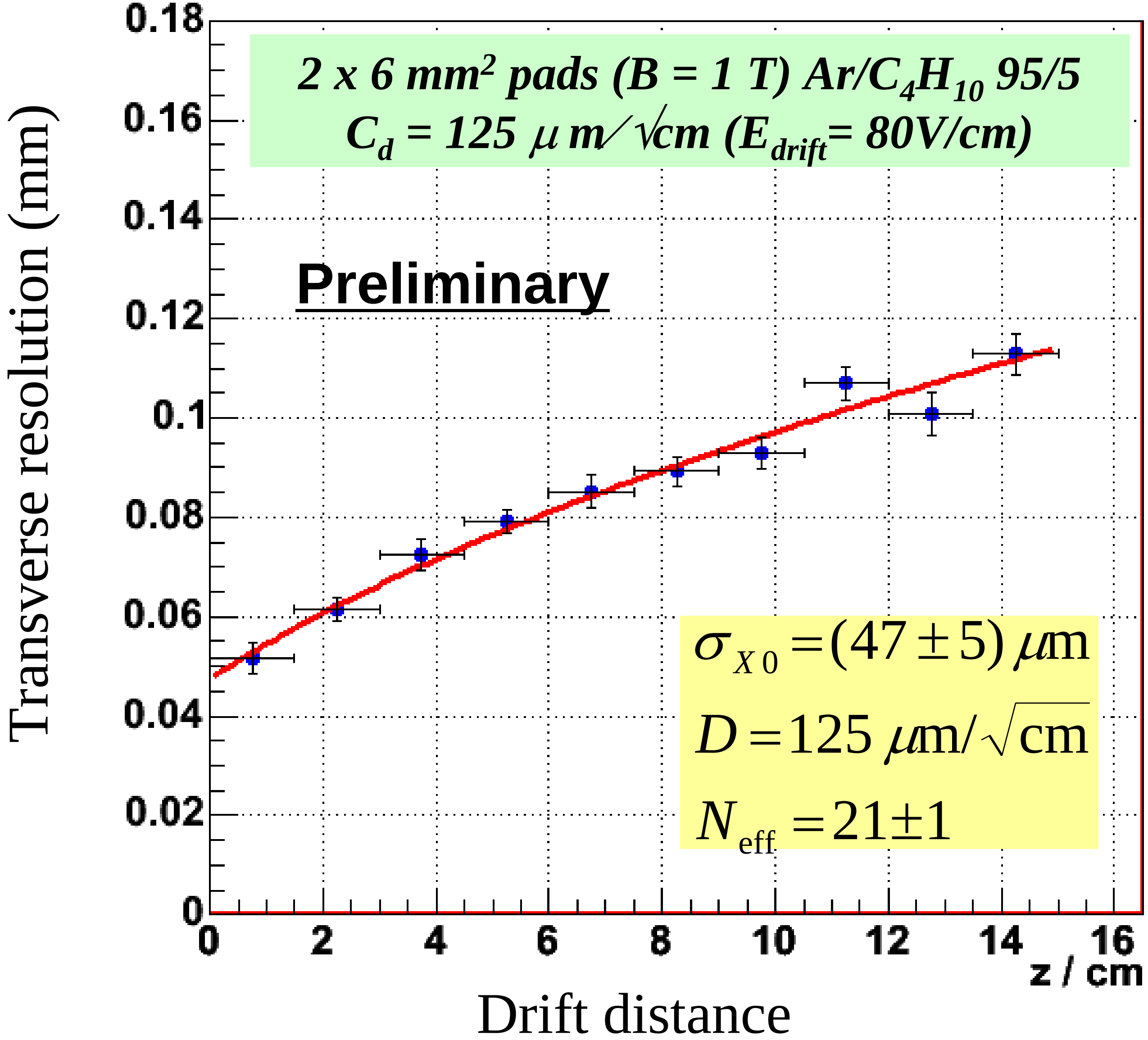




Carleton UNIVERSITY
Canada's Capital University

TPC resolution with charge dispersion

Micromegas-TPC with a resistive anode readout
ILC-TPC collaboration, KEK beam test (October 2005)



Summary

- TPC prototypes with MPGD readout have been operated successfully.
- Spatial resolution is understood in terms of pad pitch, diffusion, PRF, and the effective number of electrons (Neff).
- The expected spatial resolution can be estimated by a simple numerical calculation (NOT a Monte-Carlo) for given geometry, gas mixture and PRF if the relevant parameters are known.
- It is essential to make pad pitch small, *physically* or *effectively*, in order to minimize the pad-pitch dominant volume in the TPC.
- Resistive anode technique reduces the effective pad pitch, thereby eliminating the pad-pitch dominant region.

Future Prospects

- Performance tests with a larger prototype at DESY using a test beam and the super conducting magnet, PCMAG.
- Search for better gas mixtures.

high ionization statistics (electron yield)

small diffusion

large $(\omega)\tau$

small avalanche fluctuation

high electron mobility

small fraction of hydrocarbons

Ar – CF4 (- isobutane) ?

Future Prospects (Cont'd)

- Measurement of the pad response function and avalanche fluctuation using single electrons for better understanding of the pad response and spatial resolution.
- Study of positive ion backflow.
- Detailed Monte-Carlo simulation of the electron transport including avalanche process for the development and geometry optimization of detection devices.

  Inclusion of UV-photon emissions in avalanches?

  Positive ion buildup in the case of GEM?
- Development of (surface mount) readout electronics.

  Digital TPC?