MP-TPC TESTS at KEK-PS
and
Analytic Formulation of Spatial Resolution
fora MPGD-Readout TPC

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ILC TPC School at Tsinghua Univ.

Toward the LC TPC
LC Detector Concept

Reconstruct final states in terms of partons (q, l, gb)

- Identify 2ndary & 3tiary Vertex ID
- Jet invariant mass --> W/Z/t ID and angular analysis -→ Energy flow
- Missing momentum --> neutrinos → Hermetic Detector

→ Visualize Events as viewing Feynman Diagrams
→ Require A State-of-the-art Detector

Requirements for the Central Trucker

- Momentum Resolution ≦ $0.5 \times 10^{-4} P_T$
- Two Hit Separation ≦ 2 mm (rΦ) x 5 mm (z)
- Truck Cluster (Cal) Matching ≦ 1 mm (rΦ, rz)
- Time Stamping O(1ns)

Momentum Resolution: What We Need to Acheive?

1. $e^+e^- \rightarrow ZH \rightarrow (Z \rightarrow \mu\mu/ee) + X$:
   If $\delta M(\mu\mu/ee) << \Gamma z$、
   then the beam energy spraed dominate.
   → Most probabaly $\delta(1/p_t) \sim 1.0 - 0.5 \times 10^{-4}$

2. Slepton and the LSP masses though the end point measurement:
   σ_M (Momentum Resolution) ~ σ_M (Parent Mass)
   Only @ 1 ab^{-1} when $\delta(1/p_t) \sim 0.5 \times 10^{-4}$

3. Rare decay: $e^+e^- \rightarrow ZH \rightarrow Z + (H \rightarrow \mu\mu)$:
   → $\delta(1/p_t) \sim 0.5 \times 10^{-4}$ sufficinet ?
   → Still need study one more time?

R&D for LC TPC

1 **Demonstration Phase** : With small TPC prototypes on mapping out MPGD operation parameters and understanding spatial resolution etc, to prove feasibility of MPGD TPC. Still need to work for the best gas and the ion feed back and gating scheme. For MOS-based pixel digital TPC, still to complete the proof-of-principle tests.

2 **Consolidation Phase**: The world-wide LC TPC collaboration and EUDET build and operate the Large TPC Prototype (LP), ϕ ~ 80cm, drift length ~ 60cm, with EUDET infrastructure as basis, to establish a proof for the target momentum resolution (in non-uniform magnetic field), as well as basic designs and manufacturing techniques of MPGD endplates, field cage and advanced electronics in next 3 – 5 years. This phase corresponds to the term of the Japanese Grant-in-Aid ("Gakujyutu Sosei").

3 **Design Phase**: During phase 2, a conclusion as to which endplate technology to be the best for the LC TPC would be approached, and final design would start as the real experimental collaboration is to be formed.

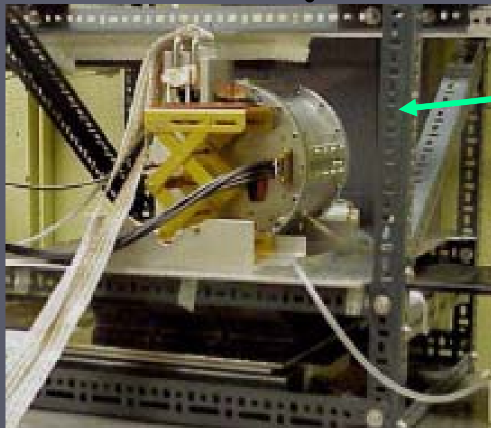
Demonstration Phase

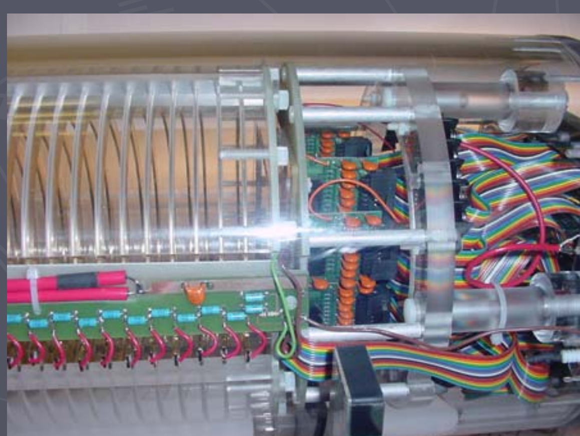
(1) Studies of New Gas Amplification System: MPGD
GEM, MicroMEGAS (MM)

＊ Basic characteristics of MPGD: Gain, electron transmission, ion feedback, signal time structure, signal spread, stabilities, gas, operation etc.

＊ New structures and new fabrication methods of MPGD: Laser etching GEM, larger MPGD (up to 30 cm x 30cm), thicker GEM, MM with pillars, Bulk MM structure,

Examples of Prototype TPCs

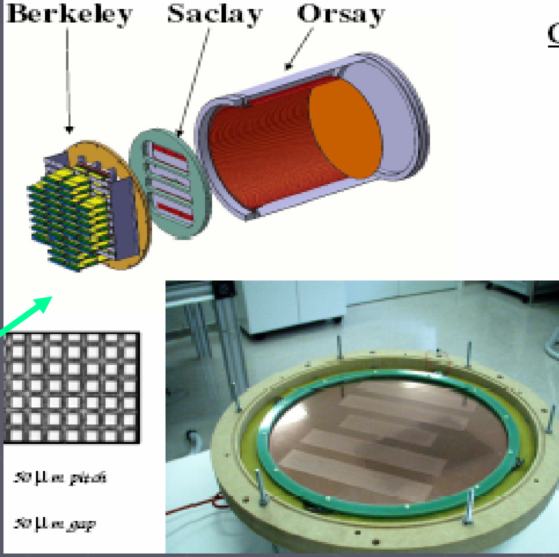


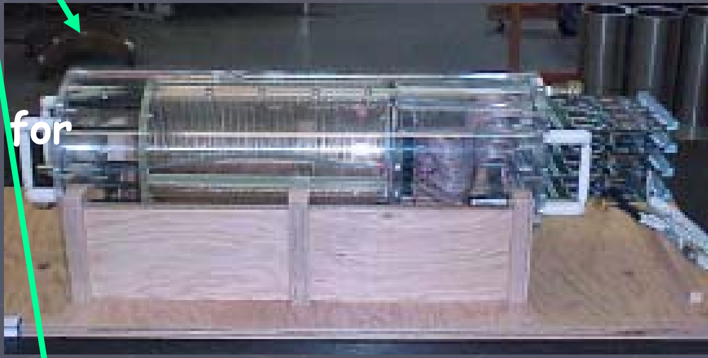


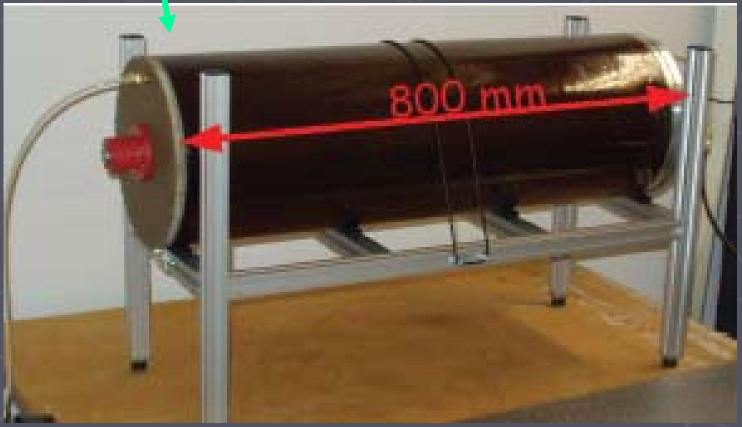
Carleton, Aachen, Cornell/Purdue, Desy(n.s.) for B=0or1T studies

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







Settles

Demonstration Phase

(2) Performance Tests with Small TPC Prototypes

Various cosmic ray tests and beam tests of GEM and MicroMEGAS for different gases with or without magnetic field (up to 5T) provided data of spatial resolution and track separation.

In 2004-2006, the MP-TPC collaboration (Saclay/Orsay, MPI/DESY, Carleton university and the CDC group including MSU group) performed a series of performance tests at KEK π 2 beam line for:

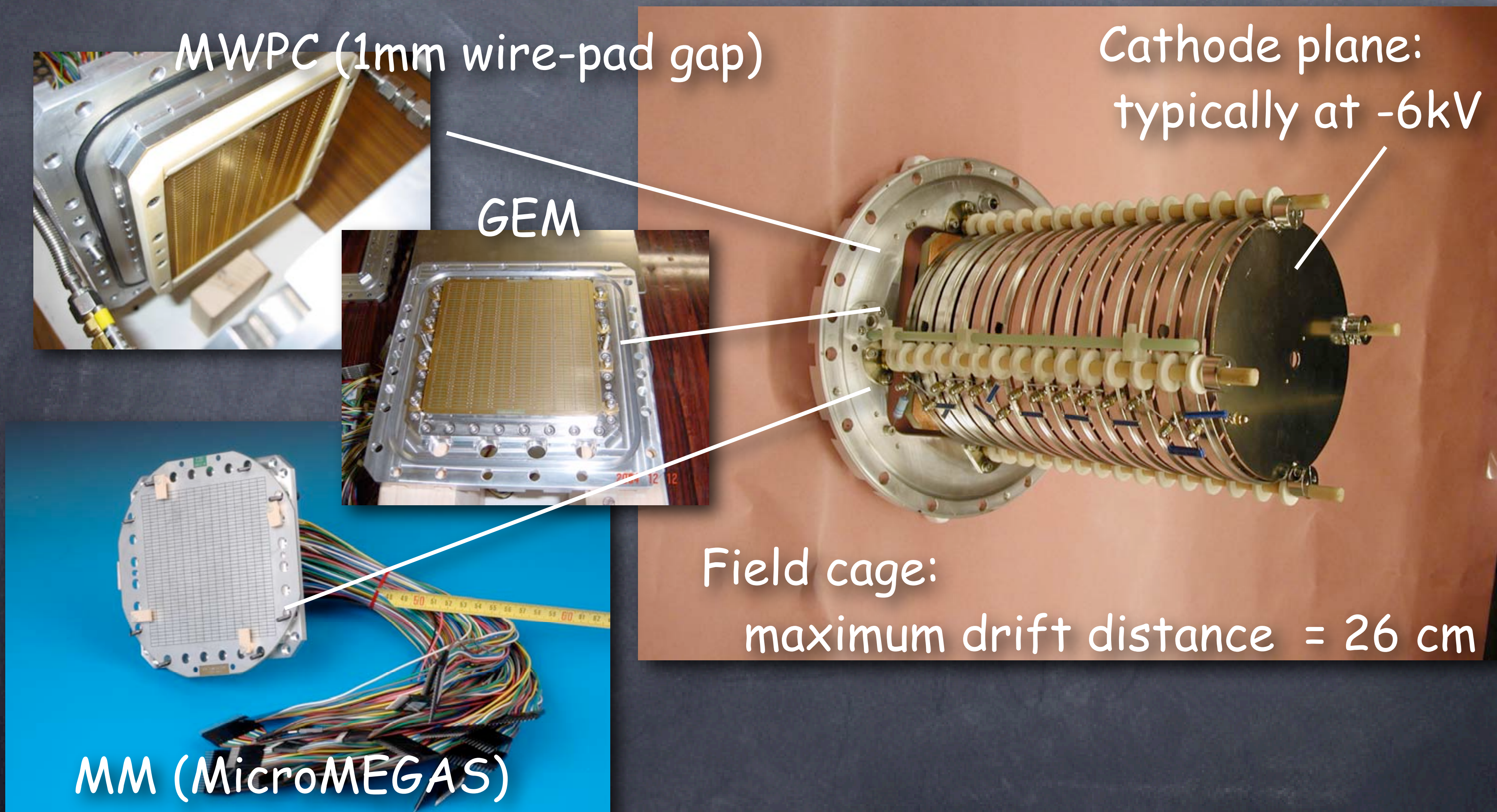
(1) MWPC with 2mm wide normal pads,
(2) 3-layer GEM (CERN) with 1mm wide normal pads,
(3) MicroMEGAS with normal pads (2 mm), and
(4) MiroMEGAS with the restive anode.

The tests utilized a small MP-TPC prototype, a thin-coil Permanent-Current superconducting MAGnet; (PCMAG), and the ALEPH TPC electronics at LEP.

A new analytic calculation of the spatial resolution was made to understand the results.

KEK Beam Tests w/ MP-TPC

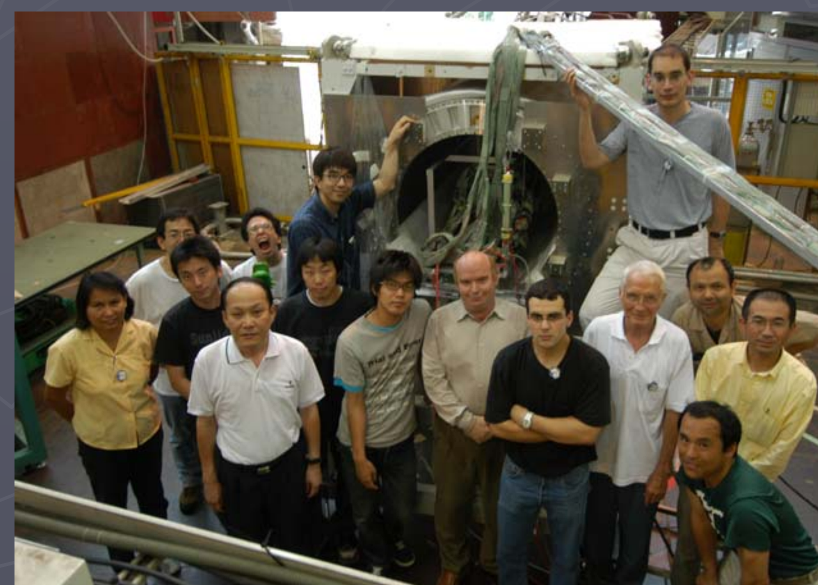
- Use the same small prototype (MP-TPC) as a test bench to compare different readout planes:




2004 7 1


2004 7 1


Take the time



MP TPC Prototype with Cosmic Rays

TPC: MP-TPC

MPGD:

- 3 layers of CERN GEM
- 10cm x 10cm
- 1.17 x 6 mm pads
- 7 pad-rows readout
- Inter-GEM and GEM-pad gap: 1mm (so far)
- Vgap = V_{GEM} (so far)

Electronics: ALEPH

Gas: Ar-CF4(3%)-Isobutene

Magnet: Max. 1T

KEK Cryogenic Center

A Question Arises!

From the old Slide by A. Sugiyama in Nov. 2004

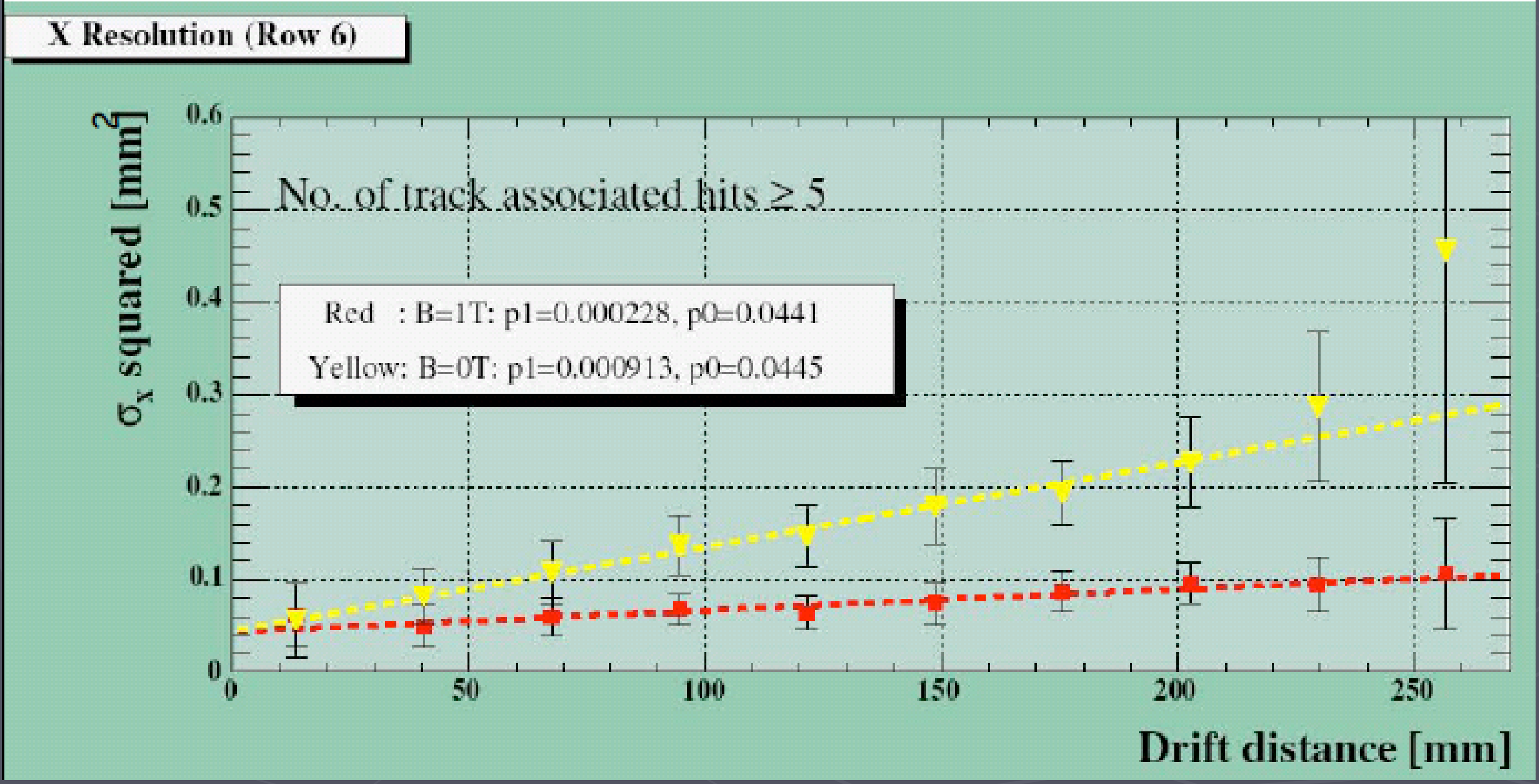
σ x resolution

can be parameterized

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

$$\begin{aligned} \sigma_0 &= 0.21 \quad mm \\ C_D/\sqrt{N_e} &= 0.048 \quad mm/\sqrt{cm} \quad (B = 1T) \\ &= 0.096 \quad mm/\sqrt{cm} \quad (B = 0T) \end{aligned}$$

if Ne=60 Cd is ~8times larger than above number
if Cd is assumed, Neff= ~0.4*Ne
parametrization is too simple!? do more study



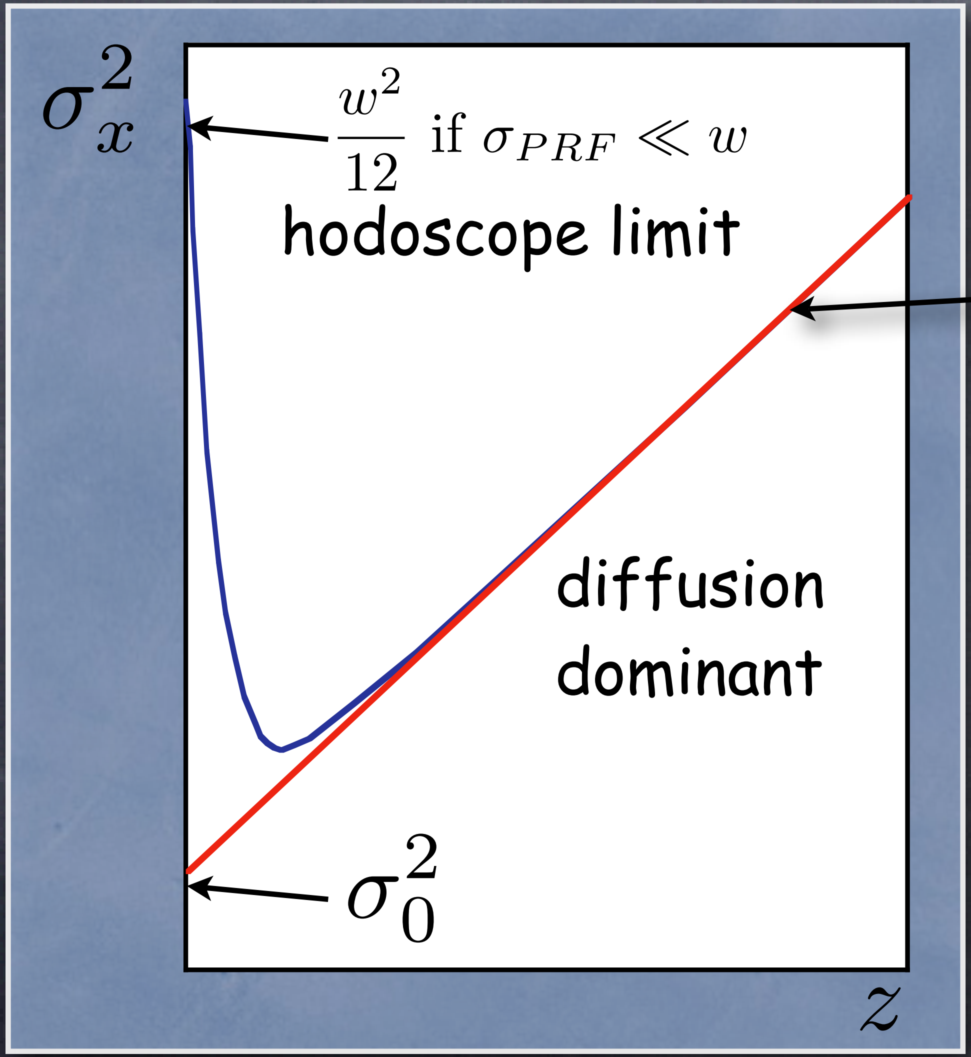
Analytic Formulation of Spatial Resolution for a MPGD-Readout TPC

-- Fundamental Limits on Spatial Resolution --

Achievement with KEK Beam Tests

Two Mysteries

Generic behaviors of resolution data



$$\sigma_x^2 = \sigma_0^2 + C_d^2 z / N_{eff}$$

- Why $N_{eff} < \langle N \rangle$?
- What is the origin of $\sigma_0 \equiv \sigma_x(z=0)$?

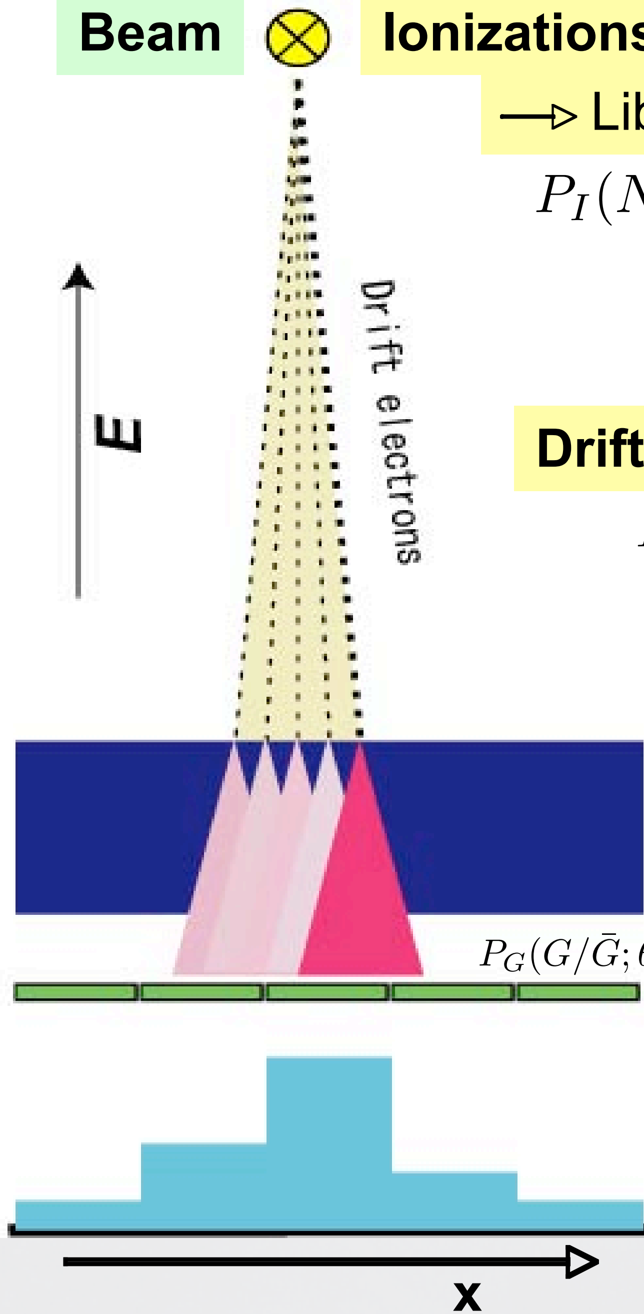
Fundamental Processes

Beam **Ionizations**

⟶ Liberation of Electrons

$P_I(N;\bar{N})$ Normal incidence (no angle effect)

No δ-ray



Drift Volume

Drift and Diffusion

$$P_D(x_i;\sigma_d) = \frac{1}{\sqrt{2\pi}\sigma_d}\exp\left(-\frac{x_i^2}{2\sigma_d^2}\right)$$

Amplification Gap

Amplification and further Diffusion

$$P_G(G/\bar{G};\theta) = \frac{(\theta+1)^{\theta+1}}{\Gamma(\theta+1)}\left(\frac{G}{\bar{G}}\right)^{\theta}\exp\left(-(\theta+1)\left(\frac{G}{\bar{G}}\right)\right)$$

Readout Pads

Pad Response

⟶ **Coordinate**

Ionization Statistics

Ideal Readout Plane: Coordinate = Simple C.O.G.

PDF for Center of gravity of N electrons

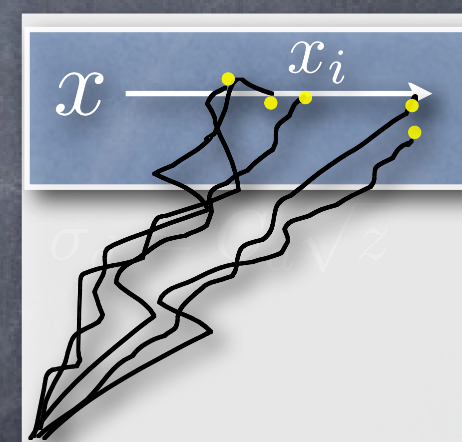
$$P(\bar{x}) = \sum_{N=1}^{\infty} P_I(N;\bar{N}) \prod_{i=1}^{N} \left(\int dx_i P_D(x_i;\sigma_d) \right) \delta\left(\bar{x} - \frac{1}{N}\sum_{i=1}^{N} x_i \right)$$

Ideal readout plane

Gaussian diffusion

$$P_D(x_i;\sigma_d) = \frac{1}{\sqrt{2\pi}\sigma_d} \exp\left(-\frac{x_i^2}{2\sigma_d^2} \right)$$

$$\sigma_d = C_d\sqrt{z}$$



$$\sigma_{\bar{x}}^2 \equiv \int d\bar{x}\, P(\bar{x})\, \bar{x}^2 = \sigma_d^2 \left\langle \frac{1}{N} \right\rangle \equiv \sigma_d^2 \frac{1}{N_{eff}}$$

$$N_{eff} \equiv 1/\langle 1/N \rangle < \langle N \rangle$$

Gas Gain Fluctuation

Coordinate = Gain-Weighted Mean

PDF for Gain-Weighted Mean of N electrons

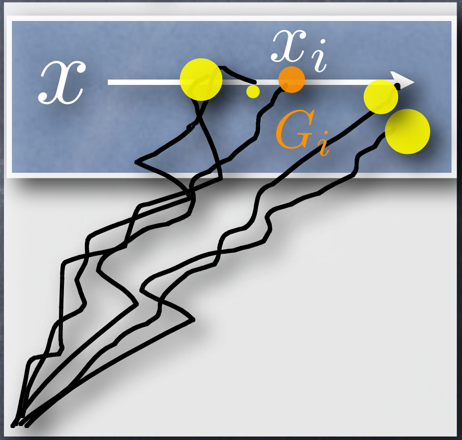
$$P(\bar{x}) = \sum_{N=1}^{\infty} P_I(N;\bar{N}) \prod_{i=1}^{N} \left(\int dx_i P_D(x_i;\sigma_d) \int d(G_i/\bar{G})\, P_G(G_i/\bar{G};\theta) \right) \delta\left(\bar{x} - \frac{\sum_{i=1}^{N} G_i\, x_i}{\sum_{i=1}^{N} G_i} \right)$$

Gaussian diffusion as before

Gain-weighted mean

Gas gain fluctuation (Polya)

$$\theta = \begin{cases} 0 & : \text{exp.} \\ \infty & : \delta\text{-fun} \end{cases}$$



$$P_G(G/\bar{G};\theta) = \frac{(\theta+1)^{\theta+1}}{\Gamma(\theta+1)} \left(\frac{G}{\bar{G}}\right)^{\theta} \exp\left(-(\theta+1)\left(\frac{G}{\bar{G}}\right)\right)$$

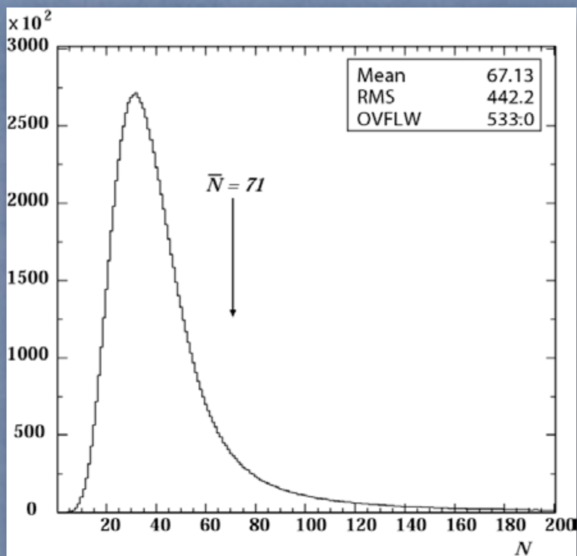
$$\sigma_{\bar{x}}^2 \equiv \int d\bar{x}\, P(\bar{x})\, \bar{x}^2 = \sigma_d^2 \left\langle \frac{1}{N} \right\rangle \left\langle \left(\frac{G}{\bar{G}}\right)^2 \right\rangle \equiv \sigma_d^2 \frac{1}{N_{eff}}$$

$$N_{eff} = \left[\left\langle \frac{1}{N} \right\rangle \left\langle \left(\frac{G}{\bar{G}}\right)^2 \right\rangle \right]^{-1} = \frac{1}{\langle \frac{1}{N} \rangle} \left(\frac{1+\theta}{2+\theta} \right) < \langle N \rangle$$

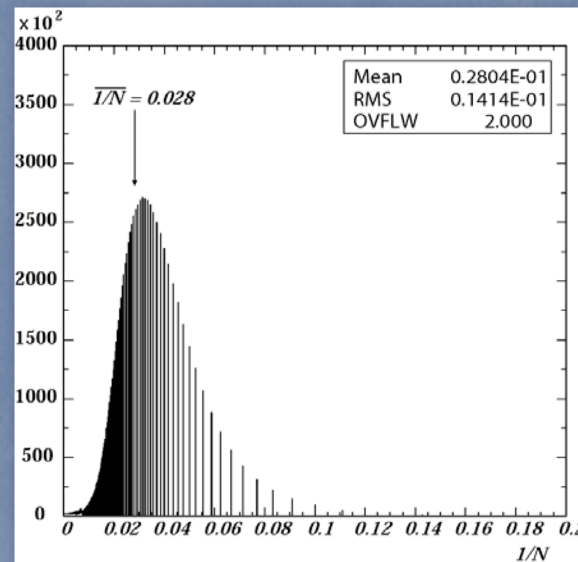
Sample Calc. for Neff

For 4 GeV pion and pad pitch of 6mm in pure Ar

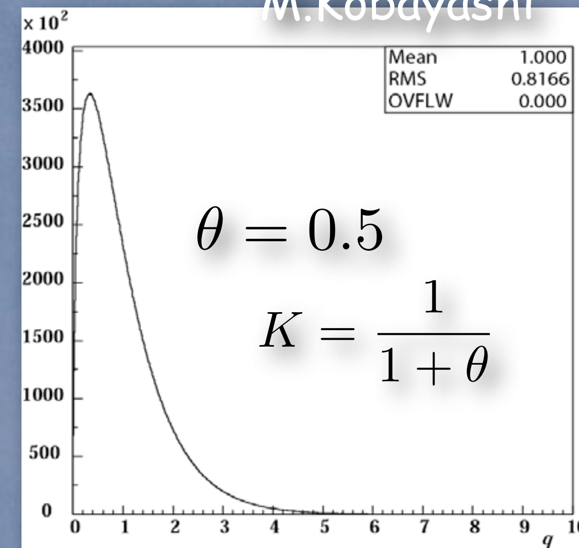
M.Kobayashi



Distribution of N
($\langle N \rangle = 71$)



Distribution of $1/N$
($\langle 1/N \rangle = 0.028$)



$$\theta = 0.5$$

$$K = \frac{1}{1+\theta}$$

Distribution of Q
($K = 0.67$)

$$\left\langle \left(\frac{G}{\bar{G}}\right)^2 \right\rangle = 1 + \left(\frac{\sigma_G}{\bar{G}}\right)^2 \equiv 1 + K$$

$$N_{eff} = \left[\left\langle \frac{1}{N} \right\rangle \left\langle \left(\frac{G}{\bar{G}}\right)^2 \right\rangle \right]^{-1} = 21 < \langle N \rangle = 71$$

Finite Size Pads

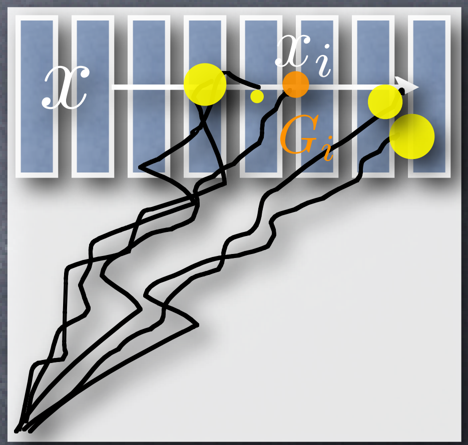
Coordinate = Charge Centroid

track position

$$x_i = \tilde{x} + \Delta x_i$$

diffusion

$$\langle \Delta x^2 \rangle = \sigma_d^2 = C_d^2 z$$



Charge on Pad j

Electronic noise

$$\langle \Delta Q^2 \rangle = \sigma_E^2$$

$$Q_j = \sum_{i=1}^{N} G_i \cdot f_j(\tilde{x} + \Delta x_i) + \Delta Q_j,$$

Normalized response fun. for pad j

$$\sum_j f_j(\tilde{x} + \Delta x_i) = 1$$

Charge Centroid

Pad pitch

$$\bar{x} = \sum_j Q_j\,(wj) / \sum_j Q_j$$

PDF for Charge Centroid

$$\begin{aligned} P(\bar{x};\tilde{x}) \;=\; & \textstyle\sum_{N=1}^{\infty} P_I(N;\bar{N}) \prod_{i=1}^{N} \left(\int d\Delta x_i P_D(\Delta x_i;\sigma_d) \int d(G_i/\bar{G})\, P_G(G_i/\bar{G};\theta)\right) \\ & \times \textstyle\prod_j \left(\int d\Delta Q_j\; P_E(\Delta Q_j;\sigma_E)\; \int dQ_j\; \delta\left(Q_j - \sum_{i=1}^{N} G_i \cdot f_j(\tilde{x} + \Delta x_i) - \Delta Q_j\right)\right) \\ & \times \delta\left(\bar{x} - \frac{\sum_j Q_j\,(wj)}{\sum_j Q_j}\right) \end{aligned}$$

Full Analytic Formula

$$\sigma_{\bar{x}}^2 \equiv \int_{-1/2}^{+1/2} d\left(\frac{\tilde{x}}{w}\right) \int d\bar{x}\, P(\bar{x};\tilde{x})\,(\bar{x}-\tilde{x})^2 = \int_{-1/2}^{+1/2} d\left(\frac{\tilde{x}}{w}\right) \left[[A] + \frac{1}{N_{eff}}[B]\right] + [C]$$

- Purely geometric term

$$[A] = \left(\sum_j (jw)\,\langle f_j(\tilde{x}+\Delta x)\rangle - \tilde{x}\right)^2$$

- Diffusion, gas gain fluctuation & finite pad pitch term

$$[B] = \sum_{j,k} jkw^2\,\langle f_j(\tilde{x}+\Delta x) f_k(\tilde{x}+\Delta x)\rangle - \left(\sum_j jw\,\langle f_j(\tilde{x}+\Delta x)\rangle\right)^2$$

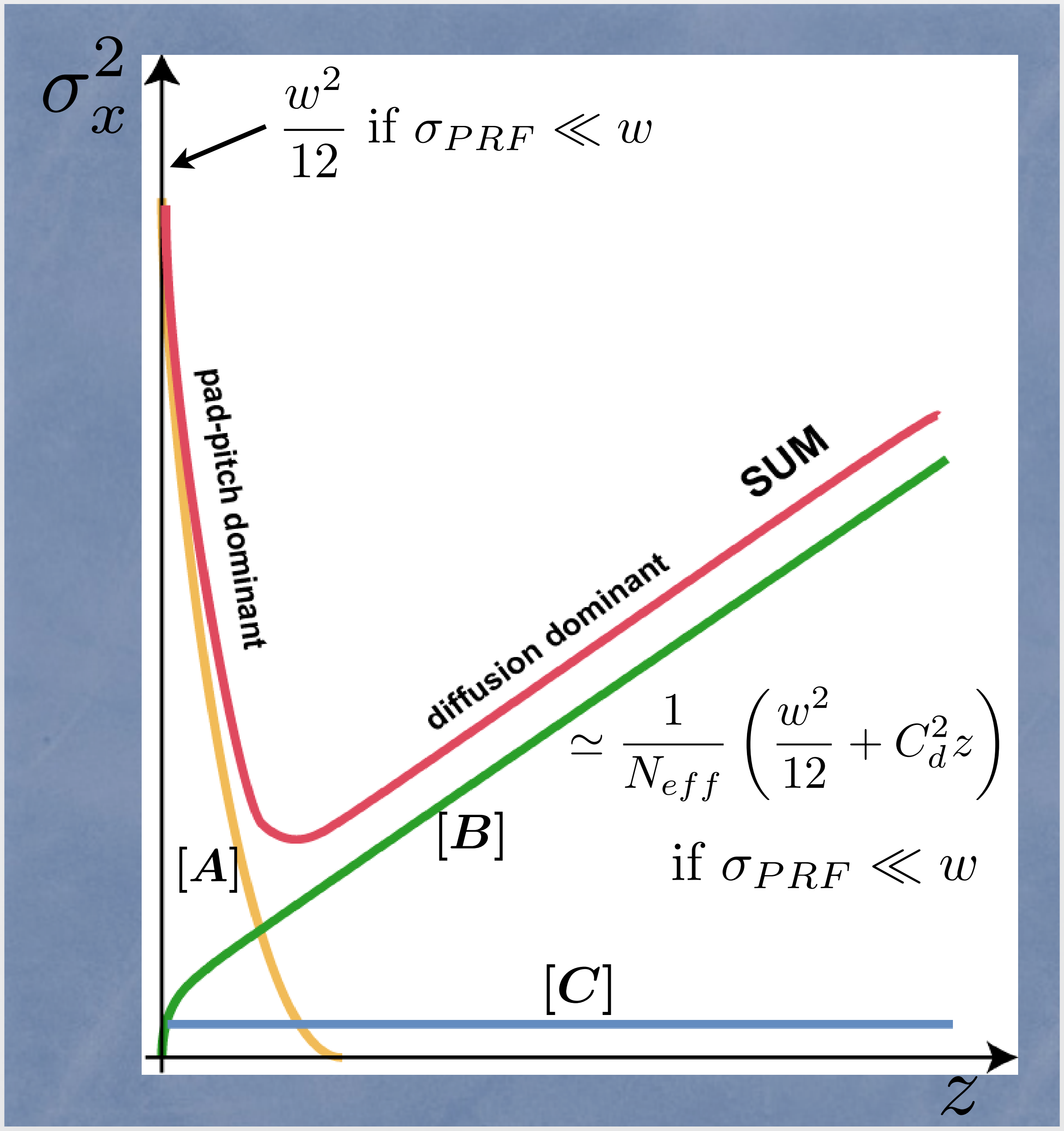
$$\langle f_j(\tilde{x}+\Delta x) f_k(\tilde{x}+\Delta x)\rangle \equiv \int d\Delta x P_D(\Delta x;\sigma_d)\, f_j(\tilde{x}+\Delta x)\, f_k(\tilde{x}+\Delta x)$$

$$\langle f_j(\tilde{x}+\Delta x)\rangle \equiv \int d\Delta x P_D(\Delta x;\sigma_d)\, f_j(\tilde{x}+\Delta x)$$

- Electronic noise term

$$[C] = \left(\frac{\sigma_E}{\bar{G}}\right)^2 \left\langle \frac{1}{N^2} \right\rangle \sum_j (jw)^2$$

Interpretation



[A] Purely geometric term (S-shape systematics from finite pad pitch): rapidly disappears as Z increases

[B] Diffusion, gas gain fluctuation & finite pad pitch term: scales as $1/N_{eff}$, for delta-fun like PRF asymptotically:

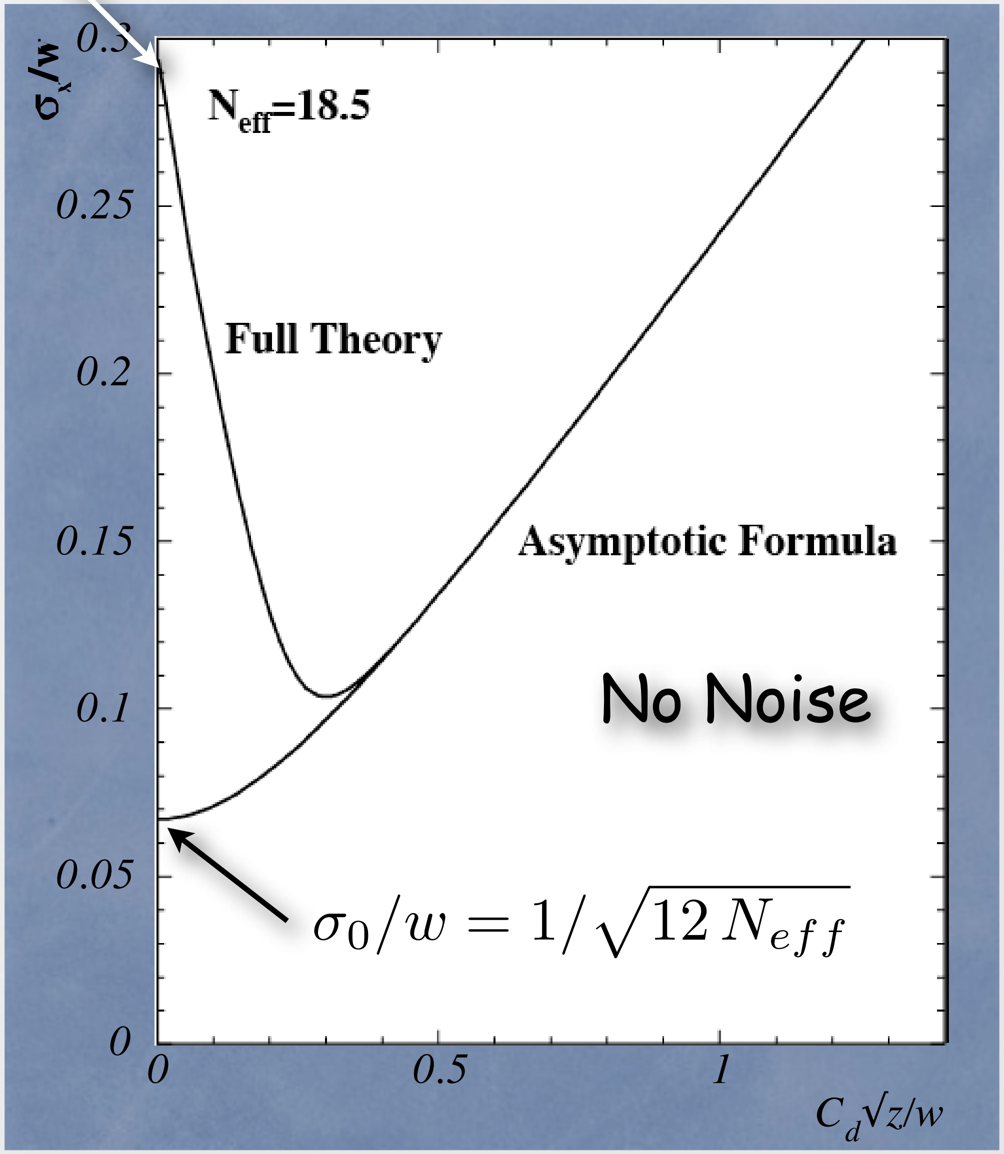
$$\sigma_{\bar{x}}^2 \simeq \frac{1}{N_{eff}} \left(\frac{w^2}{12} + C_d^2 z \right)$$

[C] Electronic noise term: Z-independent, scales as $\langle 1/N^2 \rangle$

Application to MM

- For delta-function like PRF, σ_x/w depends only on σ_d/w and N_{eff}
- Full formula has a fixed point $(0, 1/\sqrt{12})$
- Full formula enters asymptotic region at $\sigma_d/w \simeq 0.4$
- Full formula has a minimum of $\sigma_x/w \simeq 0.1$ at $\sigma_d/w \simeq 0.3$

$(0, 1/\sqrt{12})$: hodoscope limit



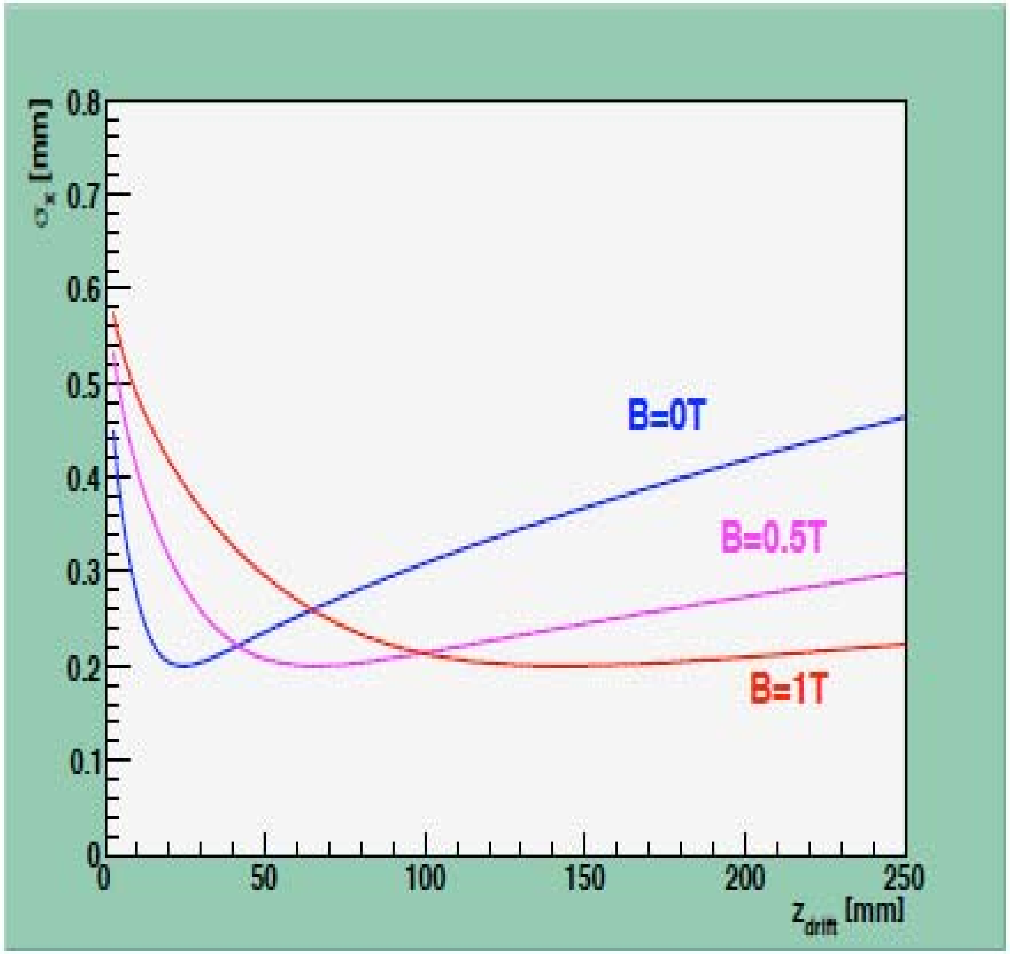
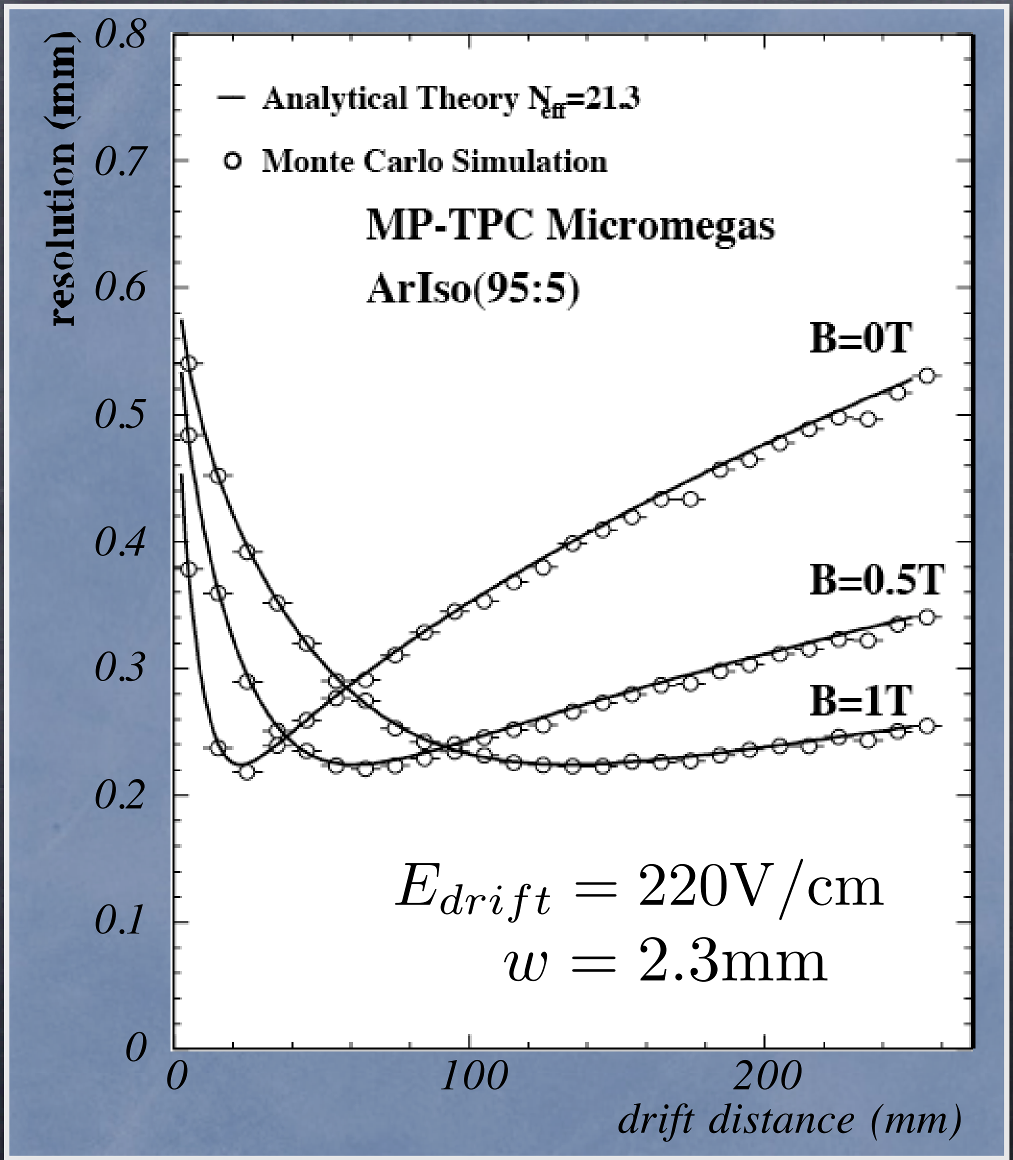


Figure 1: Expected spatial resolution with readout pads of width $w = 2.3$mm for $\langle 1/N \rangle = 1/46$ and $\theta = 0.5$, assuming Magboltz results $C_d = 0.469, 0.285$, and $0.193\text{mm}/\sqrt{\text{cm}}$ for $B = 0, 0.5$, and 1.0T, respectively.

Comparison with MC



- Theory reproduces the Monte Carlo simulation very well !
- We can estimate the resolution analytically

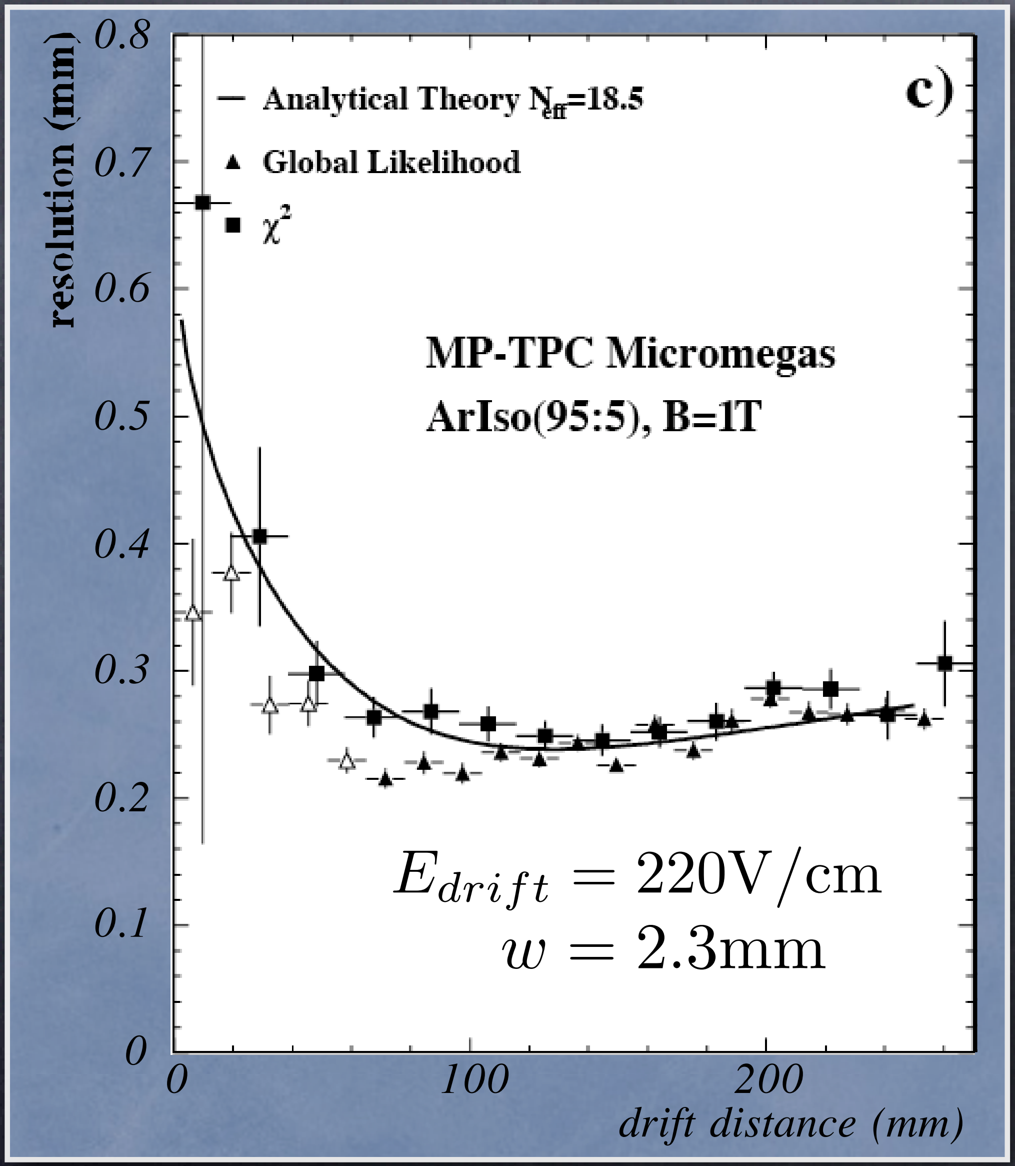
$$\sigma_x = \sigma_x(z; w, C_d, N_{eff}, [f_j])$$

drift distance (z), pad pitch (w), diffusion const. (C_d), pad response function ($[f_j]$)

δ-fun. for MM: $\sigma_{PRF} \simeq 12\mu\text{m}$

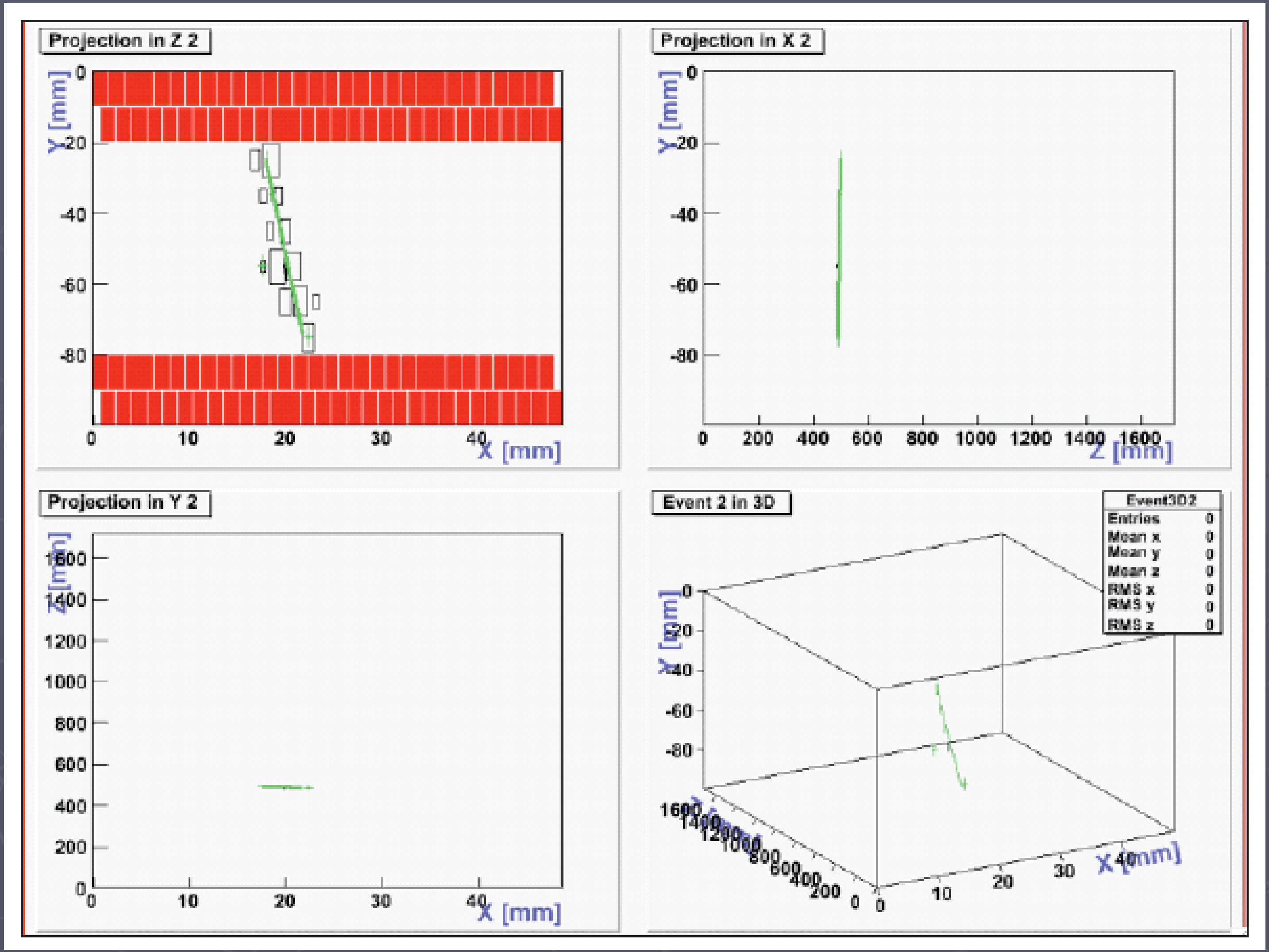
gauss. for GEM: $\sigma_{PRF} \simeq 350\mu\text{m}$

Comparison with Measurements



- Theory reproduces the data well
- Underestimation in the data of σ_x at short drift distance due to track bias
- Global likelihood method eliminates S-shape systematics at short distance when possible

A Preliminary Result
TU–TPC Cosmic Ray Test at KEK
(Dec. 2007)



A Preliminary Result
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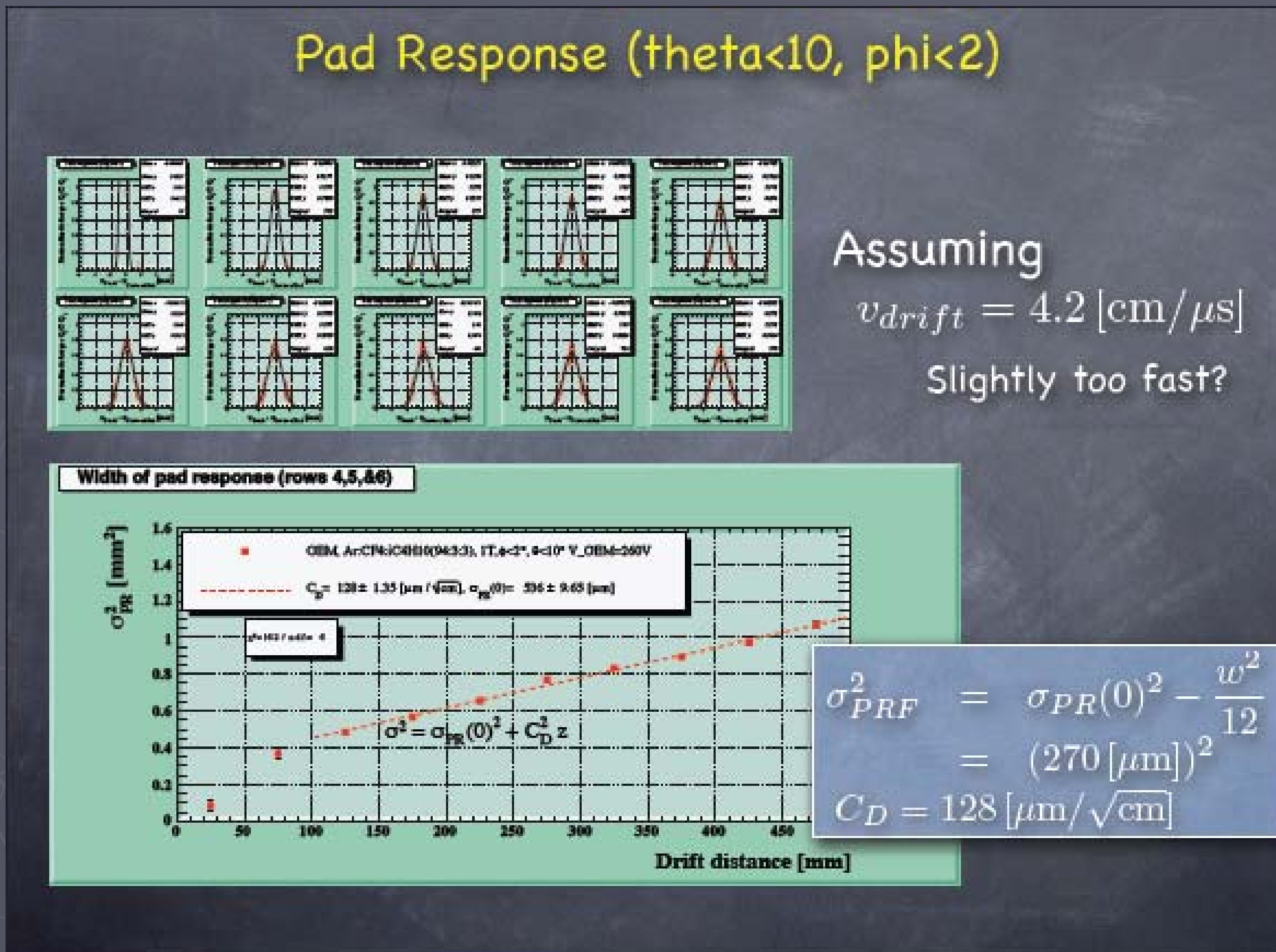


A Preliminary Result
TU–TPC Cosmic Ray Test at KEK
Dec. 2007

Spatial Resolution (theta<10, phi<2)

Compare with theory assuming

$$v_{drift} = 4.2\,[\mathrm{cm}/\mu\mathrm{s}]$$

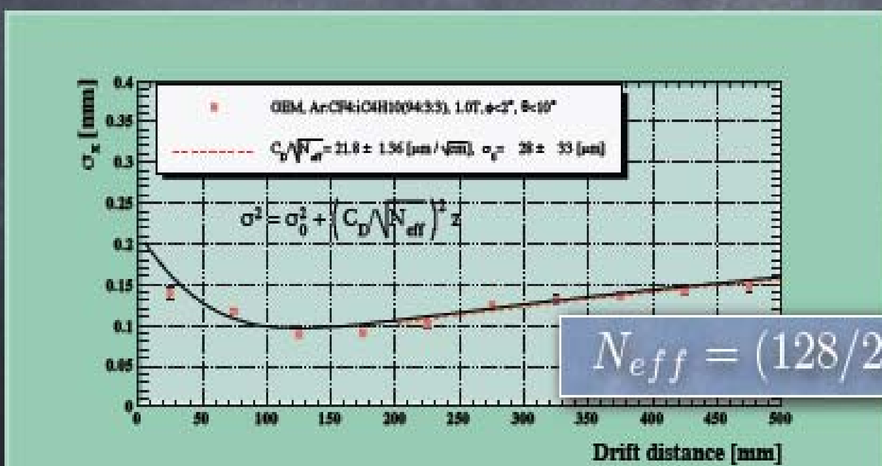
$$\sigma^2_{PRF} = \sigma_{PR}(0)^2 - \frac{w^2}{12} = (270\,[\mu\mathrm{m}])^2$$

$$C_D = 128\,[\mu\mathrm{m}/\sqrt{\mathrm{cm}}]$$

← Pad Response

$$N_{eff} = 22 \times (10./6.3) = 35$$

← MP-TPC



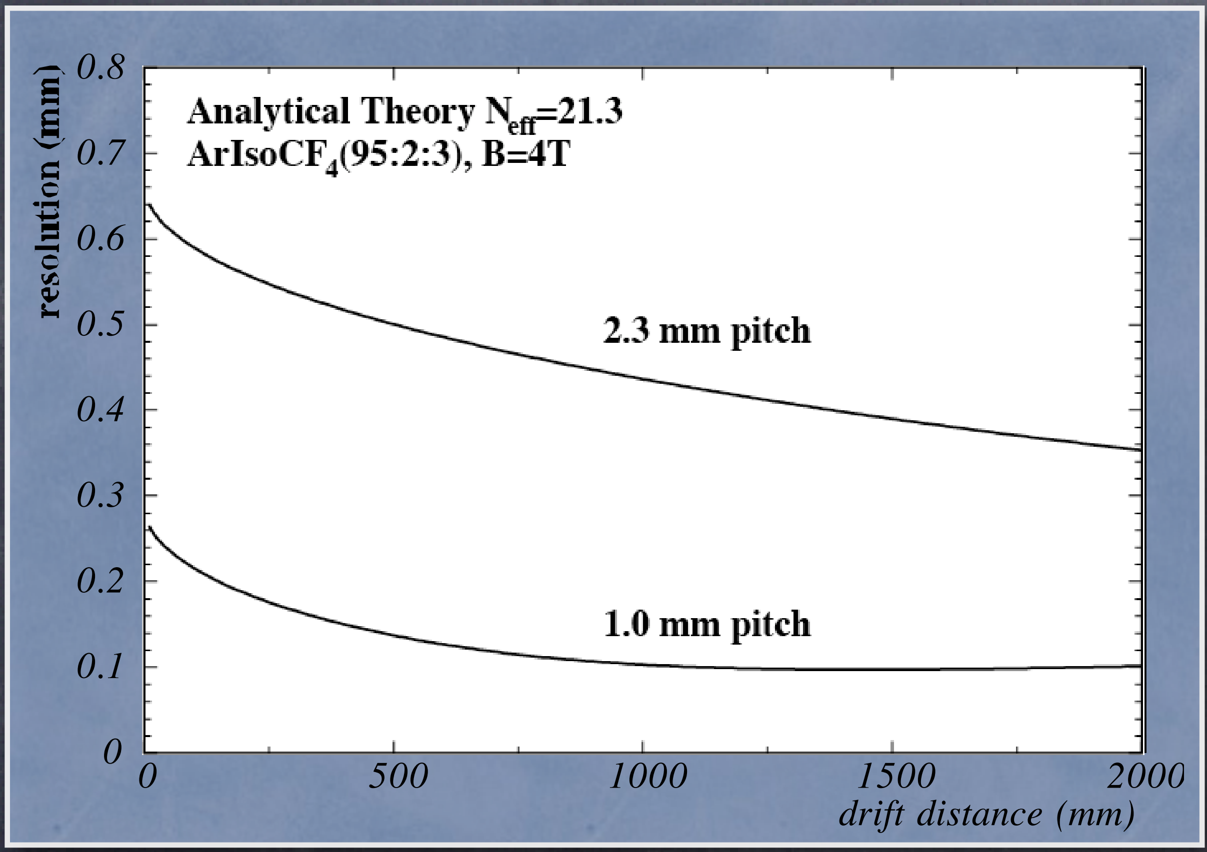
$$N_{eff} = (128/22) = 34 \pm 4$$

3 Layers of GEM

Pads: 1 x 10 mm

- Data Sample
  - About 60k triggers (~3 days) -> 4k small angle tracks
- Operation Conditions
  - Gas: Ar:CF4:iC4H10=94:3:3
  - Edrift = 124V/cm
  - VGEM = 260 V
  - B = 1T
  - T-threshold = 220

Extrapolation to LC TPC

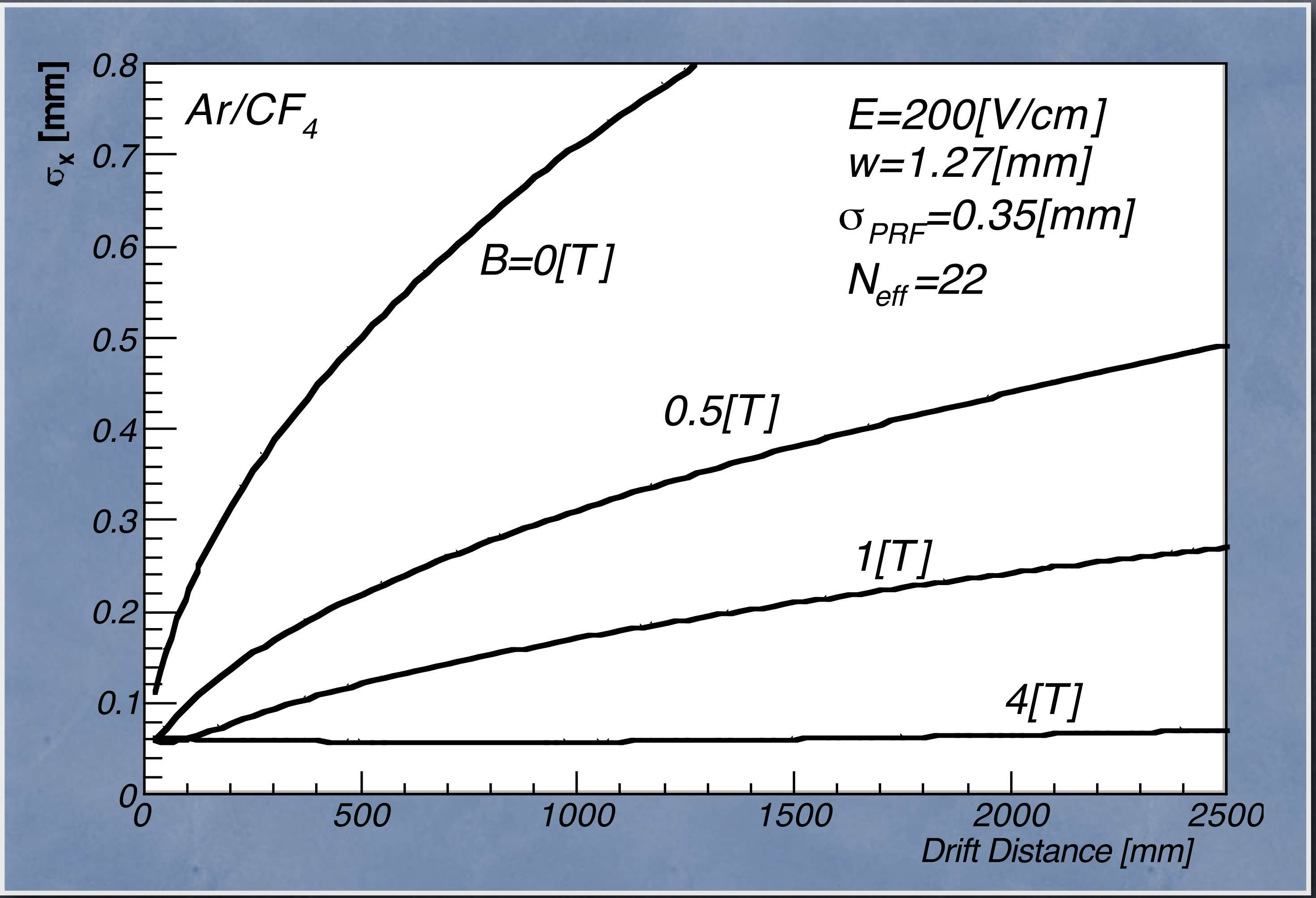


- Need to reduce pa Defocusing + narrow (1mm) pad for GEM d size relative to PRF
  - Defocusing + narrow (1mm) pad for GEM
  - Resistive anode for MM
  - Digital pixel readout? ideal to avoid effect of gain fluctuation if possible

→ Future R&D

Extrapolation to LC TPC

Sample calculation for GEM with Ar/CF4



→ promising GEM in Ar/CF4 needs R&D

Summary

- Efforts to understand KEK beam test data crystalized as an analytic formula for the spatial resolution of a MPGD readout TPC.

- We can now analytically estimate the spatial resolution

$$\sigma_x = \sigma_x(z; w, C_d, N_{eff}, [f_j])$$

drift distance (z)

pad pitch (w)

diffusion const. (C_d)

Effective No. track electrons (N_{eff})

pad response function ($[f_j]$)

→ **Theoretical basis for how to improve the spatial resolution!**

Possible improvement of theory: angle effects