Time Resolution of the Carleton prototype TPC

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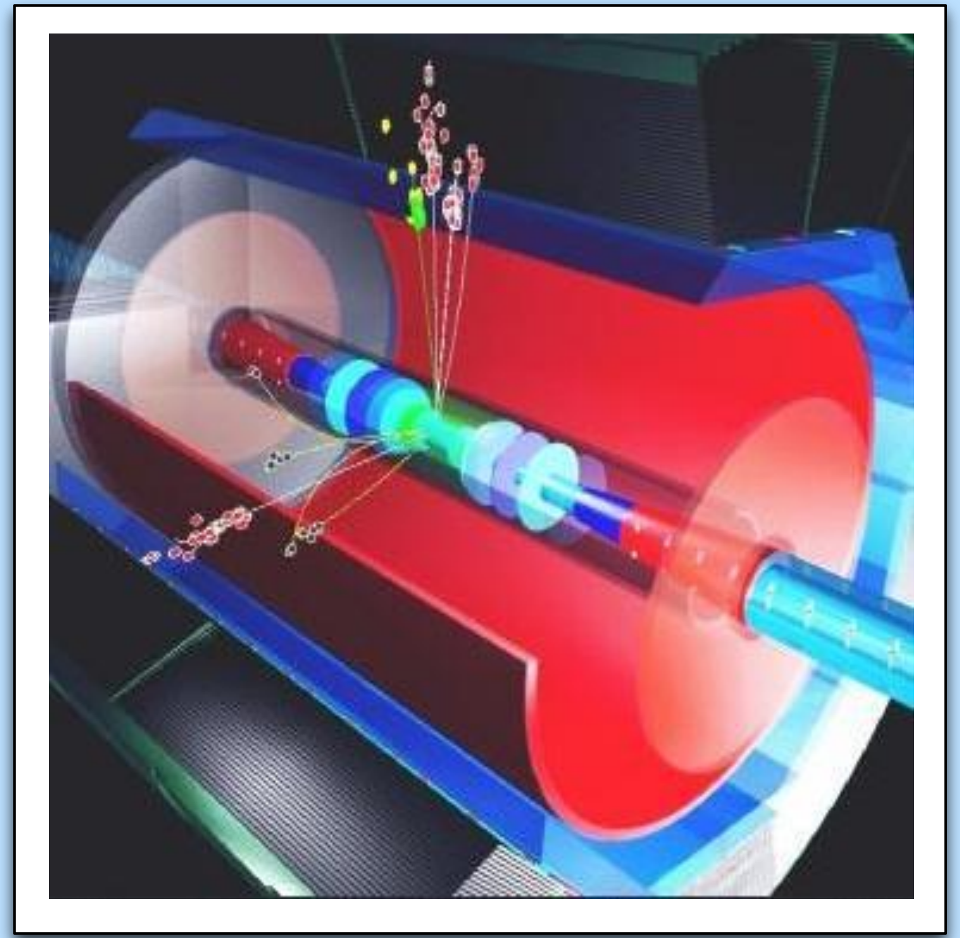
Overview

- Context: The International Linear Collider (ILC) and RD51 for MPGD
- Time Projection Chamber (TPC)
- TPC prototype
- Timing Resolution in a TPC
- Results
- Summary



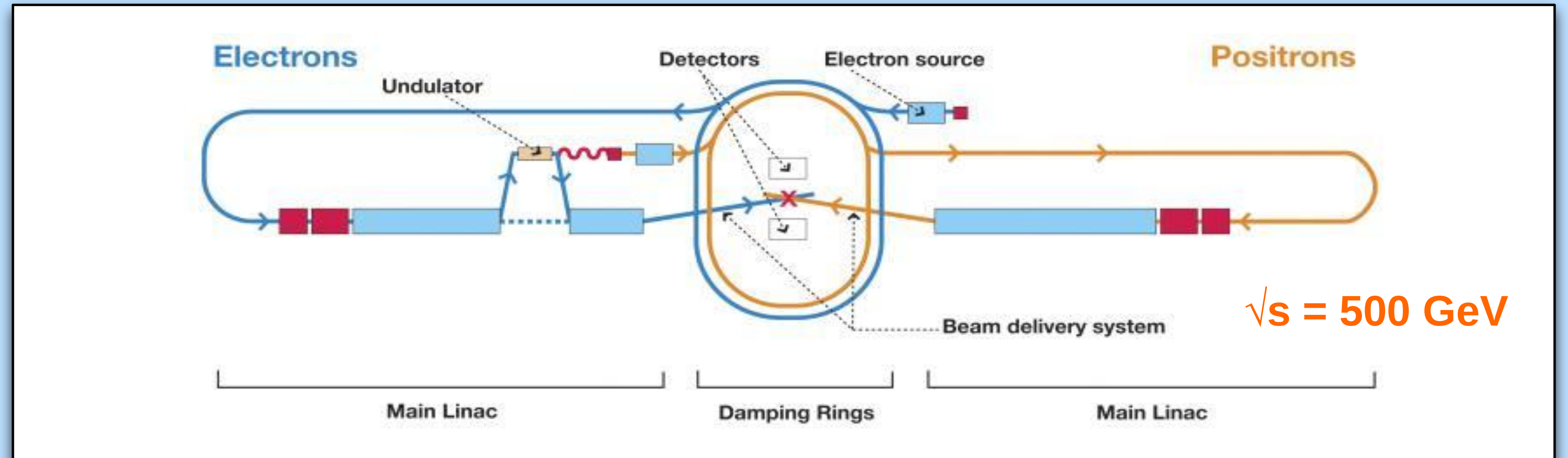
ILC – Basic Design Parameters

Basic design parameters for the ILC ($^{a)}$ values at 500 GeV center-of-mass energy).

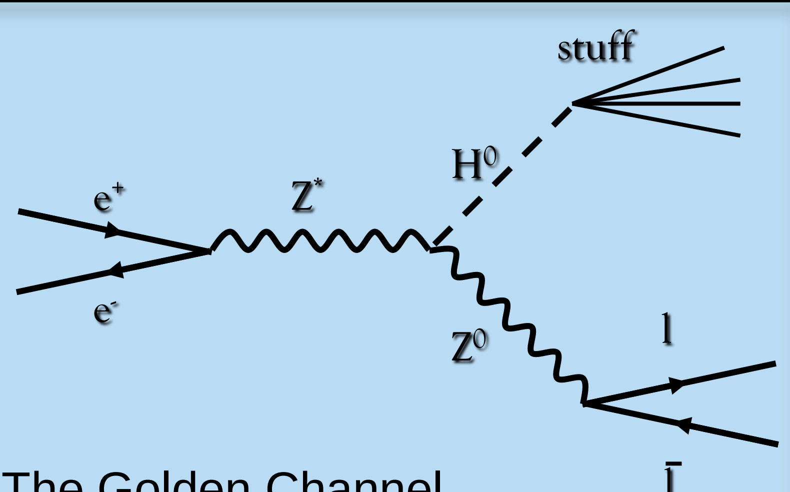
Parameter	Unit	
Center-of-mass energy range	GeV	200 - 500
Peak luminosity$^{a)}$	$cm^{-2}s^{-1}$	2×10^{34}
Average beam current in pulse	mA	9.0
Pulse rate	Hz	5.0
Pulse length (beam)	ms	~ 1
Number of bunches per pulse		1000 - 5400
Charge per bunch	nC	1.6 - 3.2
Accelerating gradient$^{a)}$	MV/m	31.5
RF pulse length	ms	1.6

	min	nominal.	max.	unit
Bunch population	1	2	2	$\times 10^{10}$
Number of bunches	1260	2625	5340	
Linac bunch interval	180	369	500	ns
RMS bunch length	200	300	500	μm
Normalized horizontal emittance at IP	10	10	12	mm·mrad
Normalized vertical emittance at IP	0.02	0.04	0.08	mm·mrad
Horizontal beta function at IP	10	20	20	mm
Vertical beta function at IP	0.2	0.4	0.6	mm
RMS horizontal beam size at IP	474	640	640	nm
RMS vertical beam size at IP	3.5	5.7	9.9	nm
Vertical disruption parameter	14	19.4	26.1	
Fractional RMS energy loss to beamstrahlung	1.7	2.4	5.5	%

International Linear Collider



- Proposed e+ e– Linear Collider to complement LHC
- Polarized Lepton Beams give well defined initial state, clean environment
- The Goal: Make precision measurements of whatever is discovered at the LHC



The Golden Channel
- model independent study

International Large Detector (ILD)

- One of two proposed detectors for the ILC

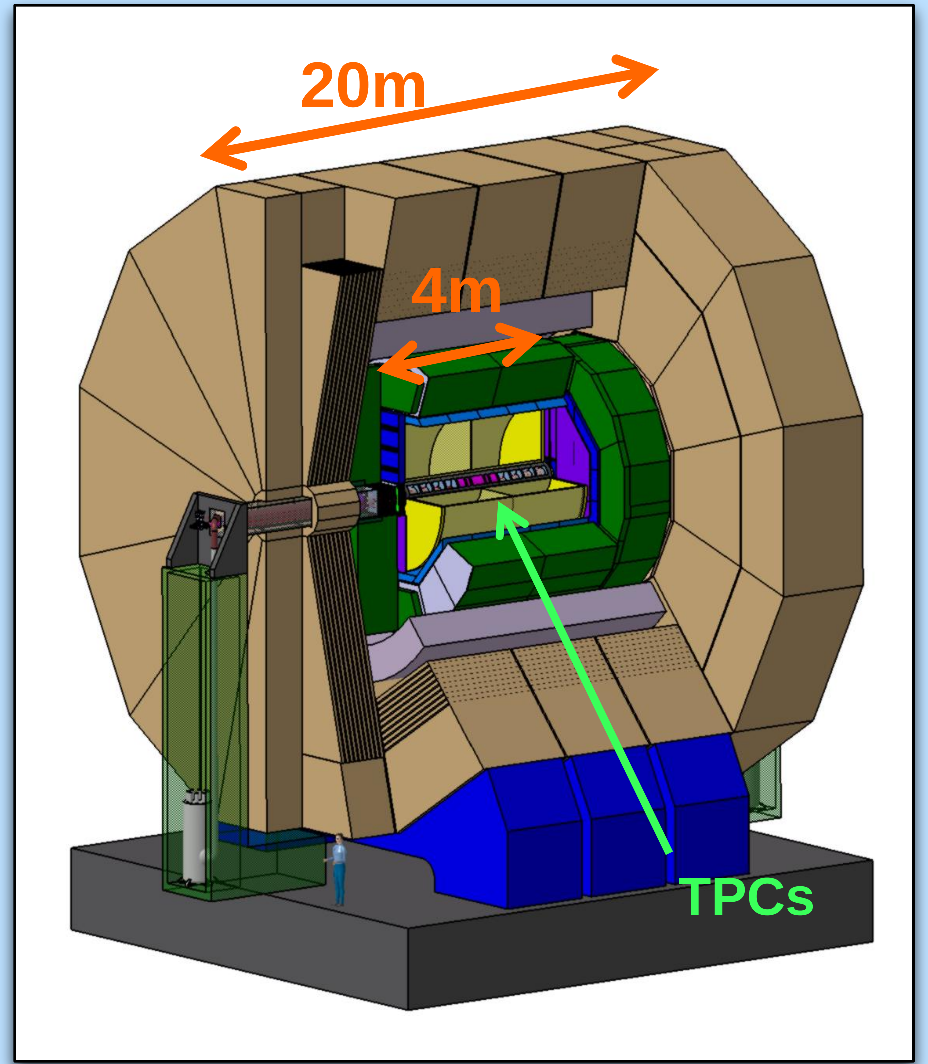
- Central Tracker will be Silicon Vertex Detector, surrounded by a TPC with 2m drift

- TPC Single Hit Resolution Goals:

→ Transverse: 100 μm (2m drift)
→ Longitudinal: 500 μm (zero drift)

- Canadian R&D toward building the TPC (Carleton, UVic, Montreal)

- International partners: LAL Orsay & IRFU, CEA Saclay (France) as well as Germany and Japan



Time Projection Chamber

A high speed 3D camera, which captures images of the passage of charged particles.

<u>Processes in a TPC:</u>

(1) Ionization →
along path of charged particle

(2) Drift & Diffusion →

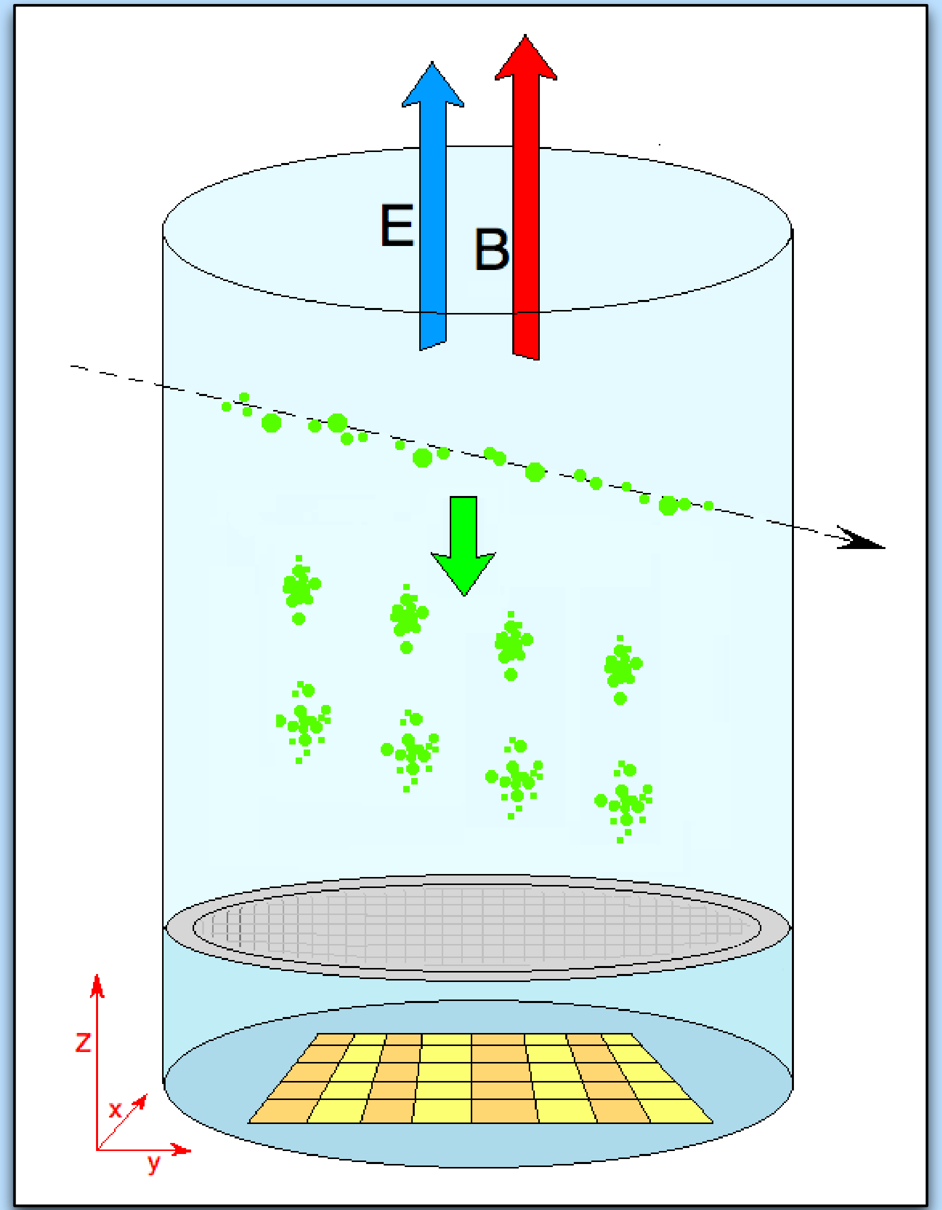
spread as Gaussians in Transverse and Longitudinal planes (statistical)

(3) Amplification →

boost number of electrons

(4) Readout Pads →

pads convert to digital record

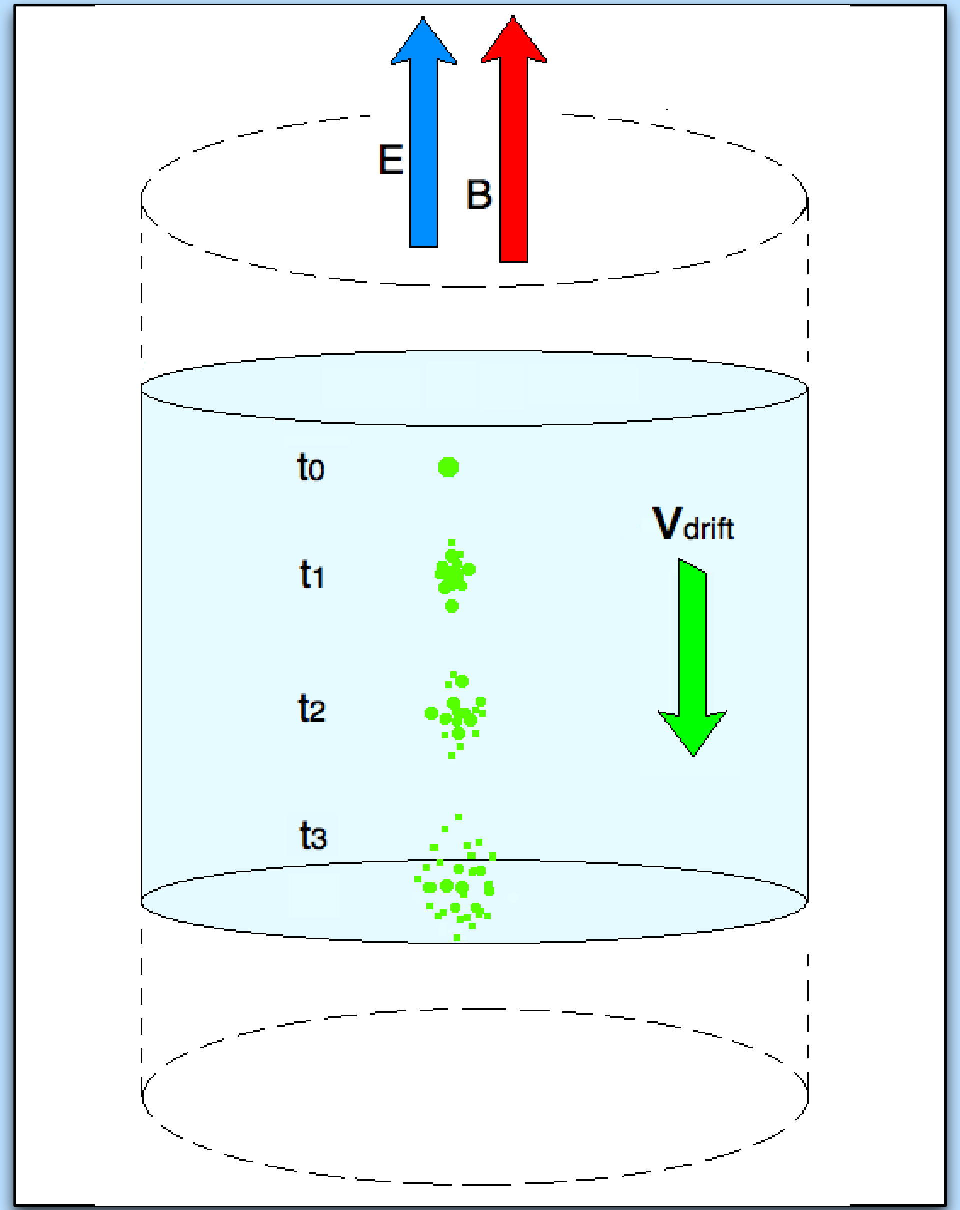


Drift Region

- Electrons drifted in a uniform E-field toward Amplification region
- Clusters diffuse as Gaussians
- Transverse diffusion is suppressed by the Magnetic field (Lorentz Force)
- Longitudinal diffusion:

$$\sigma_L^{\,2} = \sigma_0^{\,2} + D_L^2 \cdot z$$

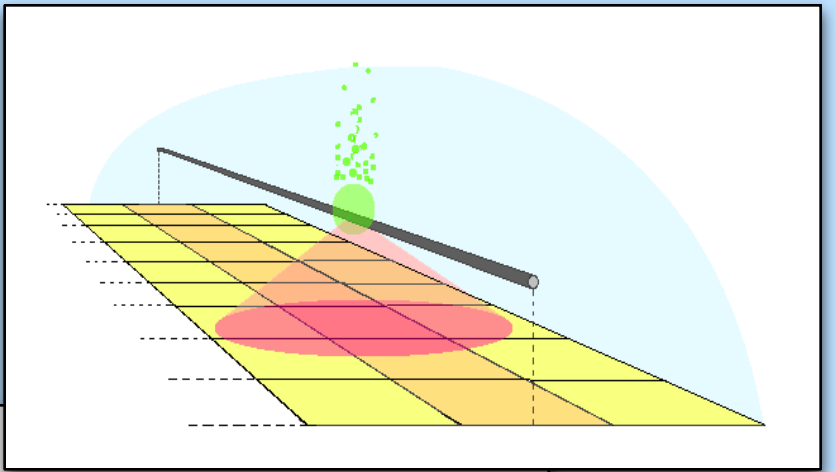
$$D_L = \text{diffusion Constant} \left(\frac{\mu m}{\sqrt{cm}} \right)$$

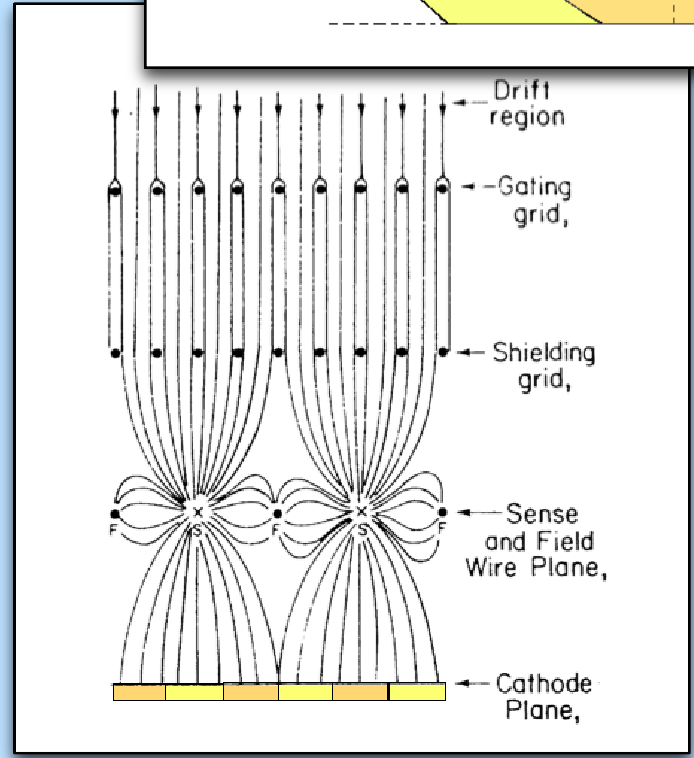


Time Projection Chamber

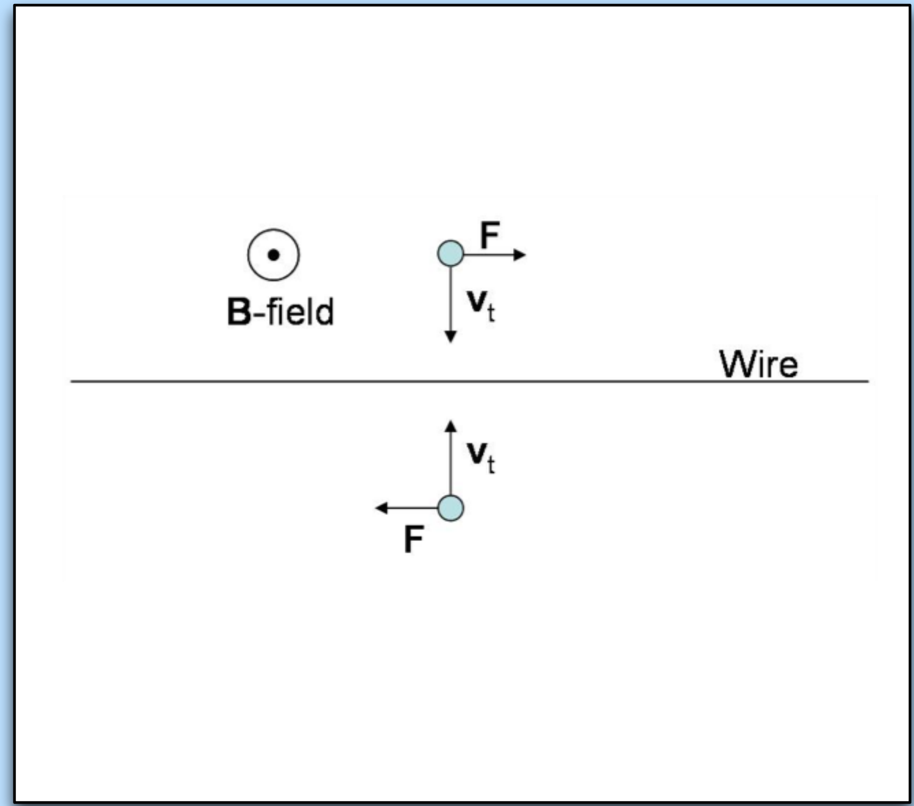
- Traditional TPC uses proportional wires to amplify the signal
- Wide Signal Spatial Width
→ More pads = Better Centroid
- Good resolution with wide pads
- Limitations:
(1) Ion Feedback into drift region

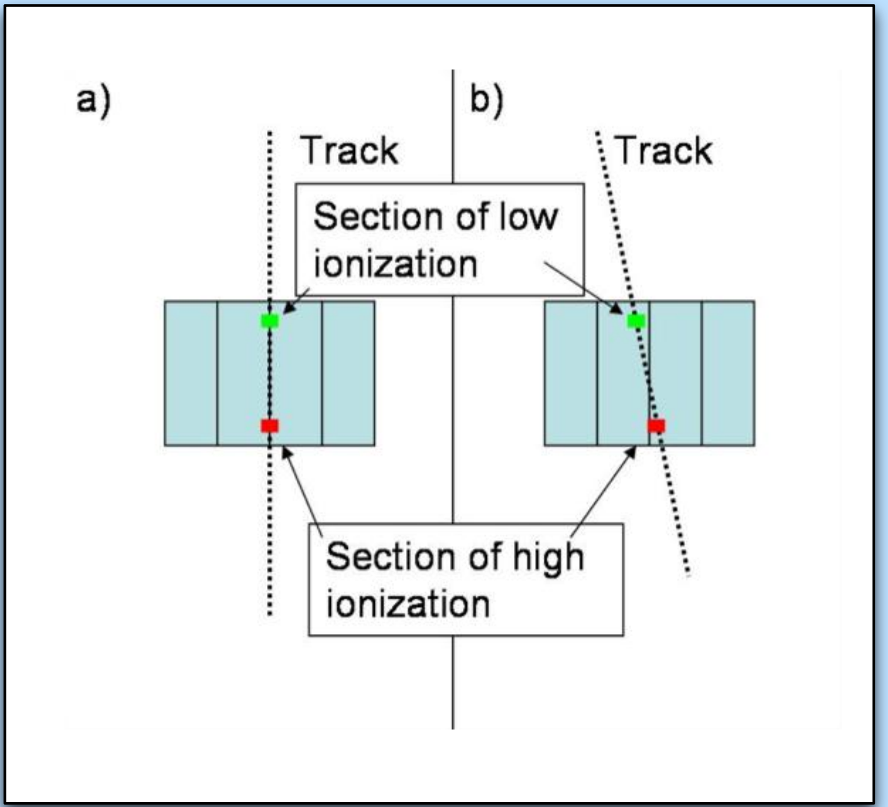
  (2) ExB limits achievable resolution





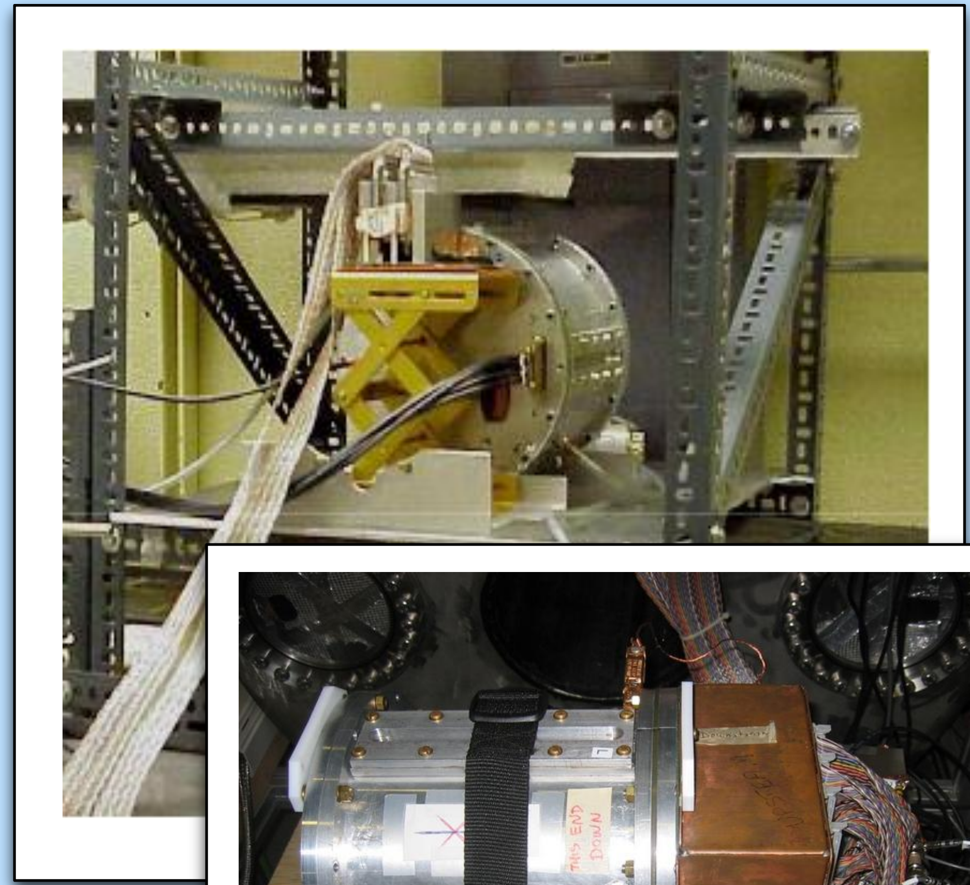
ExB & Track Angle effect

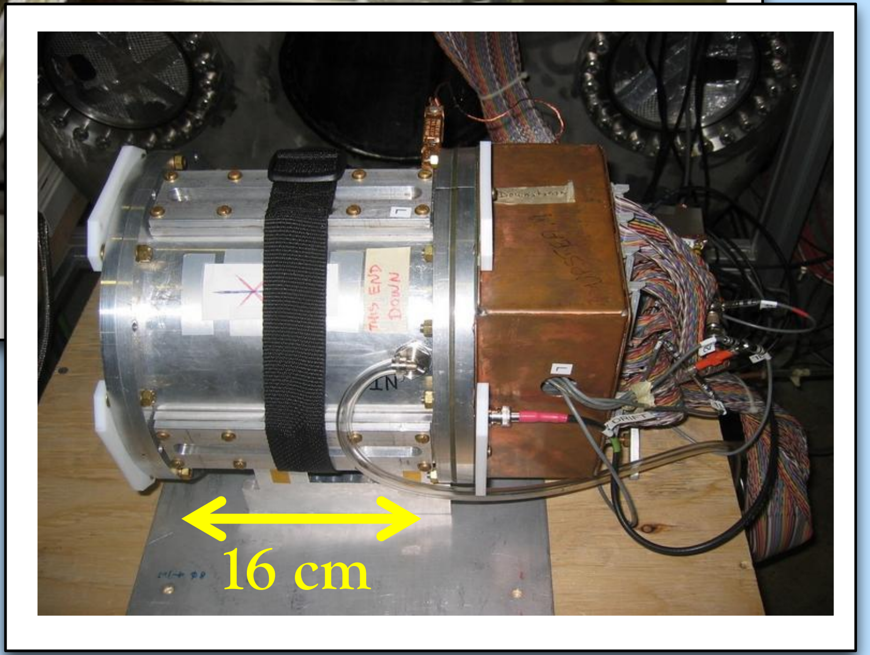




CarletonTPC

- 16 cm Drift Region
- 126 Readout Pads:
  Height = 6mm
  Width = 2mm





Why is it special ?

(1) **GEM or Micromegas gas amplification instead of wires**

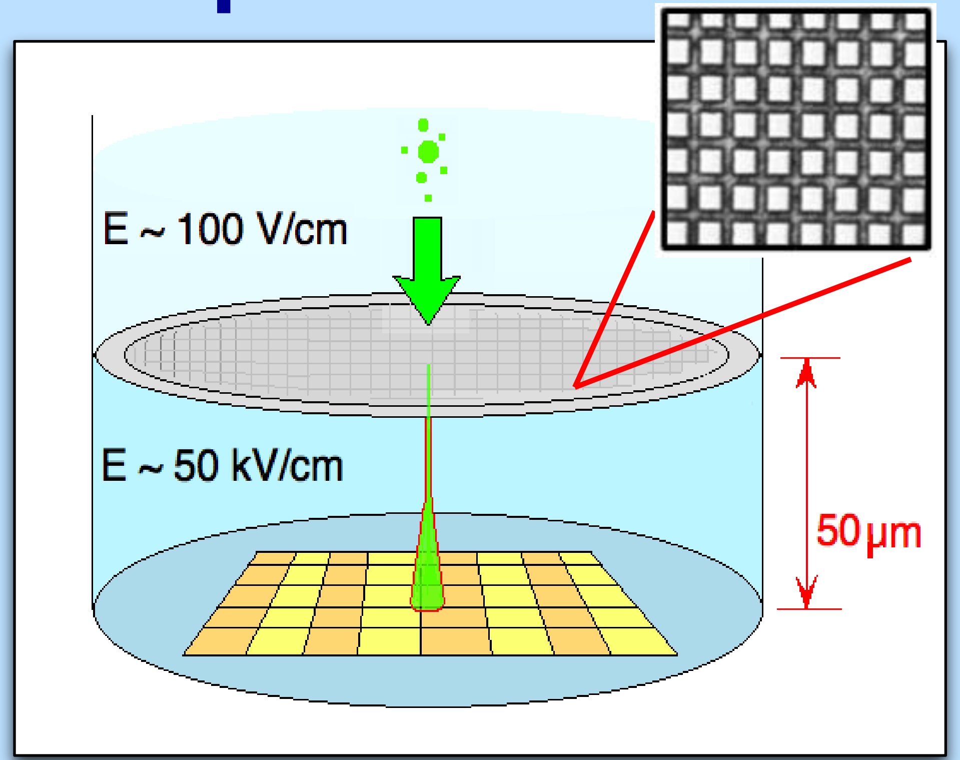
(2) **Charge Dispersion on the readout plane**

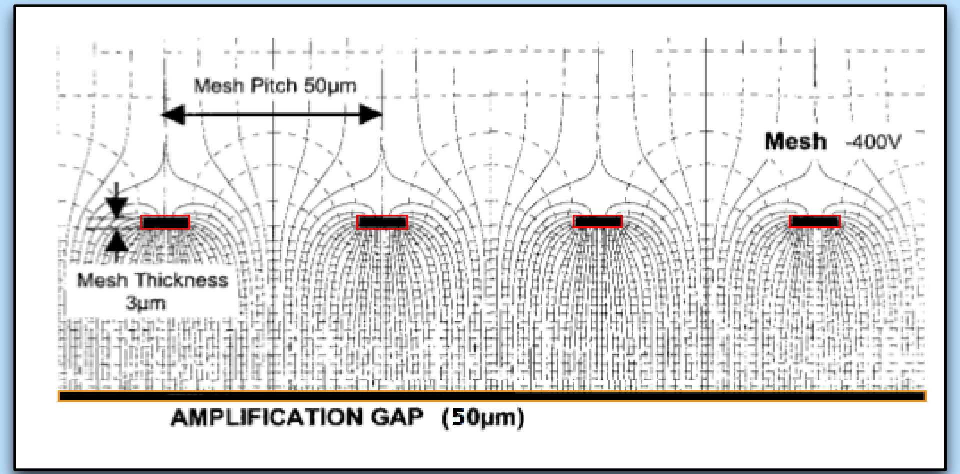
Carleton TPC - Amplification

- Amplification using Micromegas instead of wires (Mesh of ~ 50 μm holes)
- Electrons to pass from drift region into a high Electric field region
- Advantages:
  → Mesh Stops ion feedback
  → No more ExB effect

- Problem: Avalanche has very small cross-section → require very small pads (not practical)

- Solution? Charge Dispersion





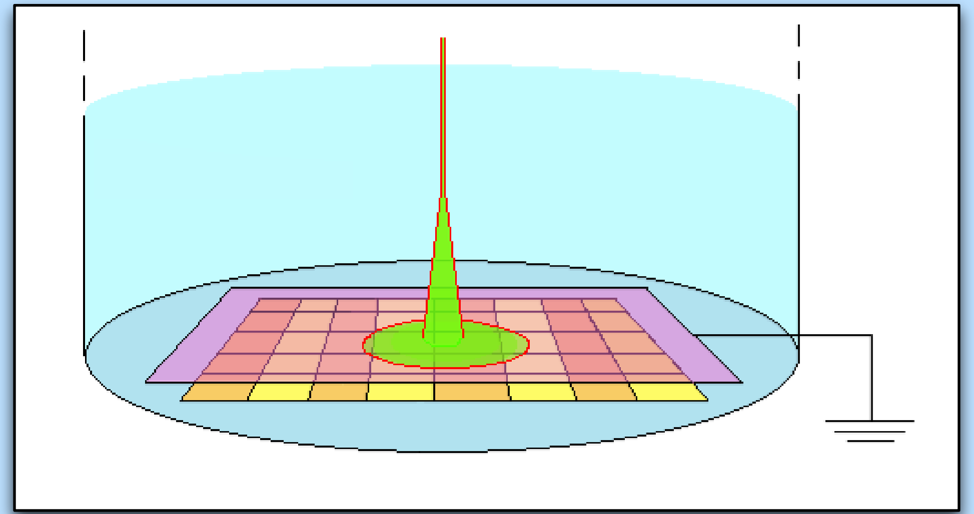
Carleton TPC – Charge Dispersion

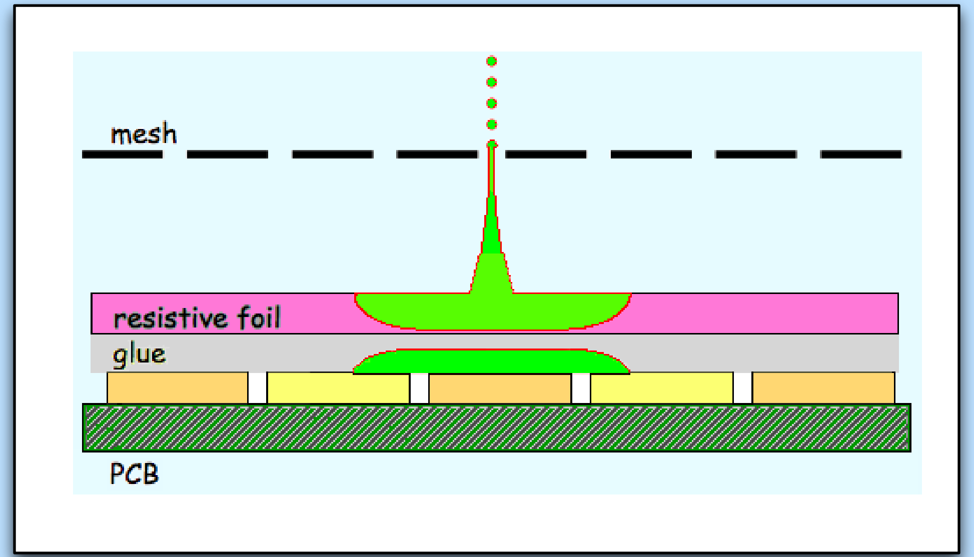
- Increases effective signal width → no need for tiny pads!
- Charge Dispersion achieved w/ resistive foil bonded to the anode
- Obeys 2D Telegraph equation:

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

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

- The anode charge density is time dependent and sampled by readout pads





Two data sets Analyzed with the improved PRF algorithm & for z(t) resolution

DESY: Cosmics November 2006

1. Number of Good Events: 5663
2. Gas Mixture: Argon(95%) + Isobutante(2%) + CF4(3%)
3. B Field: 5 T
4. E Field: 200 V/cm
5. Transverse Diffusion: 18.6 um/√cm *
6. Longitudinal Diffusion: 248 um/√cm *
7. Drift Velocity: 72.7 um/ns *
8. Theta Distribution: [-30,30]

KEK: 4 GeV pi+ October 2005

1. Number of Good Events: 12754
2. Gas Mixture: Argon(95%) + Isobutante(5%)
3. B Field: 1 T
4. E Field: 70 V/cm
5. Transverse Diffusion: 124 um/√cm *
6. Longitudinal Diffusion: 479 um/√cm *
7. Drift Velocity: 25.3 um/ns *
8. Theta Distribution: [-5,5]

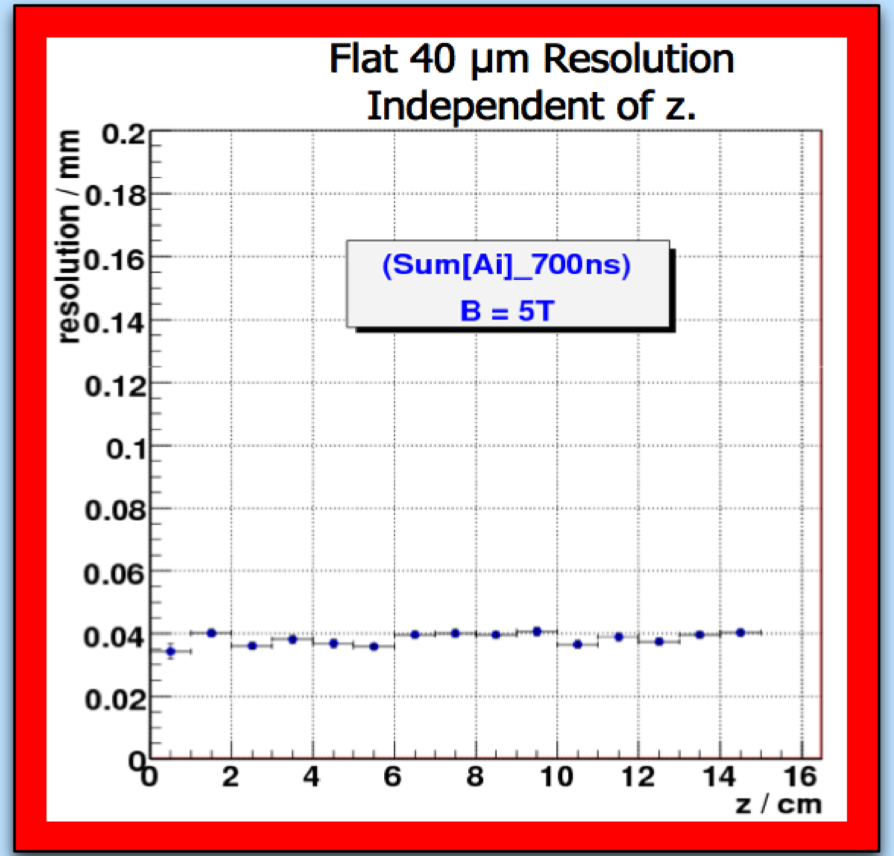
x-y Resolution

Carleton TPC – Cosmic DESY

What are the goals?

(1) Demonstrate that *Charge Dispersion* can be used to reduce number of readout channels → Done

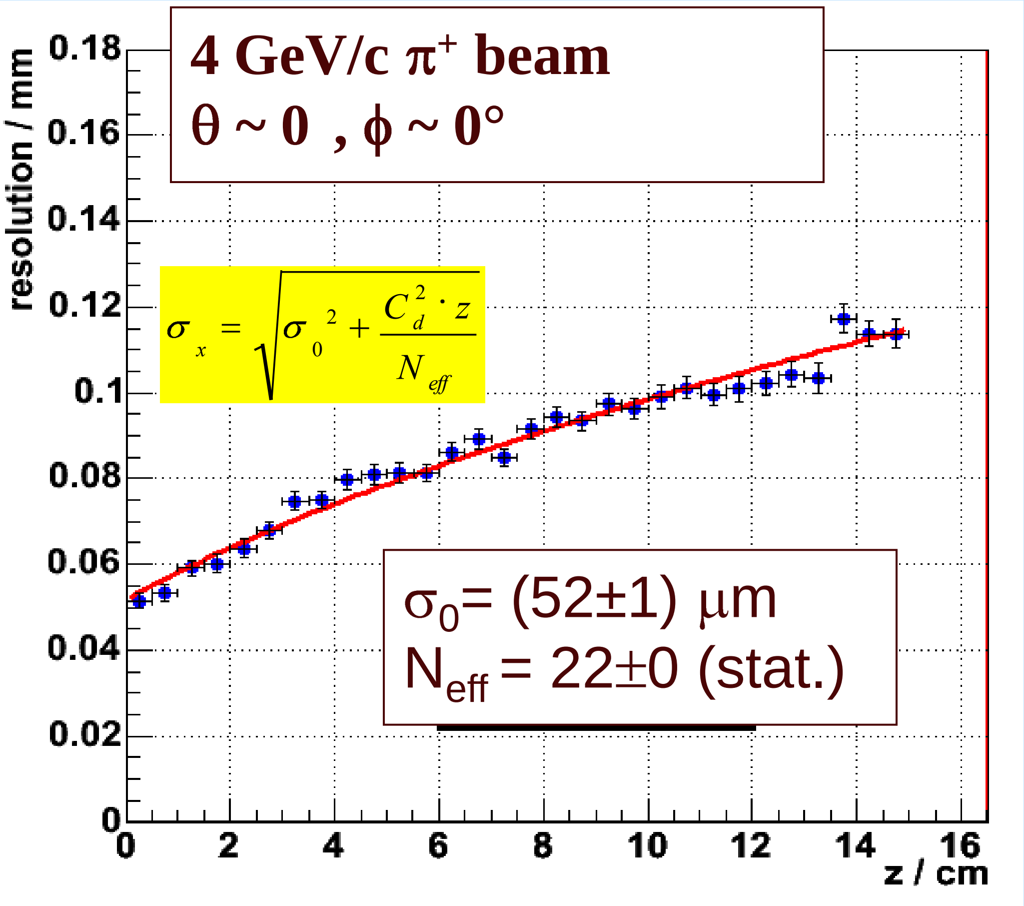
(2) Demonstrate Resolution goals of ILD are achievable
→ Transverse is excellent!
→ Longitudinal has not been investigated yet (0.5 mm goal?)



Micromegas TPC **2 x 6 mm² pads** - Charge dispersion readout

Carleton TPC – KEK: π+ beam

Micromegas TPC **2 x 6 mm² pads** - Charge dispersion readout



Data collected with B = 1T

Extrapolate to B = 4T
Resolution (2x6 mm² pads)
$\sigma_{Tr} \approx 100\ \mu m$ (2.5 m drift)

Time (z) Resolution

Timing Resolution

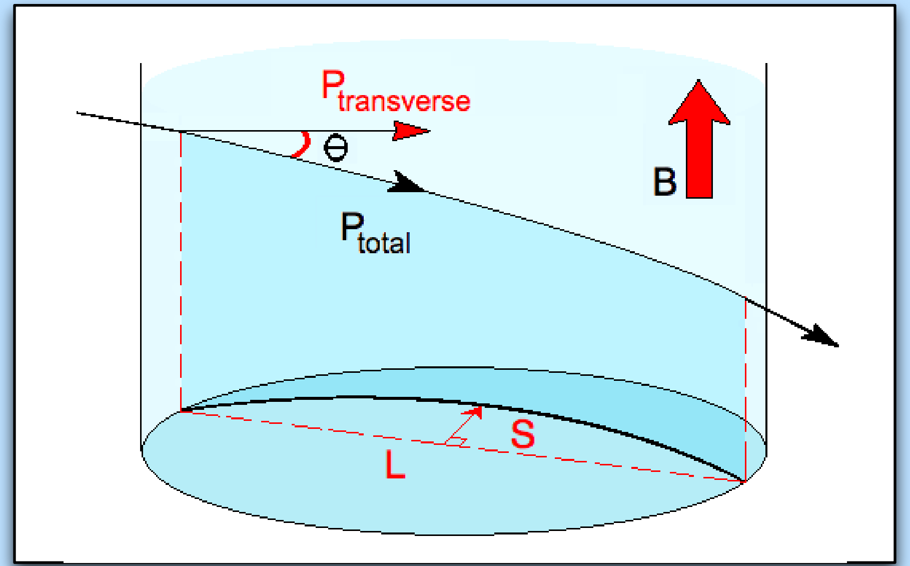
Why is it important?

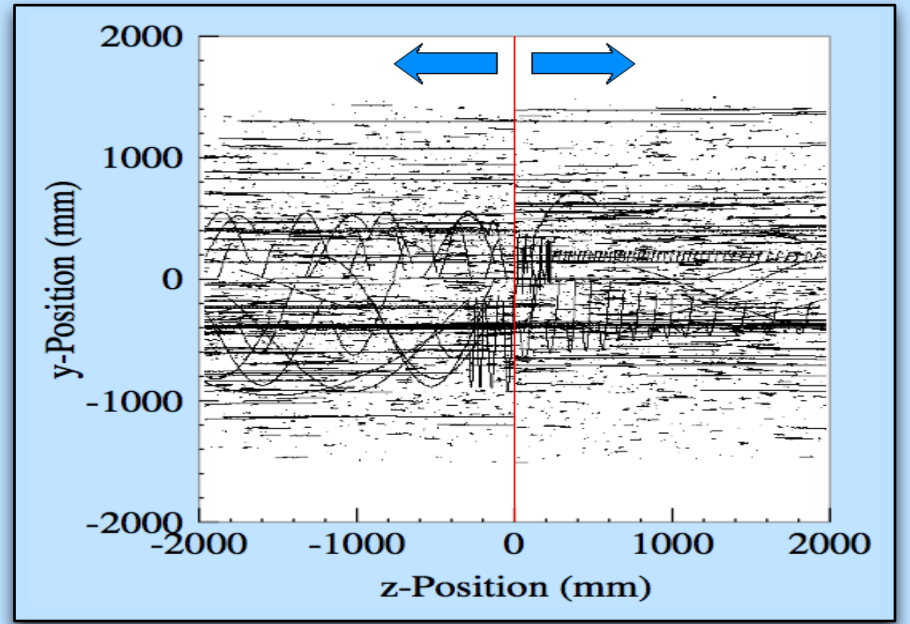
(1) Require θ to determine the total momentum

$$P = \frac{qBR}{\cos\theta} = \frac{P_{tranverse}}{\cos\theta}$$

(2) Time between collisions in ILD will be ~ 300 ns
→ 100 events drifting at the same time!
(for a fast gas)

(3) High background in ILD:
Connect track back to the Vertex

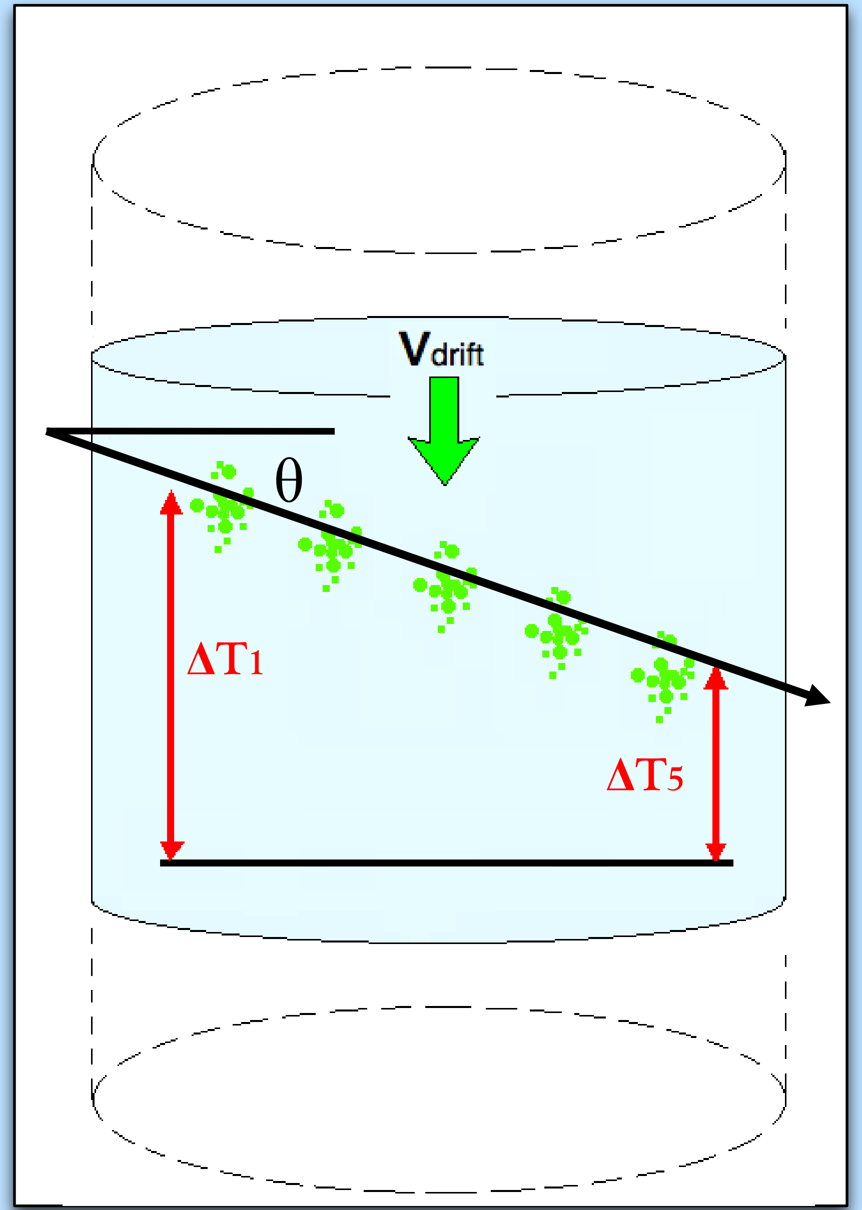




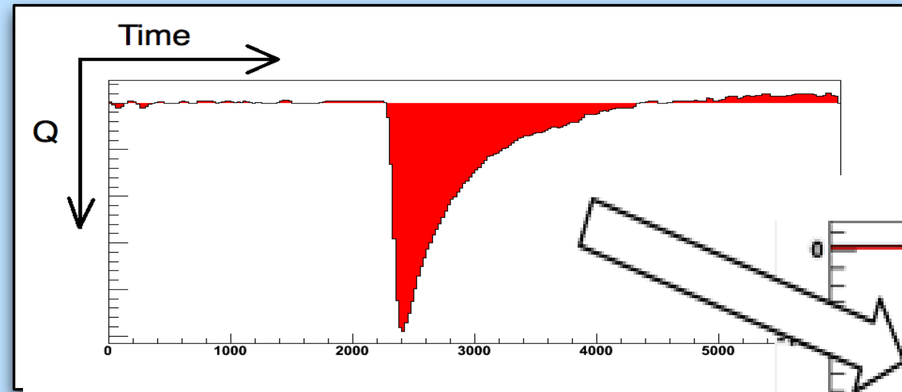
Z and Theta from Time

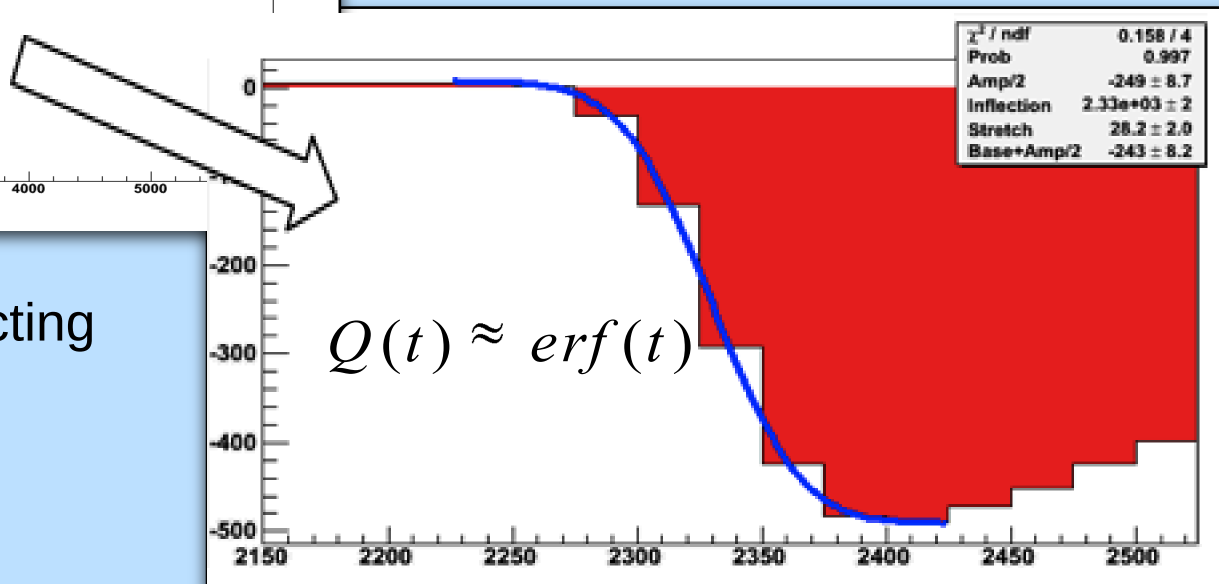
- The Drift Velocity of the clusters in the gas is well known and <u>constant</u>
  → arrival time determines Z

- Differences in arrival time at readout pads determines differences in Z position of the particle above each pad
  → gives the Theta angle



Cluster Arrival Time





- Primary charge collecting pad signal shape is determined mainly by longitudinal diffusion

- Timing determined by error function fit to the leading edge

- Arrival Time taken as the time of maximum induced current

$$Q(\tau) = \frac{1}{\sigma_L \sqrt{2\pi}} \int_{-\infty}^{\tau} \exp\left[-\frac{1}{2}\left(\frac{t - t_0}{\sigma_L}\right)^2\right] dt$$

Timing Resolution

Inclusive Track Fit:

$$\chi^2 = \sum_{i=rows} \left(\frac{t_{track} - t_i}{\delta t_i} \right)^2$$

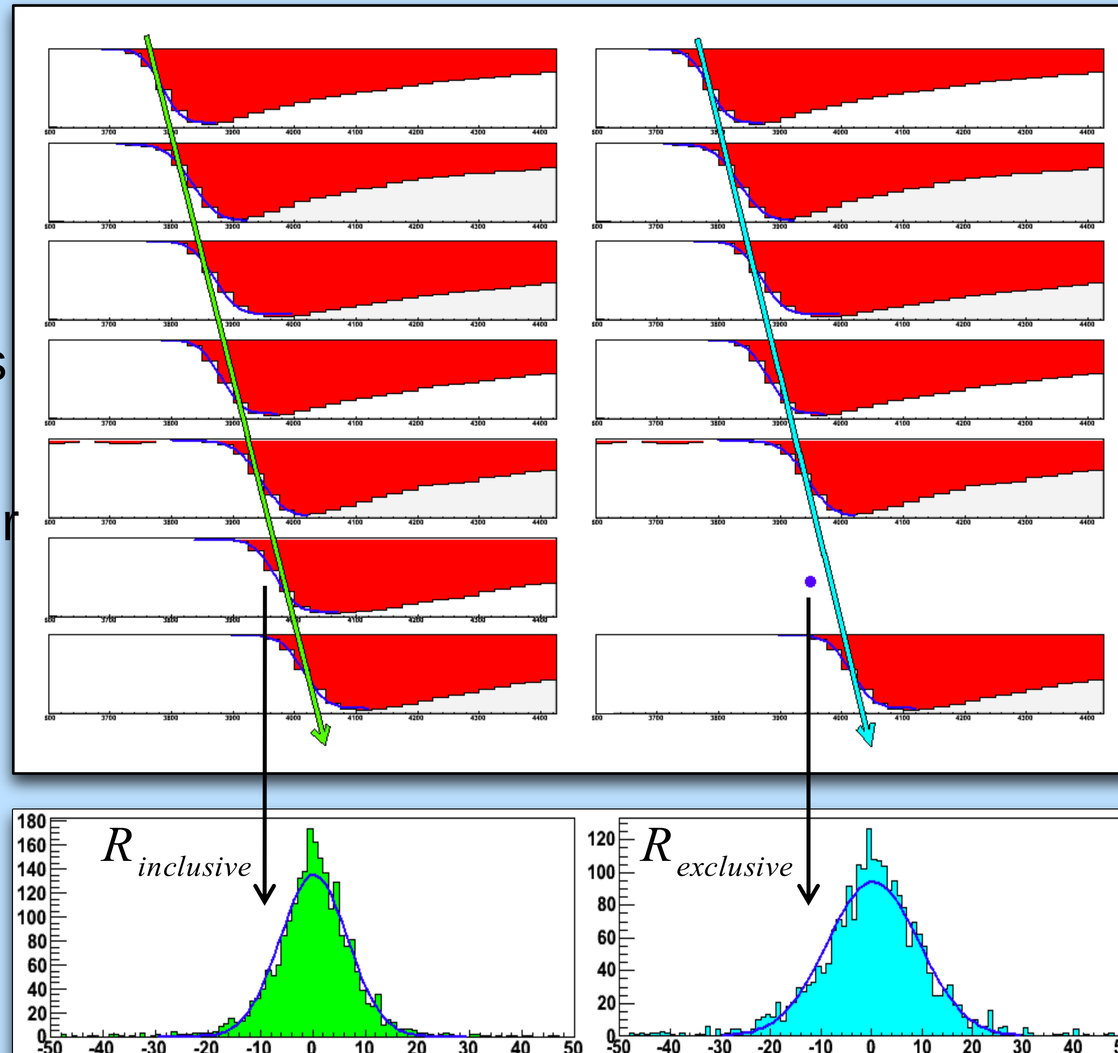
- Determine track parameters t_0 and θ for $t_{track} = t_0 + y \tan(\theta)$
- Determine t_{row} by fitting error function to main charge pulse
- Residuals: $R = t_{row} - t_{track}$

Exclusive Track Fit:

- Repeat, removing each row

Resolution:

- determined from width of residual distributions

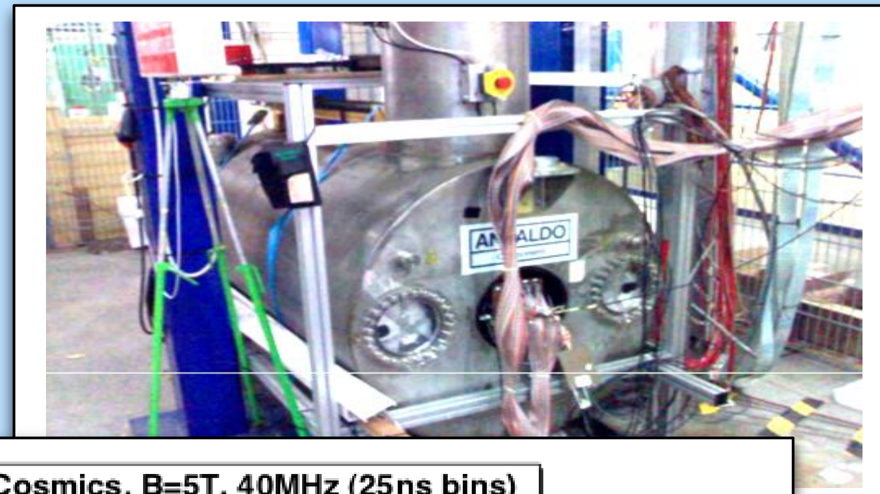


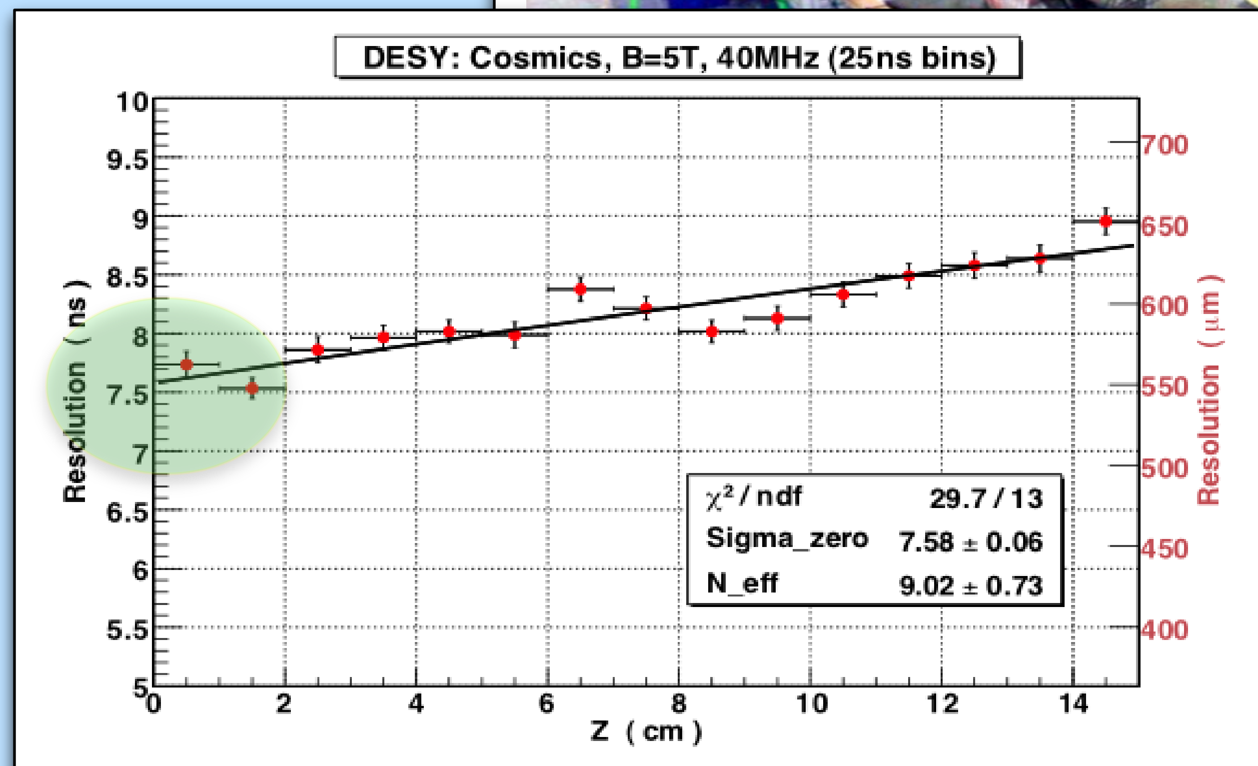
$$\sigma = \sqrt{\sigma_{inclusive} \quad \sigma_{exclusive}}$$

DESY: Cosmic test

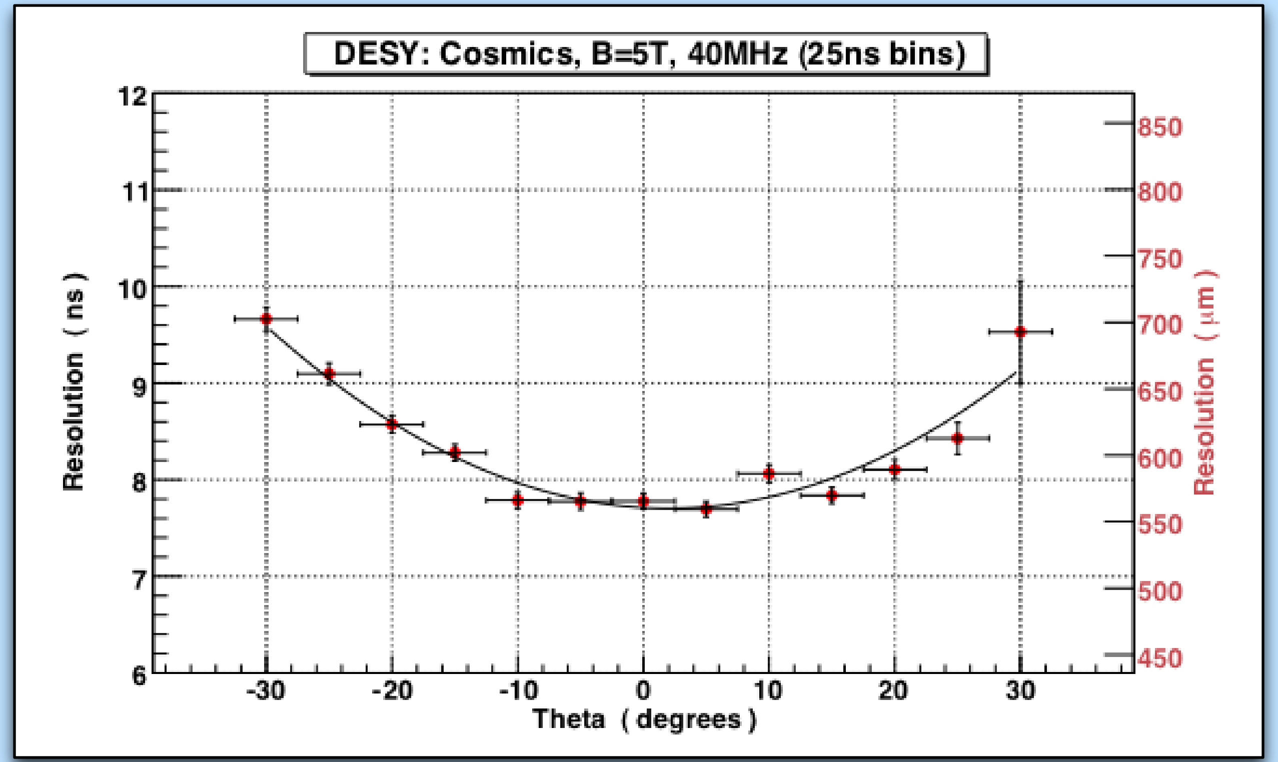
Argon + Isobutane(2%) + CF4(3%)
B = 5 T
E = 200 V/cm
V_{drift} = 73 μm/ns,
D_{Long} = 249 μ/√cm

$$\sigma_z = \sqrt{\sigma_0^2 + \frac{D_L^2 \cdot z}{N_{eff}}}$$

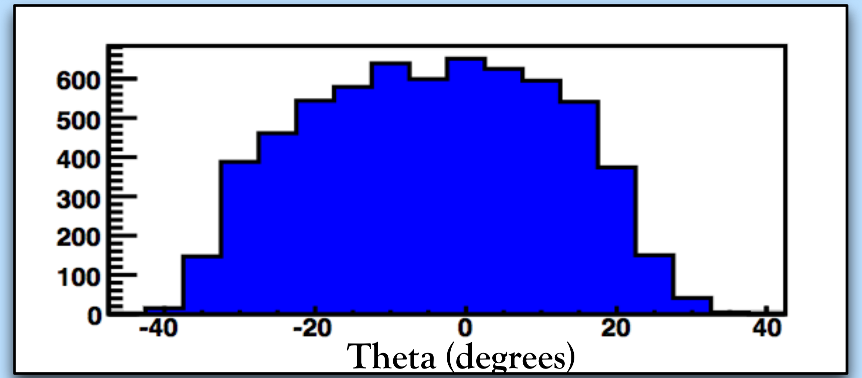




Resolution: Theta dependence



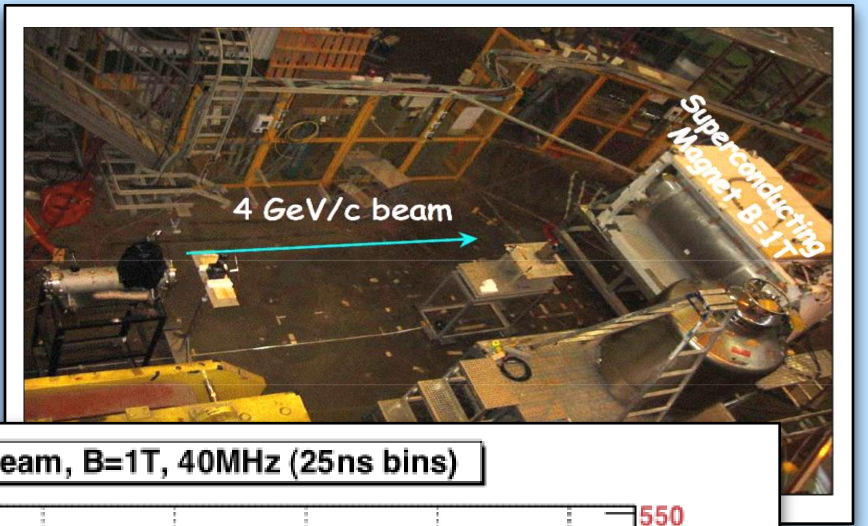
Asymmetry in the Statistics explains error bars above:

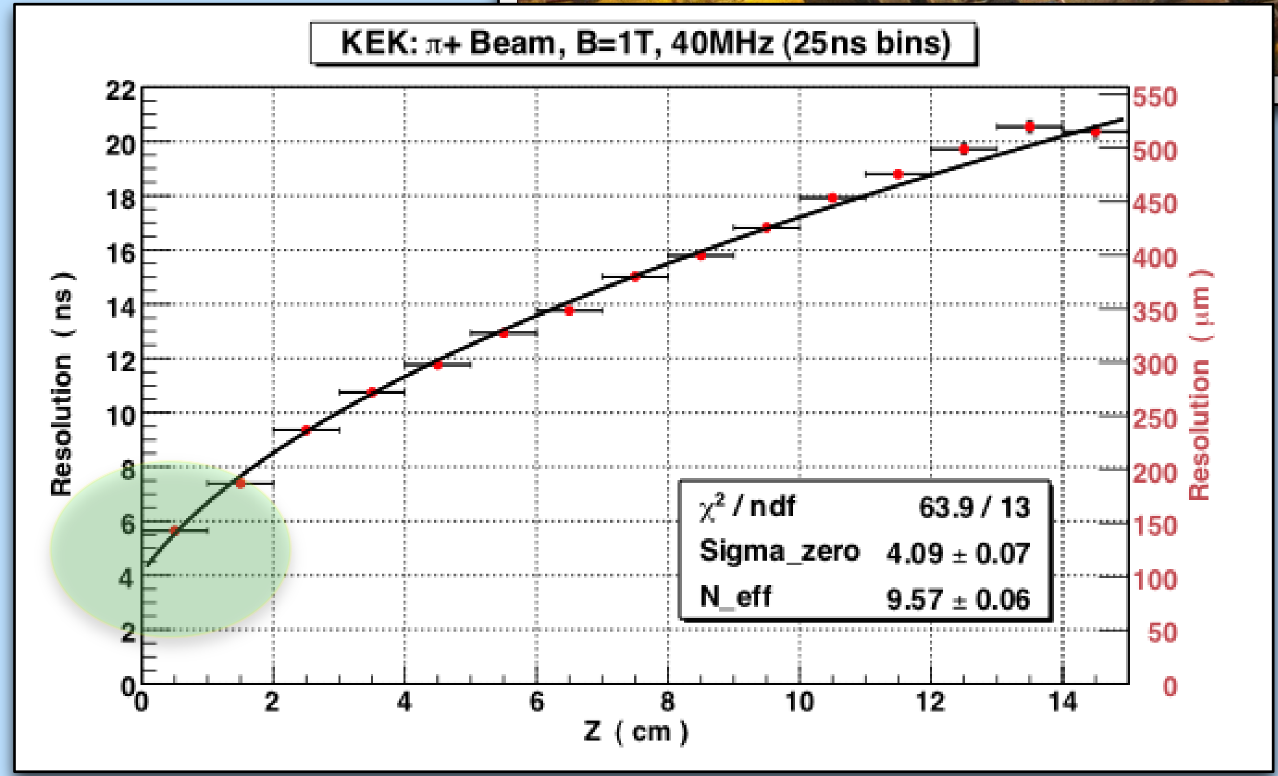


KEK: 4GeV π+ beam test

Argon + Isobutane(5%)
B = 1 T
E = 70 V/cm
V_{drift} = 25 μm/ns,
D_{Long} = 479 μ/√cm

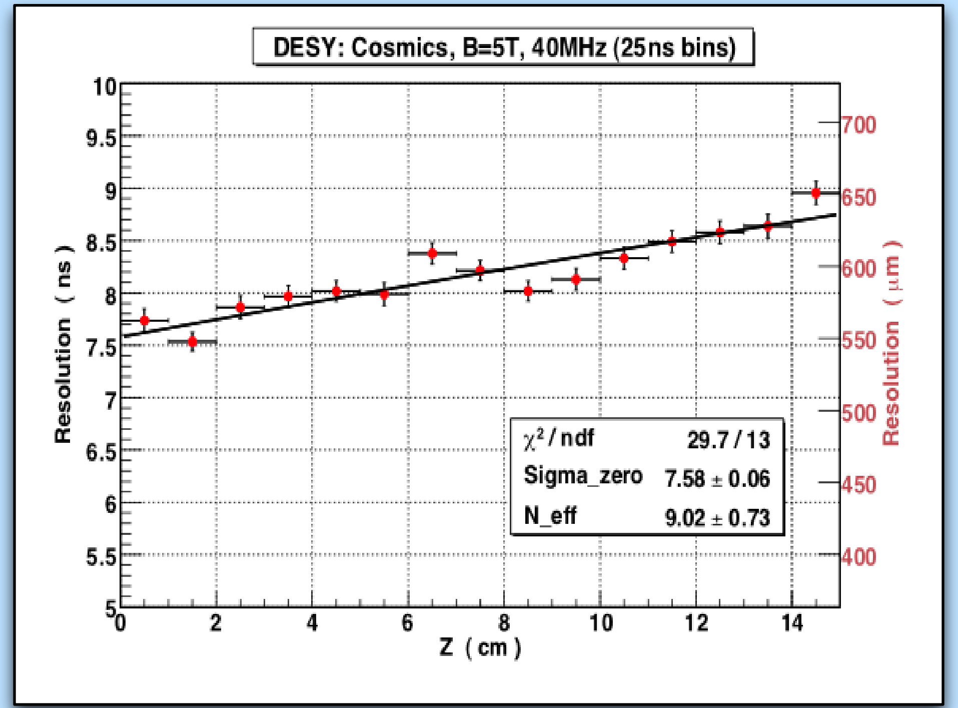
$$\sigma_z = \sqrt{\sigma_0^2 + \frac{D_L^2 \cdot z}{N_{eff}}}$$



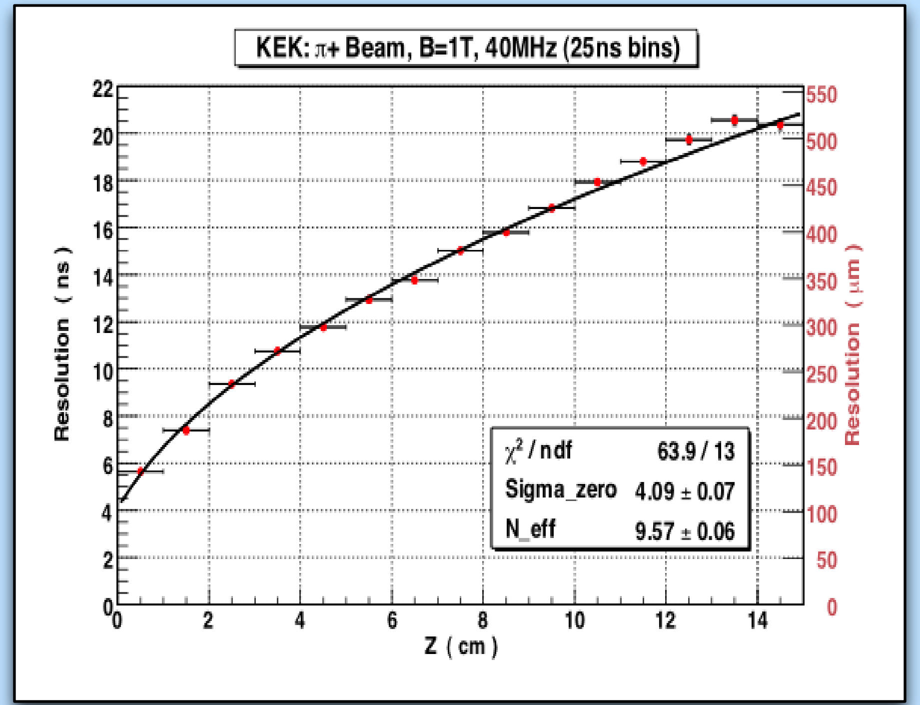


Comparison

DESY: Cosmics (Fast Gas)



KEK: π+ Beam (Slow Gas)



Diffusion Measurement

- Assume the Longitudinal width of the arriving charge distribution is proportional to from fit σ_L

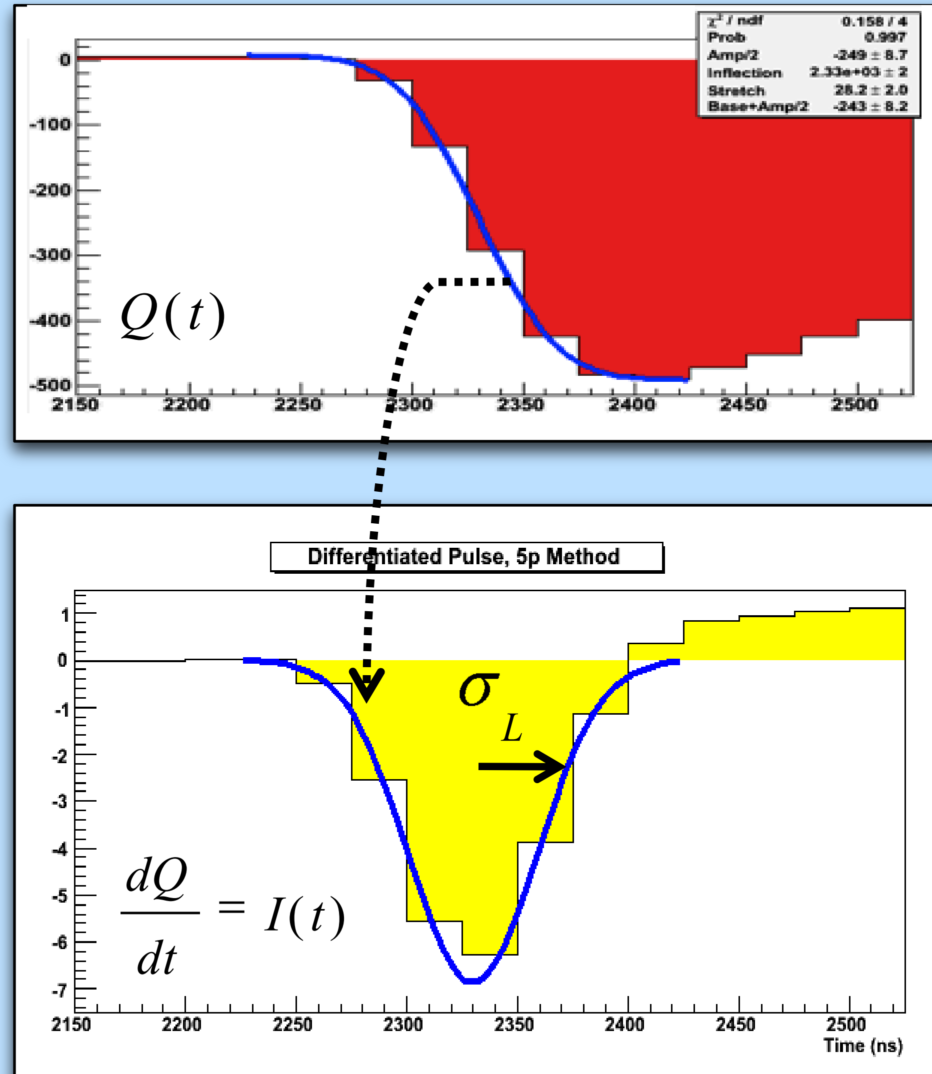
$$Q(\tau) = \frac{1}{\sigma_L \sqrt{2\pi}} \int_{-\infty}^{\tau} \exp\left[-\frac{1}{2}\left(\frac{t - t_0}{\sigma_L} \right)^2 \right] dt$$

- extract the “Current width” and plot against drift distance

- fit with diffusion curve to obtain the Diffusion Constant

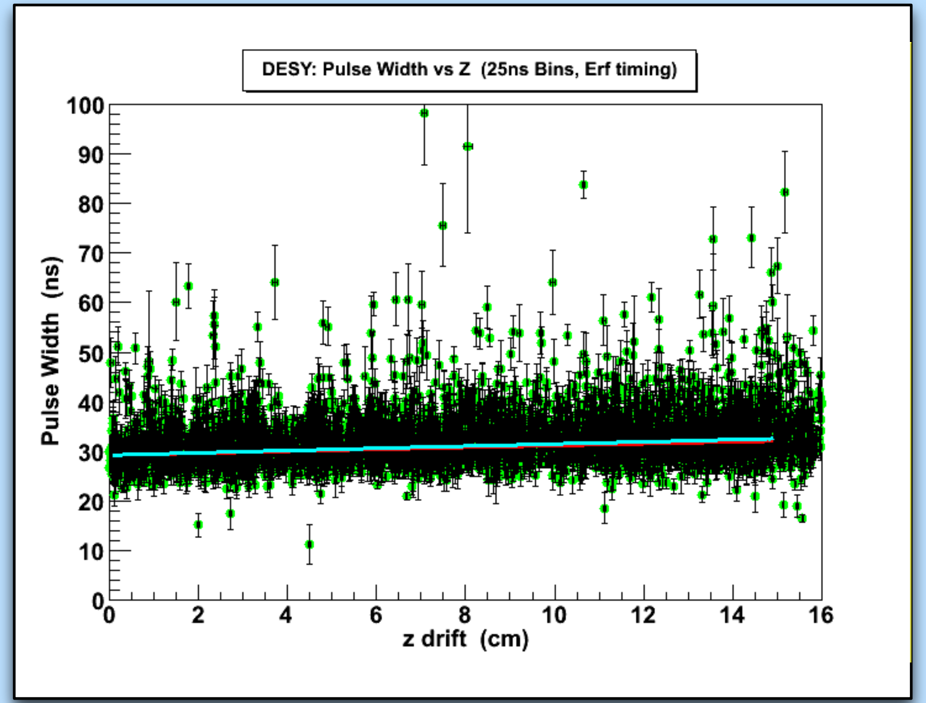
$$\sigma_L = \sqrt{\sigma_0^2 + D_L^2 \cdot z}$$

$$D_L = \text{diffusion Constant} \left(\frac{\mu m}{\sqrt{cm}} \right)$$



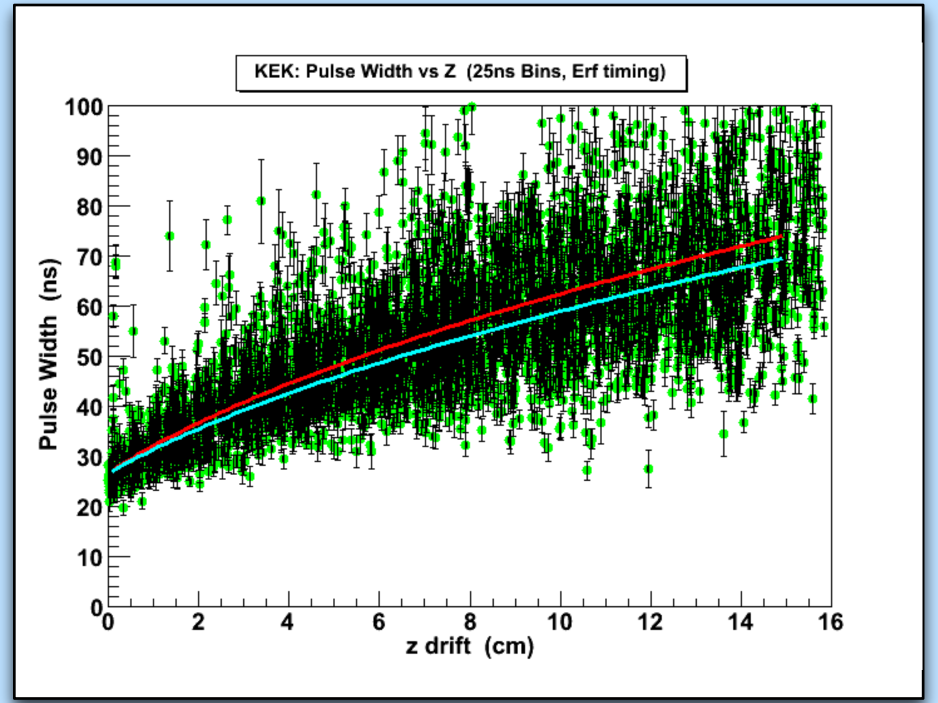
Diffusion Results

DESY: Cosmics (Fast Gas)



$$D_L = 268 \frac{\mu m}{\sqrt{cm}} \quad (magboltz : 248)$$

KEK: π+ Beam (Slow Gas)



$$D_L = 423 \frac{\mu m}{\sqrt{cm}} \quad (magboltz : 479)$$

~10% difference

Summary

- The LHC will make great discoveries (soon… to set the timescale for the next machine at the high energy frontier) and the ILC will the make precision measurements.

- The ILC Large Detector will need to reconstruct tracks in 3D with the best accuracy ever achieved by a TPC and reduced cost (reduced number of electronic channels)

- Tracking goals of the ILC Large Detector look achievable using hardware and analysis techniques developed for a charge dispersion MPGD TPC

  → Transverse: 100 μm (2m drift)
  → Longitudinal: 500 μm (zero drift)

- First study z-resolution: σ_0 = 100 μm (slow gas)

  550 μm (fast gas)

Extra Slides…

Thoughts on Diffusion

Why does uncertainty increase with drift distance???

(1) The approximation that T-rise is proportional to σ_L holds better when T-rise is small. As Z increases, T-rise increases due to longitudinal diffusion as expected, but now Charge Dispersion plays a more significant role.

→ this could be systematic though, causing the curve to be off, but not explaining the spread… humm better think about this (???)

(2) With slower rising pulses, the signal-to-noise ratio is not as good

(3) N_{eff} lower for longitudinal versus transverse diffusion… investigate

(4) Optimization: Pad width/shape, track angle effect and ionization statistics!

r/phi resolution

- charge dispersion increases charge sharing among pads, leads to a better centroid determination

- must determine PRF before track fitting, which is NOT Gaussian

- track fit gives you Curvature, hence Transverse Momentum!

- still require Theta to determine the Total Momentum