G4 for Gaseous Detectors

RD51 NIKHEF

April 16-18, 2008

- **Introduction & Motivation**
- **Applications and Remarks**
- **Benchmark**
- **Ionization/clusters**
- **Transport**
- **Interface to G4**
- **Summary**

Carleton University
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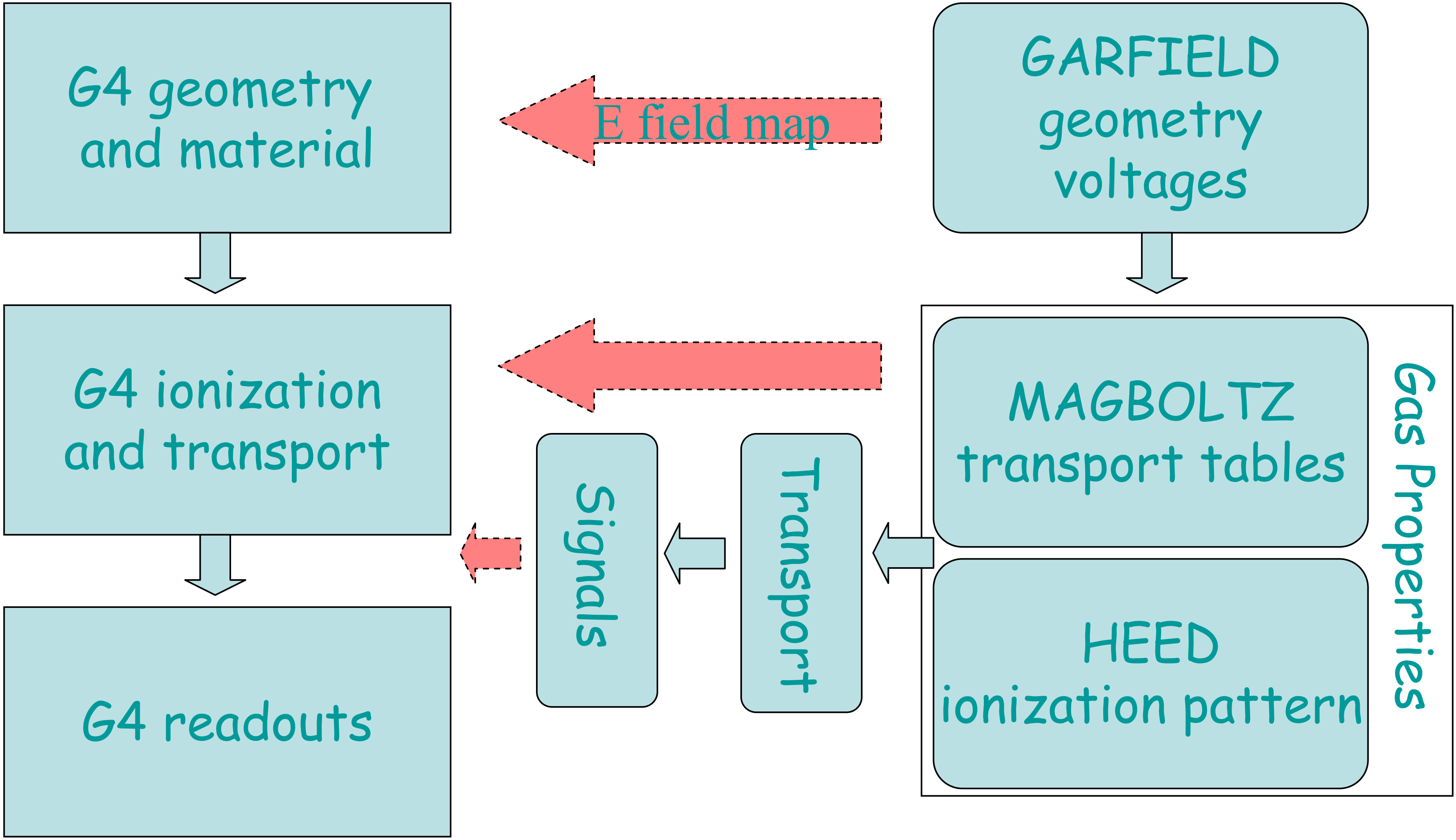
Alain Bellerive
Canada Research Chair
Canada Research Chairs
Chaires de recherche du Canada

Introduction



G4 geometry and material

E field map

GARFIELD geometry voltages

G4 ionization and transport

Signals

Transport

MAGBOLTZ transport tables

HEED ionization pattern

Gas Properties

G4 readouts

G4

- Particle and nuclear physics experiments pose enormous challenges in the creation of multipurpose software frameworks.
- Of particular importance to RD51 is the ever-increasing demand for accurate and comprehensive simulations of MPGDs.
- The GEANT4 (G4) simulation toolkit provides flexible detector **design** and physics modeling capabilities embedded in an object-oriented structure.
- G4's C++ kernel encompasses tracking; geometry description and navigation; material specification; abstract interfaces to physics processes; management of events; run configuration; stacking for track prioritization; tools for handling the detector response; and interfaces to external frameworks, graphics and user interface systems.
- I am not here to tell you that G4 will solve all your problems, but instead describe a framework in which gas detectors could be integrated for various applications

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Wishes list

- **Microscopic physics of MPGD**
- **Ionization/clusters** ☆
- **Electric field computation for complex geometry**
- **Transport** ☆
- **Induced charged** ☆
- **Signal processing** ☆
- **Ions backflow** ☆
- **Charging effect**

… lots already included in
Garfield – Heed – Magboltz

each group uses their own
cook-up software

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Types of Simulation and Scope

- **Fast analytical/parameterization**

macroscopic – **usually used for physics Monte Carlo that is CPU limited**

- **Slow detailed and complete processes**

microscopic – **usually need for full understanding of device during R&D or for calibration of the full scale experiment**

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Applications

GOALS of the *original* project:

Simulation of TPC

Design and optimization of full scale detectors

Calibration

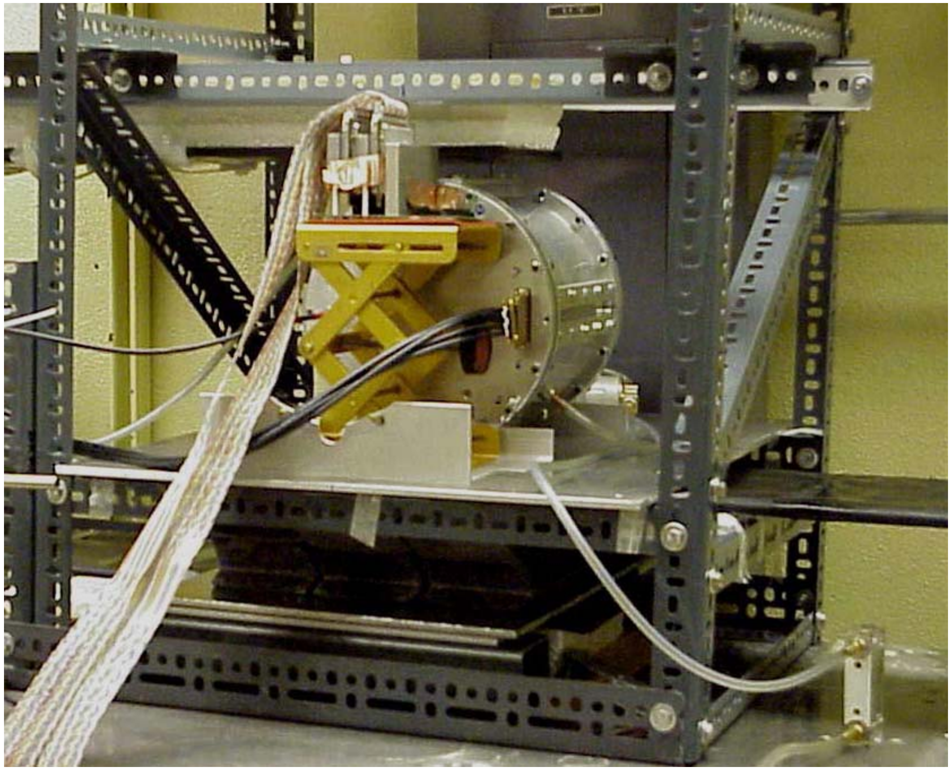
Data Analysis

- 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: EXO, ILC/TPC, T2K, Alice, etc…

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

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. τ_{Rise}= 40 ns, τ_{Fall} = 2 μs,
- 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.

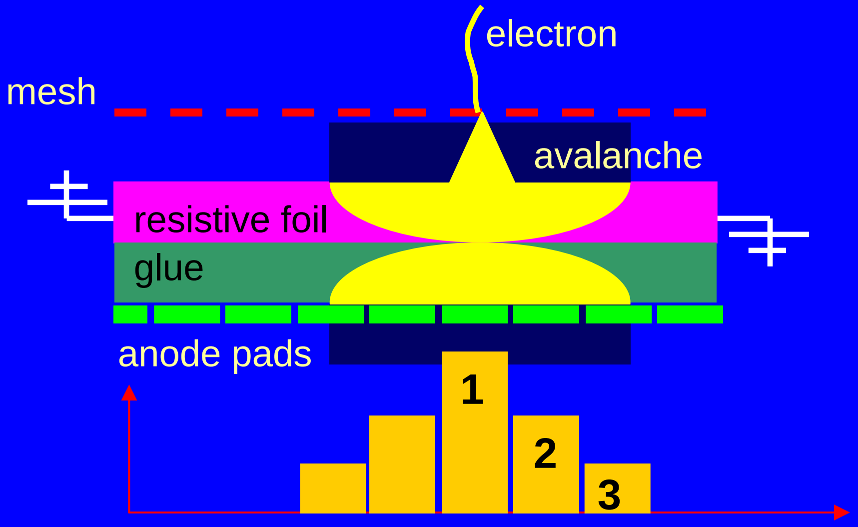
Resistive anode / charge dispersion

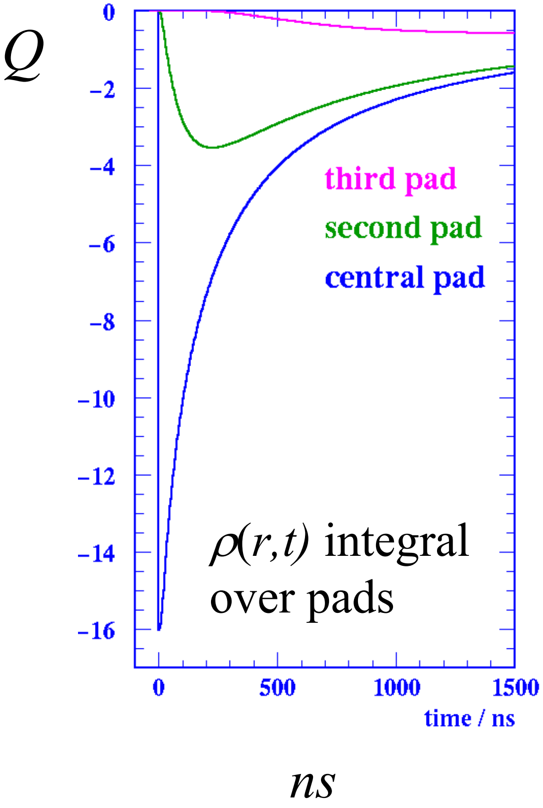
- a high resistivity film bonded to a readout plane with an insulating spacer
- 2 dim continuous RC network defined by material properties and geometry.
- point charge at r = 0 & t = 0 disperses with time.

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

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

Micromegas + resistive anode





Pulse shape origin

Transverse diffusion

$$T(x) = \frac{1}{\sigma_x\sqrt{2\pi}}\exp\left(\frac{-x^2}{2\sigma_x^2}\right)$$

Longitudinal diffusion

$$L(t) = \frac{1}{\sigma_t\sqrt{2\pi}}\exp\left(\frac{-t^2}{2\sigma_t^2}\right)$$

Intrinsic rise time

$$\begin{aligned} R(t) &= \frac{t}{T_{rise}} && \text{for} \quad 0 < t < T_{rise} \\ &= 1 && \text{for} \quad t > T_{rise} \\ &= 0 && \text{for} \quad t < 0 \end{aligned}$$

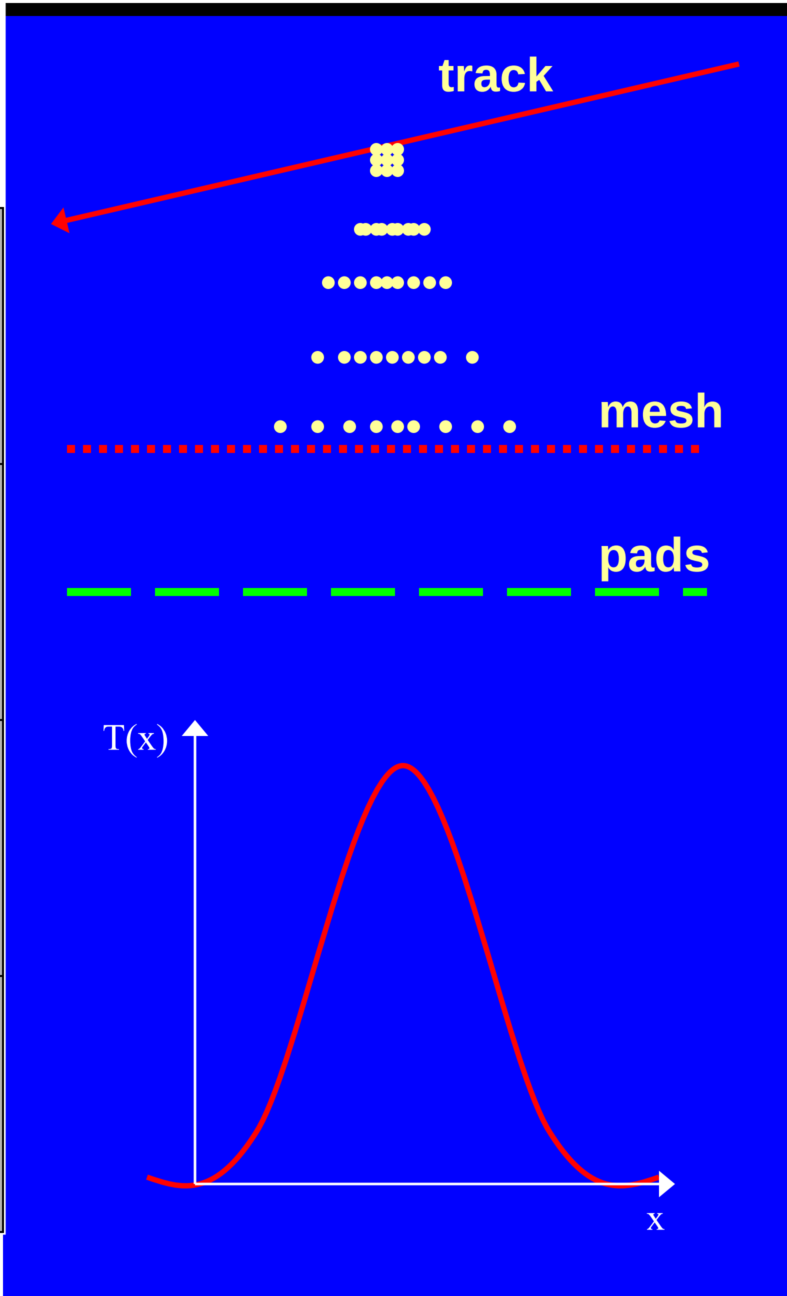
Preamplifier effect

$$\begin{aligned} A(t) &= \exp\left(-\frac{t}{t_f}\right)\left(1-\exp\left(\frac{t}{t_r}\right)\right) && \text{for} \quad t > 0 \\ &= 0 && \text{for} \quad t < 0 \end{aligned}$$

Resistive foil + glue

$$\rho(x,y,t) = \left(\frac{1}{\sigma_t\sqrt{\pi t h}}\right)^2 \exp\left(\frac{-(x^2+y^2)}{4th}\right)$$

$$h = 1/RC$$



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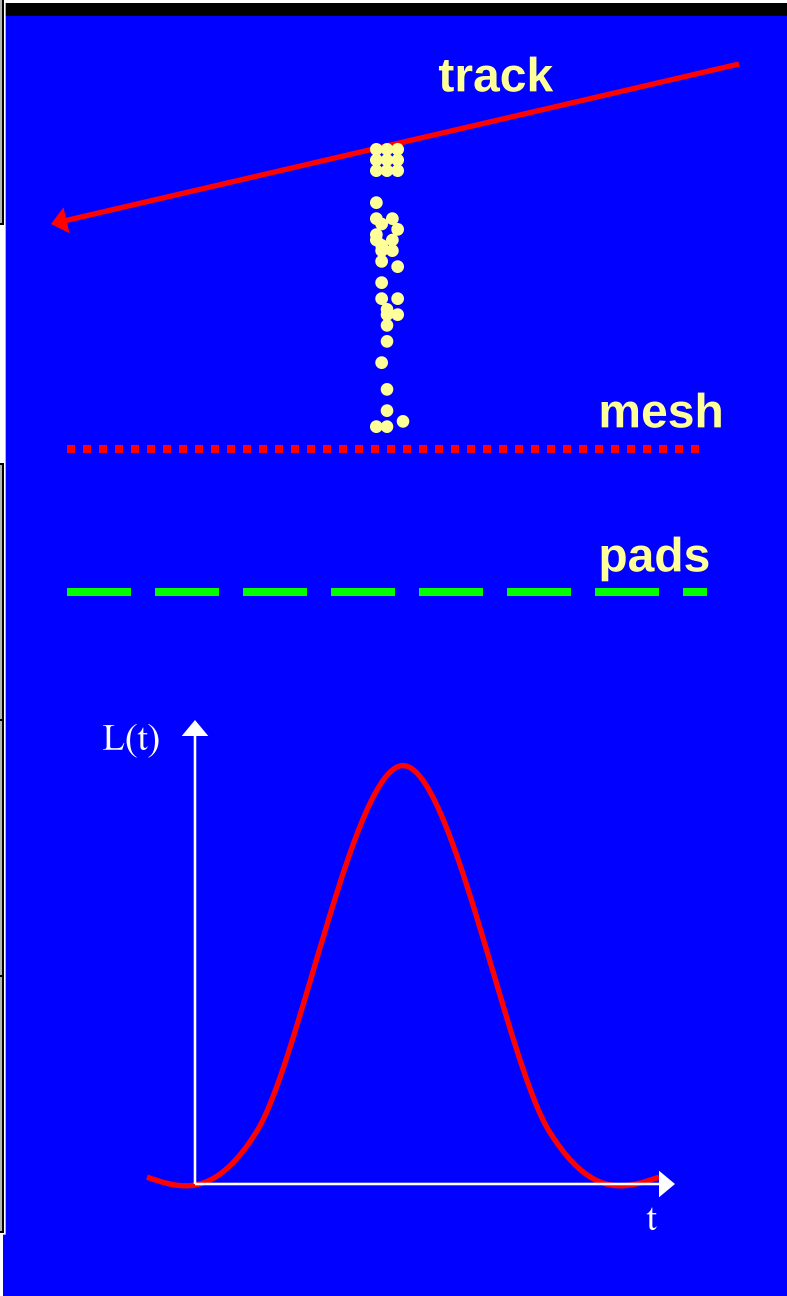

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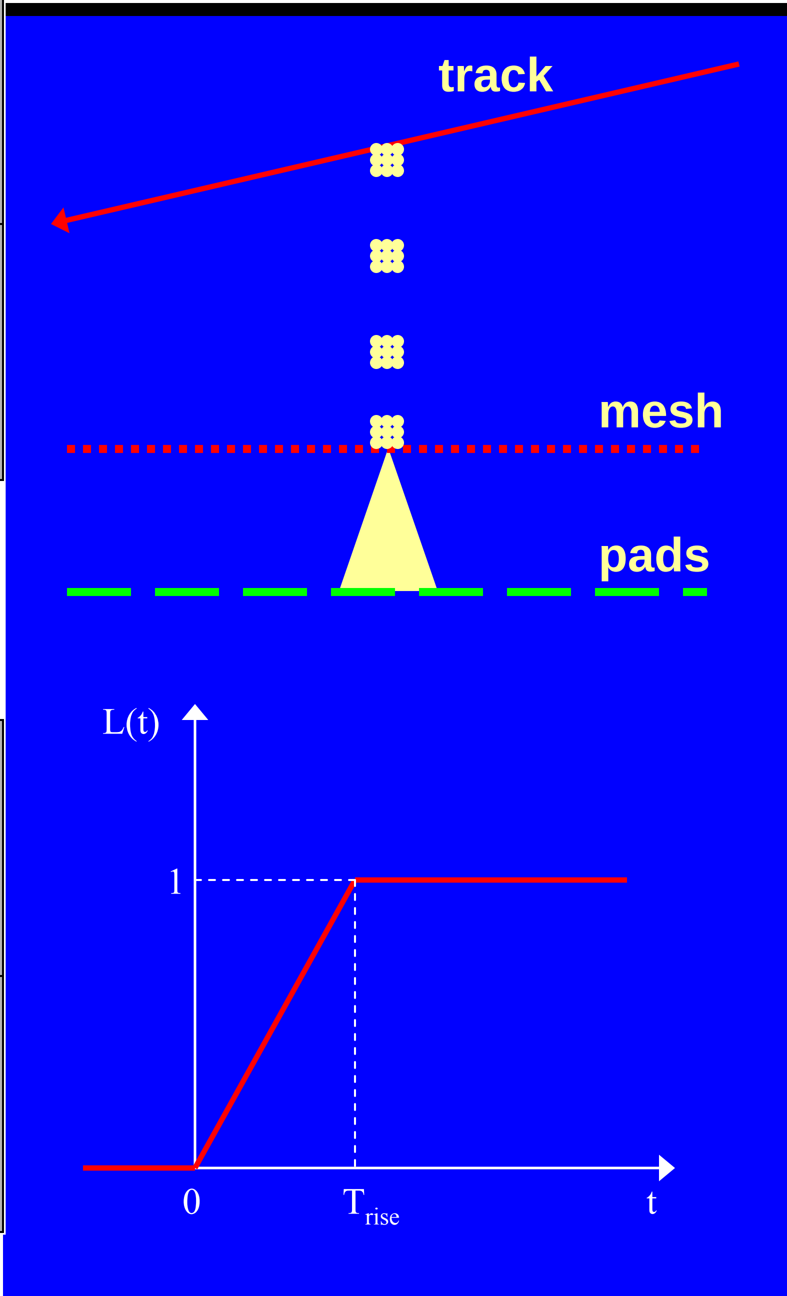

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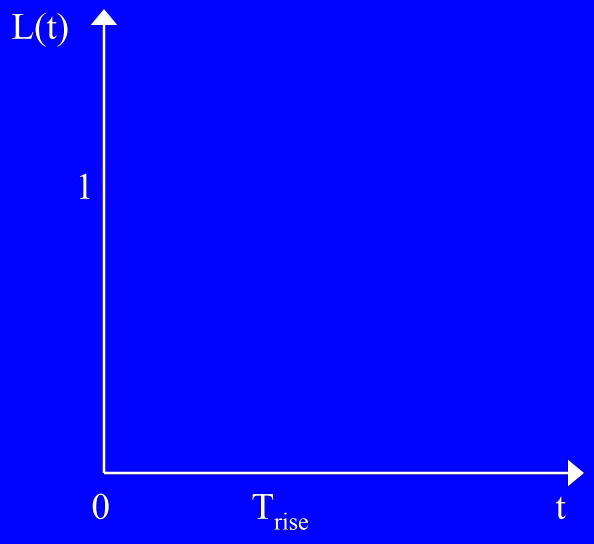

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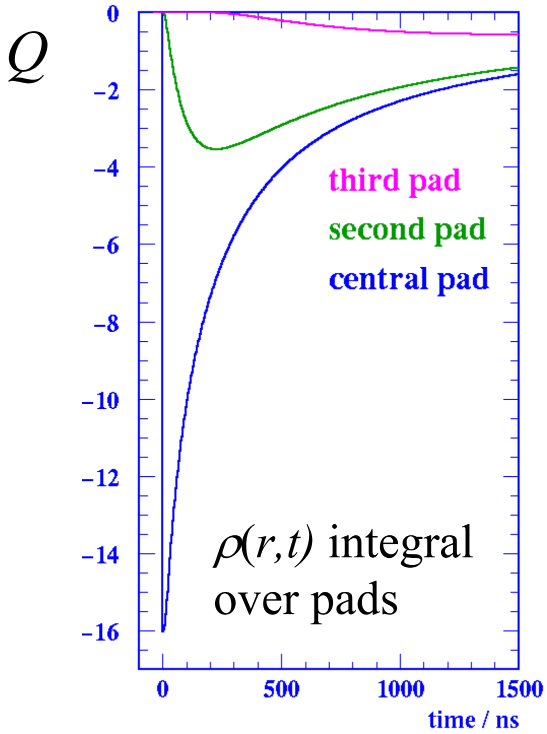


ns

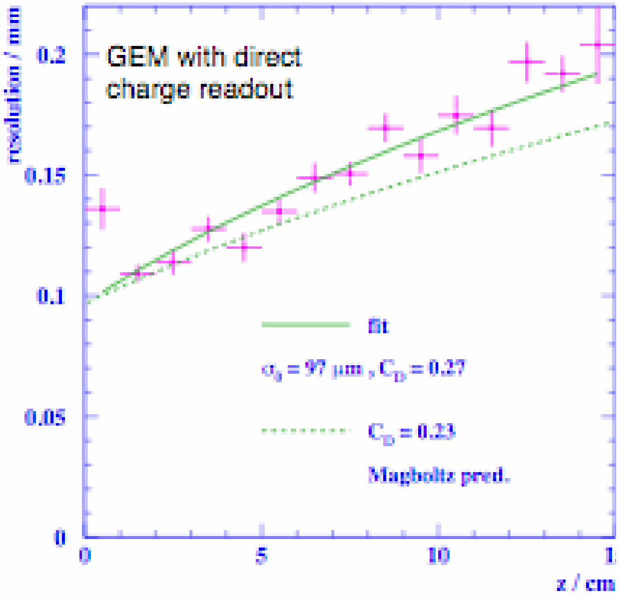
M.S. Dixit & A. Rankin, NIM A566, 281 (2006)

C++ code developed during summer 2007

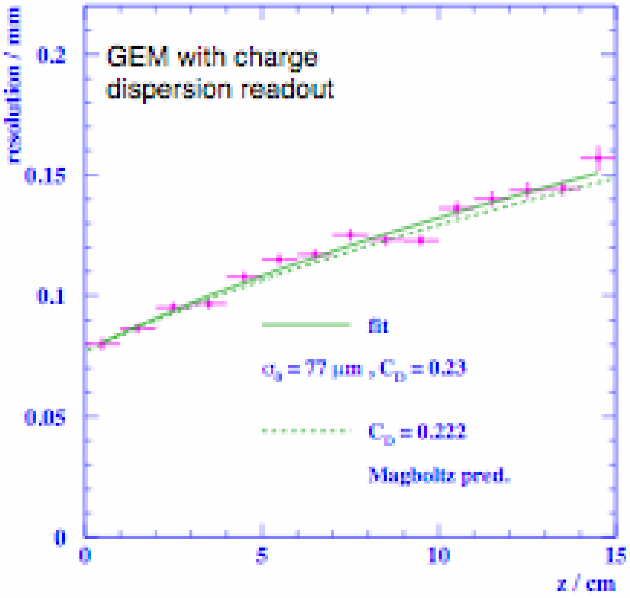
Resistive anode

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

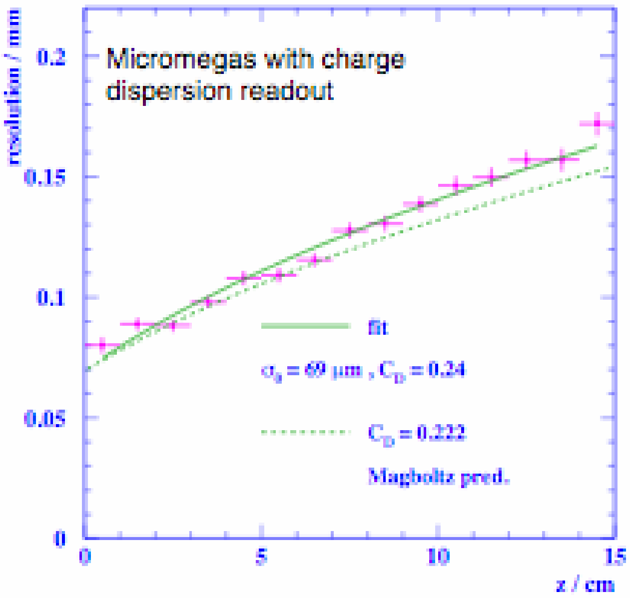
R.K.Carnegie et.al.,
NIM A538 (2005) 372



K. Boudjemline et.al.,
NIM A574 (2007) 22



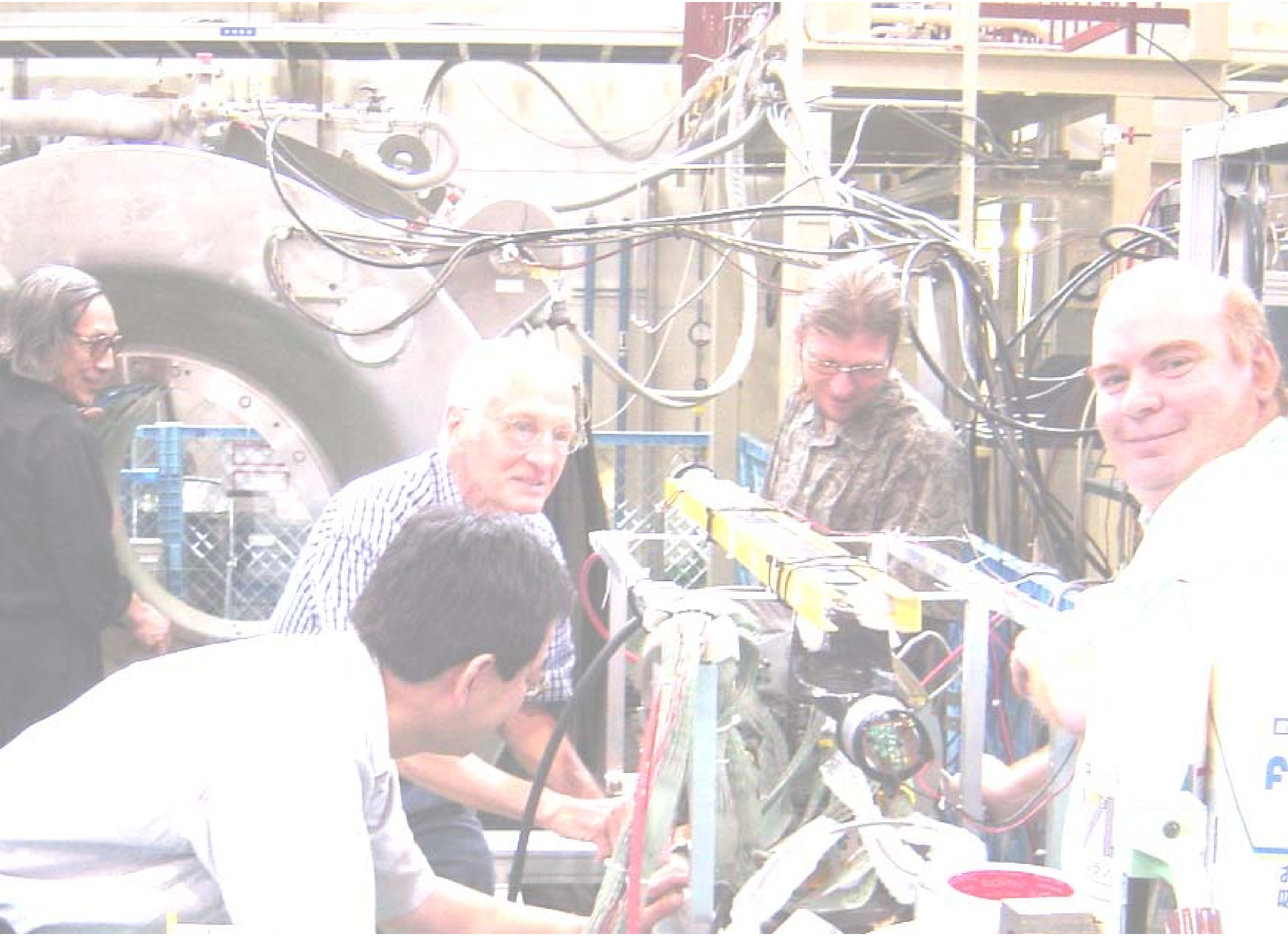
A. Bellerive et.al,
LCWS 2005, Stanford



……

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

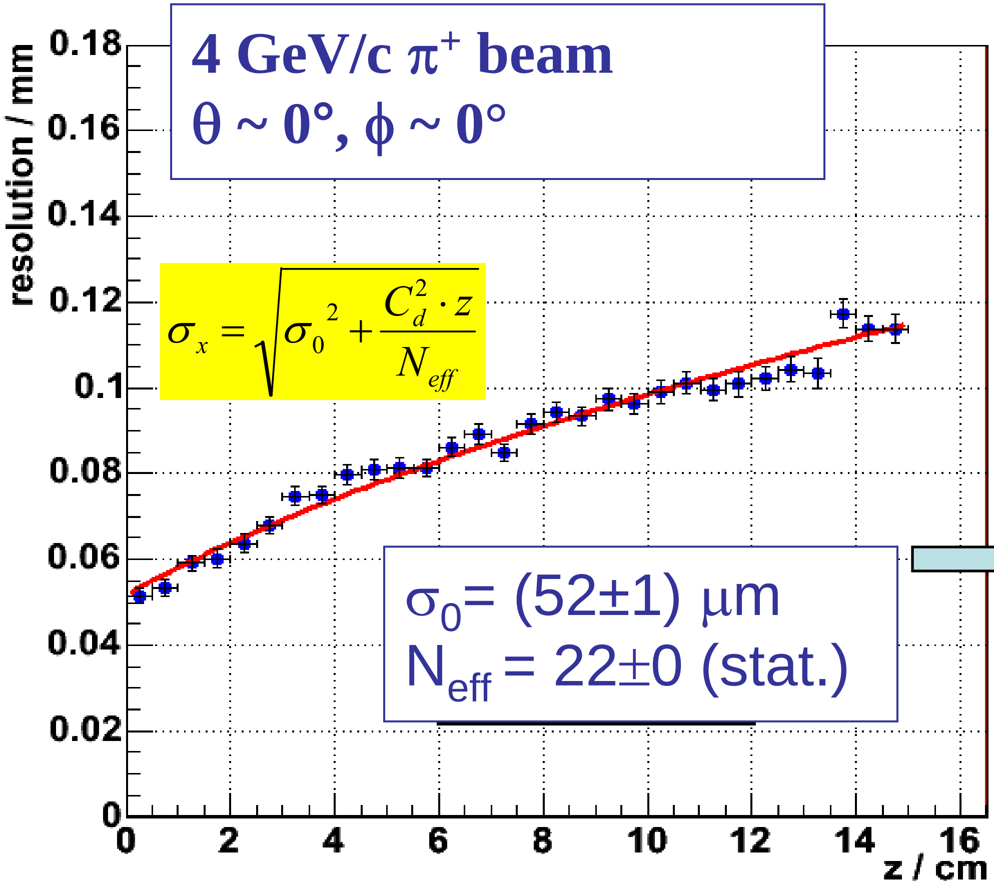
Compared to conventional readout, charge dispersion gives better resolution for the GEM and the Micromegas.



Resistive anode

Transverse spatial resolution Ar+5%iC4H10
E=70V/cm D_{Tr} = 25 µm/√cm (Magboltz) **B= 1T**

Micromegas TPC 2 x 6 mm² 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.)

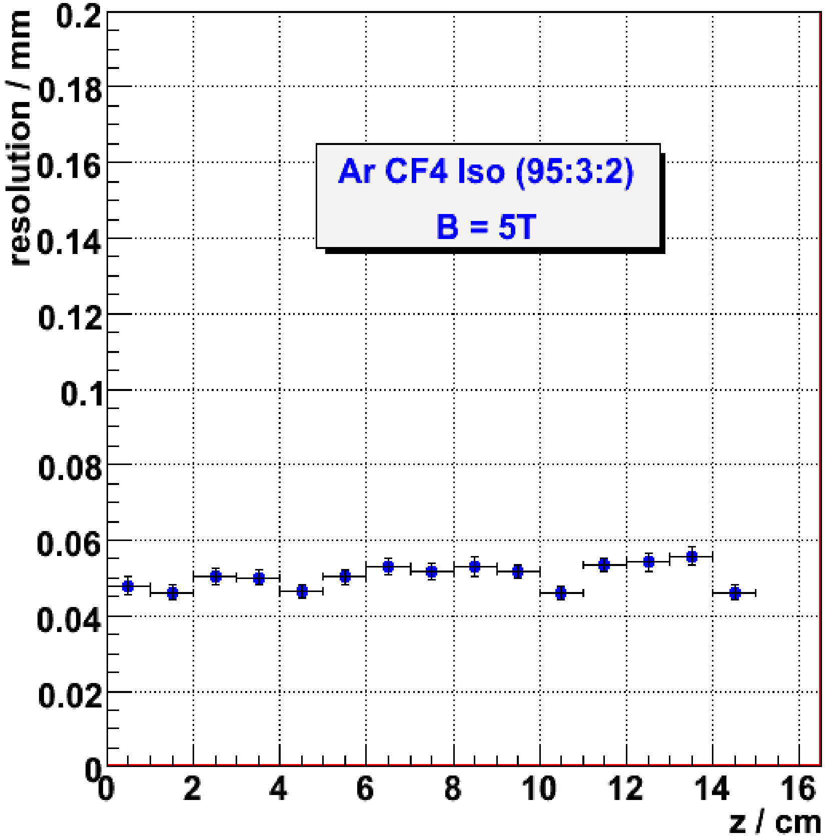
•Strong suppression of transverse diffusion at 4 T.
Examples:
D_{Tr}~ 25 µm/√cm (Ar/CH4 91/9)
Aleph TPC gas
~ 20 µm/√cm (Ar/CF4 97/3)

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

Resistive anode

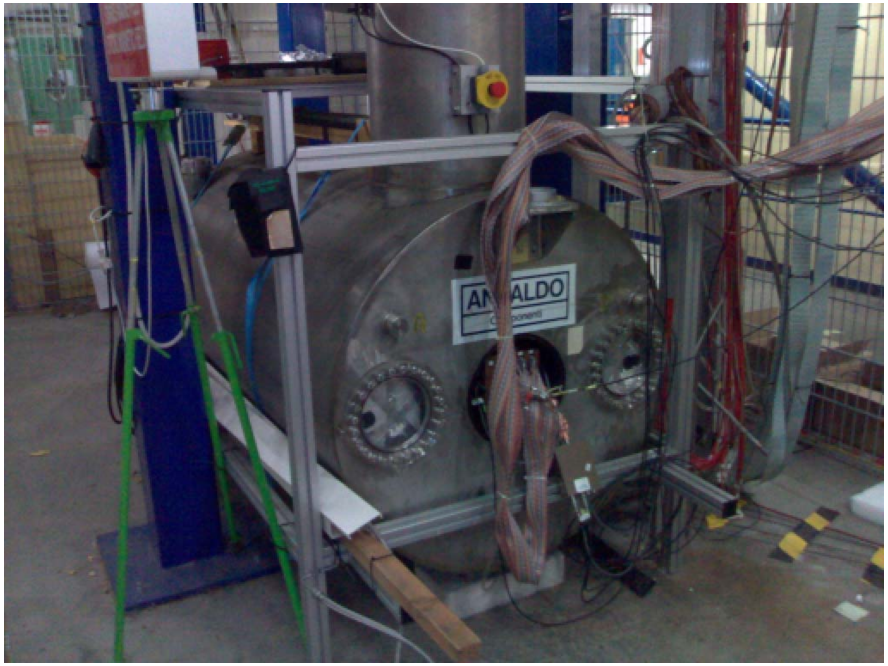
Extrapolation confirmed in 5 T cosmic tests
Carleton-Orsay-Saclay-Montreal μmegas TPC

D_{Tr}= 19 μm/√cm, **2 × 6 mm² pads**



Nov-Dec, 2006

M. Dixit et.al.
NIM A581:254-257,2007



DESY

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

G4 Development & Benchmarks

- **Ionization/clusters**

Based on new C++ Heed

- **Electron transport**

G4 native or interface to Magboltz

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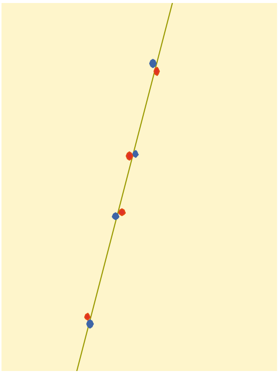
Input: Blum and Rolandi

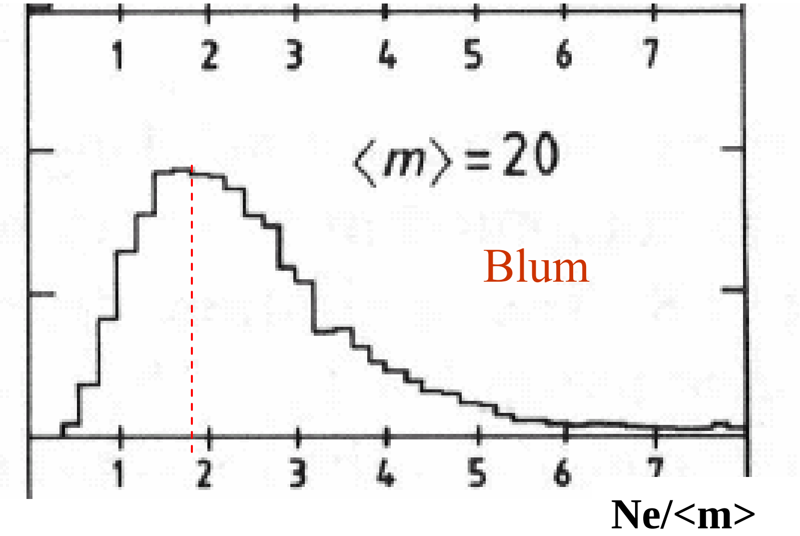
- Particles on the plateau of the energy loss curve ($\gamma = 1000$).
- Pure Argon.
- 5.7 mm track length.
- Average number of clusters <m> = 20 (35/cm).
- Cluster Size Distribution [Lapique and Piuz, NIM 175 (1980) 297-318.].

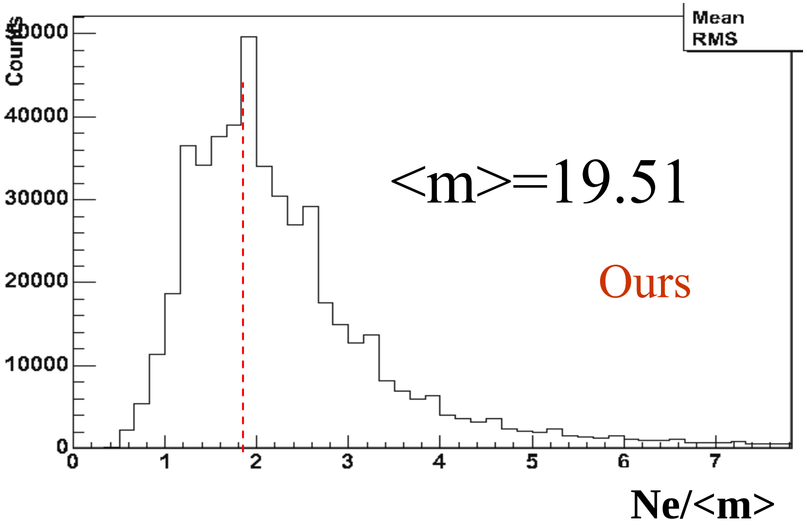


Our input:

- dE/dx ($\gamma = 1000$)/dE/dx ($\gamma = 4$ or MIPs) = 1.38 [Santovi and Cerrito, NIM A435 (1999) 348-353].
- Average Number of Clusters for Pure Argon = 24.8/cm [Zarubin, NIM A283 (1989)409-422].
- 5.7 mm track length.
- Average number of clusters <m> = 24.8*0.57*1.38 = 19.51.
- Cluster Size Distribution [H. Fischle, NIM A301 (1991) 202-214].

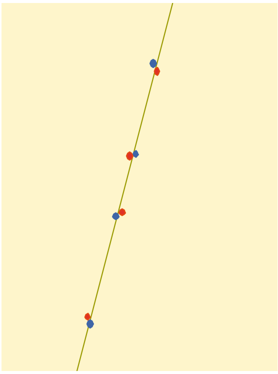
Results: Total Number of electrons divided by the Average number of clusters.





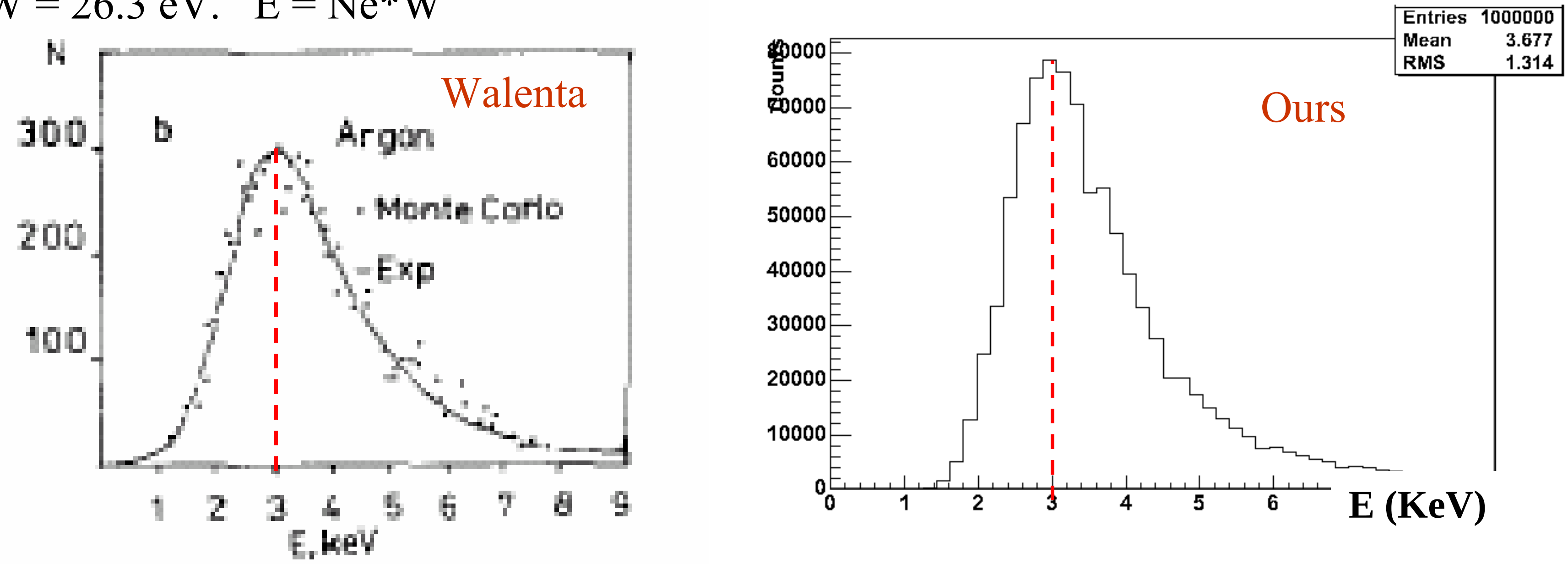
Input: A.H. Walenta, Proc. Int. Symp. Position detectors in high energy physics, Dubna (1987) JINR, D1, 13-88-172, Dubna (1988).

- MIPs ($\gamma = 4$).
- Pure Argon.
- 2.3 cm track length.



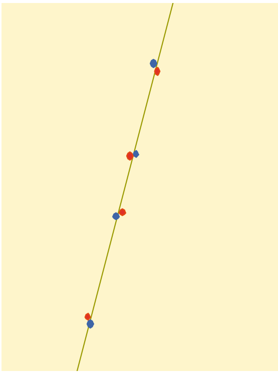
Our Input:

- Average Number of Clusters for Pure Argon = 24.8/cm [Zarubin, NIM A283 (1989) 409-422].
- 2.3 cm track length.
- Average number of clusters <m> = 24.8*2.3.
- Cluster Size Distribution [H. Fischle, NIM A301 (1991) 202-214].
- W = 26.3 eV.   E = Ne*W



Total Number of electrons versus energy

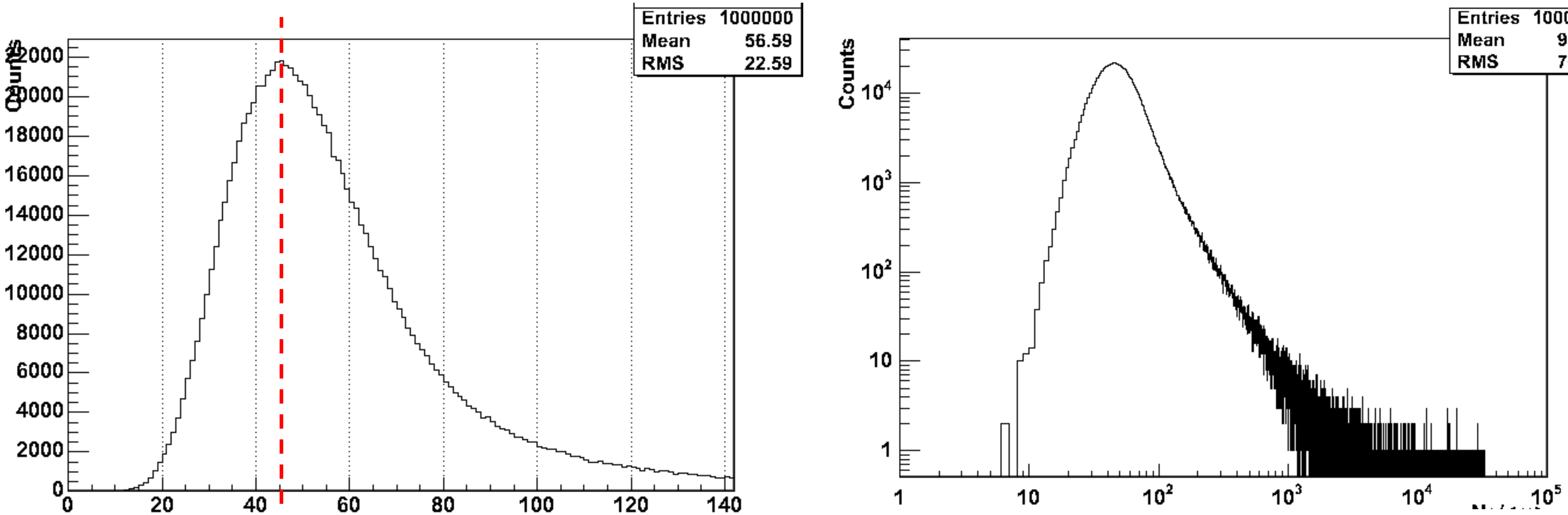
Benchmark MC Simulation (1 cm Argon)



Our Input:

-MIPs ($\gamma = 4$).

- Pure Argon.
- Average Number of Clusters = 24.8/cm [A. V. Zarubin, NIM A283 (1989) 409-422].
- 1 cm track length.
- Cluster Size Distribution [H.. Fischle, NIM A301 (1991) 202-214].



Total Number of electrons

$N_{Mean} \sim 95.7e$ (96.6 [from Zarubin])

$N_{MPV} \sim 46e$

Transport (G4)

$$m\frac{d\vec{u}}{dt} = \mathrm{e}\,\vec{\mathrm{E}} + \mathrm{e}\,[\vec{\mathrm{u}} \times \vec{B}] - K\vec{u}$$

equation of motion
with friction

$$\vec{u} = \frac{\mu}{(1+\mathrm{w}^2\tau^2)}\,|\,\vec{\mathrm{E}}\,|\left(\hat{\mathrm{E}} + \omega\tau\,[\hat{\mathrm{E}} \times \hat{\mathrm{B}}] + \mathrm{w}^2\tau^2\,[\hat{\mathrm{E}} \cdot \hat{\mathrm{B}}]\,\hat{\mathrm{B}}\right)$$

Use RK step function (*e.g.* 3D RK4 method)

$$\mathrm{x}' = \mathrm{u}(\mathrm{t},\mathrm{x}) \quad \mathrm{x}(\mathrm{t}_0) = \mathrm{x}_0 \quad \mathrm{t}_{\mathrm{n}+1} = \mathrm{t}_\mathrm{n} + \mathrm{h}$$

$$\mathrm{x}_{\mathrm{n}+1} = \mathrm{x}_\mathrm{n} + \frac{\mathrm{h}}{6}(\mathrm{k}_1 + 2\mathrm{k}_2 + 2\mathrm{k}_3 + \mathrm{k}_4)$$

$$\mathrm{k}_1 = \mathrm{u}(\mathrm{t}_\mathrm{n}, \mathrm{x}_\mathrm{n}) \quad \mathrm{k}_2 = \mathrm{u}(\mathrm{t}_\mathrm{n} + \frac{\mathrm{h}}{2}, \mathrm{x}_\mathrm{n} + \frac{\mathrm{h}}{2}\mathrm{k}_1)$$

$$\mathrm{k}_3 = \mathrm{u}(\mathrm{t}_\mathrm{n} + \frac{\mathrm{h}}{2}, \mathrm{x}_\mathrm{n} + \frac{\mathrm{h}}{2}\mathrm{k}_2) \quad \mathrm{k}_4 = \mathrm{u}(\mathrm{t}_\mathrm{n} + \mathrm{h}, \mathrm{x}_\mathrm{n} + \mathrm{h}\mathrm{k}_3)$$

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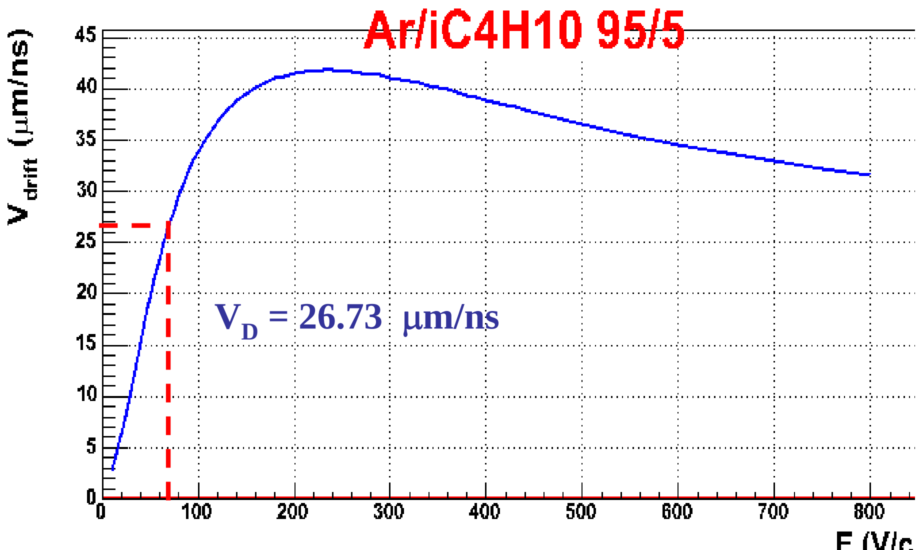
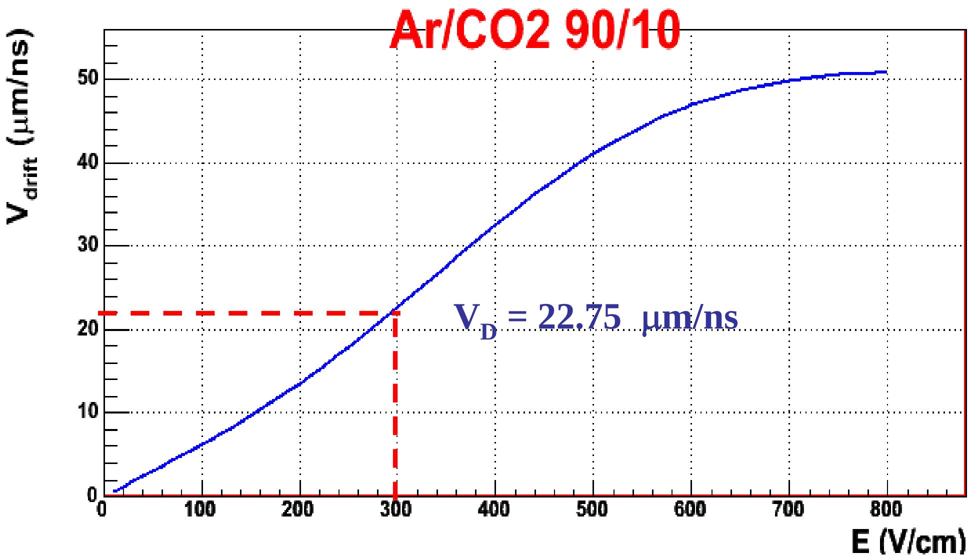
Magboltz [drift velocity, lorentz angle & diffusion]



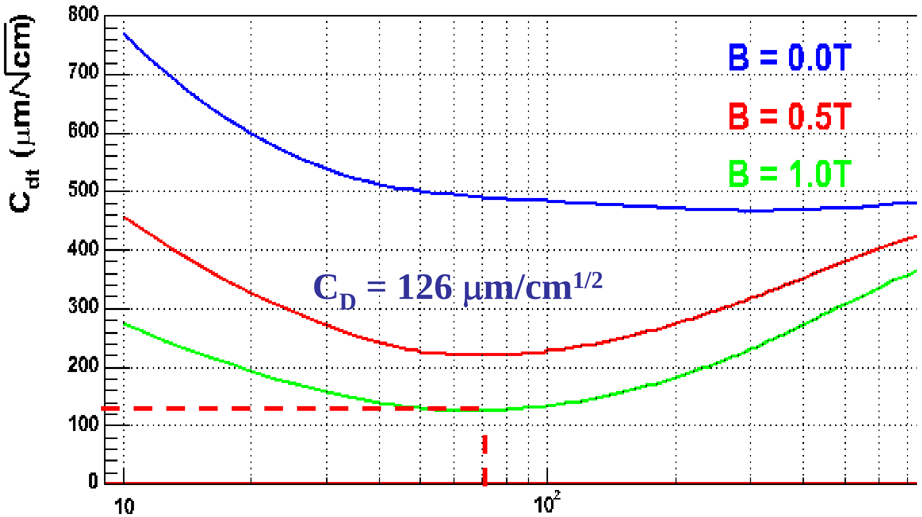
V_D = 26.73 µm/ns

E = 70 V/cm



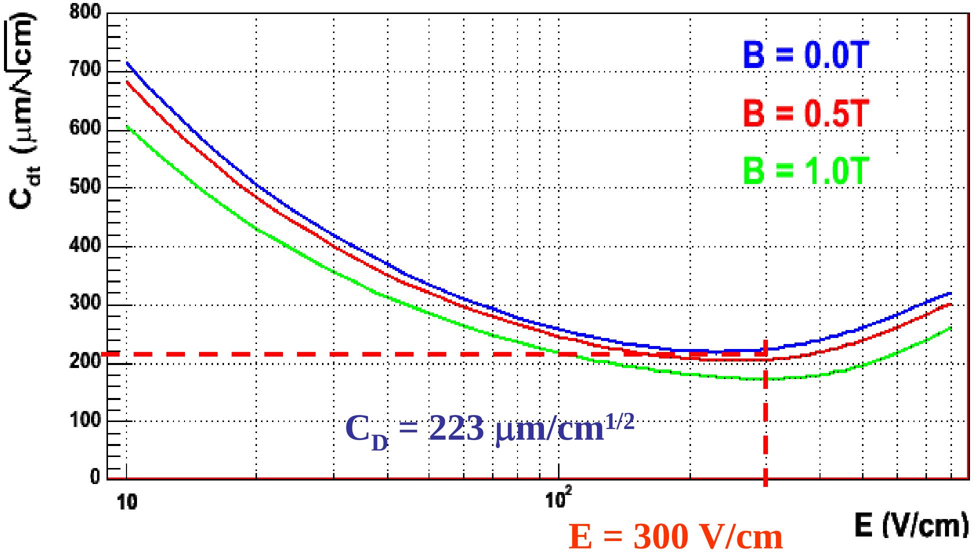
V_D = 22.75 µm/ns

E = 300 V/cm



C_D = 126 µm/cm$^{1/2}$

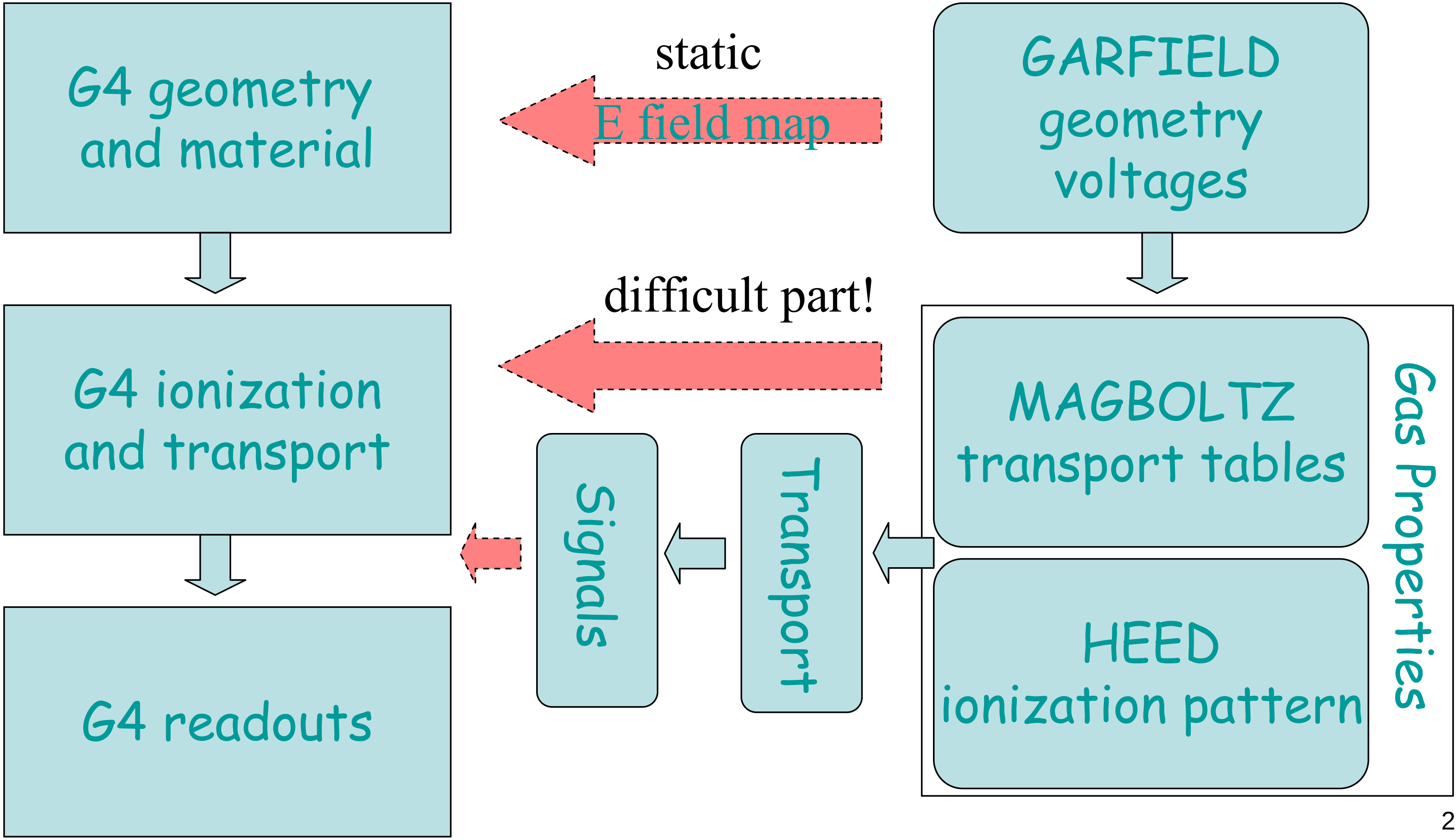
E = 70 V/cm



C_D = 223 µm/cm$^{1/2}$

E = 300 V/cm

Main difficulty: interfaces!



G4 geometry and material

static

E field map

GARFIELD geometry voltages

G4 ionization and transport

difficult part!

Signals

Transport

MAGBOLTZ transport tables

HEED ionization pattern

Gas Properties

G4 readouts

G4 native…

Argon(gas)

G4Material Ar = new G4Material(”Argon”, z=18.,*
*a=39.948*g/mol, density =1.7834*mg/cm3, kStateGas,*
*temperature=298.15*kelvin, pressure= 1*atmosphere);*

Drift Electrons

G4ProcessManager

G4ParticleDefiniton

Transport

DriftStepper = new G4ClassicalRK(EquationOfMotion);

DriftFieldManager= new G4FieldManager();

G4TransportationManager::GetTransportationManager()
→ *SetFieldManager(DriftFieldManager);*

Summary

- Possible G4 framework for gas detectors
- Coupled with Garfield dev interface to ROOT
- Plan to include ionization/clusters in G4 from new C++ Heed
- Transport from G4 native or Garfield
- Need (still) to finalize an interface to G4 for field map and transport parameters (solve Bolztman equation / Magboltz program)
- Small team… here work from Carleton/TRIUMF
- Room to grow and include more capabilities