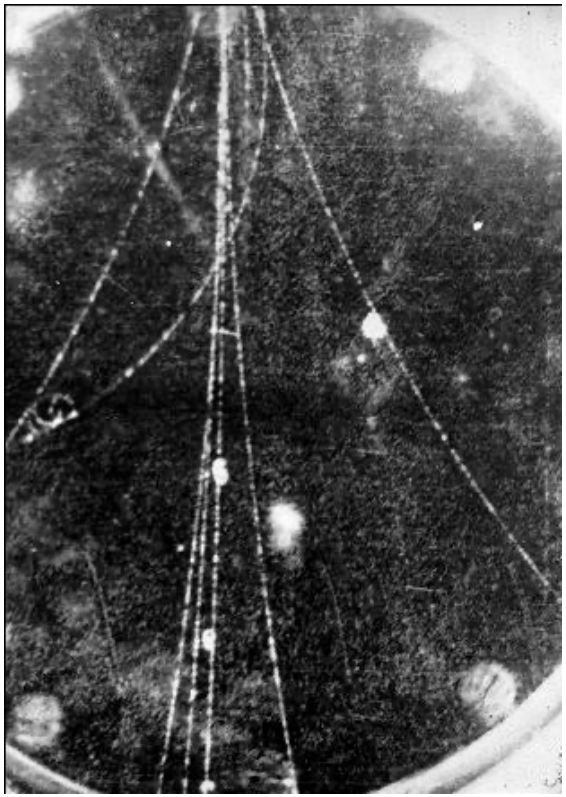
Gas Detectors Physics 1

Basic Detection Processes

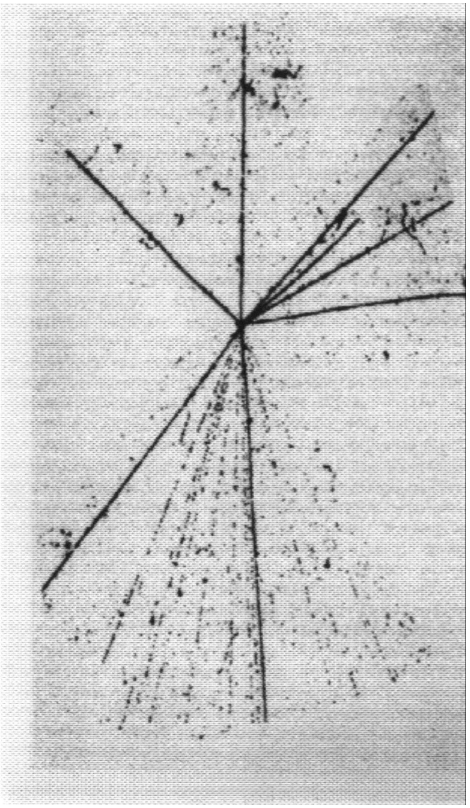
- Energy Loss: Coulomb Interactions
- Drift and Diffusion of Charges
- Collisional Excitation and Ionization
- Avalanche Charge Multiplication
- Signal Formation and Detection

Imaging of Charged Particles Interactions



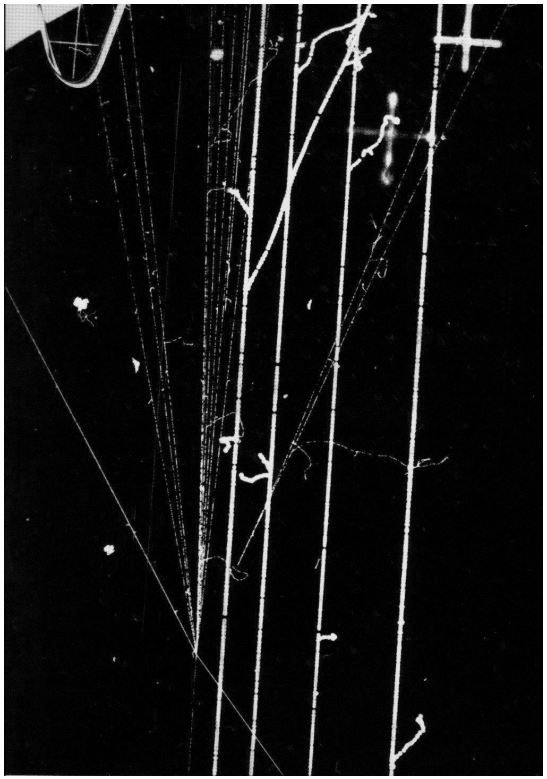
~ 1930

Cloud Chamber



~1940

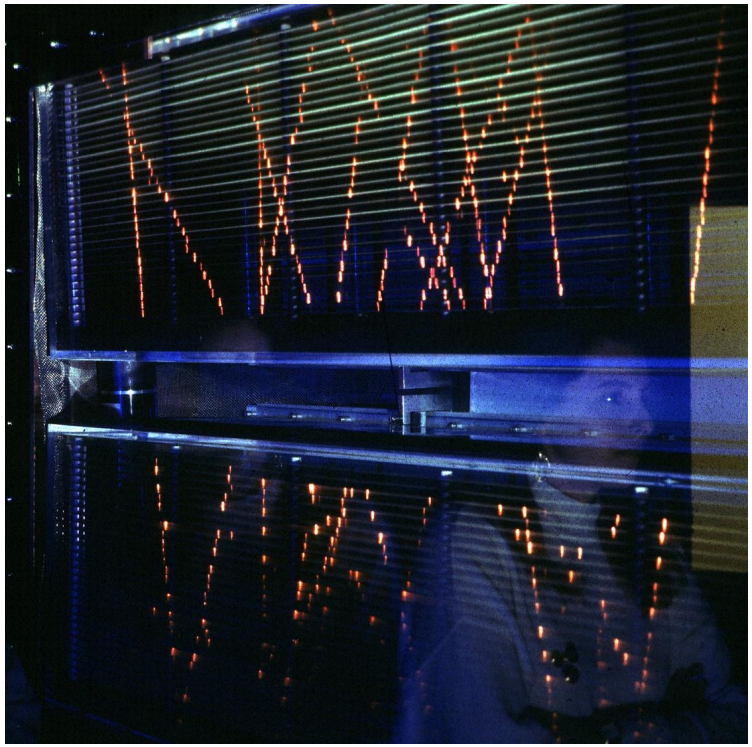
Emulsions

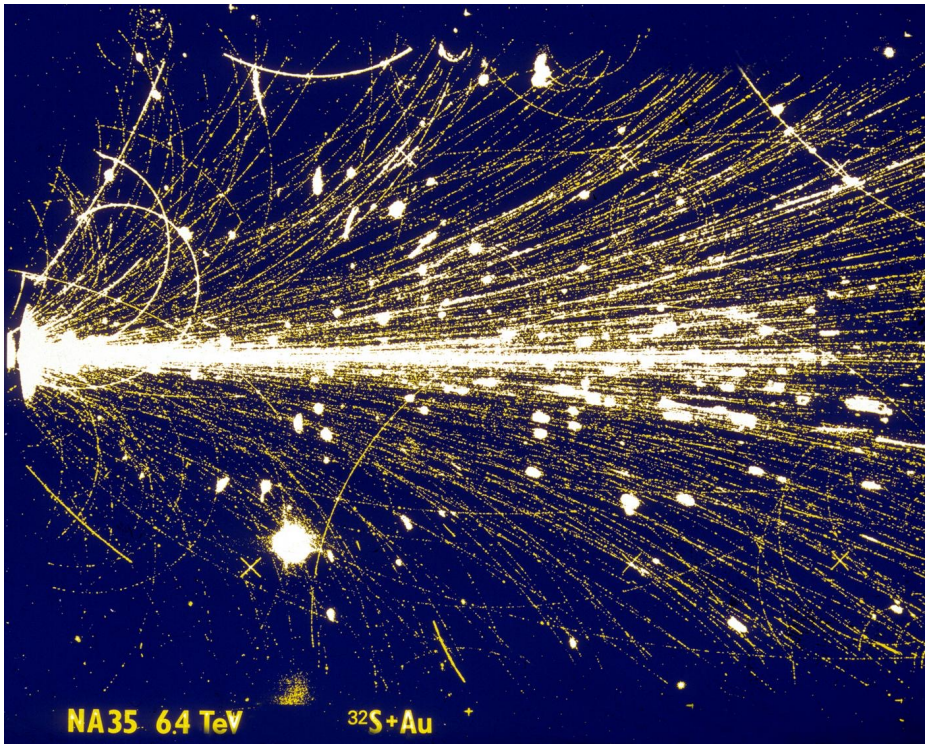


~ 1960

Bubble Chamber

Imaging of Charged Particles Interactions

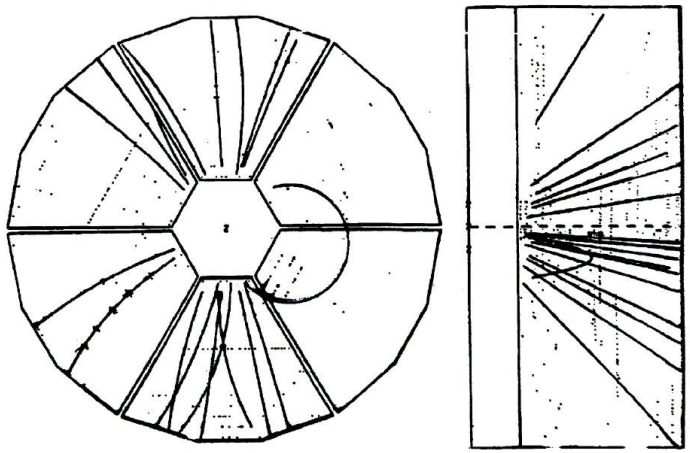




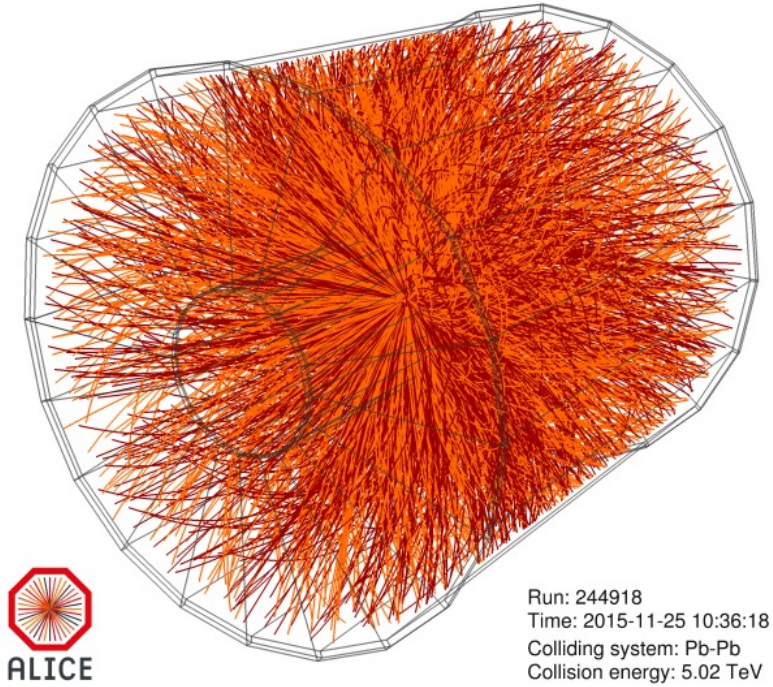
~1960

Spark and Streamer Chambers

Imaging of Charged Particles Interactions



~1970



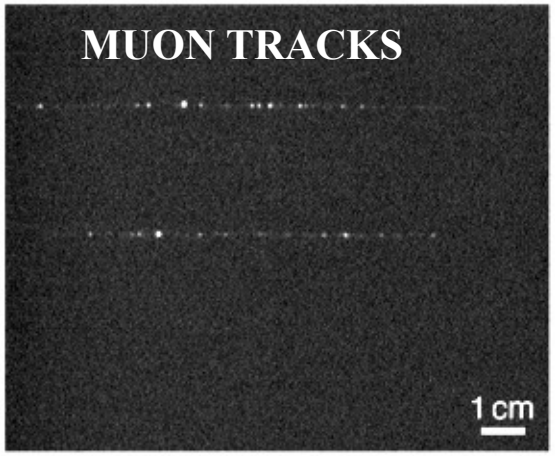
~2000

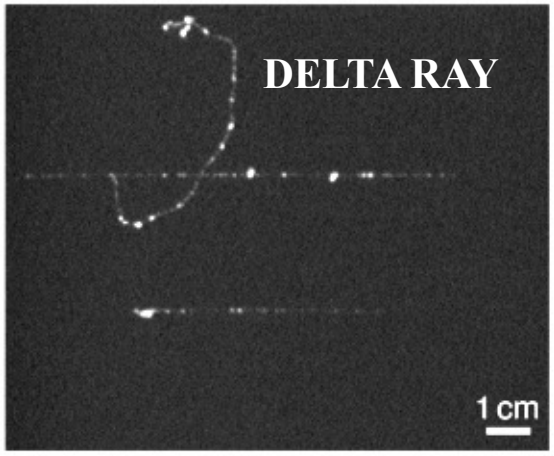
2016: GEM TPC UPGRADE

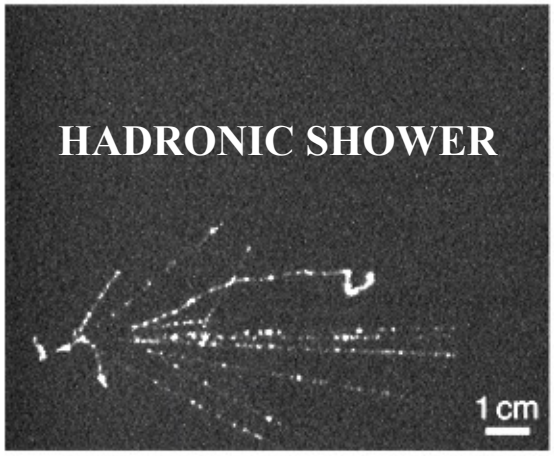
Time Projection Chamber (TPC)

Imaging of Charged Particles Interactions

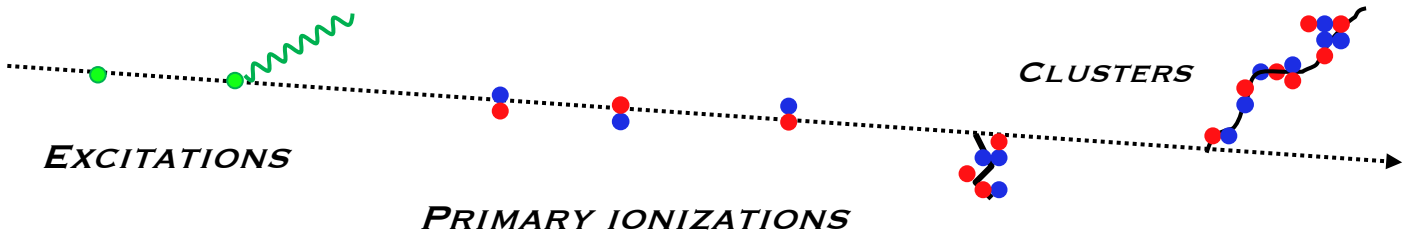
The future?



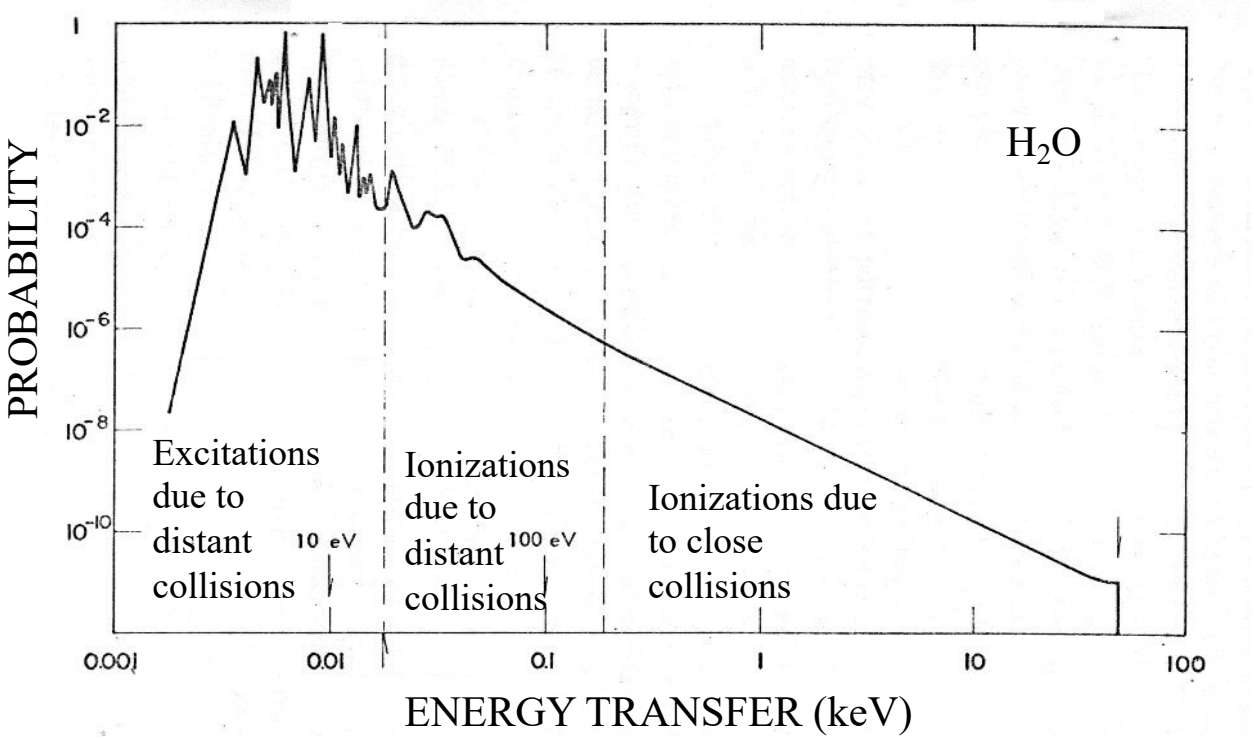


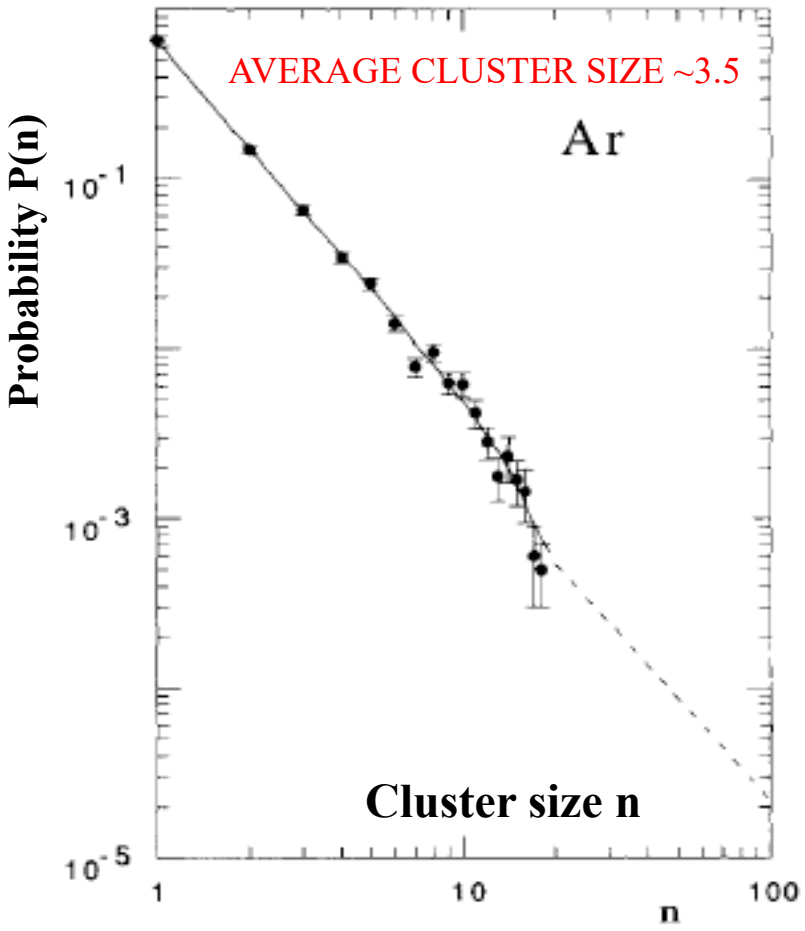


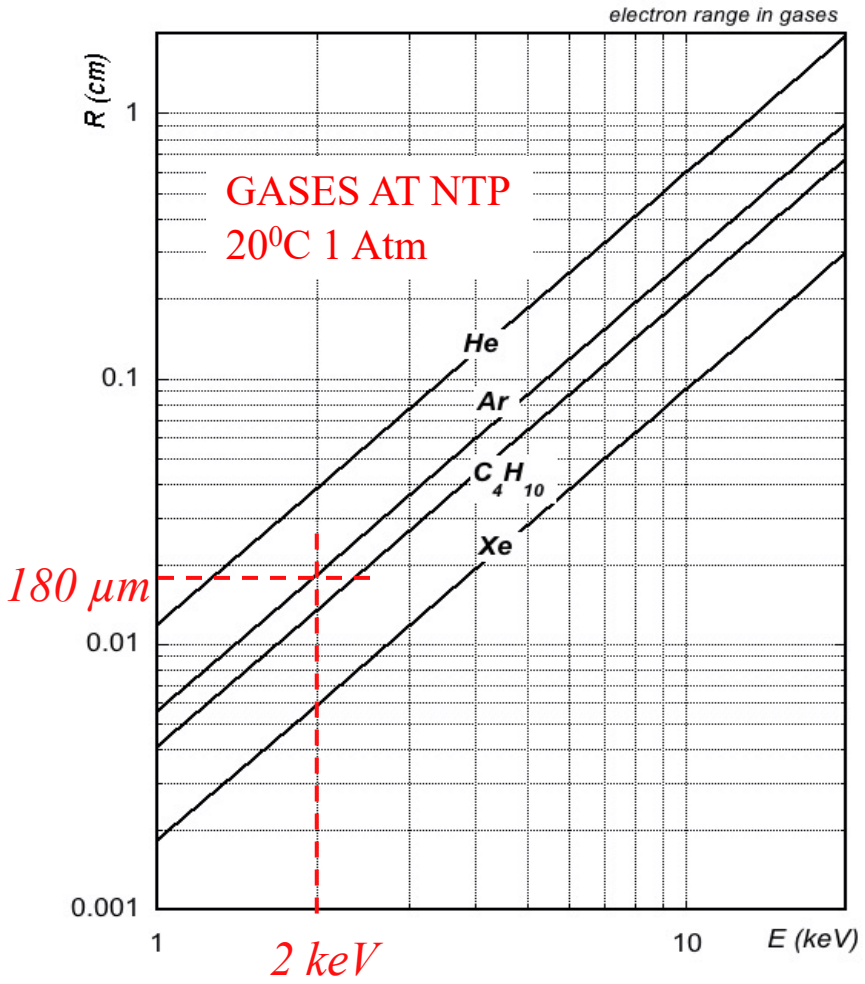
Optical Gas Electron Multiplier (GEM)



δ Rays: Secondary ionizations



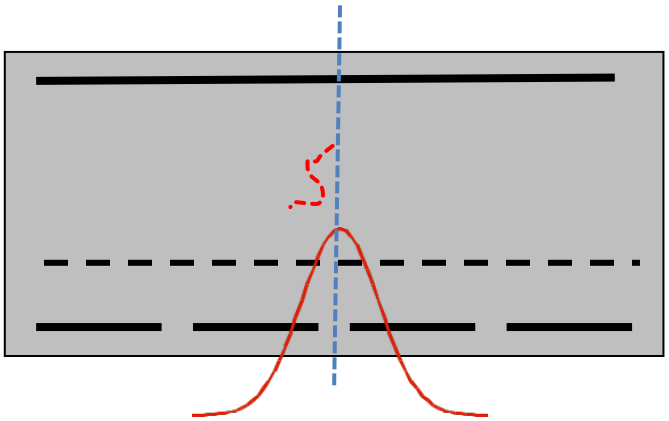


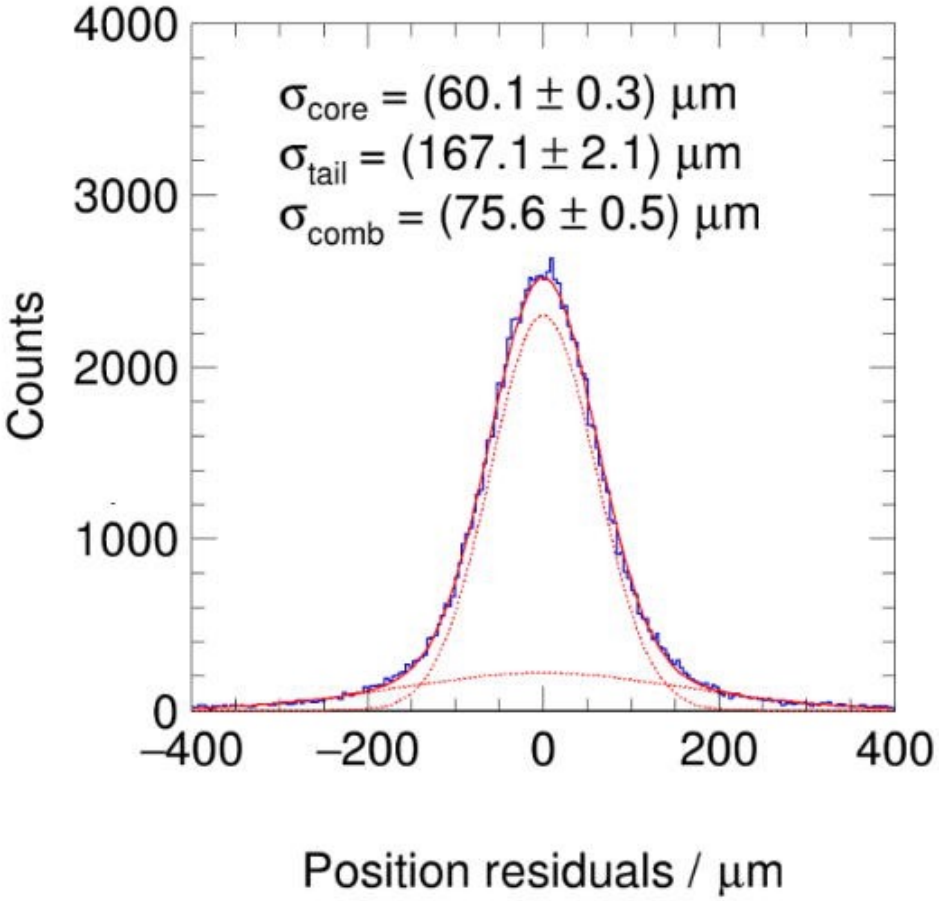


H. Fischle et al, Nucl. Instr. and Meth. A301 (1991) 202

Energy Loss Asymmetry:
Core Gaussian + Tails

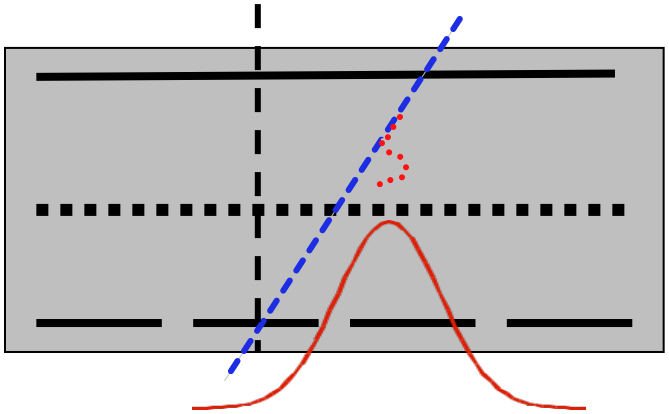
Perpendicular Tracks



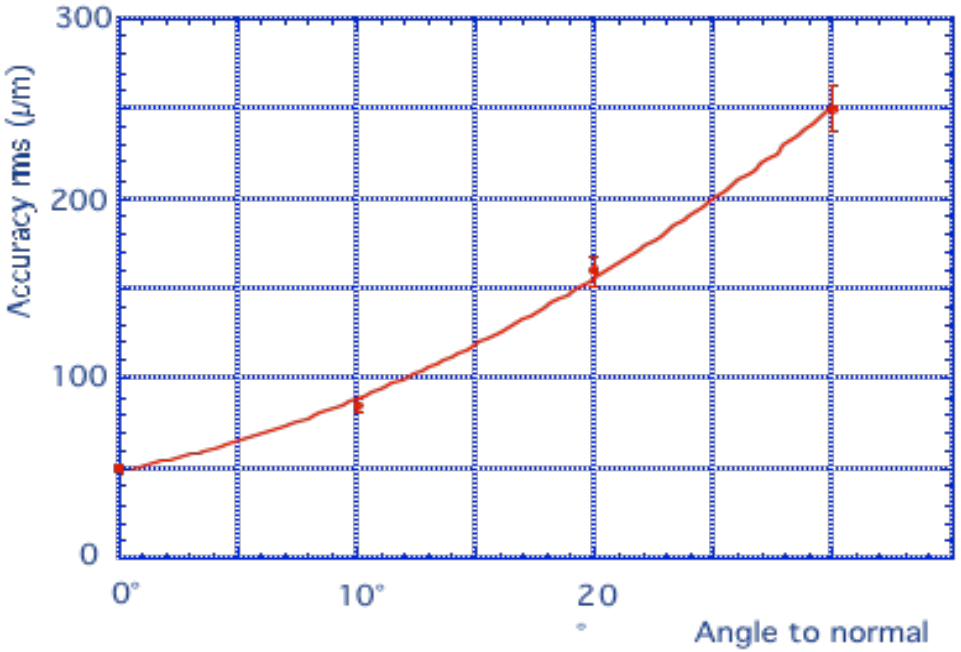


L. Scharenberg, MPGD 2022

Energy loss asymmetry: large incidence angles

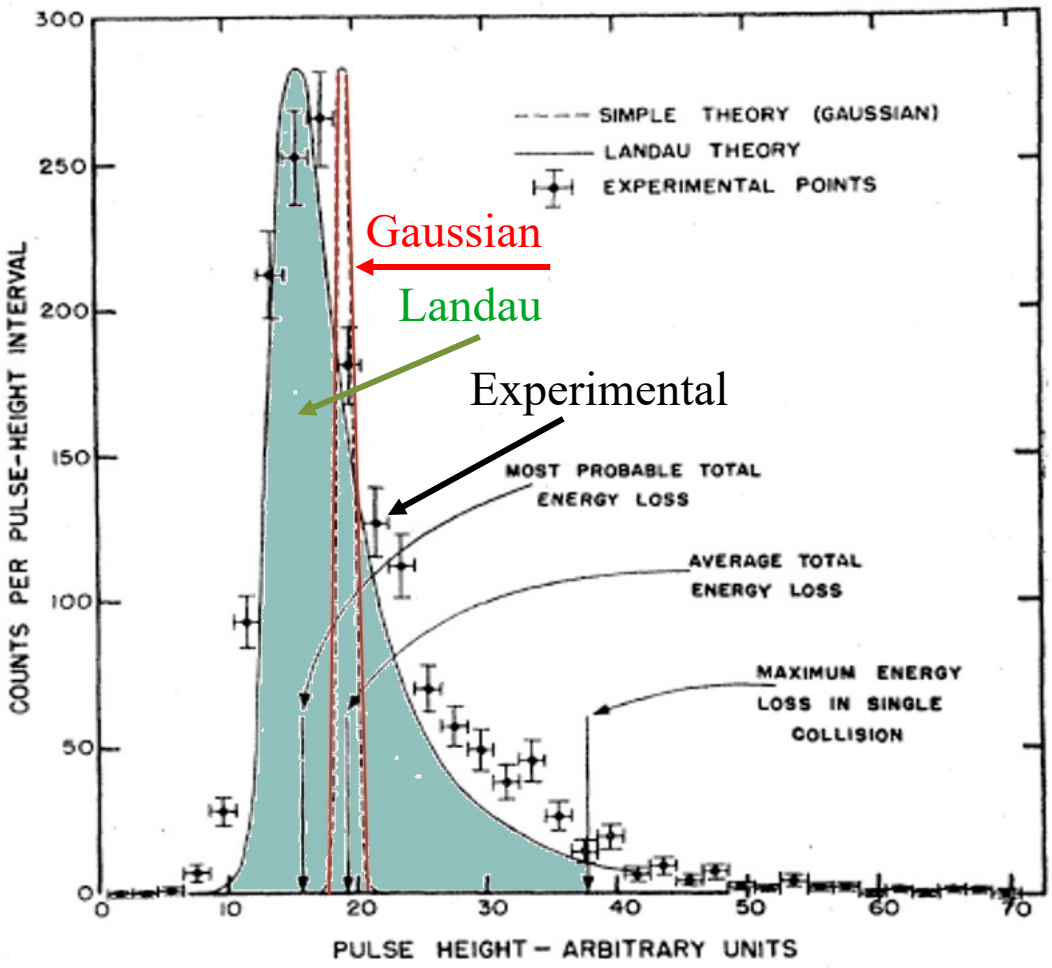


Position Accuracy vs Incidence Angle:

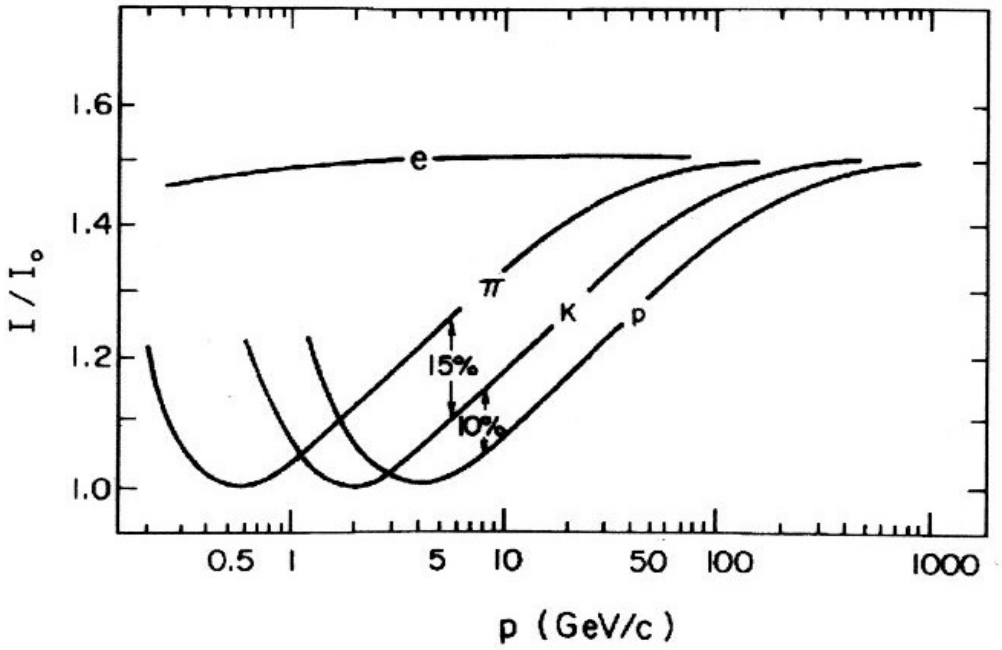


G. Charpak et al, NIM 167 (1979) 455

Differential Energy Loss in thin Gas Samples:

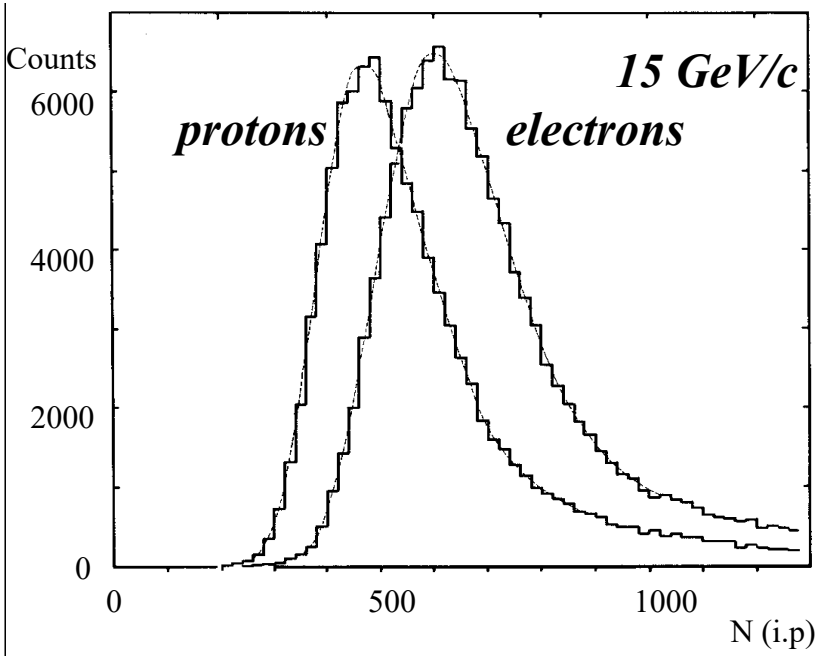


Particle Identification: Most Probable Energy Loss



I. Lehraus et al, Phys. Scripta 23(1981)727

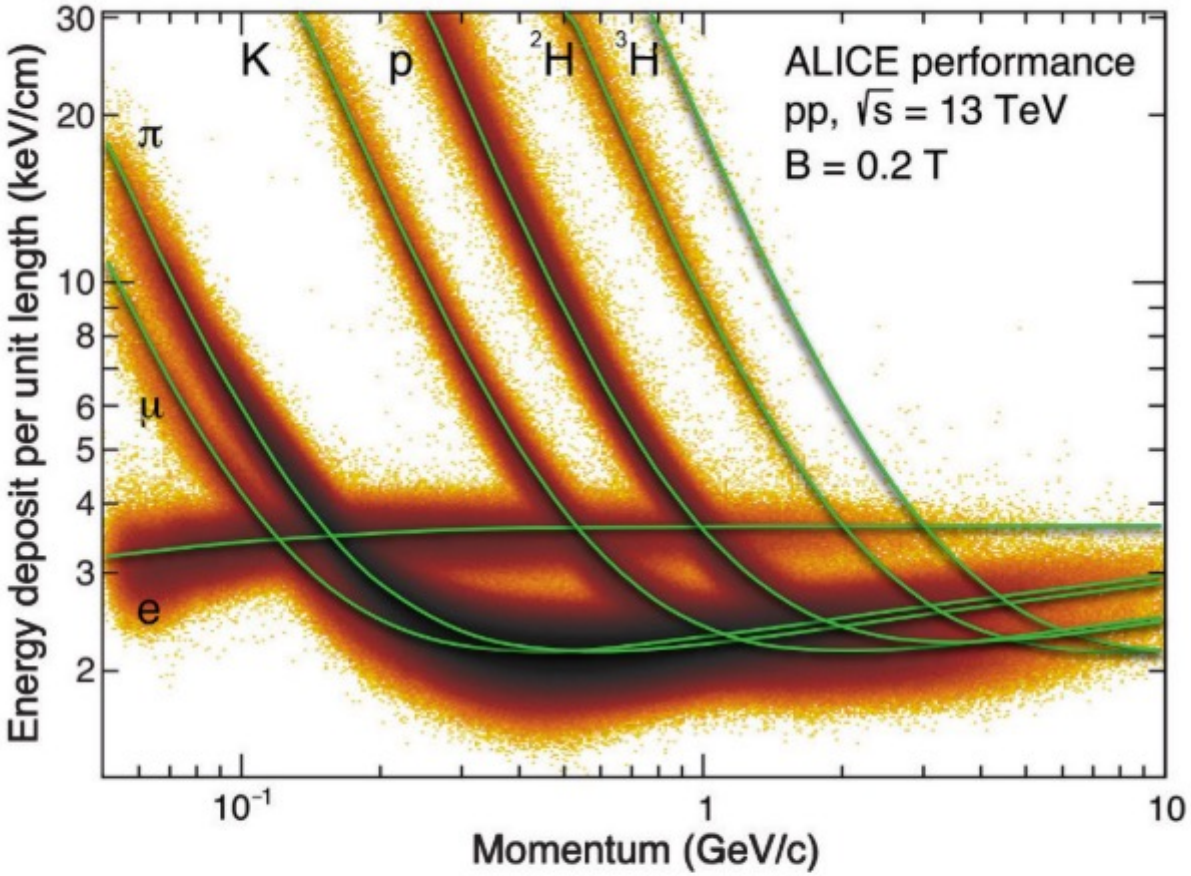
Single Sample Energy Loss:



Enery Loss resolution: Statistical Multisample Analysis

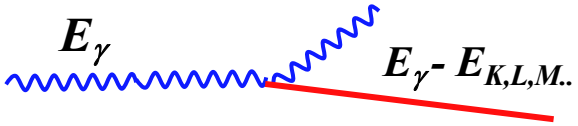
Alice GEM-TPC

Differential Energy Loss (Truncated mean)

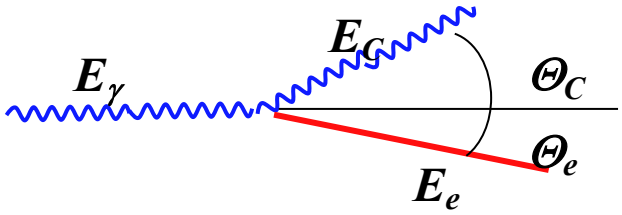


Ph. Hauer, Nucl. Instr. Meth. 1039 (2022)167023

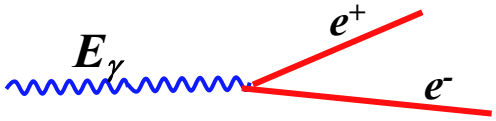
PHOTOELECTRIC:

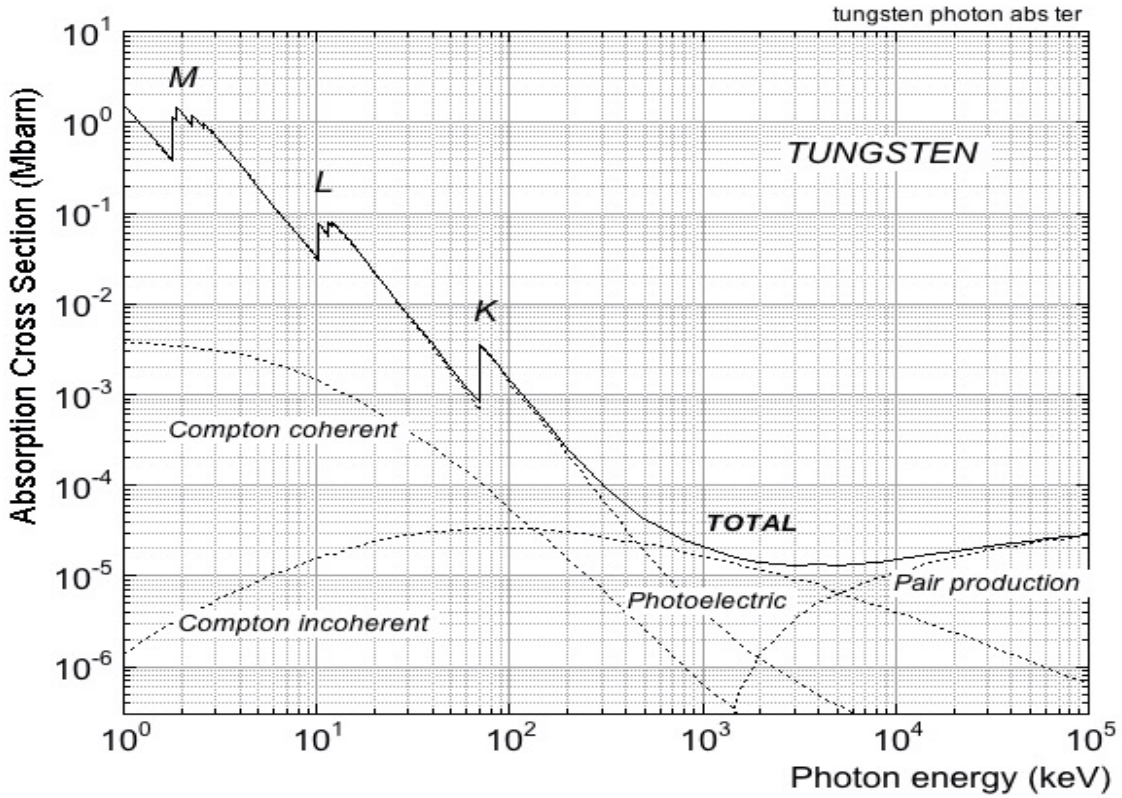


COMPTON:



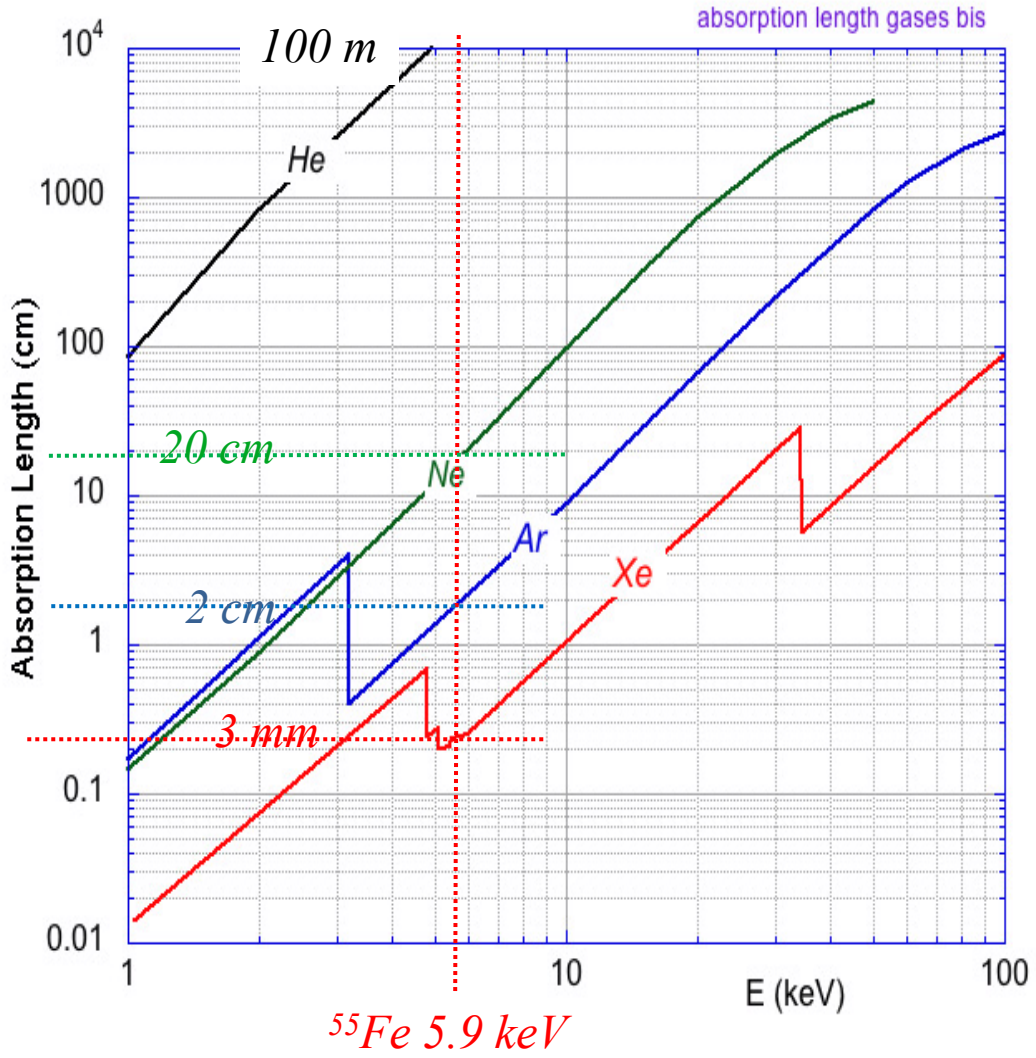
PAIR PRODUCTION:



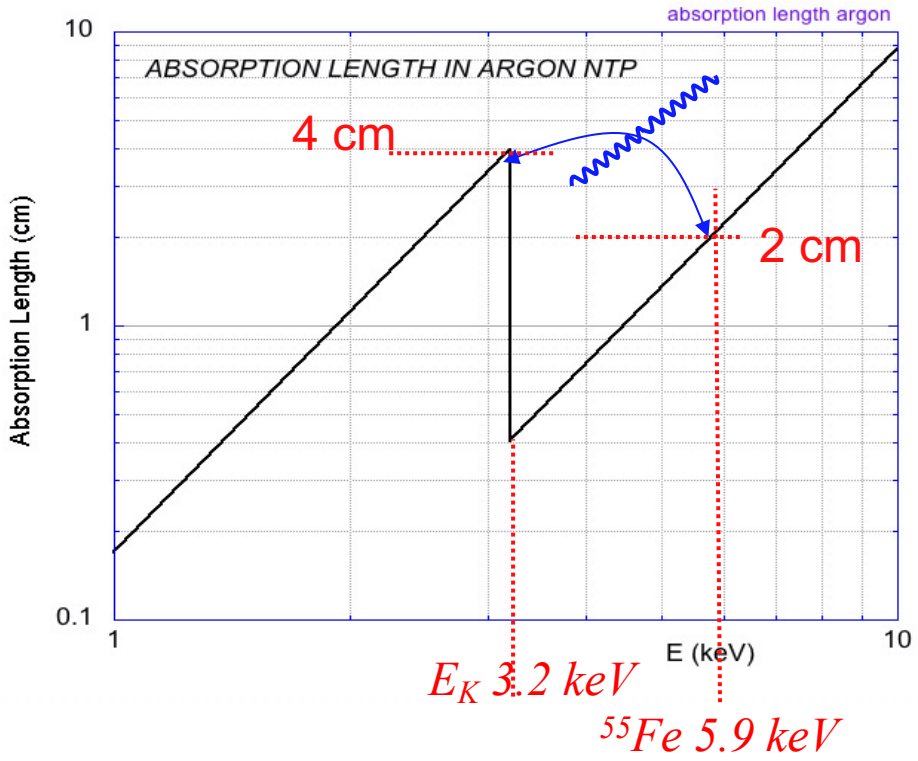


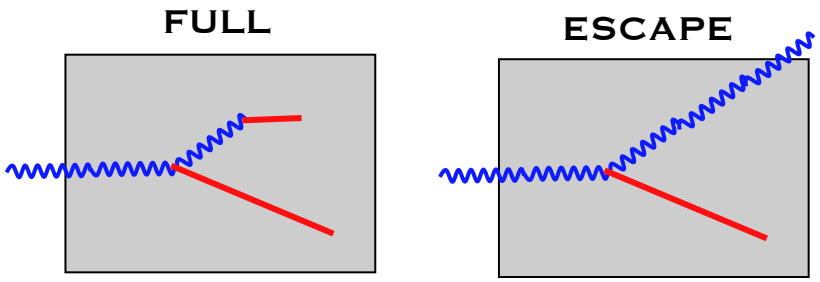
A. Thompson et al, X-RAY DATA BOOKLET (2001)

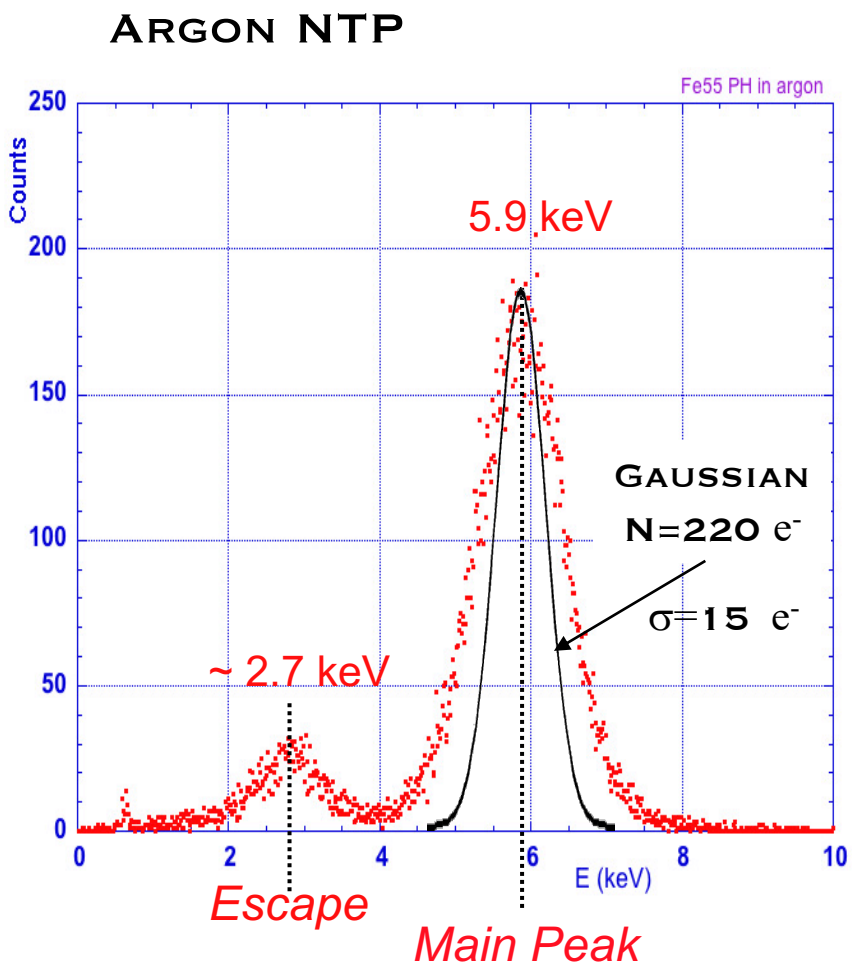
Absorption Length in Gases at NTP



Soft X-Rays
escape peak







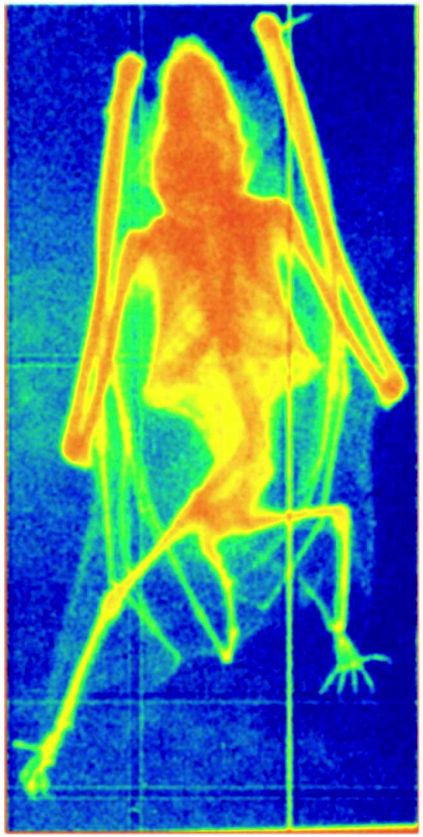
2001:

GEM with Electronic Readout

2018:

GEM with Optical Readout

The GDD Bat



F. Sauli
Nucl. Instr. Meth. A461(2001)47

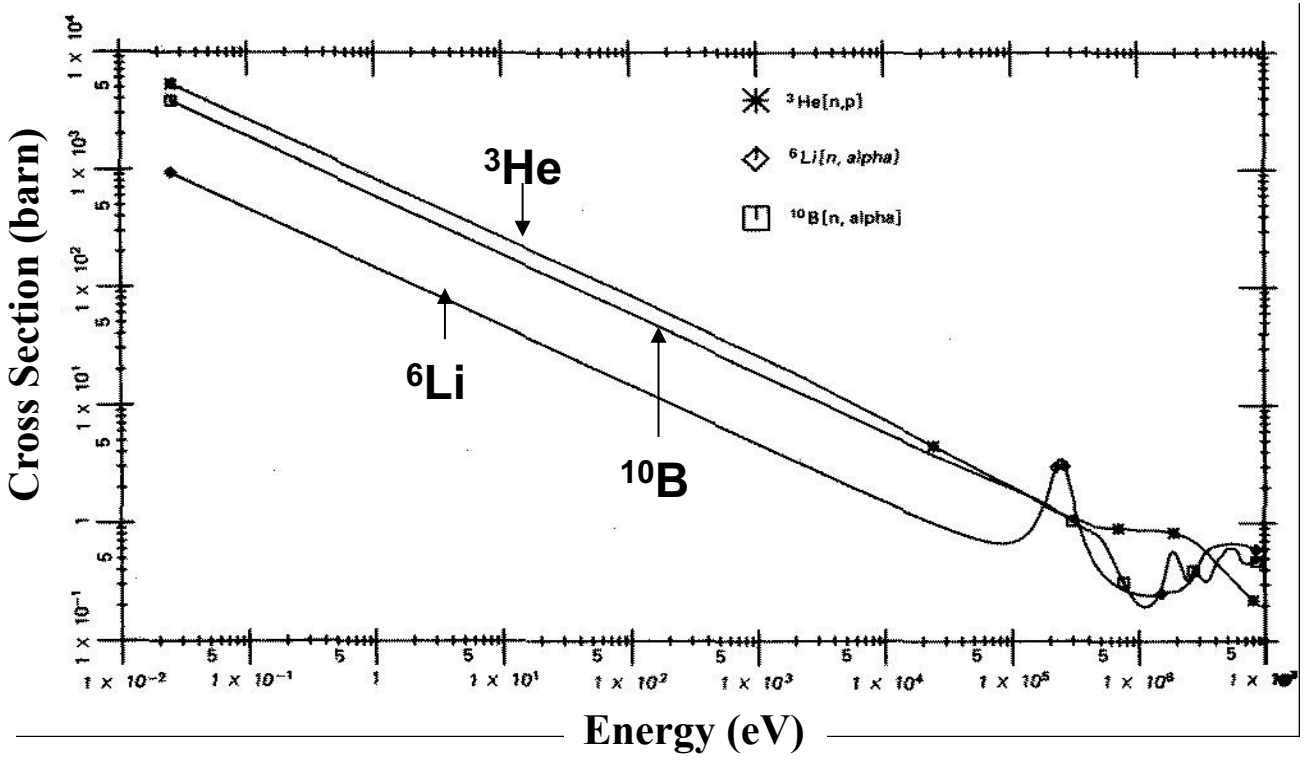
F. Brunbauer et al,
JINST13 (2018)T02006

$n + M$ --> { protons, tritons, α particles, fission fragments }

$$^{10}_{5}B + n \rightarrow ^{7}_{3}Li + \alpha$$

$$^{6}_{3}Li + n \rightarrow ^{3}_{1}H + \alpha$$

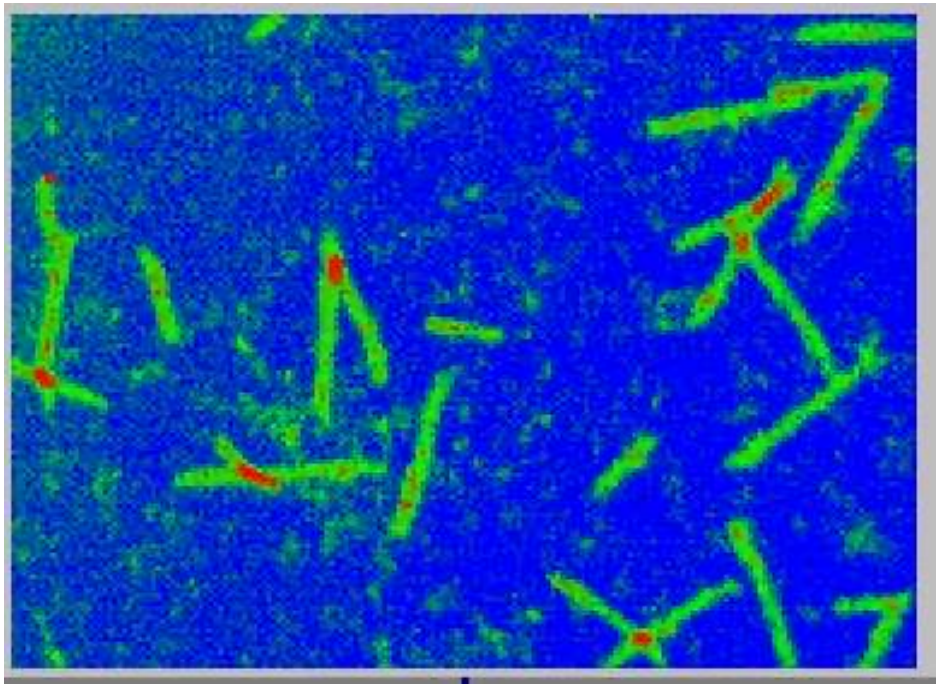
$$^{3}_{2}He + n \rightarrow ^{3}_{1}H + p$$



Detection of Neutrons

$$^{3}_{2}He + n \rightarrow ^{3}_{1}H + p$$

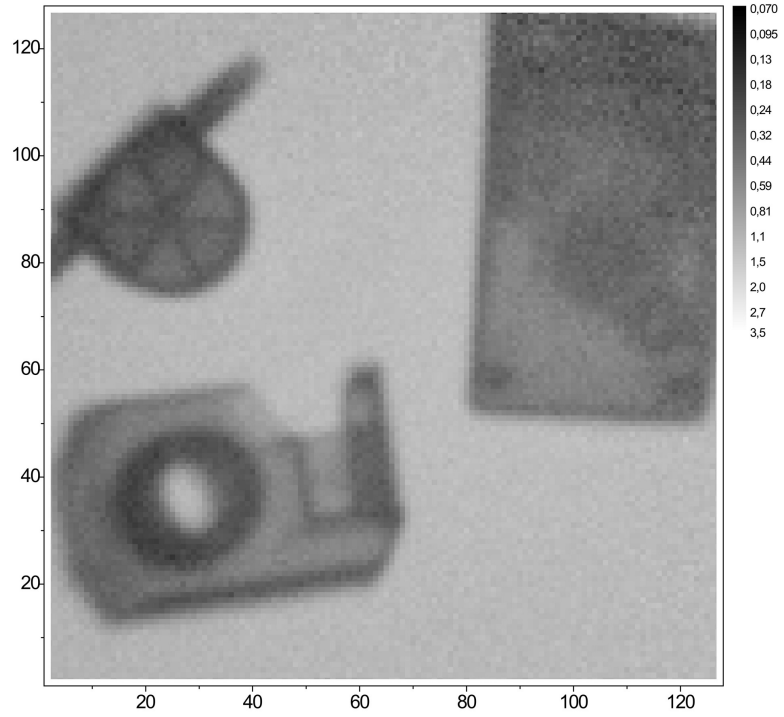
Ionization Chamber with Otical GEM Readout



F.A.F. Fraga et al,
Nucl. Instr. and Meth. A478 (2002) 357

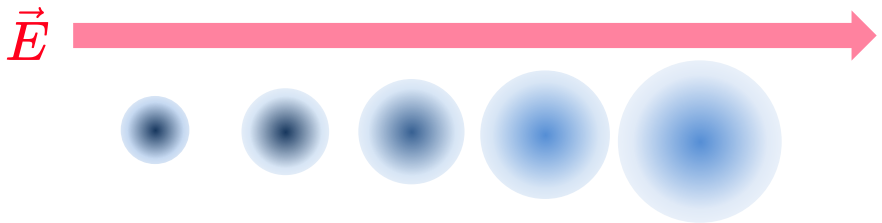
$$^{10}_{5}B + n \rightarrow ^{7}_{3}Li + \alpha$$

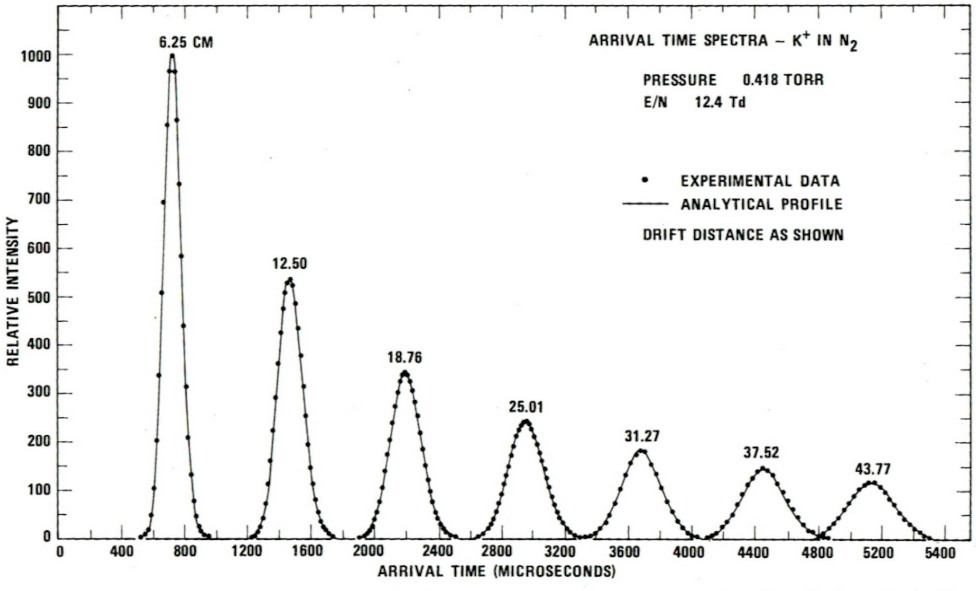
Thermal Neutrons Radiography ^{10}B Coated GEM



M. Klein and Ch. Schmidt
Nucl. Instr. and Meth. A628 (2011) 9

Drift and Diffusion of Ions



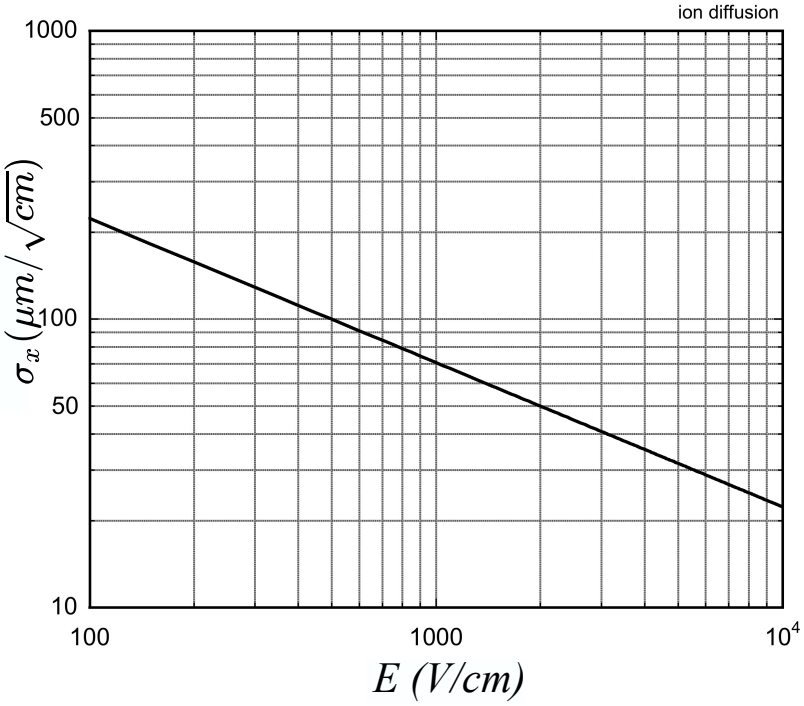


Drift Velocity: $W = \frac{s}{t}$

Mobility: $\mu = \frac{W}{E}$ $\quad \mu^+ \approx \mu^-$

Diffusion: $\sigma_x = \sqrt{\frac{2kTx}{eE}}$

Independent from Ion Type



@ 1 kV/cm $\quad \sigma_x = 70\ \mu m/\sqrt{cm}$

GAS	ION	μ ($cm^2 V^{-1} s^{-1}$)
He	He^+	13.0
Ar	Ar^+	1.7
CH_4	CH_4^+	2.22
Ar	CH_4^+	1.87
Ar	CO_2^+	1.72

Collisional Charge Transfer:

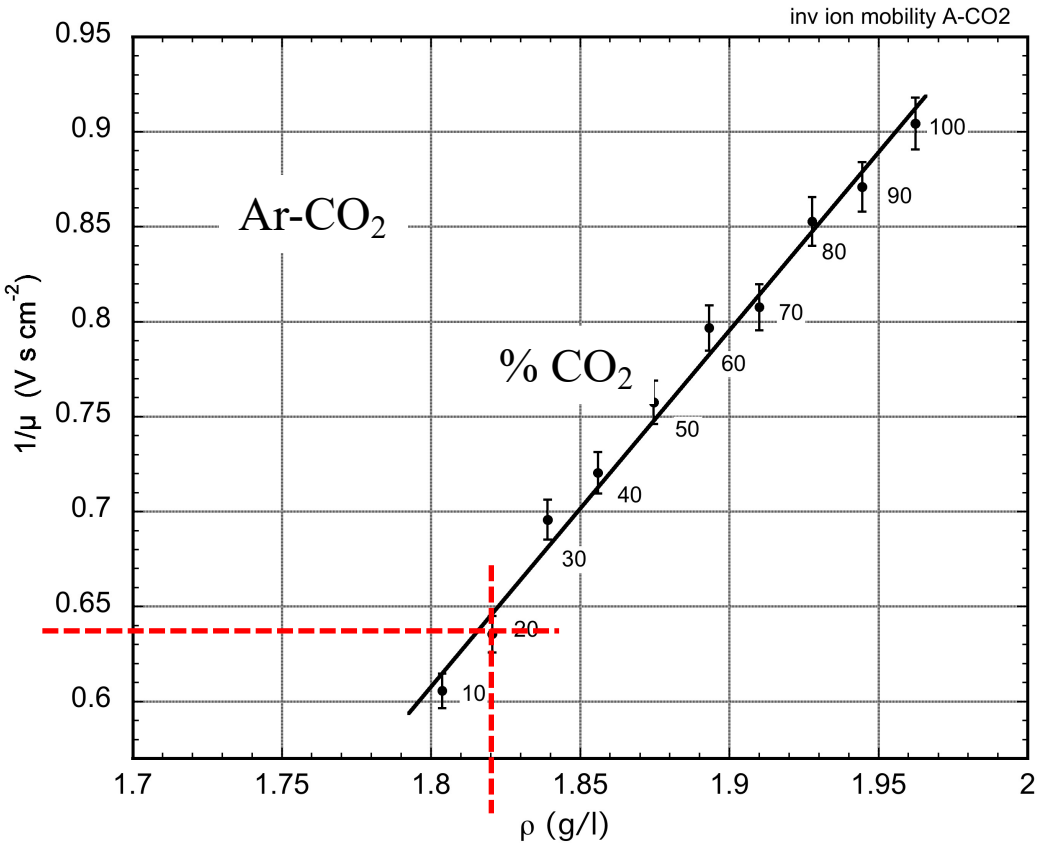
If $E_I(B) < E_I(A)$:

$A^+ + B \rightarrow A + B^+$

Blanc's Law:

$$\frac{1}{\mu_i} = \sum_{j=1}^{n} \frac{P_j}{\mu_{ij}}$$

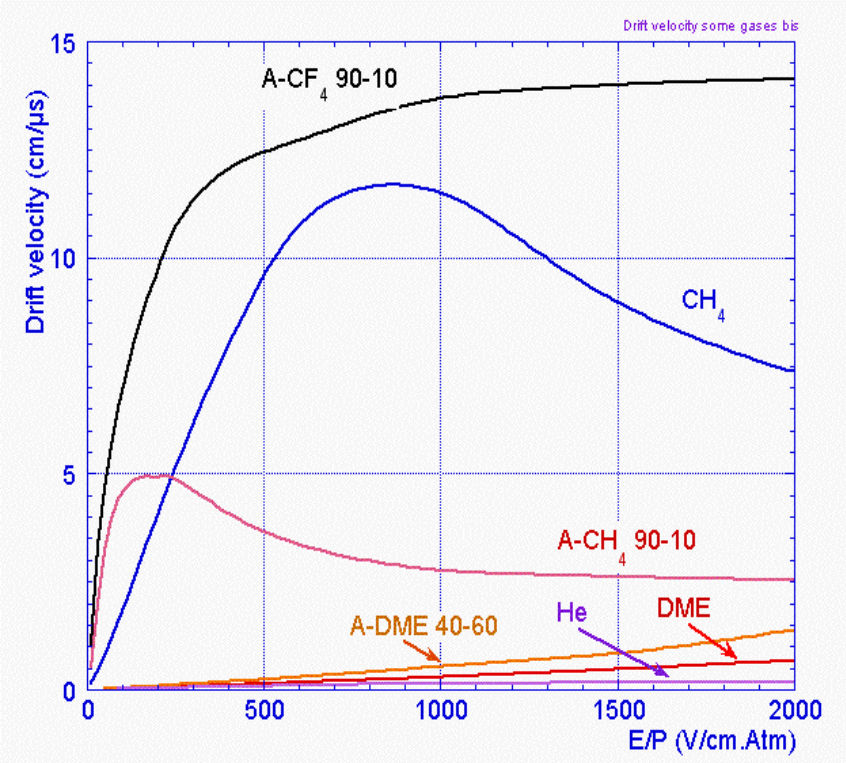
CO_2^+ Ions Mobility Ar-CO_2 Mixtures:



Ar-CO_2 80-20. $\mu = 0.64\ cm^2\ V^{-1}\ s^{-1}$
@ E=200 V cm^{-1} *W ~ 130 cm s^{-1}*

Ions Backflow and Space Charge

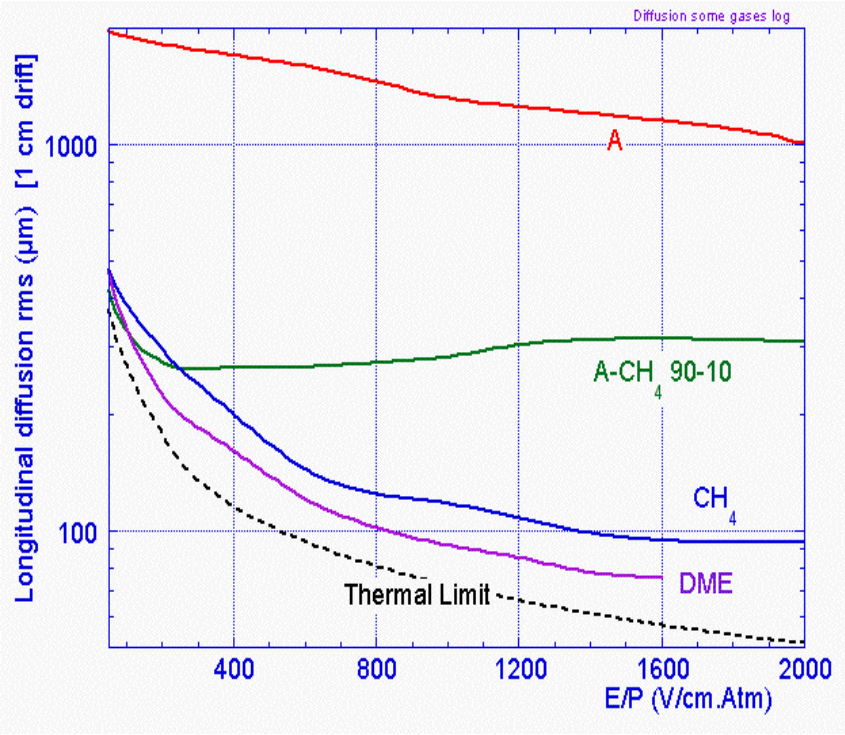
Drift Velocity $w^- = s/t$



Diffusion $\sigma^- = \sqrt{\frac{2\epsilon_k x}{eE}}$

ε_κ: *Characteristic Energy*

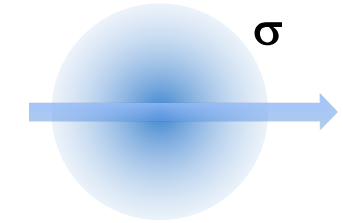
$\varepsilon_\kappa = kT$: *Thermal Limit*



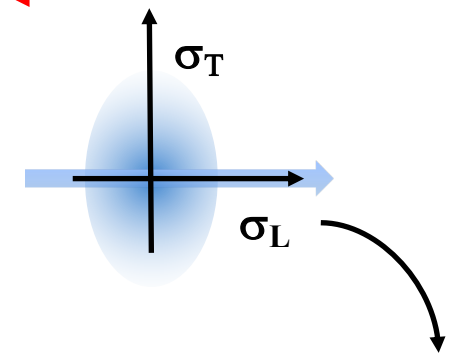
Rob Veenhof and Piet Verwilligen: MODELLING AND SIMULATIONS

Longitudinal and Transverse Diffusion

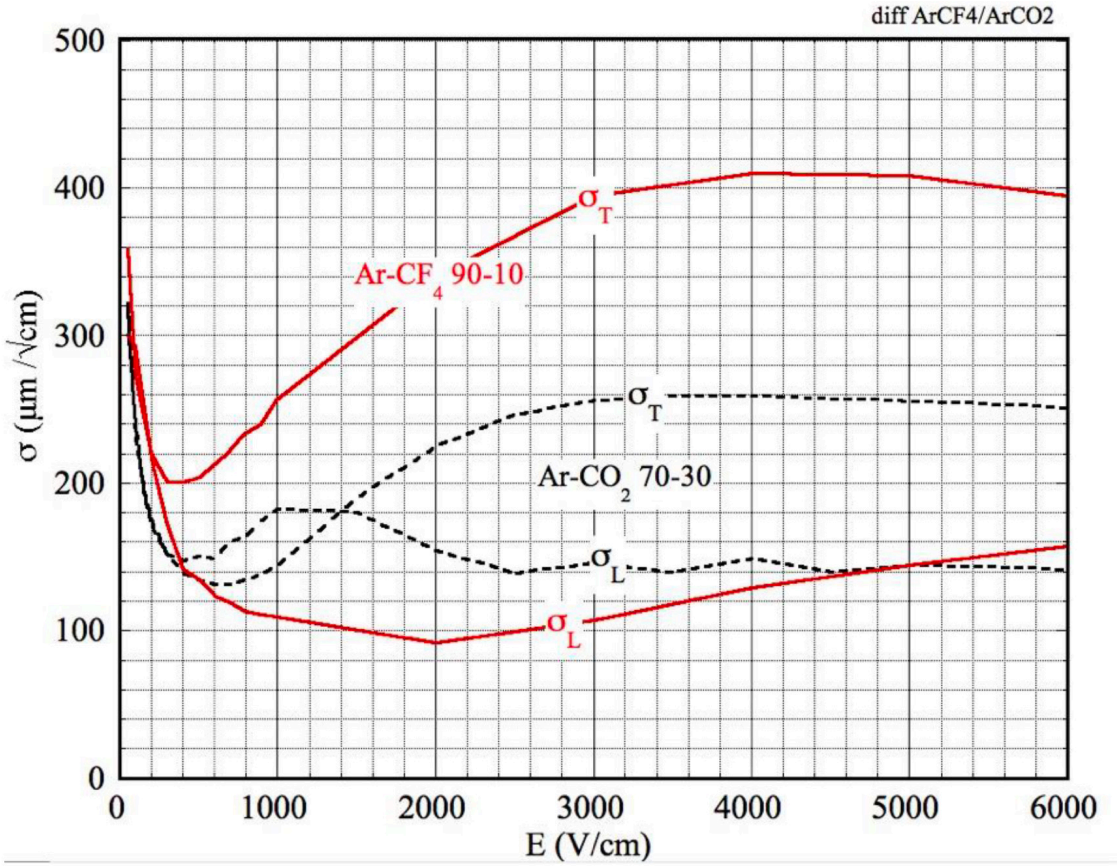
Low Electric Field



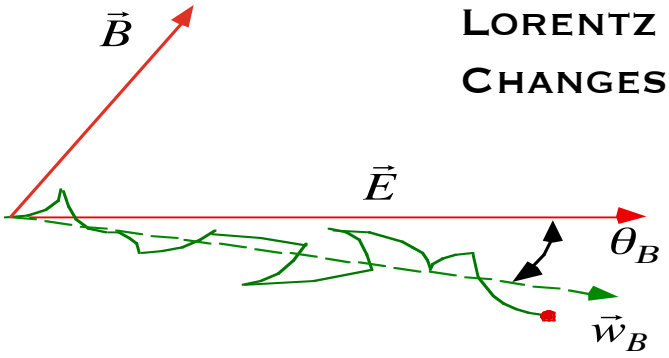
High Electric Field



Better Longitudinal (Drif) Accuracy



F. Sauli, Gaseous Detectors Handbook (CERN 2022)
http://fabio.home.cern.ch/fabio/

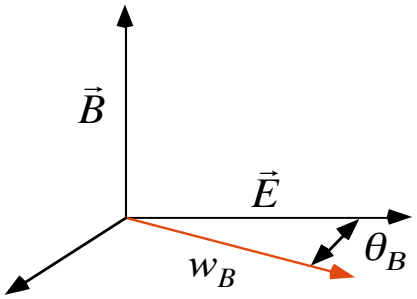


Lorentz Force:

Changes Drift Velocity, Direction and Diffusion

Particular Cases:

$\vec{E} \perp \vec{B}$

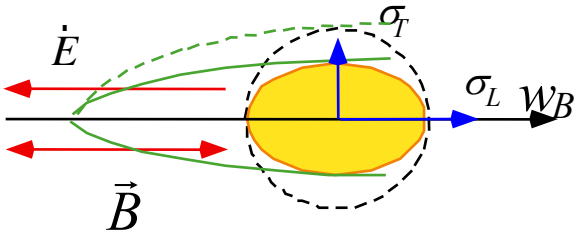


$$\tan\theta_B = \omega\tau \qquad w_B = \frac{E}{B}\frac{\omega\tau}{\sqrt{1+\omega^2\tau^2}}$$

$$\omega = eB/m \qquad \textit{Larmor frequency}$$

τ : *Average time between electron-molecule collisions*

$\vec{E} \parallel \vec{B}$



$$w_B = w_0$$

$$\sigma_L = \sigma_0$$

$$\sigma_T = \frac{\sigma_0}{\sqrt{1+\omega^2\tau^2}}$$

Time Projection Chambers:

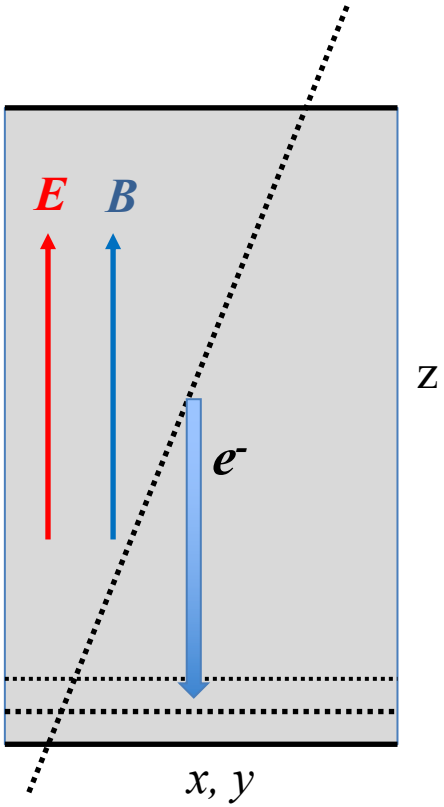
Better Transverse (X-Y)

Position Resolution

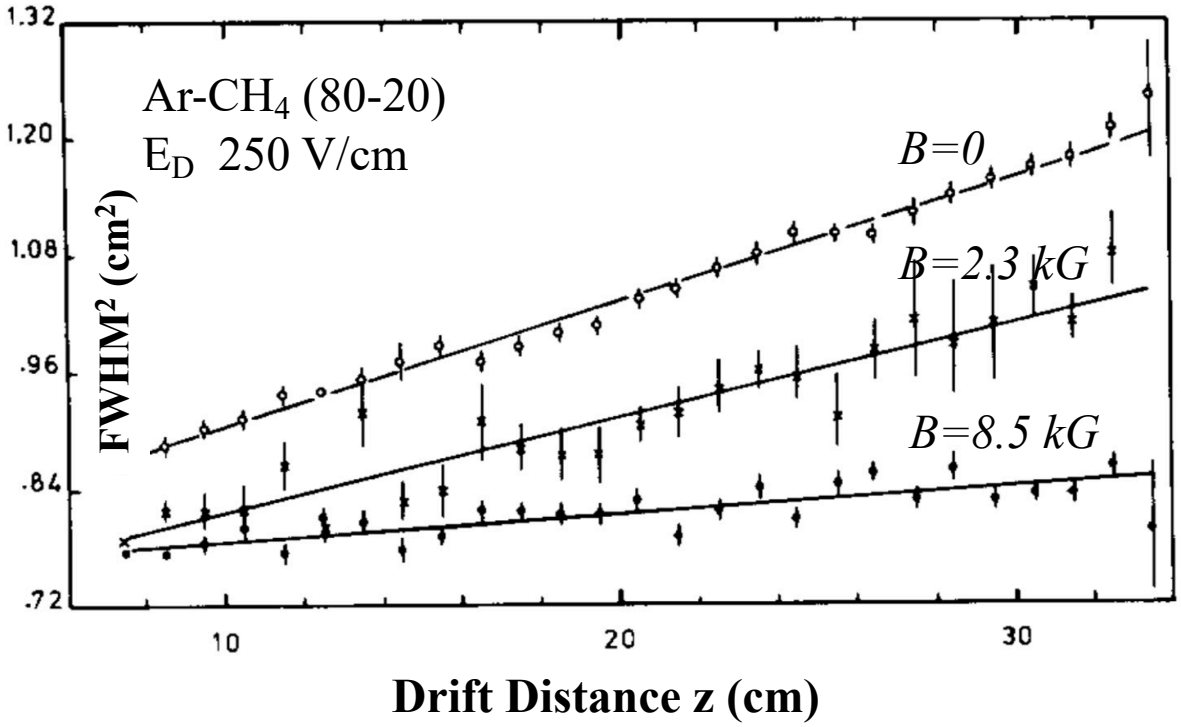
Drift of Electrons in Magnetic Field: E // B

Time Projection Chambers:

Longitudinal Position Accuracy vs Drift Length



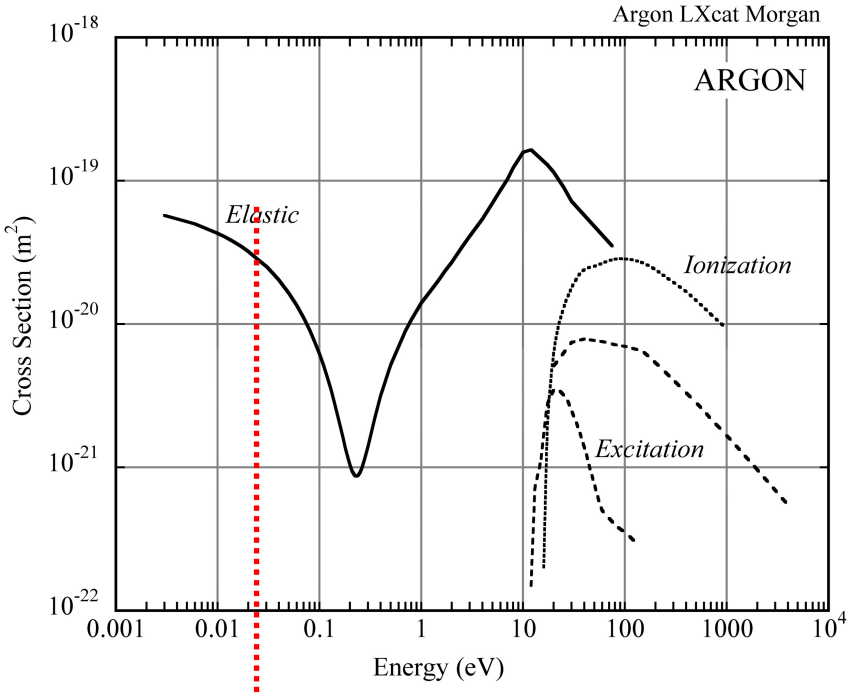
Magnetic Field Dependence:

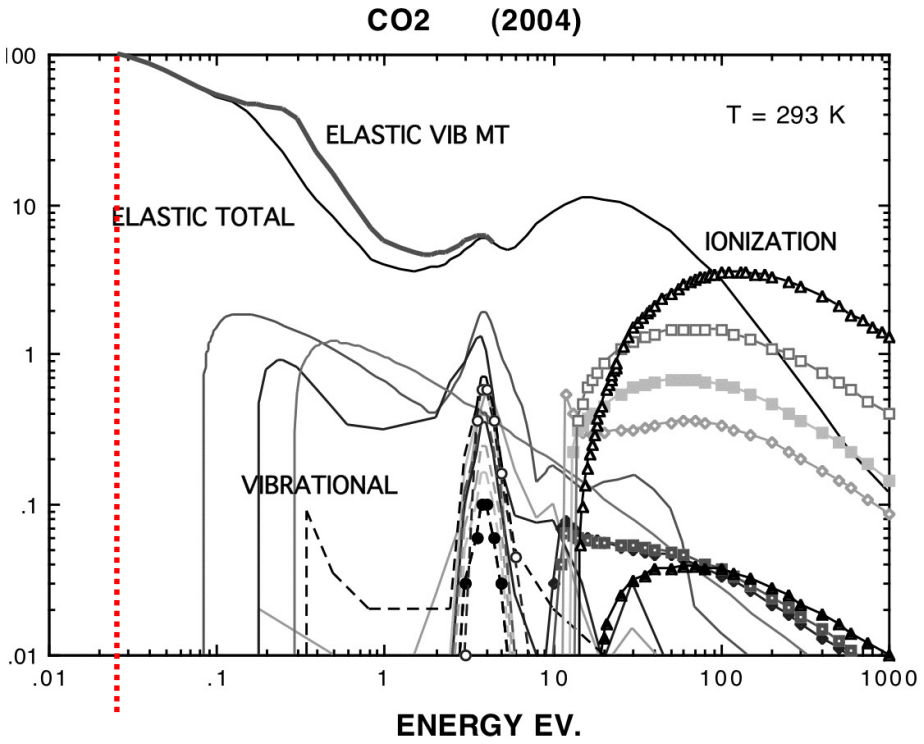


C. Hargrove et al, Nucl. Instr. Meth. 219(1984)481

Depends from Gas and Fields

Eletron-Molecule Cross Section at Increasing Electric Fields:





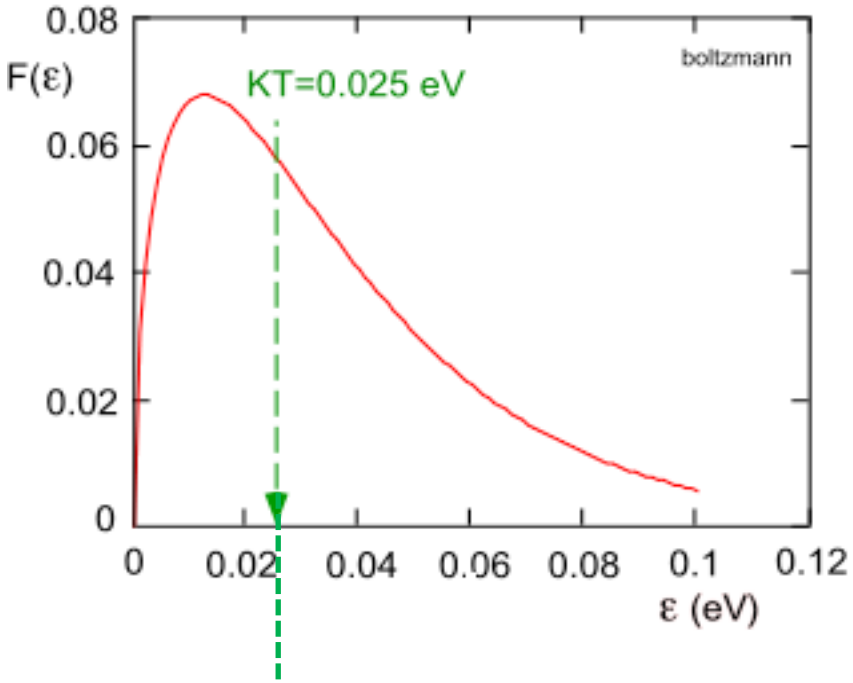
Thermal

0.025 eV @ 20 ^{0}C

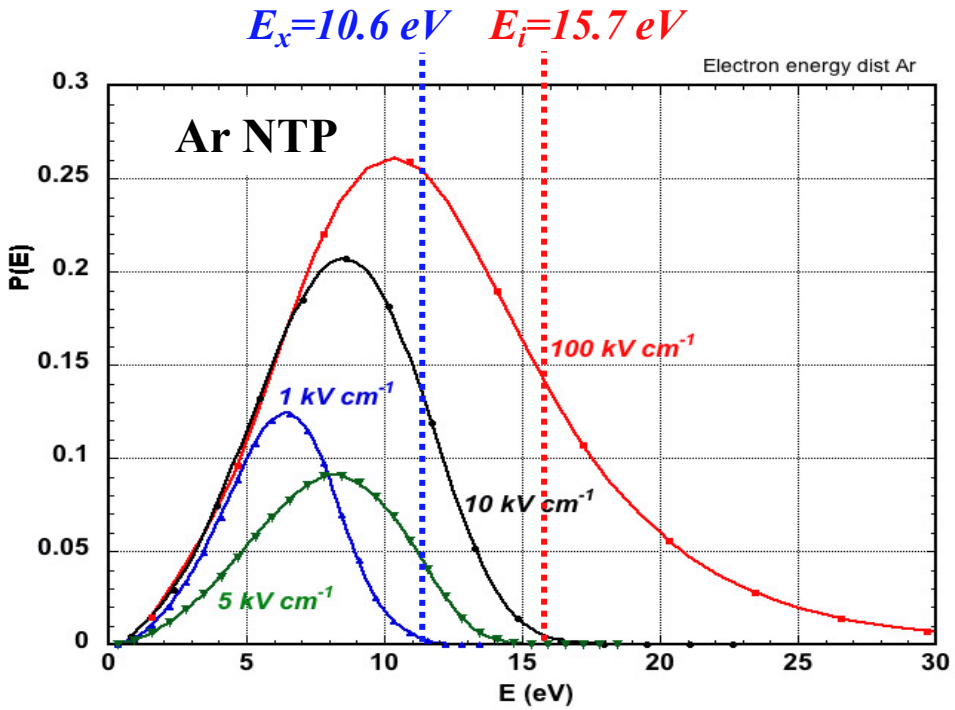
https://nl.lxcat.net/home/

Electrons Energy Distribution

Room Temperature E=0 Electrons in Any Gas:



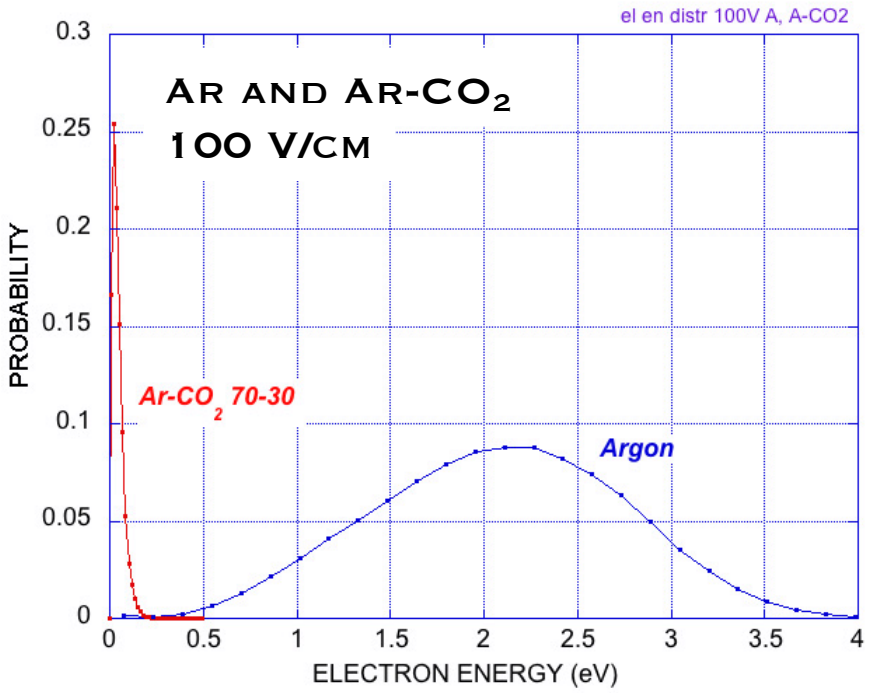
High Electric Fields: Pure Argon

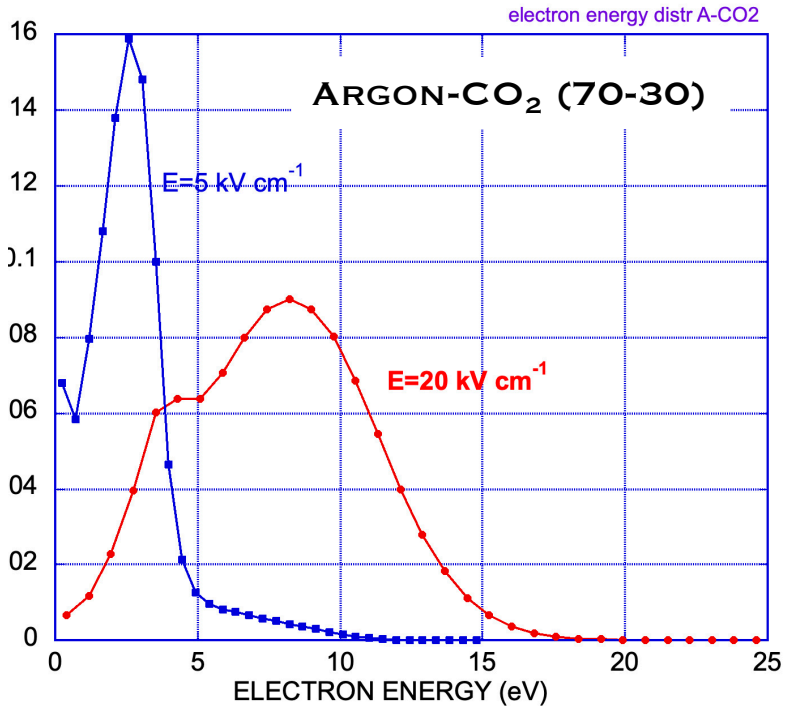


	E_X (eV)	E_I (eV)
ARGON	11.6	15.8
CO_2	5.2	13.7

Electrons Energy Distribution

"Cooling" Effect of Molecular Gas Additions





Major Outcomes of the Electron-Molecule Colllisions

$e + A \rightarrow e + A^*$ Excitation

$e + A \rightarrow e + e + A^{+\cdot}$ Ionization → Charge Multiplication

$A^* \rightarrow A + \gamma$ Radiative Deexcitation

$e + A^+ \rightarrow A + \gamma$ Radiative recombination

$A^+ + B \rightarrow AB + \gamma.$ Radiative recombination

$e + M \rightarrow M^- + \gamma$ Radiative capture

Fluorescence

$A^* + A \rightarrow A^*_2 \rightarrow A + A + \gamma$ Dimers formation

$e + AB \rightarrow AB^- \rightarrow A + B^-$ Dissociative capture

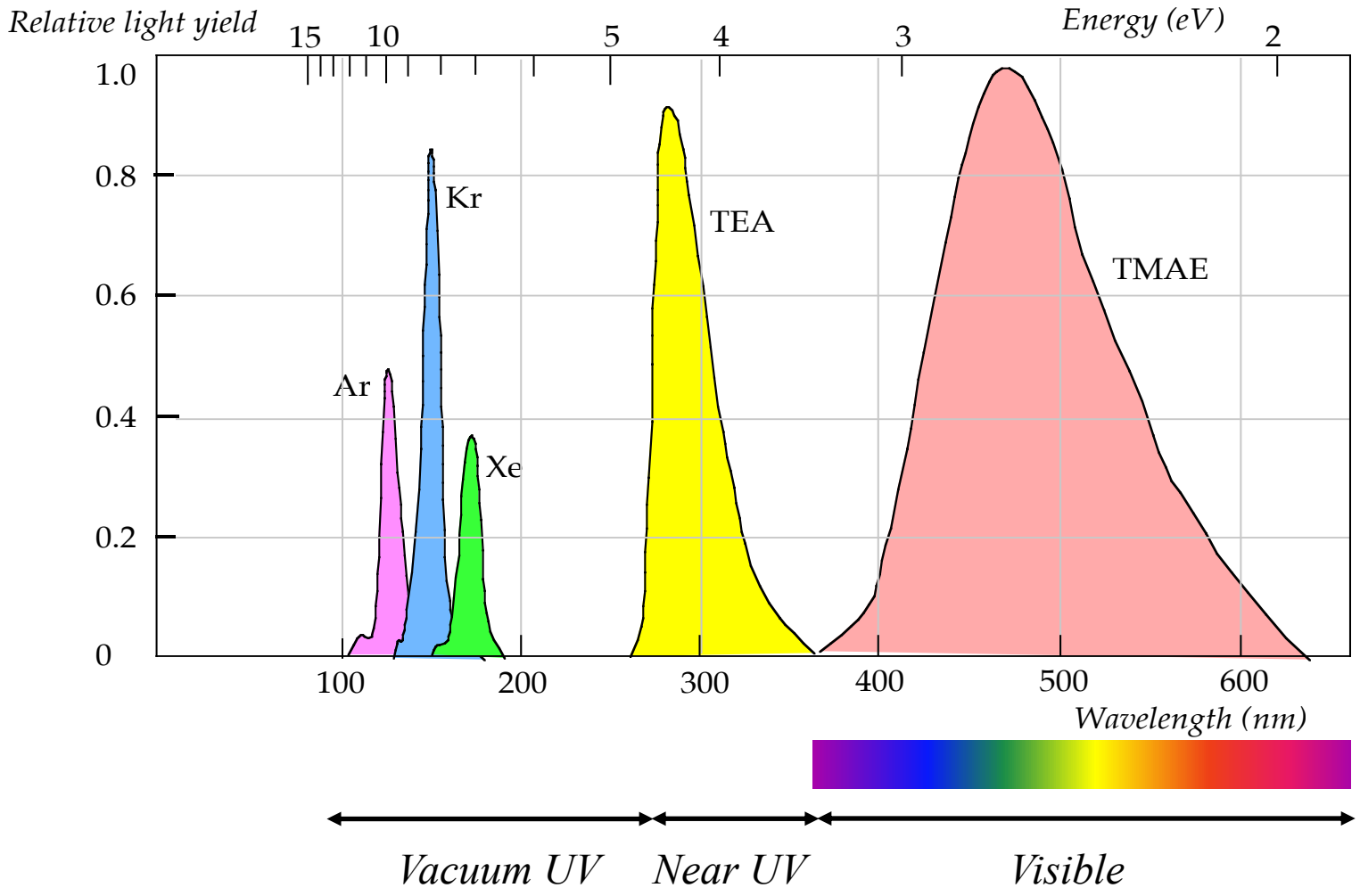
$e + A + B \rightarrow A^- + B$ Three body collision

$A^* + B \rightarrow A + B^* + e$ Penning effect (if $E_i(B) < E_x(A)$) → Improved Energy Loss Resolution

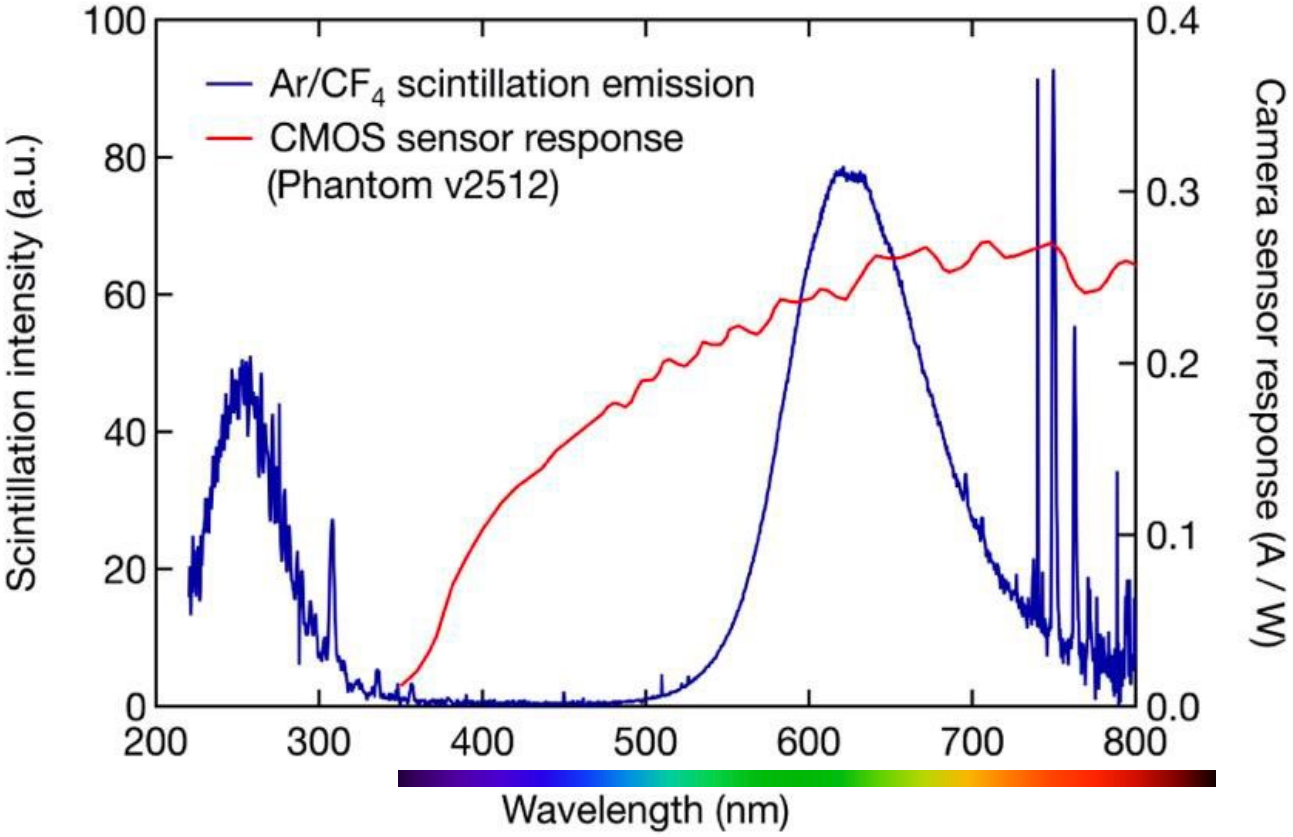
.....

.....

Noble Gases and Low Ionization Potential Vapors:



CF4 Scintillation:



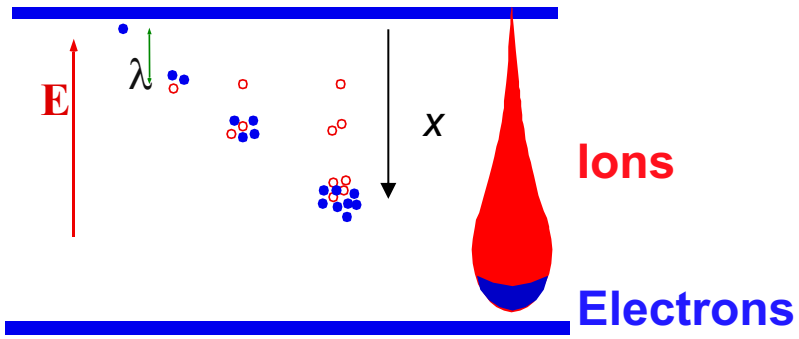
F. Brunbauer, CERN GDD (2020)

Decay of Excited Molecular States:

$(CF_3^+)^*$

and

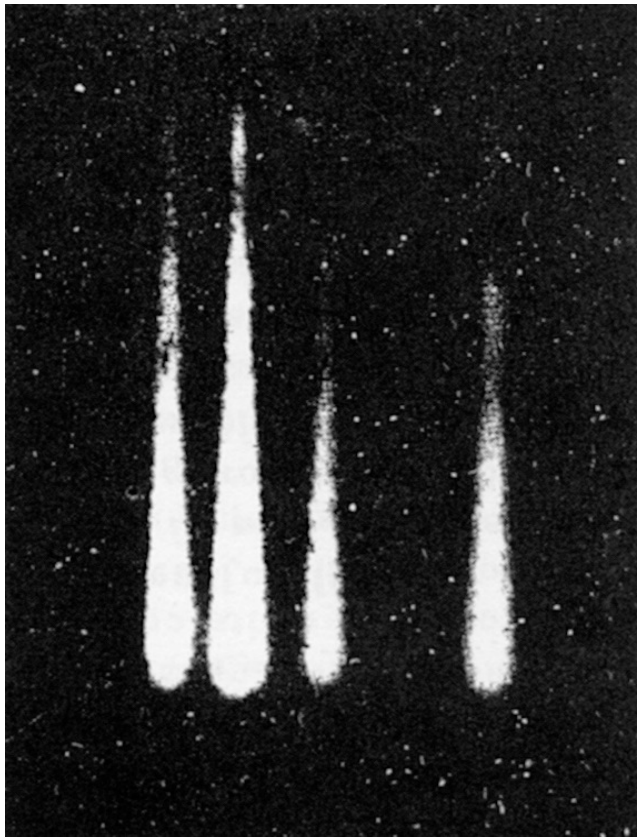
$(CF_4^+)^*$



$$n(x) = n_0 e^{\alpha x} \qquad \alpha = \alpha(E)\text{: Townsend coefficient}$$

$$M(x) = \frac{n}{n_0} = e^{\alpha x} \qquad \text{Charge Gain}$$

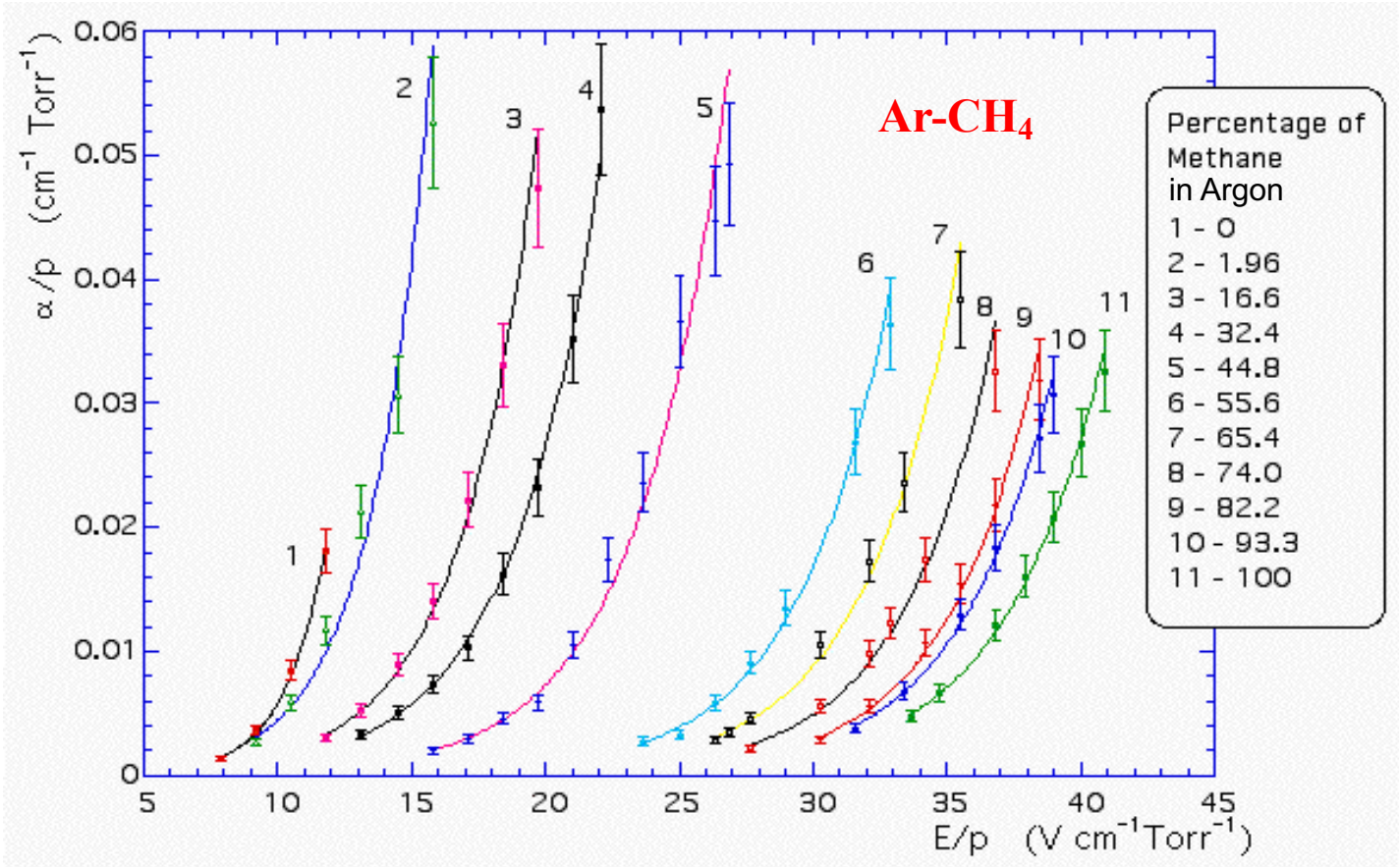
Cloud chamber Images of Avalanches:



H. Raether
Electron Avalanches and Breakdown in Gases (Butterworth 1964)

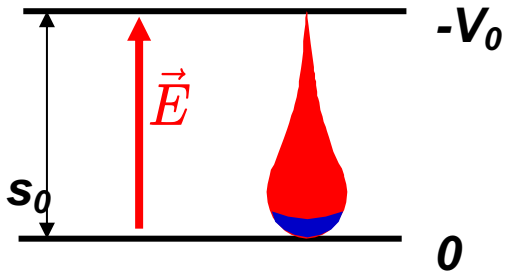
Townsend Coefficient α in Ar-Methane Mixtures

$$\frac{\alpha}{P} = f\left(\frac{E}{P}\right)$$

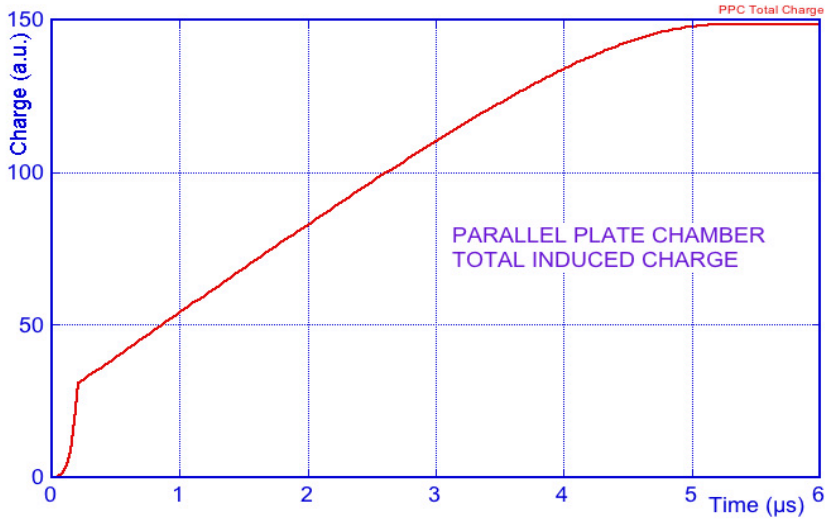


A. Sharma and F. Sauli, Nucl. Instr. and Meth. A334(1993)420

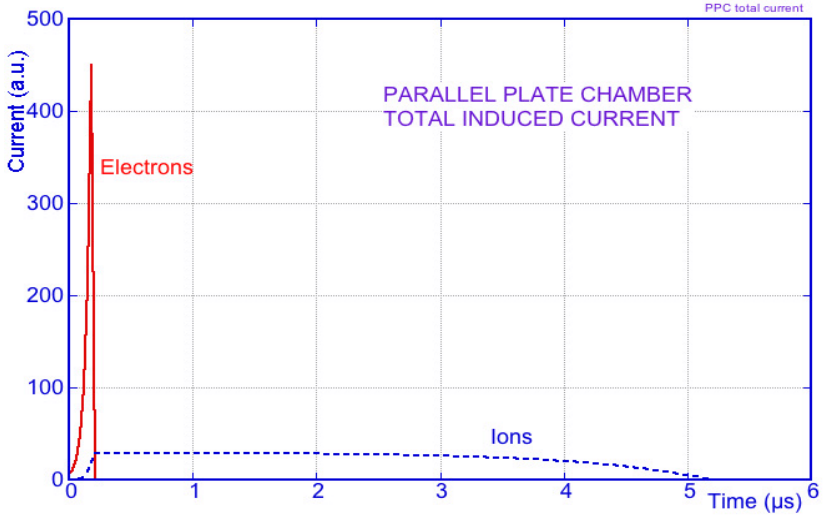
Parallel Plate Counter



Induced Charge on Anode:



Induced Current on Anode:

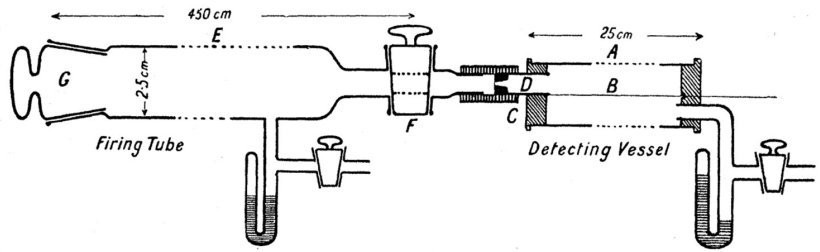


On Cathode:

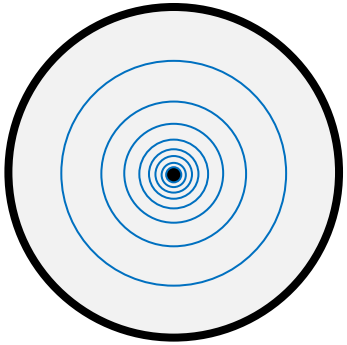
$Q_C(t) = -Q_A(t)$ $I_C(t) = -I_A(t)$

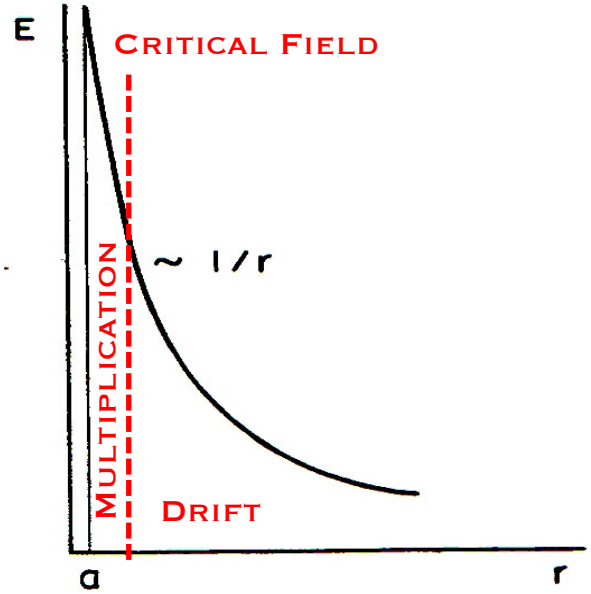
PROPORTIONAL COUNTER

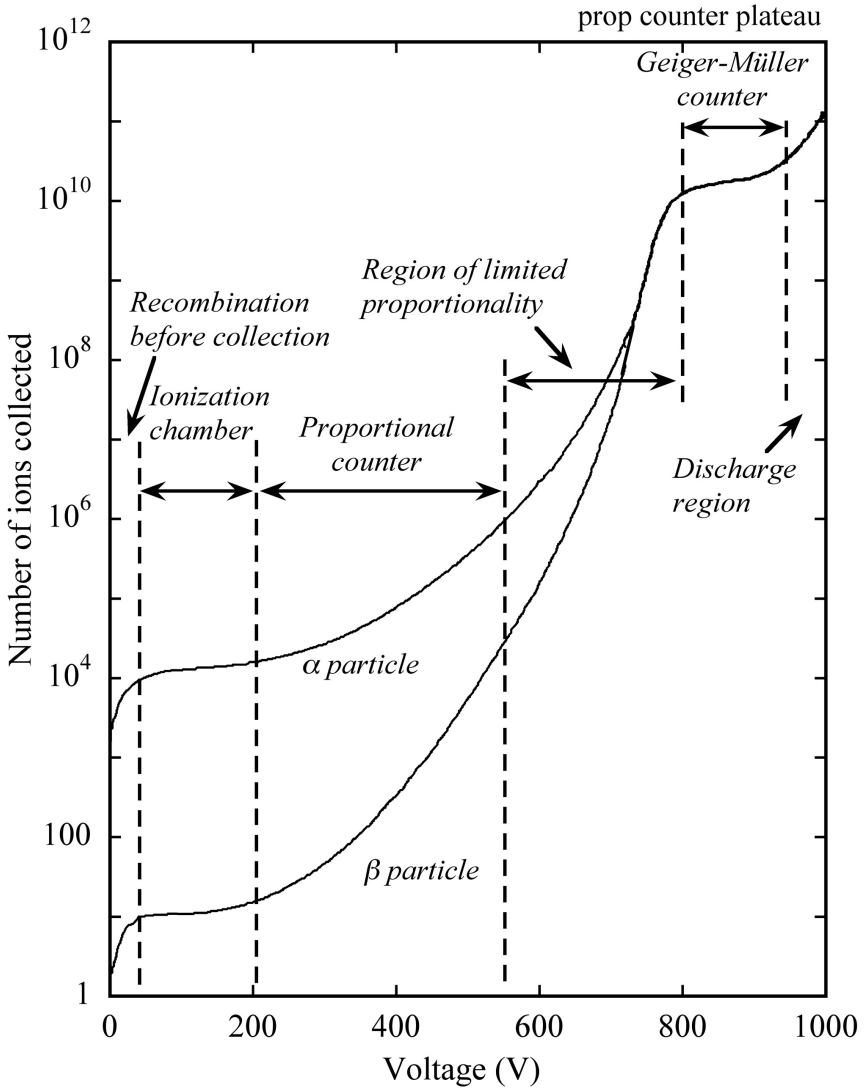
SINGLE WIRE COUNTER
RUTHERFORD AND GEIGER (1908)



RADIAL ELECTRIC FIELD





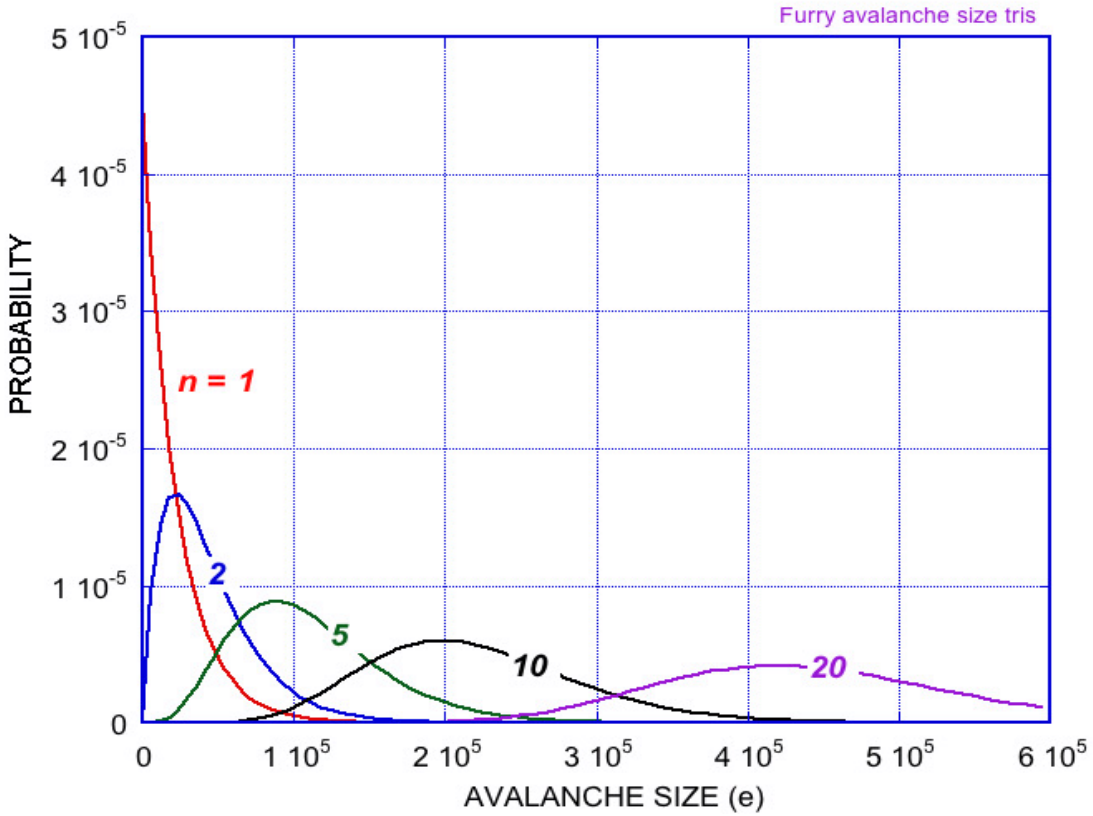


Avalanche Size Probablility for 1 Primary Electron (Furry Law):

$$P(N) = \frac{1}{\overline{N}} e^{-\frac{N}{\overline{N}}}$$

Avalanche Size Probablility for n Primary Electrons:

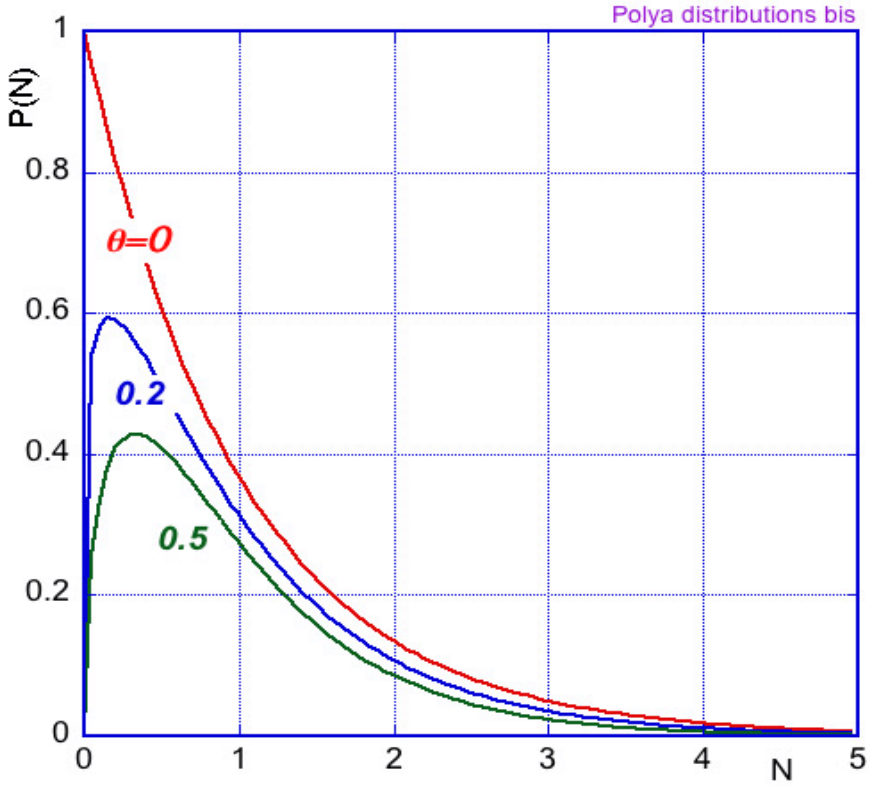
$$P(n,N) = \left(\frac{N}{\overline{N}}\right)^{n-1} \frac{e^{-\frac{N}{\overline{N}}}}{(N-1)!}$$



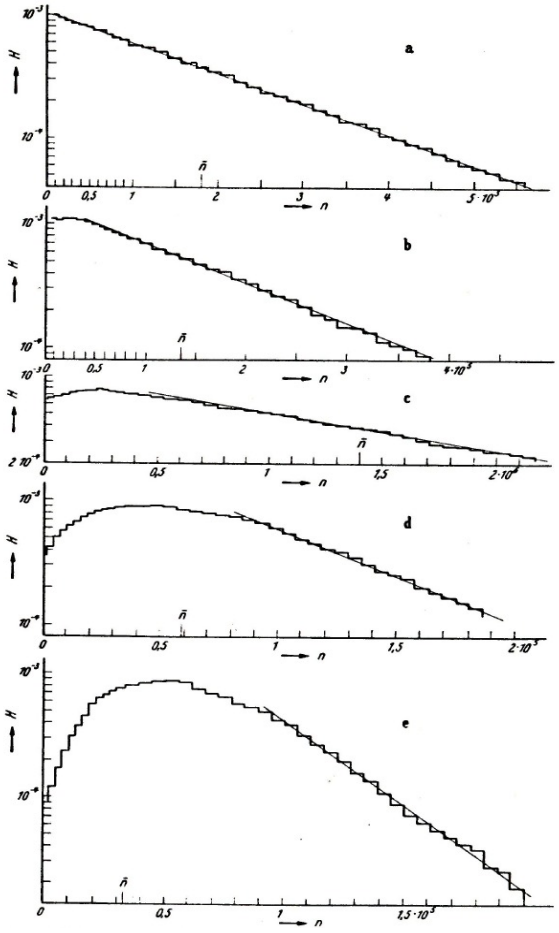
Avalanche Size Probability at High Fields (High Gains)

Polya function:

$$P(N) = \left[\frac{N(1+\theta)}{\overline{N}}\right]^{\theta} e^{-\frac{N(1+\theta)}{\overline{N}}}$$



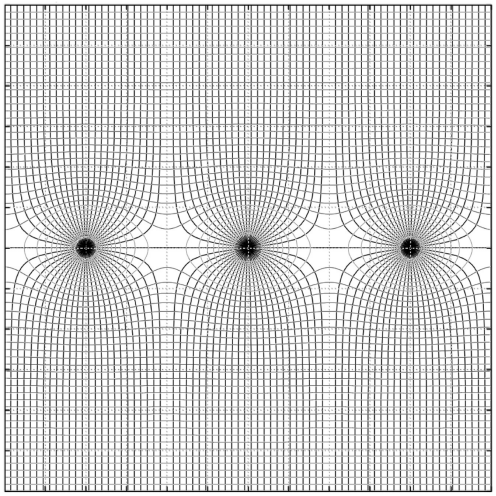
Single Electron Avalanche Size at Increasing Gains (Experimental):



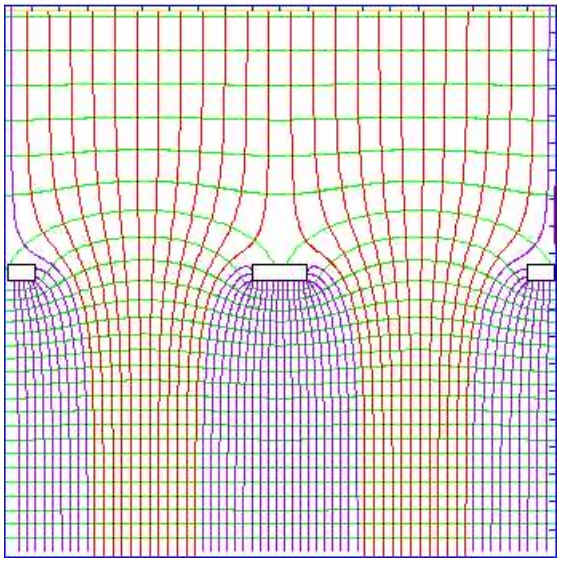
H. Sclumbohm, Zeit. Physik 151(1958)563

GASEOUS COUNTERS: MWPCs TO MPGDs

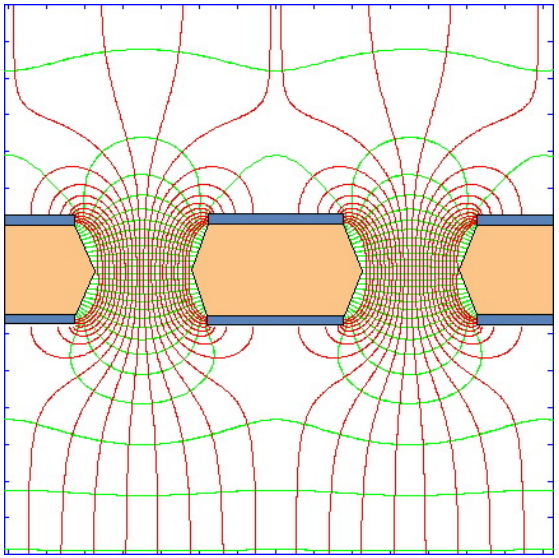
MWPC



MICROMEGAS

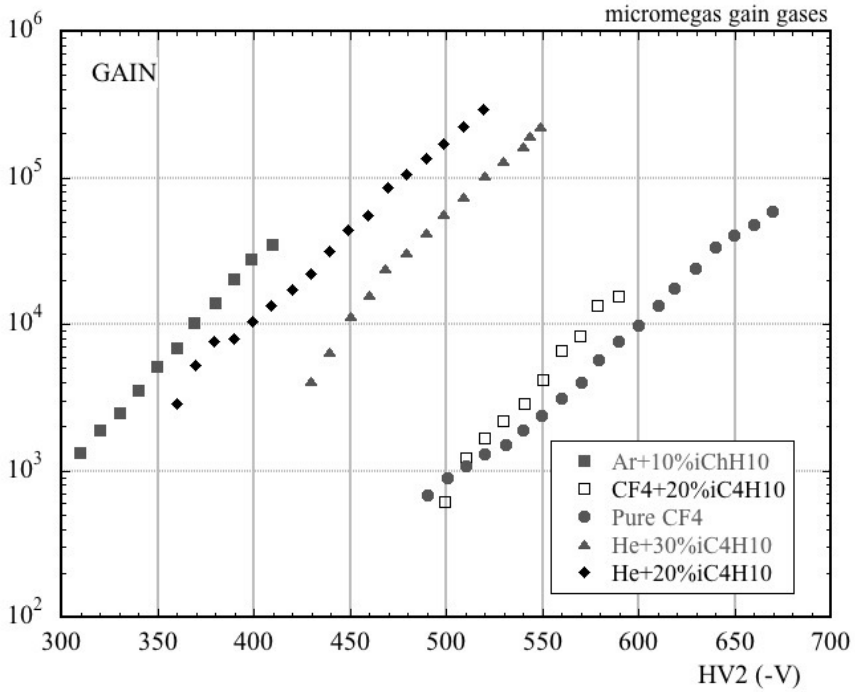


GEM

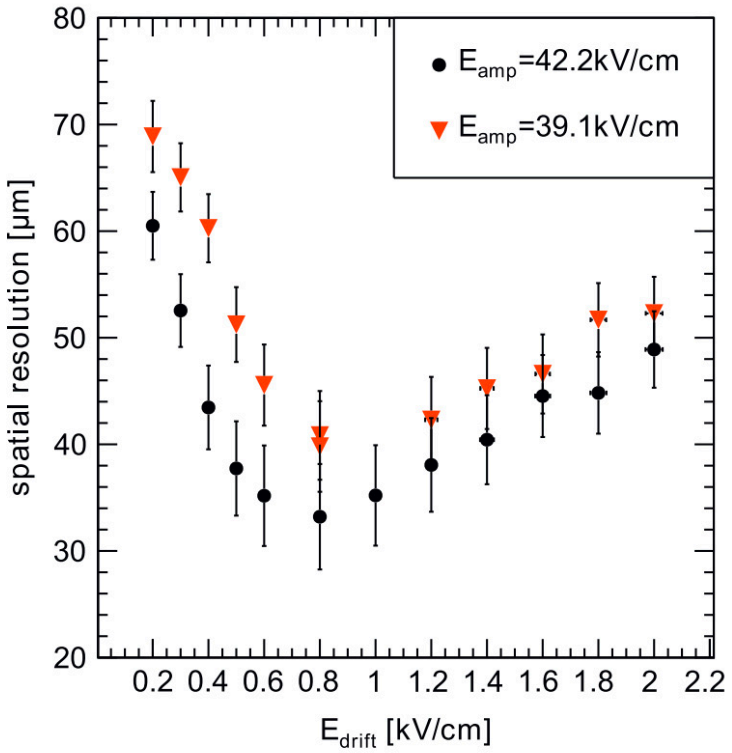


\+ MiroGroove, MicroGap,MicroPixel
Resistive Plate Well .....

Proportional Gain

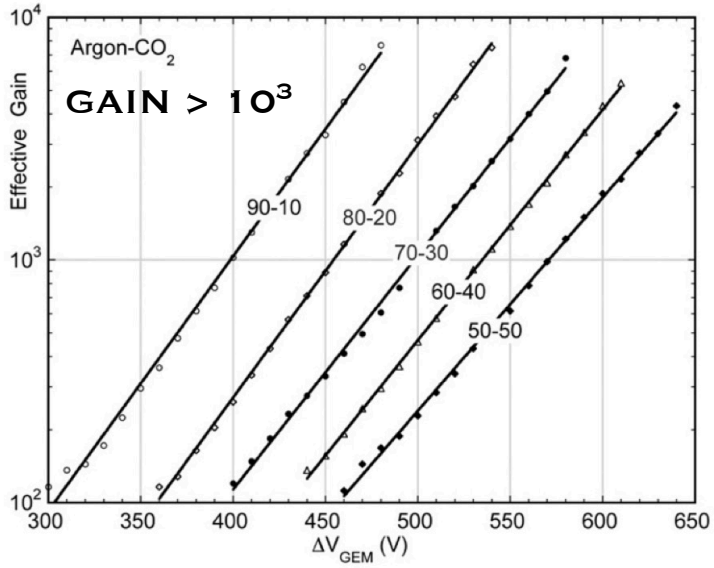


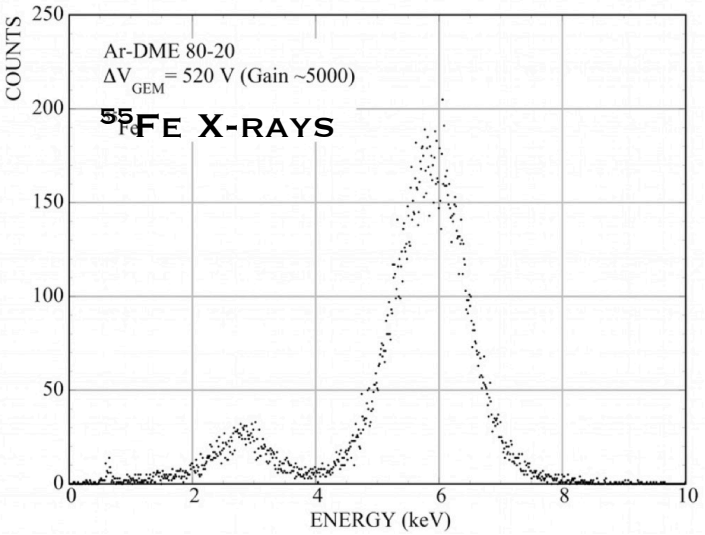
Localization Accuracy for MIPs



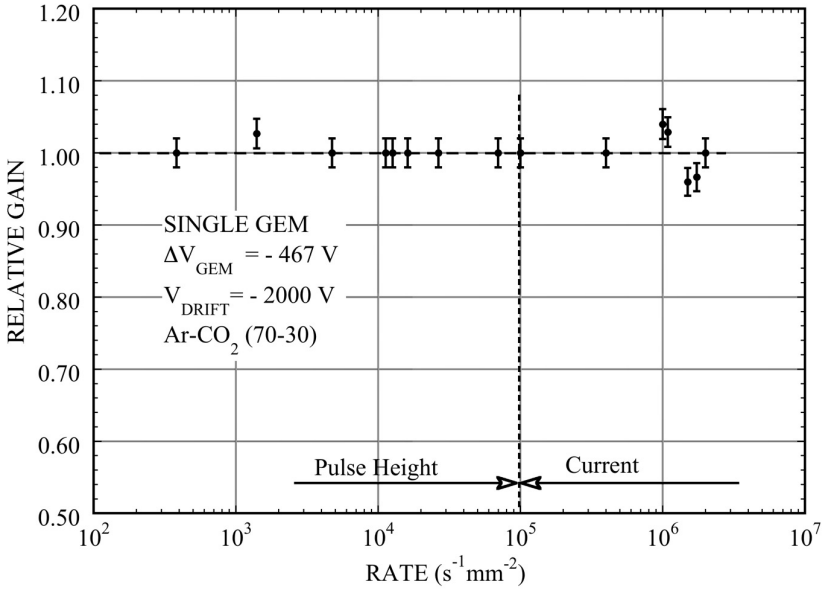
J. Bortfieldt et al, Nucl. Instr. Meth. 718A(2013)406

GEM



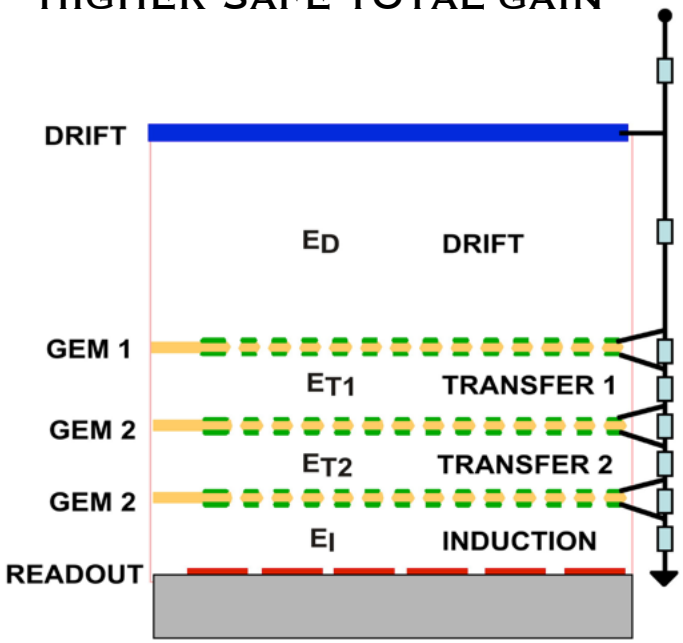


RATE CAPABILITY > 10^6 mm^{-2} s^{-1}

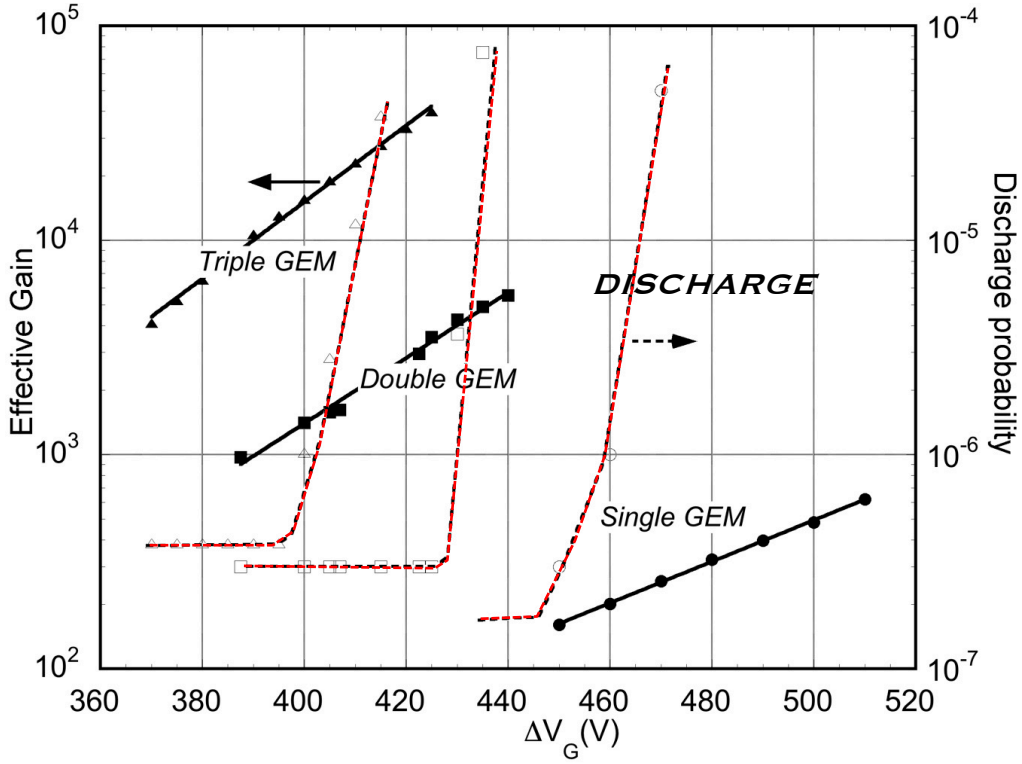


J. Benlloch et al,
Nucl. Instr. Meth. 419A(1998)410

TRIPLE-GEM
CASCADED GEM ELECTRODES
LOWER VOLTAGE ON EACH GEM
HIGHER SAFE TOTAL GAIN



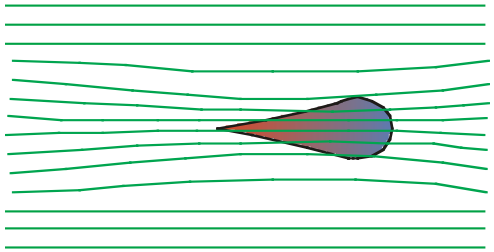
GAIN AND DISCHARGE PROBABILITY
ON 5 MeV α

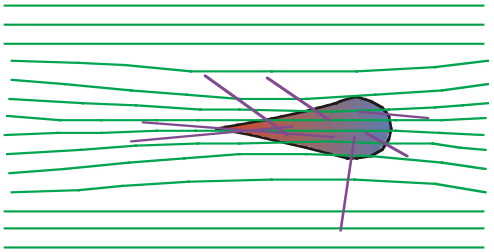


C. Büttner et al, Nucl. Instr. and Meth. A409(1998)79

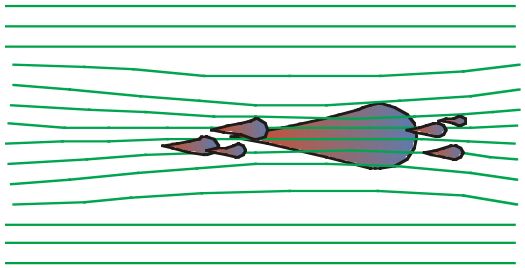
Very High Fields:
Transition Avalanche → Streamer → Discharge

The field is Increased in Front and Behind the Avalanche
Photons are Emitted and Reconverted in the High Field:

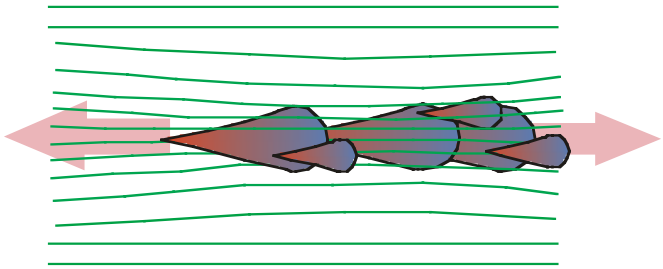




Secondary Avalanches Formation:



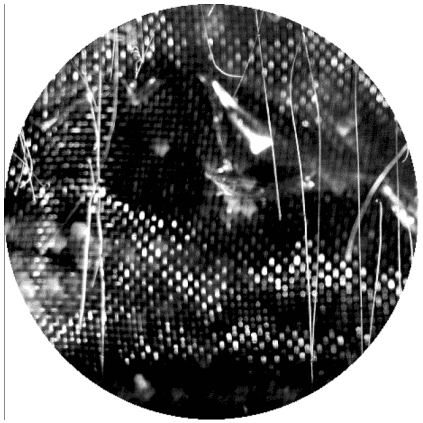
Tansition to Forward-Backward Streamer:



DISCHARGE !

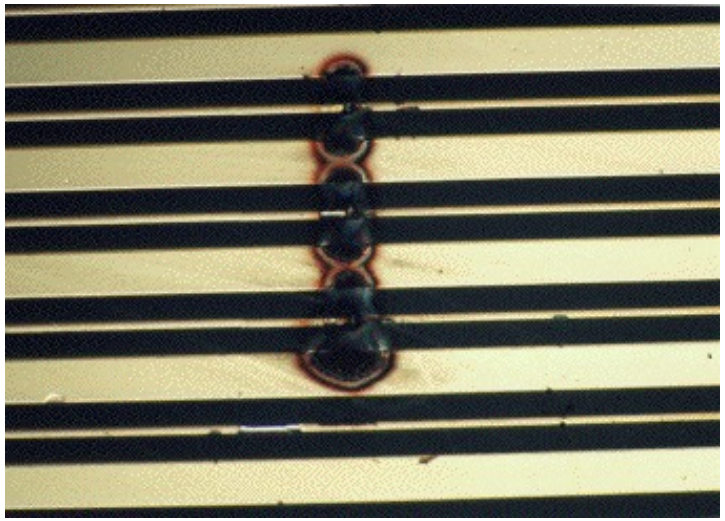
Raether Limit: ~ 10^7 electrons-ions

Destructive Effects of Discharges:



Drift Chamber (1974)

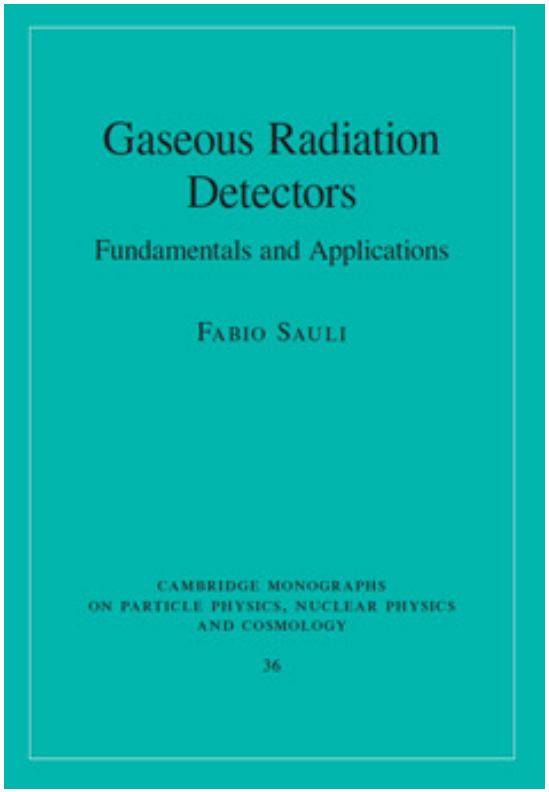
MSGC (1994)

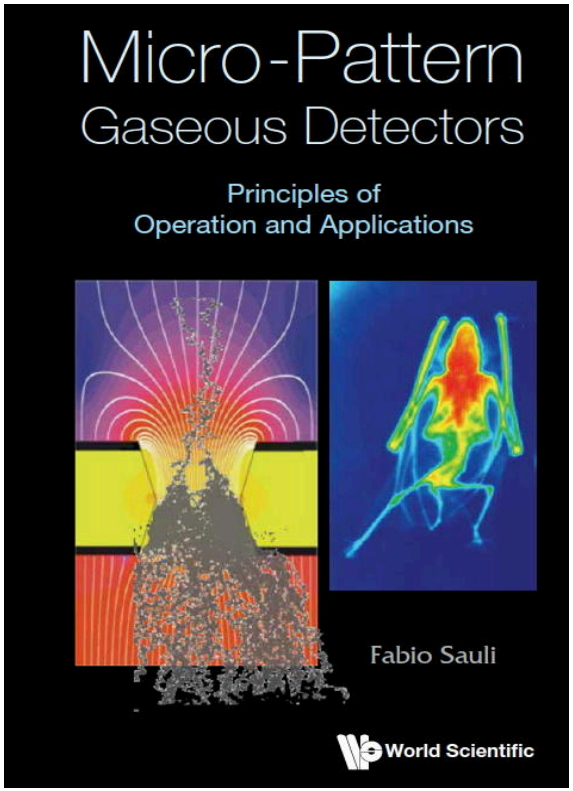


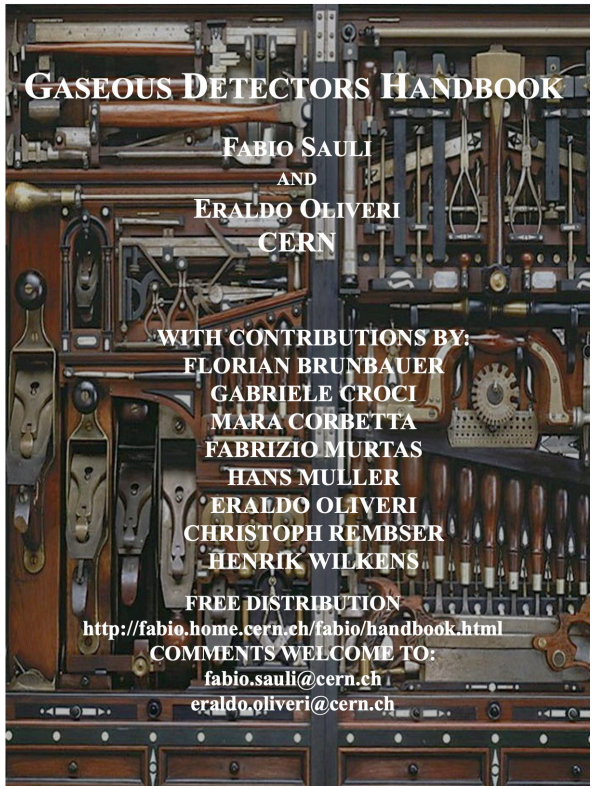
Discharge Prevention and Mitigation in MPGDs:

Piotr Gasik: GAS DETECTORS PHYSICS 2

To Know More on Gaseous Detectors:







F. Sauli and E. Oliveri: Gas Detectors Handbook

http://fabio.home.cern.ch/fabio/handbook.html

.... and the other lectures at this School!