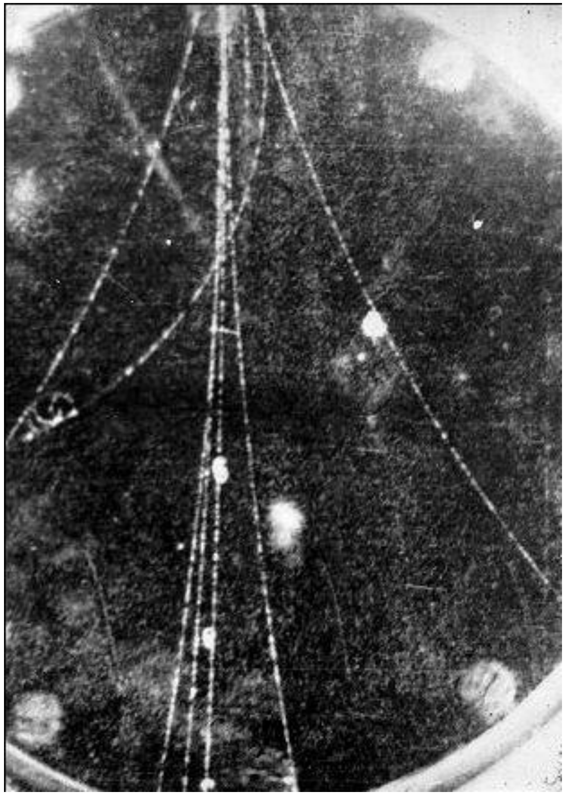
Gas Detectors Physics 1

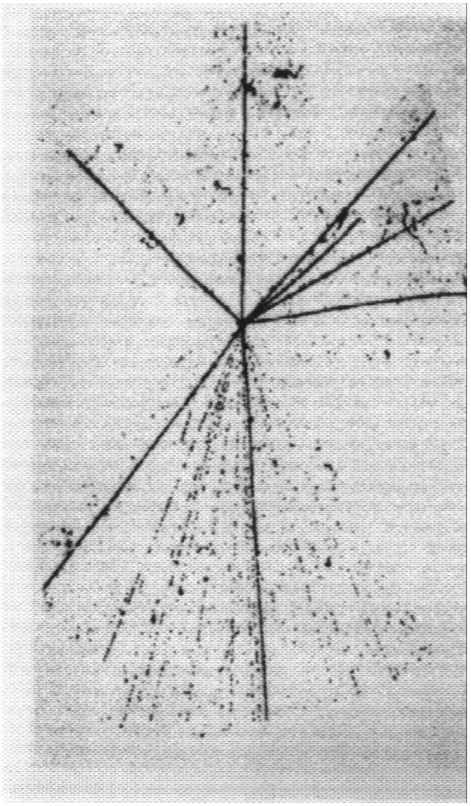
Basic Detection Processes

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

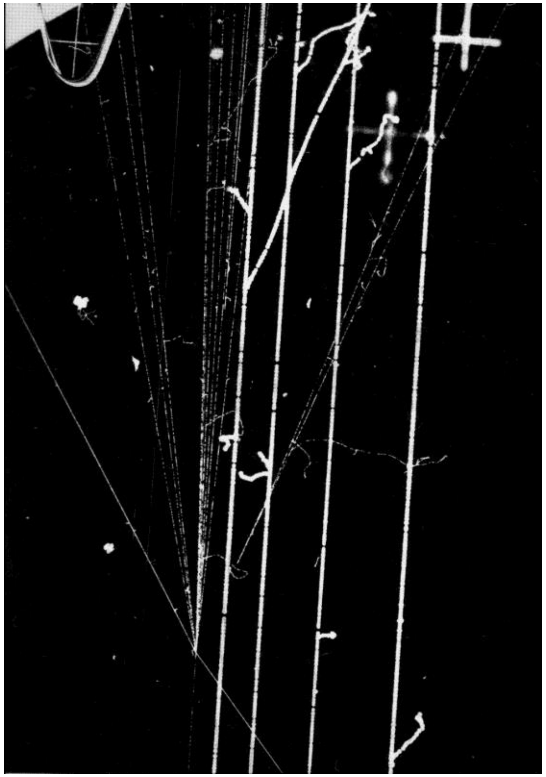
Imaging of Charged Particles Interactions



~ 1930
Cloud Chamber

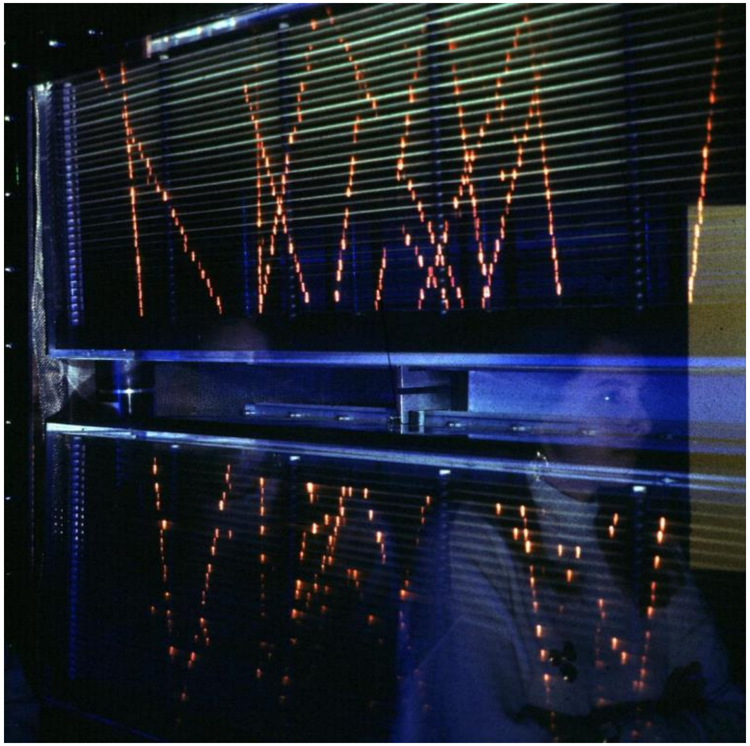


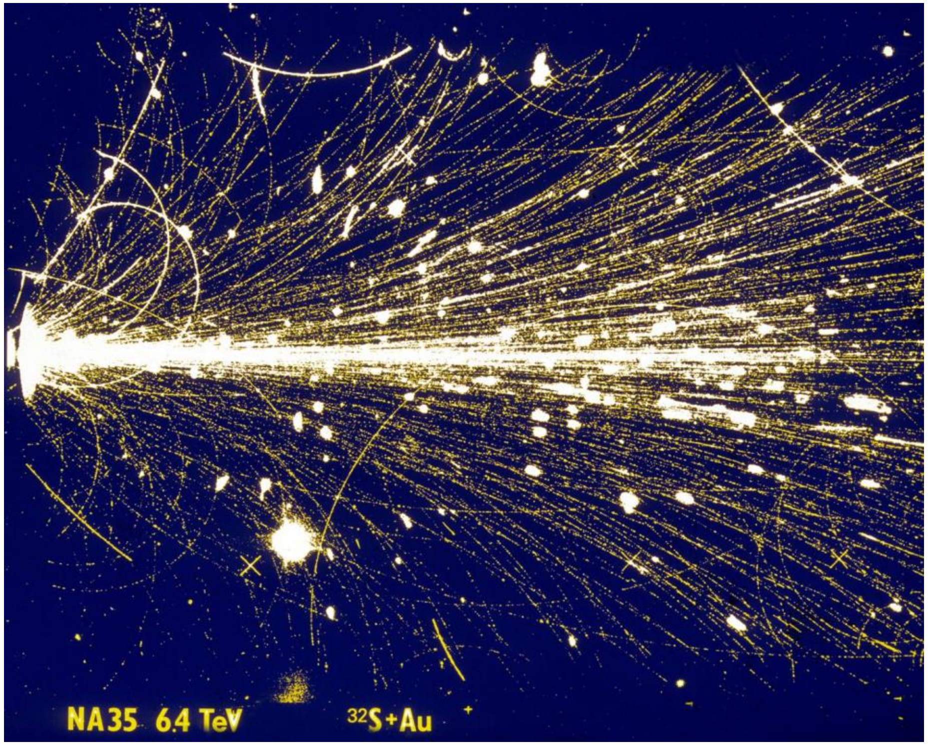
~1940
Emulsions



~ 1960
Bubble Chamber

Imaging of Charged Particles Interactions

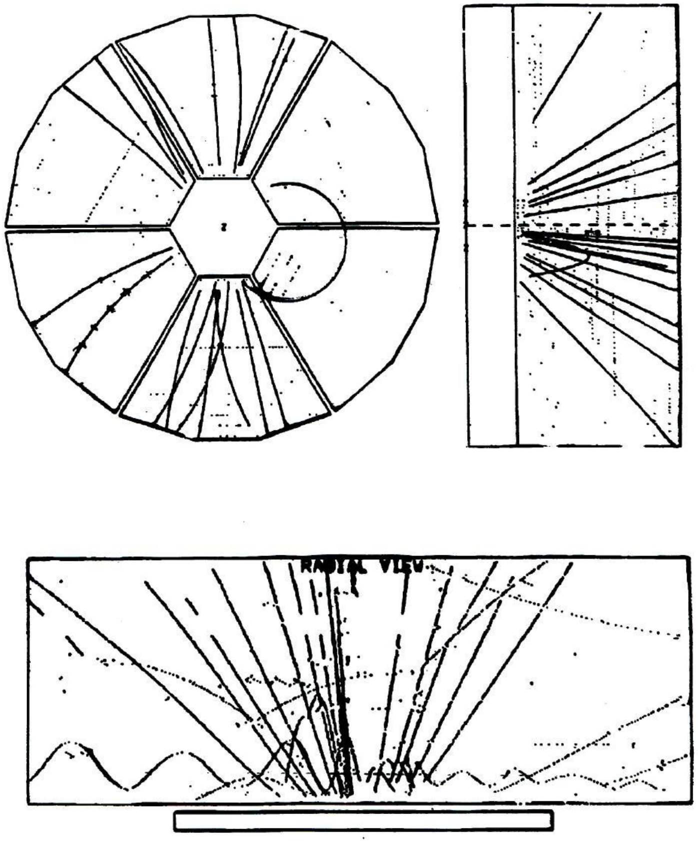




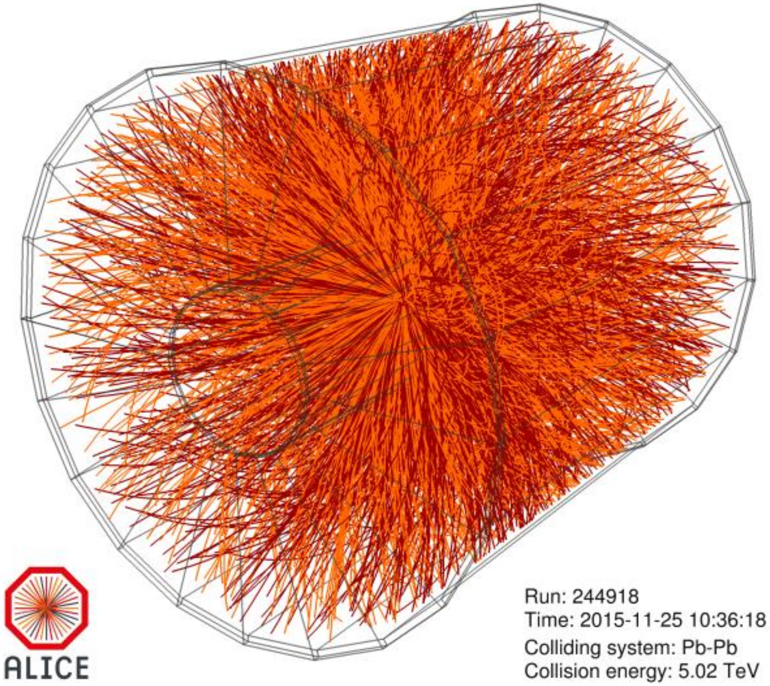
~1960

Spark and Streamer Chambers

Imaging of Charged Particles Interactions



~1970



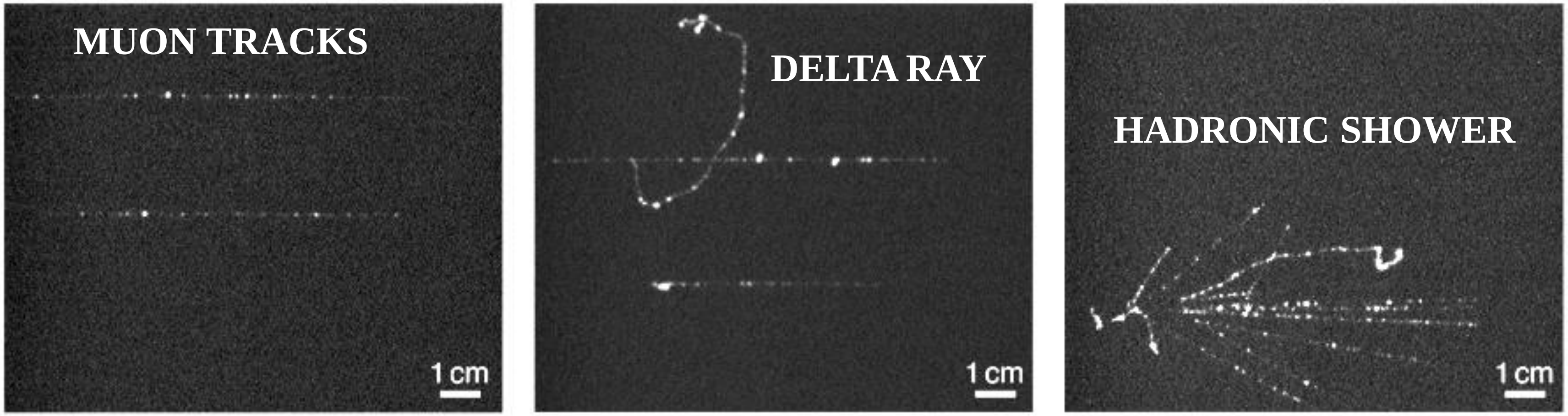
~2000

2016: GEM TPC UPGRADE

Time Projection Chamber (TPC)

Imaging of Charged Particles Interactions

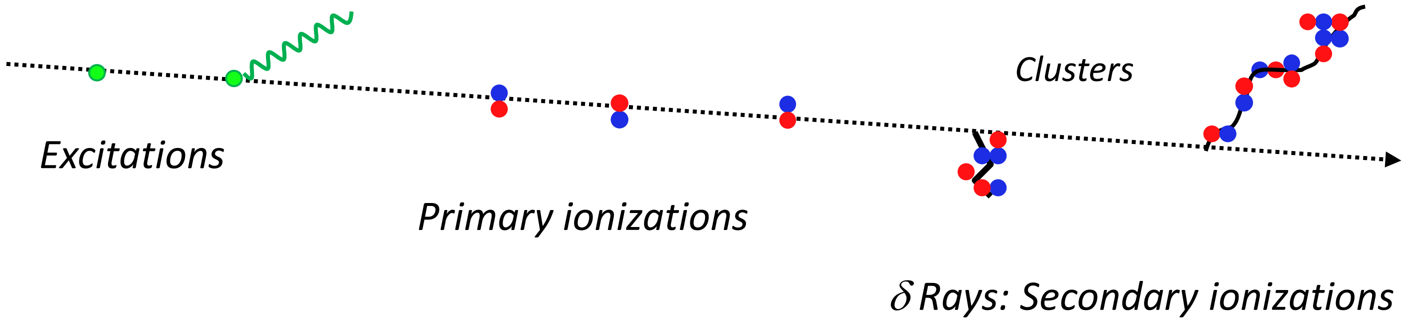
THE FUTURE?



Optical Gas Electron Multiplier (GEM)

Charged Particles

Coulomb Interactions: Excitations and Ionizations

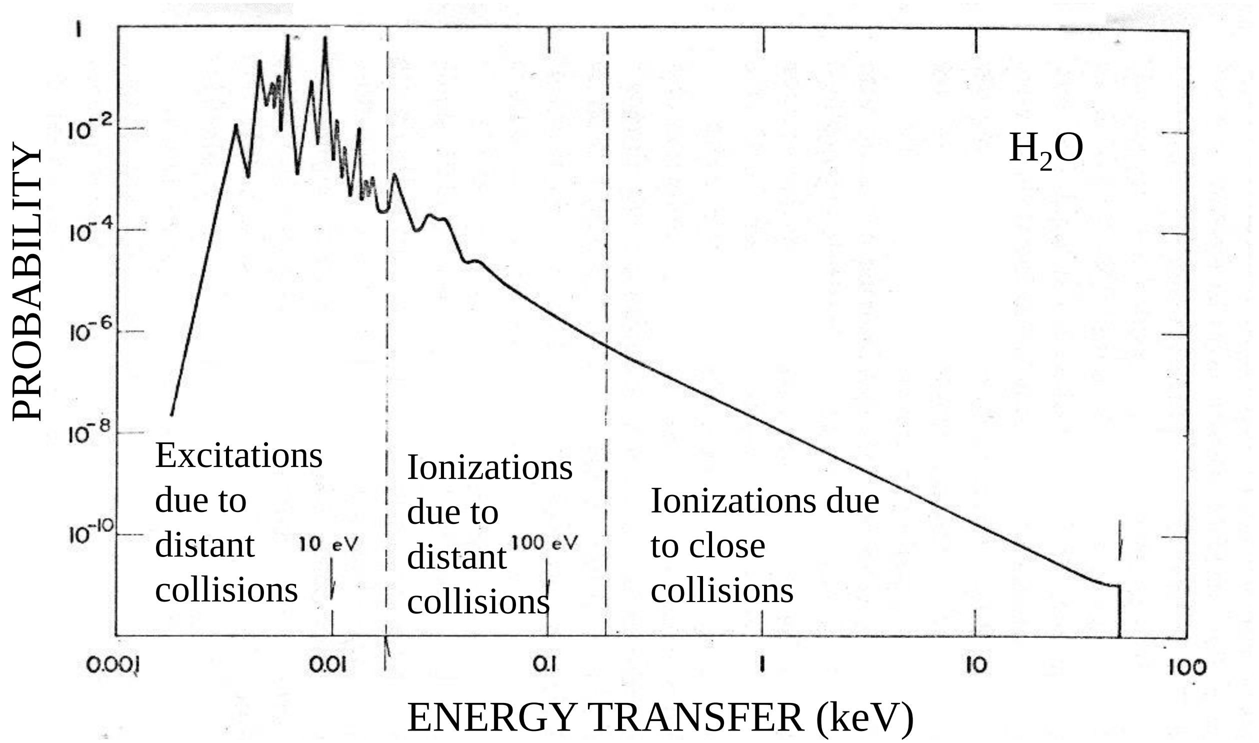


Excitations

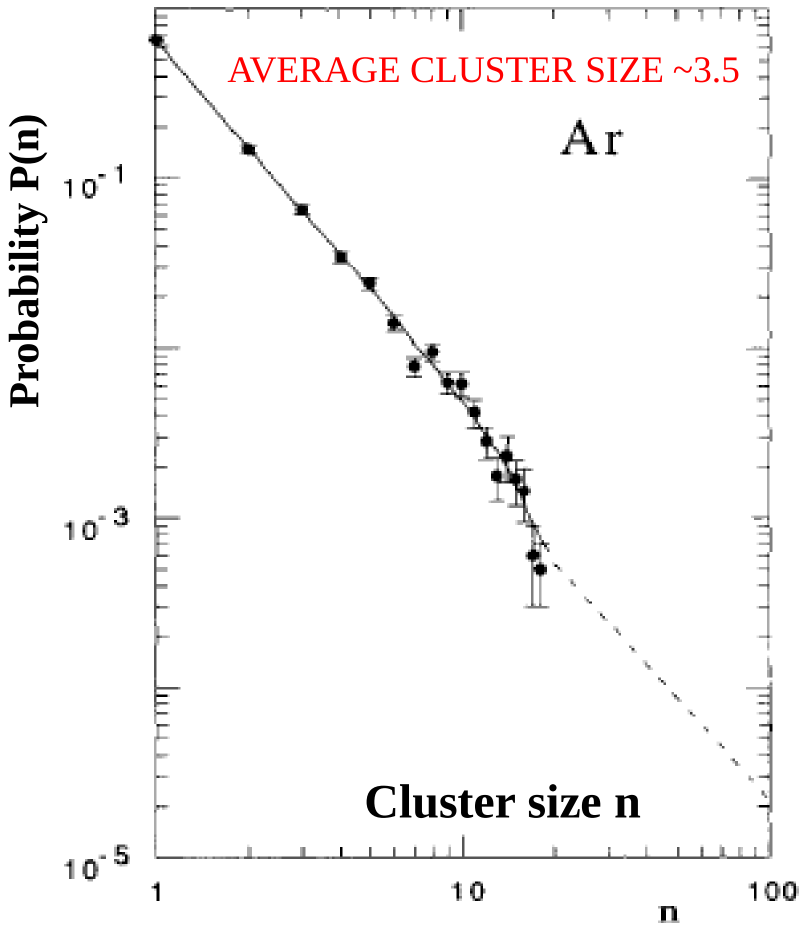
Primary ionizations

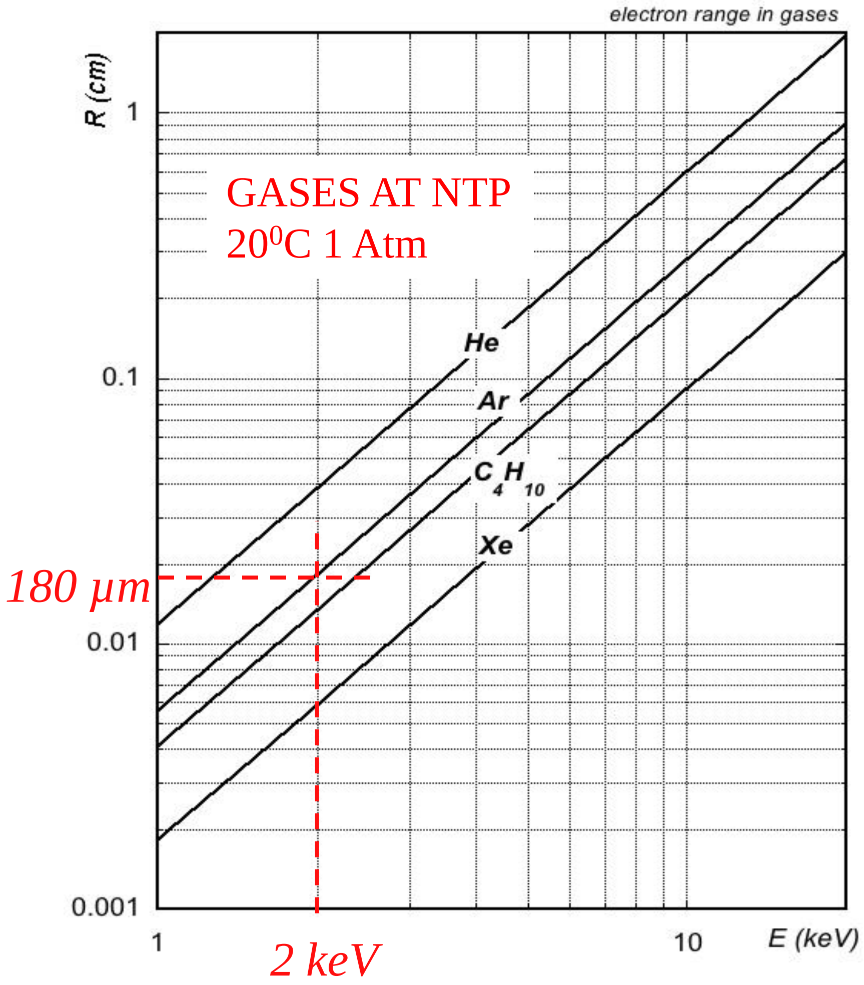
Clusters

δ Rays: Secondary ionizations



Charged Particles
Cluster Size and δ Electrons Range



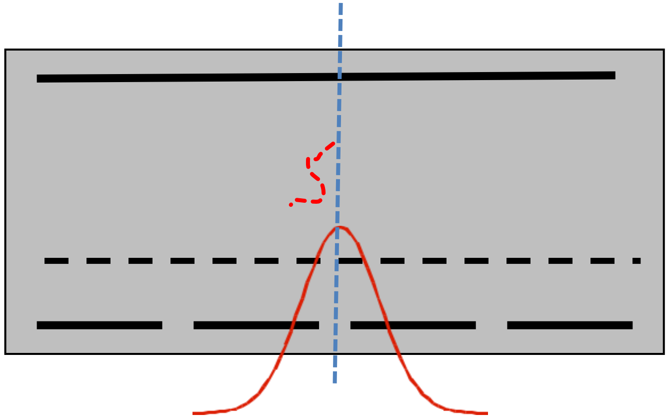


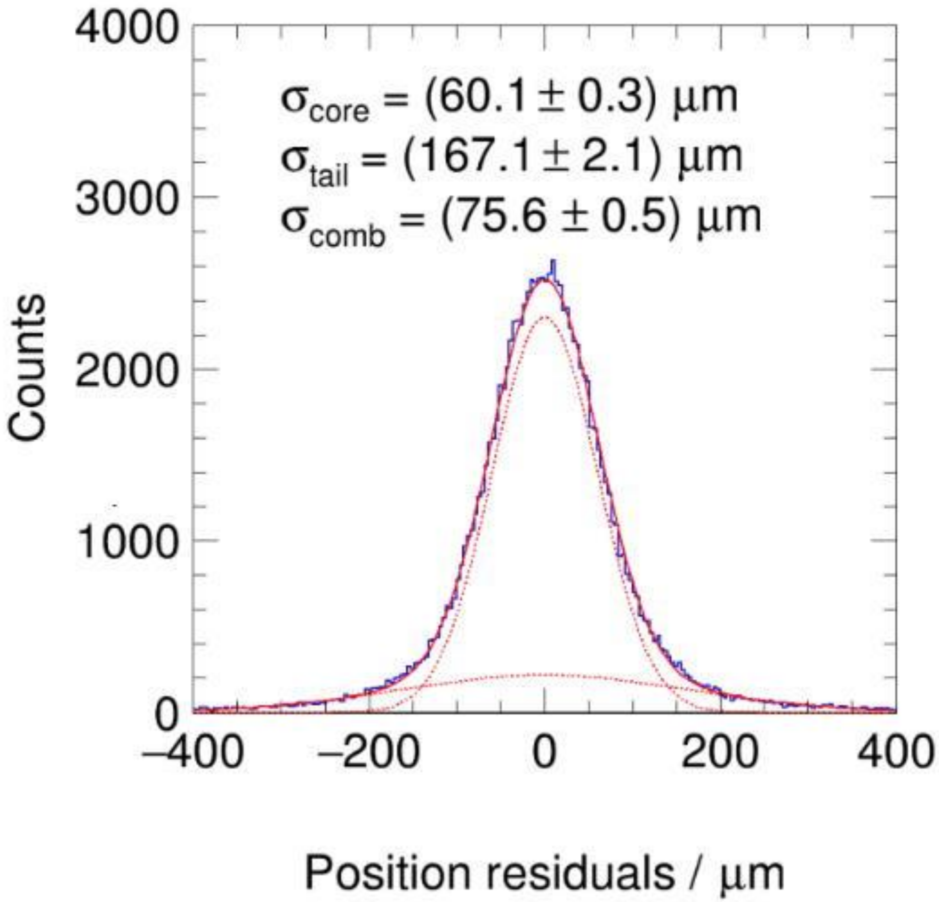
H. Fischle et al, Nucl. Instr. and Meth. A301 (1991) 202

Charged Particles
δ Electrons

Energy Loss Asymmetry:
Core Gaussian + Tails

Perpendicular Tracks



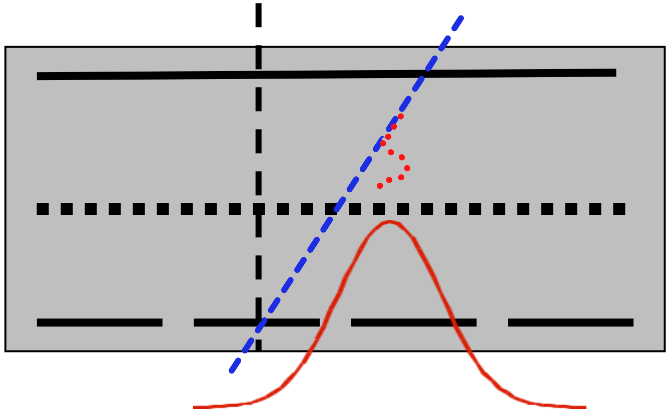


L. Scharenberg, MPGD 2022

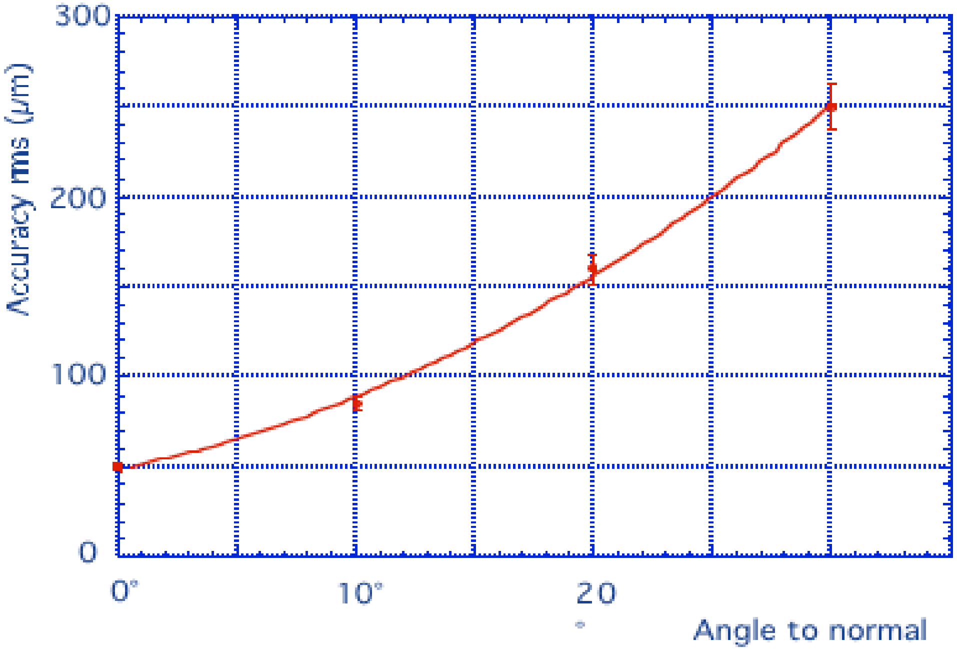
Charged Particles

δ Electrons

Energy loss asymmetry:
large incidence angles



Position Accuracy
vs
Incidence Angle:

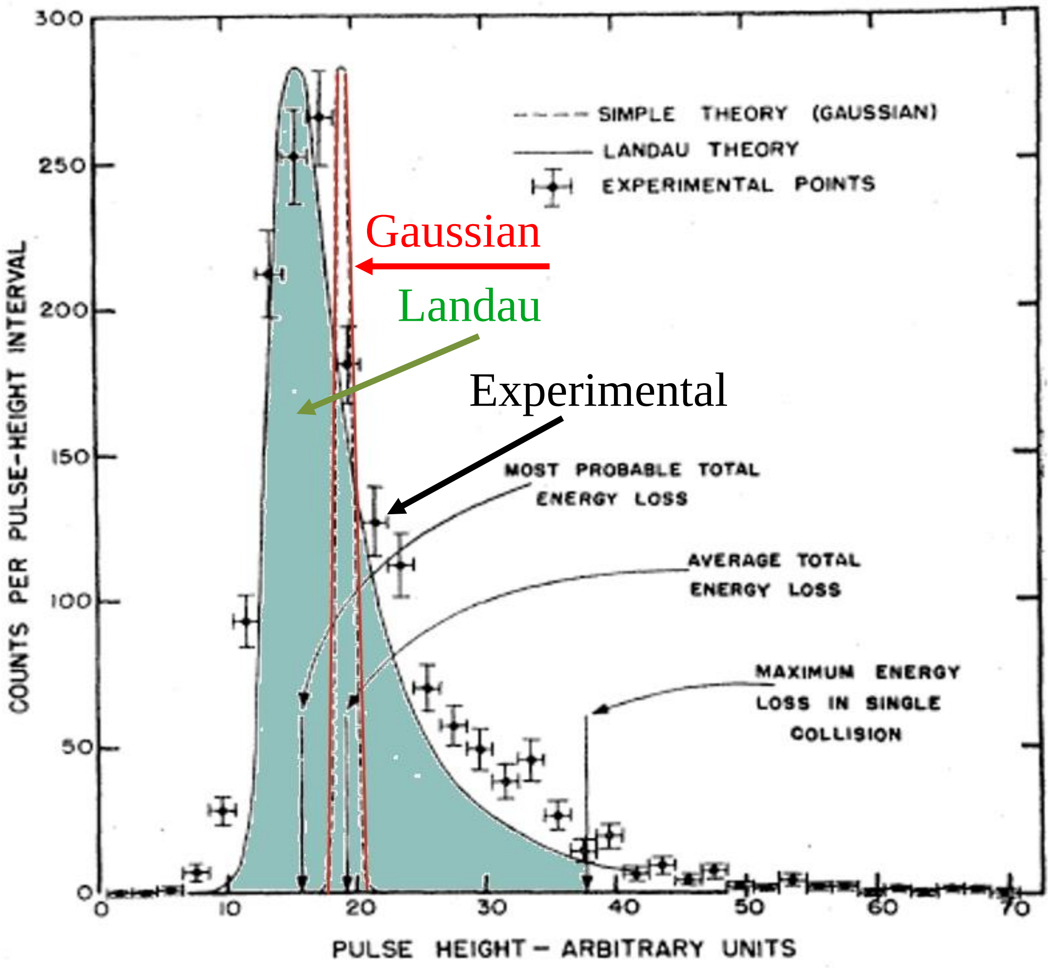


G. Charpak et al, NIM 167 (1979) 455

Charged Particles

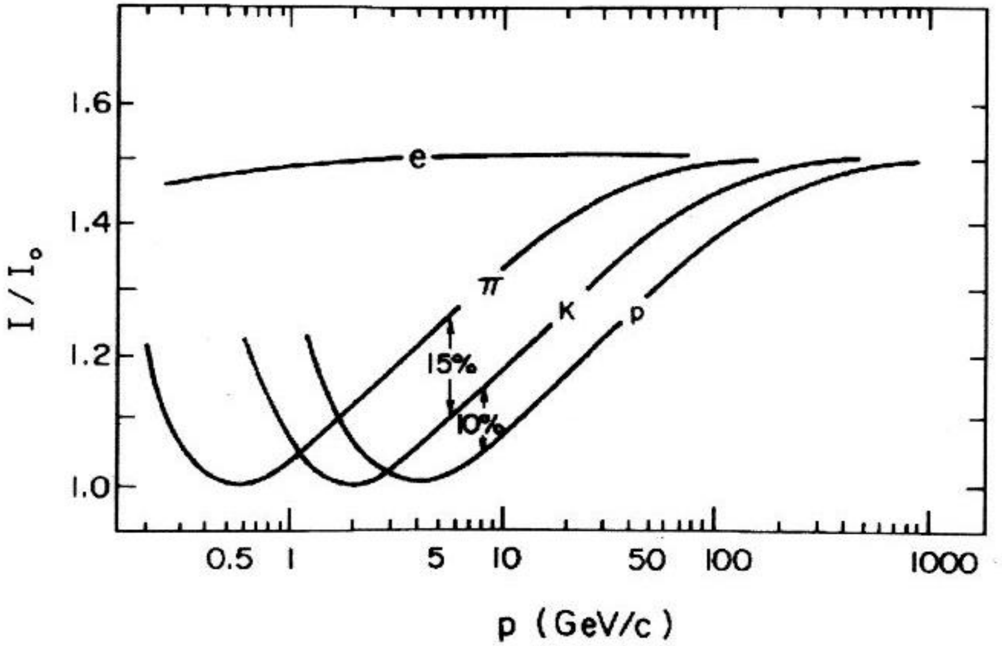
Energy Loss Statistics: Gauss vs Landau

Differential Energy Loss in thin Gas Samples:

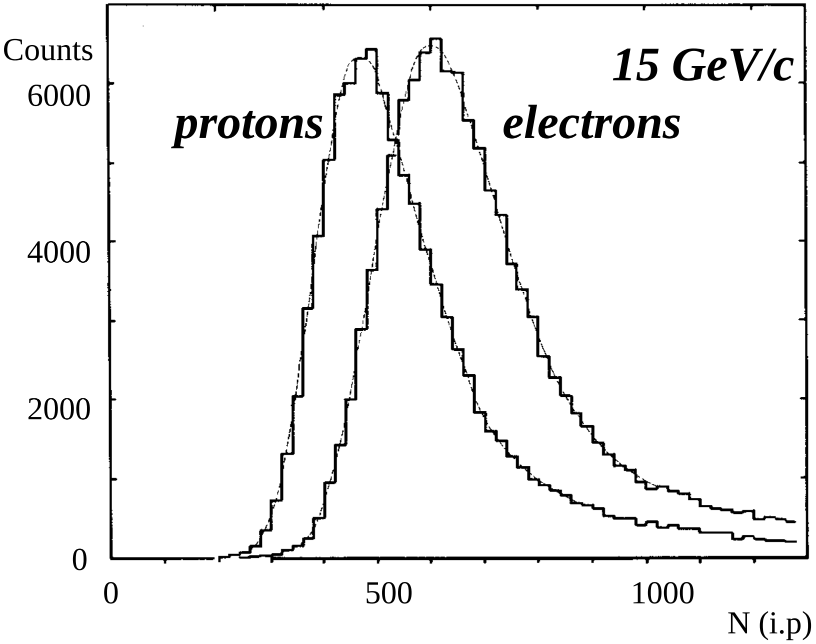


Charged Particles
Energy Loss Statistics: Gauss vs Landau

Particle Identification:
Most Probable Energy Loss



SINGLE SAMPLE
Energy Loss:



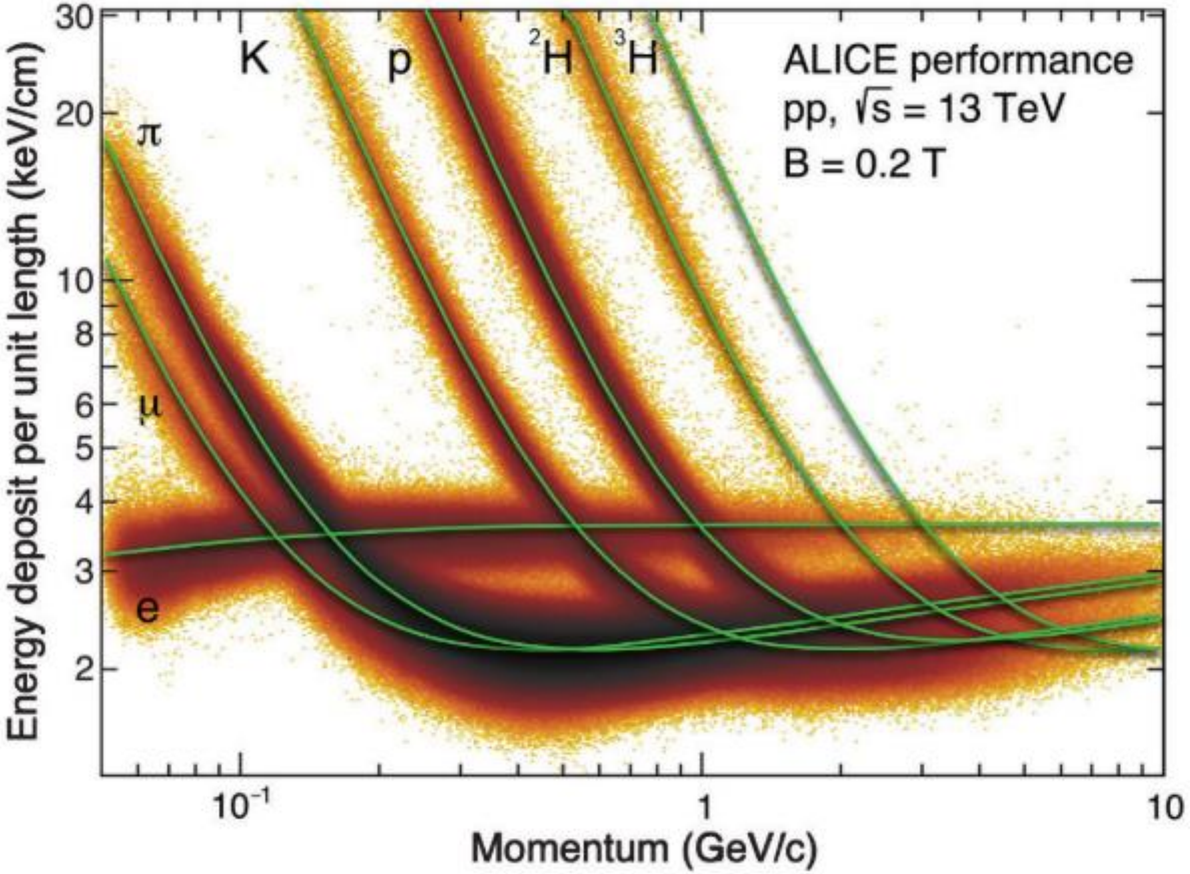
I. Lehraus et al, Phys. Scripta 23(1981)727

Enery Loss resolution:
Statistical Multisample Analysis

Charged Particles
Particle Identification

Alice GEM-TPC

Differential Energy Loss (Truncated mean)

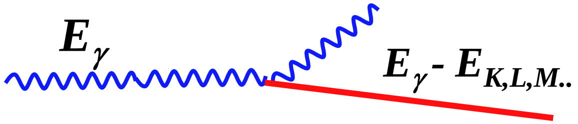


Ph. Hauer, Nucl. Instr. Meth. 1039 (2022)167023

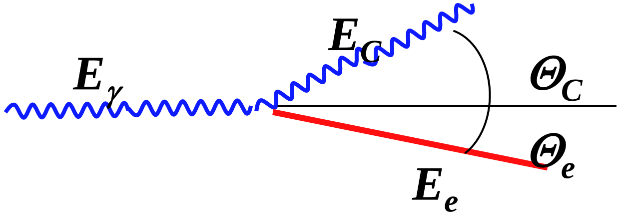
Photons

Photoelectric, Compton, Pair Production

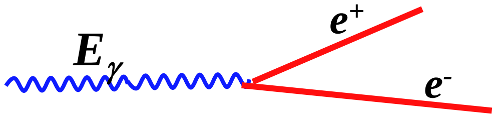
Photoelectric:

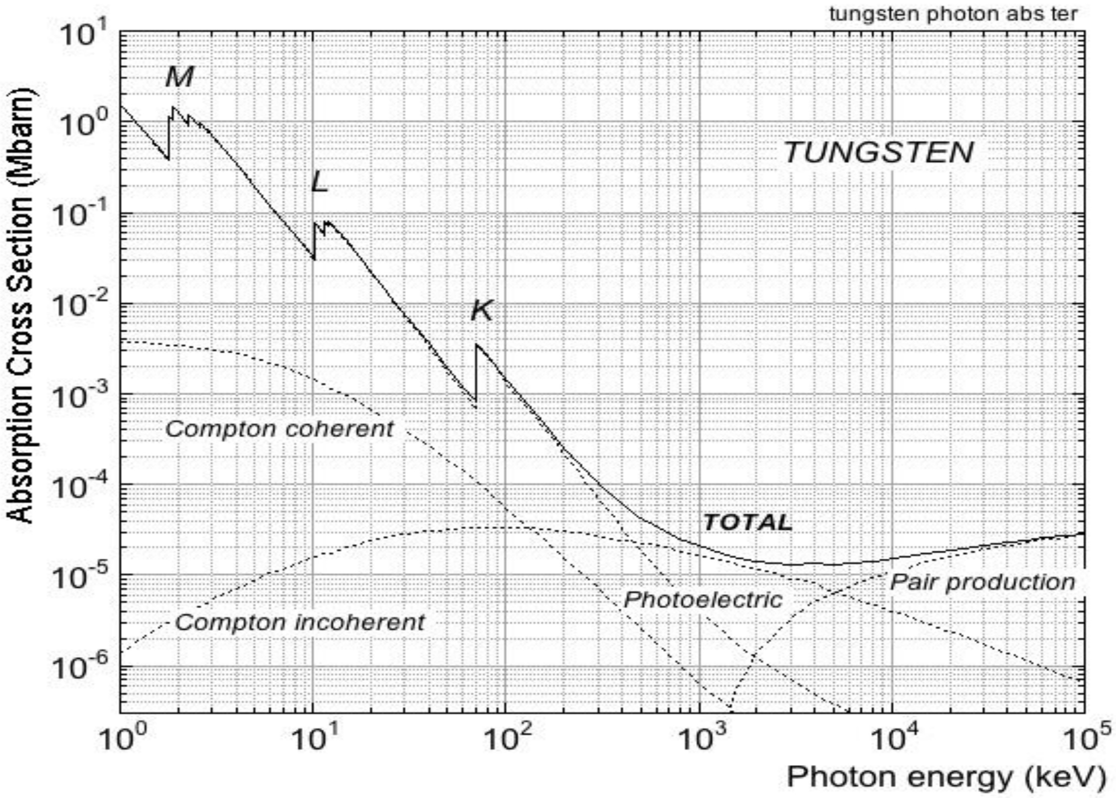


Compton:



Pair Production:

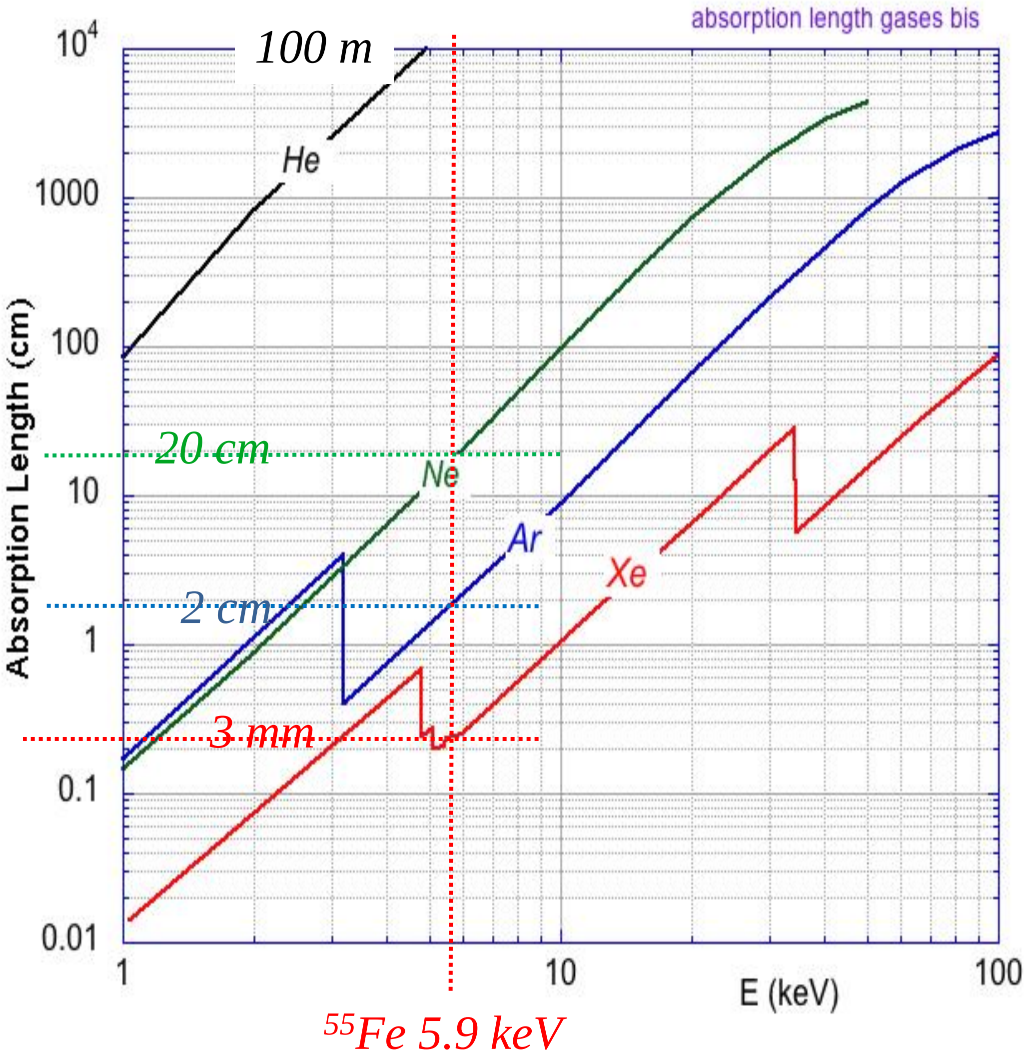




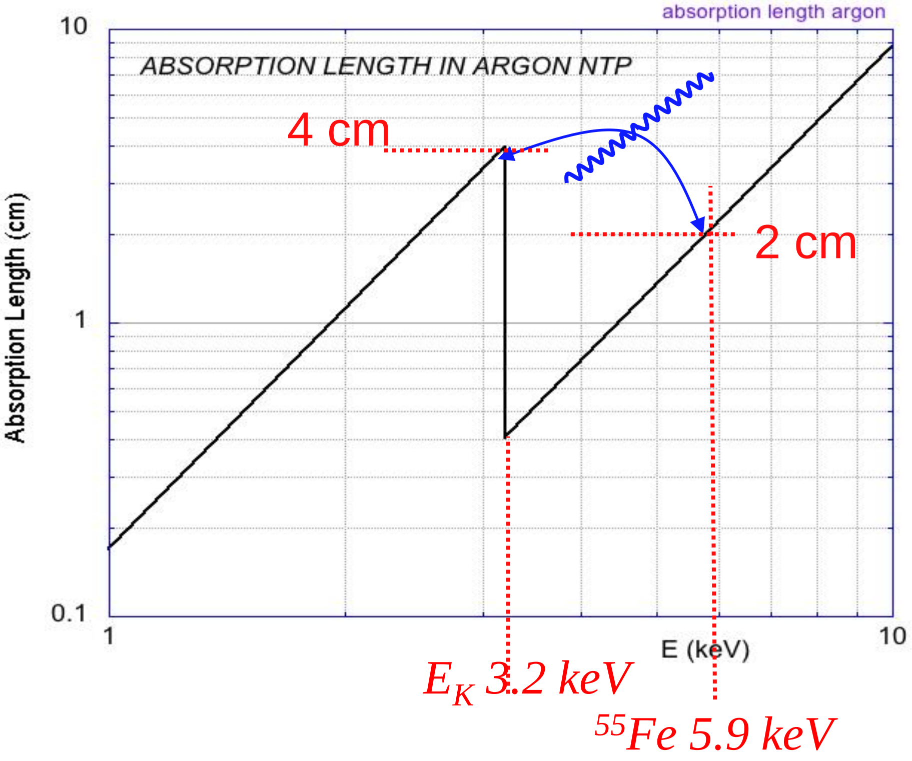
A. Thompson et al, X-RAY DATA BOOKLET (2001)

Soft X-Rays

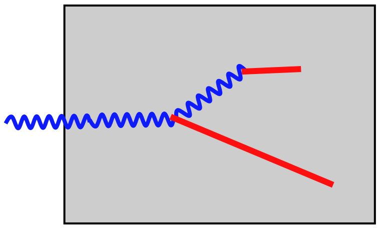
Absorption Length
in Gases at NTP



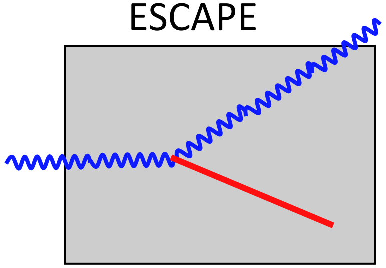
Soft X-Rays
ESCAPE PEAK



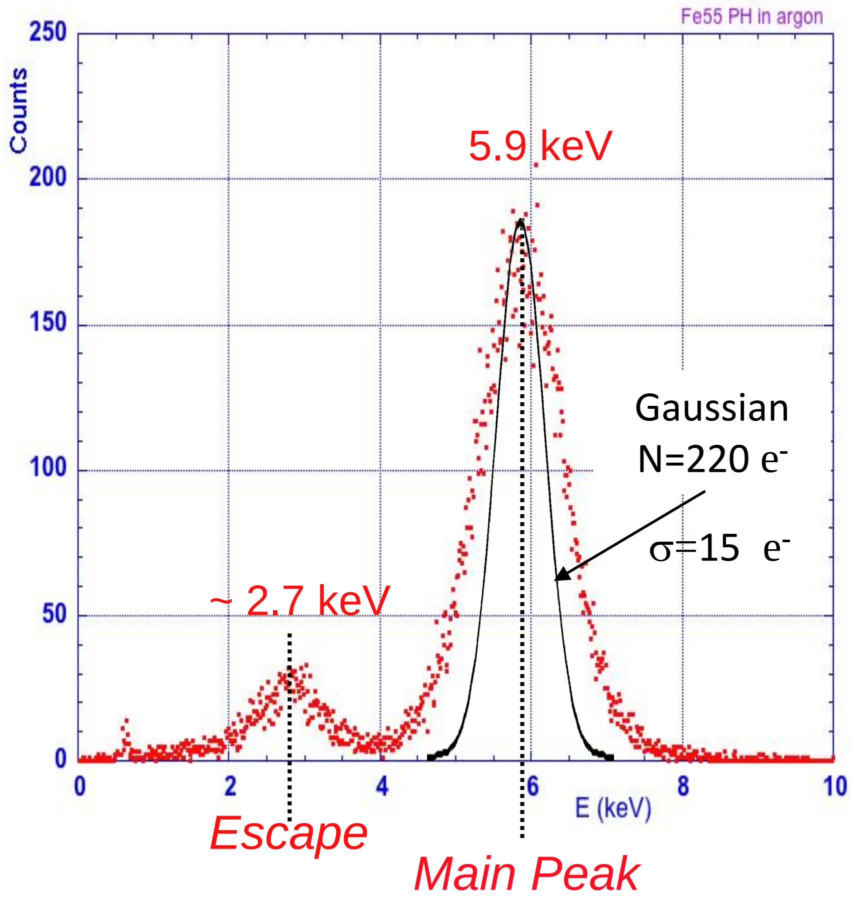
FULL



ESCAPE



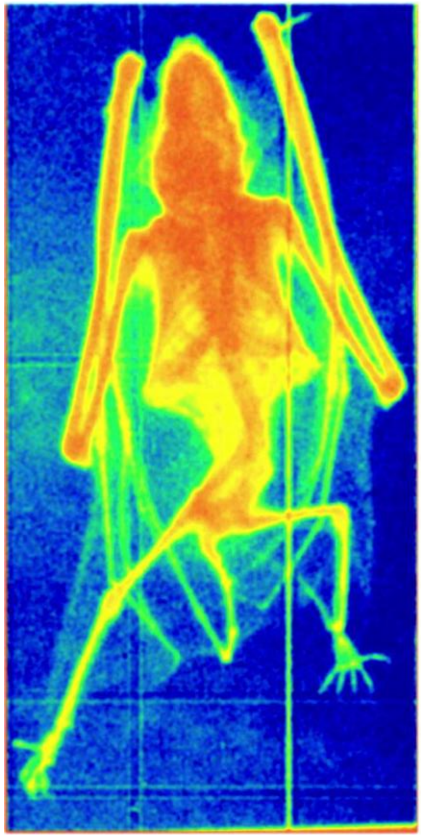
Argon NTP



Soft X-Rays Absorption Radiography

The GDD Bat

2001:
GEM with Electronic Readout



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

2018:
GEM with Optical Readout

F. Brunbauer et al,
JINST13 (2018)T02006

Detection of Neutrons

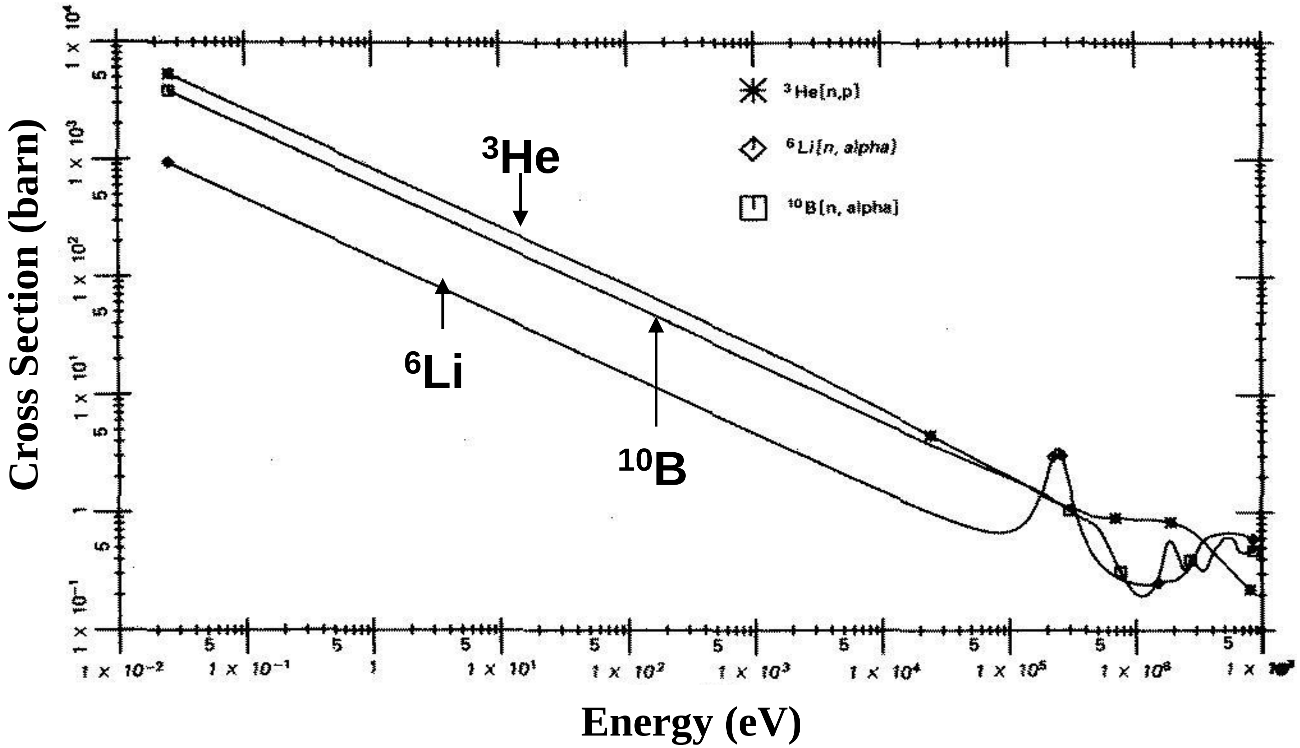
n + *M* -->

- protons
- tritons
- α particles
- fission fragments

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

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

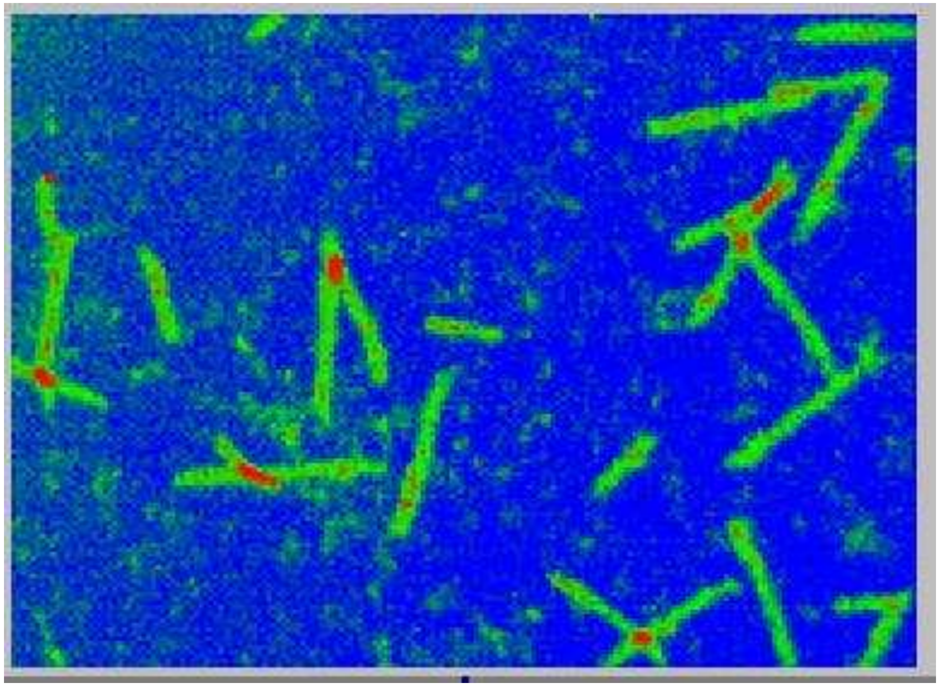
$$ {}^{3}_{2}He + n \rightarrow {}^{3}_{1}H + p $$



Detection of Neutrons

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

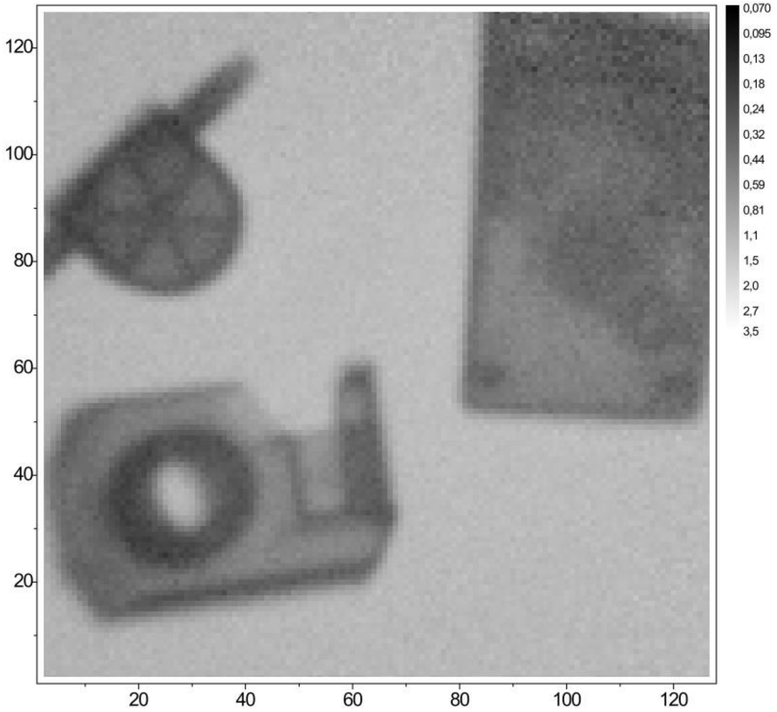
Ionization Chamber with
Otical GEM Readout



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

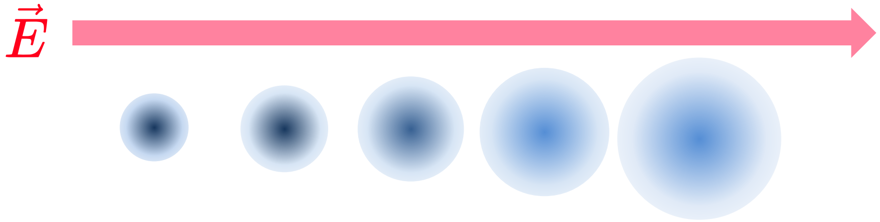
$${}^{10}_{5}B + n \rightarrow {}^{7}_{3}Li + \alpha$$

Thermal Neutrons Radiography
^{10}B Coated GEM



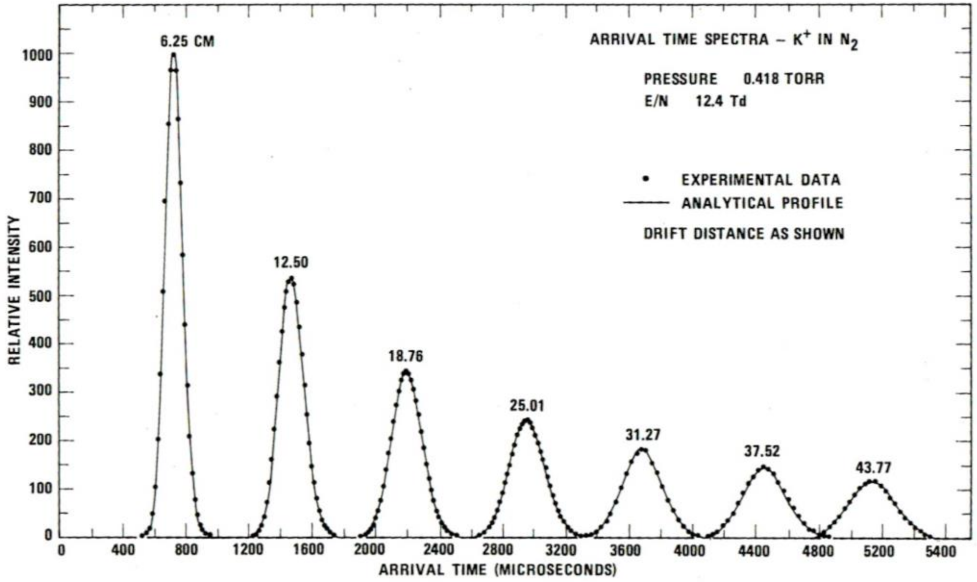
M. Klein and Ch. Schmidt
Nucl. Instr. and Meth. A628 (2011) 9

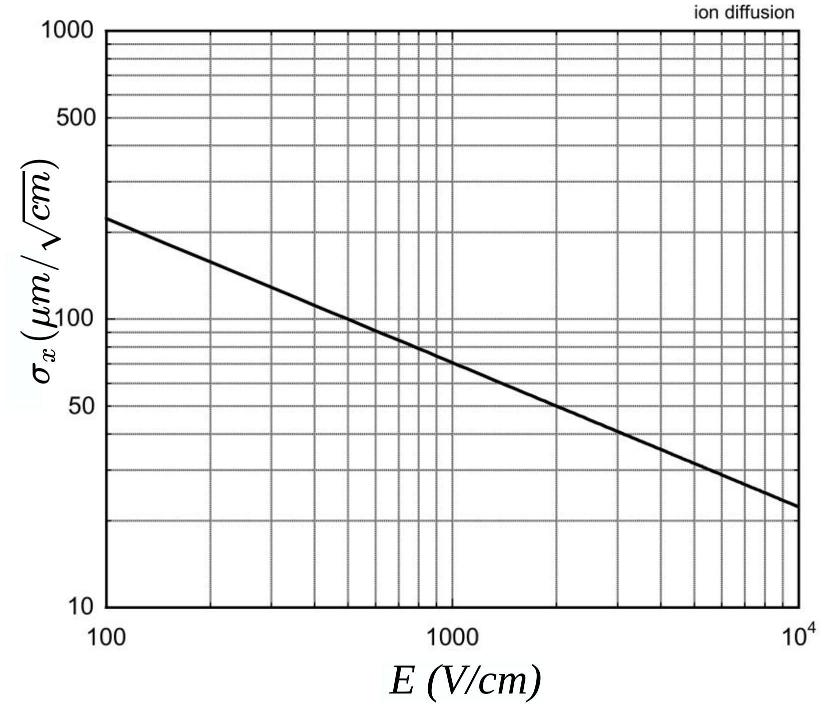
Drift and Diffusion of Ions



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

Independent from Ion Type





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

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

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

Drift and Diffusion of Ions

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:

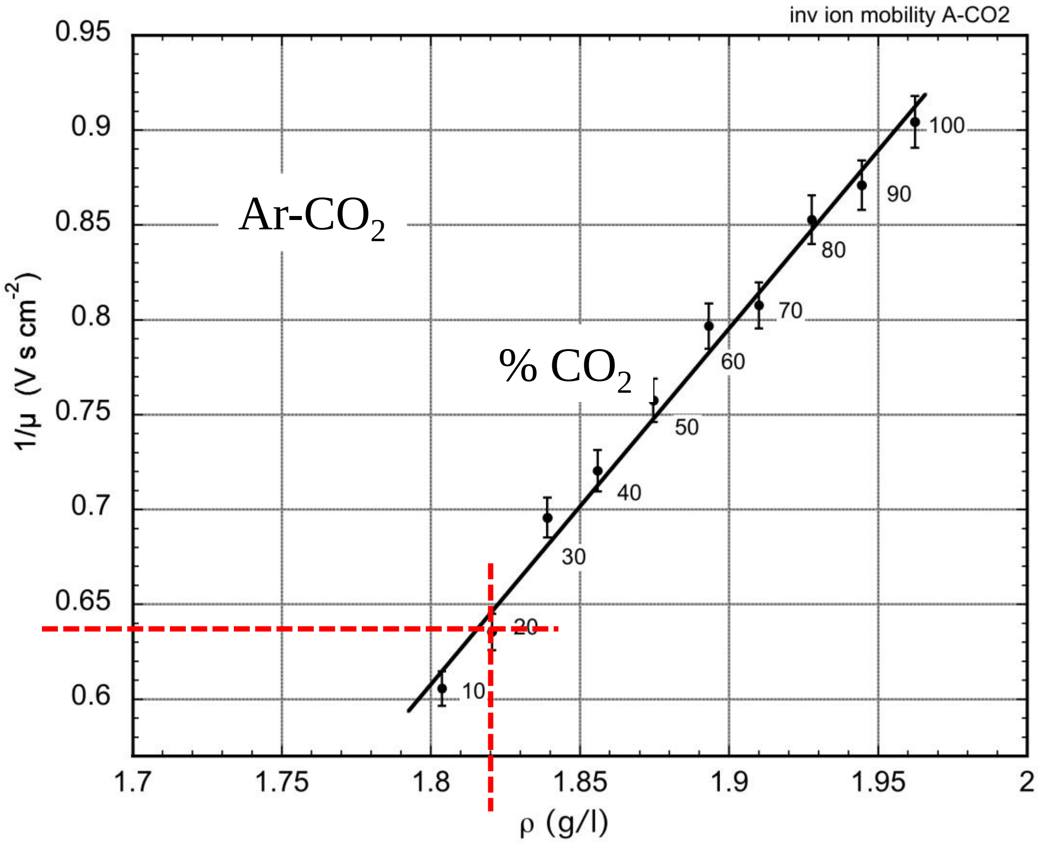
If $E_i(B) < E_i(A)$:

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

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. *μ = 0.64 $cm^2 V^{-1} s^{-1}$*
@ E=200 V cm^{-1} *W ~ 130 cm s^{-1}*

Ions Backflow and Space Charge

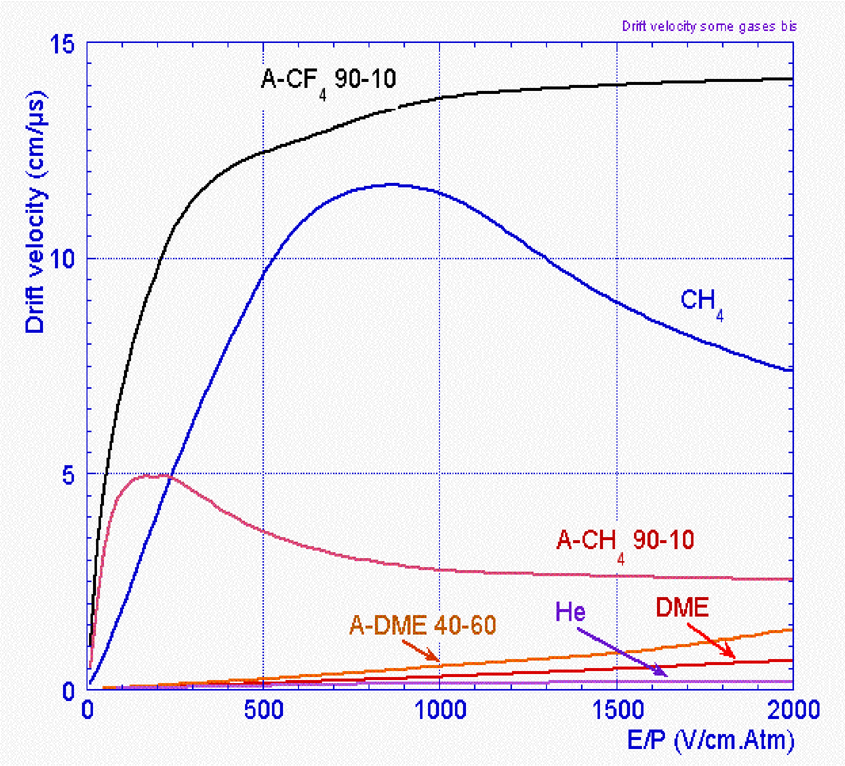
Drift and Diffusion of Electrons

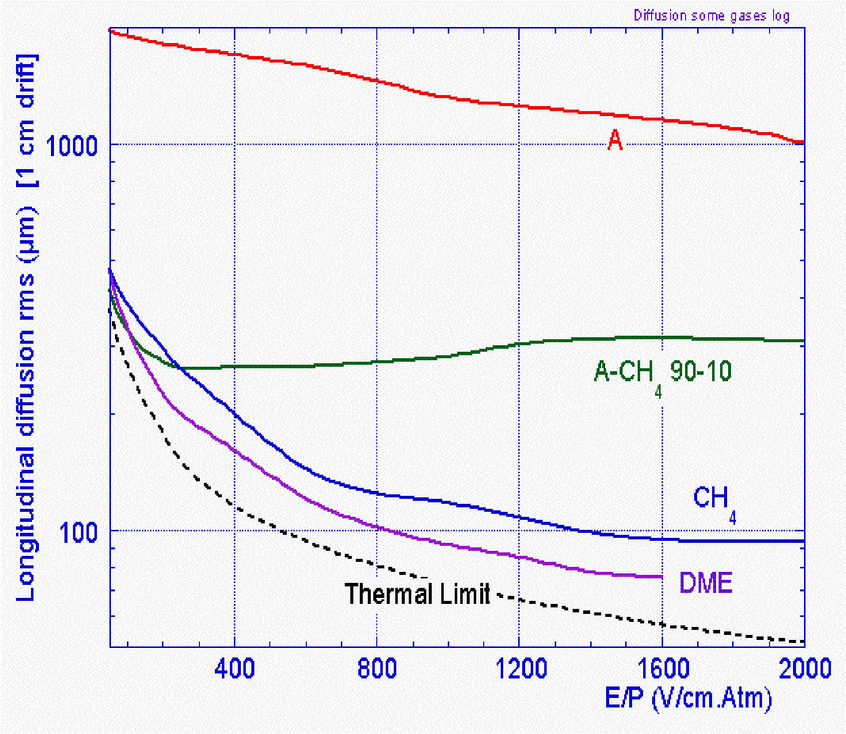
Drift Velocity $w^{-} = s/t$

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

ε_κ: *Characteristic Energy*

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



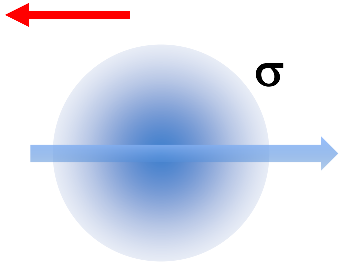


Rob Veenhof and Piet Verwilligen: MODELLING AND SIMULATIONS

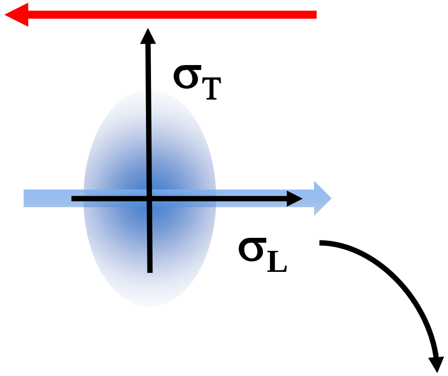
Drift and Diffusion of Electrons

Longitudinal and Transverse Diffusion

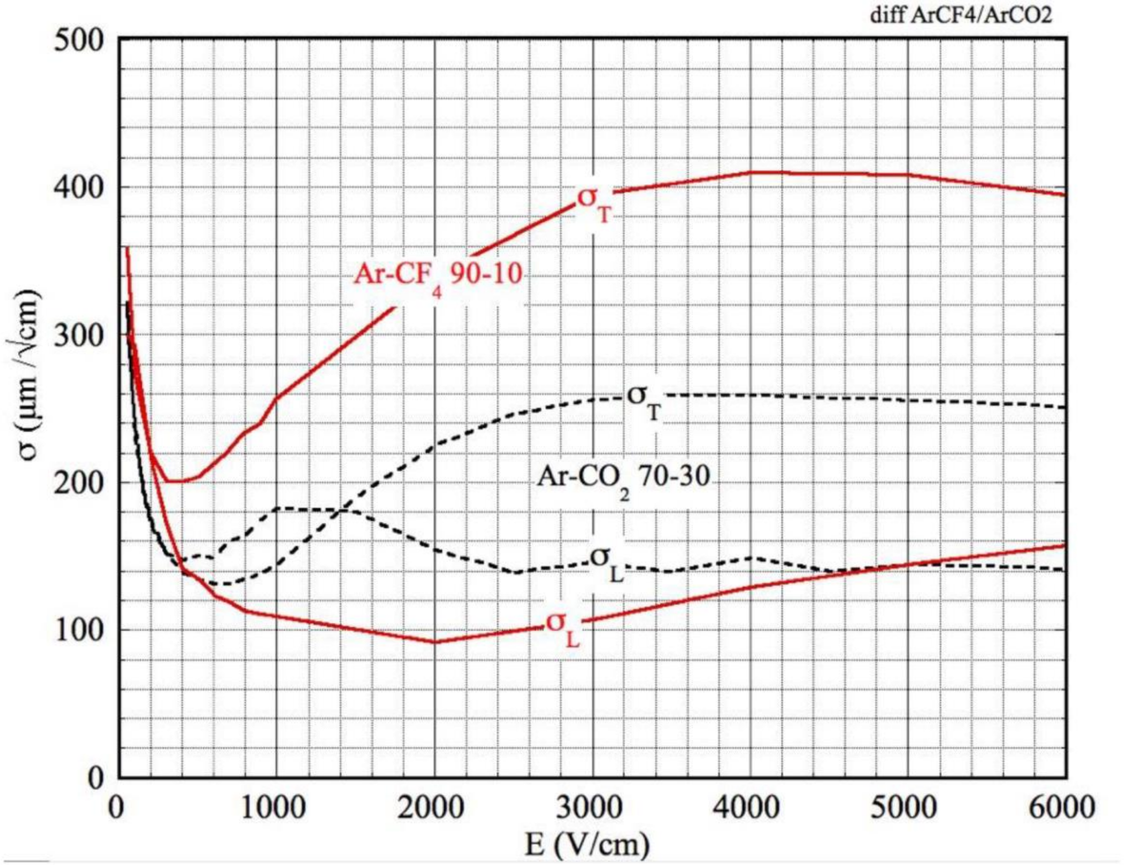
Low Electric Field



High Electric Field

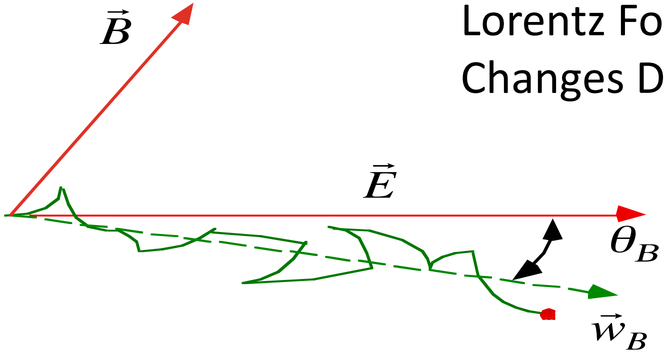


Better Longitudinal
(Drif) Accuracy



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

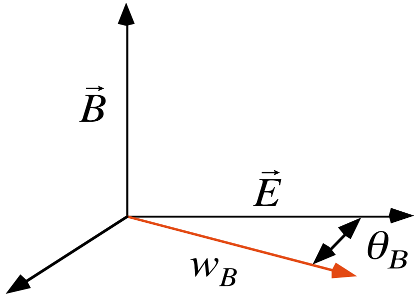
Drift of Electrons in Magnetic Field



Lorentz Force:
Changes Drift Velocity, Direction and Diffusion

Particular Cases:

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

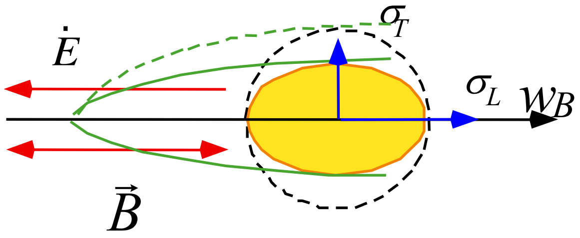


$$\tan\theta_B = \omega\tau \qquad w_B = \frac{E}{B}\frac{\omega\tau}{\sqrt{1+\omega^2\tau^2}}$$

$\omega = eB/m$ *Larmor frequency*

τ *: Average time between electron-molecule collisions*

$\vec{E} \,//\, \vec{B}$

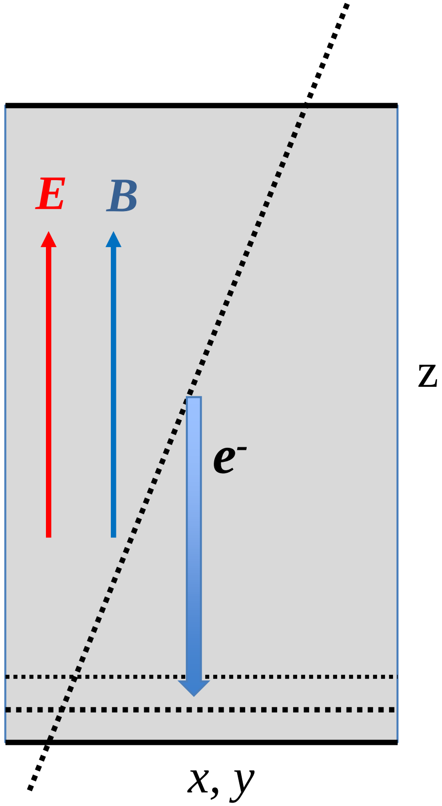


$$w_B = w_0$$
$$\sigma_L = \sigma_0$$
$$\sigma_T = \frac{\sigma_0}{\sqrt{1+\omega^2\tau^2}}$$

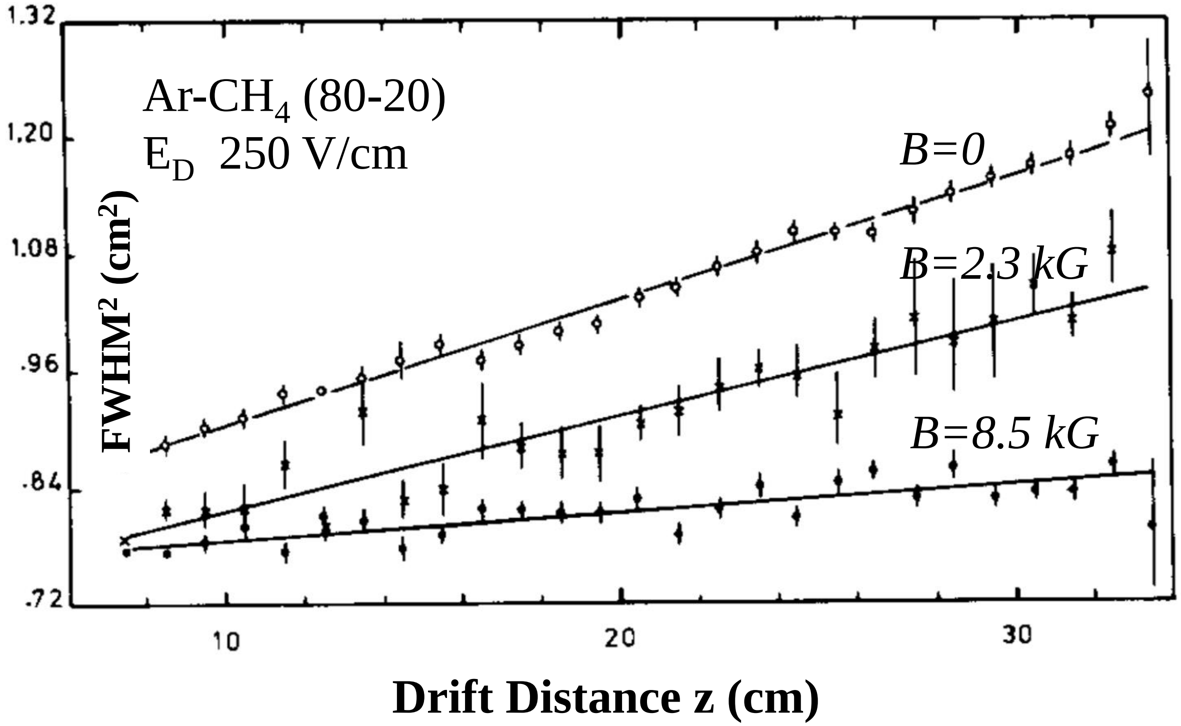
Time Projection Chambers:
Better Transverse (X-Y)
Position Resolution

Drift of Electrons in Magnetic Field: E // B

Time Projection Chambers:
Longitudinal Position Accuracy vs Drift Length



Magnetic Field Dependence:

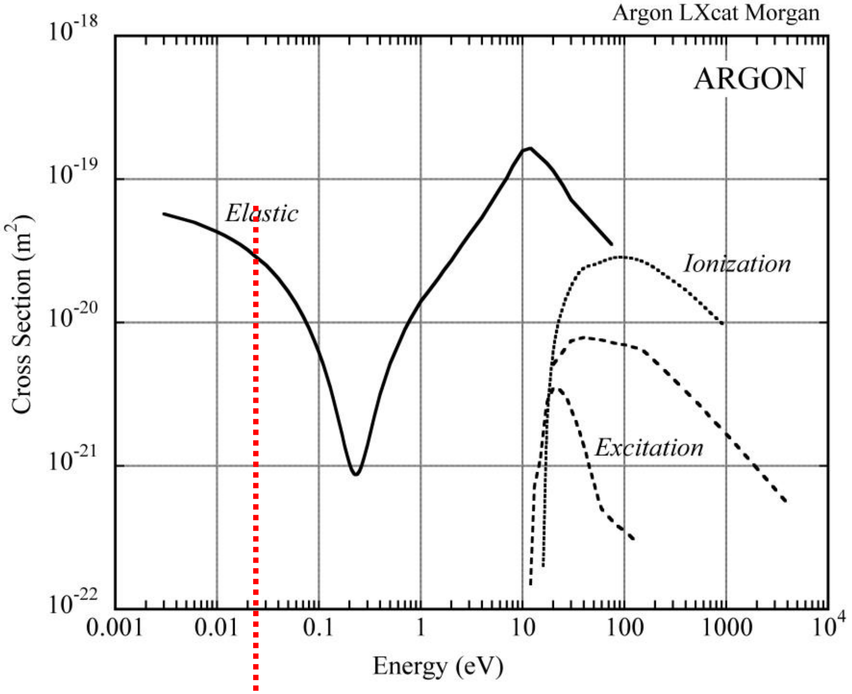


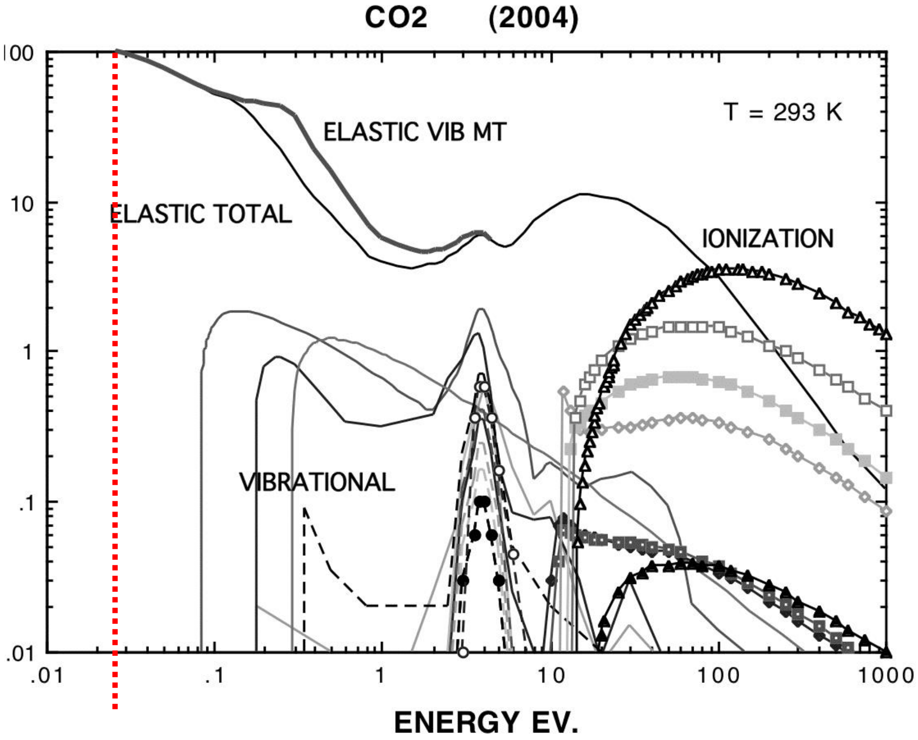
C. Hargrove et al, Nucl. Instr. Meth. 219(1984)481

Depends from Gas and Fields

Electron-Molecule Collisions

Eletron-Molecule Cross Section at Increasing Electric Fields:





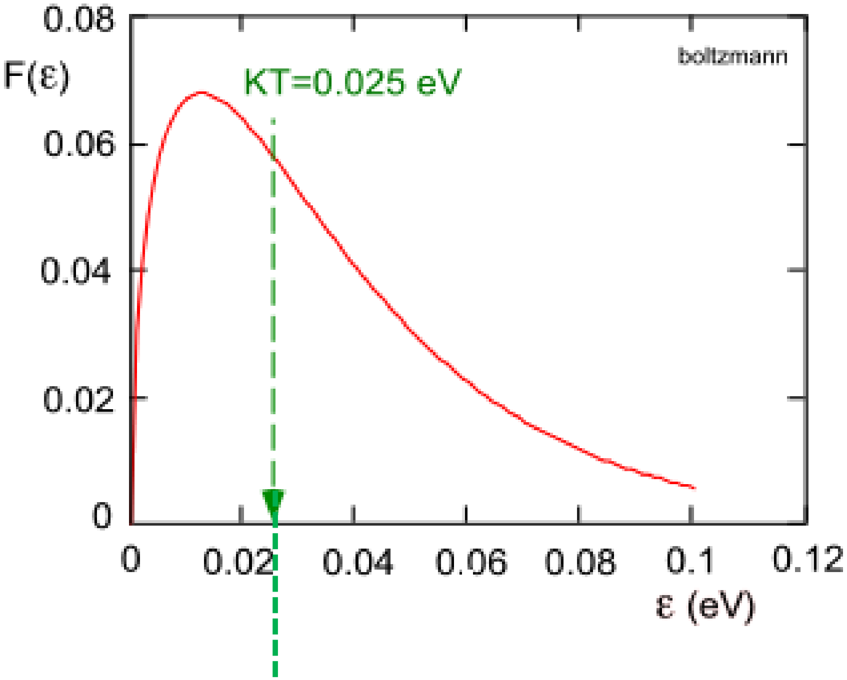
Thermal

0.025 eV @ 20 ^{0}C

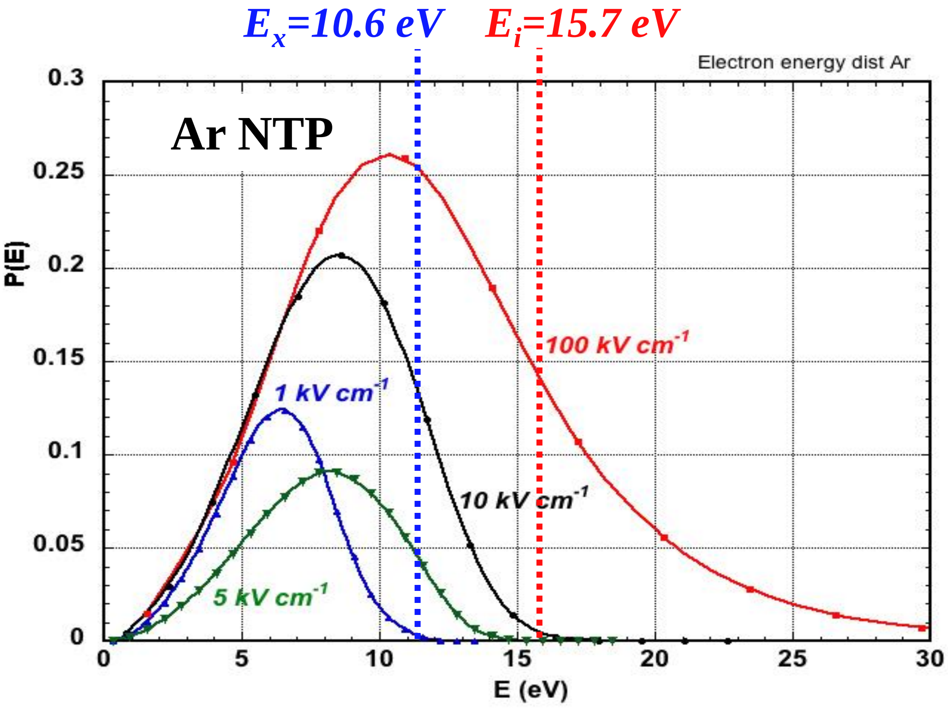
https://nl.lxcat.net/home/

Electrons Energy Distribution

Room Temperature E=0
Electrons in Any Gas:



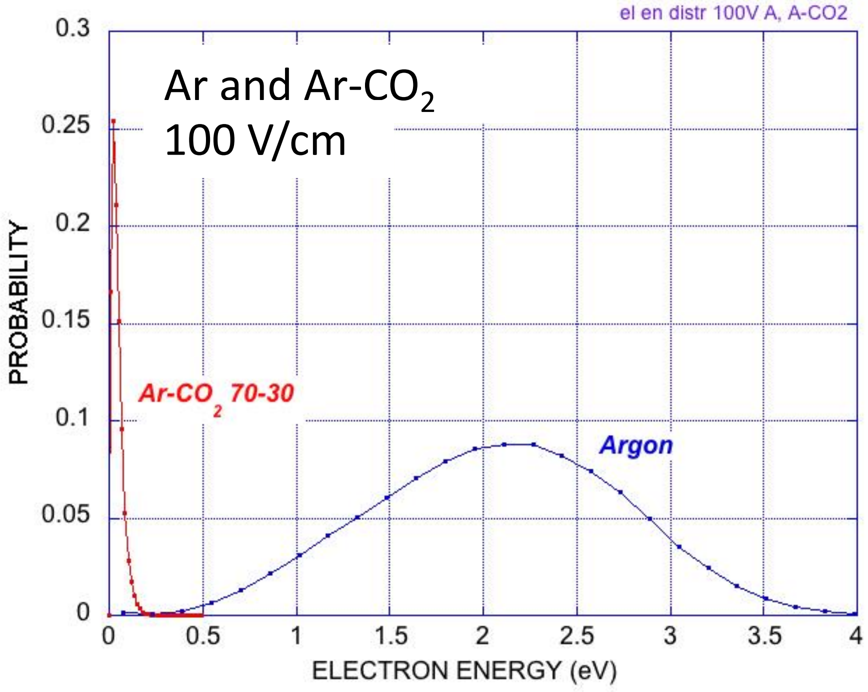
High Electric Fields: Pure Argon

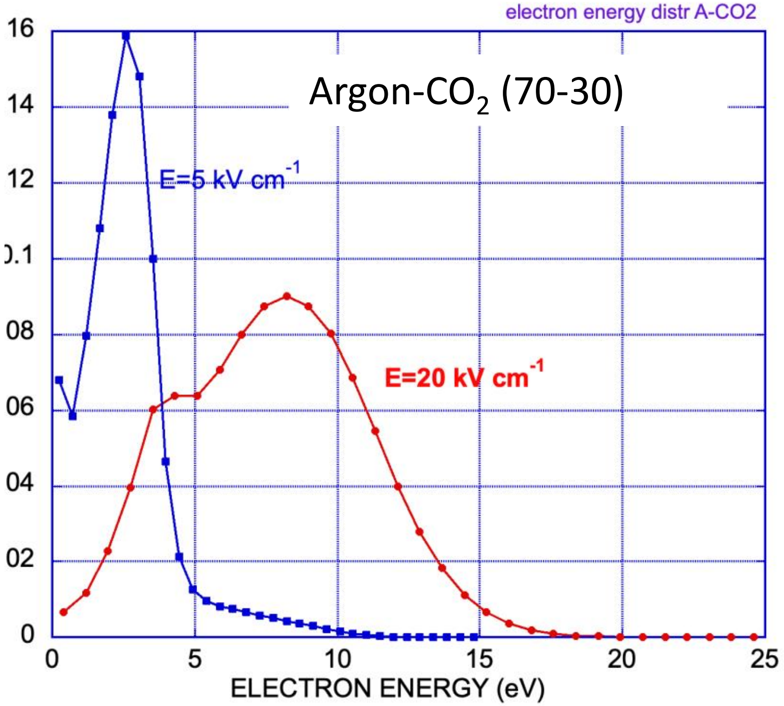


	E_X (eV)	E_I (eV)
ARGON	11.6	15.8
CO_2	5.2	13.7

Electrons Energy Distribution

“Cooling” Effect of Molecular Gas Additions





Inelastic Electron-Molecule Collisions

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	Fluorescence
$e + A^+ \rightarrow A + \gamma$	Radiative recombination	
$A^+ + B \rightarrow AB + \gamma$.	Radiative recombination	
$e + M \rightarrow M^- + \gamma$	Radiative capture	
$A^* + A \rightarrow A^*_2 \rightarrow A + A + \gamma$	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

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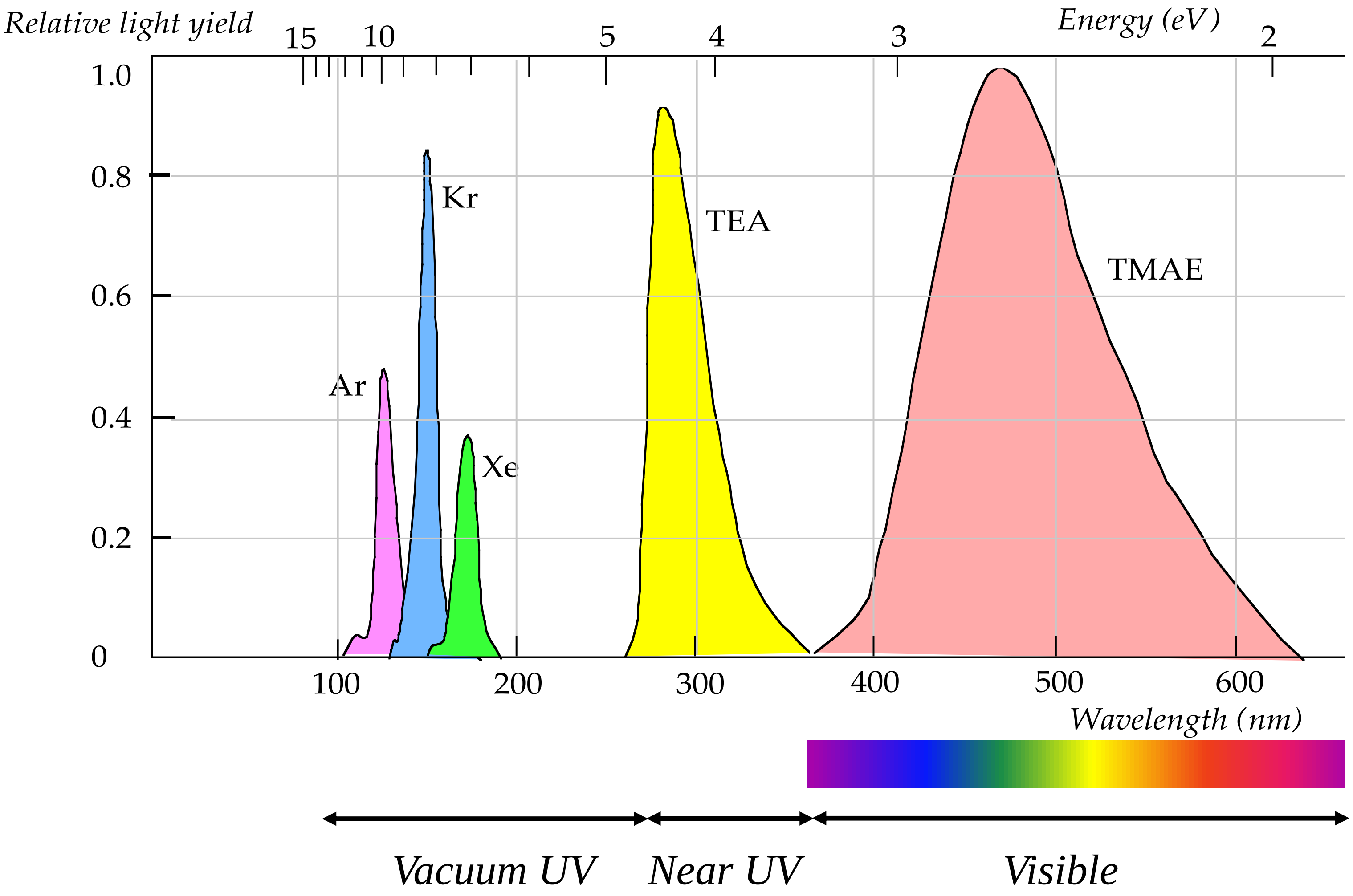
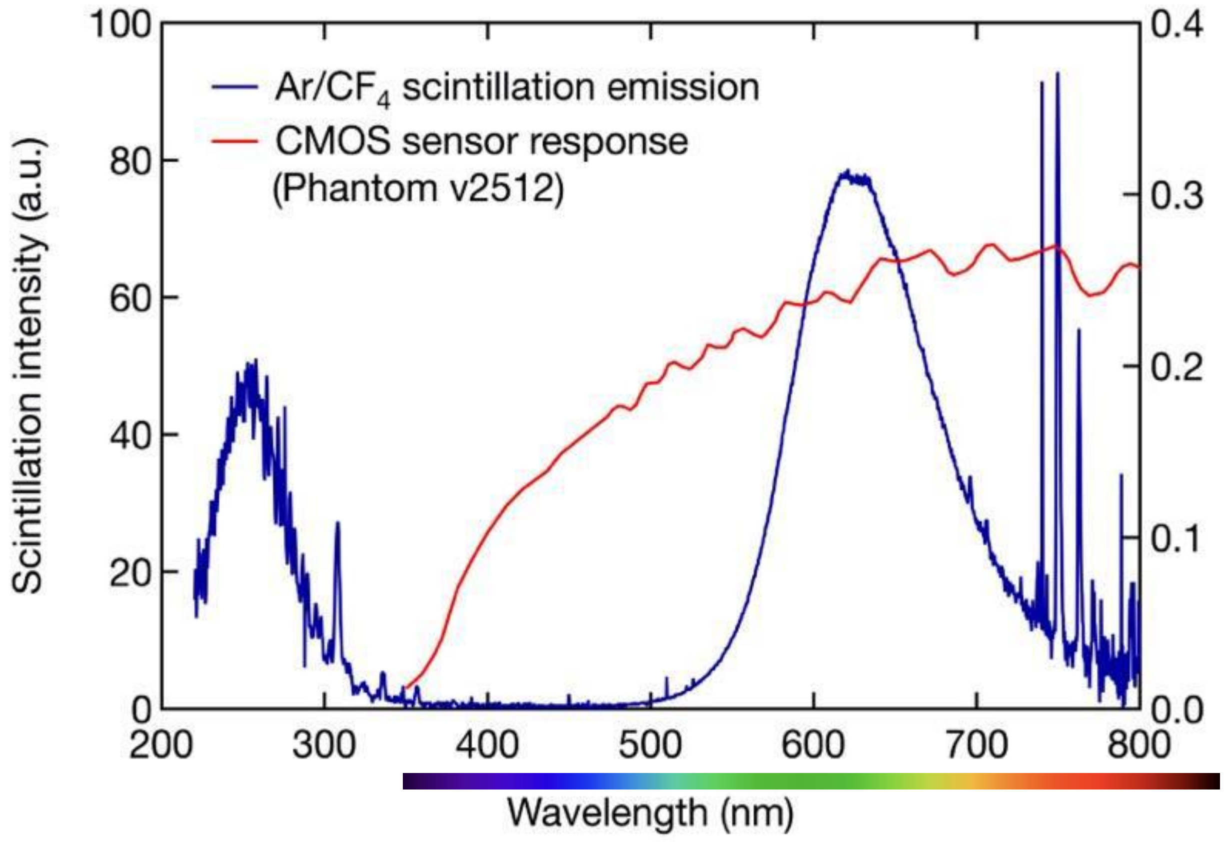
Fluorescence ad Scintillation

Noble Gases and Low Ionization Potential Vapors:



Fluorescence ad Scintillation

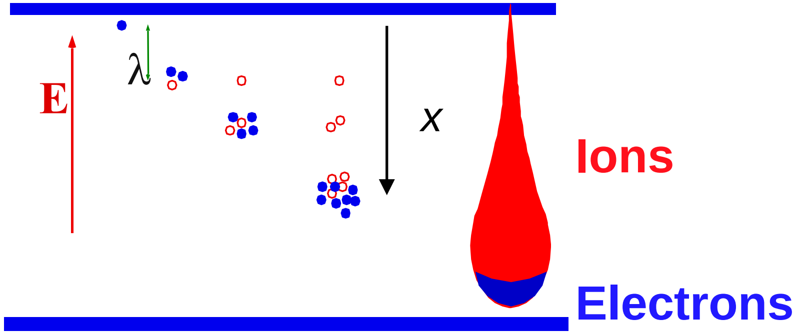
CF4 Scintillation:



F. Brunbauer, CERN GDD (2020)

Decay of Excited Molecular States:
$(CF_3^+)^*$
and
$(CF_4^+)^*$

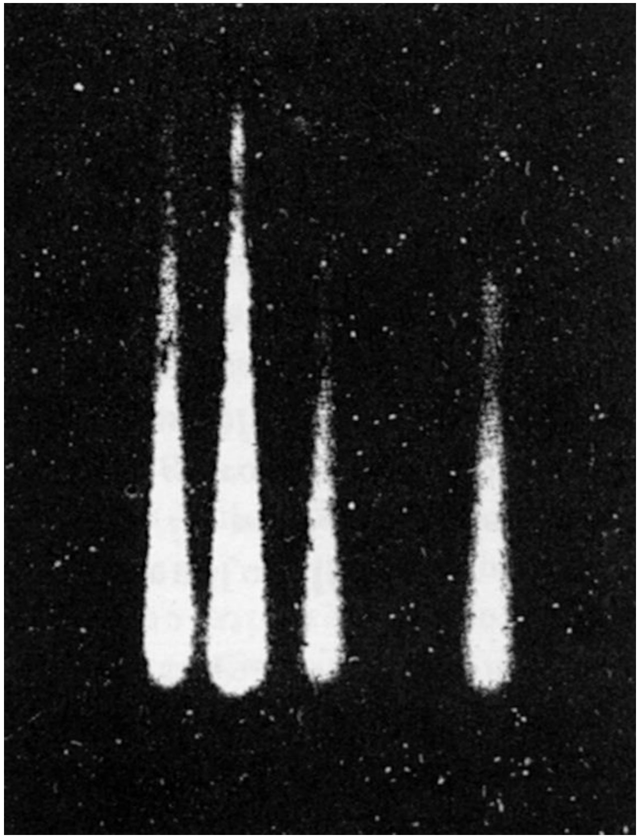
High Fields : Charge Multiplication



$$n(x) = n_0 e^{a\,x}$$ α = α(E): *Townsend coefficient*

$$M(x) = \frac{n}{n_0} = e^{a\,x}$$ *Charge Gain*

Cloud chamber Images of Avalanches:

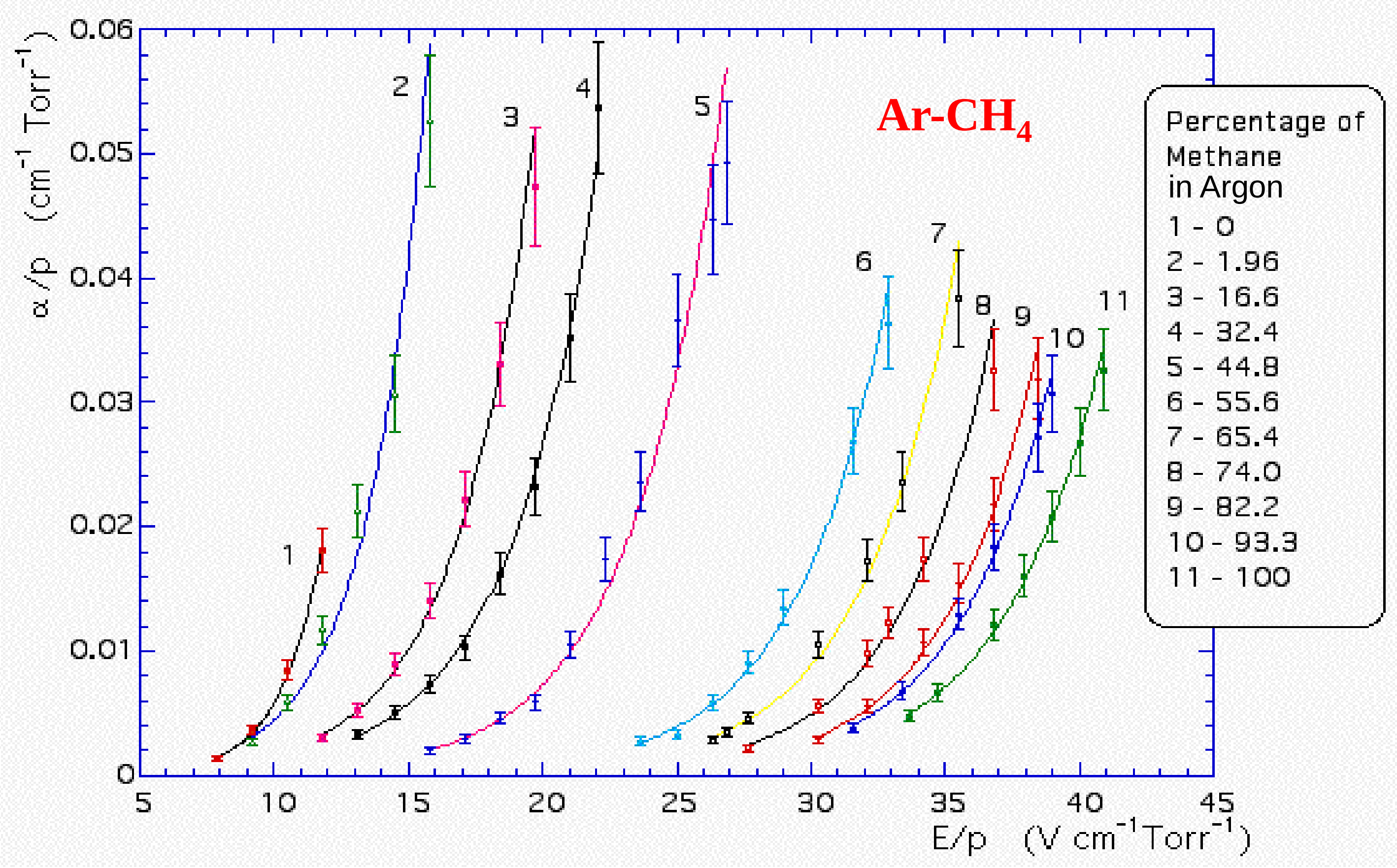


H. Raether
Electron Avalanches and Breakdown in Gases (Butterworth 1964)

Charge Multiplication

Townsend Coefficient α in Ar-Methane Mixtures

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



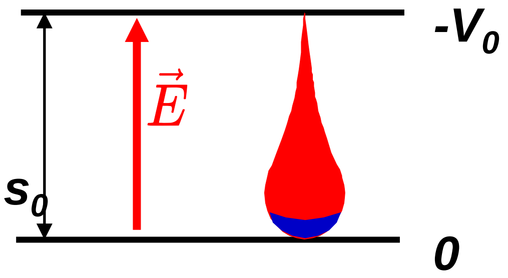
Percentage of Methane in Argon

1 -	0
2 -	1.96
3 -	16.6
4 -	32.4
5 -	44.8
6 -	55.6
7 -	65.4
8 -	74.0
9 -	82.2
10 -	93.3
11 -	100

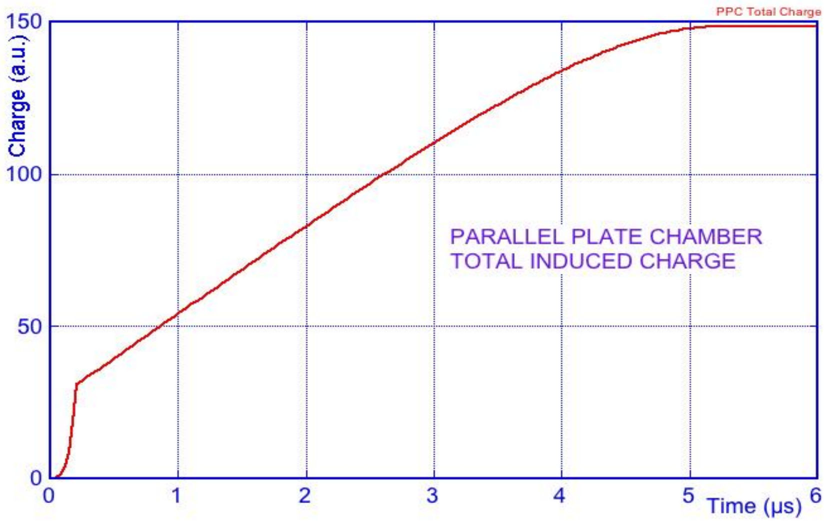
A. Sharma and F. Sauli, Nucl. Instr. and Meth. A334(1993)420

Charge Multiplication

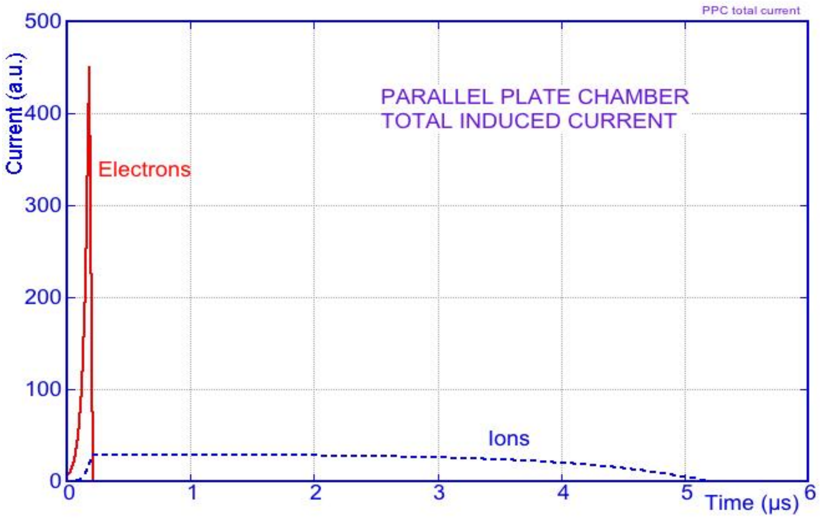
Parallel Plate Counter



Induced Charge on Anode:



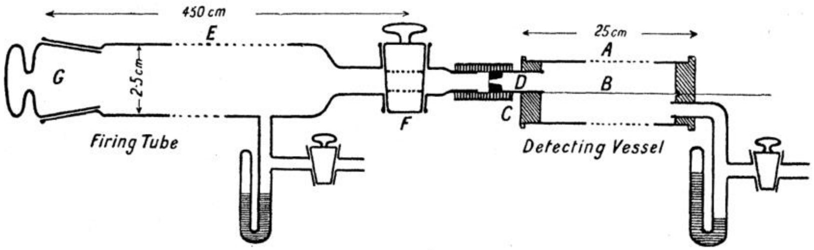
Induced Current on Anode:



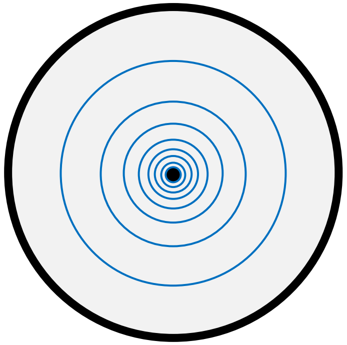
On Cathode: $Q_C(t) = - Q_A(t)$ $I_C(t) = - I_A(t)$

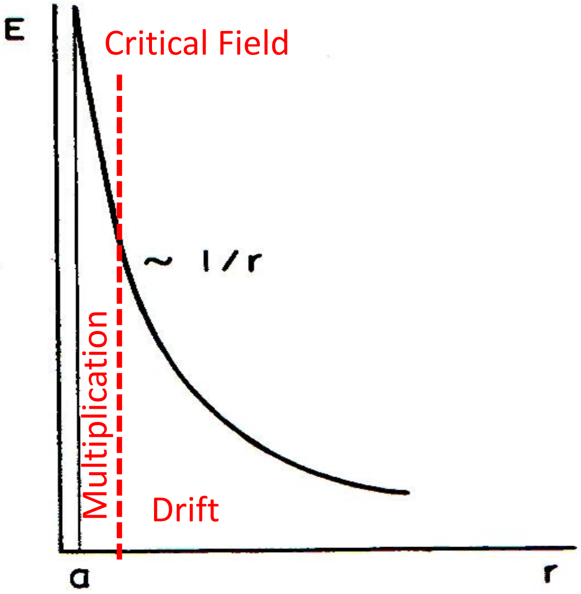
PROPORTIONAL COUNTER

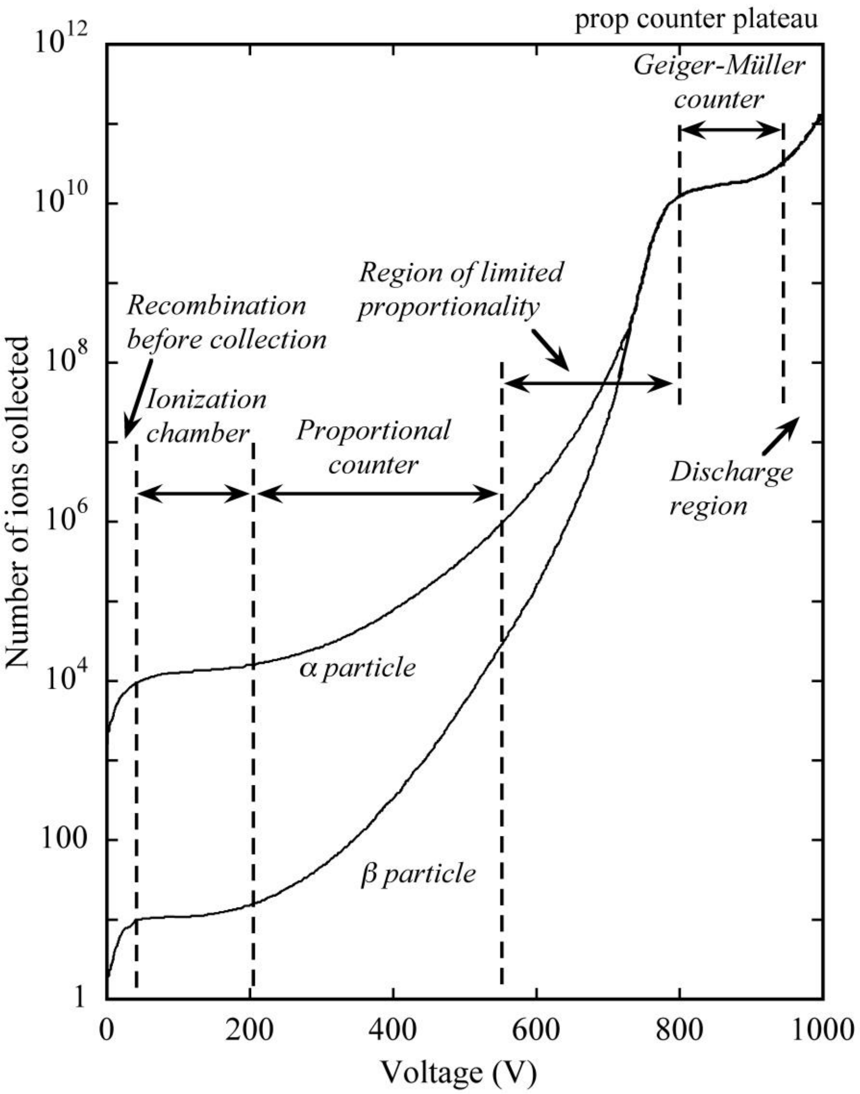
Single Wire Counter
Rutherford and Geiger (1908)



Radial Electric Field







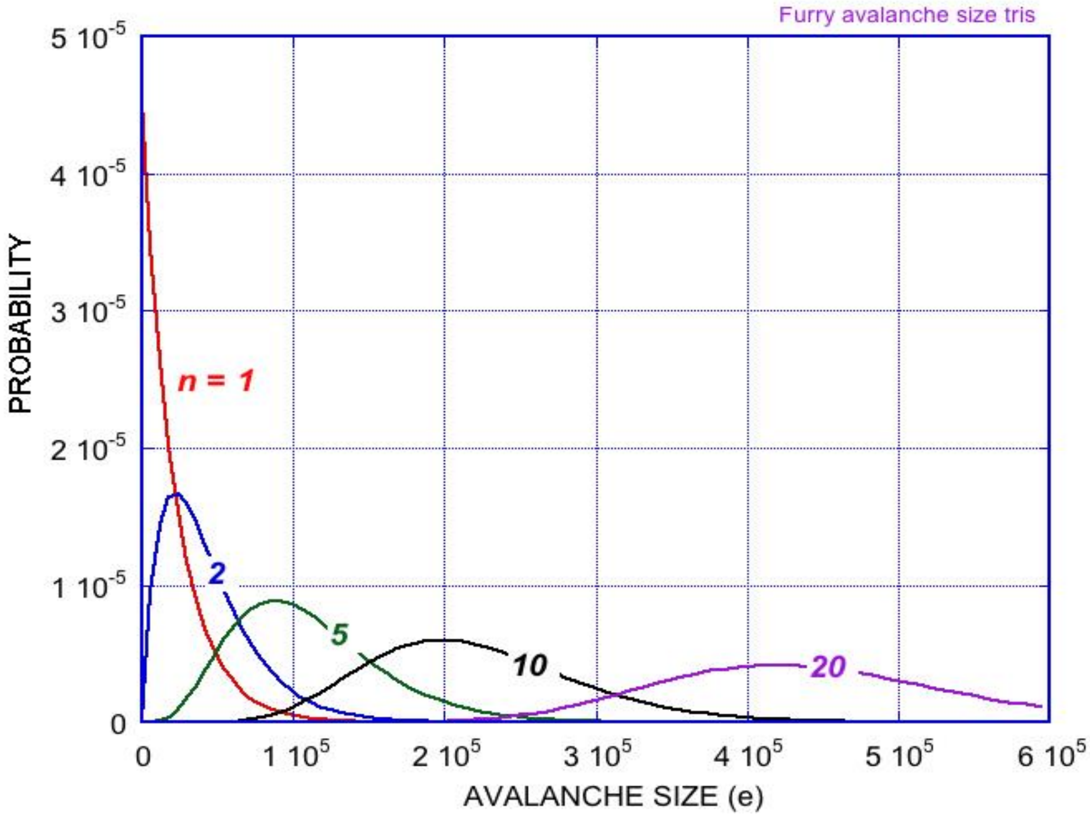
Charge Multiplication

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:

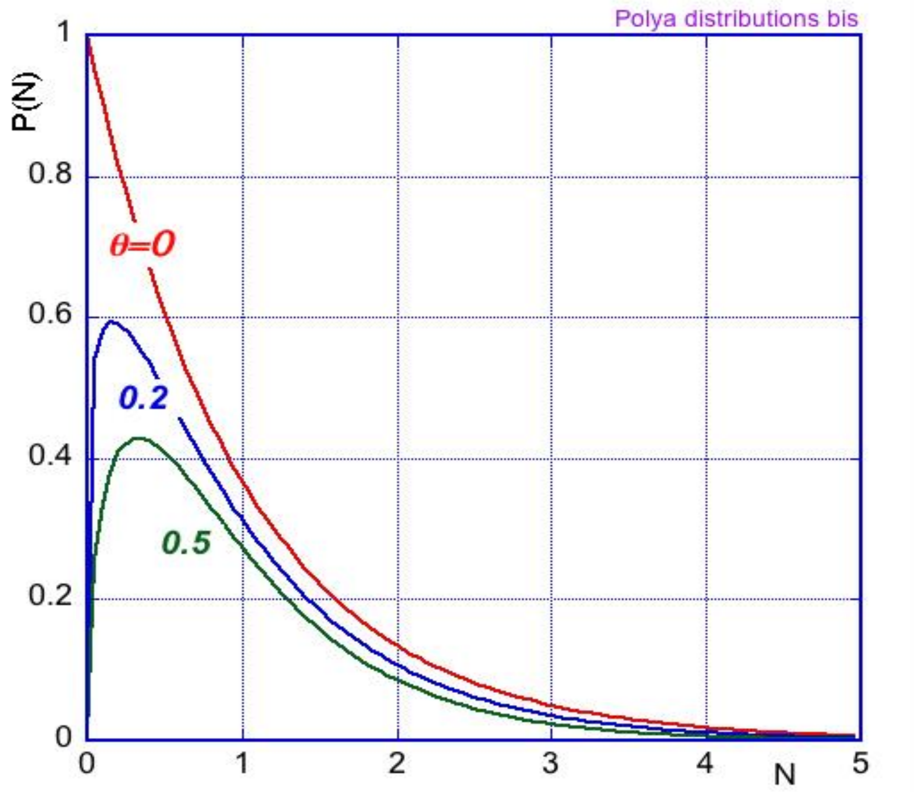
$$P(n,N) = \left(\frac{N}{\overline{N}}\right)^{n-1} \frac{e^{-\frac{N}{\overline{N}}}}{(N-1)!}$$



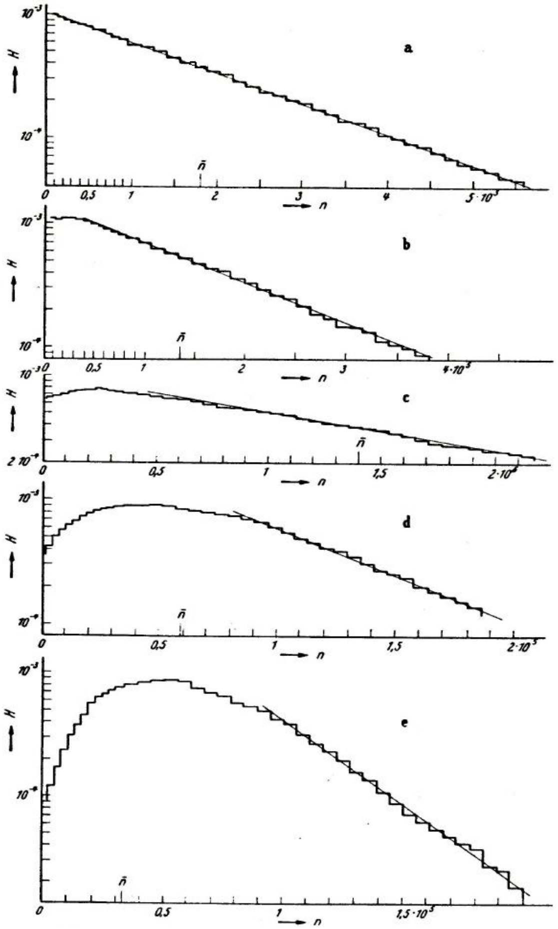
Charge Multiplication

Avalanche Size Probability at
High Fields (High Gains)
Polya function:

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



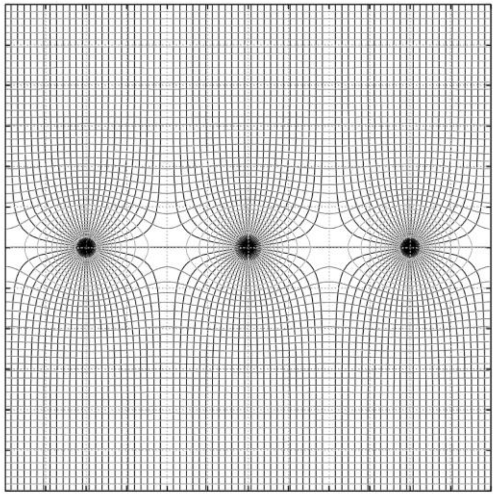
Single Electron Avalanche Size
at Increasing Gains (Experimental):



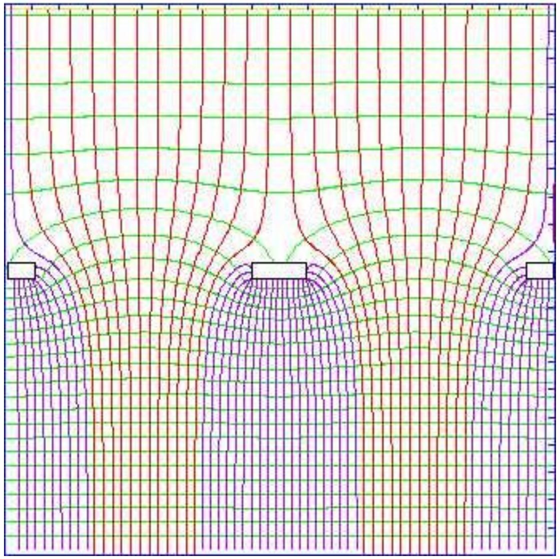
H. Sclumbohm, Zeit. Physik 151(1958)563

GASEOUS COUNTERS: MWPCs TO MPGDs

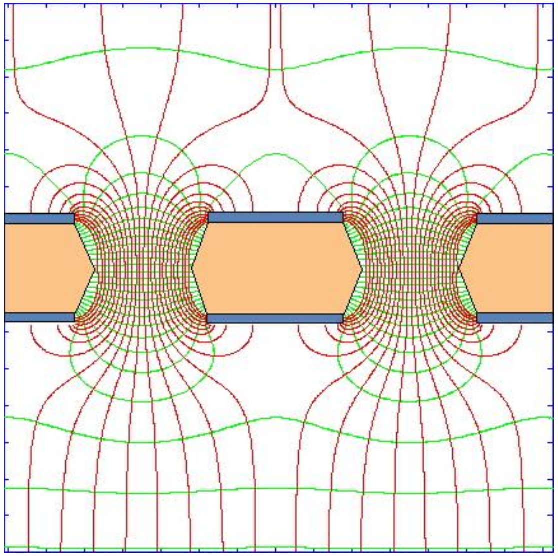
MWPC



MICROMEGAS



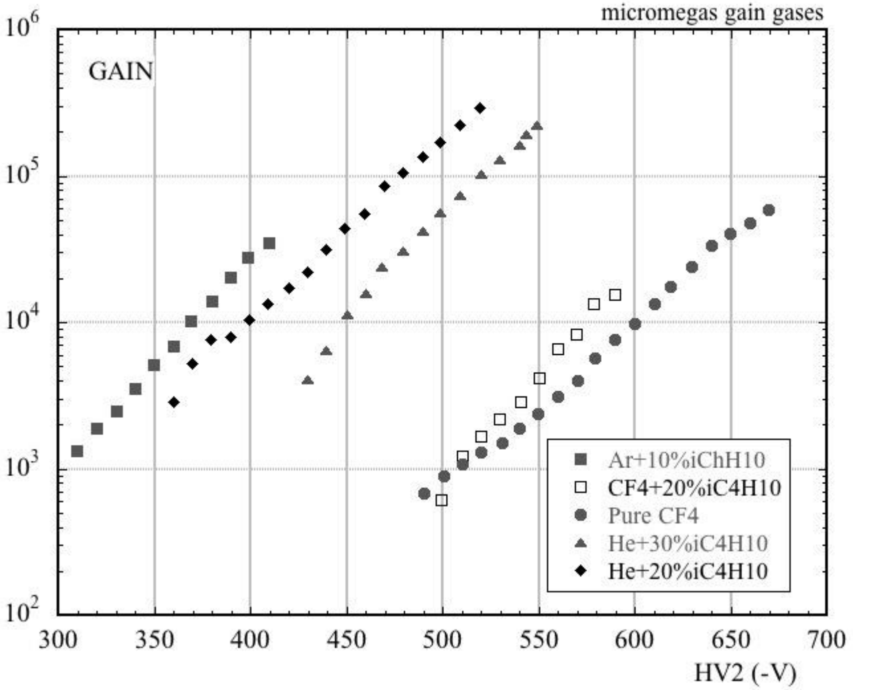
GEM



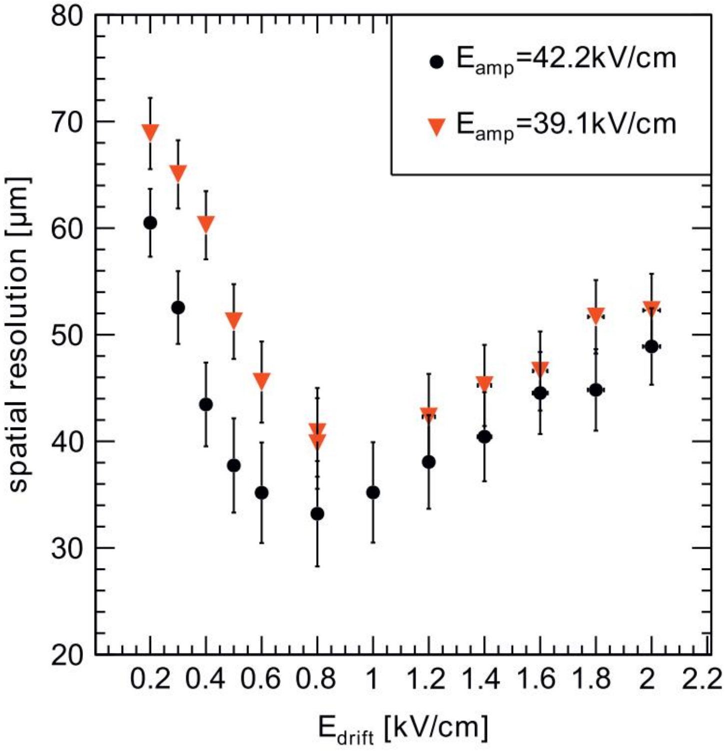
+ MiroGroove, MicroGap,MicroPixel
Resistive Plate Well ………..

MICROMEGAS

Proportional Gain

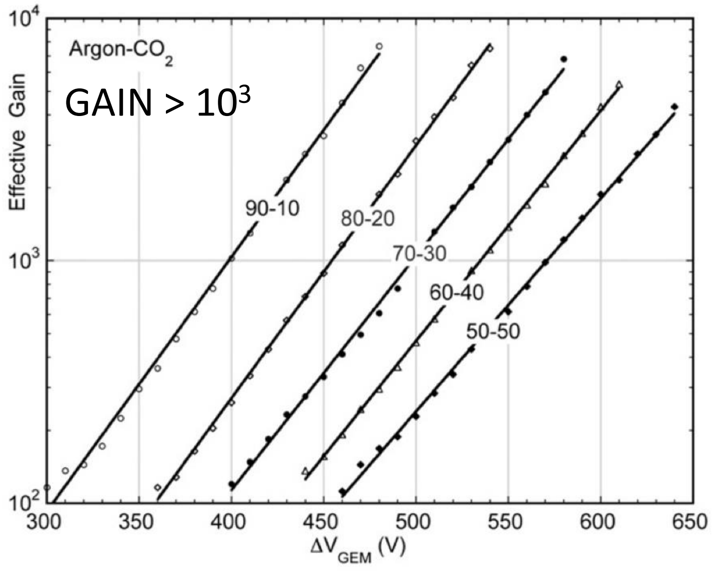


Localization Accuracy for MIPs

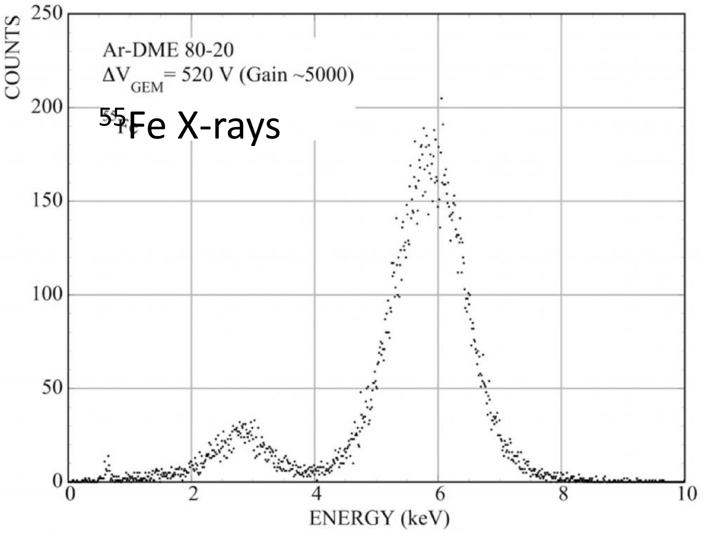


J. Bortfieldt et al, Nucl. Instr. Meth. 718A(2013)406

GEM

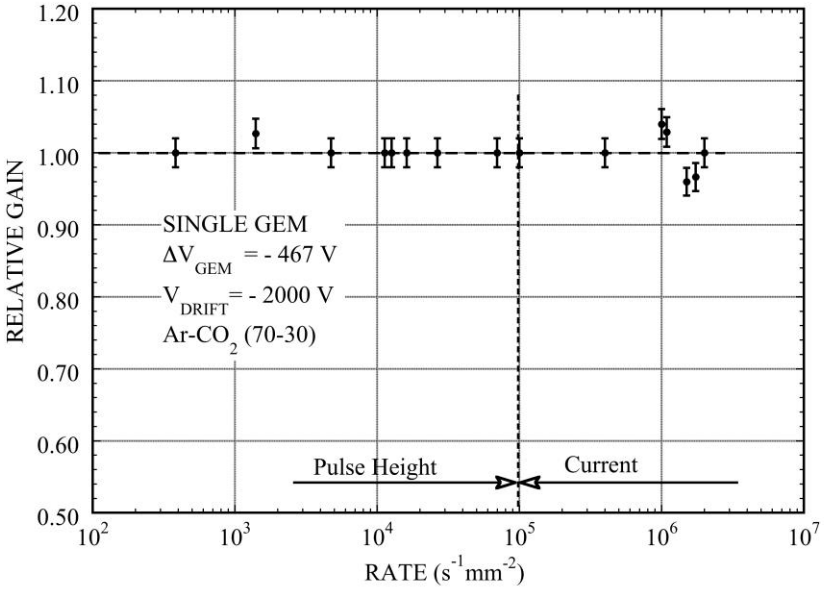


GAIN > 10^3



^{55}Fe X-rays

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



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

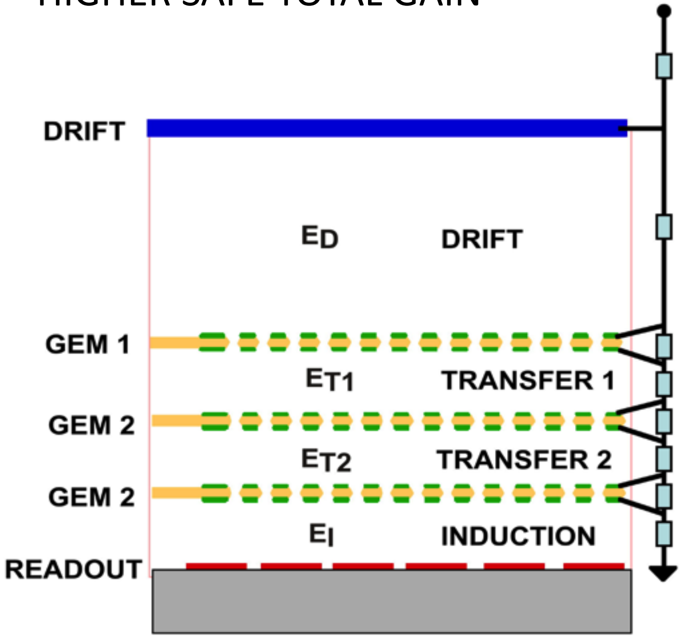
MULTIGEM

TRIPLE-GEM

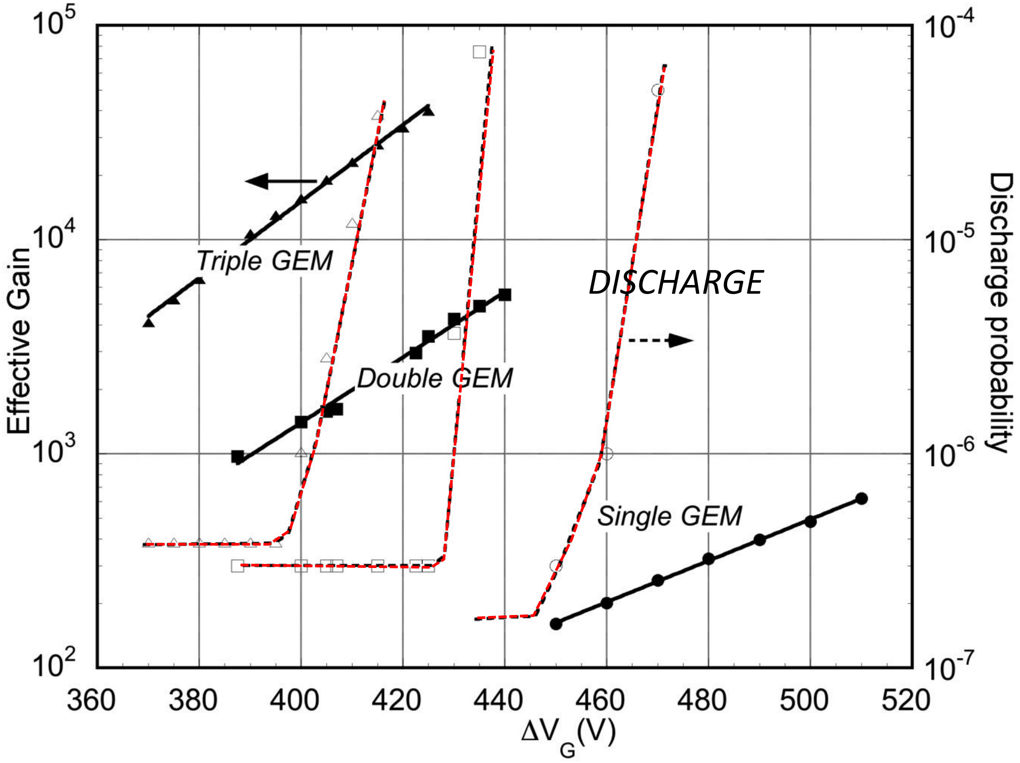
CASCADED GEM ELECTRODES

LOWER VOLTAGE ON EACH GEM

HIGHER SAFE TOTAL GAIN



GAIN AND DISCHARGE PROBABILITY ON 5 MeV α

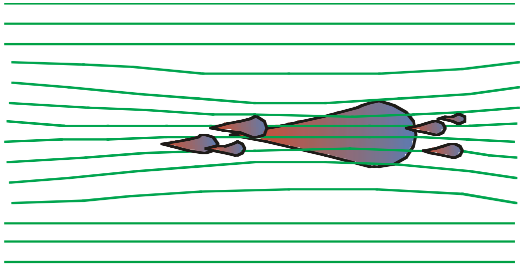


C. Büttner et al, Nucl. Instr. and Meth. A409(1998)79

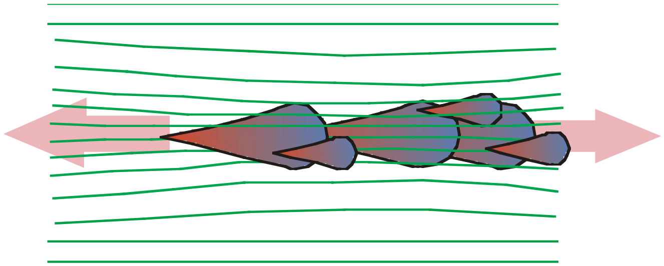
Very High Fields:
Transition Avalanche → Streamer → Discharge

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:

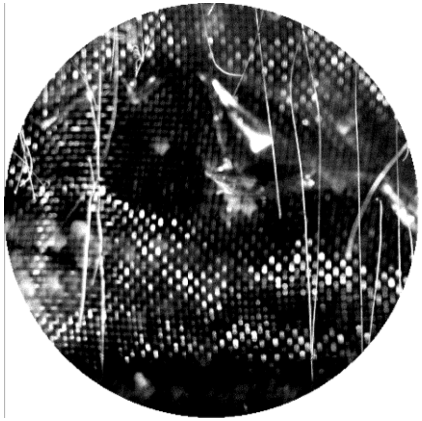


DISCHARGE !

Raether Limit: ~ 10^7 electrons-ions

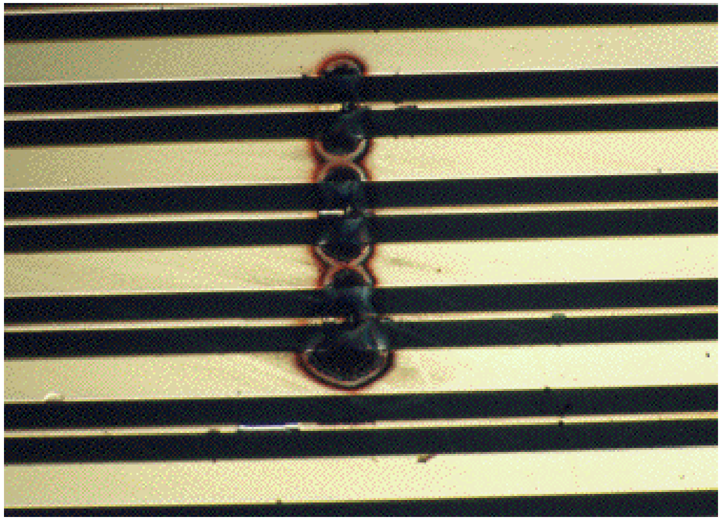
Discharge

Destructive Effects of Discharges:



Drift Chamber (1974)

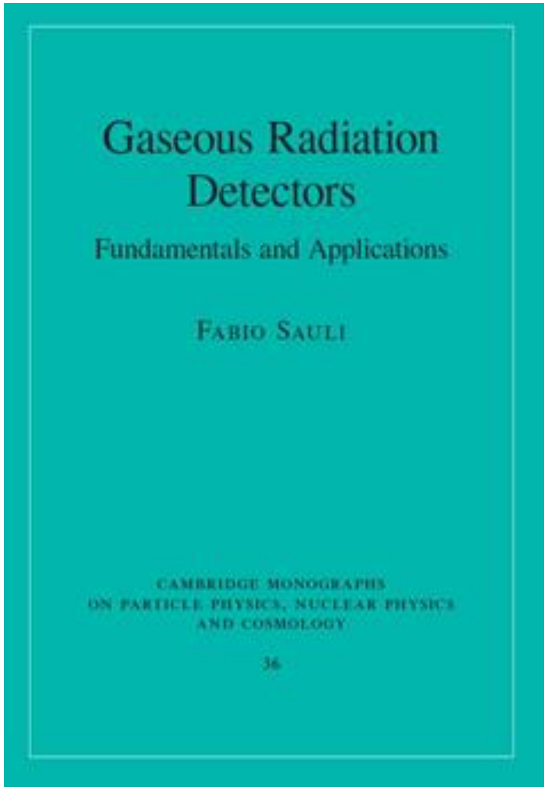
MSGC (1994)



Discharge Prevention and Mitigation in MPGDs:

Piotr Gasik: GAS DETECTORS PHYSICS 2

To Know More on Gaseous Detectors:



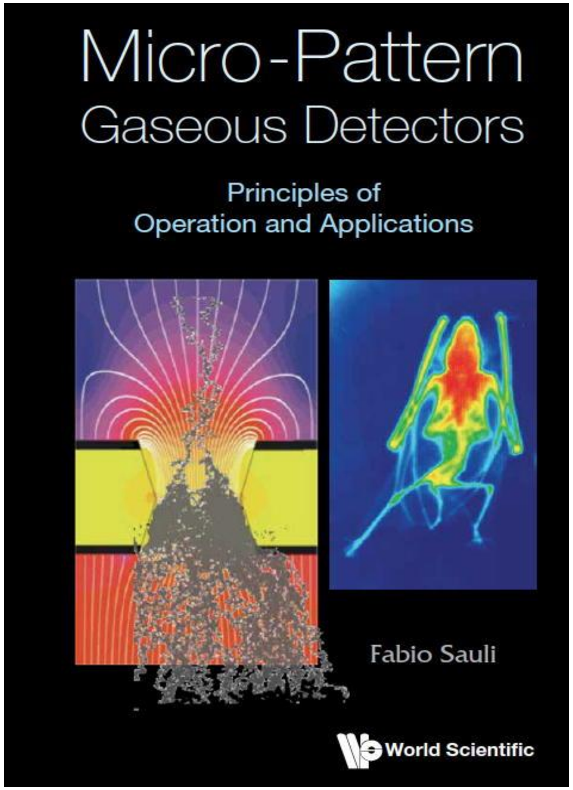
Gaseous Radiation Detectors

Fundamentals and Applications

FABIO SAULI

CAMBRIDGE MONOGRAPHS ON PARTICLE PHYSICS, NUCLEAR PHYSICS AND COSMOLOGY

36

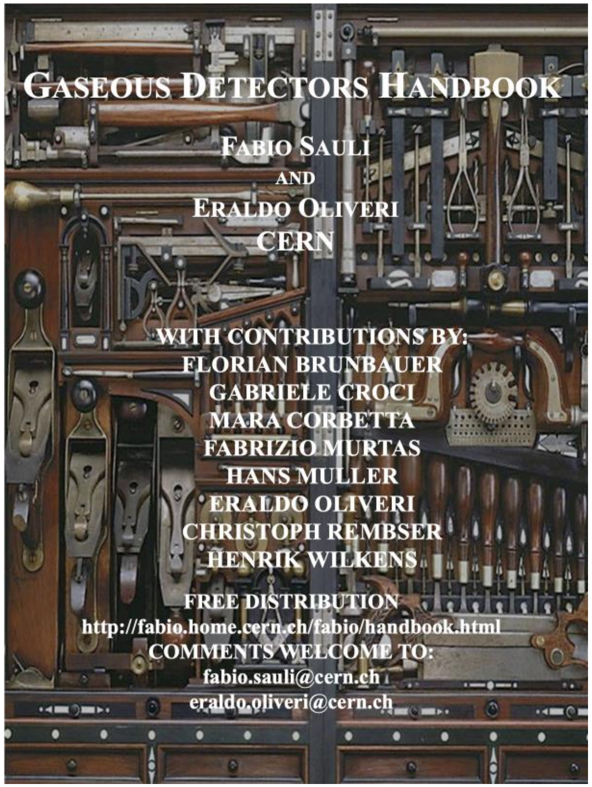


Micro-Pattern Gaseous Detectors

Principles of Operation and Applications

Fabio Sauli

World Scientific



GASEOUS DETECTORS HANDBOOK

FABIO SAULI
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ERALDO OLIVERI
CERN

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…. and the other lectures at this School!