Fundamental of the Gas Detectors

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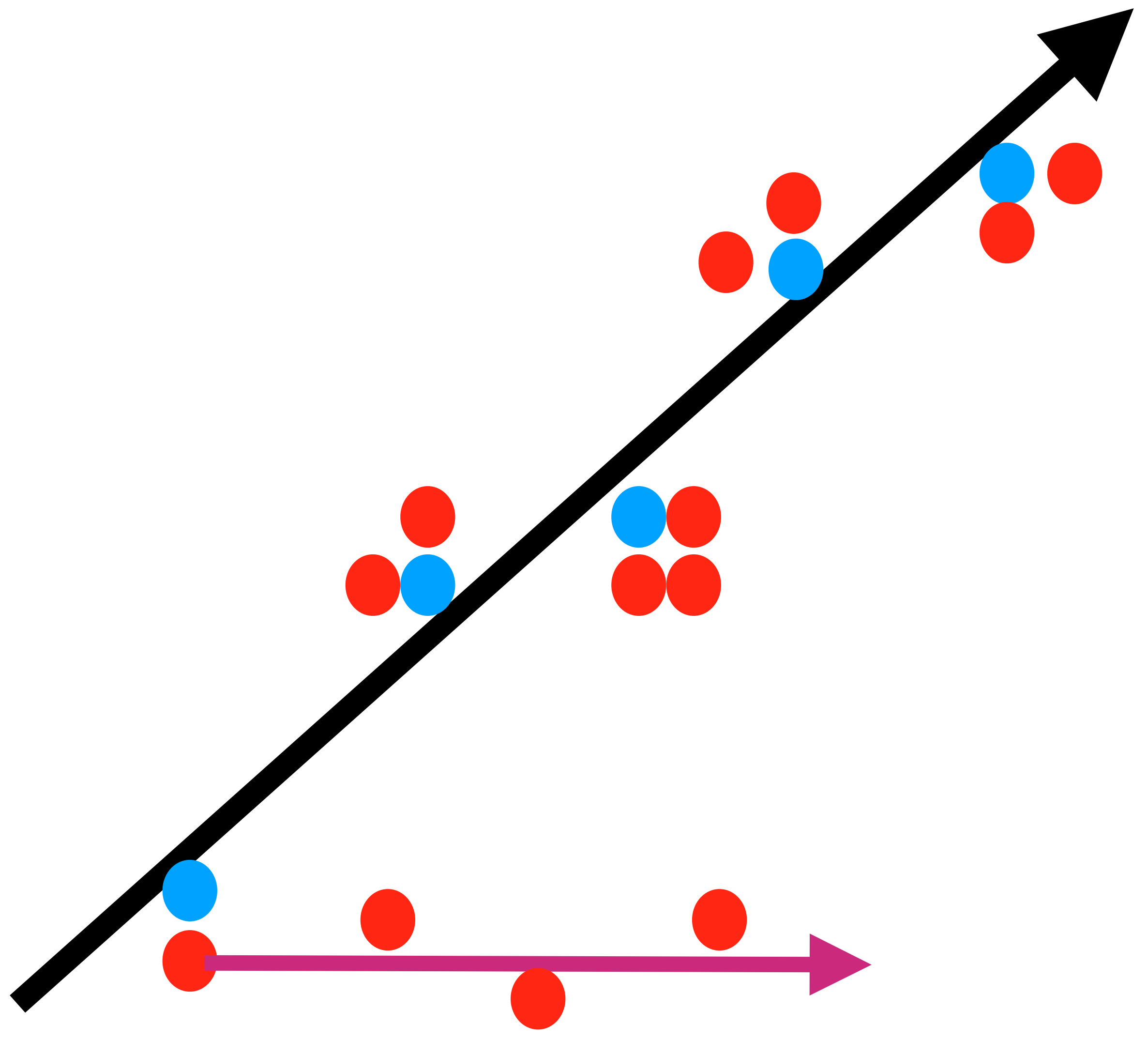
Introduction

Gas Ionization by Fast Charged Particles:



Ionizing Radiation
Primary Electrons
Secondary Electrons
Delta rays (~keV)

- A fast charged particle, traversing a gaseous or condensed medium, can interact with it in many ways.

- Most dominant one is Coulomb interactions between the electromagnetic fields of the incoming charged particle and of the medium, resulting in both excitation and ionization of the atoms of the medium itself.

- The contribution of other electromagnetic processes (at least for particles heavier than electrons), such as bremsstrahlung, Cherenkov, and transition radiation, to the total energy loss is negligible in gas detectors and we will ignore them in our discussion.

Ionizing Collisions:

The encounters with the gas atoms are purely random and are characterized by a mean free flight path λ between ionizing encounters given by the ionization cross-section per electron σ_I and the density N of electrons:

$$\lambda = 1/(N\sigma_I)$$

Therefore, the number of encounters along any length L has a mean of L/λ, and the frequency distribution is the Poisson distribution:

$$P(L/\lambda, k) = \frac{(L/\lambda)^k}{k!} \exp(-L/\lambda)$$

Gas	1 cm/λ	γ
H_2	5.32 ± 0.06	4.0
	4.55 ± 0.35	3.2
	5.1 ± 0.8	3.2
He	5.02 ± 0.06	4.0
	3.83 ± 0.11	3.4
	3.5 ± 0.2[a]	3.6
Ne	12.4 ± 0.13	4.0
	11.6 ± 0.3[a]	3.6
Ar	27.8 ± 0.3	4.0
	28.6 ± 0.5	3.5
	26.4 ± 1.8	3.5
Xe	44	4.0
N_2	19.3	4.9
O_2	22.2 ± 2.3	4.3
Air	25.4	9.4
	18.5 ± 1.3	3.5

Different Ionization Mechanisms:

In primary ionization, one or sometimes two or three electrons are ejected from the atom **A** encountered by the fast particle

$\pi A \rightarrow \pi A^+ e^-, \pi A^{++} e^- e^-, \ldots$

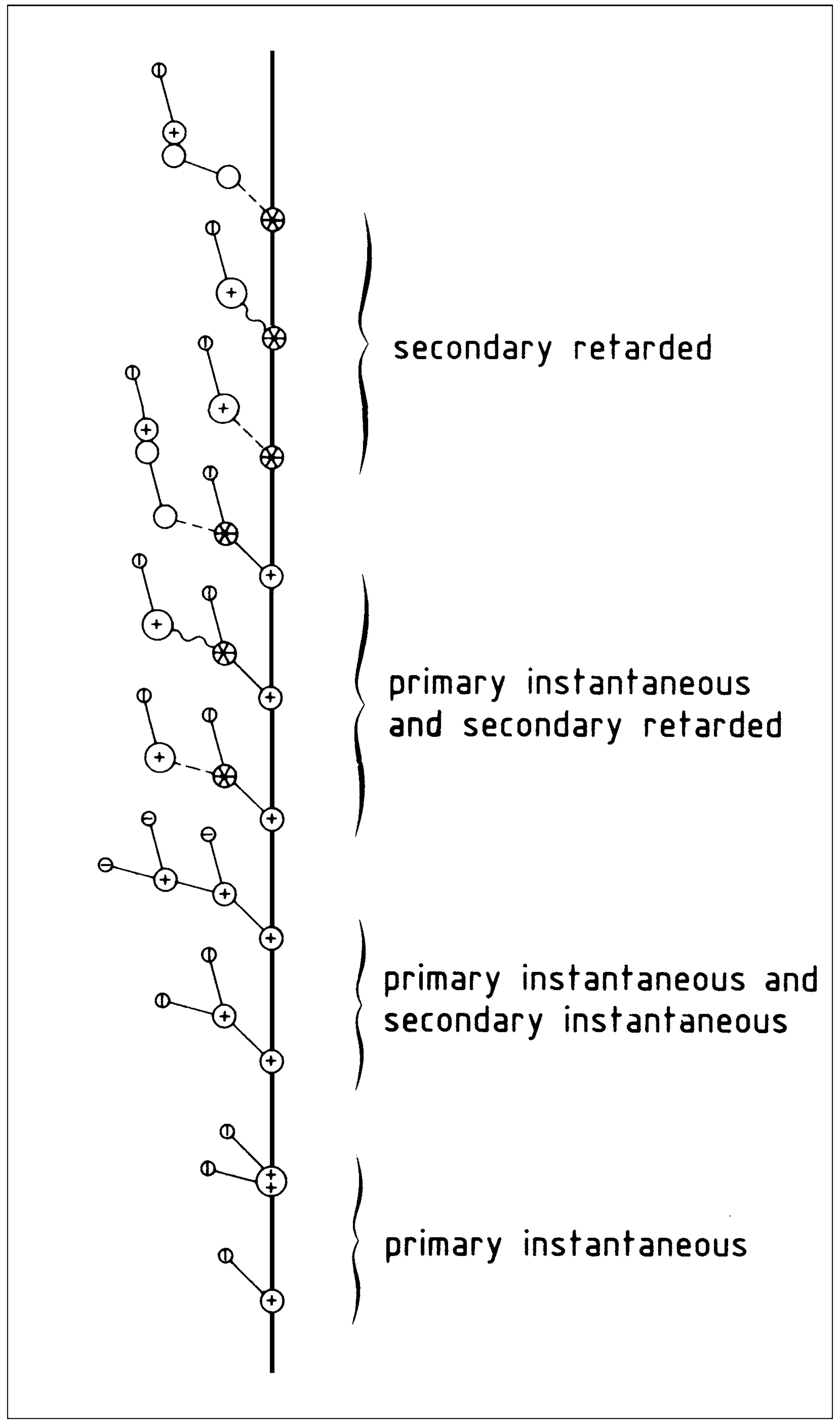
Most of the charge along a track is from secondary ionization where the electrons are ejected from atoms not encountered by the fast particle. This happens either in collisions of ionization electrons with atoms,

$$e^- A \rightarrow e^- A^+ e^-, \quad e^- A^{++} e^- e^-$$

or through intermediate excited states $A*$. An example is the following chain of reactions involving the collision of the excited state with a second species, B, of atoms or molecules that is present in the gas:

$\pi A \rightarrow \pi A^*$ or $e^- A \rightarrow e^- A^*$ $\quad A^* B \rightarrow A B^+ e^-$

Penning effect (involving metastable) and *Jesse effect* (involving optical excitations)



Average Energy Required to Produce One Ion Pair

Only a certain fraction of all the energy lost by the fast particle is spent in ionization. The total amount of ionization from all processes is characterized by the energy W that is spent, on the average, on the creation of one free electron.

$$W < N_I > = L < dE/dx >$$

Energy *W* spent, on the average, for the creation of one ionization electron in various gases and gas mixtures; *W*α and *W*β are from measurements using α or β sources, respectively. The lowest ionization potential is also indicated:

Gas	W_α (eV)	W_β (eV)	I (eV)	Gas mixture[a]	W_α (eV)
H_2	36.4	36.3	15.43	Ar (96.5%) + C_2H_6 (3.5%)	24.4
He	46.0	42.3	24.58	Ar (99.6%) + C_2H_2 (0.4%)	20.4
Ne	36.6	36.4	21.56	Ar (97%) + CH_4 (3%)	26.0
Ar	26.4	26.3	15.76	Ar (98%) + C_3H_8 (2%)	23.5
Kr	24.0	24.05	14.00	Ar (99.9%) + C_6H_6 (0.1%)	22.4
Xe	21.7	21.9	12.13	Ar (98.8%) + C_3H_6 (1.2%)	23.8
CO_2	34.3	32.8	13.81	Kr (99.5%) + C_4H_8-2 (0.5%)	22.5
CH_4	29.1	27.1	12.99	Kr (93.2%) + C_2H_2 (6.8%)	23.2
C_2H_6	26.6	24.4	11.65	Kr (99%) + C_3H_6 (1%)	22.8
C_2H_2	27.5	25.8	11.40		
Air	35.0	33.8	12.15		
H_2O	30.5	29.9	12.60		

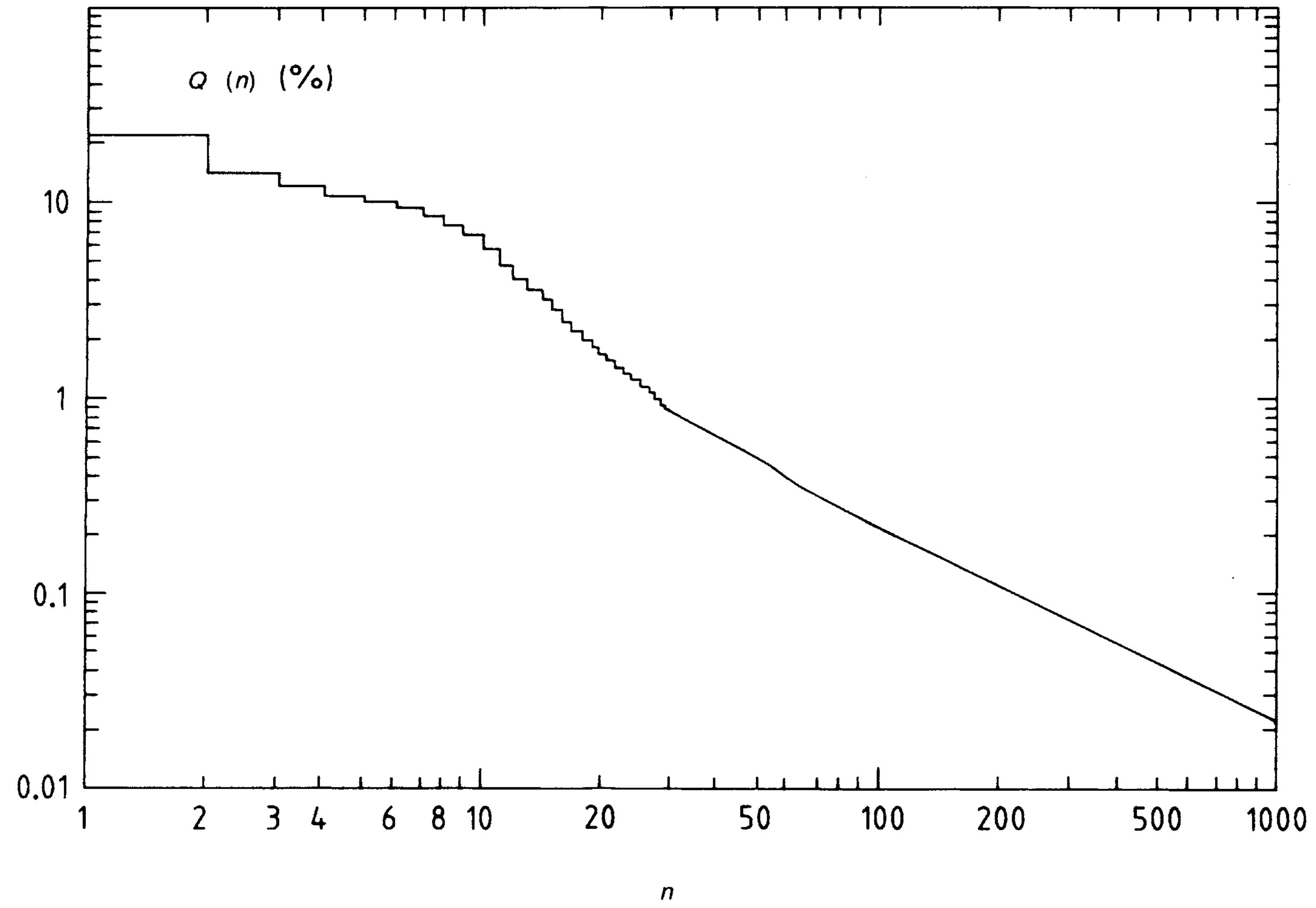
Cluster Size Distribution:

- An effective description of the ionization left by the particle along its trajectory is provided by a probability distribution of the number of electrons liberated directly or indirectly with each primary encounter.
- Because the secondary electrons are usually created in the immediate vicinity of the primary encounter and, together with the primary electrons, form clusters of one or several – sometimes many – electrons.
- Cluster-size distribution P(k)

$$P(k) = \int F(E)p(E,k)\mathrm{d}E$$

spectrum of energy loss= F(E) dE

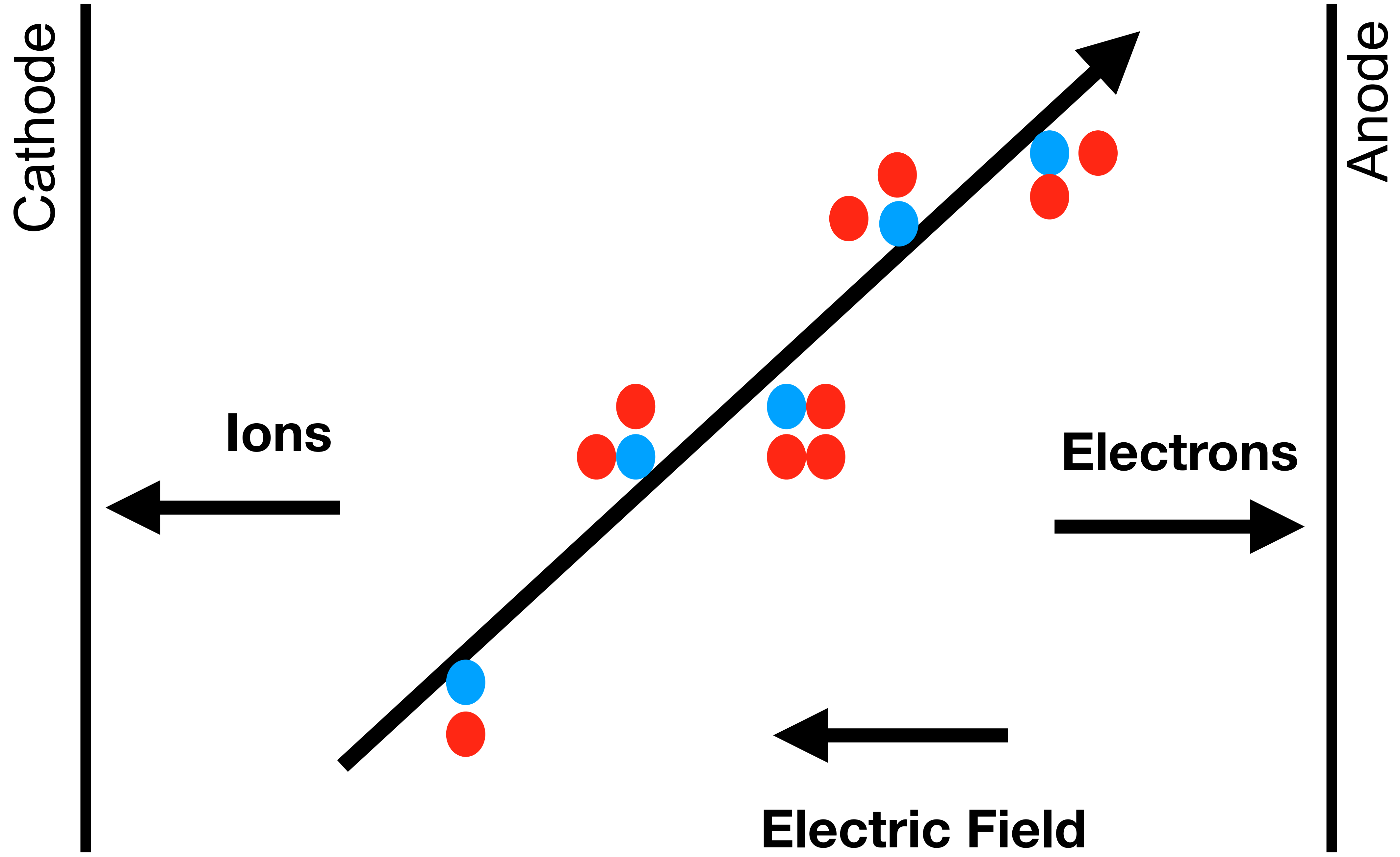
Probability of producing exactly k ionization electrons = p(E, k)



Integral cluster-size distribution for fast particles (γ = 1000) in argon;

Q(n) is the probability that the cluster has more than n electrons.

Transport of Electrons and Ions



- The behavior of the gaseous detectors crucially dependent on the drift of the electrons and ions that are created by the particles measured or in the avalanches at the electrodes.
- In addition to the electric drift field, there is often a magnetic field, which is necessary for measuring particle momentum.
- Important to understand how the drift velocity vector in electric and magnetic fields depends on the properties of the gas molecules, including their density and temperature.

The motion of charged particles under the influence of electric and magnetic fields, $\boldsymbol{E}$ and $\boldsymbol{B}$ in terms of an equation of motion [Langevin Equation]

$$m\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t} = e\boldsymbol{E} + e[\boldsymbol{u} \times \boldsymbol{B}] - K\boldsymbol{u}$$

m and e = mass and electric charge of the particle,

u = velocity vector,

K = a frictional force proportional to u that is caused by the interaction of the particle with the gas.

characteristic time

$$\tau = m/k$$

Drift of Electrons:

Let us consider an electron between two collisions.

Because of its light mass, the electron scatters isotropically and, immediately after the collision, it has forgotten any preferential direction.

Some short time later, in addition to its instantaneous and randomly oriented velocity c, the electron has picked up the extra velocity u equal to its acceleration along the field, multiplied by the average time that has elapsed since the last collision:

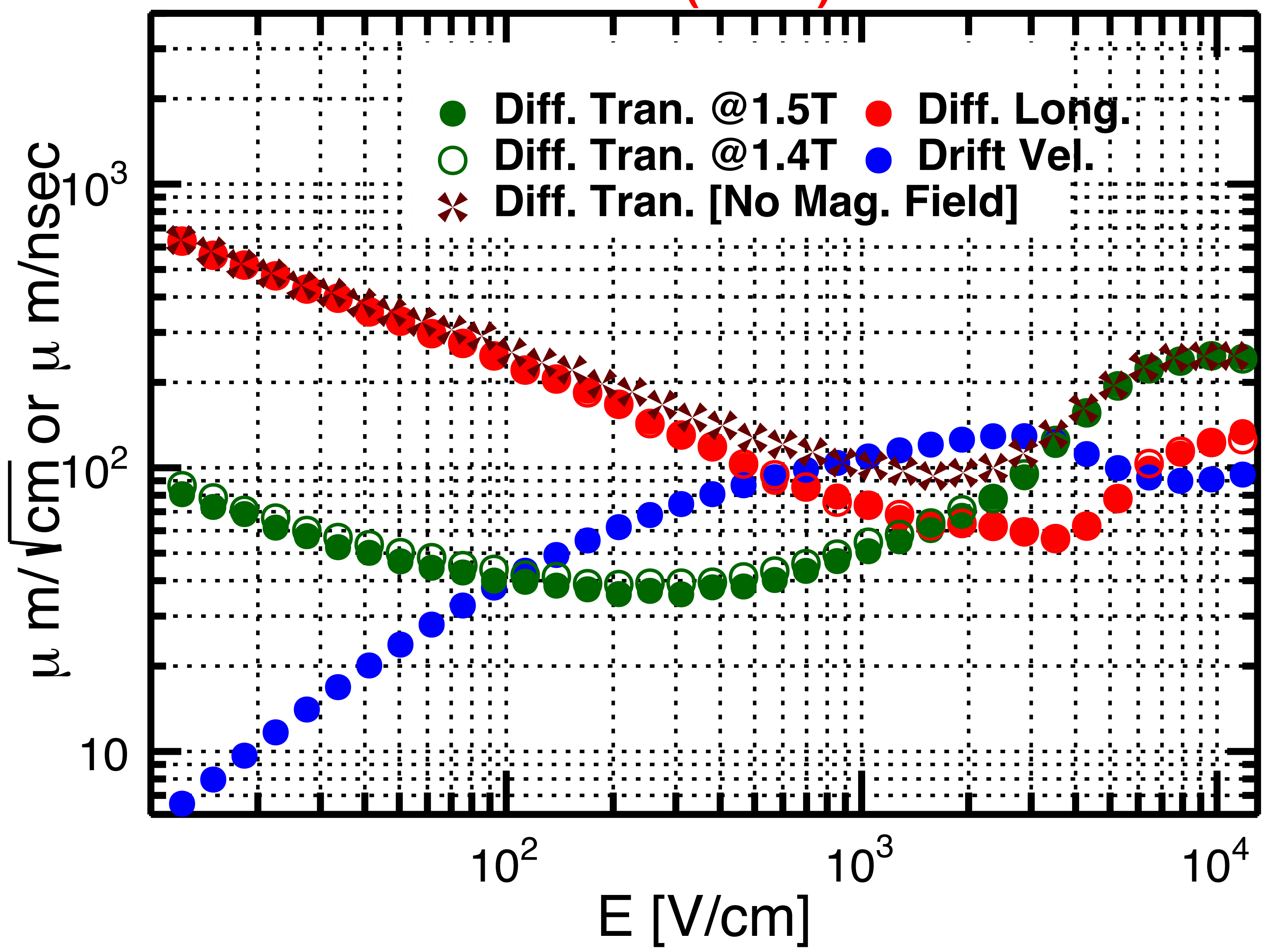
$$u = \frac{eE}{m}\tau.$$

This extra velocity appears macroscopically as the drift velocity

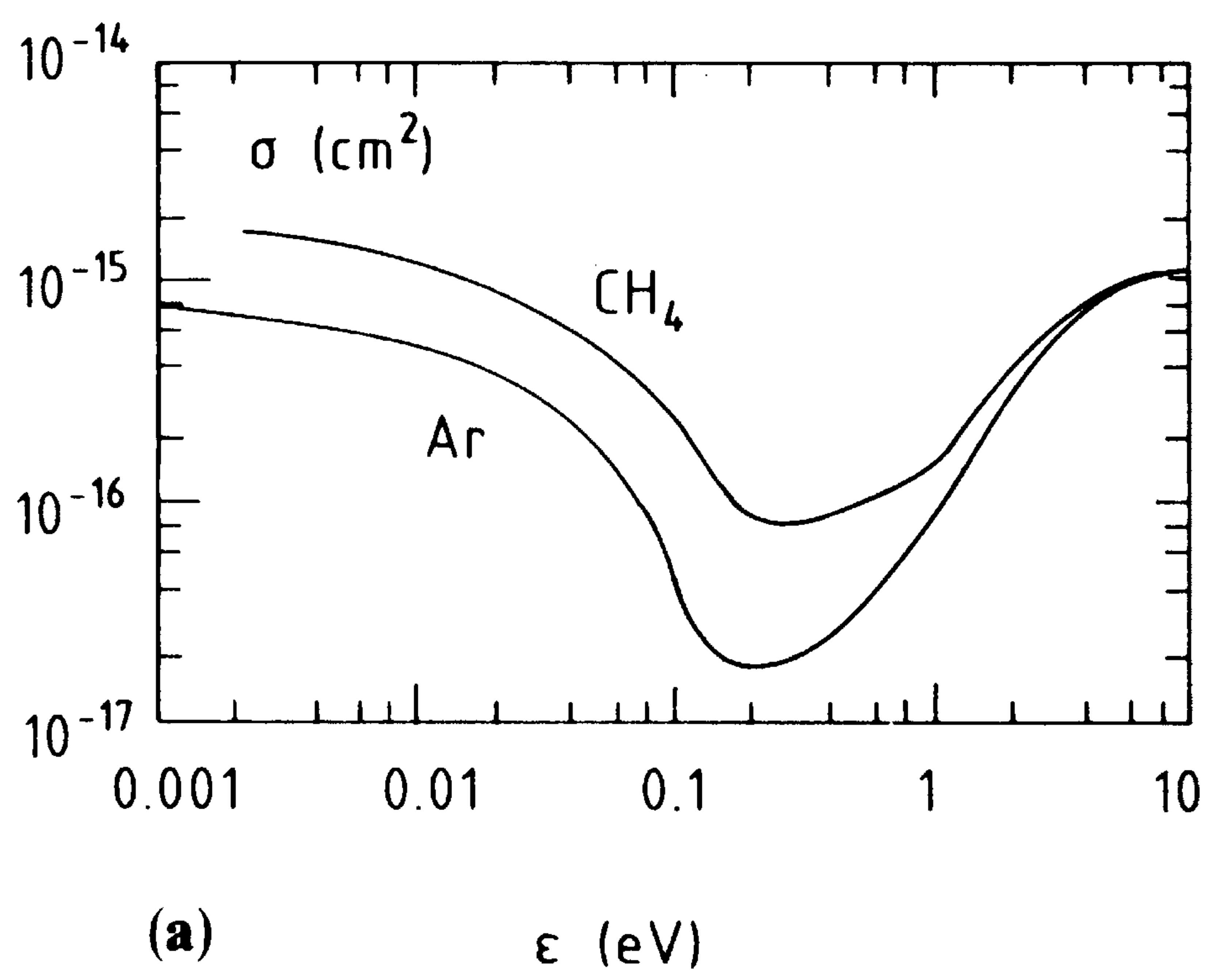
In the next encounter, the extra energy, on the average, is lost in the collision through recoil or excitation.

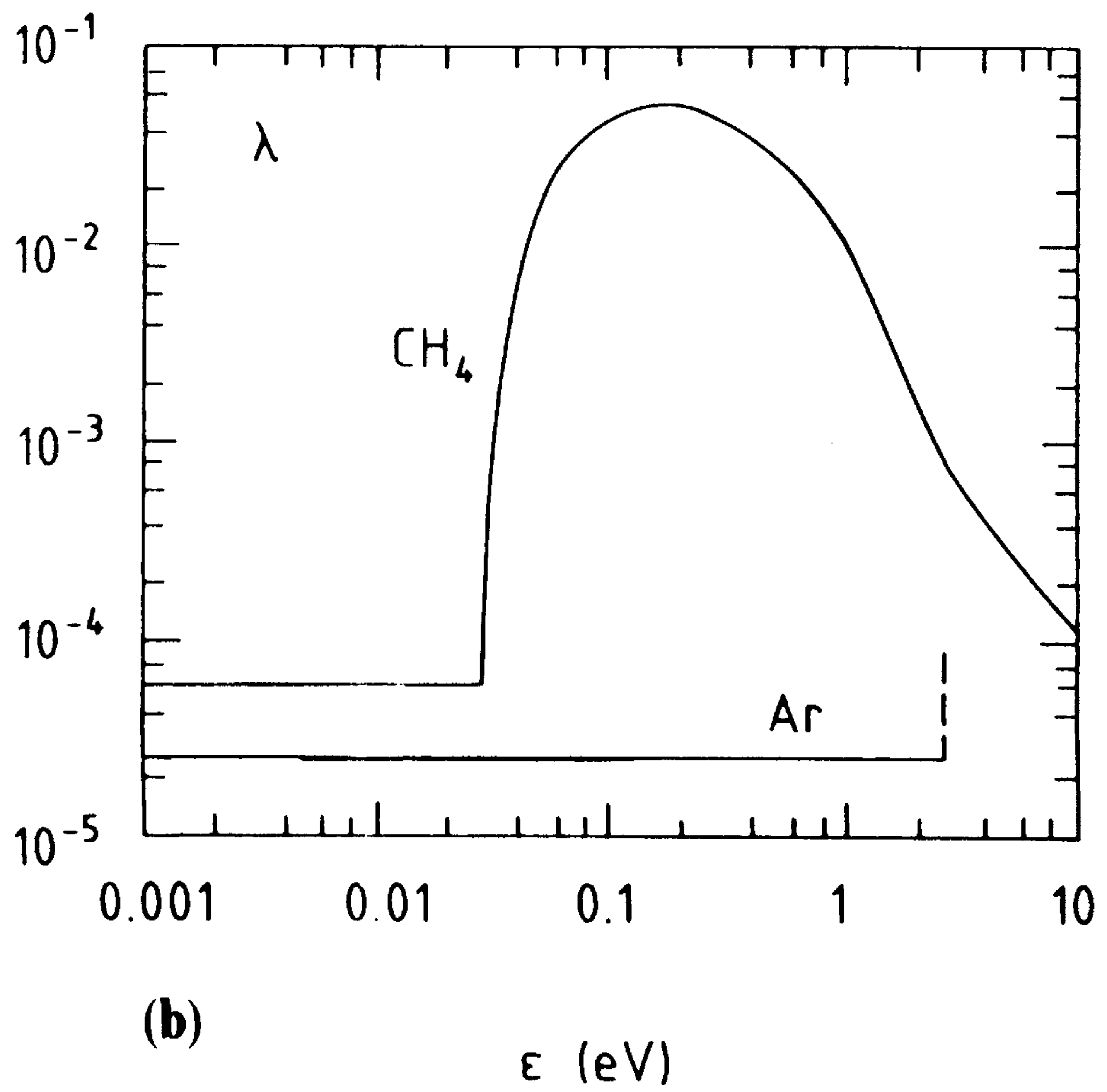
Therefore there is a balance between the energy picked up and the collision losses.

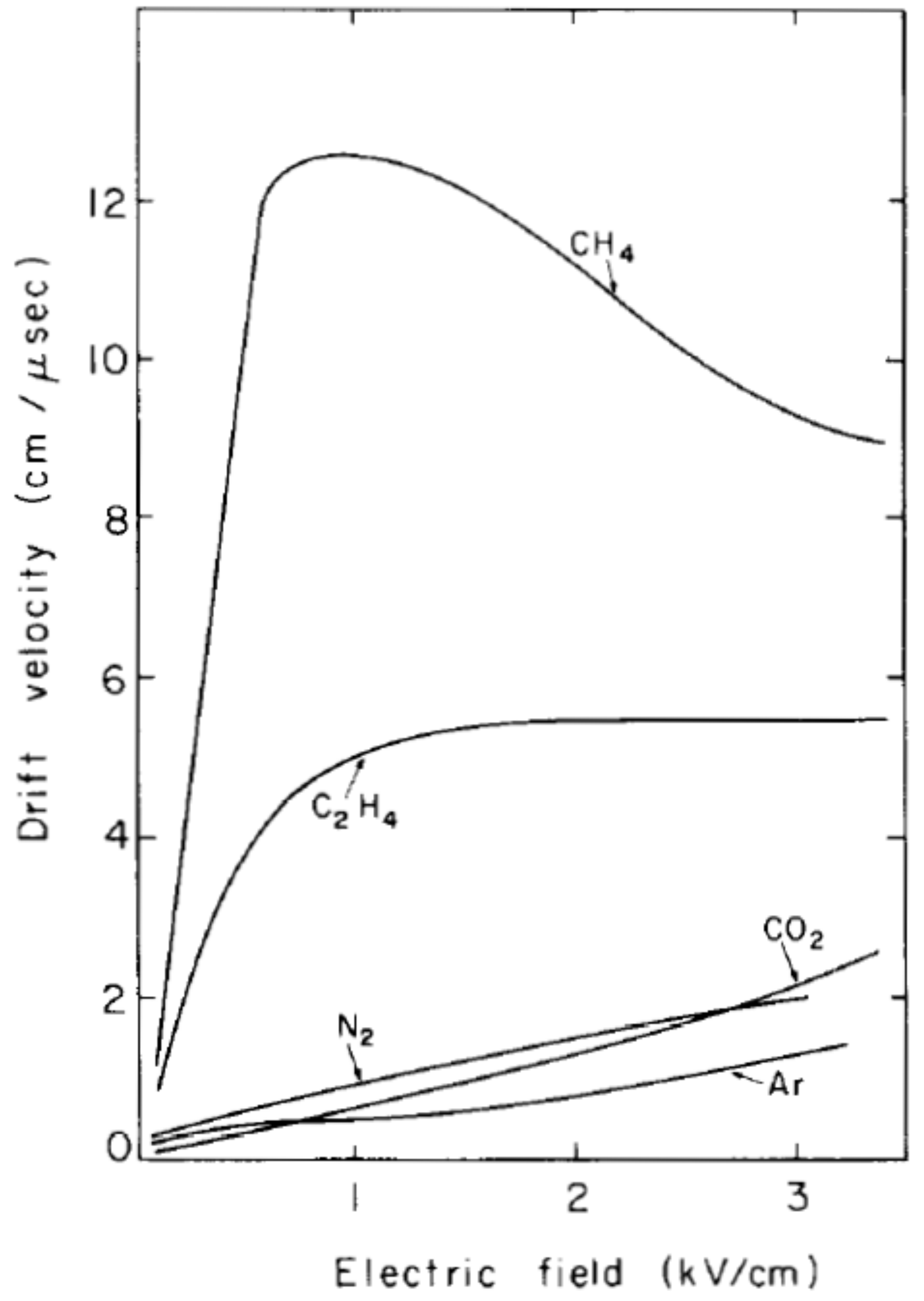
Ne:CF4 (50:50)



Drift of Electrons







(a) Effective ('momentum transfer') cross- section σ(ε) for argon and methane. (b) Fraction λ(ε) of energy loss per collision for argon and methane.

The general behavior of electron drift velocities is that they rise with increasing electric field, then level off or decrease as a result of the combined effects of σ(ε) and λ(ε) as ε increases with increasing *E*.

Influence of a magnetic field on drifting electrons and ions

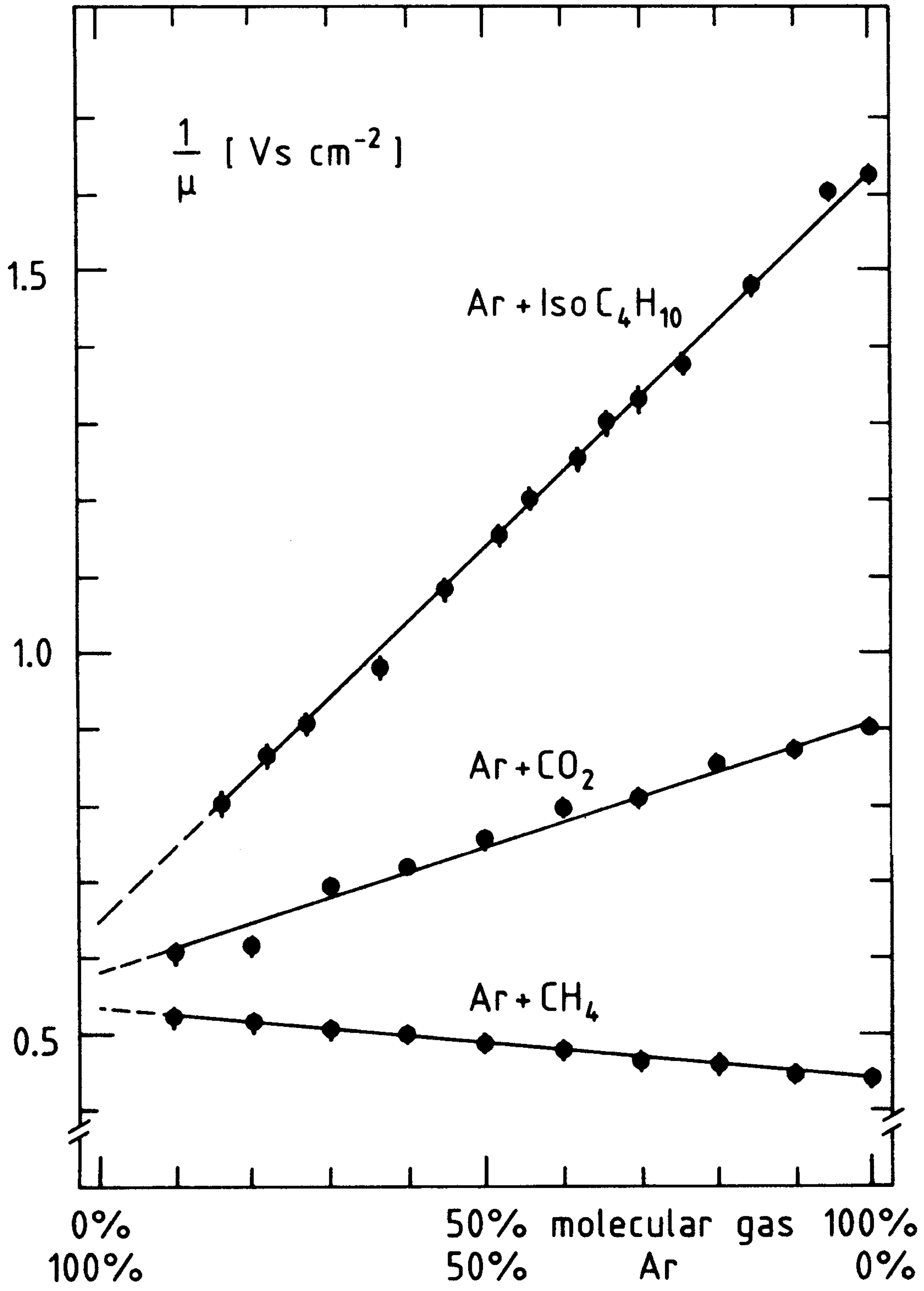
The order of magnitude of Mobility

$\mu \simeq 10^4$ cm^2 V^{-1} s^{-1} for electrons

$\mu = 1$ cm^2 V^{-1} s^{-1} for ions

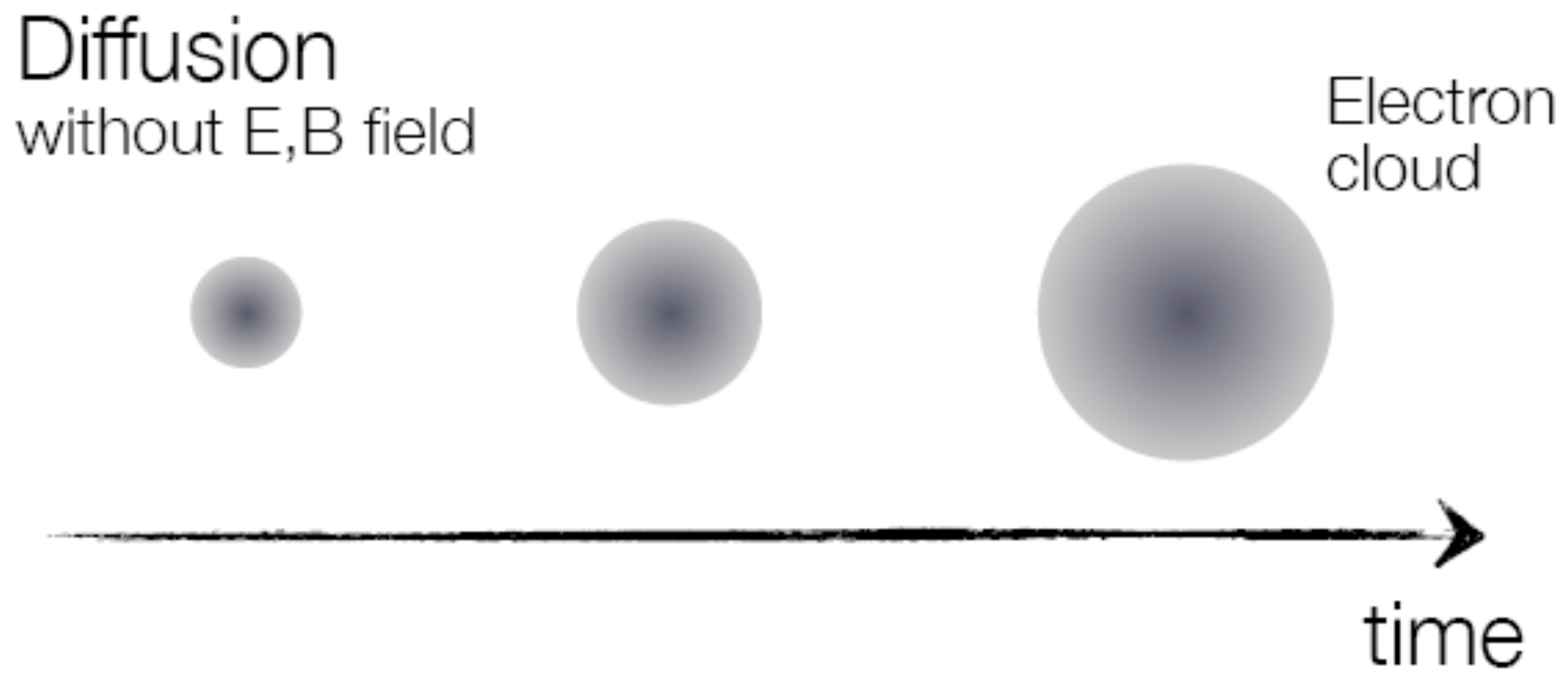
$$\omega\tau = (e/m)B\tau$$

$$\omega\tau = B\mu \simeq \begin{cases} 10^{-4} & \text{for ions} \\ 1 & \text{for electrons} \end{cases}$$



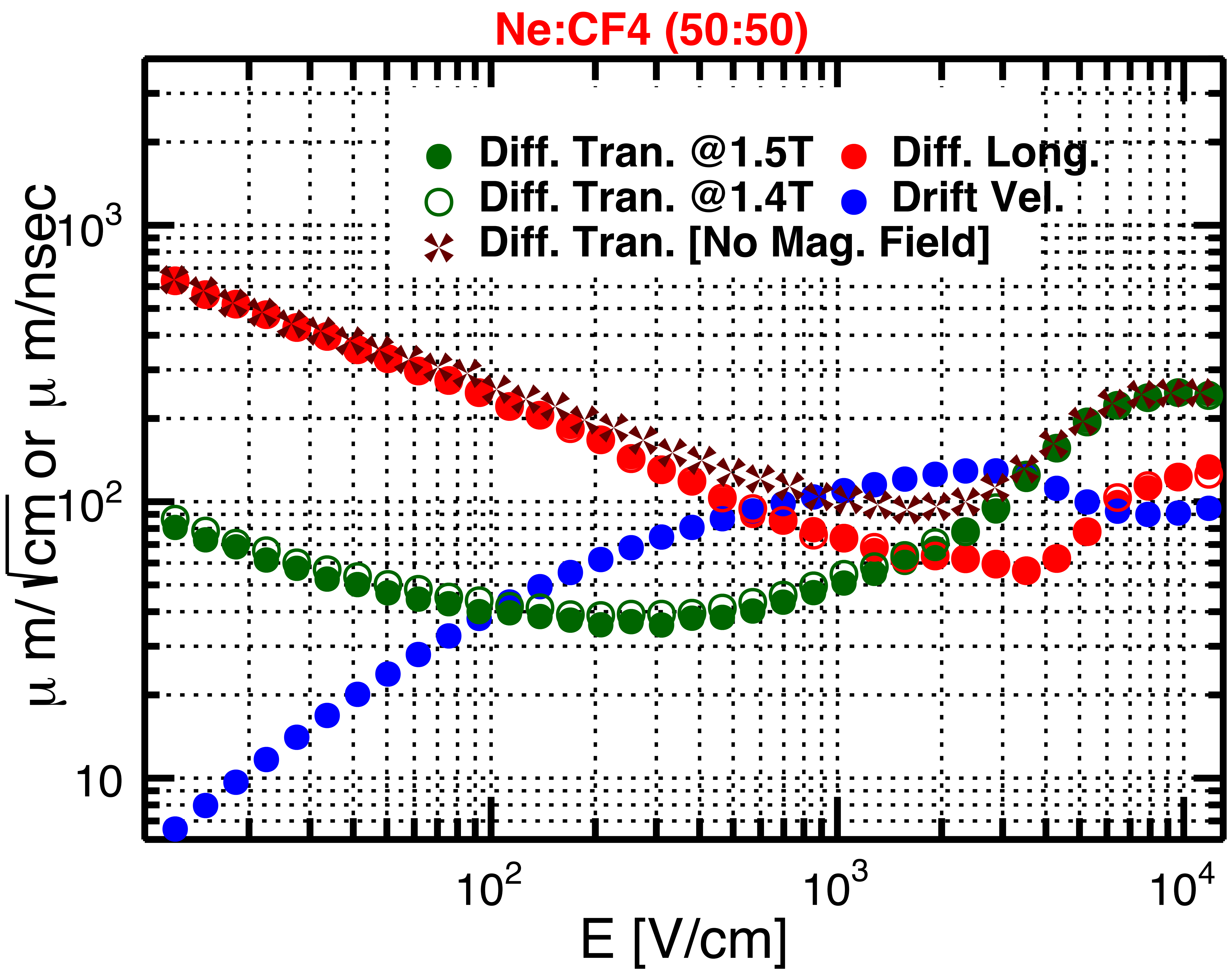
Therefore, the effect of such magnetic fields on ion drift is negligible,

Diffusion

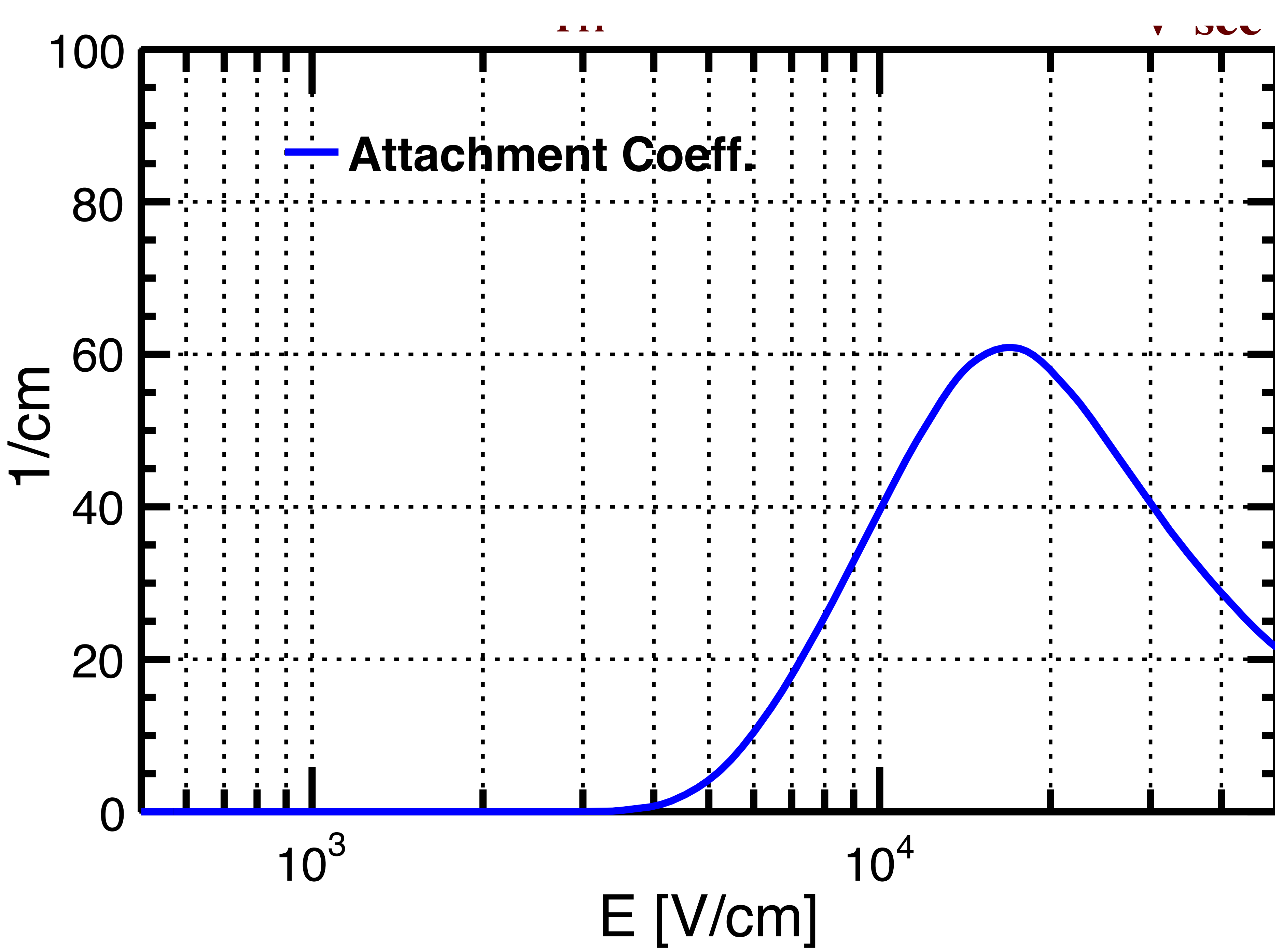


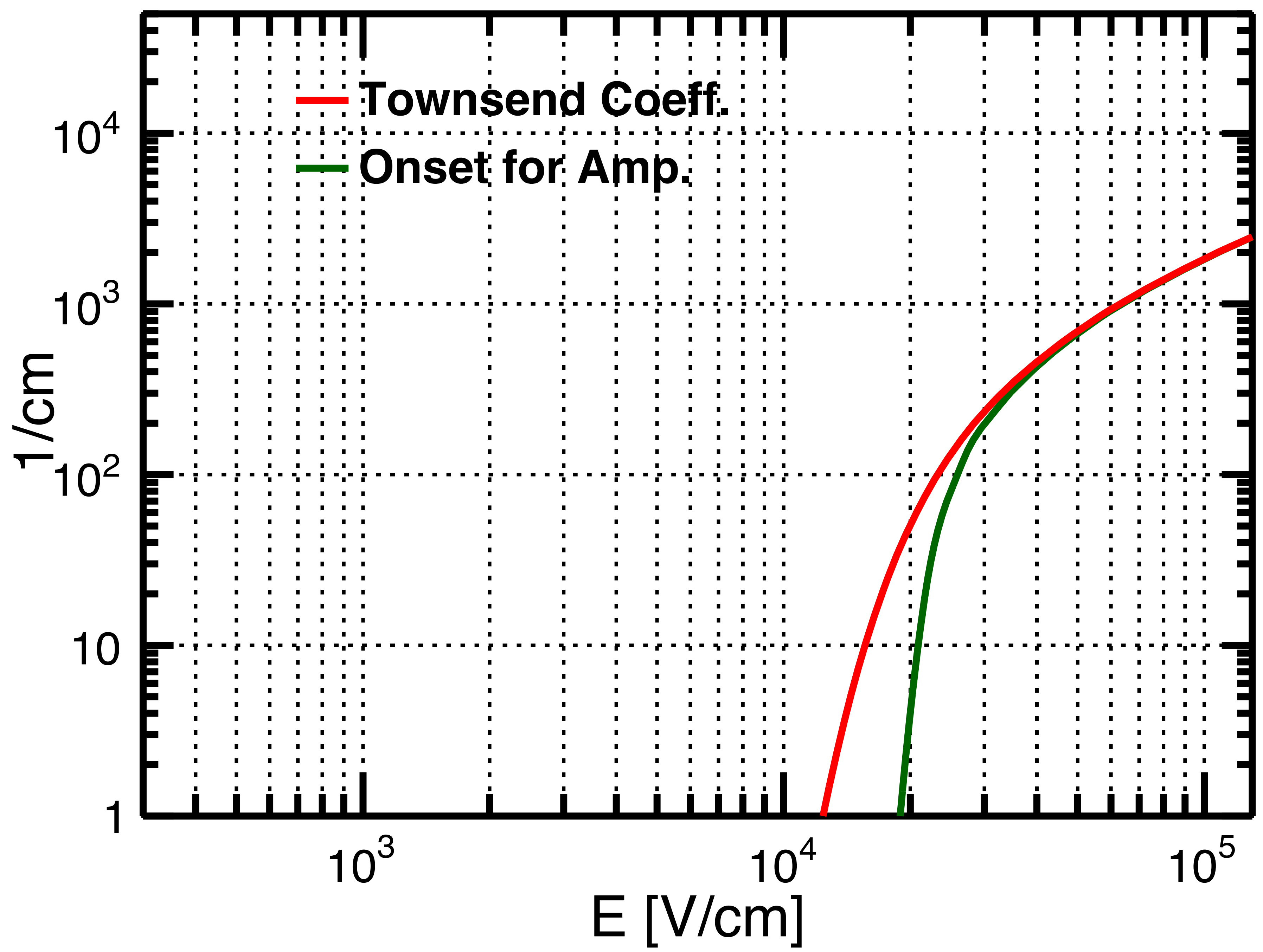
- During the drift in electric fields, electrons diffuse following a Gaussian distribution
- The change in the energy distribution due to the electric field does, of course, result in a coefficient of diffusion dependent on E.
- The energy determines the diffusion width σ_x of an electron cloud which, after starting point-like, has travelled over a distance L:

$$\sigma_x^2 = 2Dt = \frac{2DL}{\mu E} = \frac{4\varepsilon L}{3eE}.$$



Townsend and Attachment





During their drift, electrons may be absorbed in the gas by the formation of negative ions, while Townsend reflects the multiplication of electrons.

Avalanche Multiplication

Large electric field yields
large kinetic energy of electrons ...

➛ Avalanche formation

Larger mobility of electrons results in liquid drop like avalanche with electrons near head ...

Mean free path: λ_{ion}
[for a secondary ionization]

Probability of an ionization per unit path length: $\alpha = 1/\lambda_{ion}$ [1st Townsend coefficient]

$$dn = n \cdot \alpha\, dx$$

$$n = n_0 e^{\alpha x}$$

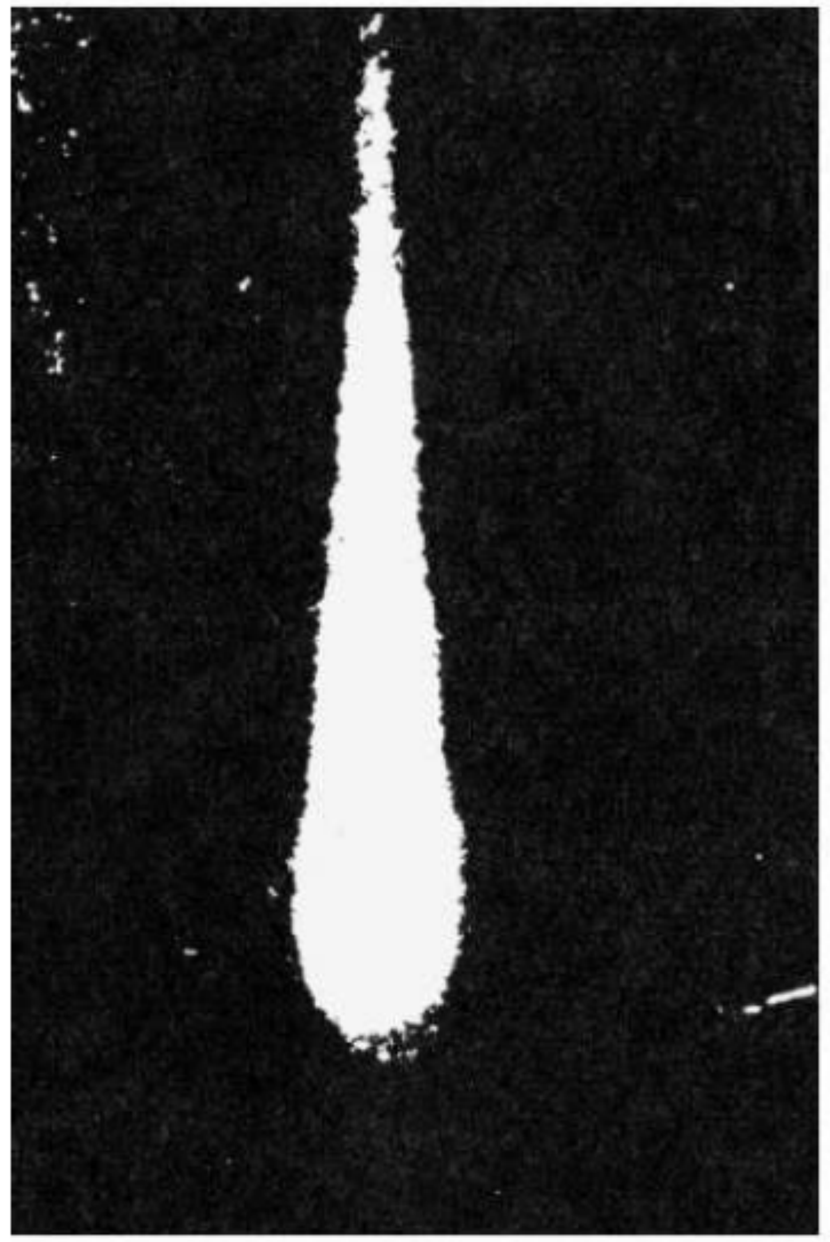
n(x) = electrons at location x

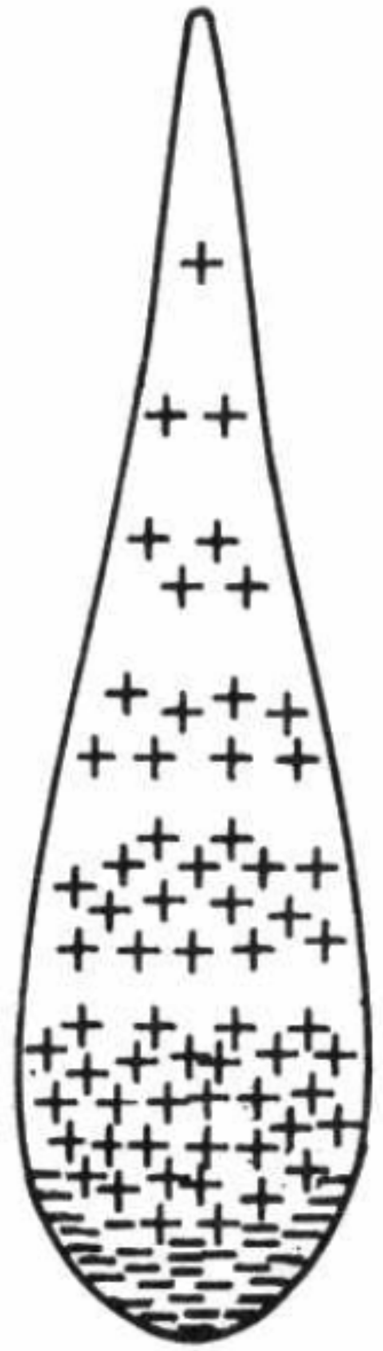
Gain:

$$G = \frac{n}{n_0} = e^{\alpha x}$$

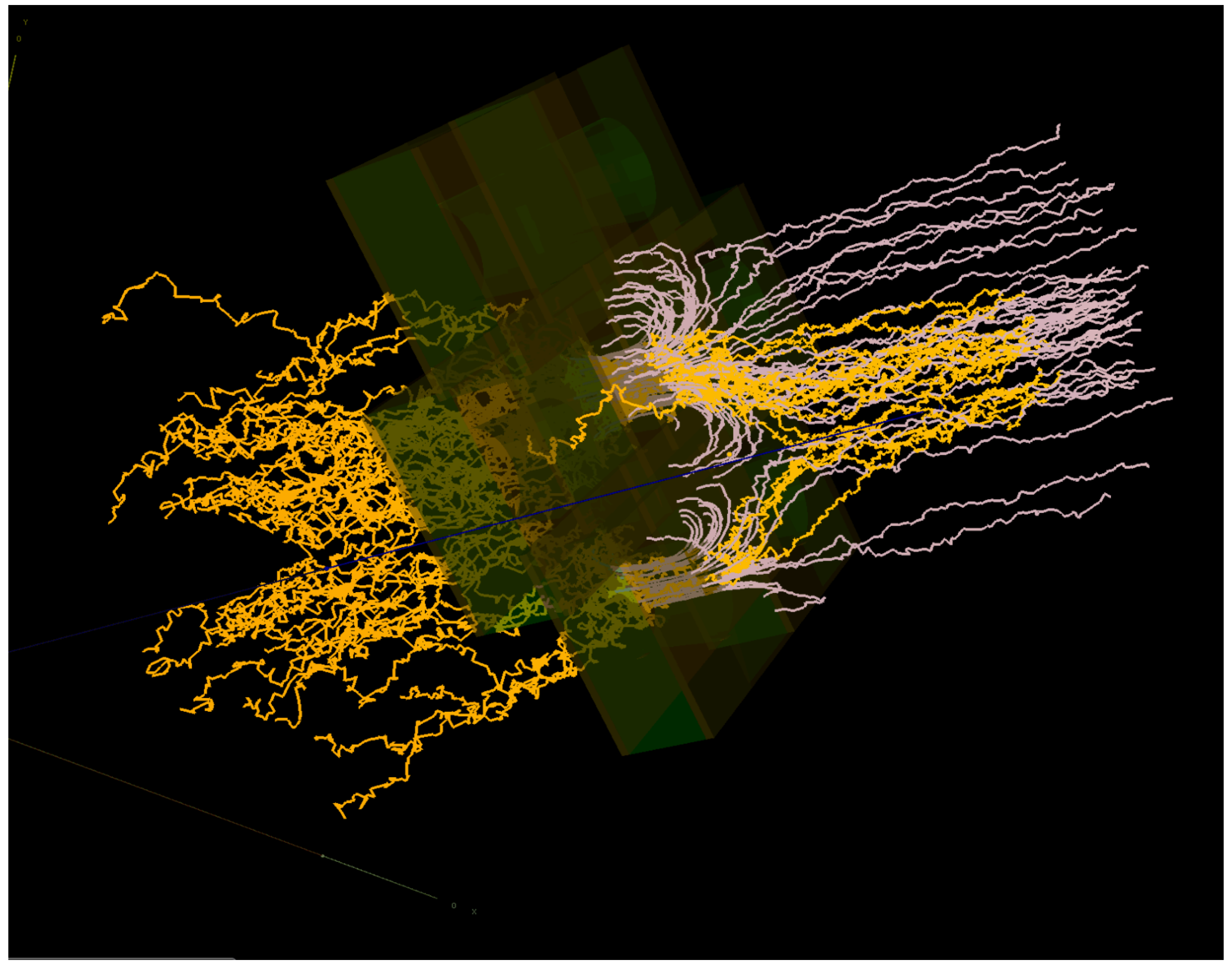
and more general for α = α(x): $$G = \frac{n}{n_0} = \exp\left[\int_{x_1}^{x_2} \alpha(x)dx\right]$$

Townsend avalanche





Drop-like shape of an avalanche
Left: cloud champer picture
Right: schematic view



Avalanche @ GEM hole

Gain Amplification Factor

Ionization mode:

full charge collection
no multiplication; gain ≈ 1

Proportional mode:

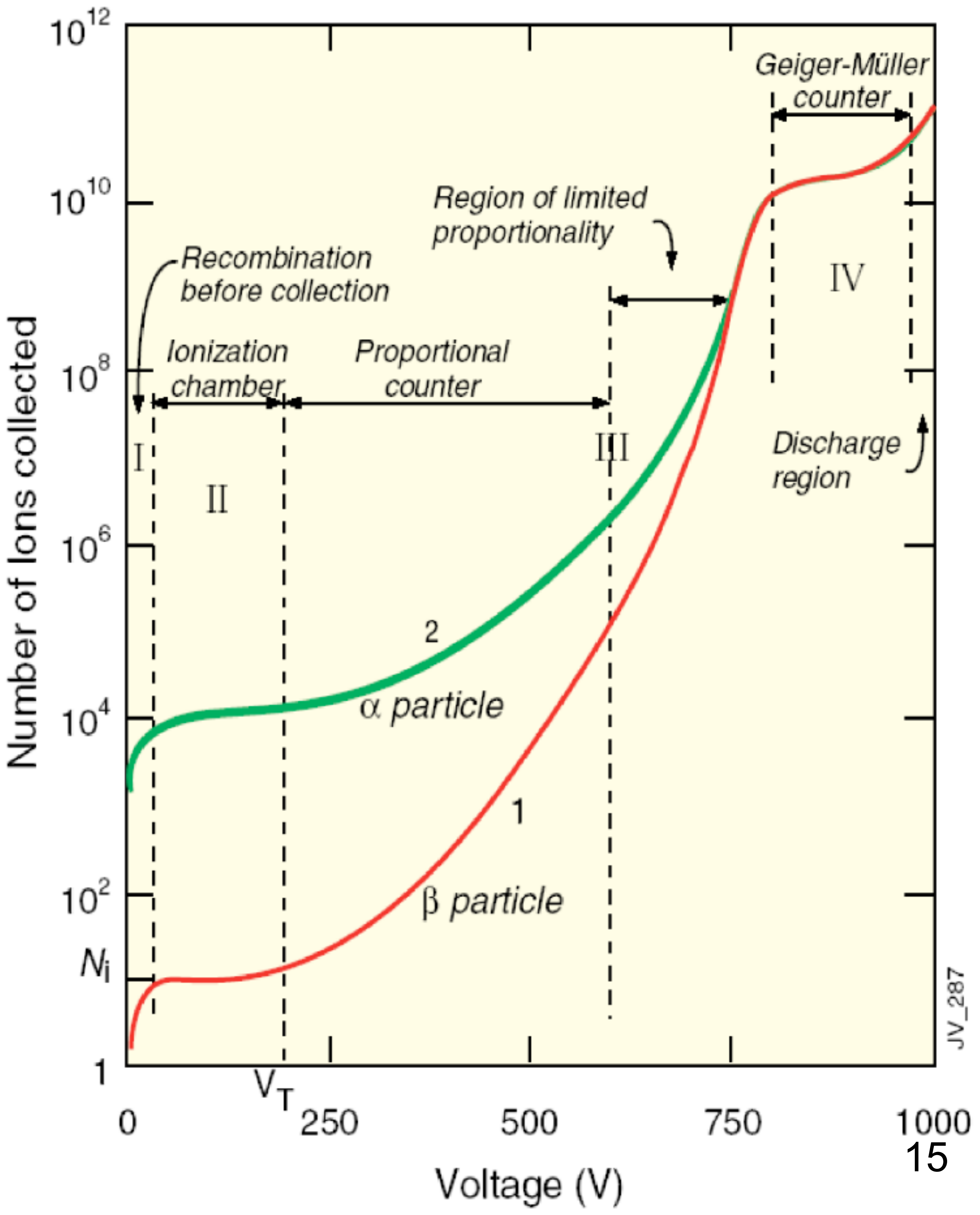
multiplication of ionization
signal proportional to ionization
measurement of dE/dx
secondary avalanches need quenching;
gain ≈ $10^4 - 10^5$

Limited proportional mode:
[saturated, streamer]

strong photoemission
requires strong quenchers or pulsed HV;
gain ≈ 10^{10}

Geiger mode:

massive photoemission;
full length of the anode wire affected;
discharge stopped by HV cut



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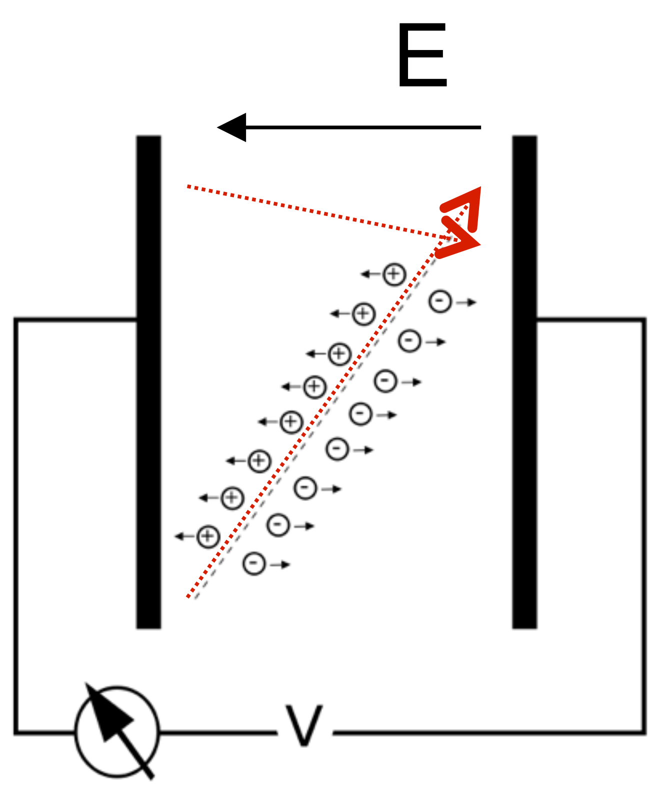
Proportional counter

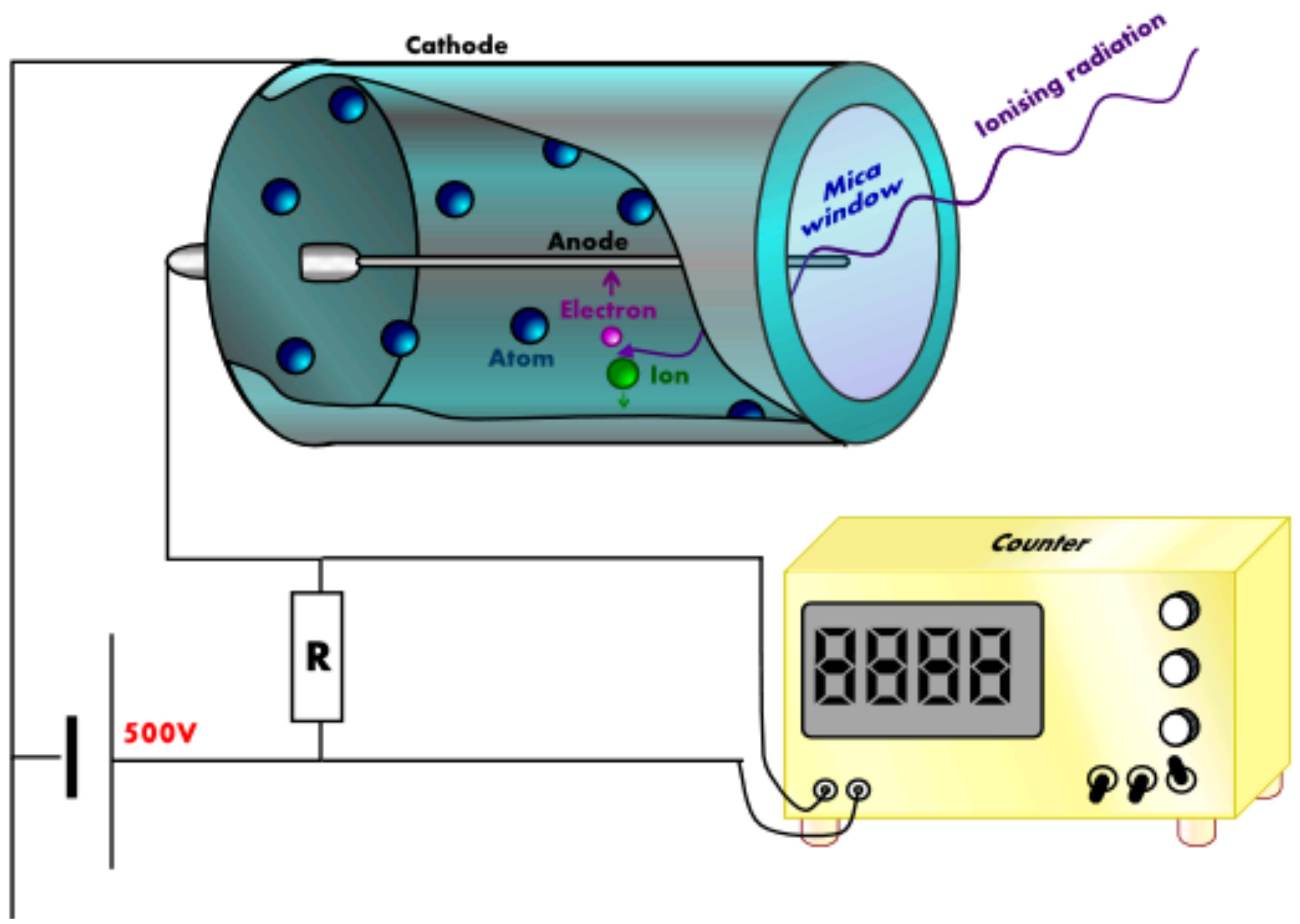


Planar design disadvantage:

E uniform and ⊥ to the electrodes
amount of ionization produced proportional to path length and to position where the ionization occurs
➔ not proportional to energy

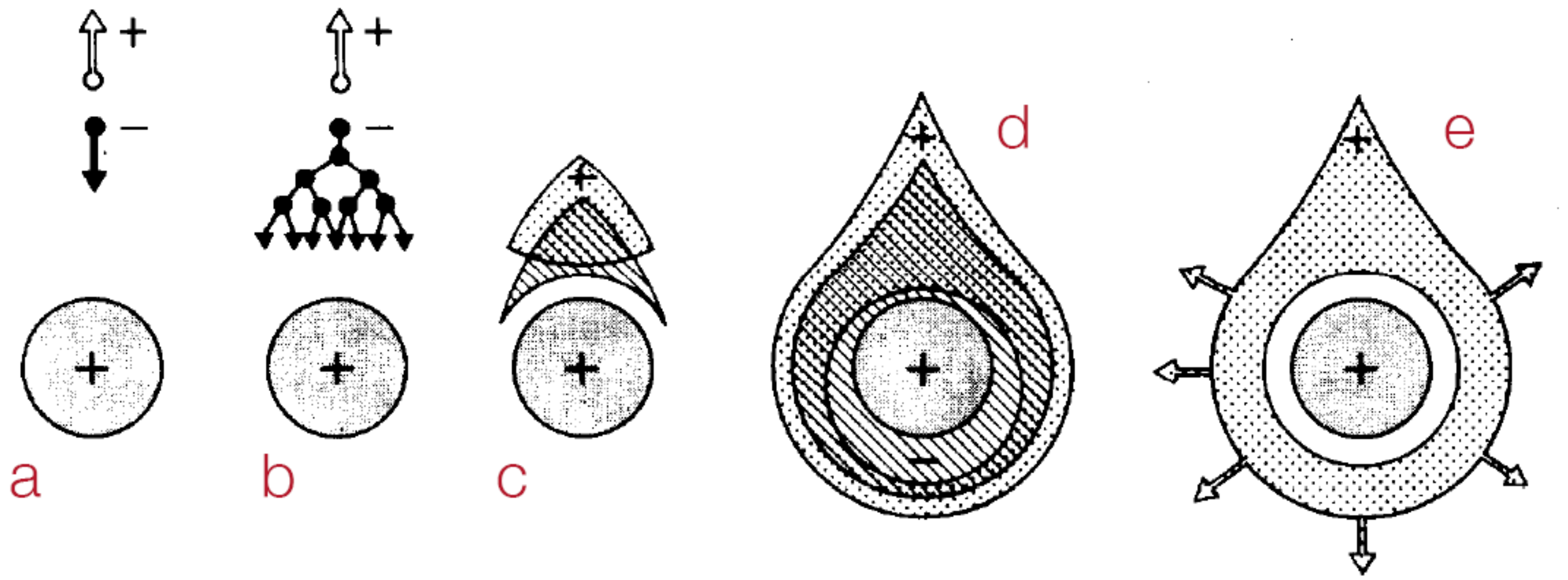
Problem solved using Cylindrical proportional counter:

Single anode wire in a cylindrical cathode
E~1/r: weak field far from the wire
electrons/ions drift in the volume
multiplication occurs only near the anode



Avalanche Development

Time development of an avalanche near the wire of a proportional counter



(A) single primary electron proceeds towards the wire anode,

(B) in the region of increasingly high field the electron experiences ionizing collisions (avalanche multiplication),

(C) electrons and ions are subject to lateral diffusion,

(D) a drop-like avalanche develops which surrounds the anode wire,

(E) The electrons are quickly collected (~1ns) while the ions begin drifting towards the cathode generating the signal at the electrodes.

How Gas Detectors are used (in the context of accelerator based experiments) w/ Not very Old Examples

Particle Identification (PID) ~ Velocity

p = m$\gamma\beta$ E = mγ velocity(β) measurement yields

Direct measurement:

➡Record signal time at multiple locations, calculate v.

➡"Fast" detector = low transit time spread (most easily achieved at small transit time)

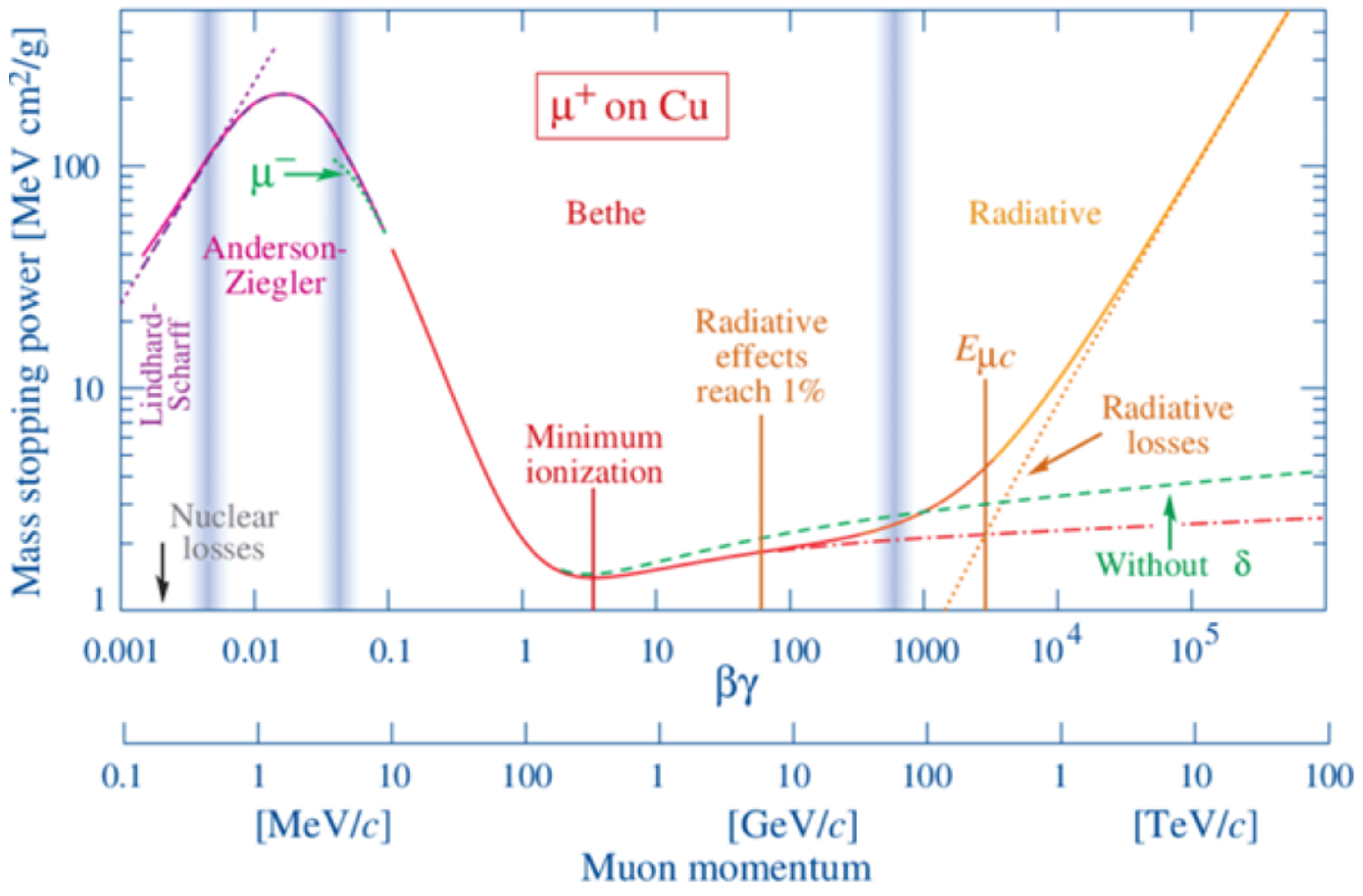
Velocity-dependent interaction(s) with detector:

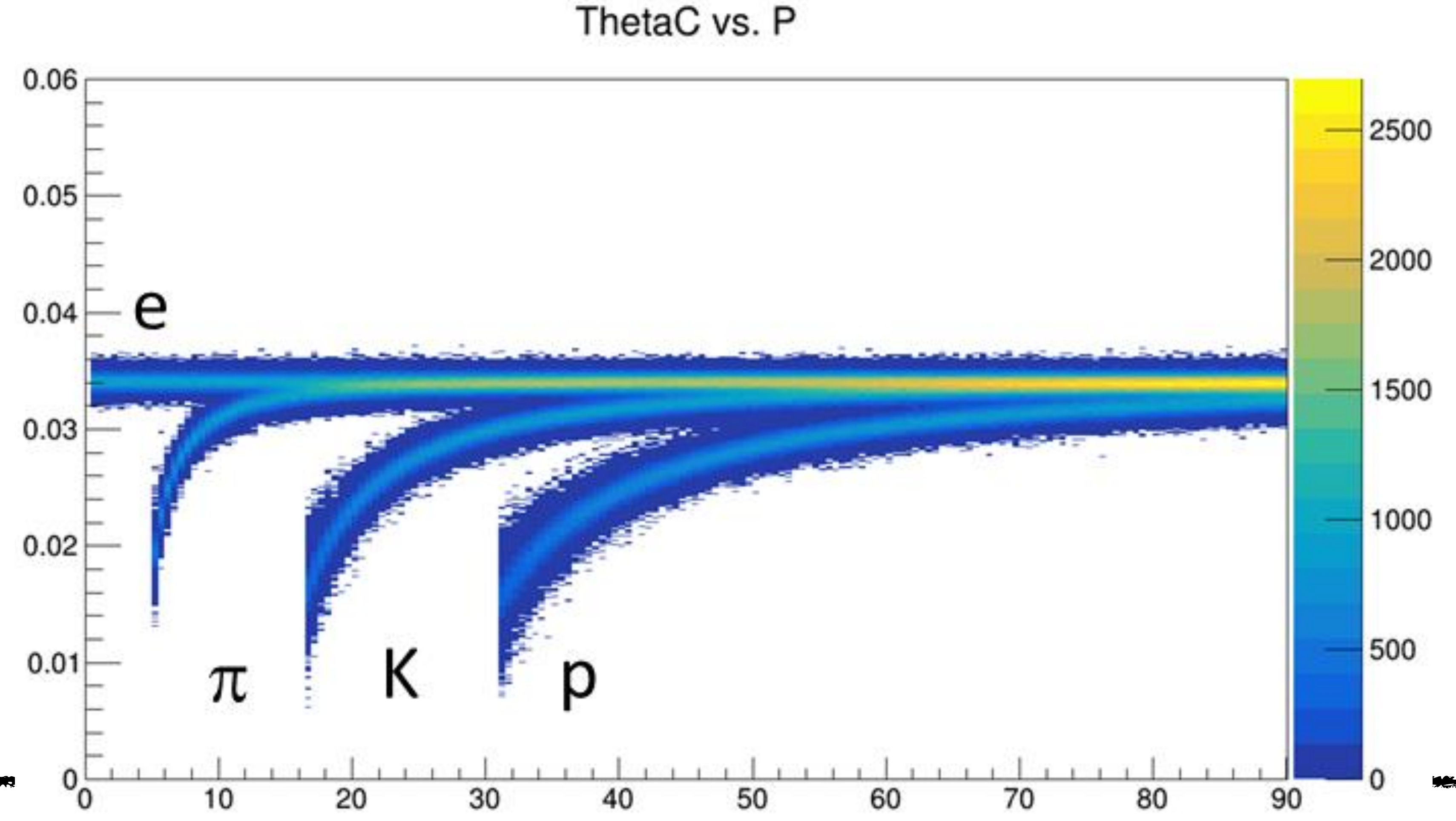
❖ Specific Ionization ($\frac{dE}{dx}$)

❖ Cherenkov Radiation: $cos\theta_c = 1/n\beta$

θ_c measured wrt. track direction.

Transition Radiation and Bremsstrahlung:eID mechanisms



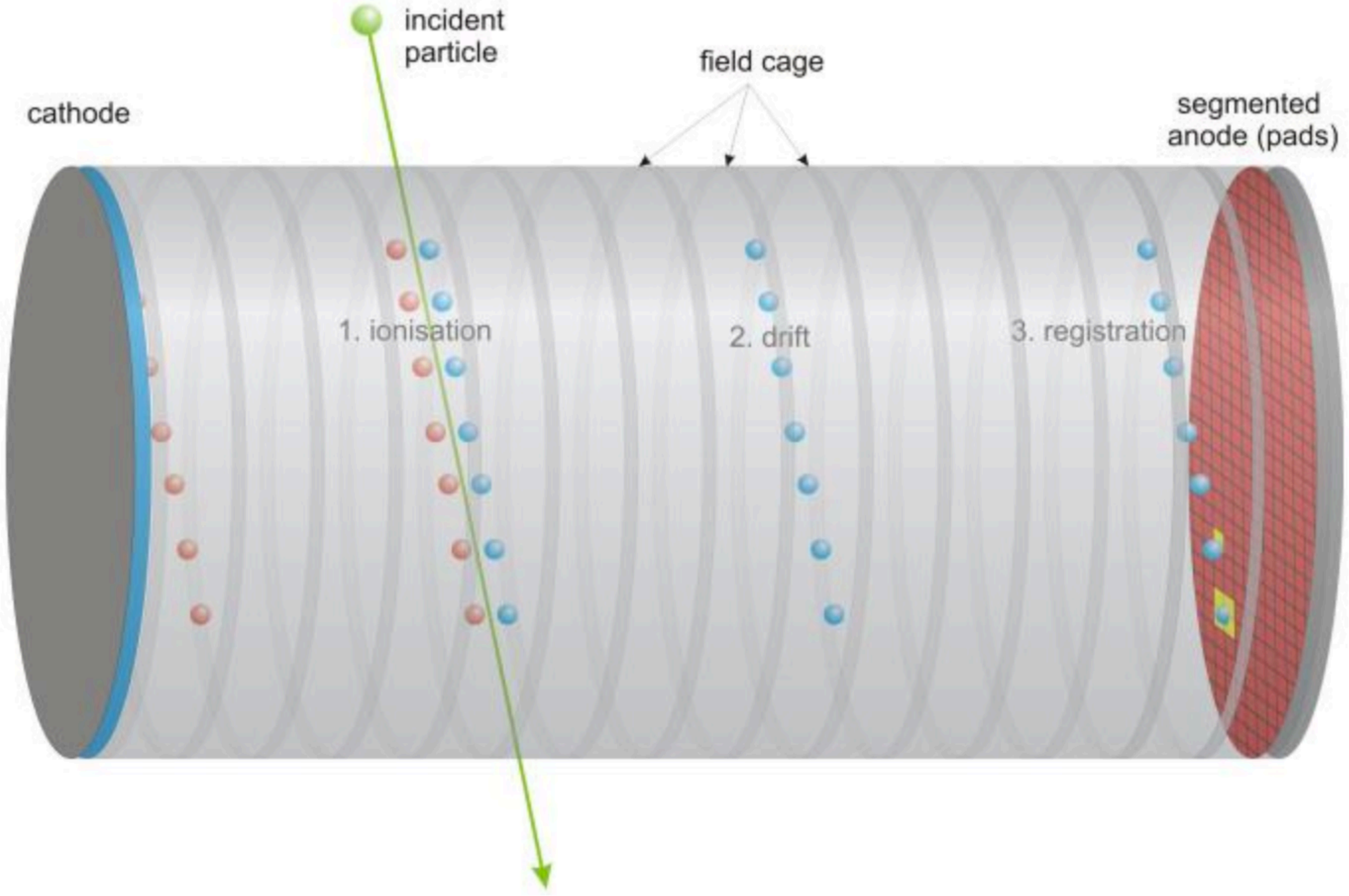


Tracking

- Measure and reconstruct the trajectories of charged particles.

- High magnetic field parallel to the electric field is used to "bend" the trajectory of the particle on a spiral track due to the Lorenz force.

- Calculate the momentum of the particle from the knowledge of the curvature and the B-field.



ALICE TPC w/ wire chambers

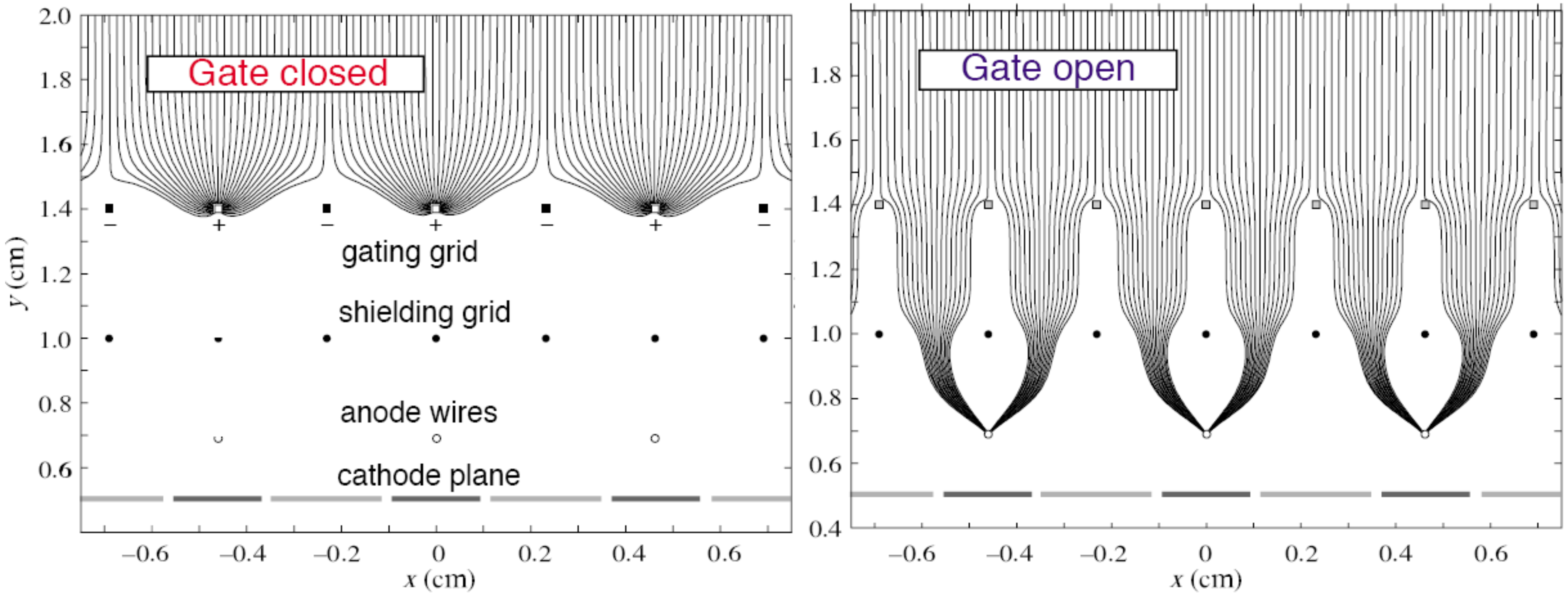
Difficulty: space charge effects due to slow moving ions change effective E-field in drift region ....

Important: most ions come from amplification region

Solution: Invention of gating grid; ions drift towards grid ...

[Also: shielding grid to avoid sense wire disturbance when switching]

Requires external trigger to switch gating grid ...



ALICE TPC Upgrade at LHC

Old TPC: Wire chamber end plates

✤pT Resolution: s /p <3.5%atp =50GeV/c and below 1%atp =1GeV/c.

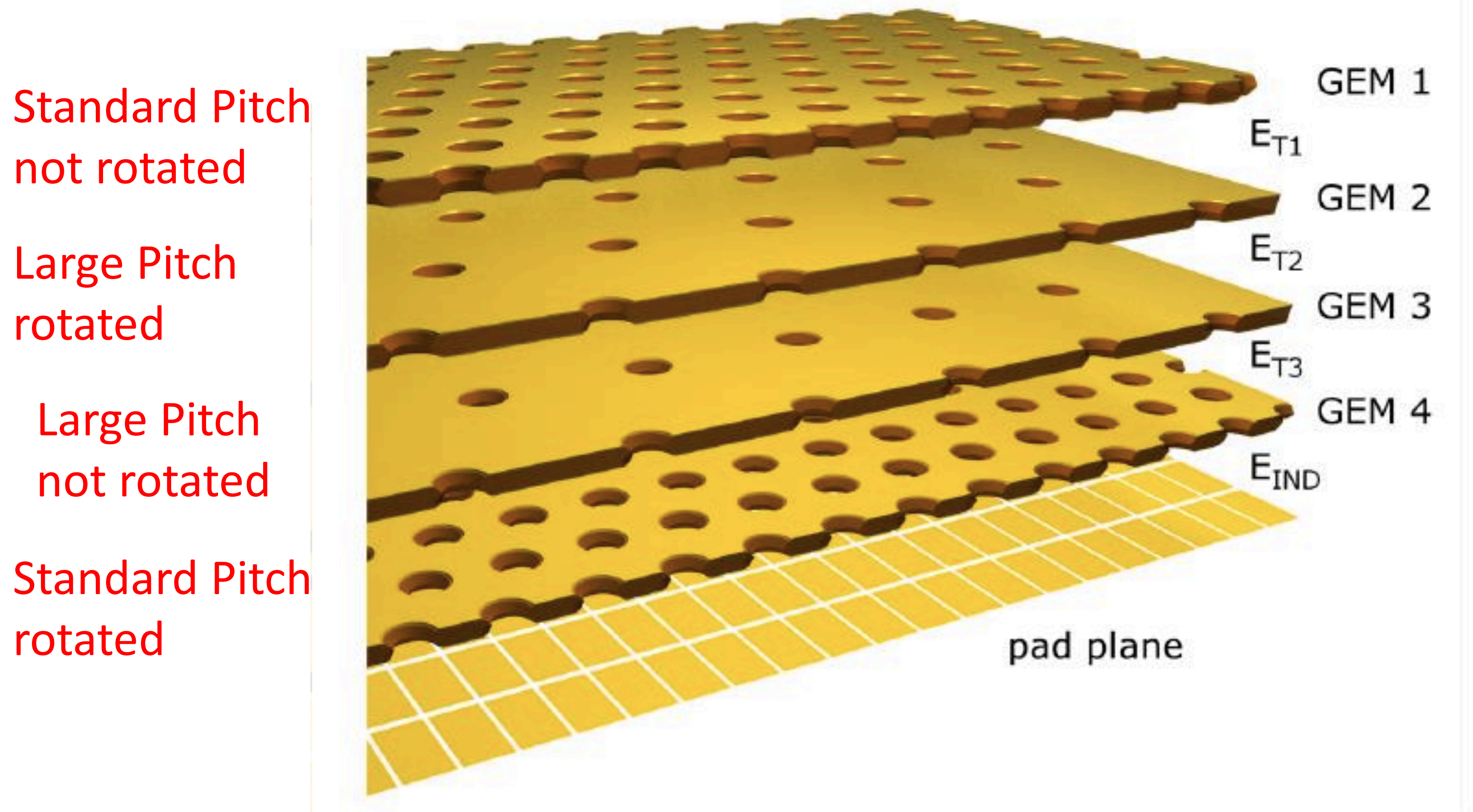
✤dE/dx resolution: 5% (p-p) – 6.5% (central Pb-Pb) (158 max. samples)

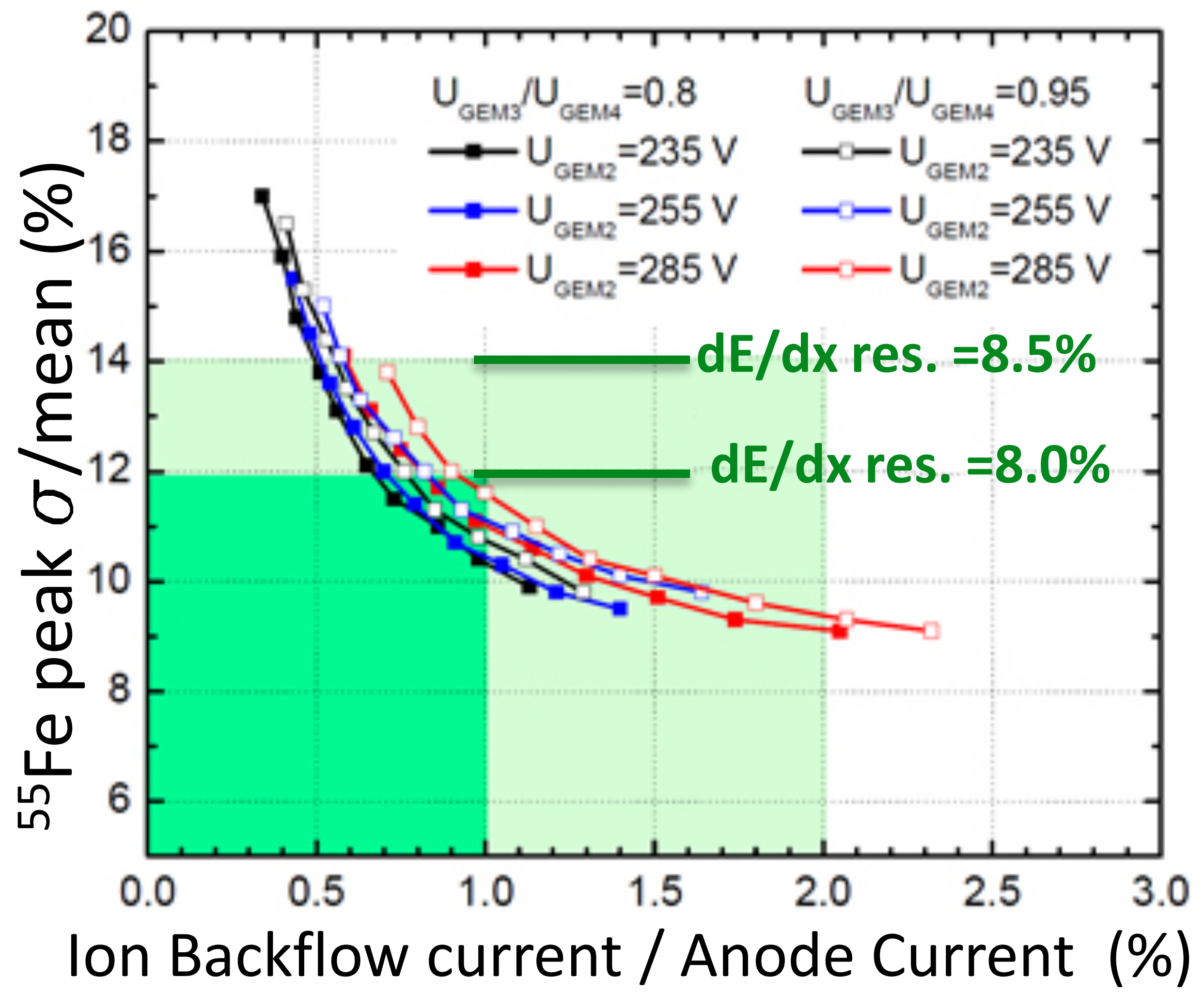
✤Event rate: 1 kHz Pb-Pb minimum bias

✤Want to be able to record 50 kHz Pb-Pb collision rate and maintain the current performance

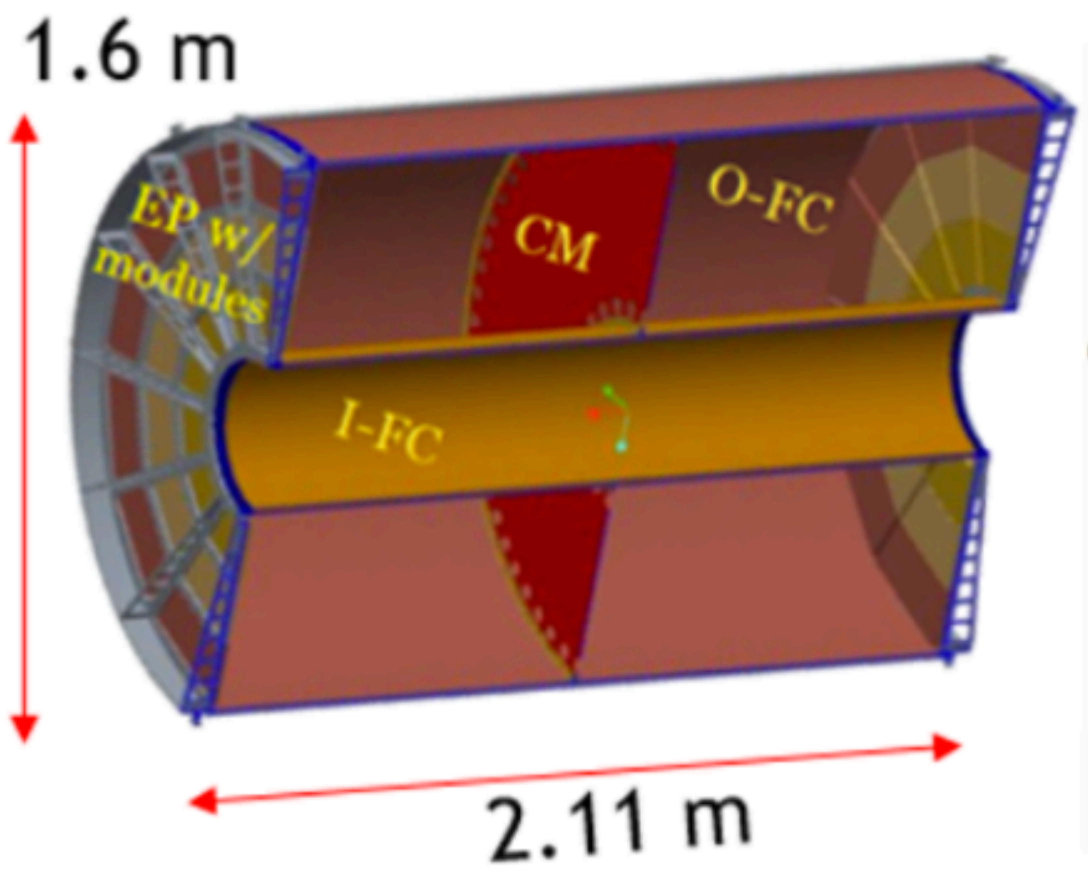
BUT

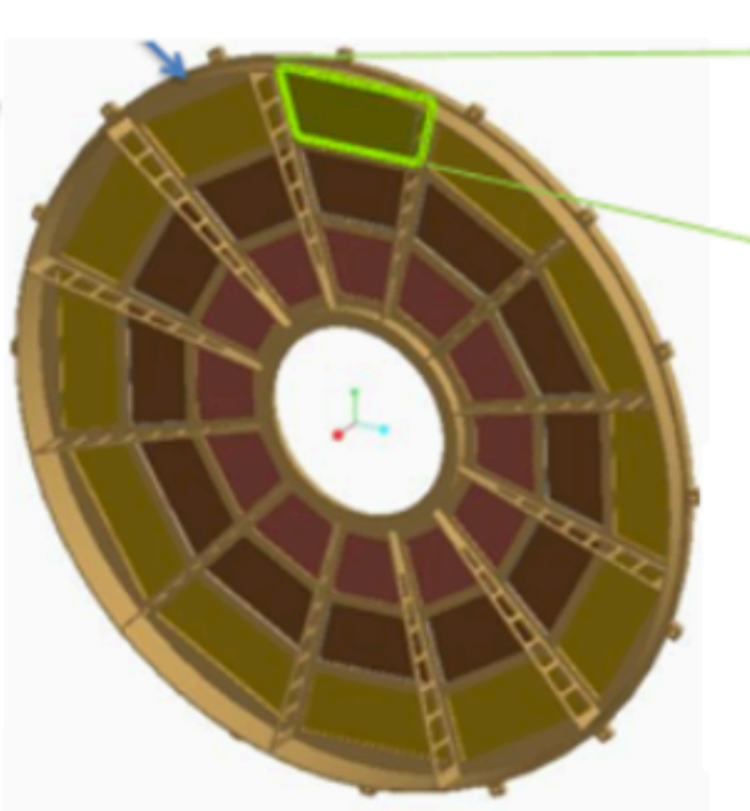
- Drift time for ionization electrons from central electrode to end plate is O (100 μs) Drift time for ions from end plate to central electrode is O (160 ms)
- Build up of positive ions in the drift volume → electric field distortion → distortion of the ionization electron tracks as they drift to the end plates
- Ions produced by charged particles traversing the detector are unavoidable – this is the signal
- Ions from the gain structure - typically a few thousand times the initial ionization - must be prevented from getting to main drift volume

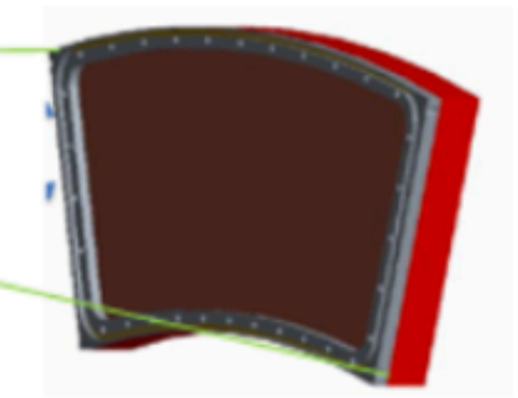




sPHENIX TPC @ RHIC



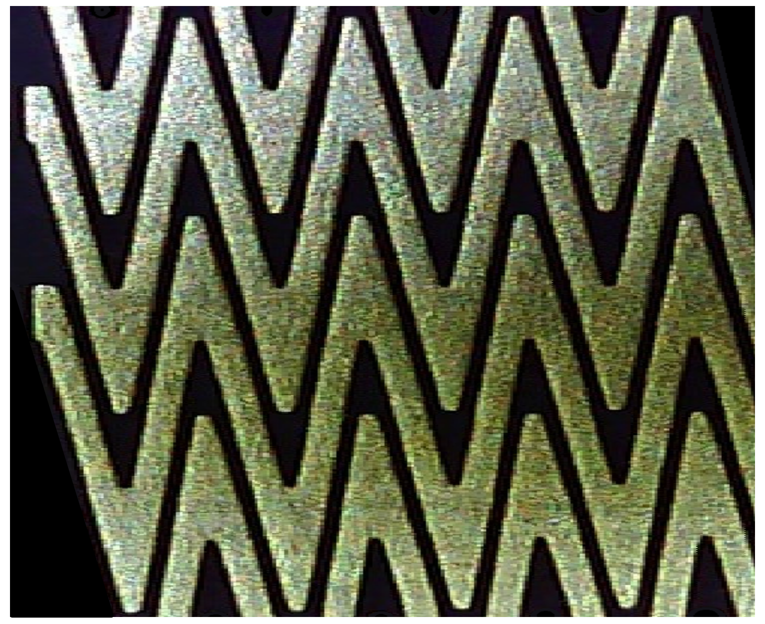




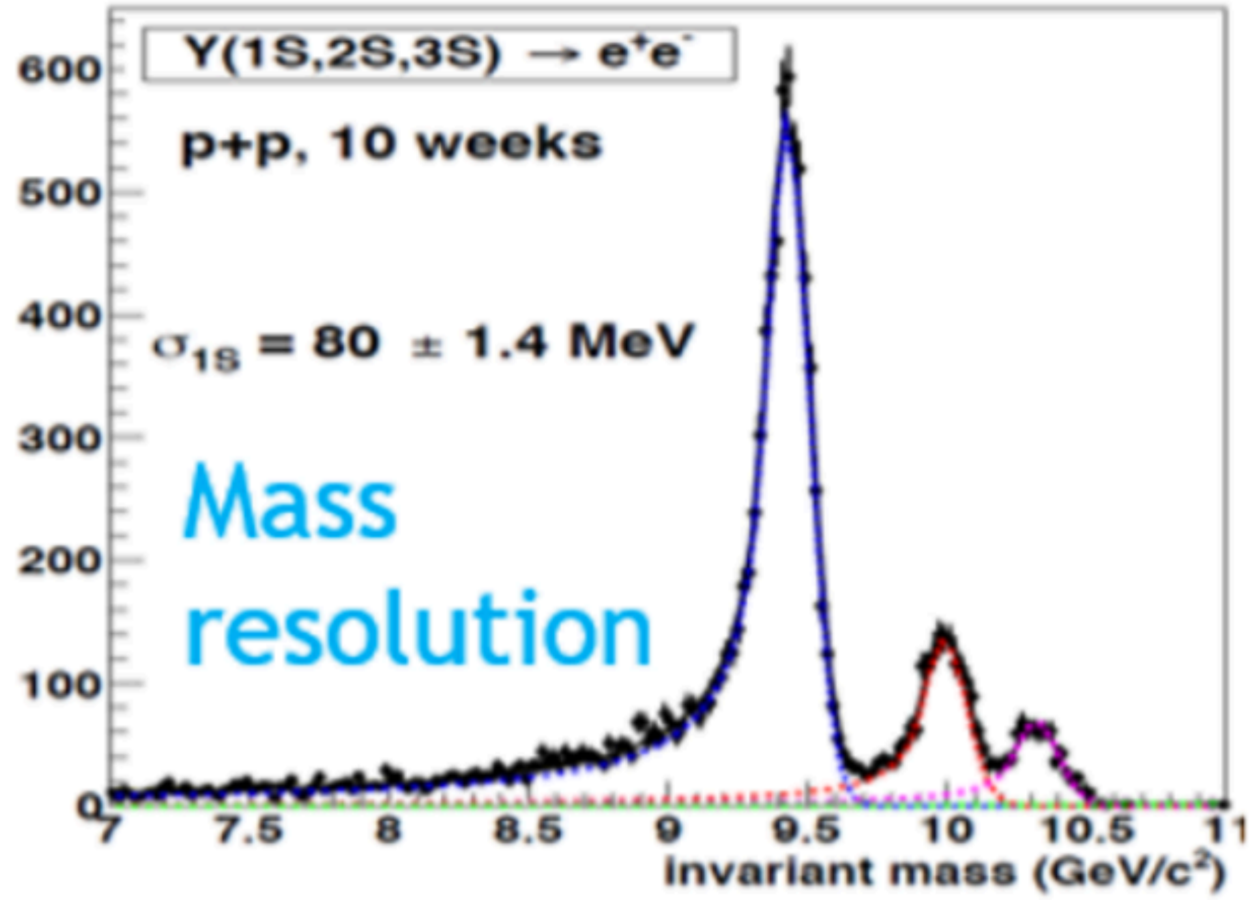
72 modules
2(z), 12(ϕ), 3(r)

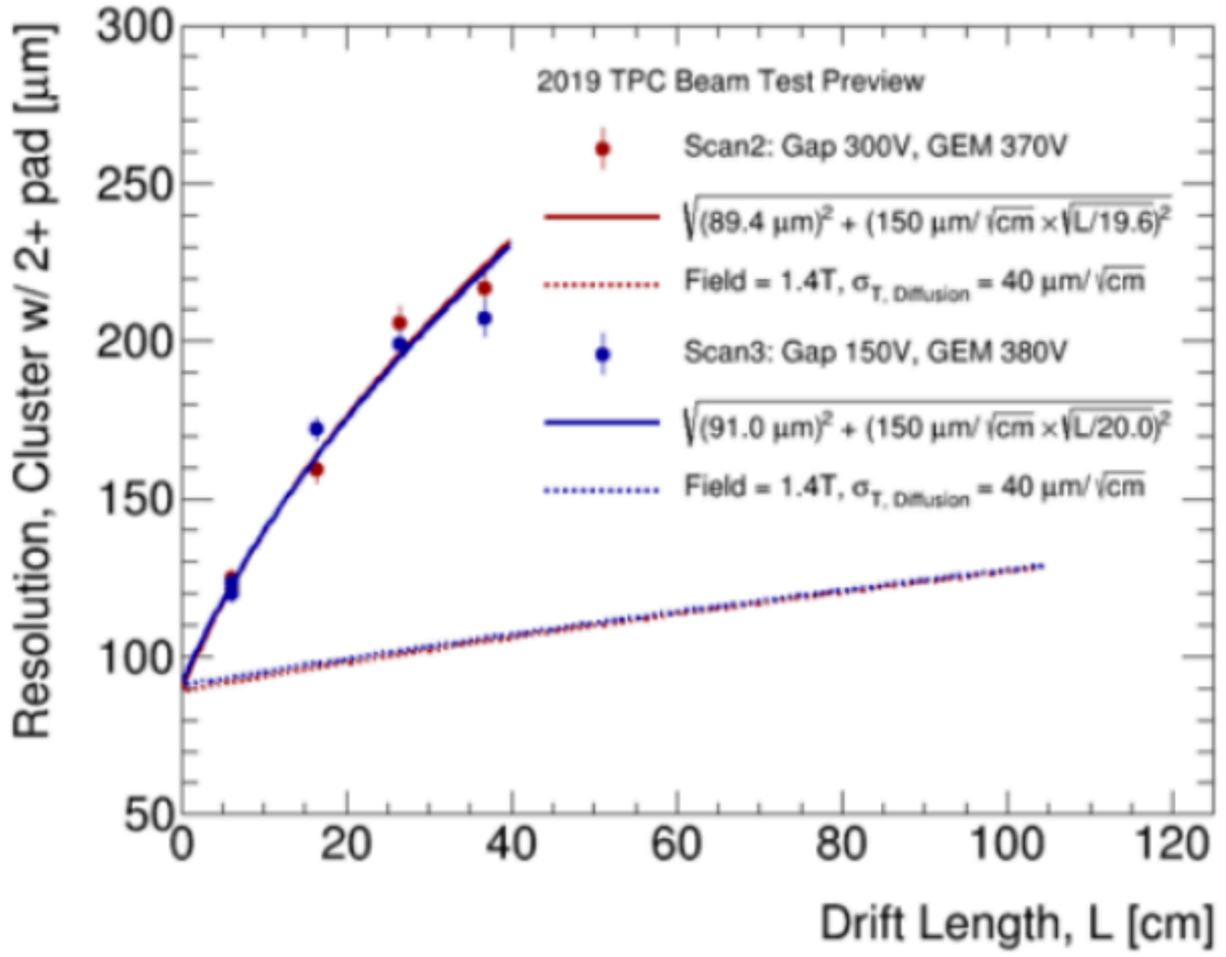
Quad-GEM Gain Stage
Operated @ low IBF

Same as ALICE GEM scheme
Exploits ZigZag Pads for Readout

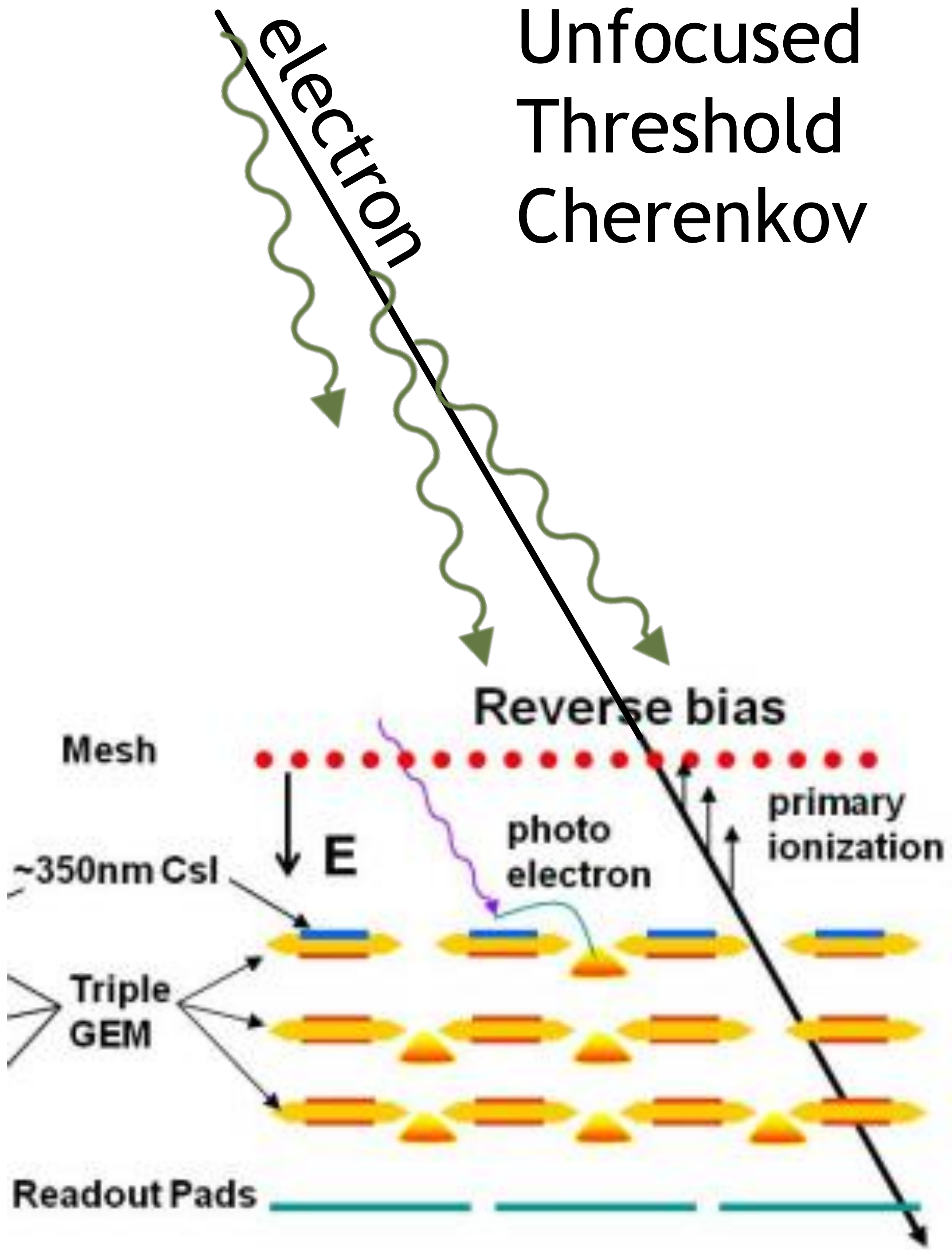


Unique Zig-Zag shape

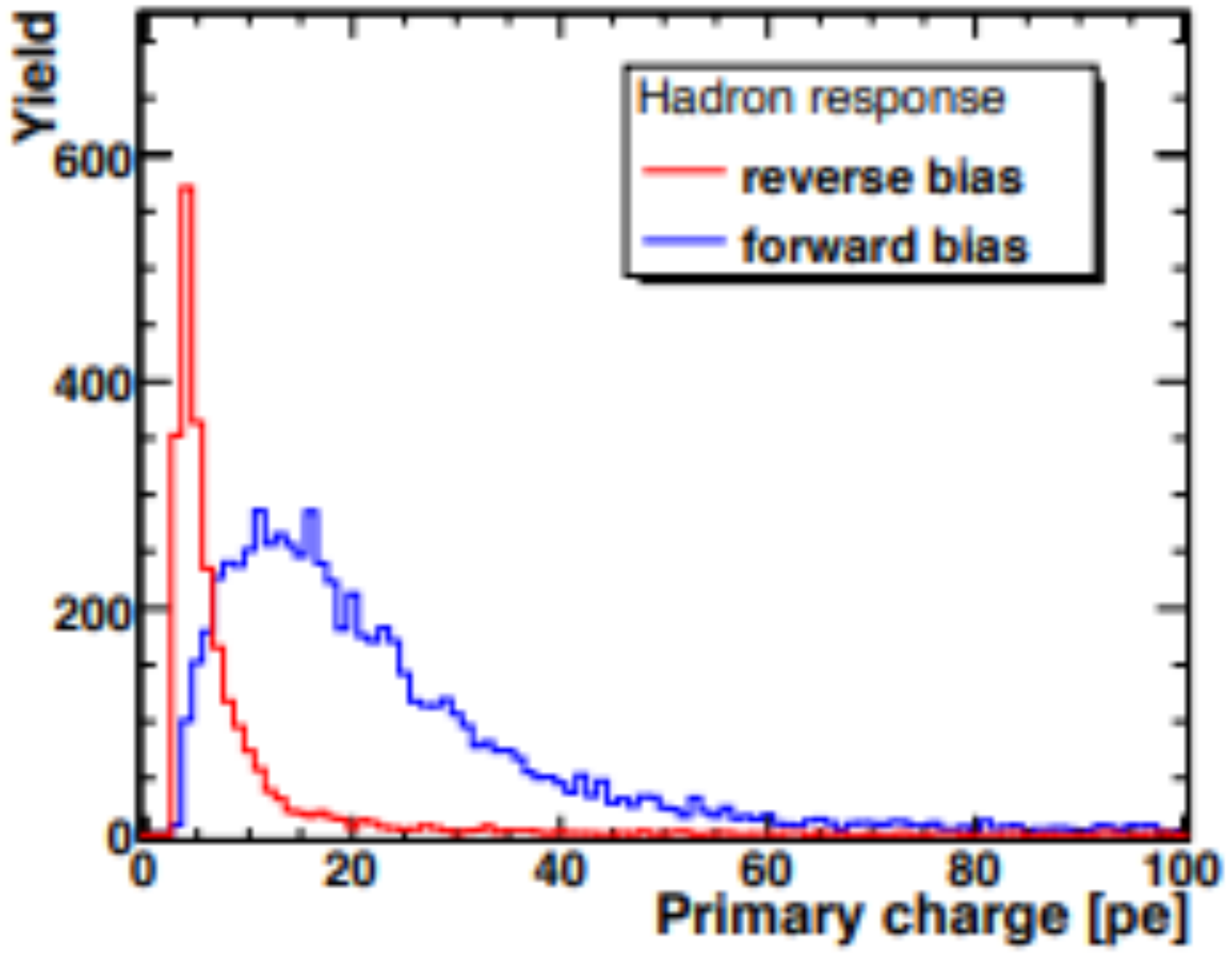


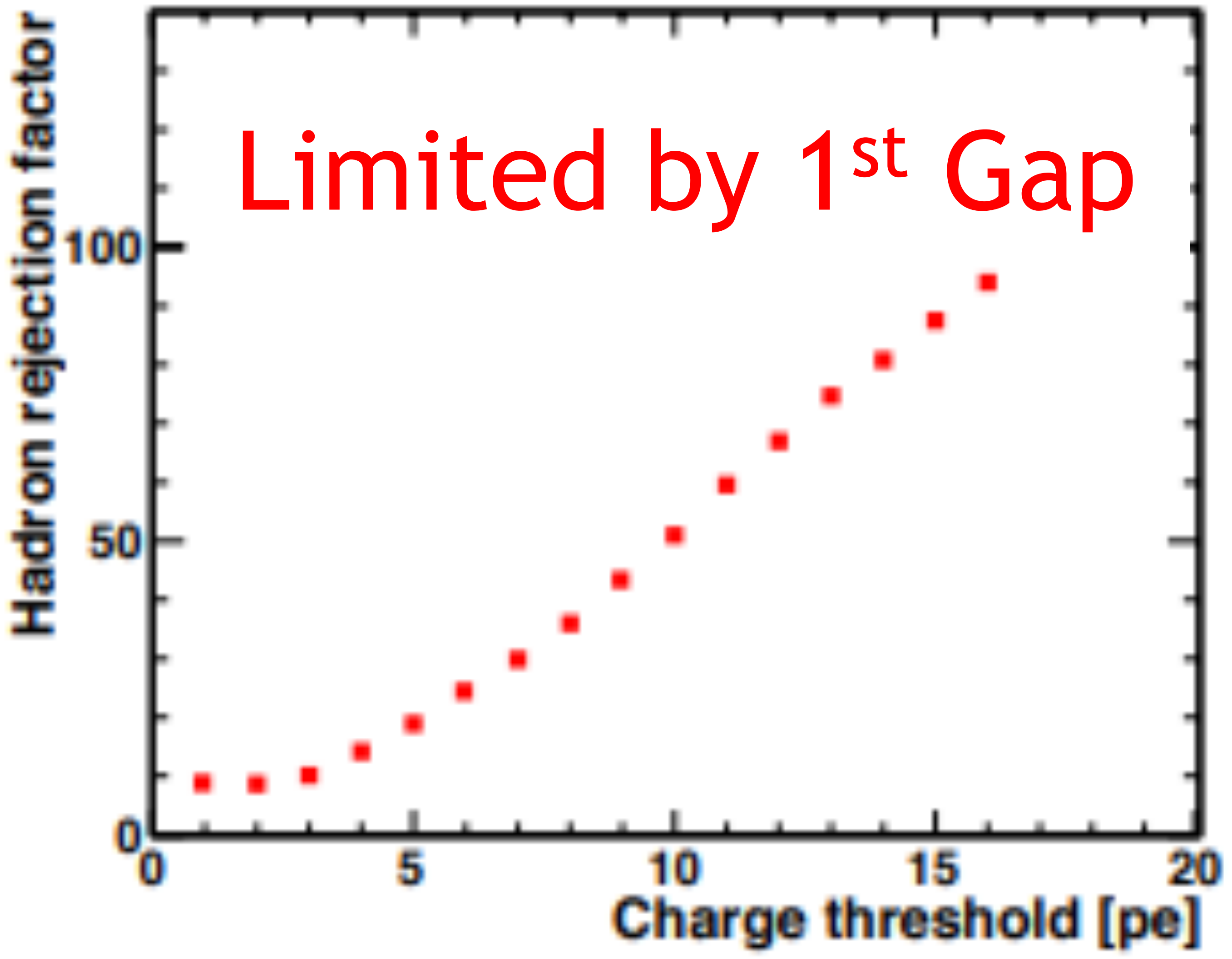


Hadron Blind Detector @PHENIX



- PHENIX HBD optimized for 1e-vs-2e separation.
- 20 photoelectrons vs 40 photoelectrons
- Non-zero hadron response.





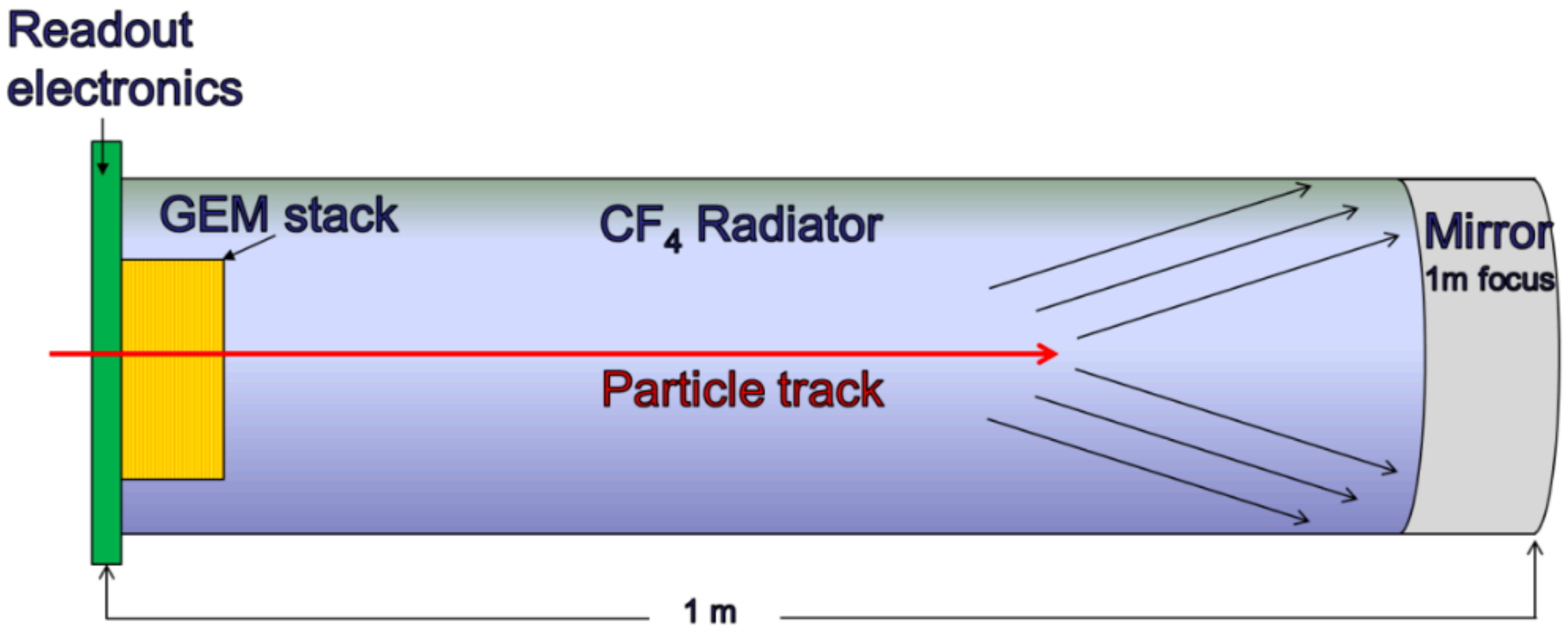
Quintuple GEM based RICH

❖Tested a Ring-Imaging Cherenkov detector prototype with:

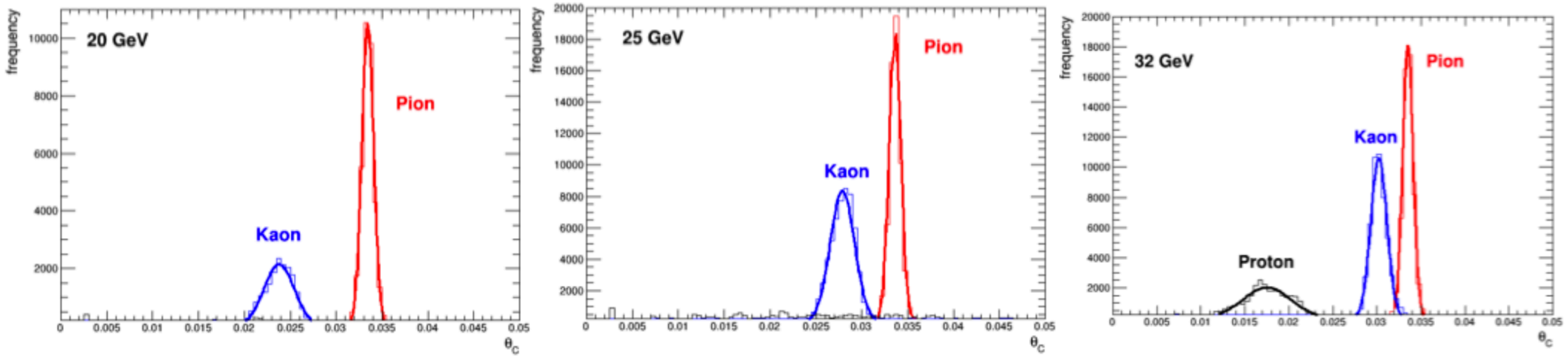
◉CsI Photocathode on top GEM
◉Mirror in deep UV -> MgF2 coating
◉Single Photon Capability ->quintuple GEM stack
◉Radiator choice: CF4

❖The windowless technology + wave-length-tuned mirror: Minimize the loss of photons

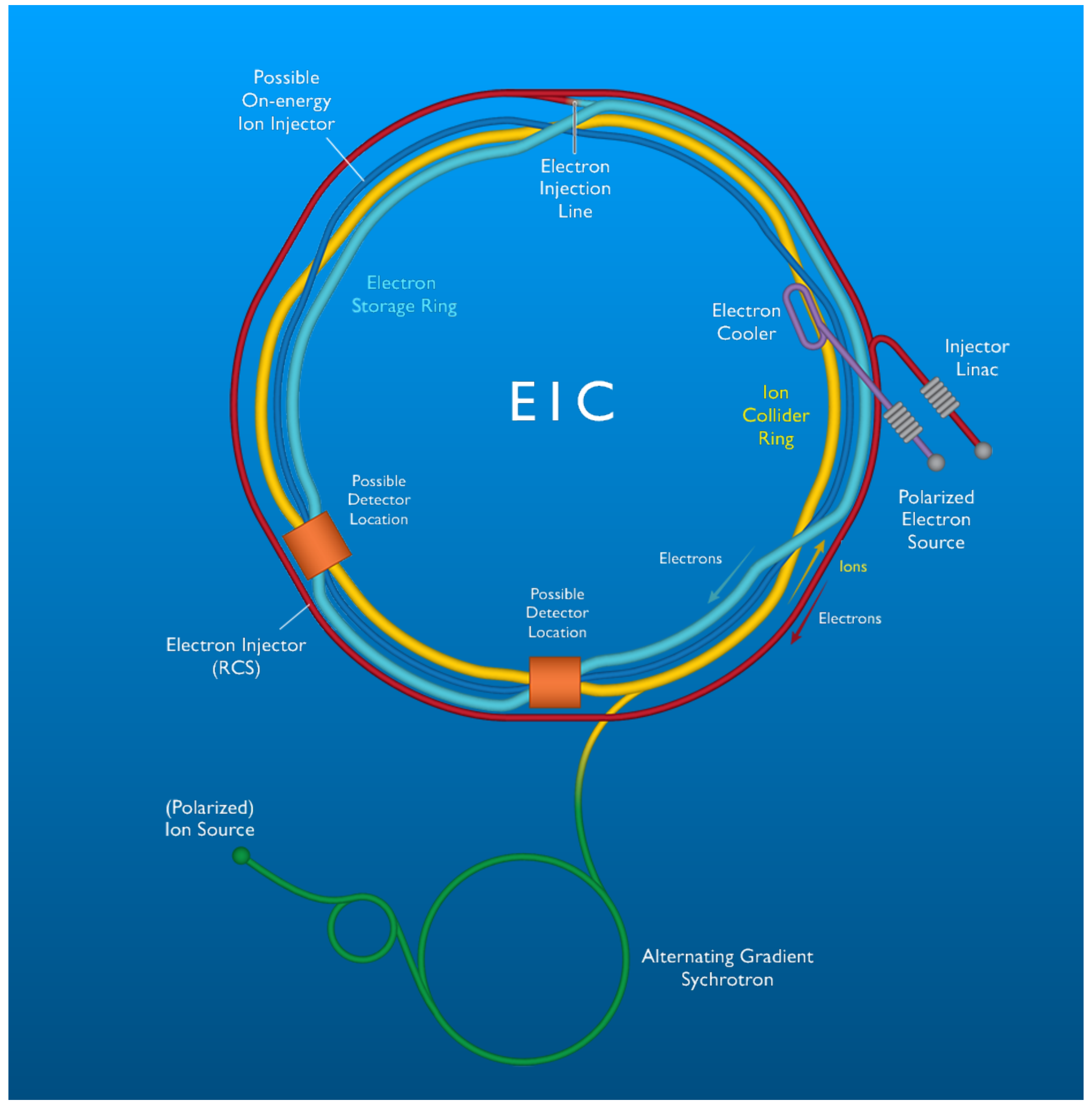
❖ Small Ref. Index: Particle identification (PID) reaching out to high momenta

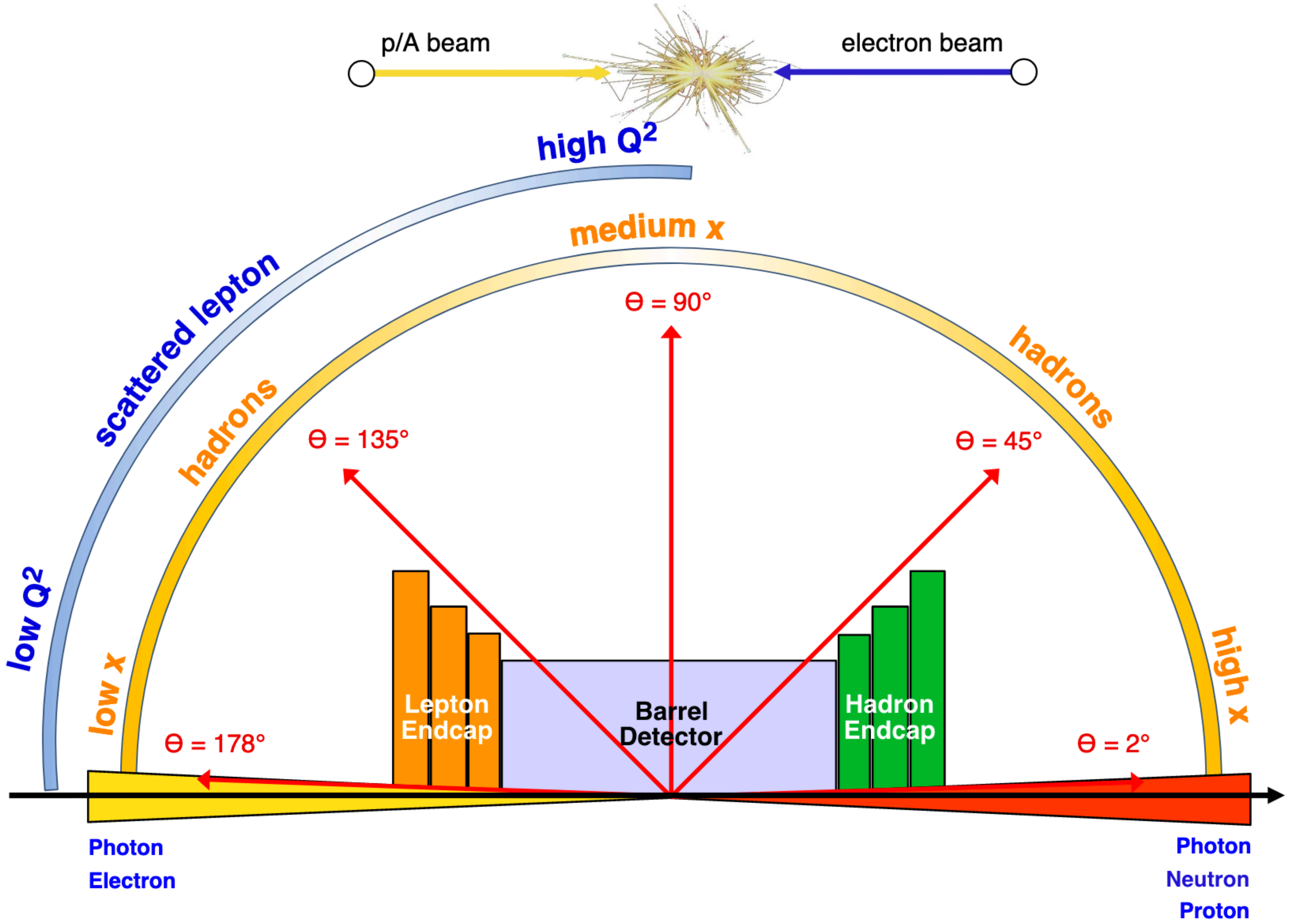


Ref: IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 62, NO. 6, DECEMBER 2015



Electron Ion Collider @ RHIC





Many Proposals for Gas detectors in the upcoming EIC @RHIC

Thank You