

Ionization detectors (Leo ch. 6)

Lecture 2:

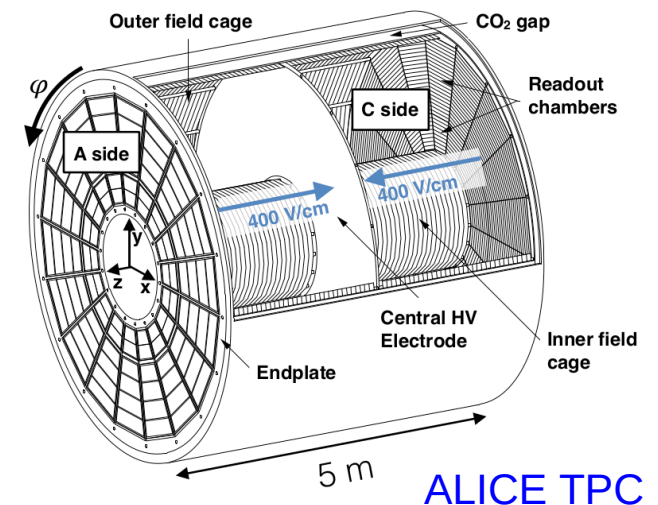
Motivation: High-energy particles require position sensitive detectors

6.6: The multiwire proportional chamber

6.7: The drift chamber

6.8: The time projection chamber

If time: A few extra applications of gas ionization detectors

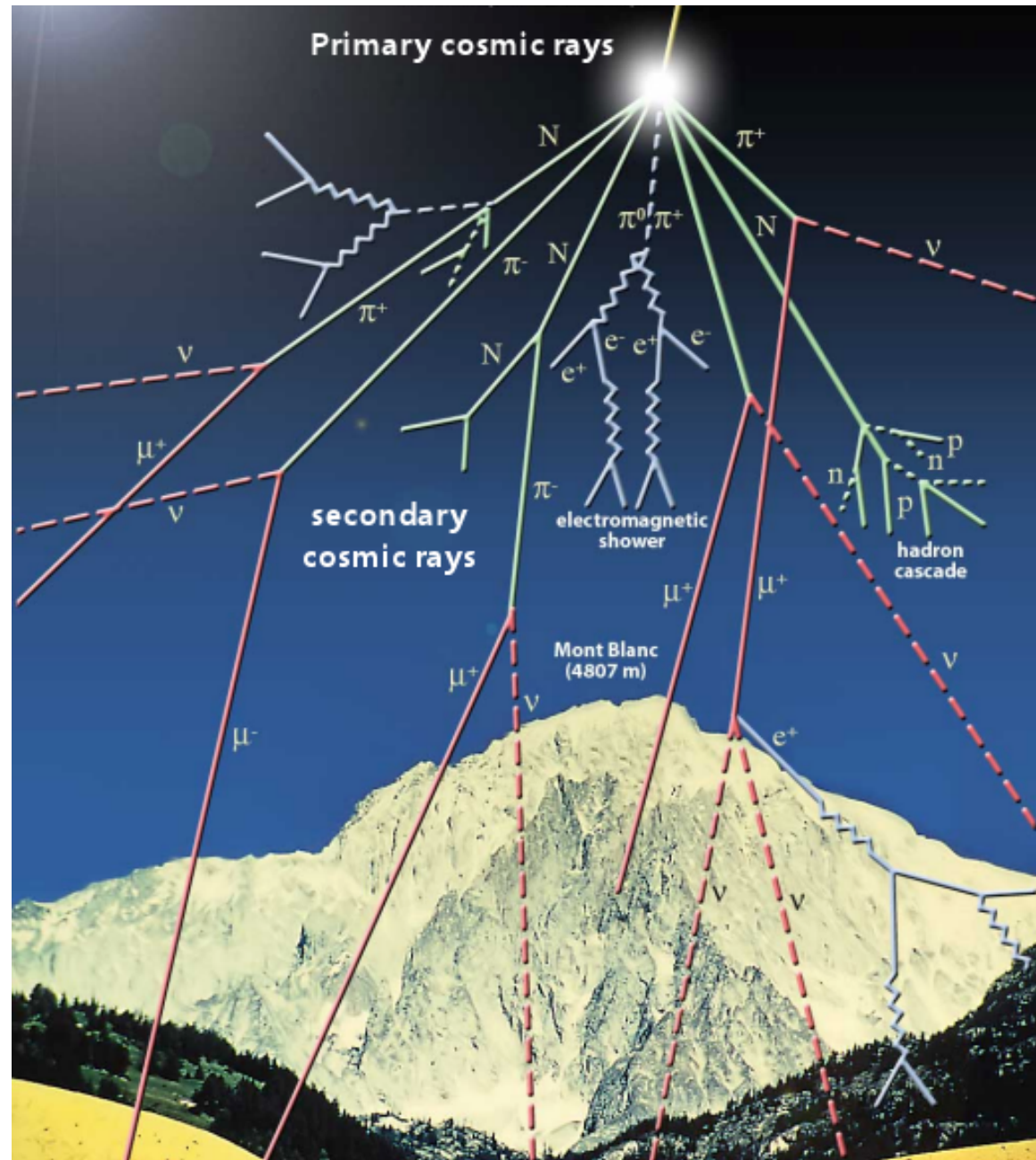
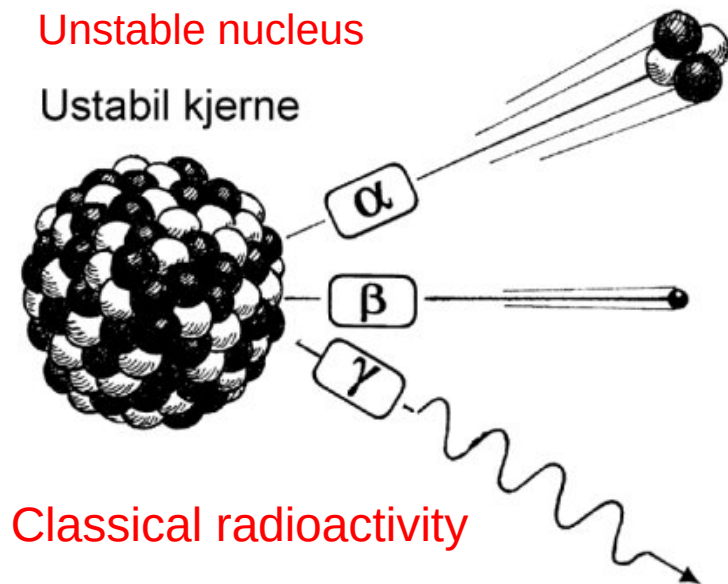


Production of subatomic particles – natural processes

Most subatomic particles and systems are unstable, decaying to more stable particles. They are identified by measuring their more long-lived decay products.

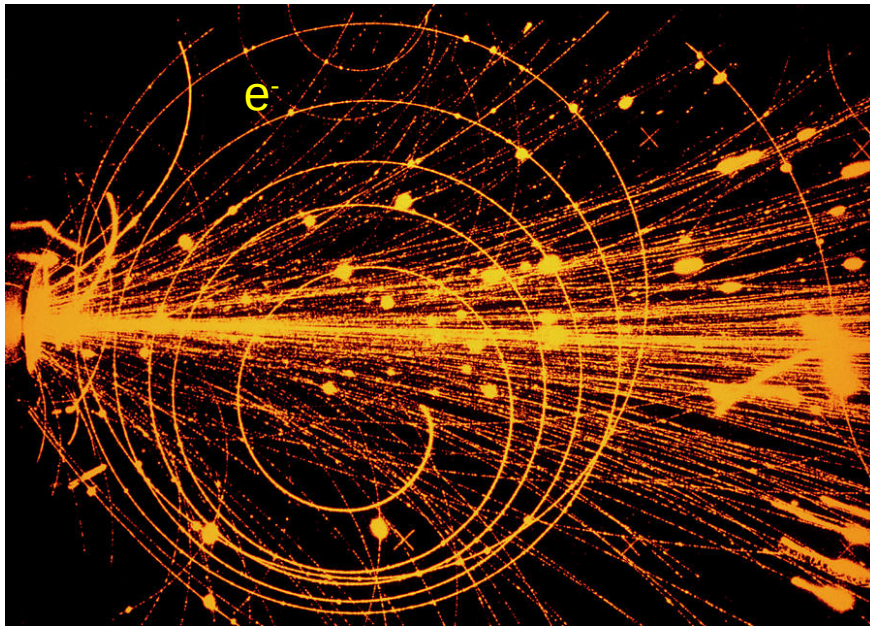
Examples of systems involving decays:

- Naturally radioactive nuclides (typically α -, β -, γ -radiation)
- Cosmic rays (energetic showers produced in atmosphere, particles reaching the surface are mostly muons). Very penetrating.

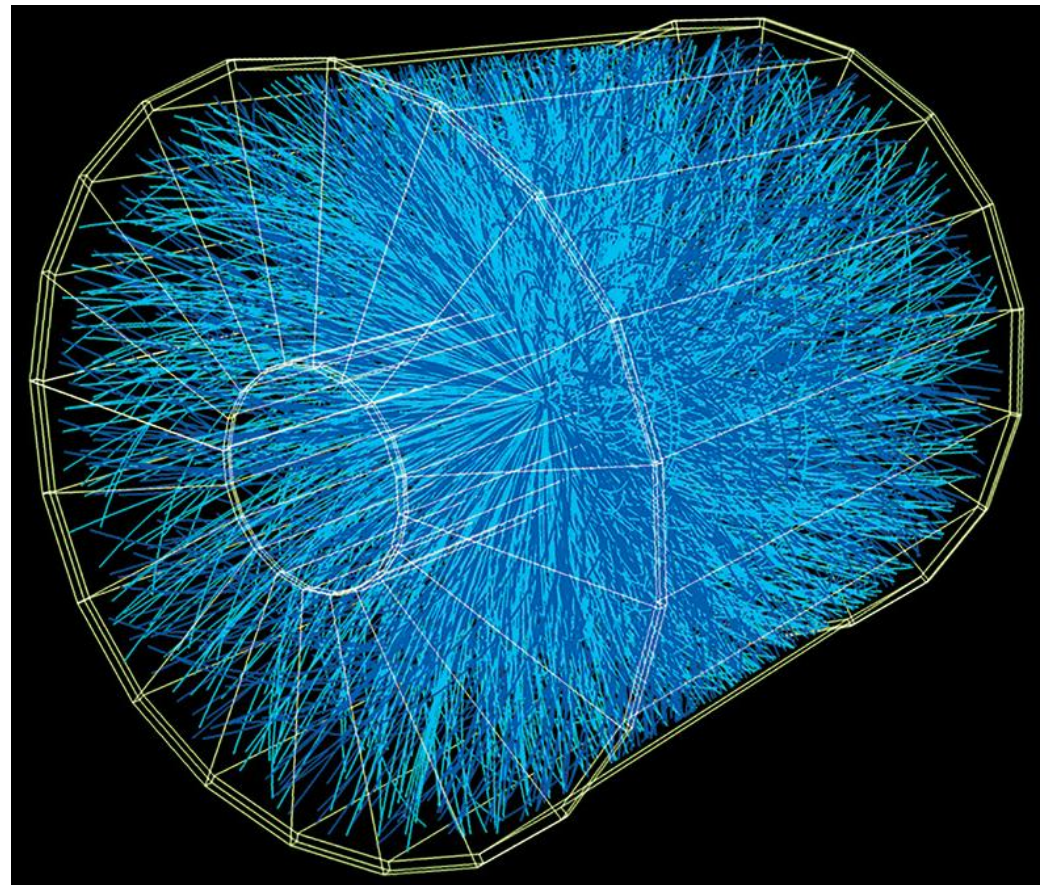


Production of subatomic particles – accelerator experiments

Streamer chamber photo of an oxygen-lead ion collision in the NA35 experiment at the SPS (Super Proton Synchrotron) at CERN. Collision point to the left, spray of produced particles towards the right. One particle is a low-energy electron which spirals inwards in the chamber's magnetic field while losing energy in the chamber gas.



Event display from a lead-lead collision in the ALICE experiment at CERN, showing charged particle tracks (mostly hadrons) in the Time Projection Chamber. Several thousands of very energetic particles (momenta $p \sim \text{GeV}/c$) created in each collision.



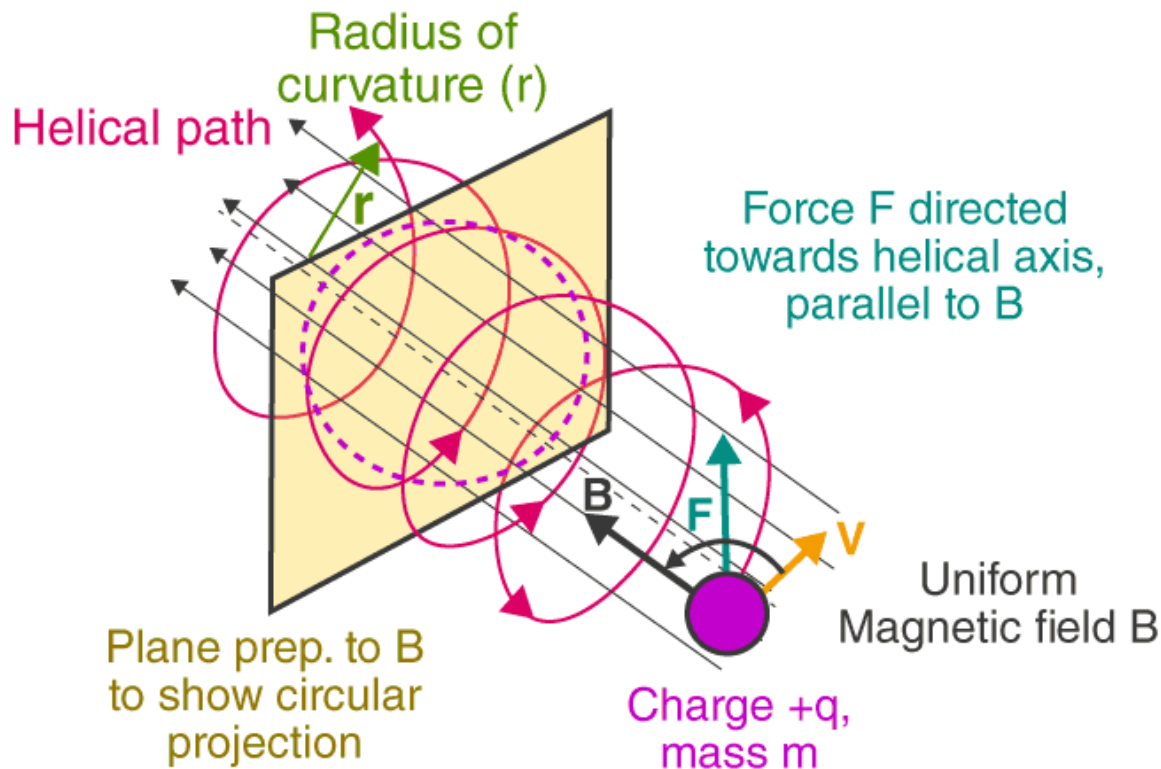
High energy charged particle tracking / momentum determination

High-energy charged particles move long distances and follow helical trajectories in a B field.

Force on charged particle in magnetic field: $\vec{F} = q\vec{v} \times \vec{B}$

Radius of curvature: $R = \frac{mv}{qB}$

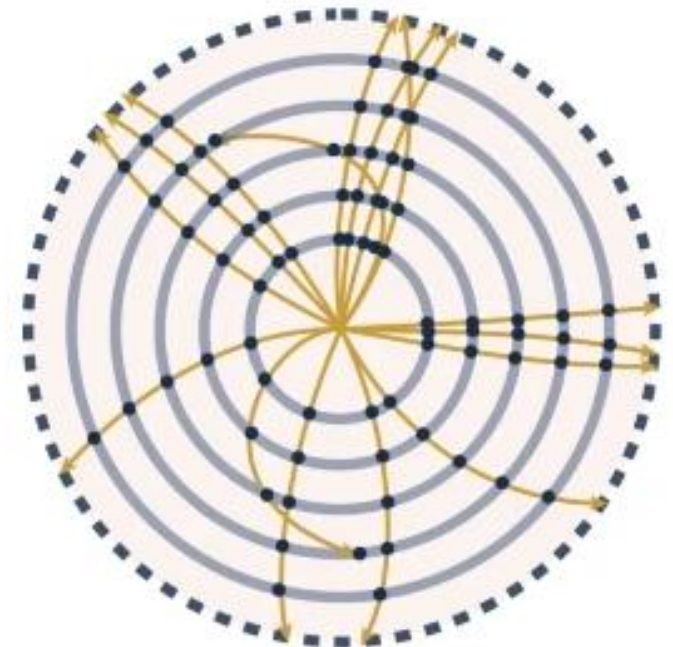
where q , m , v are charge, mass, velocity of particle, B is magnetic flux density



Charged particle tracking is typically done by recording hits along trajectory, using position sensitive detectors in B field.

Tracks reconstructed from hits in sensitive detector elements.

Momentum $p = mv$ and charge sign obtained from track curvature.



Generic particle detector for high energy physics

What we can actually measure in our detectors:

Stable or long-lived particles, typically photons, electrons, muons, protons, neutrons (also pions and kaons)

HEP detectors typically have an onion-like layout, from innermost to outermost layer:

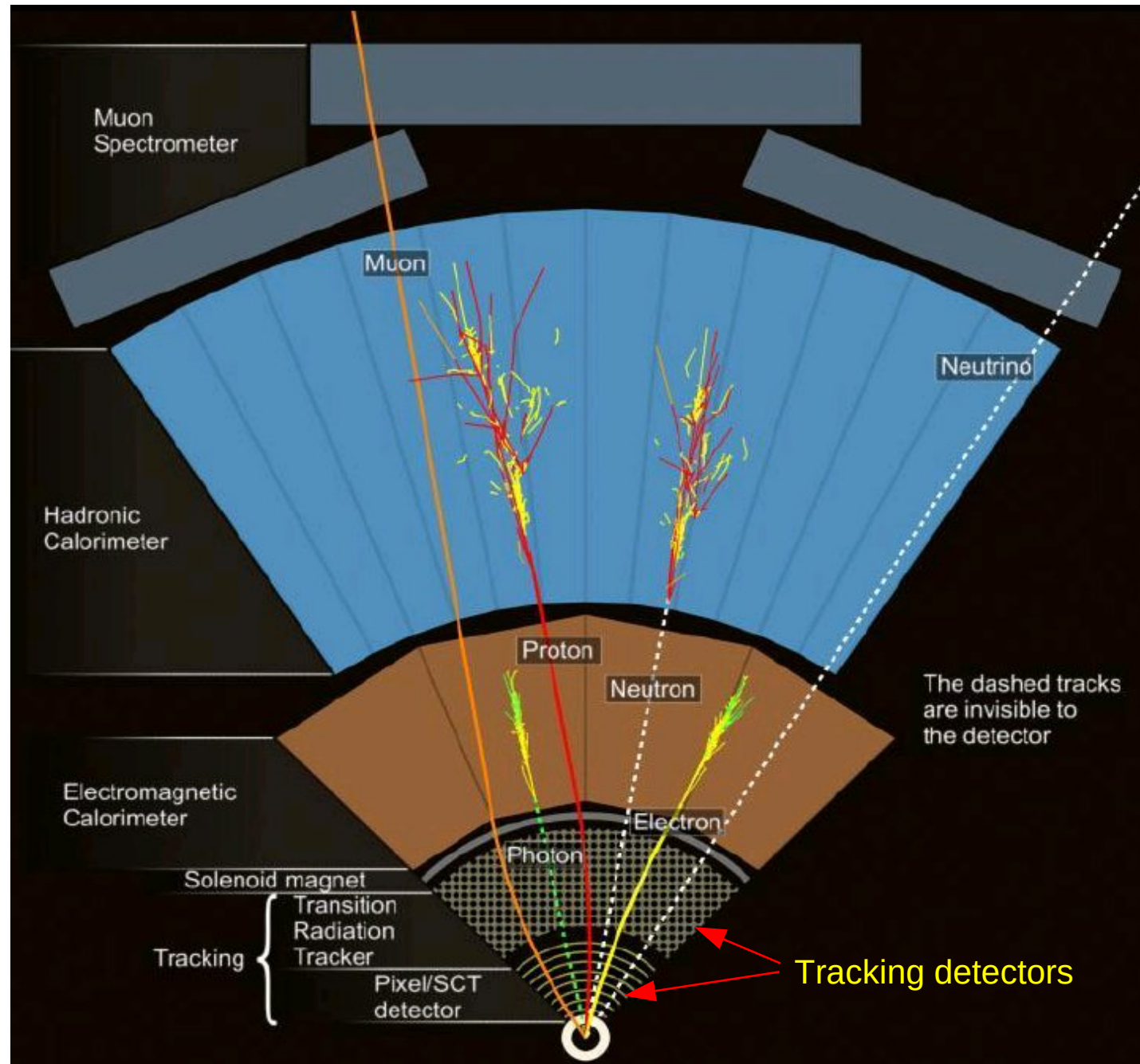
- Charged particle tracking detectors (with B field) → momentum measurements, small energy loss (but particle identification from dE/dx). Position sensitive and based on light materials, typically gas or silicon.

Not stopping particles here!

- Electromagnetic and hadronic calorimeters → measure total energy (also neutral particles)

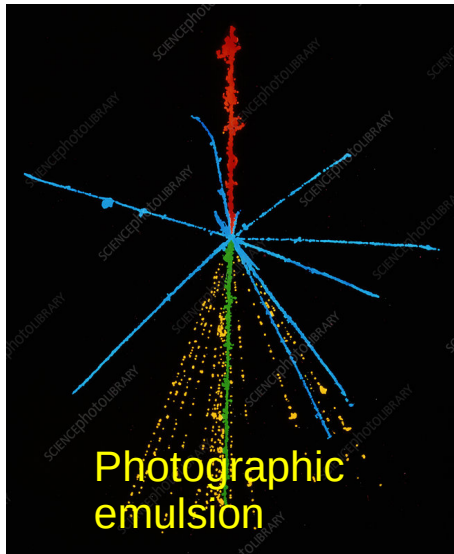
Stopping particles!

- Also muon spectrometer → registers penetrating muons



6.6: The multiwire proportional chamber (MWPC)

Recording charged particle tracks before ~1970: Frame-by-frame manual analysis.



CERN, 1968: Georges Charpak invented the multiwire proportional chamber (awarded Nobel Prize 1992).

THE USE OF MULTIWIRED PROPORTIONAL COUNTERS TO SELECT AND LOCALIZE CHARGED PARTICLES

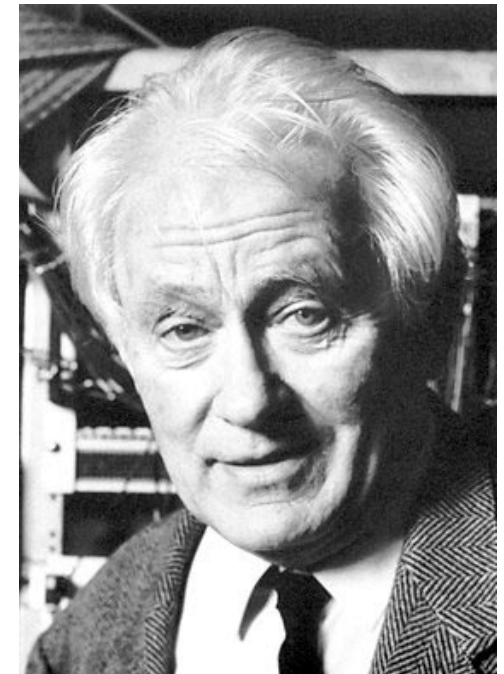
(February 23, 1968)

G. Charpak, R. Bouclier, T. Bressani, J. Favier
and Č. Zupančič

CERN, Geneva, Switzerland.

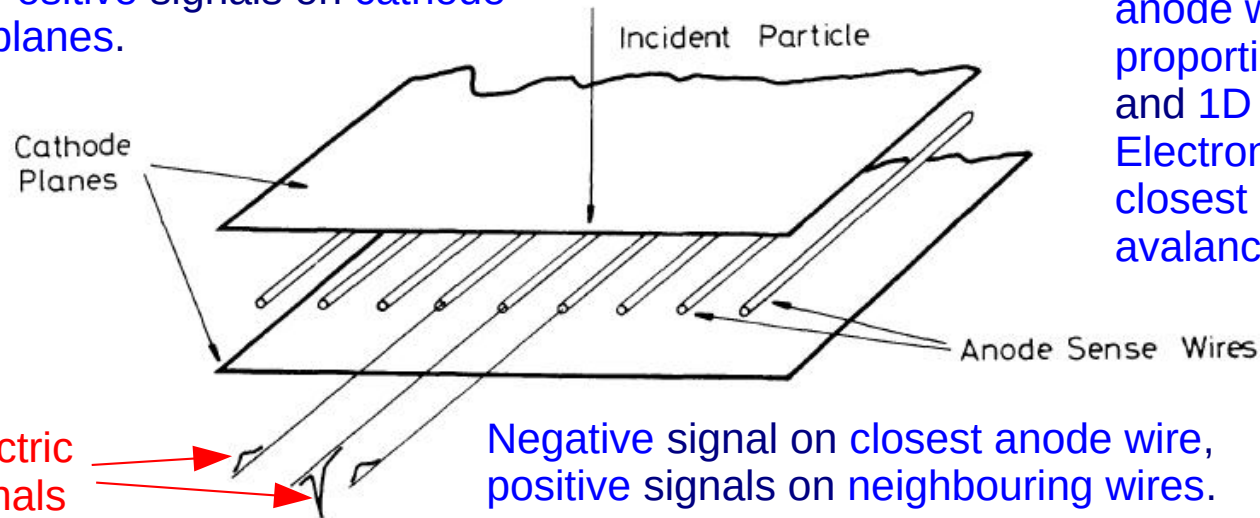
NIM 62 (1968)

Array of thin parallel anode wires between two cathode planes, all with individual amplifiers. First all-electronic multi-track detector!



Basic operating principle of a MWPC:

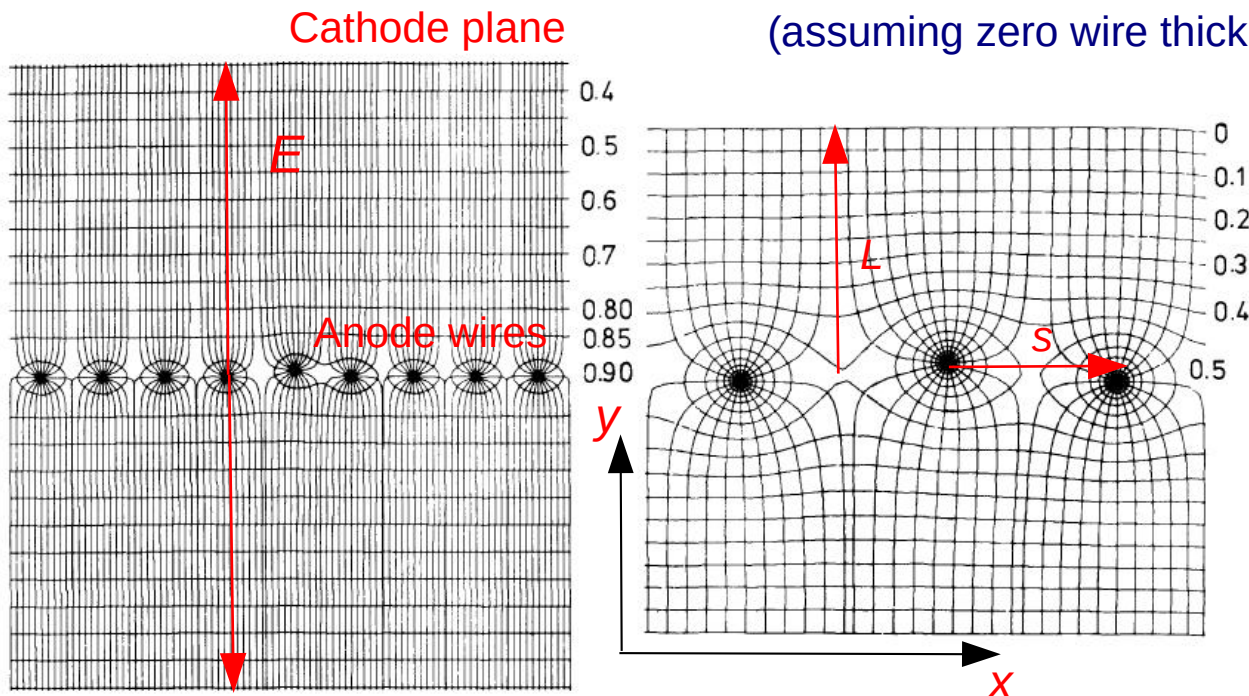
Positive signals on cathode planes.



Negative signal on closest anode wire, positive signals on neighbouring wires.

Parallel, closely spaced anode wires between two cathode planes. Each anode wire acts as an independent proportional counter → gives energy and 1D position (x). Electrons drift along field lines to closest anode wire, produce an avalanche and are collected. Drift of free ions induce (most of the) signals on anode wires and cathode plane.

Electric field configuration



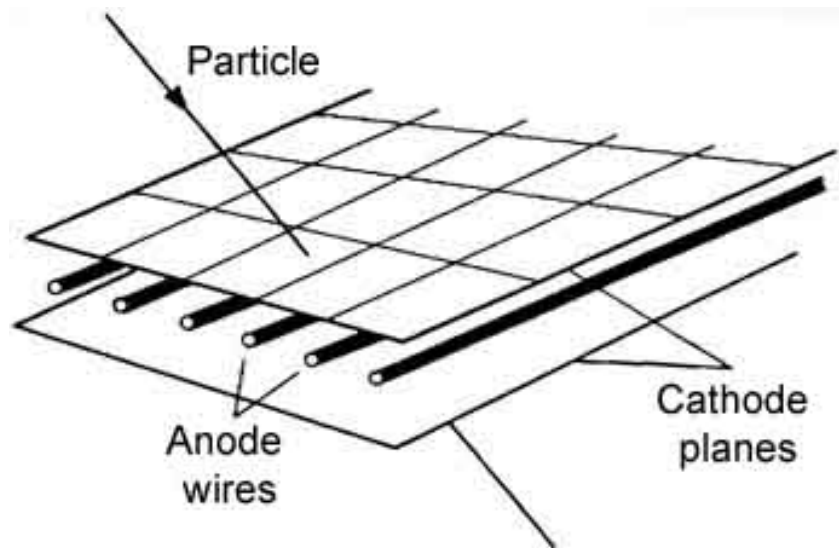
Potential:
$$\phi(x, y) = -\frac{CV}{4\pi\epsilon} \ln \left[4 \left(\sin^2 \frac{\pi x}{s} + \sinh^2 \frac{\pi y}{s} \right) \right]$$

(assuming zero wire thickness)

s : wire spacing, V voltage, C capacitance (determined by chamber dimensions)

E -field has $\sim 1/r$ dependence near anode wires (similar to cylindrical proportional counter). $\sim$ Uniform drift field closer to cathode plane.

Construction of a multiwire proportional chamber



Cathode planes may be metal wires / strips / mesh or foils.

Choice of gas for a MWPC:

Similar considerations as for simple proportional counter.

Frequently used (historically): Magic gas – main gas Ar (75%), isobutane C_4H_{10} (24.5%), as quencher, electronegative gas freon (CF_3Br) (0.5%). Gives gains up to 10^7 . Other gas mixtures can be considered to optimize functionality.

Typical dimensions:

Anode wire diameter d : $\sim 20 - 40 \mu m$

Anode wire spacing s : $\sim 2 mm$

Anode-cathode gap: $L \sim 7 - 8 mm$

Wire length and extension of planes in general: Can be large, for tracking over wide area.

Each anode wire / cathode element has its own electronics integrated on frame.

Mechanical / electrical stability crucial.

Electrostatic forces in chamber (wire-wire and wire-cathode plane) compensated by wire tension.

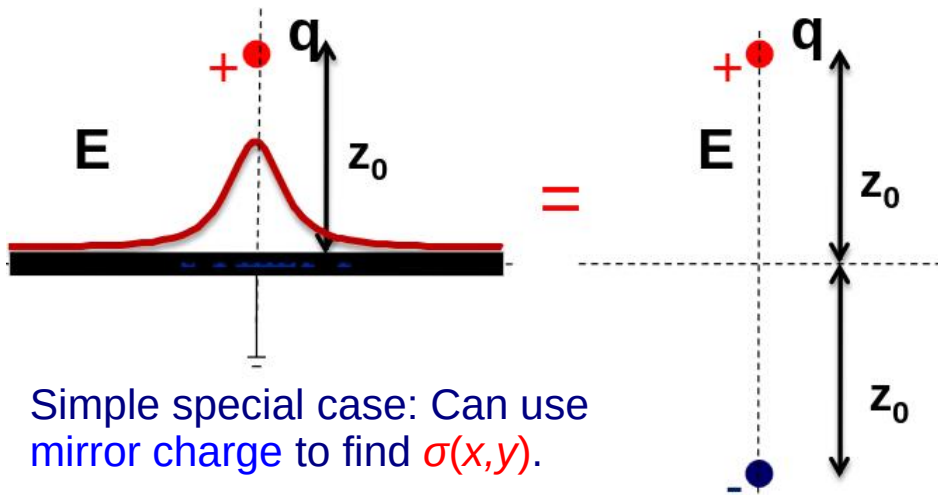
Timing resolution:

MWPC quite fast detector, depends essentially on drift time of electrons (but signal induced by ions drifting away from avalanche region).

Leading edge of ion signal $\sim 10 ns$.

Limiting factor: For traversing particle, primary ionization distributed over cathode-anode gap.

Induction of signals on electrodes by moving charges



Simple special case: Can use mirror charge to find $\sigma(x,y)$.

Charge q above grounded electrode:
 E -field perpendicular to conductor surface,
 surface charge density $\sigma(x,y) = \epsilon E(x,y)$.
 Need to solve Poisson equation:

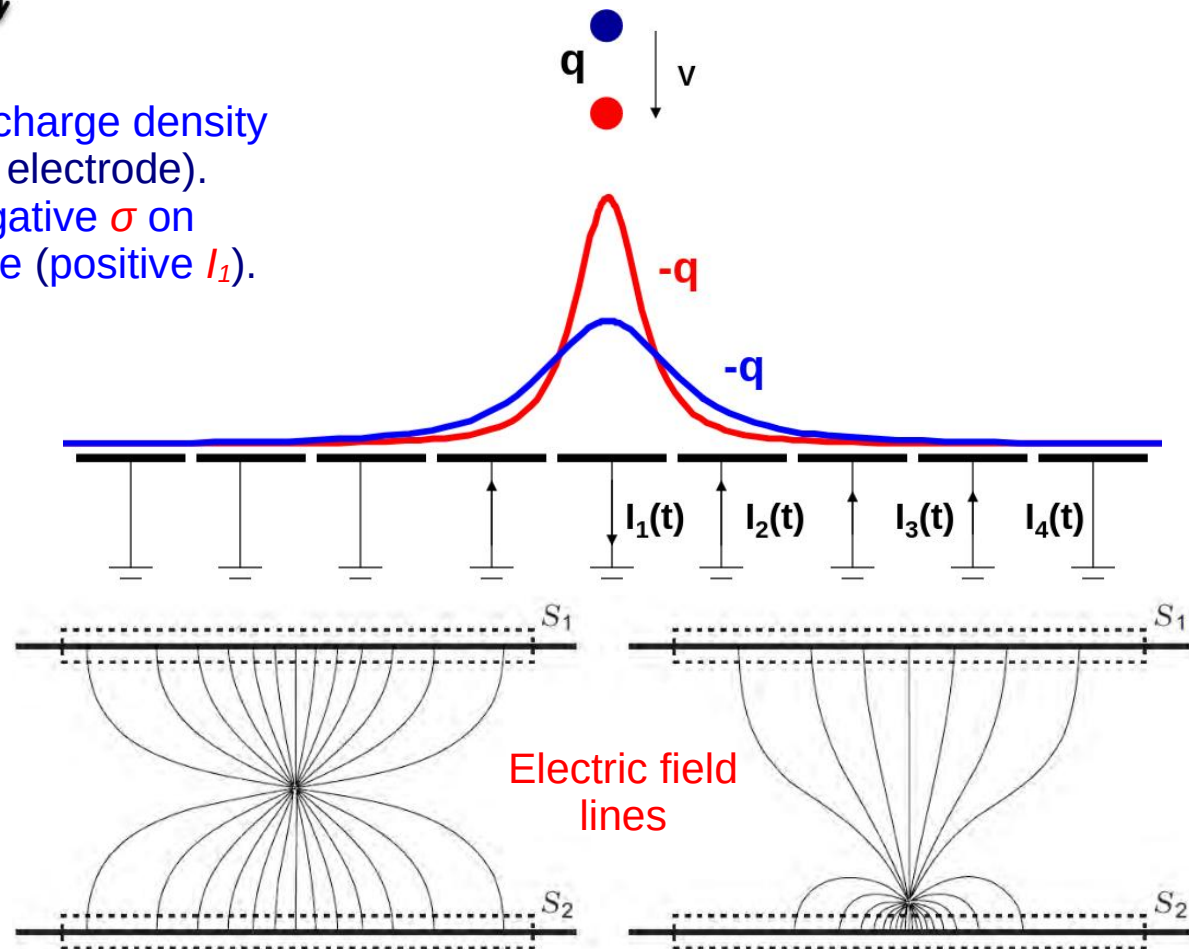
$$\nabla^2 \phi = -\frac{\rho(\vec{r})}{\epsilon}; \quad \vec{E} = -\nabla \phi(\vec{r}); \quad \phi = 0 \text{ on surface}$$

Not trivial for arbitrary geometry!

Moving charge: Changes induced surface charge density (but $\sigma(x,y)$ independent of segmentation of electrode).
 Approaching positive charge increases negative σ on closest segment $\rightarrow$ current out of electrode (positive I_1).
 Decreasing negative σ on neighbouring segments $\rightarrow$ current into electrode (negative $I_i, i \neq 1$).

Similar to situation on MWPC anode plane, here with negative I on wire closest to avalanche (ions drifting away), positive I on other wires.

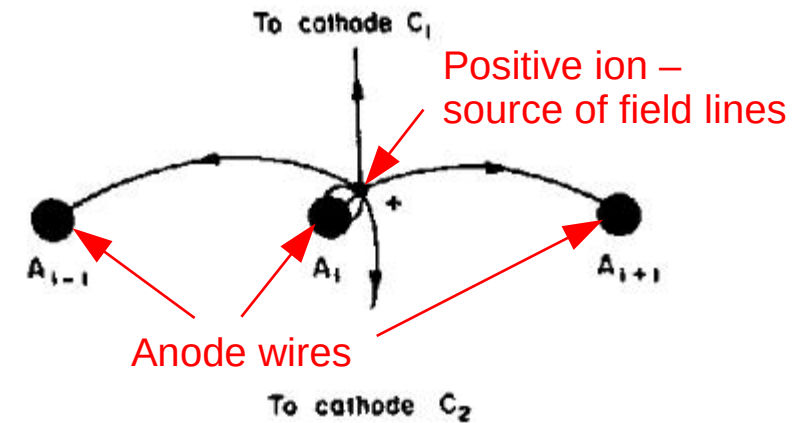
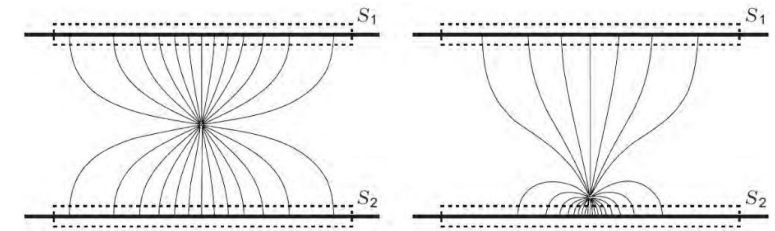
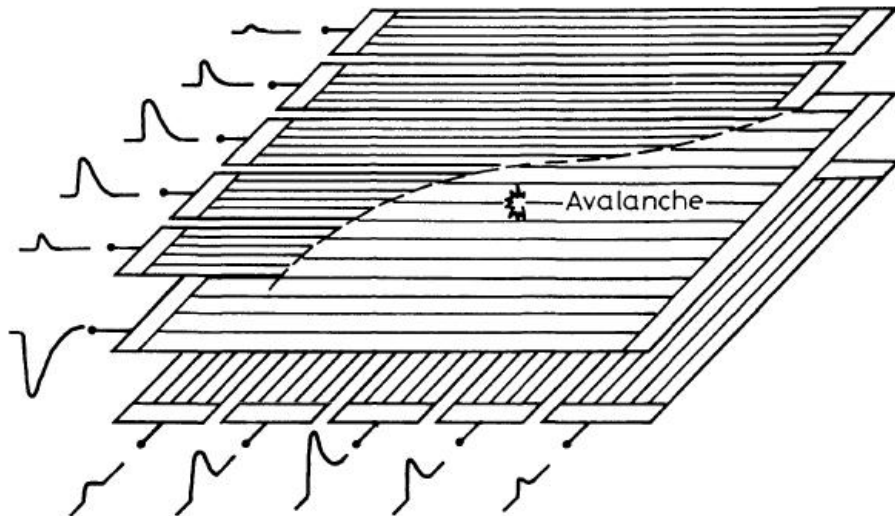
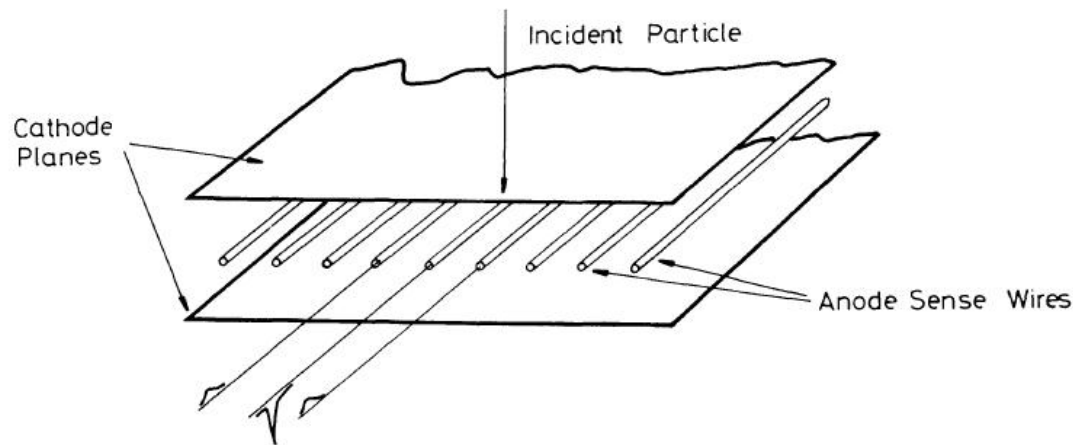
E -field lines and their density on conductor surface ($\sim \sigma$) change with movement of charge.



Induction of signals on electrodes by moving charges

Charpak and Sauli, NIM 162 (1979):

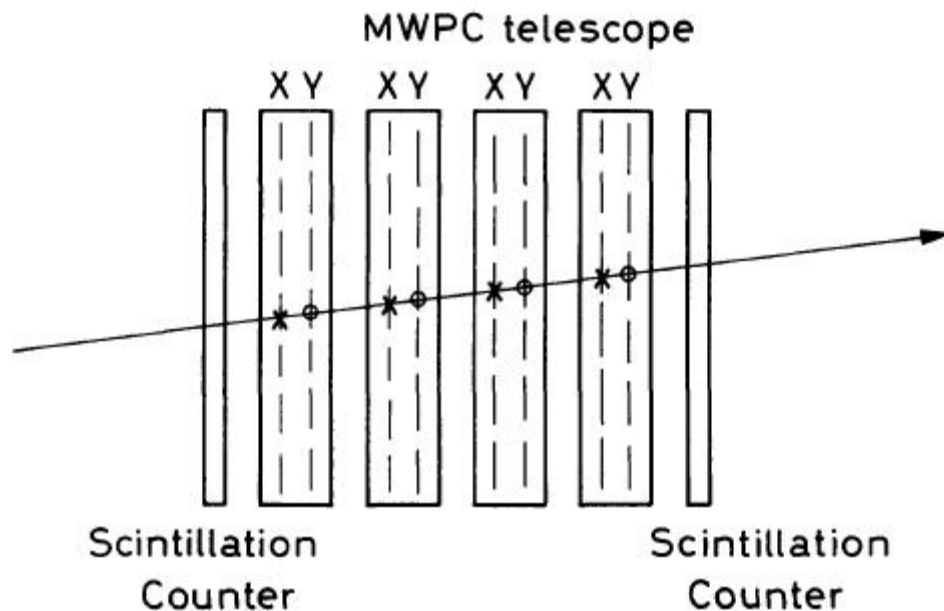
“The motion of the ions liberated in the avalanches controls all the important information that can be extracted from a chamber. This is why a clear qualitative understanding of the mechanism of inducing the positive pulses seems to us a useful preliminary”.



E -field flux from each charge conserved. Ions drifting away from anode wire $A_i \rightarrow$ density of E -field lines $\sim \sigma$ decreasing, negative pulse, while density of field lines increases everywhere else $\rightarrow$ positive pulses on other electrodes (time dependent).

General problem solved by Shockley-Ramo theorem: Instantaneous current in electrode is due to instantaneous change in electrostatic flux lines ending on the electrode (details beyond the scope of this course).

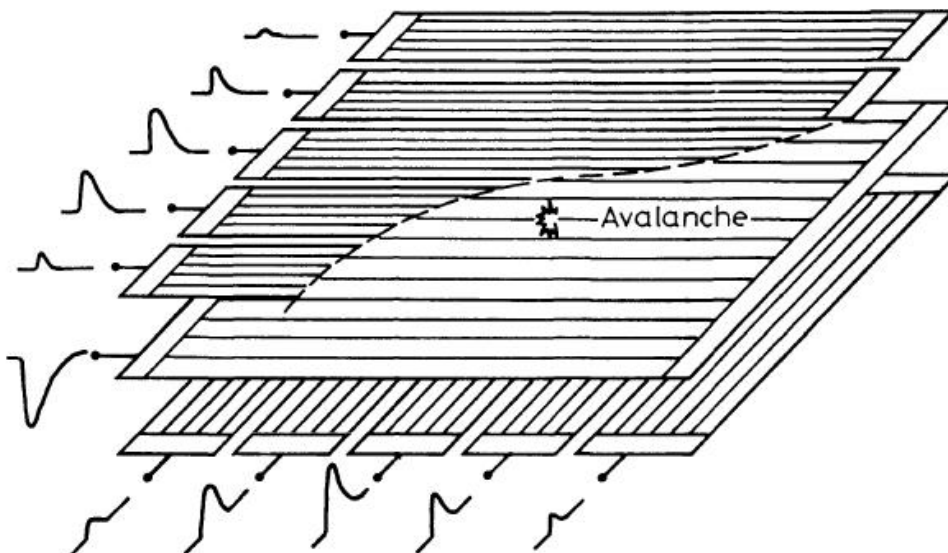
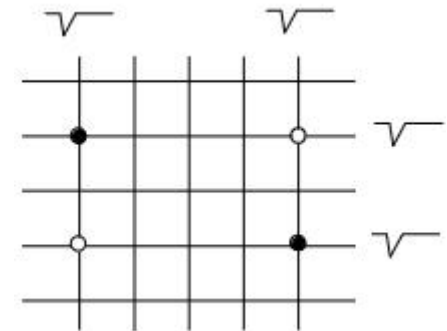
Extraction of 2D position information from a MWPC (1)



Direct use of signal from anode plane:
Anode wire with negative signal is the one closest to the avalanche → gives x or y coordinate.

Resolution: $\sigma(x(y)) = s/\sqrt{12}$ (uniform probability over an interval s) ~ 0.6 mm
2 anode planes (x, y) needed to obtain 2D information.

High track density:
Spurious (x, y) combinations (ghost hits). Remedied e.g. by adding planes with diagonal wire orientations.

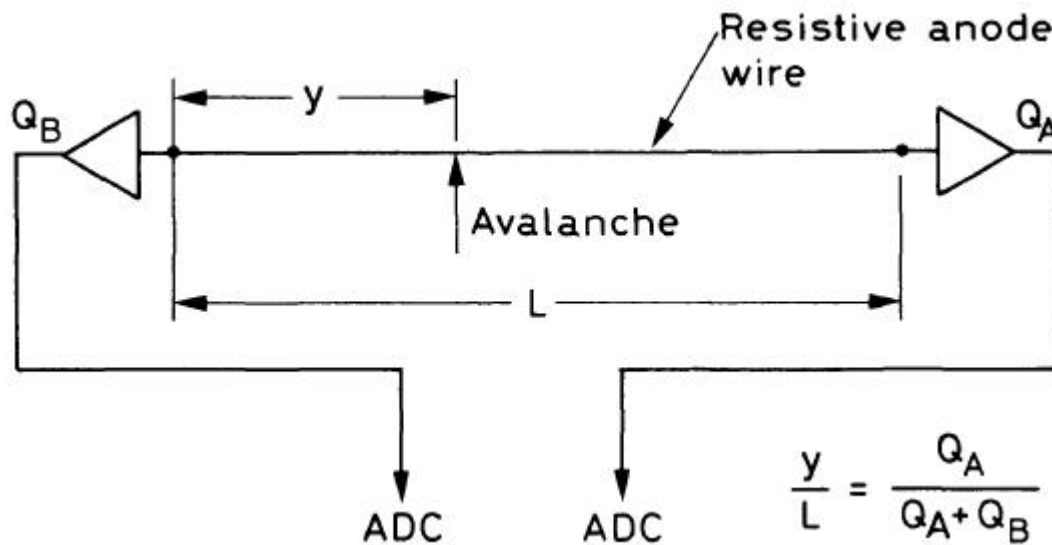


Centre of gravity (centroid) method:
Weighted sums of positions on cathode strips for x and y planes:

$$x = \frac{\sum (Q_i - b_i) x_i}{\sum (Q_i - b_i)} \quad y = \frac{\sum (Q_j - b_j) y_j}{\sum (Q_j - b_j)}$$

x_i (y_j) coordinate of cathode strip,
 Q_{ij} charge collected on strip, b_{ij} small noise correction.
Resolution $\sigma \sim 50 - 300$ μm .

Extraction of 2D position information from a MWPC (2)

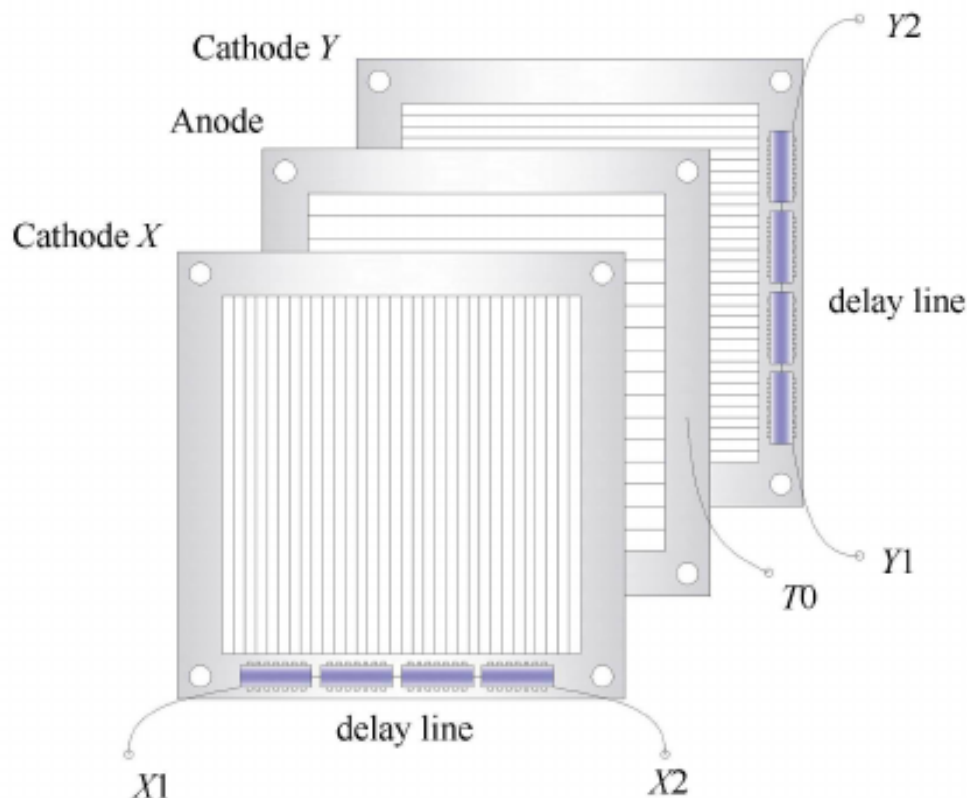


Charge division:

Charge collected at either end of a resistive anode wire is divided in proportion to the inverse resistance ~ length of the wire from the injected charge (avalanche position):

$$y = L \frac{Q_A}{Q_A + Q_B} \quad L: \text{wire length}$$

Accuracy: $\sigma(y/L) \sim 0.4\%$ obtained



Time difference (delay line technique):

Delay lines capacitively coupled to cathode or anode planes. Anode signal (arrival of avalanche, fast) used as trigger, time difference between arrivals of the signals at the two ends of the delay lines are measured. Coordinates found as:

$$x = k_x \frac{T_{x1} - T_{x2}}{2} + x_{offset} \quad k_x, k_y: \text{signal speeds}$$

$$y = k_y \frac{T_{y1} - T_{y2}}{2} + y_{offset} \quad x_{offset}, y_{offset}: \text{offsets}$$

6.7 The drift chamber (DC)

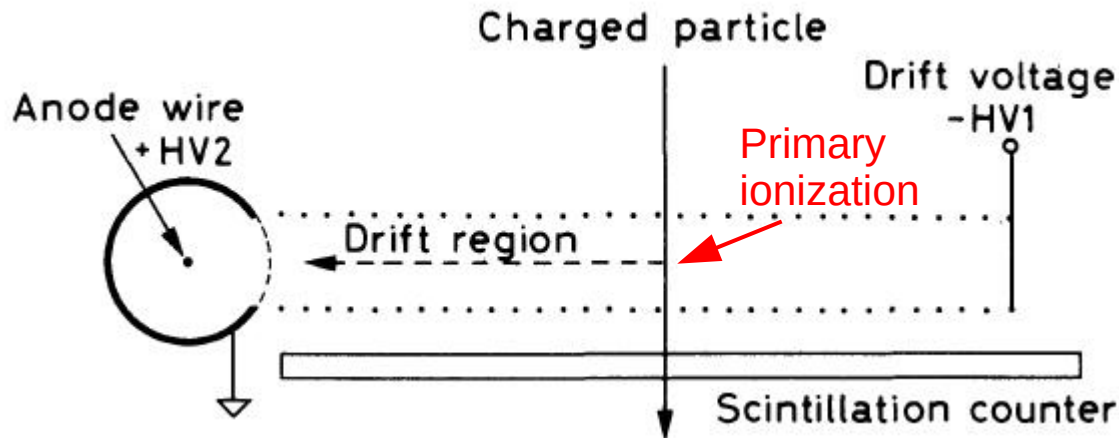
Drift chamber operating principle:
Spatial information from electron drift
time from ionizing event to sense wire:

$$x = \int_{t_0}^{t_1} u \, dt$$

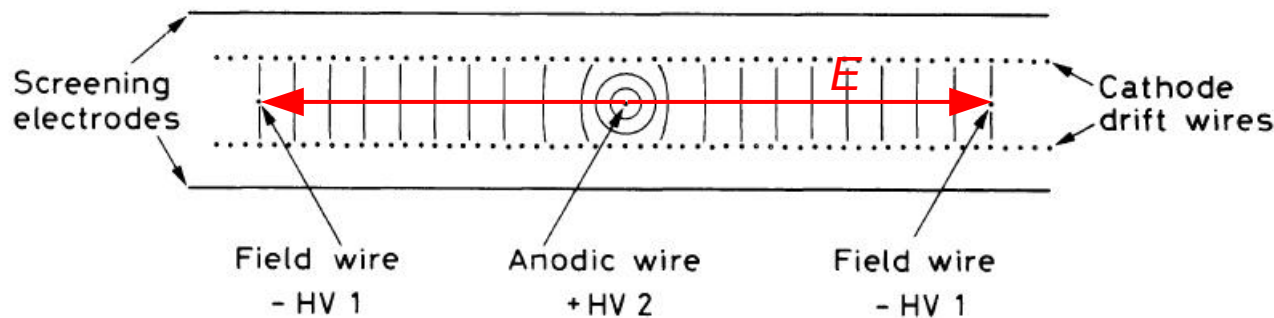
u : drift velocity

t_0 : start time (from trigger)

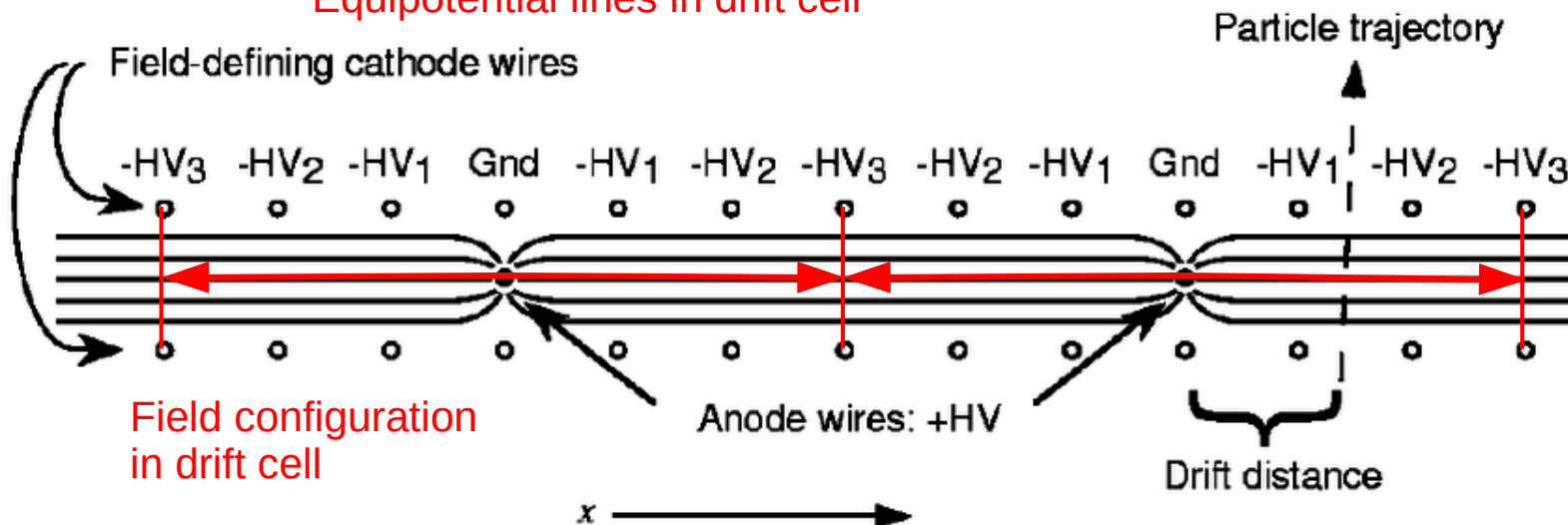
t_1 : signal arrival time at anode wire



DC operating principle



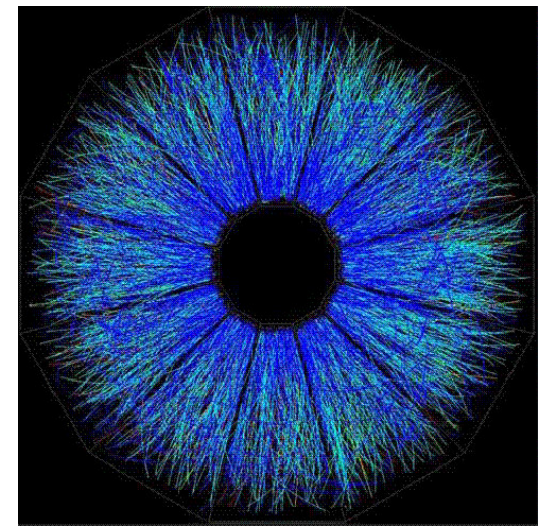
Equipotential lines in drift cell



Typical drift
region: ~ 10 cm
Typical drift
times: a few μ s.

Possible drift chamber geometries

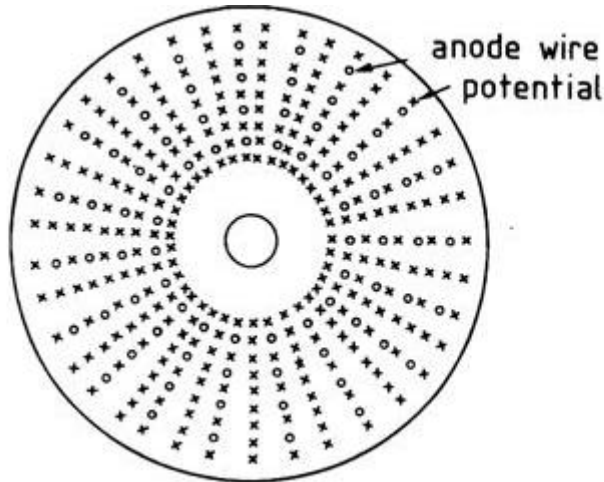
- Planar design (shown on previous slide), stacked layers give (x,y) coordinates
 - Cylindrical design – well suited for HEP applications, information on (r,ϕ) coordinates of trajectory
- Many possible configurations of potential wires relative to anode wires (typically polygons). Can have many wires in same gas volume, or tube chamber.
- Drift time Δt gives distance from ionization event to anode wire.



Tracks in high energy collision, viewed in the (r,ϕ) plane

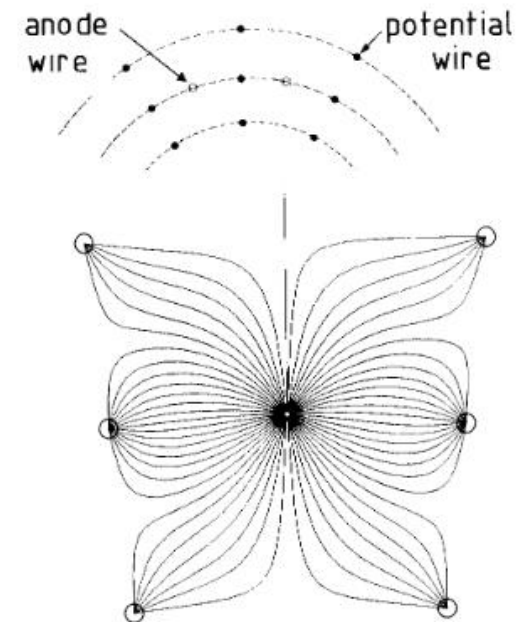
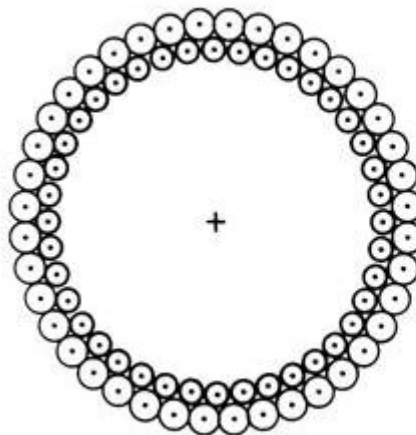
Typical cylindrical DC:

Many wires in same gas volume.
Use small angle stereo for z .
Usually use single hit electronics.
Sense (anode) and field wires.
CLEO, CDF, BELLE, BABAR



Tube Chamber:

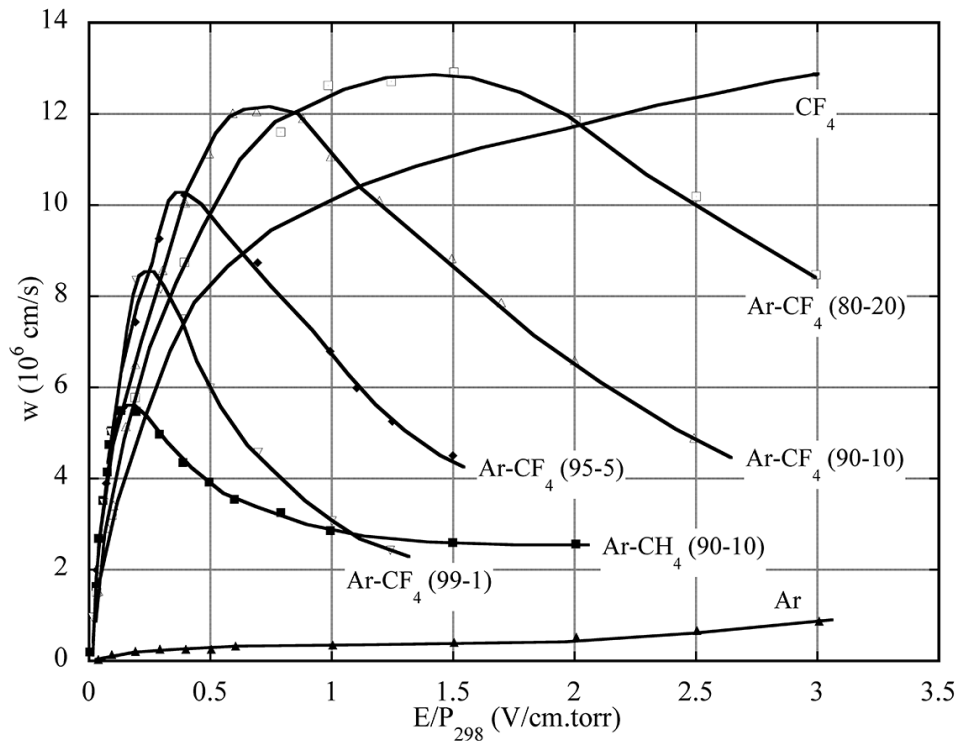
Single sense wire in a cylinder
Can make out of very thin wall tubes.
 $\Rightarrow$ very little material
Small drift cell $\Rightarrow$ single hit electronics
Good cell isolation
 $\Rightarrow$ broken wire only affects one tube
CLEO's PTL detector



Example of wire and field configuration for cylindrical geometry. Attempts to minimize position dependence in E field strength.

Tracking in drift chambers

Drift velocities u vs E/p



Choice of gas (mixture) crucial to optimize drift velocity u . Preferable to work in the $u(E)$ saturation regime where $u \sim \text{constant}$. Distance $x \sim \text{linear}$ with Δt (but calibration needed).

$$x = \int_{t_0}^{t_1} u \, dt$$

High counting rates: Need high u to minimize dead time.

For high spatial precision: Need lower u to minimize relative timing errors (but relatively short drift paths, to minimize diffusion).

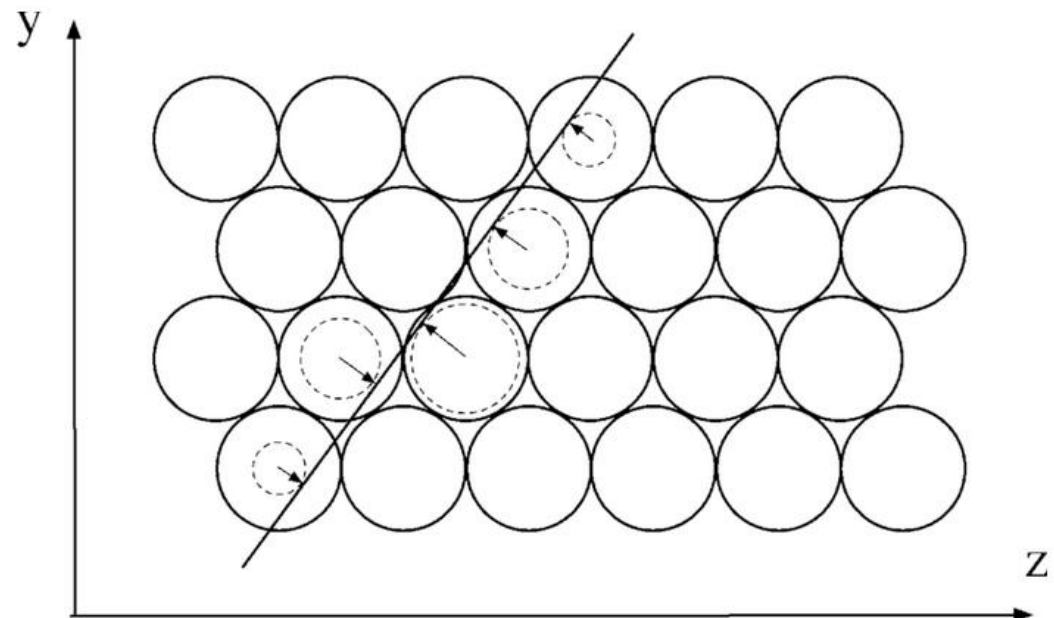
Tracking in drift chamber:

Drift time Δt_i gives distance r_i from anode wire i . Track fitted to be a tangent to all drift circles.

Calibration of $r(\Delta t)$ involves fit optimization. Complicated parametrization in practice:

- $u(E(r))$ not perfectly constant over drift region
- Presence of B field for momentum determination introduces Lorentz force $E \times B$.

Tracking in tube chamber



Spatial resolution

Typical spatial resolution: $\sigma_x \sim 50 \mu\text{m}$, mostly better than for MWPC ($\sigma_x \sim 50 - 300 \mu\text{m}$).

Contributions from:

- Electron diffusion during drift
- Statistical fluctuations in primary ionization clusters $\rightarrow$ fluctuations in drift distance
- Instabilities in time measurement electronics

Electron cloud broadening due to diffusion depends on drift distance ($\sigma \sim \sqrt{x}$):

$$\sigma_{diff} = \sqrt{2Dt} = \sqrt{\frac{2Dx}{u}} \quad \begin{array}{l} x: \text{drift distance} \\ u = \mu E: \text{drift velocity} \end{array}$$

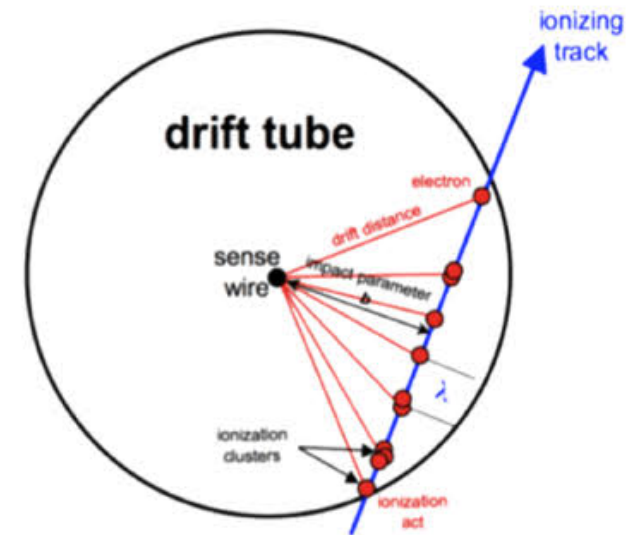
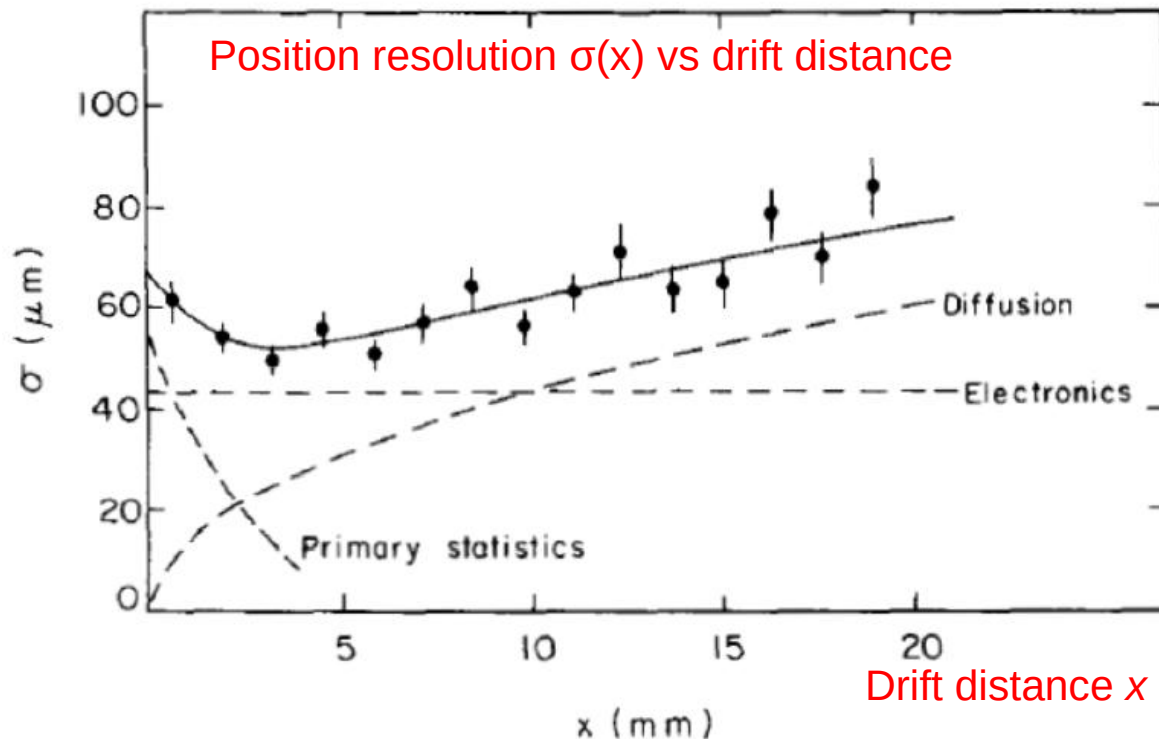
In the saturation region where $u \sim \text{constant}$:

$\sigma_{diff} \sim \sqrt{Dx}$ where

$D \sim \lambda$ (mean free path) $\sim 1/p$ (pressure)

Diffusion reduced at higher pressure p .

Variations in positions of primary ionization clusters relative to anode wire $\rightarrow$ larger σ for tracks close to anode wire ($\sigma \sim 1/x$). Also improved at high pressure (smaller fluctuations).



Effects from electronics on time resolution $\sim$ independent of x .

6.8 The time projection chamber (TPC)



TPC: Conceived
February 1974 by
David Nygren.

Very precise
3D information
in large volume!

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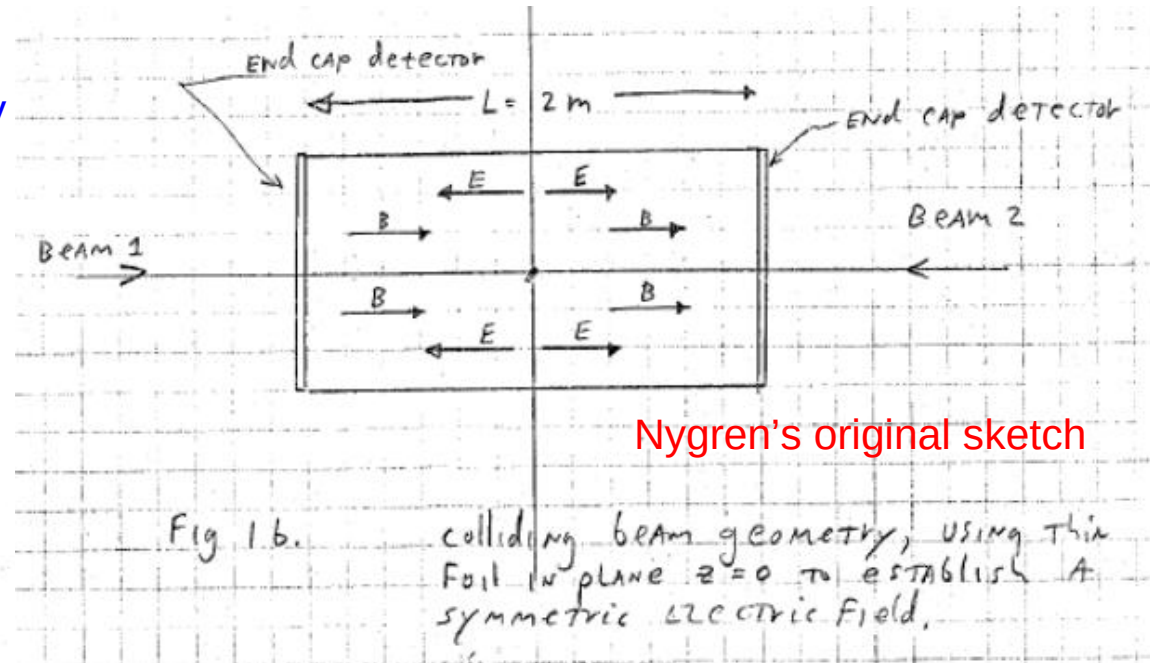
PROPOSAL TO INVESTIGATE THE FEASIBILITY OF A
NOVEL CONCEPT IN PARTICLE DETECTION

David R. Nygren

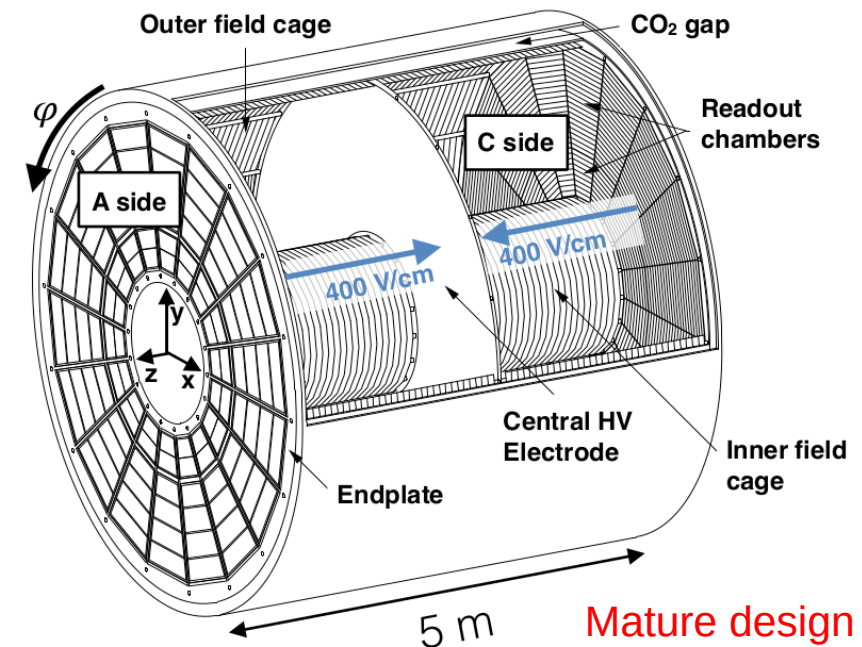
Nygren's proposal abstract

Abstract

A new approach to the problem of high energy particle detection is described, in which parallel electric and magnetic fields are employed. It appears that a particular regime of operating conditions will allow a very substantial suppression of diffusion transverse to the fields in a suitably prepared drift chamber. If the more optimistic estimates are in fact achievable, single track-segment measurement errors of only a few tens of microns in a volume $\sim 1 \text{ m}^3$ should be feasible. Additional benefits are the possibilities of unambiguous spatial reconstruction, as well as high data rate capability, high multitrack efficiency, and easy applicability to 4π geometry. A program is outlined which is designed to gain further experience with the concept, provide needed data about electronic diffusion within various gas/field environments, and hopefully lead to practical detectors.



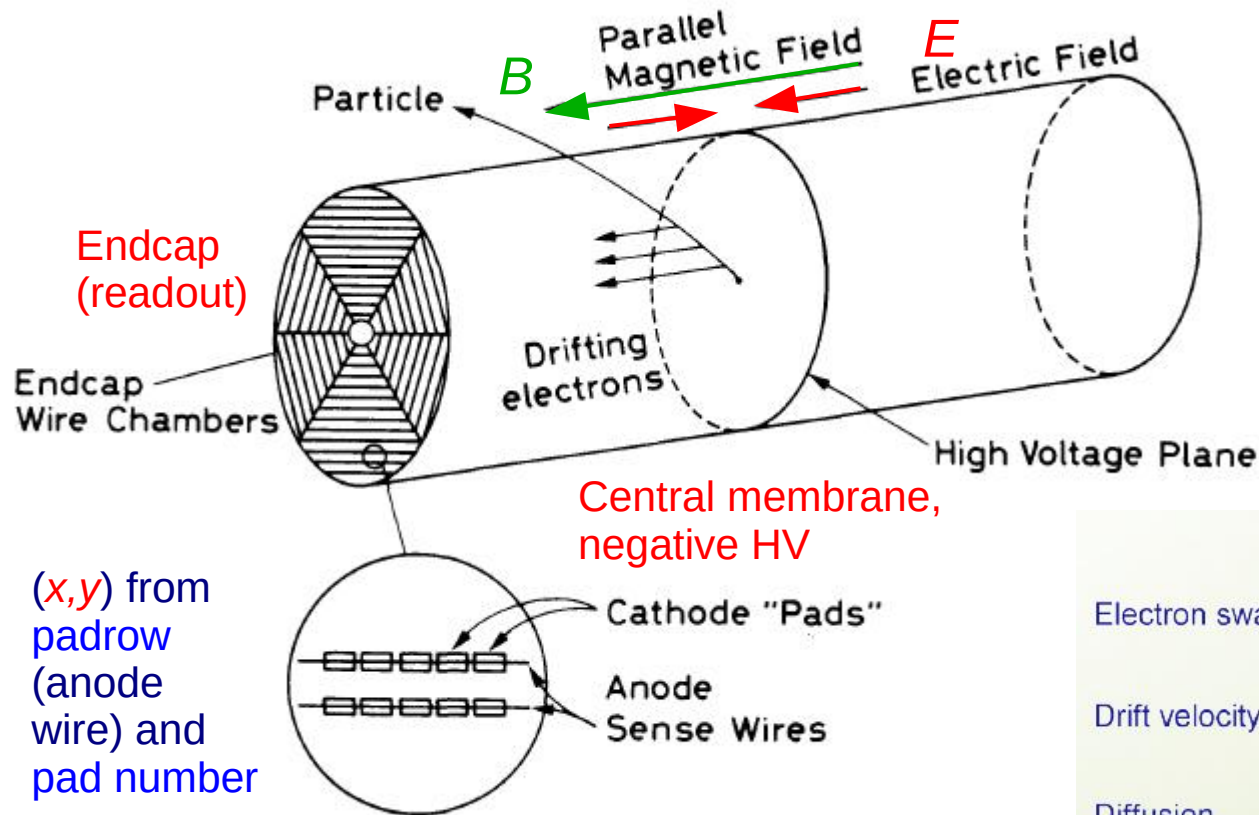
Nygren's original sketch



Mature design
ALICE TPC

TPC operating principle

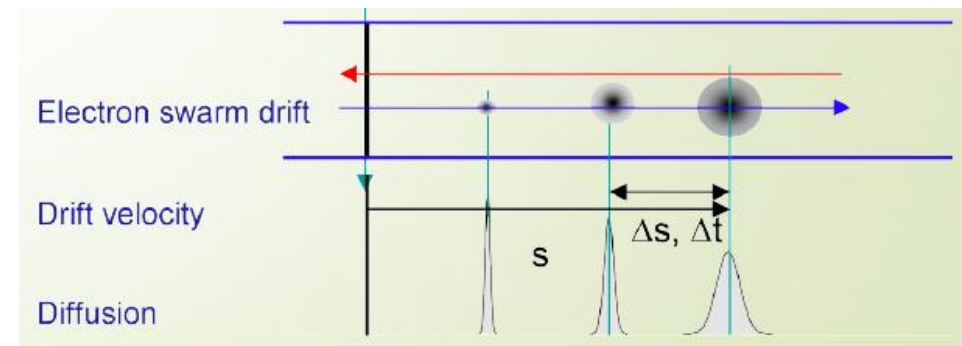
New: Parallel electric and magnetic fields
(usually parallel to beam direction).
Central membrane at negative HV
Liberated electrons drift in the E -field to
endcaps (readout planes), spiraling in B -field.



3D information of primary ionization points in large volume immediately and unambiguously available:

2D readout plane (x,y) via the segmentation of readout planes, the third dimension (z) is computed from the drift time to readout plane. Combines design concepts from both the MWPC and the DC. Track curvature in B -field provides momentum measurement.

Problem with long drift distance: Transverse diffusion.



B field dramatically limits diffusion:

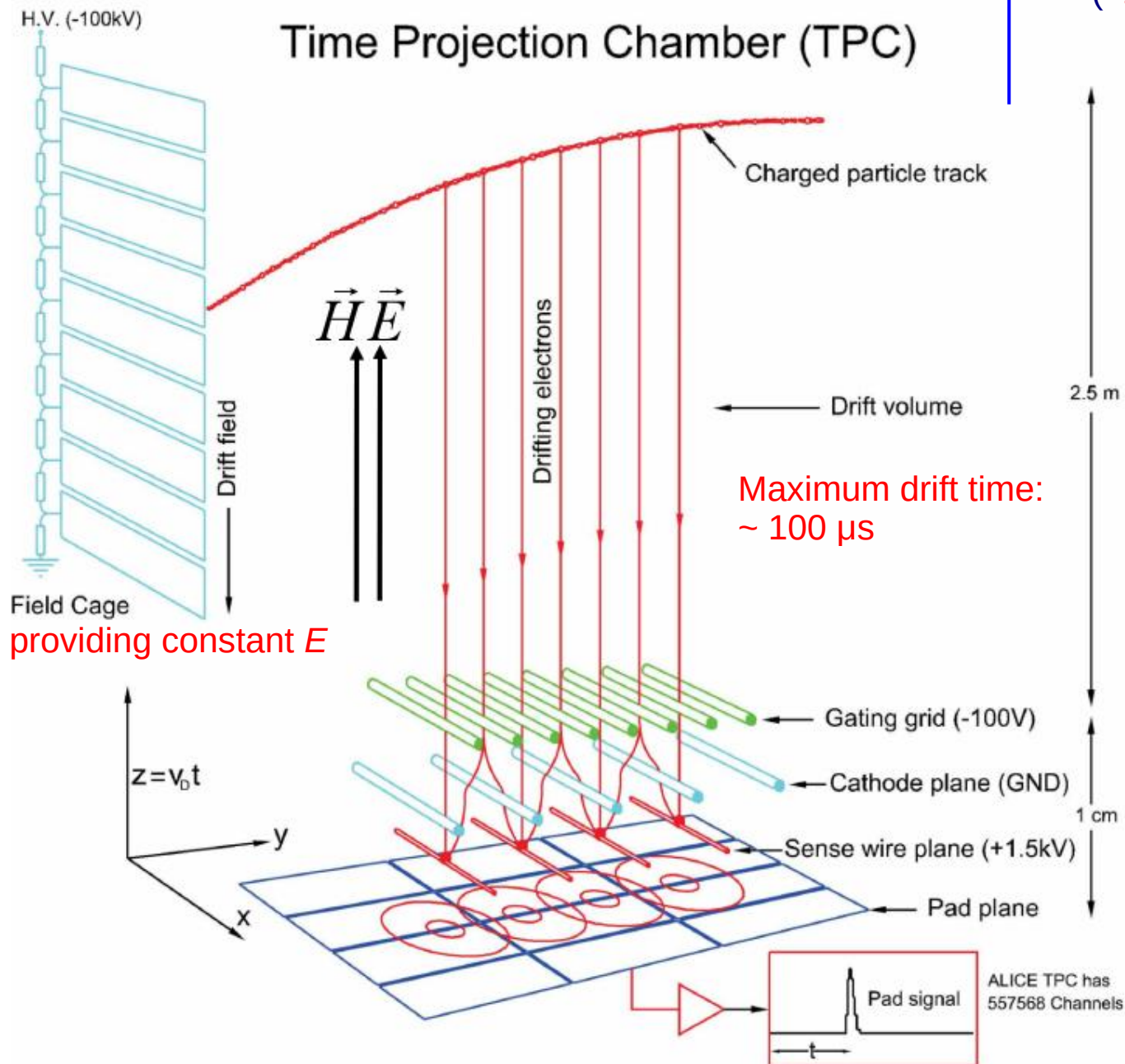
$$\sigma_{\parallel} = \sqrt{2D_0 t} \quad \sigma_{\perp} = \sqrt{\frac{2D_0 t}{1 + \omega^2 \tau^2}}$$

D_0 : diffusion constant when $B=0$

τ : time between collisions

ω : angular spiraling frequency, "cyclotron frequency": $\omega = eB / m_e$

TPC operating principle



To central HV membrane
(-100 kV)

Primary ionization along
helical track in large gas
volume

Electrons follow E -field
through drift volume to
readout plane, spiraling
around B (H) field lines.
 z coordinate = $u \Delta t$,
 $u \sim$ constant

Three wire planes near
endcap:
– Gating grid
– Cathode wire plane
– Anode wire (sense wire)
plane (avalanche formation)

Readout on cathode pad
plane (induction of signals
read out by front-end
electronics)

Choice of gas for TPC applications

The usual considerations apply.

Noble gases preferred as main drift gas, most often **Ar** or **Ne**. Low operational voltage, high gain, good proportionality.

Admixture of quencher gas (polyatomic gas absorbing photons, e.g. **CH₄**, **CO₂**) to prevent secondary avalanche formation and facilitate higher anode voltage → higher gain during operation. Frequently used gas mixture: **90% Ar**, **10% CH₄** (P10).

First TPC experiment (PEP-4, Fermilab) used **80% Ar**, **20% CH₄** at $p \sim 8.5$ atm.

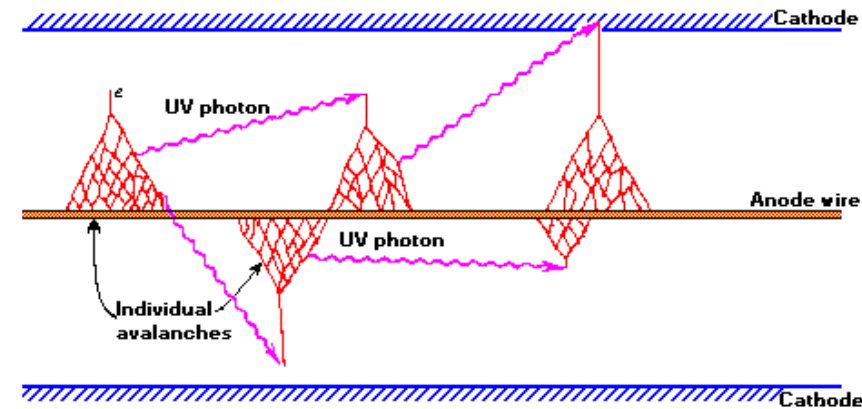
ALICE, LHC: High event rates and/or high charged particle density in detector.

Accumulation of slowly drifting positive ions → distortion of **E** field, poorer tracking precision. Need high ion mobility for swift dissipation → **Ne** chosen noble gas.

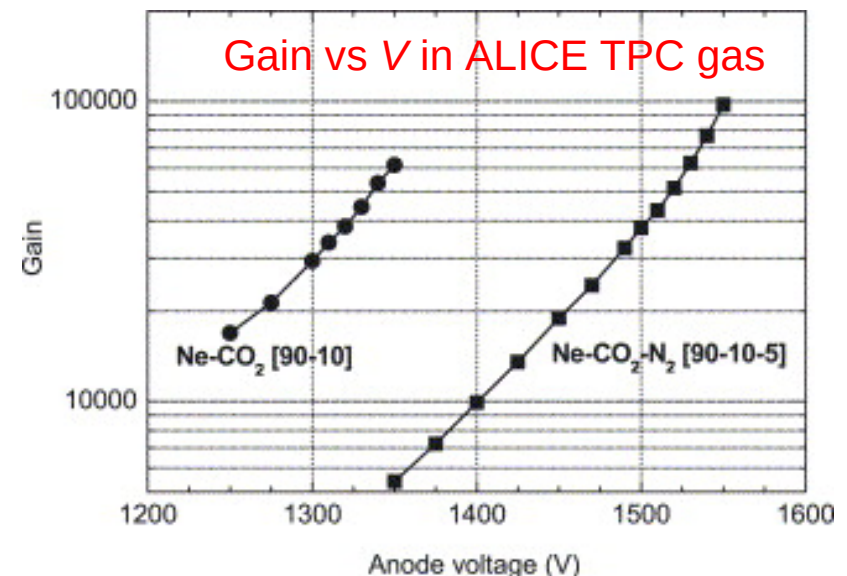
Need chemically stable and non-toxic quencher for aging / safety purposes → **CO₂** chosen (not the most efficient quencher).

Adding **N₂** (mildly electronegative) reduces discharges at high gain (catching electrons liberated from cathode).

ALICE: Chosen gas mixture **90% Ne**, **10% CO₂**, **5% N₂** at $p \sim 1$ atm.



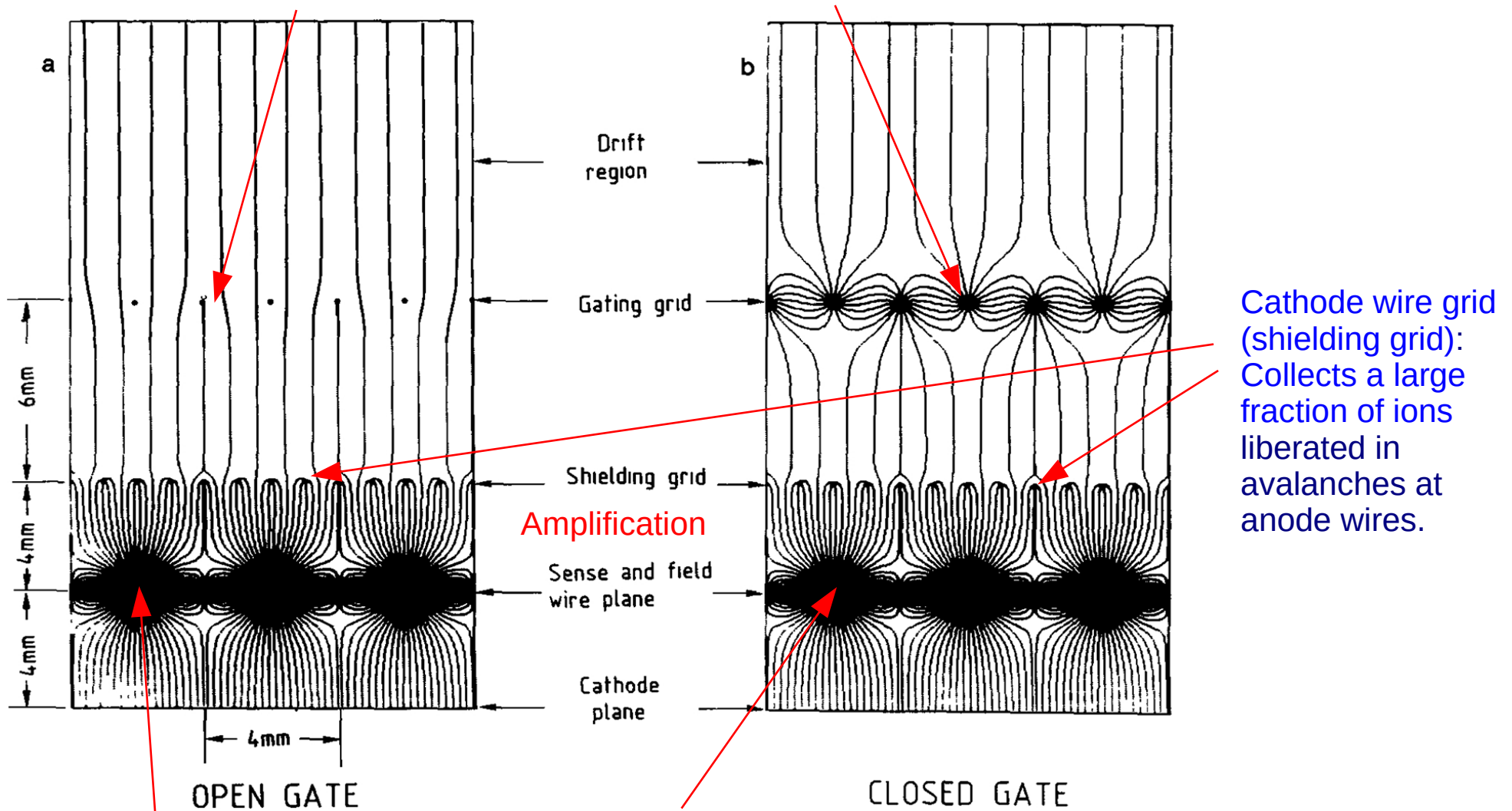
Photon triggered secondary avalanches, frequently starting with electron liberated from cathode.



Wire plane configuration and functionality

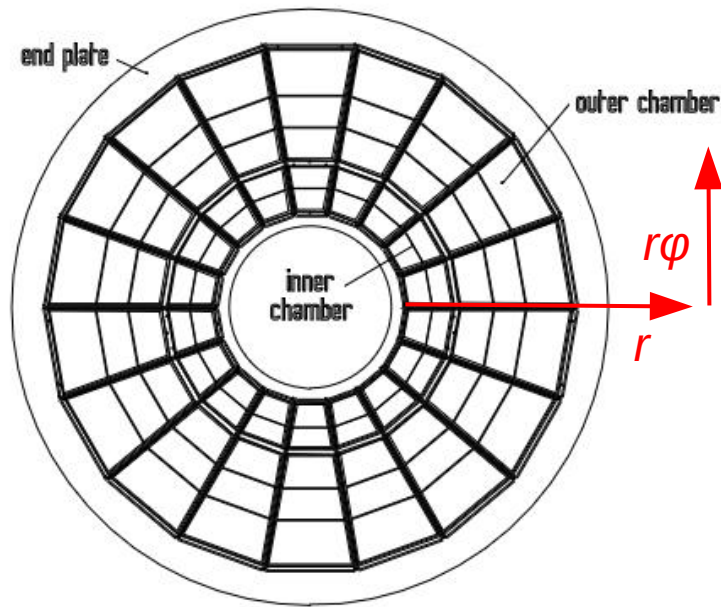
Gating grid: Open when valid event trigger – wires all at same potential U_G → admits electrons from drift region to amplification region.

Closed otherwise – wires at alternating potential $U_G \pm \Delta U$, prevents electrons from entering and ions from leaving amplification region.

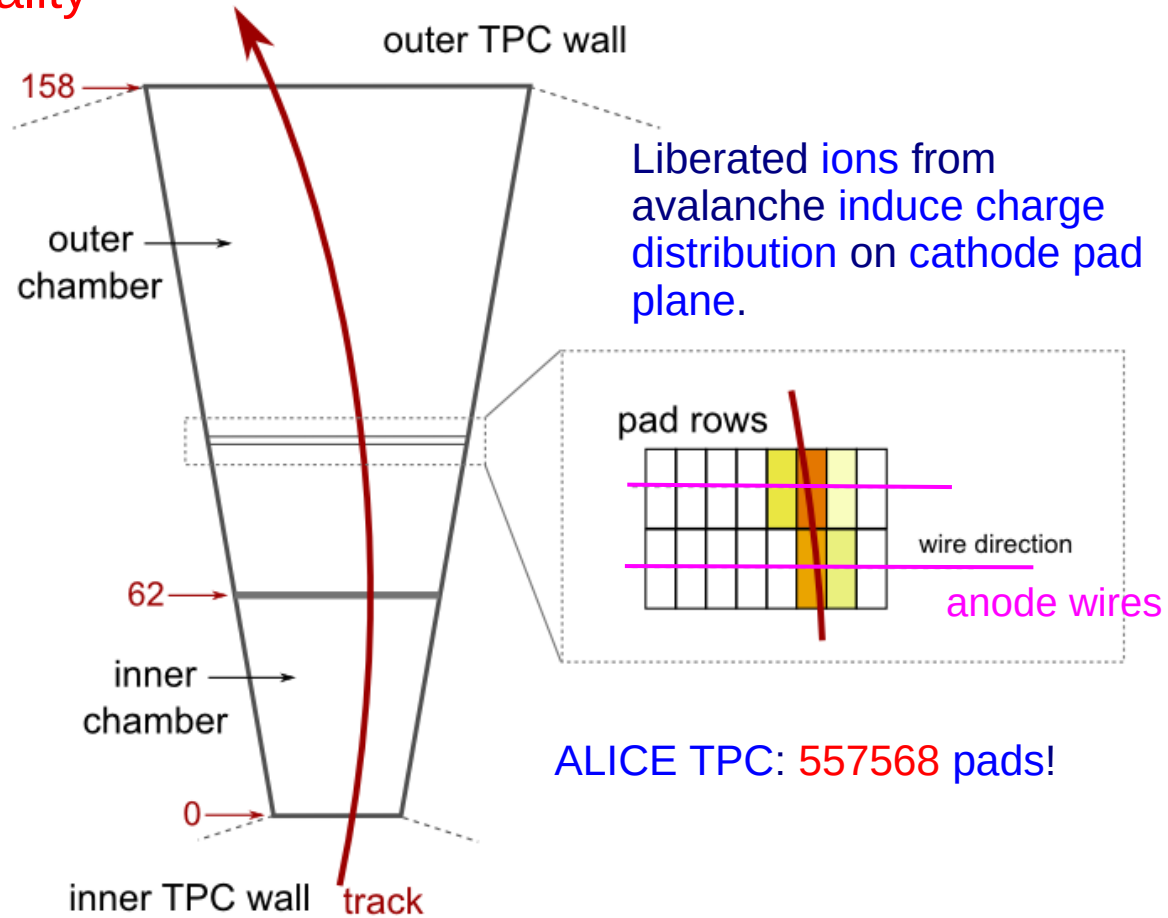


Anode wire plane (+ HV): Site for avalanches creating electron-ion pairs (amplification region). Grid closest to cathode pad plane.
Field wires optional (not present in ALICE TPC).

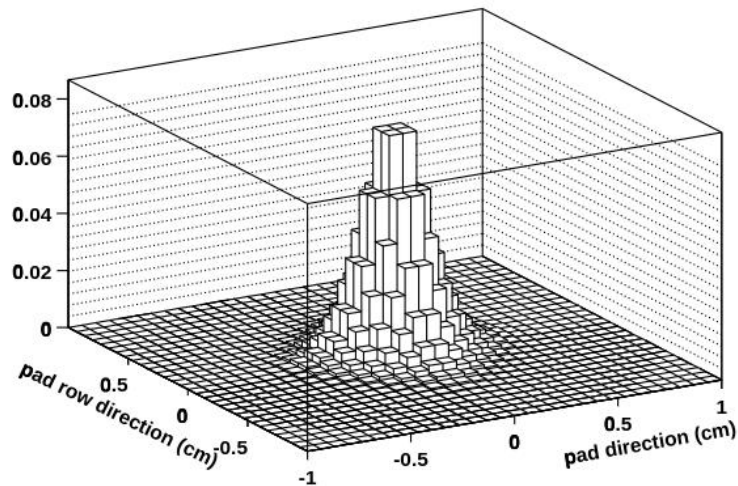
Readout plane layout and functionality



ALICE endcap: Divided in inner and outer chamber, and in 18 azimuthal sectors.



ALICE TPC: 557568 pads!



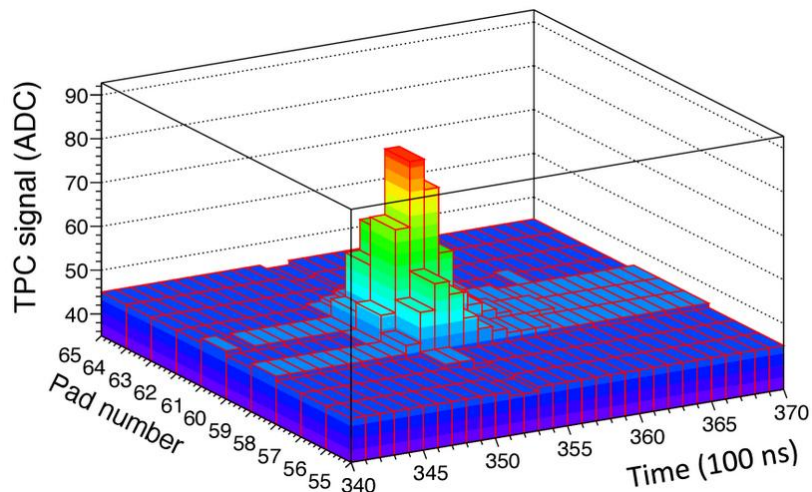
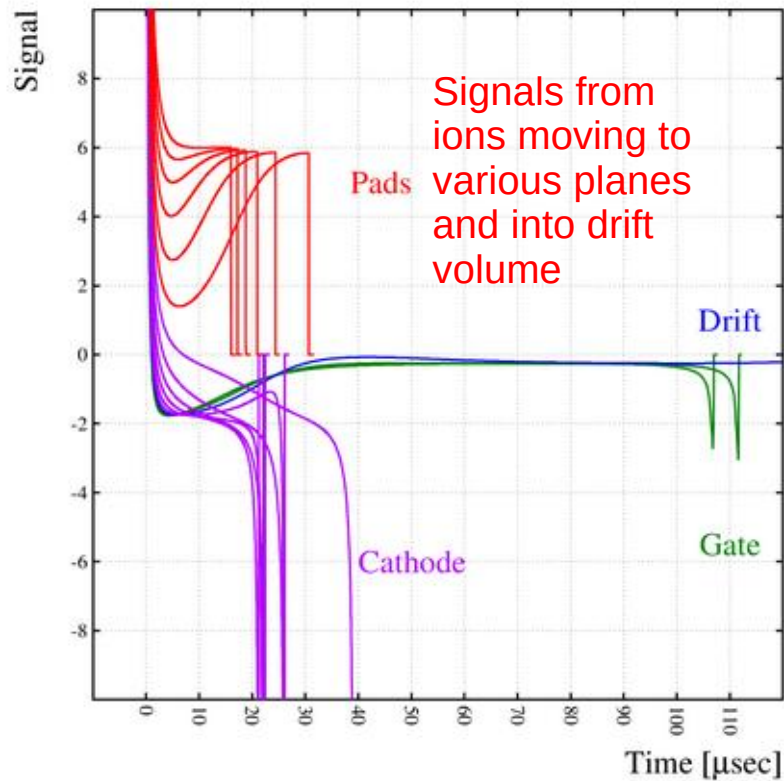
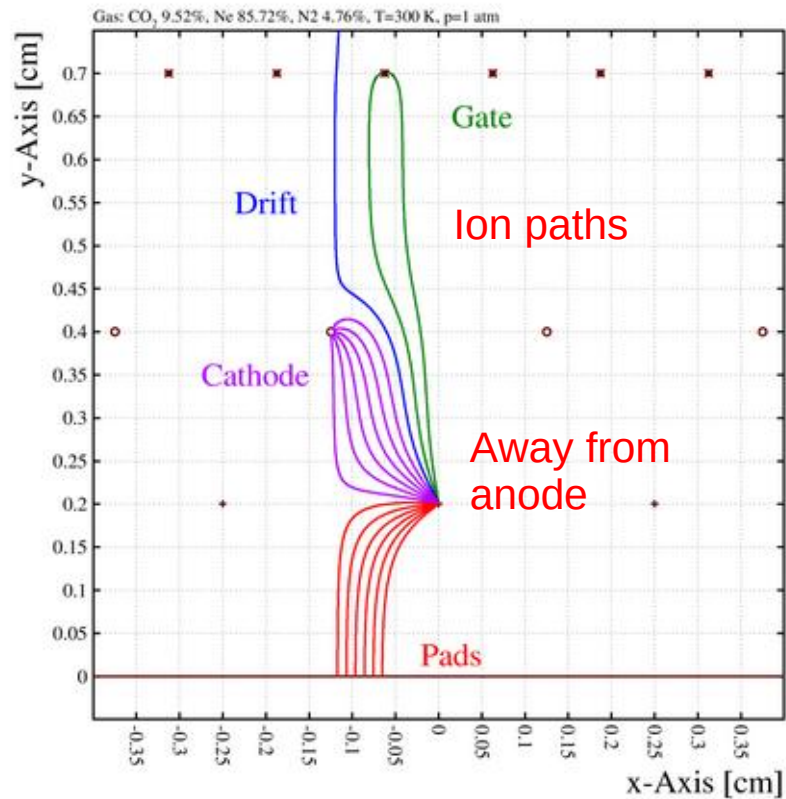
Pad response for ion at $(x,y) = (0,0)$

Charge distribution induced on pad plane depends on:

- Spread in electron cloud due to diffusion during flight
- Pad response (depends on geometric configuration of pad plane and anode wires)

Ion drift and signal induction on pad plane

GARFIELD simulations of ALICE TPC (using Shockley-Ramo theorem)

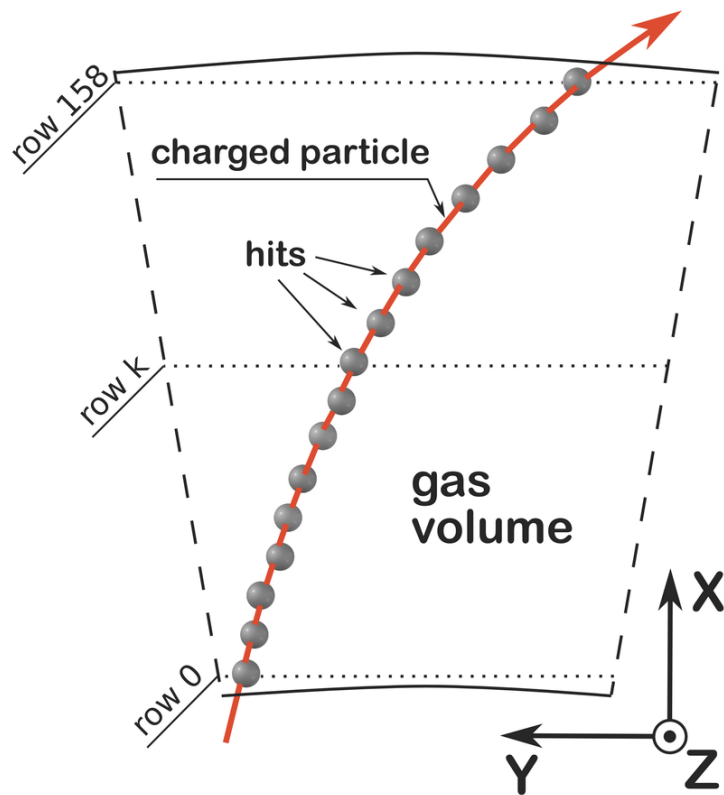


Electrons immediately collected on anode wire.
Positive ions slowly drift in various directions away from anode, giving different contributions to signal on cathode pads.
Net signal on readout plane: Fast positive component with long tail in time, possibly oscillating.

Track finding in the TPC

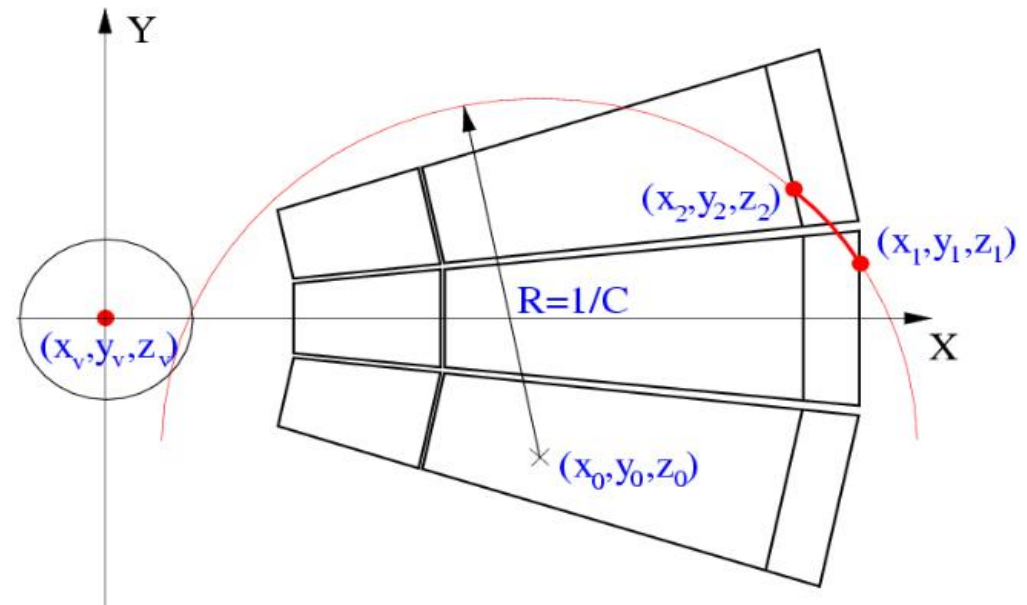
3D space points in TPC: (x, y, z) constructed from signal vs (padrow, pad number, timebin).
Given as 3D centroid of cluster, weighted over pads and timebins.

TPC operates in proportional region – total signal amplitudes are proportional to dE/dx of primary ionization by traversing particle.



Tracking procedure:

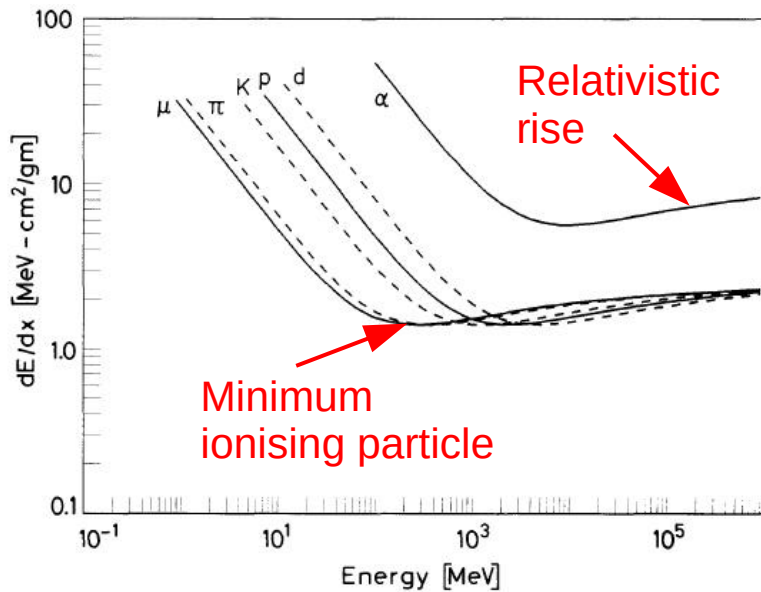
Generate track seeds: start from hits in 2 outermost padrows in a TPC sector, use primary (production) vertex constraint to find approximate momentum p and construct helical track segment.



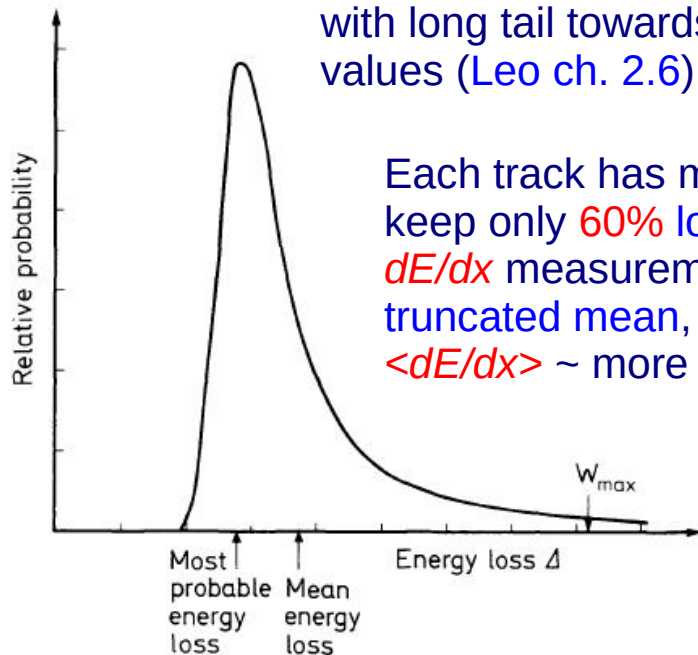
Move inwards in TPC row by row, pick up hits and refine track seed parameters for each step, taking uncertainties into account (Kalman filter).

Many track seeds $\rightarrow$ keep best candidates after maximum likelihood fit. Finally, perform more accurate refit of track to best set of hits.

TPC particle identification



Energy loss in gas: Low medium density, thin absorber. Large fluctuations in dE/dx , with long tail towards large values (Leo ch. 2.6)



Each track has many hits → keep only 60% lowest dE/dx measurements → truncated mean, track $\langle dE/dx \rangle \sim$ more Gaussian.

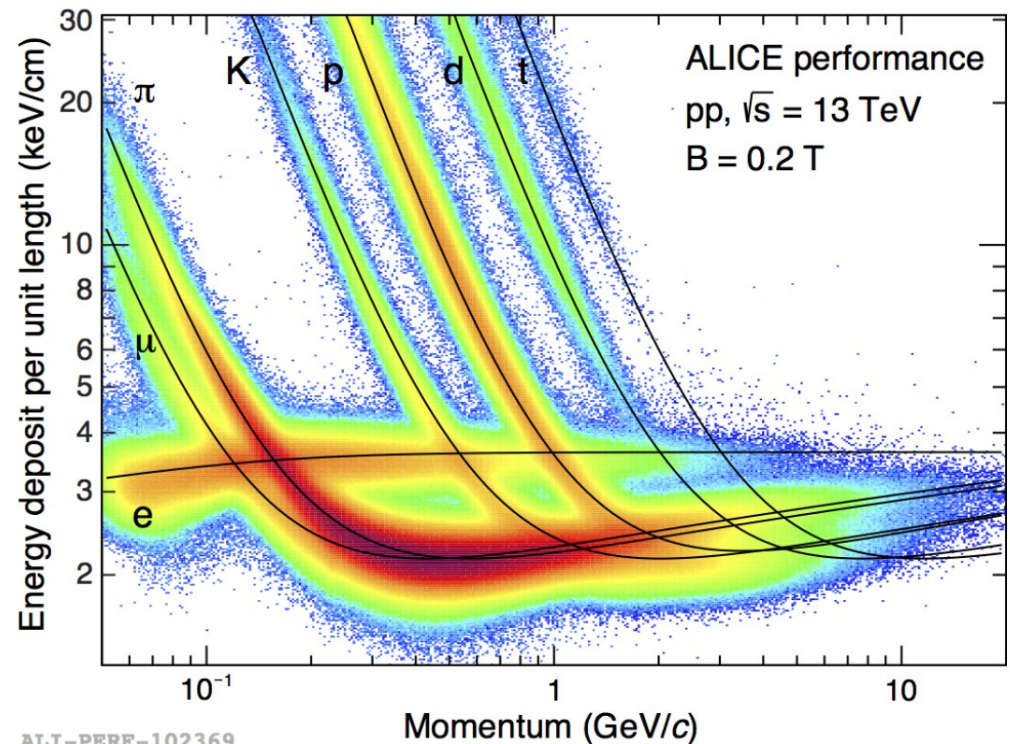
Bethe-Bloch energy loss for heavy charged particles:

$$-\frac{dE}{dx} \propto \frac{Z z^2}{A \beta^2} \left[\ln \left(\frac{2m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right]$$

Given momentum p : Energy loss depends on charge z and velocity v ($\beta = v/c$) → mass m .

Density correction δ small for gases → relativistic rise pronounced in TPC, advantage for PID at higher energy.

Particle identification: Using cuts on $\langle dE/dx \rangle$ including or excluding particle species according to expectation value $\langle dE/dx \rangle_i$ for species i and resolution σ_i .



Possible questions for the FYS4505 examination

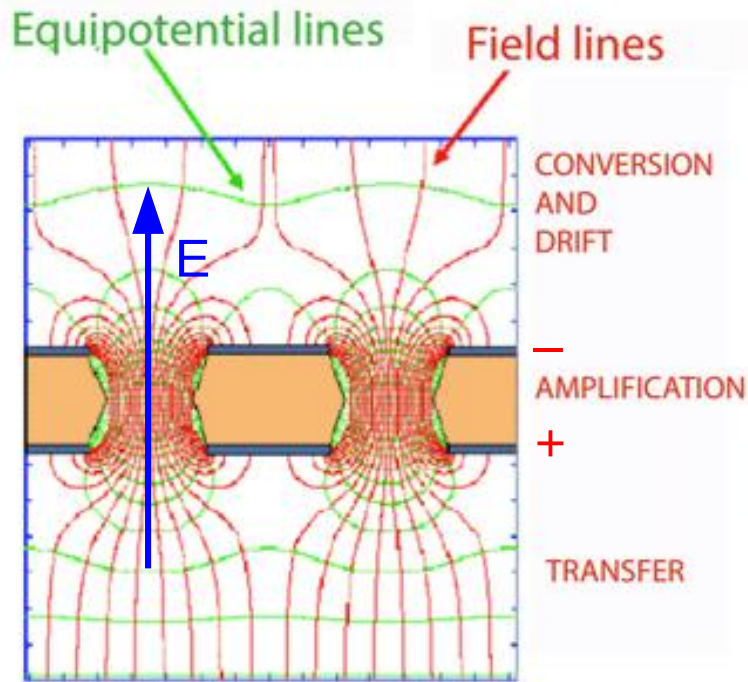
- Describe the principle of operation for a multiwire proportional chamber, and the extraction of 2D position information
- Describe the principle of operation for a drift chamber
- Describe the principle of operation for a time projection chamber, with 3D position information
- Explain briefly how tracking, momentum determination and particle identification can be performed in ionization detectors

A few extra HEP applications of ionization detectors (if time)

- Gas Electron Multipliers: A new readout system for ALICE TPC at high collision rates
- Transition Radiation Detectors – detecting X-rays with Xe gas
- Multigap Resistive Plate Chambers – fast signal for precise timing

New readout system for the ALICE TPC: Gas Electron Multipliers

GEM: F. Sauli,
CERN, ~1997



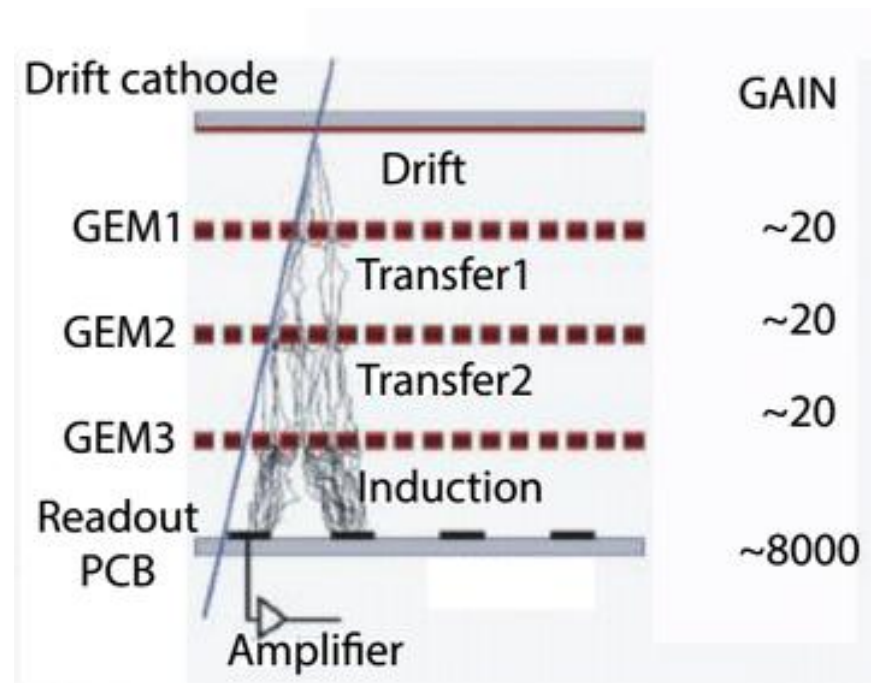
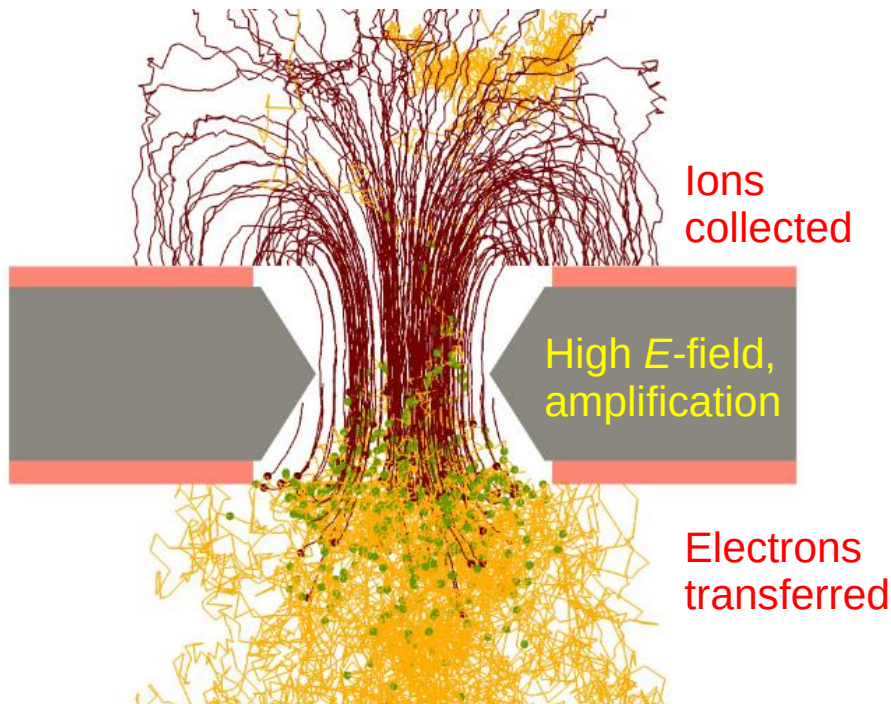
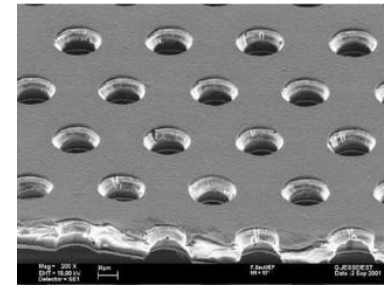
Problem with ALICE TPC at high rates:
Buildup of ion space charge in drift volume $\rightarrow$ distortion of E -field.

New endcap readout system since 2022:
Based on **Gas Electron Multipliers (GEM)**.
Mesh with insulator sandwiched between 2 electrodes and with $\sim 10^2 \mu\text{m}$ holes.

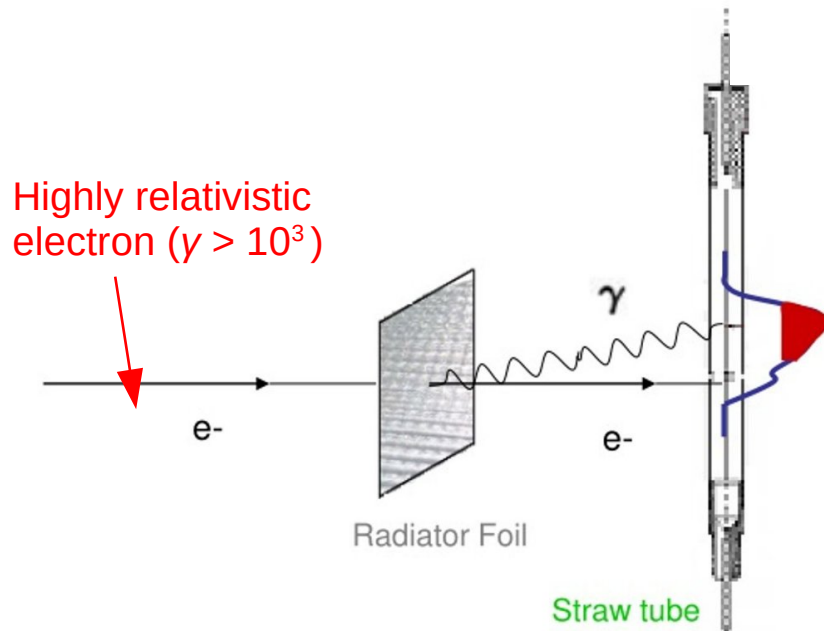
Voltage between electrodes (a few 10^2 V) creates high E -field in holes $\rightarrow$ amplification region. Ions caught on negative side of foil, electrons amplified and transferred further, to pad readout plane or to next amplification structure.

Typical gain $\sim 10^3 - 10^4$.

Very fast signal on pad plane induced by electron cascade.
Most ions collected on GEM upper surface(s). Well suited for high luminosity conditions. No gating grid needed!



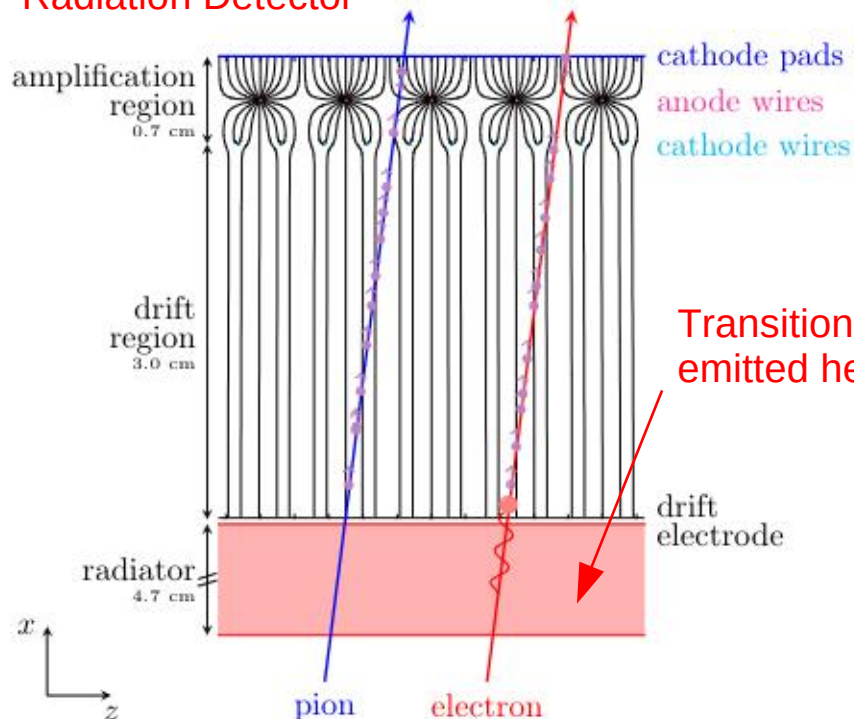
Transition Radiation Detectors



Transition radiation (X-rays) emitted when a particle with Lorentz factor $\gamma = (1 - \beta^2)^{-1/2} > 10^3$ crosses the boundary between media with different dielectric constants. Very useful for electron identification.

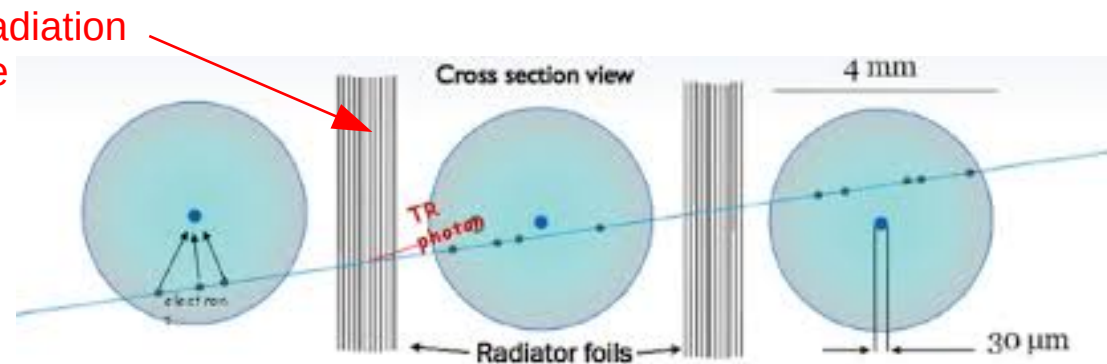
X-ray detection: Heavy noble gas (Xe) preferred, photoelectric absorption cross section strongly dependent on Z ($\sim Z^4 - Z^5$).

ALICE Transition Radiation Detector



ALICE TRD: MWPC with a Xe (85%), CO₂ (15%) gas mixture with a 3 cm drift region, drift field 700 V/cm. Preceded by a radiator of sandwiched organic foam / fibre material. 6 MWPC layers surrounding TPC.

ATLAS TRT: Layer of straw tubes (proportional counters) with radiator foils interleaved with straws. Anode-cathode $V_0 = 1.5$ kV. Gas mixture Xe (70%), CO₂ (27%), O₂ (3%),



ATLAS Transition Radiation Tracker

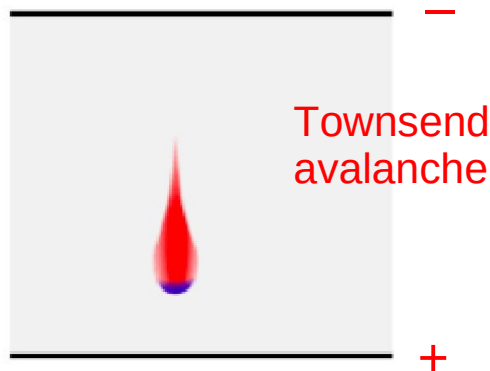
Multigap Resistive Plate Chambers

Fast timing applications in HEP:

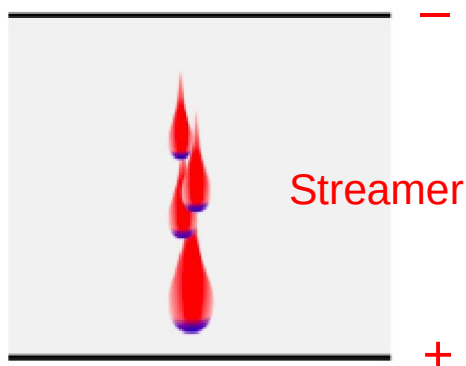
Planar ionization detectors with very high electric fields E between anode and cathode are frequently used, for fast and uniform response.

At high multiplication M : Large probability of development of streamers (sparks) – large buildup of charge, compromising rate capability. Need to limit gain at high E → use electronegative gases (e.g. freon, $C_2H_2F_4$) to control avalanche development.

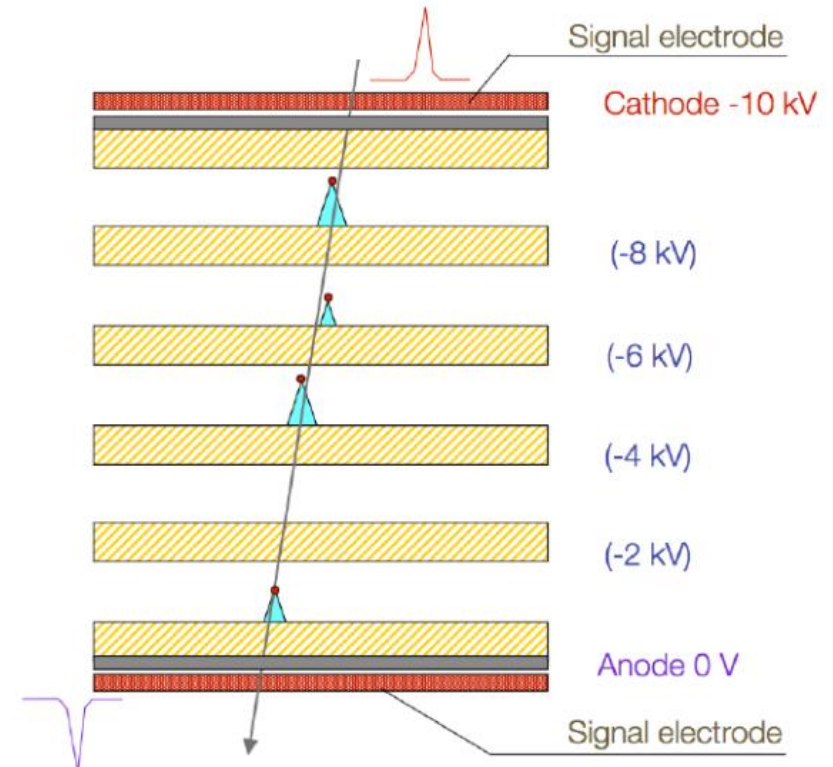
NORMAL AVALANCHE



PHOTON MEDIATED BACKWARD PROPAGATION: STREAMER



ALICE TOF (1 of 2 stacks shown)



ALICE Time-of-flight detector: Based on Multigap Resistive Plate Chamber technology. Gas detector operated in avalanche mode. HV applied to external electrodes, internal plates (glass) electrically floating and transparent to (very fast) signal.

2 stacks with 5 $250\ \mu\text{m}$ gaps each.
Gas mixture 93% $C_2H_2F_4$, 7% SF_6
Time resolution: $\sim 50\ \text{ps}$.