Gaseous Detectors

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Outline

- **Part 1: Introductions**
  - **Why gaseous detectors?**
  - **Basics of charged particle propagation through gaseous matter**

- **Part 2: Gaseous detectors in HEP**
  - **Detectors picking up ionization signal**
    - How it all started: cloud chamber
    - **Wire detectors:** Proportional Counters, Drift Chambers, Cathode Strip Chambers
    - **Wireless detectors:** RPCs, GEM, MSGC, MicroMegas
  - **Detectors picking up light**
    - Cherenkov detectors
    - Transition Radiation Detectors

Part 1: introduction

Particles that matter and their interactions with matter

- **Nine particles that matter:**
  - out of hundreds different particles produced in high energy collisions, only the following few that can actually be directly observed via their interactions with a detector in general purpose experiments: $\gamma,\ \mathrm{e},\ \mu,\ \pi^{\pm},\ K^{\pm},\ K_L,\ K_S,\ p,\ n$
  - all others are too short lived and three neutrinos; there are inferred…

- **Particle interactions with matter:**
  - all five charged particles ($\mathrm{e},\ \mu,\ \pi^{\pm},\ K^{\pm}, p$): ionization (plus light emission)
  - e/γ: EM shower
  - all hadrons (last six): Hadronic shower

- **Ionization vs showers:**
  - Ionization:
    - interactions every 300 μm in gas
    - very little disturbance for a particle itself (energy losses ~2 keV per cm in the gas, very small multiple scattering)
  - EM/Hadronic showers:
    - interactions every 300/800 m in N_2 (as reference)
    - catastrophic loss of energy in every interaction

Why gaseous detectors?

- **Ionization properties provide perfect means for tracking charged particles in large gas-filled volumes, without much affecting the particles themselves**

- **Gaseous detectors provide tracking accuracy with a spatial precision of O(100) μm and time resolution of 1-10 ns; both are often quite sufficient**

- **Gaseous detectors are inexpensive and are nearly the only choice for very large volume detectors, such as muon systems**

Propagation of charged particles through gaseous matter

- **Charged particle leaves behind:**
  - **ionization:**
    - average ionization density (dE/dx)
    - ionization clusters, delta-electrons, Landau fluctuations
  - **light, when conditions are right:**
    - Scintillation (not discussed further)
    - Cherenkov radiation
    - Transition radiation
- **Transport of ionization in gases**
  - **drift velocity in electric field**
  - **diffusion**

Ionization: Average energy losses

- **Bethe-Bloch formula:**

$$-\frac{dE}{dx} = 4\pi \frac{z^2\alpha^2}{\beta^2}\frac{Z\rho}{Am_N m_e}\left[\frac{1}{2}\ln\frac{2m_e\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

m_e, m_N, α—universal constants:
electron and nucleon masses; fine structure constant;

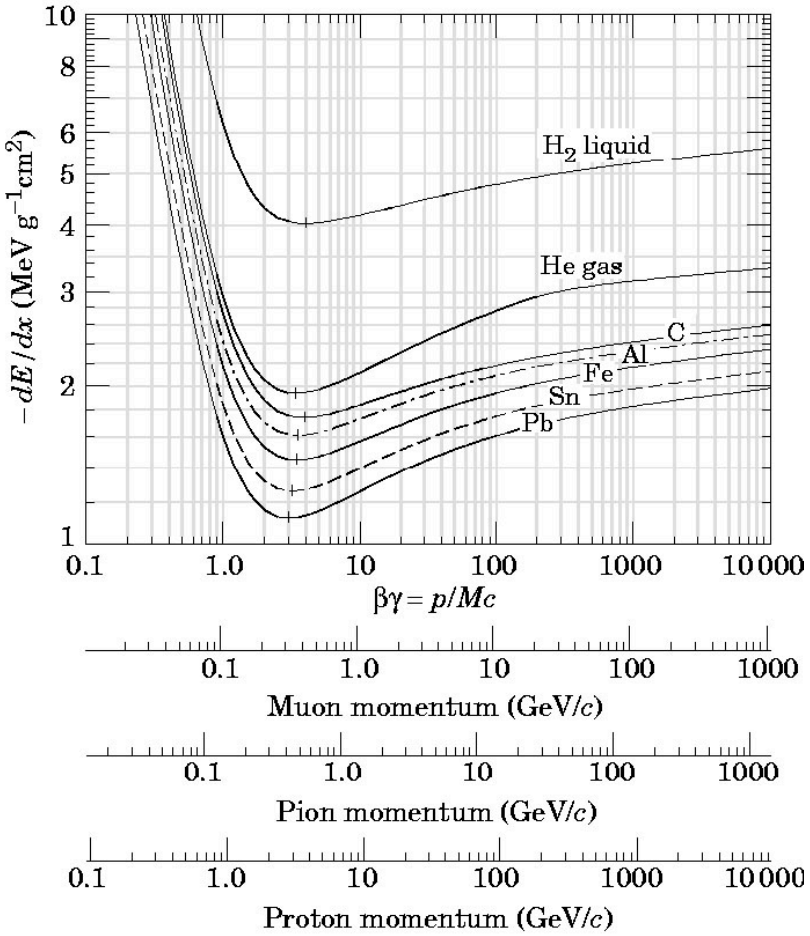
z, β, γ—**incoming particle parameters:**
charge in units of e, velocity β=v/c, gamma factor)

Z, A, ρ, I—**media properties**:
charge and atomic number, density, average ionization potential

T_{max} – maximum energy that can be transferred
from an incoming particle of mass m to an electron

$$T_{\max} = \frac{2m_e\beta^2\gamma^2}{1+2\gamma(m_e/m)+(m_e/m)^2}$$

δ—small correction due to media polarization
(for gasses, it is negligibly small)



Ionization: Average energy losses

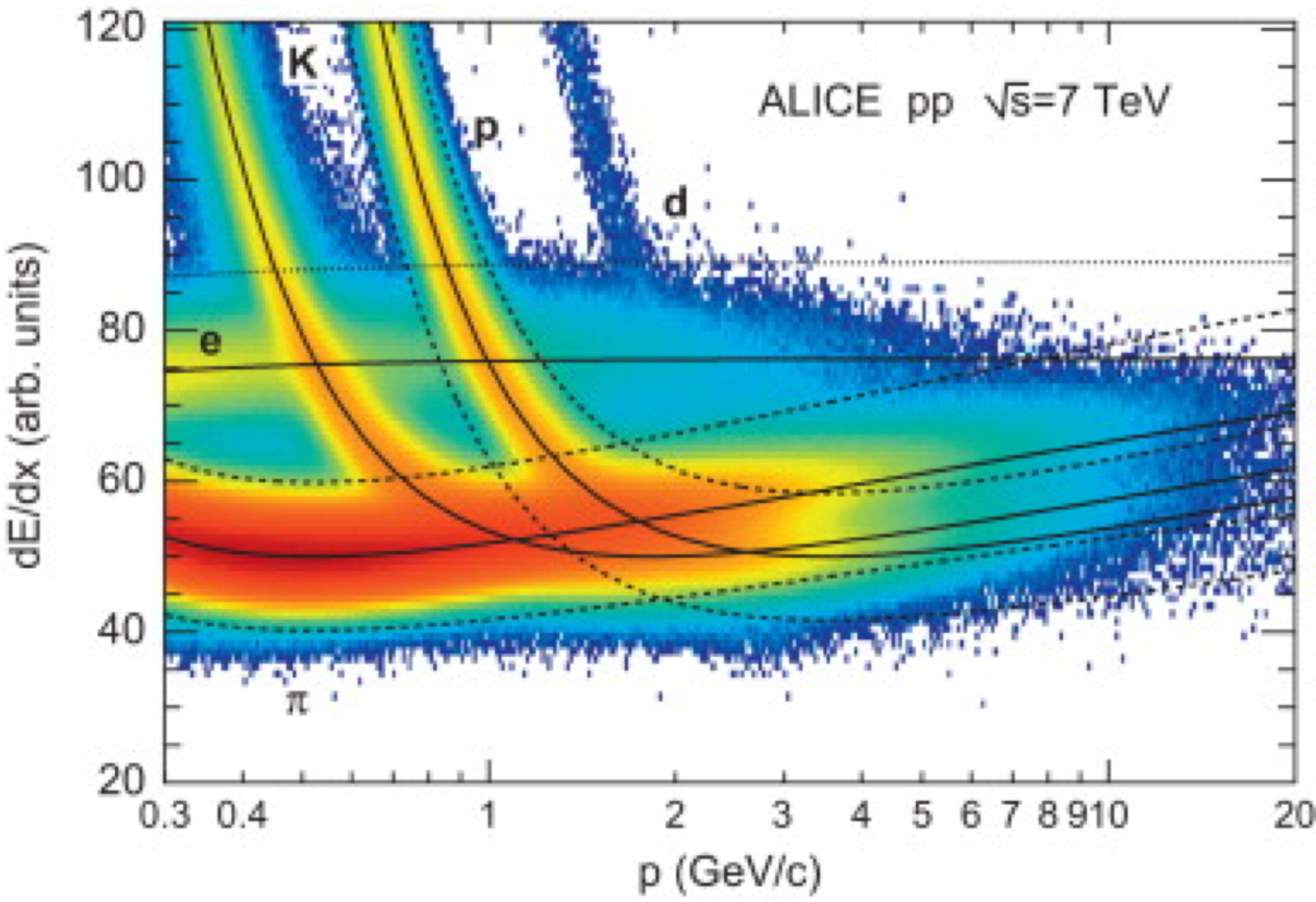
- **Bethe-Bloch formula:**

$$-\frac{1}{\rho}\frac{dE}{dx} = \frac{4\pi\alpha^2}{m_N m_e}\frac{z^2}{\beta^2}\frac{Z}{A}\left[\frac{1}{2}\ln\frac{2m_e\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

- **Dependence on media is very weak:**
  - Z/A ~ 1/2 , except for hydrogen (=1)
  - log of ionization potential

- **Main dependence on incoming particle properties via its charge and velocity: z^2/β^2**

can identify non-relativistic particles



- **Charged particle with β~1 is called minimum ionizing particle (mip)**

all charged relativistic particles look alike

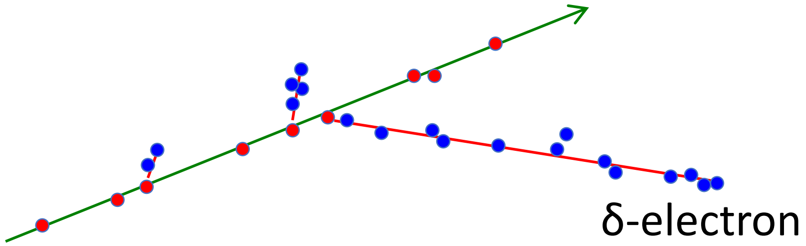
Rule of thumb:

ΔE ~2 keV per cm in gas at nominal pressure

Ionization: dE/dx fluctuations

Charged particle leaves behind

- **electrons of the primary ionization,**
- **which can produce their own mini-tracks…**
- **(particularly energetic primary electrons are called δ-electrons)**

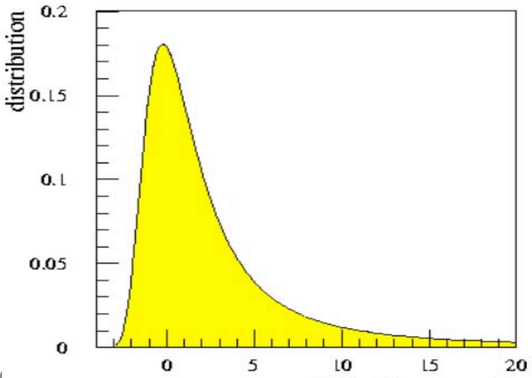


Clusters of primary ionization are spaced according to Poisson distribution with $n_{primary}$

	eV/pair	$n_{primary}$	n_{total}
CO_2	33	34 per 1 cm	**91 per 1 cm**

typical electronic noise >1000 e
(gaseous detectors need additional amplification somewhere)

Total energy loss distribution in thin layers of media have long tails due to δ-electrons.



$$L(\lambda) = \frac{1}{\sqrt{2\pi}} \exp\left\{ -\frac{1}{2}\left(\lambda + e^{-\lambda}\right) \right\}$$

$$\lambda = \frac{E - E_0}{\xi}$$

Light emission: Cherenkov radiation

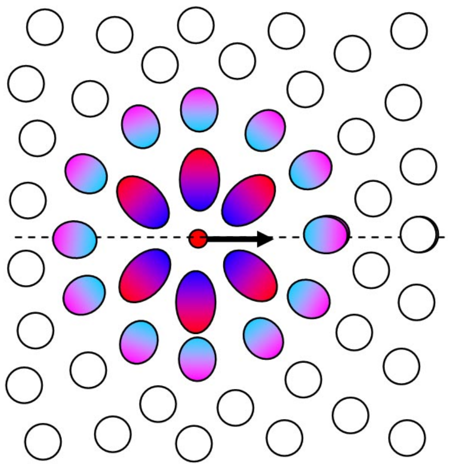
- **Charged particle leaves a wake of polarized media**
- **As molecules/atoms depolarize, they emit radiation in all directions**
- **If particle travels with speed greater than speed of light in media, the depolarization radiation interferes constructively and builds up a shock wave emitted at the "classic" shock wave angle:**

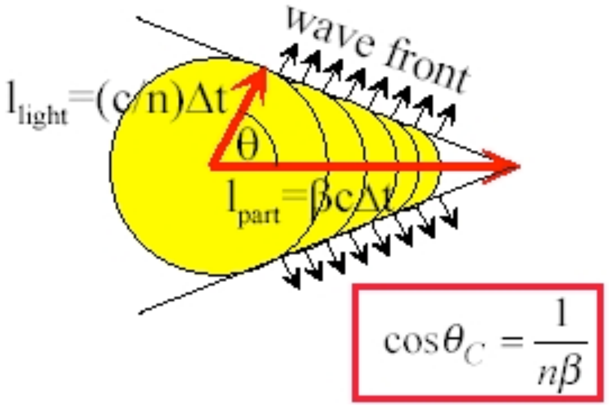
$$\cos\theta_C = \frac{v_{light}}{v_{particle}} = \frac{1}{n\beta}$$

can be used to measure β

- **Energy carried away by Cherenkov radiation is tiny**
  - **~$10^{-4} \times$ (dE/dx)**
  - **about 100 vis. light photons per MeV of dE/dx**

few

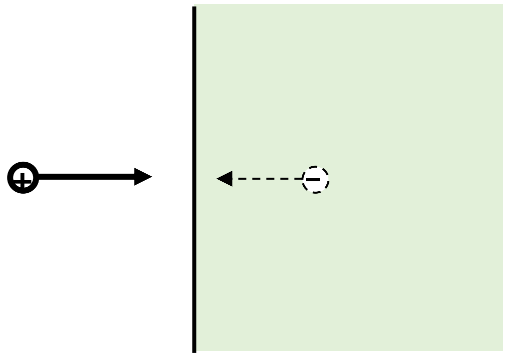




Light emission: Transition radiation

- **Consider boundary between two media with different dielectric constants**

  Classical EM point of view:
  - **Static point charge:**
    - induces dipole-like electric field
  - **Moving charged particle:**
    - changing dipole field
    - this must give rise to radiation



- **Probability of emitting a photon per one boundary transition:** $p = \alpha = \frac{1}{137}$

very small

- **Typical energy of a photon for plastics:** $E \sim (5\ e\mathrm{V}) \cdot \gamma$

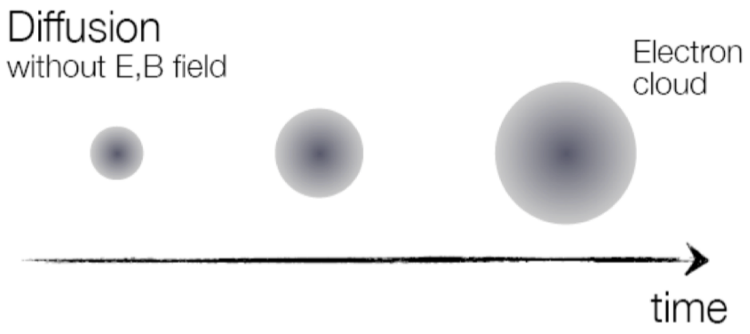
- **Very boosted charged particles can produce distinct localized clusters of large ionization induced by X-ray photons, e.g.:**
  - **20-GeV electrons → 200 keV**
  - **while 20-GeV pions → 1 keV**

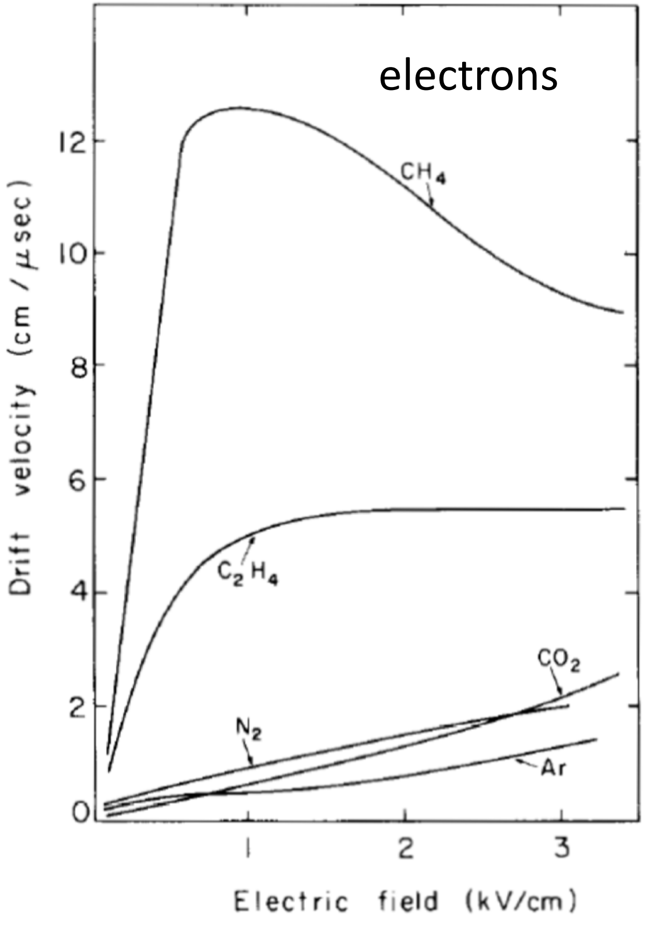
can be used to help identify electrons,
but one needs many transitions to be practical

Transport of electrons and ions in gas

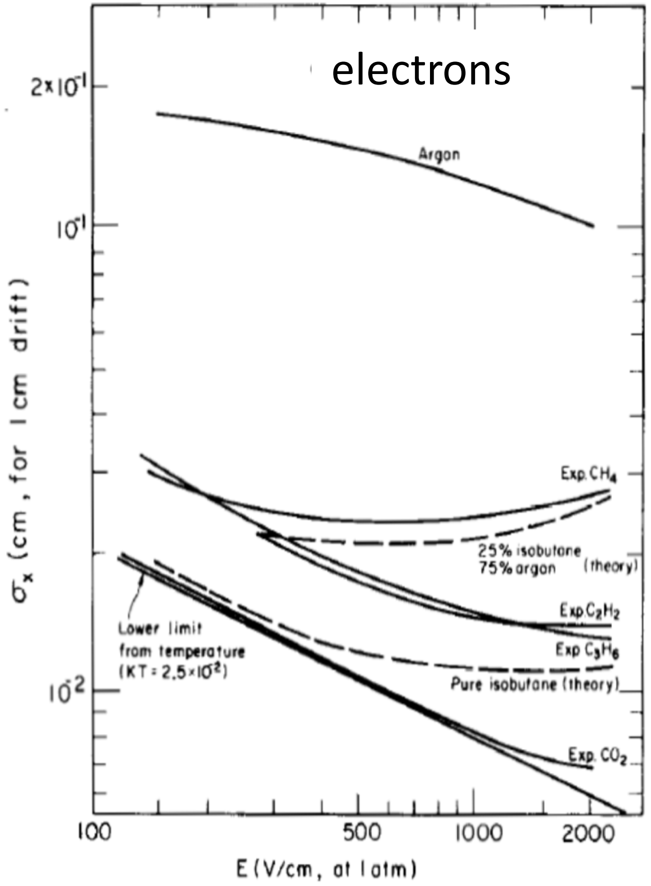
- **Drift velocity in electric field (relevant field is O(1) kV/cm)**
  - Cold approximation (K.E. ~ kT): $\mathbf{v}_{\mathbf{drift}} = \mu E$, where mobility μ=const
  - Hot approximation (K.E. >> kT): $\mathbf{v}_{\mathbf{drift}} = \mathbf{const}$
  - Ions always "cold" and move O(1000) times slower than electrons

- **Diffusion**
  - Random walk: x_{rms}~1/sqrt(t)~1/sqrt(x)





10—100 mm/μs



0.1—1 mm for 1 cm drift

Part 2: gaseous detectors

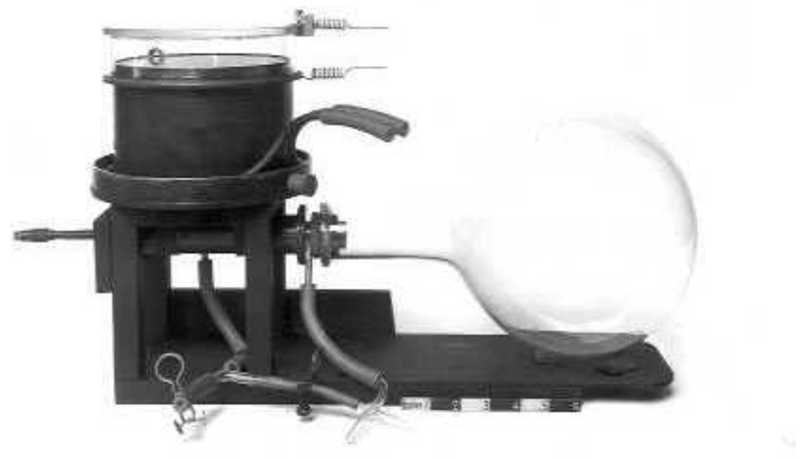
How it all started: Cloud chamber

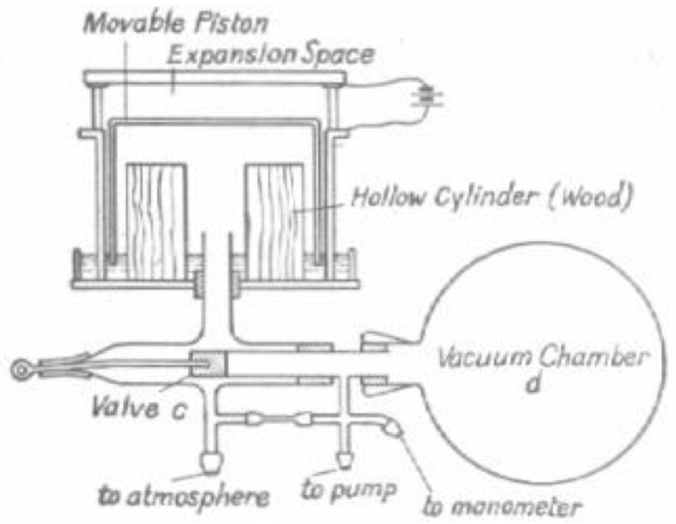
- **Invented by Charles Wilson in 1899. Nobel prize in 1927** ***"for his method of charged particles detection"***

- **Used through mid-1950s**

- **Principle:**
  - **chamber with oversaturated vapor**
  - **oversaturation is set by fast expansion of the volume**
  - **ionization clusters left behind by a charged particle become centers of condensation**
  - **droplets can be photographed**

- **Basic performance parameters:**
  - **moderate spatial resolution (mm)**
  - **small/moderate volume (up to ~1 m)**
  - **slow (a few pictures per min)**
  - **measure**
    - p from curvature of track in magnetic field: R ~ 1/p
    - v from ionization density: $dE/dx \sim 1/v^2$

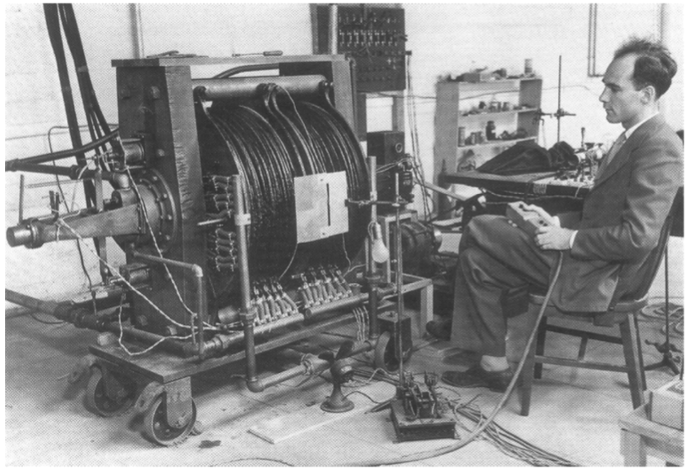


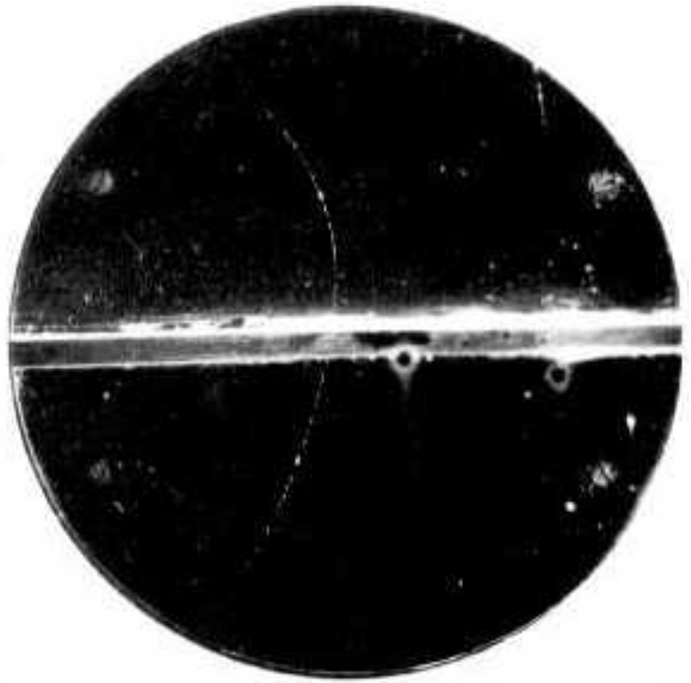


Discovery of positron in cloud chamber

- **Carl Anderson discovered positron in 1932. Nobel prize in 1936 *"for his discovery of antimatter when he observed positrons in a cloud chamber"***

- **Photograph shows:**
  - **a single track crosses the lead plate in the middle**
  - **the track is bent by a magnetic field pointing into the picture**
  - **curvature of the track is higher in the upper portion, which means momentum is smaller there**
  - **hence, particles goes upward and its charge is positive**
  - **proton, the only known positively charged particle at that time, with the measured momentum would**
    - **have very low velocity**
    - **produce much higher ionization density along the track ($1/v^2$)**
    - **lose much more energy in the lead plate**
  - **the only possible explanation: particle's mass must be much smaller than proton's (and actually comparable to the electron mass)**





Wire detectors: proportional counter

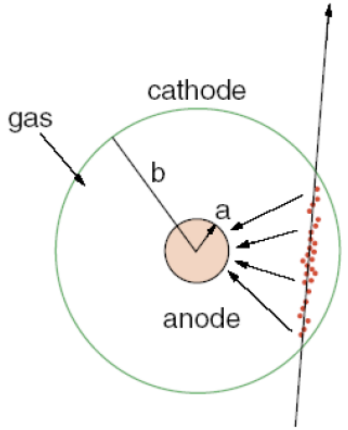
- **Ionization in gas:**

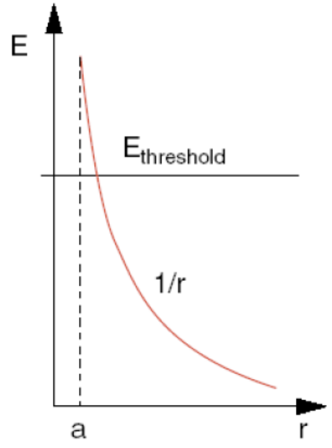
  Recall: ~100 e/cm (too few to detect directly)

- **Solution: Rutherford & Geiger (1908)**

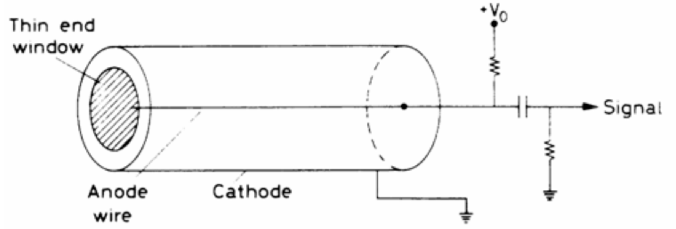
  Introduce thin wires (typically, 20-100 μm) at positive high potential (typically, a few kV) for signal amplification in gas (gas amplification)
  - Electric field in the tube E ~ 1/r
  - At a certain distance from the wire where the electric field becomes large enough, electrons get sufficient energy between collisions with gas atoms to ionize them
  - An avalanche develops exponentially; the overall electron multiplication factor (gas gain) can easily be 10^4 (and much larger in right conditions)

- **The net observed signal on the anode wire is proportional to the initial ionization left by a particle in the counter**





simulation of an avalanche near a thin anode wire



Wire detectors: maximum signal multiplication

How large can an avalanche be?

increasing HV

proportional: G~10^4

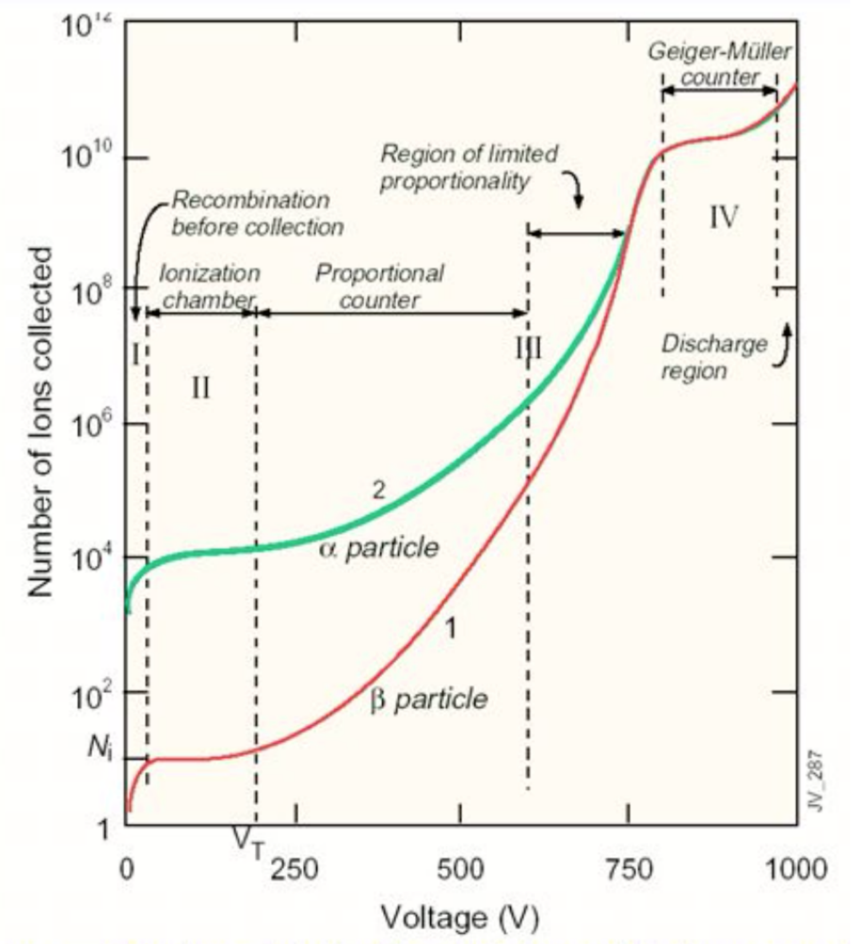
limited proportional: G~10^5

saturation: q ~ 1 pC

Geiger-Muller: >1 nC

Localized streamer: q~1 nC

discharge: Q=VC



Maximal gas gain before onset of discharges (sparking) depends on amount of quenching gas.
Discharges can easily lead to wire breaking.
Gases efficient in absorption of UV are called quenching gases (e.g. organic molecules).

Gas choice considerations

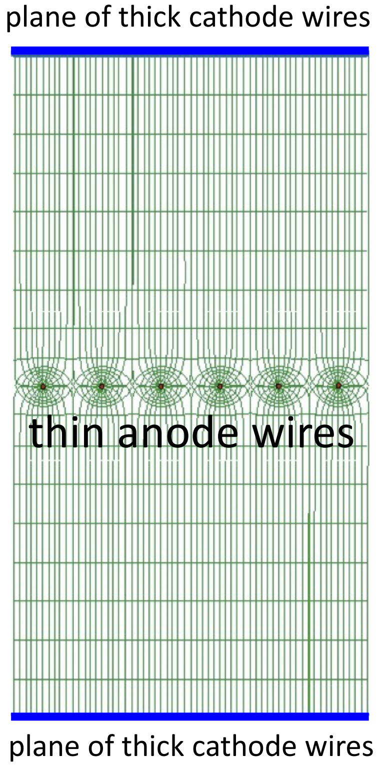
- **Nobel gas: to obtain a large gas gain at lower HV**
  - In noble gases, electron energy is not wasted on breaking up molecules without releasing new electrons
  - The larger atomic number is, the lower the ionization potential is
  - However, Xe and Kr are fairly expensive
  - Hence, Ar is the noble gas of choice

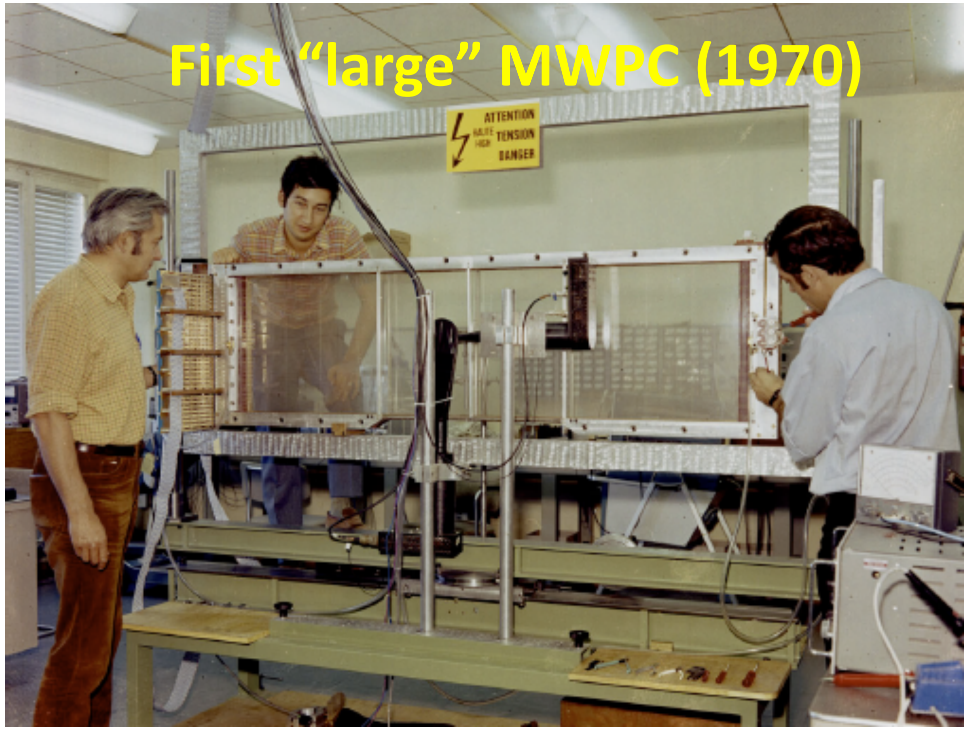
- **Quenching gas: to prevent discharges**
  - Add gas with complex molecules that absorb easily de-excitation photons produced in avalanches before they reach cathode surface and knock out new electrons…
  - CO_2 , isobutane (i-C_4H_{10}), pentane (C_5H_{12}), etc.
  - Typically, the more complex the molecule is, the better its quenching properties are
  - However, complex organic molecules tend to polymerize under radiation leading to detector "aging"

- **Other special considerations:**
  - Add H_20, O_2, CF_4 to prevent detector aging under radiation…
  - Drift velocity varies between gasses…
  - Electron diffusion varies between gasses…
  - Beware of electronegative properties of gases (electron attachment), their physical and chemical activity…
  - When enhanced gamma detection is needed, use Xe…
  - Etc., etc., etc.

Wire chambers: Multi-Wire Proportional Chambers

- **Principle: Charpak (1968)**
  - **chambers made of planes of wires**
  - **typical geometry:**
    - anode-cathode gap is 5 mm
    - 20 µm anode wires, 1-2 mm pitch
    - Yes/No readout
    - Spatial resolution: ~500 µm
  - **MWPC revolution (and demise of bubble chambers)**
    - wire signals **could be directly recorded to computers**
    - **very high rate capabilities**
    - mechanics: **fairly simple**
    - electronics: thousands of electronic channels became **affordable** by 1970s

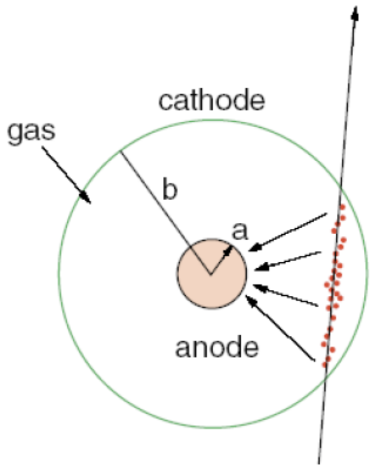


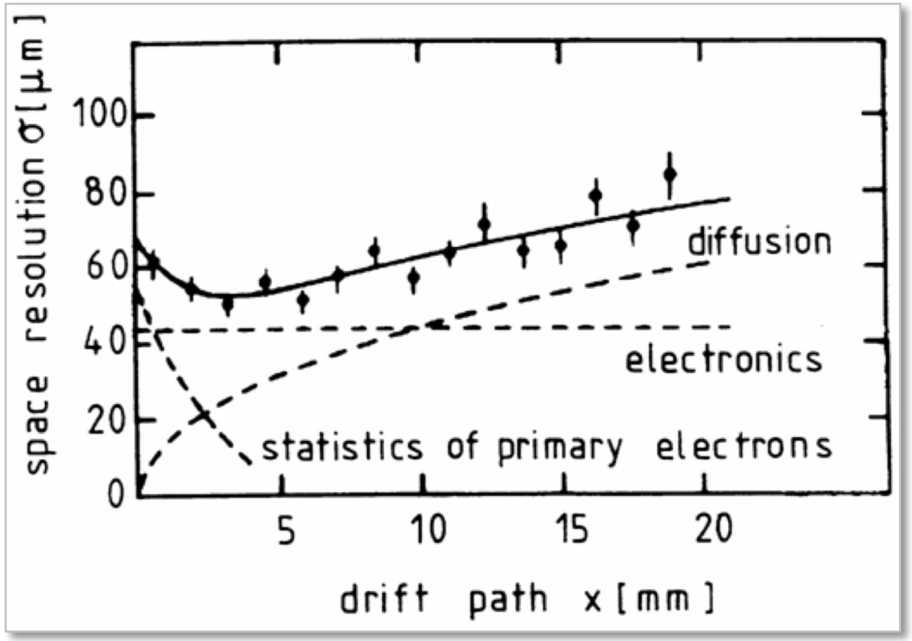


Wire detectors: Drift Chambers

Drift chambers allow one to reduce the number of readout channels (at a cost of a signal arrival time digitization)

- **Principle**
  - assume one knows when particles go through detector: t_0
  - measure drift time: $T = t_{signal} - t_0$
  - calculate distance via a calibrated time-distance dependence: $x = f(T)$
  - with saturated drift velocity (i.e. when $v_{drift} \sim$ const, independent of E), the calculation becomes trivial:
    - $x \sim v \cdot T$, where v is typically 50 μm/ns

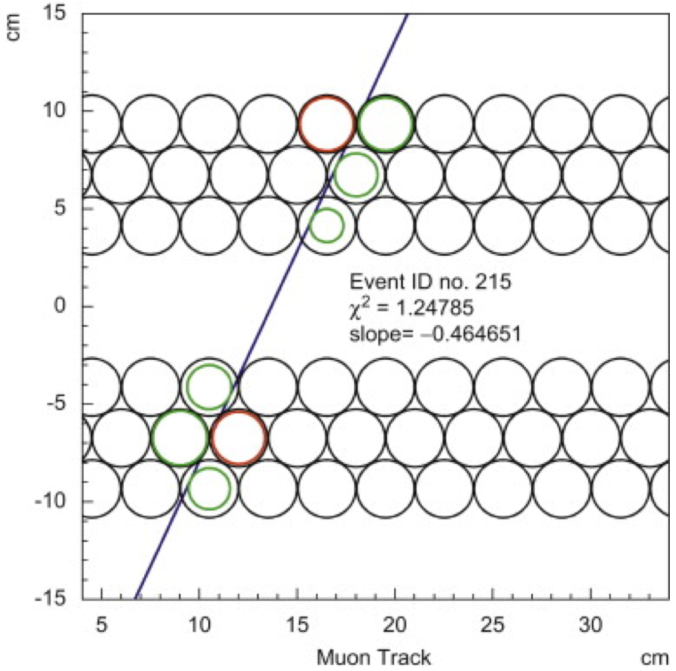




- **Performance**
  - Drift time range varies wildly according to drift distances from a few mm to meters
  - Spatial resolution O(100) μm

Wire detectors: Drift Chambers

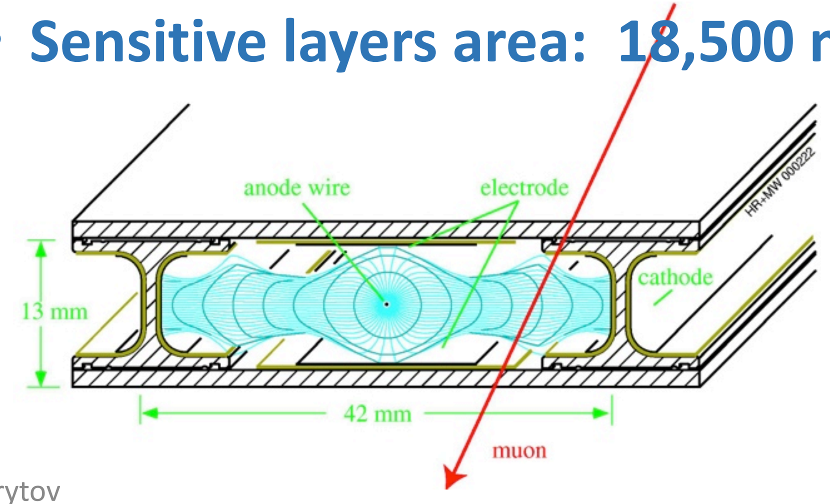
- **Example: Monitored Drift Tubes in ATLAS Muon System**
  - **3 cm tubes**
  - **pressure 3 bar (Ar+CO2=93%+7%)**
  - **spatial resolution 80 µm**
  - **350K tubes, gas volume 700 m^3**



Wire detectors: Drift Chambers

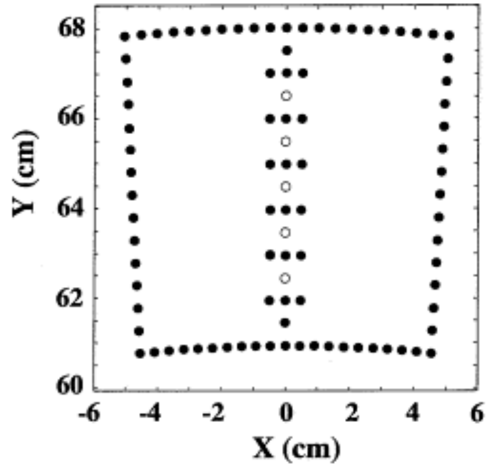
Example: Drift Tubes in the CMS Muon System

- **Rectangular 10x40 mm^2 tubes with electric field shaping electrodes**
  - Rectangular shapes extends the drift distance while keeping the detectors thin
- **Max drift time 400 ns**
- **Spatial resolution 250 μm**
- **Number of channels: 172K**
- **Sensitive layers area: 18,500 m^2**

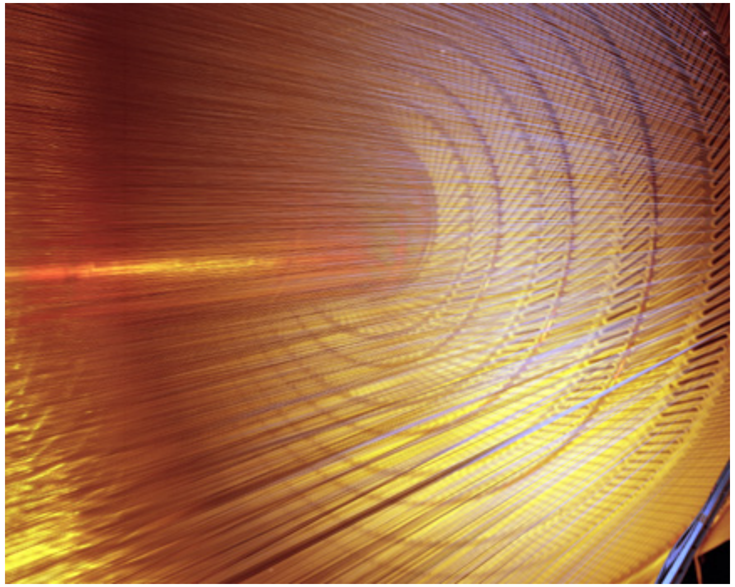


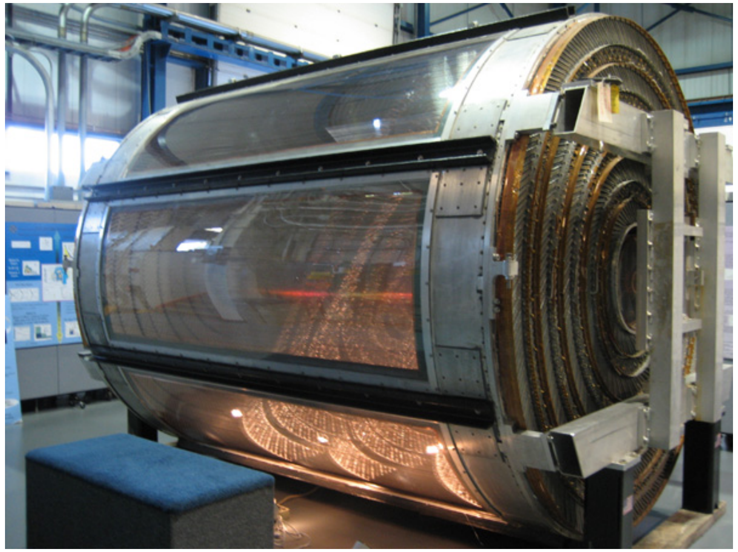
Wire detectors: Drift Chambers

- **Example: Open cell drift chambers**
  (e.g. the CDF Central Tracker in Tevatron Run 1)
  - **use thin wires to form "open cells" with the desired electric drift field**
  - **the open-cell design allows for very low material amount in the tracking detector and, hence, low multiple scattering of charged particles**



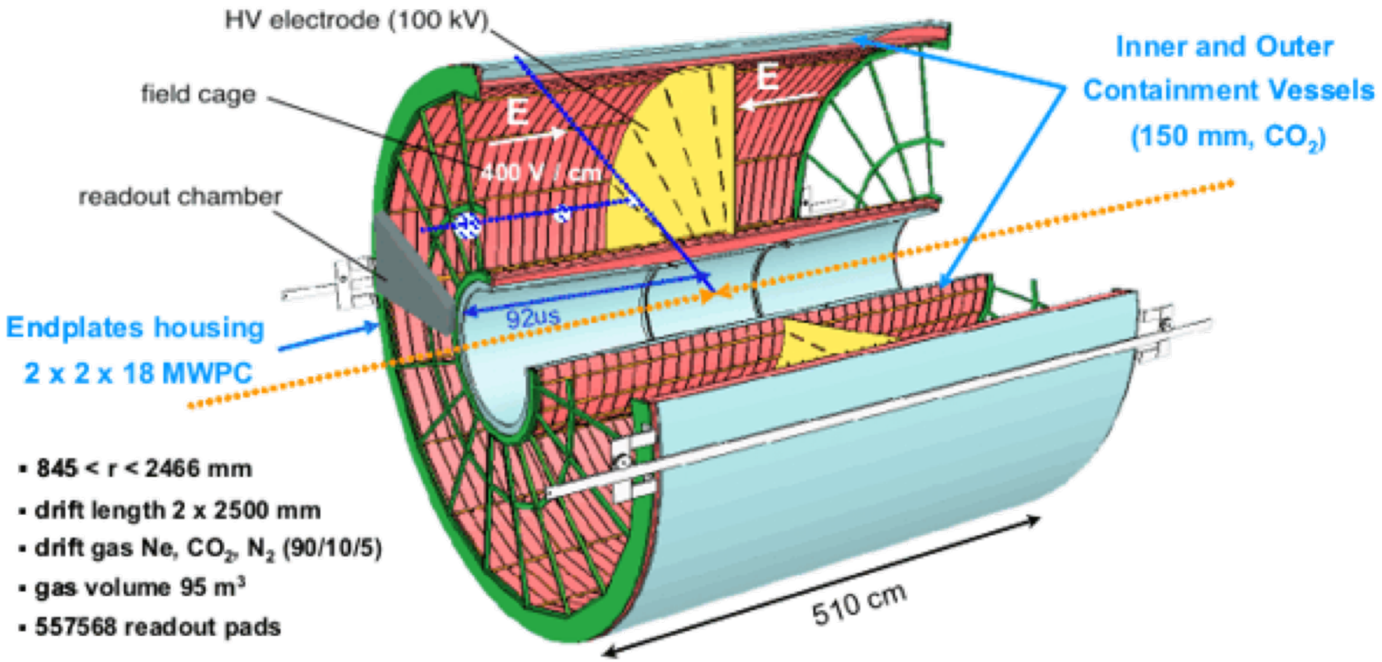
This cell is for illustration of the concept only (it is not from the CDF Central Tracker)





Wire detectors: Drift Chambers

- **Example: Time Projection Chamber in the ALICE Detector**
  - large cylindrical chamber (100 m^3) with gas and an axial electric field
  - ionization electrons drift toward endcaps where MWPCs are placed
  - MWPCs have pads that give (x,y) coordinates of ionization clusters, while clusters' z-coordinates are measured from the drift time

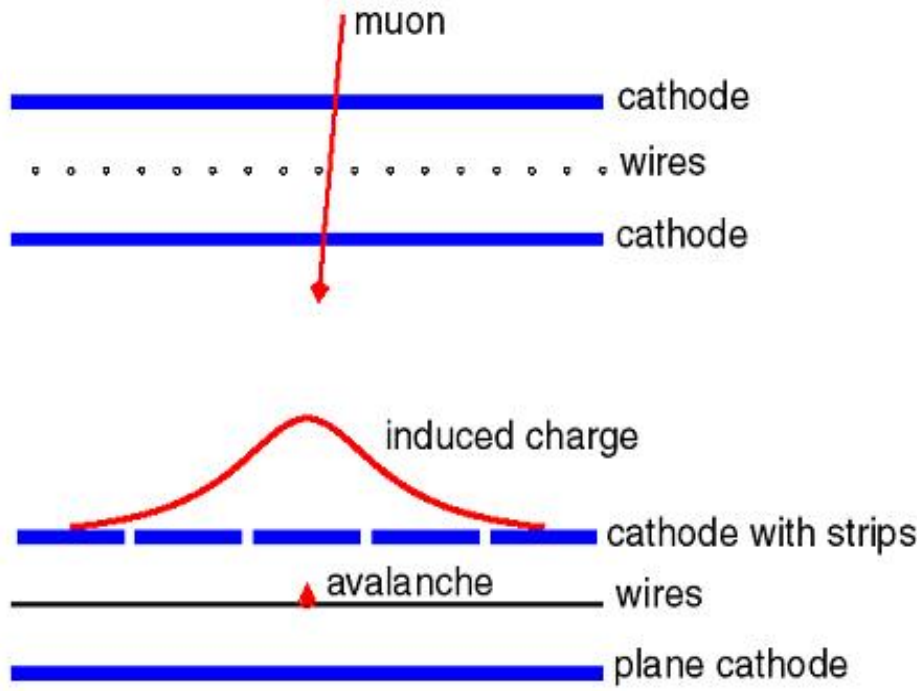


- **Performance:**
  - Long drift times, O(100) μs (OK when rates are not high, like in the case of HI collisions)

Wire detectors: Cathode Strip Chambers

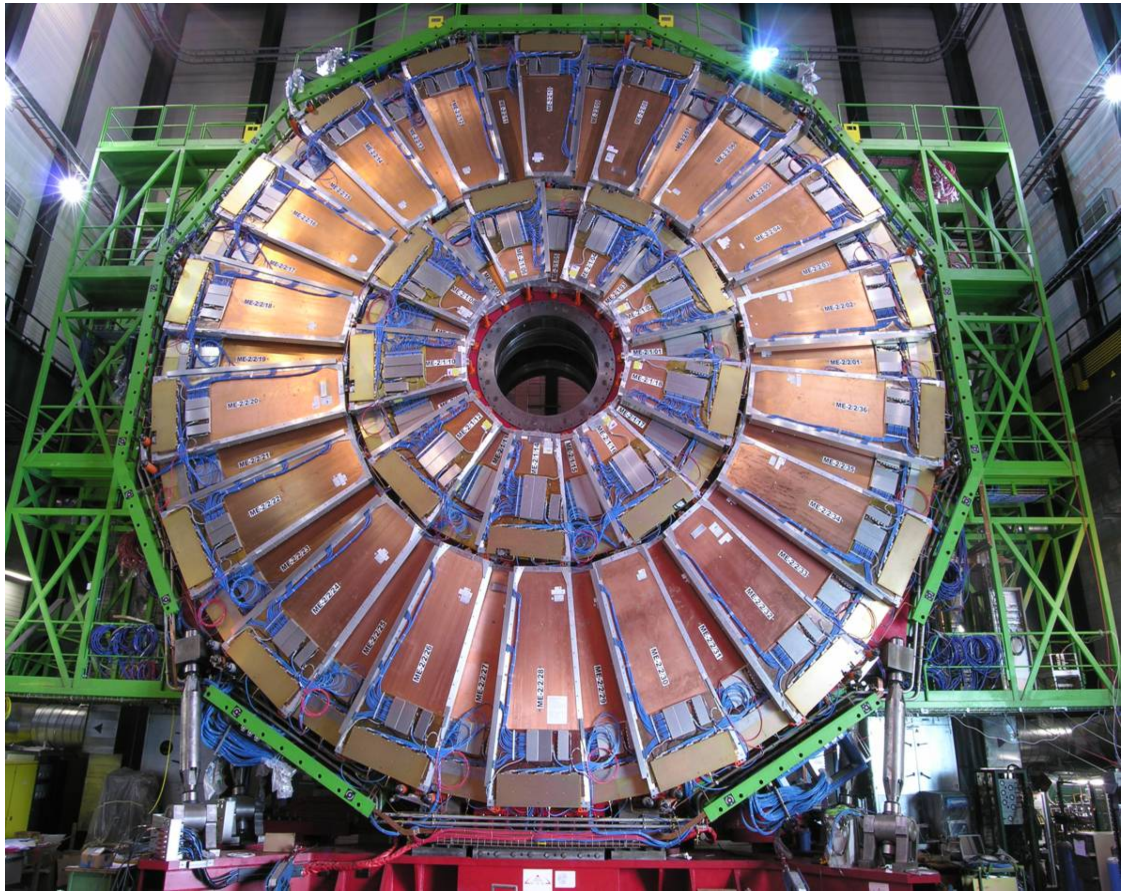
Cathode Strip Chambers allow one to reduce the number of readout channels (at a cost of a signal amplitude digitization)

- **Principle: G. Charpak (1979)**
  - MWPC with cathode planes segmented into strips running perpendicular to wires
  - The shape of induced charge on the cathode surface is defined by the plain electrostatics
  - Amplitudes of induced charges on strips are digitized
  - Center-of-gravity of the digitized pulses allows one to find the avalanche position along the direction of wires
- **Performance:**
  - All typical parameters of MWPCs
  - Spatial resolution O(100) μm



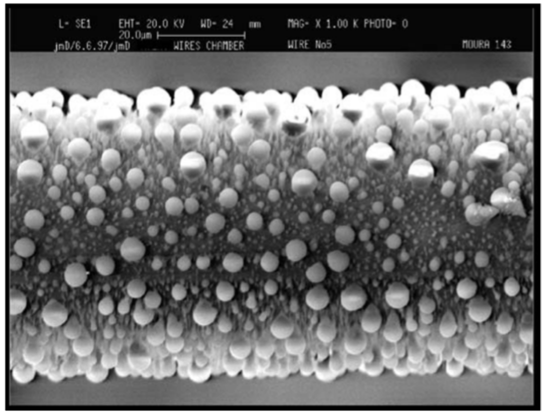
Wire detectors: Cathode Strip Chambers

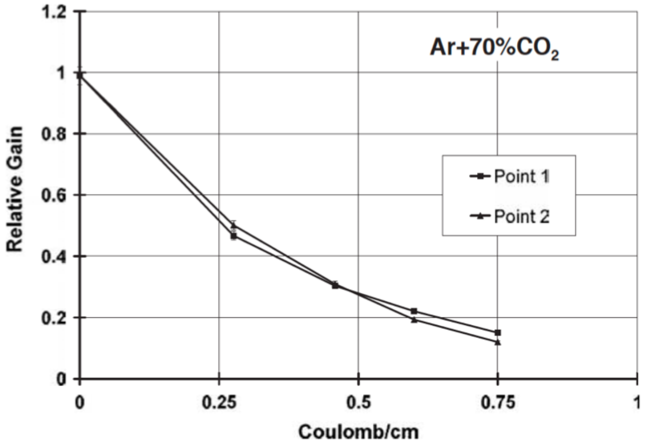
- **Example: Cathode Strip Chambers in the CMS Muon System**
  - Gas gaps ~1 cm
  - Largest chambers ~3x1.5 m^2
  - Total sensitive area: 7,000 m^2
  - Total number of wires: 2M
  - Total number of strips: 270K



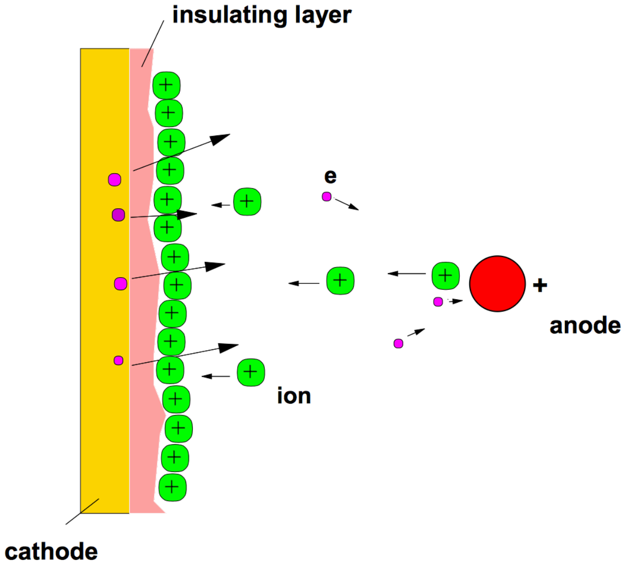
Wire detectors: problems

- **Wire aging**
  - complex organic molecules tend to polymerize
  - plasma chemistry inside an avalanche is not well understood; the processes is often driven by minute gas impurities and material outgasing
  - as the cumulative charge released in avalanches increases, deposits start appearing on either wires or cathode
  - **Wire deposits on wires decrease gas gain and cause operational instabilities**



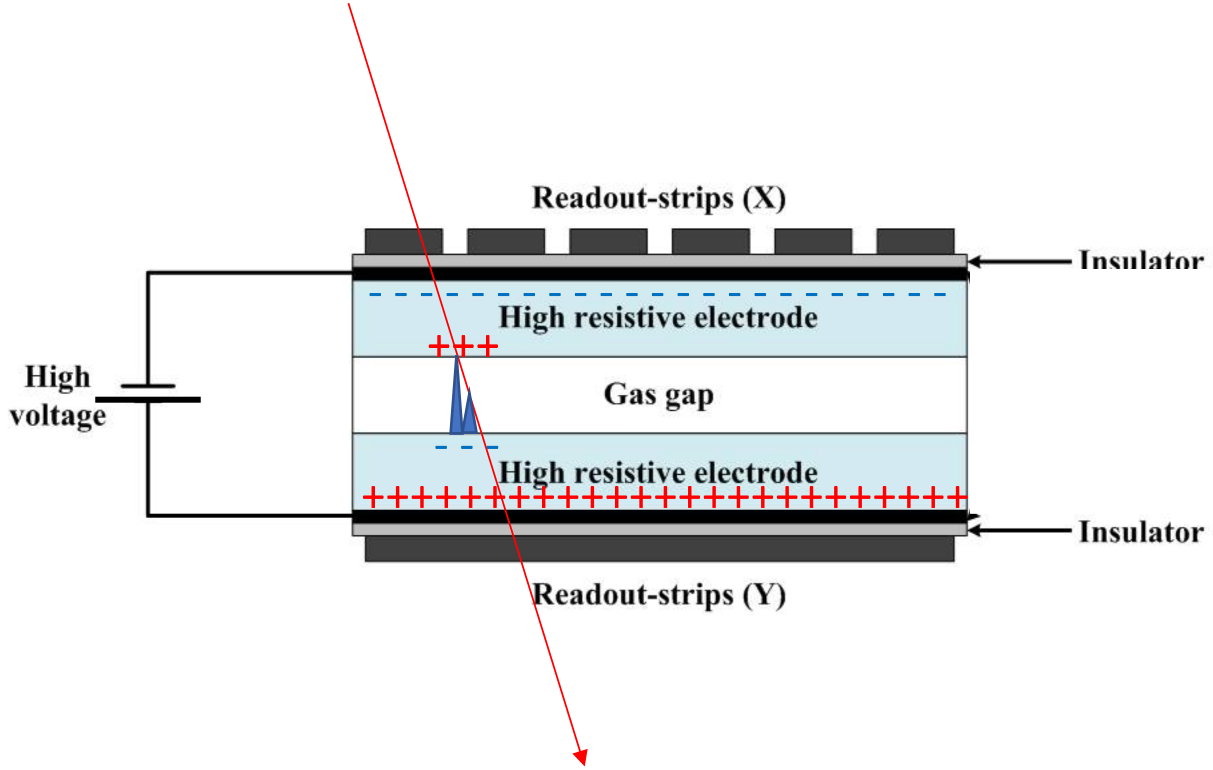


- **Malter currents**
  - thin film insulator deposits on cathode charge up under irradiation
  - Large electric field across the thin film can cause electron emission from cathode
  - **This positive feedback can create a self-sustained discharge with a very large local current density, which will eventually lead to HV breakdown**



Wireless detectors: Resistive Plate Chambers (RPC)

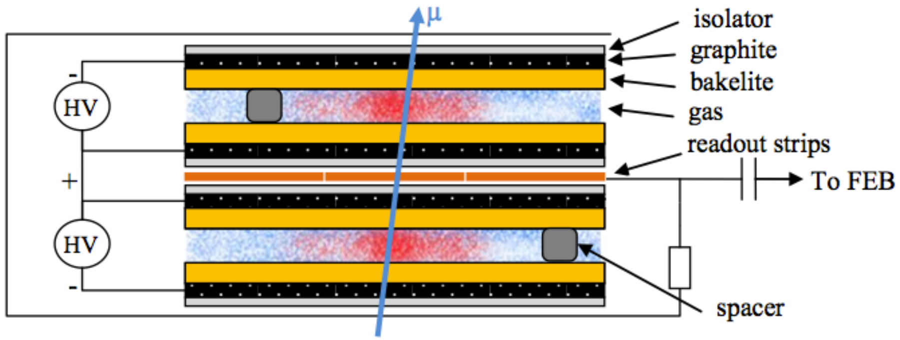
- **Principle**
  - two plates of high resistivity material, $\rho \sim O(10^{10})\ \Omega\text{m}$, with a gas gap in between (typically, a few mm)
  - as avalanche develops,
    - high resistivity does not allow for fast replenishing of stored charge on resistive electrodes
    - local difference of potentials drops
    - the discharge terminates
    - the local place of $O(1)\ \text{mm}^2$ where the discharge took place remains dead until the charge gets restored with a time constant ($\tau \sim \rho\varepsilon\varepsilon_0 \sim 0.1$ s)
  - conductive strips or pads are placed outside for reading out induced signal readout

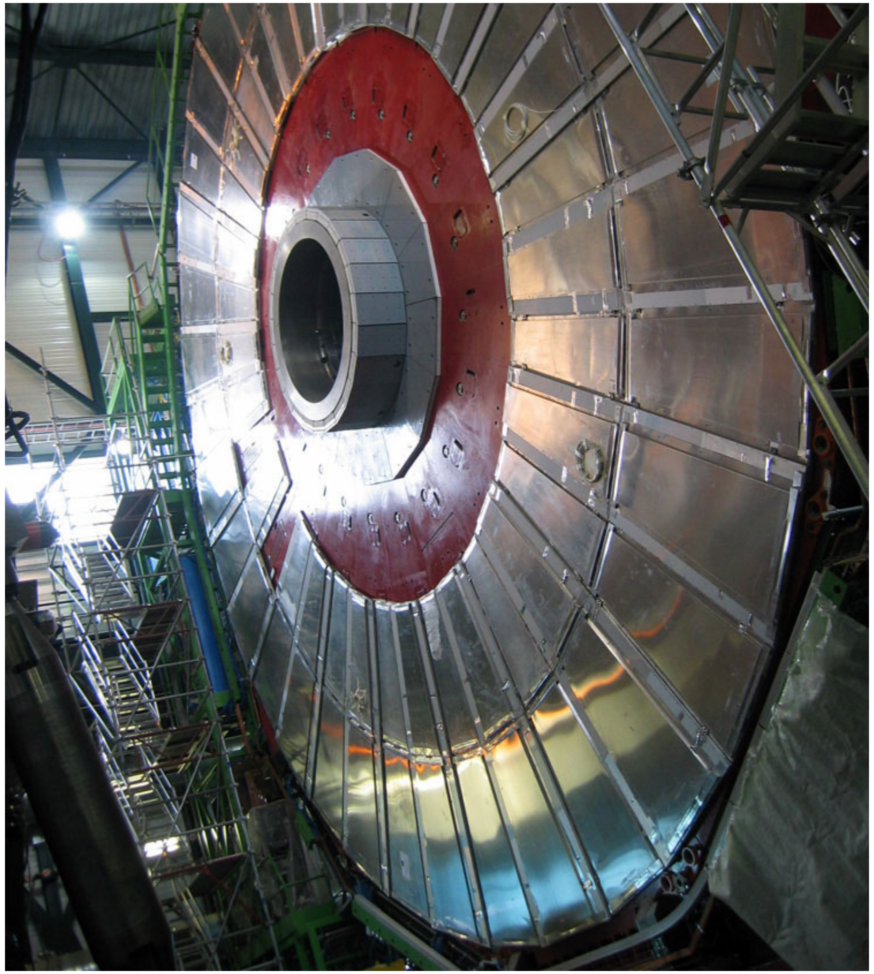


- **Performance:**
  - excellent timing <1 ns
  - intrinsic resolution <1 mm
  - rate capabilities <1 kHz/cm^2

Wireless detectors: Resistive Plate Chambers (RPC)

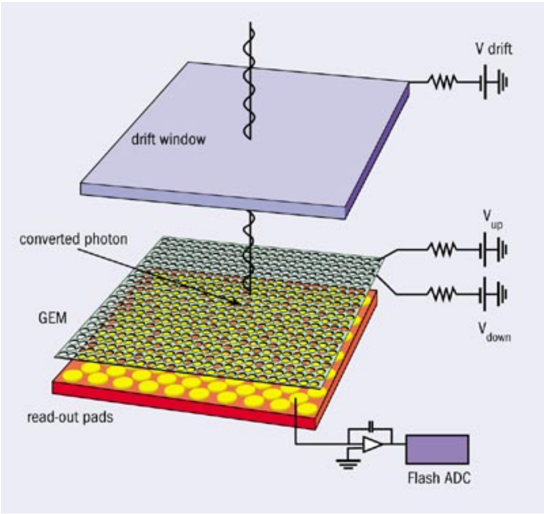
- **Example: Resistive Plate Chambers in the CMS Muon System**
  - **Double-gap design: one plane of strips picks up signals from two RPC gaps, which gives a higher efficiency**
  - **Total sensitive area: 4,000 m^2**
  - **Total number of strips: 140K**
  - **Spatial resolution: 1 cm**
  - **Time resolution: for HL-LHC, electronics will be upgraded to take advantage of the RPC time resolution, O(1) ns**

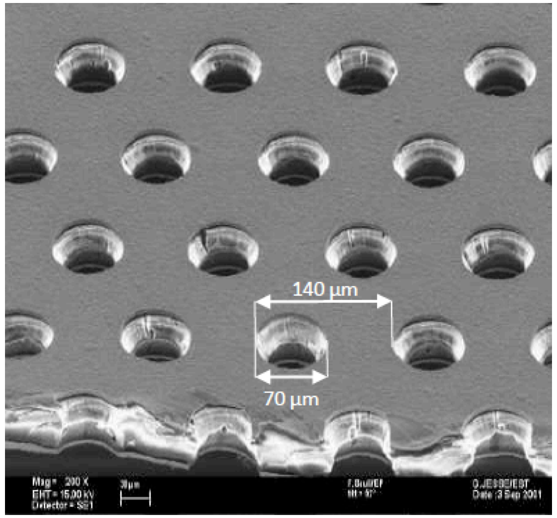


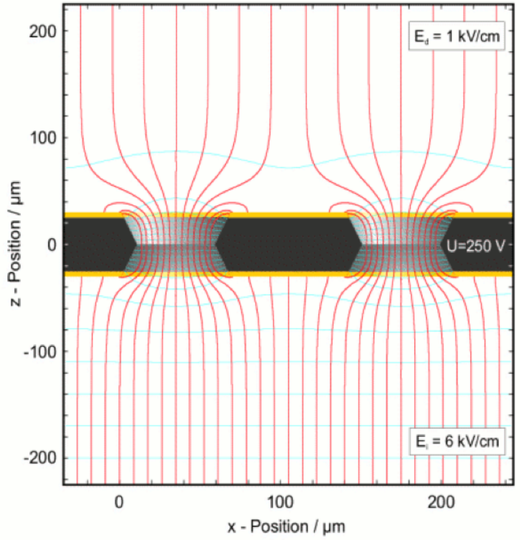


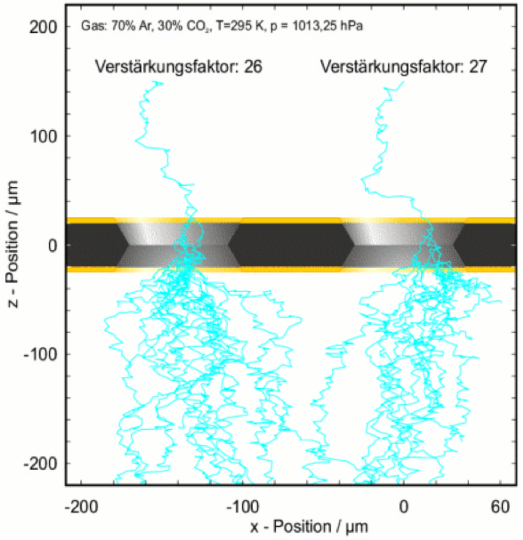
Wireless detectors: Gas Electron Multipliers (GEM)

- **Principle: F. Sauli (1997)**
  - **Parallel-plate chamber with a GEM film in the middle:**
    - **thin insulating film**
    - **copper clad on both sides**
    - **punctured with a pattern of micro-holes, O(50) μm**
  - **Two sides of the film are kept at a difference of potentials of O(500) V**
  - **This creates strong electric field in the holes, where the gas amplifications happens**
  - **Signal is read out from strips or pads on the plane "under" the foil**
  - **Gas Gain O(10^3)**
  - **Time resolution ~5 ns**
  - **Spatial resolution ~100 μm**
  - **Rate capabilities ~10 MHz/mm^2**
- **Care must be taken to**
  - **maintain the quality of micro-holes so as to avoid sparking (and consequent short circuit) across holes**



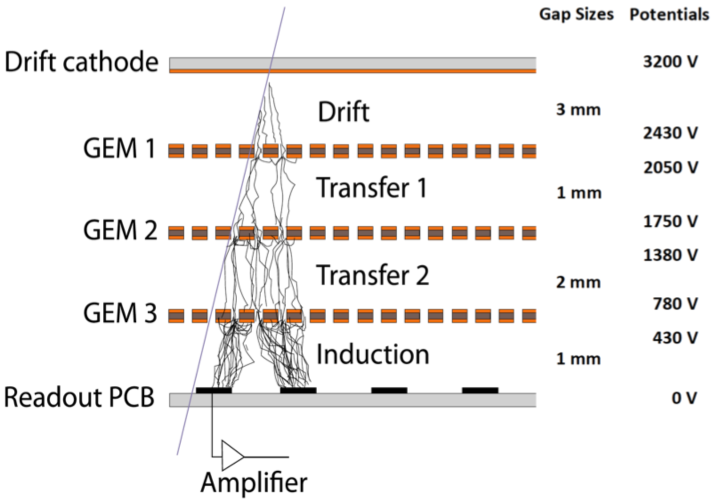






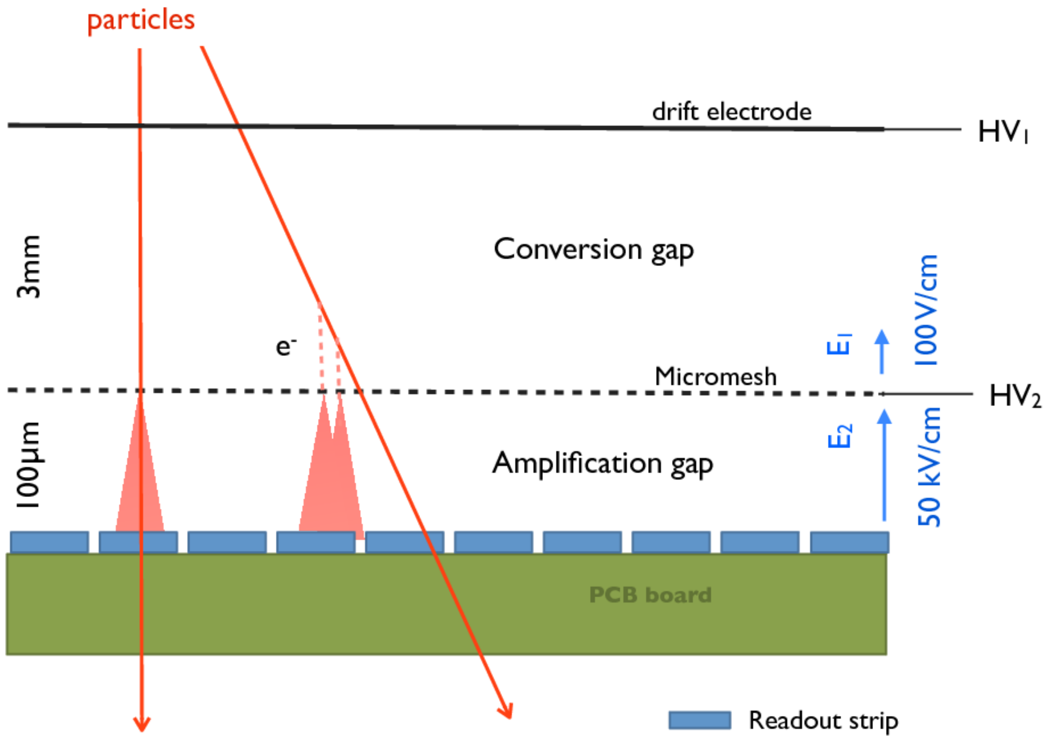
Wireless detectors: Gas Electron Multipliers (GEM)

- **Example: GEMs being built for the forward CMS Muon System Upgrade**
  - **Triple-foil GEM chambers**
    - **Overall gas gain 10^4, while gas gain of a single foil is $\sim$30**
    - **Much more reliable operation**
  - **Largest GEMs: 1x0.5 m^2**
  - **Overall chamber area: 220 m^2**
  - **Number of channels (pads): 1.5M**



Wireless detectors: Micro-mesh gaseous chambers (MicroMegas)

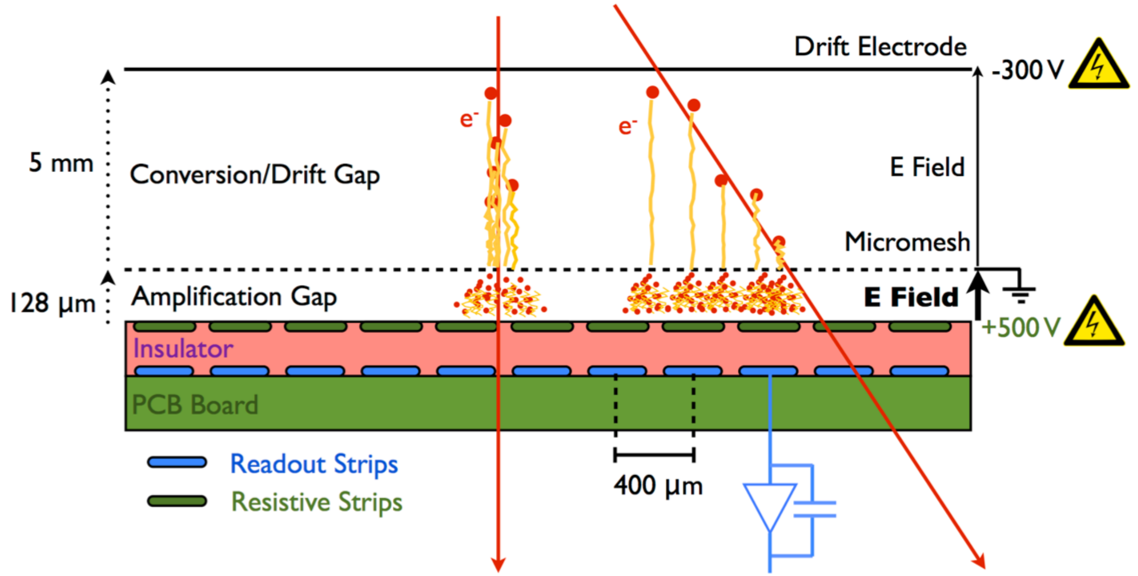
- **Principle: Charpak & Giomataris (1992)**
  - Parallel-plate chamber
  - Micromesh separates the ionization and drift gap (few mm) is separated from a thin, O(100 μm), gas amplification gap:
  - Gas Gain ~10^4
  - Signal is read out from narrow strips (<1 mm)
  - Time resolution ~ 5 ns
  - Spatial resolution ~ 100 μm
  - Rate capabilities >10 MHz/cm^2 with a good two-track resolution
- **Care must be taken to**
  - maintain the gas amplification gap thickness to a high tolerance (pillars are made as a part of the PCB production)
  - and protect the detector from sparking (resistive cover is added over readout strips, similar to RPC)

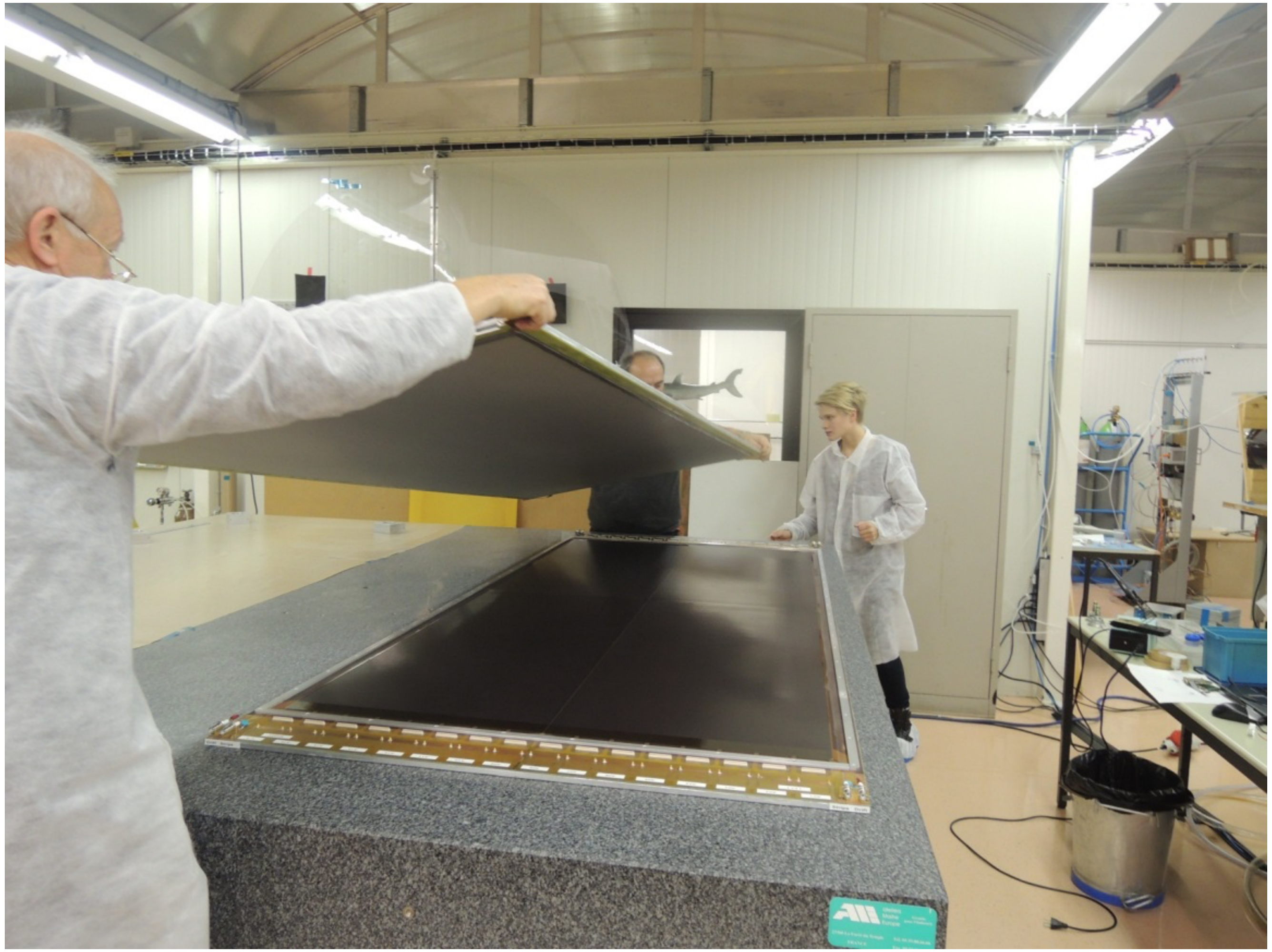


Wireless detectors: Micro-mesh gaseous chambers (MicroMegas)

- **Example:**

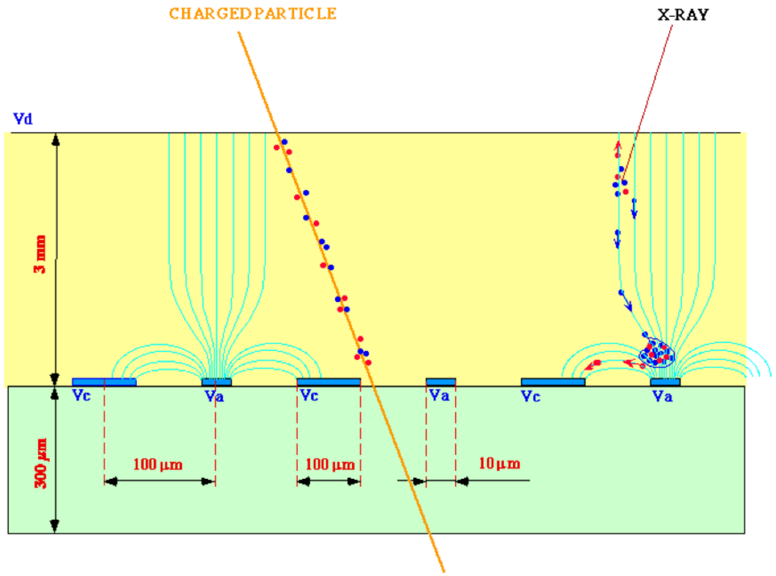
  ATLAS forward muon system upgrade (during Long Shutdown 2)
  - **Individual chambers: ~1.5 x 2.5 m^2**
  - **Total sensitive area: 1,200 m^2**
  - **Readout channels: 2.1M**

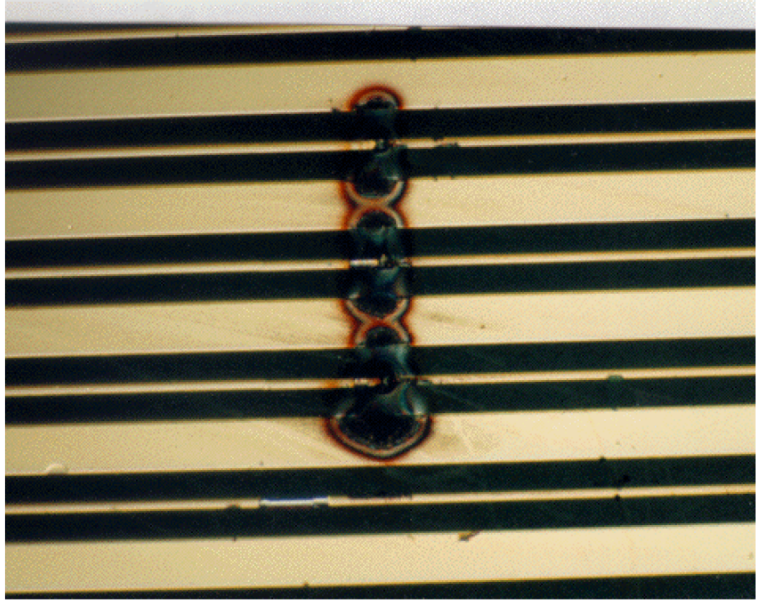




Wireless detectors: Micro-strip gaseous chambers (MSGC)

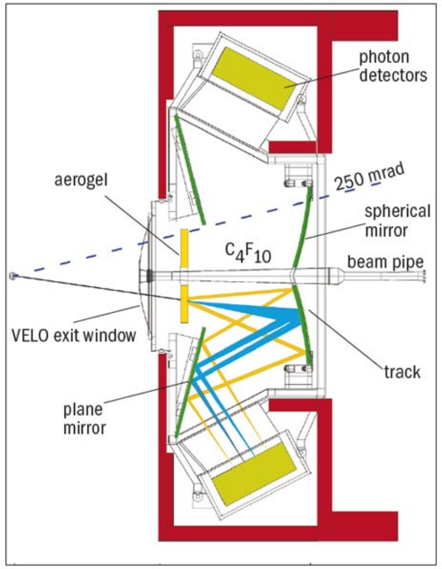
- **Principle: Oed (1988)**
  - A pattern of thin (10 μm) anode and thicker cathode strips on a insulating substrate with a pitch of a few hundred μm.
  - Anode strips work as anode wires and provide moderate gas gain (x100) before transitioning into a discharge mode.
  - Spatial resolution: <50 μm
  - Size: ~30x30 cm^2
- **Remain problematic**
  - Unlike for wires, discharge in MSGC may cause serious permanent damage to strips; MSGC with damaged strips are not operational
  - Highly ionizing slow particles are notoriously problematic



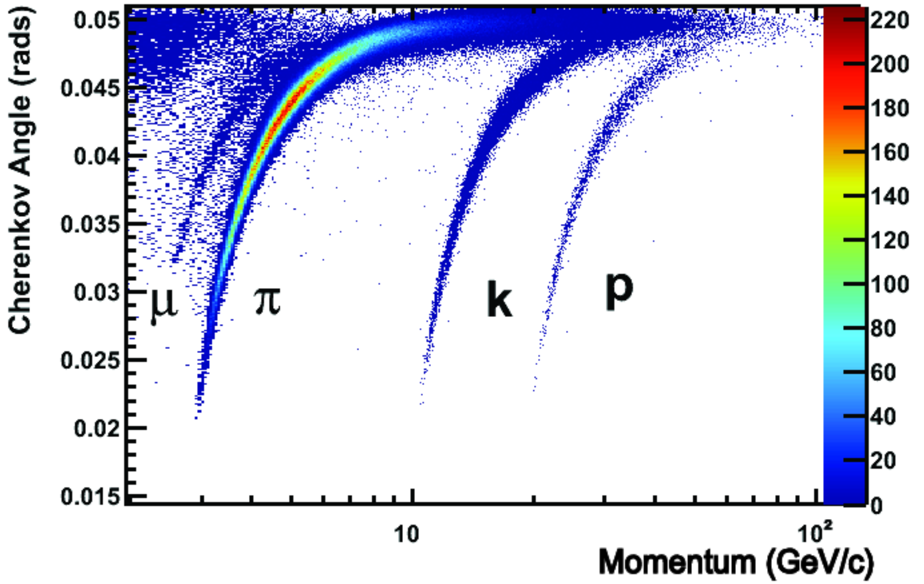


Picking up light: Cherenkov detectors

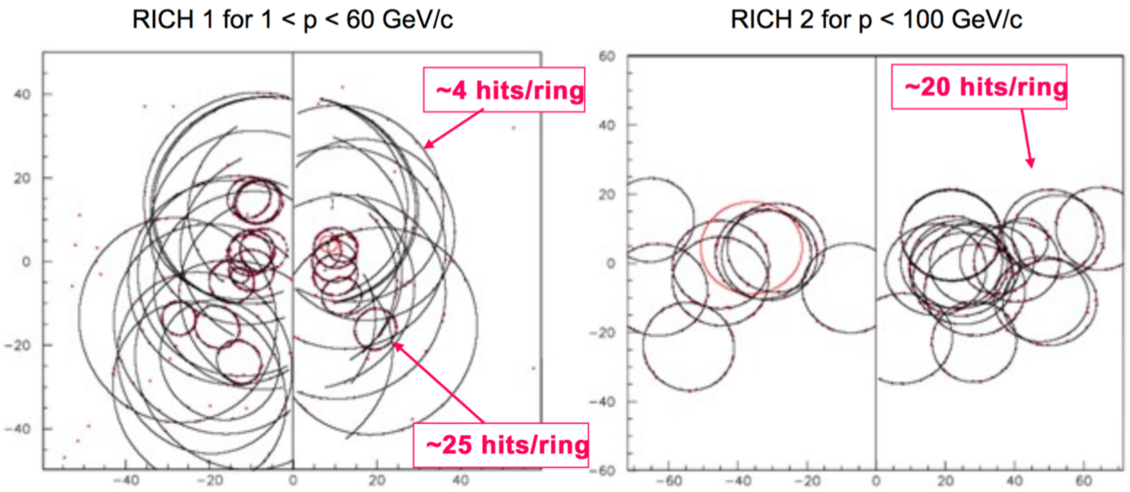
- **Example: Ring Imaging Cherenkov detectors at LHCb**
  - **RICH1**
    - aerogel: n=1.03
    - C_4F_{10} gas: n=1.0014
  - **RICH2**
    - CF_4: n=1.0005
  - **charged particles emit Cherenkov light at $\cos\theta = 1/(n\beta)$**
  - **When focused by spherical mirrors, the photons form rings. Different particles of the same momentum form different size rings.**



C_4F_{10} radiator



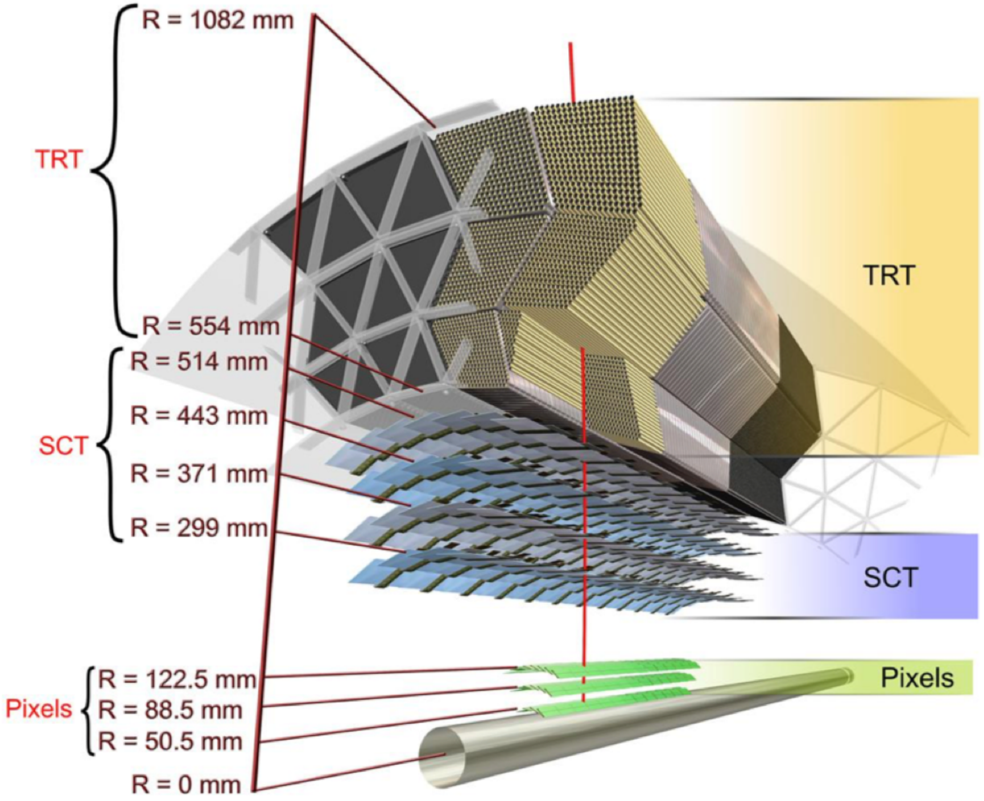
- **Performance**
  - **which helps LHCb to identify charged particles as long as their momenta are not too high (up to 100 GeV)**

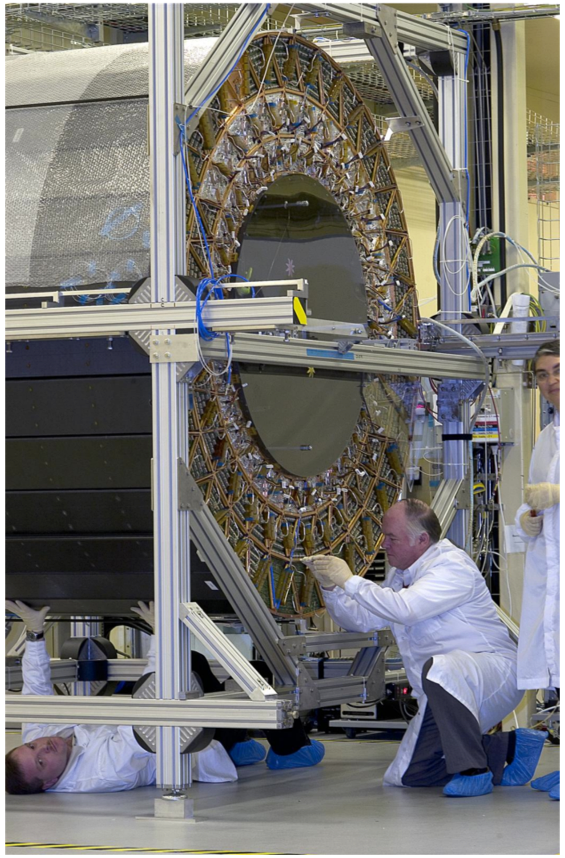


Picking up light: Transition Radiation Detectors

- **Example: Transition Radiation Tracker in ATLAS**
  - “straws”: multilayer kapton tubes, 4 mm in diameter
  - 300K tubes in the system
  - 36 straws per track
  - Gas: $Xe+CO_2+O_2$

- **Performance**
  - 40 ns drift time
  - spatial resolution ~130 μm
  - 90% electron identification efficiency at ~5% pion mis-tagging rate





Summary

- **Gaseous detectors allow for tracking charged particles in large gas-filled volumes, without much affecting the particles themselves**
- **Typical tracking accuracy: spatial precision O(100) μm, and time resolution 1-10 ns; both are often quite sufficient**
- **One can take advantage of a few handles (dE/dx, Cherenkov light, Transition radiation) to improve particle ID**
- **Gaseous detectors are inexpensive; nearly the only choice for very large volume detectors**
- **Gaseous detectors come in many shapes and forms in terms of the underlying principles of their operation; new ideas keep coming**

Backup slides

Multiple Coulomb scattering

- **Rutherford scattering formula:**
  - **projectile: q=ze, p, β**
  - **target: Q=Ze**

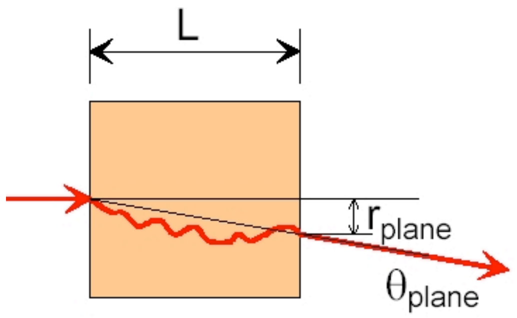
$$\frac{d\sigma}{d\Omega} = \frac{1}{4}\left(\frac{zZ\alpha}{\beta p}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

- **Displacement in a random walk (N steps of size d) has a Gaussian distribution of width D**

$$D \sim \sqrt{d \cdot N}$$

- **After many scatterings, <u>expect</u> the following dependence for deflection angle:**

$$\theta_{rms} \sim \frac{zZ}{\beta p}\sqrt{L \cdot n_A}$$



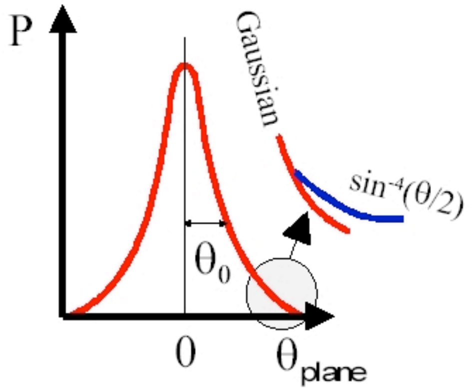
Actual formulae:

$$\theta_{rms} = (14 MeV)\frac{z}{\beta p}\sqrt{L / X_0}$$

$$r_{rms} = \frac{1}{\sqrt{3}} L\theta_{rms}$$

where radiation length X_0 is a characteristic of media

$$\frac{1}{X_0} \approx Z(Z+1) \cdot \frac{\rho}{A} \cdot \frac{\ln(287 / Z^{0.5})}{\left(716\ g/cm^2\right)}$$



Light emission: Scintillation

- Charged particle leaves a wake of <u>excited</u> molecules

- Certain type of media can release some of this excitation energy in a form of low energy photons (visible light, UV) for which media can be fairly transparent

- Energy carried away by scintillation is small

- <1% ✕ (dE/dx)
  up to 10^4 photons per MeV of dE/dx

many; can be used instead of ionization

- Light emission decay time:
  ~10 μs in noble gases
  10 – 1000 ns in inorganic materials (10 ns in $PbWO_4$)
  ~ 2 ns in fast organic scintillators

fast

Scintillation in noble gases

(note original excitation/ionization energy is much higher than the energy of scintillation light photons)