Tracking of Charged Particles

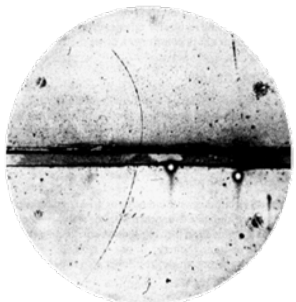
- Physics of gaseous chambers for charges particle tracking
- Types of tracking chambers

- not covered: solid state detectors
  $\rightarrow$ see lecture of Richard Bates

Tracking Detectors

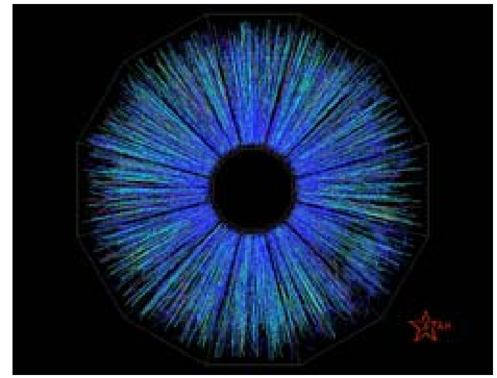
- Tracking in 1932: Cloud Chamber (detection of antimatter)

~5 cm

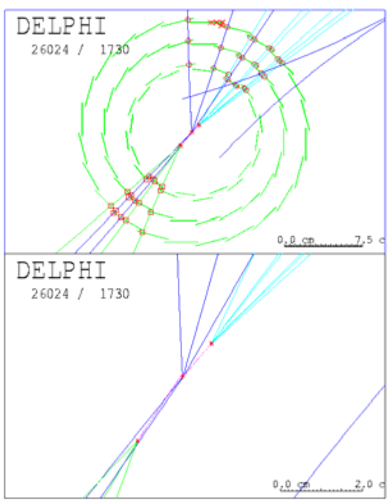


- Tracking in 2001: STAR TPC (study of Quark-Gluon-Plasma)

200 cm



- ~1994: DELPHI B meson

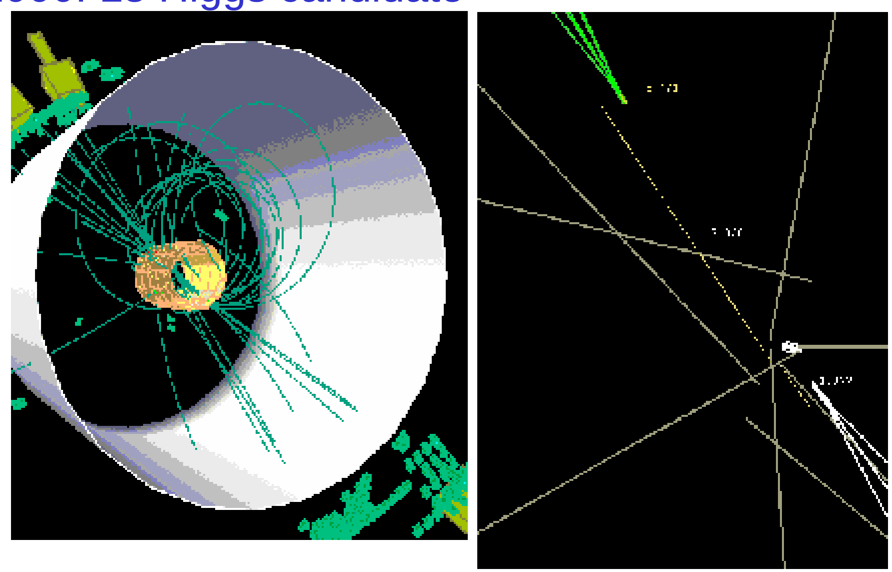


$\tau_B \approx 1.6$ ps

$L = \beta\gamma\, c\tau$

$\approx \beta\gamma \cdot 480\ \mu m$

- 2000: L3 Higgs candidate



Momentum Measurement I

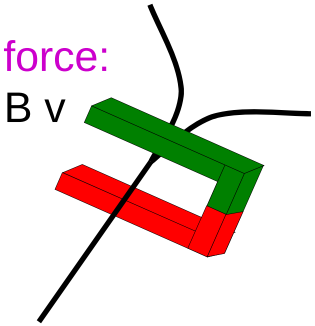
- Sagitta s: measures momentum

$$F = \frac{mv^2}{r} \quad \rightarrow \quad p_T = qBr \quad \text{or} \quad p_T\,[\text{GeV/c}] = 0.3Br[Tm]$$

$$L = 2r\sin\theta/2 \approx r\theta \quad \text{and} \quad s = r(1-\cos\theta/2) \approx r\frac{\theta^2}{8} \quad \rightarrow \quad s = \frac{L^2}{8r}$$

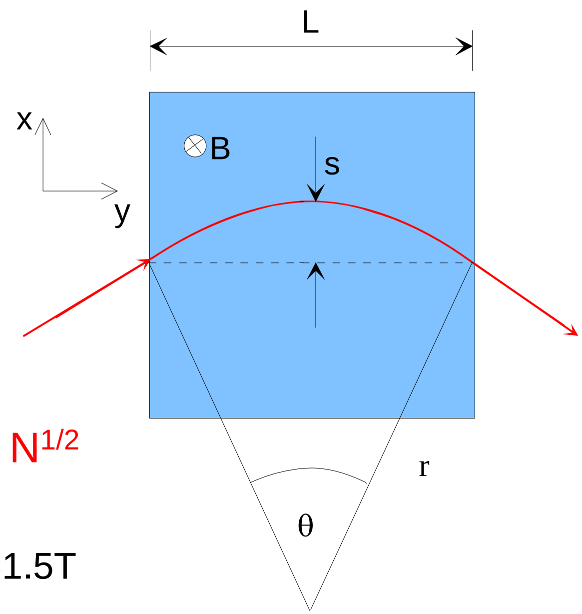
$$\Delta p_T = p_T \sin\theta \approx p_T\theta = 0.3LB \quad \text{and} \quad s \approx \frac{0.3}{8}\frac{L^2B}{p_T}$$

Lorentz force:
F = q B v



- Need at least 3 measurements:

$$s = x_2 - \frac{x_1 + x_3}{2} \qquad \frac{\sigma(p_T)}{p_T} = \frac{\sigma(s)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)\cdot 8p_T}{0.3\cdot BL^2}$$



- For N equidistant measurements (Glückstern, NIM 24 (1963)381)

$$\frac{\sigma(p_T)}{p_T}^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3\cdot BL^2}\sqrt{\frac{720}{(N+4)}}$$

improves with BL^2!! and $N^{1/2}$

- Examples:
  - p_T=1GeV/c, L=1m, B=1T
    σ(x)=200μm, N=10 :

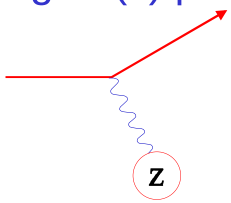
$$\frac{\sigma(p_T)}{p_T} \approx 0.48\% \quad \text{and} \quad s = 37.5\text{mm}$$

  - p_T=100GeV/c, L=5m, B=1.5T
    σ(x)=1.5mm, N=6 :

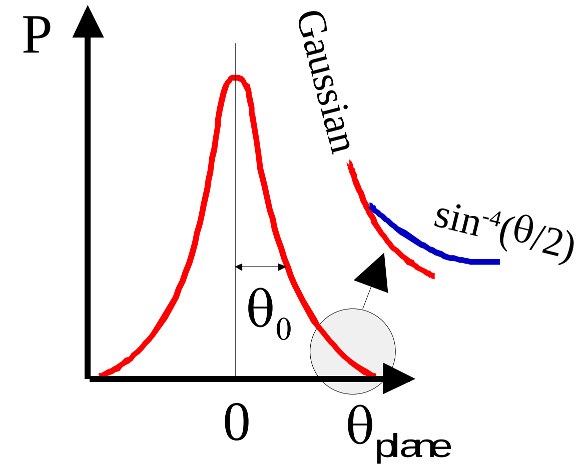
$$\frac{\sigma(p_T)}{p_T} \approx 11\% \quad \text{and} \quad s = 1.4\text{mm}$$

Multiple Scattering

- Charged (z) particles suffer elastic Coulomb scatterings from nuclei (Z):

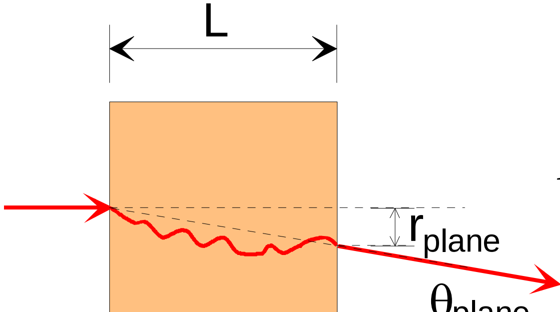


$$\frac{d\sigma}{d\Omega} = 4zZr_e^2\left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4 \theta/2}$$ Rutherford formula



- Average scattering angle: $\langle\theta\rangle = 0$

- Multiple Scattering: width = $\theta_0 = \sqrt{\langle\theta_{plane}{}^2\rangle} = \theta_{plane}^{RMS} = \frac{1}{\sqrt{2}}\theta_{space}^{RMS}$
- In thick material layer:



$$P(\theta_{plane}) = \frac{1}{\sqrt{2\pi}\theta_0}\exp\left\{-\frac{\theta_{plane}{}^2}{2\theta_0^2}\right\}$$

- Gaussian shape for central 98% of distribution:
  - X_0 = radiation length
  - accuracy ≤ 11% for $10^{-3} < L/X_0 < 100$

$$\theta_0 = \frac{13.6\,MeV}{\beta c p} z\sqrt{\frac{L}{X_0}}\left\{1 + 0.038\ln\left(\frac{L}{X_0}\right)\right\}$$

Momentum Measurement II

- Multiple scattering contributes to momentum measurement error:

$$\sigma(p)^{MS} = p \sin \theta_{RMS}^{plane} \approx p \cdot 0.0136 \frac{1}{p} \sqrt{\frac{L}{X_0}}$$

Example:
Ar (X_0=110m)
L=1m, B=1T

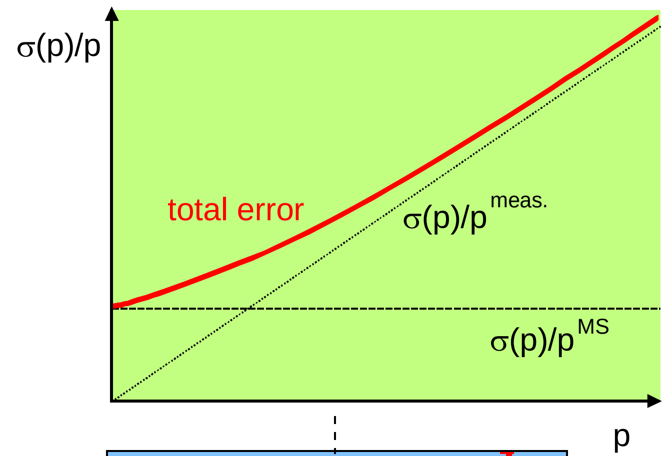
$$\frac{\sigma(p)}{p_T}^{MS} \approx 0.5\%$$

$$\frac{\sigma(p)}{p_T}^{MS} = \frac{0.0136\sqrt{\frac{L}{X_0}}}{0.3BL} = 0.045 \frac{1}{B\sqrt{LX_0}}$$

independent of p!
but $X_0 \propto N$

- Total measurement error:

$$\left(\frac{\sigma(p)}{p_T}\right)^2 = a_{meas.}^2 \cdot p_T^{\;2} + b_{MS}^2$$

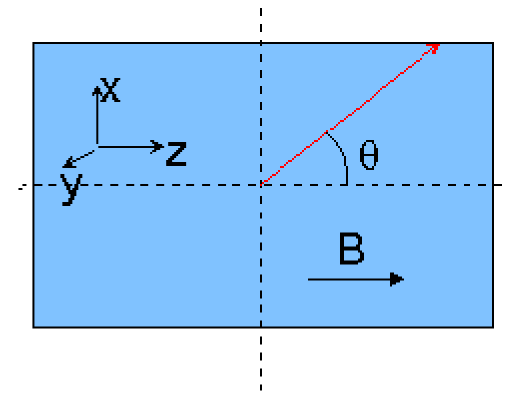


- Experiments with solenoid magnet:

$$p_T = p \sin \theta$$

measurement error:

$$\sigma(\theta)^{meas.} = \frac{\sigma(z)}{L} \sqrt{\frac{12(N-1)}{N(N+1)}}$$

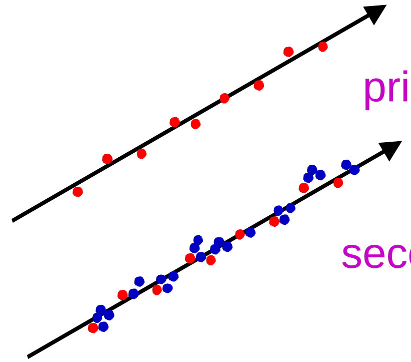


- Optimum N: trade measurement resolution against material budget

- In practice often: $\frac{\sigma(p)}{p} \approx \frac{\sigma(p_T)}{p_T}$

Ionisation of Gases

- Charged particles ionise the atoms of a gas:
  - $X + p \rightarrow X^* + p$ excitation
  - $X + p \rightarrow X^+ + p + e^-$ ionisation



- δ-rays: e^- with enough energy to create new e^--ion pairs:

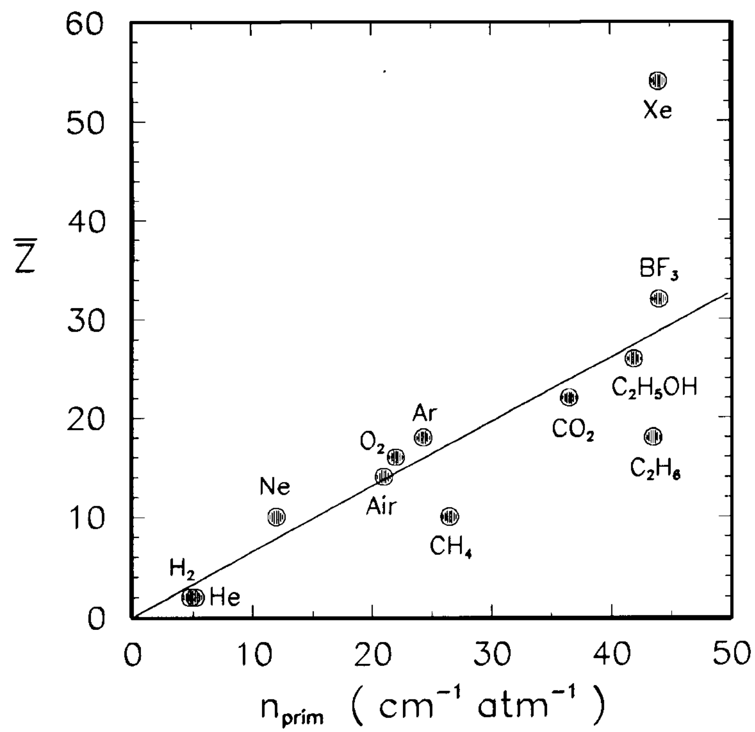
- Number of created e^--ion pairs:

$$n_{\text{primary}} \approx 1.45\, Z\, \text{cm}^{-1}\text{atm}^{-1}$$

$$n_{\text{total}} \approx 3\ldots4 \cdot n_{\text{primary}} \approx 4.55\, Z\, \text{cm}^{-1}\text{atm}^{-1}$$

$$n_{\text{total}} = \frac{\Delta E}{W_i} = \frac{dE}{dx}\frac{\Delta x}{W_i}$$

  - ΔE = total energy loss
  - Δx = distance traveled
  - W_i = effective <energy loss> per pair ≈ 30 eV

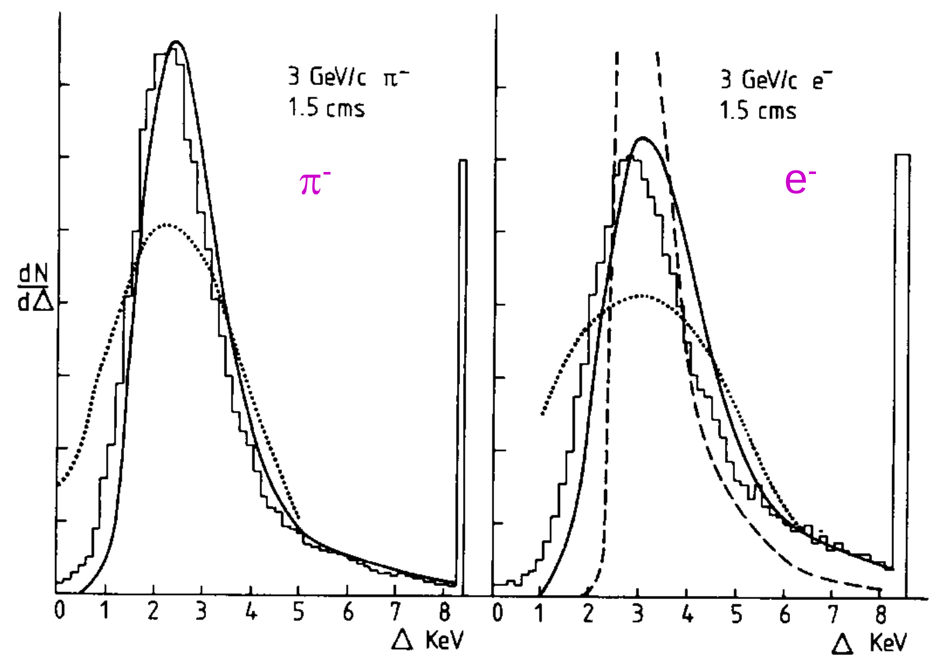


- Example: CO_2
  - ΔE ≈ 3 keV cm^{-1}
  - n_{total} ≈ 100 e^--ion pairs / cm

Landau Fluctuations

- mean energy loss: <dE/dx>
- ΔE = energy loss deposited in a layer of finite thickness
- For thin layers and gases (low density):
  - ΔE has large fluctuations!
  - only few collisions, some with high ΔE
  - ΔE distribution has large contributions at high losses $\rightarrow$ “Landau tails”
  - first parameterised by Landau in 1944
  - subsequently improved
- For many measurements in a detector:
  - truncated mean of ΔE as estimate for <dE/dx>

Energy loss ΔE in 1.5cm Argon +7% CH_4



data: Harris et al. (1977)
dotted curve: Landau(1944)
dashed curve: Maccabee & Papworth(1969) (Landau’s method)
solid curve: Allison and Cobb (1980)

Gaseous Ionisation Detectors

- Reminder: Basic Principle

~100 e^--ion pairs / cm

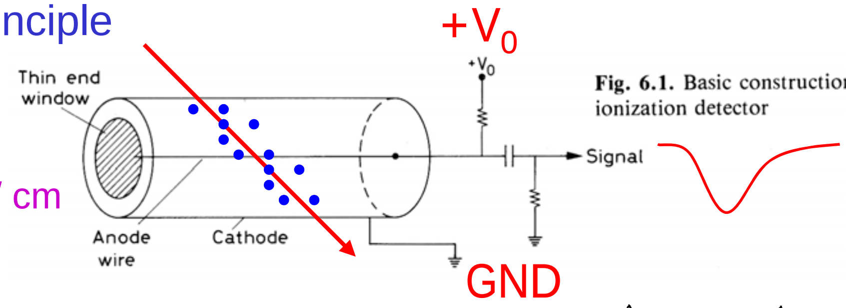
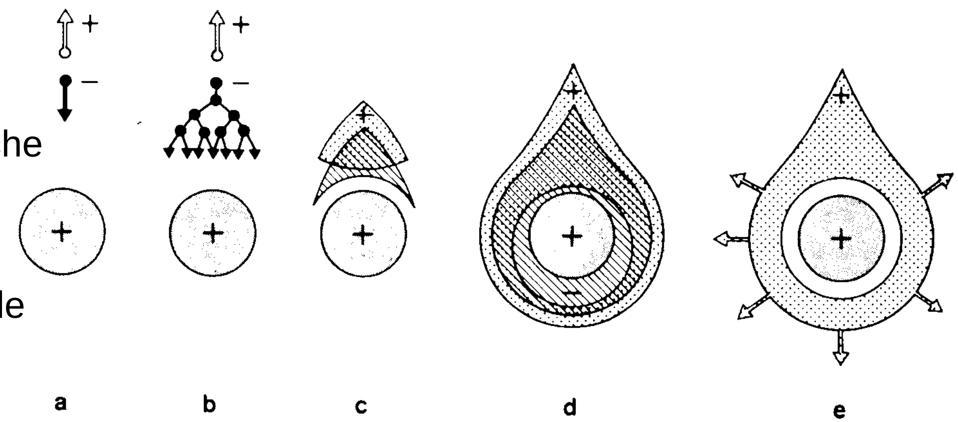


Fig. 6.1. Basic construction of a simple gas ionization detector

$$E(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \frac{1}{r}$$

$$V(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \ln\frac{r}{a}$$

- Need Gas Amplification:
  - a) primary e^- drift towards anode
  - b) with gained T_{kin} e^- ionises further atoms → avalanche
  - c) e^- and ion cloud drift apart
  - d) e^- cloud surround anode wire, induces signal
  - e) ion cloud withdraws from anode on larger time scale and induces signal
  - – close to wire: large E ≥ 1kV/cm
  - – gas amplification A with gain up to 10^6



$$A = \frac{n}{n_0} = \exp\left[\int_a^{r_C} \alpha(r)\,dr\right]$$

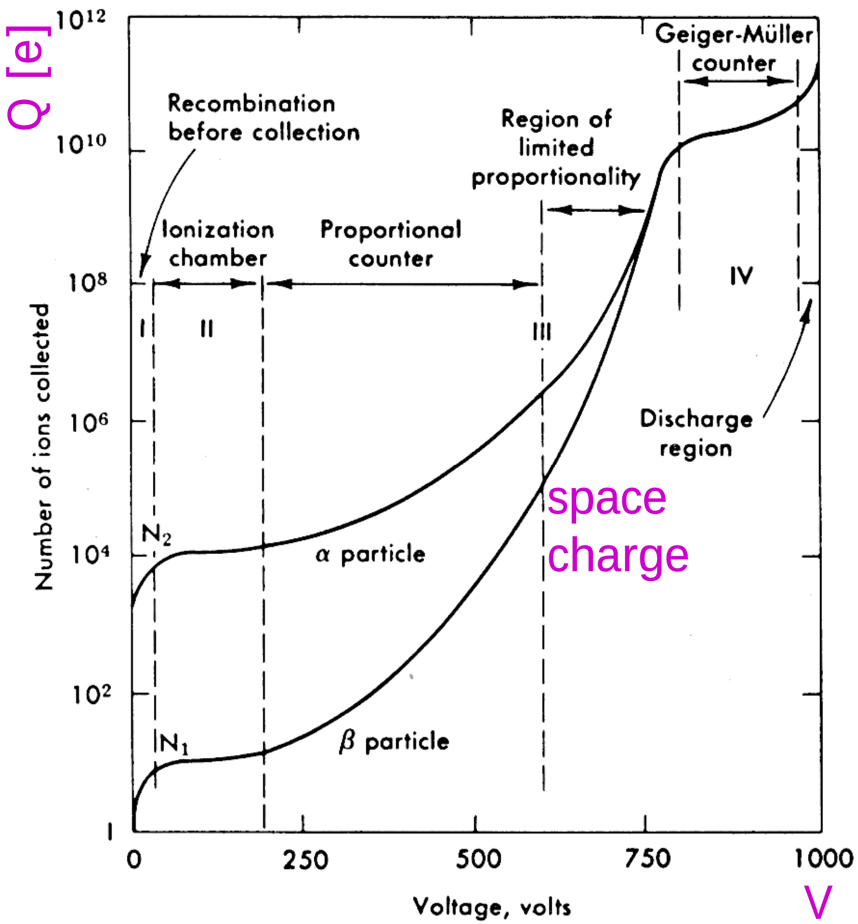
exponential gain

either $n = n_0 e^{\alpha(E)x}$ or $n = n_0 e^{\alpha(r)x}$

α = Townsend coefficient (e^--ion pairs/cm)

Operation Modes

- Reminder:



- Ionisation chamber
  - no multiplication
- Proportional counter
  - Signal proportional to $n_{primary}$
  - dE/dx measurement
  - localised avalanche
- Limited proportional / Streamer mode
  - secondary avalanches along wire
  - high gain
- Geiger-Müeller counter
  - avalanche along full wire

Fig. 6.2. Number of ions collected versus applied voltage in a single wire gas chamber (from *Melissinos* [6.1])

Signal Shape

- Cylindrical proportional chamber: with electrostatic energy of field $W=1/2\, lCV_0^2$ (l = cylinder length)
  - a = wire radius e.g. 10 μm
  - b = chamber radius e.g. 10 mm
  - r_c = critical radius, where avalanche starts e.g. 1 μm
- Electron avalanche and drifting ions induce signals on anode:
  - with different strength: ions dominate: $V^-/V^+ \sim 0.01$!!
  - on different time scales: e^-: O(10ns), ions: O(100ns)

$$V^- = \frac{-q}{lCV_0}\int_{a+r_c}^{a} E(r)dr = \frac{-q}{2\pi\varepsilon_0 l}\cdot\ln\frac{a+r_c}{a}$$

$$V^+ = \frac{q}{lCV_0}\int_{a+r_c}^{b} E(r)dr = \frac{q}{2\pi\varepsilon_0 l}\cdot\ln\frac{b}{a+r_c}$$

- Drift velocity v: (using V^+ only)
  - μ = mobility

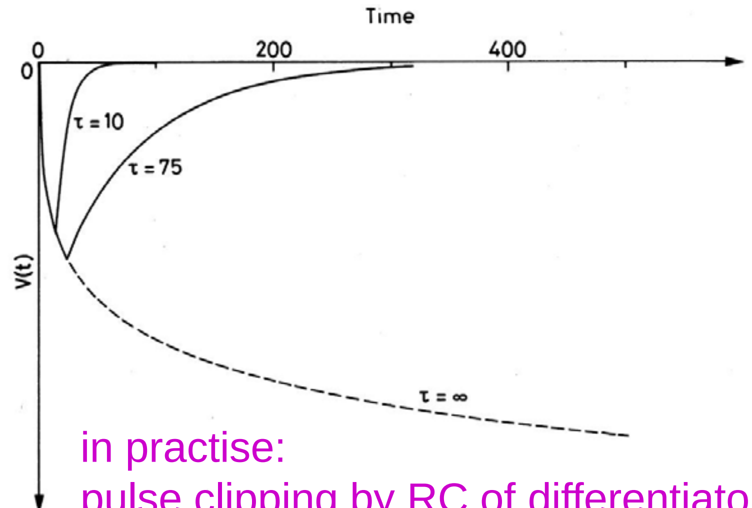
$$v = \frac{dr}{dt} = \mu E(r) = \frac{\mu C V_0}{2\pi\varepsilon_0}\frac{1}{r}$$

$$\Rightarrow \quad r(t) = \left(a^2 + \frac{\mu C V_0}{\pi\varepsilon_0}t\right)^{1/2}$$

- Time development of pulse:

$$V(t) = \int_a^{r(t)} \frac{dV}{dr}dt = -\frac{q}{2\pi\varepsilon_0 l}\ln\frac{r(t)}{a}$$

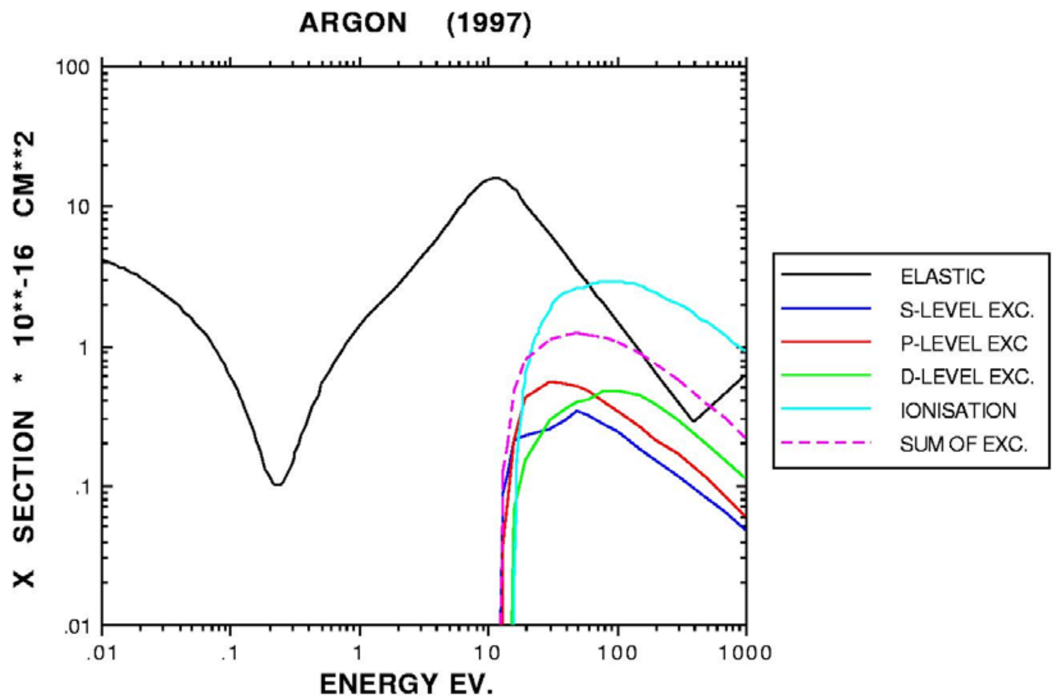
$$= -\frac{q}{4\pi\varepsilon_0 l}\ln\left(1+\frac{\mu C V_0}{\pi\varepsilon_0 a^2}t\right)$$

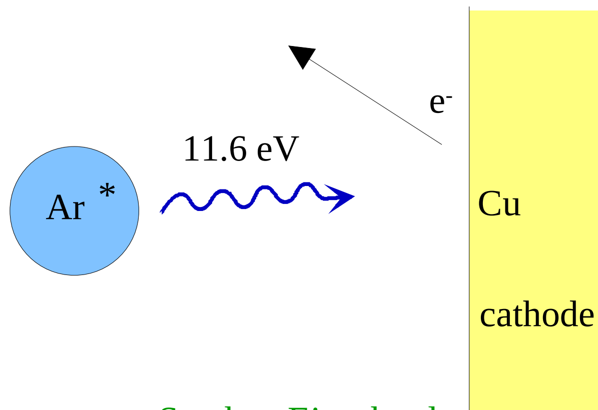


in practise:
pulse clipping by RC of differentiator

Choice of Gas

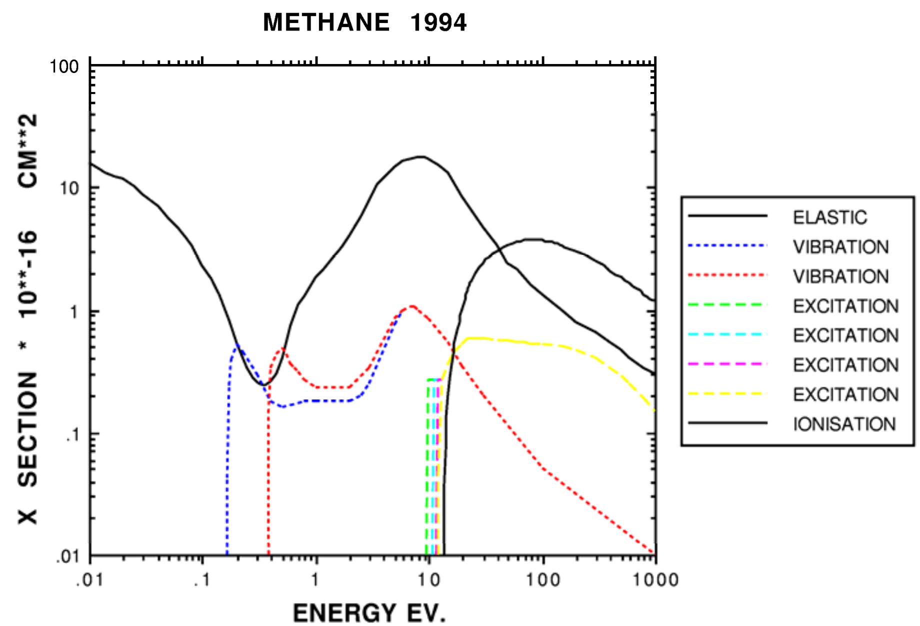
- Gas selection:
  - noble, inert: Ar, CO_2, He
  - high specific ionisation
- But: secondary emission of electrons
  - from de-excitation of UV γ
  - new avalanches started
  - leads to constant discharges
- Example: Argon
  - photons with E = 11.6 eV
  - produces e⁻ at cathode
- Quenching needed!!





Quenching

- Polyatomic gases act as “quenchers”:
  - C_2H_5OH, CH_4, C_2H_6, C_4H_{10}, …
  - Absorption of photons in large energy range by vibration and rotation energy levels
  - concentration chosen to limit free path of γ to O(a)
    → UV γ don’t reach cathode
    → ions transfer ionisation to quenching gas where energy too small for ionisation…

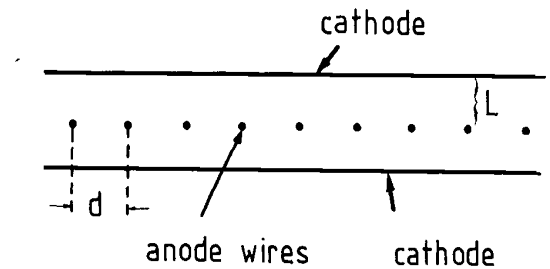


- Possible problems
  - dissociation of molecules
    → whiskers on wires
    → breakdown
  - coating of wires
    → “aging”

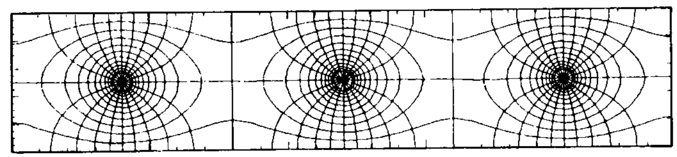
- Solutions
  - a few 100 ppm of water !?!

Multiwire Proportional Chambers

- Until about 1970
  - mostly optical tracking devices:
    cloud chamber, bubble chamber, spark chamber, emulsions
  - slow for data taking and analysis



- Revolution of 1968
  - MWPC invented by Charpak (Nobel prize 1992)
  - plane of anode wires act as individual proportional counters



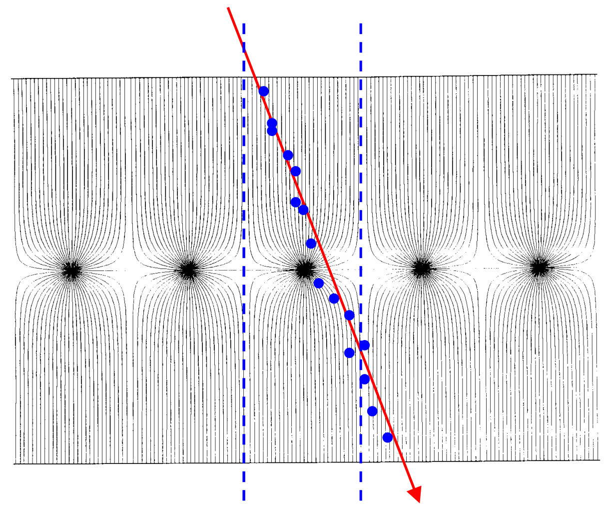
field and equipotential lines around anode wires

- Typical dimensions: L = 5 mm, d = 1 mm, a_{wire} = 20 μm

- MWPC:
  - fast electronic device
  - wire address: 1-dimensional spatial resolution

$$\sigma_x \approx \frac{d}{\sqrt{12}} \geq 300\,\mu\text{m}$$

  - high cost in channels (electronics)
  - further improvement on resolution desirable



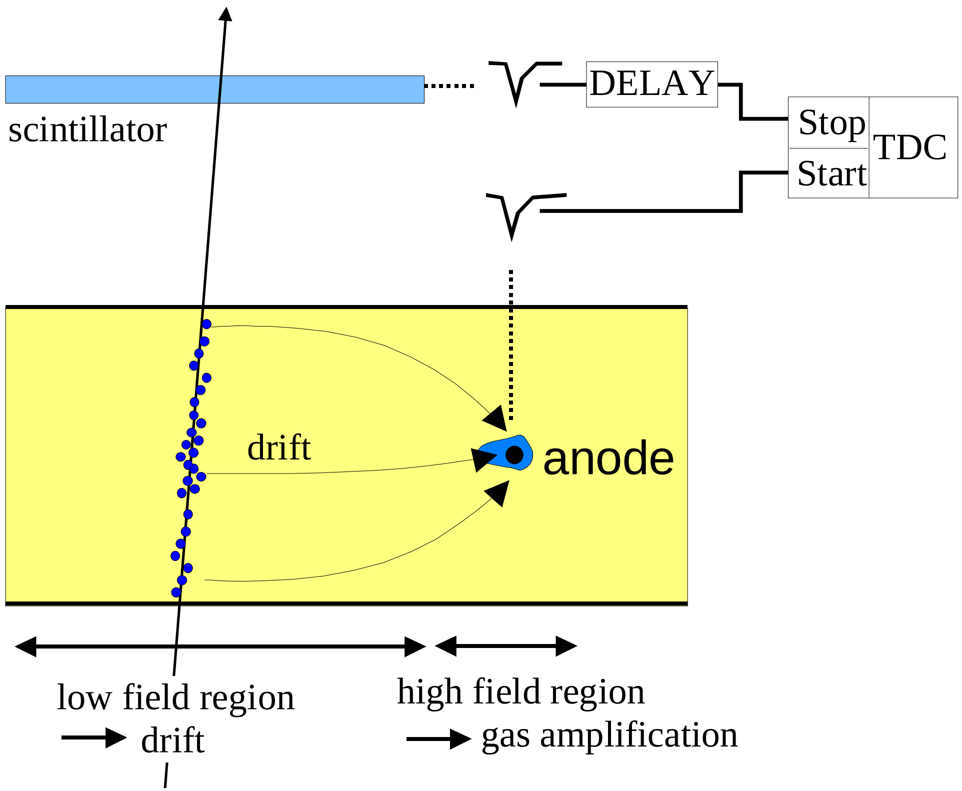
Drift Chambers

- Improvement of spatial resolution: Drift Chamber
  - large volume with low field region (~constant field): drift
  - high field region: gas amplification

- Time measurement:
  - start: scintillator trigger, collider bunches
  - stop: arrival time of drift e⁻

- Complications:
  - Drift velocity
  - Diffusion
  - Magnetic fields

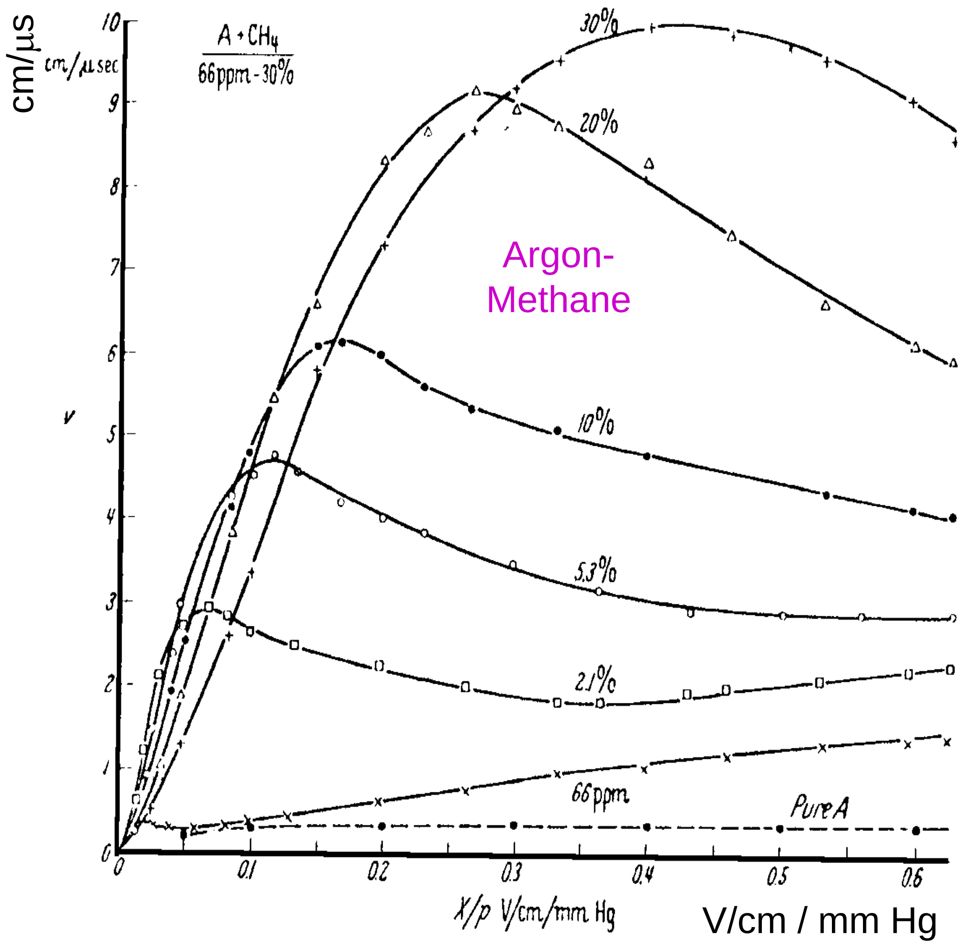
- Spatial resolution:
  - electronics, ionisation, diffusion
  - not limited by cell size
  - fewer wires than MWPC electronics, structure cost



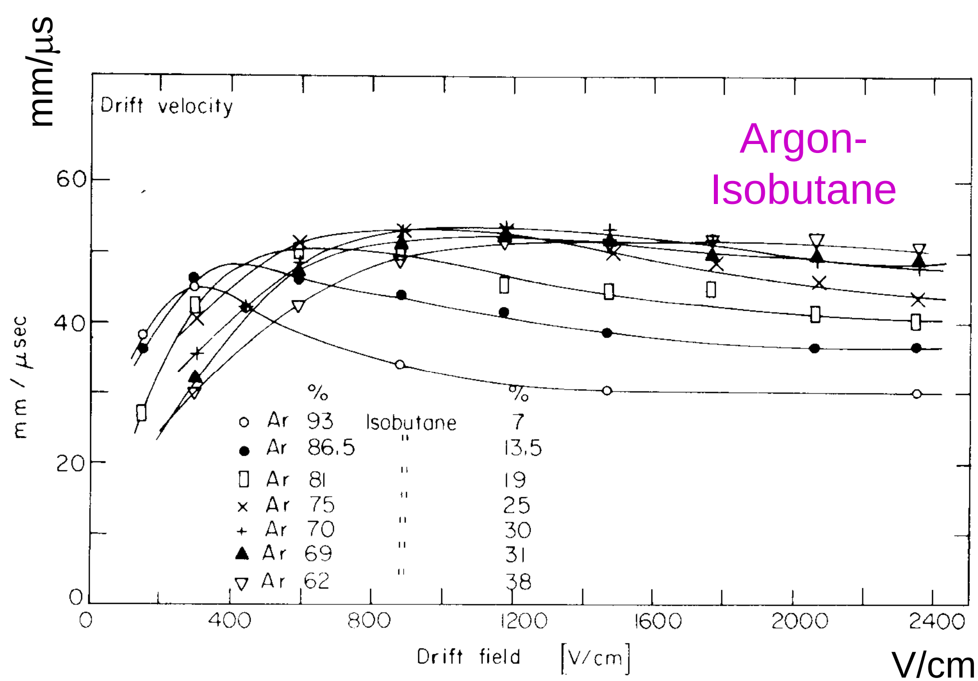
First studies:
T. Bressani, G. Charpak, D. Rahm, C. Zupancic, 1969
First operation drift chamber:
A.H. Walenta, J. Heintze, B. Schürlein, NIM 92 (1971) 373

Drift Velocities

- Range of v_D:
  - 50 mm/μs --- fast gases (Ar, …)
  - 5 mm/μs --- slow gases (CO_2)



(F. Sauli, CERN 77-09)



(A. Breskin et al. NIM 124 (1975) 189)

Diffusion

- Drift with no external fields: Diffusion
  - e^- and ions thermalise due to collisions with atoms

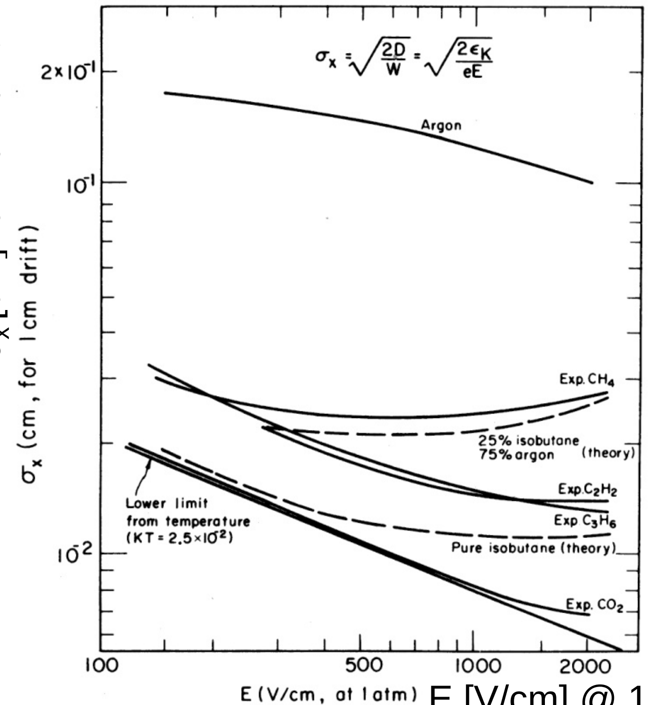
$$T_{kin} = \frac{3}{2} kT \approx 35\,\mathrm{meV}$$

  - linear and volume diffusion coefficient:

$$\sigma_x = \sqrt{2Dt} = \sqrt{2x\frac{D}{\mu E}} \qquad \sigma_L = \sqrt{6Dt}$$

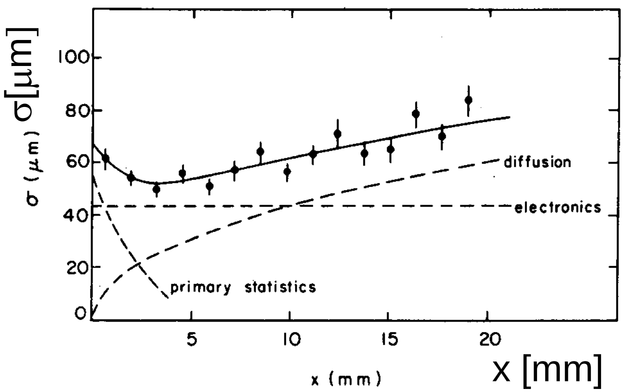
- "Cool" gases, e.g. CO_2
  - e^- thermal up to E ~ 2kV/cm
  - expect small and isotropic diffusion
- "Hot" gases, e.g. Argon
  - e^- non thermal at E ~V/cm
  - expect non-isotropic Diffusion, D_L along E-field

σ_x [cm] for 1cm drift



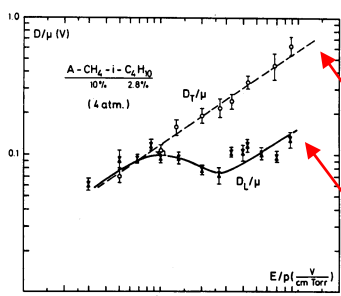
E [V/cm] @ 1 atm

σ[μm]



x [mm]

D/μ



V/cm / Torr

Ar-10%CH_4-i-2.8%C_4H_{10}

σ_T (1 cm) = 180 μm

σ_L (1 cm) = 57 μm

Drift in Fields

- External fields E and B:
  - diffusion equation, interested in time-independent solution

$$\left\langle \frac{d\vec{v}}{dt} \right\rangle = 0 = e\vec{E} + e(\vec{v}_D \times \vec{B}) - \frac{m}{\tau}\vec{v}_D$$

$$\vec{v}_D = \frac{\mu}{1+\omega^2\tau^2}\left[\vec{E} + \omega\tau\frac{(\vec{E}\times\vec{B})}{B} + \omega^2\tau^2\frac{(\vec{E}\cdot\vec{B})\vec{B}}{B^2}\right]$$

τ : (mean time between collisions)

$\mu = \frac{e\tau}{m}$: (mobility)

$\omega = \frac{e\vec{B}}{m}$: (cyclotron frequency)

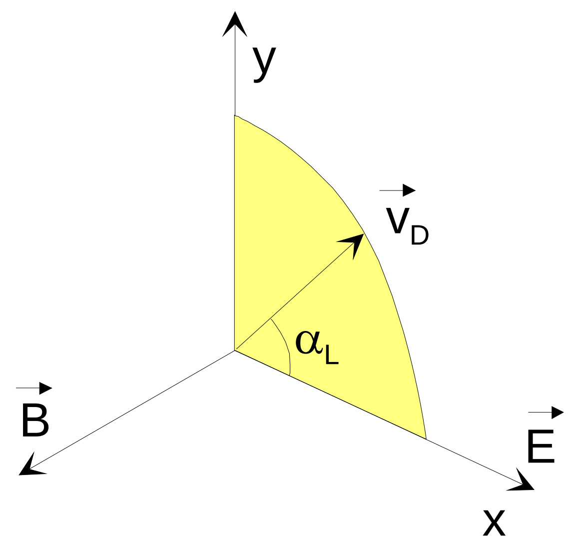
  - B = 0 : $\vec{v}_D = \mu\vec{E}$

- E and B perpendicular:

$$v_x = \mu E_x \frac{1}{1+\omega^2\tau^2}$$

$$v_y = -\mu E_x \frac{\omega\tau}{1+\omega^2\tau^2}$$

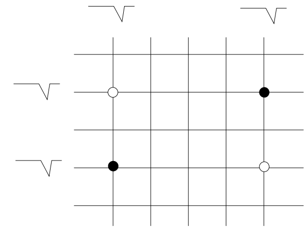
$$v_z = \mu E_z$$



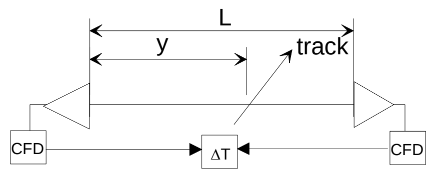
- Lorentz angle α_L: $\tan\alpha_L = \omega\tau$

Determination of z-Coordinate

- crossed wires (2-dim chamber, usually small angle):
- segmented cathode readout



- Differential timing:
  - measure arrival time at both wire ends
  - time difference gives z-coordinate

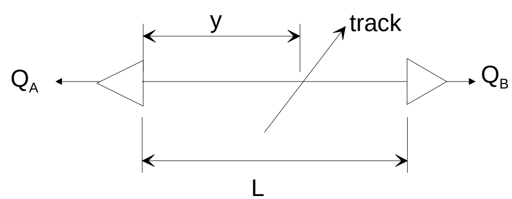


$$\sigma_z \propto \sigma_t v_{signal} \quad \text{with} \quad v_{signal} \approx 0.2\,\mathrm{m/ns}$$

- Charge division:
  - resistive anode wire (Carbon R = 2kΩ/cm)
  - charge division proportional to wire length L:
  - reached accuracy:
    down to:

$$z = L\frac{Q_A}{Q_A + Q_B}$$

$$\sigma_z = 0.4\% \cdot L$$



- Stereo-Layers:
  - alternated with axial layers
  - $\gamma = \pm 2\text{-}6°$
  - match signal hits of layers
  - occupancy limit: combinatorics!

- Example: OPAL drift chamber
  - σ_t = 100 ps
  - σ_z = 4cm

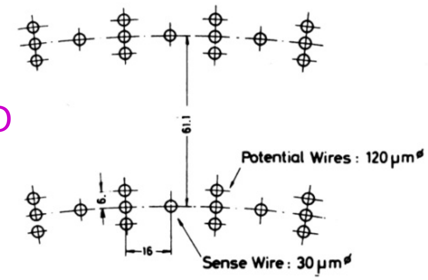
- Example: JADE drift chamber
  - L = 234cm
  - σ_z = 1.6cm = 0.7%·L

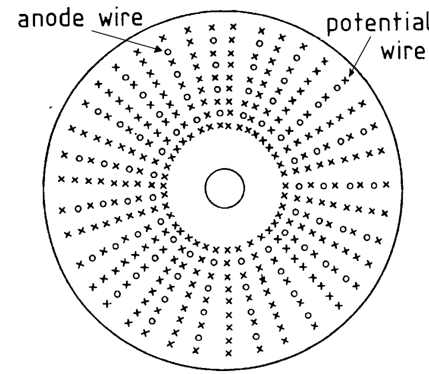
- Example: TASSO drift chamber
  - L = 350cm
  - $\gamma = \pm 4°$
  - σ_z ~ 3mm

Drift Chamber Geometries

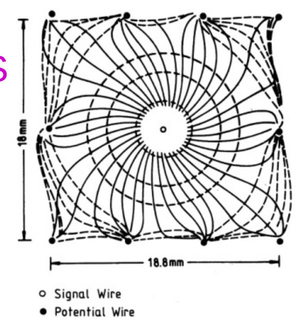
- Potential wires mandatory
- Various drift cell geometries in use:
  - cylinder, square, hexagonal:
    short drift paths, small B effects
  - closed, open:
    many vs. few potential wires
    at cost of homogeneity of E
  - jet (projecting):
    many points along track
    at cost of long drift paths, B effects!
    and complicated E field

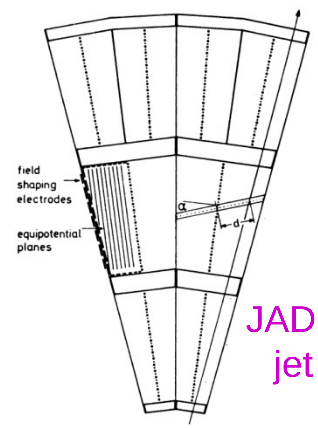
TASSO
open



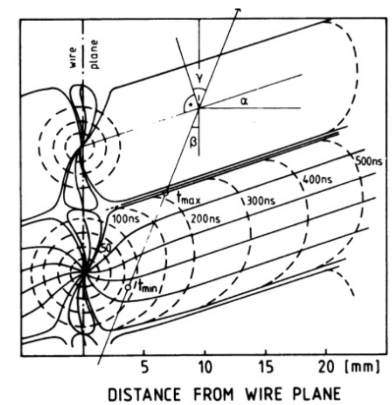


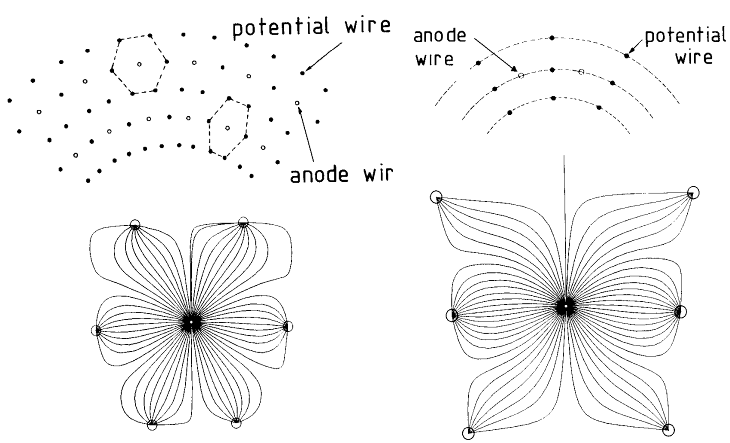
ARGUS
closed





JADE
jet

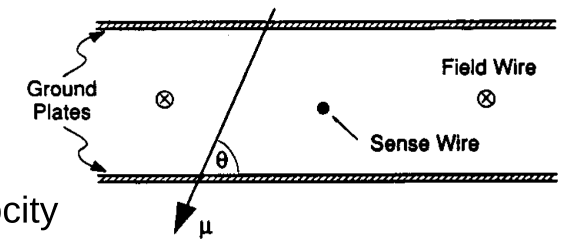


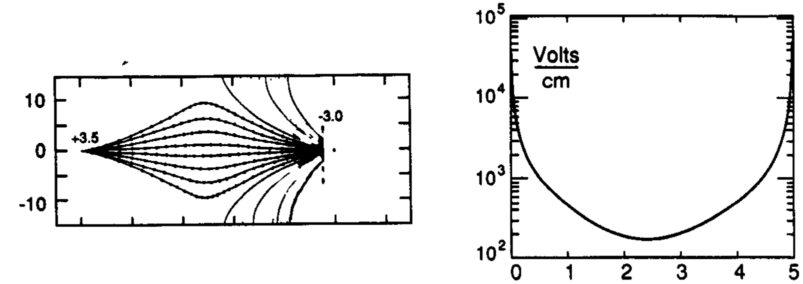


- Example: BaBar
  - 40 layers
  - resolution: $\frac{\sigma_{P_T}}{P_T} = 0.15\% \cdot P_T + 0.45\%$

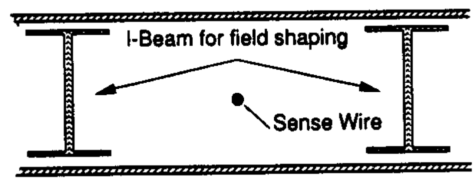
Planar Drift Chambers

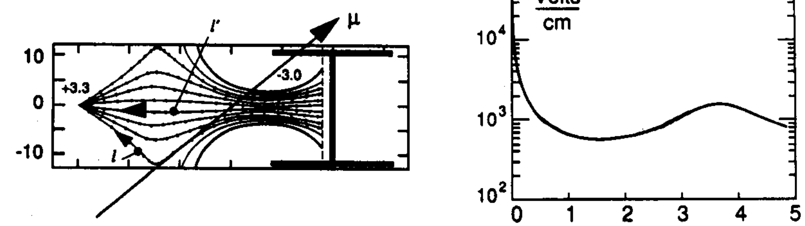
- Geometry optimisation:



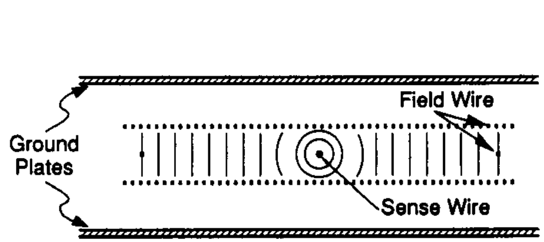


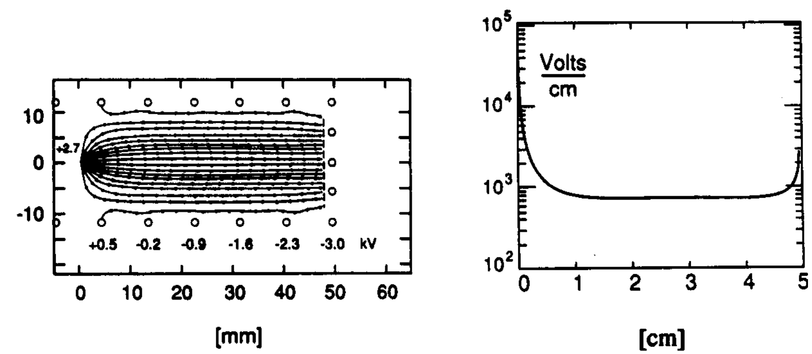
  - want constant drift velocity
    → choose gas with little variation $v_D(E)$
    → linear space - drift time relation





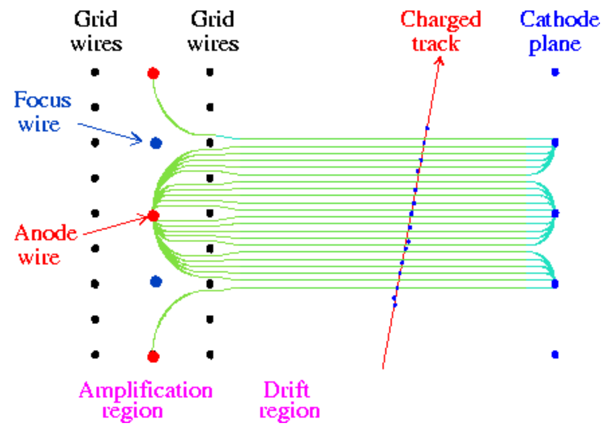
  - shape E field

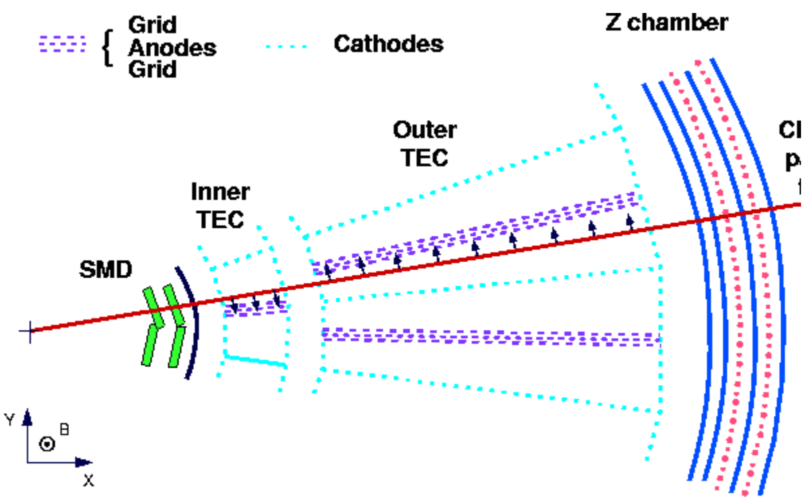


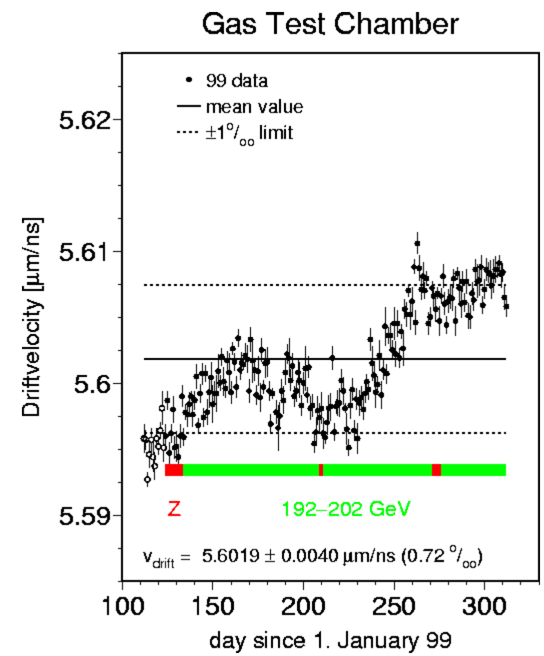


Time Expansion Chamber

- L3:
  - Cool gas: CO_2-i-C_4H_{10}
  - small diffusion
  - grid wires to prevent ions entering the drift volume
  - very good time resolution
  - maintain drift velocity to ‰ level

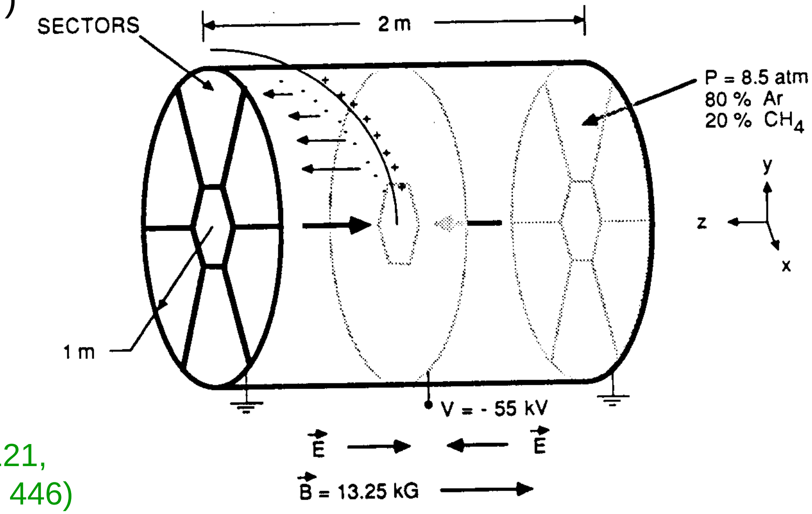






Time Projection Chamber

- Allows full 3-dimensional reconstruction & dE/dx measurement: "el. Bubble Chamber"
  - big gas cylinder (ALEPH: Ø 3.6M, L=4.4 m, Ar-Methane @ 10bar)
  - E and B field parallel: Lorentz force vanishes
  - B field reduces diffusion
  - End caps equipped with MWPC
  - x-y from wires and segmented cathodes
  - z from drift time
  - dE/dx information
    $\rightarrow$ particle identification, still very difficult for systematics



ALEPH TPC

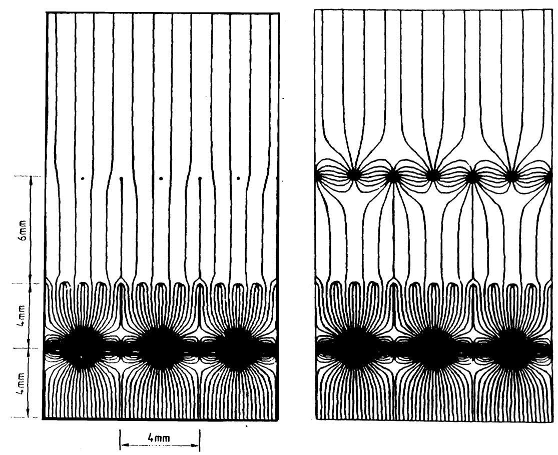
(ALEPH coll., NIM A 294 (1990) 121,
W. Atwood et. Al, NIM A 306 (1991) 446)

- Long drift distances
  - need excellent gas quality
  - precise calibration of v_D

- Space charge problem:
  - from positive ions entering drift volume
  - solution: gating (needs trigger)

$\Delta V_g = 150$ V

Gate open Gate closed



- ALEPH resolution: (isolated leptons)

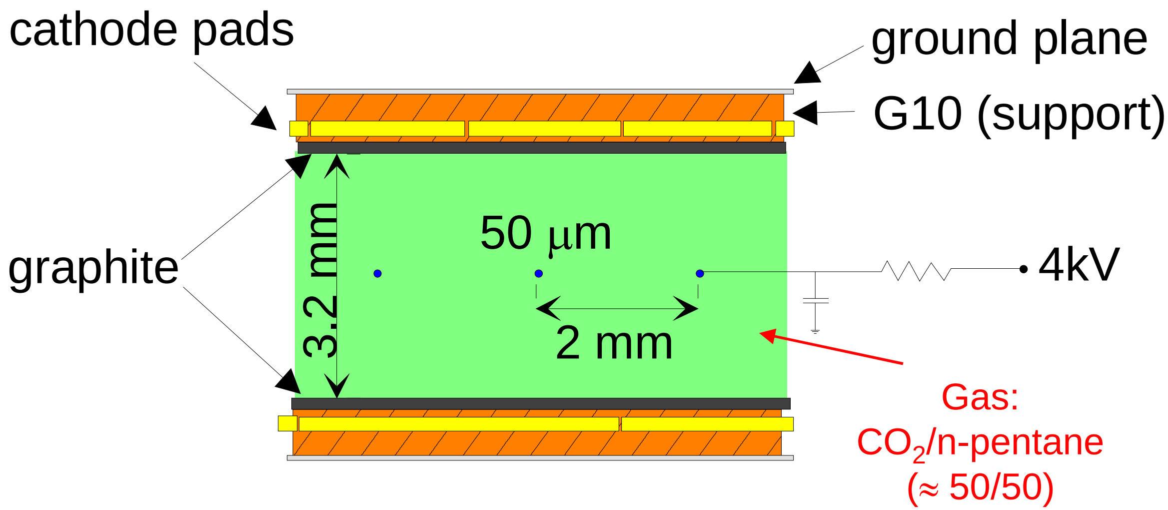
$\sigma_{R\phi} = 173\ \mu m$

$\sigma_z = 740\ \mu m$

Thin Gap Chambers

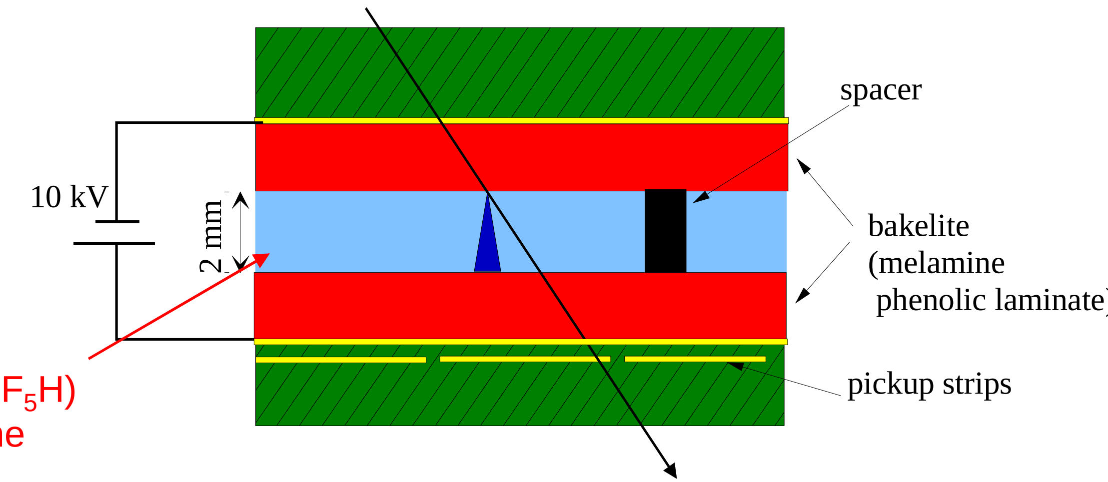
- Thin Gap chambers (TPC)
  - saturated mode
  - thin insulator prevents sparking
  - limited by graphite resistitivity
  - large gain 10^6
  - fast, 2 ns risetime

- Cheap
- Large area
  → Muon chambers



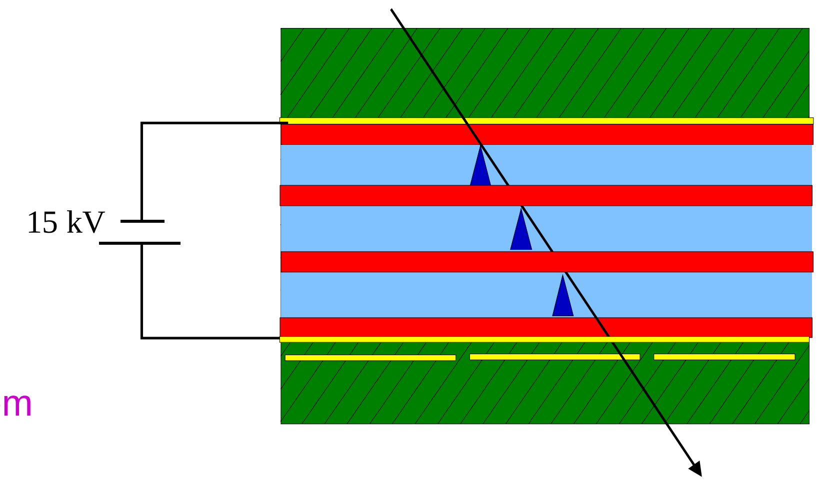
Resistive Plate Chambers

- Single-Gap RPC:
  - close to streamer mode
  - fast time dispersion (1…2 ns)
  - rasonable rate capabilities:
    up to 1 kHz/cm^2
  - cheap



Gas: $C_2F_4H_2$, (C_2F_5H)
+ few % isobutane

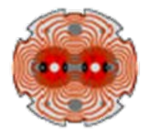
- Double-Gap and Multi-Gap RPC:
  - improves efficiency and timing



used for:
LHCb muon system

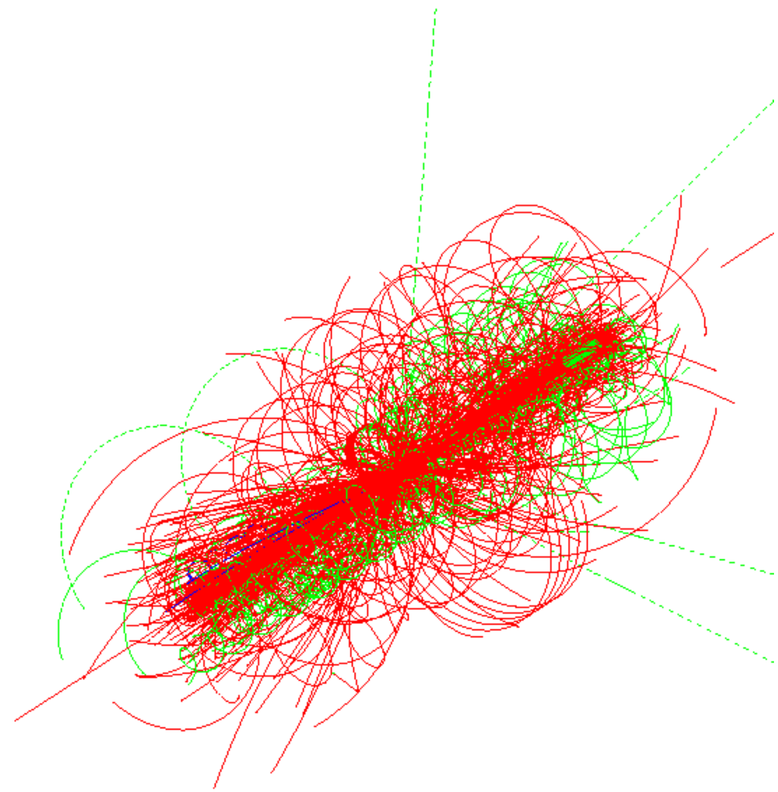
Tracking for the New Millenium

- 1980s and 90s:
  - golden area of gaseous wire chambers
  - e^+e^- colliders: LEP, SLC, B-factories
  - hadron colliders/fixed target: CDF, NA48/49, H1/ZEUS
- LHC (and ILC is not too far as well):



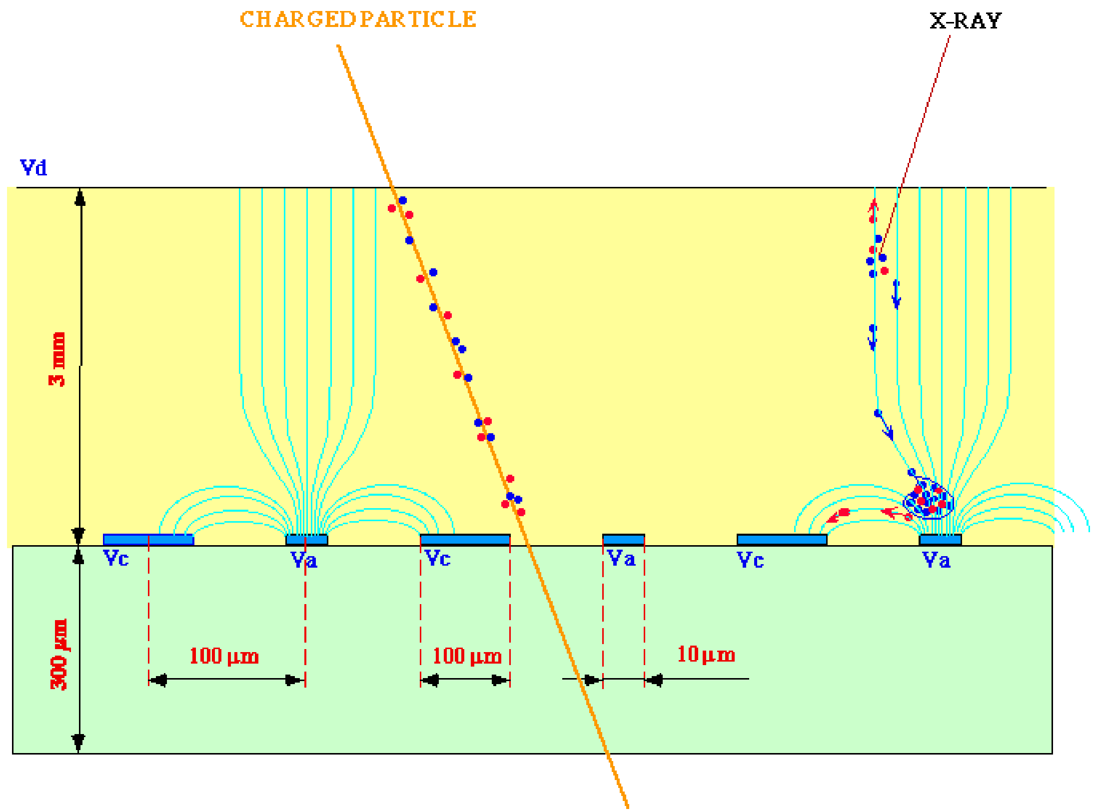
  - bunch crossing rate 40 MHz / 25 ns
  - Luminosity 10^{34} cm^{-2} s^{-1}
  - ~ 30 overlapping events per bunch crossing
  - 1900 charged + 1600 neutral particles
- Are we up for this new challenge?
  - need faster tracking detectors
  - need higher rate capabilities
  - need larger areas, lower cost

Simulated H $\rightarrow$ 4μ event in ATLAS



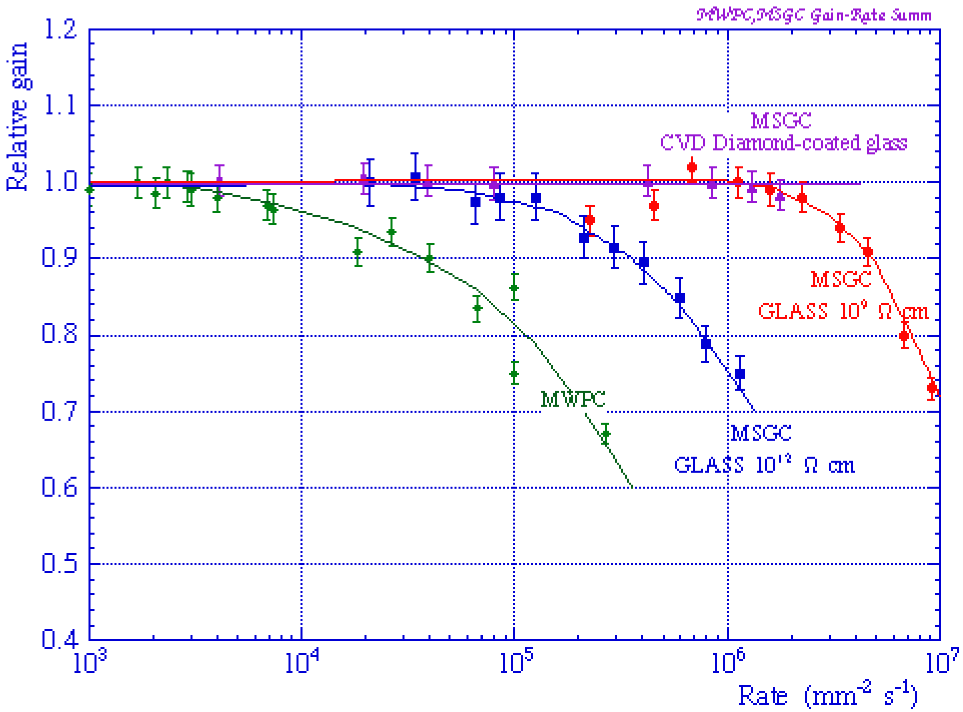
Micro-Strip Gas Chambers I

- Micro-Strip Gas Chambers (A. Oed, NIM A 263 (1988) 352)
  - thin metal (Au) strips on insulating (glass) surface
  - photolithography for production
  - mechanically small and precise
  - relatively cheap
- Gas multiplication
  - fast ion drift time, reduced built-up of charge
  - high rate capability ~10^6 /cm^2 s

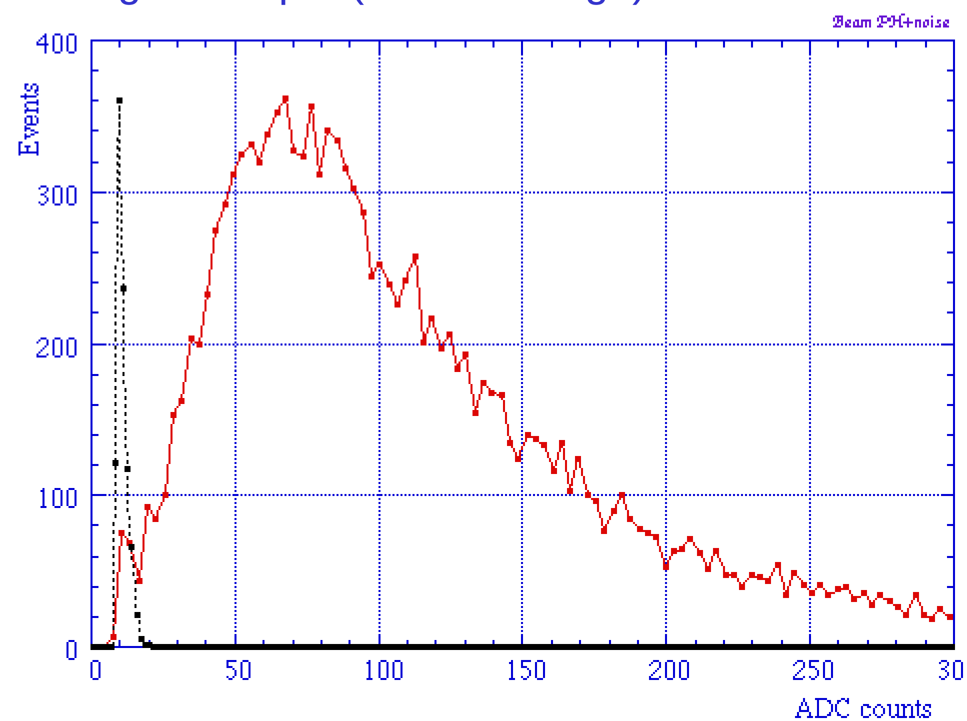


Micro-Strip Gas Chambers II

- Rate capability:

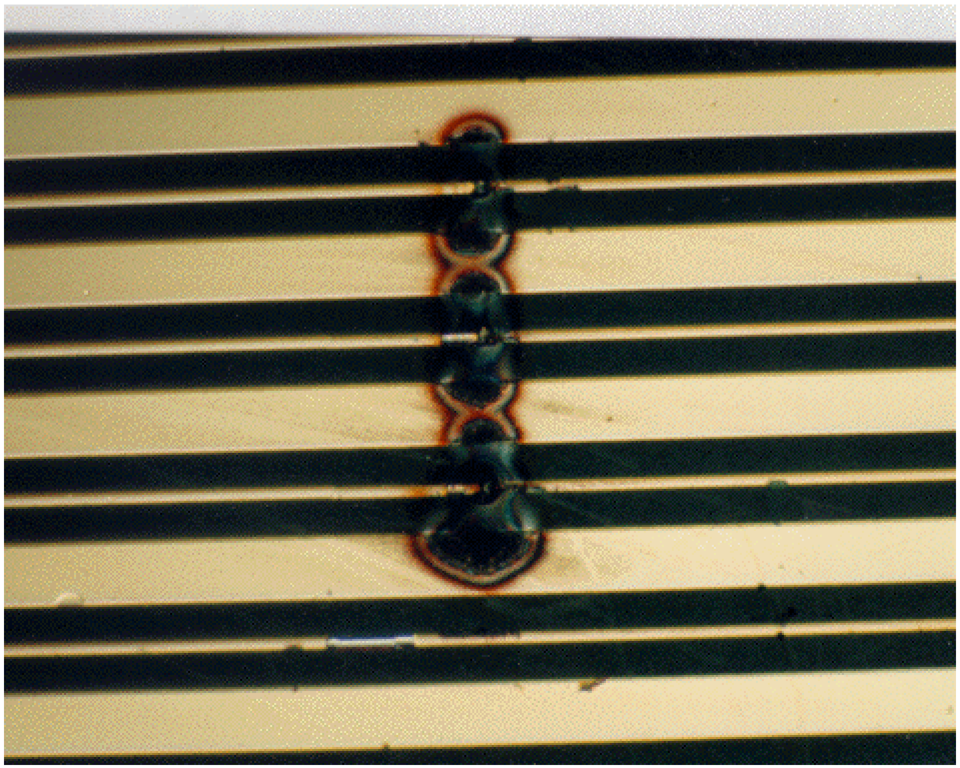


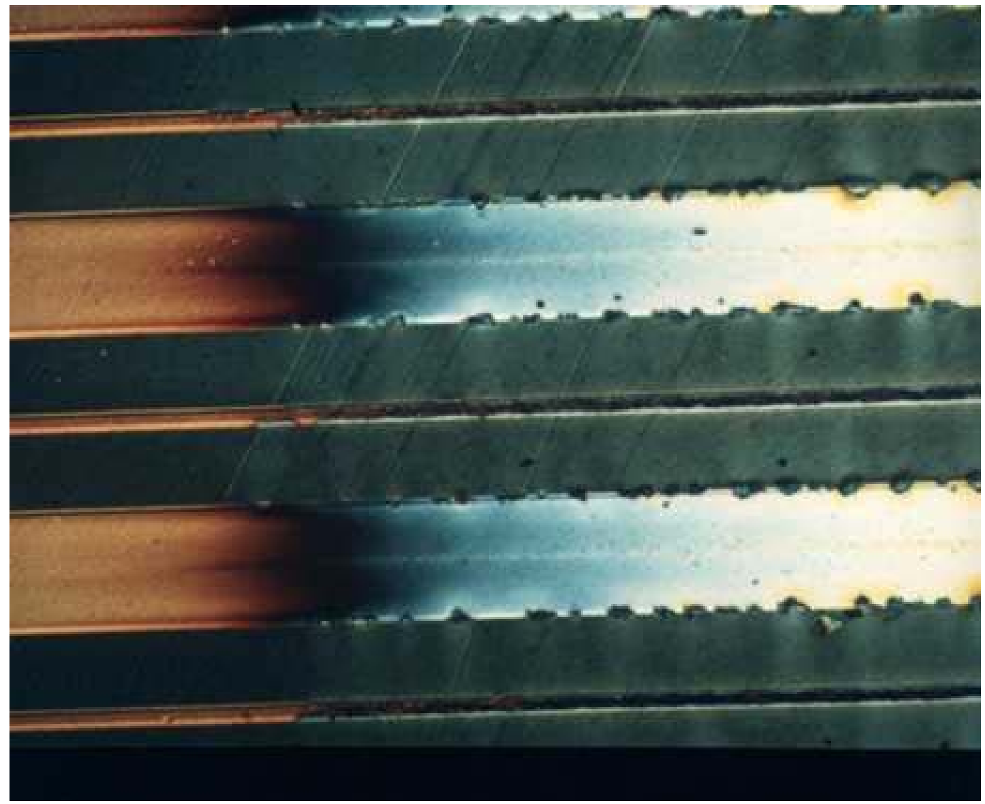
- Signal shape: (cluster charge)



Discharges and Ageing

- Discharges:
  - If gain > 10^7-10^8: Raether's limit
    growth of filament
  - Passivation needed:
    non-conductive protection of cathode edges
- Ageing:
  - production of polymeric compounds in avalanches
    sticking to the electrodes or to the insulator
  - careful selection of materials and gas
  - 10 yrs LHC or ~0.1 C/cm^2

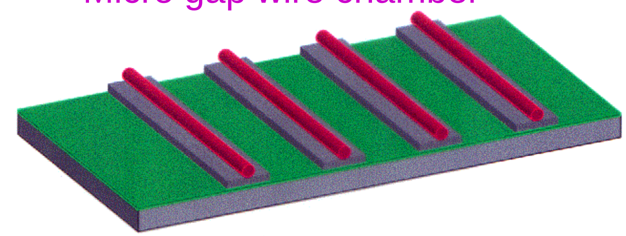




Micro – Anything Goes

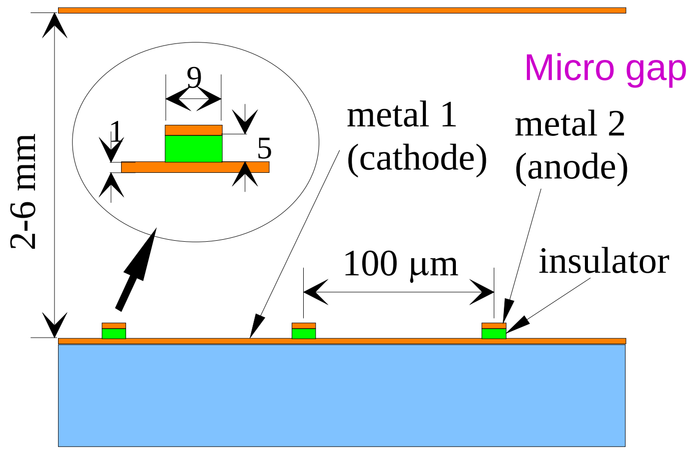
- Micro-Gap Chamber: Lots of Micro-maniacs are having fun!
  - MSGC, micro-wire, micro-dot
  - compteur à trous (CAT), micro-CAT/WELL
  - micro groove
  - gas electron multiplier (GEM)

Micro gap wire chamber

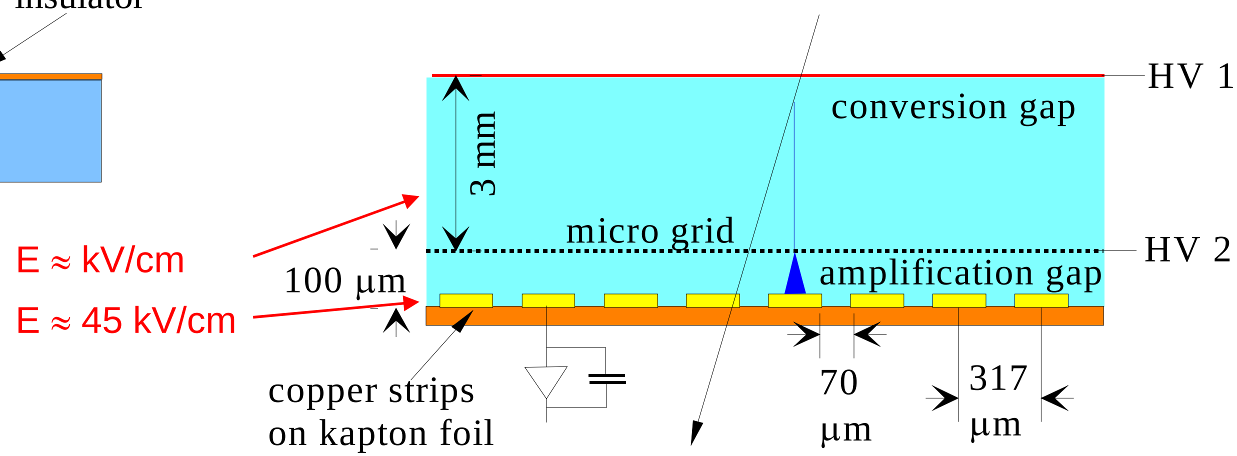


gold cathode on ceramic substrate
5 µm wire on 40 µm wide polyimide strips

Micro gap chamber



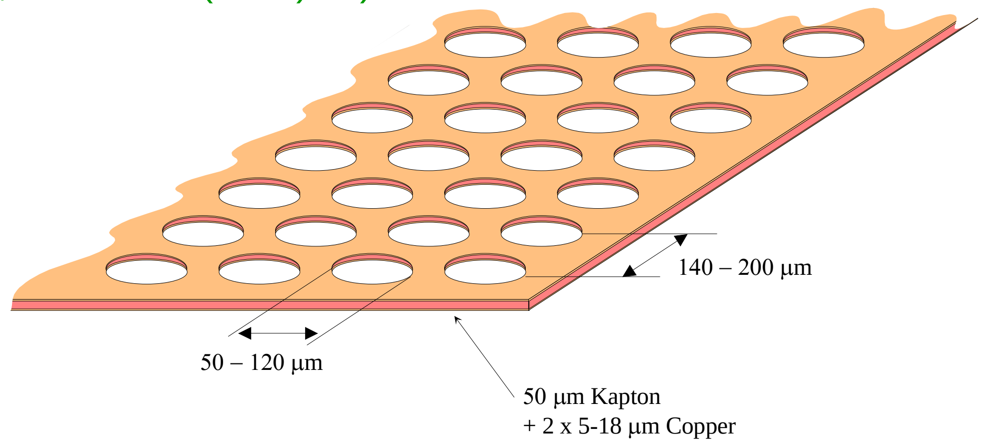
- Micomegas:
  - Gas: Ar-DME (≈80:20)

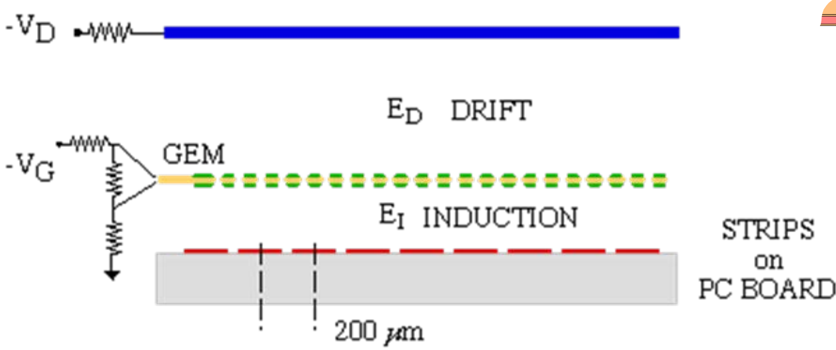


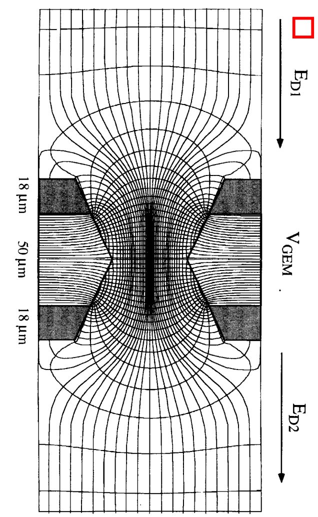
… but life is complicated…

Gas Electron Multiplier

- Gas Electron Multiplier (R. Bouclier et al., NIM A 396 (1997) 50)
  - drift region
  - GEM foil (Kapton)
  - induction region
  - e.g. Printed Circuit Board for collection





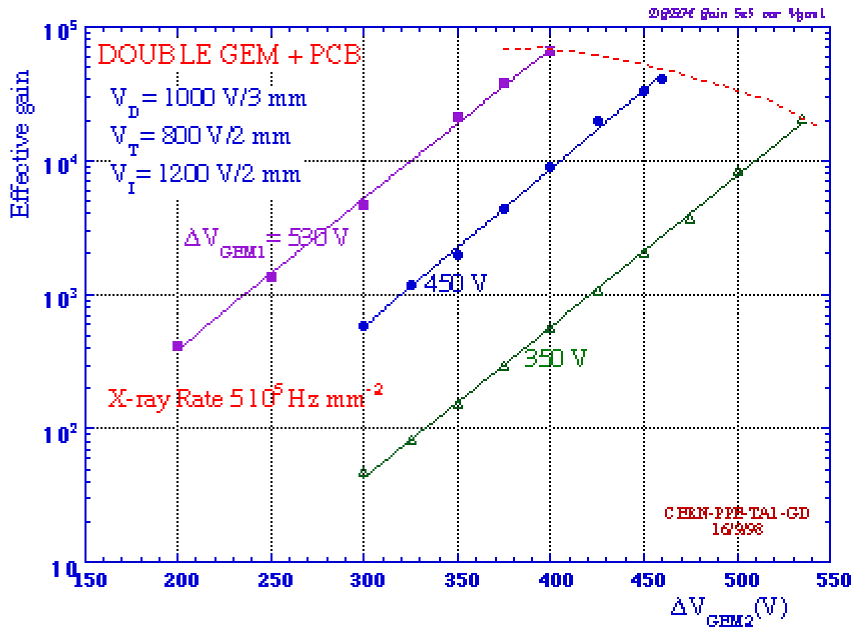


- GEM foil:
  - shaped to produce high E field → high local e$^-$ multiplication

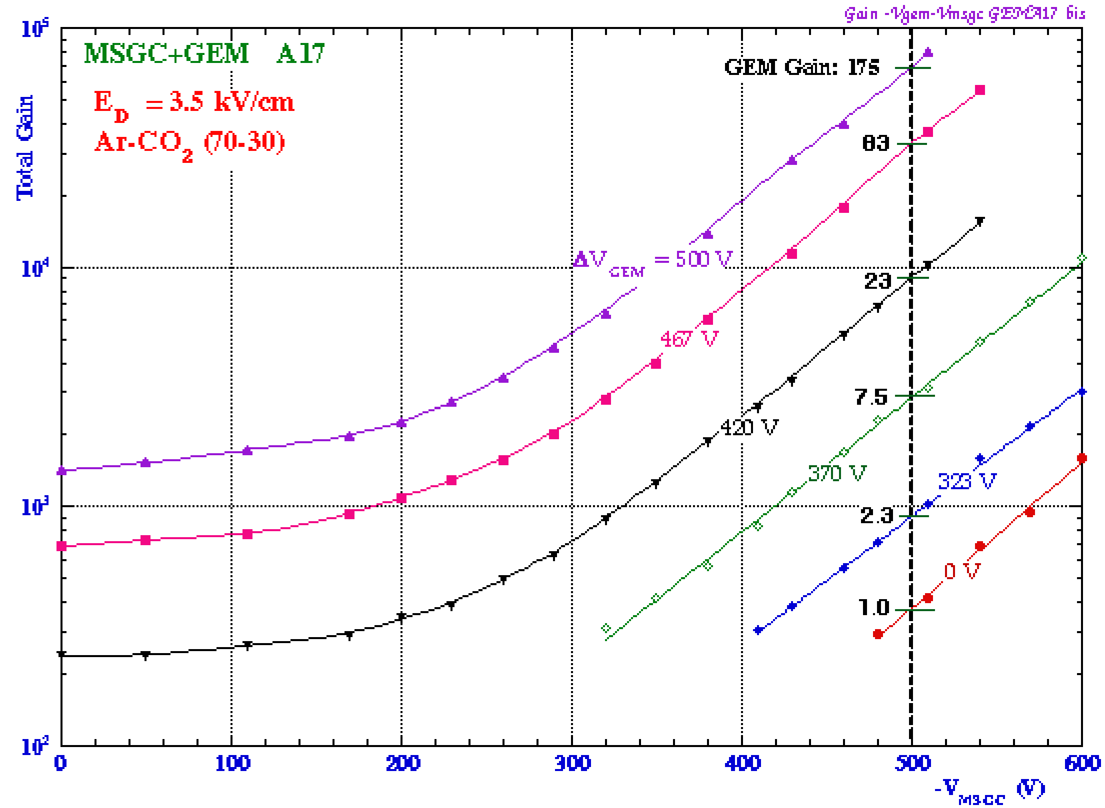
- Why GEMs?
  - for rate capability when combined with MWPC or MSGC for collection
  - Double GEM, Triple GEM

GEM - Gain and Rates

- Double-GEM + PCB:
  - very high rate: $5 \cdot 10^7$ /cm^2 s
  - reasonable gain: > 10^4



- GEM + MSGC:



GEM+MSGC

- Example: HERA-B experiment
  - 184 chambers of area 25x25 cm^2
  - particle flux 2-25 kHz/mm^2 (outer-inner part)
  - radiation: 1Mrad/year