Particle Detectors

Stephan Paul
TU-München
stephan.paul@ph.tum.de

Double course - Novosibirsk Physics School
17-21.9.2018

Detectors

What do we want to determine ?

Goal: measure 4-momentum and spatial position of particles

Methods:

- position sensitive detectors	direction and position of 4-vectors	$\left(\vec{x}, \frac{\vec{p}}{\lvert\vec{p}\rvert}\right)$
- deflection in magnetic fields	modulus of $\lvert p \rvert$	
- absorption in calorimeter	energy E	
- mass	e, p, n, π, . (only well defined mass values can occur)	

- Cherenkov radiation,	velocity β	$\beta = \frac{\upsilon}{c} = \frac{p}{E}$
- time of flight		
- transition radiation	γ	$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{E}{m_0 c^2}$

- energy loss	β , γ
- characteristic decays	secondary particles

detection in detector:

- small energy loss ΔE << E
- large energy loss ΔE ~ E(calorimetry)

What do we want to determine ?

Electrically charged particles
- Ionisation: charge
- Excitation: scintillation light
- Polarisation: Cherenkov light, transition radiation
- Bremsstrahlung + pair production: electromagnetic shower

Photons
- photo electric effect, Compton scattering: charge
  pair production: charge, 511 keV photons
- pair production + Bremsstrahlung: electromagnetic shower

Neutrons

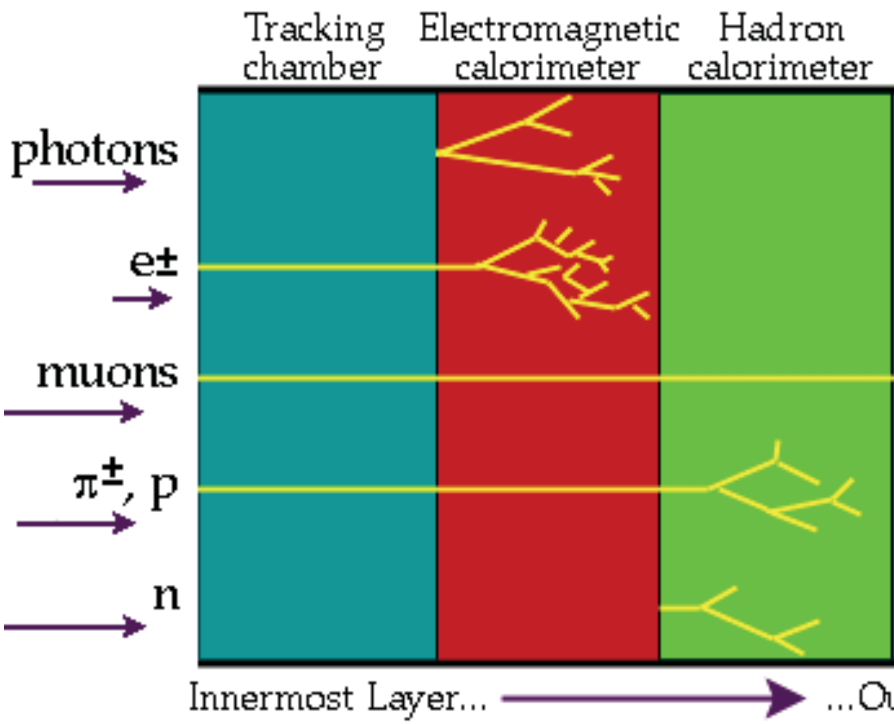
nuclear reactions (n,γ), (n,α), (n,p): detection of decay product

n-p elastic scattering: detection of recoil protons

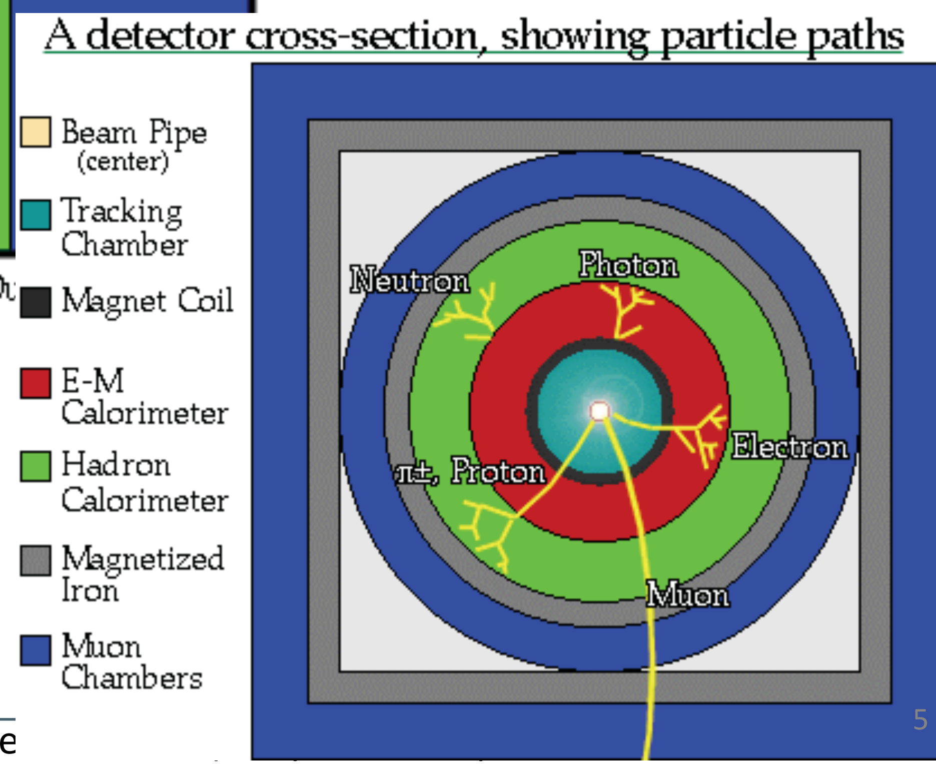
Hadrons

Strong interaction: hadronic showers

1 Typical Arrangement of a Detector



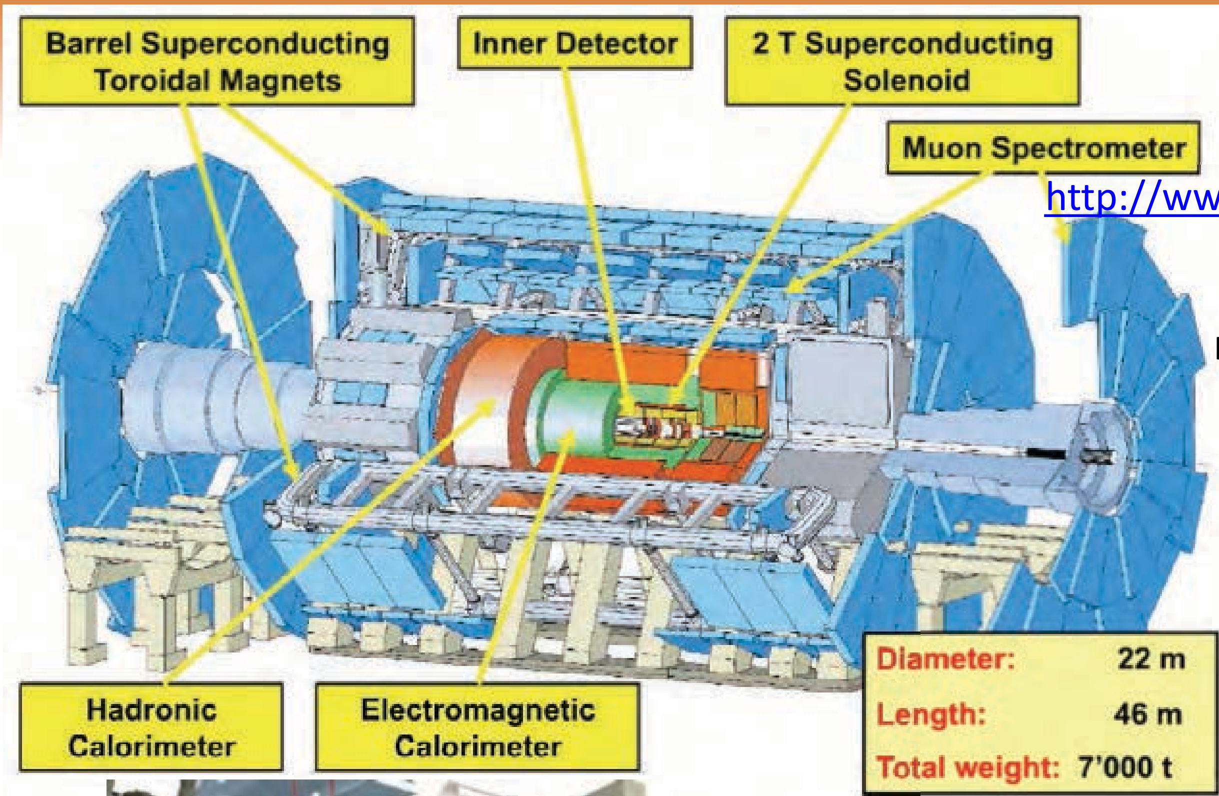
calorimeter: “shower detector“



Components of a detector:

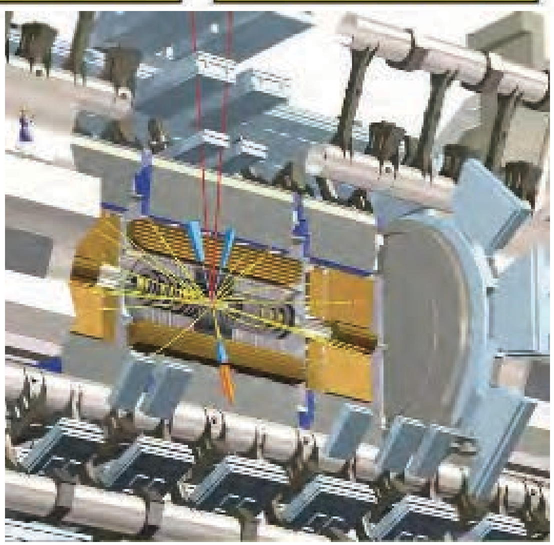
measurement of different aspects:

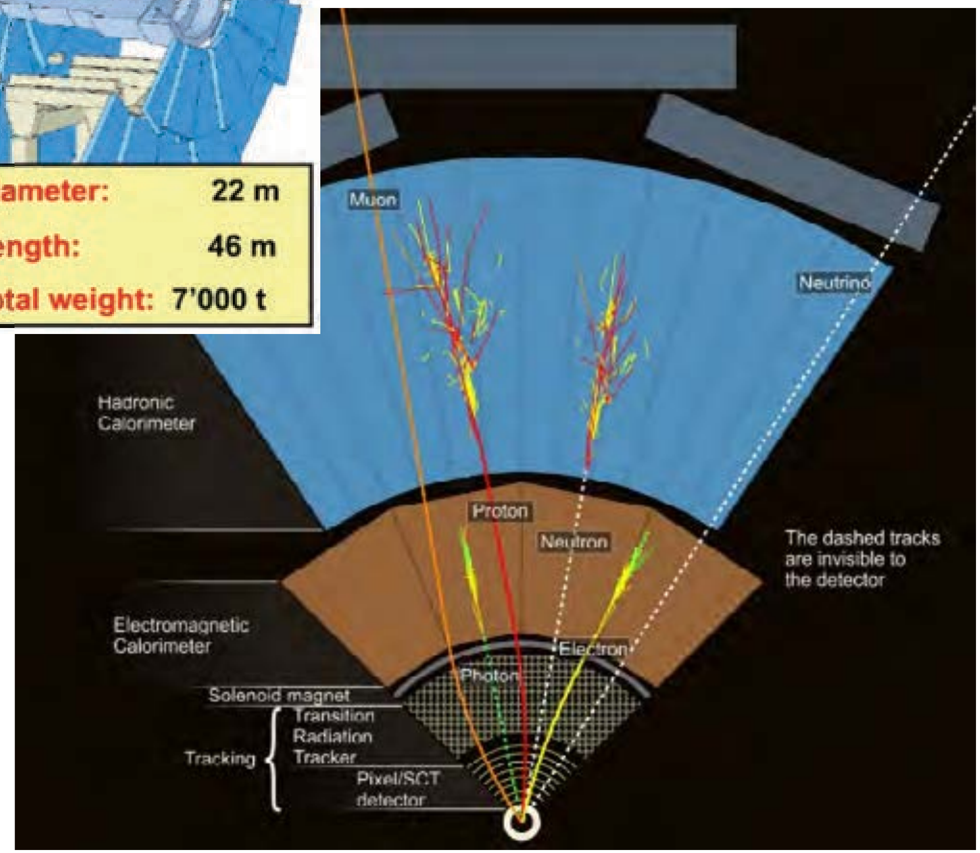
- trajectory, charge, momentum, energy, particle species,



http://www.lhc.facts.ch/index.php?page=atlas

more details later





1.1 Energy Loss of Particles in Matter

Interactions of charged particles with matter:

1. **Inelastic collisions** with electrons in atomic shell
   - energy loss
   - excitation or ionisation of atoms
   - scattering

2. **Elastic collisions**
   - scattering
   - energy loss (mostly negligible as m « M)
   - no excitations

3. Emission of **Bremsstrahlung**
   - Typical for e^+, e^-

4. **Cherenkov** radiation, transition radiation in inhomogenous materialis

5. **Nuclear reactions**

Example:
relativistic, heavy, charged particles (μ,π,α,p):

almost always scatter inelastically

properties of inelastic collisions :

- statistical
- energy loss fluctuates

number of collisions very large: fluctuations become small

Characteristic quantity: mean energy loss per unit length

$$\left\langle -\frac{dE}{dx} \right\rangle$$ ‚Stopping-power'

1.1 Energy Loss in Collisions

Exzellenzcluster Universe

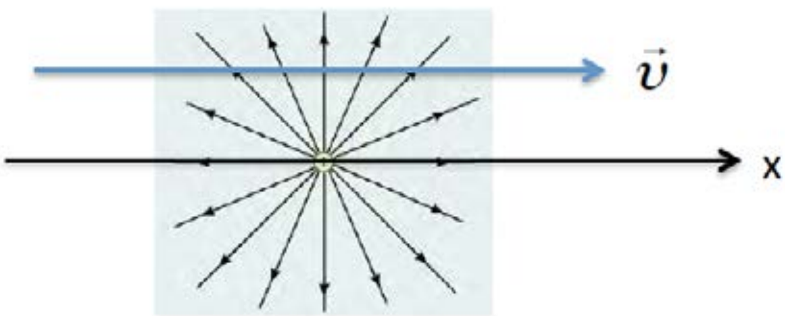
Inelastic collisions with electron cloud of an atom

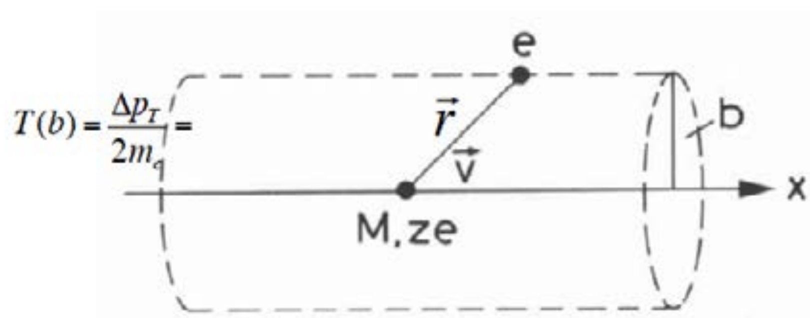
momentum loss

$$\Delta p = \int_{-\infty}^{+\infty} F_{\text{Coulomb}}\, dt$$

Only transverse forces
horizontal forces cancel

$$F_{c\perp} = F_{\text{Coulomb}} \cdot \frac{b}{|\vec{r}|} = F_{\text{Coulomb}} \frac{b}{\sqrt{x^2 + b^2}}$$





$\vec{v}$ velocity of incoming particles

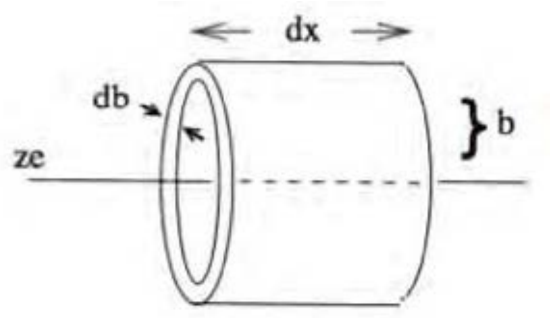
$$\Delta p = \int_{-\infty}^{+\infty} F_{c\perp}\, dt = \int_{-\infty}^{+\infty} F_{c\perp} \frac{dx}{v} = \frac{2ze^2}{vb}$$

Energy transfer ΔE(b) on atomic shell electron

$$\Delta E(b) = \frac{\Delta p^2}{2m_e} = \frac{2z^2 e^4}{m_e v^2 b^2}$$

1.1 Energy Loss in Collisions II

Energy loss of incoming particles: how many electrons does the incoming particle see with an impact parameter b ?



probability, to meet an e^- with impact parameter [b, d+db] = number of e^- in volume = *P(b)db*

$$P(b)db = n_e \cdot 2\pi b \cdot db \cdot dx$$

$$n_e = \frac{Z}{A} N_A \rho \equiv \text{number of } e^- \text{ per unit volume}$$

N_A = *Avogadro Numero*
ρ = *density*
Z = *charge* = # e^- pro Atom
A = mass number

$$-dE(b) = \Delta E(\mathrm{b}) \cdot 2\pi \cdot n_e \cdot b \cdot db \cdot dx = \frac{4z^2e^4}{2b^2\upsilon^2 m_e} 2\pi \cdot n_e \cdot b \cdot db \cdot dx = \frac{4\pi n_e z^2 e^4}{\upsilon^2 m_e} \frac{db}{b} dx$$

for particles of charge z

integrate over $b_{min} < b < b_{max}$

$$-\frac{dE}{dx} = \frac{4\pi n z^2 e^4}{m_e \upsilon^2} \int_{b\min}^{b\max} \frac{db}{b} = \frac{4\pi n z^2 e^4}{m_e \upsilon^2} \ln \frac{b_{\max}}{b_{\min}}$$

1.1 Energy loss in Collisions III

Integrate over all impact parameters in the range from b_{min} to b_{max}

- maximum b: momentum transfer must be large enough to separate atomic electron

$$\Delta E(b_{max}) = \Delta E_{min} = I = Ionisationsenergie$$

- minimum b : $\Delta E(b_{min}) = \Delta E_{max}$

$$\Delta E_{max} = \frac{1}{2} m v^2 \left(\frac{4 m_e}{m} \right) = \frac{2 z^2 e^4}{m_e v^2 b^2}$$

$\frac{1}{2} m v^2 =$ *energy of incoming particle of mass m*

impact parameter: $b_{min} = \frac{ze^2}{m_e v^2}; \quad b_{max} = \frac{ze^2}{v} \sqrt{\frac{2}{m_e I}}$

classical formula $-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{m v^2} \frac{Z}{A} \cdot N_0 \cdot \ln \sqrt{\frac{2 m_e v^2}{I}}$

Bethe-Bloch Formel: $-\frac{dE}{dx} = 4\pi N_0 \frac{Z}{A} \frac{z^2 e^4}{m v^2} \cdot \left[\ln \frac{2 m_e v^2}{I} - \ln(1-\beta^2) - \beta^2 - \frac{c_K}{Z} \right]$

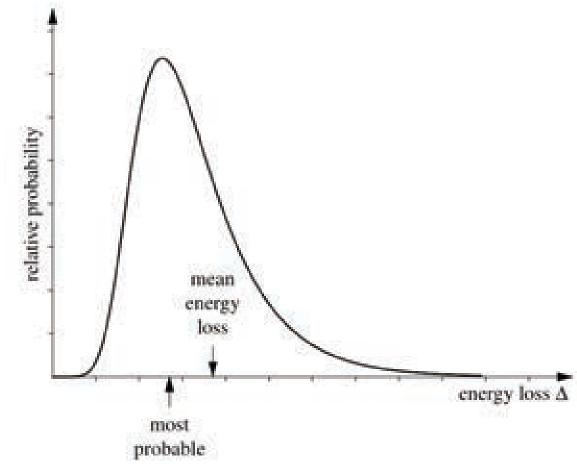
z: charge of incoming projectile
Z: charge of target nucleus (e.g. Z=6 for carbon)
x: thickness traversed [g/cm²]
N_A/A: number of nuclei/unit volume

I: effective ionisation potential
c_k: correction factor: binding in K-shell
β: v/c

1.1 Energy Loss in Collisions IV

Fluctuation of energy loss

- energy loss is statistical process
- specific energy loss (dE/dx) is sum of many individual processes → statistical fluctuations
    - number of processes
    - energy transfer inn individual process
- energy loss described via **Landau distribution**



$$P\left(\Delta E - \Delta E_{mp}\right) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}\left(\lambda + e^{-\lambda}\right)}$$

$$\lambda = \frac{\Delta E - \Delta E_{mp}}{\xi}$$ mit ξ as material dependent constant

ΔE_{mp} : most probably value for ΔE

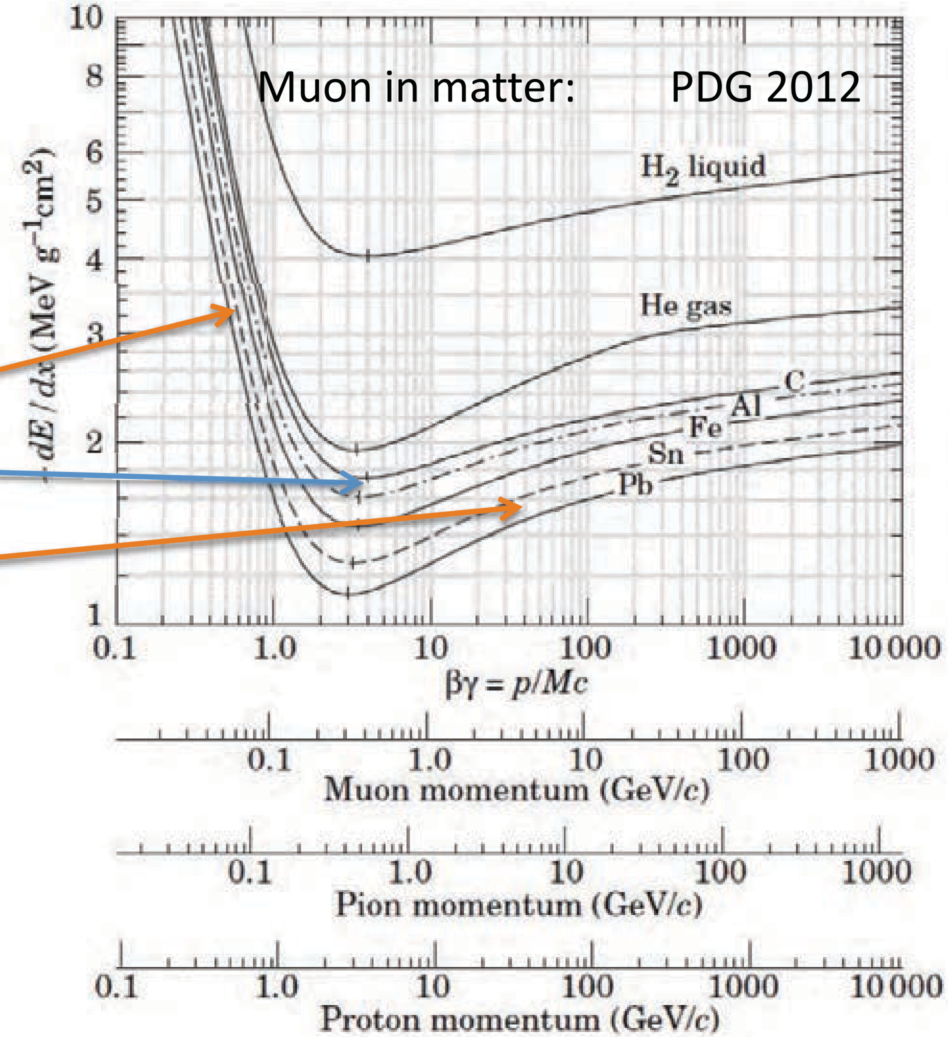
Bsp. Argon: ξ = 125 keV
Δx = 1cm
ΔE_{mp}= 1.2 KeV
ΔE_{mittel}= 2.69 KeV

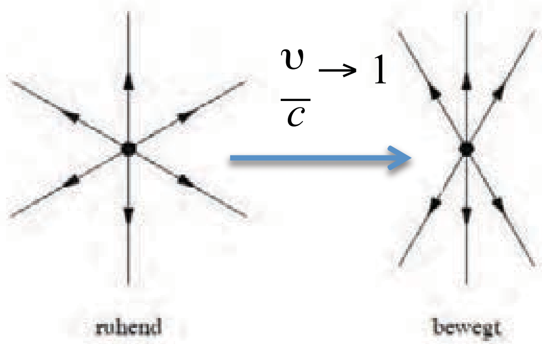
- Thick layers: distribution of dE/dx is gaussian around $(dE/dx)_{Mittel}$
- Thin layers:
    - large fluctuations of ΔE
    - individual processes with high individual energy loss ΔE contribute to „tail" of distribution
    - generation of δ-electrons

1.1 Energy loss in collisions VI

Properties:

- Independent of the particle mass
- Speed dependent
- Depending on ionization potential
- **at low** energies: $-\left\langle \frac{dE}{dx} \right\rangle \propto 1/\beta^2$
- **Minimum** for $\beta\gamma \sim 3$
- at **high energies**: $-\left\langle \frac{dE}{dx} \right\rangle \propto \ln \beta^2\gamma^2$





Transverse electric field amplified due to Lorentz contraction

Increase in range → relativistic rise

1.1 Energy Loss in Collisions VII

- (almost) material independent $-\left\langle \frac{dE}{dx} \right\rangle \propto z^2 (Z/A) \cdot f(\beta, I)$

- density dependent effect : polarisation of atoms along trajectory if *b* becomes atomic distance: → screening
  → reduction of effective n_e

$$R = \left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\text{saturation}} / \left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\text{min}}$$

R = 1.8 for gases
R ca. 1.2 for solids

Material	$\mathrm{d}E/\mathrm{d}x\|_{\text{min}}$ [MeV/cm]
plexiglas	2.3
iron	11.65
uranium	20.66
xenon (gas)	$7.3 \cdot 10^{-3}$

Stephan Paul | KT für Lehramt WS 2014/2015 ‹Nr.›

1.1 Energy loss of heavy projectiles

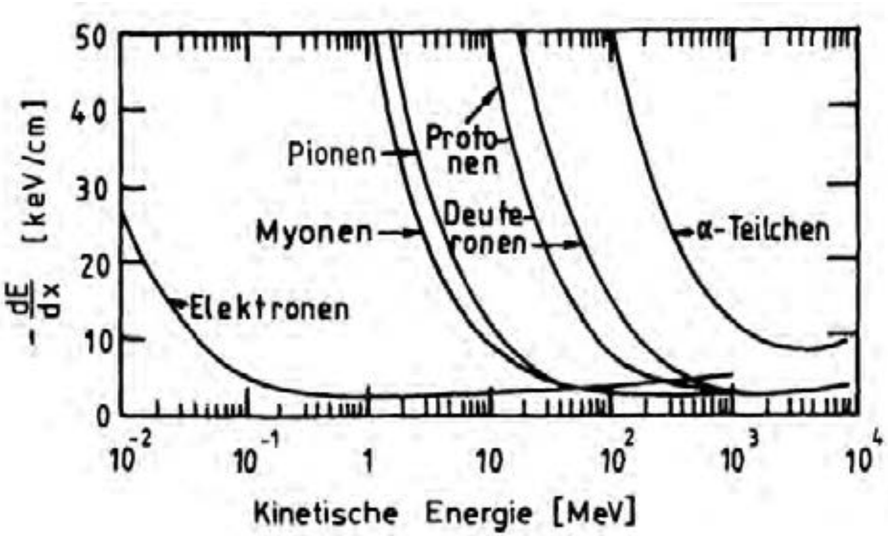
Heavy projectiles make collisions with atomic nuclei

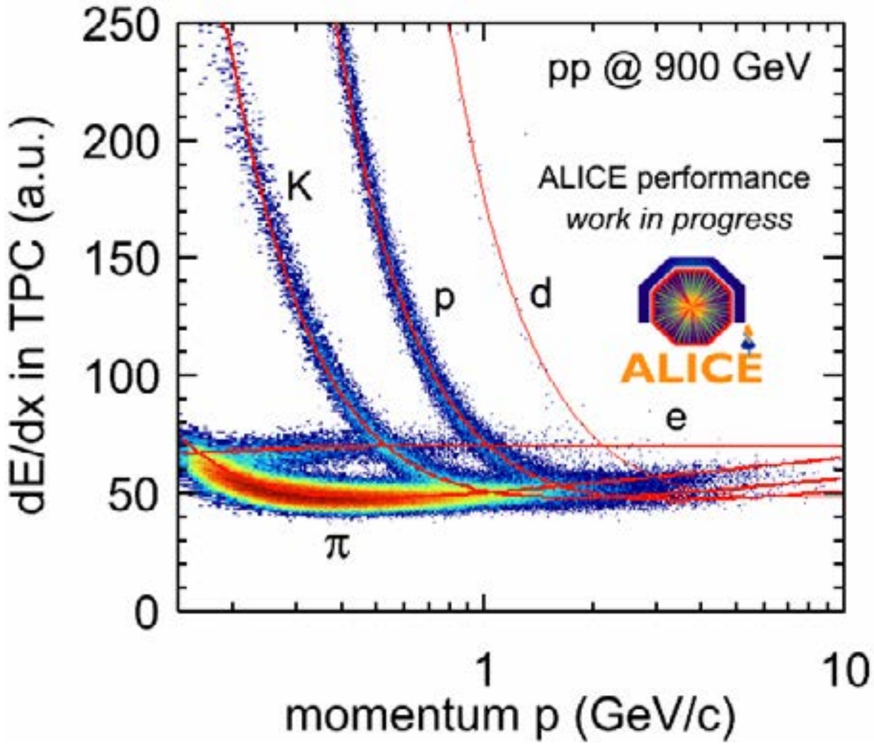
- High energy transfer, greater stopping power
- Breaking of the core/projectile - inelastic collisions → hadronic shower

1.2 Particle ID through Energy Loss

Energy loss for electrons higher: due to $m=m_e$ ΔE_{max} increases

Particle identification by detection of energy loss: determine E and dE/dx of a particle

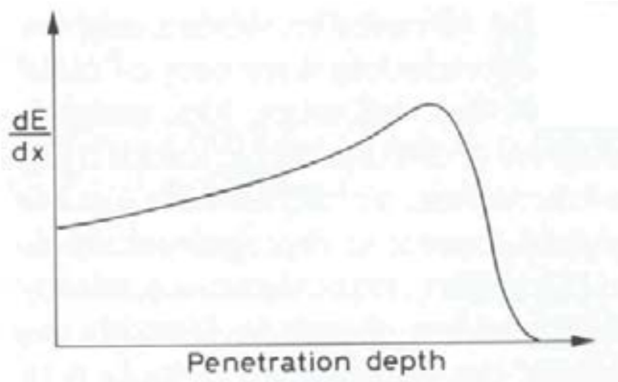




1.2 Energy loss in the event of collisions VIII

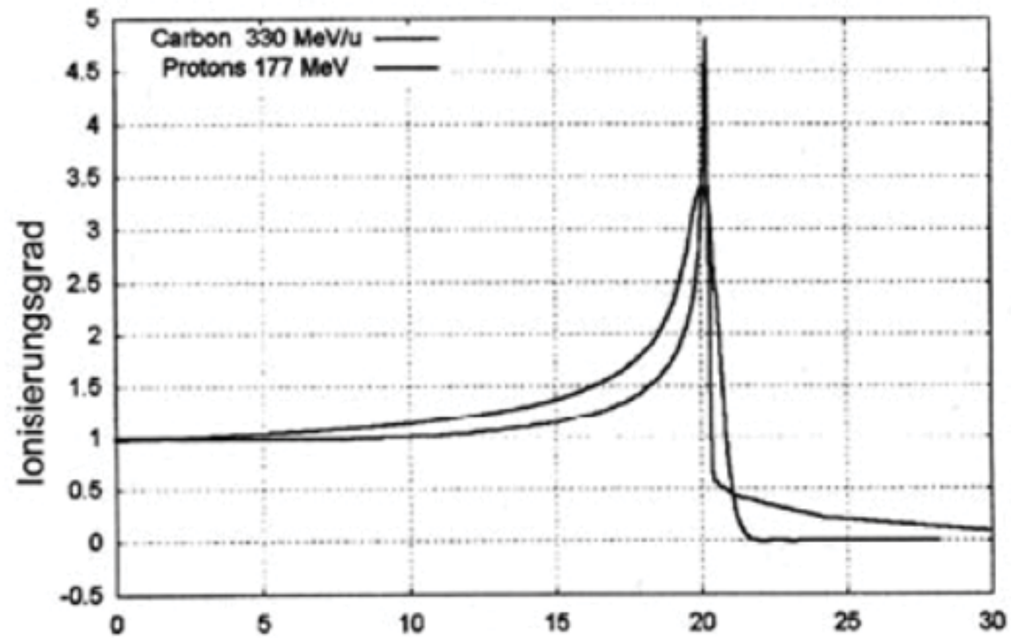
Depth of penetration into matter:

Schematic



-integrated energy loss = stopping power
-stopping power increases with decreasing particle energy
-energy deposition is maximal at end of flight path

. . . e.g. medical applications



Depth in Water

medical applications !
radiation therapy (tumor)

detection of very low energy particles

1.3 Energy Loss of e- and e+

Energy loss in Materie:

$$\left(-\frac{dE}{dx}\right)_{total} = \left(-\frac{dE}{dx}\right)_{coll} + \left(-\frac{dE}{dx}\right)_{rad}$$

losses through Bremsstrahlung:

$$-\frac{dE}{dx}_{rad} \propto \frac{Z^2}{A}\frac{e^4}{m^2}E_0\, z^2$$

$$-\frac{dE}{E} \propto \frac{dx}{X_0} \ldots$$

$$E = E_0\, e^{-x/X_0}$$

„radiation length“ $X_0 \propto A/Z^2$

radiation length: Δx for which :

$$\frac{E_0 - \Delta E_{rad}}{E_0} = \frac{E}{E_0} = \frac{1}{e}$$

1.3 Energy Loss of e^- and e^+

Processes:

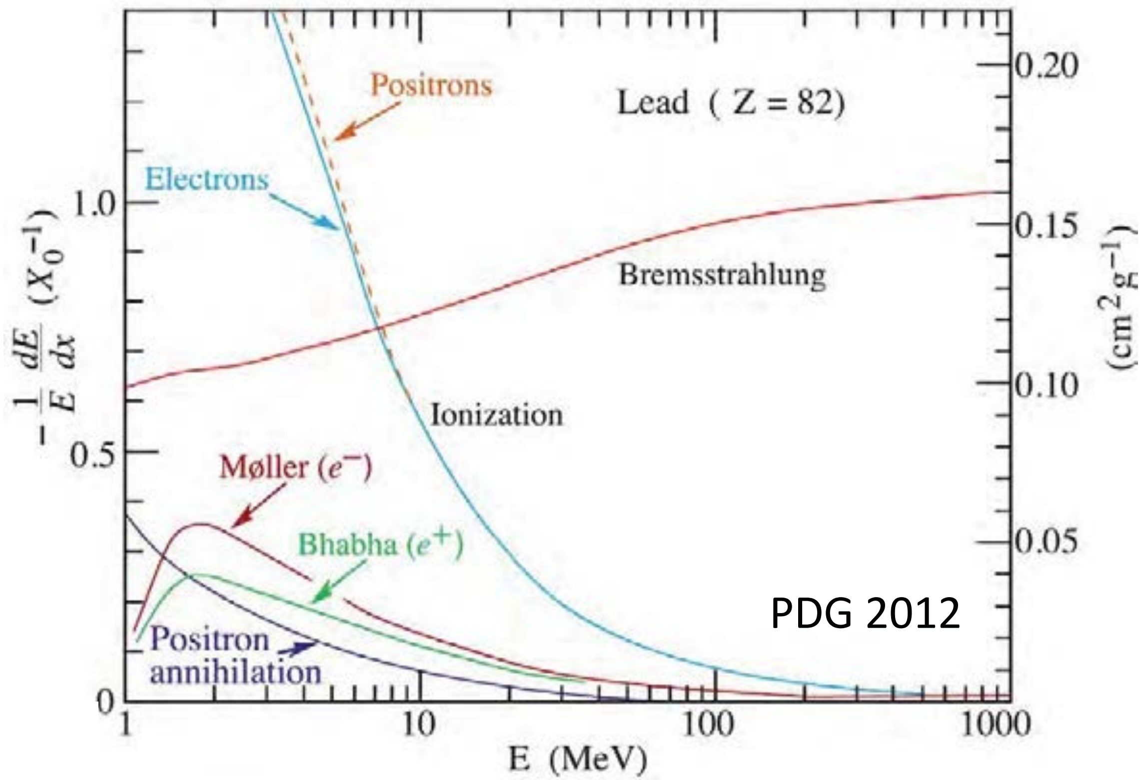
1. inelastic collisions with electrons, excitation and ionisation
   differences to heavy particles… modification of the Bethe-Bloch formula:
   - recoil
   - spin dependence

2. Bremsstrahlung: Scattering in electric field nucleus and atomic electrons

3. Møller scattering $e^-e^- \to e^-e^-$

4. Bhabha scattering: e^-e^+ e^-e^+

5. e^-e^+ annihilation



1.3 Energy Loss of e- and e+

critical energy:

$$\left(\frac{dE}{dx}\right)_{coll} = \left(\frac{dE}{dx}\right)_{rad}$$

critical energy is material dependent:

$$E_C = \frac{610\,\text{MeV}}{Z + 1.24} \quad \text{(solid)} \qquad E_C = \frac{710\,\text{MeV}}{Z + 0.92} \quad \text{(gaseous medium)}$$

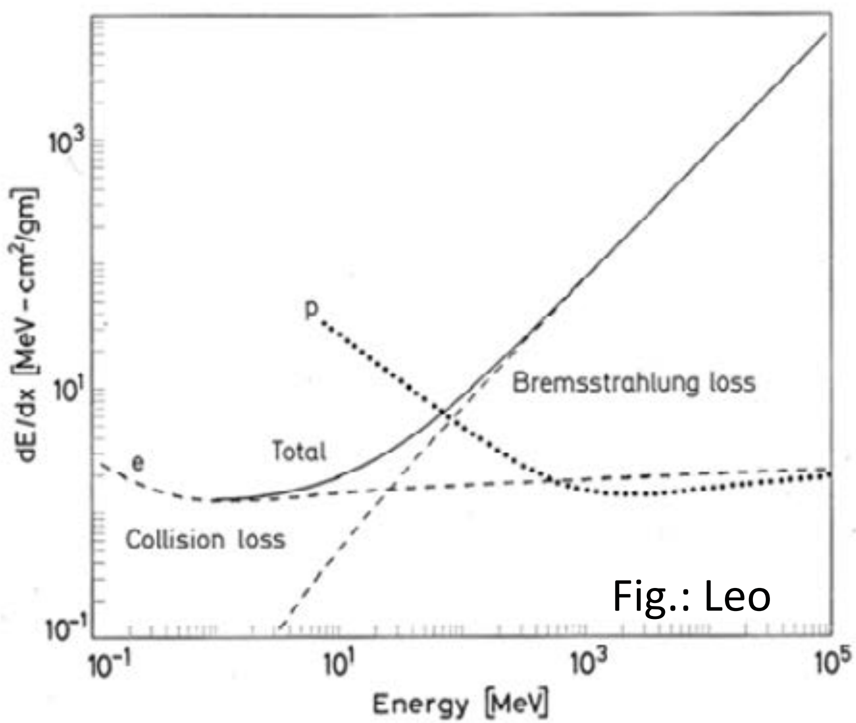
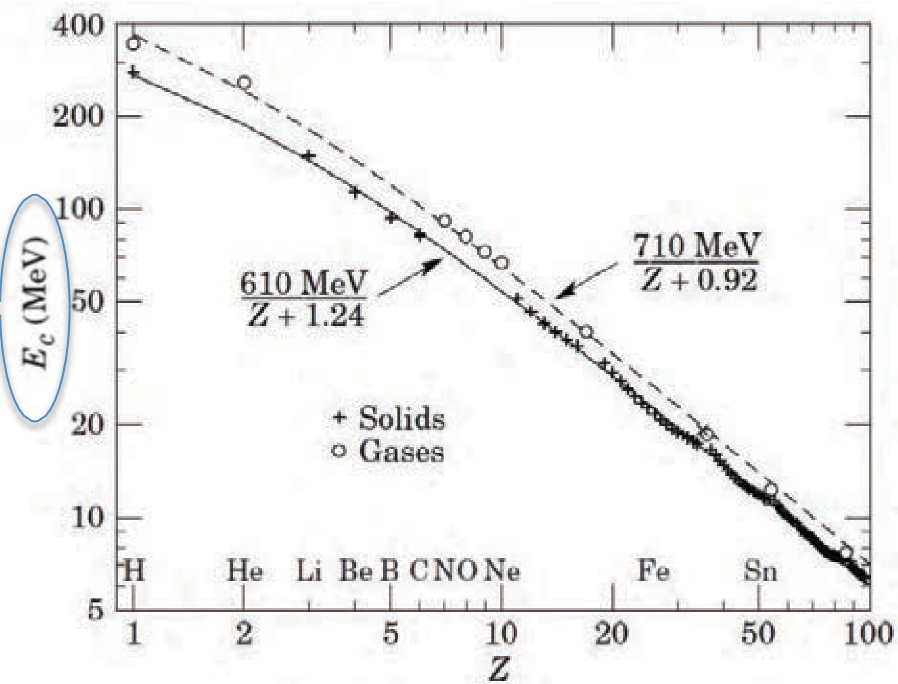


Fig.: Leo

critical energy for electrons



… for muons

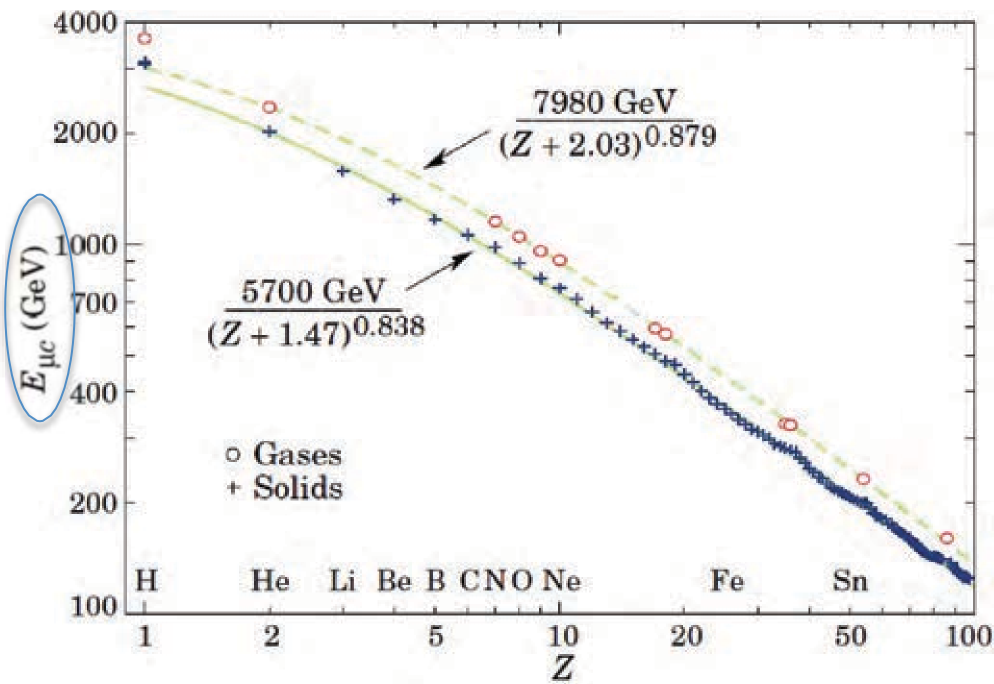


Fig: PDG 2012

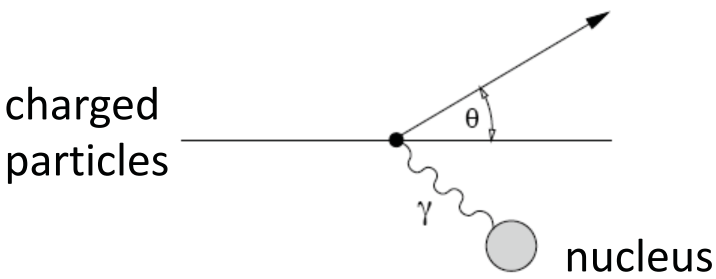
1.4 Multiple Scattering

At high energies:

Scattering off nuclear Coulomb potential is dominant:

Rutherford scattering from a nucleus

$$\frac{d\sigma_{Ruth}}{d\Omega} \sim \frac{1}{\sin^4\frac{\theta}{2}}$$



many scatterings in matter

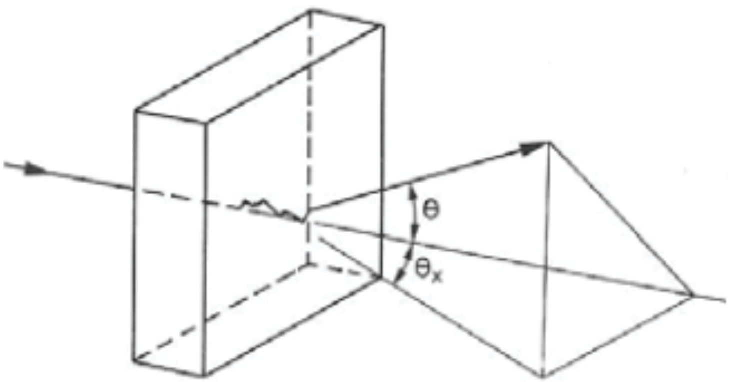
For $m_{Particles} << m_{Kern}$ ...

change of direction, small energy transfer

Infinitely many scattering centres:

- Gaussian distribution of the scattering angle (Molière Scattering)
- individual scattering events with larger angles

1.4 Multiple Scattering



- random path

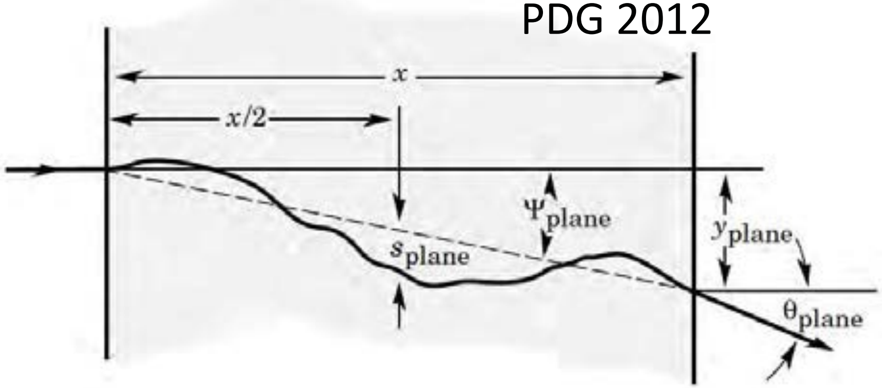
Probability of exit angle:

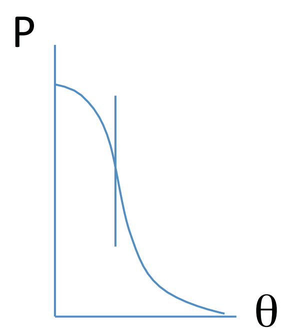
$$P(\theta)d\theta = \frac{1}{\sqrt{2\pi\theta_0}}\exp\left(-\frac{\theta^2}{2\theta_0^2}\right)d\theta$$

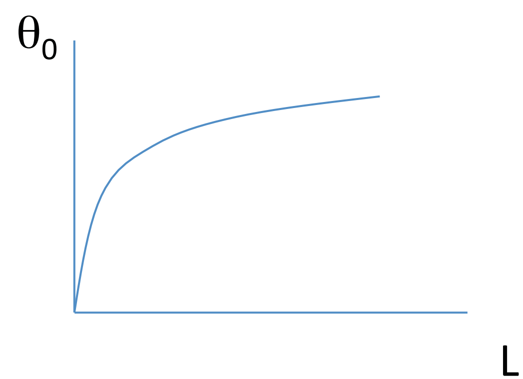
θ_0 ... width of Gaussian
mean broadening

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

PDG 2012





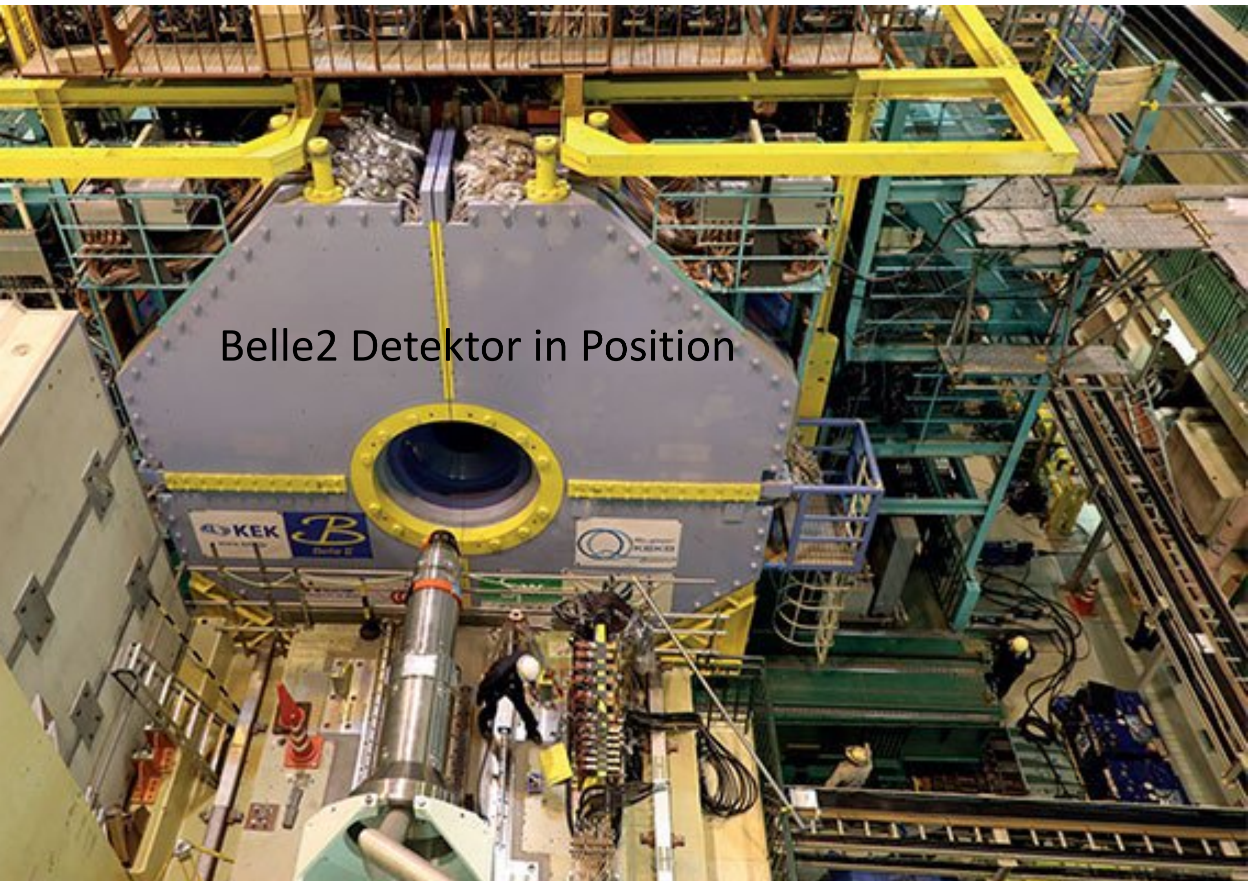


Example: 1 GeV/c proton in 1m Argon: θ_0 = 0.03° (Atlas) θ_0

Particle Detectors

Exzellenzcluster Universe

Stephan Paul
TU-München
stephan.paul@ph.tum.de



2. Ionization Detection

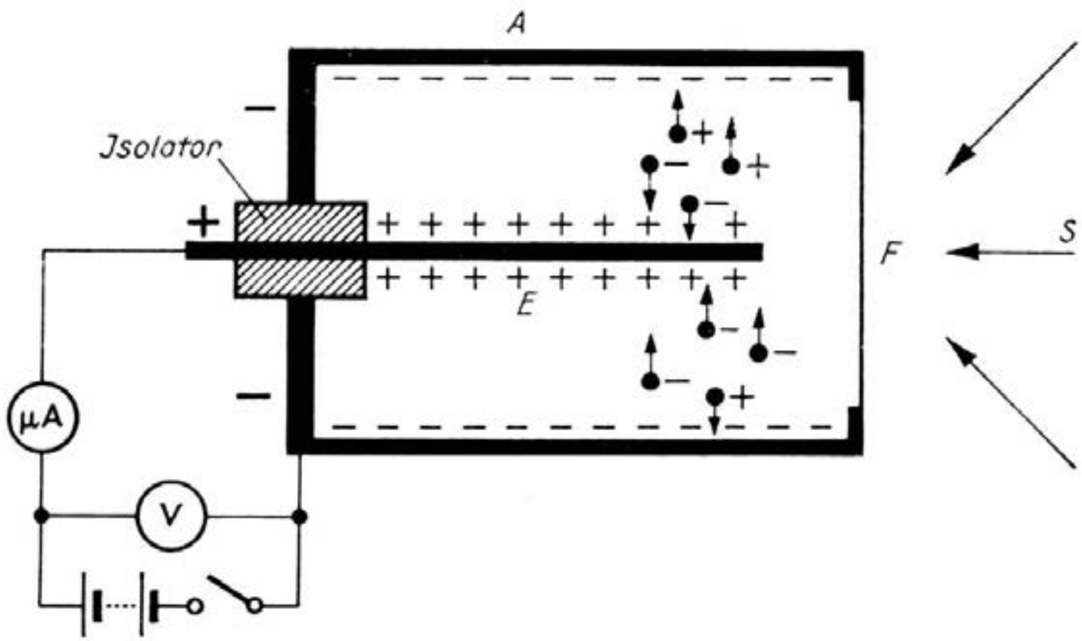
Principle:
- Ionising radiation generates electrons and holes (ions)
- Collecting electrons and holes in the detector

Detector material:
-Gas:
  Fast collection of e^- and ions. Detector gases: Ar, Ne, ...
- Liquid:
  High density, e.g. liquid Ar, Xe,
- Solids:
  High density, mechanically stable, e.g. semiconductor (Si, Ge, .)

Experiment:
- Vessel with electrodes and entrance window
- Filled with active medium for interaction with ionising radiation (e^- - hole(ion) pairs)
- Electrical field between electrodes for collecting the charge carriers:
  - e^- and holes (ions) collected separately
  - Drift, diffusion
  - Signal = ‚current' from collected batches in Cathode/Anode

2. Ionization Detection

Ionization chamber:



Prinzip der Ionisationskammer.

F Eintrittsfenster; *E* Innenelektrode; *I* Isolator; *A* Abschirmung; kV Spannungsmesser; A Strommesser

- **Generation of charge carriers in electric field E**
- **Historical:**
  V.Hess could only detect the change in voltage
- **current detection**

Direct detection of pulses in the gas detector requires internal amplification

Typical gas: Ar/CO_2: 100 e- / cm flight distance
Comparison: solid-state detector ~10000 e-/ 100 µm

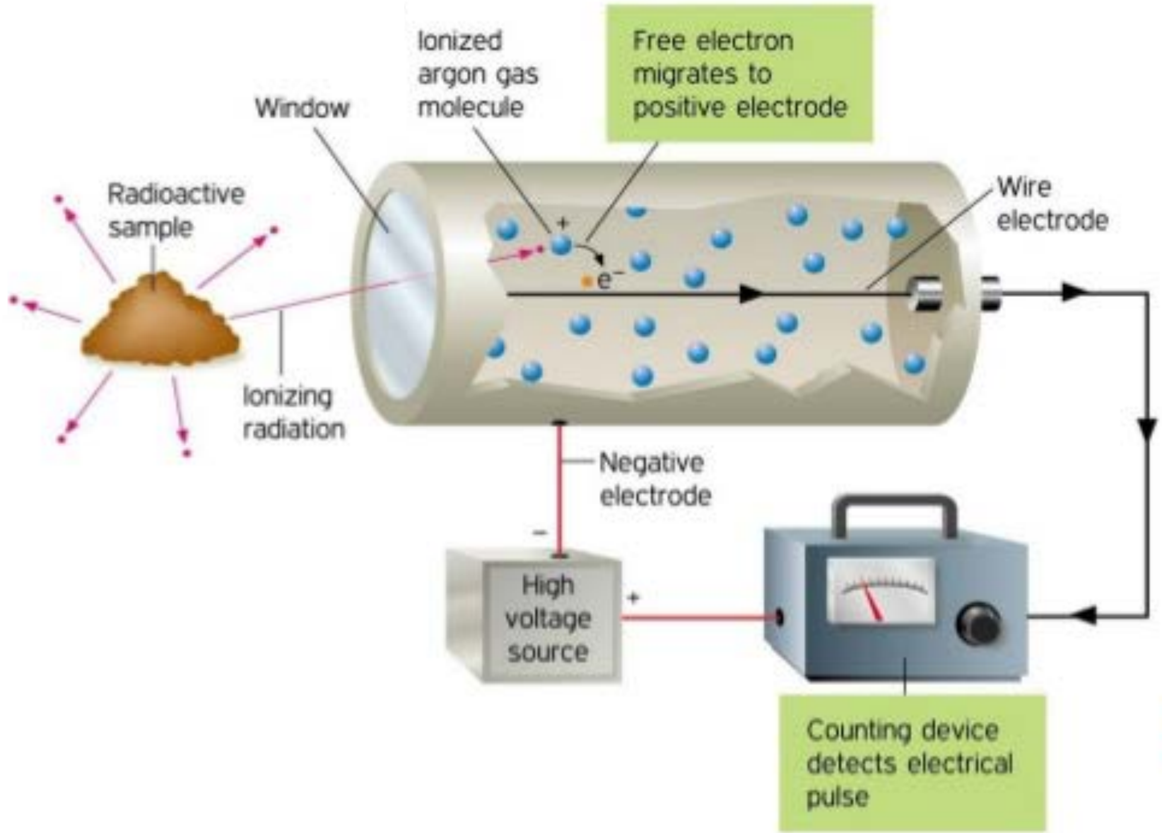
Example: Geiger-Müller counter tube

electric field around wire

$$E(r) = V_0 \frac{1}{r \ln\left(\frac{r_2}{r_1}\right)}$$

r_1 = radius of counting wire

r_2 = radius of tube

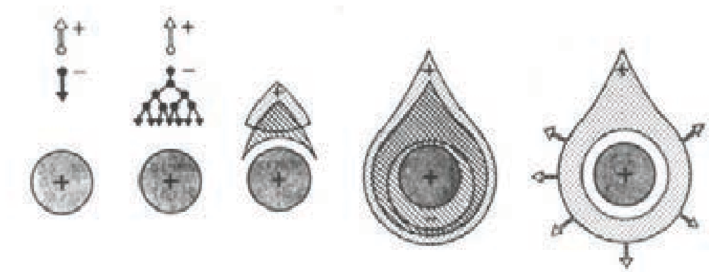


2. Ionization Detection - Gas Amplification

Gas amplification :

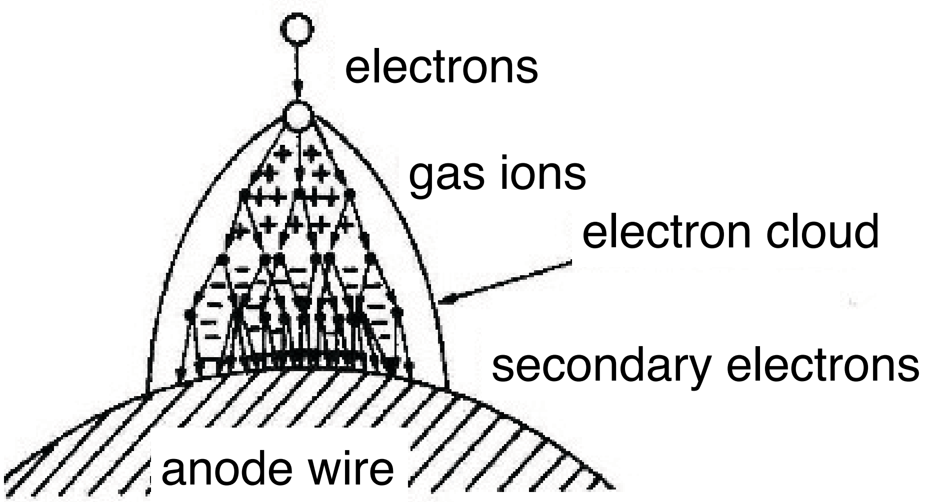
Electric fields ~ kV/cm:

- electrons gain sufficient energy between collisions with gas molecules to further ionization
- avalanche charge



Probability of ionization per unit length ~ „Townsend Coefficient“

Paschen law



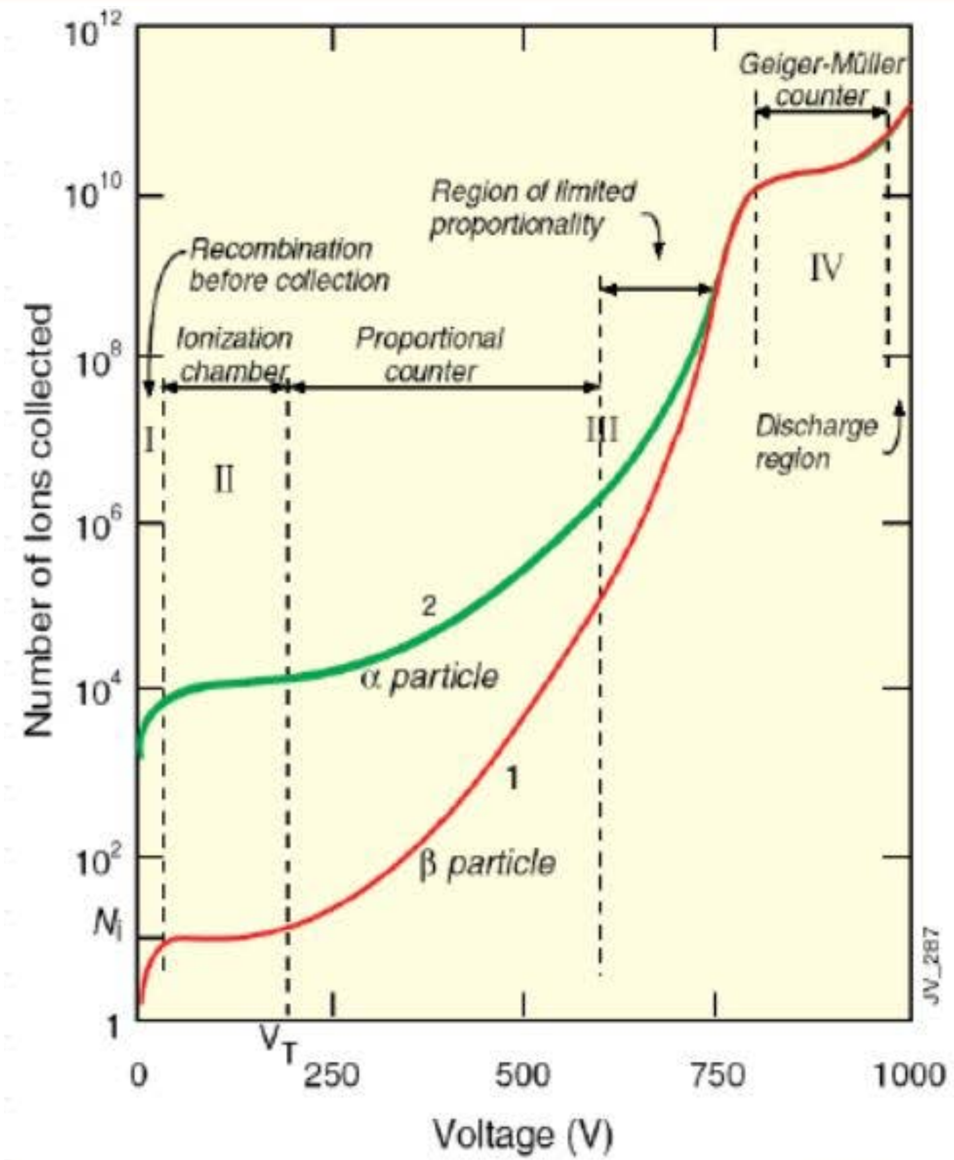
$$\alpha \propto \frac{1}{\lambda}$$ inverse free path length

amplification of a detector (“gain“):

$$dN = N \cdot \alpha \cdot dx \rightarrow N = N_0 e^{\alpha \cdot x}$$

$$G = \frac{N}{N_0} e^{\alpha \cdot x}$$

2. Ionization Detection



Typical values for amplification:

- Proportional counter tube ~ 10^4 - 10^6
- GEM ~ 10^3 - 10^5

In the proportional region, the avalanche charge is proportional to the deposited energy

The maximum avalanche charge is always produced in the Geiger-Müller region

Recapitulation

- What is the electronic energy loss??
  - collisions with atomic electrons with subsequent energy transfer: sum of all processes along a path length dx
- What is the momentum dependence of the energy loss ?
  - drops towards higher γ towards a minimum (3γ), rises and saturates
- What is critical energy and for which particles is it important ?
  - Energy for which electronic and Bremsstrahlung energy-loss are equal (only important for electrons)
- What is multiple scattering and which effect has it ?
  - Sum of many small direction changing collisions with atomic shell electrons. Directional spreading of a particle beam
- What is an ionisation chamber ?
  - Gas volume in which ions are connected in an electric field
- What is an avalanche amplification and where is it used ?
  - Series of processes for the self multiplication of ion pairs in strong electric fields: Geiger-counter

2.1 Ionisation detection

Examples for ionisation detectors:

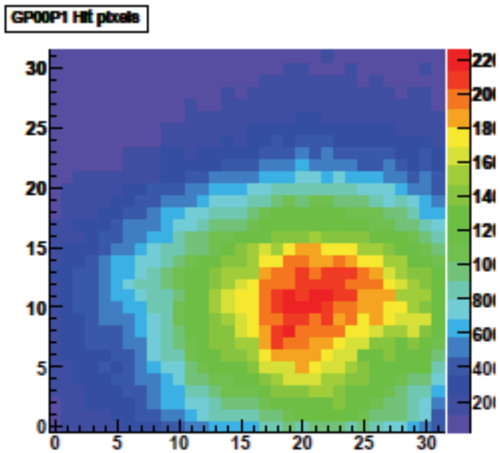
position sensitive detectors:

beam profiles, imaging (medical applications), particle track determination

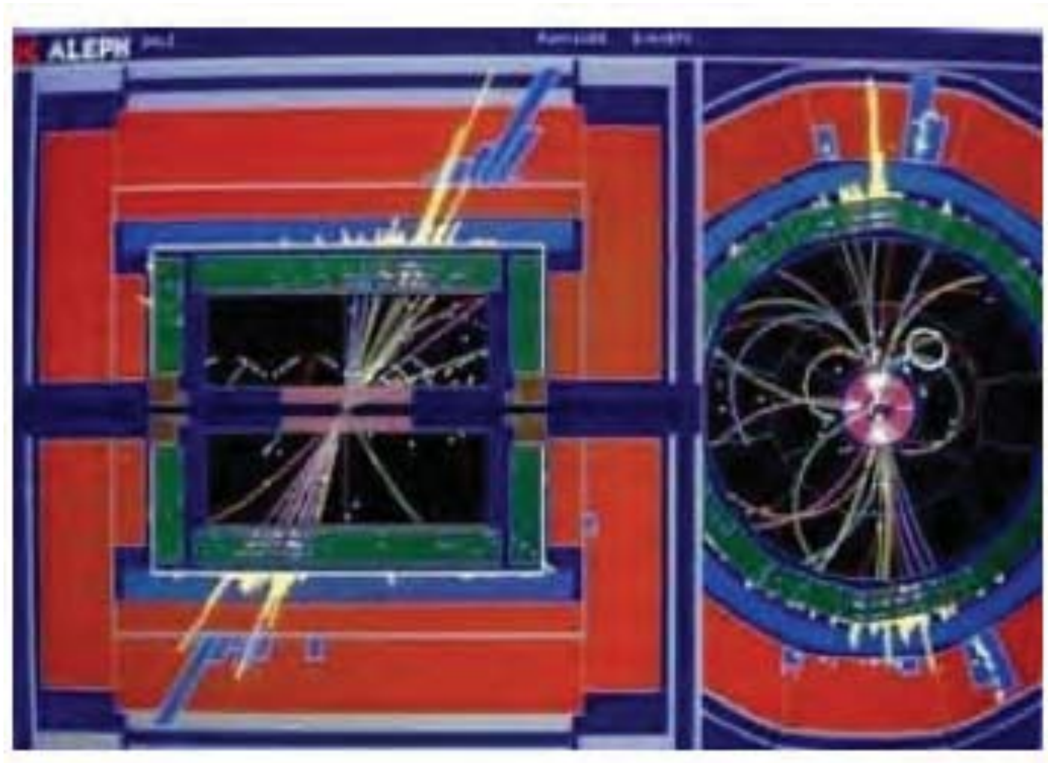
MWPC: Multiwire proportional chamber
^{3}He neutronen detectors
GEM detectors
Drift chambers
TPC: Time projection chambers
Semiconductor detectors

2.1 Examples: ionisation detection

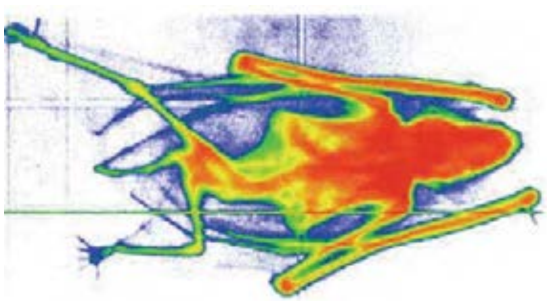
Measurements of beam profiles



Determination of particle tracks and momenta



Tomographie (bat)

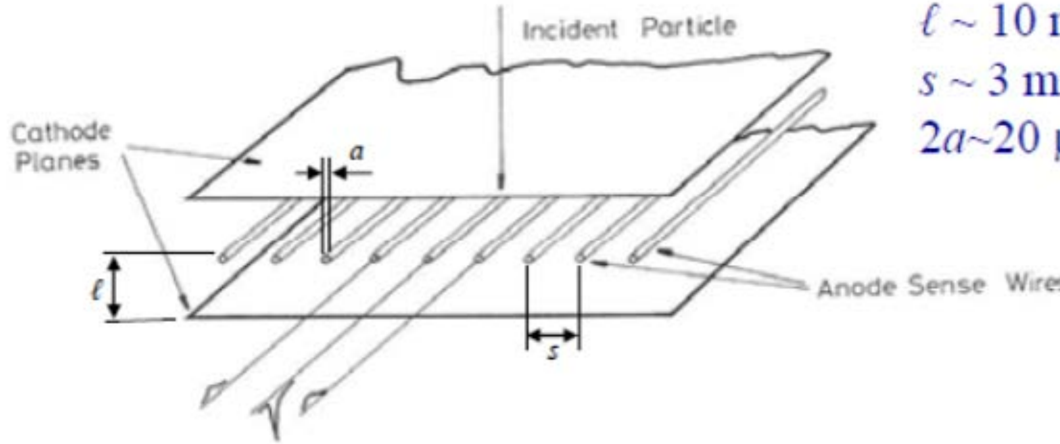


CERN Courier 2001 Archama Sharma-

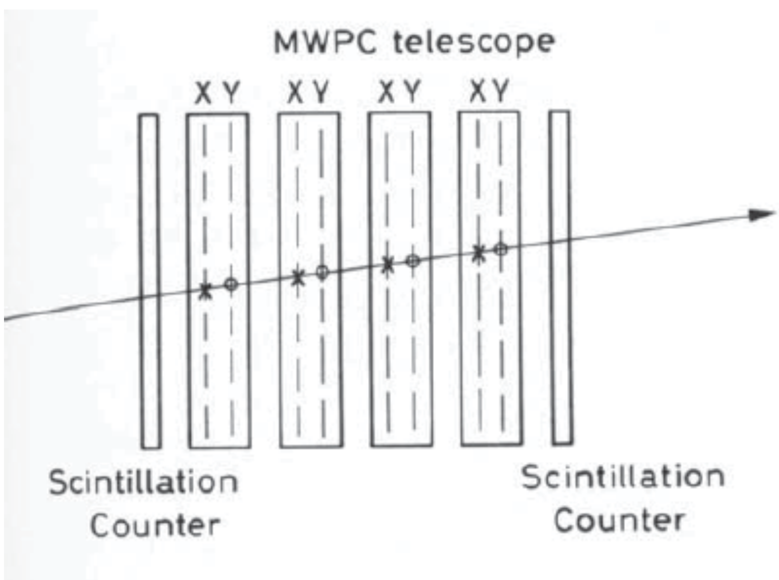
2.1 MWPC

Multi Wire Proportional Chamber

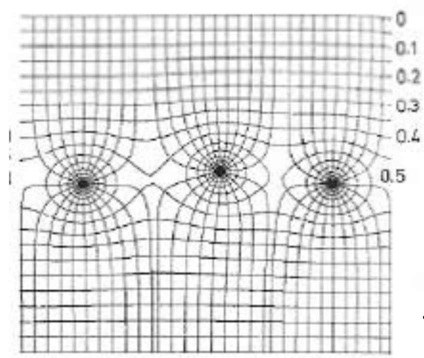
Dimensions:
distances: l ~1 cm, s ~3 mm, a ~10µm



$\ell \sim 10$ mm
$s \sim 3$ mm
$2a{\sim}20$ µm



electric field distribution:



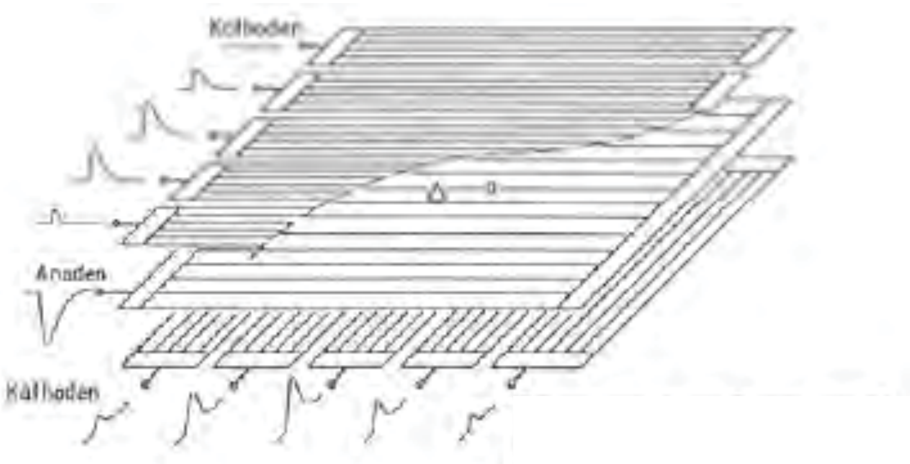
pictures:
- Leo;
- Charpak et al. NIM 62, 262 (1968)

2.1 Multiwire proportional chamber

NIM : Volume 419, Issues 2-3, 21 December 1998, Pages 189-201

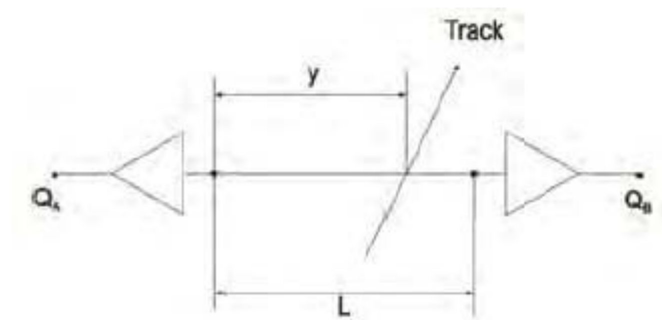
2.1 Ionisation detection

Position detection :



resolution ~ 50 – 100 µm

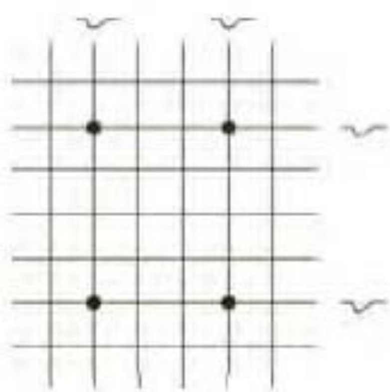
sharing of charges:



distance from time measurement

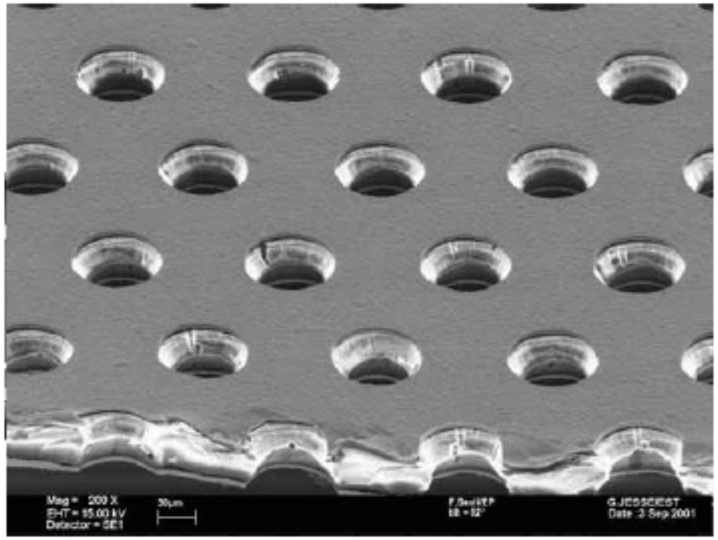
typical resolution ~ cm

Problem:
ambiguities in x/y
association

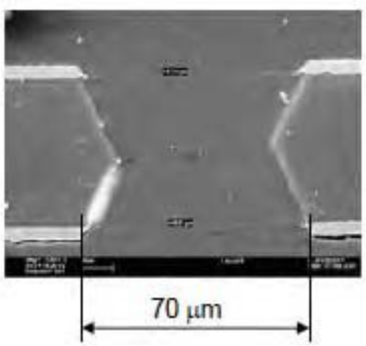


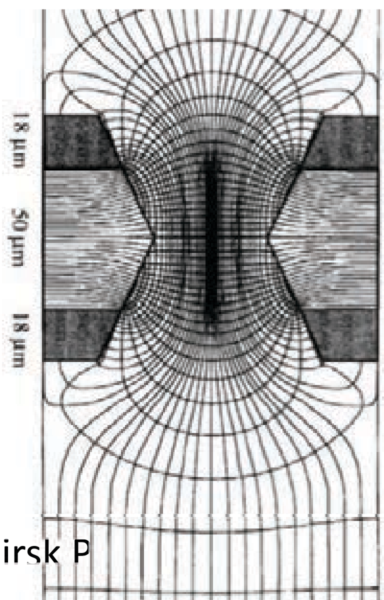
Bilder aus Leo

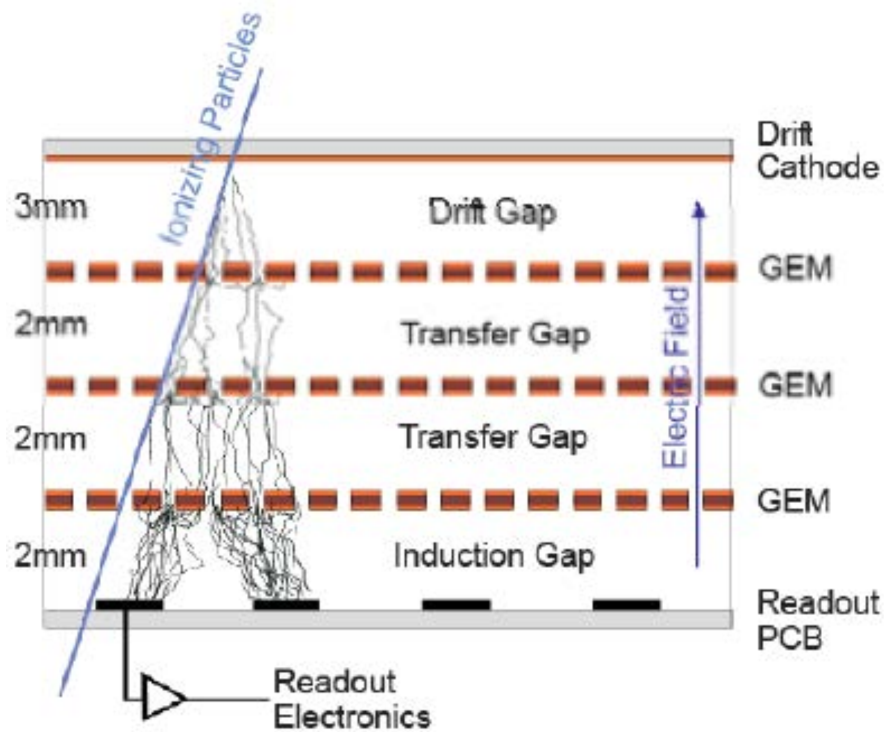
2.2 GEM Detectors



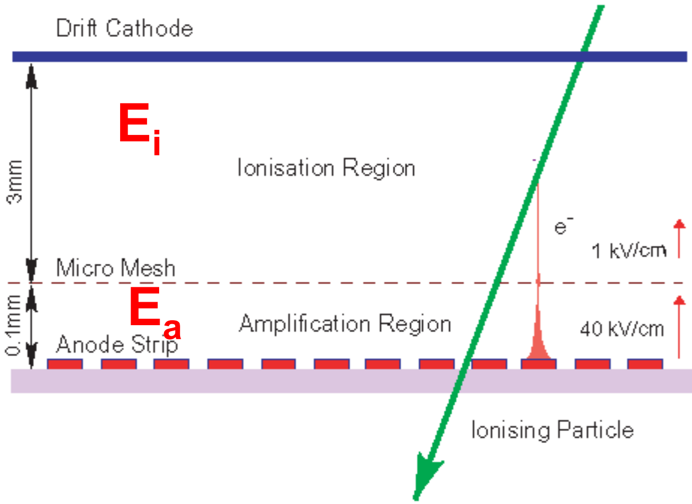
GEM: Gas Electron Multiplier
- better resolution than MWPC (10x)
- amplification stages
- cascading of several foils possible







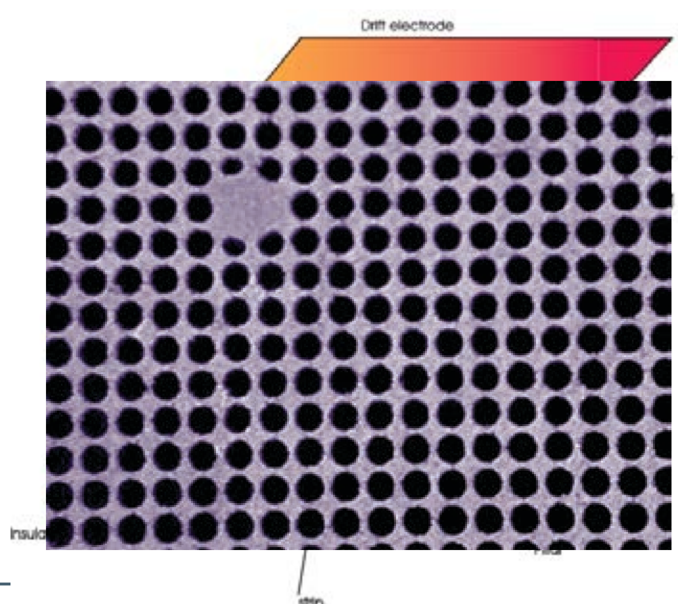
2.2 Micromegas

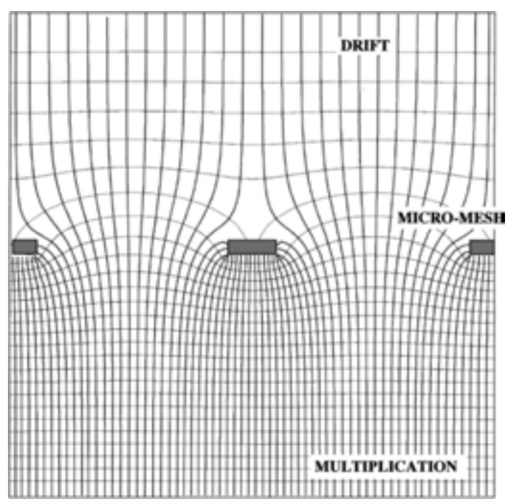


Micromesh Gaseous Structure

[I. Giomataris et al., NIM A376, 29 (1996)]

- Thin gap parallel plate structure
- Fine metal grid (Ni, Cu) separates conversion (~ 3 mm) and amplification gap (50-100 µm)
- Very asymmetric field configuration: 1 kV/cm vs. 50 kV/cm





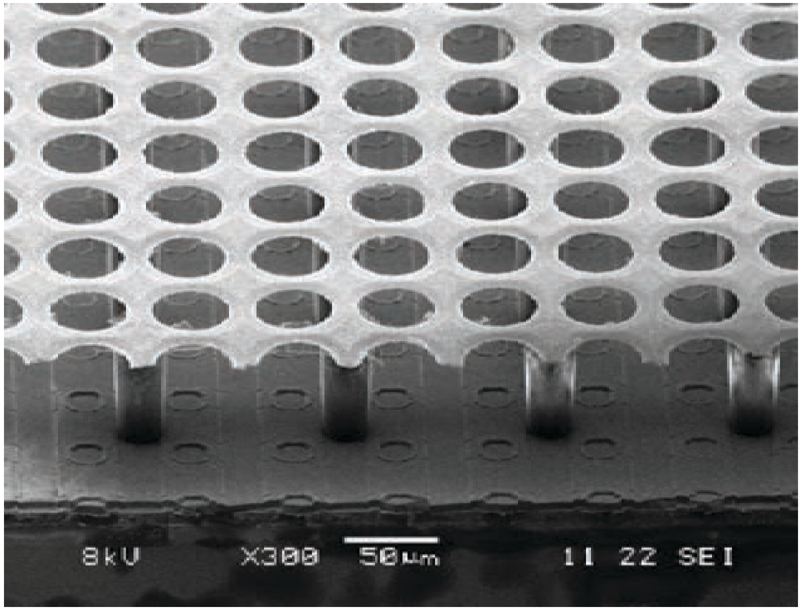
➡ Fast collection of ions (~ 100 ns)

➡ Saturation of Townsend coefficient (mechanical tolerances)

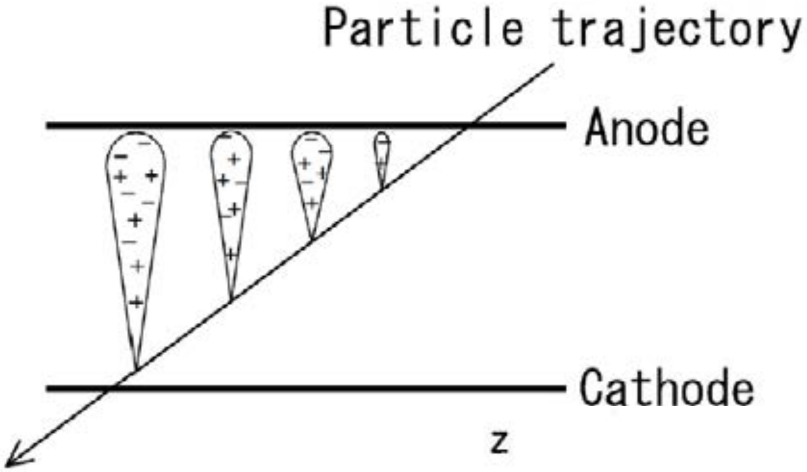
➡ good energy resolution

2.2 Micromegas

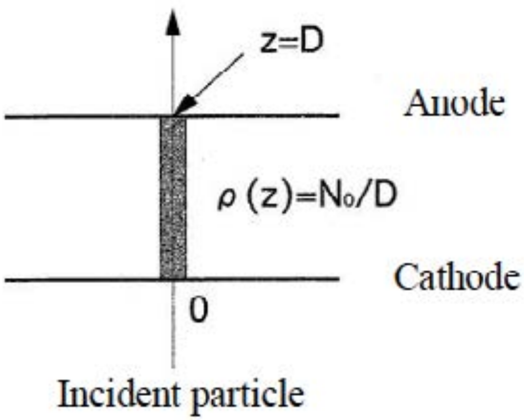
Mesh with pillars:



Principle of Parallel Plate avalanche detector

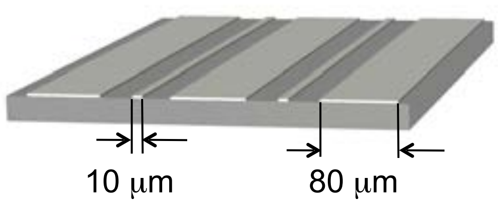


$$N = \frac{N_0}{\alpha D} \exp(\alpha D)$$

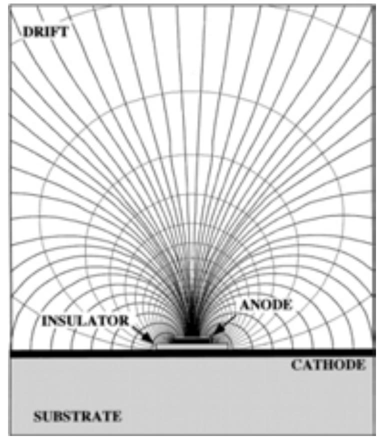


2.2 The MPGD Zoo (Examples)

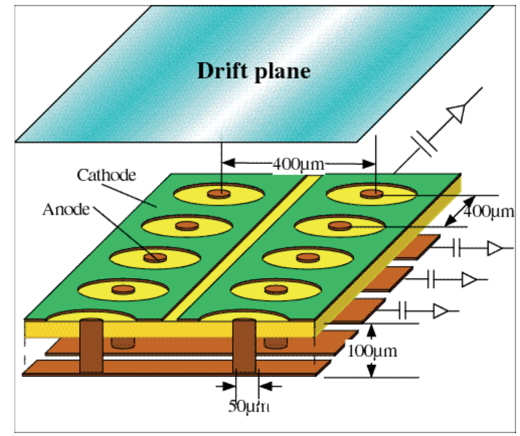
Microstrip Gas Chamber
[A. Oed, NIM A263, 351 (1988)]



Microgap Chamber (MGC)
[F. Angelini et al., NIM A335, 69 (1993)]

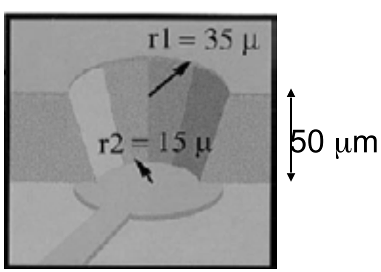


Microdot Chamber
[S.F. Biagi et al., NIM A361, 72 (1995)]

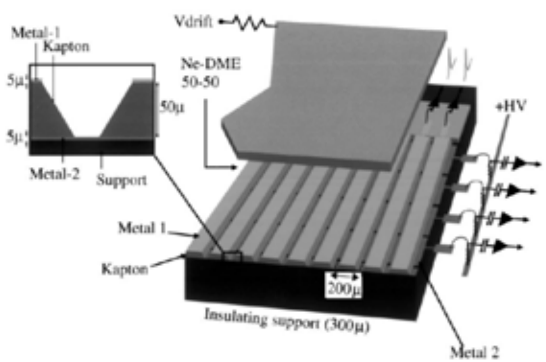


Compteur à Trous (CAT)
[F. Bartol et al., J. Phys. III 6, 337 (1996)]

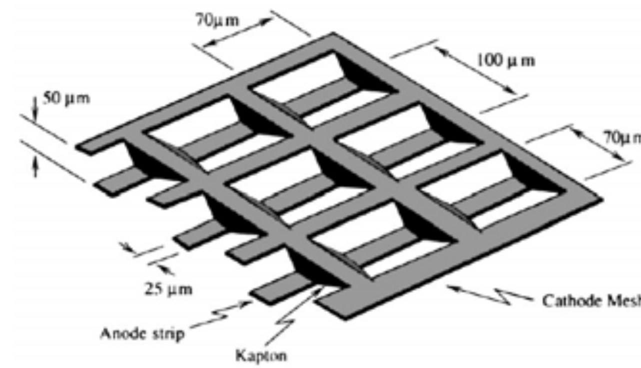
WELL Detector (µCAT)
[R. Bellazzini et al., NIM A423, 125 (1999)]



Micro Groove Counter
[Bellazzini et al., NIM A424, 444 (1999)]



Micro Wire Detector
[B. Adeva et al., NIM A435, 402 (1999)]



2.3 Drift detectors

- Electrons drift* in computing gas with $v=v_D$
- at high E-fields v_D quasi constant
- v_D(typ)=50 cm/µs

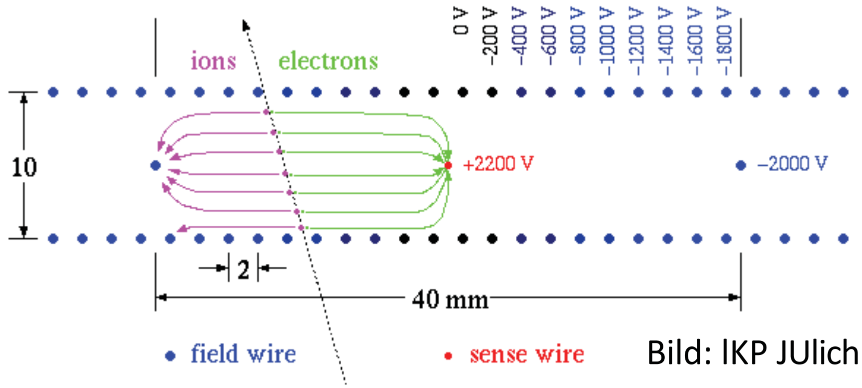


Bild: IKP JUlich

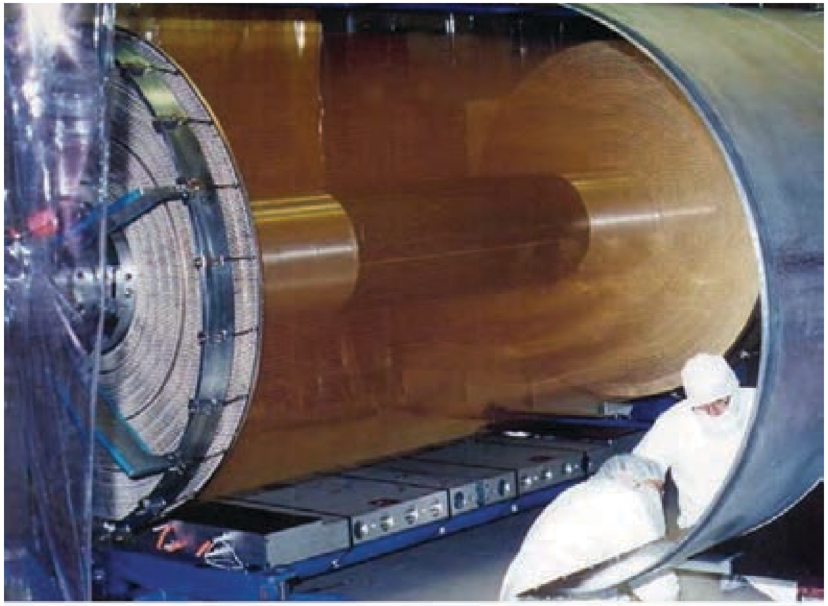
with impact at distance Δx from outing wire

$$\Delta t = \frac{\Delta x}{v_{Drift}}$$

determine impact time t_0 extern (scintillators)

determine t from charge signal at counting wire

from $t-t_0=\Delta T$ obtain position coordinate



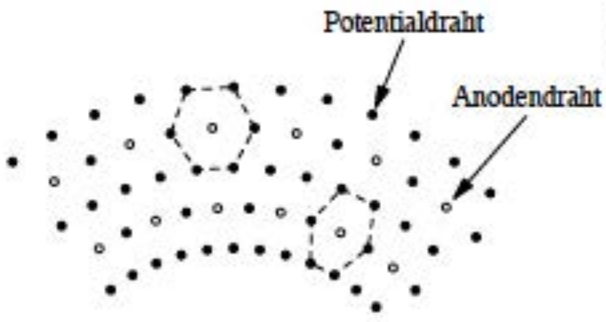
- good time resolution electronic (1ns)
- spatial resolution: σ_{Ort} = 100-200 µm
- wire distance: 2-4cm

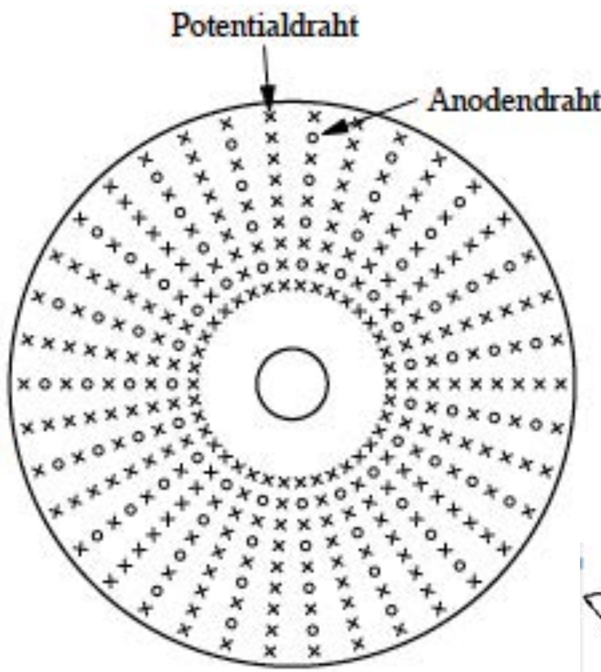
small number of electronic channels

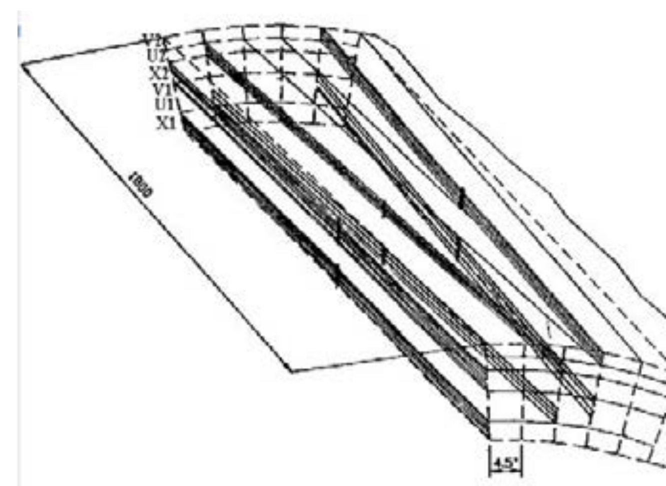
keeping excellent spatial resolution

*acceleration in E-field and deceleration through collisions with gas molecules are in balance

2.3 Drift detectors

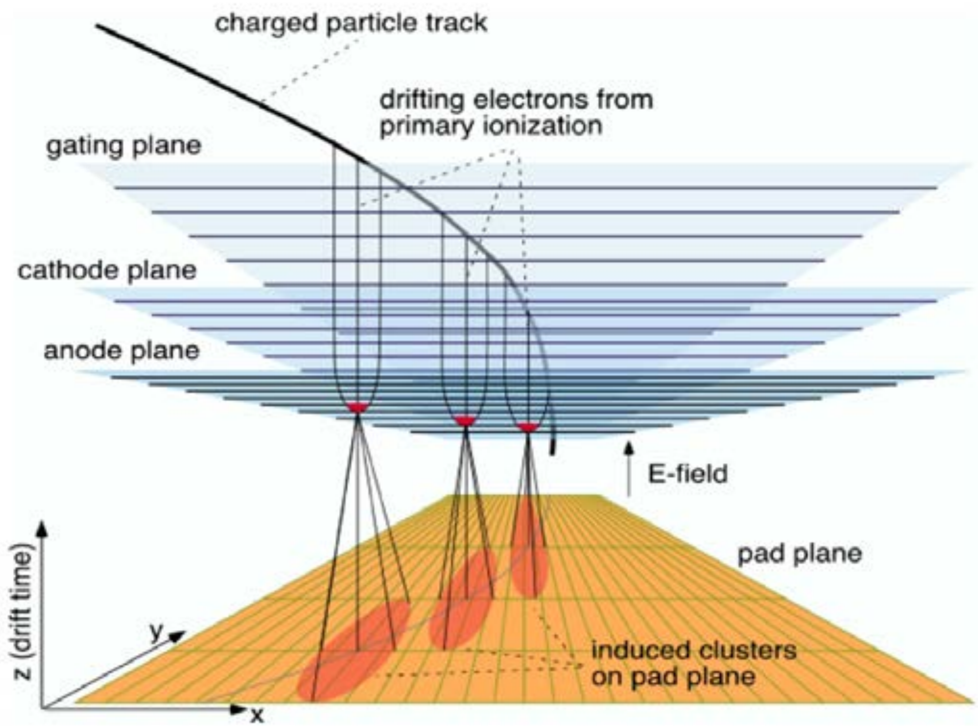


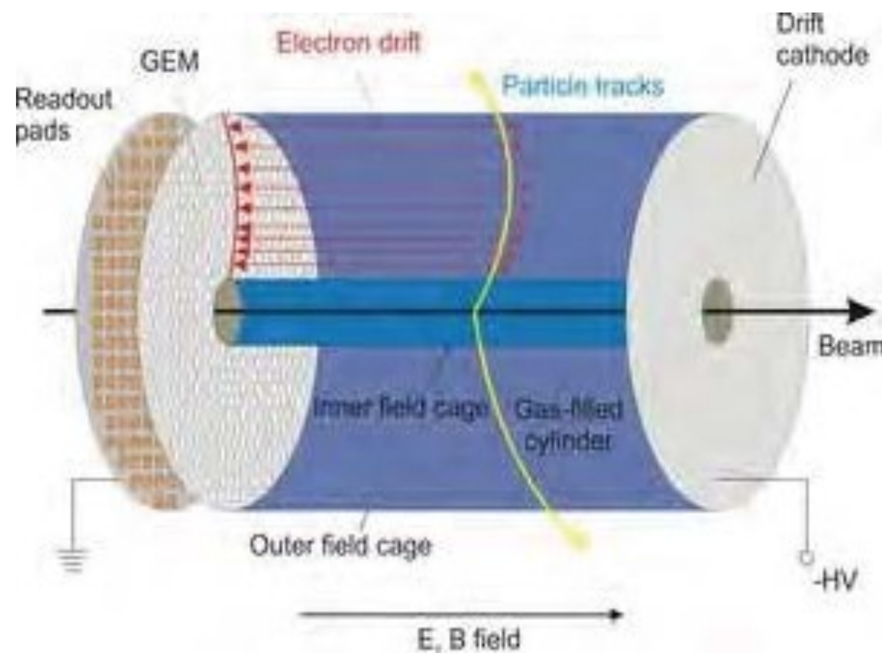




3D- detection device [D.R. Nygren et al., Phys. Today 31, 46 (1978)]

Combine 2-D planar amplification chamber (e.g. GEM) for x/y coordinates
with drift principle for z-coordinate

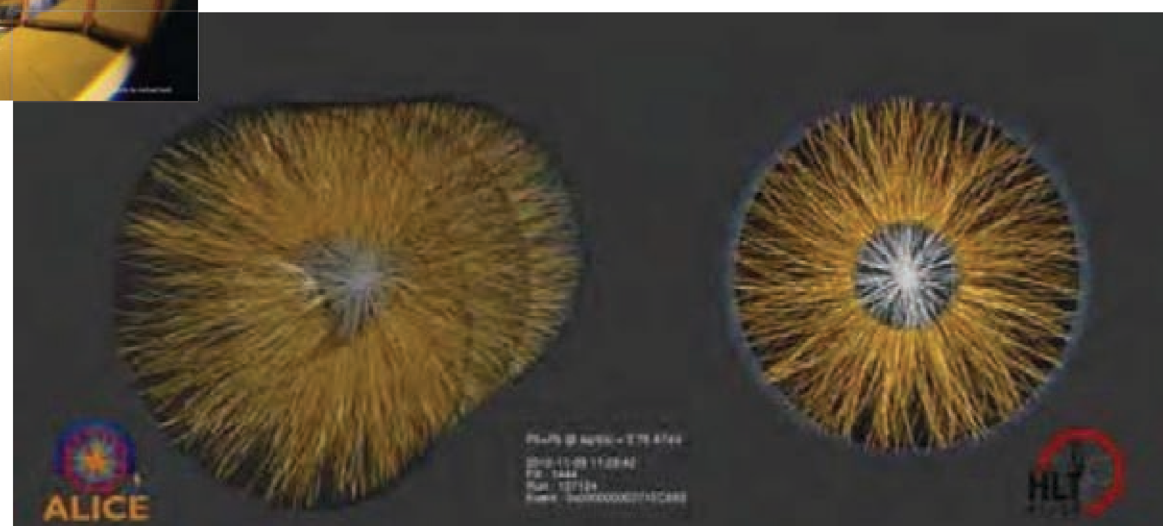




E18 - TUM

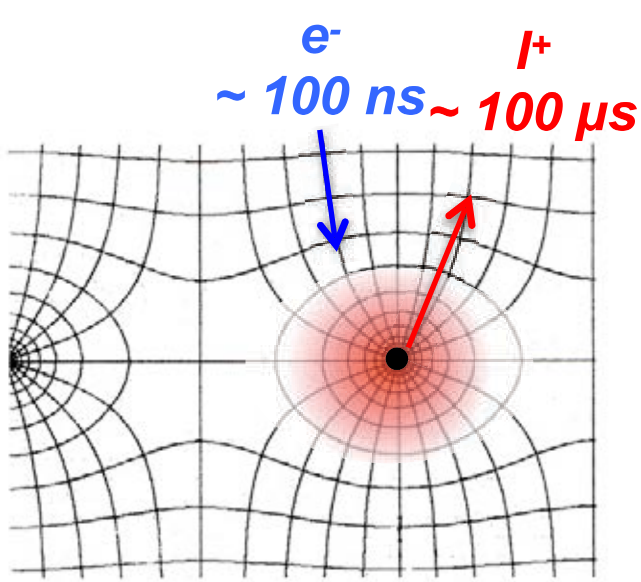
2.4 TPC II

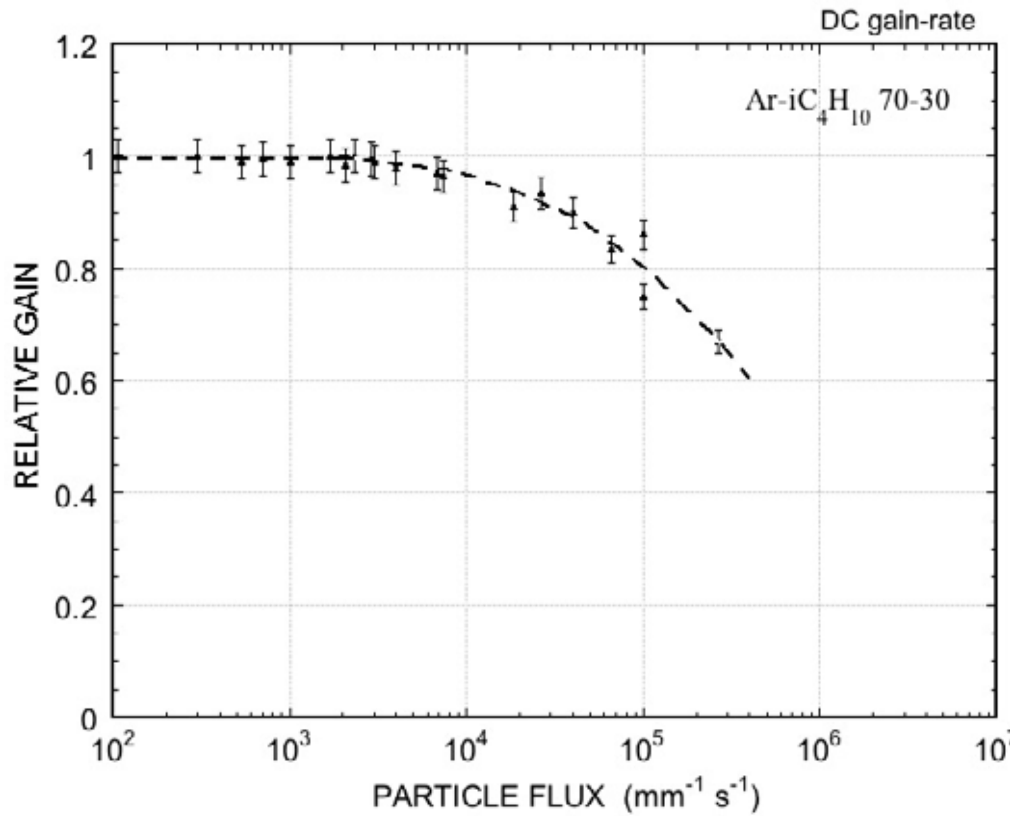
ALICE@CERN TPC field cage



Limitations of Wire-based Detectors

- Localization accuracy: typ. 100-500 μm
- Volume / 2-track resolution: typ. 10×10×10 mm³ (signal induction on pads)
- Rate capability: limited by build-up of positive space-charge around anode

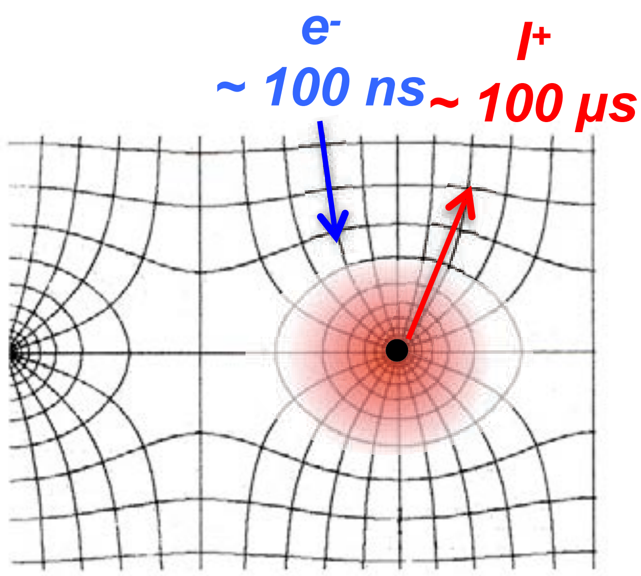




[A. Breskin et al., NIM 124, 189 (1974)]

Limitations of Wire-based Detectors

- Localization accuracy: typ. 100-500 μm
- Volume / 2-track resolution: typ. 10×10×10 mm³ (signal induction on pads)
- Rate capability: limited by build-up of positive space-charge around anode
- Ion backflow: $IB = I_{cathode} / I_{anode}$ ~ 30% for TPC with MWPC

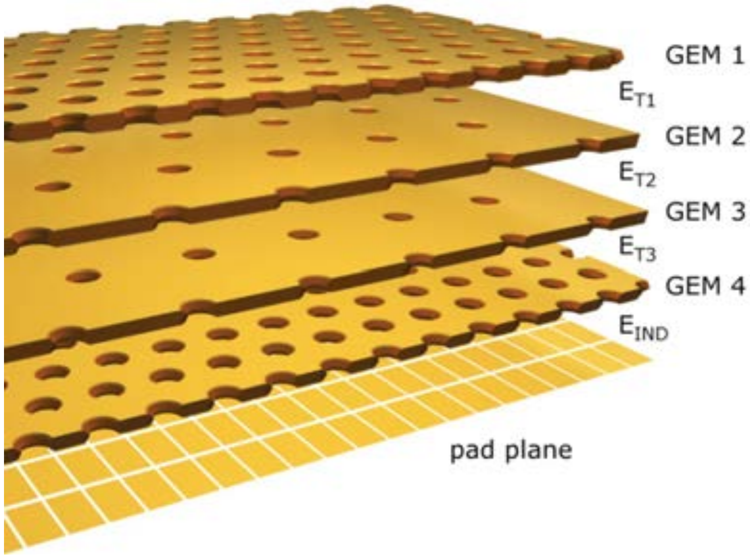


2.4 TPC II

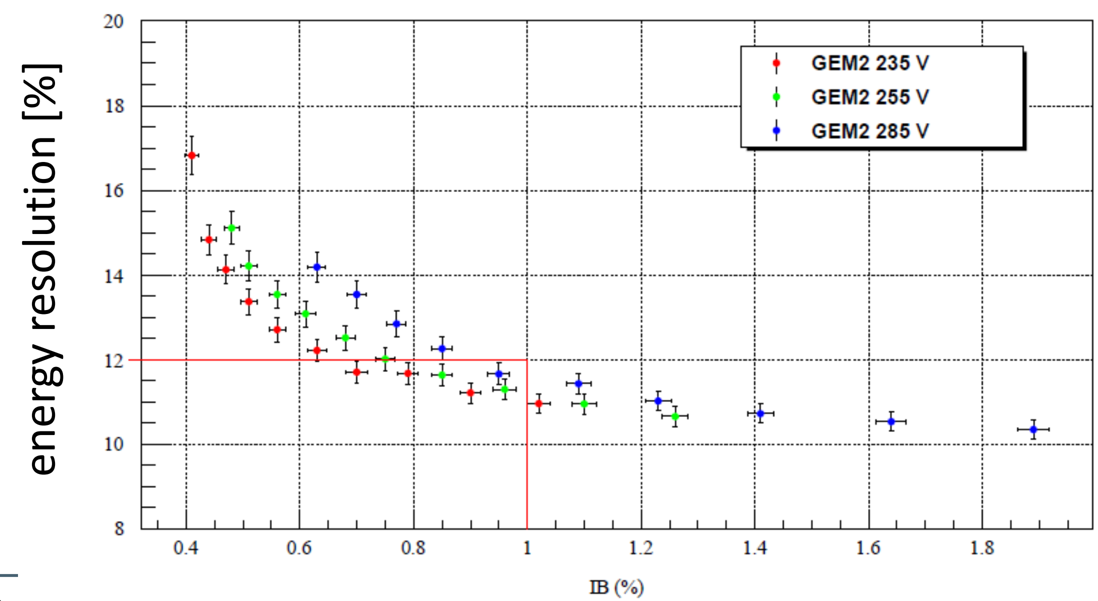
Use GEM detectors to reduce ion feed back problem

This allows continuous readout (film), no gating of amplification region required

2.4 Ion Backflow – ALICE Solution

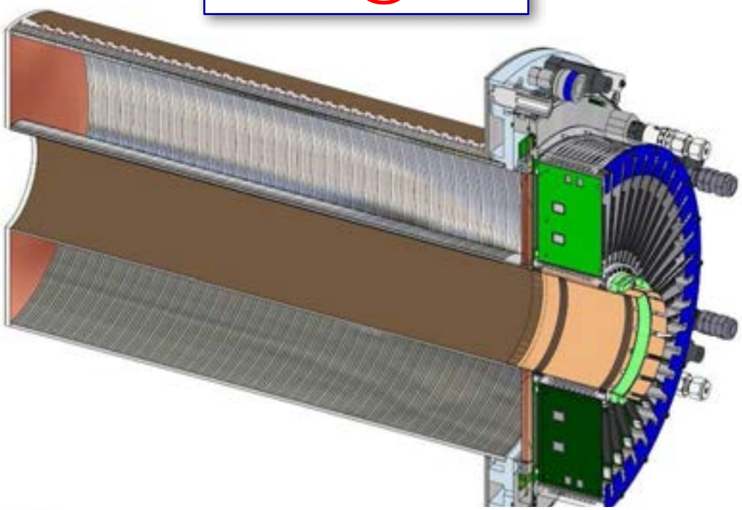


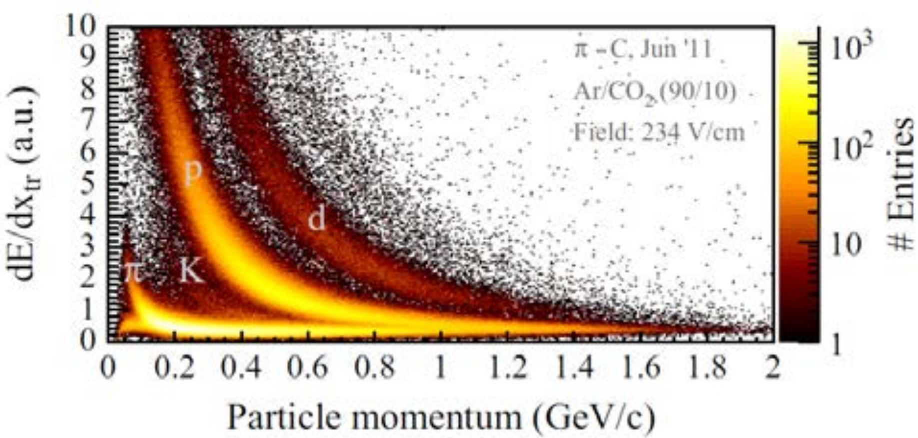
- Triple-GEM setup not sufficient
- New chambers: 4-GEM setup with standard (S) and large pitch (LP)
- Field configuration optimized to provide
  - IB < 1%
  - $\sigma_E/E < 12\%$ (for ^{55}Fe X-rays)
  - Discharge stability



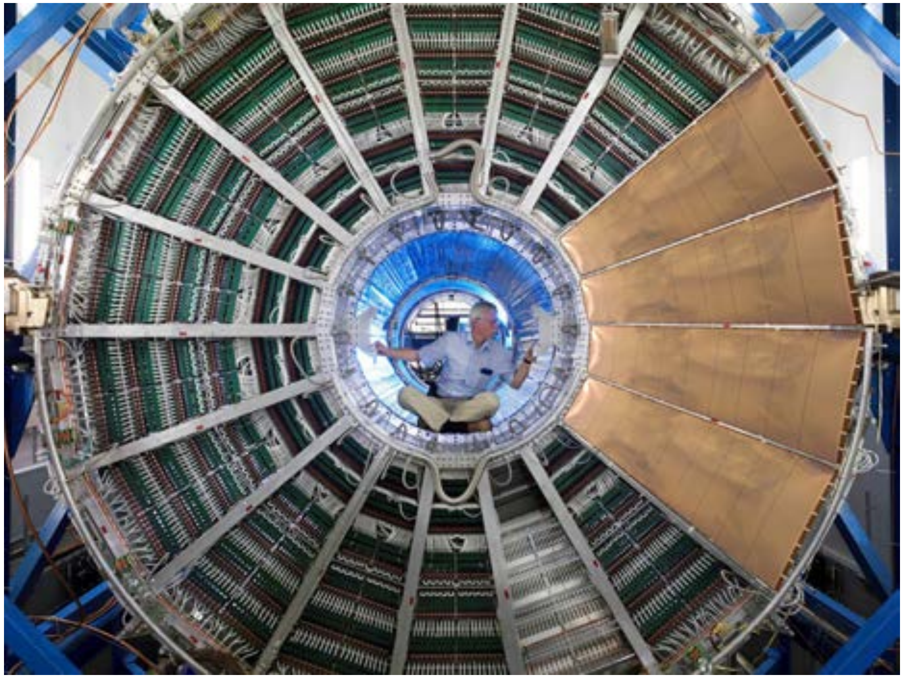
2.4 GEM-TPC

FOPI @ GSI





ALICE



[B. Ketzer et al., NIM A 732, 237 (2013),
M. Ball et al., arXiv1207.0013, 2012,
F.V. Böhmer et al., NIM A 737, 214 (2014)]