Mitglied der Helmholtz-Gemeinschaft

JÜLICH
FORSCHUNGSZENTRUM

Lecture B4

DETECTION CONCEPTS

Detlev Gotta

Institut für Kernphysik, Forschungszentrum Jülich / Universität zu Köln

“Autumn Lectures” – Nuclear and Medical Physics

Tbilisi, Georgian Technical University (GTU)

October 18, 2013

OVERVIEW

SIGNAL CREATION

ELECTRONICS PULSE

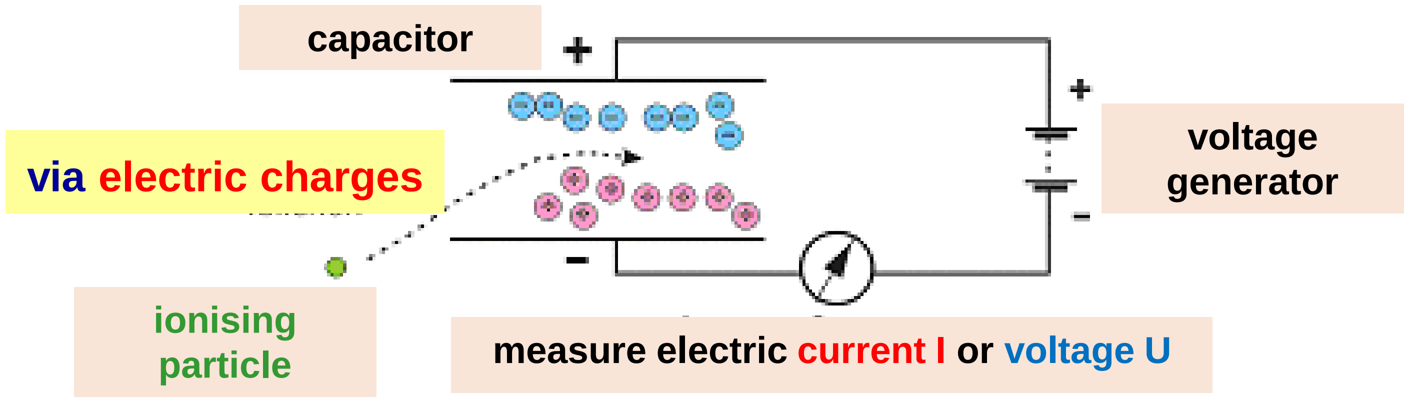
COUNTING & STATISTICS

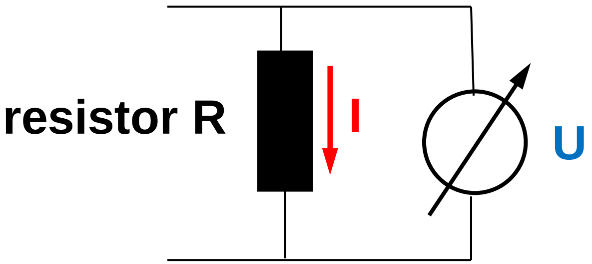
PARTICLE IDENTIFICATION

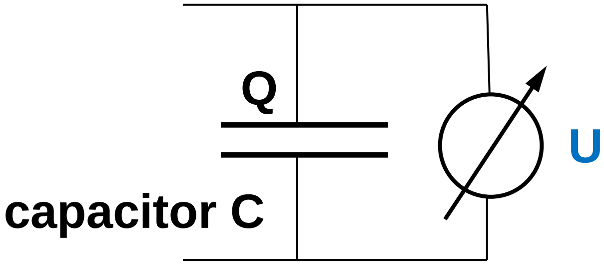
TRACKING

CONTINUOUS SYMMETRIES - CONSERVATION LAWS OF “MOTION”

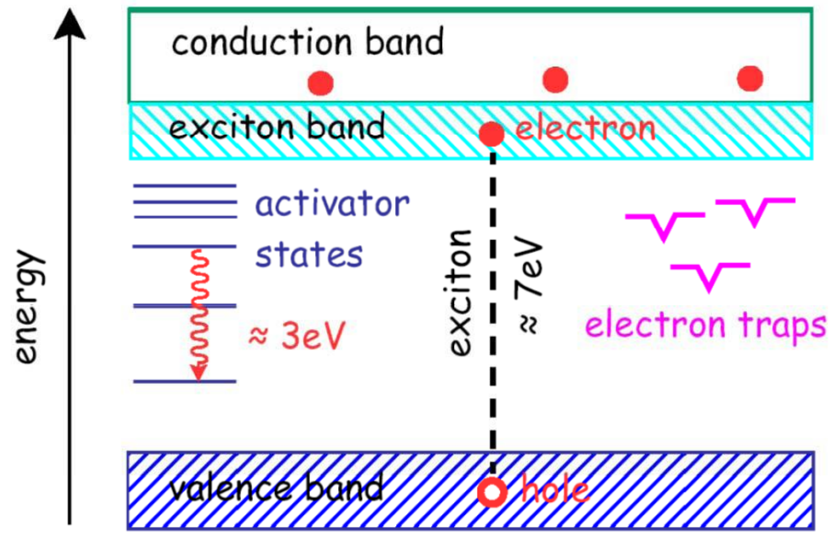
SIGNAL CREATION







SCINTILLATORS produce “CHARGE → LIGHT → CHARGE”



⇒

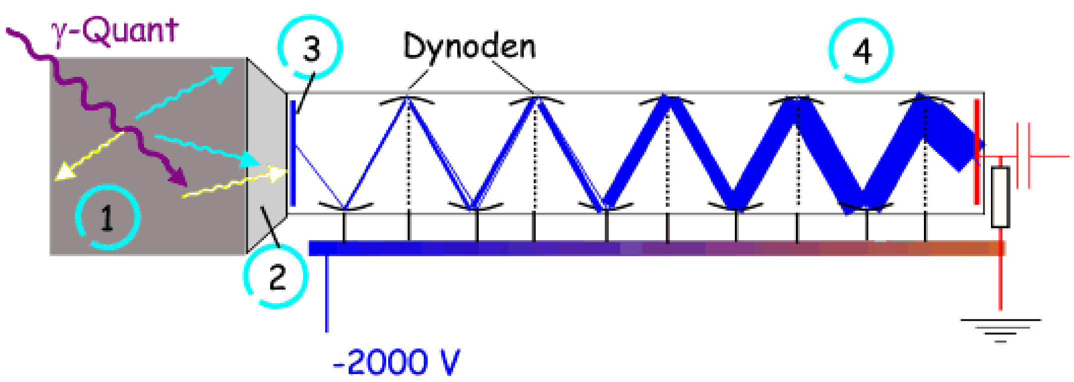
ionisation caused by

charged particles or light

excitation and delayed light emission

usually in the UV range

anorganic	NaI(Tl), CSI, BaF_2, …
inorganic	*doped „plastics“*



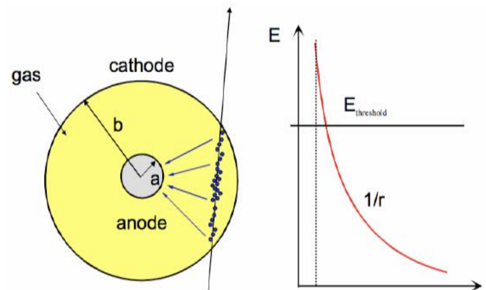
UV light is converted to charge

at a photo cathode and

multiplied by a multi stage

photo „multiplier“

CHARGE MULTIPLICATION



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

$$V(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \ln\frac{r}{a} \qquad C = \text{capacitance / unit length}$$

electron multiplication around anode (fast)

drift of ions (slow)

typical ion drift velocity:
1 - 10 cm/(μs·kV)
Ar CH_4

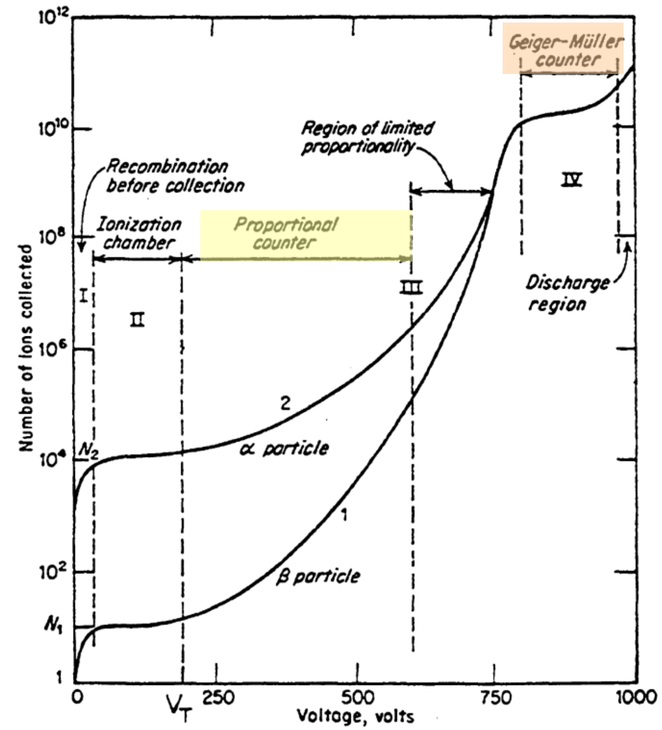
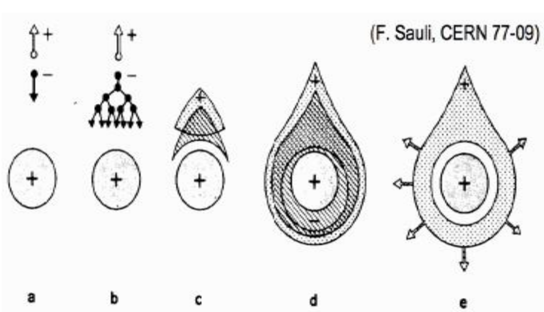


Fig. 50 Gain-voltage characteristics for a proportional counter, showing the different regions of operation (from W. Price, see bibliography for Sections 2 and 3).

multiplication → avalanche

gain 10^5 - 10^6



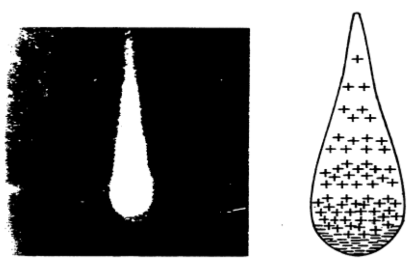


Fig. 46 Drop-like shape of an avalanche, showing the positive ions left behind the fast electron front. The photograph shows the actual avalanche shape, as made visible in a cloud chamber by droplets condensing around ions[18].

measuring gas: e.g., Ar, Xe, …

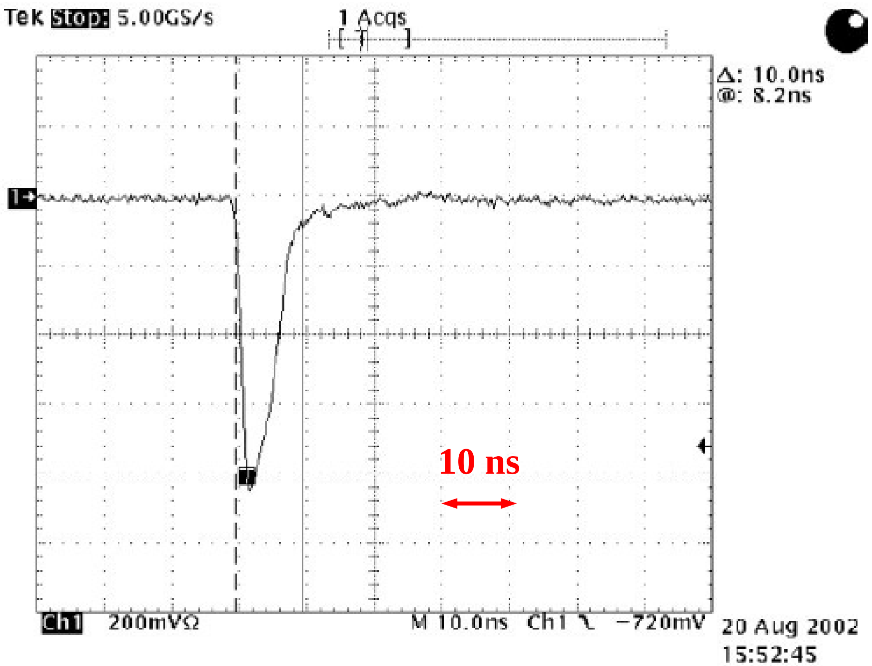
to control avalanche: add quench gases, e.g. CO_2, CH_4, C_2H_6

wire chambers tutorial:

F. Sauli, CERN yellow report 99-07

ELECTRONICS PULSE I

as seen on an oscillopscope



deposited energy ~
# of elektrons

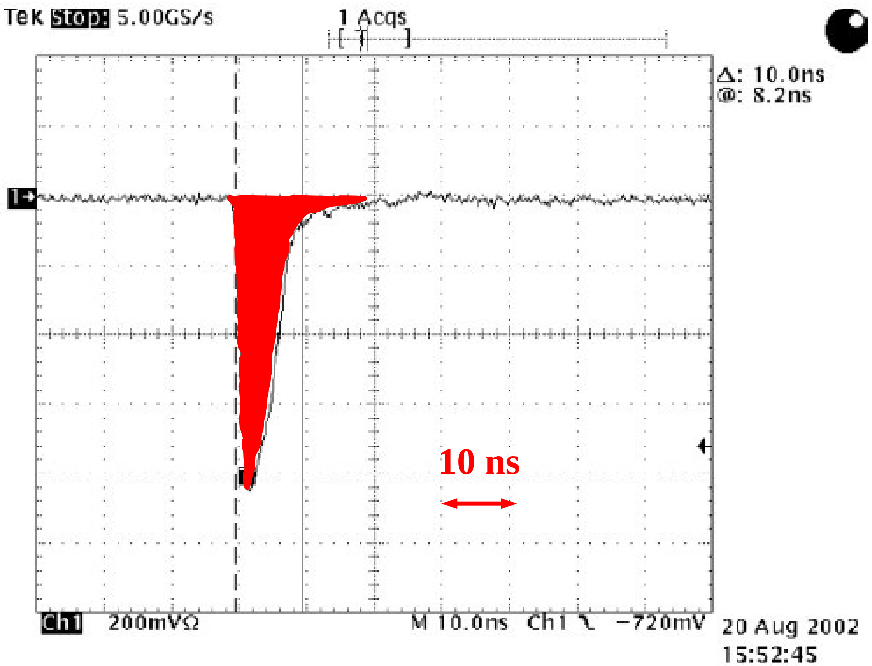
= integrated charge

= area under the peak
dQ = I dt = U/R dt

voltage peak at phototube anode: pulse height and integrated charge
result per event: energy information
for many events: **histogram or spectrum**

ELECTRONICS PULSE II - ENERGY

as seen on an oscillopscope



deposited energy ~
\# of elektrons

= integrated charge

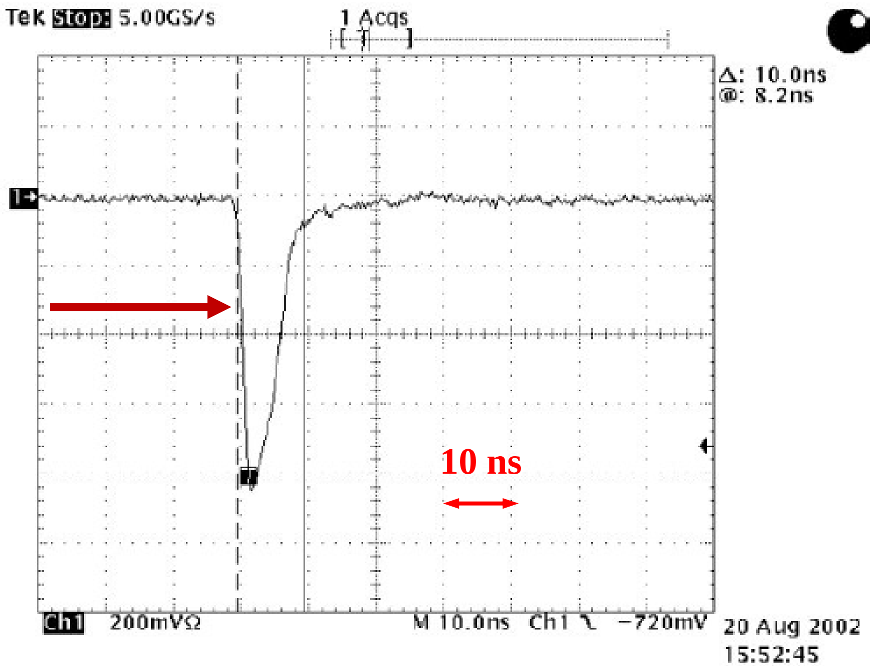
= area under the peak
dQ = I dt = U/R dt

Integral ∝ deposited charge ∝ deposited energy

→ *digitization by ADC*

ELECTRONICS PULSE - TIME

as seen on an oscillopscope



deposited energy ~
# of elektrons

= integrated charge

= area under the peak
dQ = I dt = U/R dt

→ trigger level of discriminator - analogue → digital pulse

COUNTING & STATISTICS

signal

R: ***true event rate***

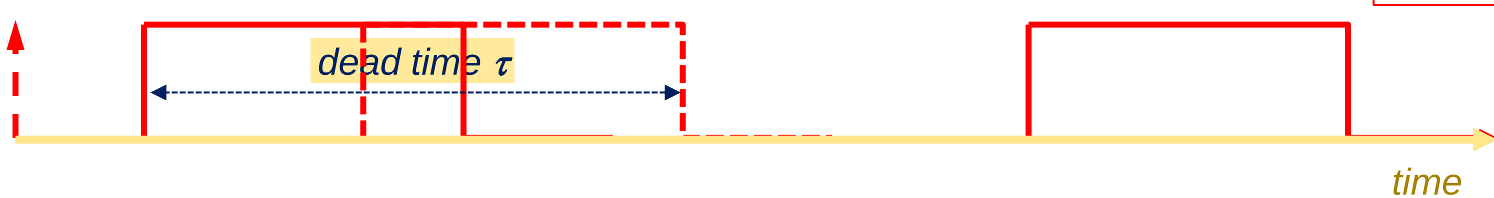
R‘: measured event rate

response on non-paralyzing device

$$R = \frac{R'}{1 - R \cdot \tau}$$

response on paralyzing device

$$R' = R \cdot e^{-R \cdot \tau}$$



PARTICLE IDENTIFICATION I

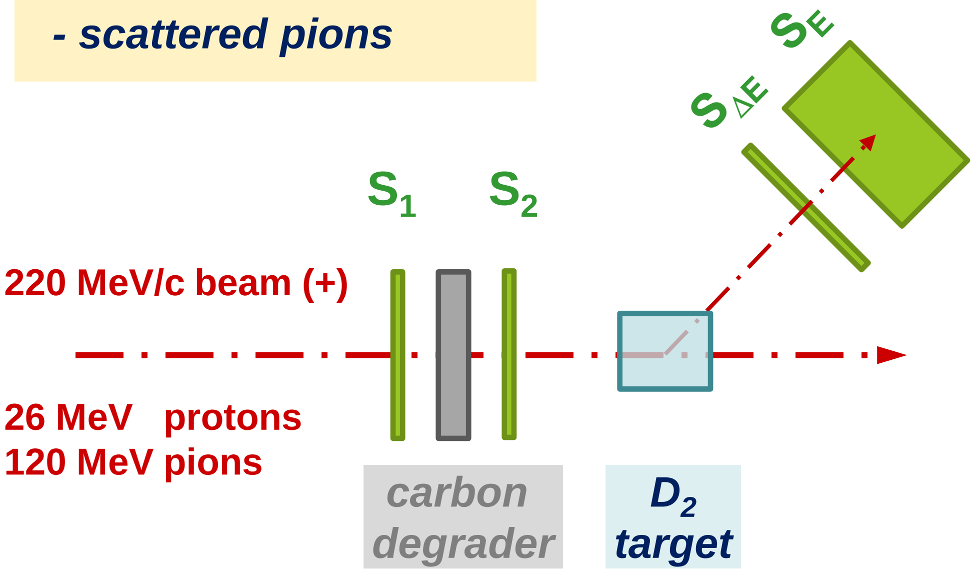
$\pi^+ d \rightarrow p\, p$

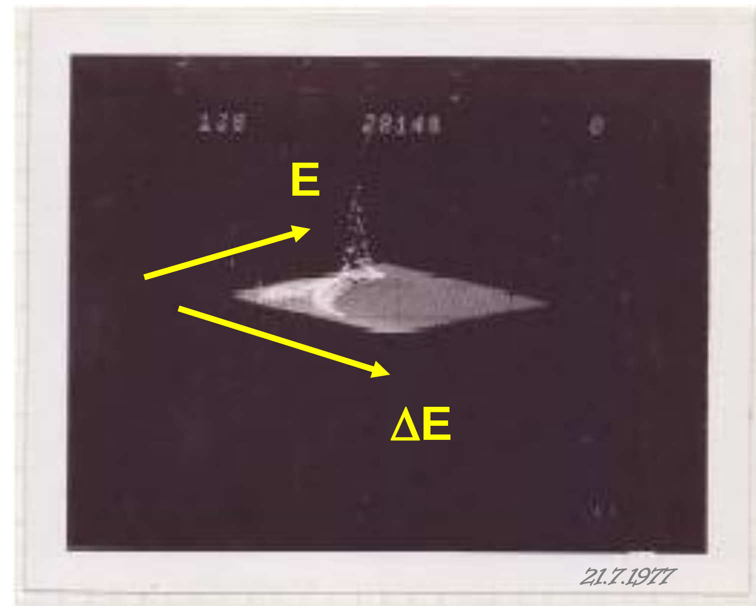
problems

- beam contamination

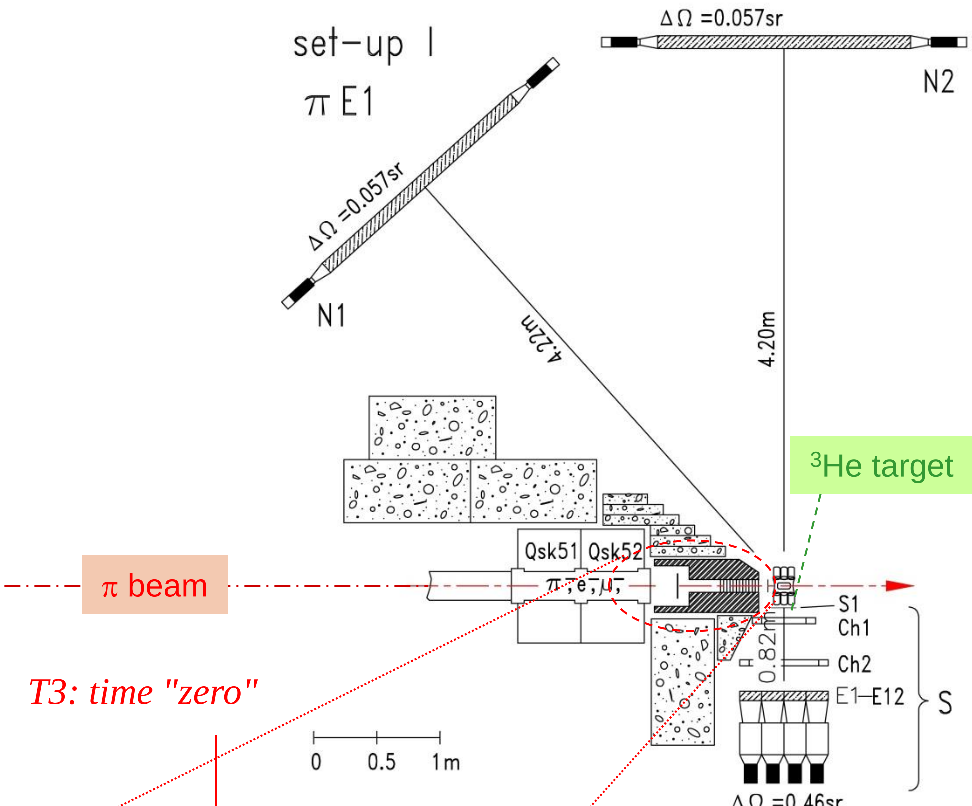
- scattered pions

particle identification by energy loss (ΔE)

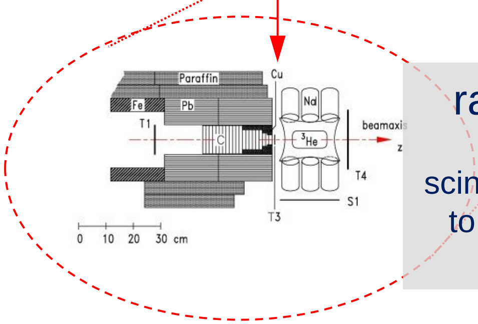




PARTICLE IDENTIFICATION II



T3: time "zero"

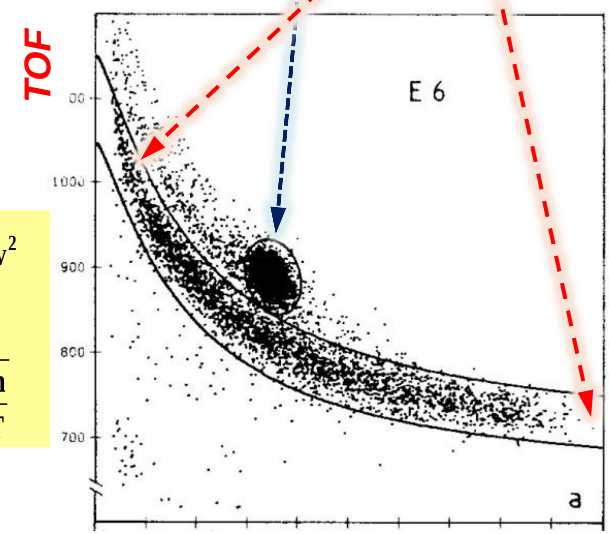


range telescope
=
scintillator/degrader stack
to stop beam particles
in the target

particle identification by time-of-flight (TOF)

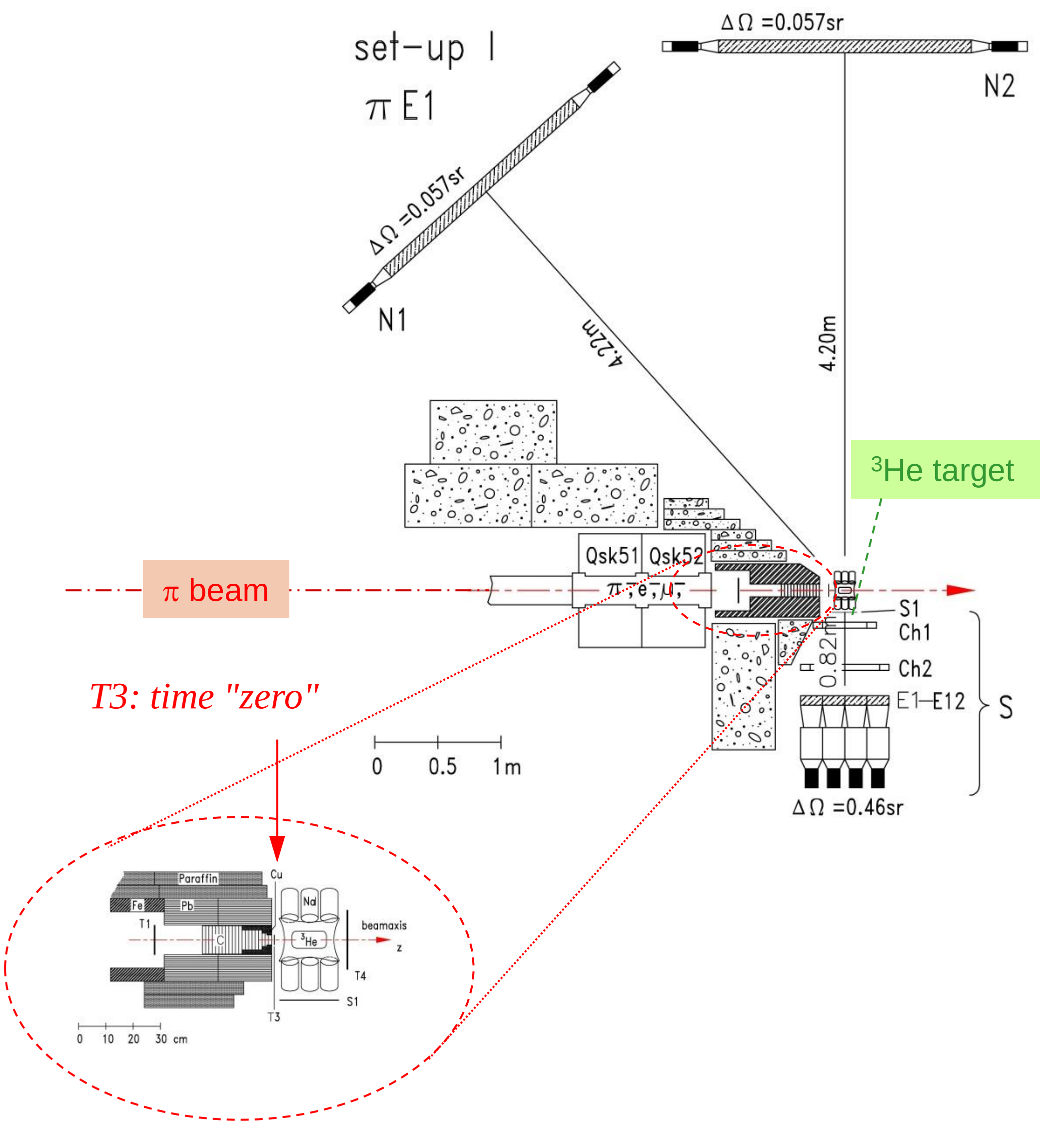
$$\pi^- \, ^3He \rightarrow dn + pnn$$

$$T = \frac{m}{2} v^2$$
$$\Downarrow$$
$$\Delta t \propto \sqrt{\frac{m}{T}}$$



ADC value $\propto T_{kin}$

PARTICLE IDENTIFICATION III

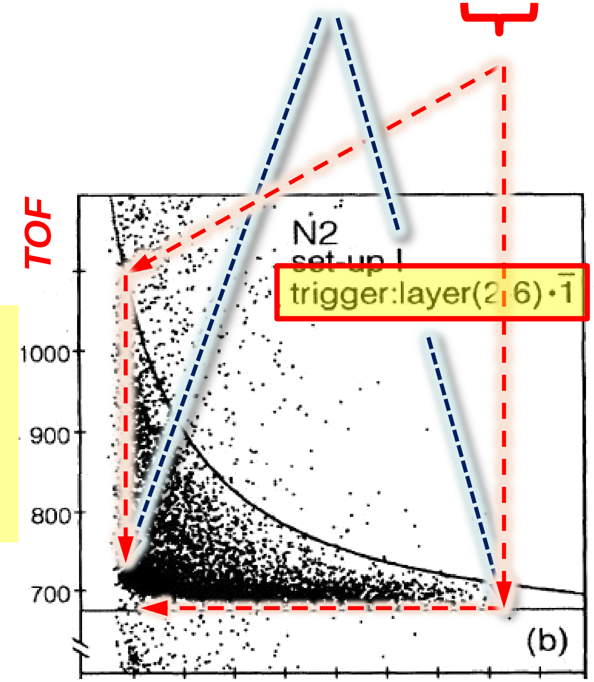


neutron identification by

VETO & time-of-flight (TOF)

$$\pi^- \, {}^3He \rightarrow dn + pnn$$

$$T = \frac{m}{2} v^2 \quad \Downarrow \quad \Delta t \propto \sqrt{\frac{m}{T}}$$



ADC value not ∝ T_{kin}

PARTICLE IDENTIFICATION IV

transition radiation detector (TRD)

about 1% probability per boundary crossing
→ many layers

Usually gas X-ray detectors
like cylindrical proportional chambers
(*straw tube*) filled with a gas mixture
(80% xenon, 20% CO_2)
to minimize the energy loss
of the charged particles.

---

from
http://pamela.physik.uni-siegen.de/pamela/bitmaps/

One straw tube module

One radiator layer

The mass model of the TRD

particle identification by transition radiation

- threshold detectors
- particle discrimination *e.g., e/π separation 1 – 100 GeV*

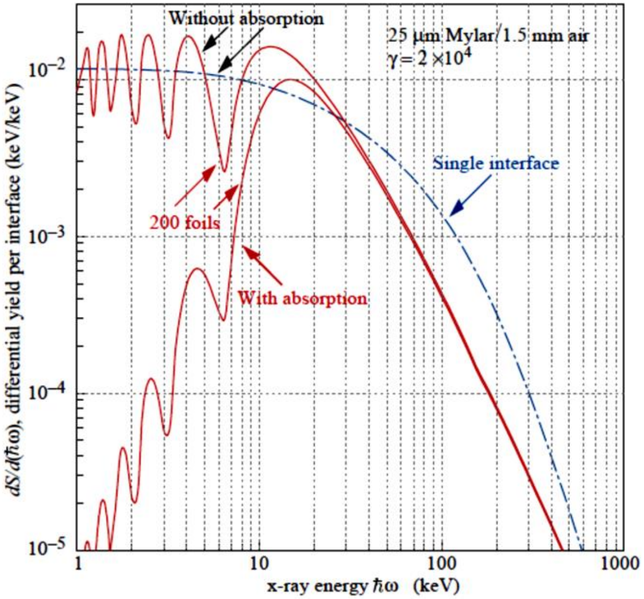


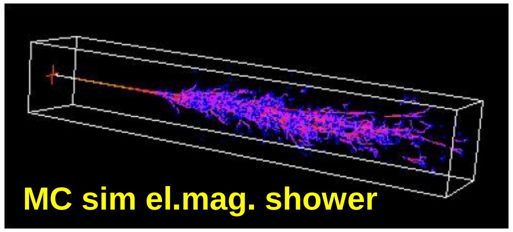
Figure 30.27: X-ray photon energy spectra for a radiator consisting of 200 25 μm thick foils of Mylar with 1.5 mm spacing in air (solid lines) and for a single surface (dashed line). Curves are shown with and without absorption.

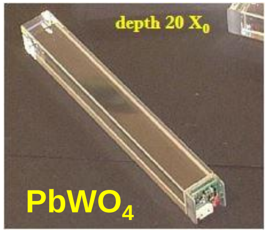
2012 Review of Particle Physics (Particle Data Group), J. Beringer et al., Phys. Rev. D86, 010001 (2012)

CALORIMETRY = measure total energy

electromagnetic shower	short & concentrated	$dE/dx = -E/X_0$
hadronic shower	large & fluctuations	longitudinal $\lambda = A/N_A \cdot \sigma_{abs}$
		transversal fluctuating

resolution $\sigma/E \propto few\,\%/\sqrt{E}$





XIV International Conference on Calorimetry in High Energy Physics (CALOR 2010) IOP Publishing
Journal of Physics: Conference Series **293** (2011) 012073 doi:10.1088/1742-6596/293/1/012073

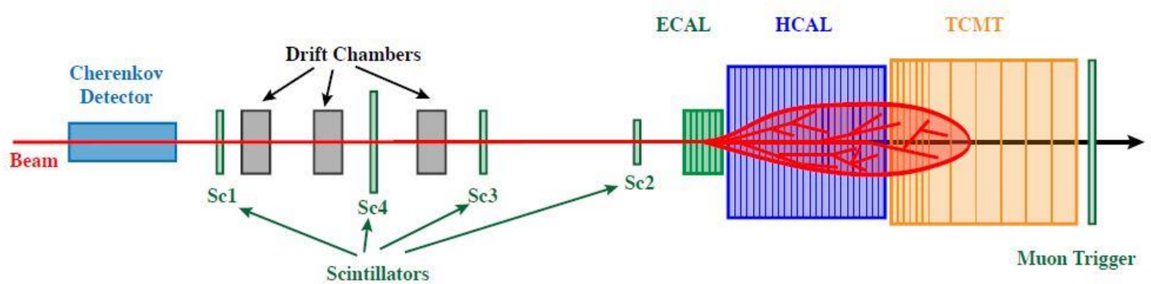


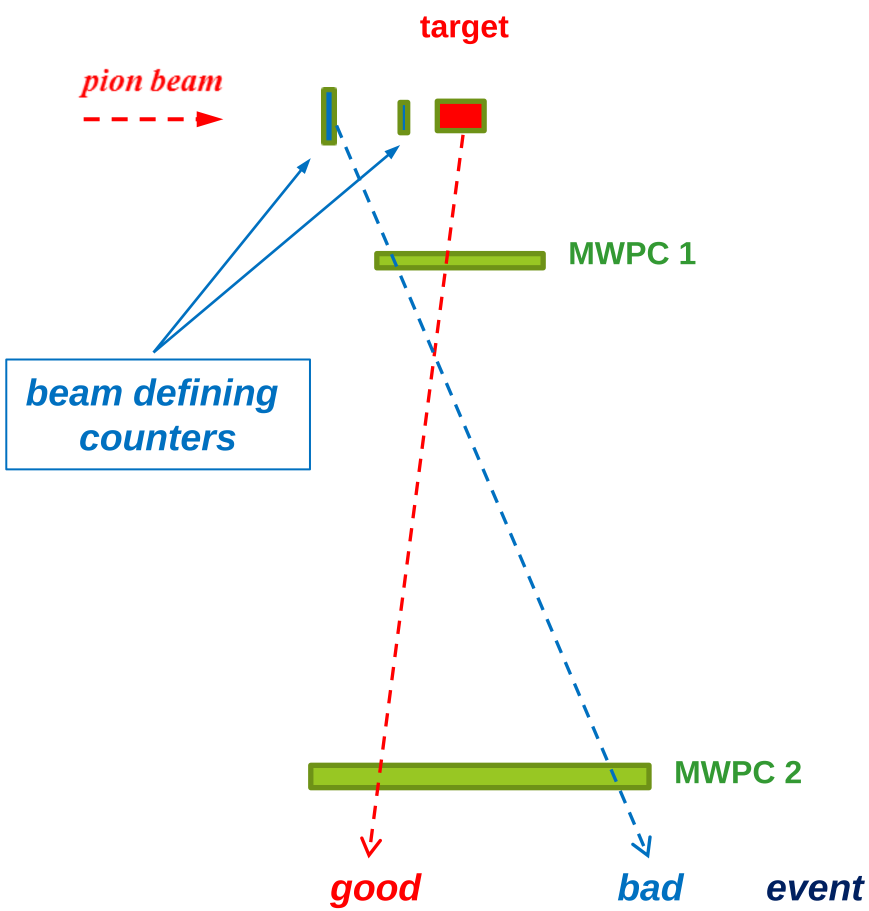
Figure 1. Schematic of the CALICE experimental setup at CERN with electromagnetic and hadronic calorimetry as well as a tail catcher and muon tracker downstream of the calorimeters.

sampling calorimeter

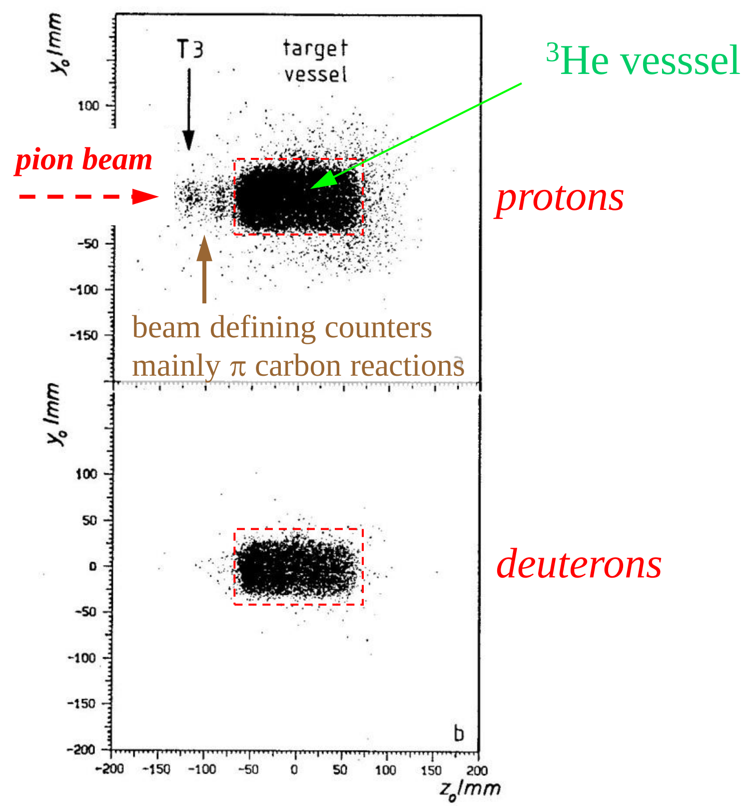
=

segmentation in depth

TRACKING - CUT ON FIDUCIAL VOLUME



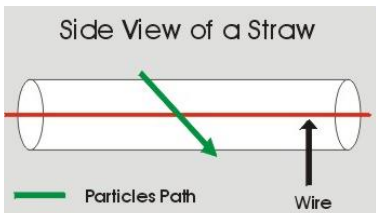
example: $\pi^{-3}He \rightarrow pnn$ or dn



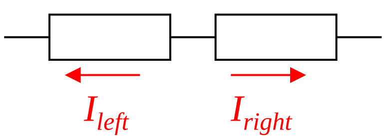
TRACKING DEVICES I - STRAW TUBES

"simple" mechanics
10 MHz rate
inside magnetic field

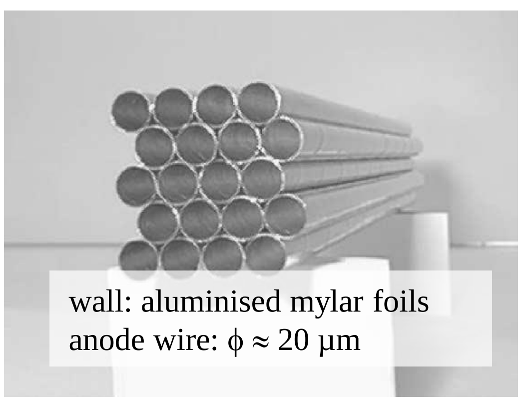
individual counters, timing 20 ns
HV: coat, ground: sense wire (~ kV)
typical size: length 1 - 2 m, ϕ mm - cm

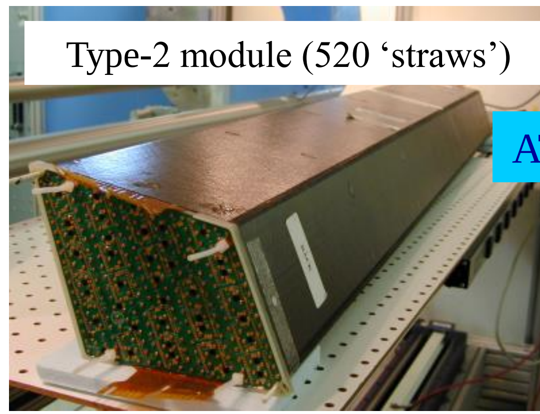


gas filling
e.g., Ar/C_2H_6

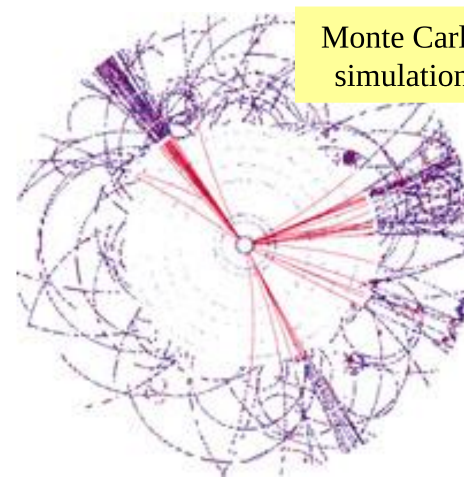


resistive read out
$\Delta z < 1$ mm
z

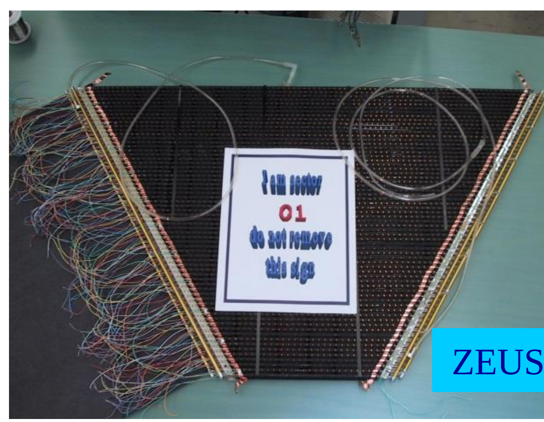




ATLAS at the LHC



Monte Carlo simulation



ZEUS - DESY wedge

TRACKING DEVICES II - WIRE CHAMBERS

many wires: MWPC = multiwire proportional chamber

position resolution ≅ wire distance typically 2 mm

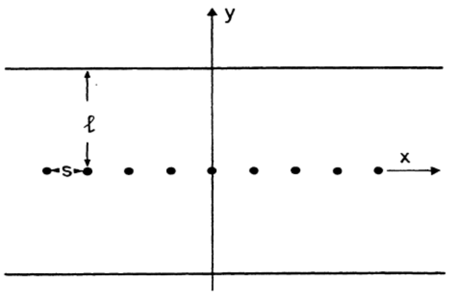


Fig. 55 Principle of construction and definition of parameters in a multiwire proportional chamber. A set of parallel anode wires is mounted symmetrically between two cathode planes (wires or foils).

field configuration

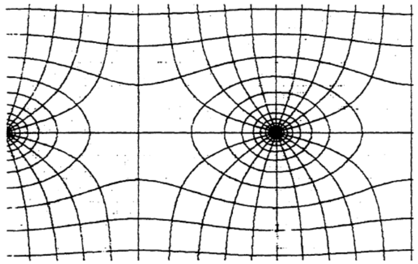
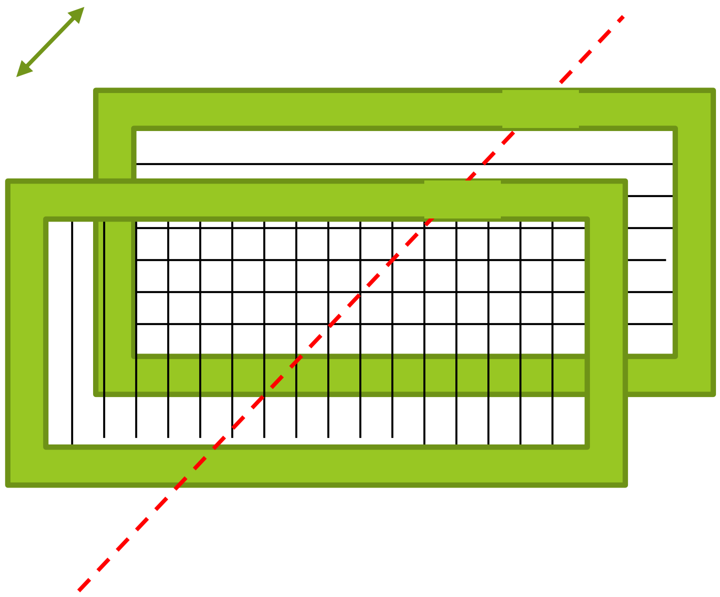


Fig. 57 Enlarged view of the field around the anode wires (wire spacing 2 mm, wire diameter 20 μm) [37]



- ***(x,y) - coordinate per pair of frames***
- ***trajectory from MWPC stacks***

TRACKING DEVICES III - DRIFT CHAMBERS a

time ⇔ position

external time reference, e.g., plastic scintillator

trick: choose field configuration, which keeps the nonlinearity of time-to-position relation small

position resolution

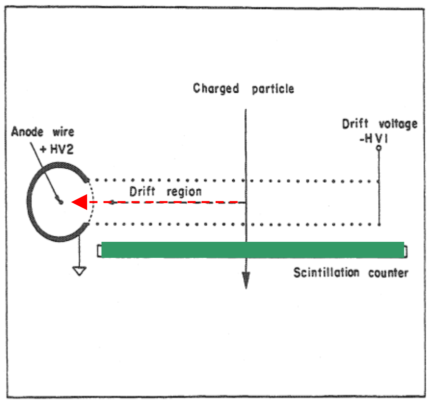


Fig. 85 Principle of operation of a single-cell drift chamber. A set of cathode wires, at suitable potentials, generate in the drift space a region of uniform field. The electrons produced by an ionizing event migrate to one end of the cell, where avalanche multiplication occurs in a single wire proportional counter. The coordinate is then proportional to the time of drift (the time reference being given by an external scintillation counter).

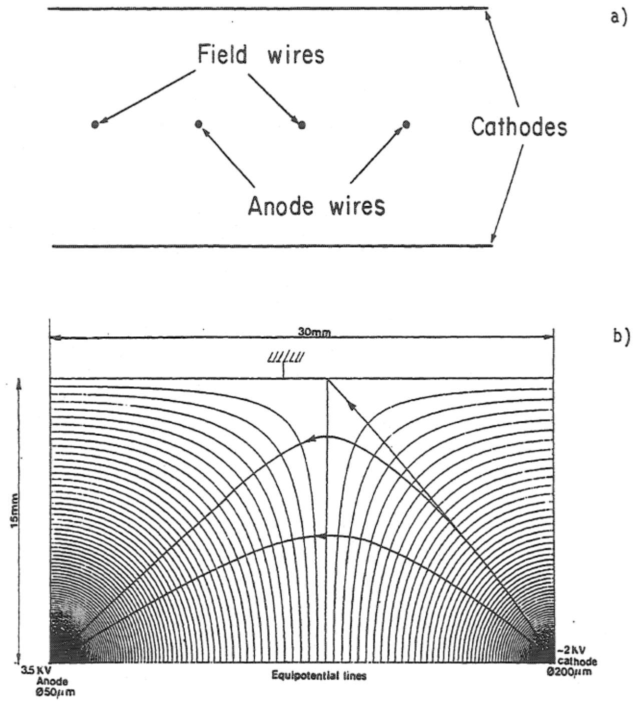


Fig. 86 Principle of the multiwire drift chambers with uniform cathode planes: (a) the basic geometry and (b) the electric field equipotentials in a chamber having 2 × 15 mm gap and 60 mm between anode wires[75].

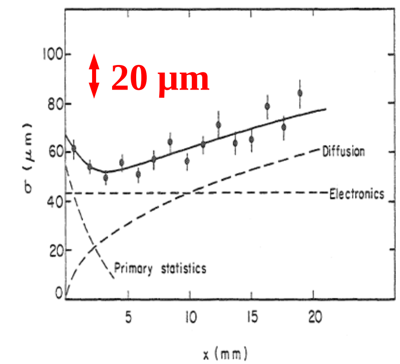
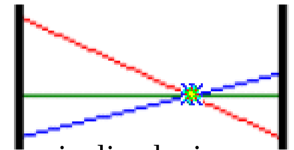
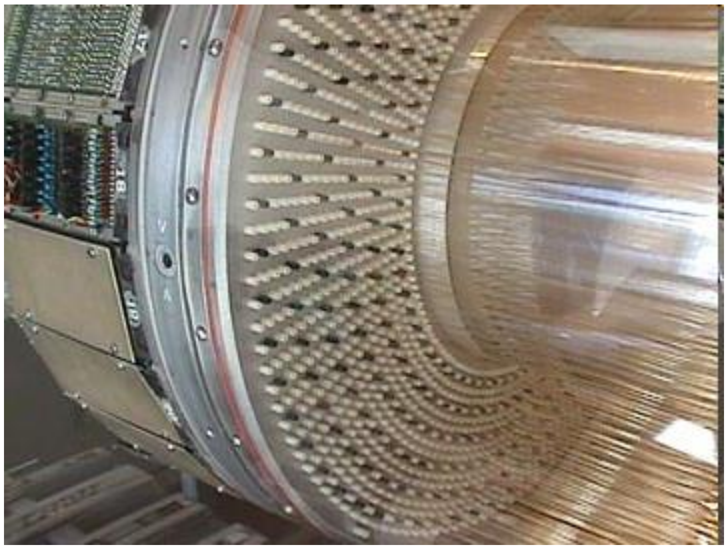


Fig. 94 Measured intrinsic accuracy in the drift chamber of Fig. 88, as a function of drift space[10]. The experimental results have been decomposed into three contributions: a constant electronics dispersion, a physical diffusion term function of the square root of the drift space, and a contribution of the primary ion pair statistics.

TRACKING DEVICES III - DRIFT CHAMBERS b

improved position resolution by nearest 3 wires method





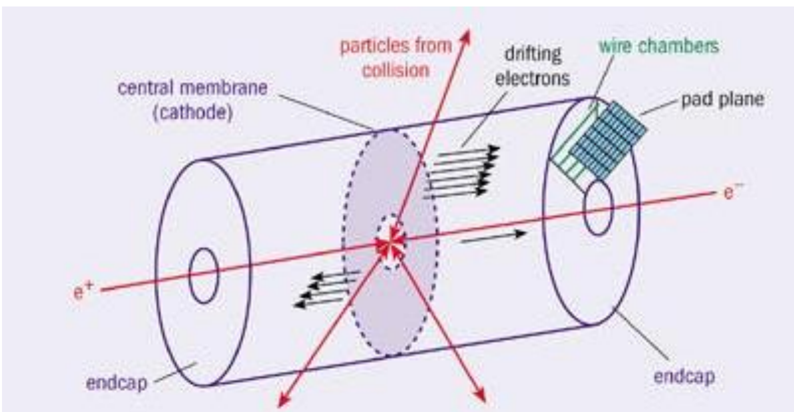
The wires are arranged in layers that pass through the cylinder at three different angles. The set of wires that give a signal can be used to allow computer reconstruction of the paths (or tracks) of all the charged particles through the chamber.

The "drift" in the name of this chamber refers to the time it takes electrons to drift to the nearest sense wire from the place where the high-energy particle ionized an atom. Any three sense wires are only nearby in one place so a set of "hits" on these three fix a particle track in this region. By measuring the drift time, the location of the original track can be determined much more precisely than the actual spacing between the wires.

TRACKING DEVICES IV - TIME PROJECTION CHAMBER

motivation: *avoid to pile-up many MWPC planes (typical gas thickness of 1 cm)*
David Nygren, 1974

principle: ***electrons produced follow the <u>constant</u> electric field lines to a single MPWC plane located at one end of the volume (x-y coordinates on this plane)***
Third coordinate, z, from the drift time of the electrons to the anode plane



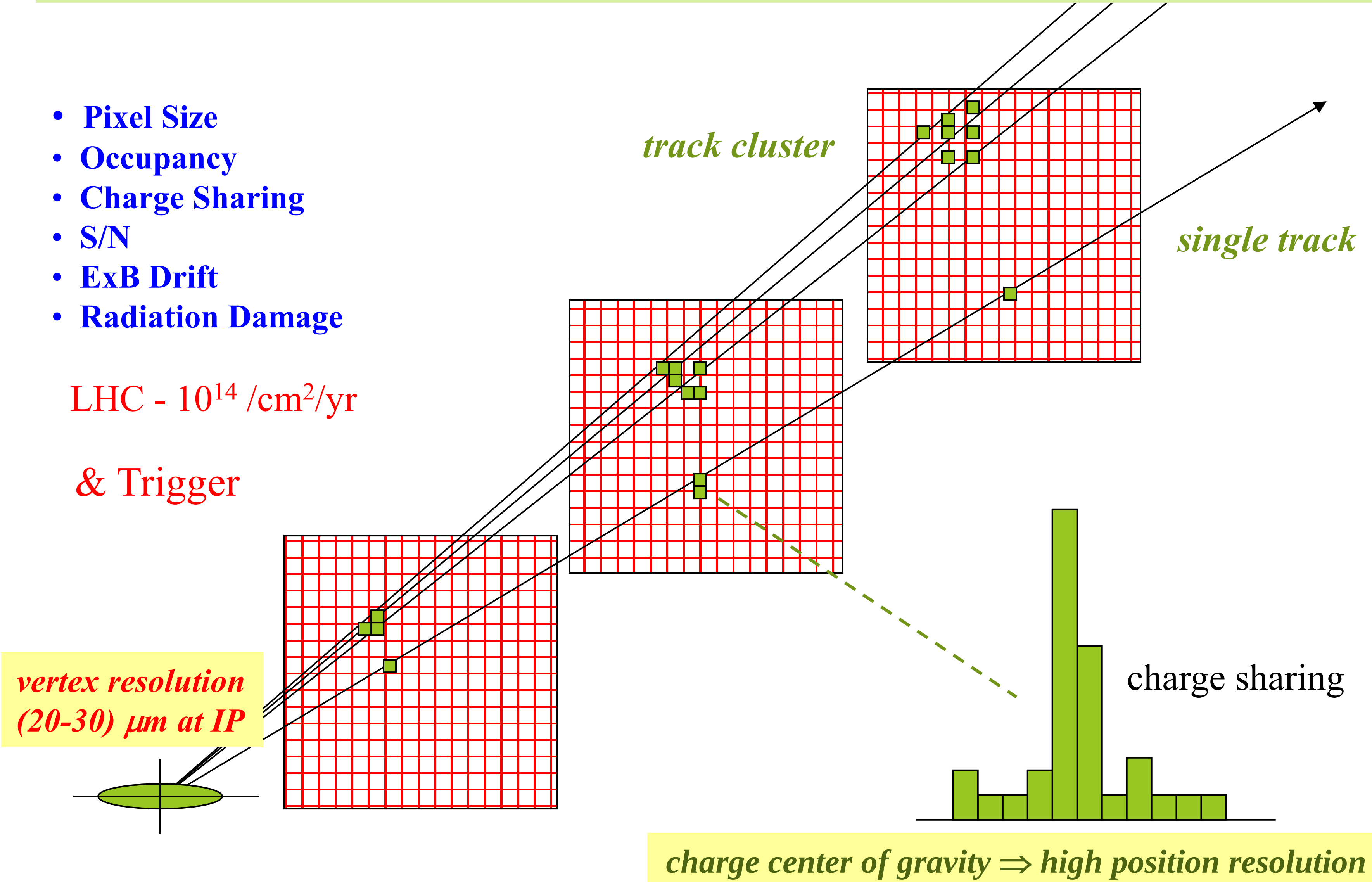
properties:
- full 3-dimensional detector
- constant drift velocity due to the collisions in the gas mixture (typical a few cm/µs).
- low occupancy even for high background (high rates)
- large dE/dx due to large gas thickness (particle identification)

TRACKING DEVICES V - PIXEL TRACKER

- **Pixel Size**
- **Occupancy**
- **Charge Sharing**
- **S/N**
- **ExB Drift**
- **Radiation Damage**

LHC - 10^{14} /cm^2/yr

& Trigger



TRACKING DEVICES VI - SILICON MICRO-STRIP DETECTORS a

principle

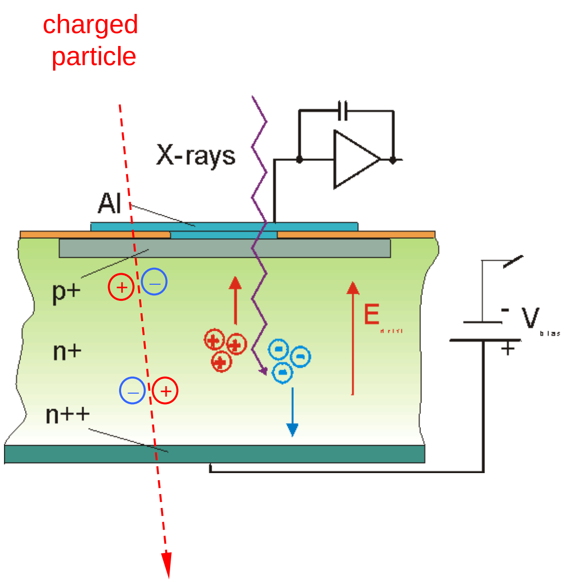
pn diode

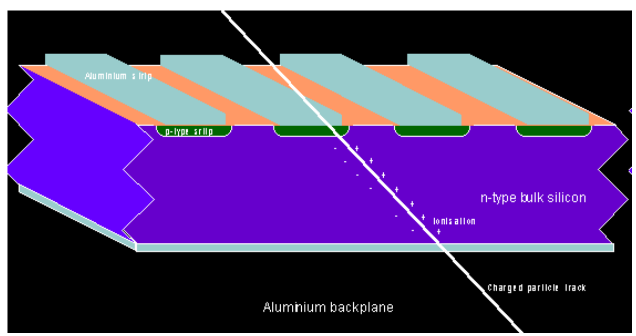
as almost all
semiconductor detectors

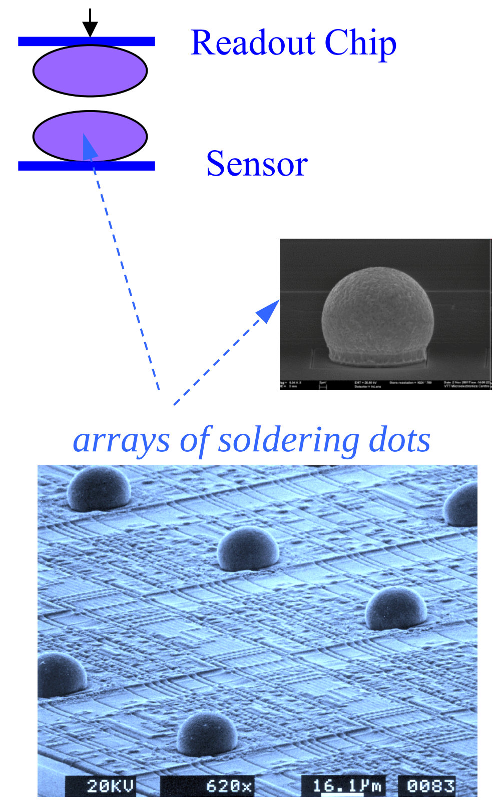
typical x-y (front-back)
arrangements

200 µm strips
layer thickness 300 µm

miniaturisation



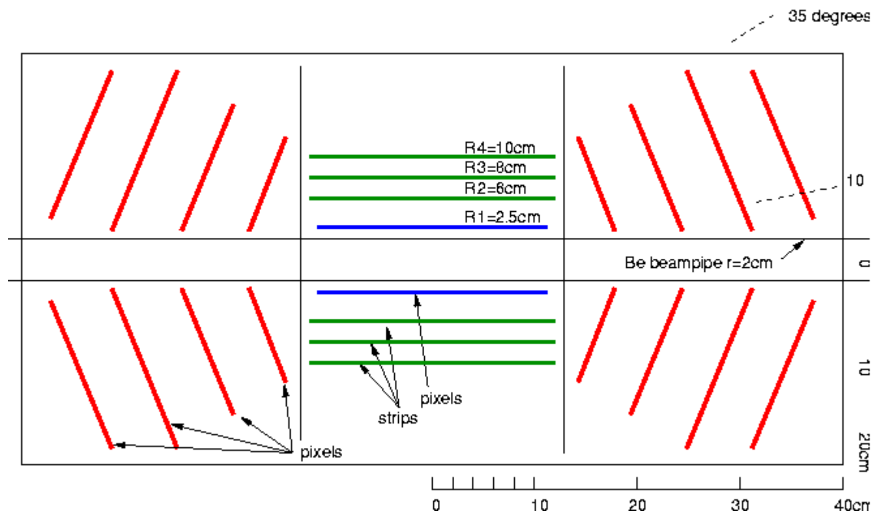




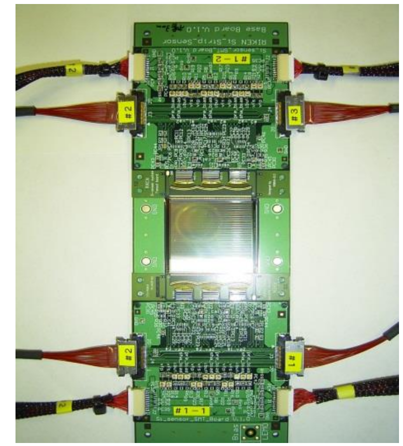
TRACKING DEVICES VI - SILICON MICRO-STRIP DETECTORS b

CMS - LHC scheme

- *inner tracker*

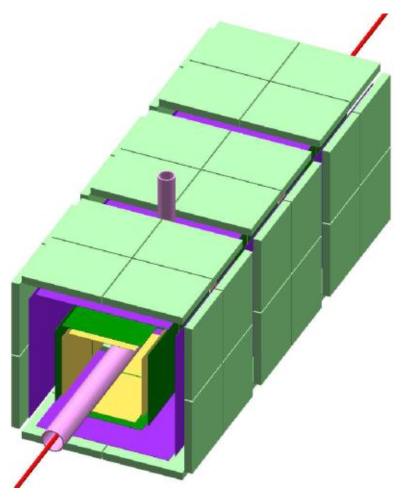


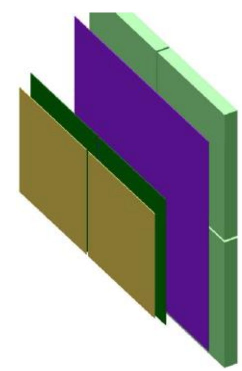
silicon µ-strip module



ANKE - COSY

- *vertex detection*
- *recoils*
- *polarisation (left-right asymmetry)*





semiconductor telescope
65/300/300/5500 µm thick
double-sided Si-strip detectors

CONTINUOUS SYMMETRIES - CONSERVATION LAWS OF "MOTION"

reactions

SYMMETRY	2-2 scattering	decay $1 \to 2 + 3 + 4$
total energy *TIME*	$E_1 + E_2 = E_3^{'} + E_4^{'}$	$E_1 = E_2^{'} + E_3^{'} + E_4^{'}$
momentum *TRANSLATION*	$\vec{p}_1 + \vec{p}_2 = \vec{p}_3^{\,'} + \vec{p}_4^{\,'}$	$\vec{p}_1 = \vec{p}_2^{\,'} + \vec{p}_3^{\,'} + \vec{p}_4^{\,'}$
angular momentum *ROTATION*	$\vec{L}_{12} + \vec{S}_1 + \vec{S}_2 = \vec{L}_{34} + \vec{S}_3 + \vec{S}_4$	$\vec{S}_1 = \vec{L}_{23} + \vec{L}_{(23)4} + \vec{S}_2 + \vec{S}_3 + \vec{S}_4$
examples	elastic scattering $p + p \to p + p$	β - decay $n \to p + e^{-} + \bar{\nu}_e$

KINEMATICS EXAMPLE : $A \rightarrow 1 + 2 + 3$

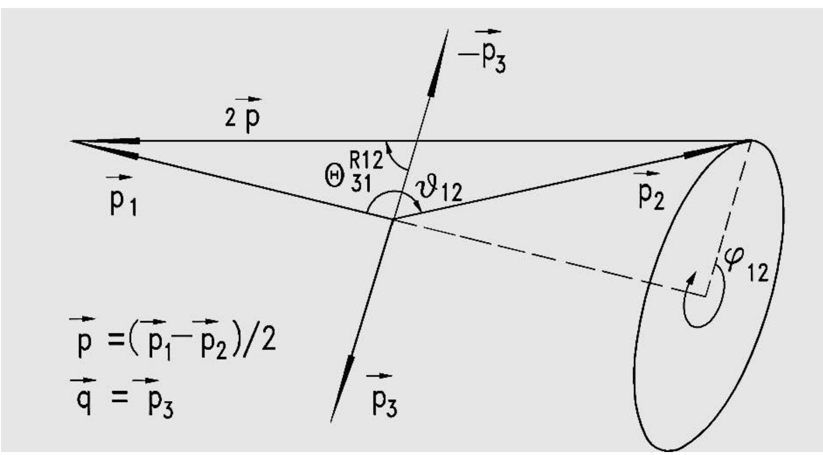
3-particle decay of particle $A \rightarrow 1 + 2 + 3$ in its rest frame *without polarisation*

final state **9 degrees of freedom** $\vec{p}_1, \vec{p}_2, \vec{p}_3$

- 4 energy-momentum conservation

- 2 isotropy in space of e.g. particle 1 (2 angles)

- 1 isotropy of azimuthal angle ϕ_{12}



if masses known = particles identified

experiment kinematically complete

by measuring at rest - 2 independent variables
e.g. T_1, T_2
T_1, Θ_{12}

in flight - 5 independent variables
e.g. $T_1, T_2, \Theta_1, \Theta_2, \Theta_{13}$

$\vec{p}_1, \vec{p}_2$ *already onefold overdetermined*