# *Particle Detection*
# *in*
# *High-Energy Physics Experiments*
# *Part -II*

*Naba K Mondal*
*TIFR, Mumbai*

# *Silicon Detector:*

1. Photon spectroscopy with high energy resolution
2. Vertex detection with high spatial resolution
3. Energy measurement of charged particles [few MeV]

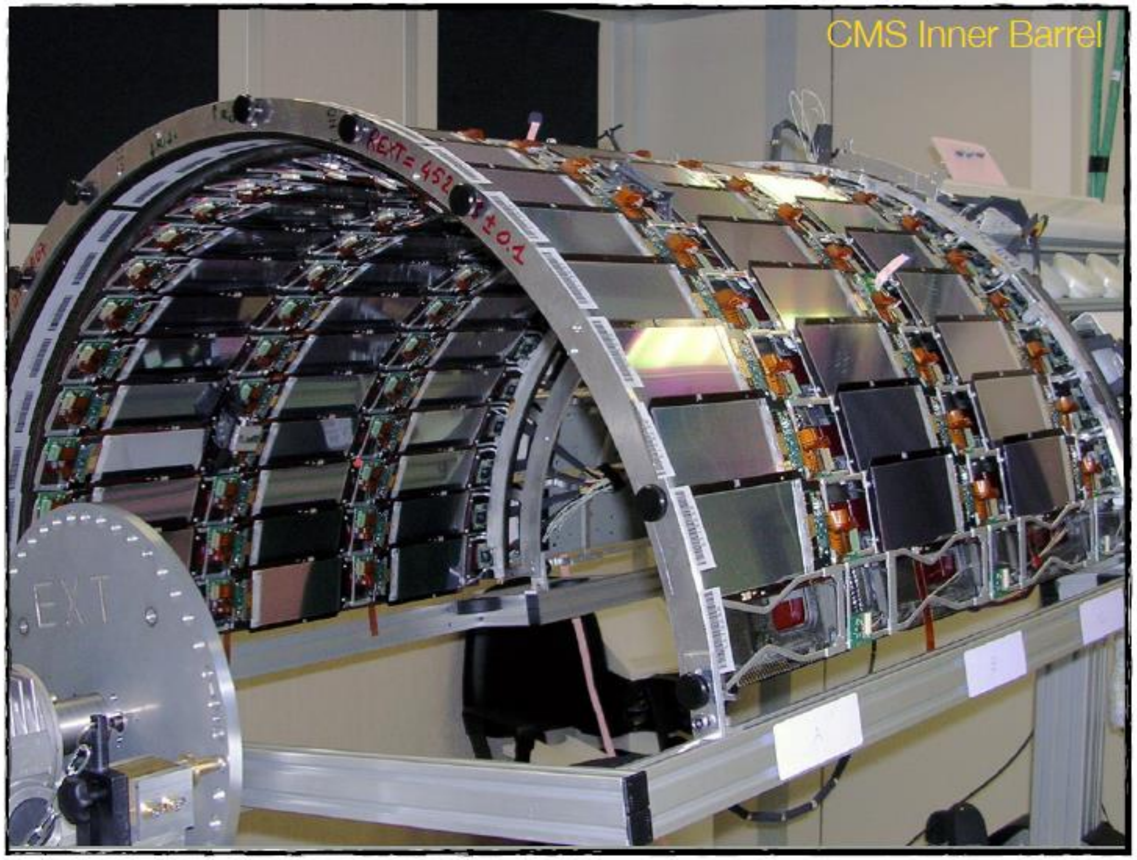
Main advantages:

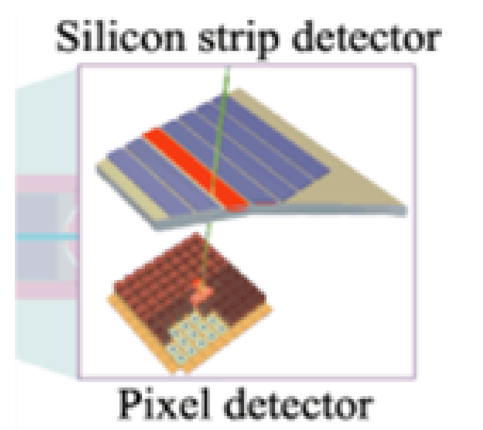
(i) Possibility to produce small structures using micro-chip technology; 10 μm precision; relatively low costs ...

(ii) Comparably low energy deposition per detectable electron-hole pair required ...

| | | | |
|---|---|---|---|
| e.g. | Silicon | : | 3.6 eV per electron-hole pair |
| | Ionization (LAr) | : | O(30 eV) for a single ion; see later |
| | Scintillators | : | O(100 eV) depending on light yield [typical 1-10%] |

# *Silicon Tracker*



# *Basic Semiconductor Detector:*

Requirement:
Large sensitive region ...

We know:

$$d \approx x_p \approx \sqrt{\frac{2\epsilon U}{eN_A}}$$

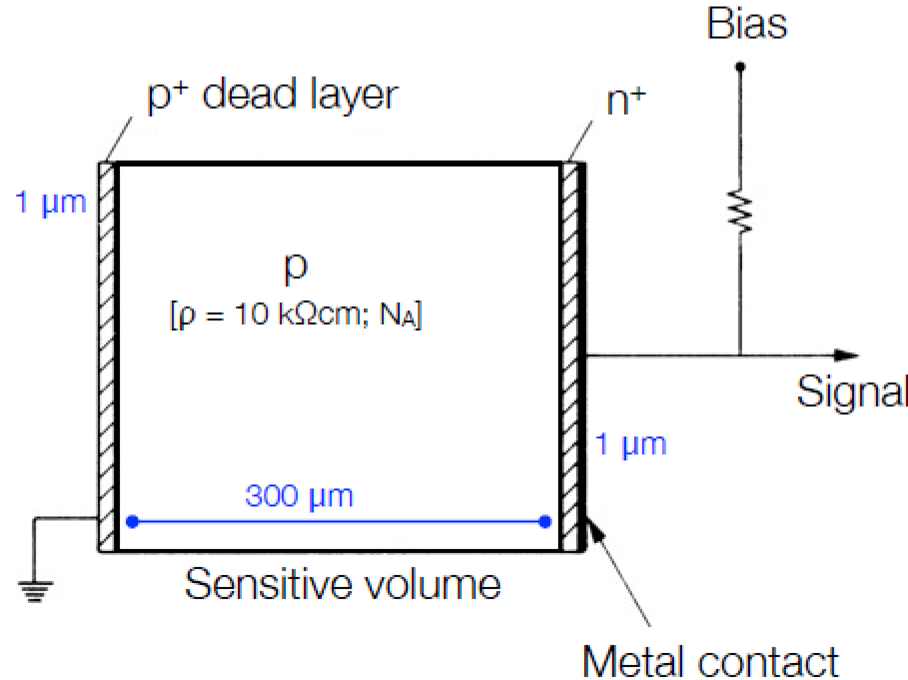
Typical: $N_A = 10^{15}/\text{cm}^3$
$n^+$ region highly doped: $N_D \gg N_A$

$$U = \frac{e}{2\epsilon} N_A d^2$$
$$= 100 \text{ V}$$

Electric field:

$$E = \frac{U}{d} = \frac{100 \text{ V}}{300 \cdot 10^{-6} \text{ m}} \approx 3 \cdot 10^5 \frac{\text{V}}{\text{m}}$$

[Safe. Breakdown limit at $10^7$ V/m]




$n^+$ and $p^+$ needed to allow metallic contacts ...
[High doping = small depletion zone]

Bias voltage supplied through series resistor ...

# *Energy Resolution:*

Comparison
of energy resolutions ...

Scintillator [NaI(Tl)]: 1 MeV photon; $\sigma/E \approx 2\%$; $\Delta E/E \approx 5\%$
[$N_i$ = 40000 photons/MeV x $\eta$ x Q.E.; $\eta$ =0.2, Q.E. = 0.25; $\sigma/E = 1/\sqrt{N_i}$]

Semiconductor [Si]: 1 MeV photon; $\sigma/E \approx 0.06\%$; $\Delta E/E \approx 0.15\%$
[$N_i$ = 300000 e/h-pairs/MeV; $\eta \approx 1$, Q.E. $\approx 1$; F = 0.1 $\sigma/E = \sqrt{F}/\sqrt{N_i}$]

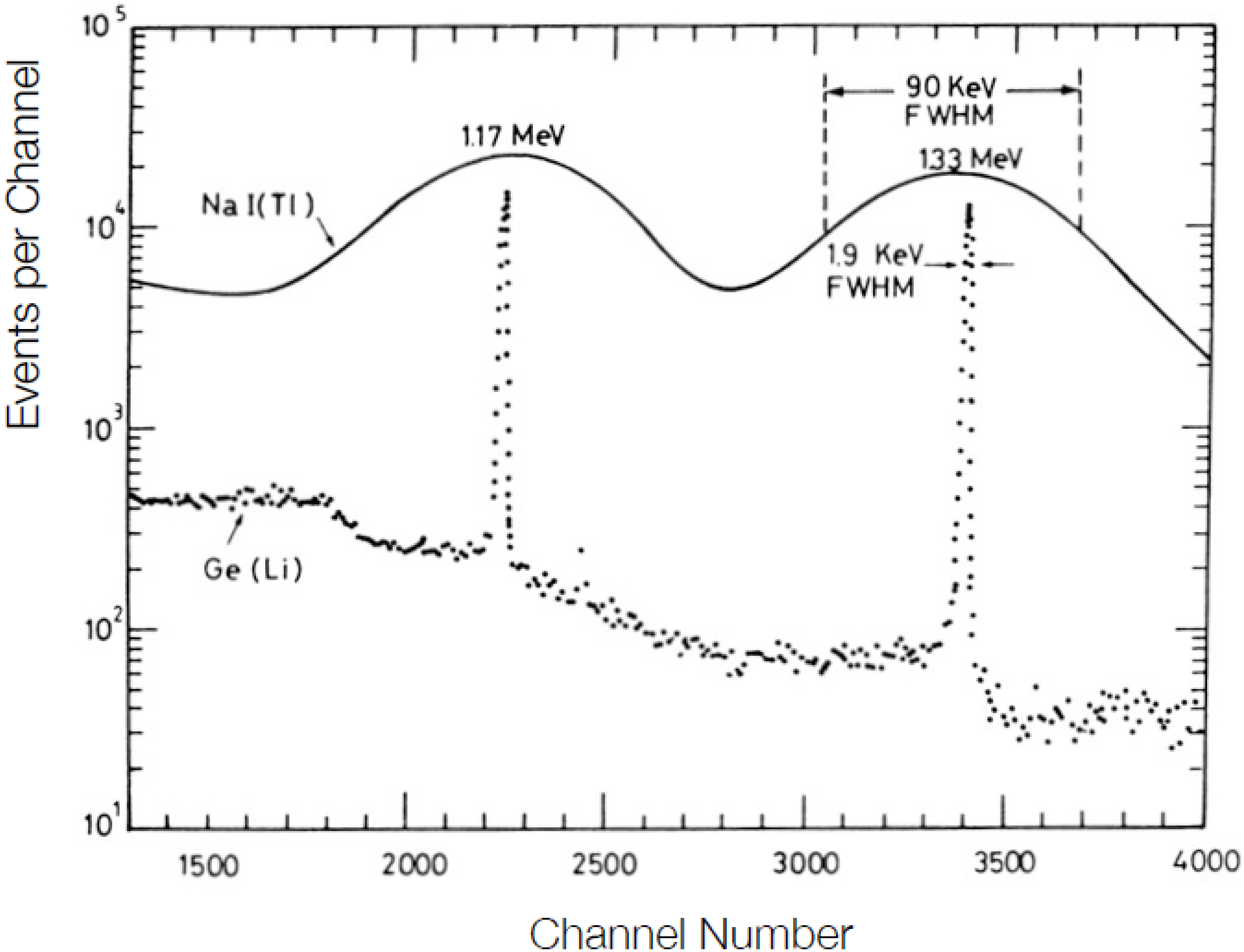
Energy resolution of a semiconductor detector
can be better by a factor 25 to 30.

This is indeed observed:
[for $E_\gamma$ = 1.33 MeV]

Ge(Li) Counter: Resolution of 0.15% possible (at ~ 1 MeV)

NaI(Tl) Detector: Resolution of about 6% (at ~ 1 MeV)

## *Energy Resolution:*




Comparison
of two $^{60}Co$ $\gamma$-spectra
one measured with NaI(Tl)
and With Ge(Li) Detector

# *Position sensitive detector:*

## Motivation:

b-Quark tagging & life time measurements
via secondary vertex finding ...

e.g.: $p\bar{p} \rightarrow t\bar{t} + X$ [Tevatron]
$\hookrightarrow b\bar{b}W^+W^-$

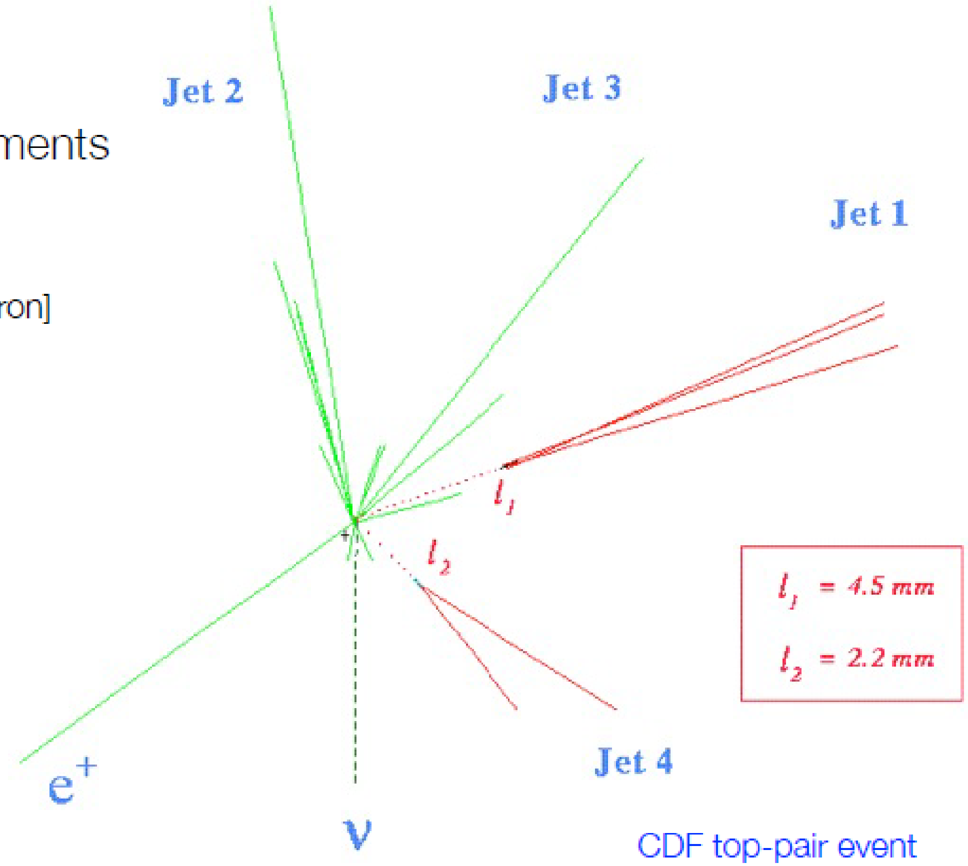
$pp \rightarrow H + X$ [LHC]
$\hookrightarrow b\bar{b}$

Typical lifetime: $\tau = 10^{-12} \ldots\ldots 10^{-13}$ s

$$\gamma c\tau = \gamma \cdot 3 \cdot 10^{10}\ \text{cm/s} \cdot 10^{-13}\ \text{s} = \gamma \cdot 30\ \mu\text{m}$$

Thus:

To measure lifetime in picosecond regime
one needs spacial resolution of the order of 5 - 30 μm ...




CDF top-pair event
[$M_{top}$ = 170 ± 10 GeV]

# *Position Sensitive Detector:*

## Principle:

Segmentation
into strips, pads, pixels ...

### Typical parameters:

Thickness: 150 - 500 μm
Strip separation (pitch): 20 - 150 μm

Resolution: 5 - 40 μm (pitch/√12)

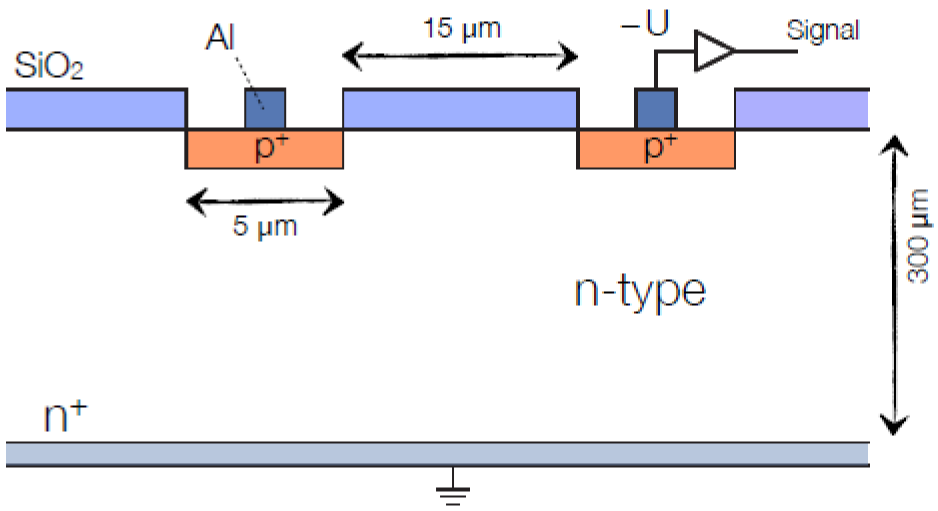
Charge collection: 20 ns
Charge integration: 120 ns

Operation voltage: 160 V

### Output signal:

Total charge: $Q_{out}$ ~ 4 fC

Average energy loss of MIP: 300 eV/μm; Si: 3.6 eV/pair.
Thus 80 electron-hole pairs per μm;
300 μm thickness → 25000 pairs/MIP




Schematics of
Silicon Strip Detector

[from 1983]

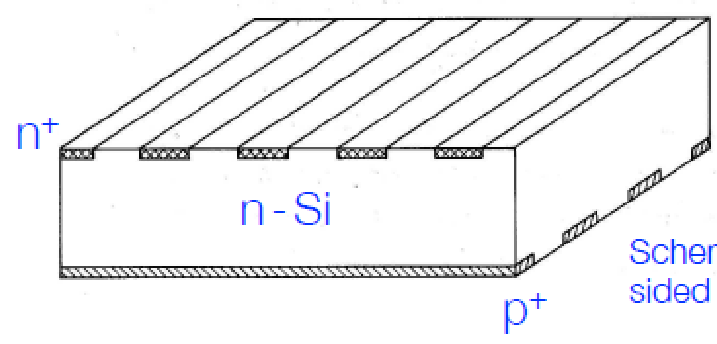
High resistive n-type silicon
onto which p+ diode strips with
aluminum contacts are implanted

# *Double sided micro-strip detector:*

Next step:
Double sided
micro-strip detectors ...

$n^+$ strips on one side
$p^+$ strips on other side

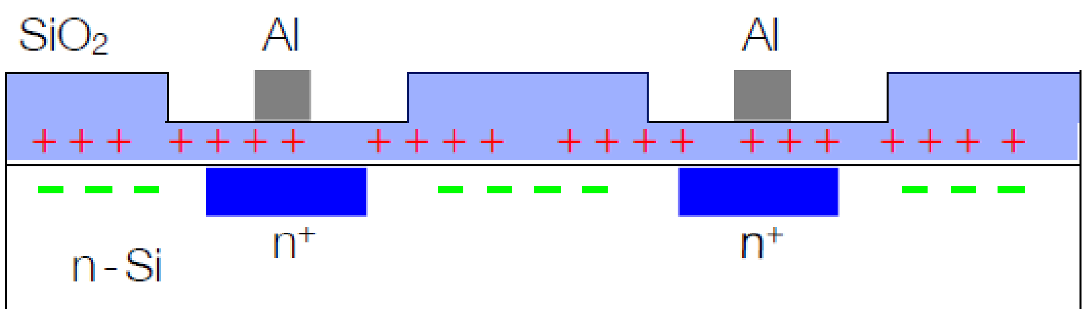
Yields high spatial resolution
in both x and y direction ...




Schematics of a double sided micro-strip detector

But:

Strips need insulation to avoid that positive space charge attracts electrons from n-layer




Need blocking electrodes to separate $n^+$ strips ...

Closeup of of $n^+$ side of double sided micro-strip detector

# *Position Sensitive Detectors:*

Pixel detectors:

Like micro-strips, but 2-dim. segmentation ...

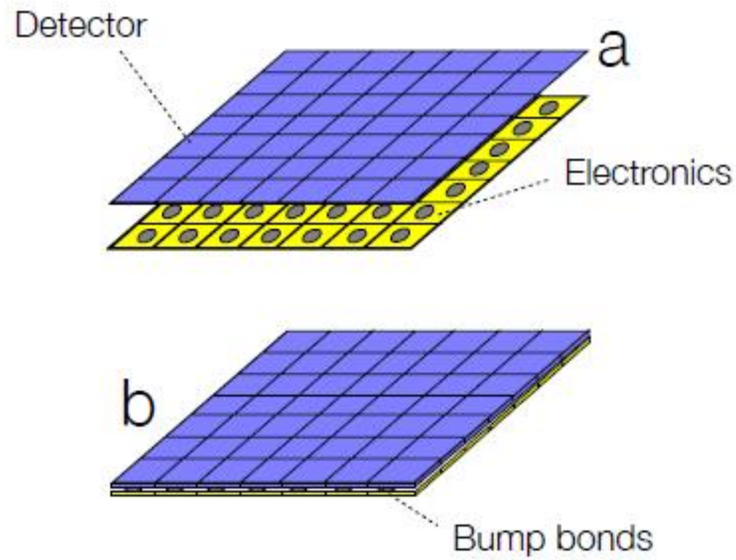
Advantage:

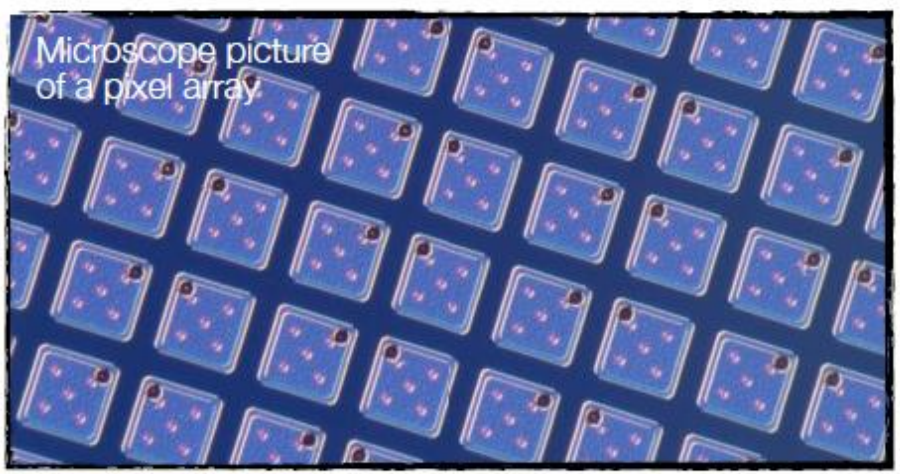
As for micro-strips 2-dim. information,
but higher occupancy allowed;

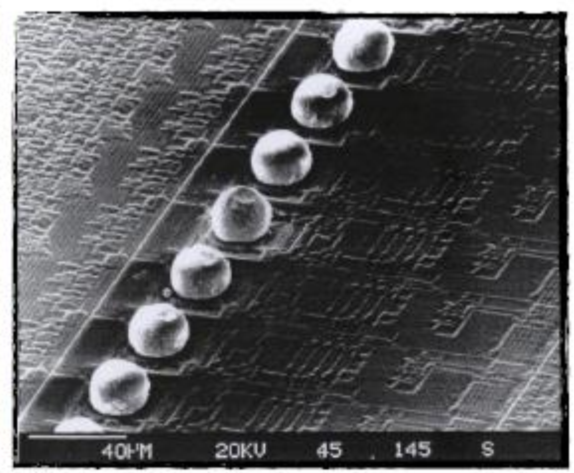
Lower noise due to lower capacitance ...

Disadvantage:

Huge number of readout channels;
Complicated technology ("bump bonding")
Requires sophisticated readout architecture ...

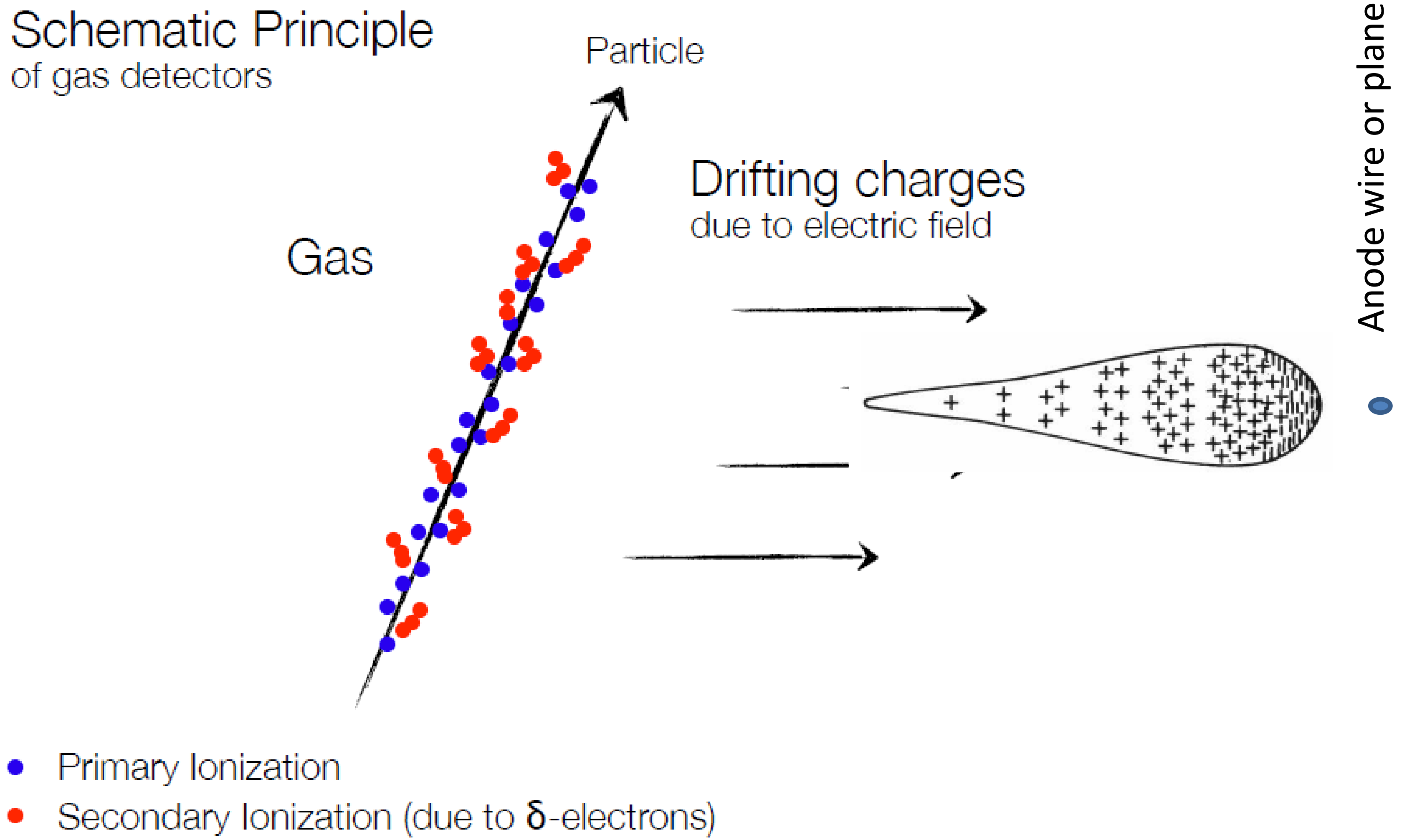


SEM Photograph
of solder bumps

# *Gas Detectors:-Basics*



***Gas Detectors:***

## Ionization mode:

full charge collection
no multiplication; gain ≈ 1

## Proportional mode:

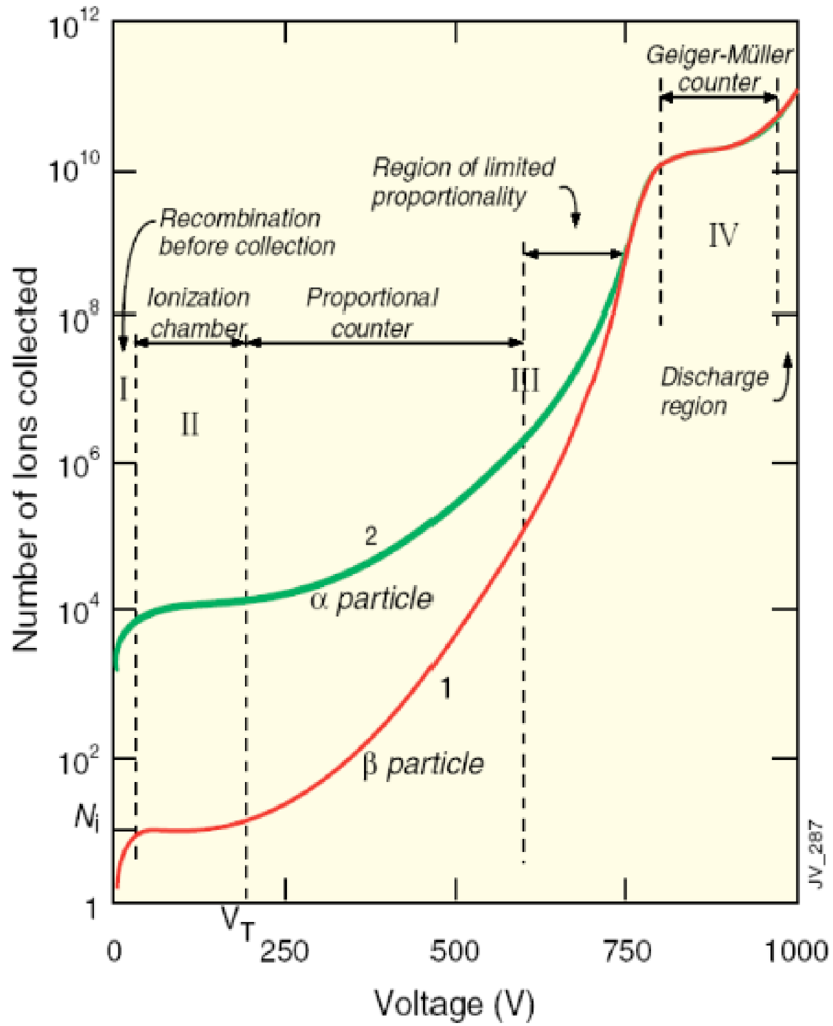
multiplication of ionization
signal proportional to ionization
measurement of dE/dx
secondary avalanches need quenching;
gain ≈ $10^4 - 10^5$

## Limited proportional mode:
[saturated, streamer]

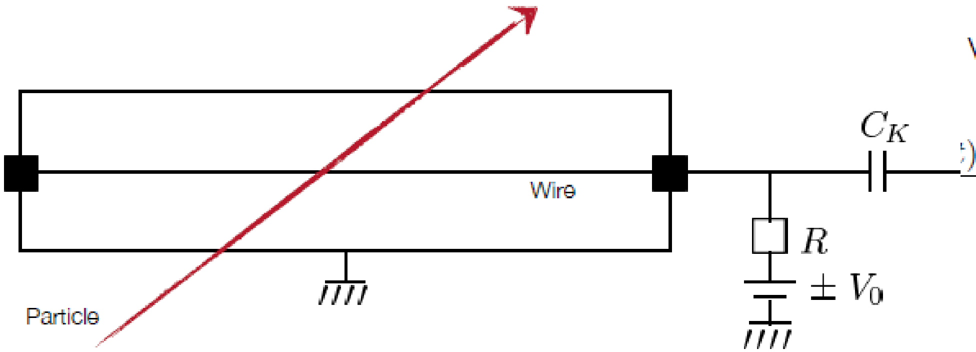
strong photoemission
requires strong quenchers or pulsed HV;
gain ≈ $10^{10}$

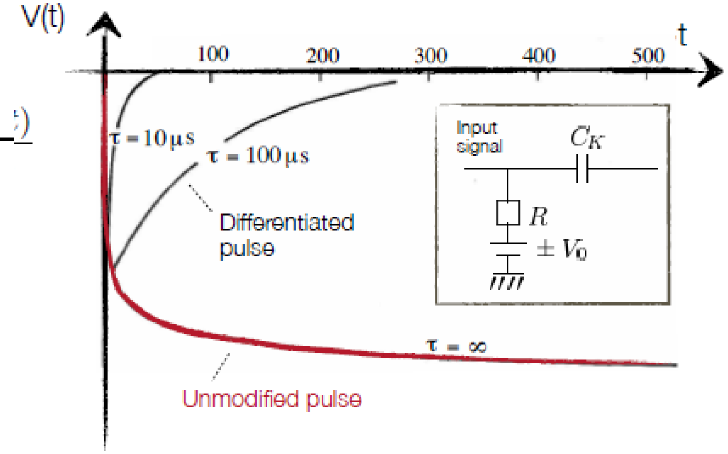
## Geiger mode:

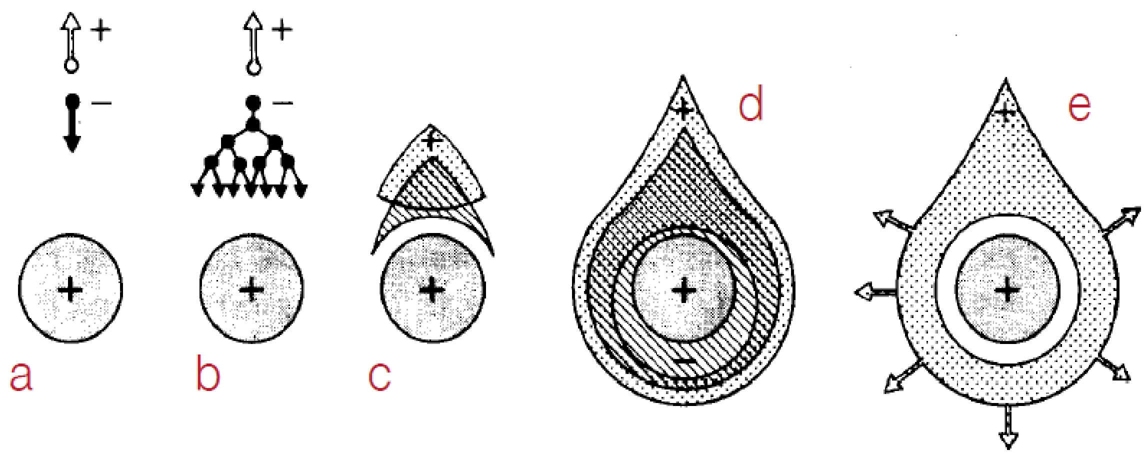
massive photoemission;
full length of the anode wire affected;
discharge stopped by HV cut



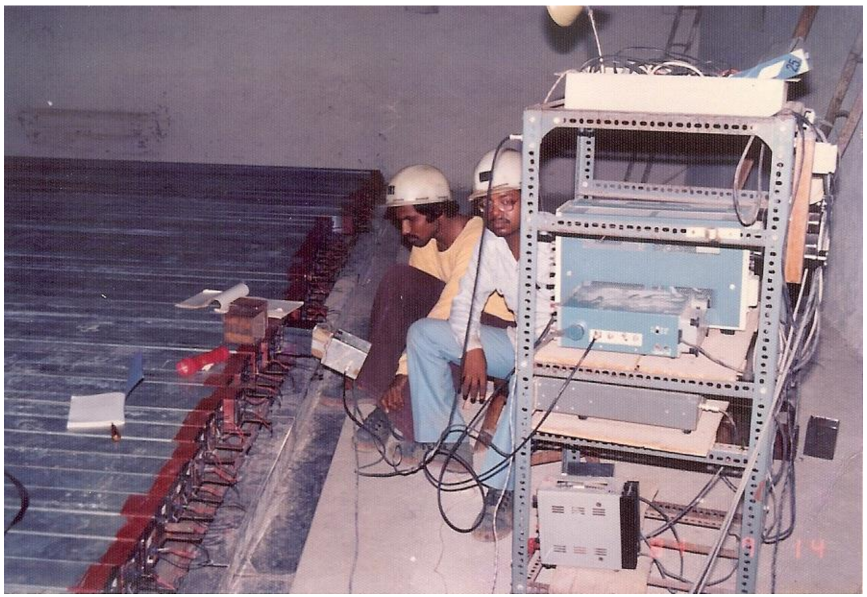
# *Single Wire Proportional counter*



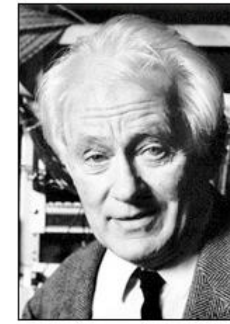



# *KGF Proportional counters*

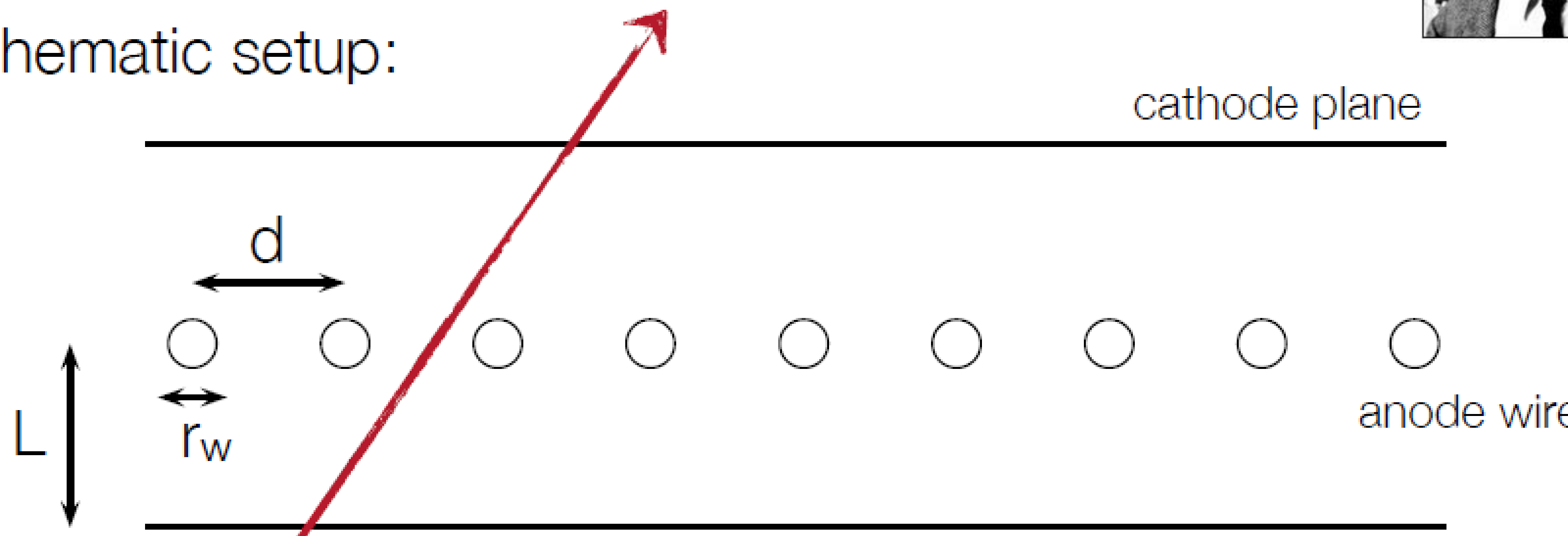


# *Multiwire Proportional Chambers*

G. Charpak
Nobel Prize 1992



Schematic setup:




particle track

**Parameters:**

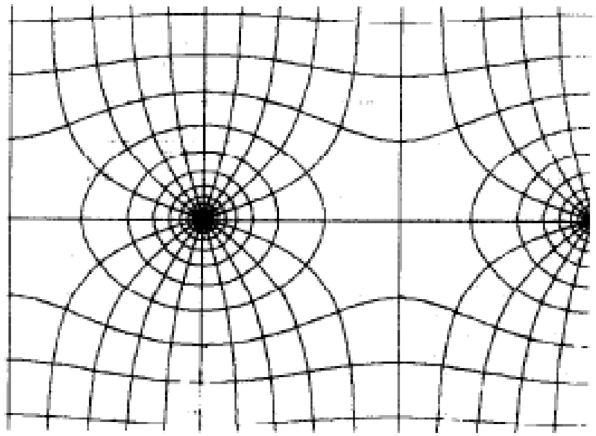
$d$ = 2 - 4 mm
$r_w$ = 20 - 25 µm
$L$ = 3 - 6 mm
$U_0$ = several kV
Total area: $O(m^2)$

**Features:**

Tracking of charged particles
Some PID capabilities via dE/dx
Large area coverage
High rate capabilities

# *Multiwire Proportional Chambers*

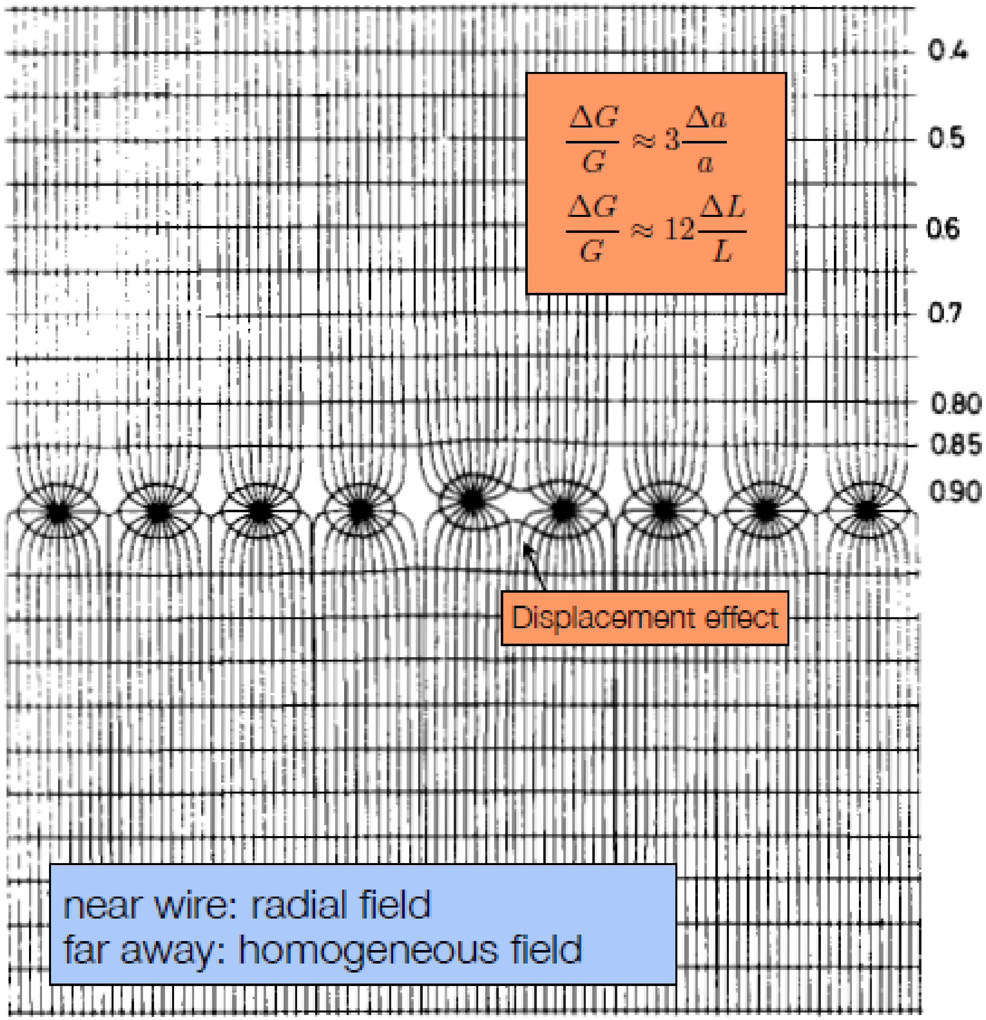
Electric field lines
and equipotentials



Small wire displacements
reduce field quality ...

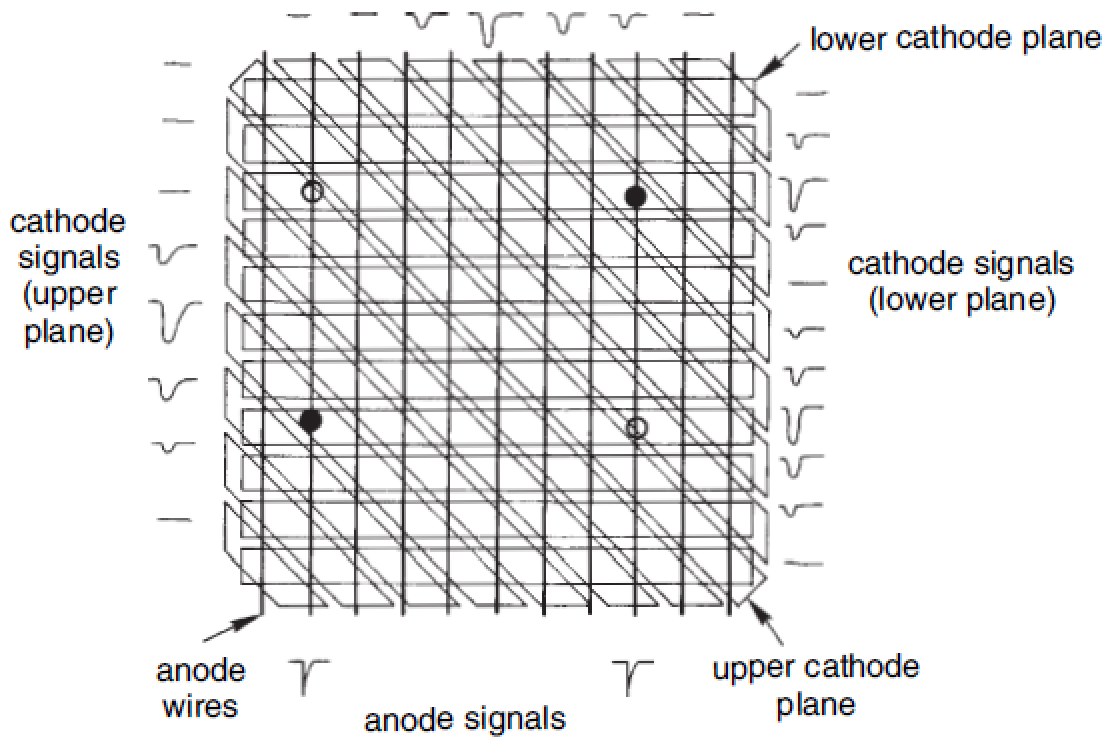
Need high mechanical precision
both for geometry and wire tension ...

[electrostatics and gravitation; wire sag]



# *MWPC:*

substantial functionality improvement
due to cathode strips/pads ...




Cathode readout yields:

- 2-dim. information
  true 2d: use pads ...
- high spatial resolution
  due to center of gravity reconstruction
- resolving ambiguities
  using second strip pattern or pads

Can wires be avoided?

# *Micro-strip Gas Chambers: (MSGC)*

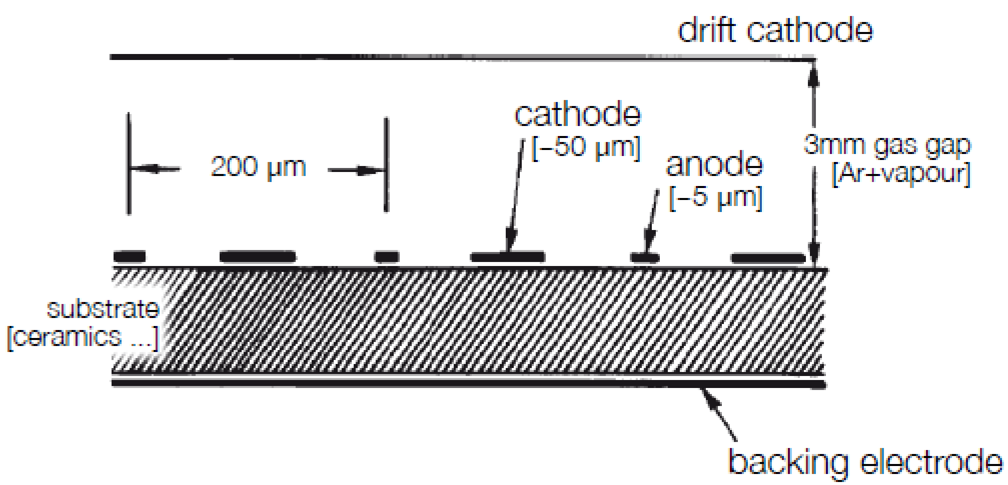
Can one avoid wires?

Anode realized via microstructures
on dielectrics ...

Simple construction (today)
Enhanced stability & flexibility
Improved rate capabilities

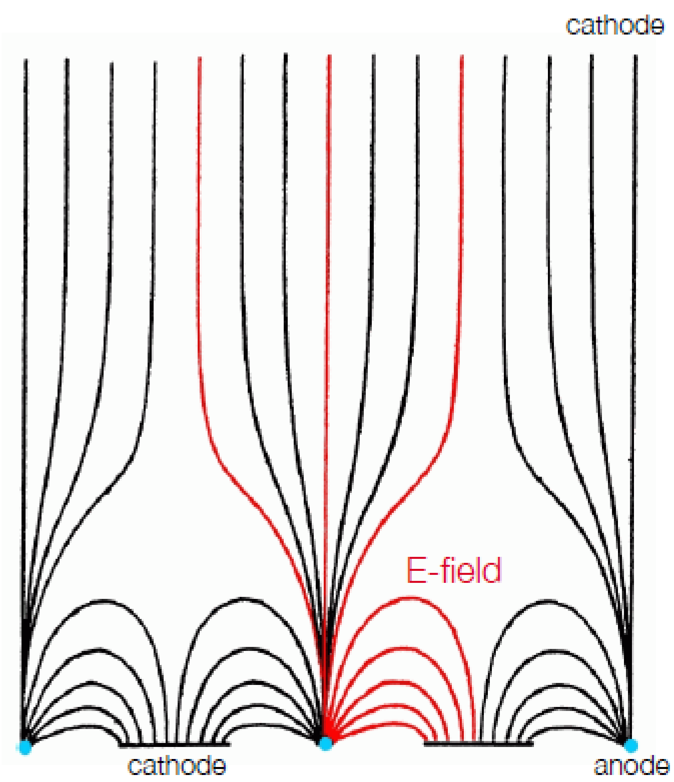
First MSGCs developed in 1990ies ...

Problems: charging of isolation structure
[→ time-dependent gain; sparks, anode destruction]




Schematics of MSGC
field lines

high field directly above anode
ions drift only 100 µm; yields low dead time ...



# MSGC → GEM

MSGCs prone to aging problems ...
Solution: intermediate grid ...

e.g.: Micromegas
GEM detectors [Sauli, 1997]

Micromegas:

Fine cathode mesh collects ions
still fast; no wires ...

GEM (Gas Electron Multiplier):

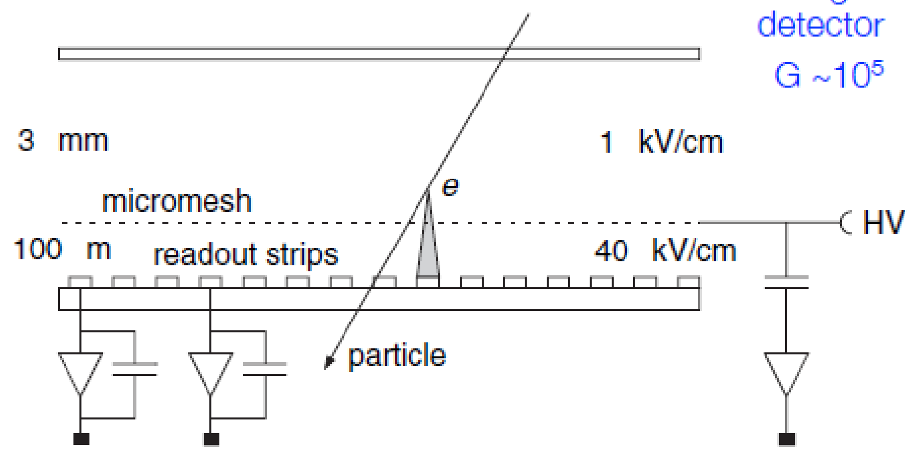
Thin insulating kapton foil
coated with metal film ...

Contains chemically produced
holes [100-200 µm]

Electrons are guided by high
electric drift field of GEMs ...

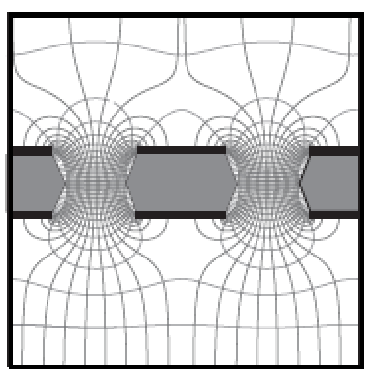
Avalanche production ...

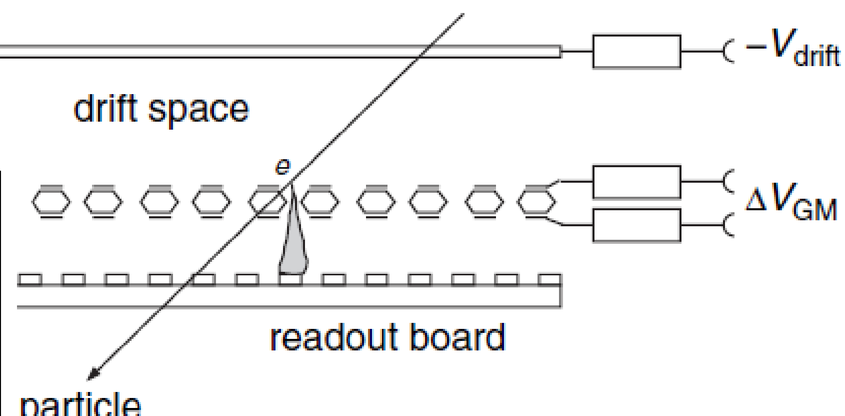
Electrons drift to anode
GEM collects ions




Micromegas
detector

$G \sim 10^5$



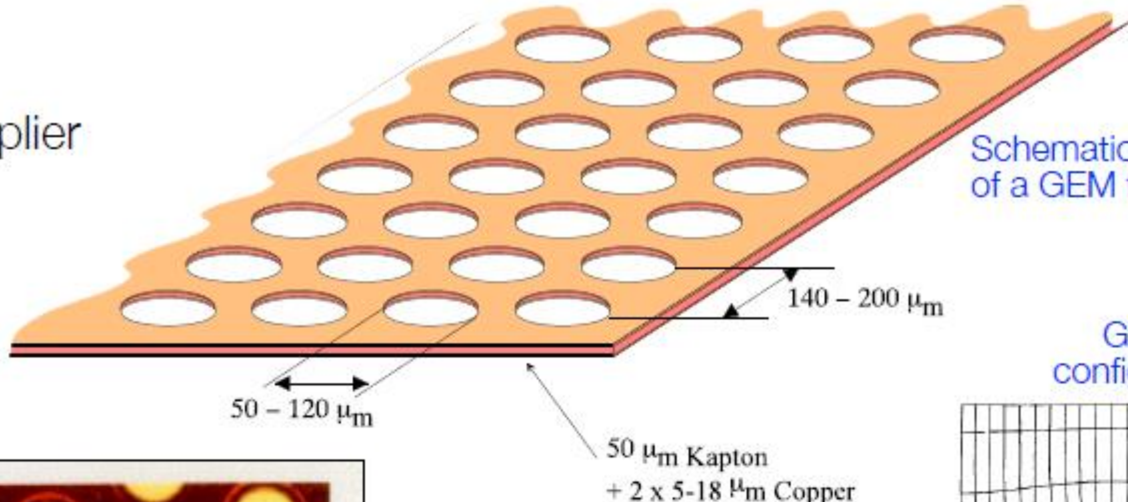



Schematics
of GEM detector

# *GEM foils:*

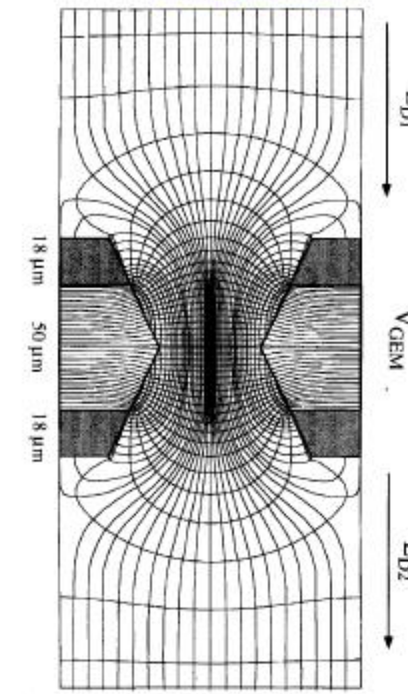
GEM

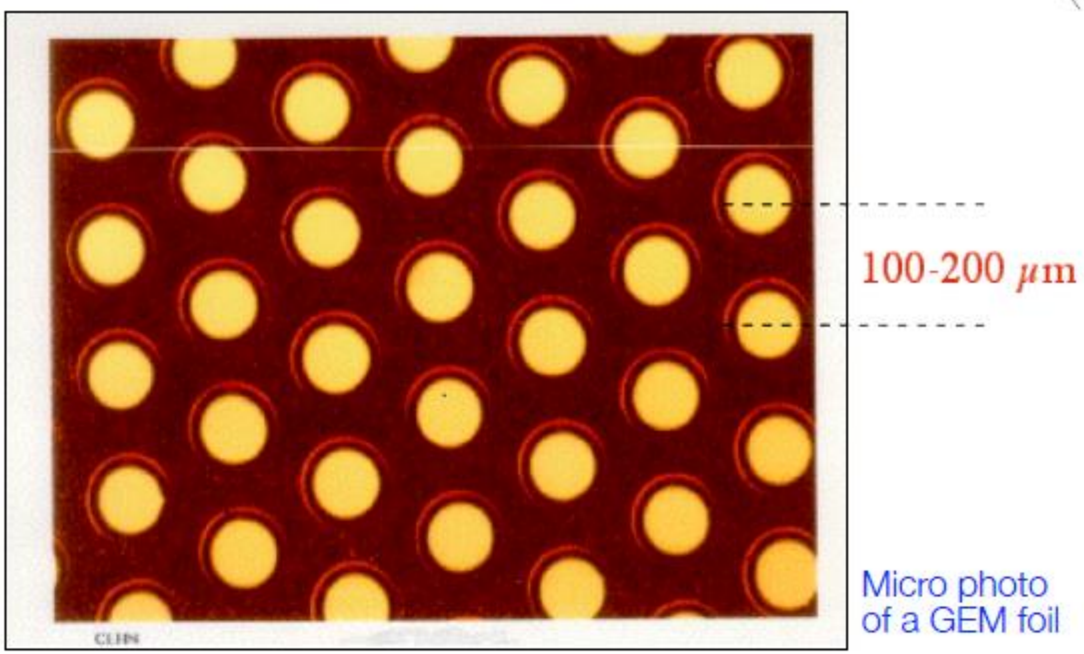
Gas Electron Multiplier




Schematics of a GEM foil

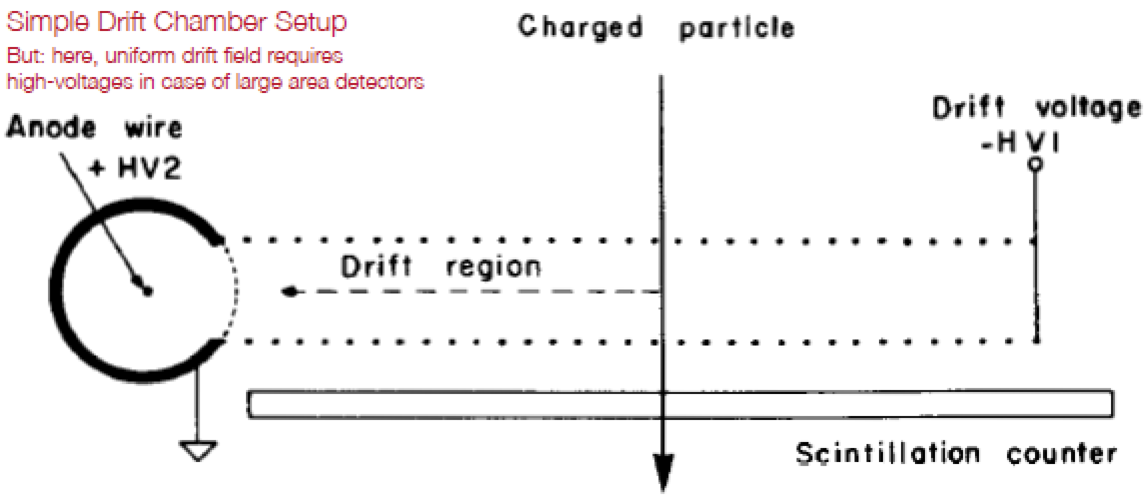
GEM field configuration

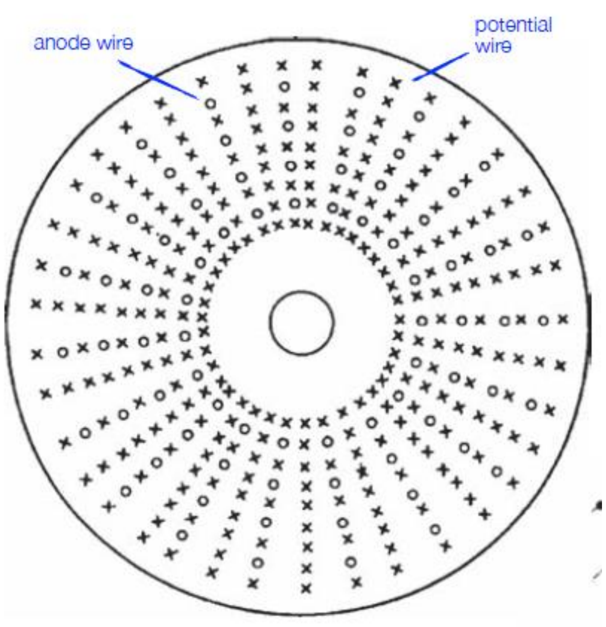


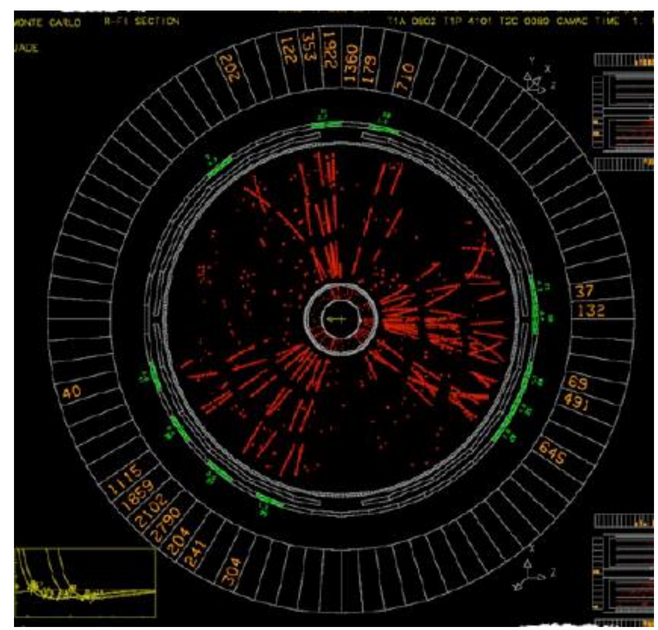




Micro photo of a GEM foil

# *Drift Chambers:*



# *Time Projection Chambers: (TPC)*

Electronic 'bubble chamber'
Full 3D reconstruction ...

xy : from wires and pads of MWPC ...
z : from drift time measurement

Momentum measurement ...

space point measurement
plus B field ...

Energy measurement ...

via dE/dx ...

TPC setup:

(mostly) cylindrical detector

central HV cathode
MWPCs at end-caps of cylinder

B || to E ➛ Lorentz angle = 0

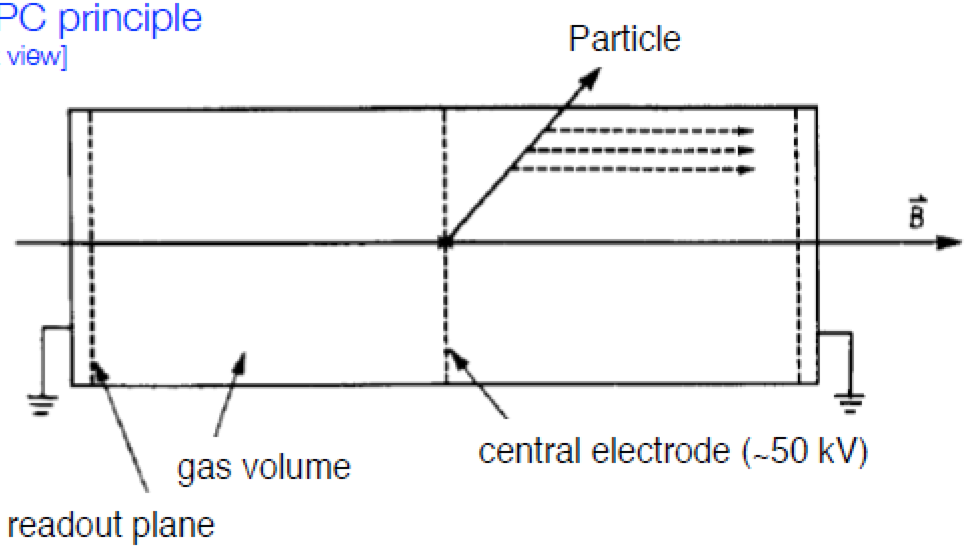
Charge transport :

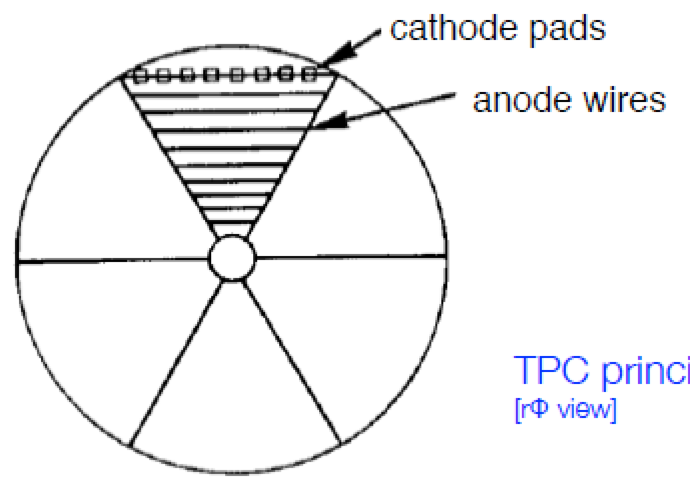
Electrons drift to end-caps

Drift distance several meters

Continuous sampling of induced charges in MWPC

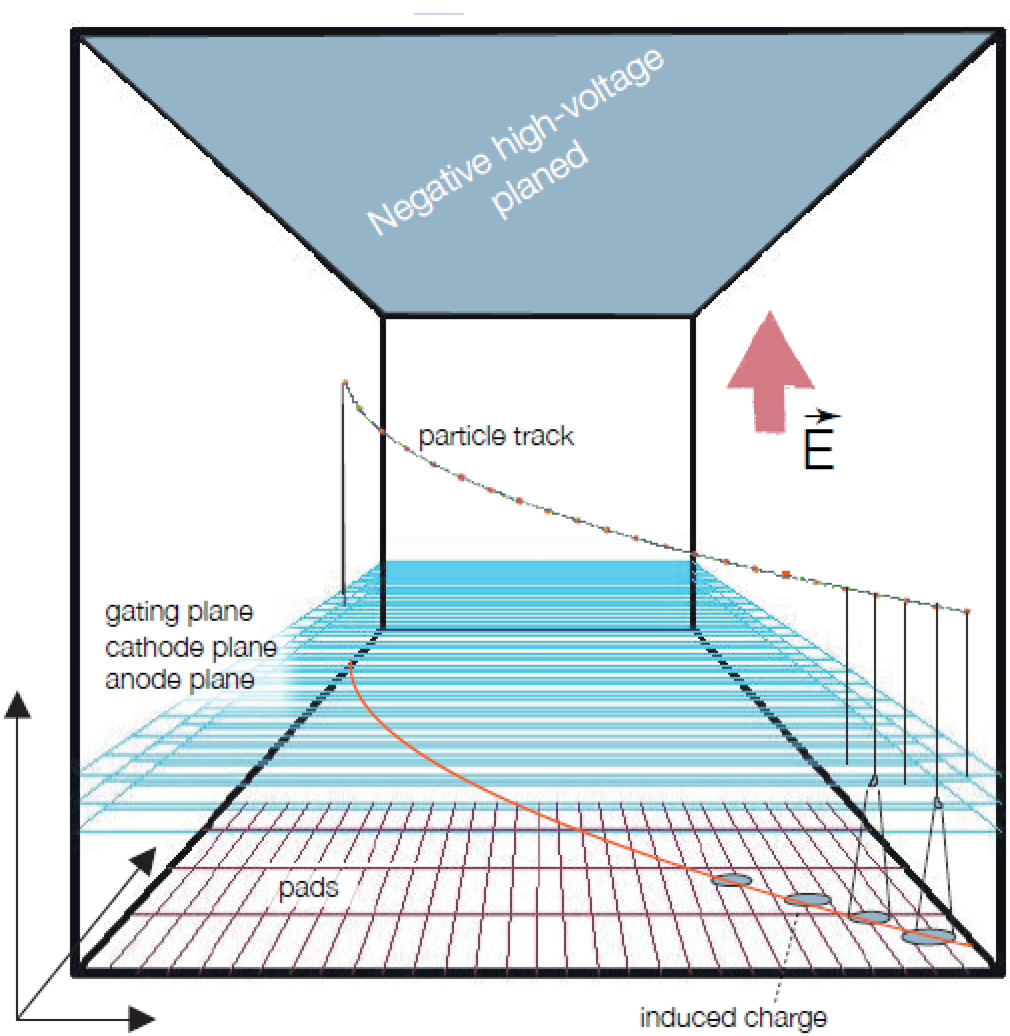
TPC principle
[rz view]




TPC principle
[rΦ view]

# TPC:




## Advantages:

Complete track within one detector yields good momentum resolution

Relative few, short wires (MWPC only)

Good particle ID via dE/dx

Drift parallel to B suppresses transverse diffusion by factors 10 to 100

## Challenges:

Long drift time; limited rate capability [attachment, diffusion ...]

Large volume [precision]

Large voltages [discharges]

Large data volume ...

Extreme load at high luminosity; gating grid opened for triggered events only ...

## Typical resolution:

z: mm; x: 150 - 300 µm; y: mm
dE/dx: 5 - 10%

# *ALICE TPC:*

ALICE TPC:

Length: 5 meter
Radius: 2.5 meter
Gas volume: 88 $m^3$

Total drift time: 92 µs
High voltage: 100 kV

End-cap detectors: 32 $m^2$
Readout pads: 557568

159 samples radially
1000 samples in time

Gas: $Ne/CO_2/N_2$ (90-10-5)
Low diffusion (cold gas)

Gain: > $10^4$

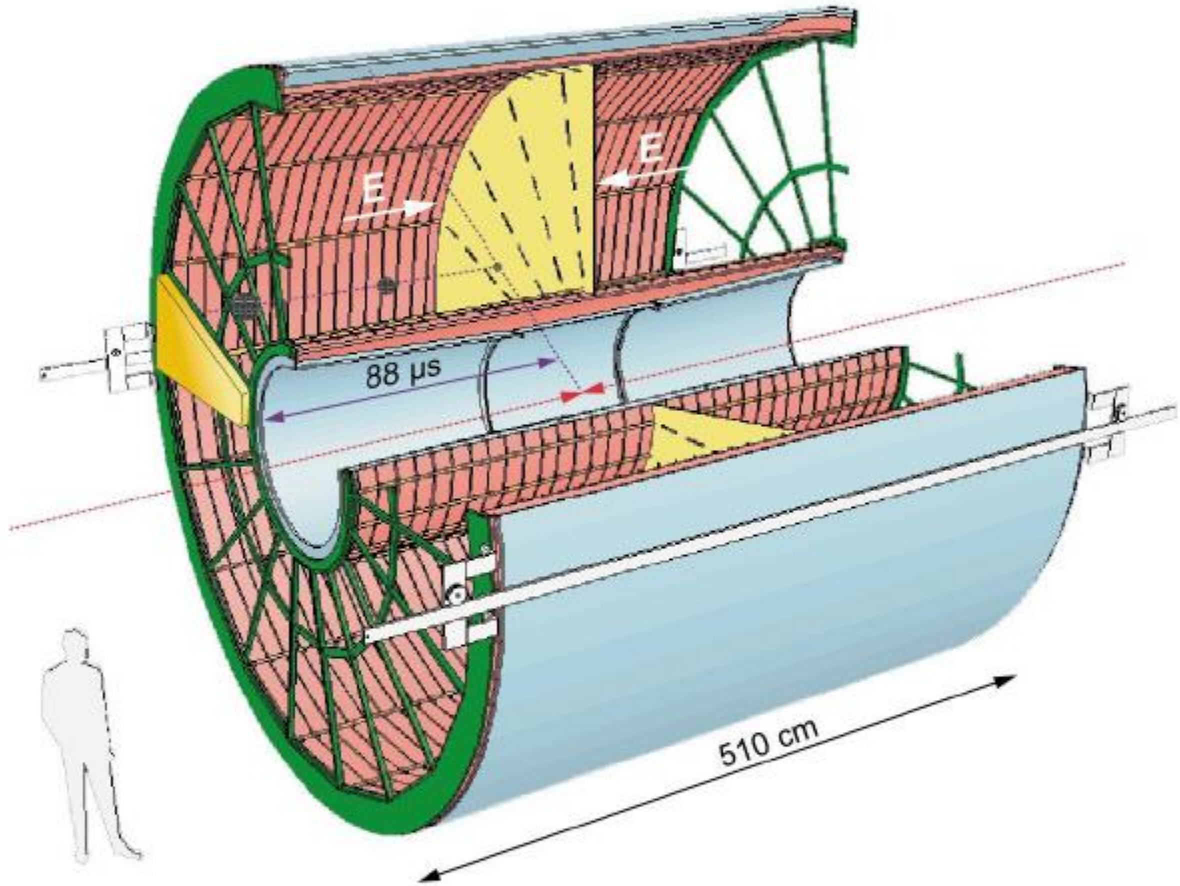
Diffusion: $\sigma_t$ = 250 µm
Resolution: $\sigma \approx$ 0.2 mm

$\sigma_p/p \sim 1\%$ p; $\varepsilon \sim 97\%$
$\sigma_{dE/dx}/(dE/dx) \sim 6\%$

Magnetic field: 0.5 T

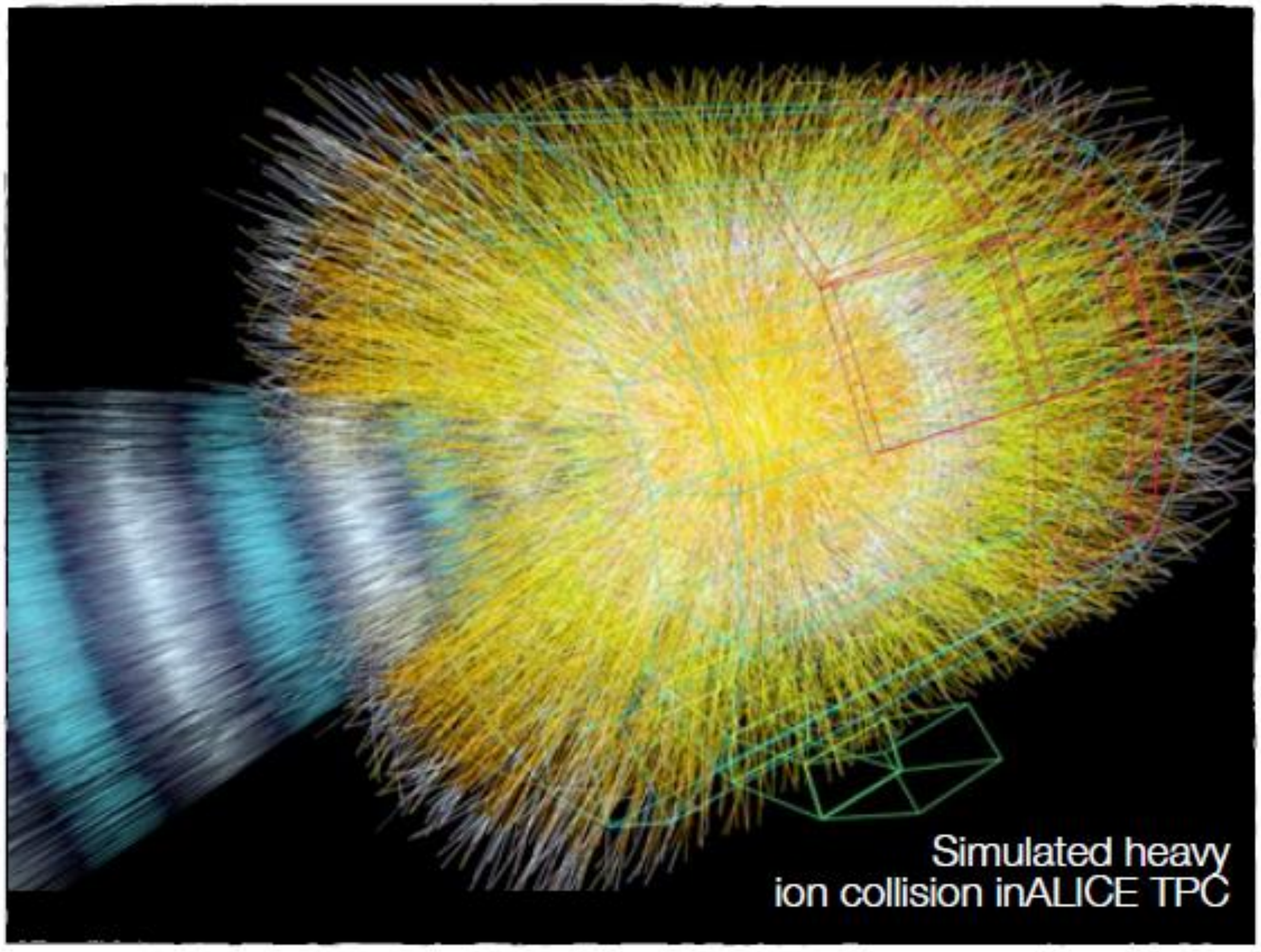
Pad size: 5x7.5 $mm^2$ (inner)
6x15 $mm^2$ (outer)

Temperature control: 0.1 K
[also resistors ...]




Material: Cylinder build from composite material of airline industry ($X_0$= ~ 3%)

## *ALICE TPC:*



# *Calorimeter:*

## Calorimeter:

Detector for energy measurement via total absorption of particles ...

Also: most calorimeters are position sensitive to measure energy depositions depending on their location ...

Principle of operation:

Incoming particle initiates particle shower ...

Shower Composition and shower dimensions depend on particle type and detector material ...

Energy deposited in form of: heat, ionization, excitation of atoms, Cherenkov light ...

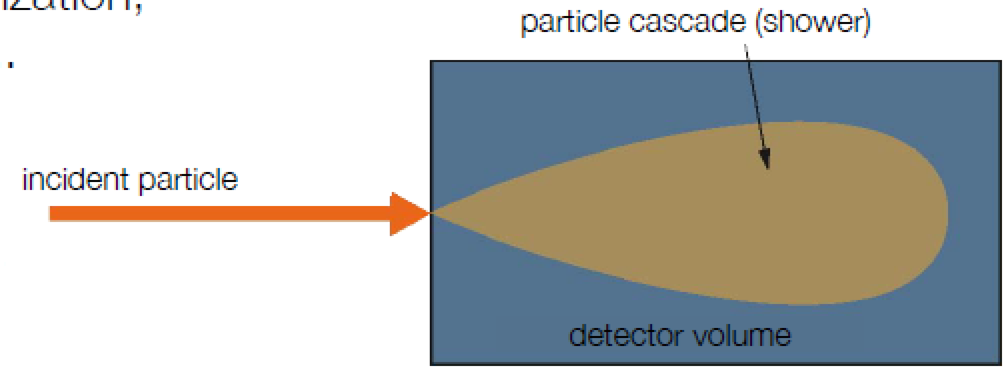
Different calorimeter types use different kinds of these signals to measure total energy ...

Important:

Signal ~ total deposited energy

[Proportionality factor determined by calibration]

Schematic of calorimeter principle



# Calorimeter:

## Energy vs. momentum measurement:

Calorimeter: $\frac{\sigma_E}{E} \sim \frac{1}{\sqrt{E}}$
[see below]

e.g. ATLAS:
$\frac{\sigma_E}{E} \approx \frac{0.1}{\sqrt{E}}$
i.e. $\sigma_E/E$ = 1% @ 100 GeV

Gas detector: $\frac{\sigma_p}{p} \sim p$
[see above]

e.g. ATLAS:
$\frac{\sigma_p}{p} \approx 5 \cdot 10^{-4} \cdot p_t$
i.e. $\sigma_p/p$ = 5% @ 100 GeV

At very high energies one has to switch to calorimeters because their resolution improves while those of a magnetic spectrometer decreases with E ...

## Shower depth:

Calorimeter: $L \sim \ln \frac{E}{E_c}$
[see below]

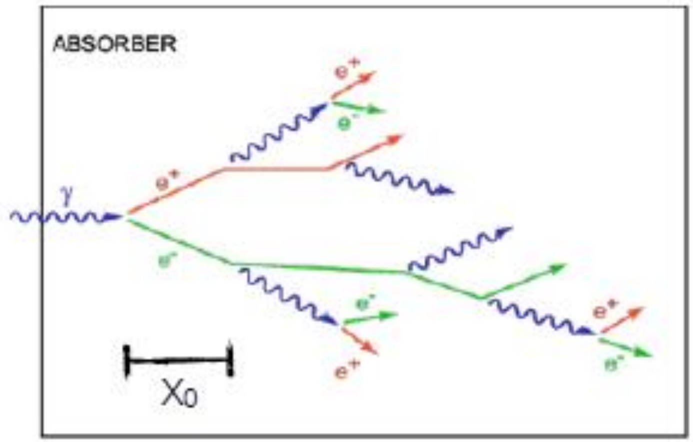
[$E_c$: critical energy]

Shower depth nearly energy independent
i.e. calorimeters can be compact ...

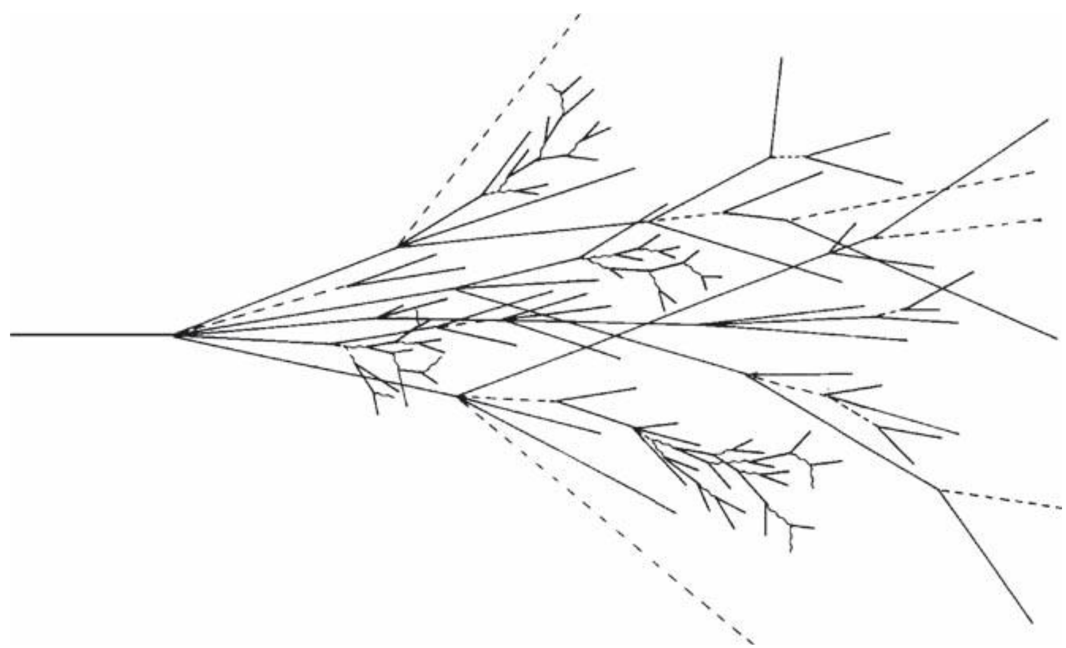
Compare with magnetic spectrometer: $\sigma_p/p \sim p/L^2$
Detector size has to grow quadratically to maintain resolution

## *Development of Shower*

**Electromagnetic Shower**



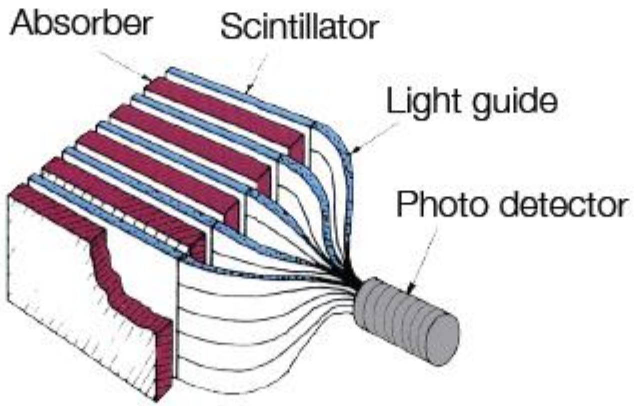

**Hadronic Shower**



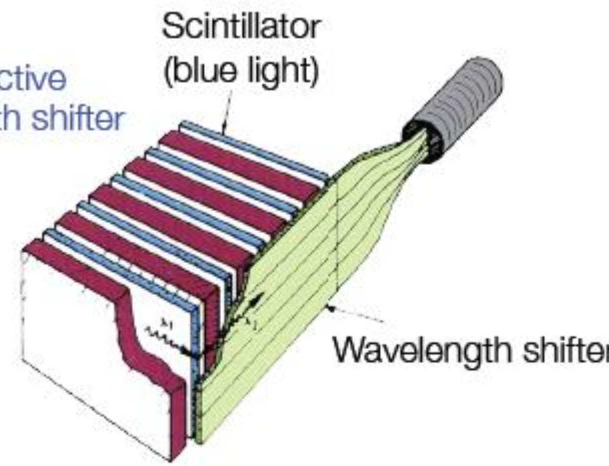
# *Sampling Calorimeter*

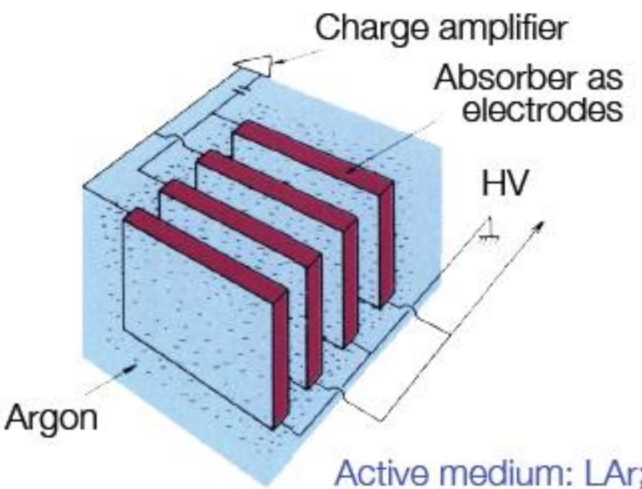
## Possible setups

Scintillators as active layer;
signal readout via photo multipliers



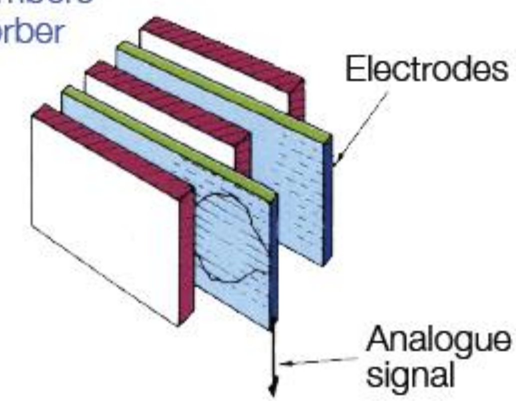

Scintillators as active layer; wave length shifter to convert light




Active medium: LAr; absorber
embedded in liquid serve as electrods

Ionization chambers
between absorber
plates



# *Typical HEP Calorimeter:*

Typical Calorimeter: two components ...

Electromagnetic (EM) +
Hadronic section (Had) ...

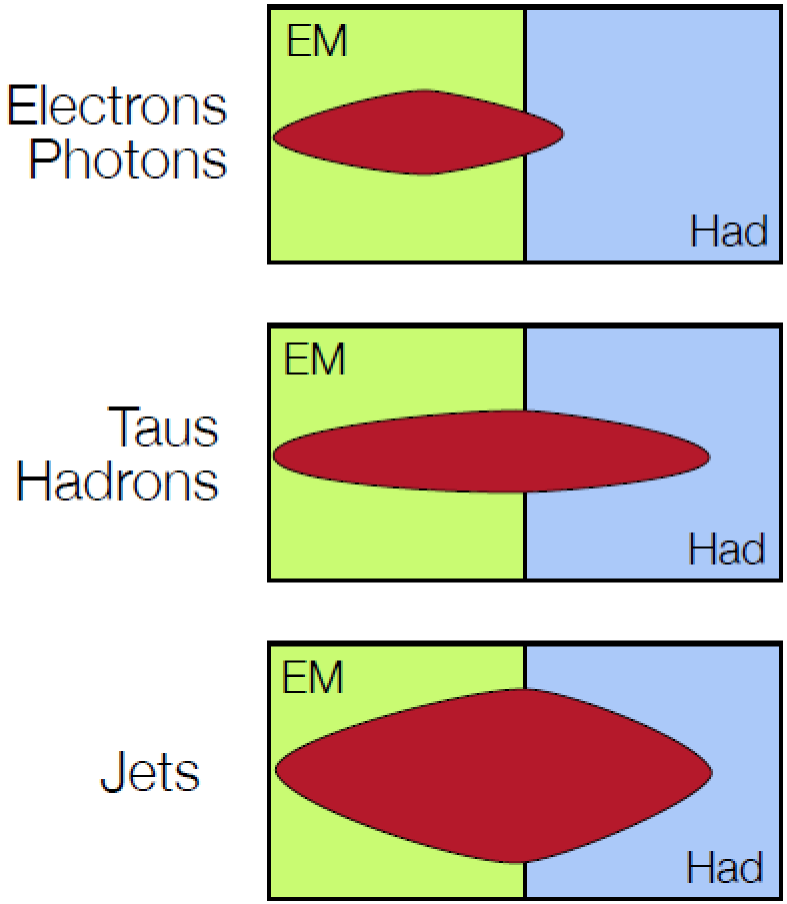
Different setups chosen for
optimal energy resolution ...

But:

Hadronic energy measured in
both parts of calorimeter ...

Needs careful consideration of
different response ...

Schematic of a
typical HEP calorimeter



## *Hadronic Energy Resolution:*

Energy resolution:

e.g. inhomogeneities
shower leakage

e.g. electronic noise
sampling fraction variations

$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus B \oplus \frac{C}{E}$$

Fluctuations:

- Sampling fluctuations
- Leakage fluctuations
- Fluctuations of electromagnetic fraction
- Nuclear excitations, fission, binding energy fluctuations ...
- Heavily ionizing particles

Typical:

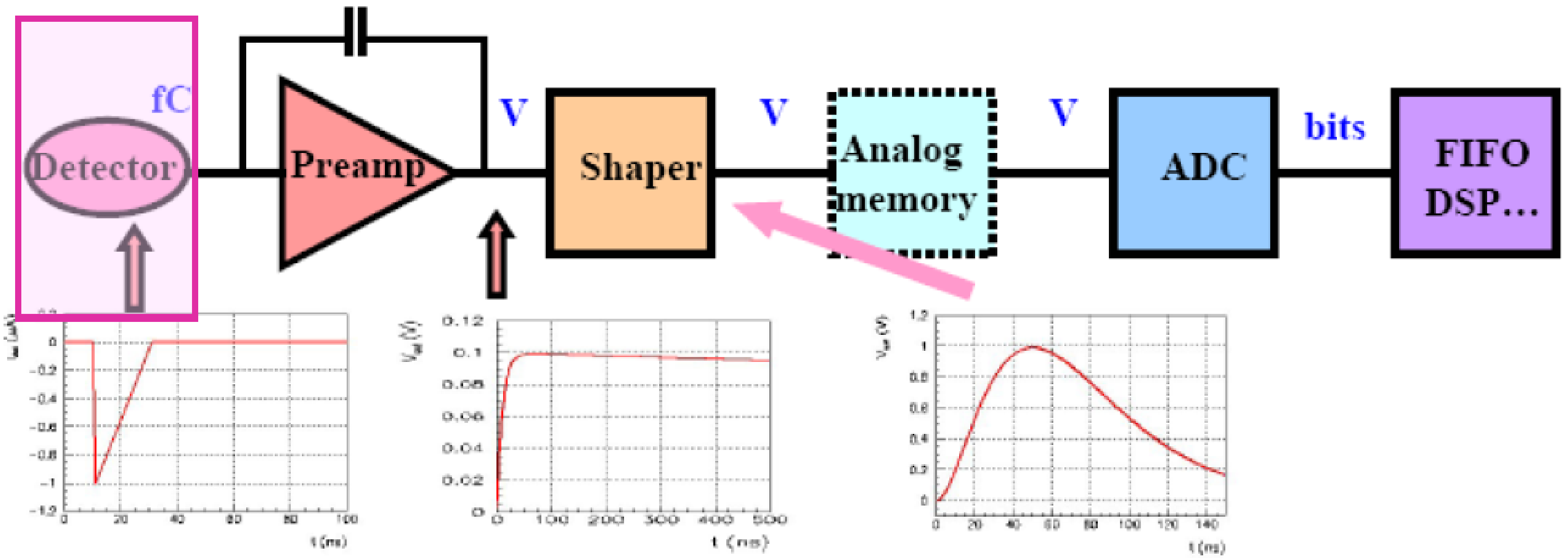
A: 0.5 – 1.0 [Record:0.35]

B: 0.03 – 0.05

C: few %

# *Path of the signal from Detection to Acquisition*

Most front-ends follow a similar architecture




- Very small signals (fC) -> need amplification
- Measurement of amplitude (ADCs)
- Thousands to millions of channels

- **Acknowledgement**

- My thanks to Hans-Christian Schultz-Coulon, Kirchhoff-Institut für Physik for his excellent lecture notes which I have used extensively in my talk here.