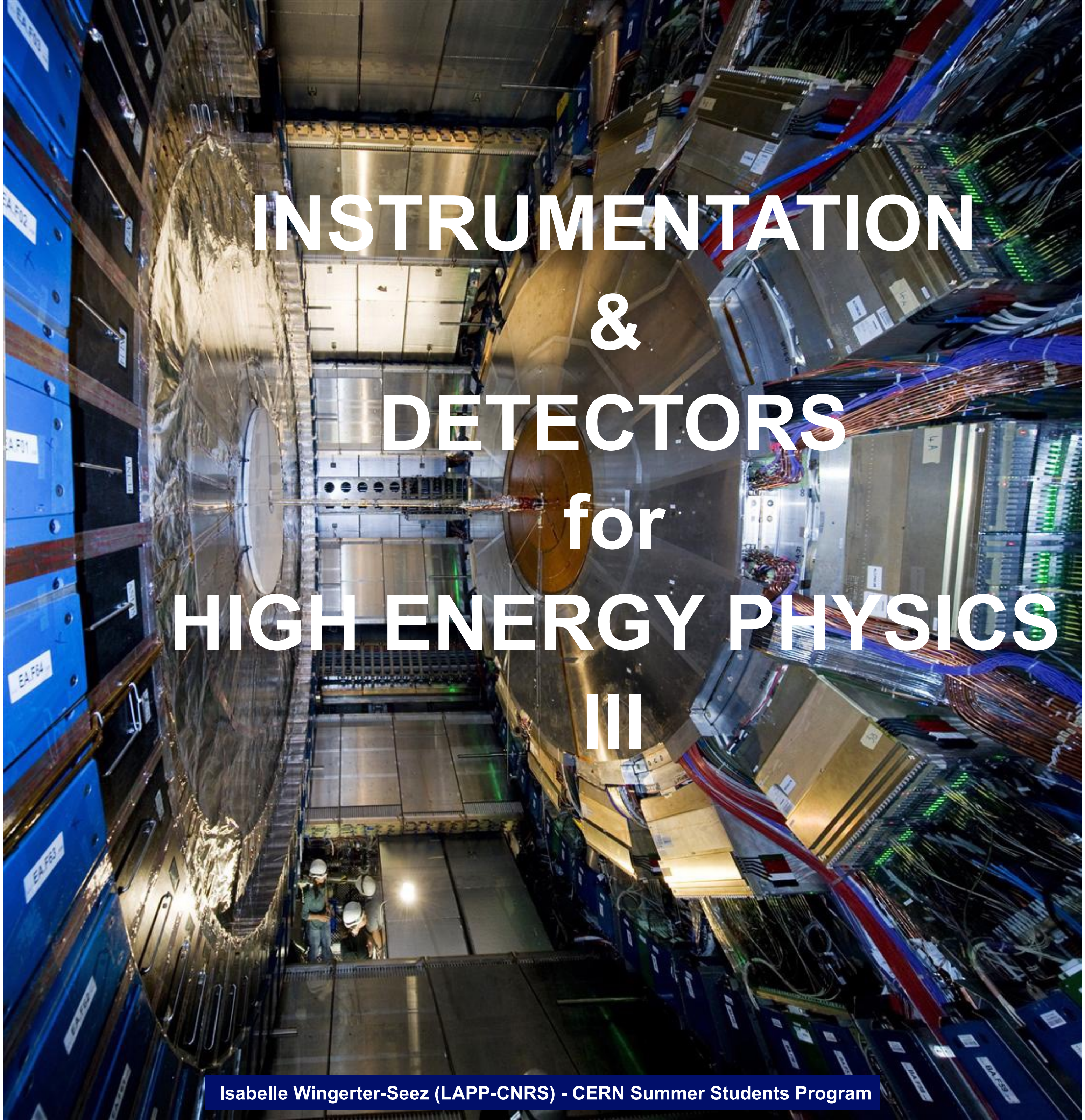
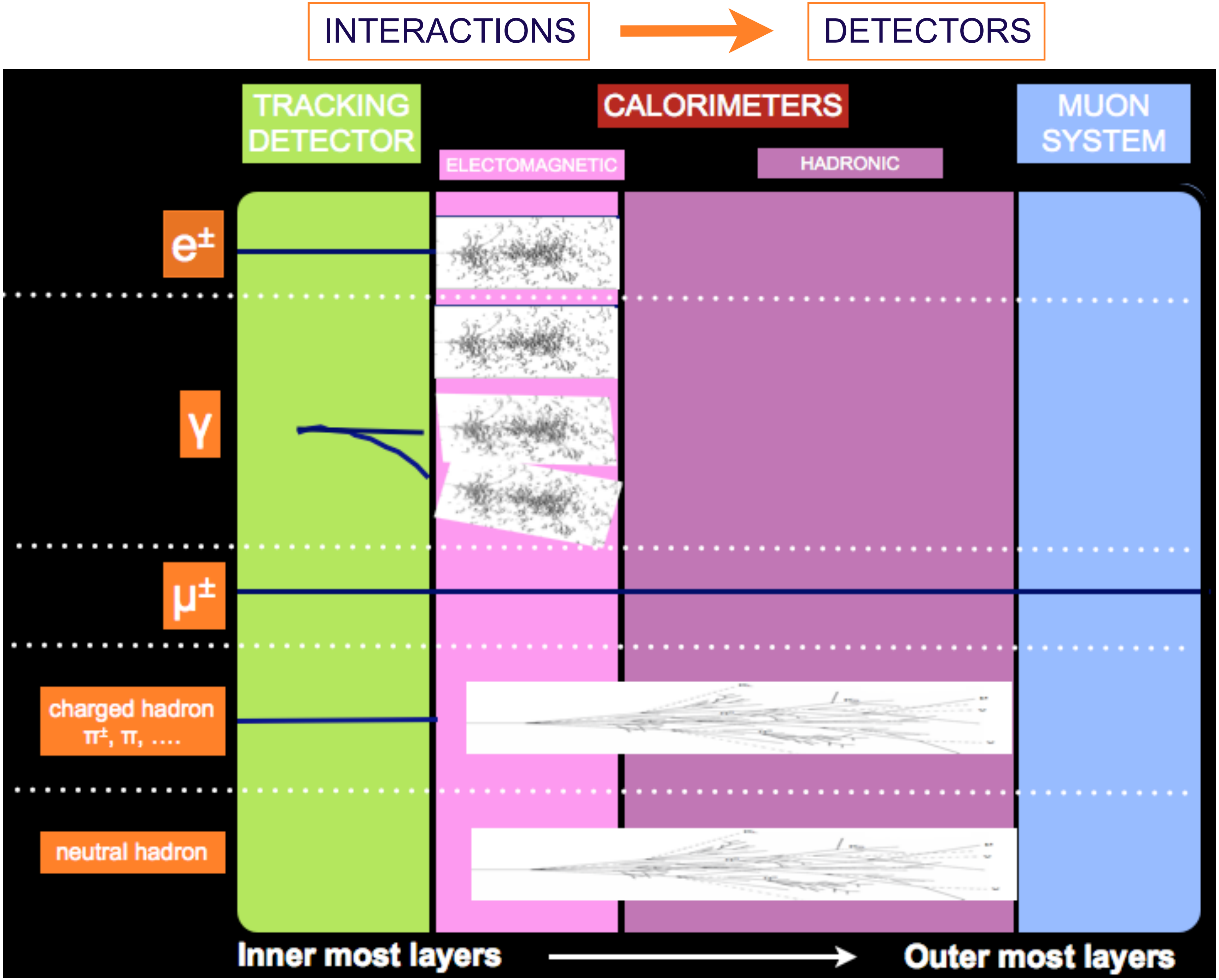


INSTRUMENTATION & DETECTORS for HIGH ENERGY PHYSICS III

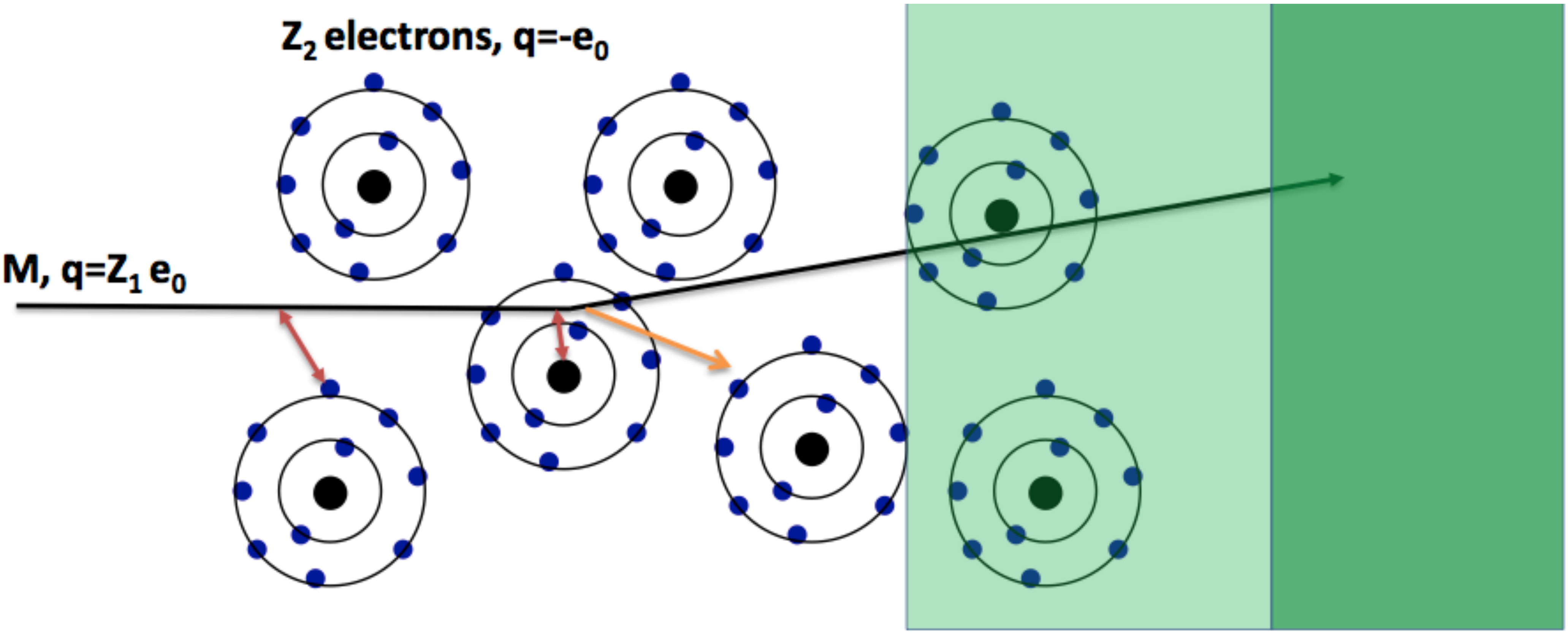
DETECTOR QUIZZ II : explain this schematic



TODAY

TRACKING DETECTORS

ELECTROMAGNETIC INTERACTION
PARTICLE - MATTER



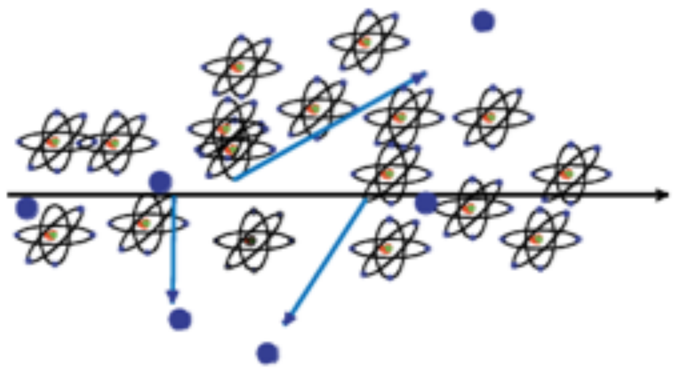
Interaction with the atomic electrons.
The incoming particle loses energy and the atoms are **exited** or **ionised**.

Interaction with the atomic nucleus.
The incoming particle is deflected causing **multiple scattering** of the particle in the material.
During this scattering a **Bremsstrahlung photon** can be emitted

In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as **Cherenkov radiation.** When the particle crosses the boundary between two media, there is a probability of 1% to produce an Xray photon called **Transition radiation.**

CREATION of the SIGNAL

Charged particles traversing matter leave excited atoms, electron-ion pairs (gas, liquid) or electrons-holes pairs (solids) behind.



Excitation

The photons emitted by the excited atoms in transparent materials can be detected with photon detectors like photomultipliers or semiconductor photon detectors.

Ionisation

By applying an electric field in the detector volume, the ionisation electrons and ions are moving, which induces signals on metal electrodes. These signals are then readout by appropriate readout electronics.

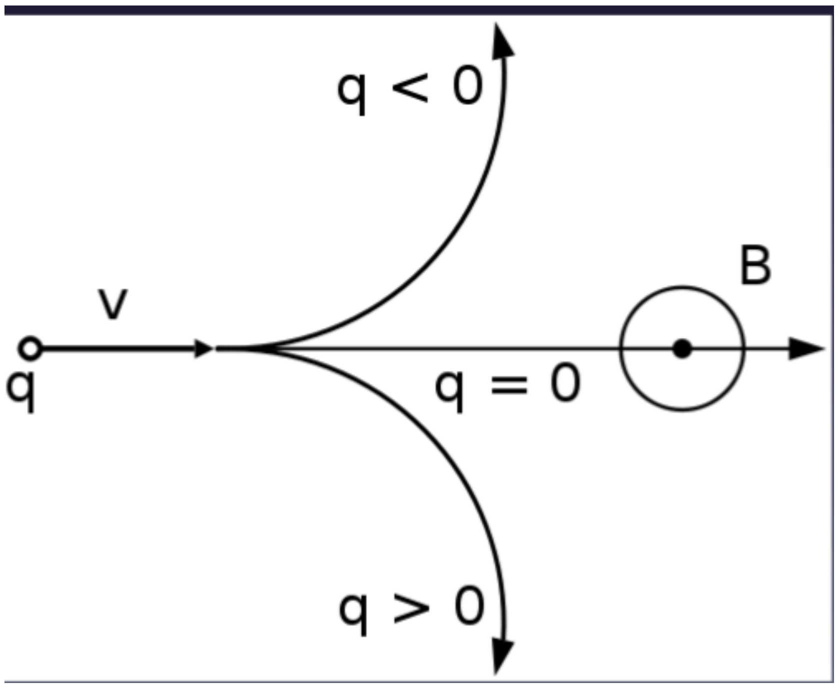
TRACKING DETECTORS

Particle detection has many aspects:

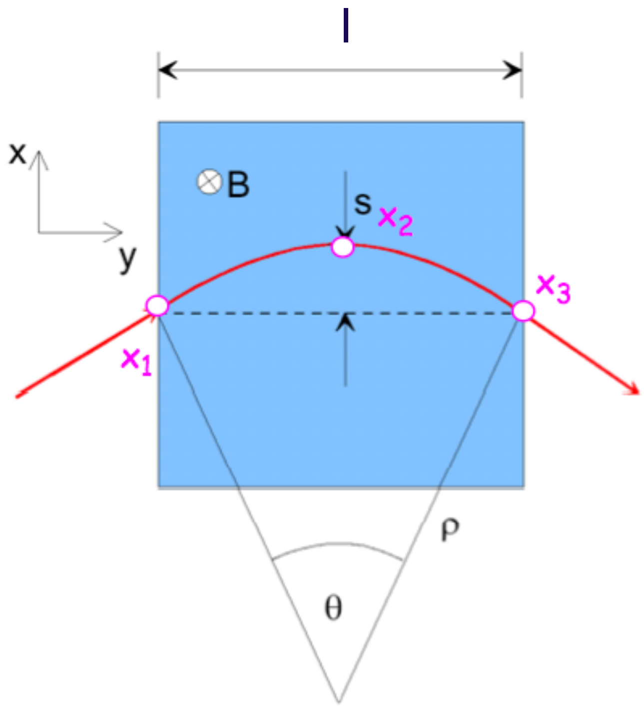
- Particles counting
- Particle identification: mass & charge of the particle
- Tracking

CHARGED particles are deflected in magnetic field

$$\boxed{\vec{F} = q\vec{v} \times \vec{B}}$$



MAGNETIC ANALYSIS



s = sagitta

l = chord

ρ = radius

$$\rho \simeq \frac{l^2}{8s} \qquad p = 0.3\frac{Bl^2}{8s} \qquad \left|\frac{\delta p}{p}\right| = \left|\frac{\delta s}{s}\right|$$

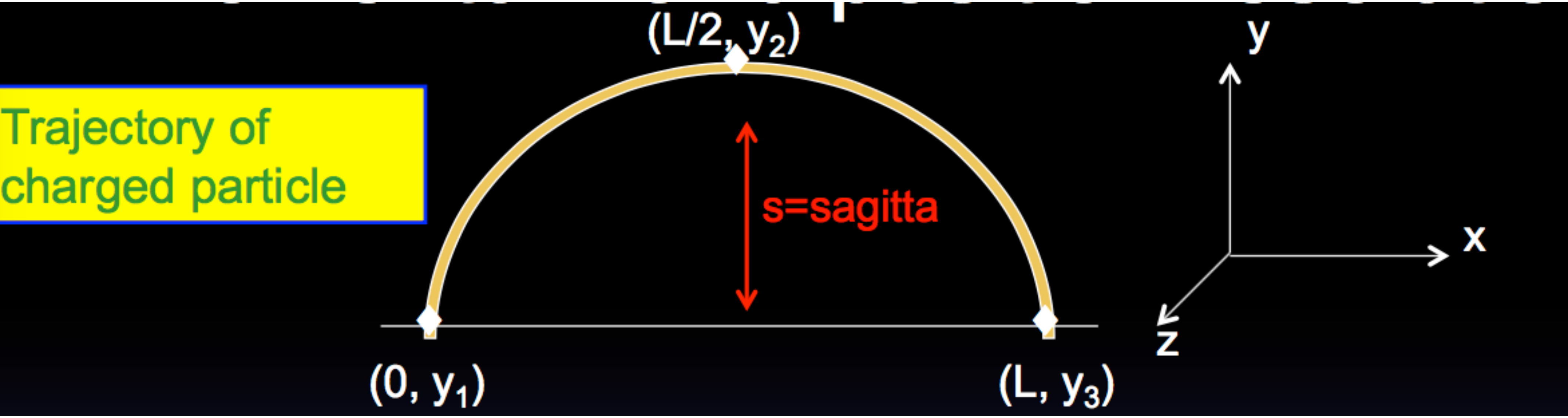
Charged particle of momentum p in a magnetic field B

$$\frac{d\vec{p}}{dt} = q\vec{\beta} \times \vec{B}$$

If the field is constant and we neglect the presence of matter, the momentum is constant with time, the trajectory is helical.

$$p[\mathrm{GeV}] = 0.3B[\mathrm{T}]\rho[\mathrm{m}]$$

TRACKING DETECTOR: momentum & position resolution



Assuming that y is measured at 3 points in the (x,y) plane (z=0) with a precision σ_y and a constant B field in the z direction so that $p_T=0.3B\rho$ ($\rho=r$, radius of curvature)

$$s = y_2 - \frac{y_1 + y_3}{2} \approx \frac{L^2}{8r} = \frac{L^2}{8p_\perp/(0.3B)} = \frac{0.3BL^2}{8p_\perp}$$

The error on the sagitta, σ_s, due to the measurements errors (error propagations) is $\boxed{\sigma_s = \sqrt{3/2}\sigma_y}$

The momentum (perpendicular to the B field direction) resolution due to position measurement error is:

$$\frac{\sigma_{p_\perp}}{p_\perp} = \frac{\sigma_s}{s} = \frac{\sqrt{3/2}\sigma_y}{(0.3L^2B)/(8p_\perp)} = \frac{8p_\perp\sqrt{3/2}\sigma_y}{0.3L^2B} = 32.6\frac{p_\perp\sigma_y}{L^2B} \quad \textbf{(m, GeV/c, T)}$$

TRACKING DETECTOR: Momentum & position resolution

The momentum resolution can be generalised for n measurements with different σ resolution to:

$$\frac{\sigma_{p_\perp}}{p_\perp} = \sqrt{\frac{720}{n+4}}\frac{\sigma_y p_\perp}{(0.3BL^2)} \quad \textbf{(m, GeV/c, T)}$$

What is striking about this formulae ? How does the momentum resolution depends on p_T ?
What can we derive from this formulae on ways to get the best momentum resolution ?

TRACKING DETECTOR: Momentum & position resolution

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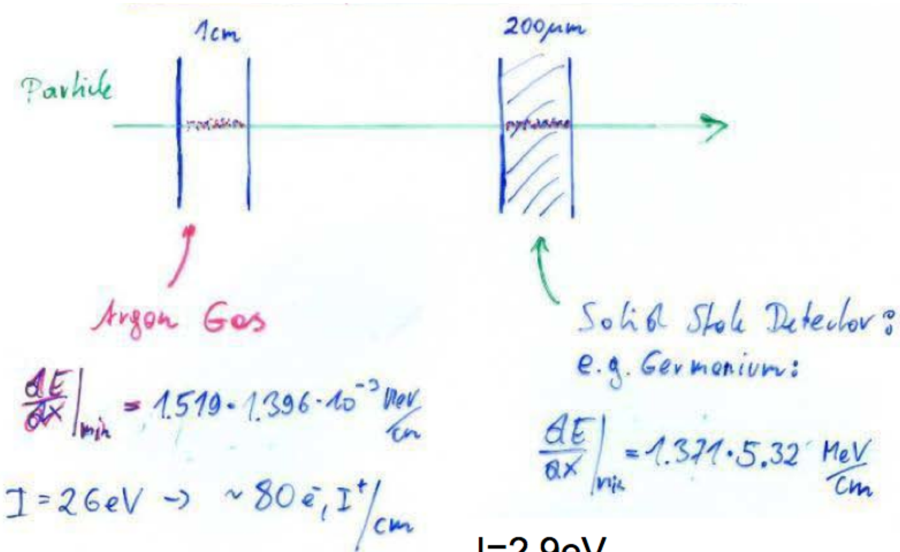
What is striking about this formulae ? How does the momentum resolution depends on p_T ?
What can we derive from this formulae on ways to get the best momentum resolution ?

(Transverse) Momentum resolution can be improved by:
- Increasing the magnetic field
- Increasing L (square), the lever arm
- Increasing the number of measurements n
- Decreasing (i.e. improving) the position resolution σ_y

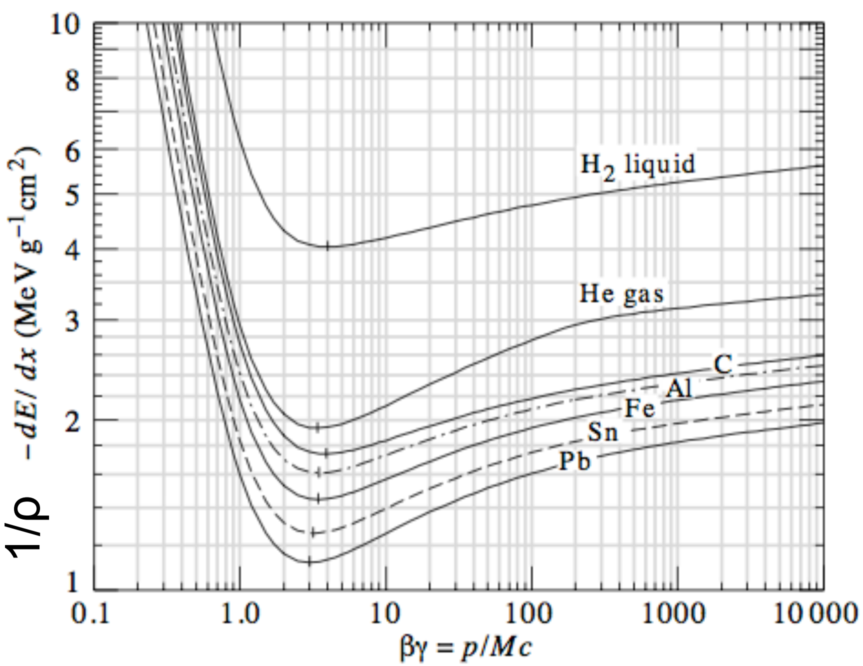
If we assume L=4m, B=1T and p=1TeV:
- R=p/(0.3B)=1000/0.3=3300m
- s≈16/(8*3300)≈0.6mm

If we want to measure the momentum with $\sigma_p/p \approx \Delta s/s \approx 10\%$ (at p = 1 TeV)
we need: $\sigma_s/s \approx 60$ μm

GAS vs SOLID DETECTOR



I=2.9eV
2.5 x 10^6 e/h pairs/cm



The induced signals are readout by dedicated electronics.

The noise and preamplifier determines whether the signal can be registered: S/N >> 1.

The noise is characterised by the *Equivalent Noise Charge* (ENC) = charge signal at the input that produces an output signal equal to the noise

ENC of very good amplifiers can be as low as 50 e^-, typical numbers are ~1000e^-

In order to register a signal, the registered charge must be q>>ENC i.e. typically q>>1000 e^-

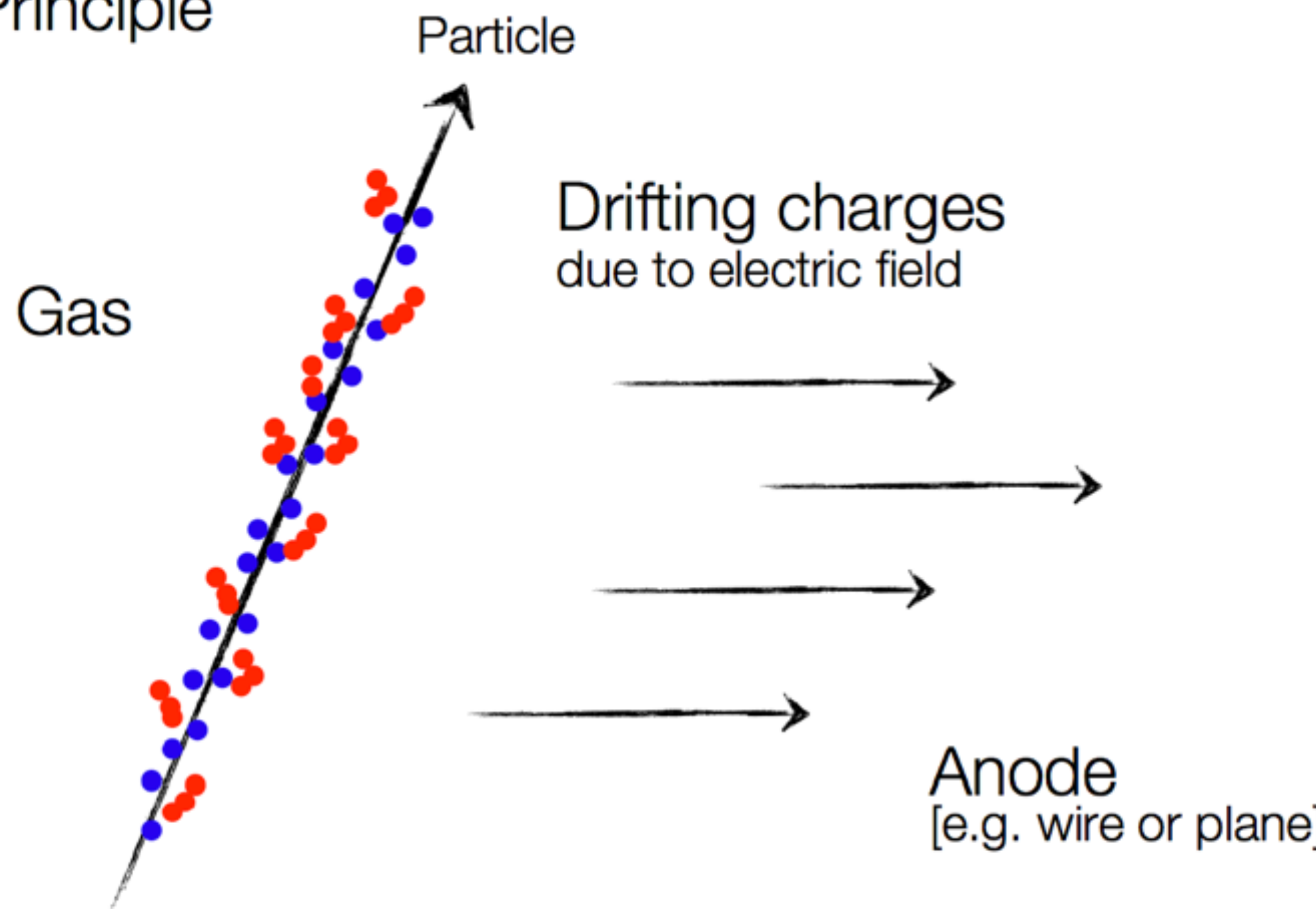
- Gas detector: q=80e^-/cm: too small
- Solid state detectors have 1000 times more density and factor 5-10 less ionisation energy: primary charge is 10^4-10^5 times larger than in gases.

Gas detectors need internal amplification in order to be sensitive to single particle tracks.

Without internal amplification they can only be used for a large number of particles that arrive at the same time (ionisation chamber).

INTRODUCTION - IONISATION

Schematic Principle
of gas detectors



- Primary Ionization
- Secondary Ionization (due to δ-electrons)

INTRODUCTION - IONISATION

Relevant Parameters
for gas detectors

Differences due to δ-electrons

Ionization energy	:	E_i
Average energy/ion pair	:	W_i
Average number of primary ion pairs [per cm]	:	n_p
Average number of ion pairs [per cm]	:	n_T

$$\langle n_T \rangle = \frac{L \cdot \left\langle \frac{dE}{dx} \right\rangle_i}{W_i}$$

[about 2-6 times n_p]
[L: layer thickness]

δ-electrons lead to secondary ionization and limit spatial resolution; typical length scale of secondary ionization: 10 μm. Example: kinetic energy: T_{kin} = 1 keV; gas: Isobutane ➛ range: R = 20 μm ...
[using R [g/cm²] = 0.71 $(T_{kin})^{1.72}$ [MeV]; valid for T_{kin} < 100 keV]

Gas	<Z>	ρ [g/cm³]	E_i [eV]	W_i [eV]	dE/dx [keV/cm]	n_p [cm⁻¹]	n_T [cm⁻¹]
He	2	$1.66\cdot10^{-4}$	24.6	41	0.32	5.9	7.8
Ar	18	$1.66\cdot10^{-3}$	15.8	27	2.44	29.4	94
CH_4	19	$6.7\cdot10^{-4}$	13.1	28	1.48	18	53
C_4H_{10}	34	$2.42\cdot10^{-3}$	10.6	23	4.50	46	195

INTRODUCTION - IONISATION

Ionization statistics:

Mean distance between two ionizations: $\lambda = 1/(n_e \sigma_I)$

Mean number of ionizations: $\langle n_p \rangle = L/\lambda$

σ_I : Ionization x-Section
n_e : Electron density
L : Thickness

Mean free path λ:
[typical values]

He	0.25 cm
Air	0.052 cm
Xe	0.023 cm

[$\rightarrow \sigma_I$(He) ≈ 100 b]

n_p Poissonian distributed:

$$P(n_p, \langle n_p \rangle) = \frac{\langle n_p \rangle^{n_p} e^{-\langle n_p \rangle}}{n_p!}$$

P(0) = exp(-L/λ) yields λ, σ_I
using (in)efficiency of gas-detectors

Also important:

Mobility of charges:
Influences the timing behavior of gas detectors ...

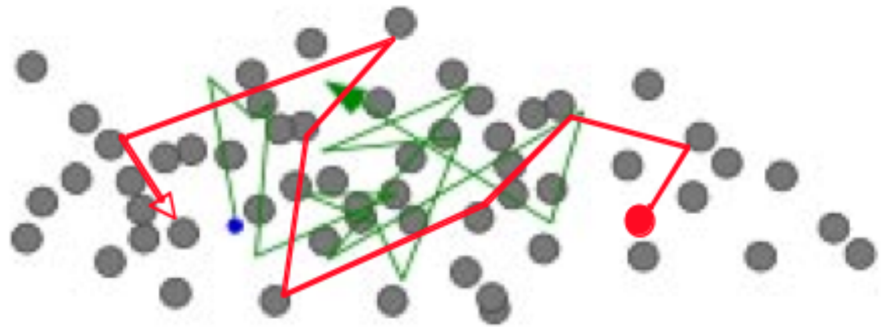
Diffusion:
Influences the spatial resolution ...

Avalanche process via impact ionization:
Important for the gain factor of the gas detector ...

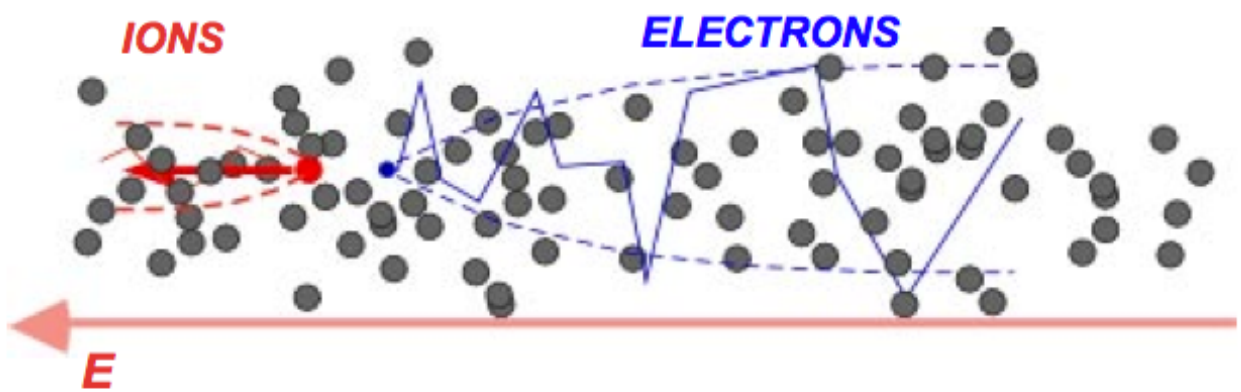
Recombination and electron attachment:
Admixture of electronegative gases (O_2, F, Cl ...) influences detection efficiency ...

DIFFUSION IN GAS

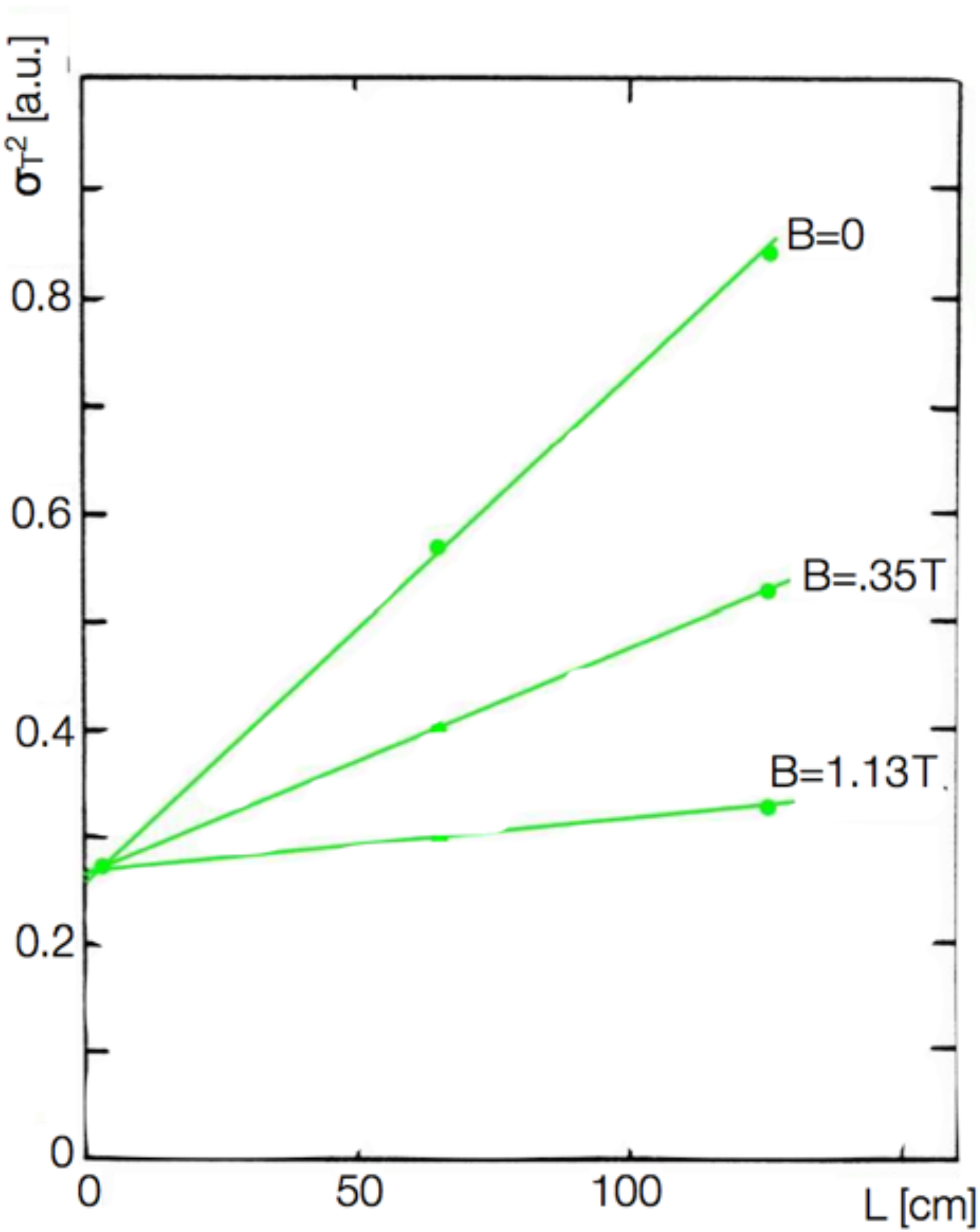
No electric field (E=0): thermal diffusion



With electric field (E>0): charge transport and diffusion



DRIFT and DIFFUSION in GASES



Transverse diffusion as function of drift length for different B fields

DETECTING IONISATION WITH GAS DETECTOR

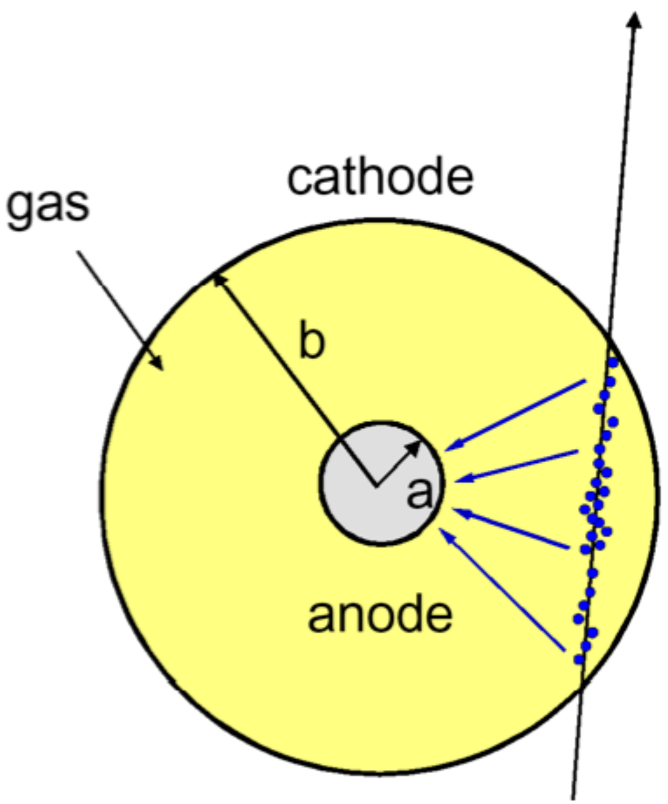
Criteria for optimal momentum resolution

- many measurement points
- large detector volume
- very good single point resolution
- as little multiple scattering as possible

Gas detectors provide a good compromise and are used in most experiments. However

- per cm in Argon, only ~100 electron-ion pairs are produced by ionisation;
- this is to be compared with the noise of a typical preamplifier of ~1000 e-.

→ a very efficient amplification mechanism is required



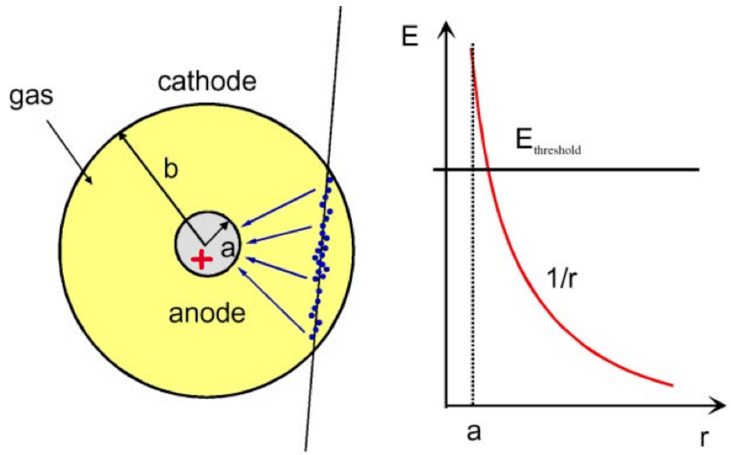
AMPLIFICATION of the SIGNAL in GAS

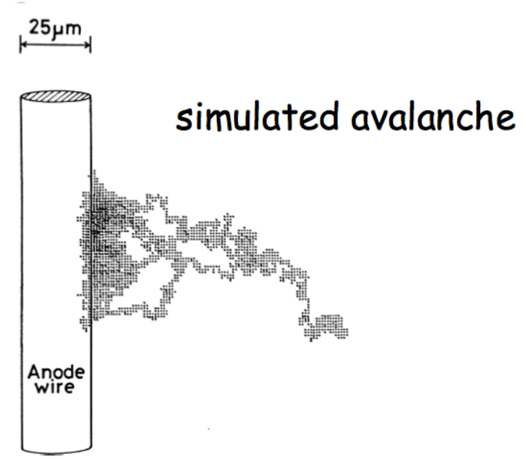
For a cylindrical geometry

$$E(r) \propto \frac{1}{r} \qquad V(r) \propto \ln\frac{r}{a}$$

The primary electrons drift towards the positive anode:

- due to 1/r dependence the electric field close to the very thin wires reaches values E>kV/cm
- in between collisions with atoms electrons gain enough energy to ionise further gas molecules
- Exponential increase in number of electron-ion pairs close (few μm) to the wire.





GAS DETECTORS with INTERNAL ELECTRON MULTIPLICATION

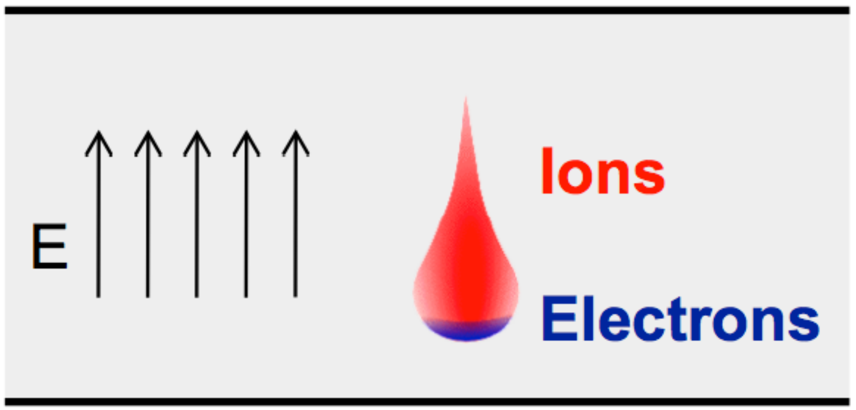
Principle: At sufficiently high electric fields (100 kV/cm) the electrons gain energy in excess of ionisation energy: secondary ionisation etc…

$dN = N \,.\, \alpha \,.\, dx$

α: Towsend coefficient

$N(x) = N_0 \, e^{\alpha x}$

N/N_0 = Amplification, Gas Gain



Avalanche in a homogeneous field

Problem: High field at electrode surface → breakdown

In an inhomogeneous field

$\alpha(E) \rightarrow N(x) = N_0 \, e^{\alpha(E(x')).dx'}$

AVALANCHE FORMATION

Wire with radius a~10-25μm in a tube of radius b~1-3 cm

$$E(r) = \frac{\lambda}{2\pi\varepsilon_0}\frac{1}{r} = \frac{V_0}{\ln\frac{b}{a}}\frac{1}{r}, \qquad V(r) = \frac{V_0}{\ln\frac{b}{a}}\ln\frac{r}{a},$$

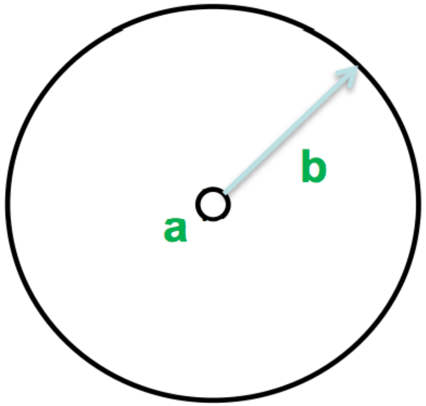
Electric field close to a thin wire (100-300 kV/cm) e.g.

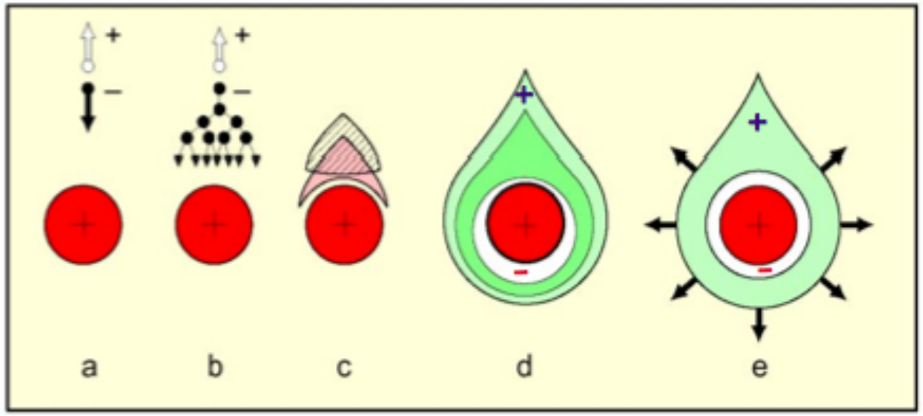
eV_0=1000V, a=10μm, b=10 mm, E(a)=150kV/cm

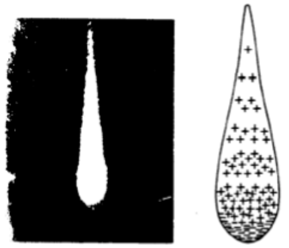
Electric field is sufficient to accelerate electrons to energies which are sufficient to produce secondary ionisation

→ electron avalanche

→ signal







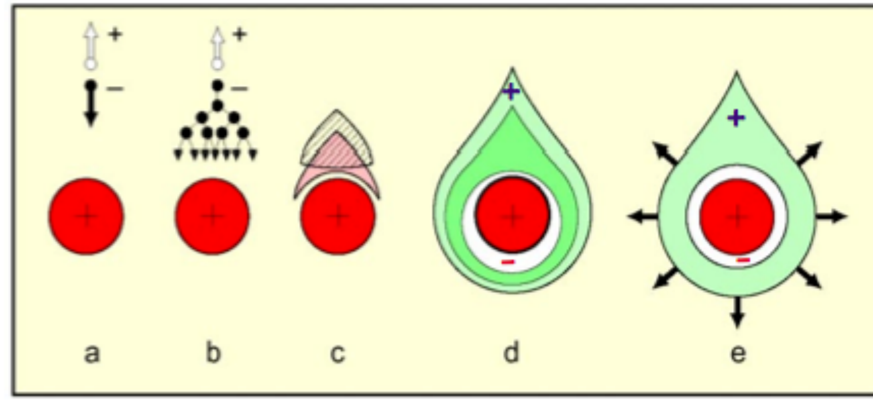
picture taken with cloud chamber

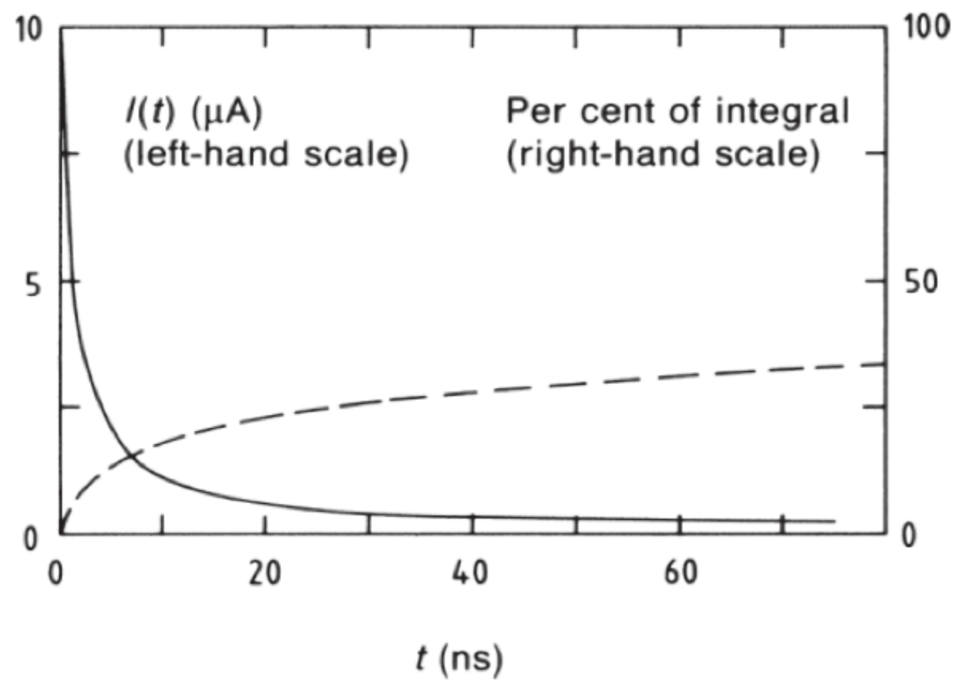
WIRE CHAMBER: SIGNAL from ELECTRON AVALANCHE

The electron avalanche happens very close to the wire; First multiplication only around R=2 x wire radius. Electrons are moving to the wire surface very quickly (<<1ns). ions are drifting towards the tube wall (~100 μs).

The signal is characterised by a very fast spike from the electrons and a long tail.

The total charge induced by the electrons, i.e. the charge of the current spike due to the short electron movement, amounts to 1-2% of the total induced charge.





MODE of OPERATIONS

Ionization mode:

full charge collection
no multiplication; gain ≈ 1

Proportional mode:

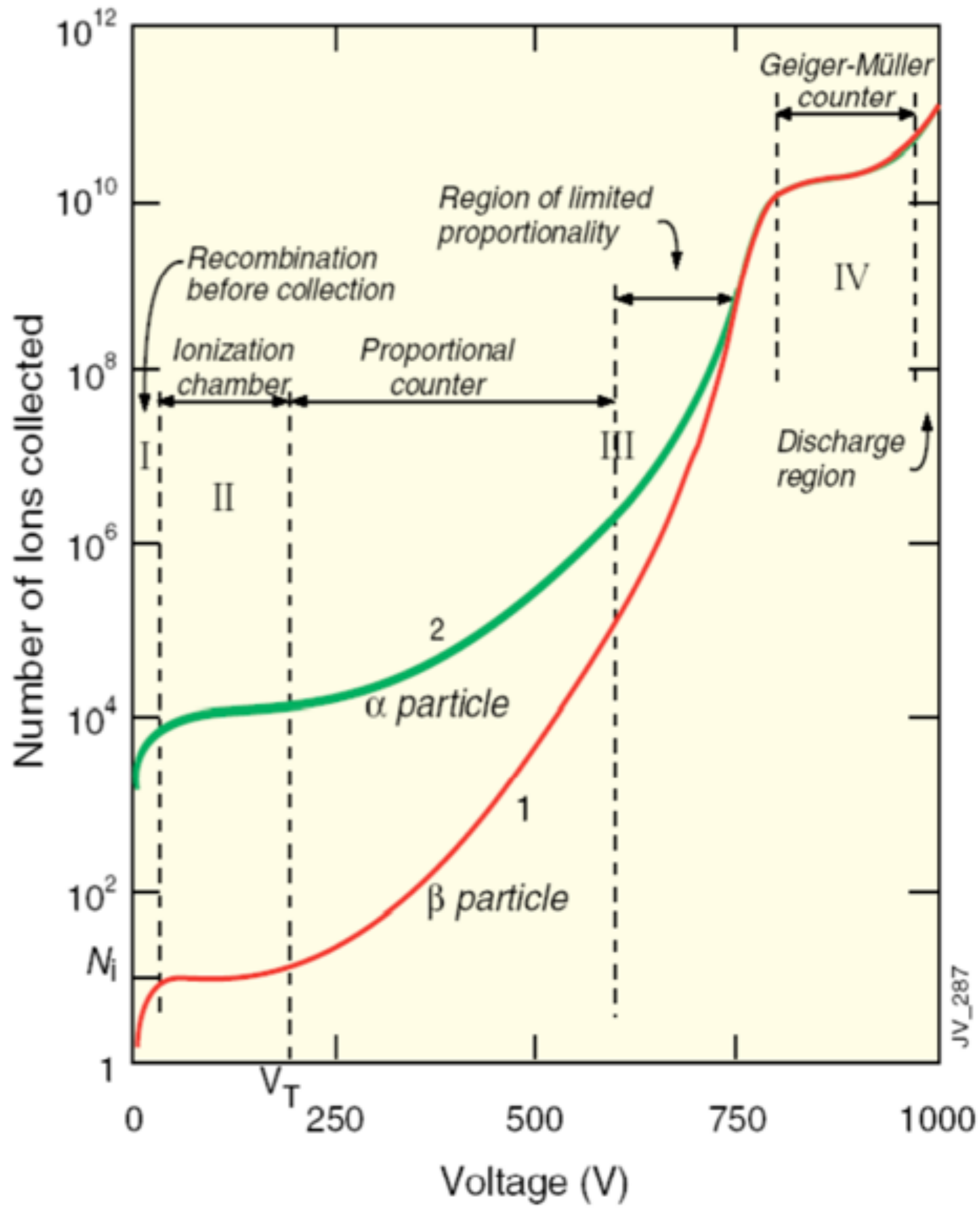
multiplication of ionization
signal proportional to ionization
measurement of dE/dx
secondary avalanches need quenching;
gain ≈ $10^4 – 10^5$

Limited proportional mode:
[saturated, streamer]

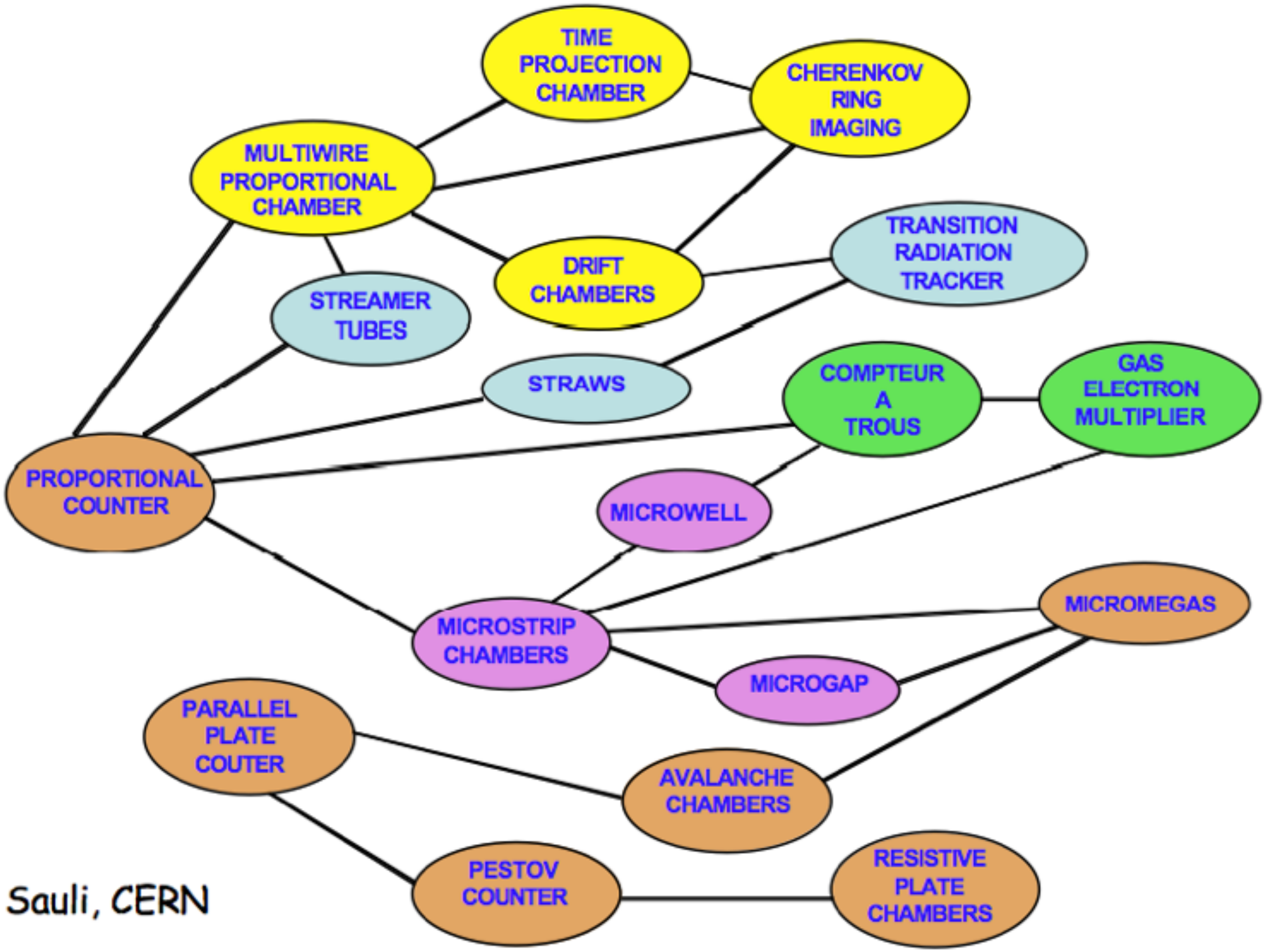
strong photoemission
requires strong quenchers or pulsed HV;
gain ≈ 10^{10}

Geiger mode:

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



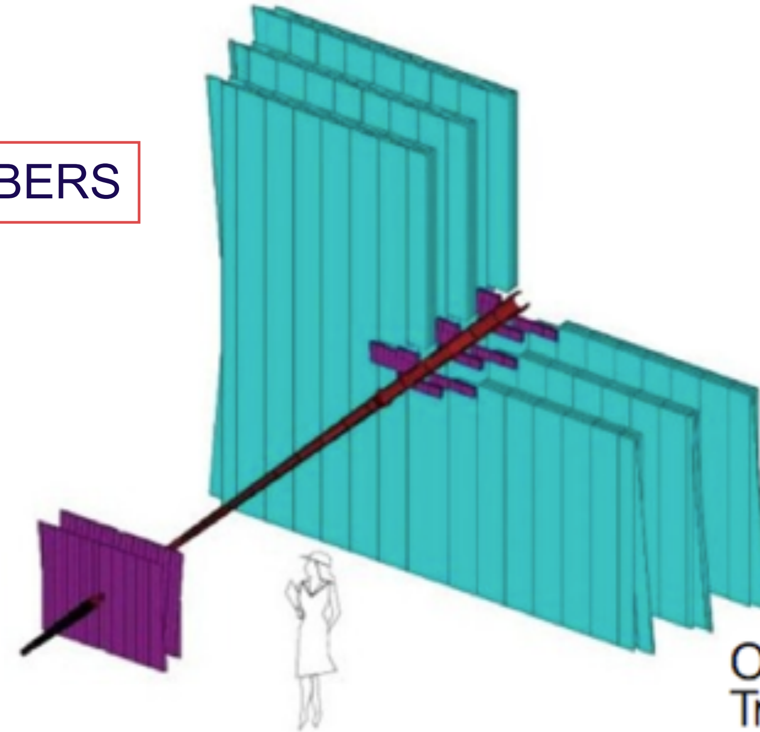
FAMILY TREE OF GASEOUS DETECTORS



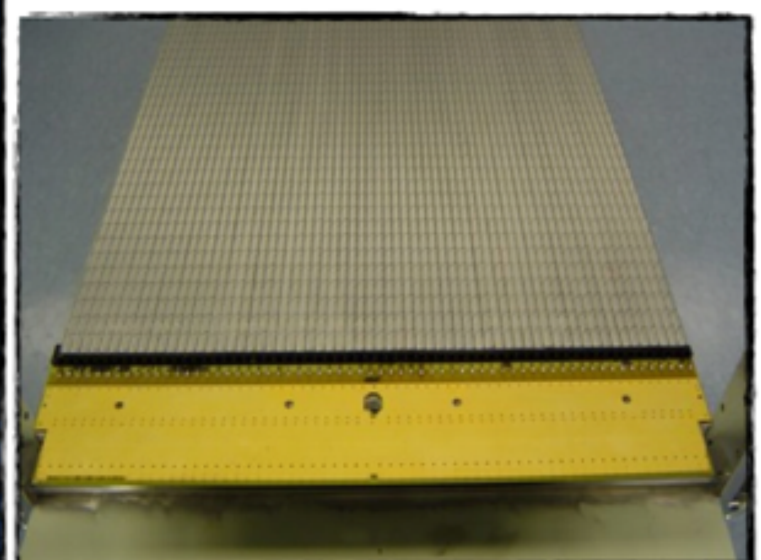
Fabio Sauli, CERN

LHCb OUTER TRACKER

SINGLE WIRE PROPORTIONAL CHAMBERS



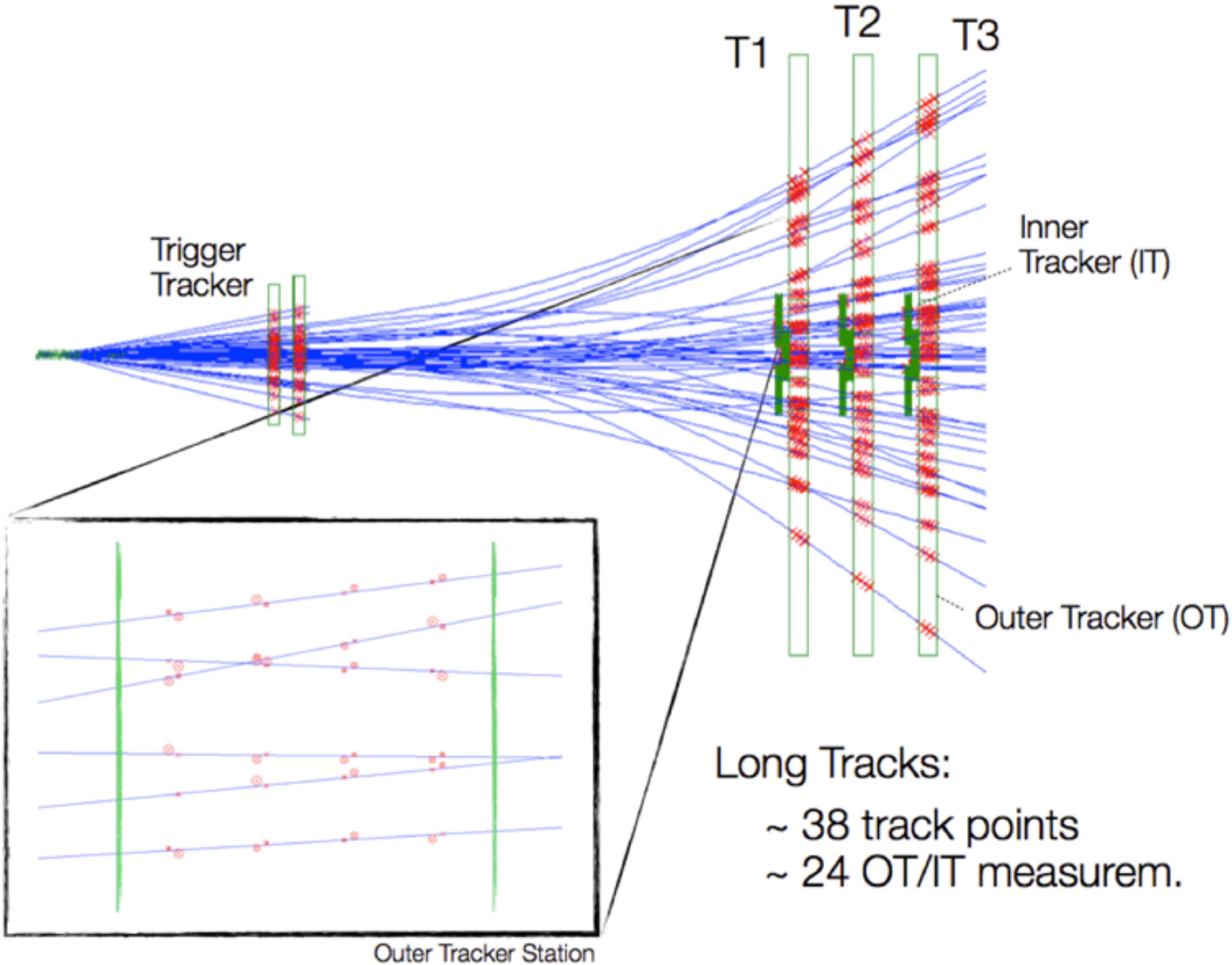
Outer Tracker



Straw Tubes
[double layers]

3 Chambers
[4 layers á 18 modules]

LHCb OUTER TRACKER



Long Tracks:

~ 38 track points
~ 24 OT/IT measurem.

MULTI WIRE PROPORTIONAL CHAMBERS

Classic geometry - Charpak 1968

One plane with thin senses wires is placed between two parallel plates

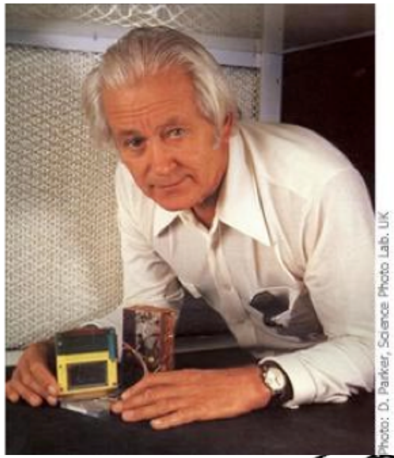
- Wire distance ~2-5 mm
- Distance between cathode planes ~10 mm

Electrons (v~5cm/μs) are collected with 100 ns. The ion tail can be eliminated by electronics filters

- → pulse of < 100 ns length

For 10% occupancy→one pulse every μs

- → 1MHz/wire rate capacity
- → Compare with bubble chamber at 10 Hz



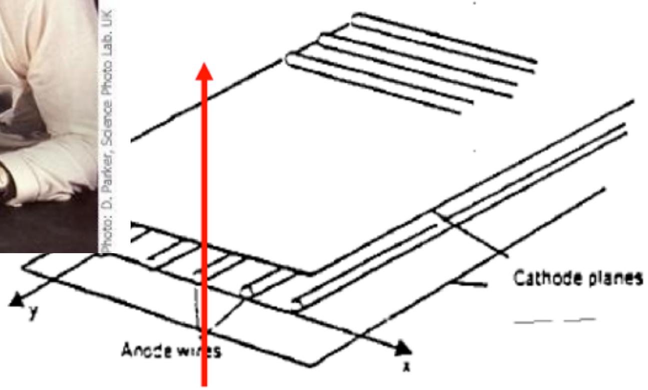
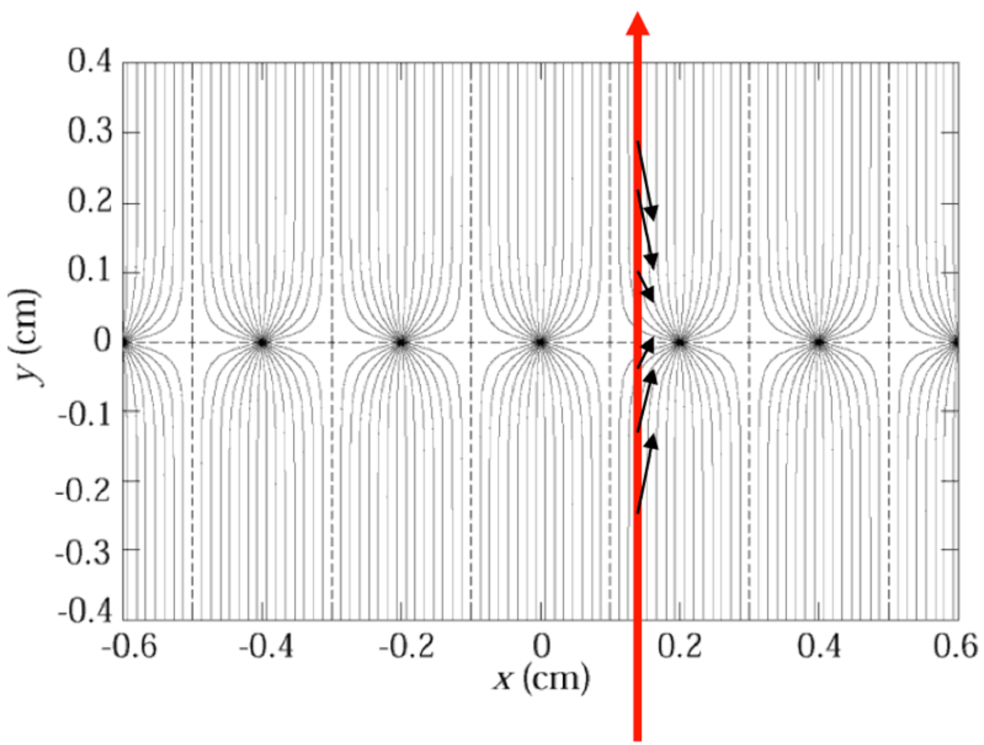


Abbildung 2.27: *Vieldrahtproportionalkammer.*



OPAL DRIFT CHAMBER

TIME PROJECTION CHAMBER

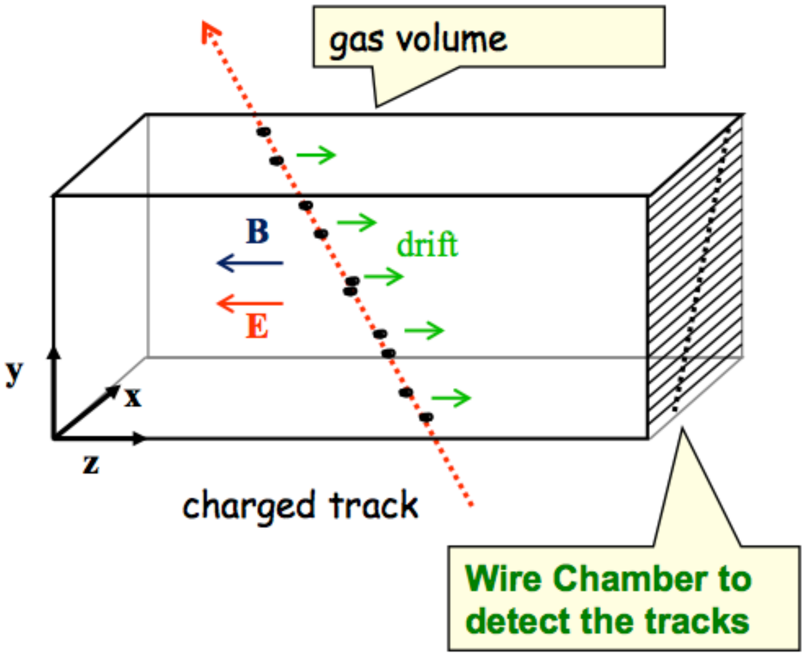
Gas volume with parallel E and B field.

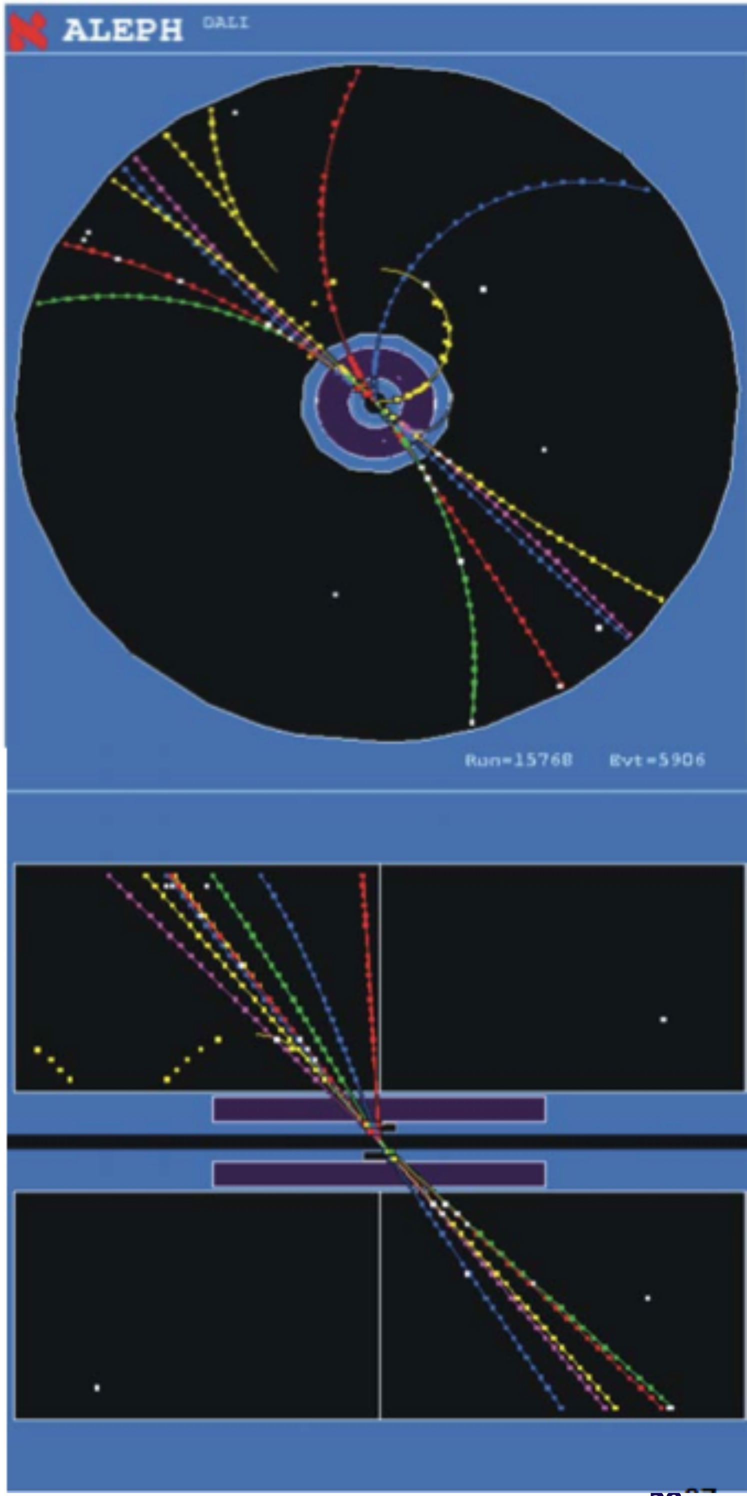
B for momentum measurement.

Positive effect:

Diffusion is strongly reduced by E//B (up to a factor 5)

Drift fields 100-400V/cm - Drift times 10-100 µs and distance up to 2.5 m.





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

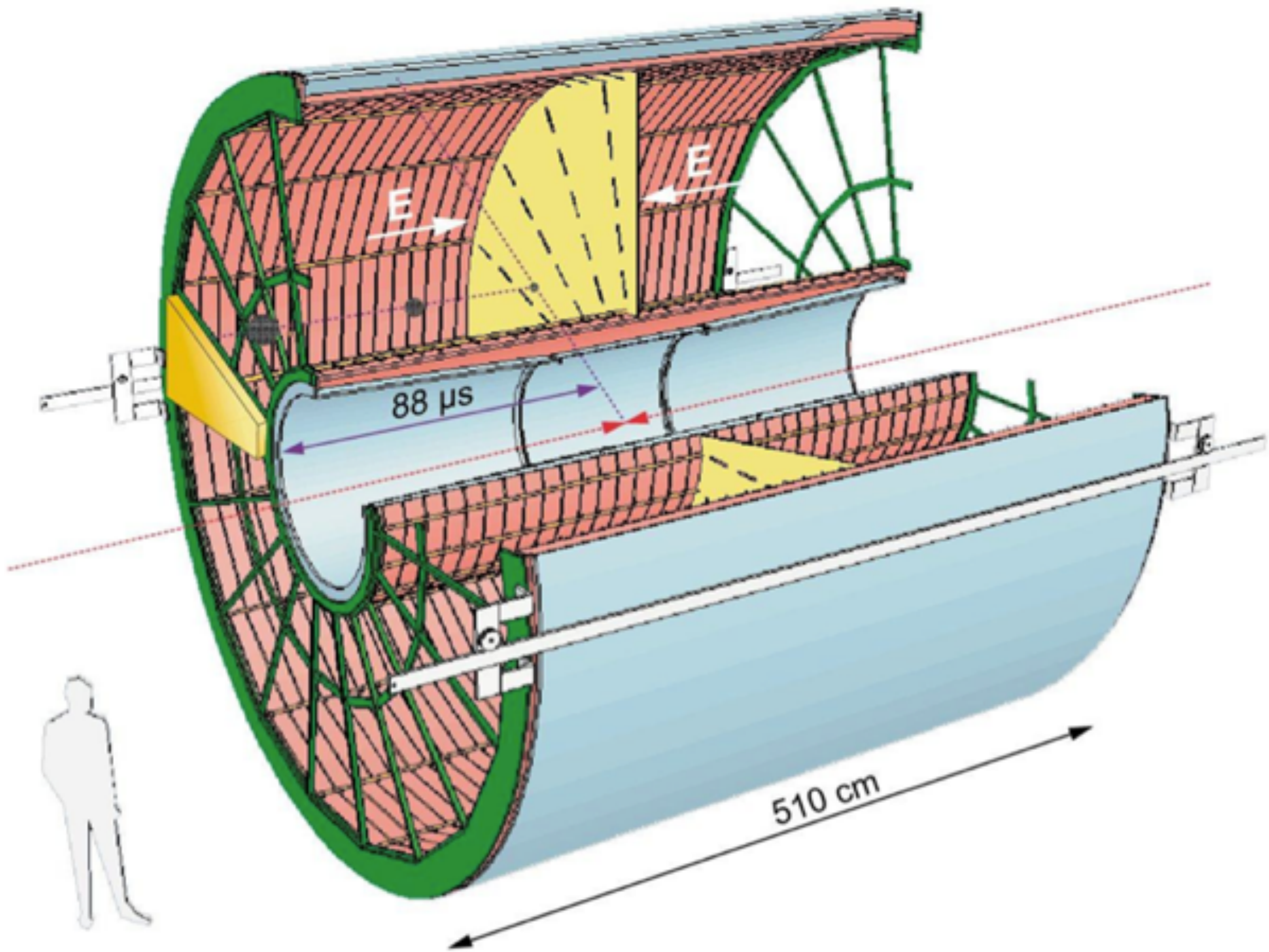
Diffusion: σ_t = 250 μm
Resolution: $\sigma \approx 0.2$ mm

σ_p/p ~ 1% p; ε ~ 97%
$\sigma_{dE/dx}/(dE/dx)$ ~ 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%)

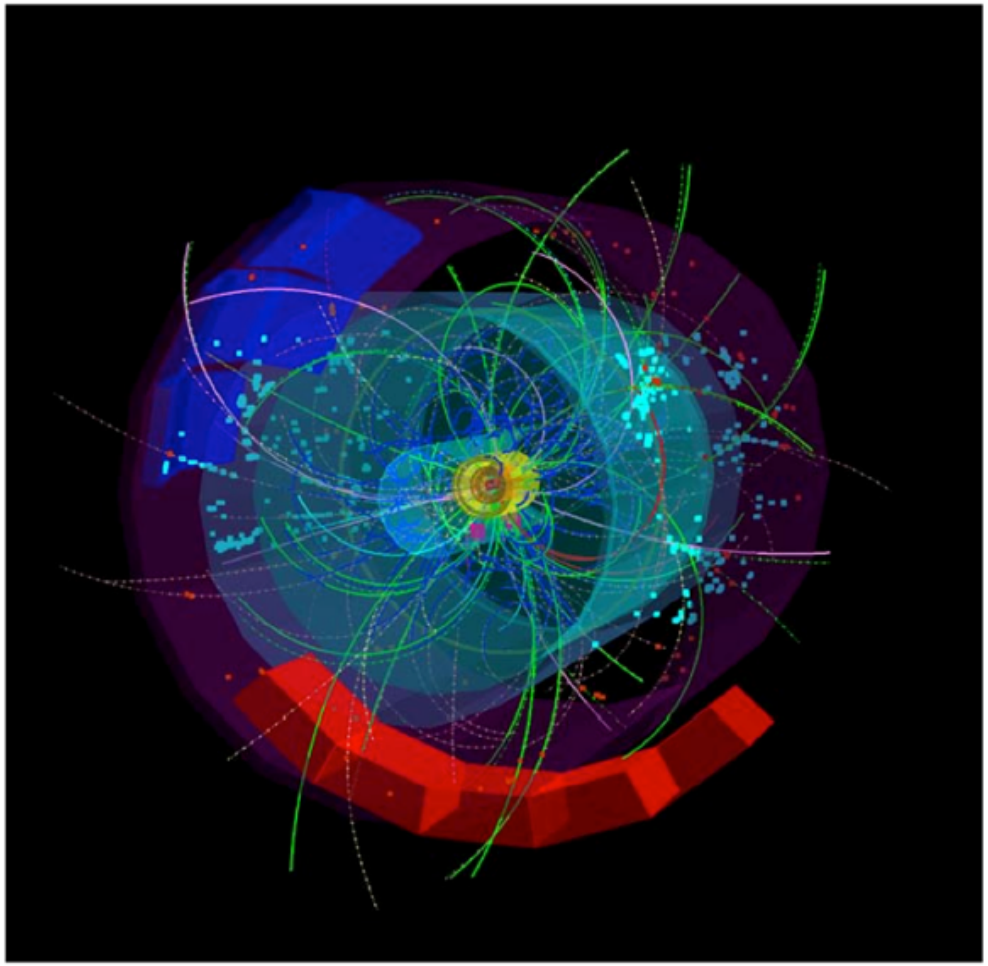
CONSTRUCTION of the ALICE TPC

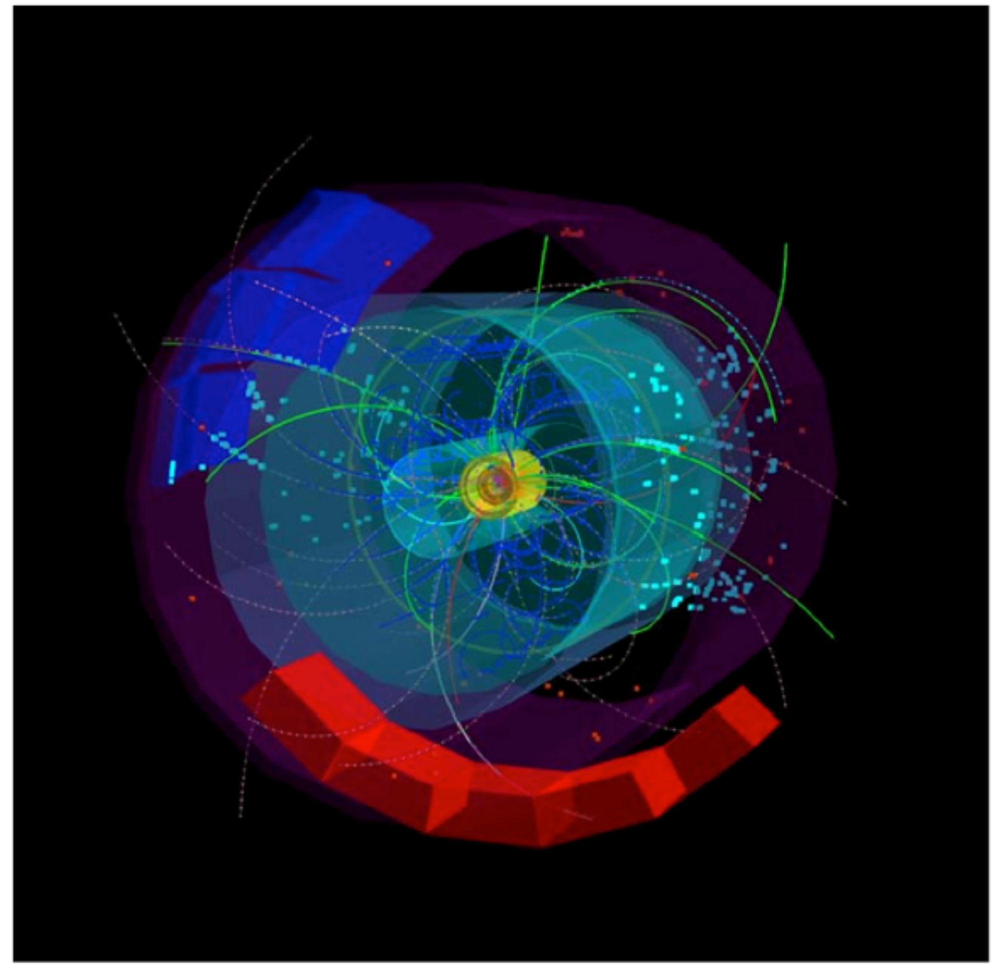
ALICE TPC Construction

A visit inside the TPC.

W. Riegler/CERN

FIRST 7 TeV COLLISIONS in the ALICE TPC (03.2010)





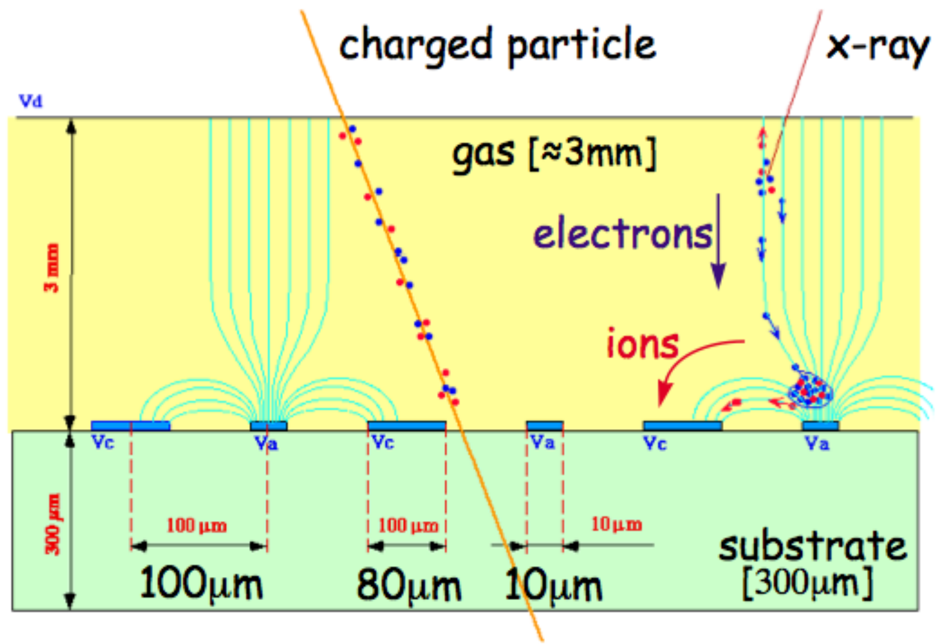
MICRO STRIPS PLATE CHAMBERS

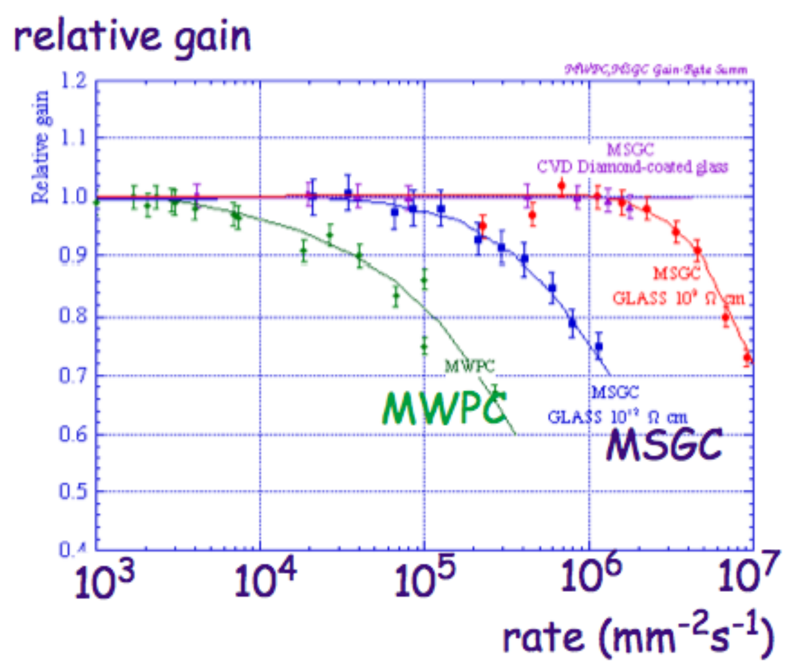
ADVANTAGE

Very precise and small anode/cathode structures can be produced with lithographical methods → very good position resolution

High mechanical stability

Small drift distance for ions → high rate capability





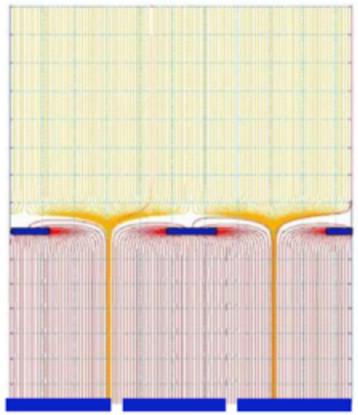
GEM & MICROMEGAS

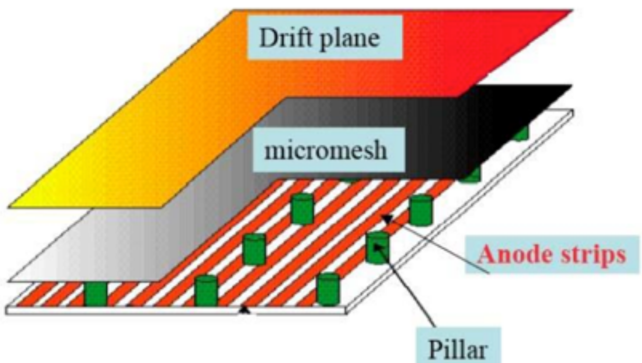
In the late 90's developped by F. Sauli at CERN [NIM A386 (1997), 531]

- Typical gain of 10^3 at 500 V
- Can stack several stages on top of each other
  - Large total gain for relatively moderate HV

MICROMEGAS
Narrow gap (50-100μm) PPC with thin cathode mesh
Insulating gap-restoring wires or pillars

GEM
Thin metal-coated polymer foils
70 μm holes at 140 mm pitch





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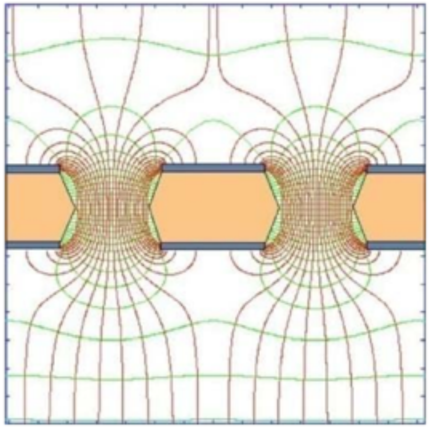

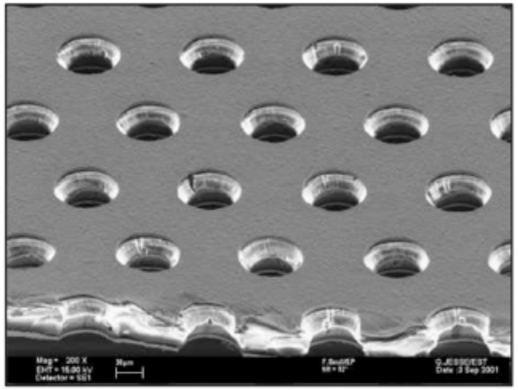

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SUMMARY on GAS DETECTORS

Wire chambers feature prominently at LHC. A decade of very extensive studies on gases and construction materials has lead to wire chambers that can track up to MHz/cm_2 of particles, accumulate up to 1-2C/cm of wire and 1-2 C/cm^2 of cathode area.

While silicon trackers currently outperform wire chambers close to the interaction regions, wire chambers are perfectly suited for the large detector areas at outer radii.

Large scale next generation experiments foresee wire chambers as large area tracking devices.

The Time Projection Chamber, if the rate allows its use, is unbeatable in terms of low material budget and channel economy.

Gas detector can be simulated very accurately due to excellent simulation programs.

Novel gas detectors, the Micro Pattern Gas Detectors, have proven to work efficiently at high rate, low material budget trackers in the *regime* between silicon tracker and large wire chambers.

SOLID STATE DETECTORS

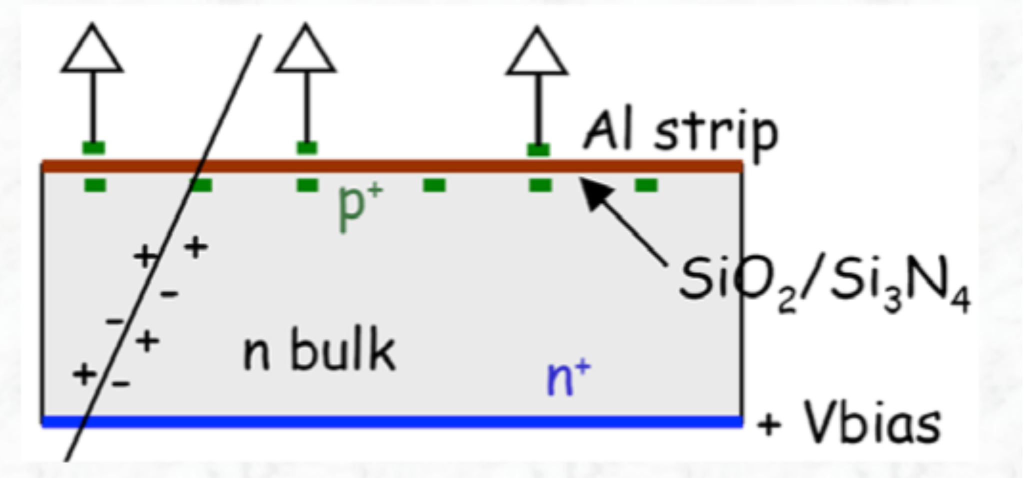
Silicon detectors: a kind of solid-state ionisation chamber

Si-detector concepts started in the 80's: expensive and difficult at first

Increased commercial use of Si-photolithography and availability of Very Large Scale Integration electronics lead to a boom for Si-detectors in the 90's - and it still goes on, though still some R&D to do, in particular concerning radiation hardness

Nearly all HEP experiments use Silicon detectors as innermost high-precision tracking device

HEP experiments are now exporting Si-technology back to the commercial world (Medical imaging).



BASIC SEMI-CONDUCTOR PROPERTIES

Intrinsic semiconductor:

Very pure material; charge carriers are created by thermal, optical or other excitations of electron-hole pairs; $N_{electrons} = N_{holes}$ holds ...

Commonly used: Silicon (Si) or Germanium (Ge); four valence electrons ...

Doped or extrinsic semiconductor:

Majority of charge carriers provided by donors (impurities; doping)

n-type : majority carriers are electrons (pentavalent dopants)
p-type : majority carriers are positive holes (trivalent dopants)

Pentavalent dopants (electron donors): P, As, Sb, ...
[5^{th} electron only weakly bound; easily excited into conduction band]

Trivalent dopants (electron acceptors): Al, B, Ga, In, ...
[One unsaturated binding; easily excepts valence electron leaving hole]

SOLID STATE DETECTORS

Primary ionisation

The average energy to produce an electron/hole pair is for Diamond/Silicon/Germanium: 13/3.6/2.9 eV.

Comparing to gas detector, the density of a solid is about a factor 1000 larger than that of a gas and the energy to produce electron/hole pair e.g. sir Si is a factor 7 smaller than the energy to produce an electron/ion pair in Argon.

Solid state vs gas detector

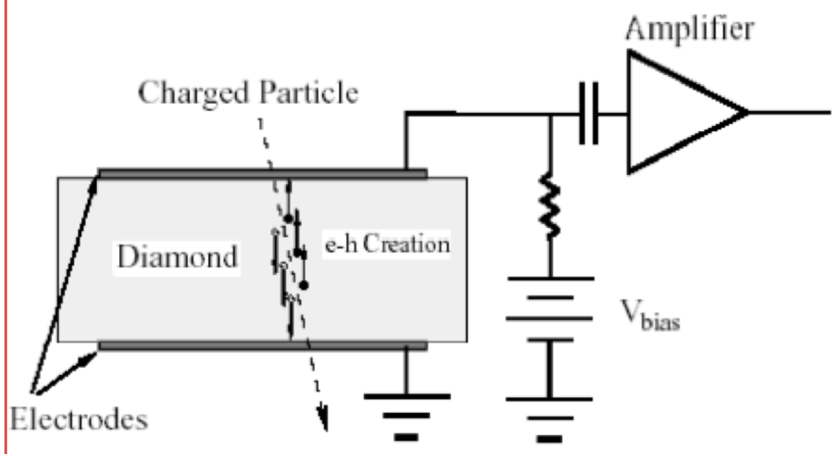
The number of primary charges in a Si detector is therefore about 10^4 times larger than the one in gas

gas detectors need internal charge amplification

solid state detectors do not need internal amplification

While in gas detectors the velocity of electrons and ions differs by a factor 1000, the velocity of electrons and holes in many semiconductors is quite similar

very short signal



SILICIUM DIODE USED as a PARTICLE DETECTOR

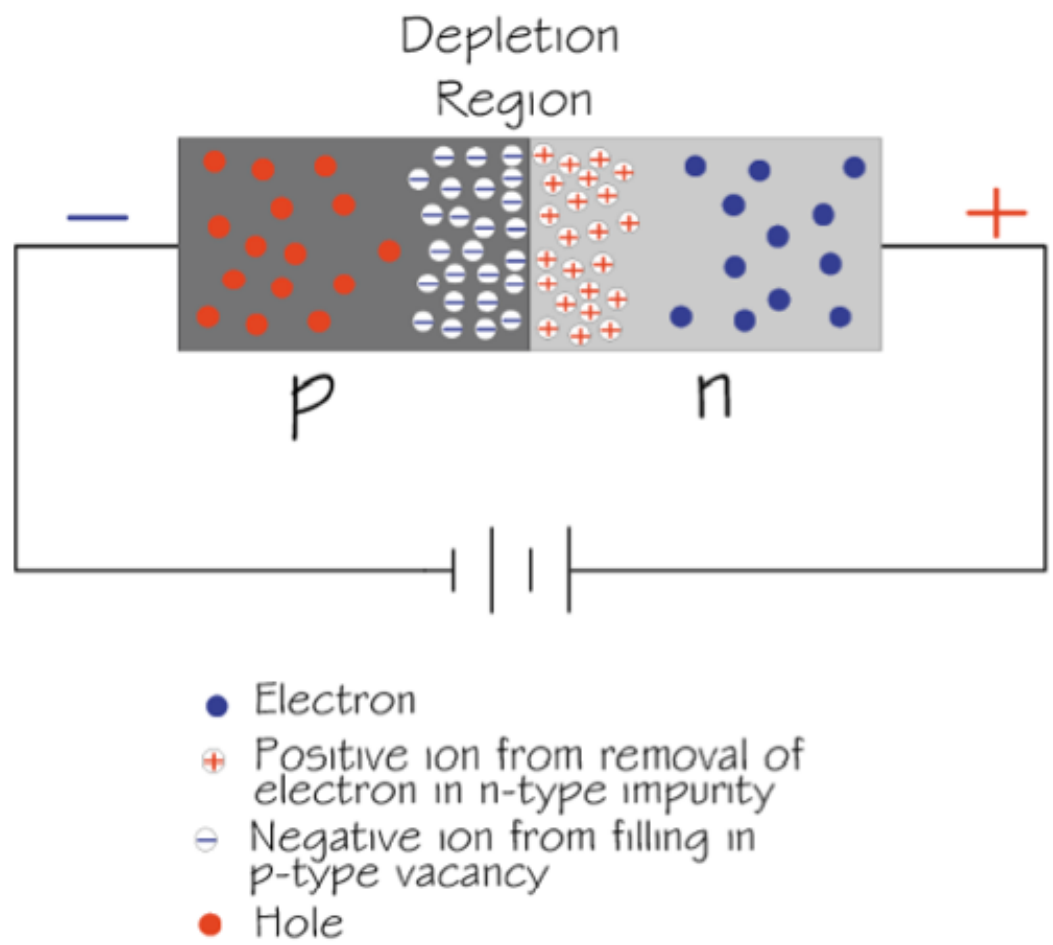
At the p-n junction the charges are depleted and a zone free of charge carriers is established

By applying a voltage, the depletion zone can be extended to the entire diode

→ highly insulating layer

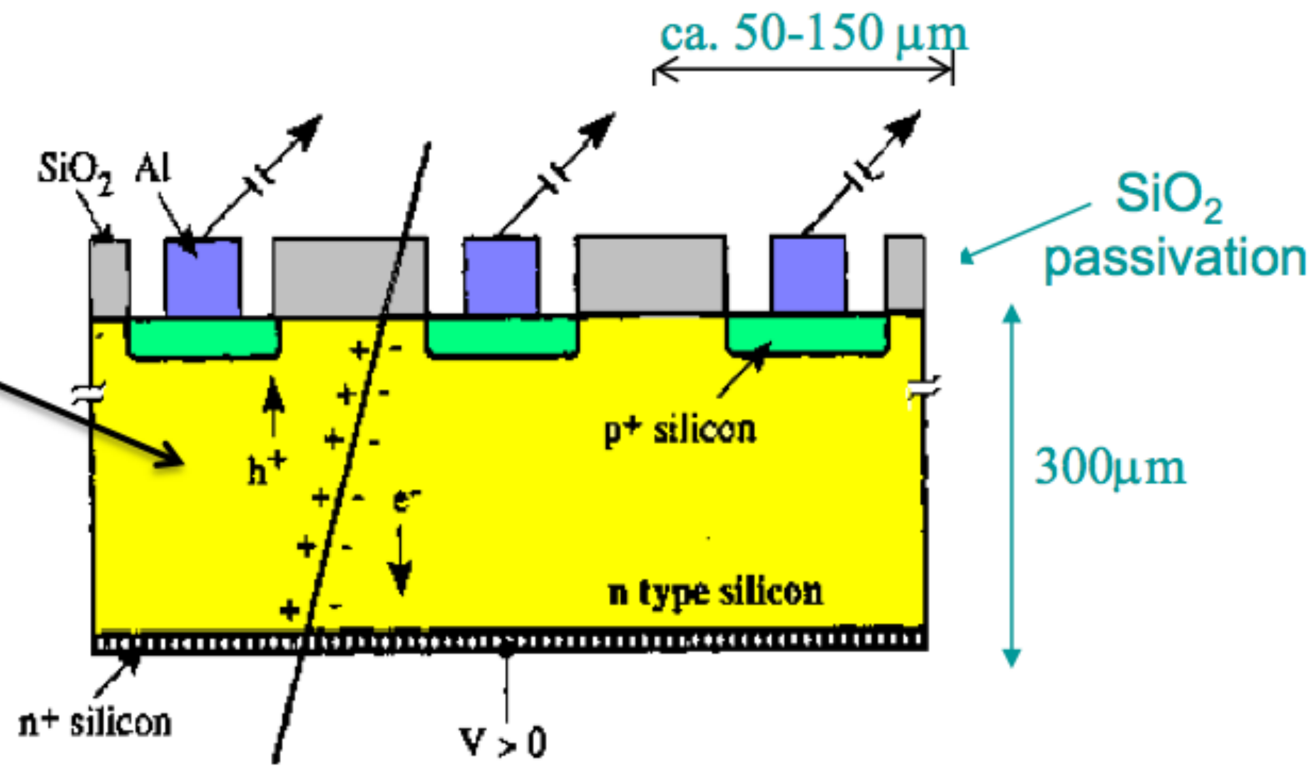
An ionising particle produces free charge carriers in the diode, which drift in the electric field and induce an electrical signal on the metal of the electrodes.

As silicon is the most commonly used material in the electronics industry, it has one big advantage with respect to other materials, namely highly developed technology.



Silicon detector

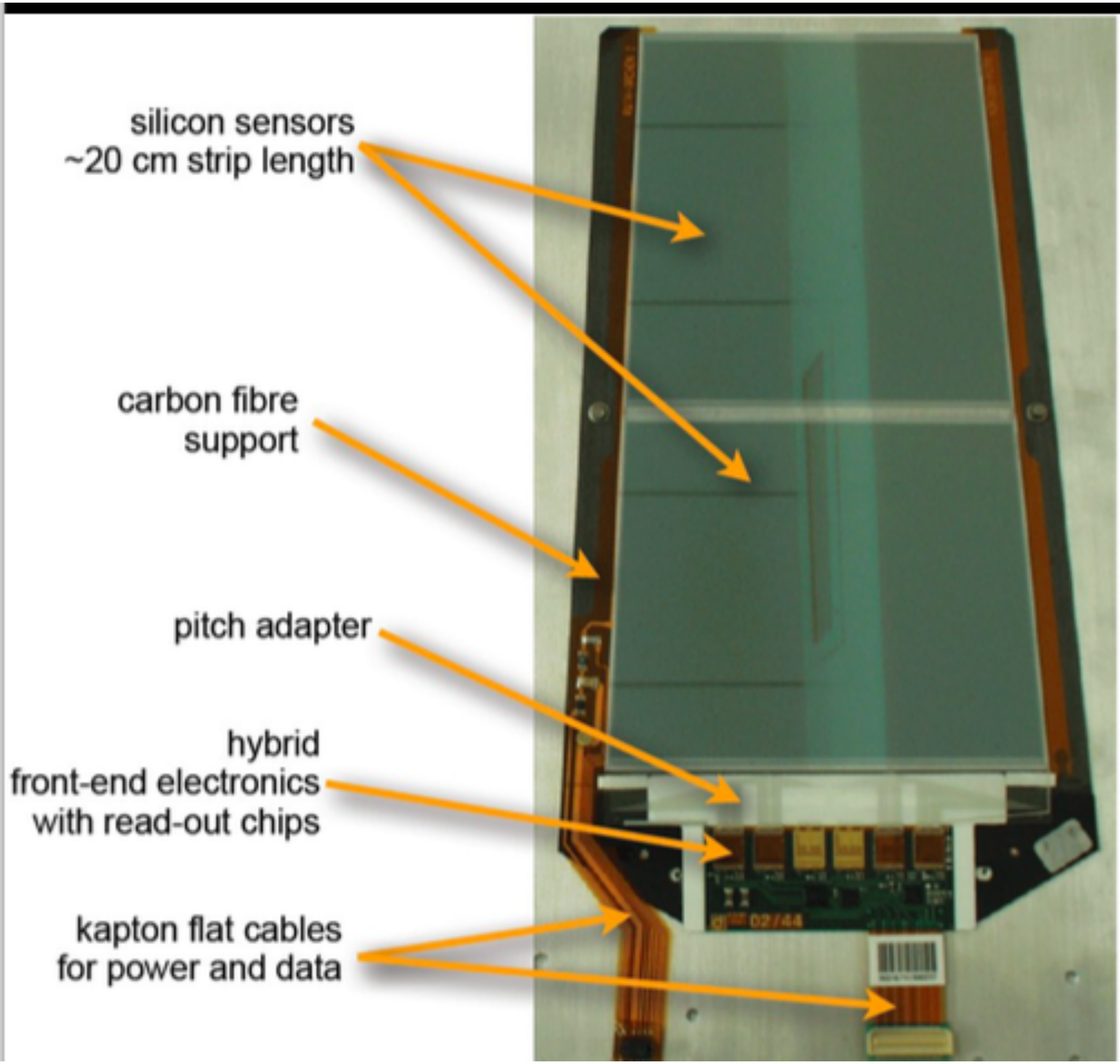
Fully depleted zone

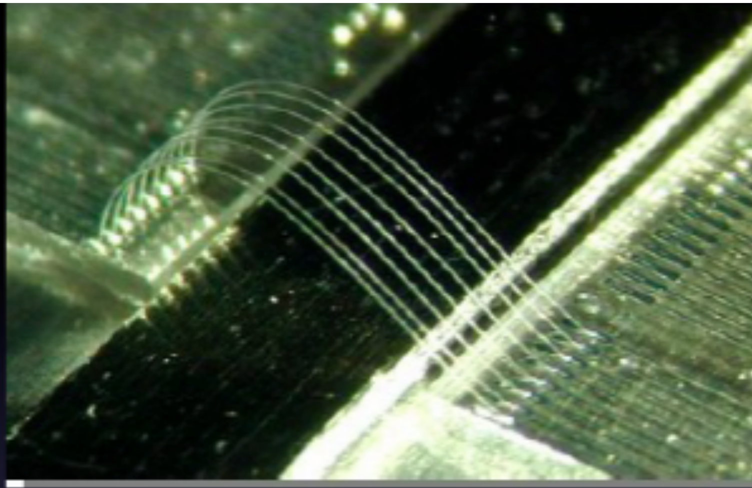


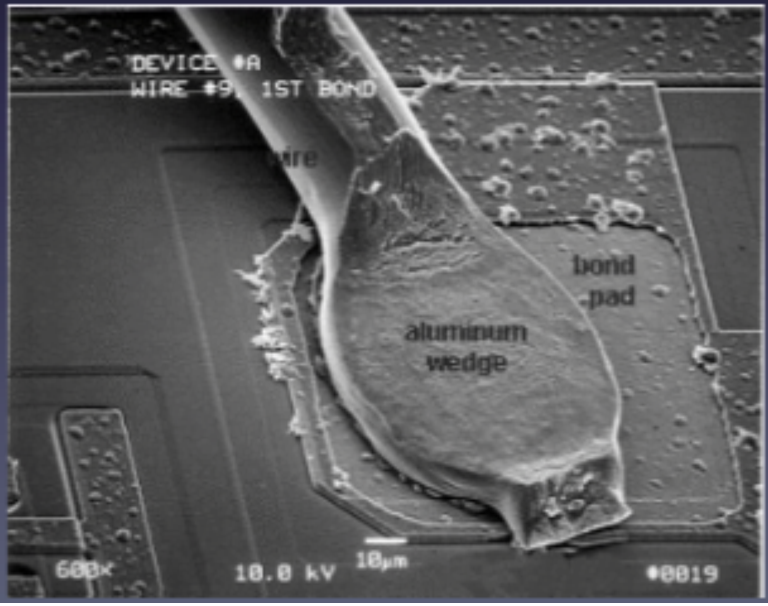
N (e-h) = 11 000/100µm

Position Resolution down to ~ 5µm !

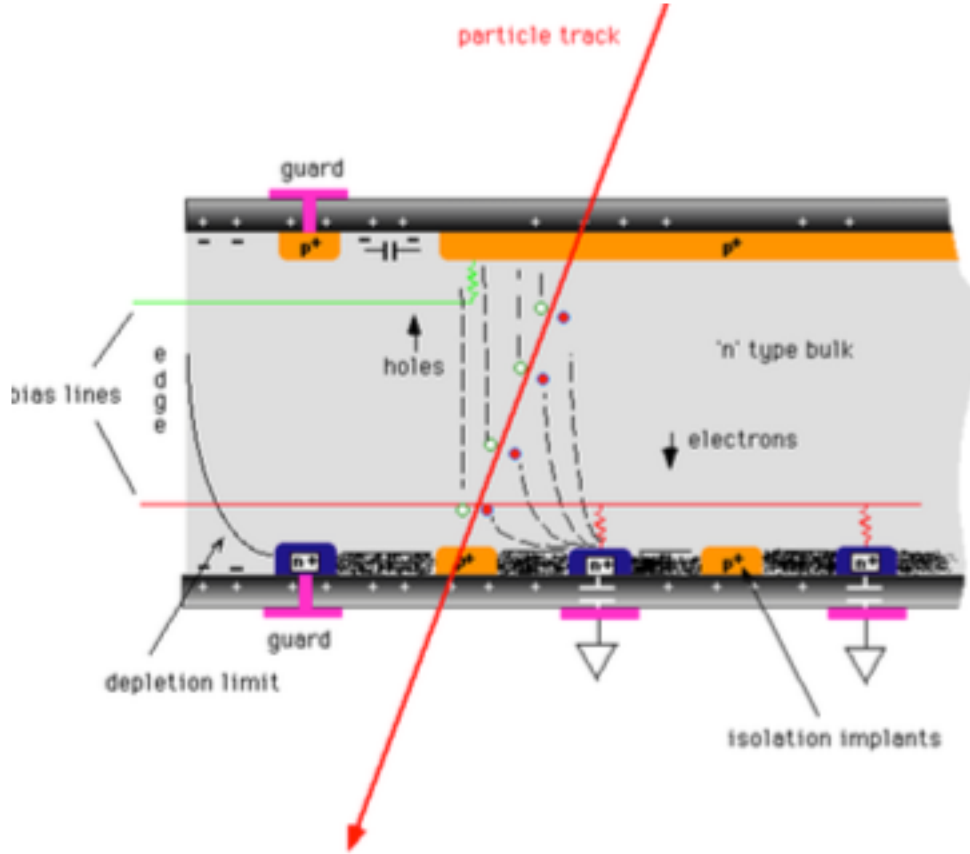
A TYPICAL STRIP MODULE



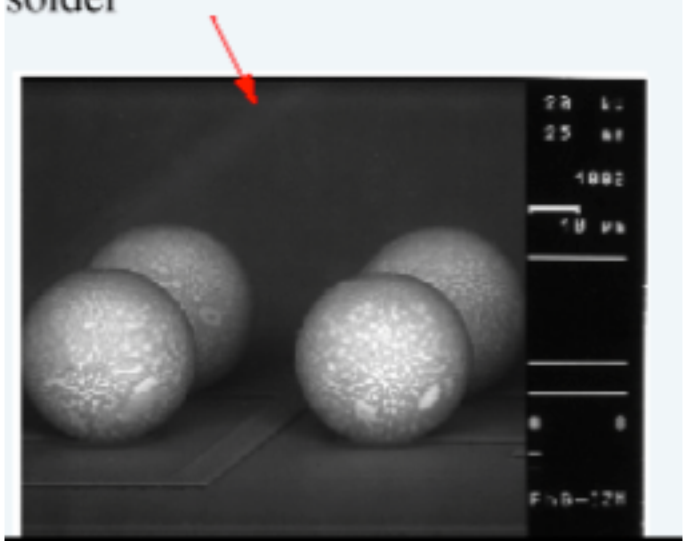




PIXEL DETECTOR



fine pitch (50 µm) bump placements
solder



Advantage

Pixel detector provides space-point information

Small pixel area

low detector capacitance (1fF/pixel)

large signal-to-noise ratio (150:1)

Small pixel volume

low leakage current

Special n+-on n technique pour LHC

Faster electron collection time

Disadvantages

Large number of readout channels

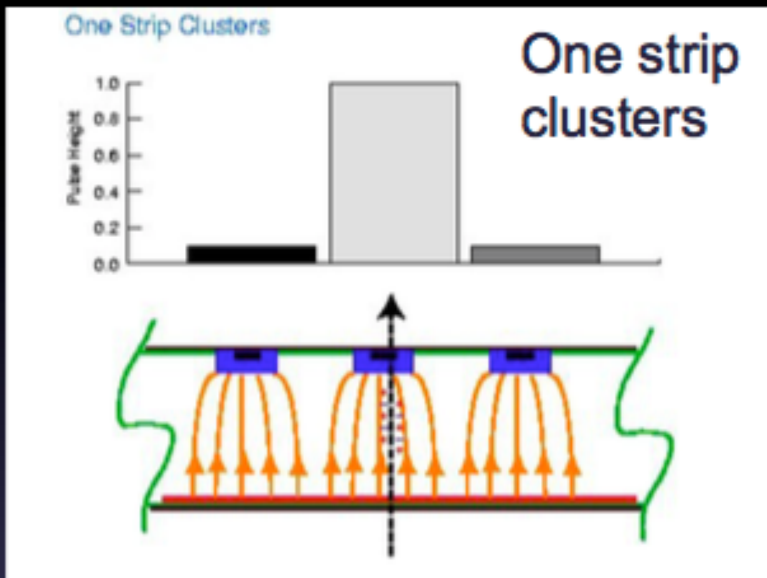
Large data bandwidth

Large power consumption

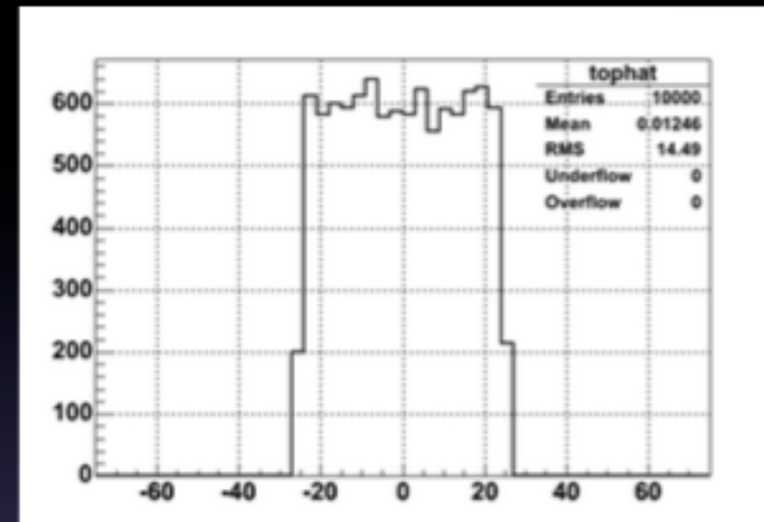
Bump bonding is costly

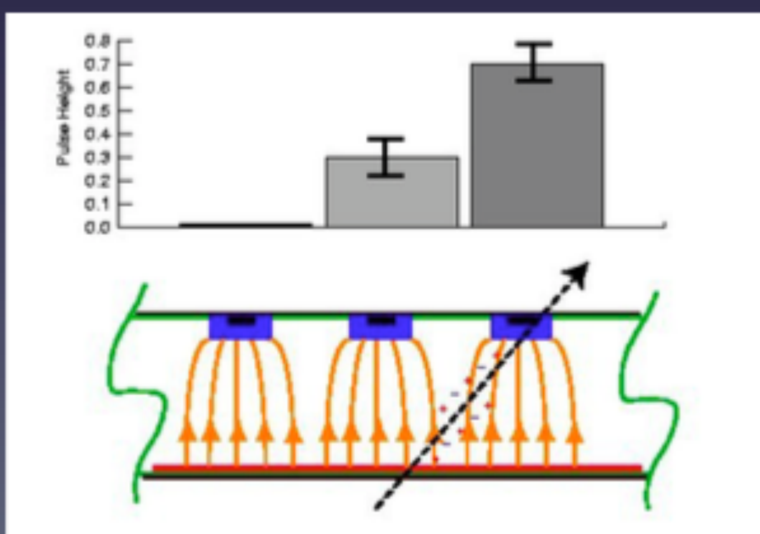
POSITION RESOLUTION

- Resolution is the spread of the reconstructed position minus the true position



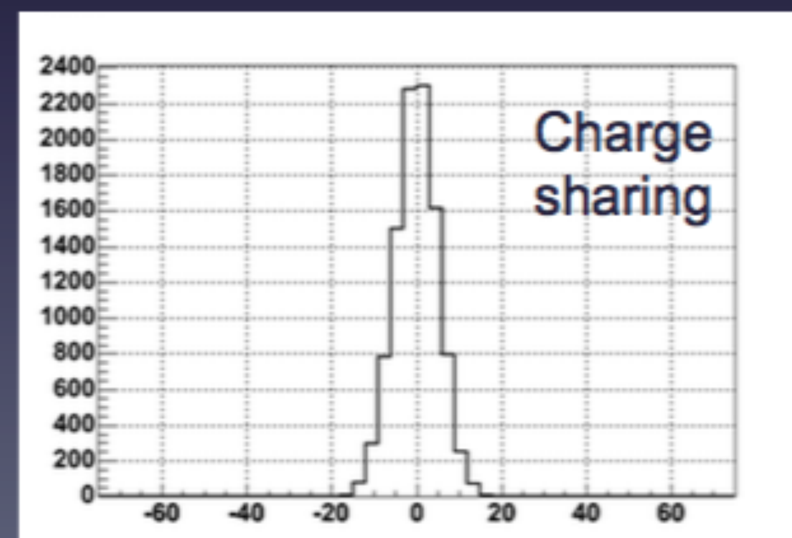
$$\sigma = \frac{pitch}{\sqrt{12}}$$





$$\sigma \approx \frac{pitch}{1.5 \cdot \sqrt{12}}$$

$$\eta = \frac{PH_R}{PH_L + PH_R}$$



SUMMARY SILICON DETECTORS

Solid state detectors provide very high precision tracking in particle physics experiments (down to 5 μm) for vertex measurement but also for momentum spectroscopy over large areas (ATLAS, CMS)

Technology is improving rapidly due to rapid Silicon development for electronics industry.

Silicon tracking detectors

Radiation hardness: detectors start to strongly degrade after 10^{14}-10^{15} hadrons/cm^2.

Developments

Monolithic solid state detectors are the ultimate goal. Ongoing developments (CMOS) but radiation hardness is an issue.

RESOLUTIONS TRACKING DETECTORS

Detector Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble chamber	10–150 μm	1 ms	50 ms[a]
Streamer chamber	300 μm	2 μs	100 ms
Proportional chamber	50–300 μm[b,c,d]	2 ns	200 ns
Drift chamber	50–300 μm	2 ns[e]	100 ns
Scintillator	—	100 ps/n[f]	10 ns
Emulsion	1 μm	—	—
Liquid Argon Drift [Ref. 6]	~175–450 μm	$\sim$ 200 ns	$\sim$ 2 μs
Gas Micro Strip [Ref. 7]	30–40 μm	$<$ 10 ns	—
Resistive Plate chamber [Ref. 8]	$\lesssim$10 μm	1–2 ns	—
Silicon strip	pitch/(3 to 7)[g]	*h*	*h*
Silicon pixel	2 μm[i]	*h*	*h*

[a] Multiple pulsing time.
[b] 300 μm is for 1 mm pitch.
[c] Delay line cathode readout can give $\pm$150 μm parallel to anode wire.
[d] wirespacing/$\sqrt{12}$.
[e] For two chambers.
[f] n = index of refraction.
[g] The highest resolution ("7") is obtained for small-pitch detectors ($\lesssim$25 μm) with pulse-height-weighted center finding.
[h] Limited by the readout electronics [9]. (Time resolution of $\leq$ 25 ns is planned for the ATLAS SCT.)
[i] Analog readout of 34 μm pitch, monolithic pixel detectors.

COMPARISON SOLID STATE vs GAS DETECTOR

Ionization chamber medium could be gas, liquid, or solid

– **Gas ⇒ electron and ion pairs; Semiconductor ⇒electron and hole pairs**

	Gas	Solid
Density	Low	High
Atomic number (Z)	Low	Moderate (Z=14)
Ionization Energy (ε_I)	Moderate (~ 30 eV)	Low (~3.6 eV)
Signal Speed	Moderate (10ns-10μs)	Fast (<20 ns)

Solid State Detectors

- Energy (E) to create e-h pairs 10 times smaller than gas ionization ⇒ increase charge⇒ good E resolution

$$\frac{\Delta E}{E} \propto \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{E/\varepsilon_I}} \propto \sqrt{\varepsilon_I}$$

- Greater density:
  – Reduced range of secondary electrons ⇒ excellent spatial resolution
  – Average E_{loss} ≈390eV/ μm ≈108 e-h/ μm (charge collected is a function of thickness d. Up-to-now no multiplication)
- To minimize multiple scattering d is small
  - 300 μm ~32,000 e-h pairs ➔ good S/N

SOME MOTIVATIONS and EXAMPLES

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]

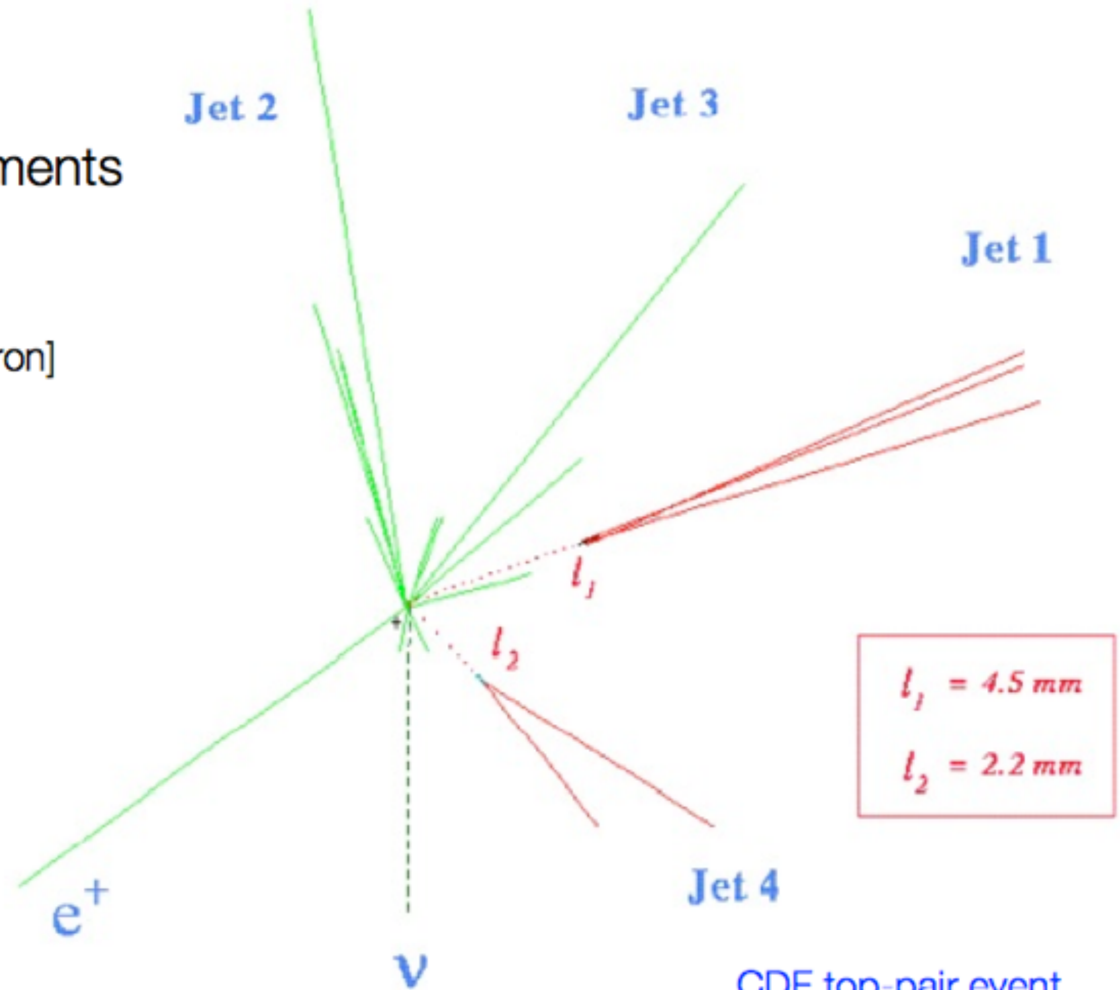
$\hookrightarrow b\bar{b}$

Typical lifetime: $\tau = 10^{-12} \;....\; 10^{-13}$ 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]

TABLE 4 Main parameters of the ATLAS and CMS tracking systems (see Table 6 for details of the pixel systems)

Parameter	ATLAS	CMS
Dimensions (cm)		
-radius of outermost measurement	101–107	107–110
-radius of innermost measurement	5.0	4.4
-total active length	560	540
Magnetic field B (T)	2	4
BR^2 ($T \cdot m^2$)	2.0 to 2.3	4.6 to 4.8
Total power on detector (kW)	70	60
Total weight in tracker volume (kg)	≈4500	≈3700
Total material (X/X_0)		
-at $\eta \approx 0$ (minimum material)	0.3	0.4
-at $\eta \approx 1.7$ (maximum material)	1.2	1.5
-at $\eta \approx 2.5$ (edge of acceptance)	0.5	0.8
Total material (λ/λ_0 at max)	0.35	0.42
Silicon microstrip detectors		
-number of hits per track	8	14
-radius of innermost meas. (cm)	30	20
-total active area of silicon (m^2)	60	200
-wafer thickness (microns)	280	320/500
-total number of channels	6.2×10^6	9.6×10^6
-cell size (μm in $R\phi$ × cm in z/R)	80×12	$80/120 \times 10$
-cell size (μm in $R\phi$ × cm in z/R)		and $120/180 \times 25$
Straw drift tubes (ATLAS only)		
-number of hits per track ($\lvert\eta\rvert < 1.8$)	35	
-total number of channels	350,000	
-cell size (mm in $R\phi$ × cm in z)	4×70 (barrel)	
	4×40 (end caps)	

MAIN PERFORMANCE OF TRACKING SYSTEMS

	ATLAS	CMS
Reconstruction efficiency for muons with $p_T = 1$ GeV	96.8%	97.0%
Reconstruction efficiency for pions with $p_T = 1$ GeV	84.0%	80.0%
Reconstruction efficiency for electrons with $p_T = 5$ GeV	90.0%	85.0%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 0$	1.3%	0.7%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 2.5$	2.0%	2.0%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 0$	3.8%	1.5%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 2.5$	11%	7%
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (μm)	75	90
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (μm)	200	220
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 0$ (μm)	11	9
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 2.5$ (μm)	11	11
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (μm)	150	125
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (μm)	900	1060

- Momentum resolution on average superior in CMS
- Similar vertexing and b-tagging performances are similar
- Impact of material and B-field already visible on efficiencies

DETECTOR: LECTURE III QUIZZ

Gas vs solid state ionisation detector ?

Typical size of a cell in a silicium detector

Why do experimentalists like small cell size ?

What is the consequence of small cell size ?

CREDIT and BIBLIOGRAPHY

A lot of material in these lectures are from:

- Daniel Fournier @ EDIT2011
- Marco Delmastro @ ESIPAP 2014
- Weiner Raigler @ AEPSHEP2013
  - Hans Christian Schultz-Coulon's lectures
- Carsten Niebuhr's lectures [1][2][3]
- Georg Streinbrueck's lecture
- Pippa Wells @ EDIT2011
- Jérôme Baudot @ ESIPAP2014