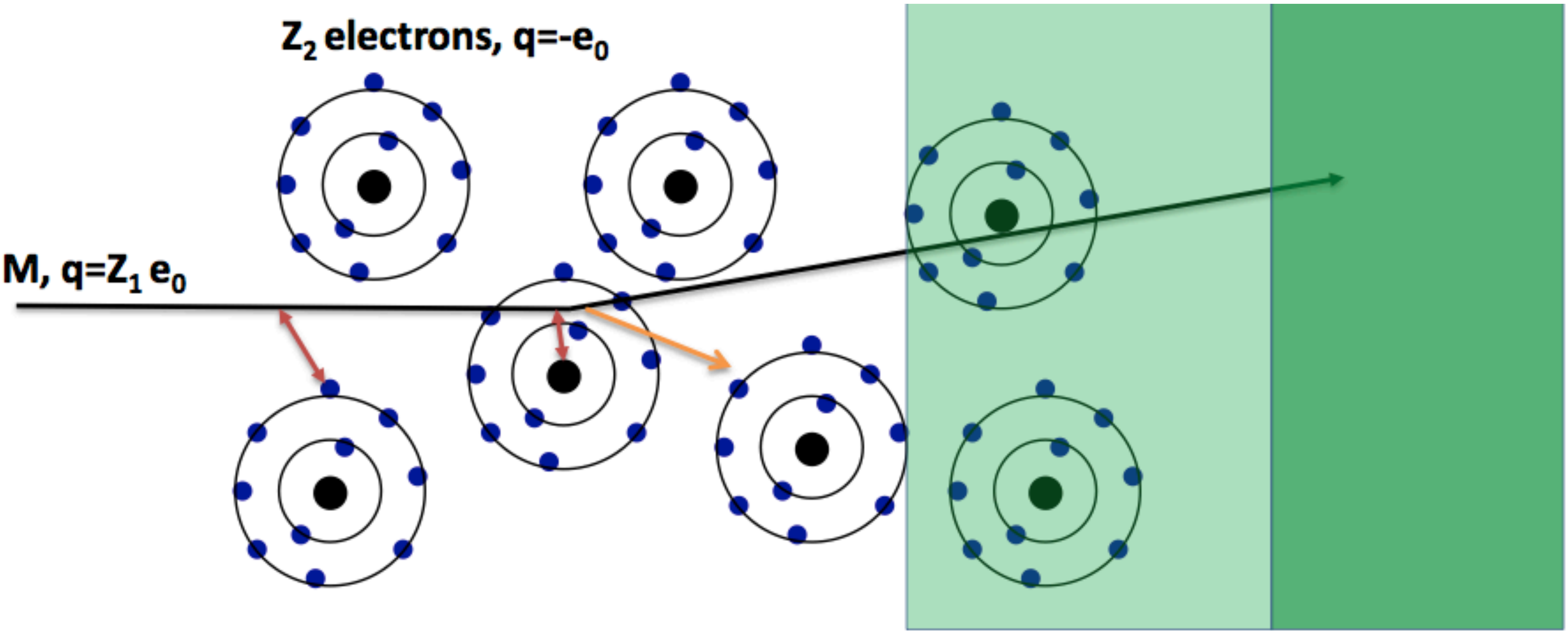
INSTRUMENTATION
&
DETECTORS
for
HIGH ENERGY PHYSICS
II

ELECTROMAGNETIC INTERACTIONS OF PARTICLES WITH MATTER

INTERACTIONS → DETECTORS



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.**

INTERACTIONS OF PARTICLES WITH MATTER

IONISATION AND EXCITATION

Charged particles traversing material and exciting and ionising atoms.

The average energy loss of the incoming particle by the process is to a good approximation described by the Bethe-Block formula.

CHERENKOV RADIATION

If a particle propagates in a material with velocity > speed of light in this material, C radiation is emitted at a characteristic angle that depends on the particle velocity and the refractive index of the medium

TRANSITION RADIATION

If a charged particle is crossing the boundary between two materials of different dielectric permittivity, there is a certain probability for emission of an X-ray photon.

MULTIPLE SCATTERING AND BREMSSTRAHLUNG

Incoming particles are scattering off the atomic nuclei which are partially shielded by the atomic electrons.

This scattering imposes a lower level on the momentum resolution of the spectrometer, when measuring the particle momentum by deflection of the particle trajectory in the magnetic field.

The deflection of the particle on the nucleus results in an acceleration that causes the emission of Bremsstrahlung photons.
The photons in turn produce e+e- pairs in the vicinity of the nucleus, which causes the EM cascade.
This effect depends on m^{-2}: only relevant for electrons.

HADRONIC INTERACTION

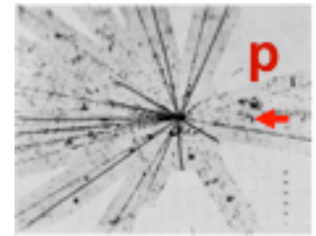
Incoming hadrons on a material will interact with the nucleus and create a shower composed of hadrons, electrons, photon.
A fraction of the energy is *lost* in the form of binding energy or neutrinos.

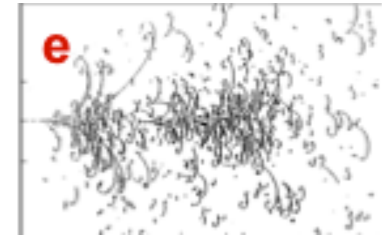
INTERACTIONS → DETECTORS

FOUR STEPS

Lesson 1

1. Particles interact with matter
depends on particle and material



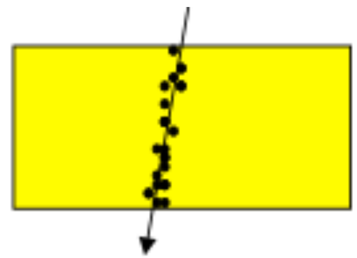


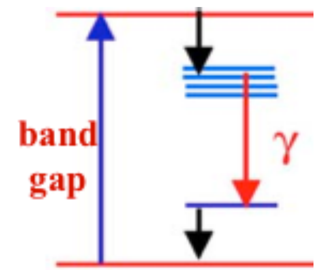
Lesson 2

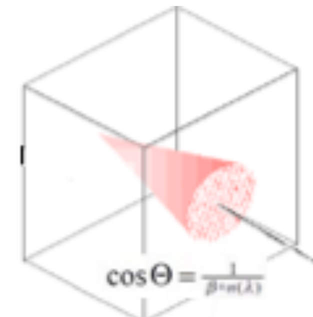
2. Energy loss transfer to detectable signal
depends on the material

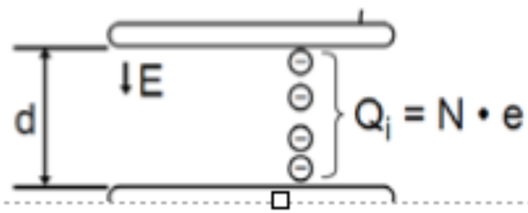
Detecting emitted light

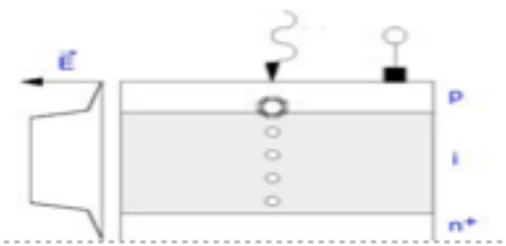
Detecting ionisation current











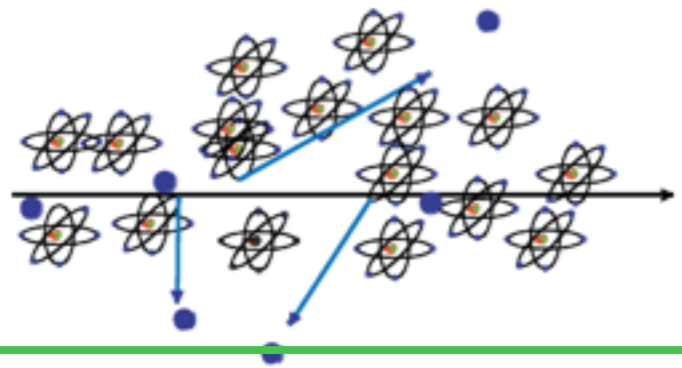
3. Signal collection
depends on signal and type of detection

Lesson 3

4. BUILD a SYSTEM
depends on physics, experimental conditions,….

CREATION of the SIGNAL

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



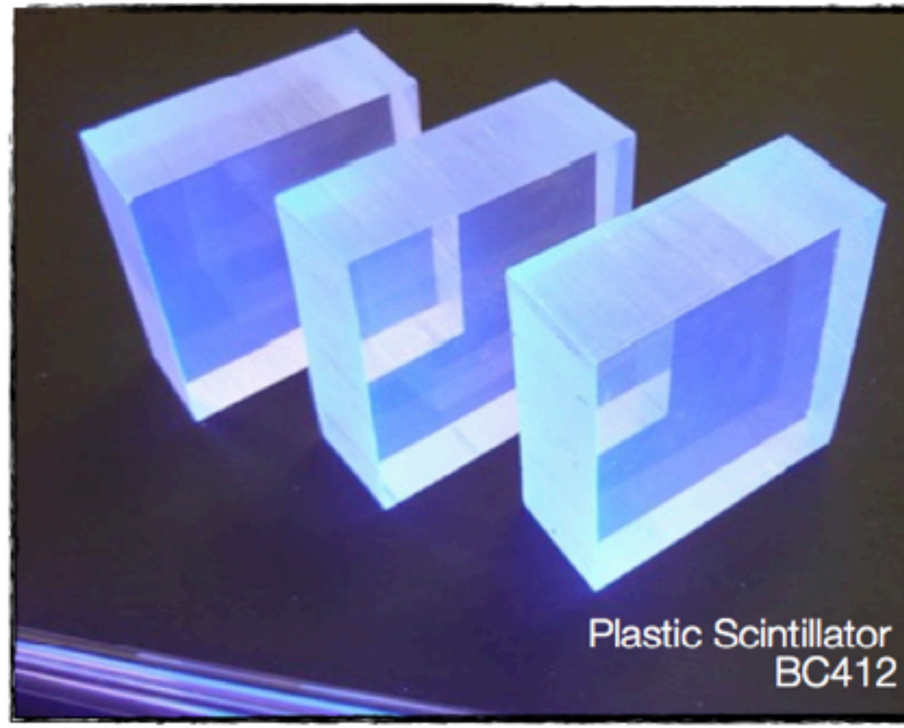
Excitation

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.

SCINTILLATORS - GENERALITIES



Principle:

dE/dx converted into visible light
Detection via photosensor
[e.g. photomultiplier, human eye ...]

Main Features:

Sensitivity to energy
Fast time response
Pulse shape discrimination

Requirements

High efficiency for conversion of excitation energy to fluorescent radiation
Transparency to its fluorescent radiation to allow transmission of light
Emission of light in a spectral range detectable for photosensors
Short decay time to allow fast response

DETECTORS BASED on REGISTRATION of EXCITED ATOMS: SCINTILLATORS

Emission of photons by excited atoms: typically UV to visible light

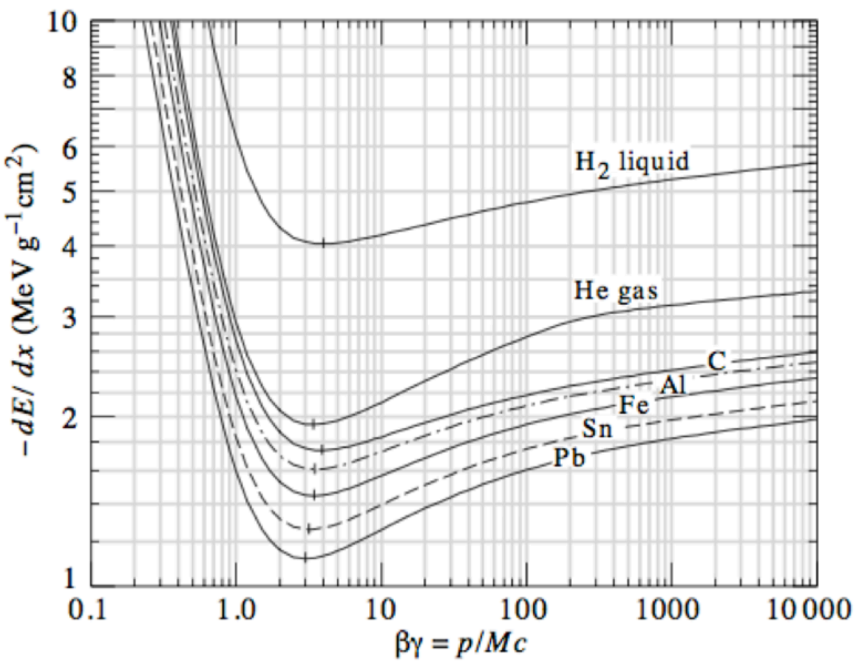
Observed in Noble Gases (an even in liquid)

Inorganic crystals

Substance with largest light yield. Used for precision measurement of energetic photons

Polyzyclic Hydrocarbons such as Naphtalen, Anthrazen, **organic scintillators**:

- Large scale industrial production: mechanically and chemically quite robust.
- Characteristic are one or two decay times of light emission

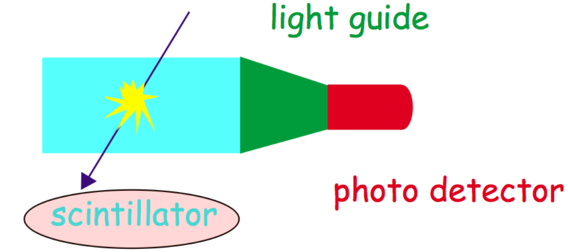


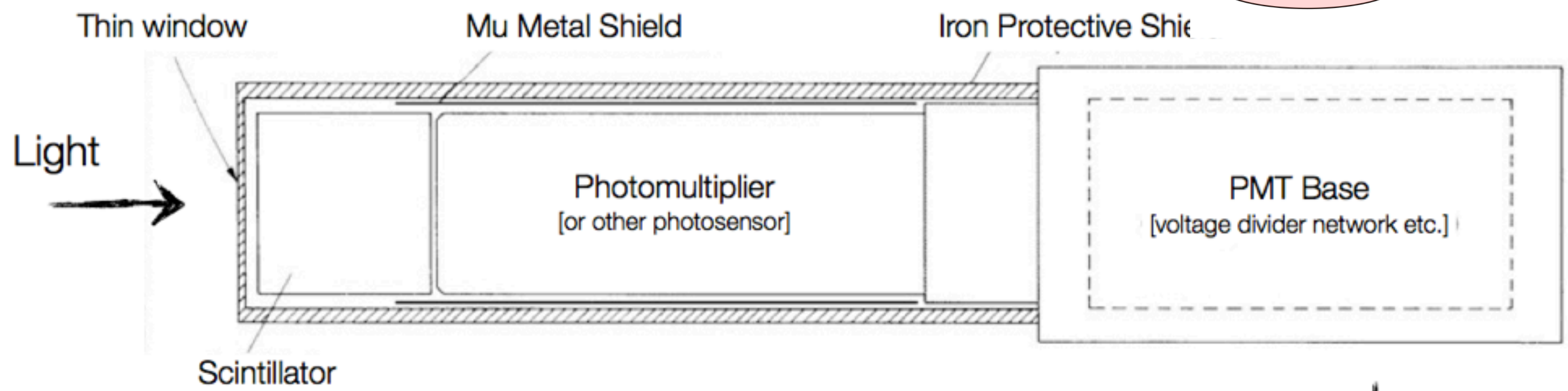
Typical light yield of scintillators

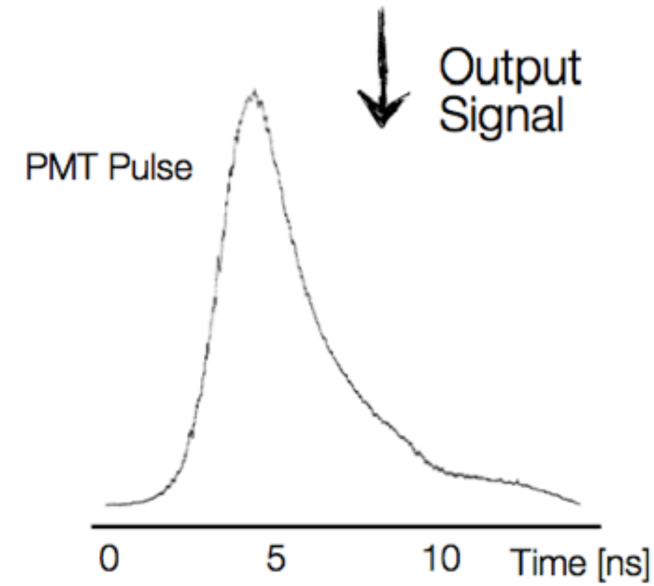
Energy (visible photons): few % of the total energy loss.

1 cm of plastic scintillator, ρ=1 g.cm^{-3}, dE/dx~1.5 MeV, ~15 keV in photons i.e. 15000 photons produced.

SCINTILLATORS: BASIC SETUPs







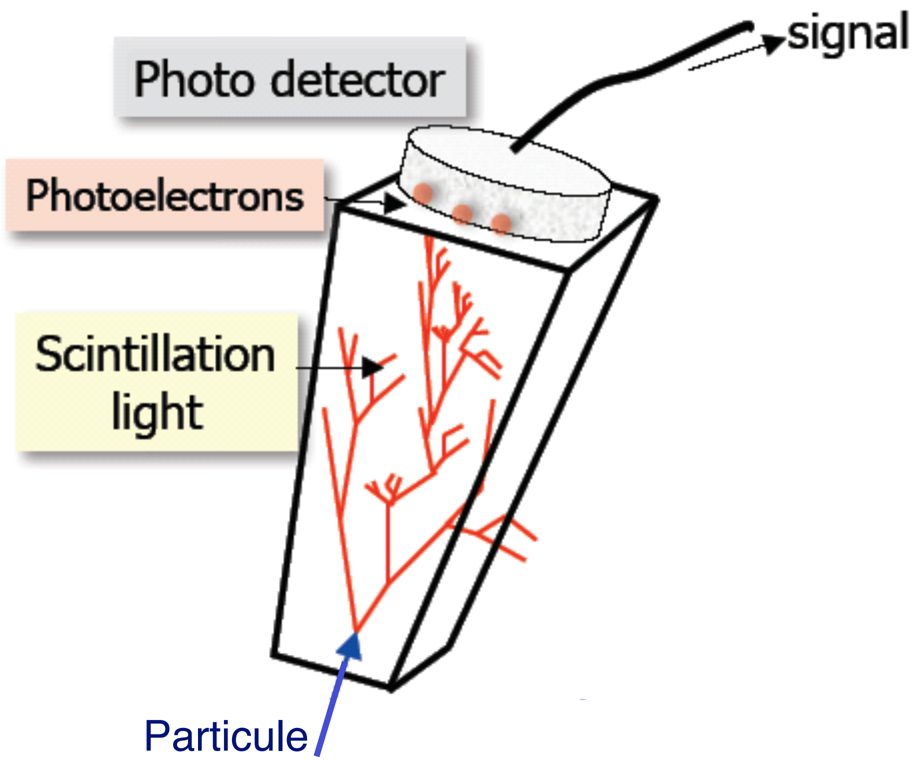
Scintillator Types:

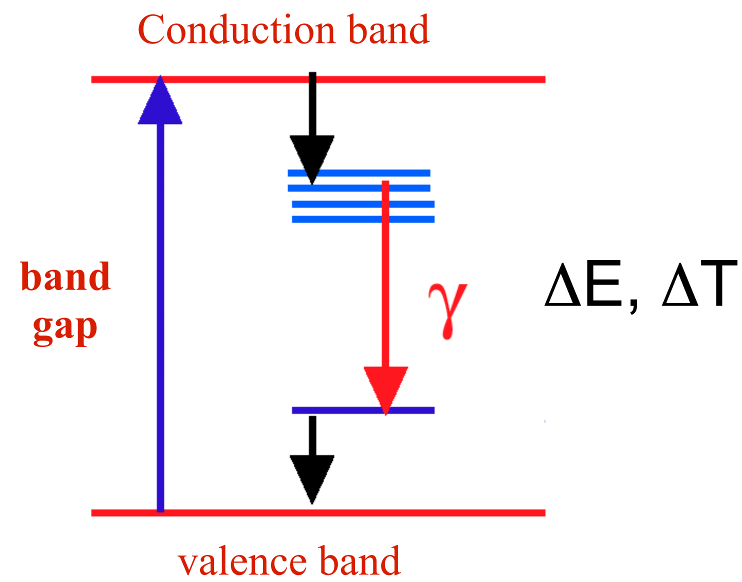
Organic Scintillators
Inorganic Crystals
Gases

Photosensors

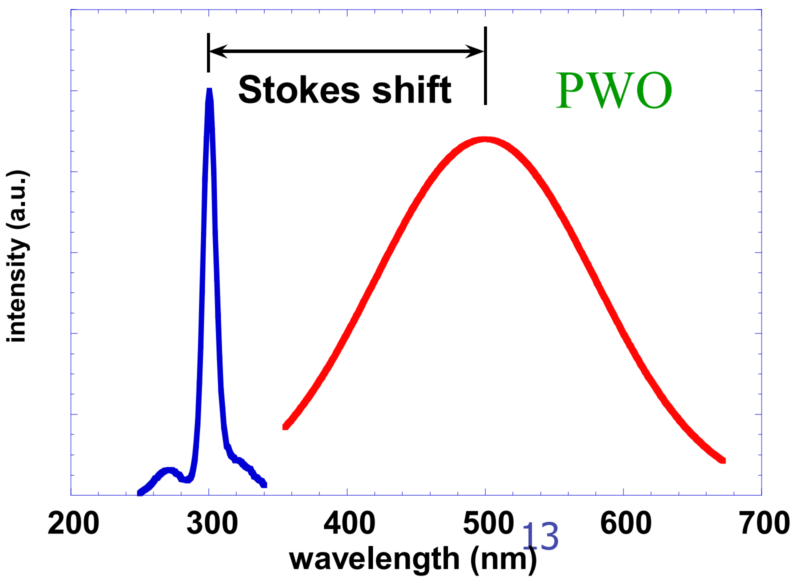
Photomultipliers
Micro-Channel Plates
Hybrid Photo Diodes
Visible Light Photon Counter
Silicon Photomultipliers

CMS CRISTALs

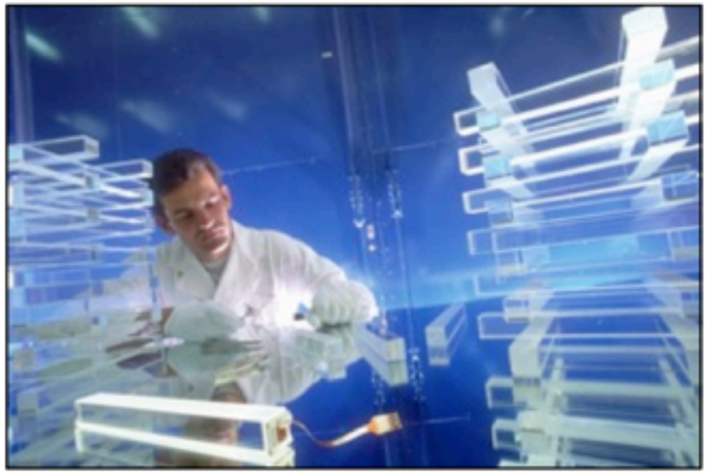




Fast light emission: ~80% in 25 ns
Peak emission ~500 nm (visible region)
Radiation resistant to very high doses

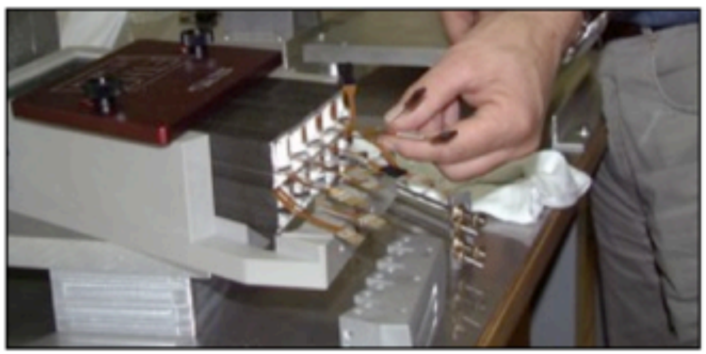


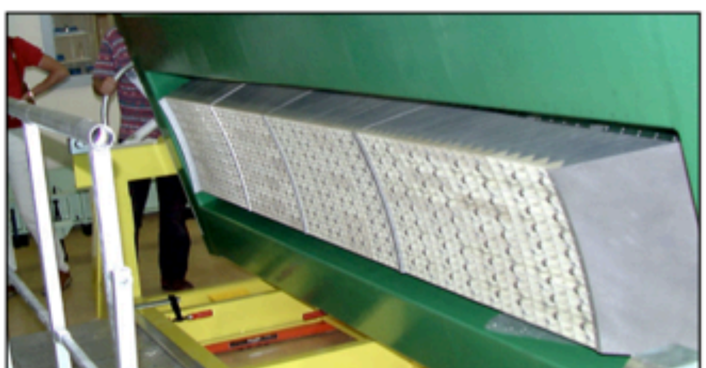
CMS BARREL ECAL

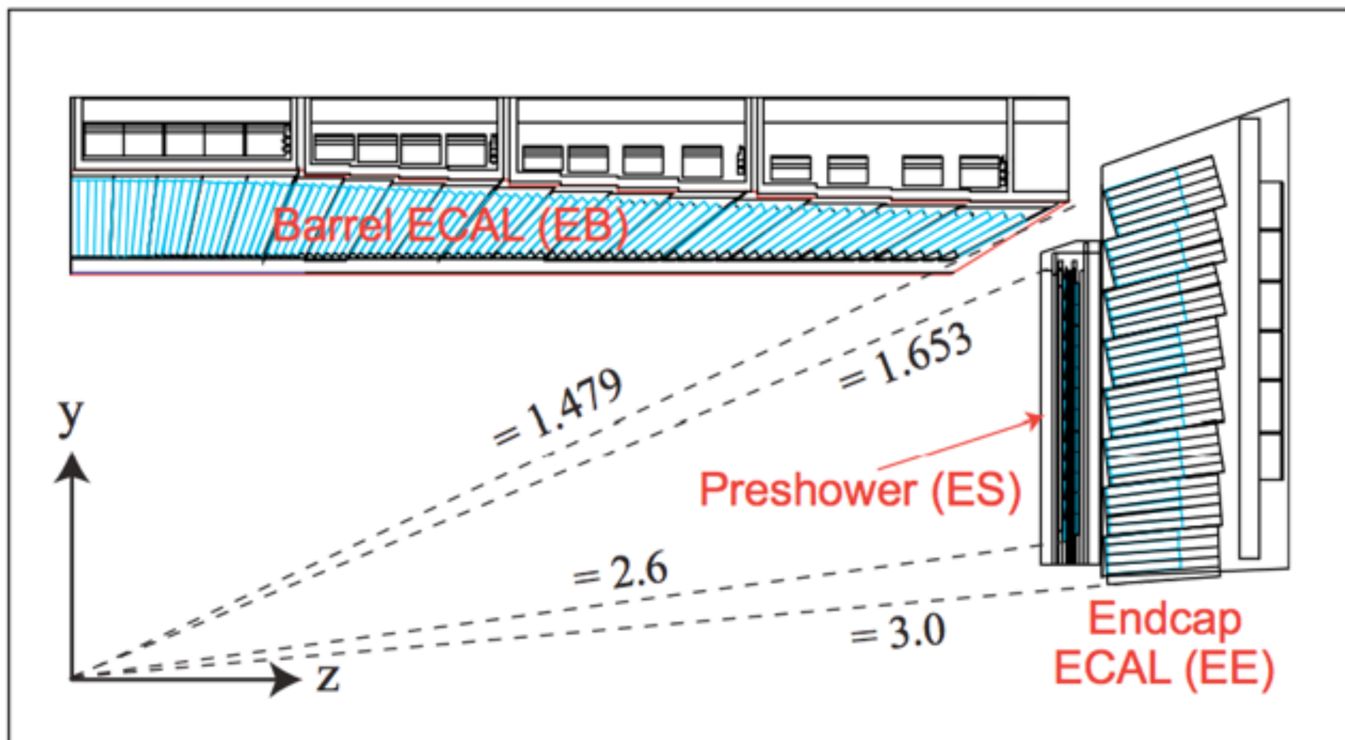


Scintillator : $PBW0_4$ [Lead Tungsten]
Photosensor : APDs [Avalanche Photodiodes]

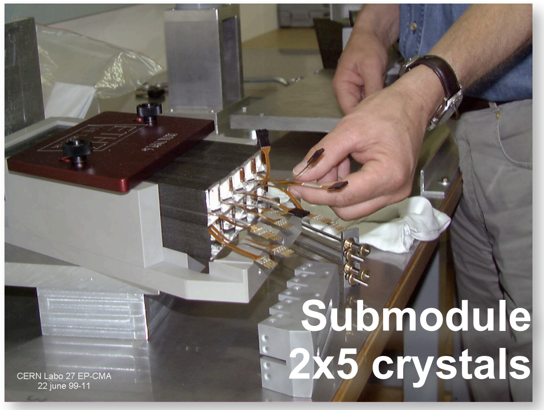
Number of crystals: ~ 70000
Light output: 4.5 photons/MeV

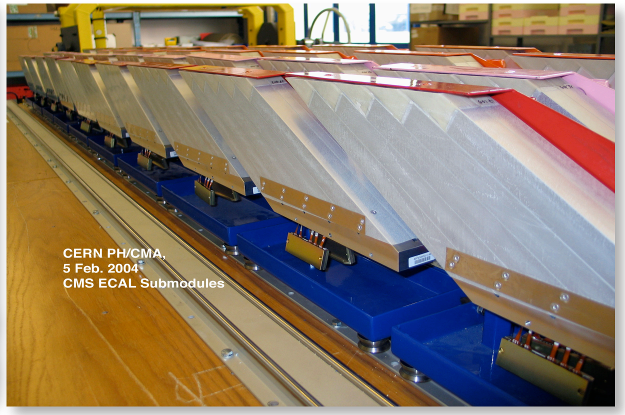


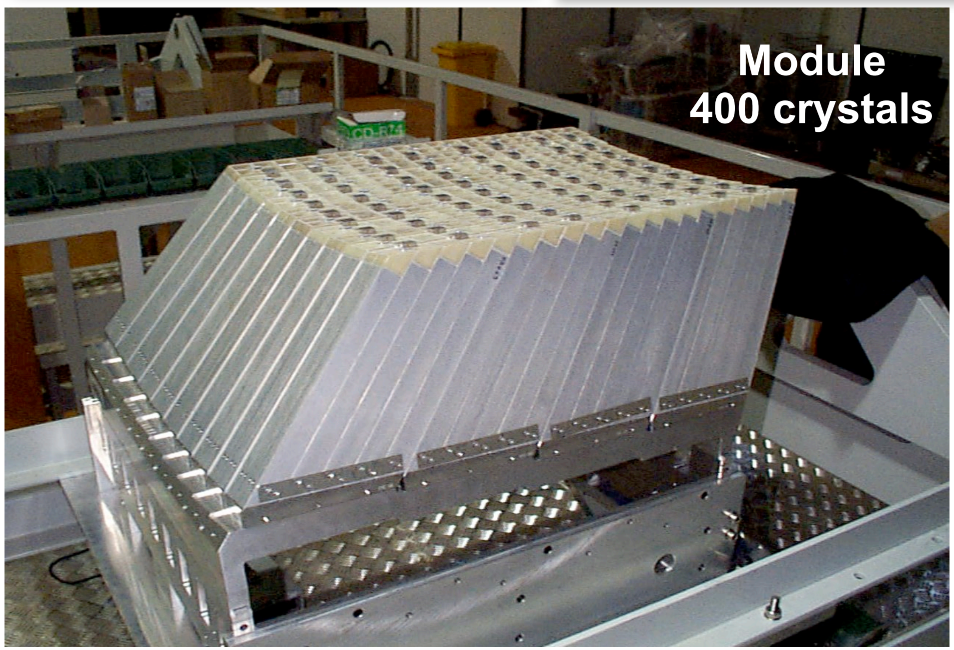


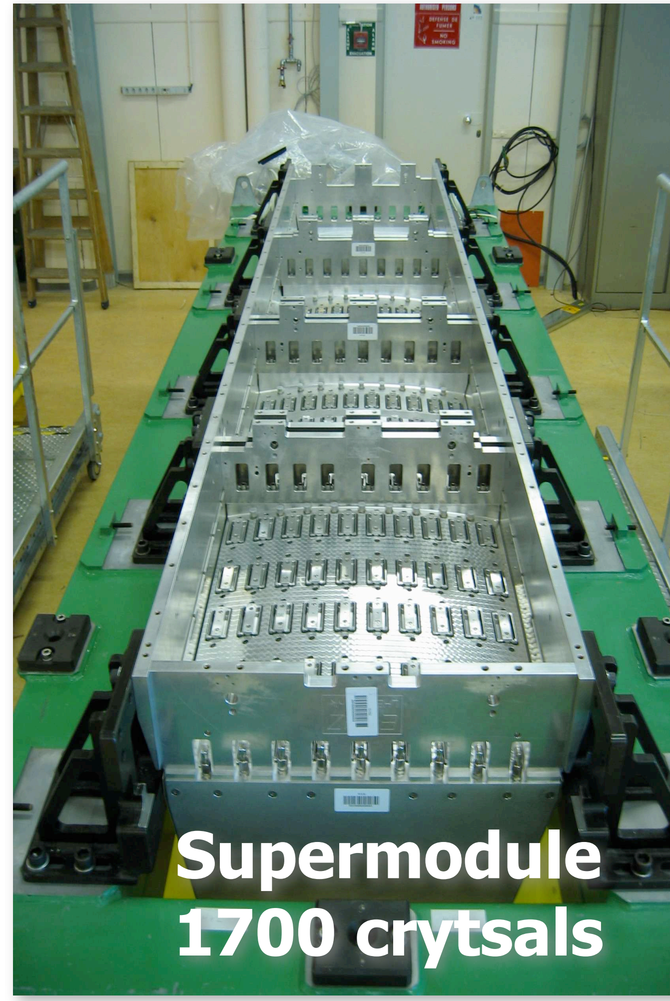


CMS ECAL CONSTRUCTION



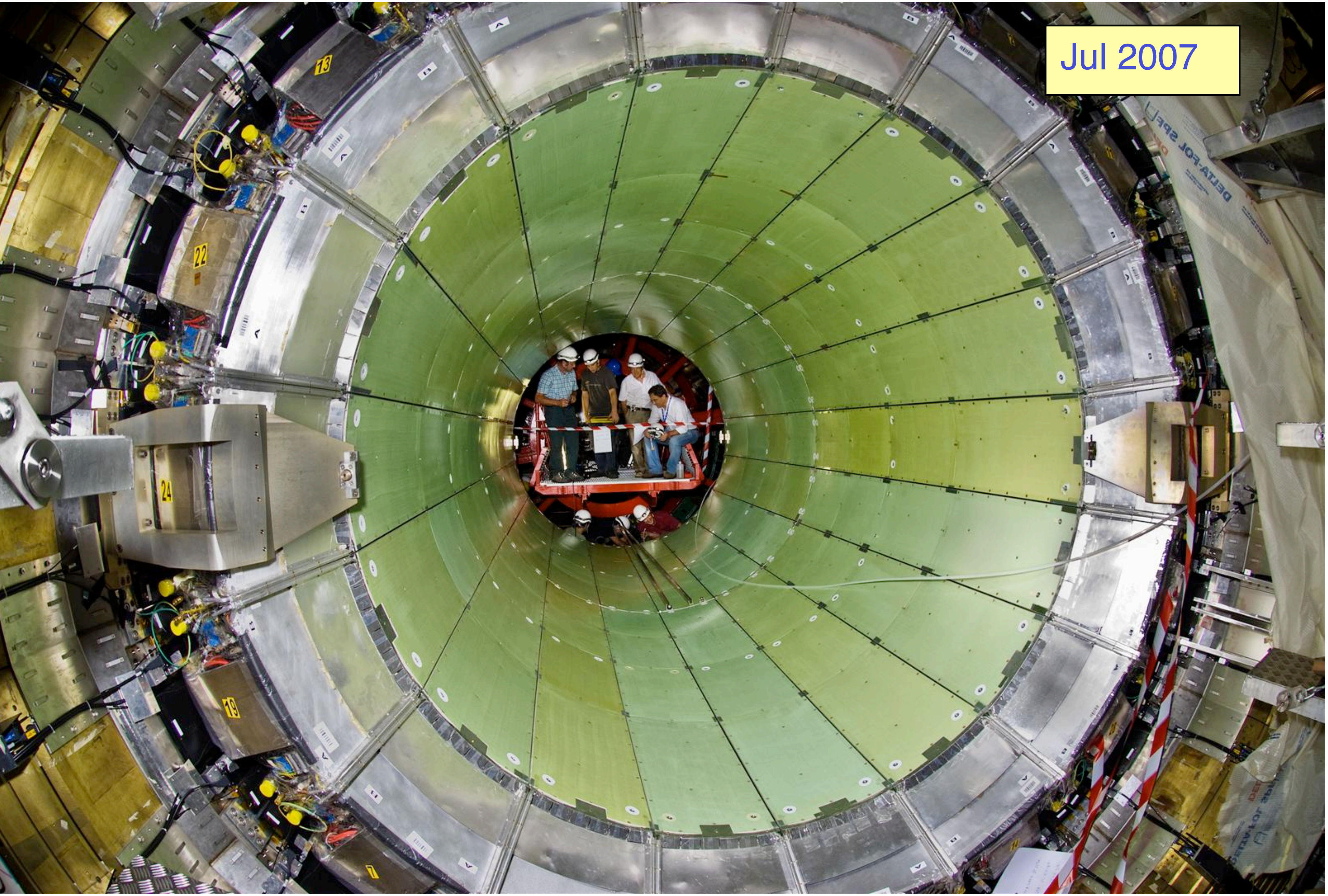






Total 36 Supermodules

CMS BARREL ECAL



ORGANIC SCINTILLATORS

Excited vibrational modes of molecules de-excite by emission of UV light

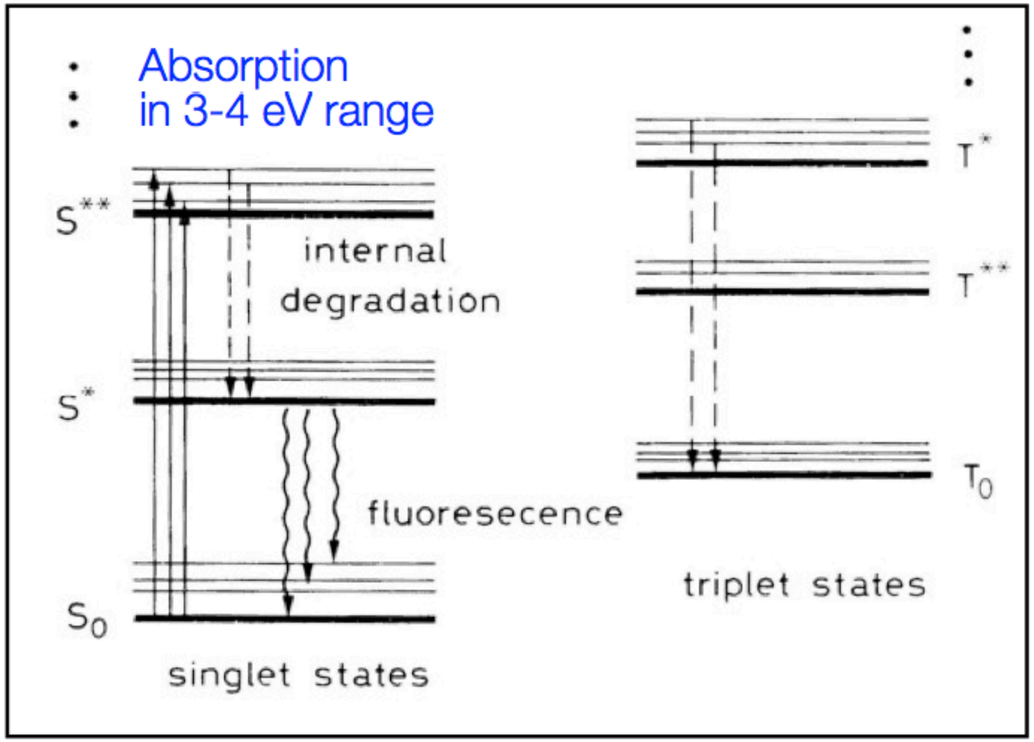
This UV light is then transformed into visible light by *wave length shifters* that are added to the materials

Mono crystals

- Naphtalen ($C_{10}H_8$)
- Anthrazen ($C_{10}H_{10}$)
- …

Liquid and plastic scintillators

- organic substance (polystyrol) + scintillating molecules (~1%)
- in addition: secondary fluor compunds as wave length shifters



Comparison organic vs inorganic scintillators

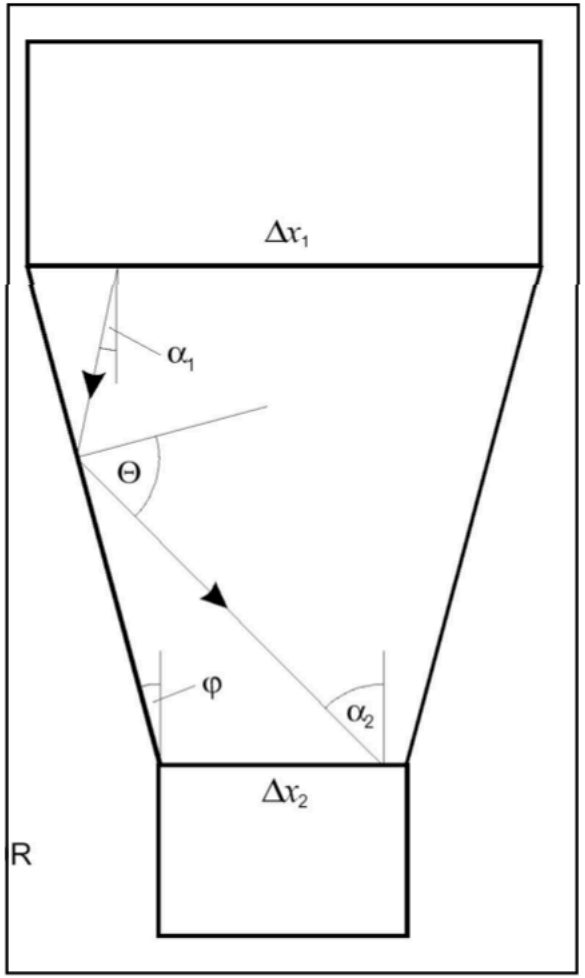
Low Light Yield **Fast: 1-3ns** **Large Light Yield** **Slow: few 100ns**

Type	Light[a] output	λ_{max}[b] (nm)	Attenuation[c] length (cm)	Risetime (ns)	Decay[d] time (ns)	Pulse FWHM (ns)
NE 102A	58–70	423	250	0.9	2.2–2.5	2.7–3.2
NE 104	68	406	120	0.6–0.7	1.7–2.0	2.2–2.5
NE 104B	59	406	120	1	3.0	3
NE 110	60	434	400	1.0	2.9–3.3	4.2
NE 111	40–55	375	8	0.13–0.4	1.3–1.7	1.2–1.6
NE 114	42–50	434	350–400	~1.0	4.0	5.3
Pilot B	60–68	408	125	0.7	1.6–1.9	2.4–2.7
Pilot F	64	425	300	0.9	2.1	3.0–3.3
Pilot U	58–67	391	100–140	0.5	1.4–1.5	1.2–1.9
BC 404	68	408	—	0.7	1.8	2.2
BC 408	64	425	—	0.9	2.1	~2.5
BC 420	64	391	—	0.5	1.5	1.3
ND 100	60	434	400	—	3.3	3.3
ND 120	65	423	250	—	2.4	2.7
ND 160	68	408	125	—	1.8	2.7

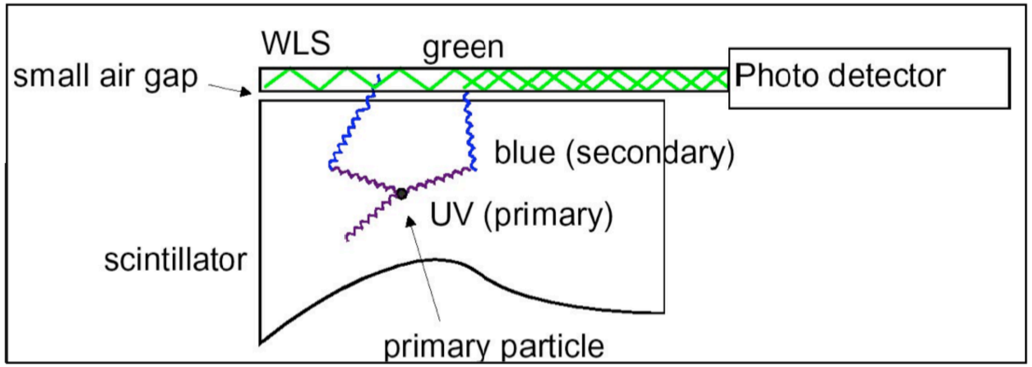
	Relative light output	λ_{max} emission (nm)	Decay time (ns)	Density (g/cm^3)
Inorganic crystals				
NaI(Tl)	230	415	230	3.67
CsI(Tl)	250	560	900	4.51
$Bi_4Ge_3O_{12}$ (BGO)	23–86	480	300	7.13
Organic crystals				
Anthracene	100	448	22	1.25
Trans-stilbene	75	384	4.5	1.16
Naphthalene	32	330–348	76–96	1.03
p,p'-Quarterphenyl	94	437	7.5	1.20
Primary activators				
2,5-Diphenyl-oxazole (PPO)	75	360–416	5[a]	
2-Phenyl-5-(4-biphenylyl)-1,3,4-oxadiazole (PBD)	96	360–5		
4,4''-Bis(2-butyloctyloxy)-*p*-quaterphenyl (BIBUQ)	60	365,393	1.30[a]	

LHC bunchcrossing 25ns **LEP bunchcrossing 25µs**

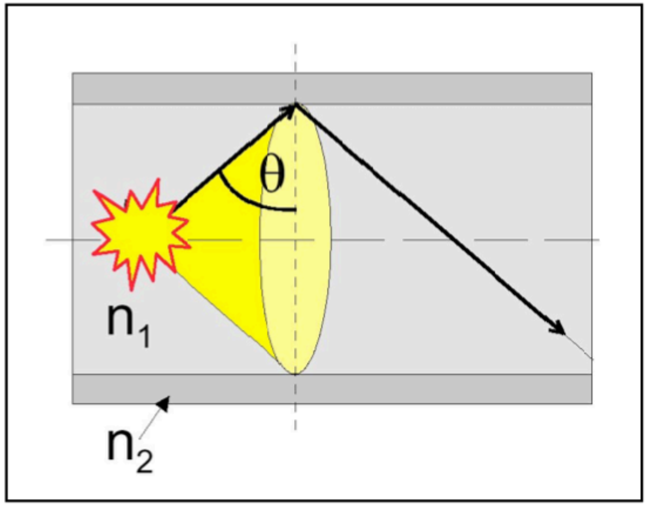
LIGHT COLLECTION



Plexiglass light guide



Wave length shifter bars

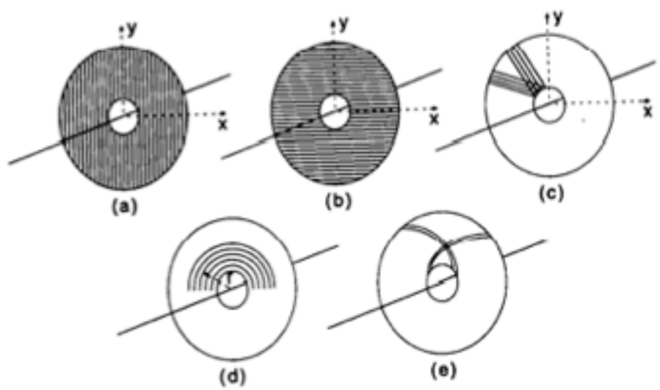


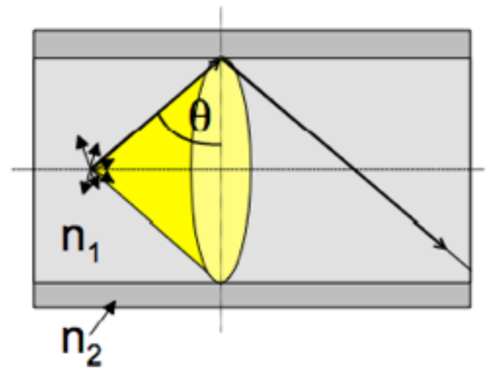
Total reflection in optical fibers

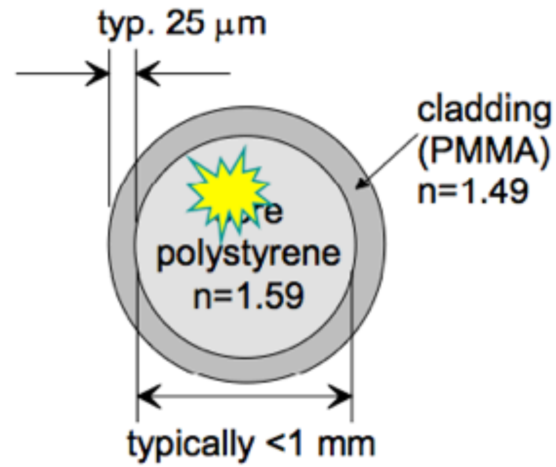
FIBER TRACKING

LIGHT TRANSPORT BY TOTAL INTERNAL REFLECTIONS

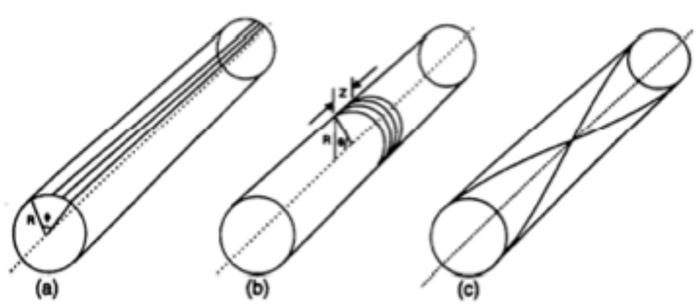
Planar geometries
(end cap)







Circular geometries
(barrel)



High geometrical flexibility

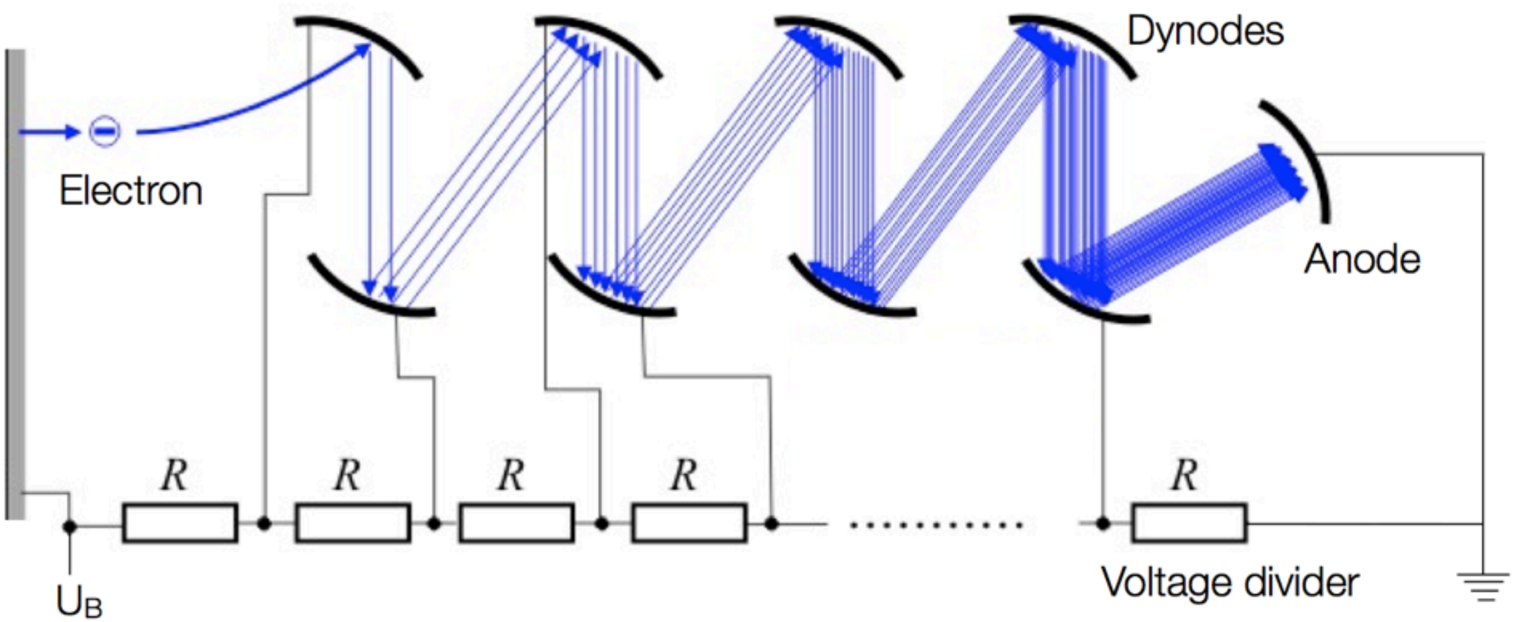
Fine granularity

Low mass

Fast response (ns)

(R.C. Ruchti, Annu. Rev. Nucl. Sci. 1996, 46,281)

Photo multipliers



Multiplication process:

Electrons accelerated toward dynode
Further electrons produced ➛ avalanche

Secondary emission coefficient:
δ = #(e⁻ produced)/#(e⁻ incoming)

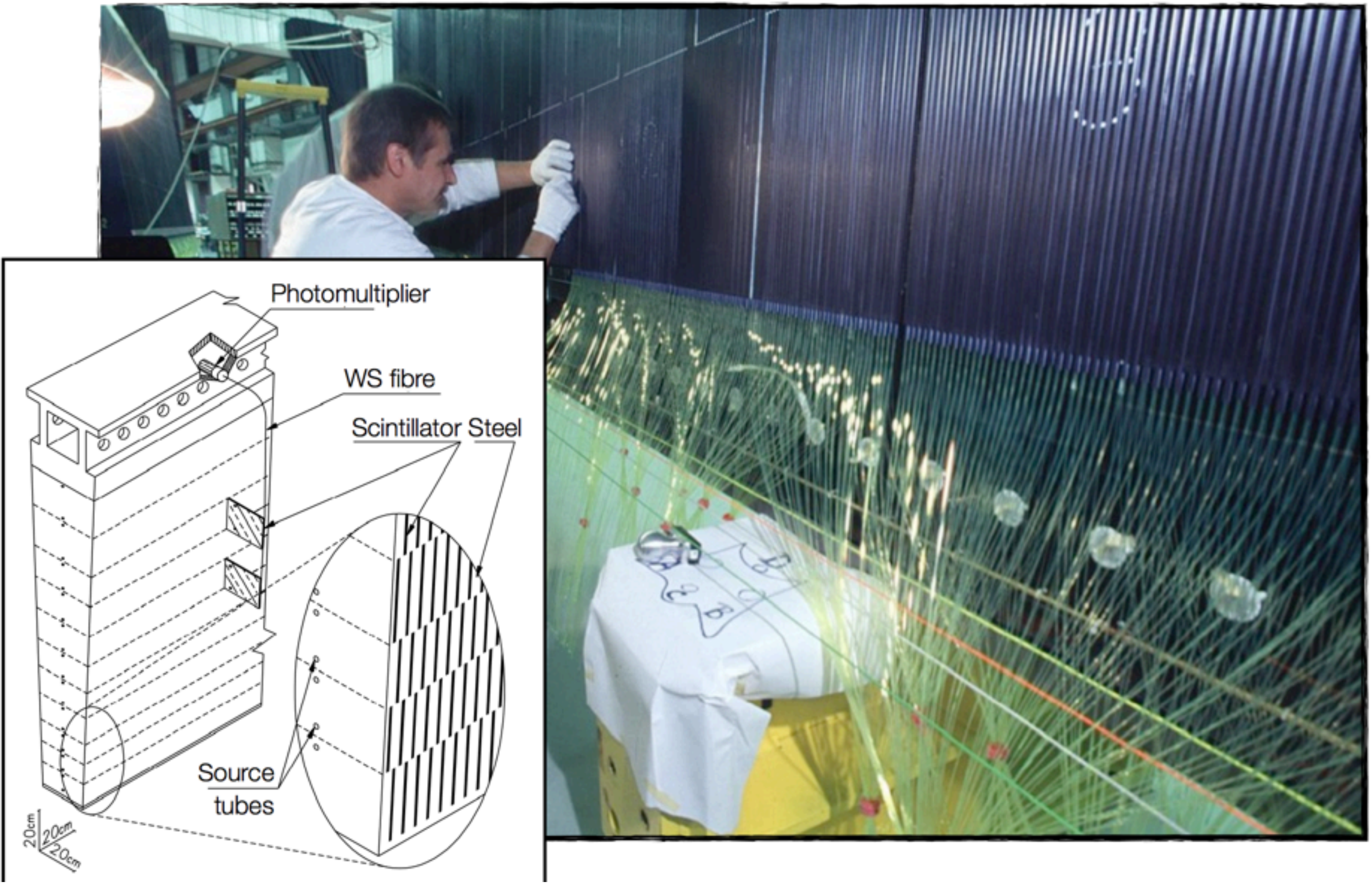
Typical: $\left.\begin{array}{l}\delta = 2 - 10 \\ n = 8 - 15\end{array}\right]$ ➛ $G = \delta^n = 10^6 - 10^8$

Gain fluctuation: $\delta = kU_D$; $G = a_0(kU_D)^n$

$dG/G = n\,dU_D/U_D = n\,dU_B/U_B$

PMT Collection

ATLAS TILES CALORIMETER



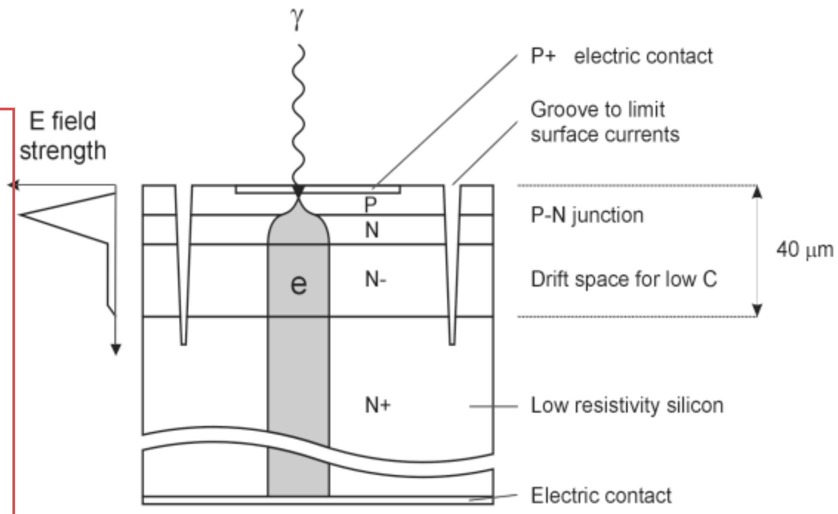
LIGHT COLLECTION: EXAMPLEs from CMS

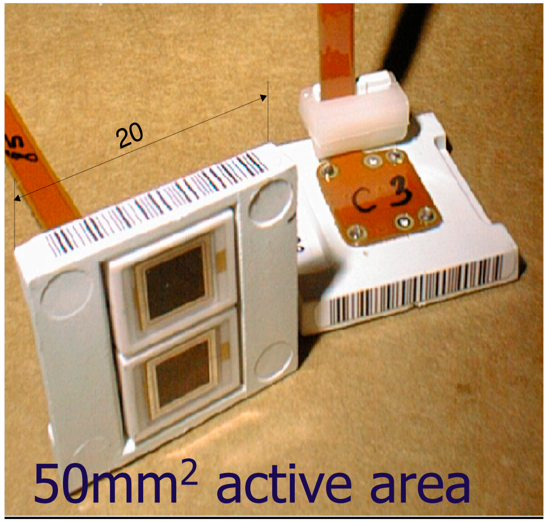
APD: ECAL barrel

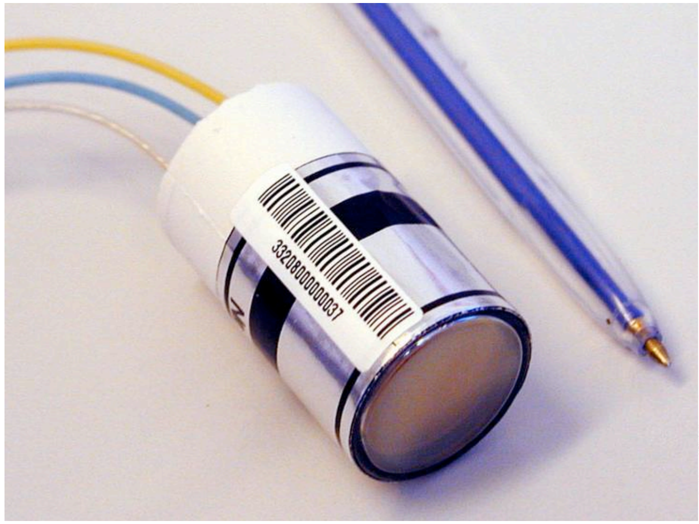
- Photo-eletrons from THIN 6µm p-layer induce avalanche in p-n junction
- Electrons from ionising particles traversing the bulk are NOT amplified

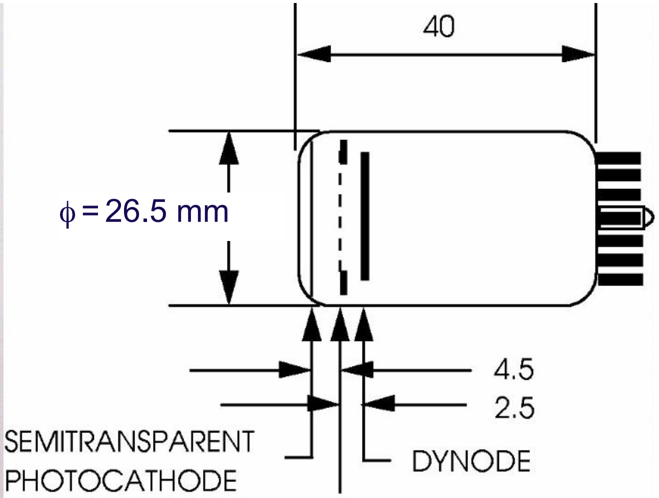
Vacuum Phototriodes: ECAL Endcaps

- Single stage PM tube with fine metal grid anode (insensitive to axial magnetic fields)
- Favourable for EC-ECAL
- Q.E. ~20% at 420nm









SILICIUM PM's

Principle:

Pixelized photo diodes operated in Geiger Mode

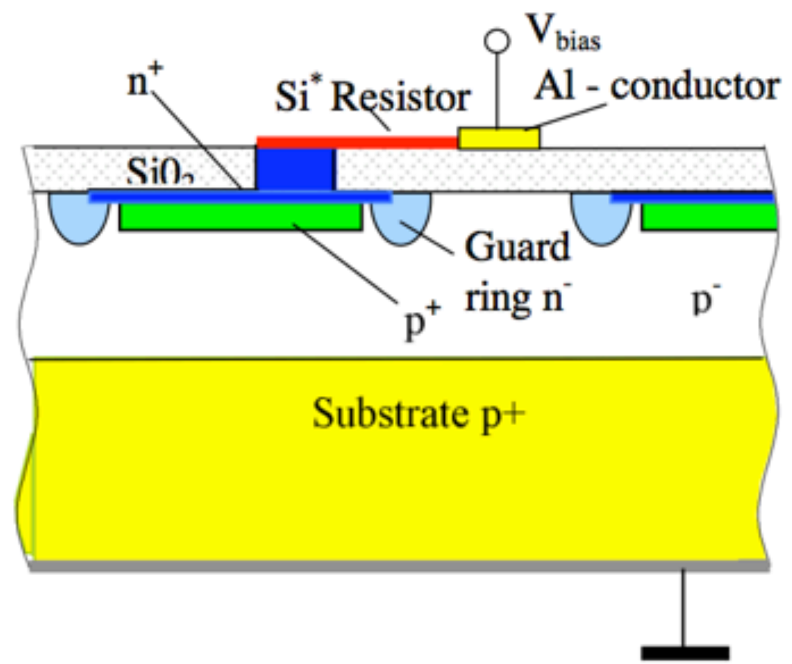
Single pixel works as a binary device

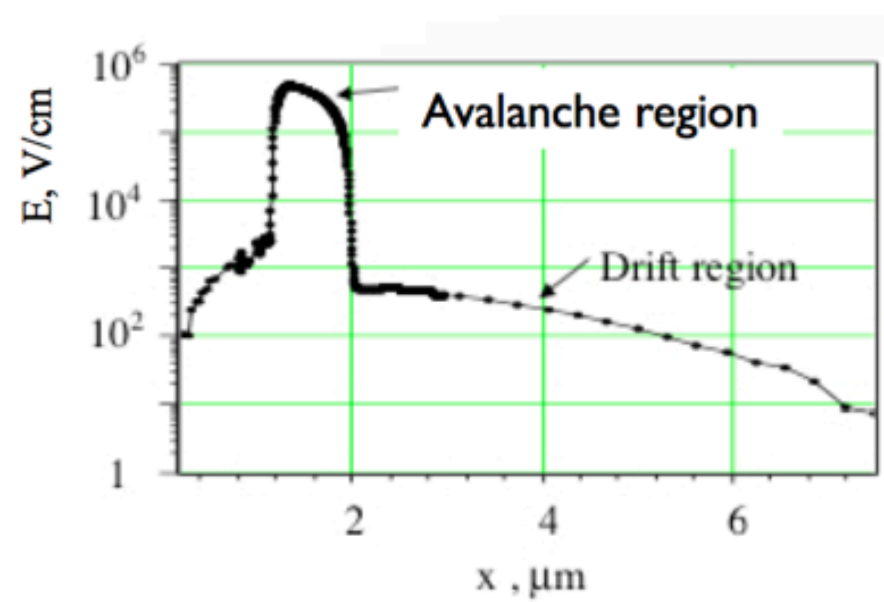
Energy = #photons seen by summing over all pixels

Features:

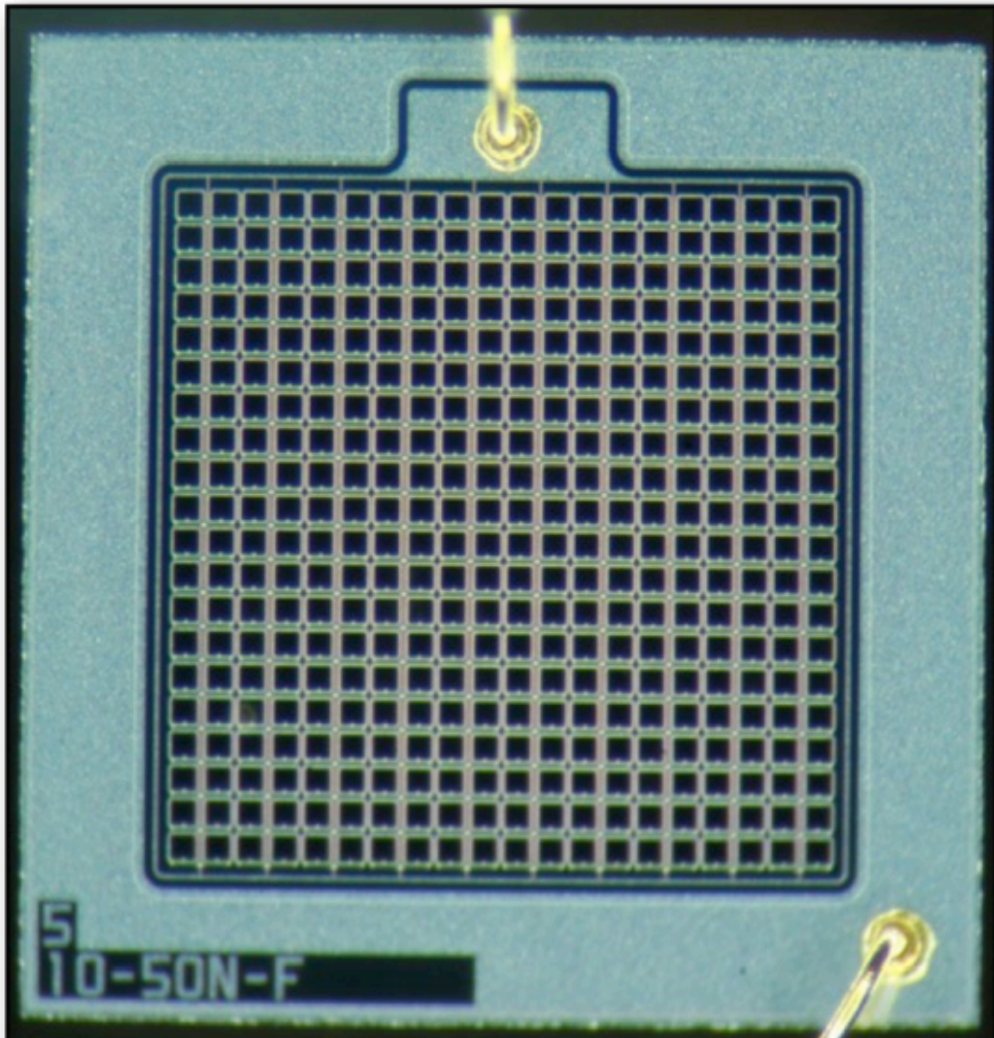
Granularity	:	10^3 pixels/mm^2
Gain	:	10^6
Bias Voltage	:	< 100 V
Efficiency	:	ca. 30 %

Insensitive to magnetic fields!
Works at room temperature ...



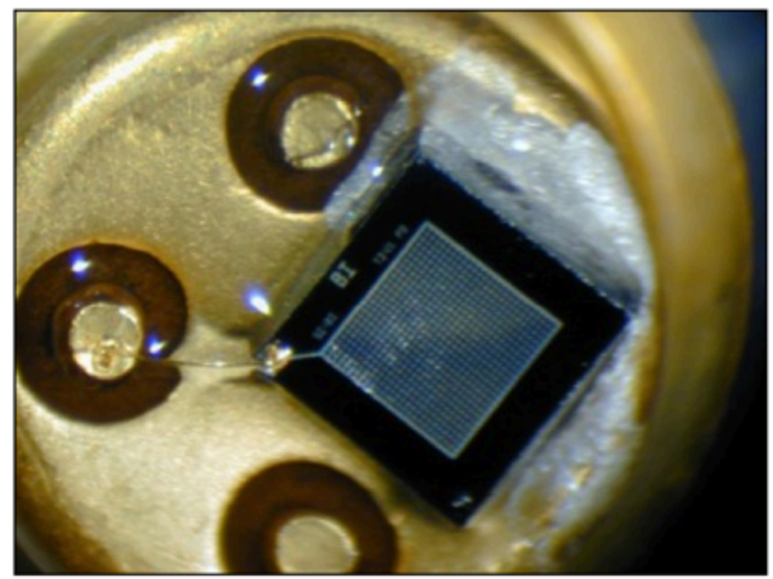


SILICIUM PM



HAMAMATSU
MPPC 400Pixels

One of the first SiPM
Pulsar, Moscow



COMPARISON of PHOTO-DETECTORS

	PMT	APD	HPD	SiPM
Photon detection efficiency:				
blue	20%	50%	20%	12%
green - yellow	a few %	60-70%	a few %	15%
red	<1%	80%	<1%	15%
Gain	10^6-10^7	100-200	10^3	10^6
High voltage	1-2 kV	100-500 V	20 kV	25 V
Operation in the magnetic field	problematic	OK	OK	OK
Threshold sensitivity S/N≫1	1 ph.e.	~10 ph.e.	1 ph.e.	1 ph.e.
Timing /10 ph.e.	~100 ps	a few ns	~100 ps	30 ps
Dynamic range	$\sim 10^6$	large	large	$\sim 10^3/mm^2$
Complexity	high (vacuum, HV)	medium (low noise electronics)	very high (hybrid technology, very HV)	relatively low

CREATION of the SIGNAL

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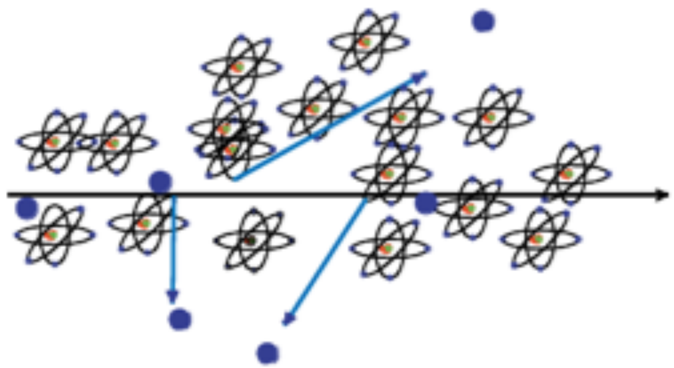


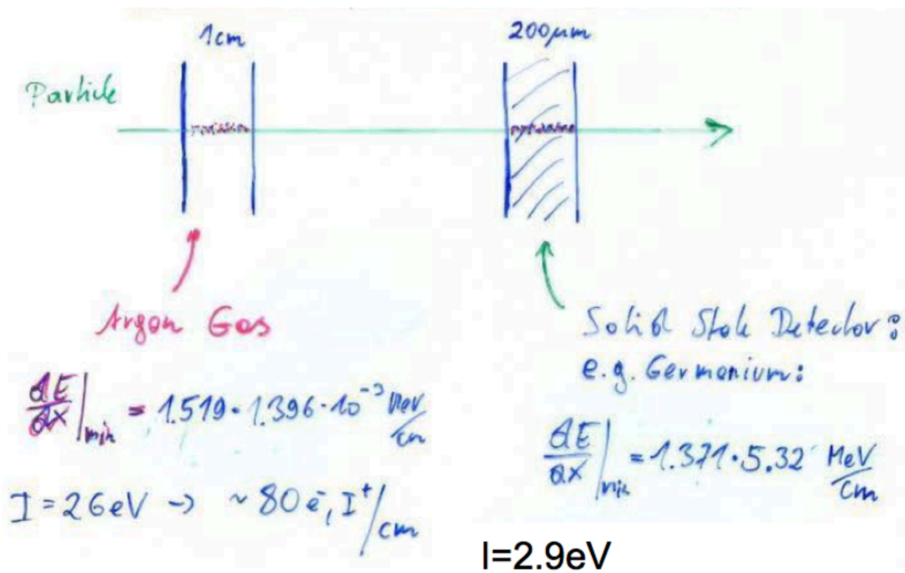
Excitation

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

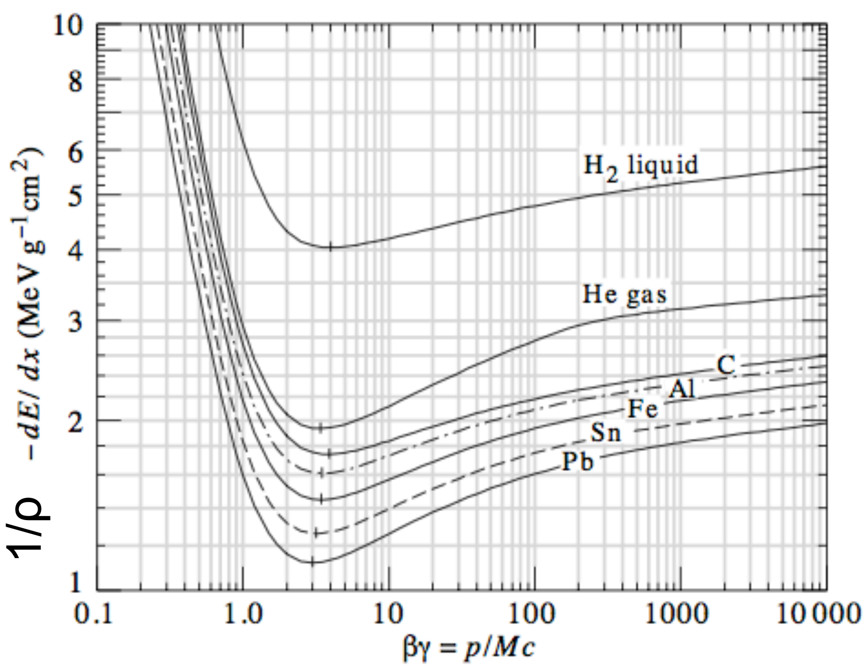
Ionisation

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.

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 characterized 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.

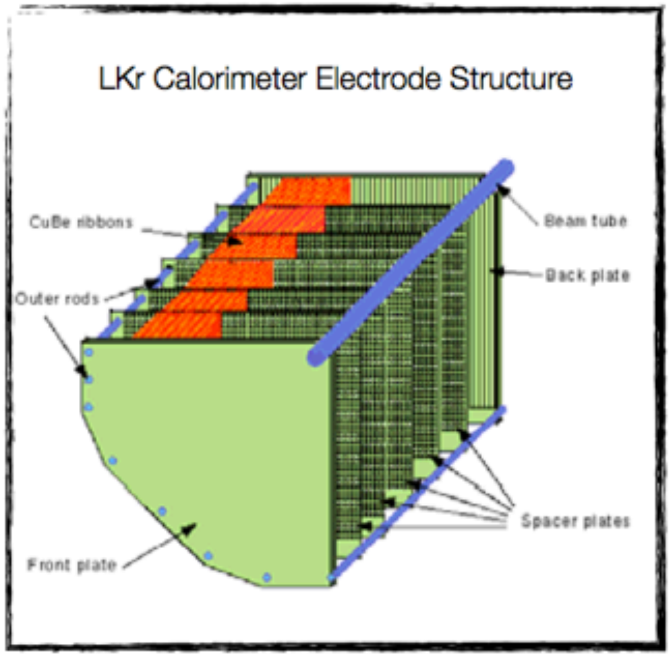
Gas detectors need internal amplification in order to be sensitive to single particle tracks.

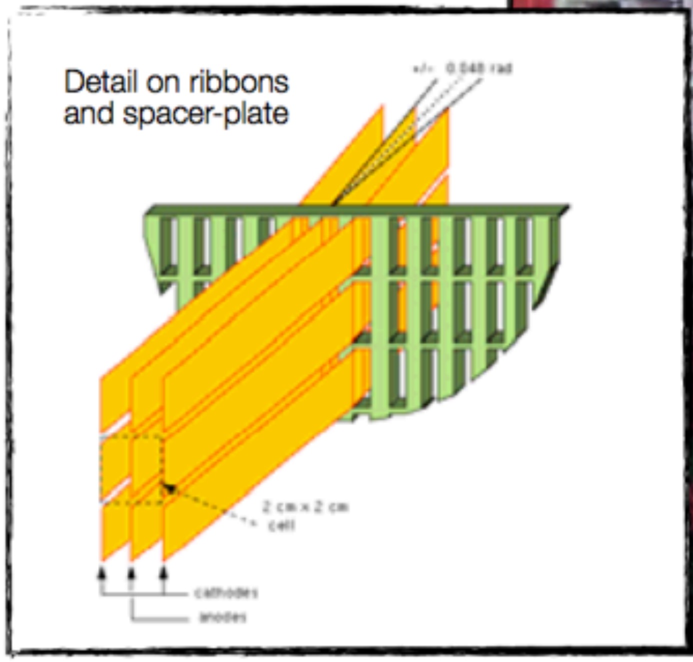
Without internal amplification they can only be used for a large number of particles that arrive at the same time (ionisation chamber).

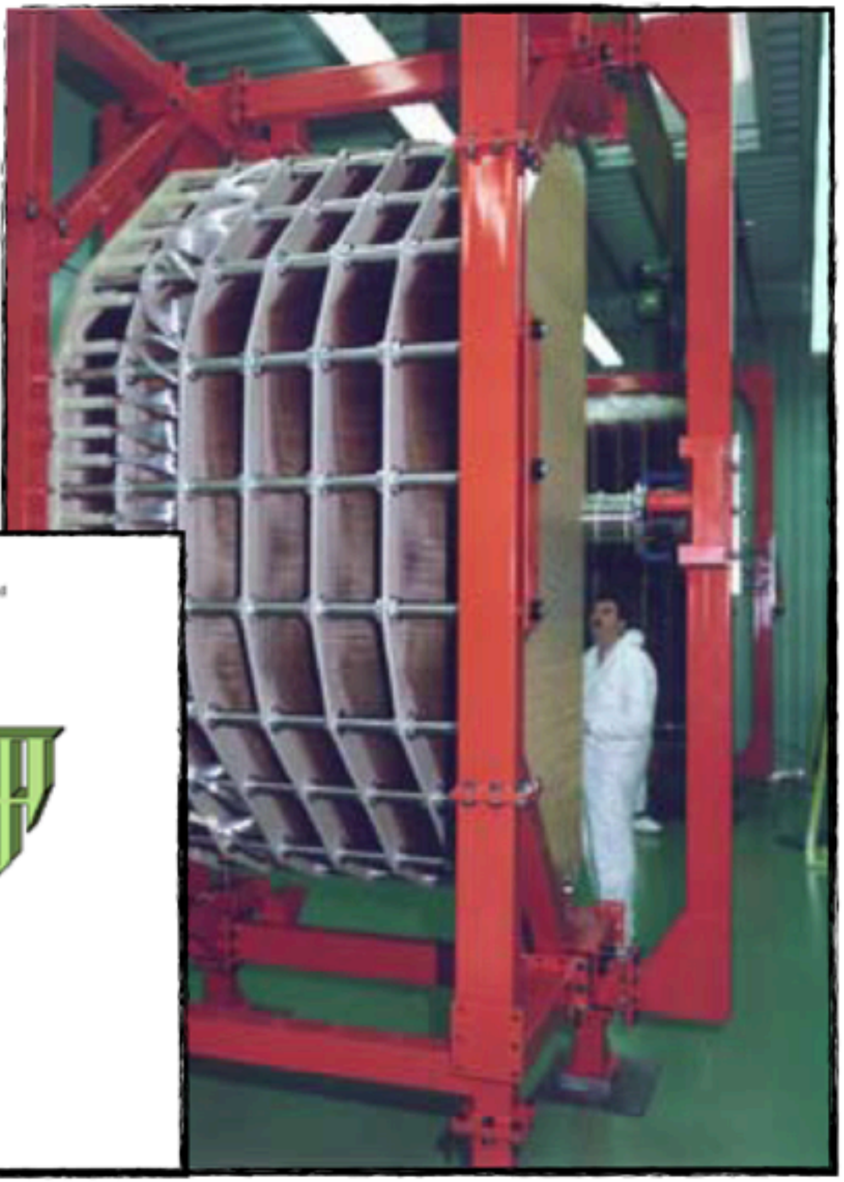
LIQUID GAS DETECTOR: IONISATION DETECTOR for NA48 EM CALORIMETER

Liquid Krypton
Ionization Chamber

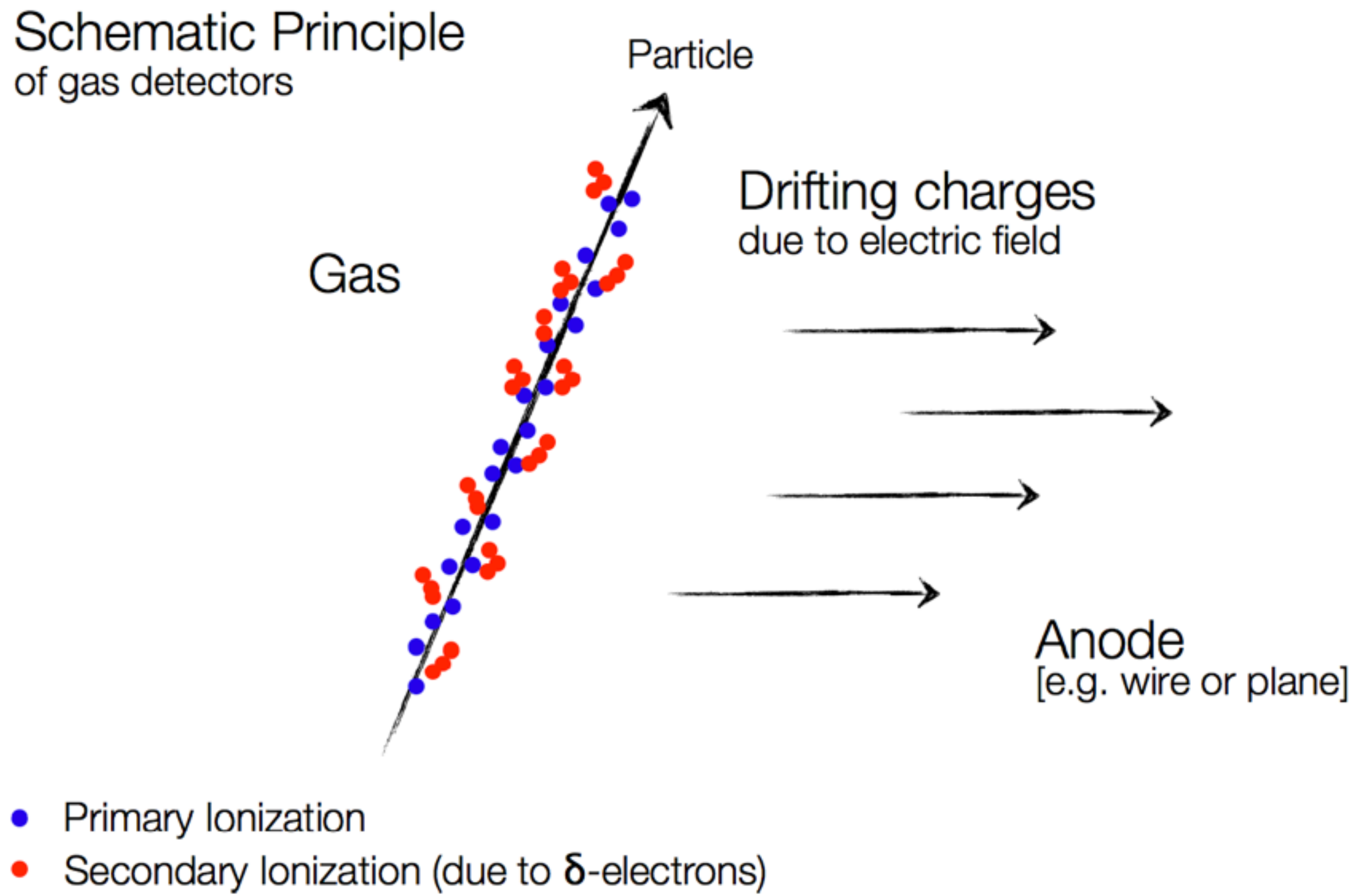
Homogeneous LKr; gain = 1
184 cells formed by thin electrodes; cell size: 2x2 cm^2
Each cell formed by two drift gaps sharing readout electrode
Electrodes: CuBe ribbons







INTRODUCTION



INTRODUCTION

Relevant Parameters
for gas detectors

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

Differences due to δ-electrons

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

[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	$1.66 \cdot 10^{-4}$	24.6	41	0.32	5.9	7.8
Ar	18	$1.66 \cdot 10^{-3}$	15.8	27	2.44	29.4	94
CH_4	19	$6.7 \cdot 10^{-4}$	13.1	28	1.48	18	53
C_4H_{10}	34	$2.42 \cdot 10^{-3}$	10.6	23	4.50	46	195

INTRODUCTION

Ionization statistics:

Mean free path λ:
[typical values]

He	0.25 cm
Air	0.052 cm
Xe	0.023 cm

[➛ σ_I(He) ≈ 100 b]

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

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:

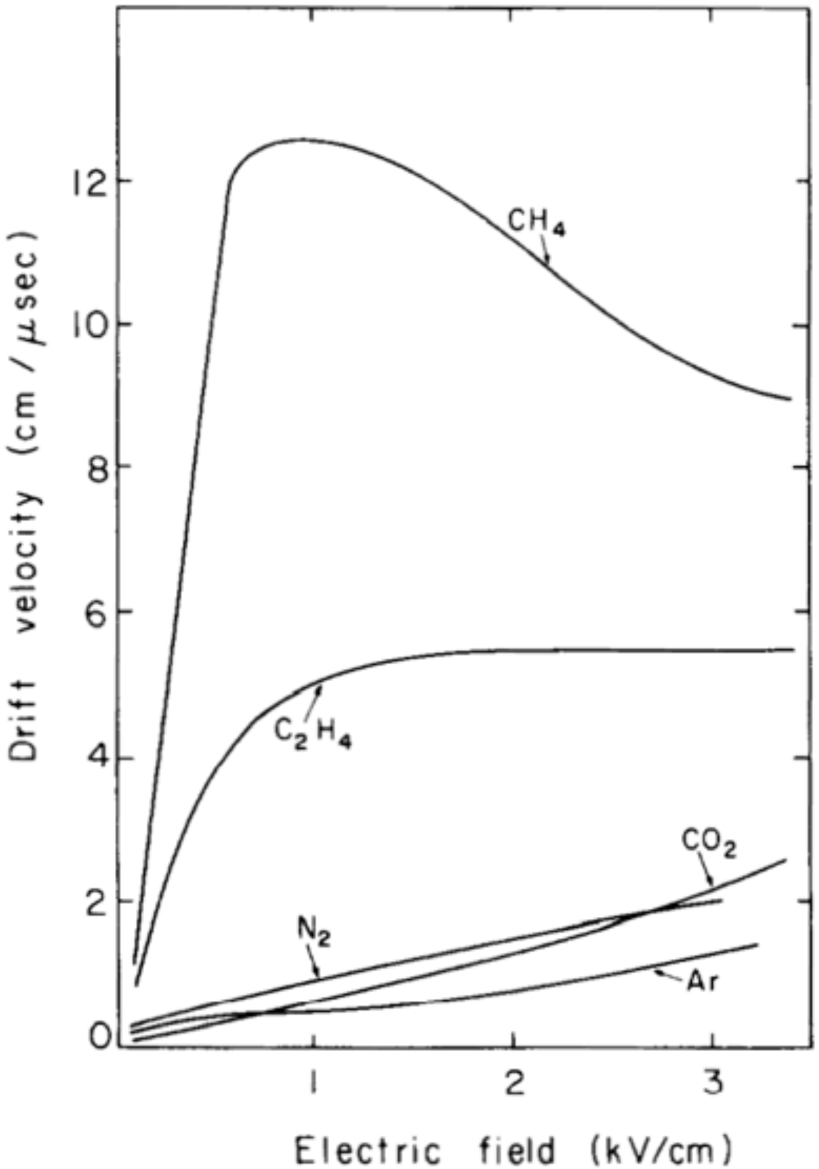
Mobility of charges:
Influences the timing behavior of gas detectors ...

Diffusion:
Influences the spatial resolution ...

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

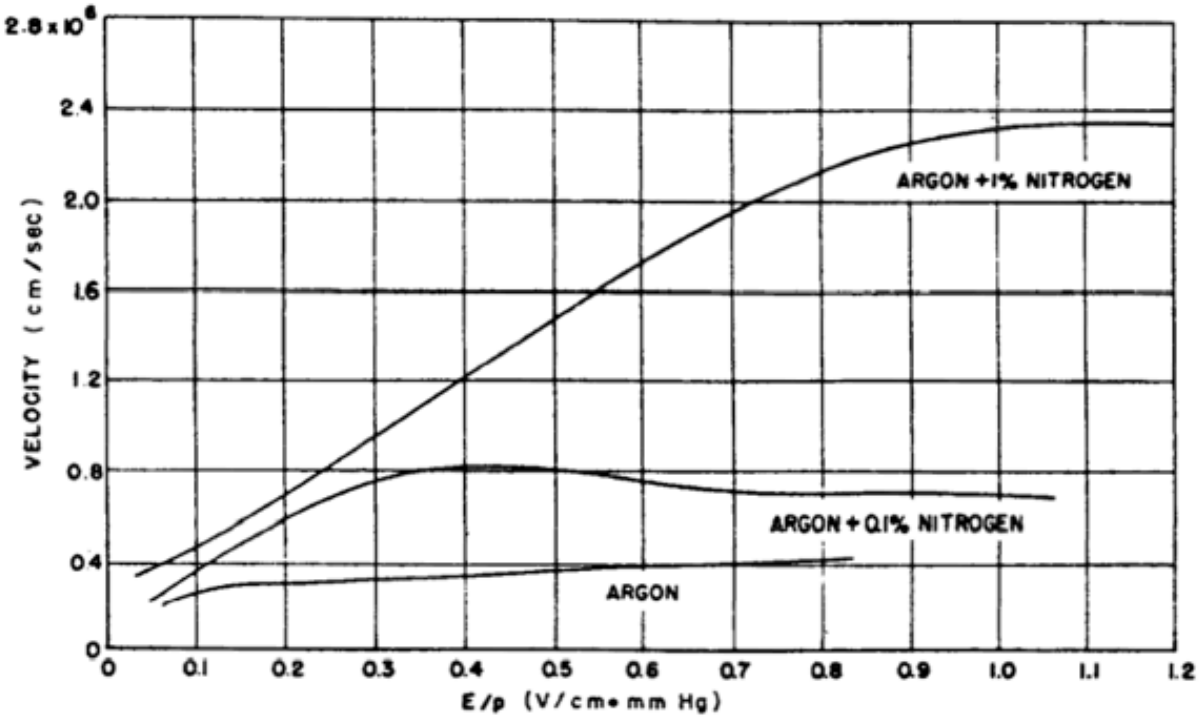
Recombination and electron attachment:
Admixture of electronegative gases (O_2, F, Cl ...) influences detection efficiency ...

DRIFT and DIFFUSION in GASES



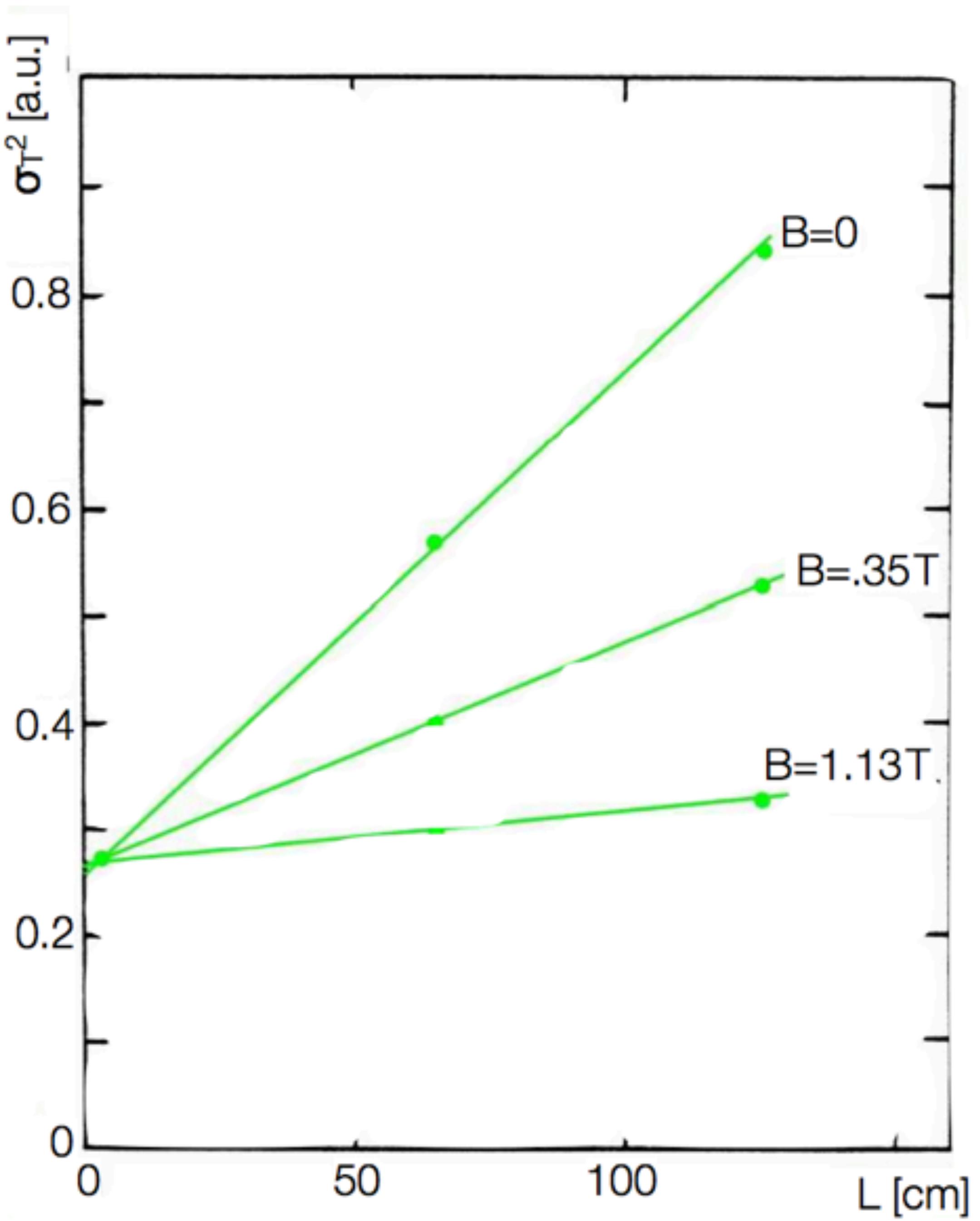
Drift velocity of electrons
in several gases at normal conditions

Use gas mixture to obtain constant v_D
Important for applications using drift time to get spatial information



E-Field/pressure

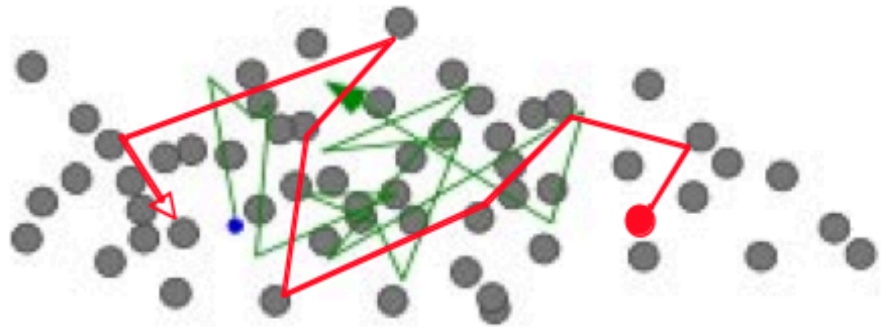
DRIFT and DIFFUSION in GASES



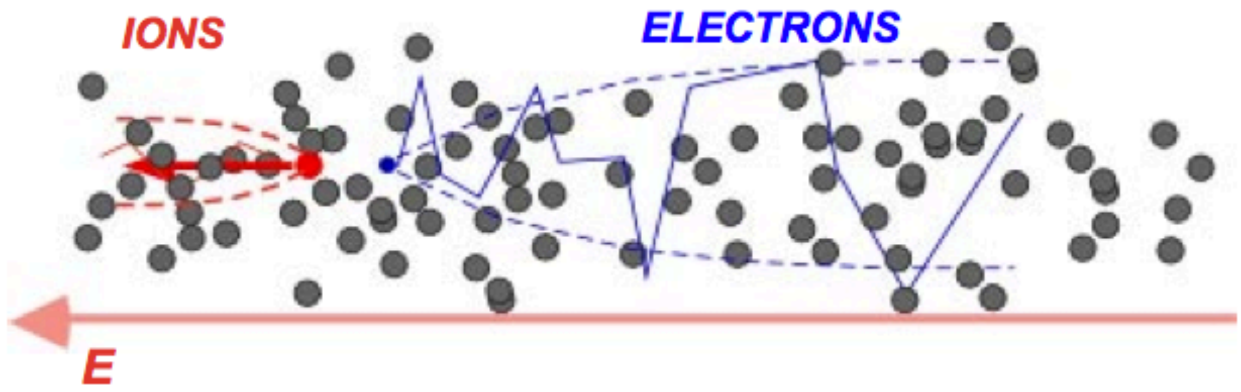
Transverse diffusion as function of drift length for different B fields

DIFFUSION IN GAS

No electric field (E=0): thermal diffusion



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



DRIFT and DIFFUSION in GASES

For exact solution:

Solve "transport equation" for electron density distribution $f(t, \vec{r}, \vec{v})$:

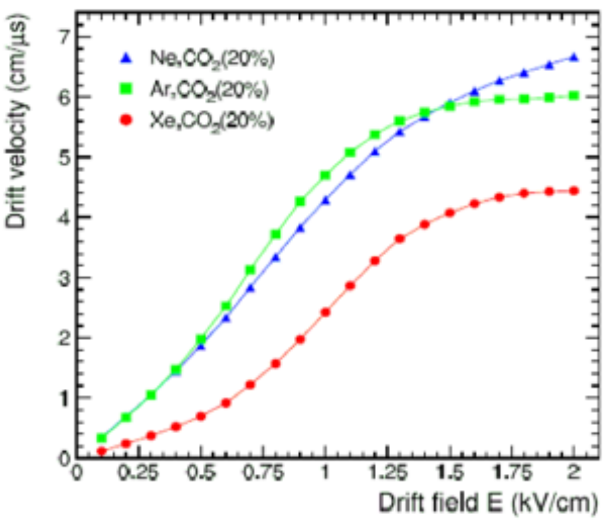
stochastic collision term

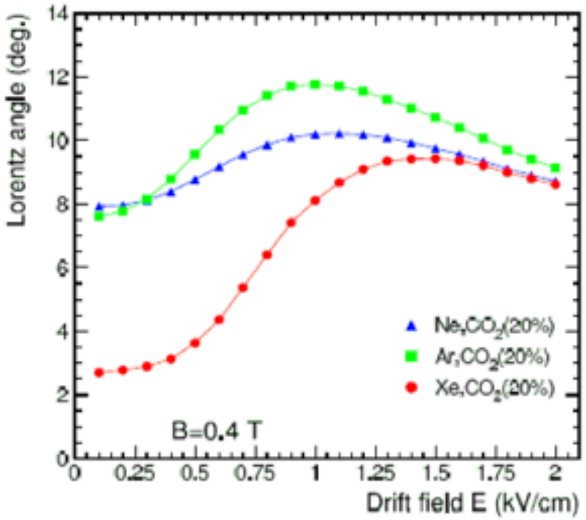
$$\frac{\partial f}{\partial t} + \underbrace{\vec{v}\frac{\partial}{\partial \vec{r}} f}_{\text{diffusion}} + \underbrace{\frac{\partial}{\partial \vec{v}}\left(\frac{e\vec{E}}{m} + \vec{\omega} \times \vec{v}\right) f}_{\text{external forces}} = Q(t)$$

Typically needs to be solved numerically ...

Available Programs:

Magboltz
Garfield





LOSS of ELECTRONS

Electrons maybe lost during drift ...
Possible processes:

i. recombination of ions and electrons

Depends on number of charge carriers and recombination coefficient ...

Generally not important ...

Recombination rate:

$$\Lambda = p_r \cdot n^+ n^-$$

➡ Recombination coefficient ≈ 10^{-7} cm^3/s

ii. electron attachment

Electro-negative gases bind electrons; e.g.: O_2, Freon, Cl_2, SF_6 ...
Attachment coefficient h strongly energy dependent ("Ramsauer effect") ...

Example O_2: $h = 10^{-4}$

Collisions of electron per second: 10^{11}
Typical drift time of electron: 10^{-6} s

Fraction lost: $X_{loss} = 10^{-4}\ 10^{11}\ s^{-1}\ 10^{-6}\ s \cdot p = 10p$
$X_{loss} < 1\% \rightarrow p < 10^{-3}$, i.e. less than 1 ‰ admixture

Oxygen should be kept out

DETECTING IONISATION WITH GAS DETECTOR

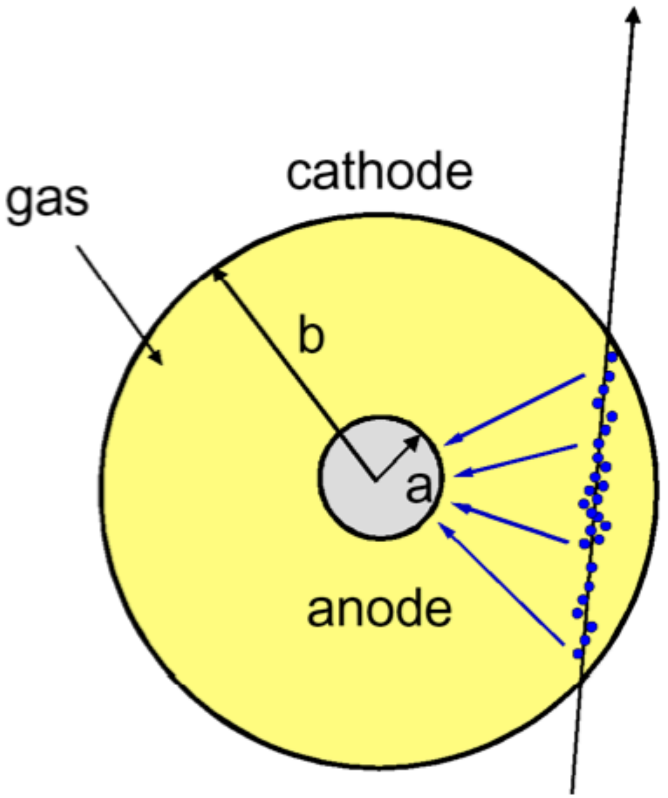
Criteria for optimal momentum resolution

- 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**



PRIMARY & TOTAL IONISATION YIELD in GAS

@ STP

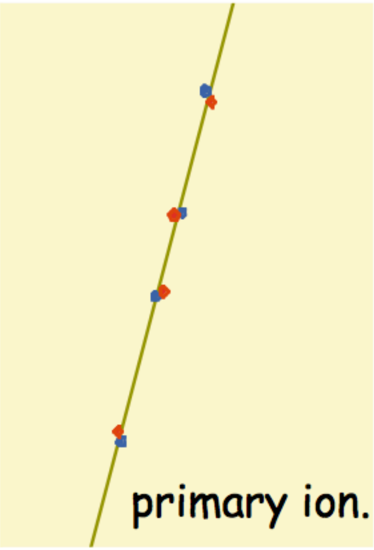
Total number of produced electron-ion pairs $n_T = \frac{\Delta E}{W_i} = \frac{\frac{dE}{dx}\Delta x}{W_i}$

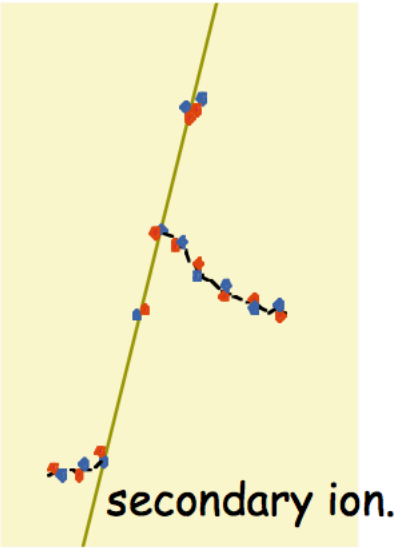
ΔE: total energy loss in Δx and

W_i: average energy loss per produced ion-pair: $n_T \sim 2 \ldots 7 \cdot n_P$

Gas	Density ρ [g/cm^3]	I_0 [eV]	W [eV]	n_P [cm^{-1}]	n_T [cm^{-1}]
H_2	8.99 x 10^{-5}	15.4	37	5.2	9.2
He	1.78 x 10^{-4}	24.6	41	5.9	7.8
N_2	1.23 x 10^{-3}	15.5	35	10	56
O_2	1.43 x 10^{-3}	12.2	31	22	73
Ne	9.00 x 10^{-4}	21.6	36	12	39
Ar	1.78 x 10^{-3}	15.8	26	29	94
Kr	3.74 x 10^{-3}	14.0	24	22	192
Xe	5.89 x 10^{-3}	12.1	22	44	307
CO_2	1.98 x 10^{-3}	13.7	33	34	91
CH_4	7.17 x 10^{-4}	13.1	28	16	53
C_4H_{10}	2.67 x 10^{-3}	10.8	23	46	195

avg. ionisation pot. / shell elect.
average energy loss./ion pair
number primary electron-ion pairs
total number electron-ion pairs





AMPLIFICATION of the SIGNAL in GAS

For a cylindral geometry

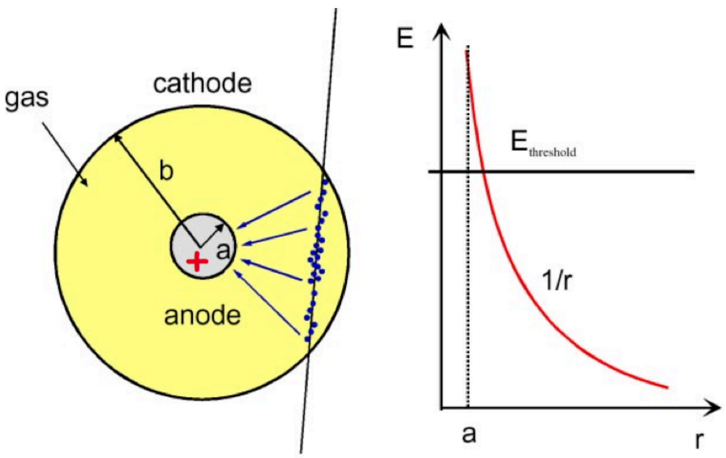
$$E(r) \propto \frac{1}{r} \quad \text{and} \quad V(r) \propto \ln\frac{r}{a}$$

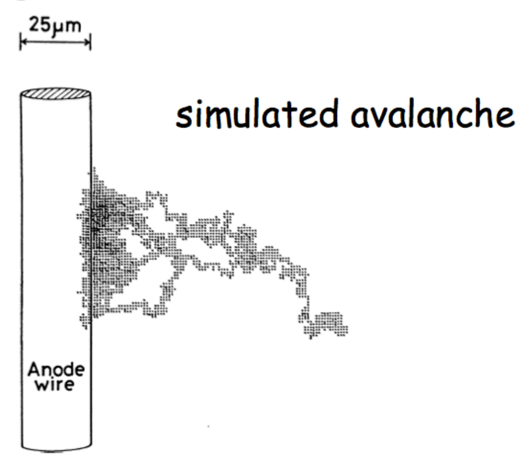
The primary electrons drift towards the positive anode:

due to 1/r dependence the electric field close to the very thin wires reaches values E>kV/cm

in between collitions with atoms electrons gain enough energy to ionise further gas molecules

exponential increase in number of electron-ion pairs close (fem 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…

$dN = N \cdot \alpha \cdot dx$

α: Towsend coefficient

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

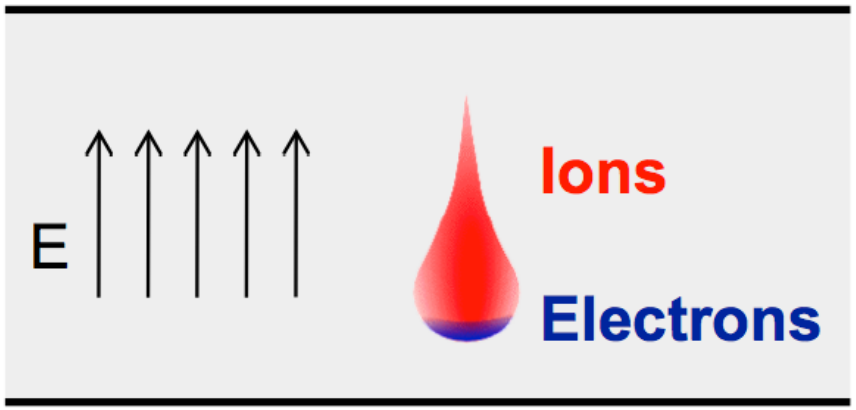
$N/N_0 = A$ Amplification, Gas Gain

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

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

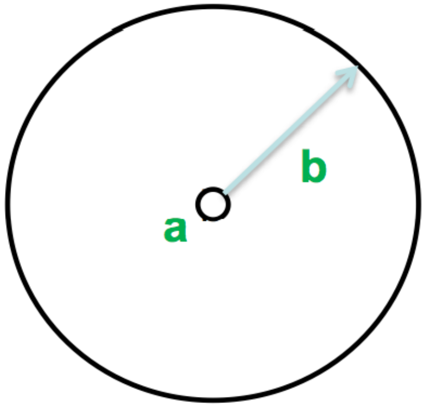
Electric field close to a thin wire (100-300 kV/cm) e.g.

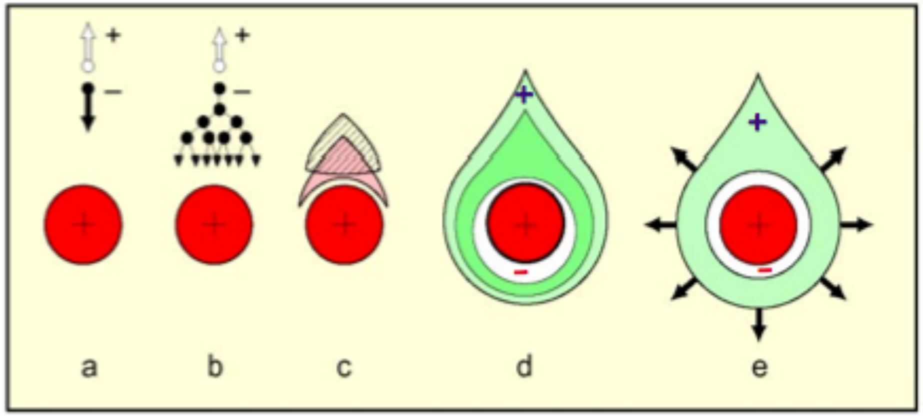
V_0=1000V, a=10µm, b=10 mm, E(a)=150kV/cm

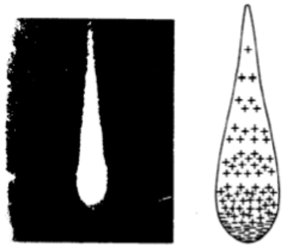
Electric field is sufficient to accelrate electrons to energies which are sufficient to produce secondary ionisation

→ electron avalanche

→ signal







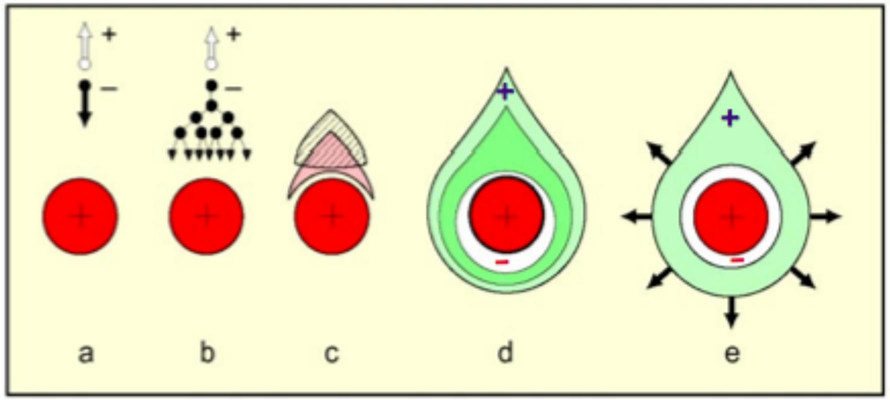
picture taken with cloud chamber

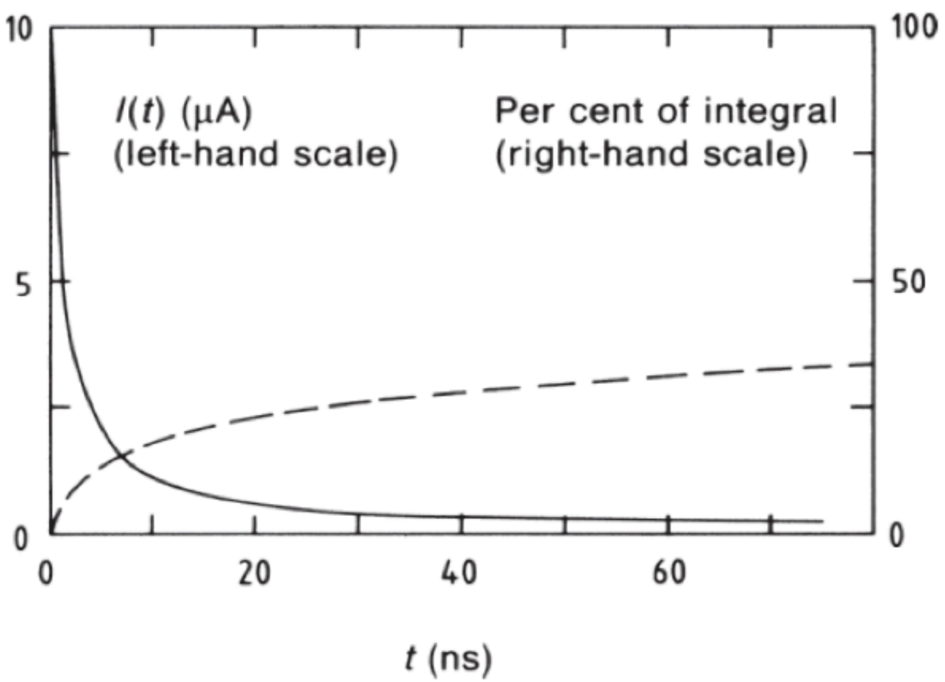
WIRE CHAMBER: SIGNAL from ELECTRON AVALANCHE

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:

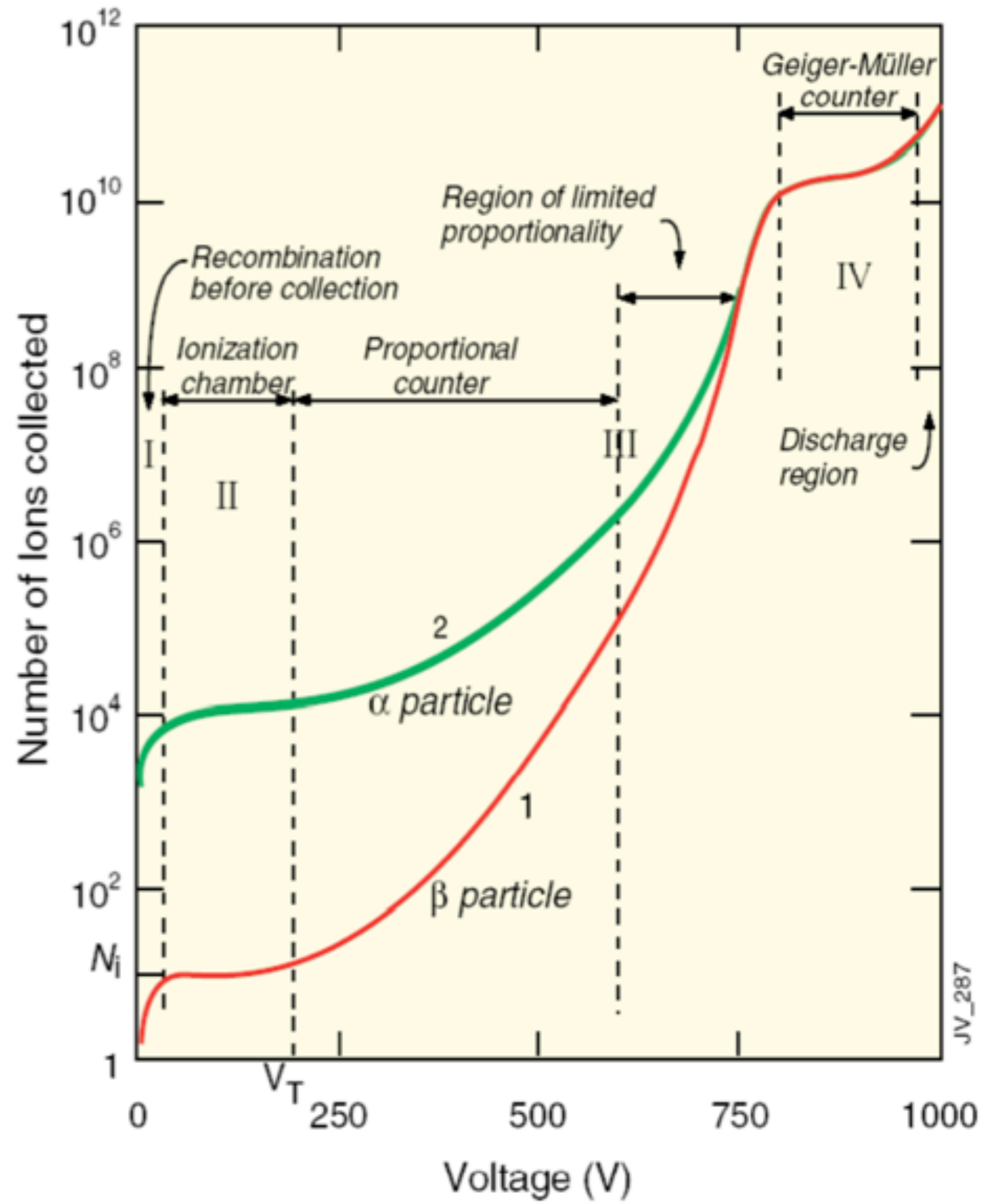
multiplication of ionization
signal proportional to ionization
measurement of dE/dx
secondary avalanches need quenching;
gain ≈ $10^4 - 10^5$

Limited proportional mode:
[saturated, streamer]

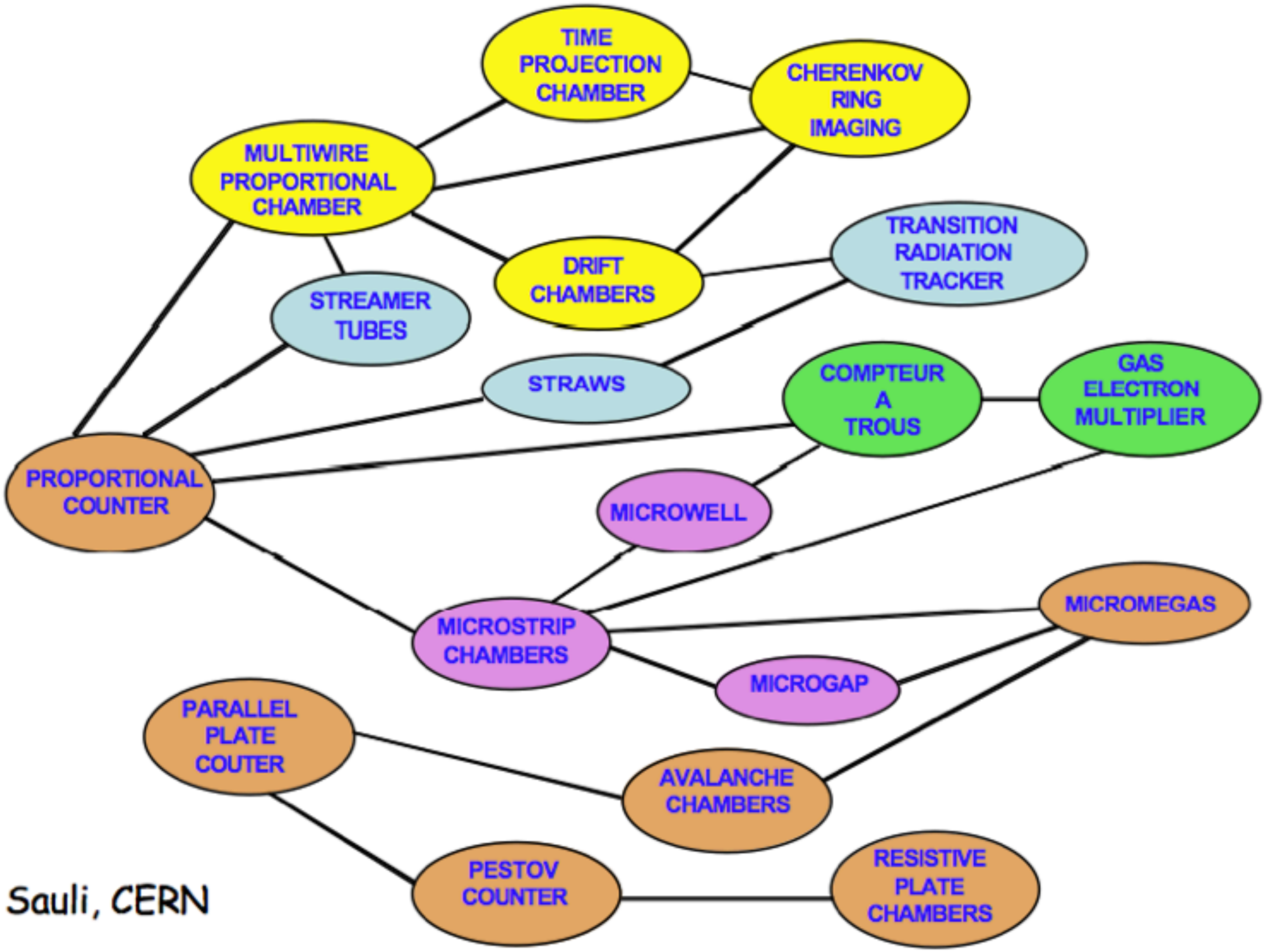
strong photoemission
requires strong quenchers or pulsed HV;
gain ≈ 10^{10}

Geiger mode:

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



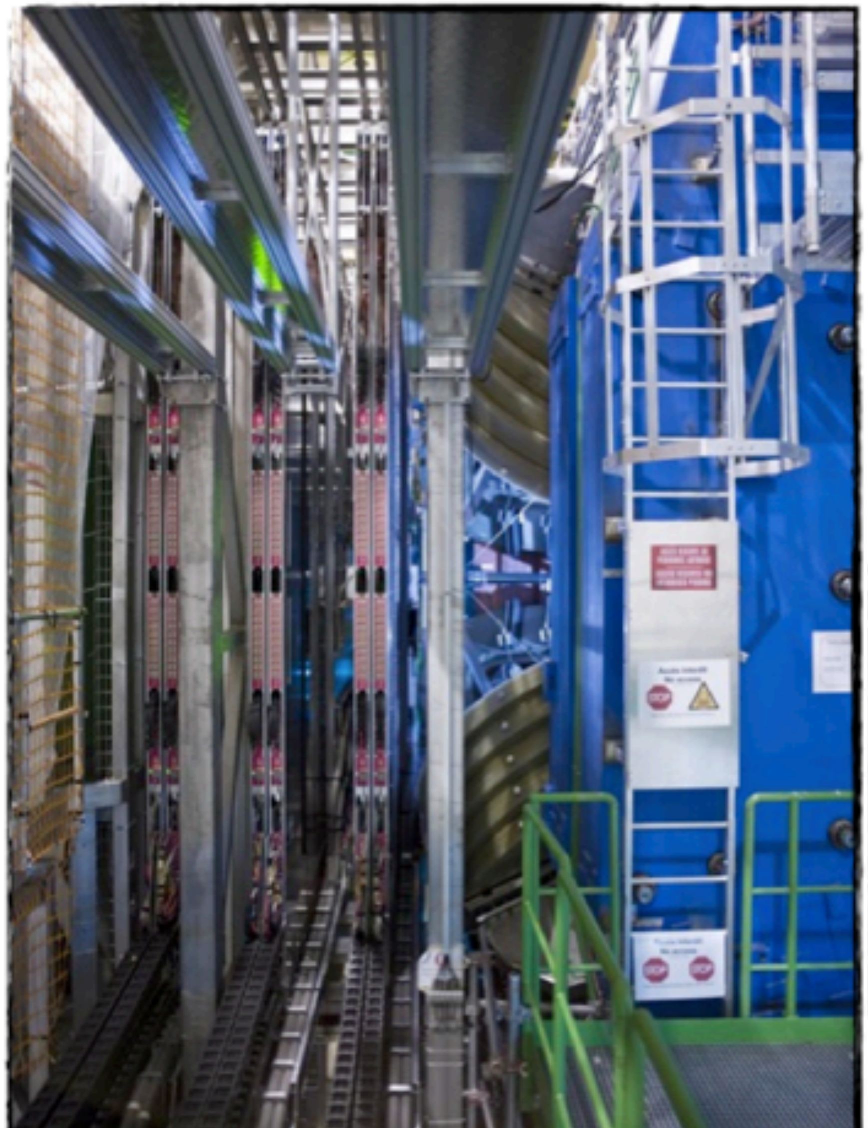
FAMILY TREE OF GASEOUS DETECTORS

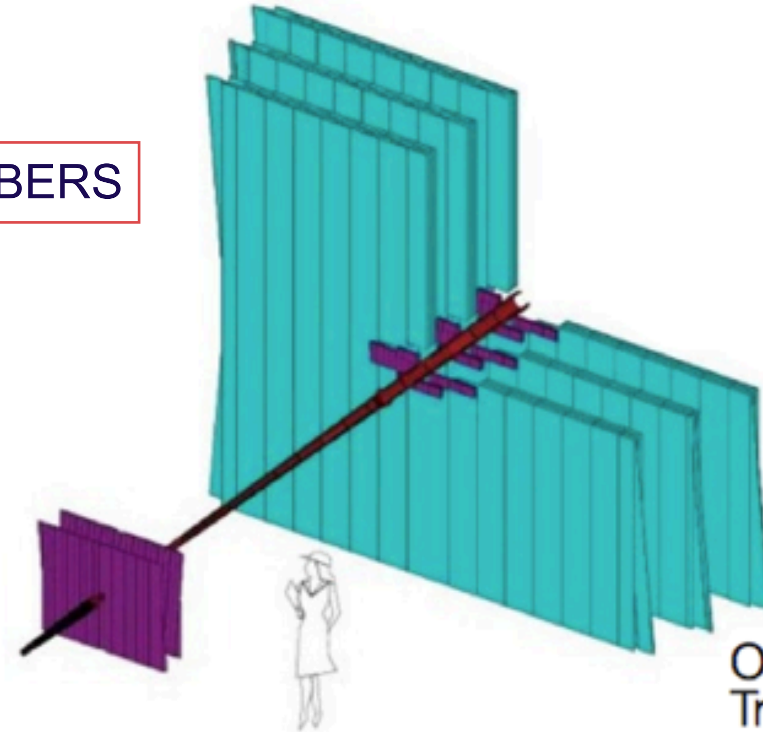


Fabio Sauli, CERN

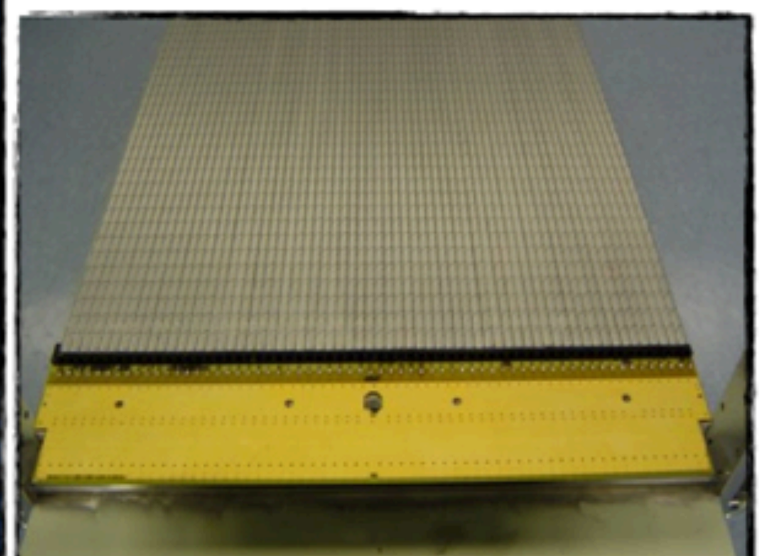
LHCb OUTER TRACKER

SINGLE WIRE PROPORTIONAL CHAMBERS

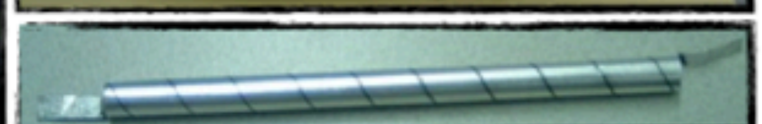




Outer
Tracker

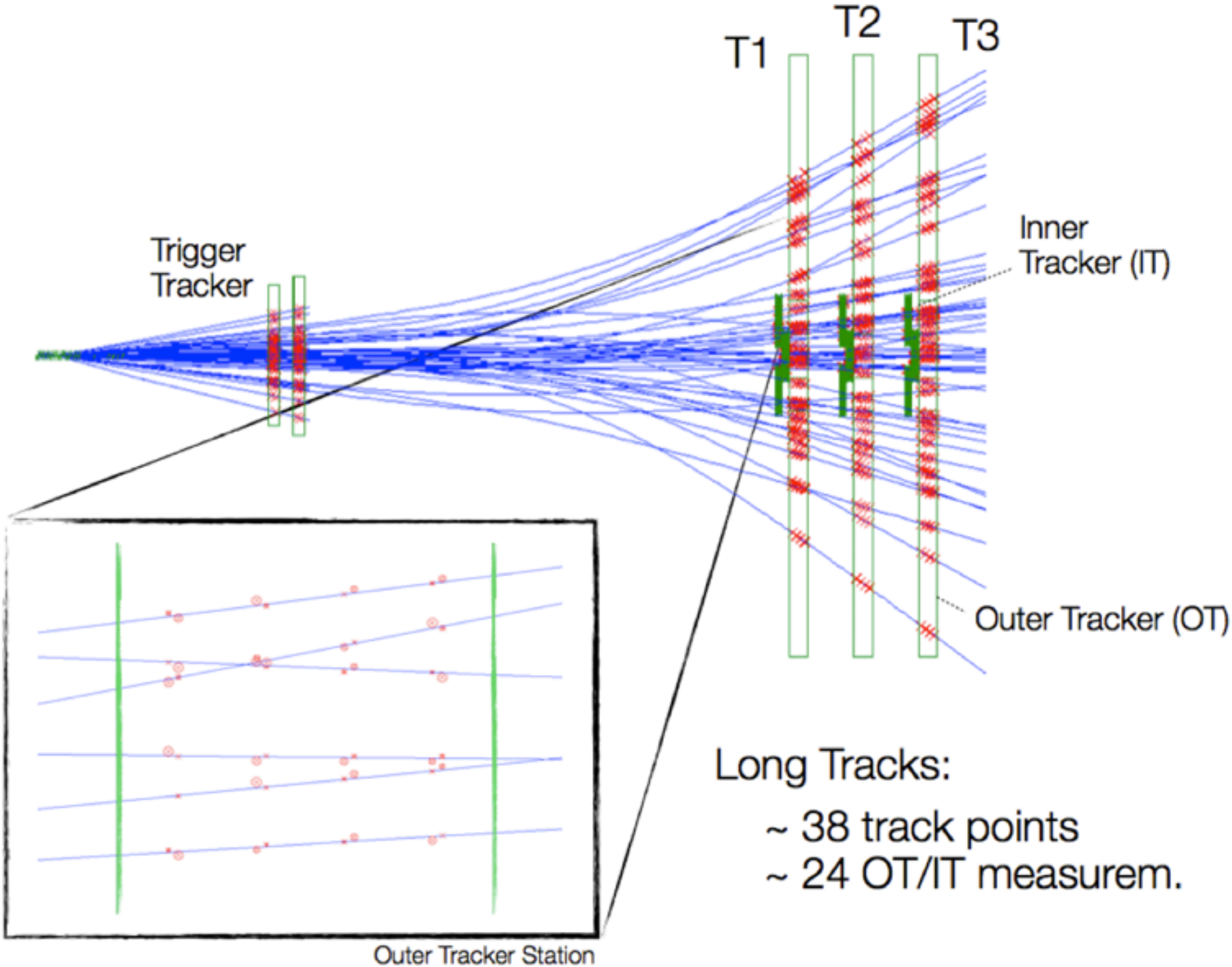


Straw Tubes
[double layers]



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

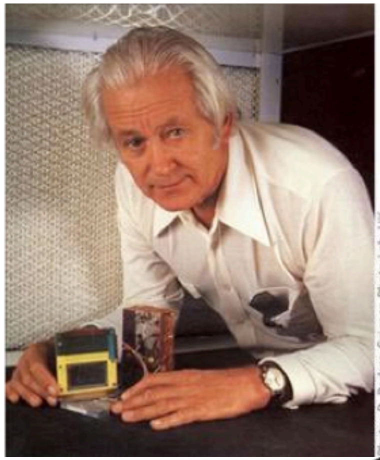
- Wire distance ~2-5 mm
- Distance between cathode planes ~10 mm

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



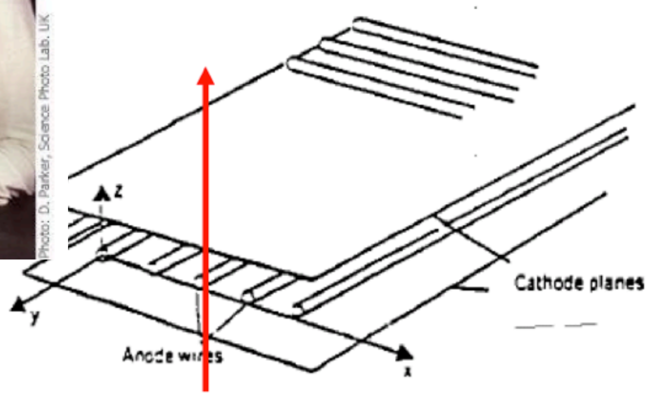
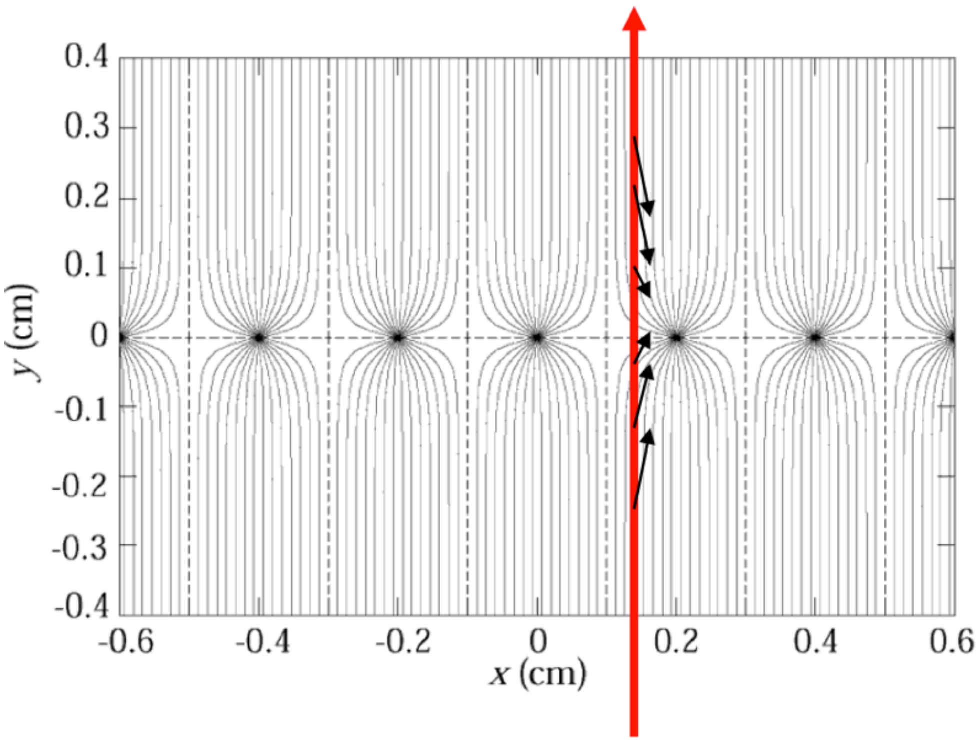
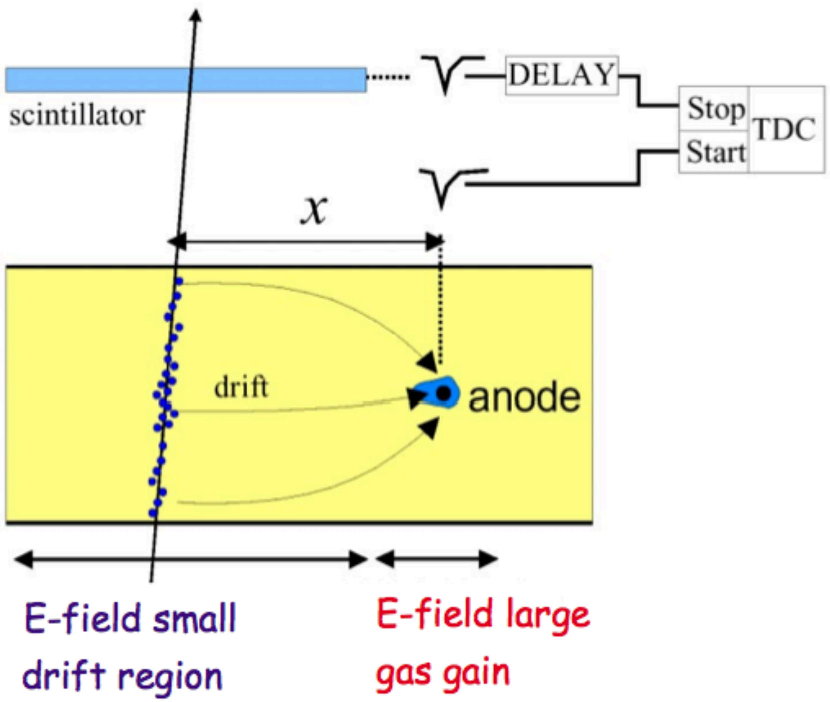


Abbildung 2.27: *Vieldrahtproportionalkammer.*



PRINCIPLE of DRIFT CHAMBER



Measure arrival time t_1 of electrons at anode wire relative to reference t_0

external definition of time reference t_0 (here by a fast scintillator signal)

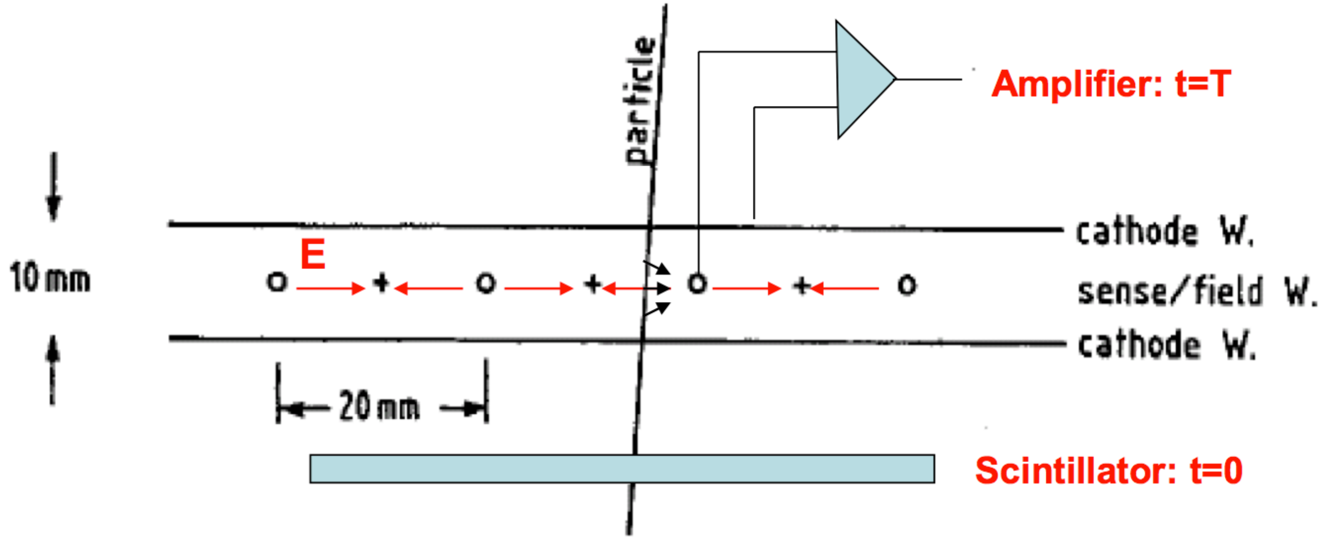
x-coordinate given by $$x = \int_{t_0}^{t_1} v_D(t)\,dt$$

if drift velocity v_D constant over full drift distance

$$x = v_D(t_1 - t_0) = v_D \Delta t$$

advantage of drift chambers: much larger sensitive volume per readout channel

DRIFT CHAMBERS



In an alternative sequence of wires with different potentials one finds an electric field between the *sense wires* and the *field wires*.

The electrons are moving to the sense wire and produce an avalanche which induces a signal that is read out by electronics

The time between the passage of the particle and the arrival of the electrons at the wire is measured.

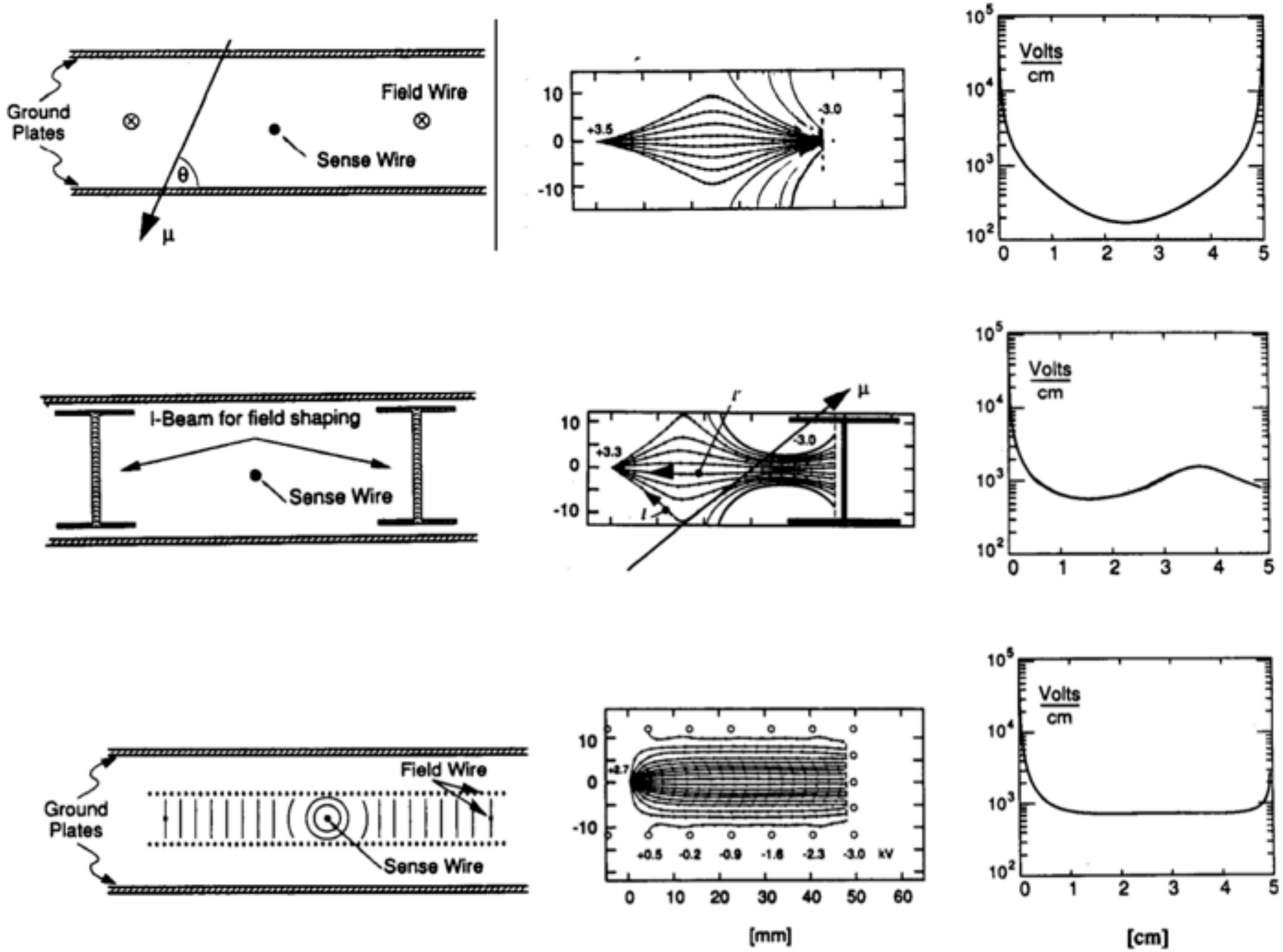
The drift time T is a measure of the position of the particle.

By measuring the drift time, the wire distance can be increased (wrt to MWPC)

→ save electronics channels

DRIFT CHAMBERS, TYPICAL GEOMETRIES

Electric Field ≈ 1kV/cm

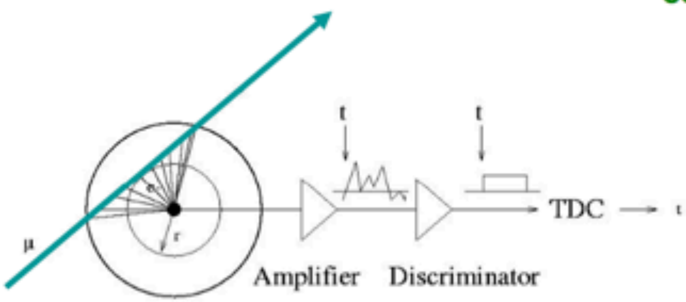


U.Becker Instr. of HEP, Vol#9, p516 World Scientific (1992) ed F.Sauli

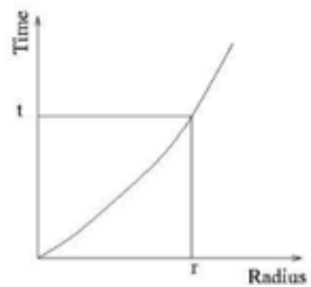
OPAL DRIFT CHAMBER

THE GEIGER COUNTER RELOADED: DRIFT TUBE

ATLAS MDT R(tube) =15mm



Calibrated Radius-Time correlation



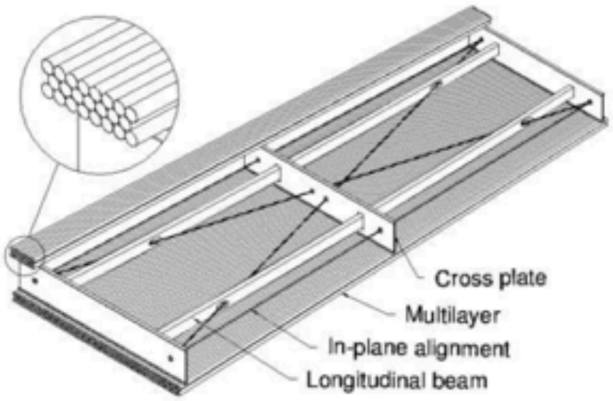
Primary electrons are drifting to the wire.

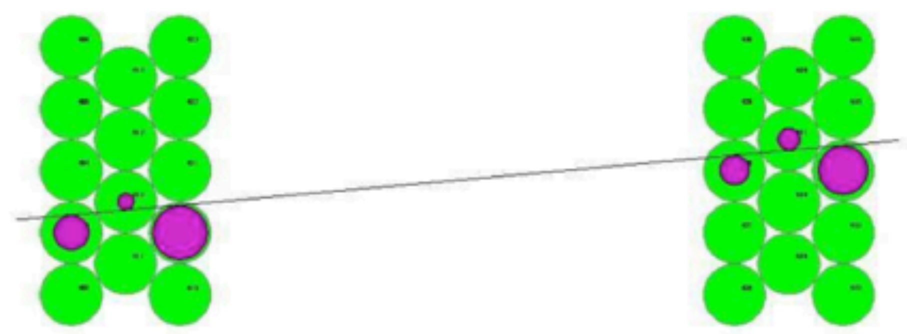
Electron avalanche at the wire.

The measured drift time is converted to a radius by a (calibrated) radius-time correlation.

Many of these circles define the particle track.

ATLAS Muon Chambers





ATLAS MDTs, 80μm per tube

THE GEIGER COUNTER RELOADED: DRIFT TUBE

Atlas Muon Spectrometer, 44m long, from r=5 to11m.

1200 Chambers

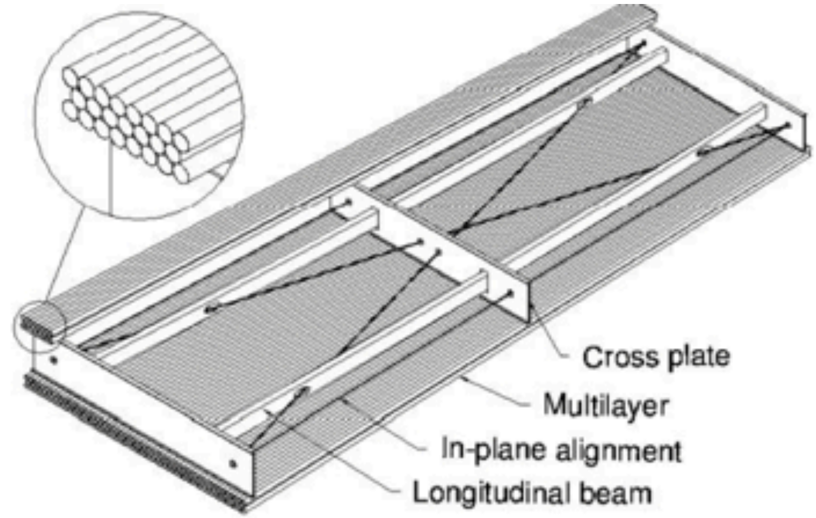
6 layers of 3cm tubes per chamber.

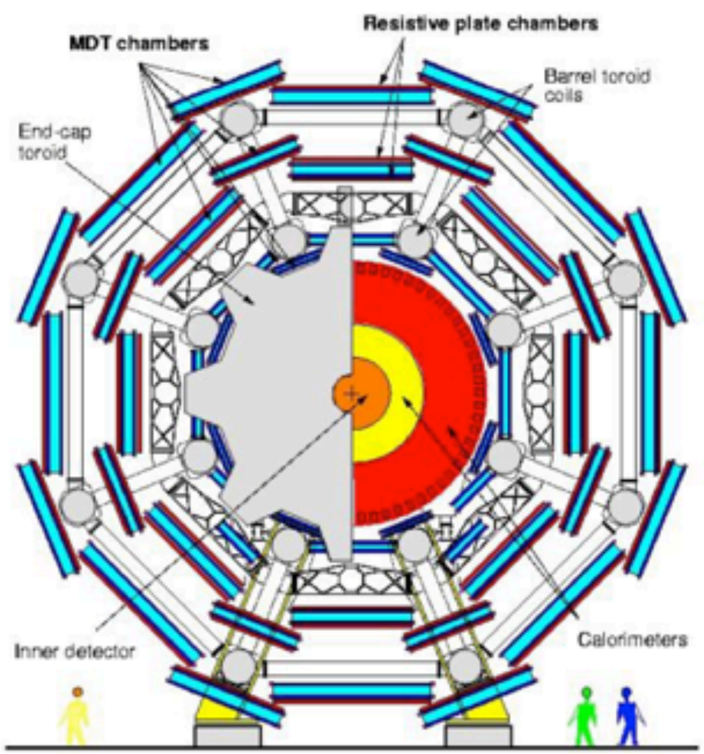
Length of the chambers 1-6m !

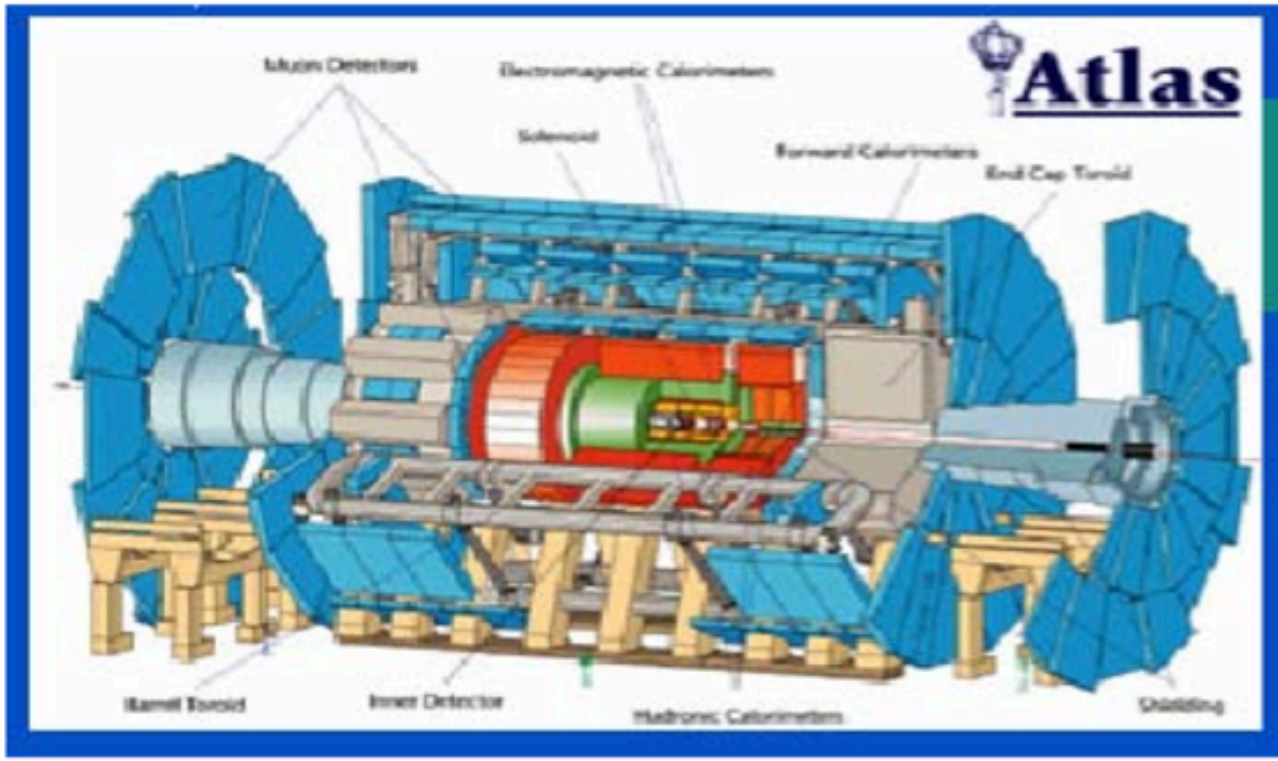
Position resolution: 80μm/tube, <50μm/chamber (3 bar)

Maximum drift time ≈700ns

Gas Ar/CO_2 93/7







TIME PROJECTION CHAMBER

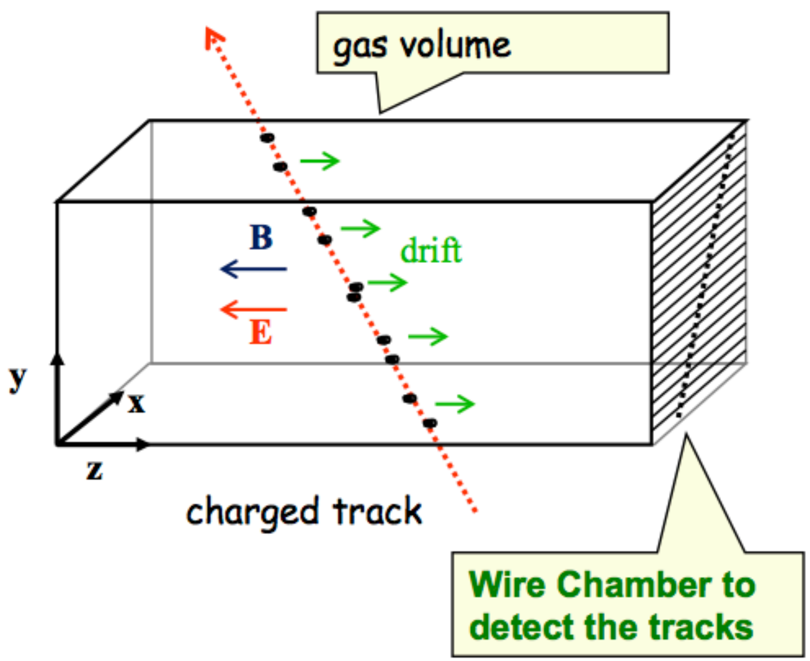
Gas volume with parallel E and B field.

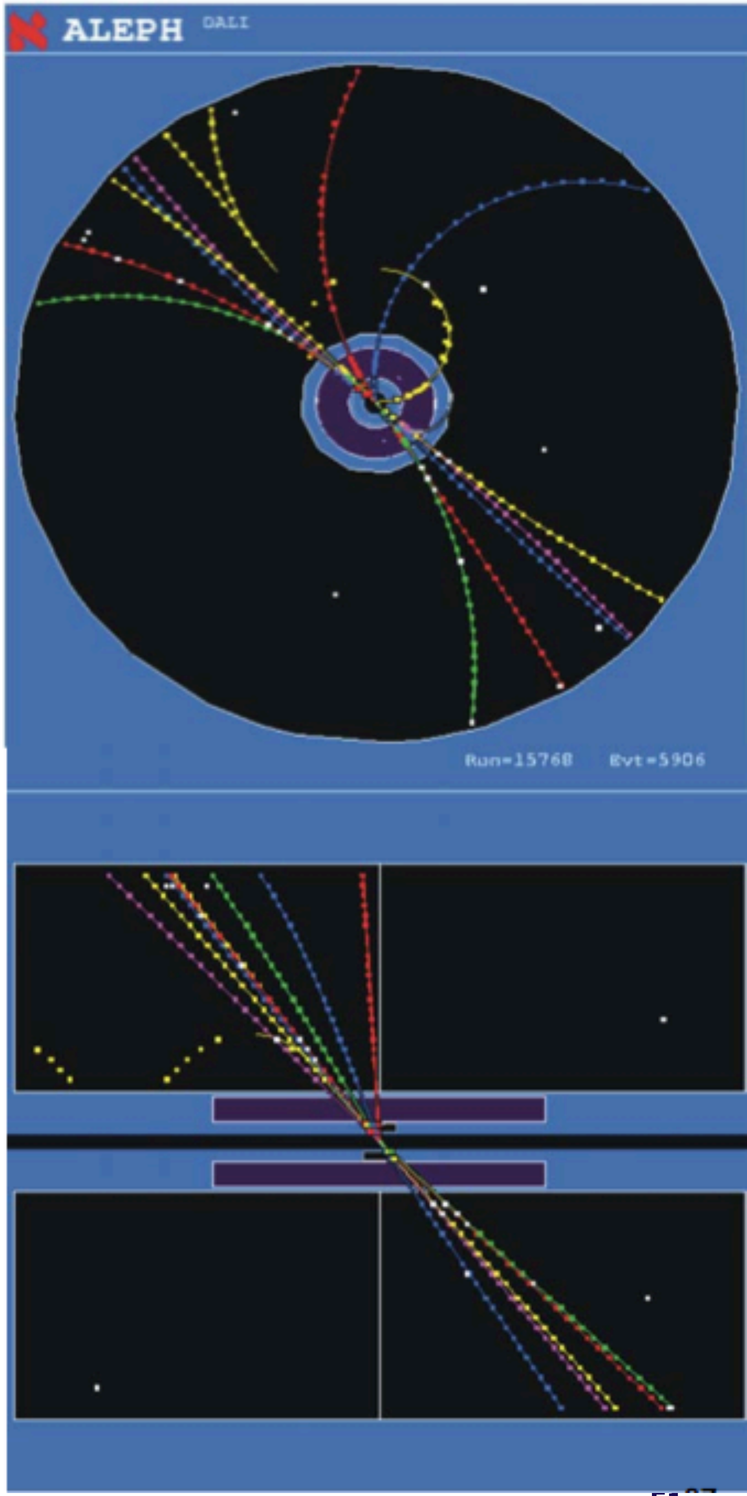
B for momentum measurement.

Positive effect:

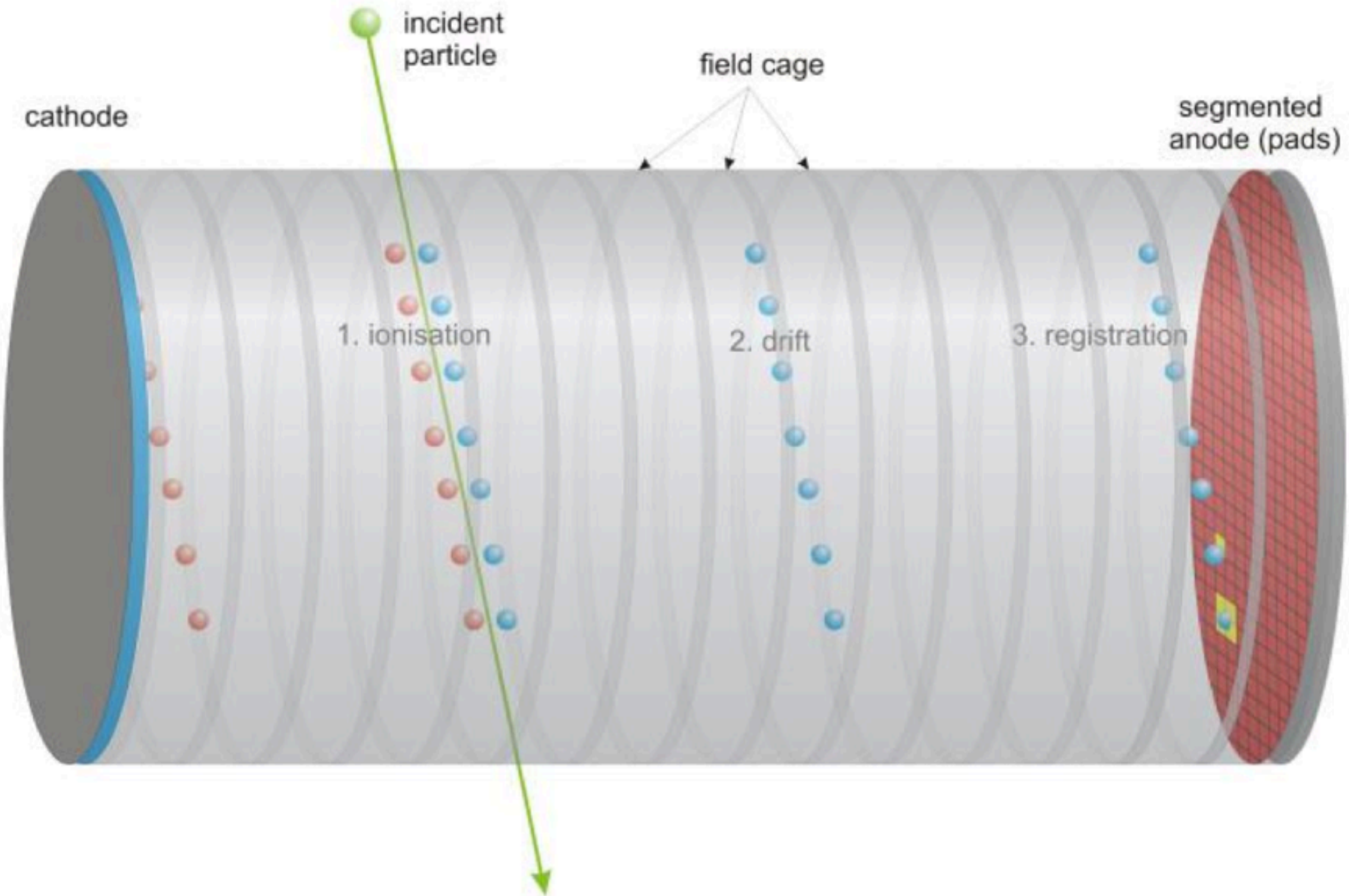
Diffusion is strongly reduced by E//B (up to a factor 5)

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

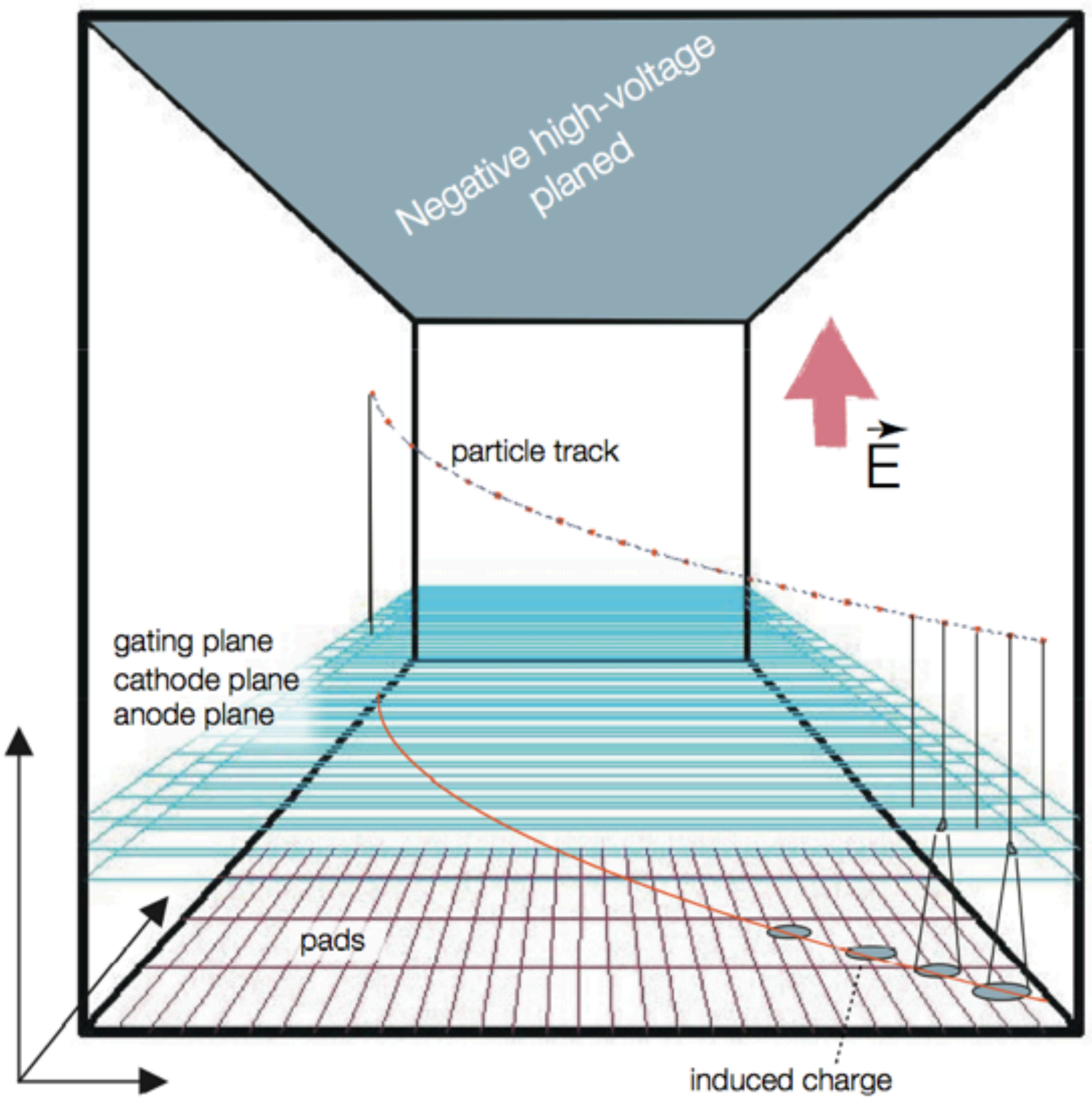




TRACKING DETECTOR: TIME PROJECTION CHAMBER



DRIFT CHAMBER: SCHEMATIC



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

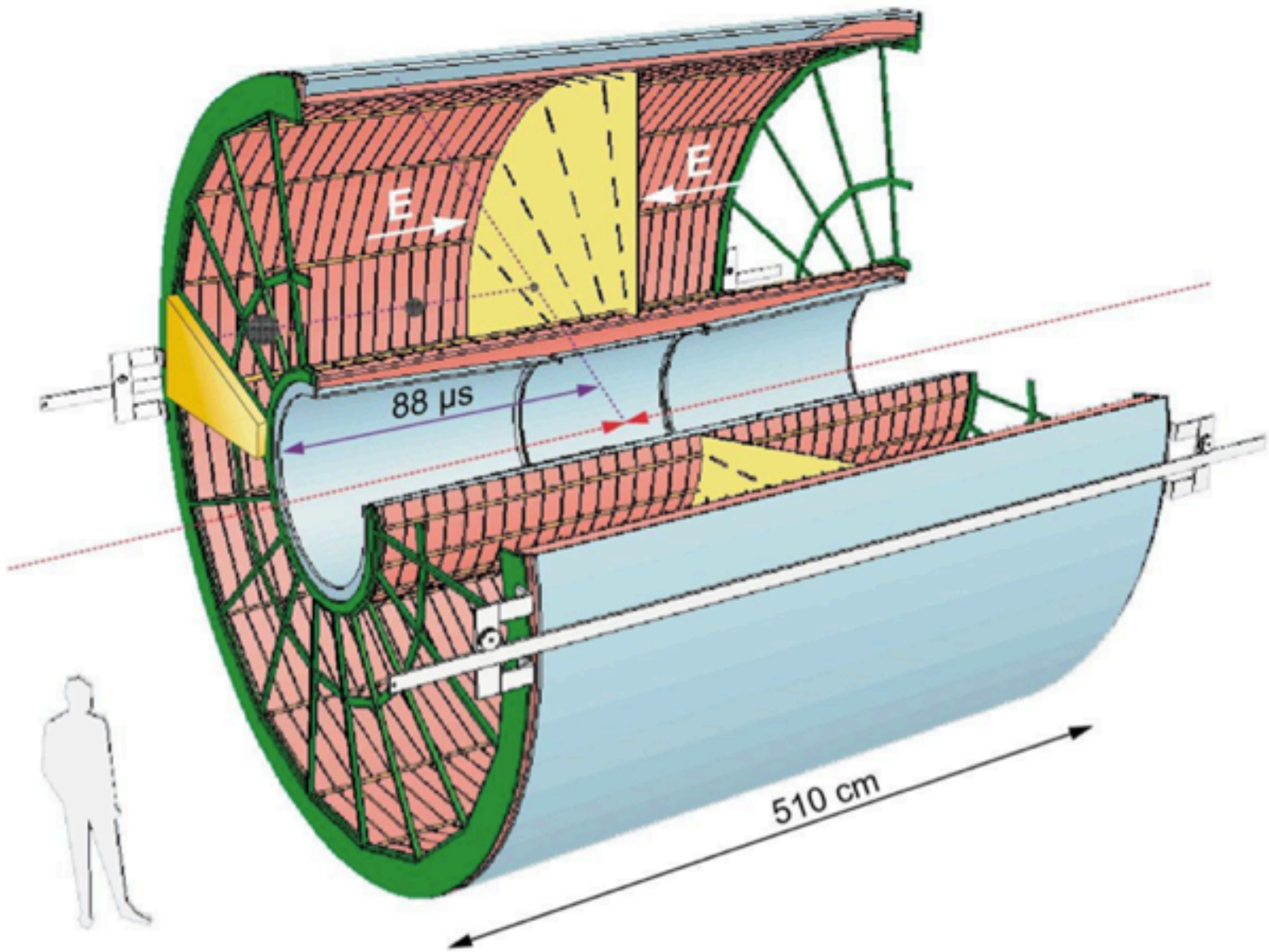
Diffusion: σ_t = 250 μm
Resolution: $\sigma \approx$ 0.2 mm

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 ...]

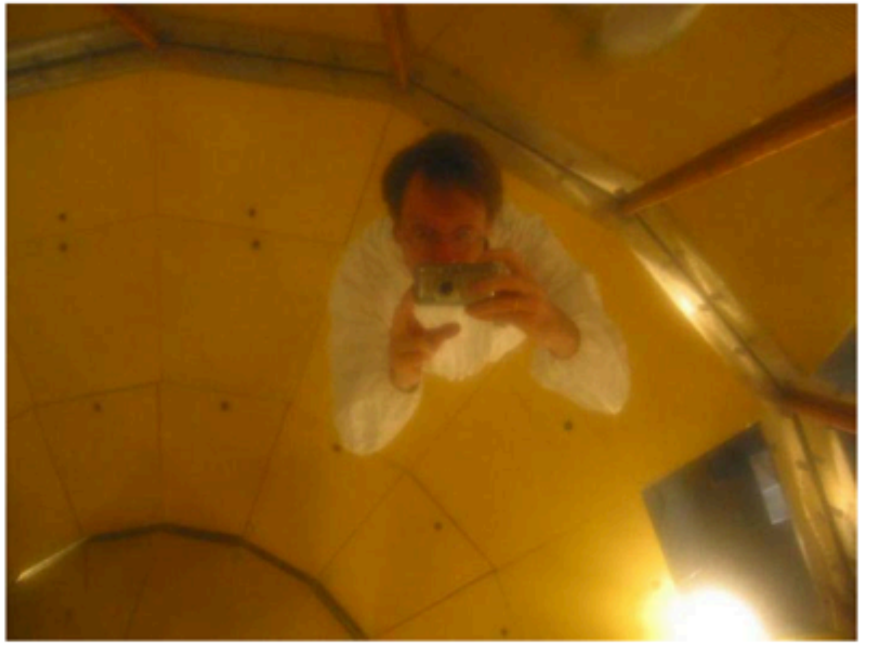


Material: Cylinder build from composite material of airline industry (X_0= ~ 3%)

CONSTRUCTION of the ALICE TPC

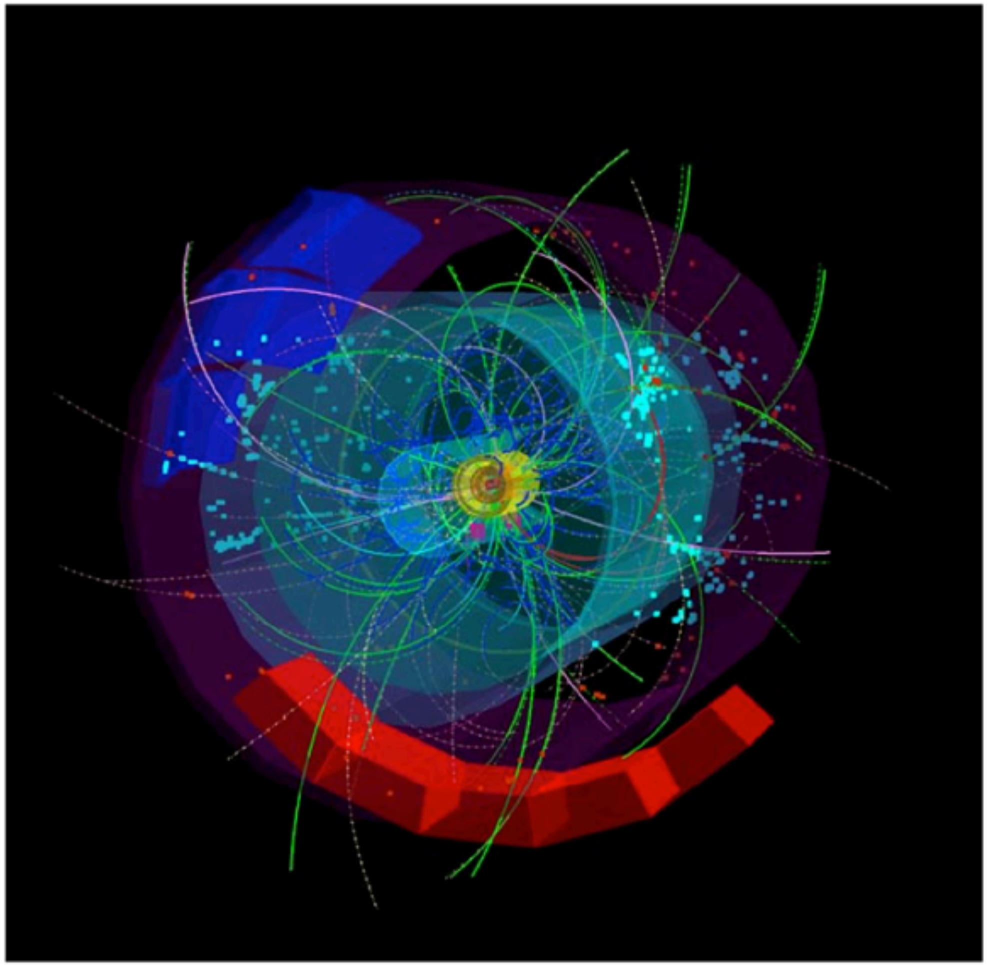
ALICE TPC Construction

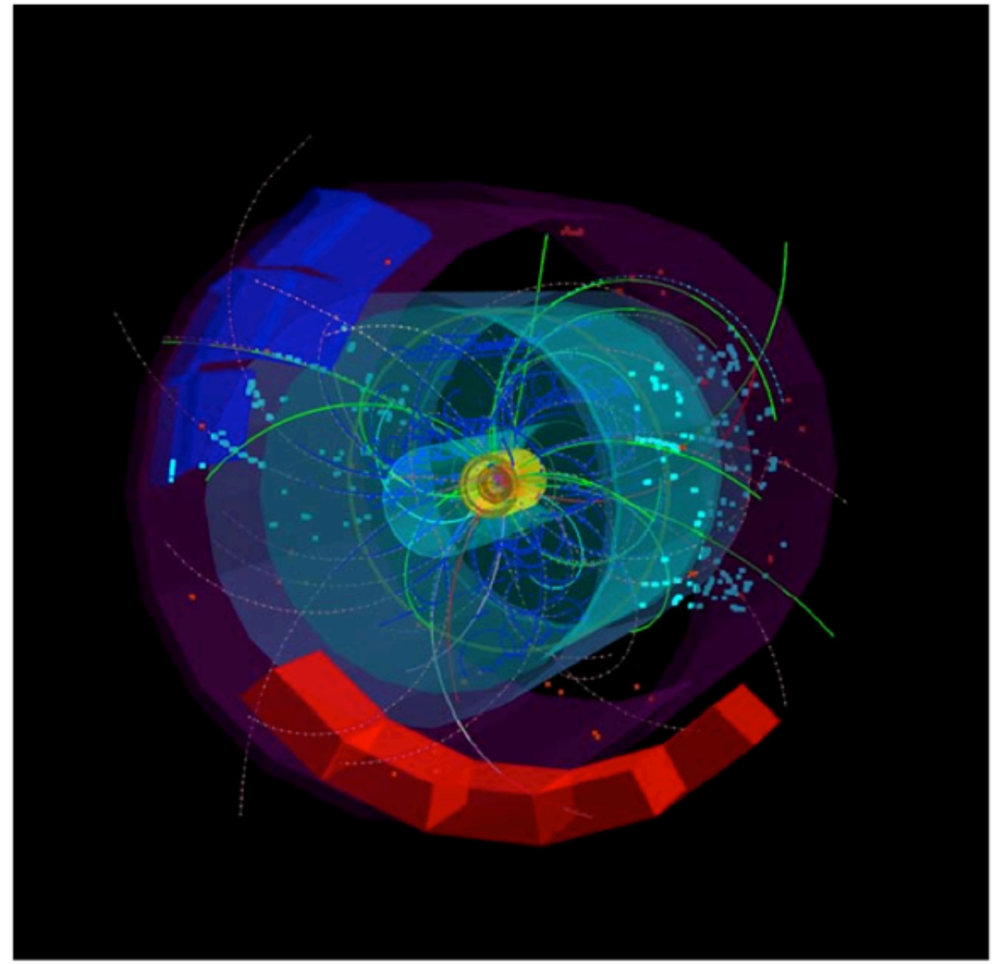
A visit inside the TPC.



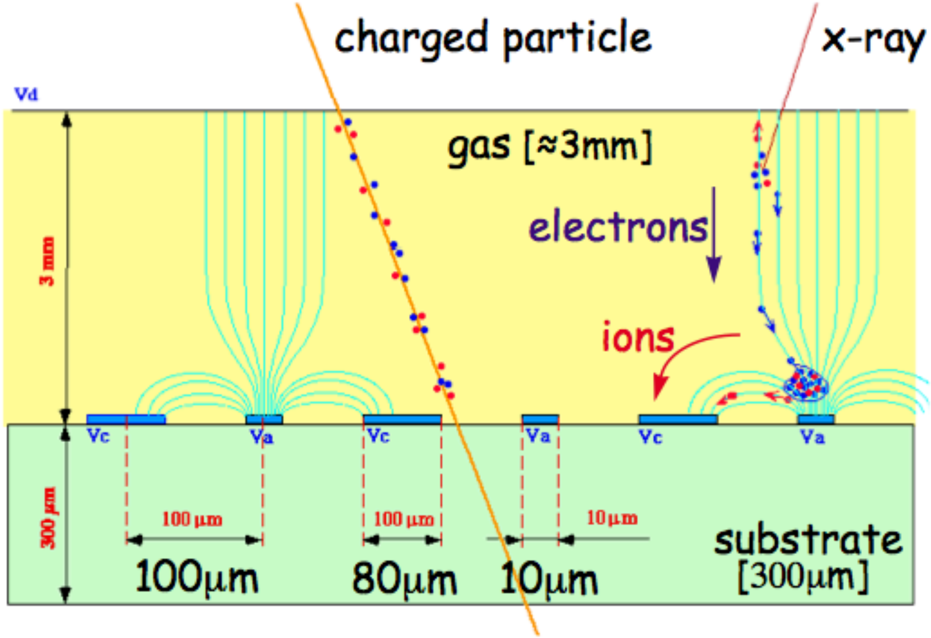
W. Riegler/CERN

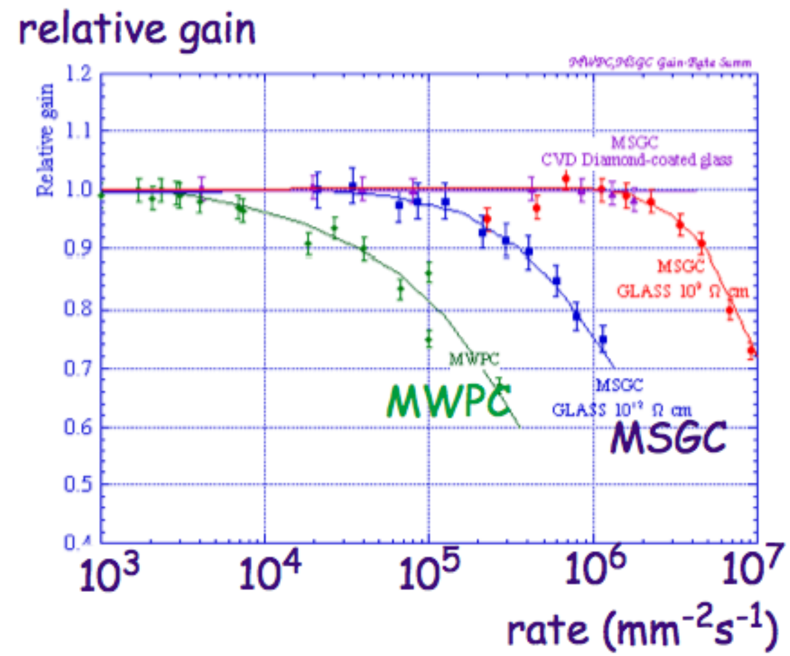
FIRST 7 TeV COLLISIONS in the ALICE TPC (03.2010)





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

RESISTIVE PLATE CHAMBER (RPC)

Robust and simple detector

- no wire

Relatively cheap

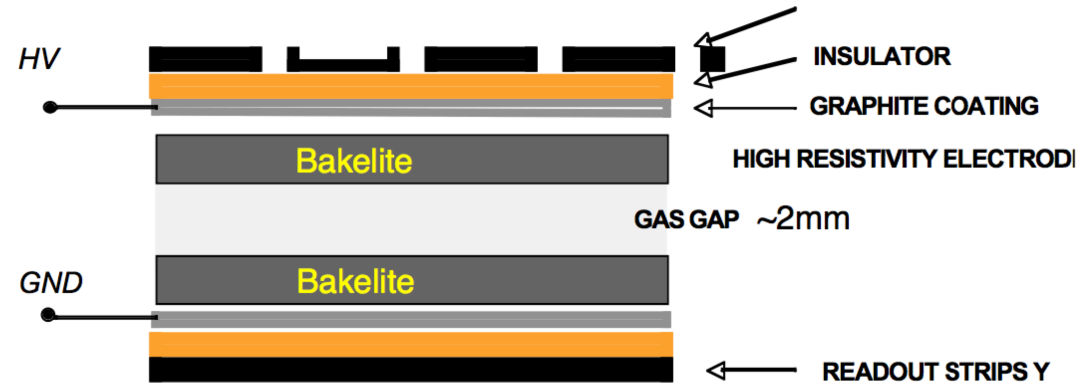
- Well suited for large areas (muon systems)

Fast signal

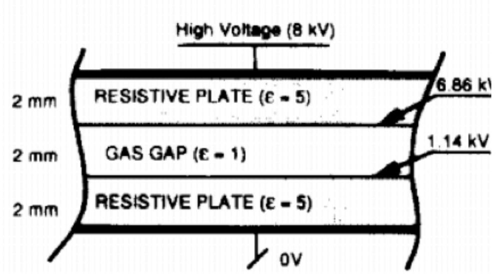
- < 5ns → trigger

Good rate capability

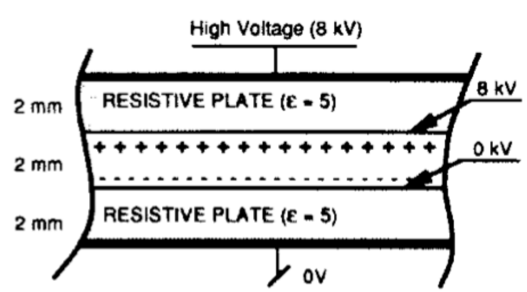
- few kHz/cm^2



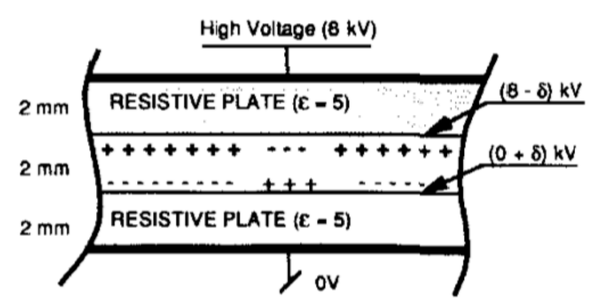
Initial condition after applying high voltage



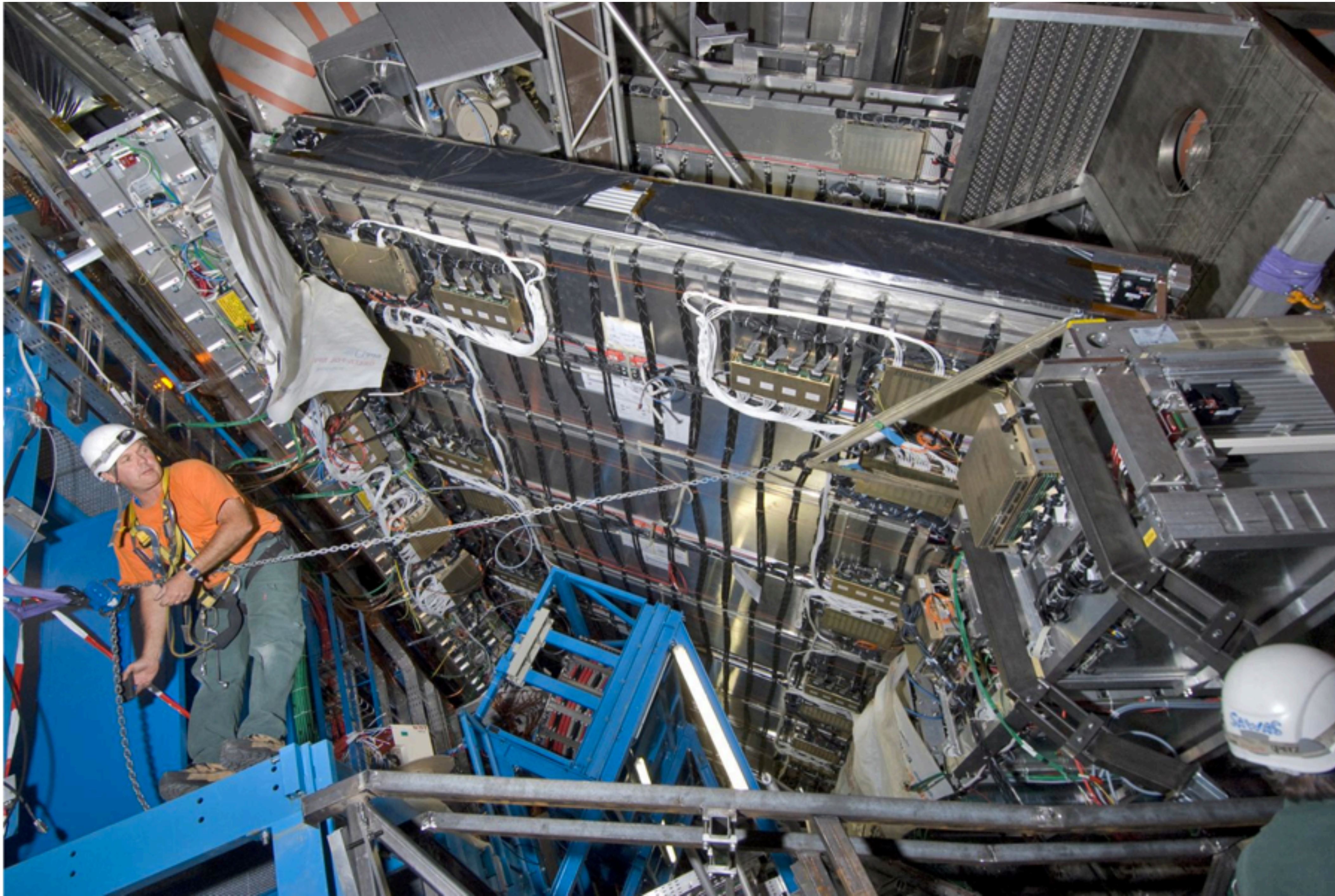
Surface charging of electrodes by current flow through resistive plates



After a discharge electrons are deposited on anode and positive ions on cathode



ATLAS RPC



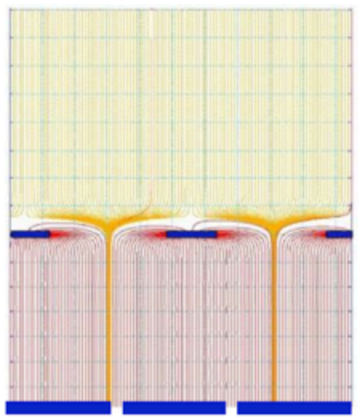
GEM & MICROMEGAS

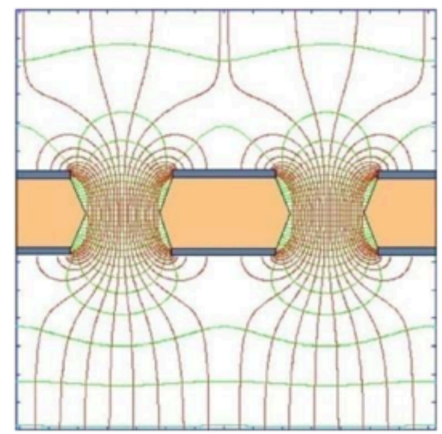
In the late 90's developped by F. Sauli at CERN [NIM A386 (1997), 531]

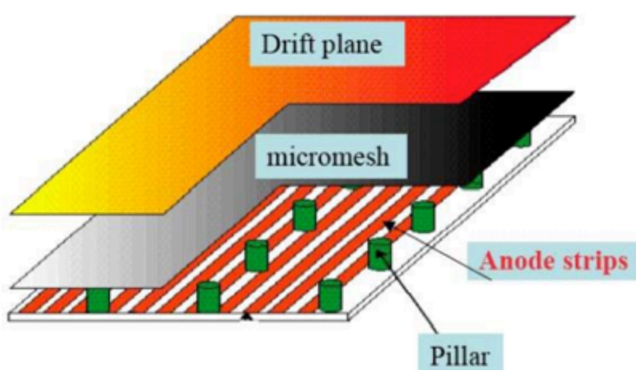
- Typical gain of 10^3 at 500 V
- Can stack several stages on top of each other
  - Large total gain for relatively moderate HV

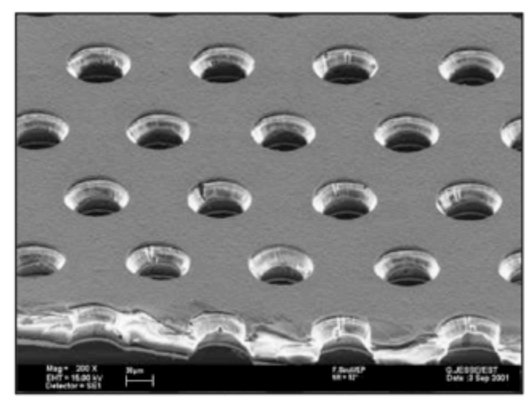
MICROMEGAS
Narrow gap (50-100µm) PPC with thin cathode mesh
Insulating gap-restoring wires or pillars

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









Y. Giomataris et al, Nucl. Instr. and Meth. A376(1996)239

F. Sauli, Nucl. Instr. and Methods A386(1997)531

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 DETECTORS

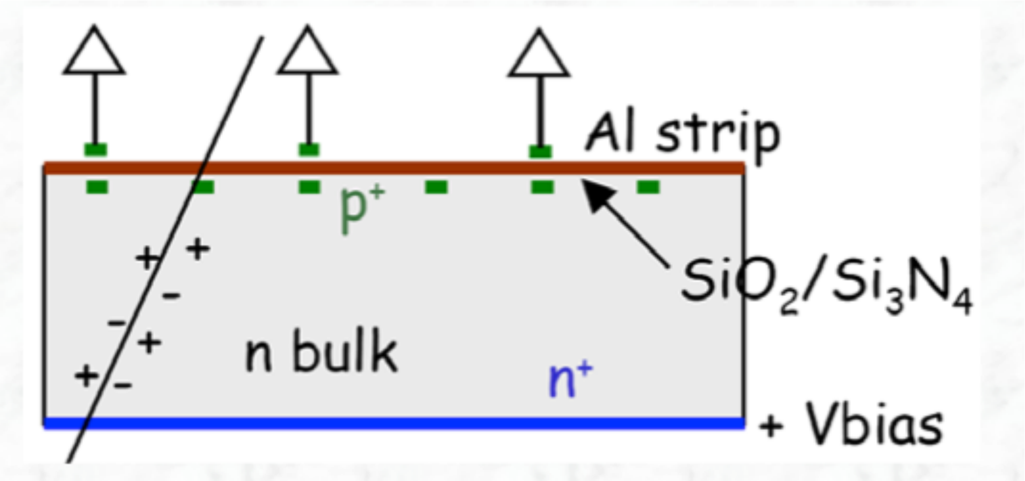
Silicon detectors: a kind of solid-state ionisation chamber

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

Increased commercial use of Si-photolithography and availibitiy of VLSI (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).



Si DETECTORS - BASIC PROPERTIES

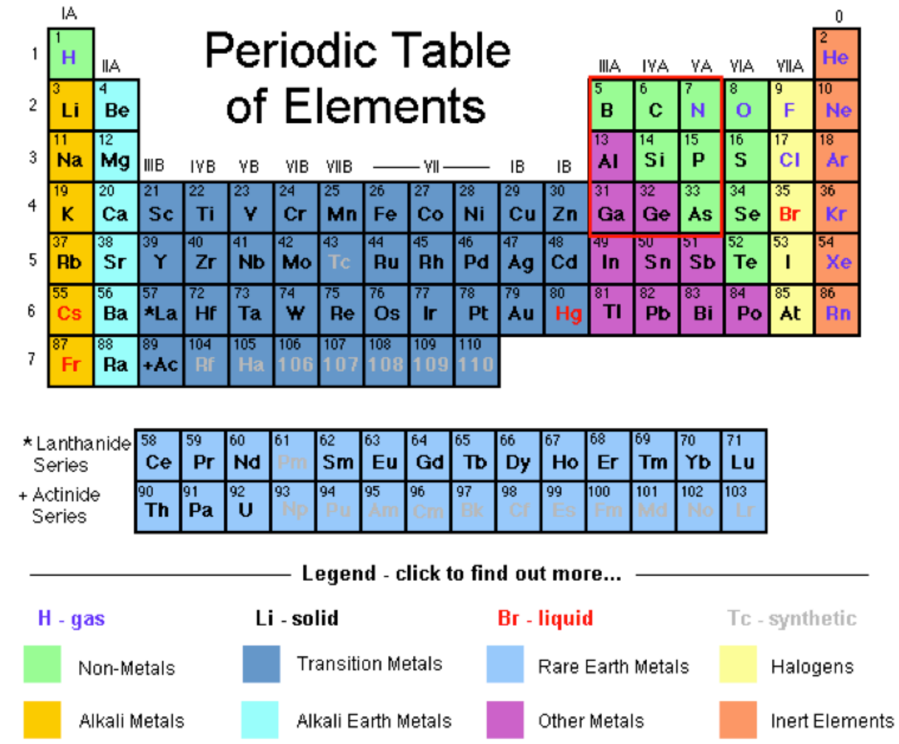
Silicon: type IV element, 1.1 eV band gap

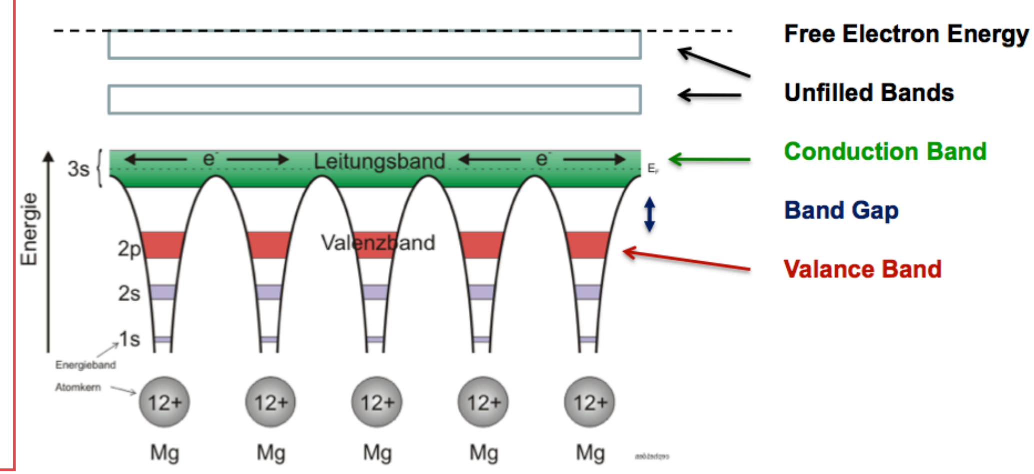
Intrinsic conductivity very low: $\sigma_i = e.n_i(\mu_e + \mu_h)$

- Carrier density at 300K
  - $1.5\ 10^{10}/cm^3$ compared to 5.10^{22} Si-atoms/cm^3
  - often dominated by impurities
- Mobility $\mu_e \sim 1800\ cm^2/Vs$, $\mu_h \sim 1600\ cm^2/Vs$ in diamond

Doping: small admixtures of type III or type V elements increase conductivity

- Donours like Phosphorous give extra electrons: n-type Si
- Acceptors (e.g. Boron) supply extra hole: p-type Si
- Contact between p- and n-Si forms p-n junction
- Doping dominates conductivity as $n_i \ll n_D$
- For n-type Si: $\sigma_D = e.n_D.\mu_e$





BASIC SEMIN 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:

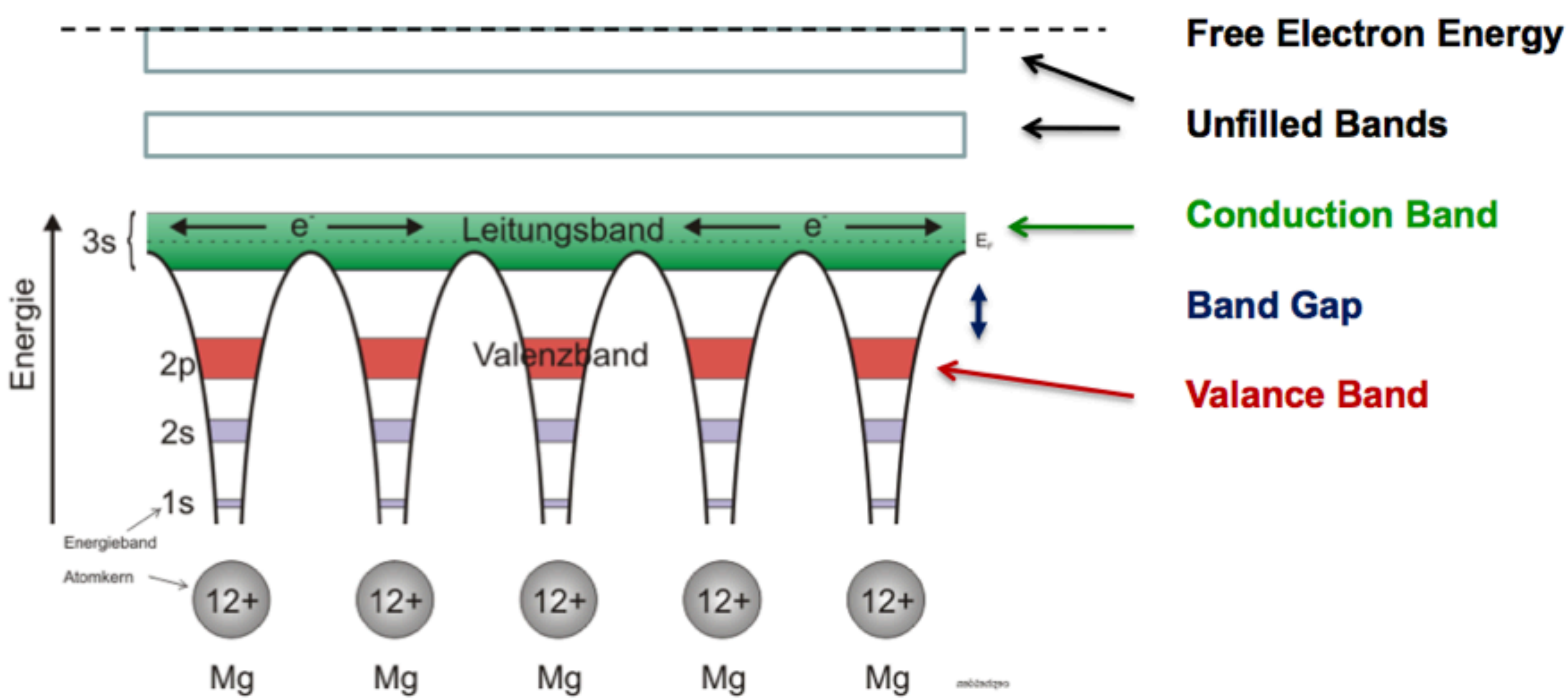
Majority of charge carriers provided by donors (impurities; doping)

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

Pentavalent dopants (electron donors): P, As, Sb, ...
[5th 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



Conductor, Insulator, Semiconductor

In case the conduction band is filled, the crytal is conductor

In case the conduction band is empty and *far away* from the valence band, the crystal is an insulator

In case the conduction band is empty, but the distance to the valence is mall, the crystal is a semi-conductor.

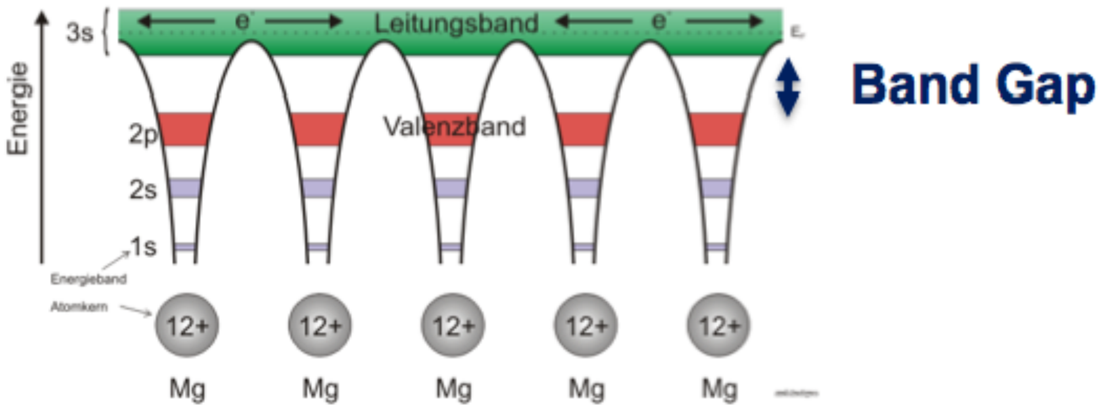
SOLID STATE DETECTORS

Band Gap, e-h pair Energy

The energy gap between the last filled band - the valence band - and the conduction band is called **band gap E_g**.

The band gap of Diamond/Silicon/Germanium is 5.5/1.12/0.66 eV.

The average energy to produce an electron/hole pair for Diamond/Silicon/Germanium is 3, 3.6, 2.9 eV.



Temperature, charged particle detection
In case an electron in the valence band gains energy by some process, it can be excited into the conduction band and a hole in the valence band is therefore created.

Such a process can be the passage of a charged particle, but also thermal excitation
probability is $e^{-E_g/kT}$

The number of electrons in the conduction band is therefore incerasing with temperature i.e. the conductivity of a semiconductor increases with tempreature.

SOLID STATE DETECTORS

Electron, hole movement

It is possible to treat electrons in the conduction band and holes in the valence band similar to free particles, but with an effective mass different from elementary electrons, not embedded in the lattice.

This mass is furthermore dependant on other parameters such as the direction of movement wrt the crystal axis. All this follows from the Quantum Mechanics treatement of the crystal.

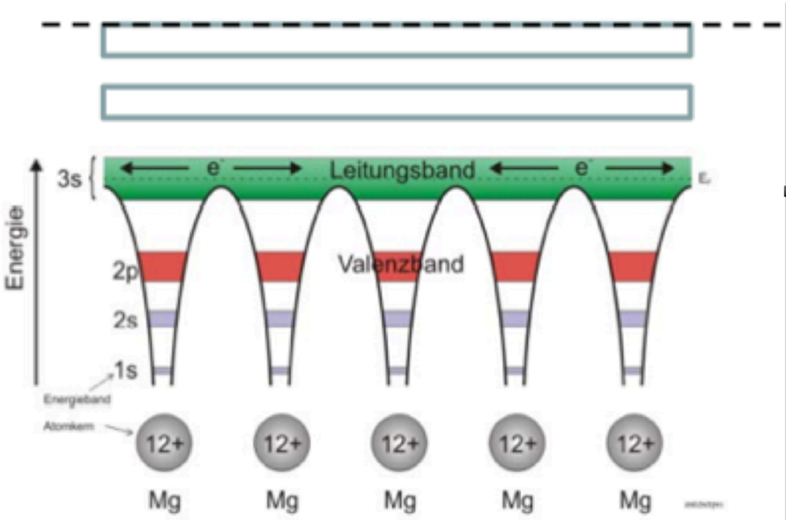
Cooling

If we want to use a semiconductor as a detector for charged particles, the number of charge carriers in the conduction band due to the thermal excitation must be smaller than the number of charge carriers in the conduction band produced by the passage of the charged particle

Diamond (E_g=5.5 eV) can be used for particle detection at room temperature.

Silicon (E_g=1.12 eV) and Germanium (E_g=0.66 eV) must be cooled, or the free charge carriers must be eliminated by other tricks

→ doping



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.

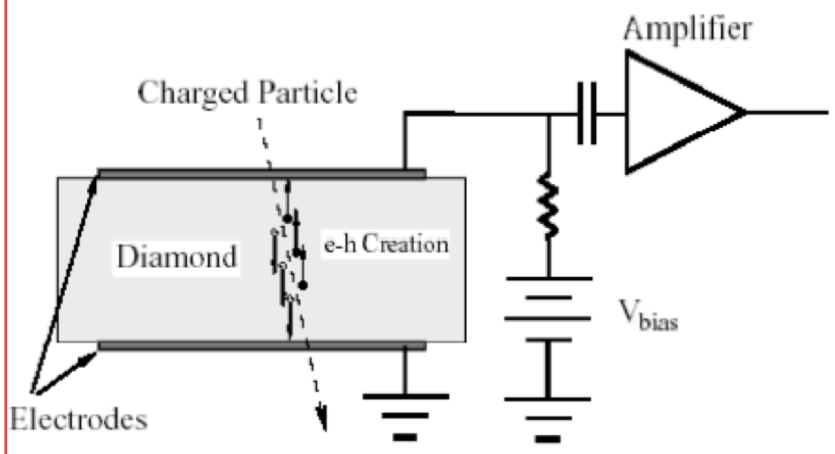
Comparing to gas detector, the density of a solid is about a factor 1000 larger than that of a gas and the energy to produce electron/hole pair e.g. sir Si is a factor 7 smaller than the energy to produce an electron/ion pair in Argon.

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

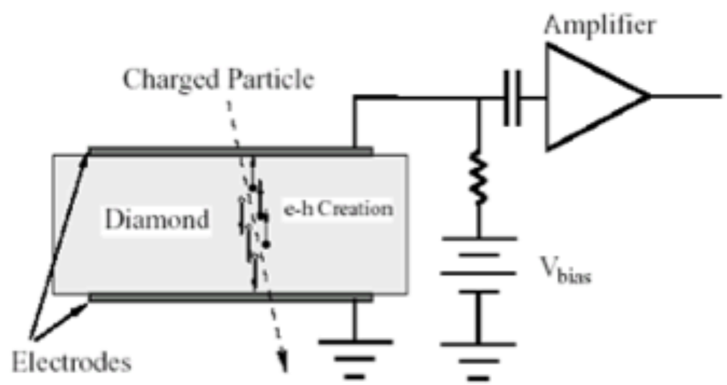
While in gas detectors the velocity of electrons and ions differs by a factor 1000, the velocity of electrons and holes in many semiconductors is quite similar

very short signal

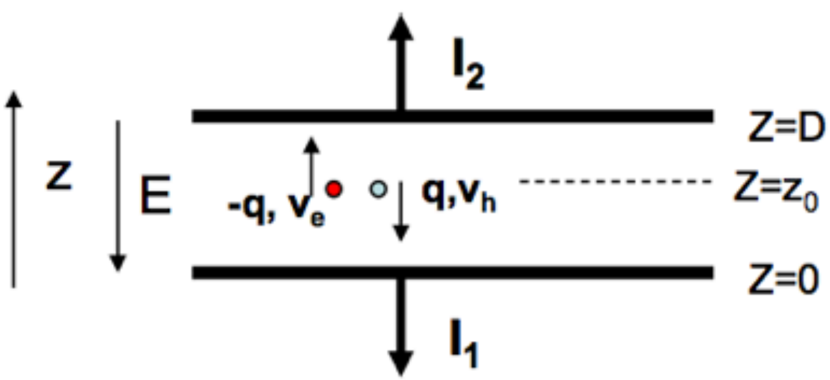


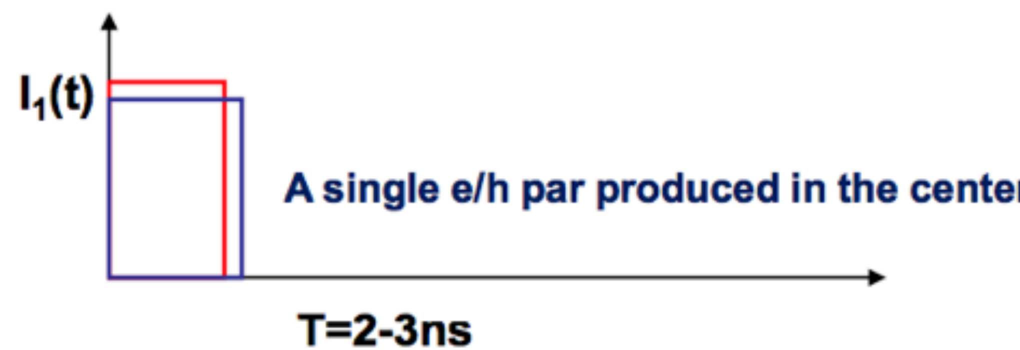
DIAMOND DETECTORS

Typical thickness of a few 100 µm
<1000 charge carrieurs/cm^3 at room temperature due to large band gap

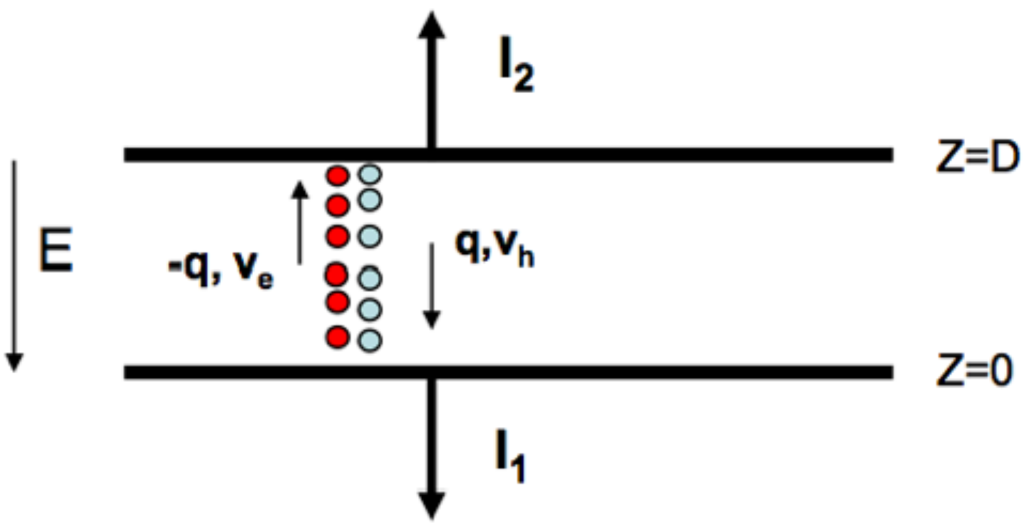


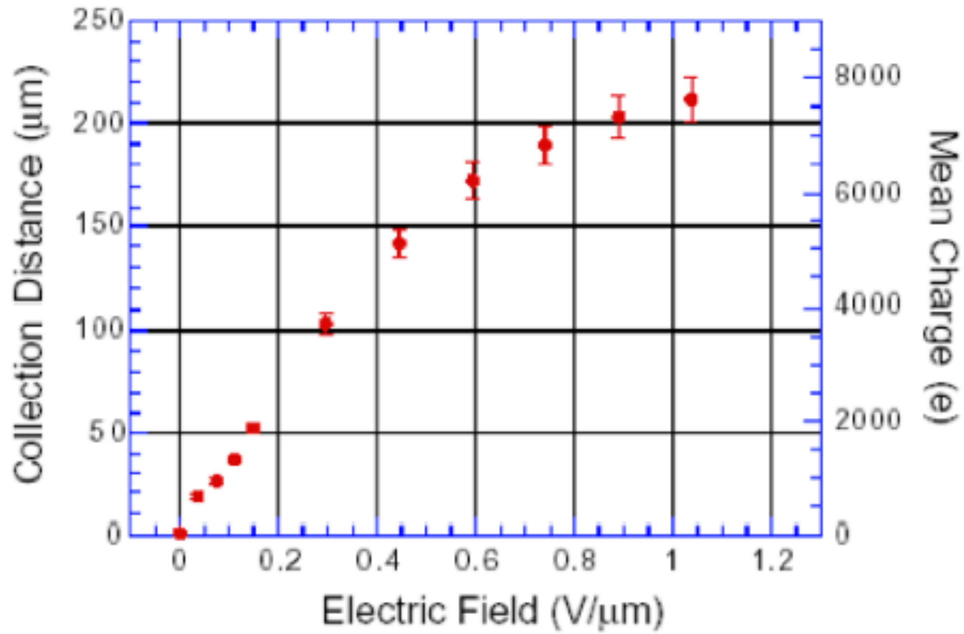
Velocity
μ_e=1800 cm^2/Vs, μ_h=1600 cm^2/Vs
Velocity = µE - E=10kV/cm → v=180 µm/ns → **very fast signals of only a few ns length.**

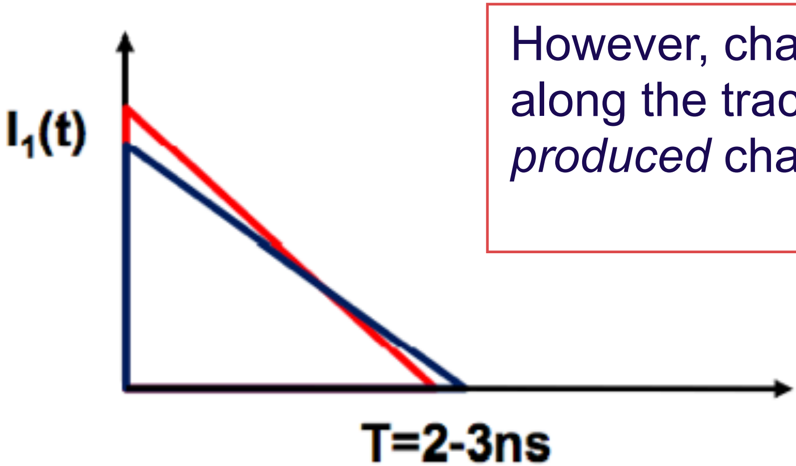




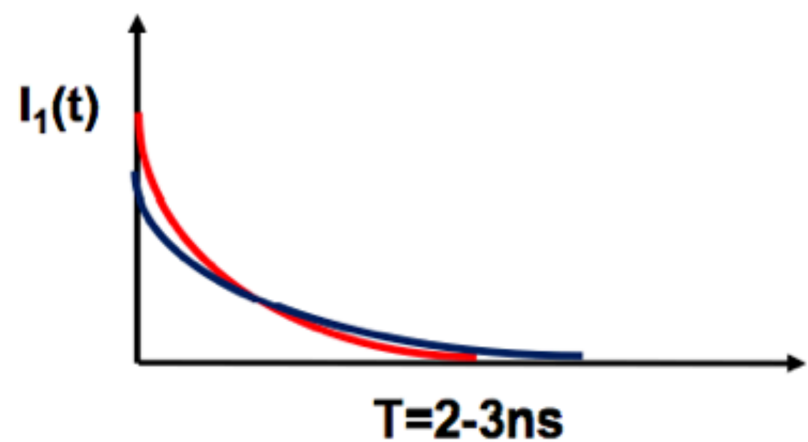
DIAMOND DETECTORS





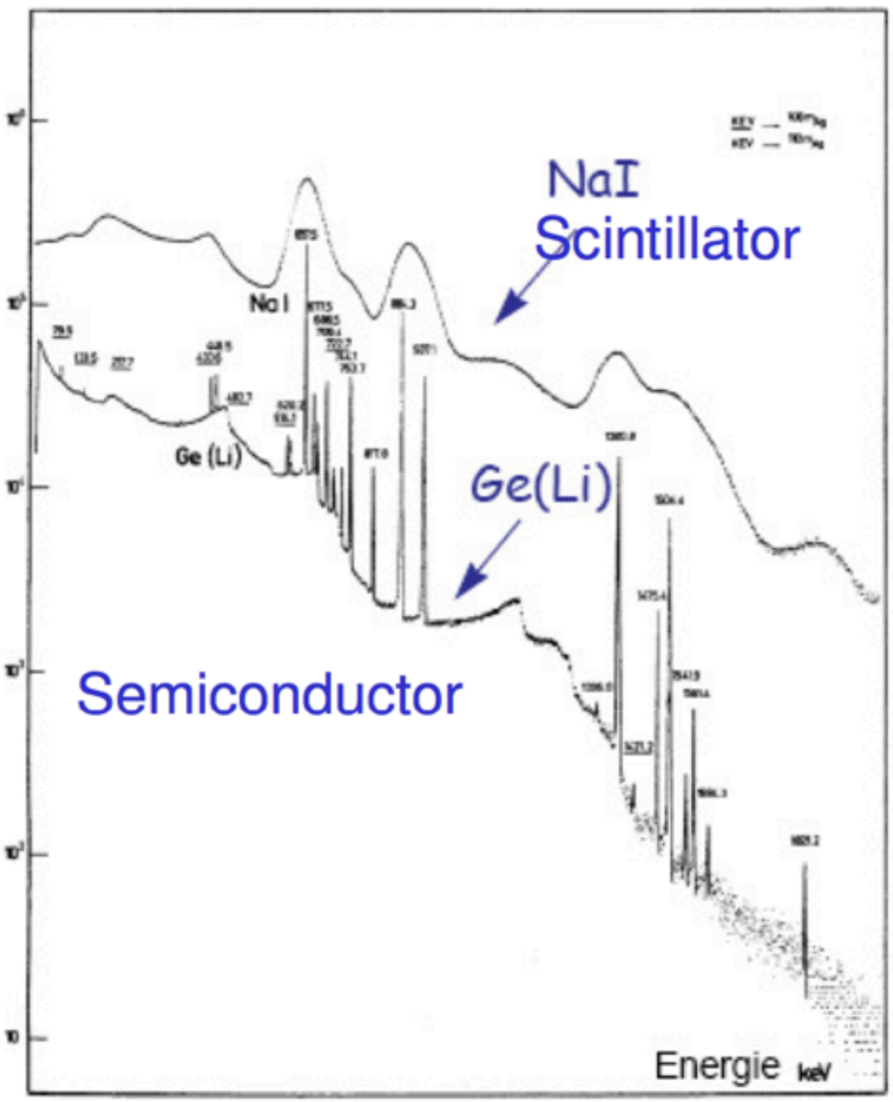


However, charges are trapped along the track, only about 50% of *produced* charge is induced →



SOLID STATE DETECTOR for ENERGY MEASUREMENT

ILLUSTRATION



SILICON DETECTORS

Velocity

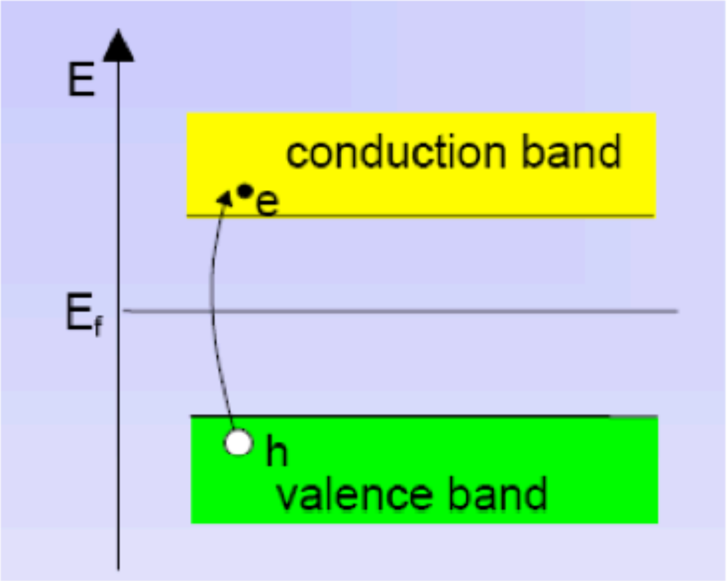
μ_e=1450 cm^2/Vs, μ_h=505 cm^2/Vs, 3.63 eV per e-h pair

~33000 e/h pairs in 300 μm of silicon

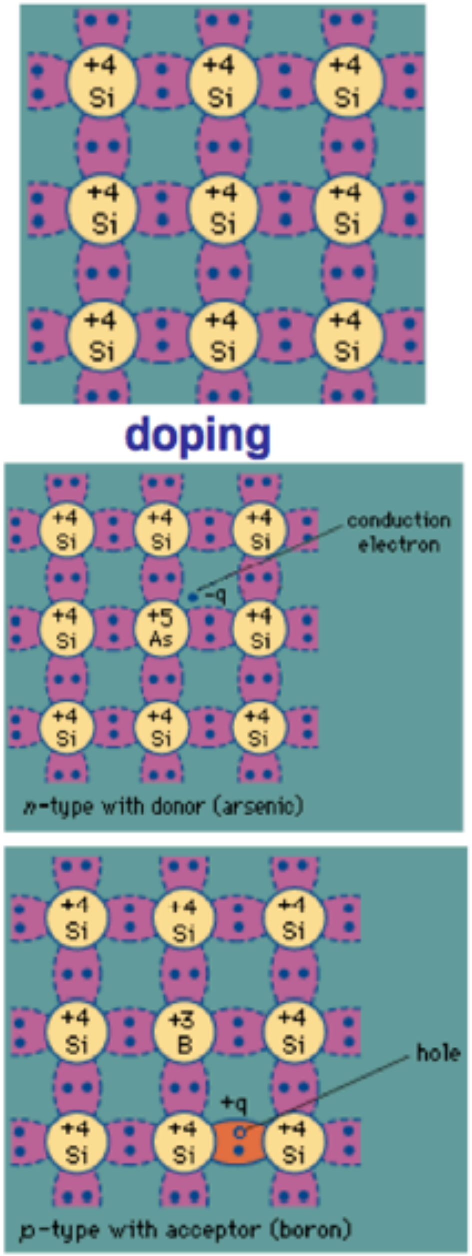
However: free charge carriers in Si

For T=300K, e/h=1.45 x 10^{10}/cm^3 but only 33000 e/h pairs in 300μm produced by a high energy particle.

How is it that Si is used a solid state detector ?



DOPING of SILICON

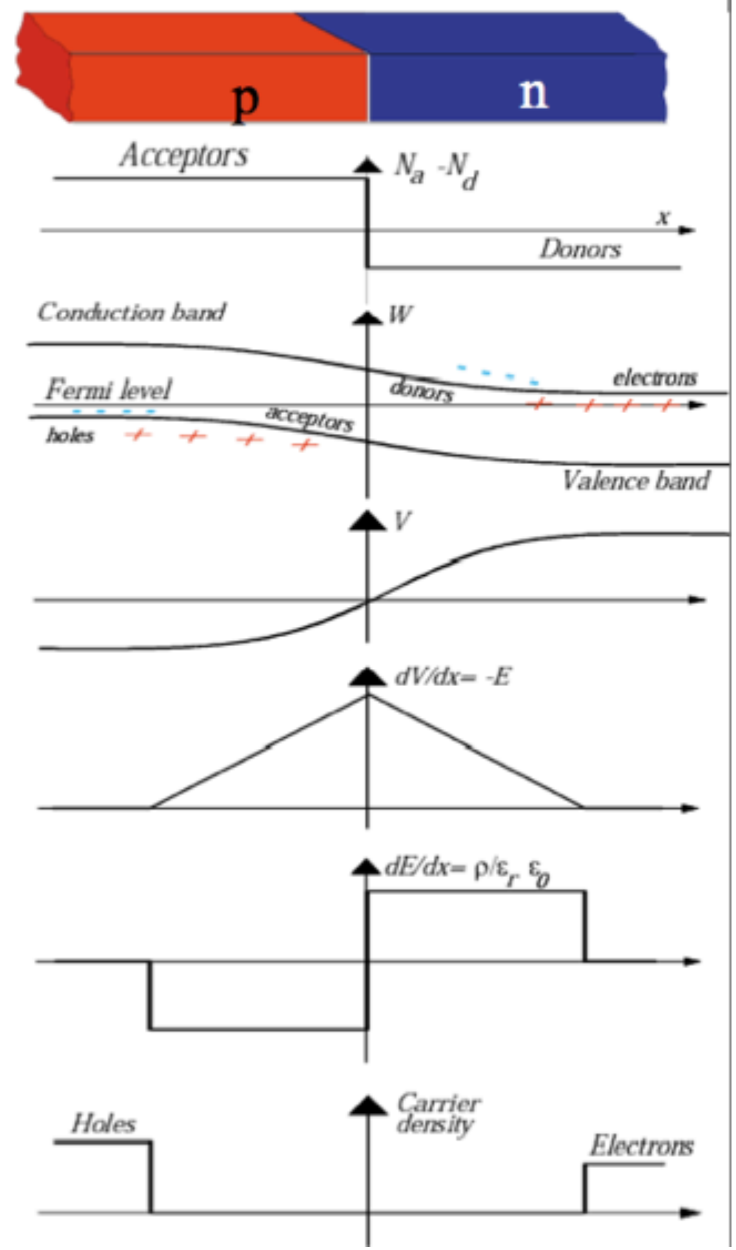


In a silicon crystal at a given temperature the number of electrons in the conduction band is equal to the number of holes in the valence band.

Doping Si with Arsen (+5) it becomes an n-type conductor (more electrons than holes)

Doping Si with Boron (+3) it becomes a p-type conductor (more holes than electrons)

Bringind p and n in contact makes a diode



SILICIUM DIODE USED as a PARTICLE DETECTOR

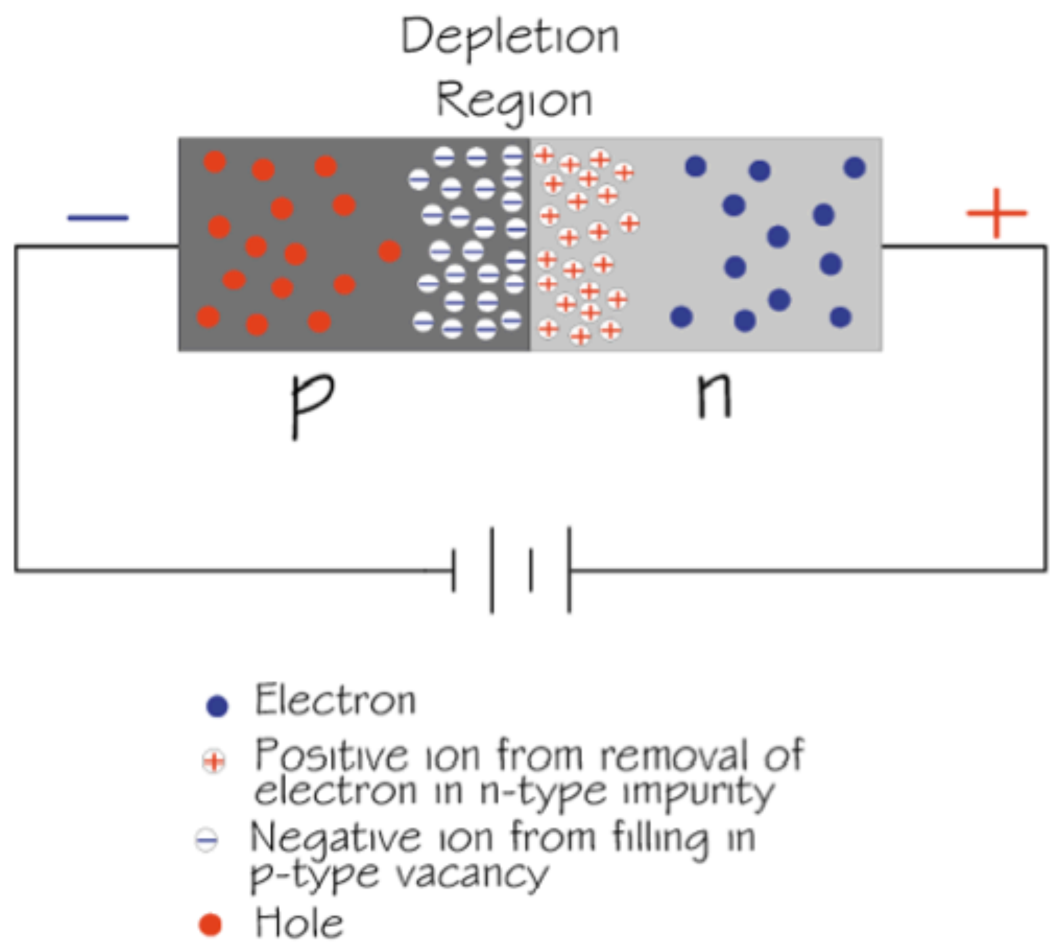
At the p-n junction the charges are depleted and a zone free of charge carriers is established

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

→ highly insulating layer

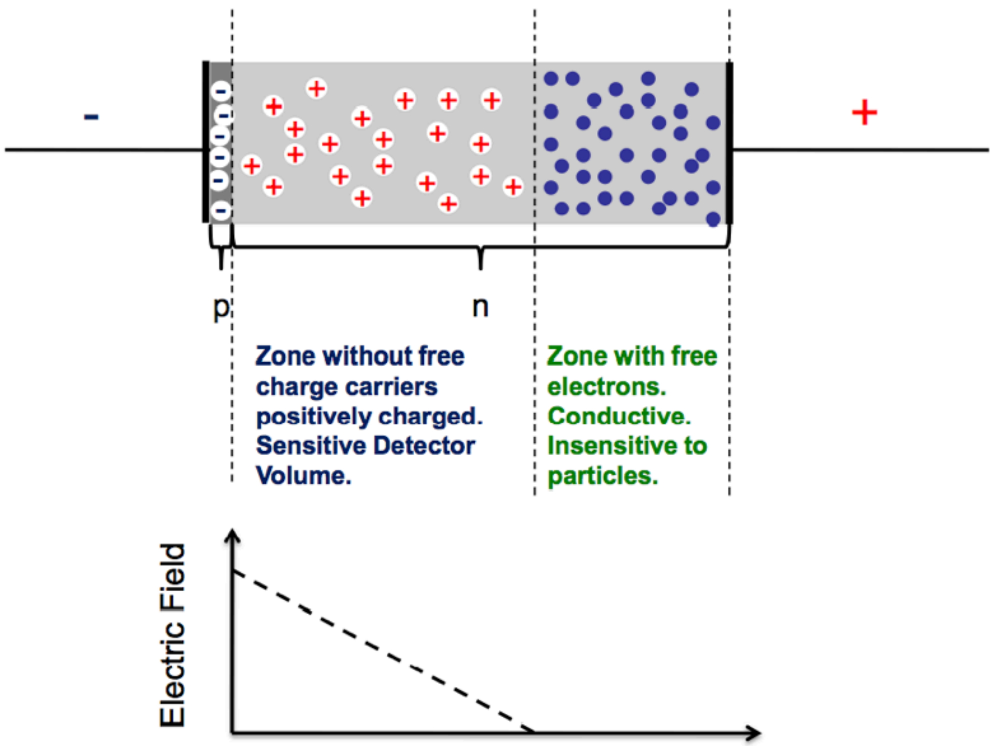
An ionising particle produces free charge carriers in the diode, which drift in the electric field and induce an electrical signal on the metal of the electrodes.

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.

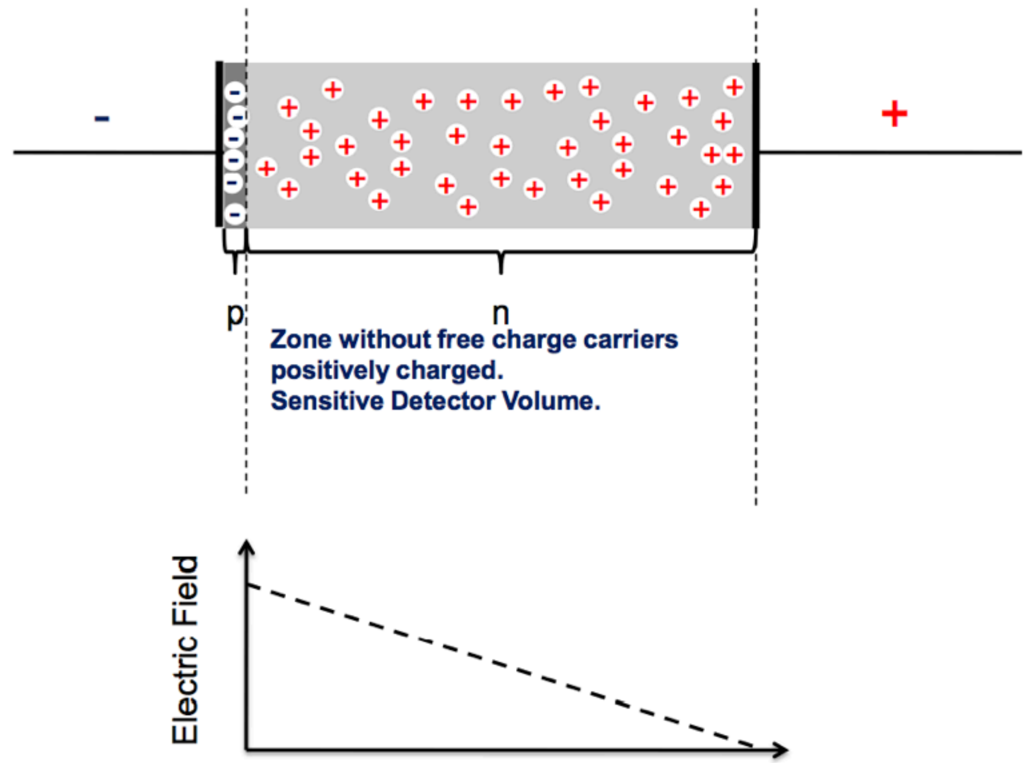


DEPLETION ZONE in SILICON DETECTOR

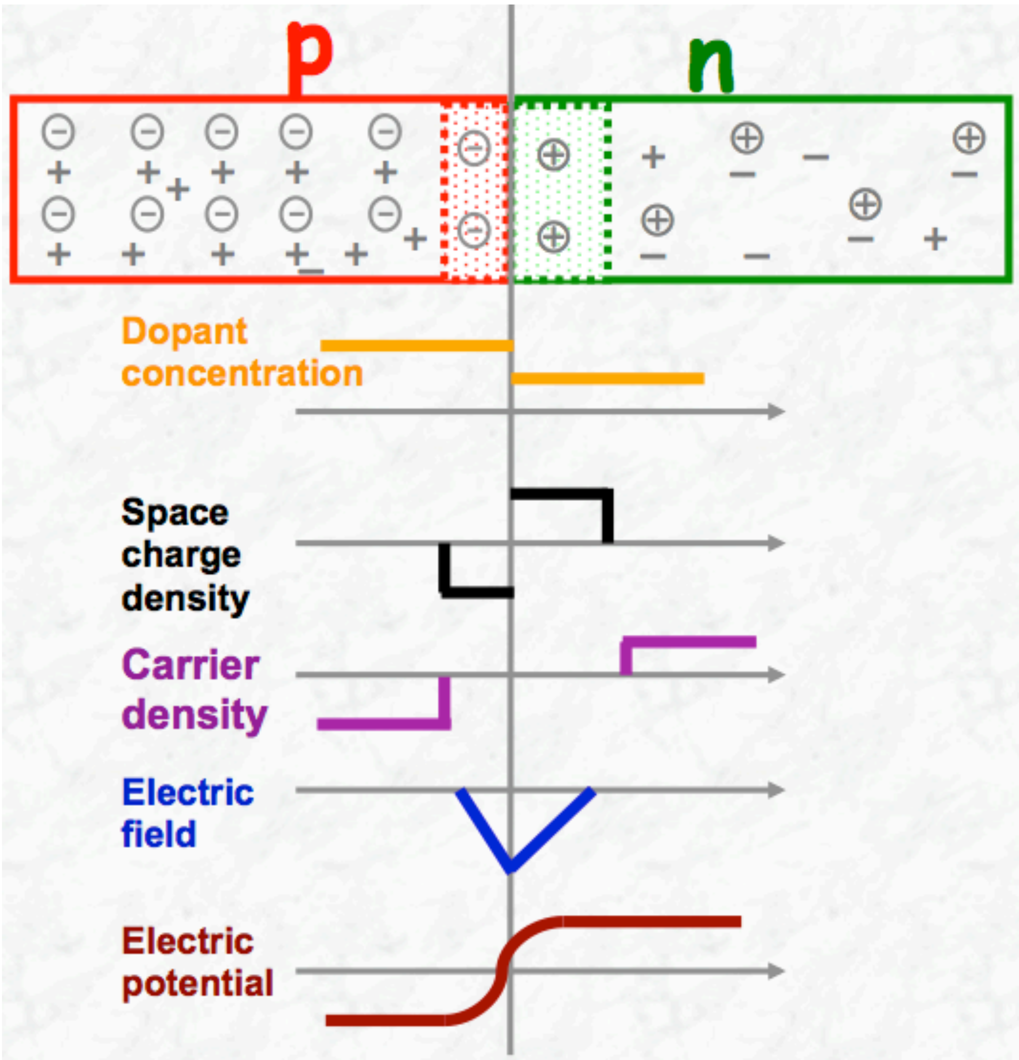
UNDER-DEPLETED



FULLY DEPLETED



p-n Junction



Diffusion of e^- from n-side and h^+ from p-side.

Recombination on the other side, free charges disappear around junction: *depletion*.

Neutral p- or n-Si becomes charged

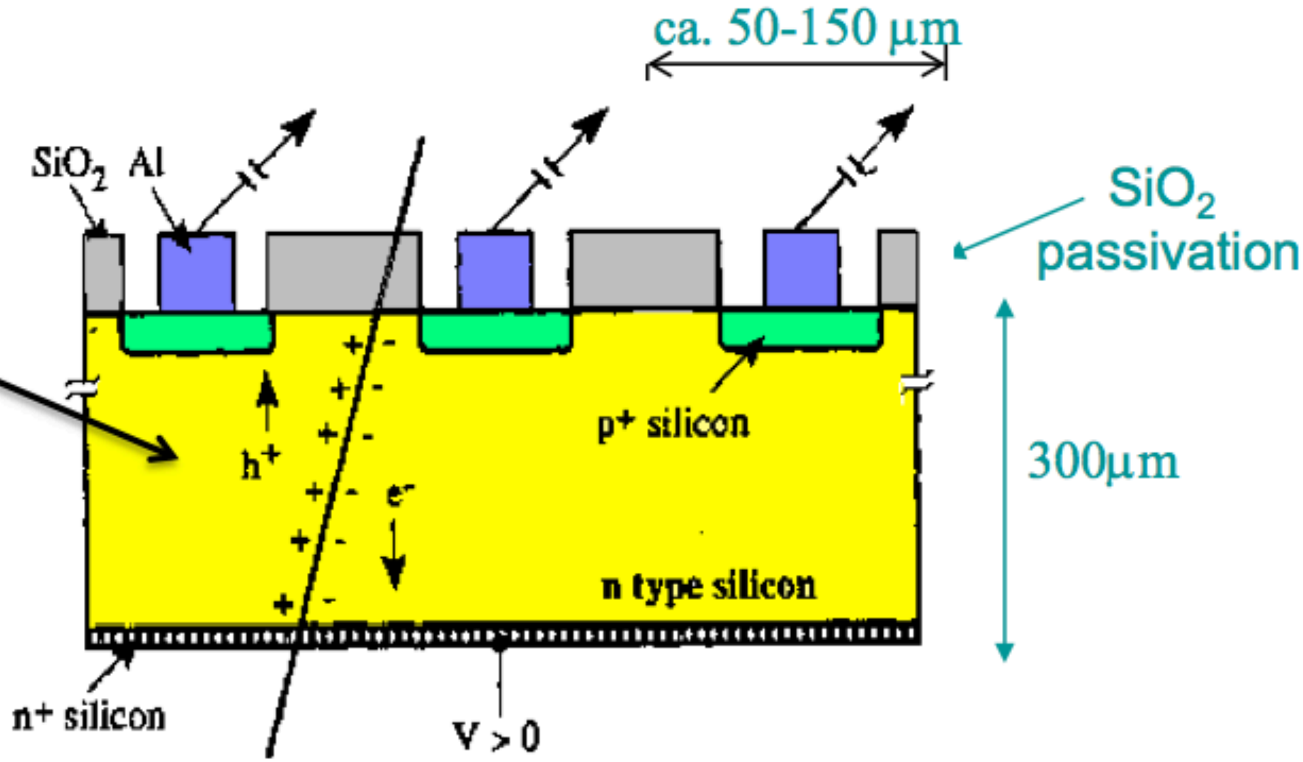
→ E-field.

External field can increase or decrease depletion zone.

Depletion is what we want for detectors.

Silicon detector

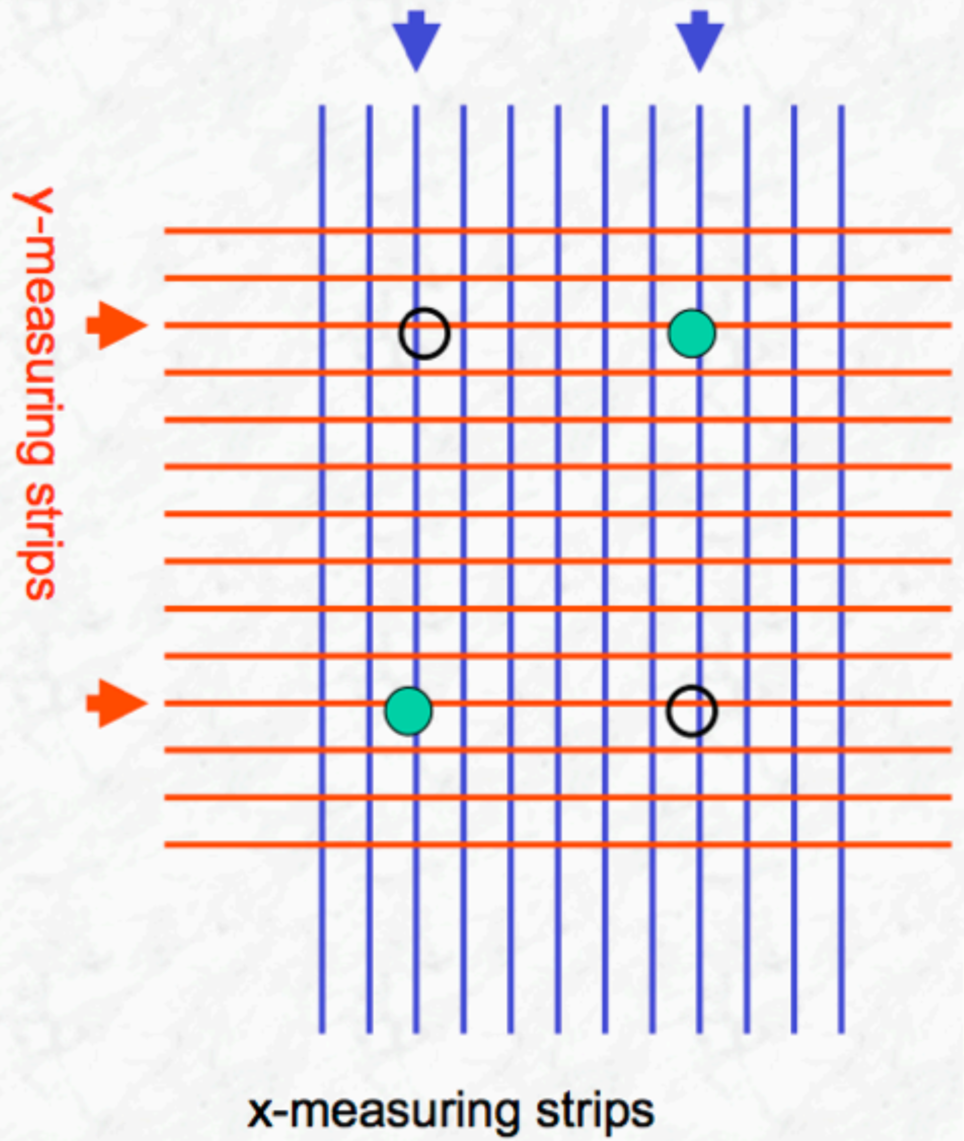
Fully depleted zone



N (e-h) = 11 000/100μm

Position Resolution down to ~ 5μm !

ANGLE BETWEEN TWO Si-DETECTORS



- Charge from MIP
- Signal strips
- "Ghost" (combinatorial hit)

N hits per readout cycle generate N^2 ambiguities in hit position

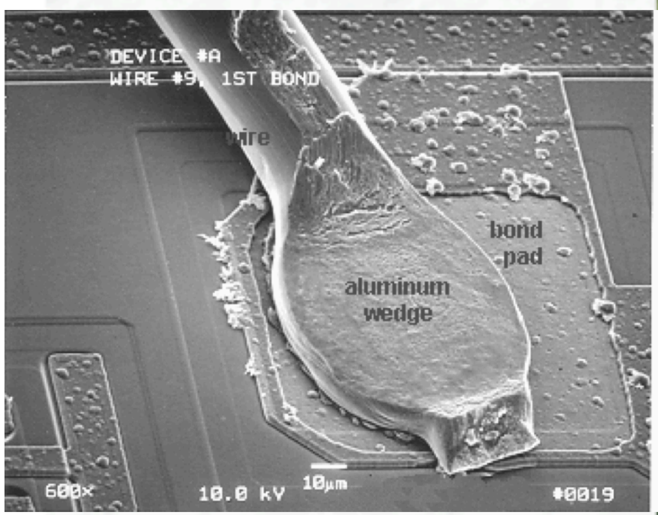
Ambiguities are reduced by stereo angle < 90°

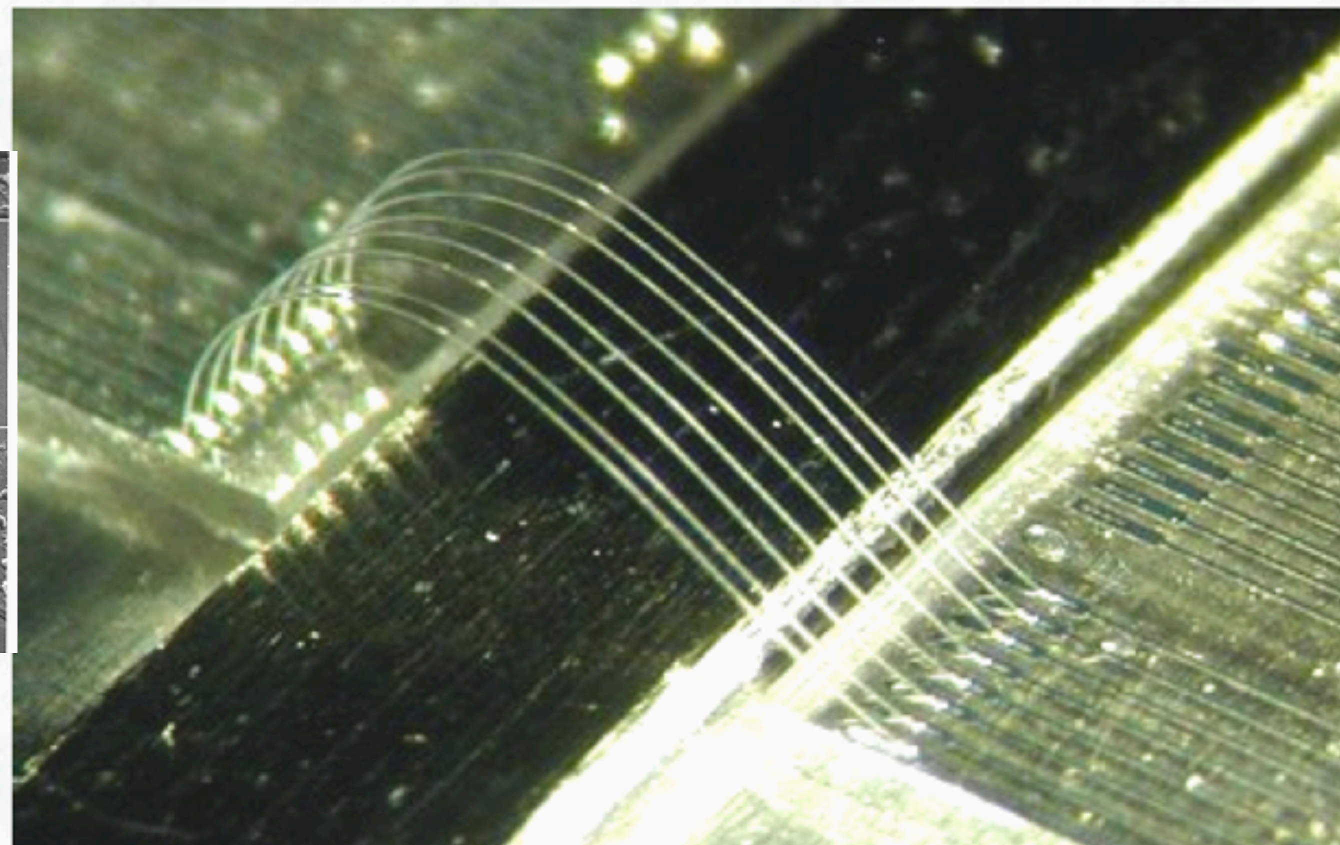
ATLAS Reality: O(10) hits per detector module per 25 ns.

Stereo angle of few degrees.

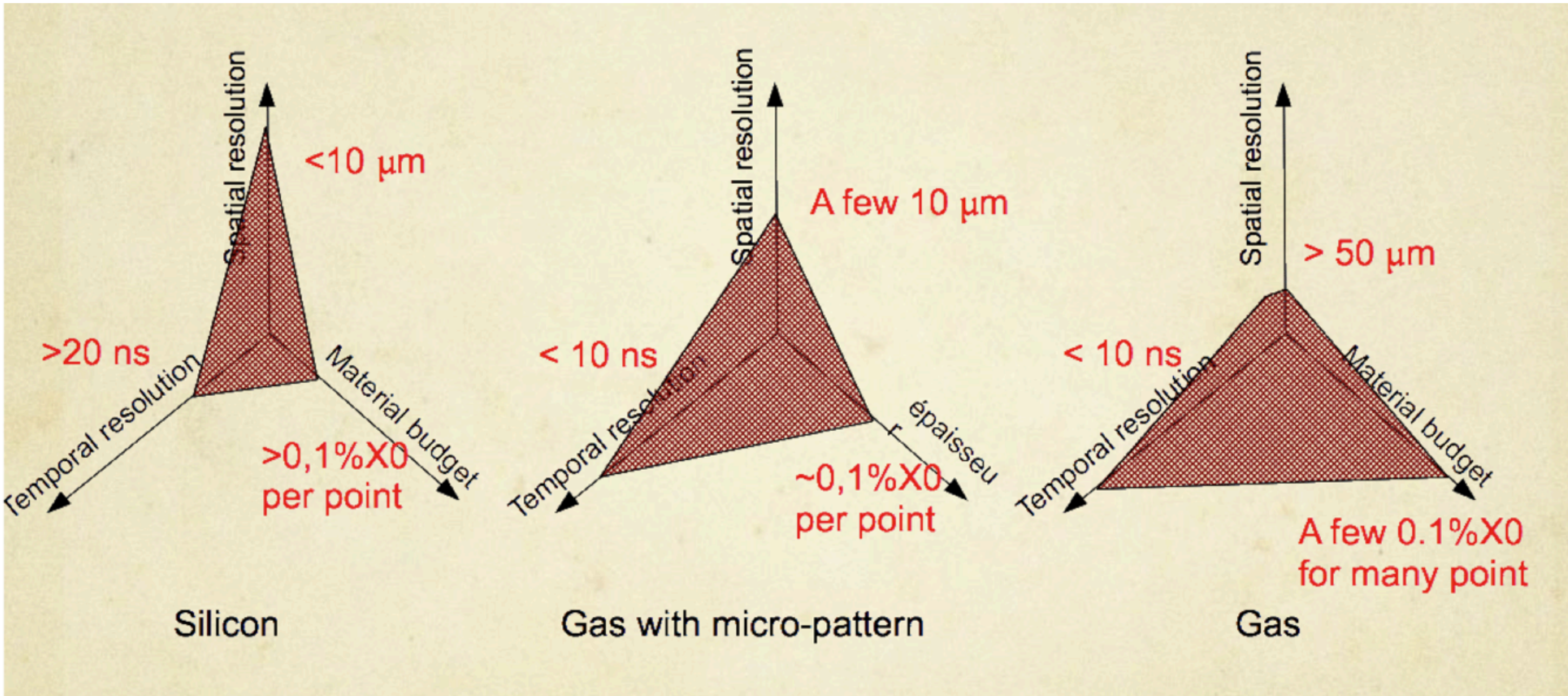
WIRE BOUNDING

- Si detector needs connection to readout electronics
- High connection density with O(15) wires per mm
- Ultra-sonic bonding of ~20μm wires with semiautomatic system





TENTATIVE COMPARISON



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)

Thechnology 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	~ 200 ns	~ 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 ±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.

SOME MOTIVATIONS and EXAMPLES

Motivation:

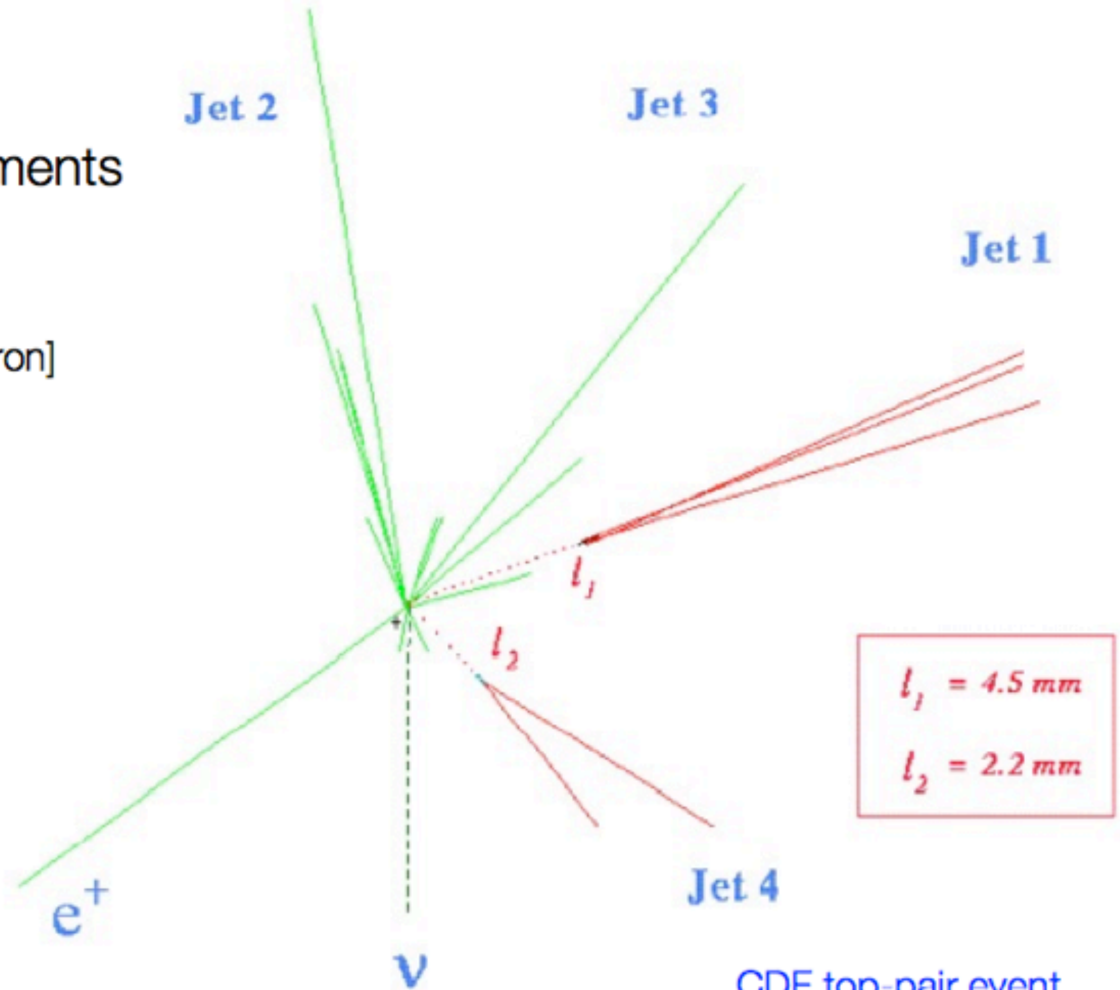
b-Quark tagging & life time measurements
via secondary vertex finding ...

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

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

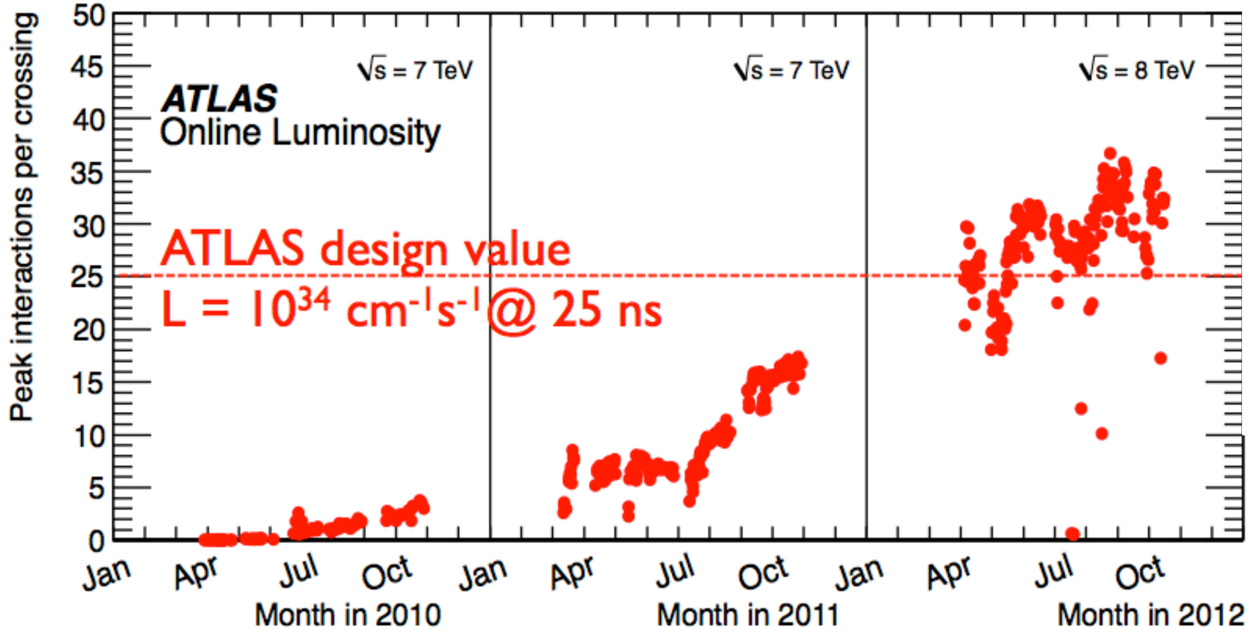


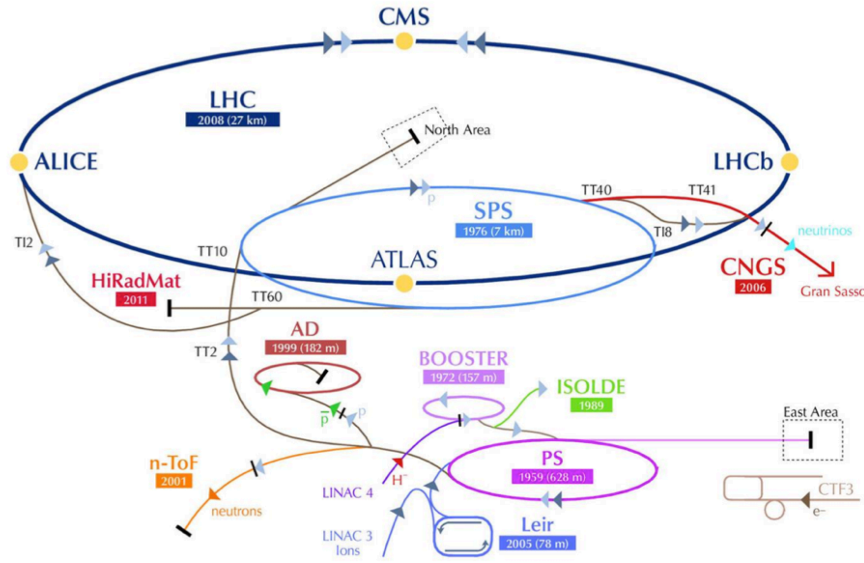
CDF top-pair event
[M_{top} = 170 ± 10 GeV]

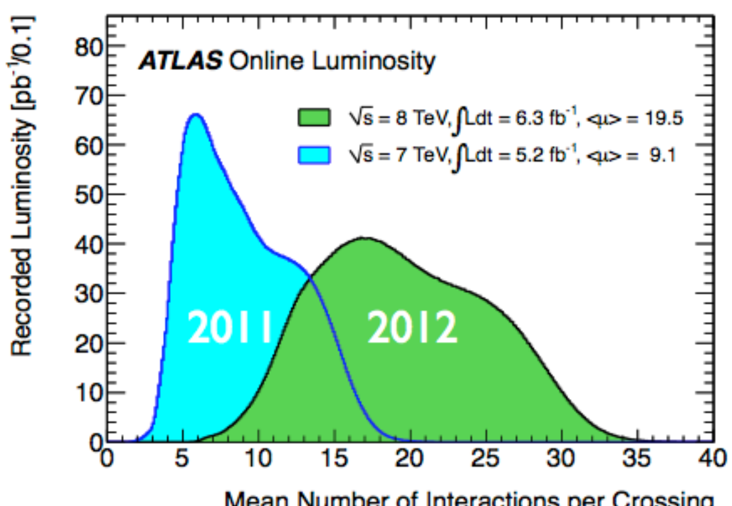
Thus:

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

INTERLUDE: PILE-UP at LHC





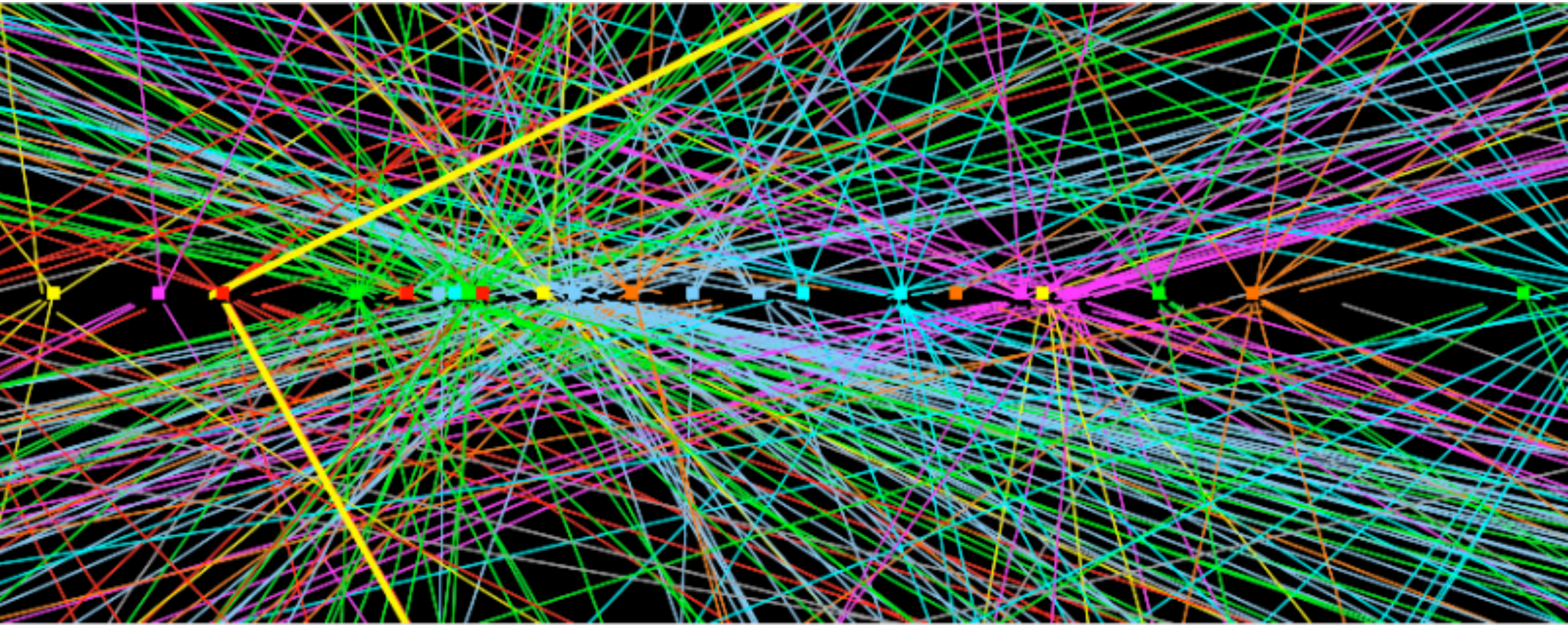


With ~10^{11} protons/bunch, multiple pp collisions when the two proton beams cross at the interaction points.

In 2010-2012, LHC run with Δτ=50 ns between two bunches, pile-up was already as high as expected the LHC nominal luminosity.

- Trigger must be pile-up resilient
- Reconstruction & optimisation has to be optimised
- Precise modelling of in-time/out-of-time pileup in MC

MOTIVATIONS and EXAMPLES



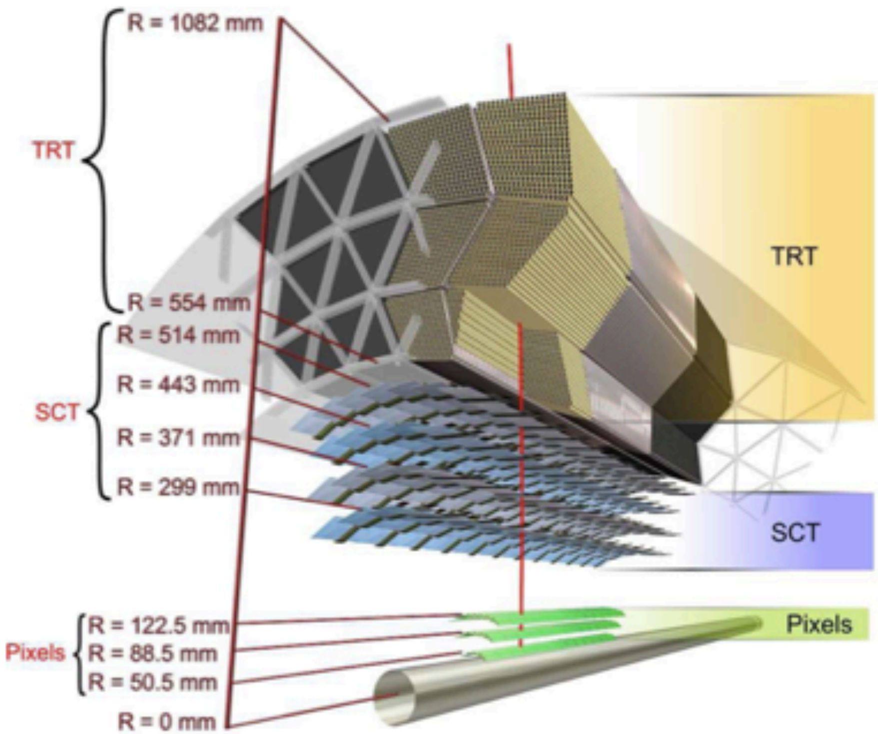
pp collisions in ATLAS at $\sqrt{s}$=8 TeV (with β^*=0.6 m)
$Z \rightarrow \mu\mu$ event with 25 pile-up events

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

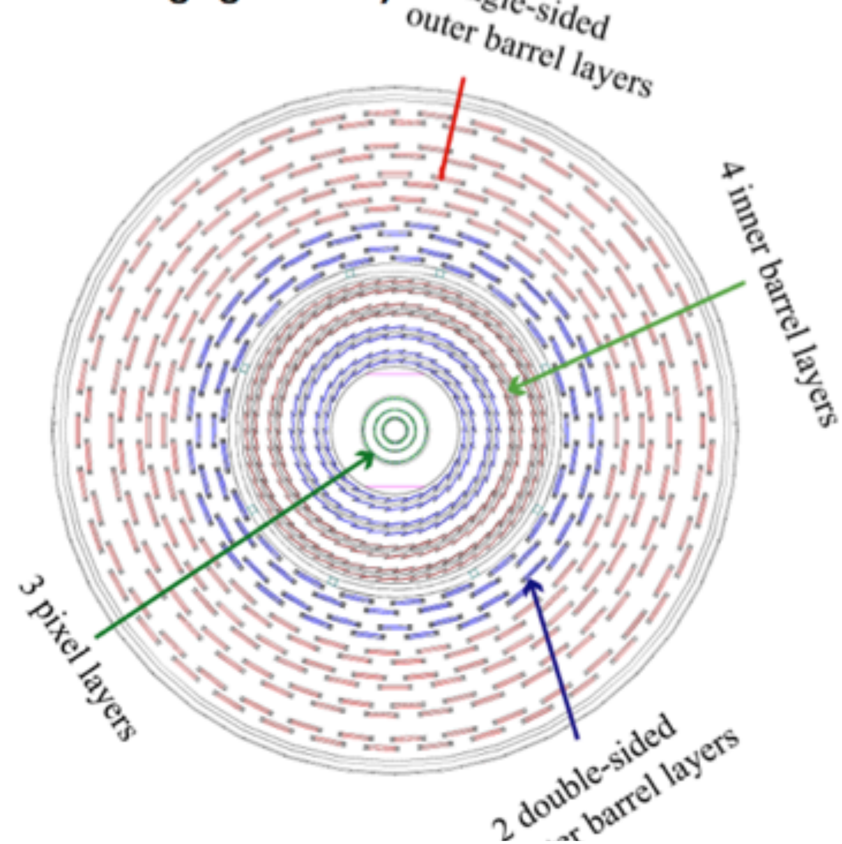
Parameter	ATLAS	CMS
Dimensions (cm)		
-radius of outermost measurement	101–107	107–110
-radius of innermost measurement	5.0	4.4
-total active length	560	540
Magnetic field B (T)	2	4
BR^2 ($T \cdot m^2$)	2.0 to 2.3	4.6 to 4.8
Total power on detector (kW)	70	60
Total weight in tracker volume (kg)	≈4500	≈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)	

INNER TRACKING SYSTEMS

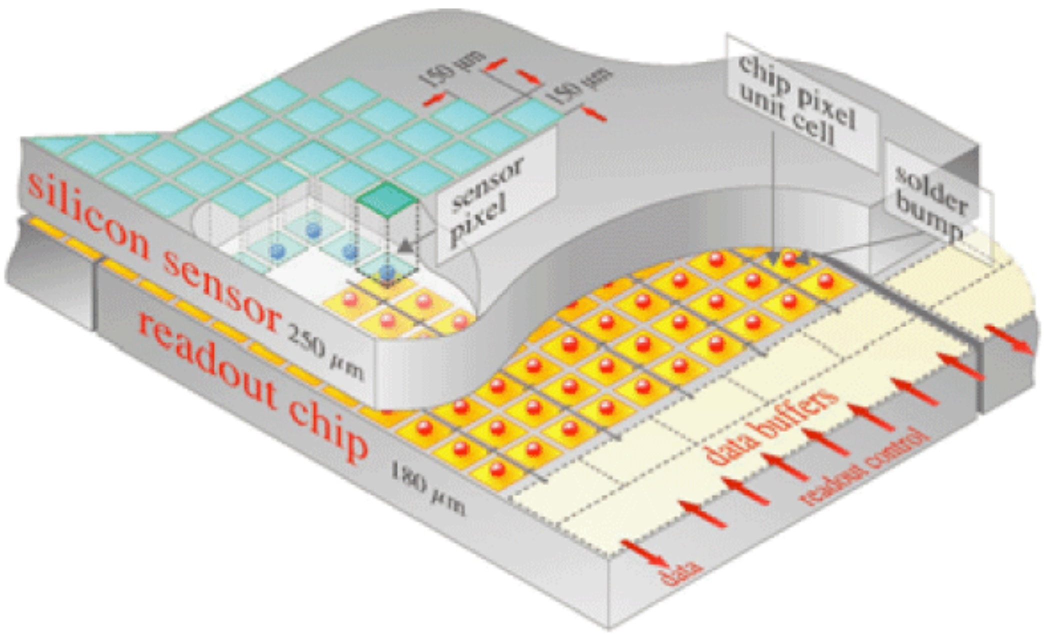
- **ATLAS**
  - ✓ Solenoidal field: 2 T
  - ✓ Silicon (strips and pixels) + TRT
    - high granularity and resolution close to interaction region
    - "continuous" tracking at large radii

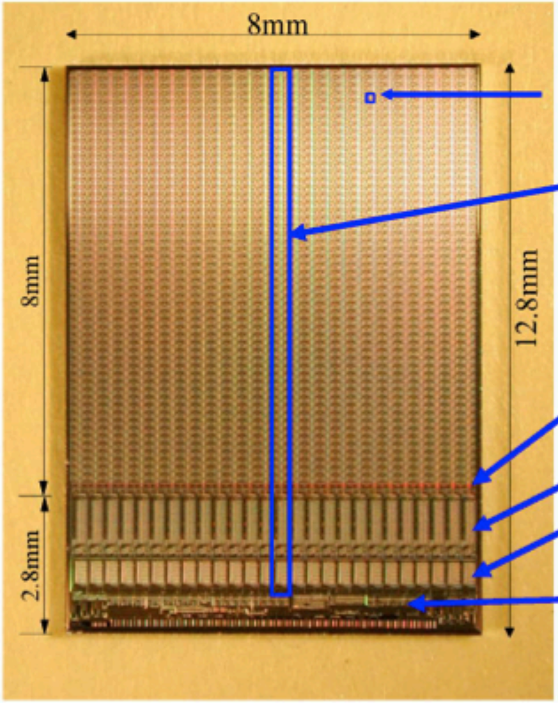


- **CMS**
  - ✓ Solenoidal filed: 4 T
  - ✓ Full silicon strip and pixel detectors
    - high resolution
    - high granularity



TRACKING DETECTORS: CMS pixel module



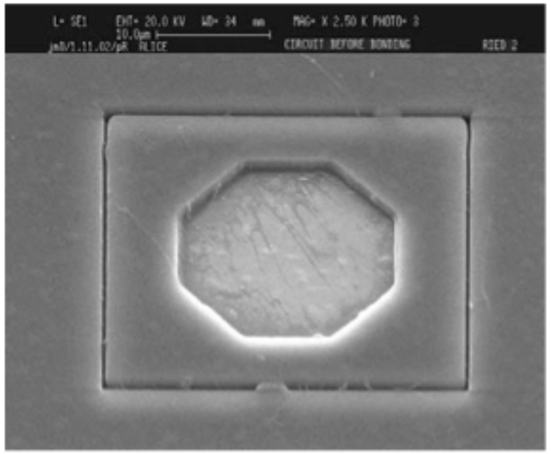


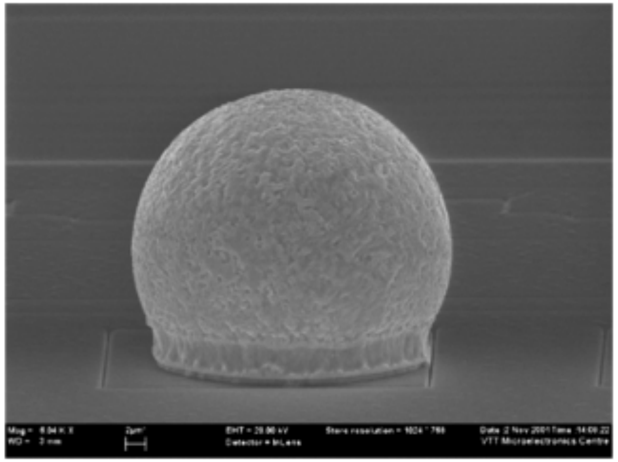
PSI43

- 150 μm x 150 μm pixel
- 52x53 pixels in 26 double columns
  345 k transistors

- Periphery:
  78 k transistors
- Pixel–column interface
- Data buffers (4x24 capacitors)
- Timestamp buffers (8x8 bits)
- I2C, DACs, regulators, counters, readout, wirebonds
  6 k transistors

10 μm



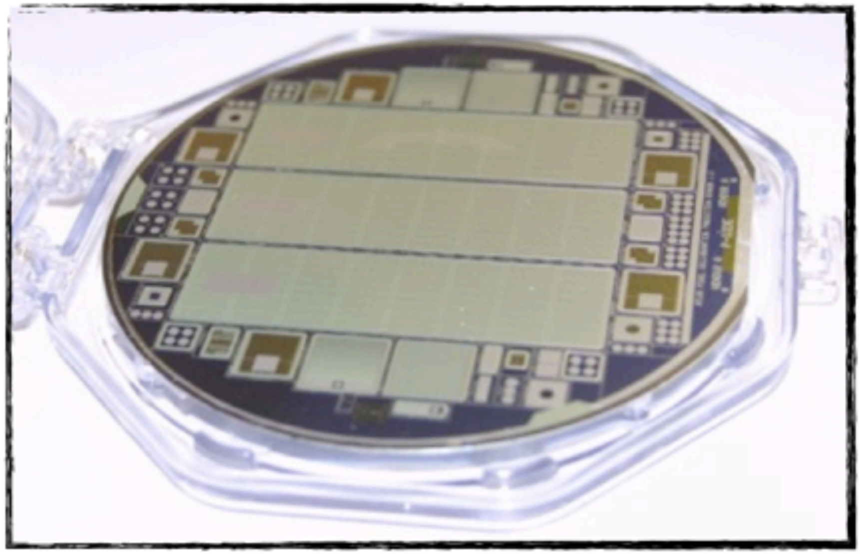


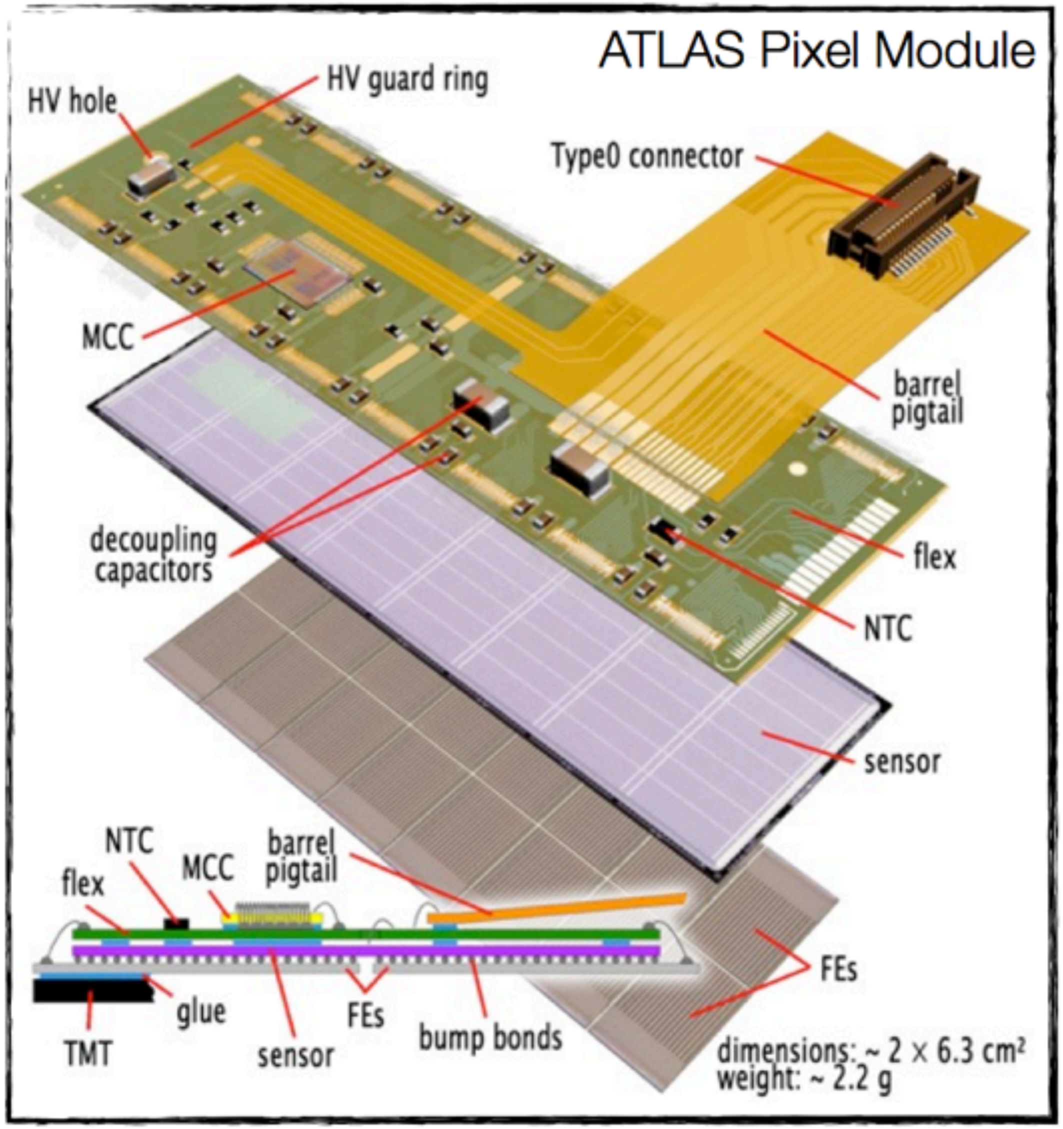
TRACKING DETECTORs: ATLAS pixel module

ATLAS
Pixel Detector

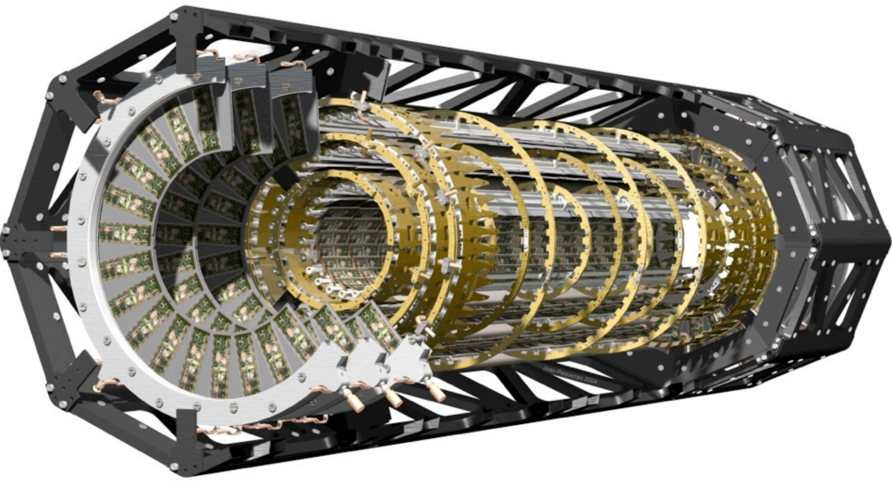
[Details]

Pixel Sensor





ATLAS PIXEL DETECTOR



1744 pixel modules with 46080 pixels/module

Each chip: 50x400 $\mu m^2 \Longrightarrow \sigma_{pos}$=14/115 μm

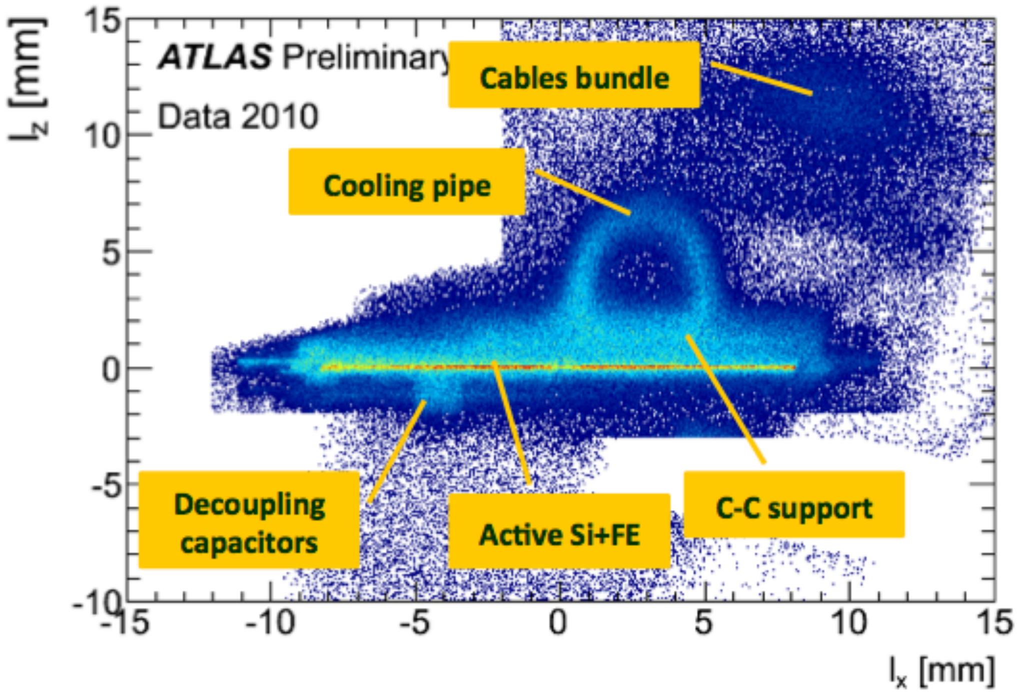
Barrel R=50.5, 88.5 & 122.5 mm

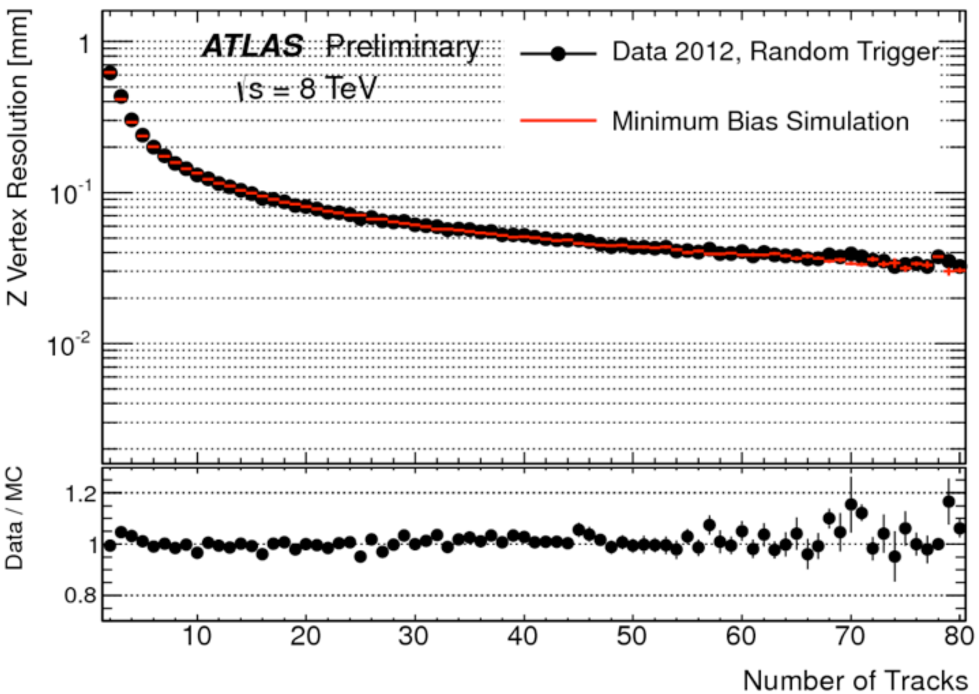
+ ONE NEW LAYER (IBL) at R=30 mm installed this summer

EndCap R coverage 9-15 cm

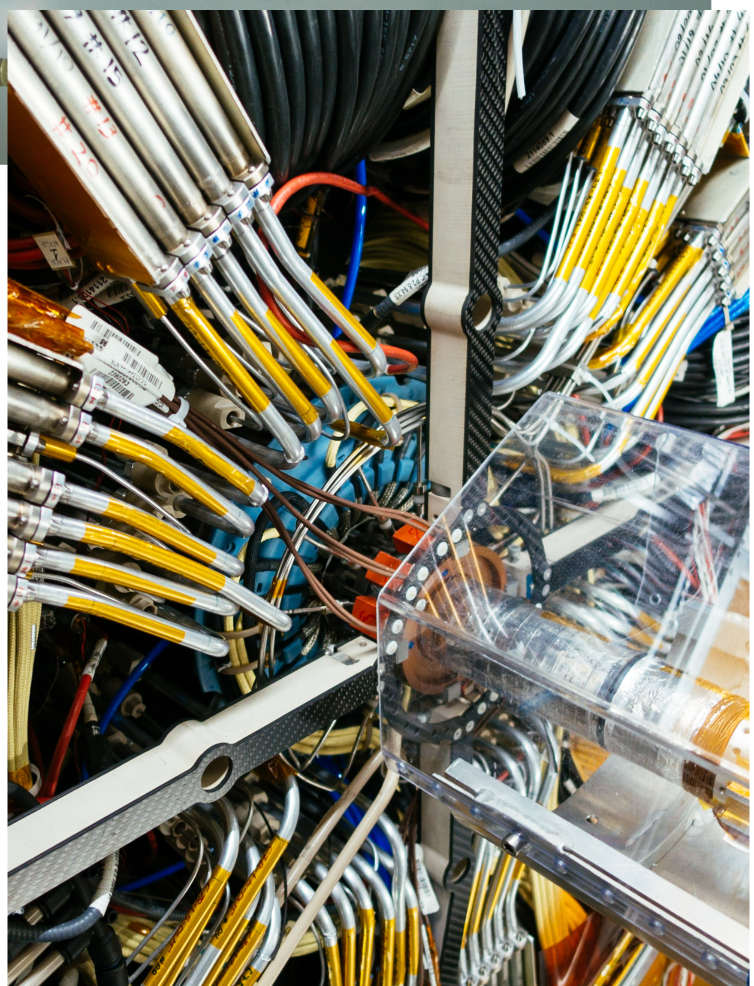
Installation 27 June 2007

LHC beam circulated in September 2008





ATLAS NEW PIXEL LAYER R=3.3 cm - IBL



6 M pixels at R=3.3 cm
Improved light quard rejection

ATLAS SILICON STRIPS DETECTOR

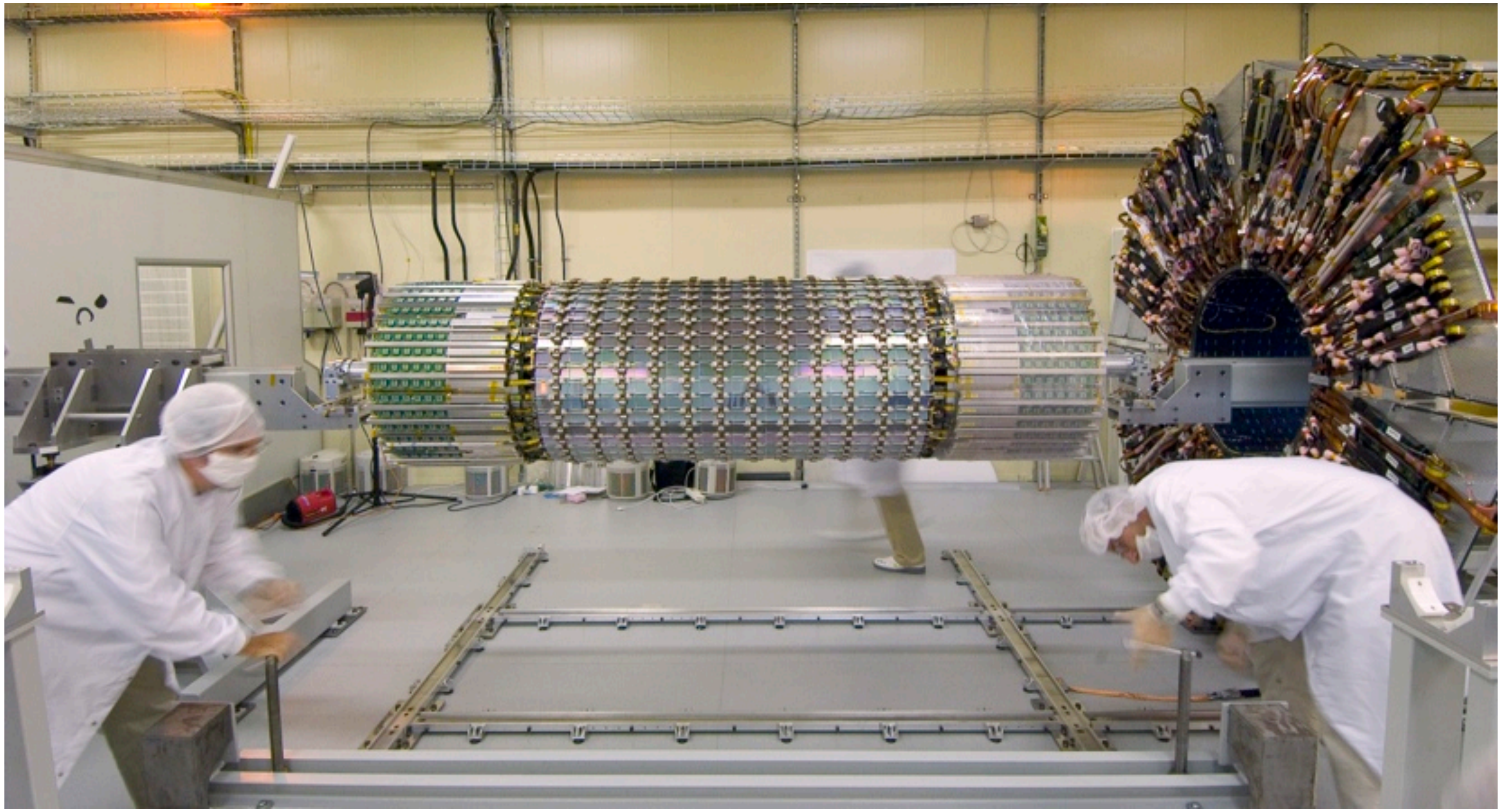
Barrel 4 cylinders at R=300, 373, 447 & 520 mm (r-φ & z precision coordinates)

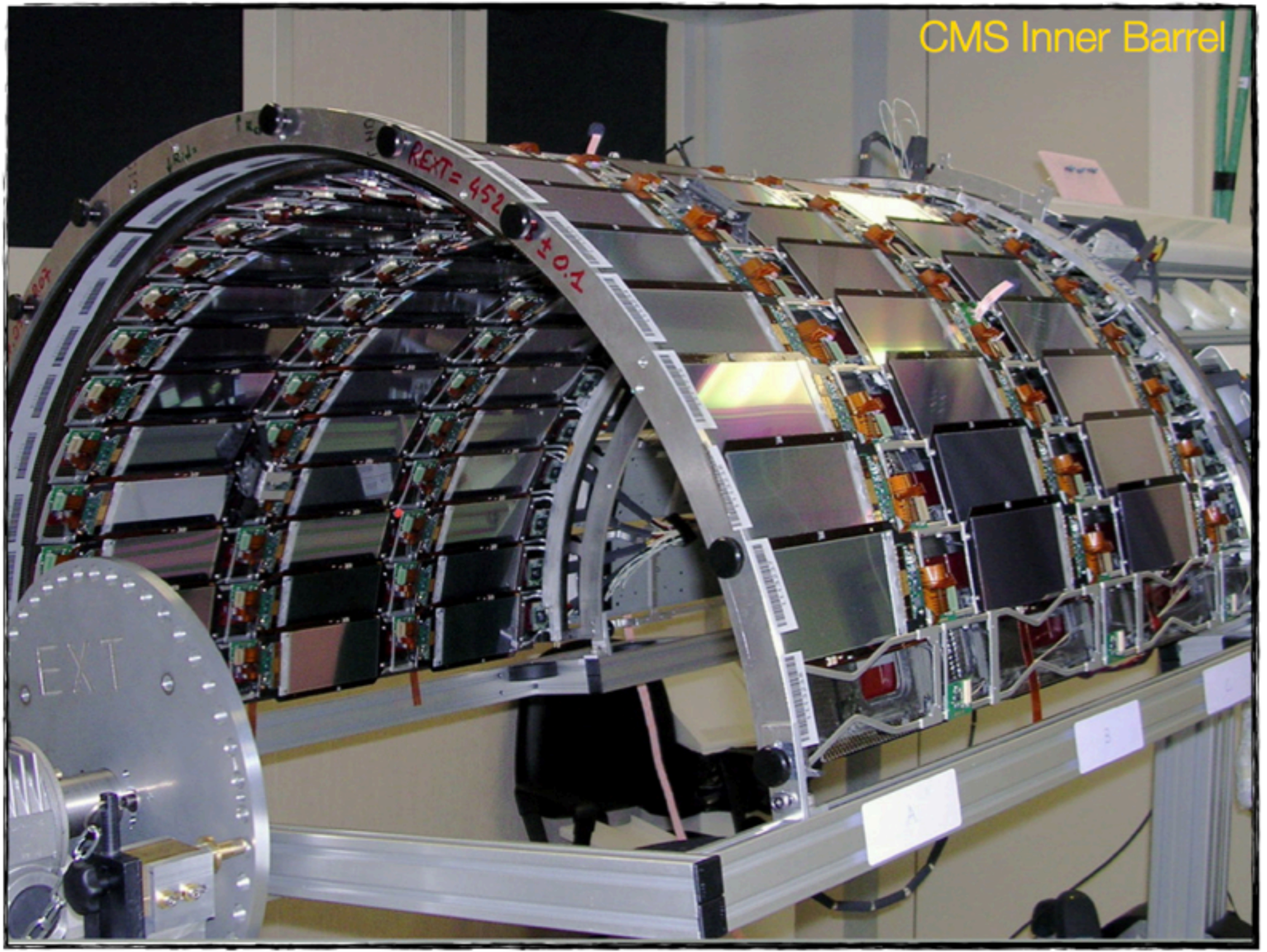
Endcap 9 disks on each side

~4000 modules

Each strip has 80 μm pitch $\Longrightarrow \sigma_{pos} = 23\ \mu m$

8 points per track




CMS Inner Barrel
EXT

MAIN PERFORMANCE OF TRACKING SYSTEMS

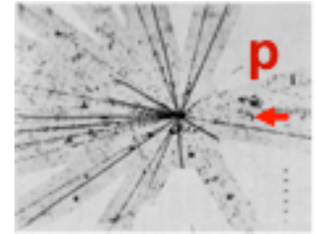
	ATLAS	CMS
Reconstruction efficiency for muons with $p_T = 1$ GeV	96.8%	97.0%
Reconstruction efficiency for pions with $p_T = 1$ GeV	84.0%	80.0%
Reconstruction efficiency for electrons with $p_T = 5$ GeV	90.0%	85.0%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 0$	1.3%	0.7%
Momentum resolution 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

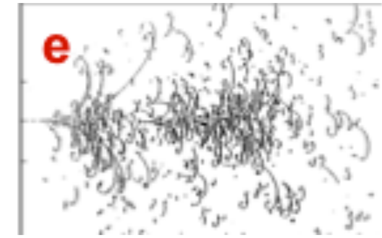
- Momentum resolution on average superior in CMS
- Similar vertexing and b-tagging performances are similar
- Impact of material and B-field already visible on efficiencies

FOUR STEPS

Lesson 1

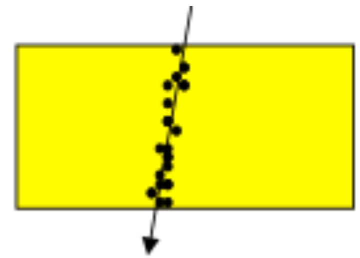
1. Particles interact with matter
depends on particle and material

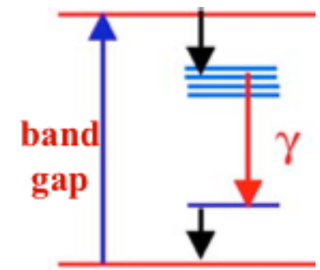


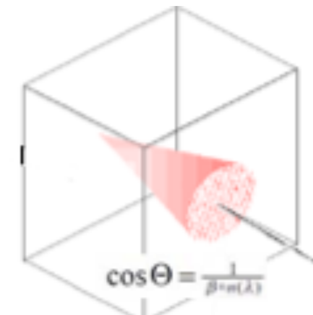


Lesson 2

2. Energy loss transfer to detectable signal
depends on the material

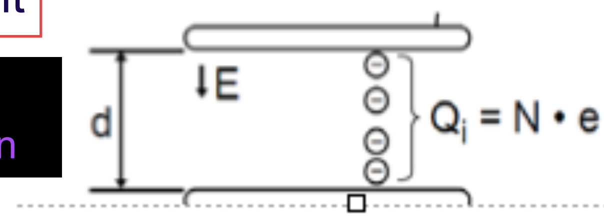


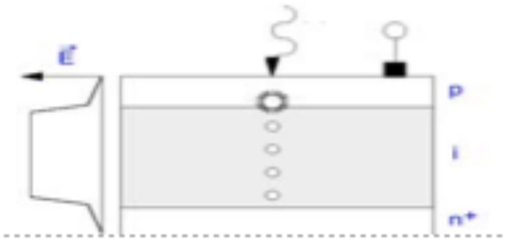




Detecting emitted light

Detecting ionisation current





3. Signal collection
depends on signal and type of detection

Lesson 3

4. BUILD a SYSTEM
depends on physics, experimental conditions,….

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