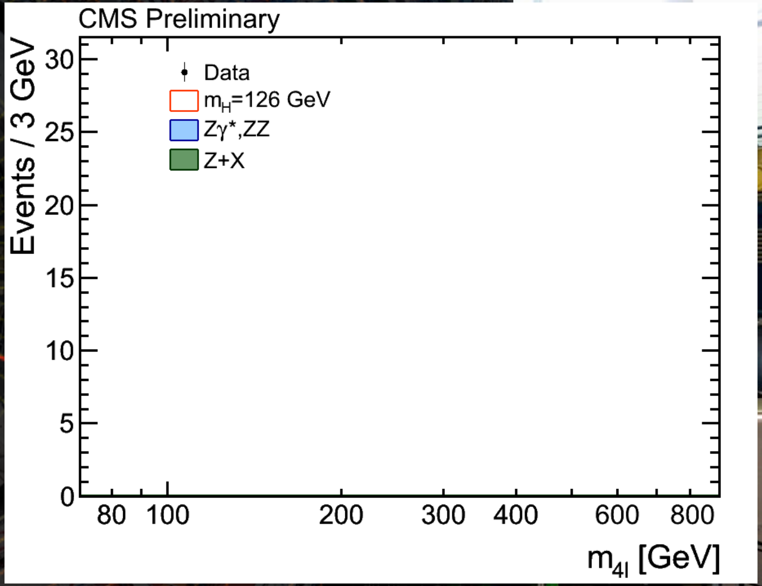
Particle Detectors

Lecture at the African School for Fundamental Physics
Kigali, Rwanda 2016



$$H^0 \rightarrow \mu^+\mu^-\mu^+\mu^-$$

CMS at the LHC

Particle Detectors

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Goal of my lecture:

to understand how particle physics experiments are being built

Main focus on the example LHC

Lecture I

- **Introduction**
- **Interaction of radiation with matter**

Lecture II

- **Simple particle identification**
- **Concepts and strategies of (LHC) experiments**
- **The basic “building blocks”, the detectors**
- **Conclusions or recommendations**

Exercises!!!!!

Particle Detectors

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First Lecture

- **Introduction**
  - how are particle physics experiments are being built ?
  - The goal: measuring subatomic particles (E, p, charge,, mass, ….
  - Collisions of proton-proton, electron-positron, CR, neutrinos, dark matter….
  - Detection of particles, how do they interact with matter, what does the interaction depend on (E, p, charge,, mass, beta, gamma ….
- **Interaction of radiation with matter**
  - Ionization/excitation, Bethe Bloch formula, range of particles, Bragg peak
  - Electrons, Bremsstrahlung, critical energy, radiation length
  - Electromagnetic showers of electrons and photons, (muons)
  - Hadronic interactions → showers, interaction length, solid and atmospheric absorbers
  - Photons: PE, Compton, Pair creation
  - Multiple scattering
  - Cerenkov, Transition radiation
- **Simple particle identification (dE/dx, E/p, e/h/μ, Cerenkov/ TR**
- ***Exercises for the WE !!!!!***

Particle Detectors

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Second Lecture

- **Detector systems, some examples, strategies**
  - Experimental conditions, fixed target or collider, neutrinos, dark matter…
  - Experiments at the LHC (Atlas and CMS, ALICE, LHCb ?
- **The basic "building blocks"**, characteristics (efficiency, resolution)
  - Gas detectors
  - Scintillators
  - Semiconductors
  - Calorimeters
  - Cerenkov and transition radiation detectors
- **System aspects**
- **Conclusions or recommendations**

- ***Exercises for Thursday !!!***

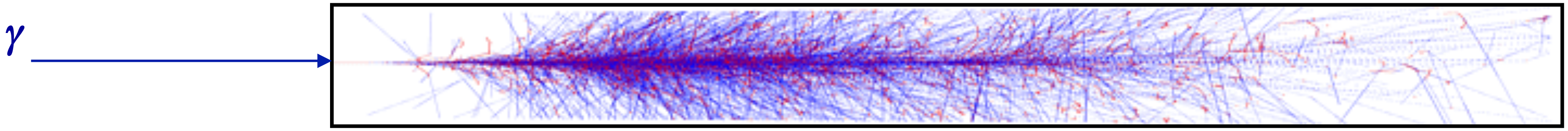
Summary
Particle interaction with matter

Photons :

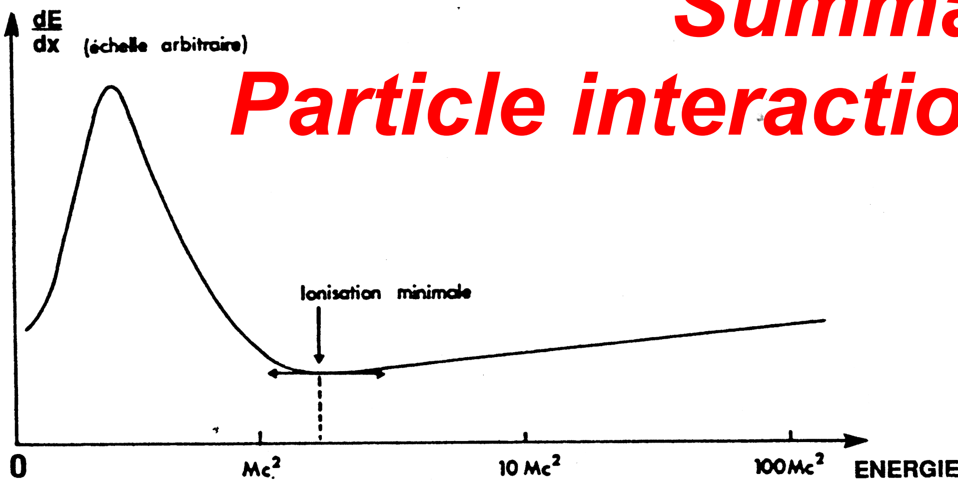
- At low energy (< 10 MeV) photons are absorbed by a single interaction (photoelectric, Compton effect or pair creation). The number of photons is attenuated exponentially, the energy of the remaining photons is not changed, however by the Compton effect lower energy photons are created.

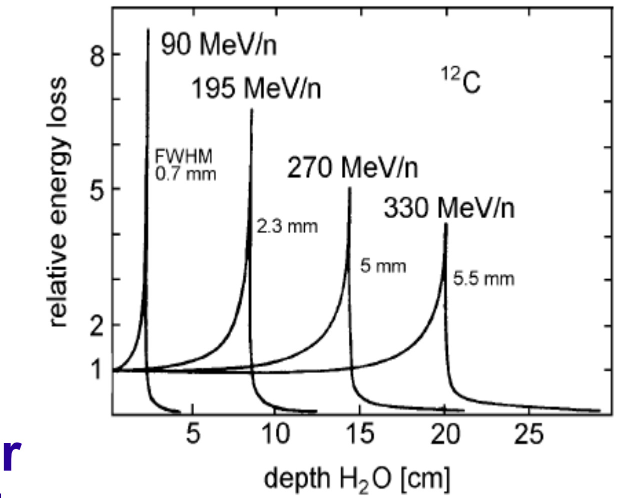
$$N(x) = N_0 \exp\left(-x/\lambda\right) \ ; \quad \frac{1}{\mu} = \lambda_{\text{specific process}} = \text{attenuation length;} \quad x = \text{thickness}$$

- At high energy (E>> 10 MeV) successive pair creation followed by electron Bremsstrahlung will lead to extended elm showers characterized by the "radiation length X_0"



Summary
Particle interaction with matter

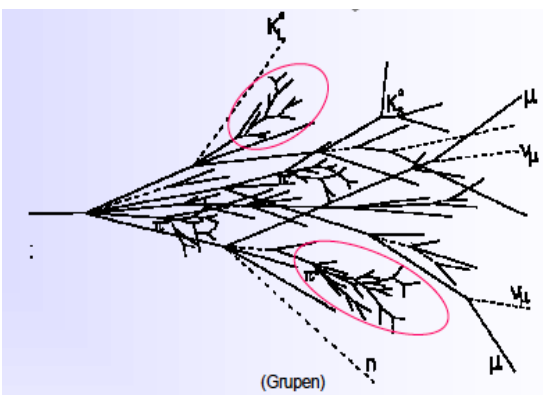




Heavy charged particles

- loose continuously kinetic energy along their path (ionization) with small fluctuations until they are stopped after a well defined distance; until that point their number remains constant and they travel on a straight line.
- At high energies also hadronic interactions may occur, leading to an hadronic shower :

$$N(x) = N_0 \exp\left(-x/\Lambda\right) \; ; \qquad \frac{1}{\Lambda} = \sigma_{\text{int}} \cdot n_b$$

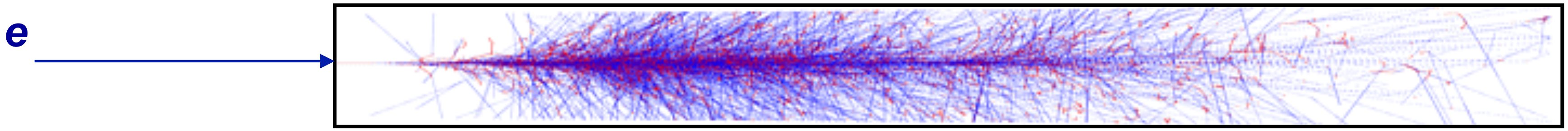


Summary
Particle interaction with matter

Electrons

- also loose their energy by ionization but with much larger fluctuations in the energy loss and deflections leading to a badly defined range in matter.
- At energies higher than a critical energy Bremsstrahlung is emitted. This process becomes rapidly dominant.
- Multiple pair creation and Bremsstrahlung will lead to extended showers characterized by the "radiation length X_0"
- The energy of the incoming electron (not the number !) decreases exponentially with the path length.

$$E^e(x) = E_0^e \exp(-x / X_0)$$



Second lecture

Some general characteristics of electronic detectors

Single detector (the building blocks)

- Energy-response function and linearity
- Time-response and dead time
- Energy, spatial or angular and time resolution
- Efficiency of a detector
- Availability and price !!!
- …

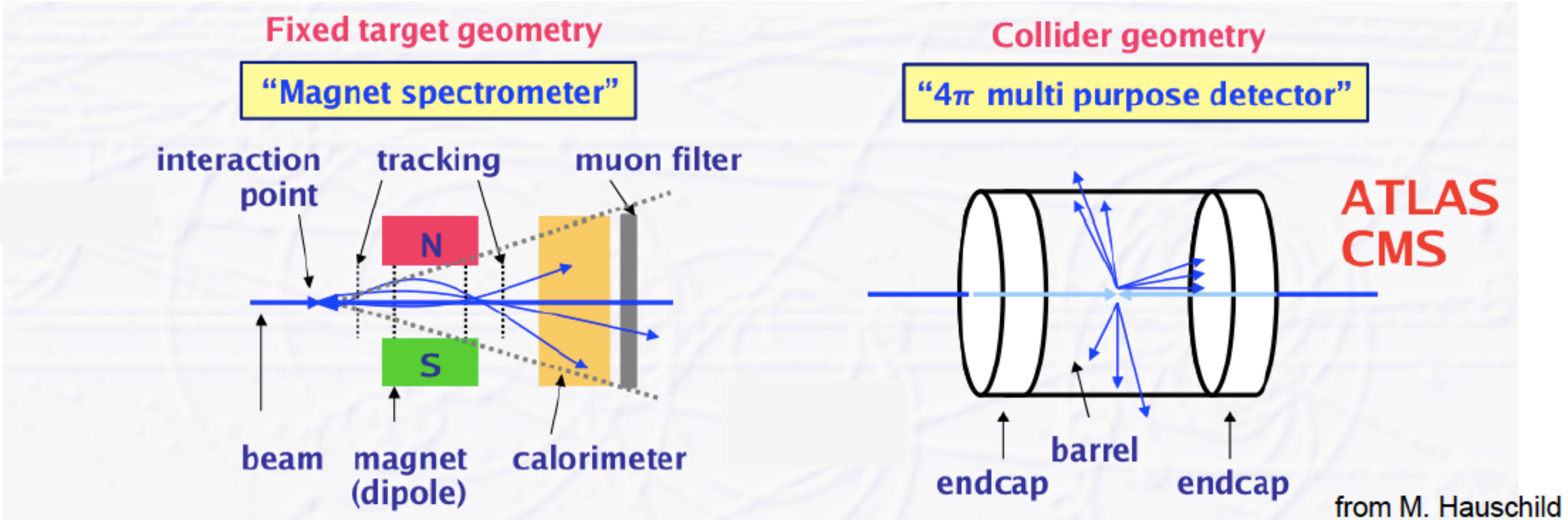
Combination of many detectors → experiment

- Propagation of charged particles in a magnetic field, reconstructing their trajectories

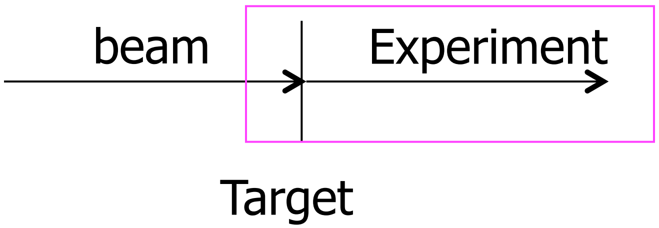
$$p_T(\mathrm{GeV}/c) = 0.3\, B(\mathrm{Tesla})\, R(\mathrm{m})$$

- Measure the energy of electrons, photons and jets
- Detect muons as penetrating particles
- Particle identification!
- Trigger (event selection) and Data acquisition (DAQ)

Experiments at colliders and fixed target geometry



$$E_{CM}^{\text{collider}} = 2E_{beam} = \sqrt{s}$$



$$E_{CM}^{\text{fixed target}} = \sqrt{2Mc^2E + M^2c^4 + m^2c^4} \cong \sqrt{2Mc^2E}$$

Le LHC

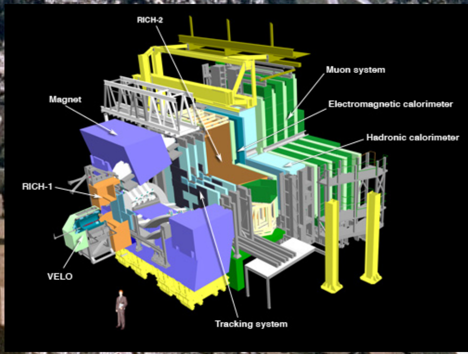
Grand Collisionneur de Hadrons

7 TeV protons + 7 TeV protons

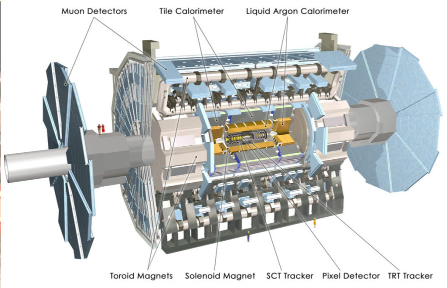
CMS

Large Hadron Collider

- **Pr rculate 11,245 times/ sec**
- **100's of millions of proton-proton collisions/second**
- **Collisions are a billion times hotter than the centre of the sun and create new particles ($E = mc^2$)**



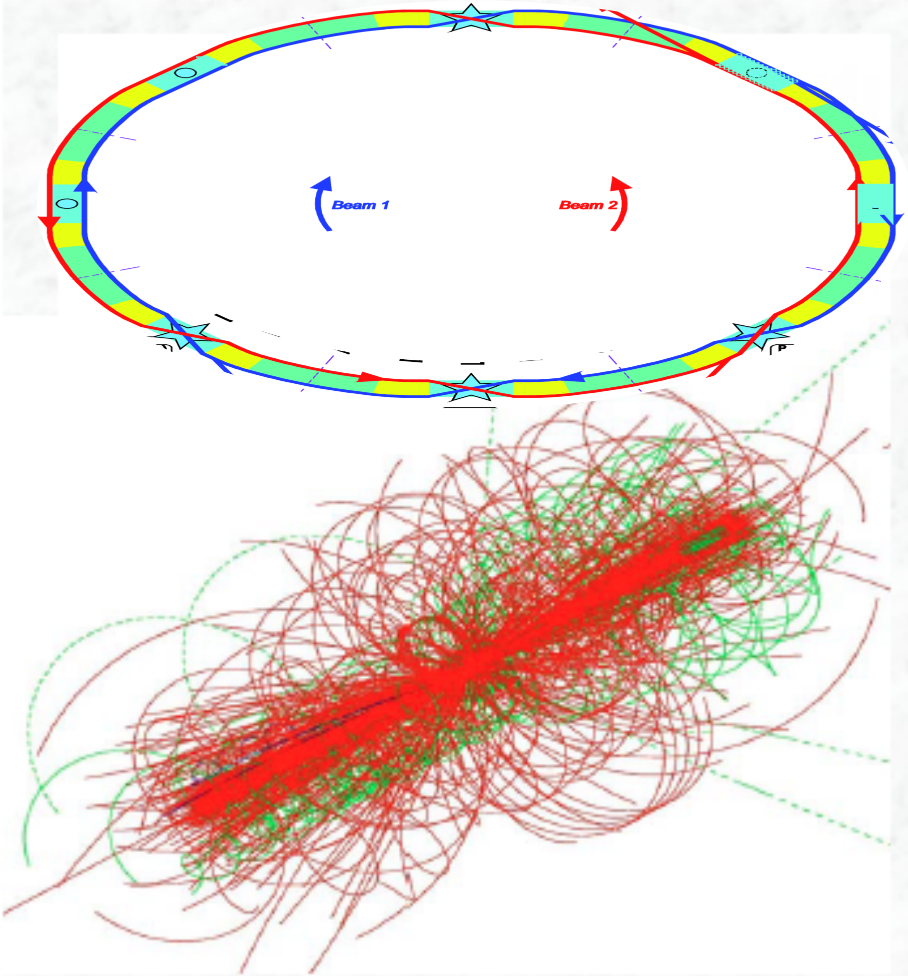
ALICE



CMS Centre @

uter Centre

Proton proton collisions at the LHC



Proton – proton:

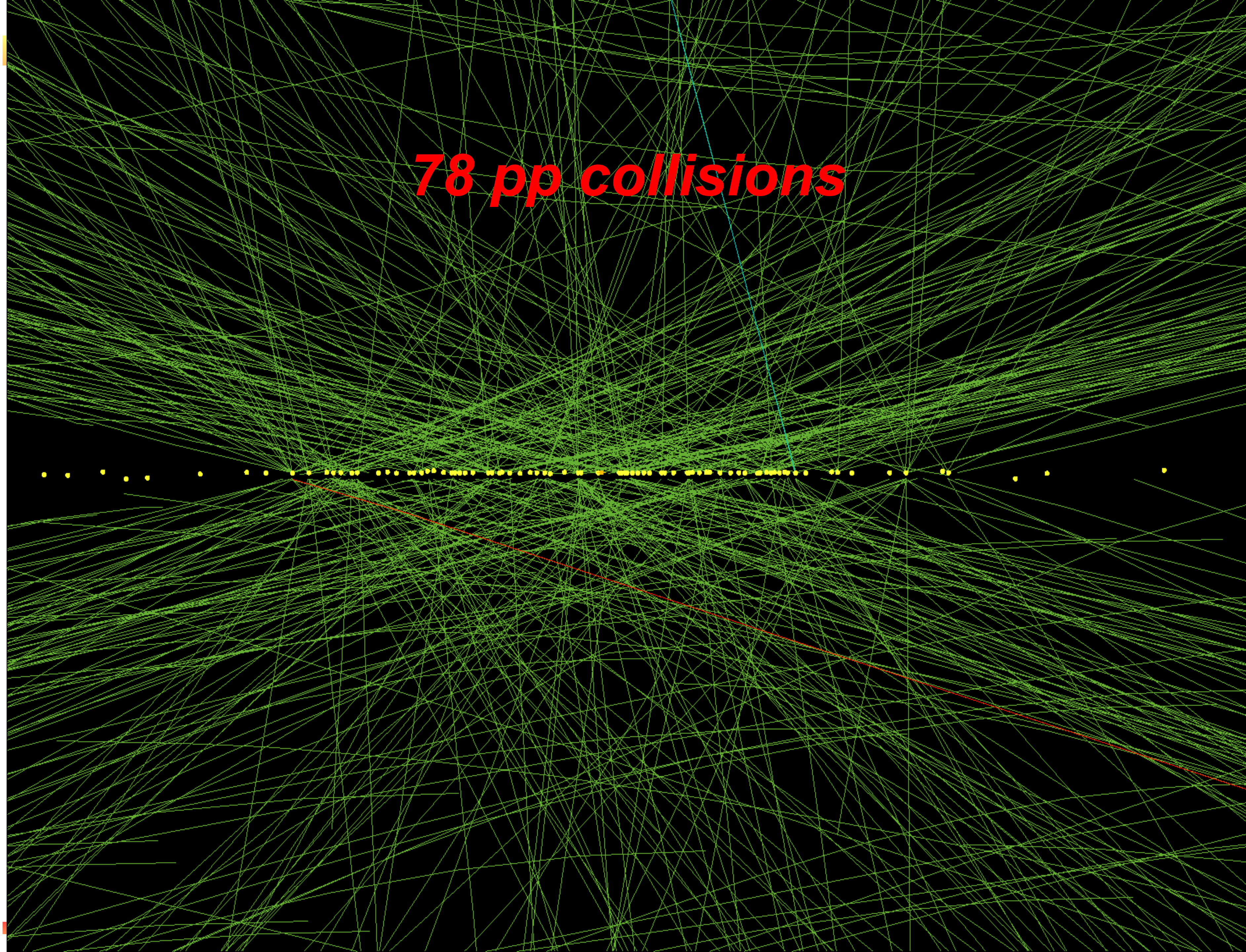
2835 x 2835 bunches
Separation: 7.5 m (25 ns)

10^{11} protons / bunch
Crossing rate of p-bunches: 40 Mio. / s
Luminosity: $L = 10^{34}$ cm^{-2} s^{-1}

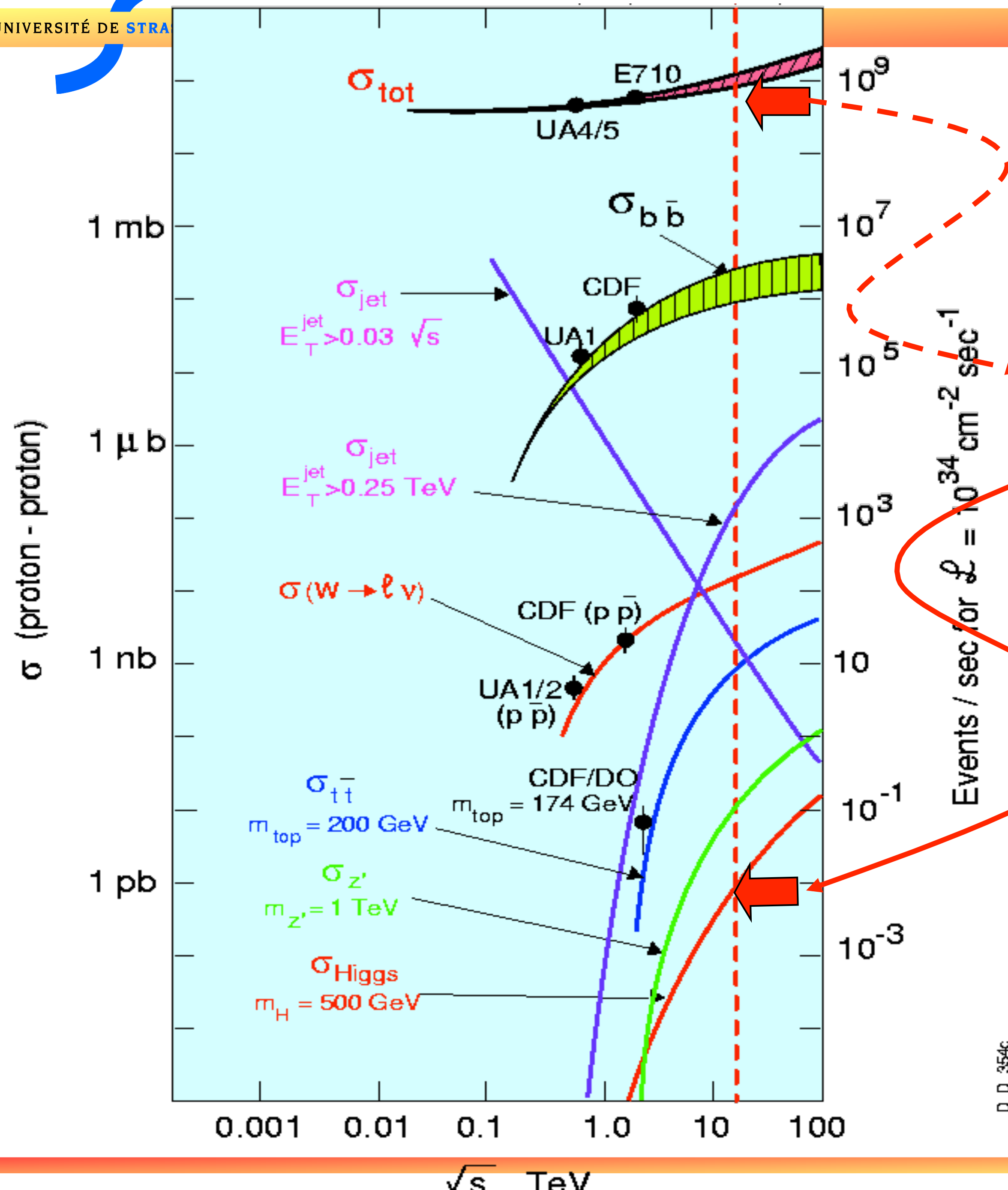
~10^9 pp collisions / s
(superposition of 23 pp-interactions
per bunch crossing: **pile-up**)

~1600 charges particles in the detector

⇒ high particle densities
high requirements for the detectors


78 pp collisions

pp Collisions at LHC



$\sigma_{\text{tot pp}} = 40 - 100 mb$

$\sigma_{\text{H(500GeV)}} \approx 1 pb$

$\mathcal{L} = 10^{34} cm^{-2} s^{-1}$

Beam crossing rate:

40 MHz

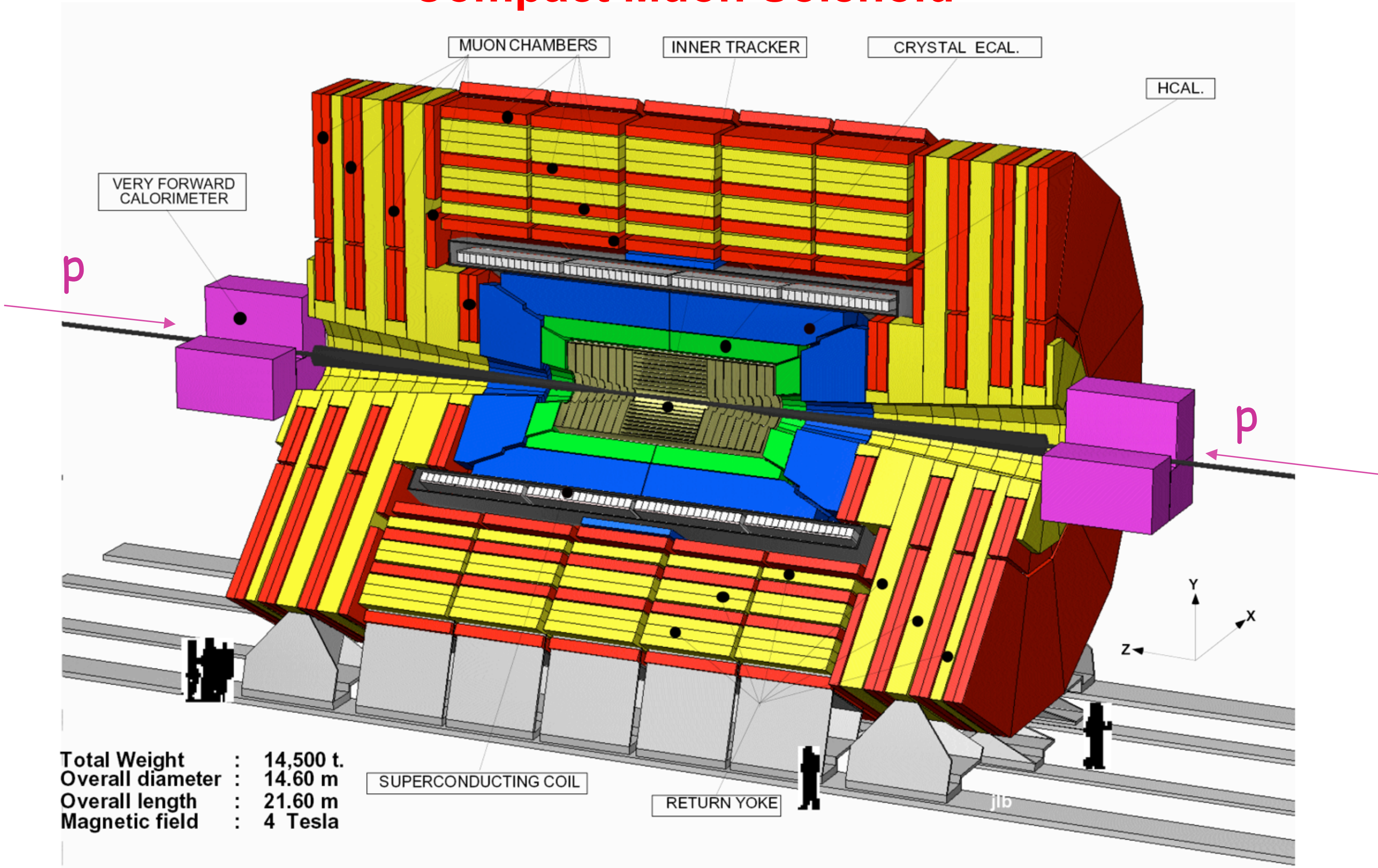
25 interactions

per crossing

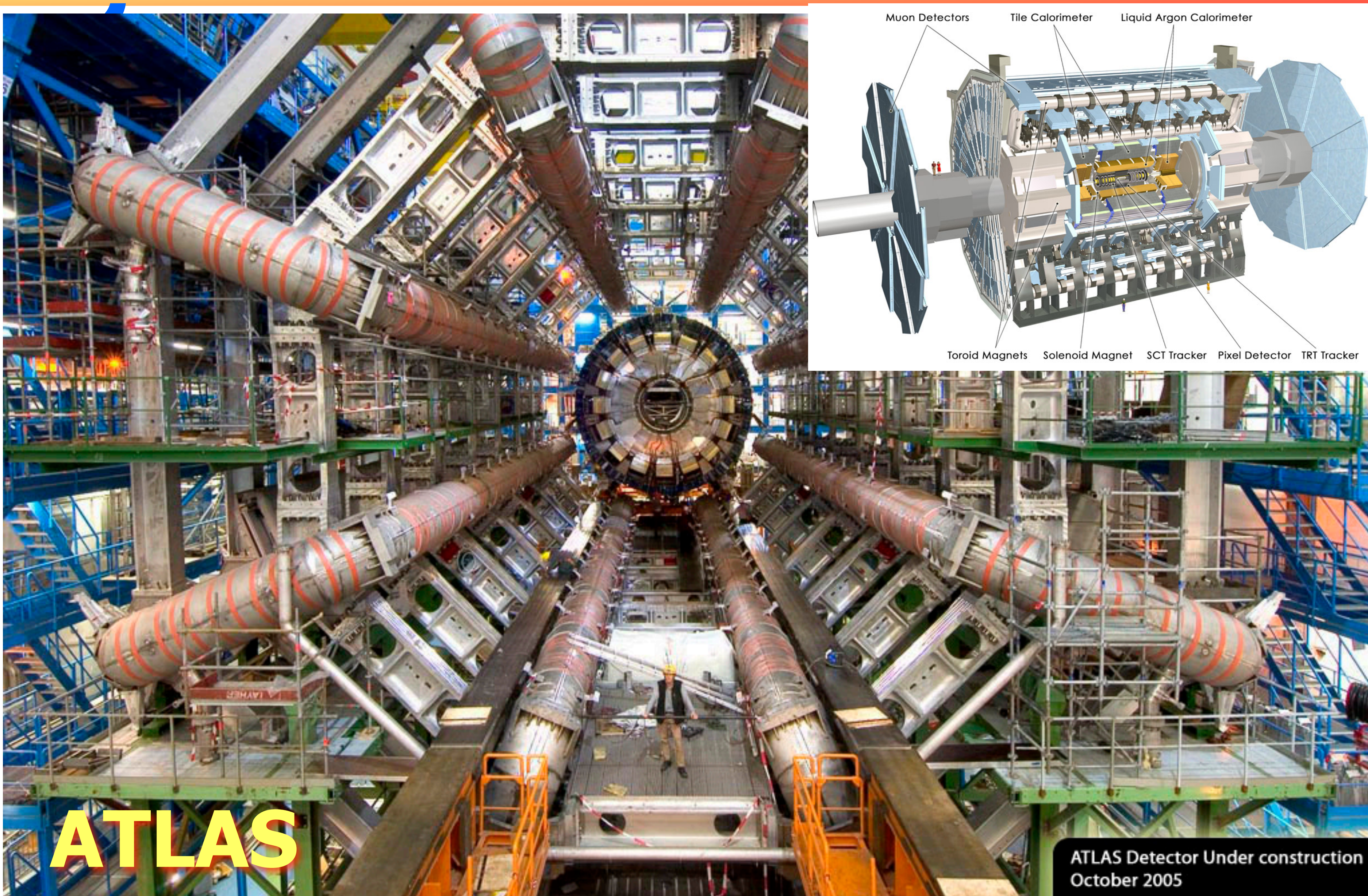
$\dot{N}_{tot} = 10^{9} s^{-1}$

$\dot{N} = 10^{-2} s^{-1}$

Compact Muon Solenoid



Total Weight : 14,500 t.
Overall diameter : 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

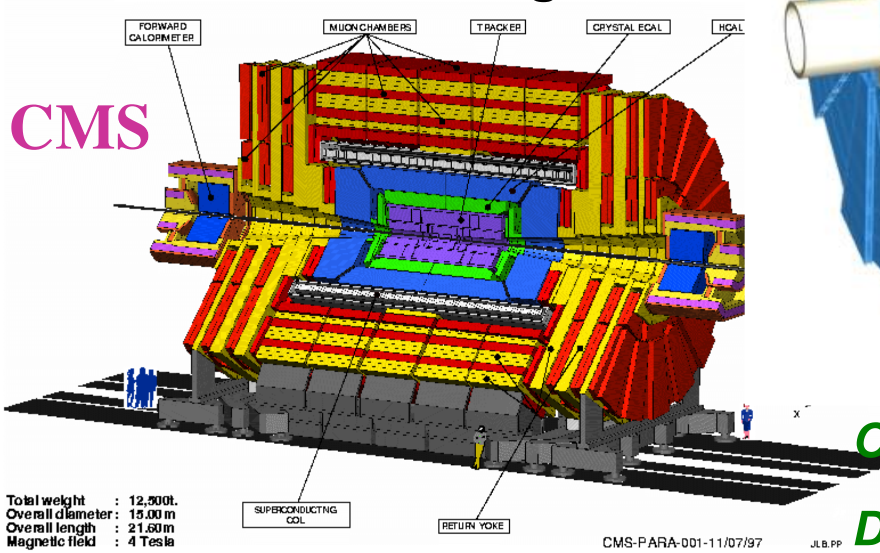

ATLAS
ATLAS Detector Under construction
October 2005
Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

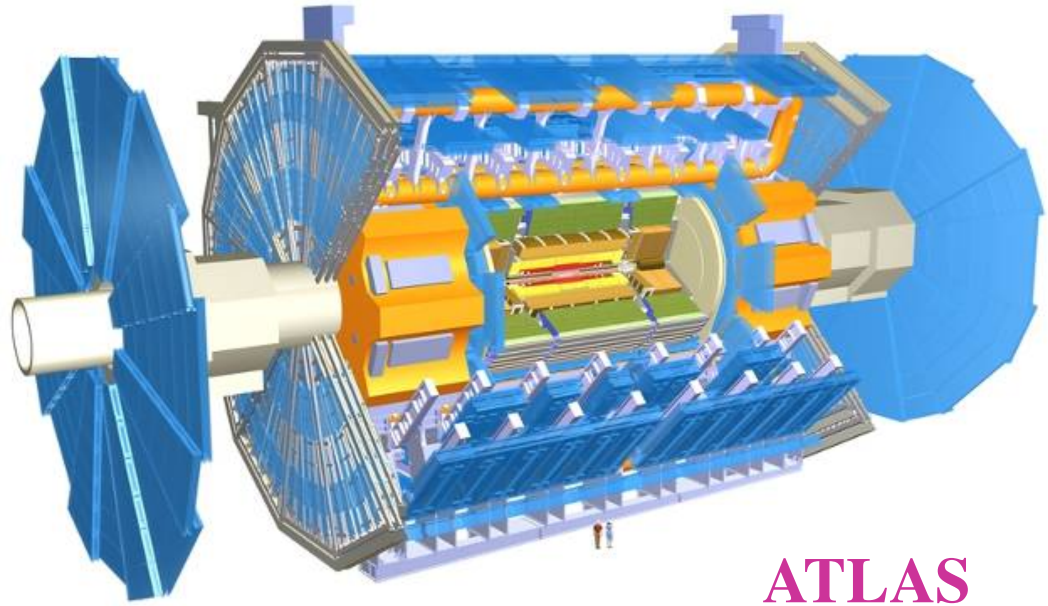
How huge are ATLAS and CMS?

ATLAS superimposed to

the 5 floors of building 40

CMS





ATLAS

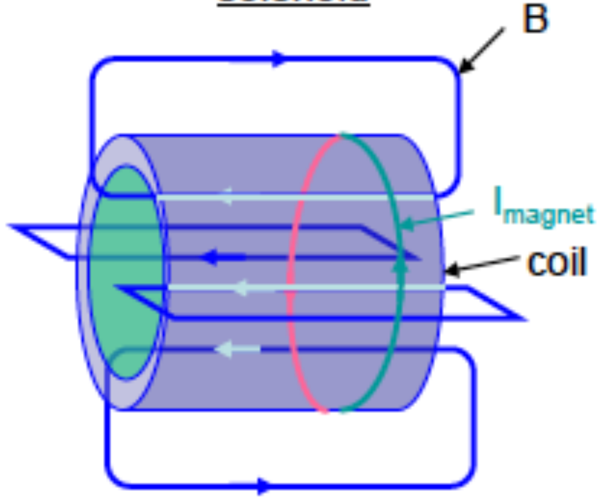
Overall weight (tons)	*7000*	*12500*
Diameter	*22 m*	*15 m*
Length	*46 m*	*22 m*
Solenoid field	*2 T*	*4 T*

Design Goals

- **A good and redundant** ***muon system*** (= many layers – if one layer fails we can fall back on the others**)**
- **The best possible** ***electromagnetic calorimeter***
- **A high quality** ***central tracking***
- **A** ***hadronic calorimeter*** **that has good energy resolution and that is as hermetic as possible**
- **Affordable! (= ~500 MCHF)**

Magnetic field configurations:

solenoid

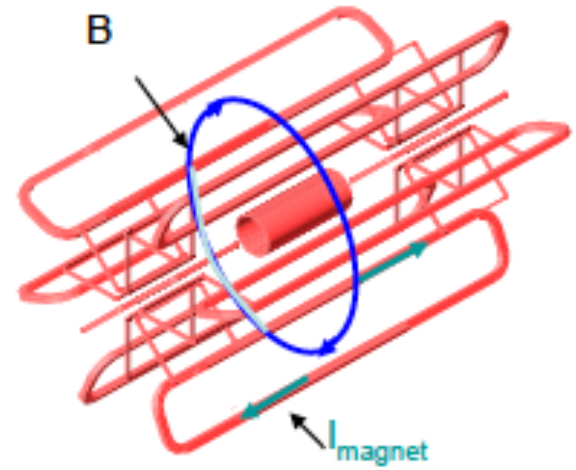


- \+ Large homogenous field inside coil
- \- weak opposite field in return yoke
- \- Size limited (cost)
- \- rel. high material budget

Examples:

- DELPHI (SC, 1.2T)
- L3 (NC, 0.5T)
- CMS (SC, 4T)

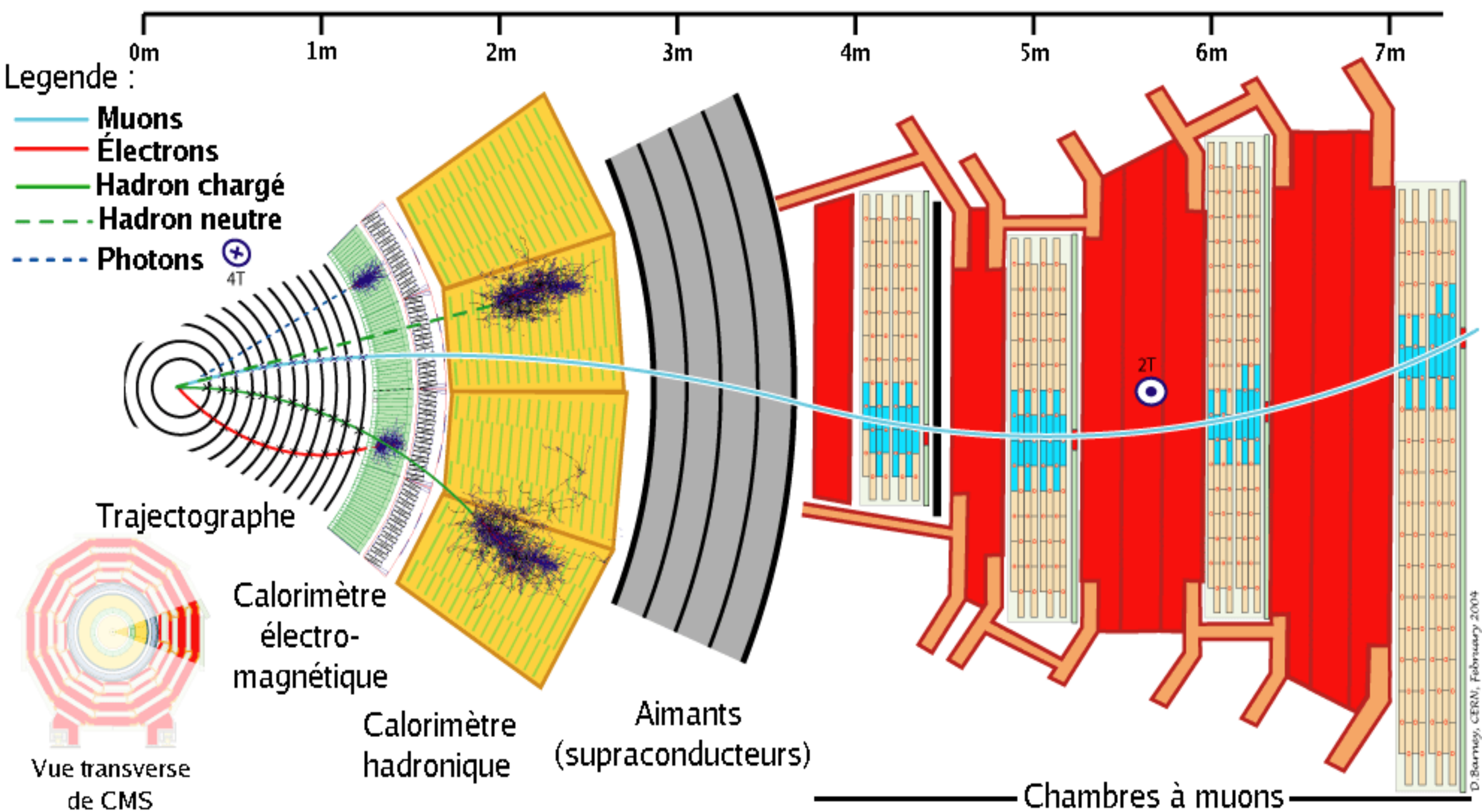
toroid



- \+ Rel. large fields over large volume
- \+ Rel. low material budget
- \- non-uniform field
- \- complex structure

Example:

- ATLAS (Barrel air toroid, SC, 0.6T)



Transverse slice through CMS detector

https://cms-docdb.cern.ch/cgi-bin/PublicEPPOGDocDB/RetrieveFile?docid=97&version=1&filename=CMS_Slice_elab.swf

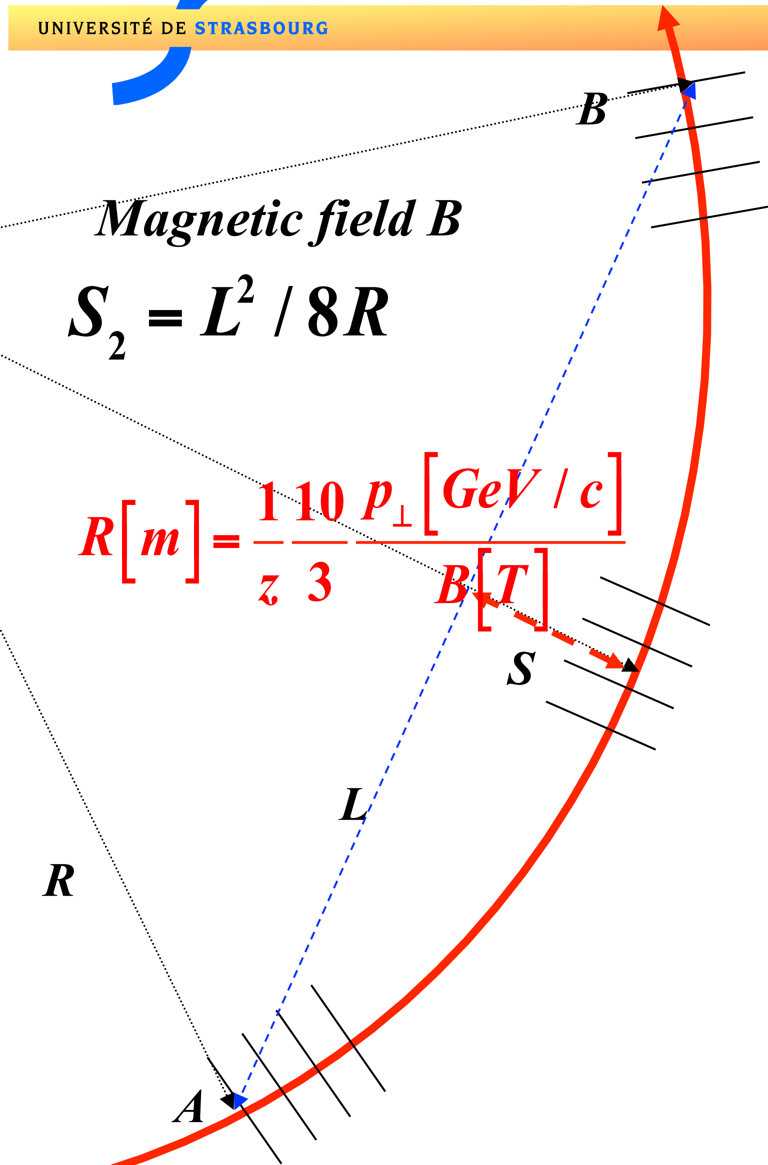
Particle Identification, (PID)

- Photon vs neutral hadron
- Electron vs hadron
- Hadrons vs muons

- Neutral particle:
  - No ionization track
  - Electromagnetic or hadronic shower
- Charged particle
  - Ionization track visible
  - Electromagnetic or hadronic shower
- Charged particle,
  - Ionization track visible
  - No absorption by a shower

Reconstruction of transverse momentum in a magnetic field

Exercise !!!



$$S_2 = L^2 / 8R$$

$$R[m] = \frac{1}{z}\frac{10}{3}\frac{p_\perp[GeV/c]}{B[T]}$$

- Movement of a charge z in a uniform magnetic field
- Momentum resolution *dp/p*
- Spatial resolution of the sagitta *dS/S*

$$\frac{dS}{S} = \frac{dp_\perp}{p_\perp} = \frac{80}{3 \cdot z}\frac{1}{BL^2} p_\perp dS$$

$$[B] = Tesla; \ [L] = m; [p_\perp] = GeV/c$$

If the trajectory is measured with *N* points:

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x) \cdot p_T}{0.3 \cdot BL^2}\sqrt{720/(N+4)} \quad \text{(for N} \geq \sim 10)$$

Momentum reconstruction in a uniform magnetic field

$$R^2 = (L/2)^2 + (R-S)^2$$

$$0 = S^2 - 2RS + L^2/4$$

$$S_{1,2} = R\left(1 \pm \sqrt{1-(L/2R)^2}\right)$$

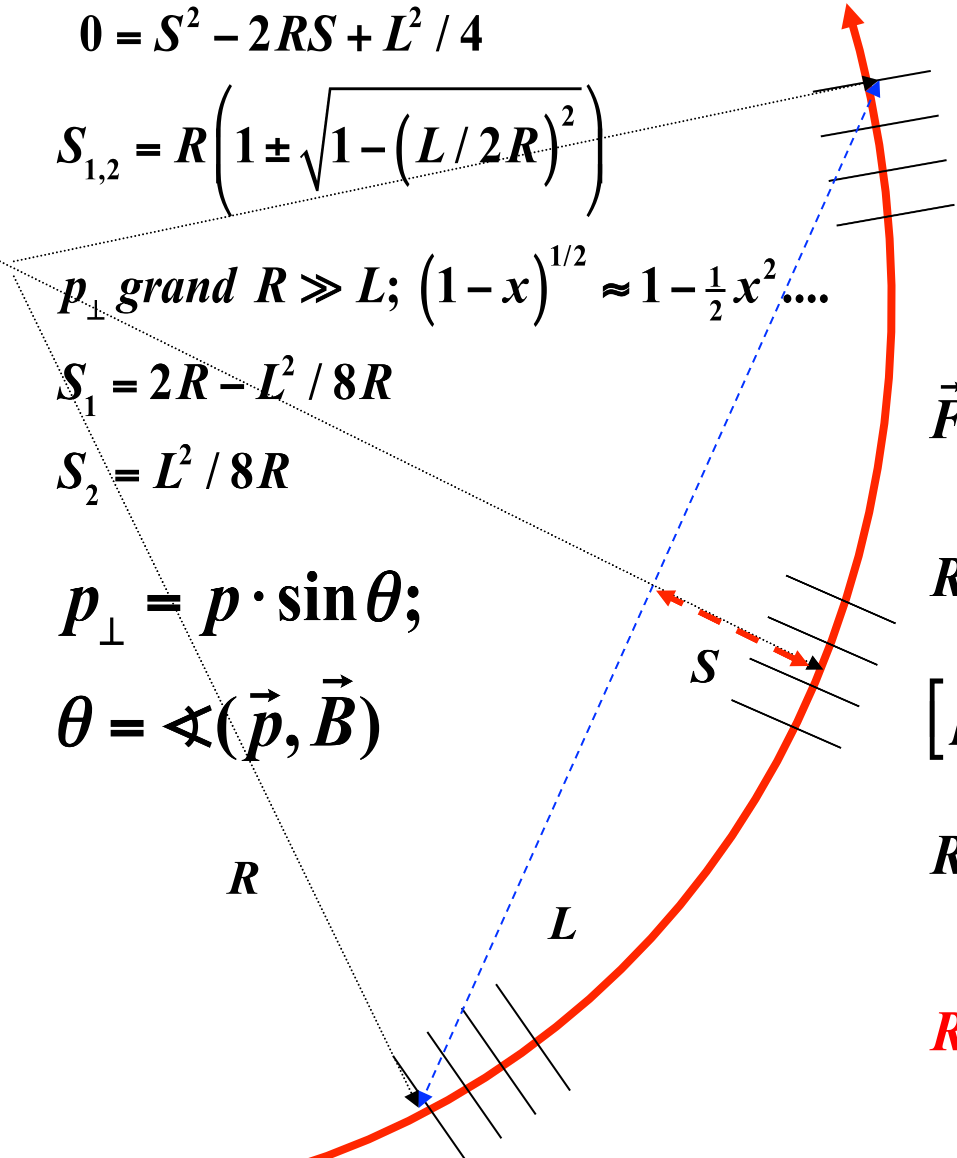
$$p_\perp \ grand \ R \gg L;\ (1-x)^{1/2} \approx 1 - \tfrac{1}{2}x^2 ....$$

$$S_1 = 2R - L^2/8R$$

$$S_2 = L^2/8R$$

$$p_\perp = p \cdot \sin\theta;$$

$$\theta = \sphericalangle(\vec{p}, \vec{B})$$



$$\vec{F} = q\cdot\left(\vec{v}\times\vec{B}\right) = m\vec{a}_R = m\frac{v^2}{R};\ \vec{v}\perp\vec{B}$$

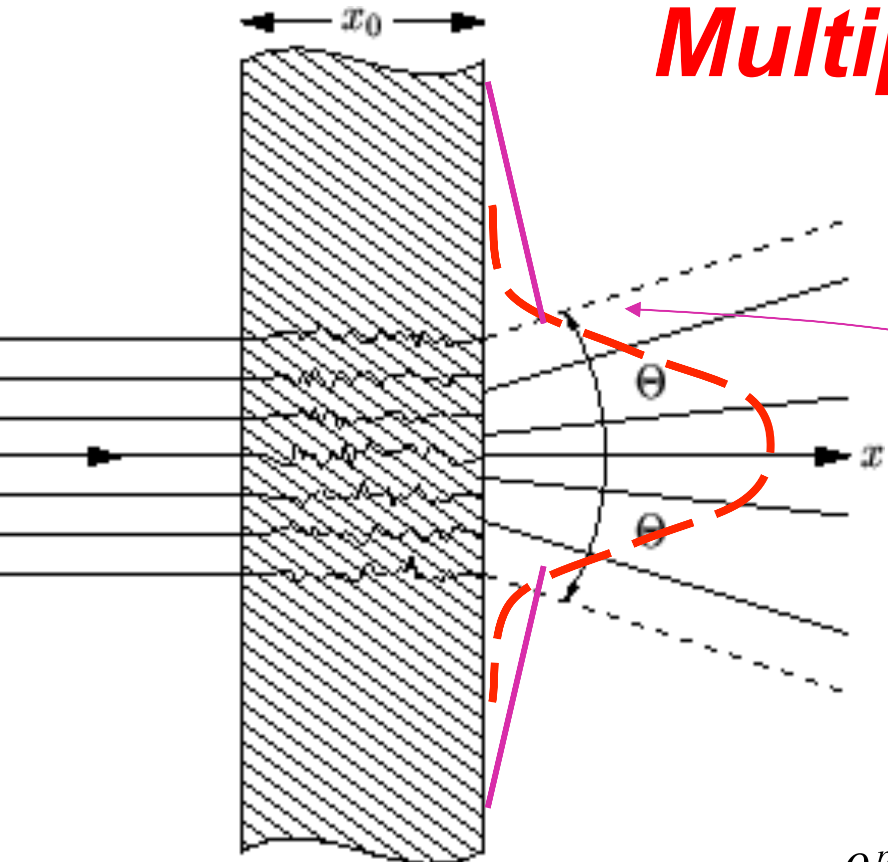
$$R = \frac{m}{q}\frac{v}{B} = \frac{p_\perp}{q\cdot B}$$

$$[p_\perp] = GeV/c;\ [q] = e\cdot z;\ [B] = T_{esla} = Vs/m^2$$

$$R = \frac{1}{z\cdot e}\frac{10^9 eV}{c}\frac{1}{Vs/m^2};\ c = 3\cdot 10^8 m/s$$

$$R[m] = \frac{1}{z}\frac{10}{3}\frac{p_\perp[GeV/c]}{B[T]}$$

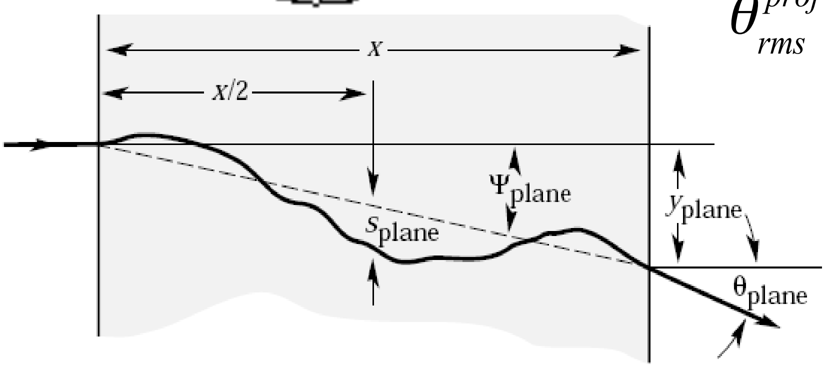
Multiple scattering



Scattering in the coulomb field of the nucleus (Rutherford)

Gaussian (θ) distribution for small angles θ,

Violant scatters can lead to large values of θ



$$\theta_{rms}^{proj} = \frac{13.6 MeV/c}{p \cdot \beta} Z_0 \sqrt{\frac{x}{X_0}} (1 + 0.038 \ln(x/X_0))$$

X_0=radiation length

Tracking in a magnetic Field: Resolution and multiple scattering

Resolution = $F_{ull}W_{idth}H_{alf}M_{ax}$/mean

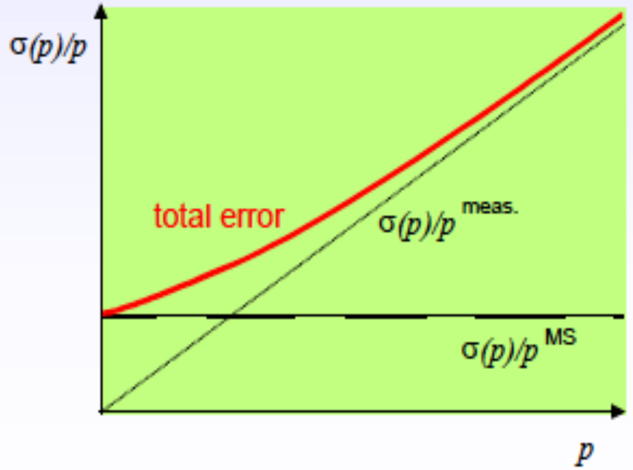
$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3\cdot BL^2}\sqrt{720/(N+4)}$$ (for N ≥ ~10)

$$\frac{\sigma(p)}{p_T} \propto \sigma(x)\cdot p_T$$

$$\left.\sigma(x)\right|^{MS} \propto \theta_0 \propto \frac{1}{p}$$

$$\left.\frac{\sigma(p)}{p_T}\right|^{MS} = \text{constant}$$, i.e. independent of p !

More precisely: $$\left.\frac{\sigma(p)}{p_T}\right|^{MS} = 0.045\frac{1}{B\sqrt{LX_0}}$$



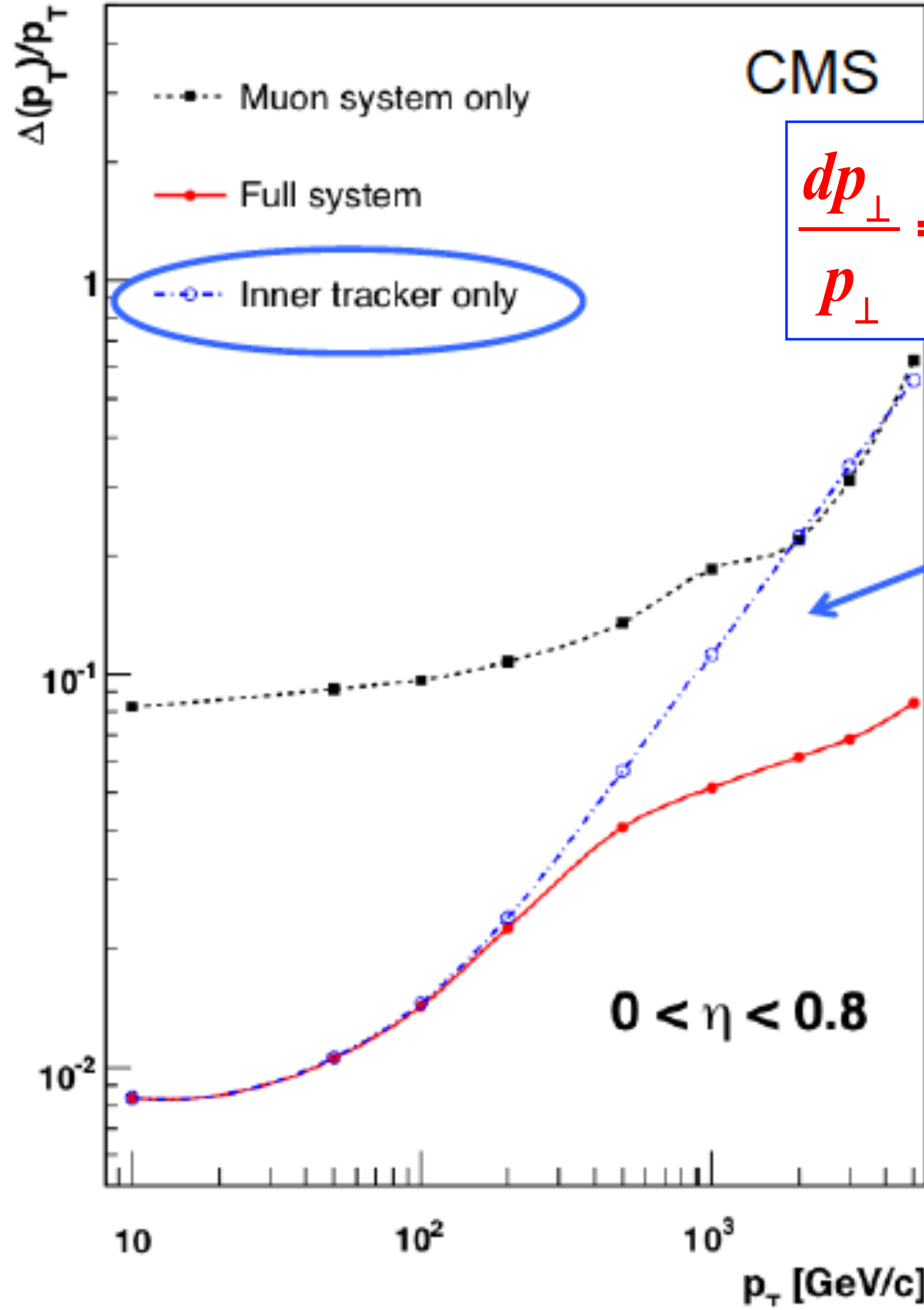
Example:

$p_t = 1$ GeV/c, $L = 1$m, $B = 1$ T, $N = 10$

$\sigma(x) = 200$ µm: $\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} \approx 0.5\%$

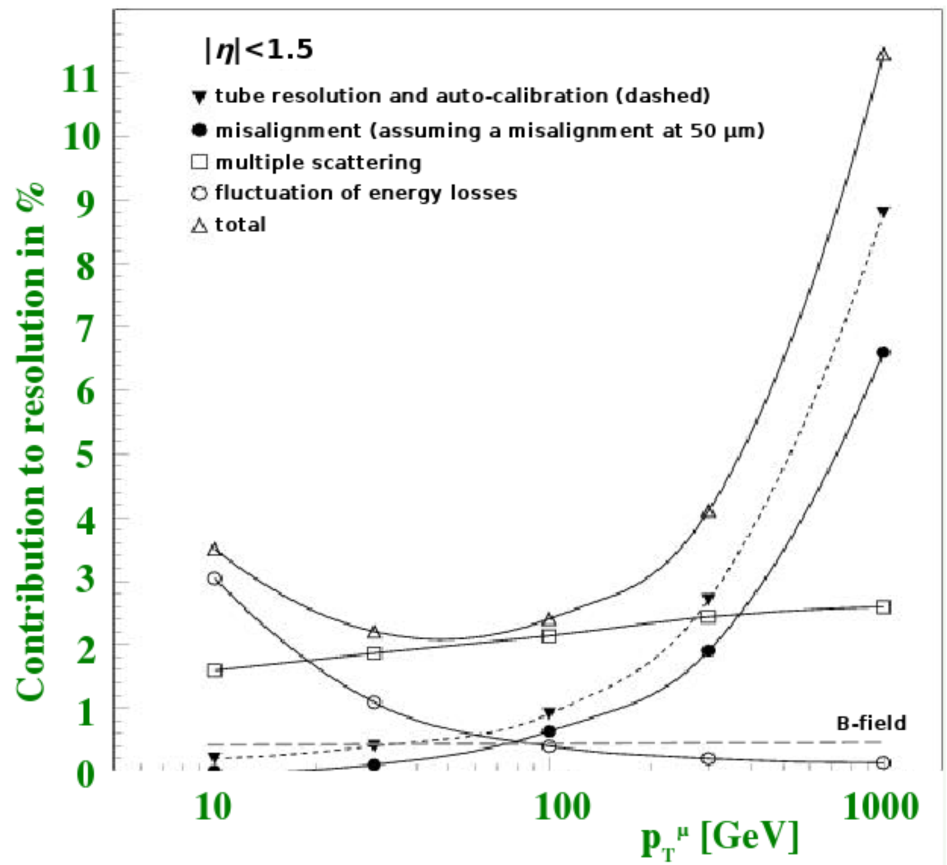
Assume detector (L = 1m) to be filled with 1 atm. Argon gas (X_0 = 110m),

$$\left.\frac{\sigma(p)}{p_T}\right|^{MS} \approx 0.5\%$$



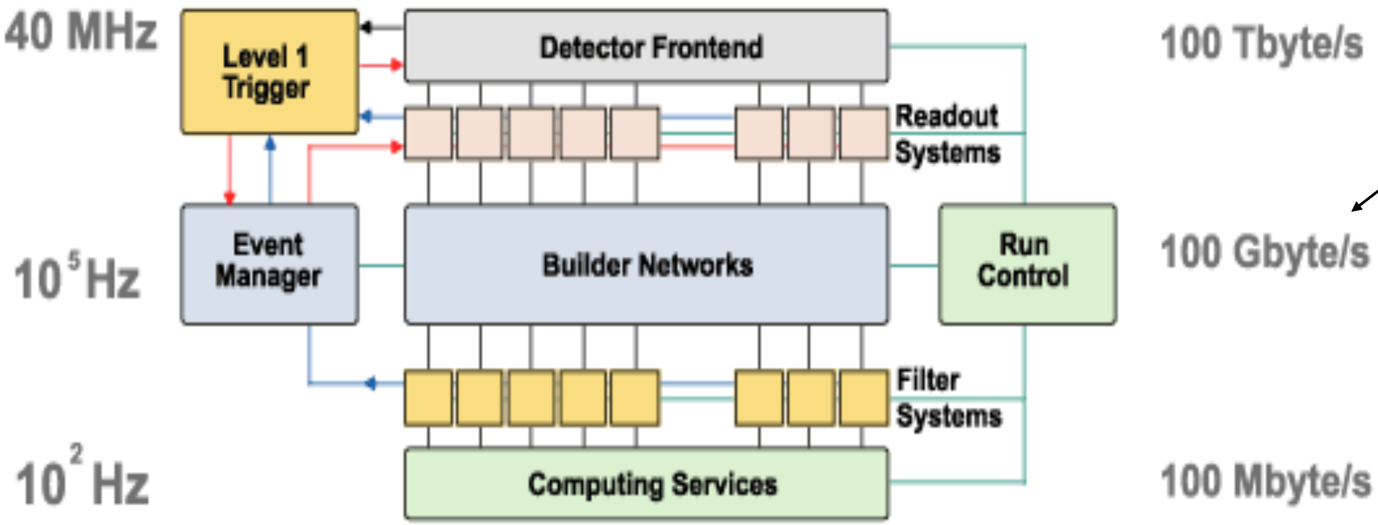
$$\frac{dp_\perp}{p_\perp} = \alpha \times p_\perp dS \oplus (\text{multiple scattering})$$

Atlas



The Trigger and Data Acquisition System

Data Acquisition Main Parameters	
Collision rate	40 MHz
Level-1 Maximum trigger rate	100 kHz
Average event size	1 Mbyte
No. of electronics boards	10000
No. of readout crates	250
No. of In-Out units (200-5000 byte/event)	1000
Event builder (1000 port switch) bandwidth	1 Terabit/s
Event filter computing power	5 10^6 MIPS
Data production	Tbyte/day



Trigger and Data Acquisition baseline structure

~same as whole world's telecom network!

Detectors for Particle and Nuclear Physics

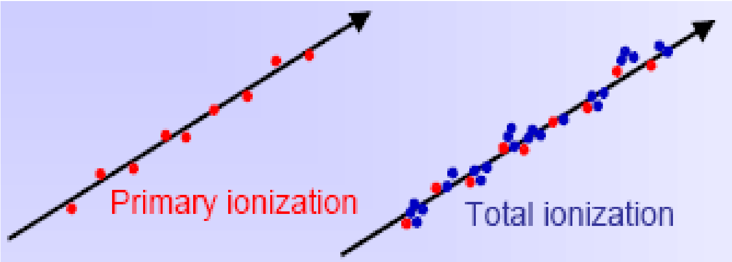
- **The building blocks and assemblies**

Gas detectors

- Ionisation chambers
- Proportional counters
- Multi Wire Proportional chambers
- Drift chambers and Time Projection Chambers
- Many many more …..

Ionisation and excitation in a gas

- **Excitation : X+p → X^*+p**
  - $\sigma \approx 10^{-17}$ cm^2
- **Ionisation : X+p → X^++p + e^-**
  - $\sigma \approx 10^{-16}$ cm^2



$n_{primary} \approx n_{total}$ x1/3

Gaz	Excitation (eV)	Ionisation (eV)	Energie moyenne pour (e^-, ion) (eV)	(e^-,ion^+) /cm au minimum d'ionisation n_{total}
H_2	10.8	15.4	37	14
He	19.8	24.6	41	16
Ne	16.6	21.6	35	42
Ar	11.6	15.8	26	103
CO_2	10.0	13.7	33	62
CH_4		13.1	33	107
C_4H_{10}		10.8	23	113

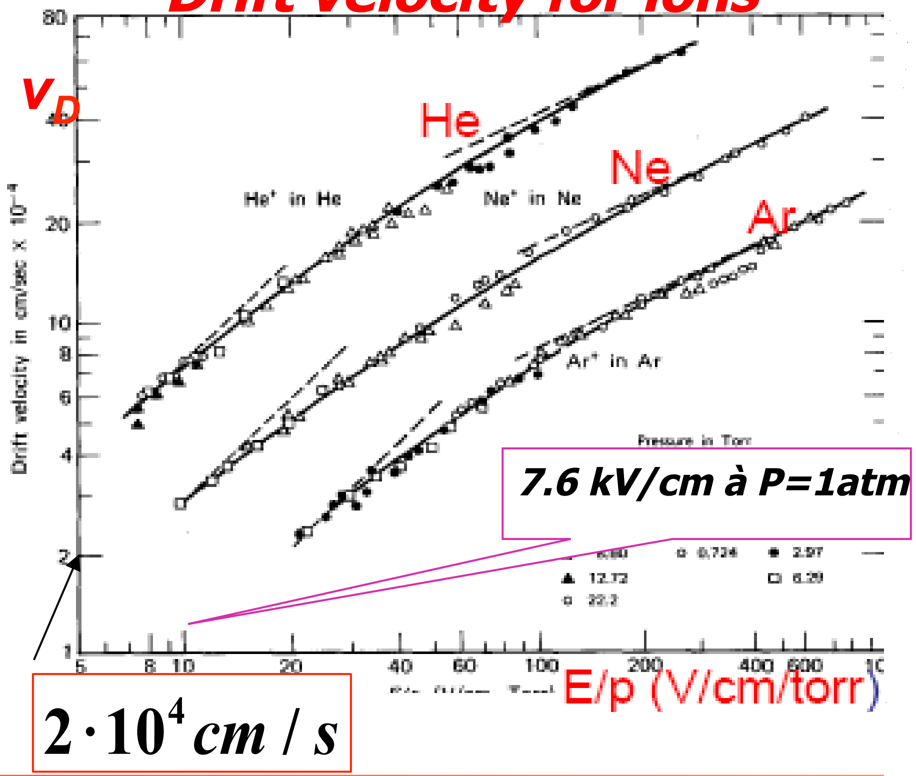
Mobility and collection of charge

$$v_D = \mu \cdot E;\ \ E = \text{electric field};\ \ p = \text{pressure}$$

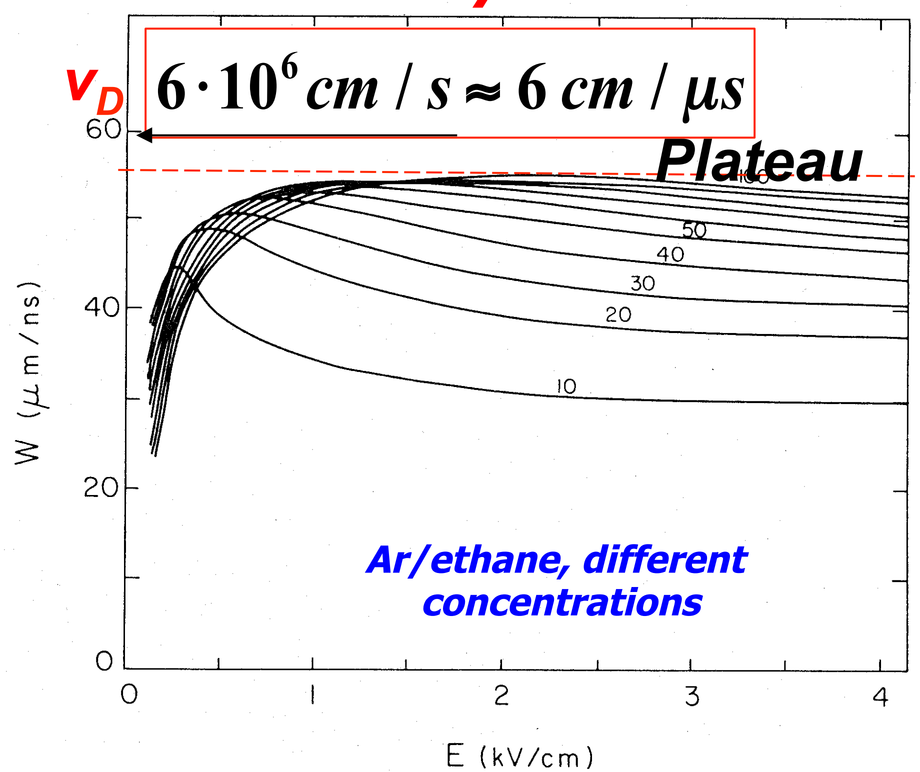
in general it's more complicated $\mu = \mu(E, p)$

$$v_D(\text{electrons}) \gg v_D(\text{ions}) \sim E/p$$

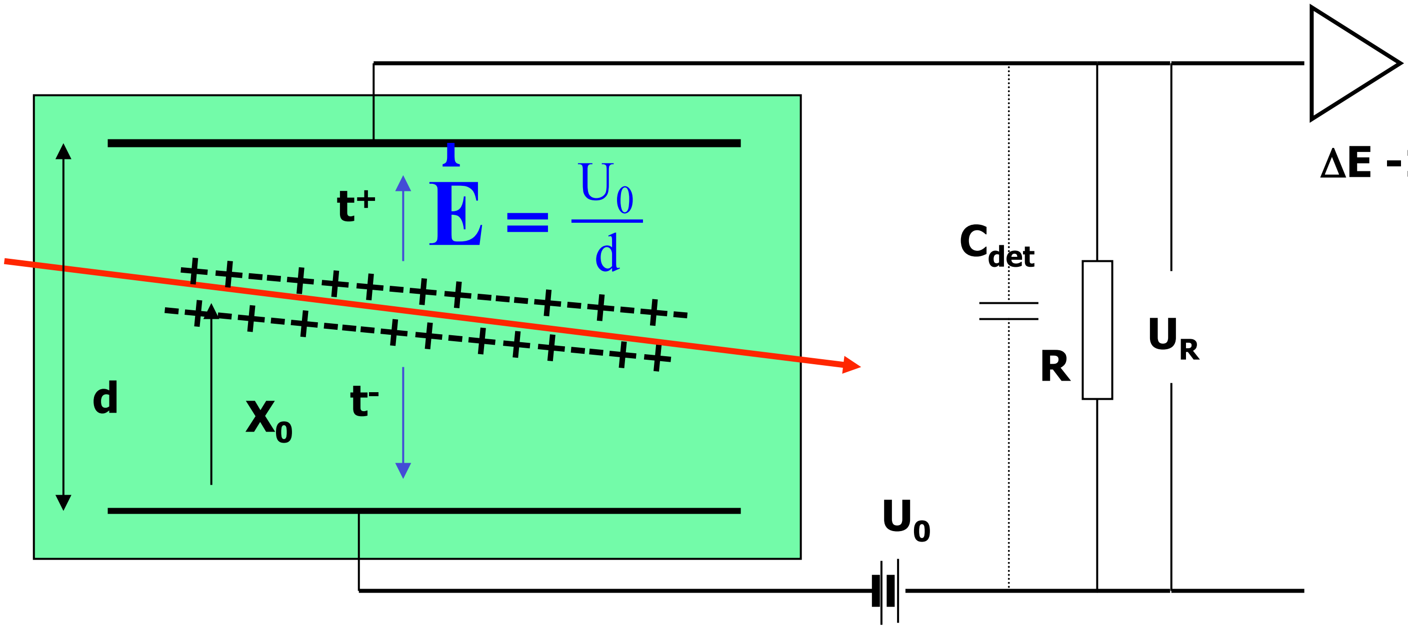
Drift velocity for ions



Drift velocity for electrons



Ionisation chamber



ΔE -> charges $\Delta Q^+ = Ne$
and $\Delta Q^- = - Ne$

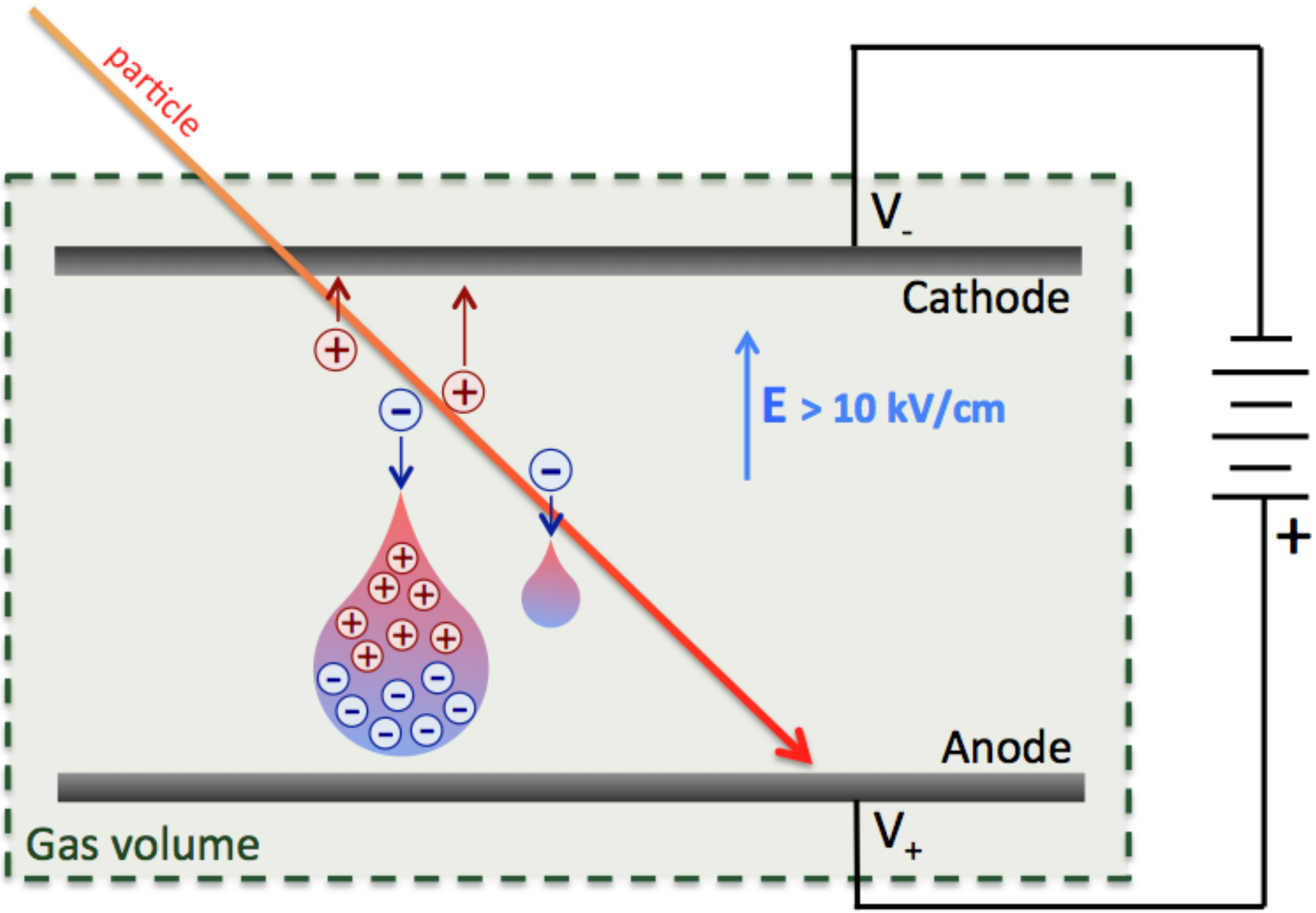
Drift velocity v_D

$v_D(e^-) >> v_D(ions)$

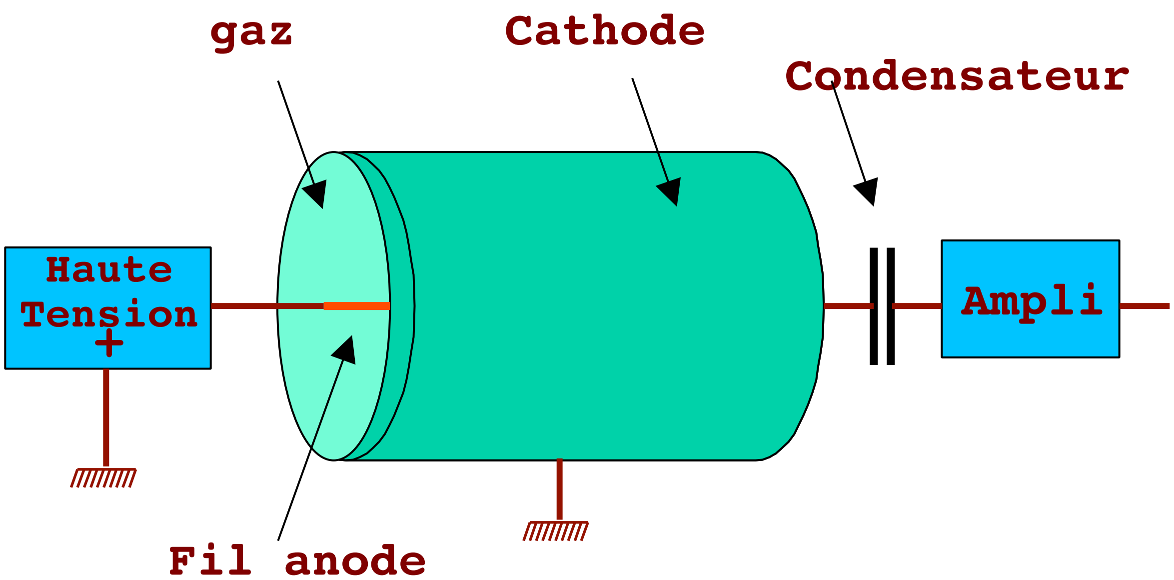
$v_D \sim E/p$

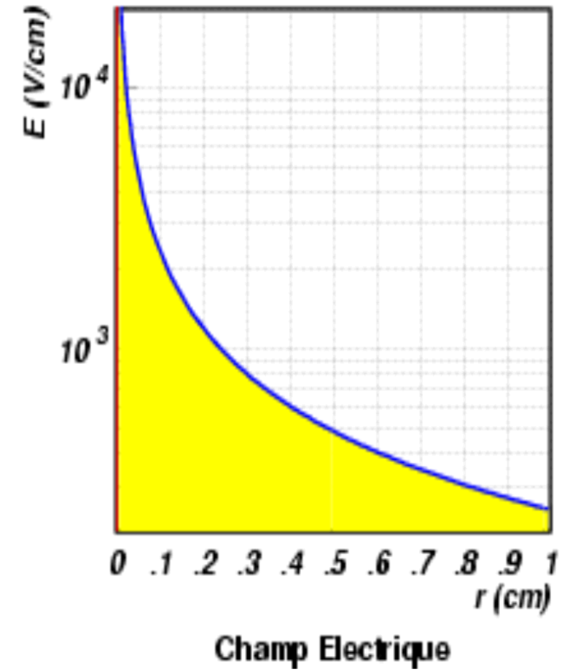
$\Delta U_{max} = \Delta Q/C$

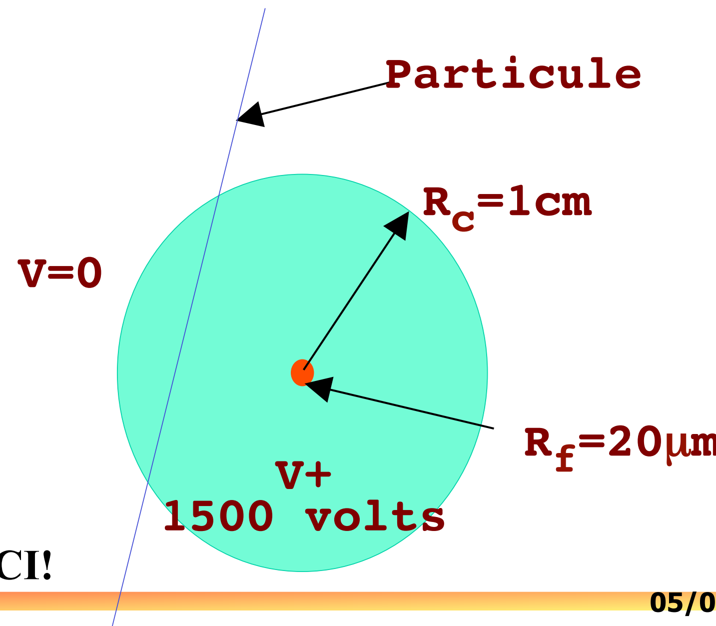
Proportional Counters



Proportional Counters





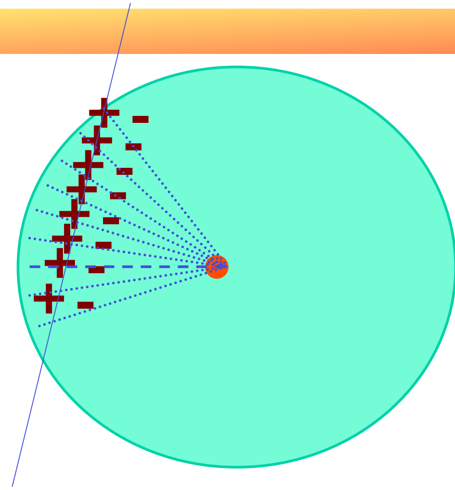


Après B.Jean-Marie, Roscoff 2000, école IN2P3, MERCI!

T=0

Passage of a charged particle

Creation of paires ion-electron.

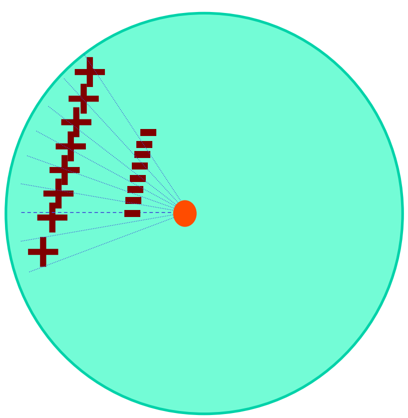


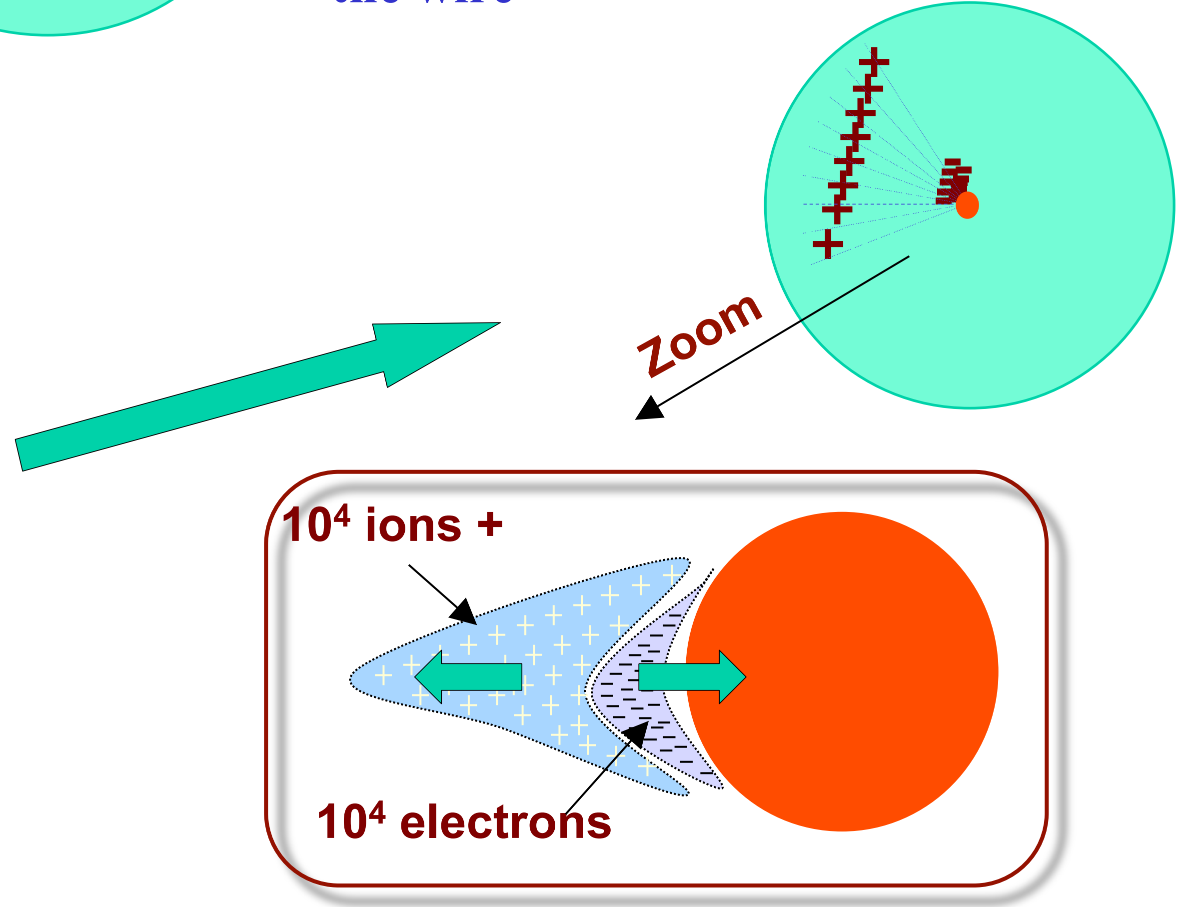
T~100ns

The primary electrons have sufficient energy to ionize the gas. This multiplication happens close to the wire, where the field is very high and stops when all electrons have reached the wire

T de 0 à 100ns

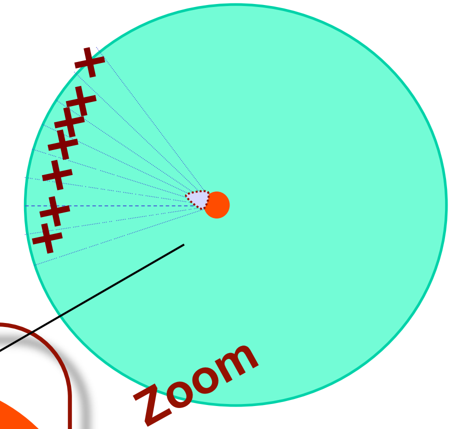
Ions and electrons are separated by the electric field.

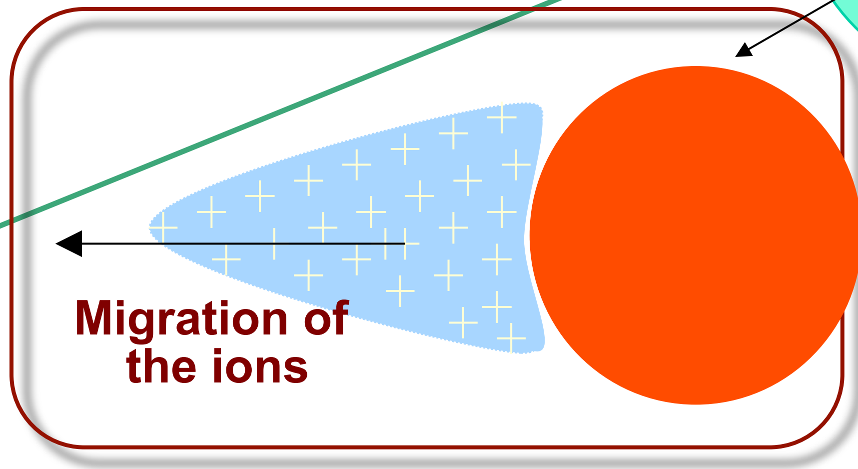


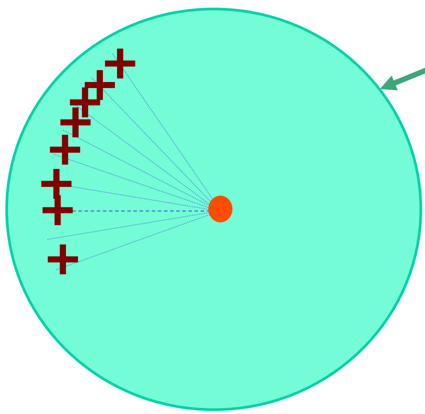


T~150ns

The electrons have been collected by the wire, all ions (primary and secondary) migrate slowly to the cathode. An electric signal is produced by this mouvement of the charges







T some ms

The secondary ions from the avalanche have reached the cathode, the counter is ready for the next particle .

The essential points:

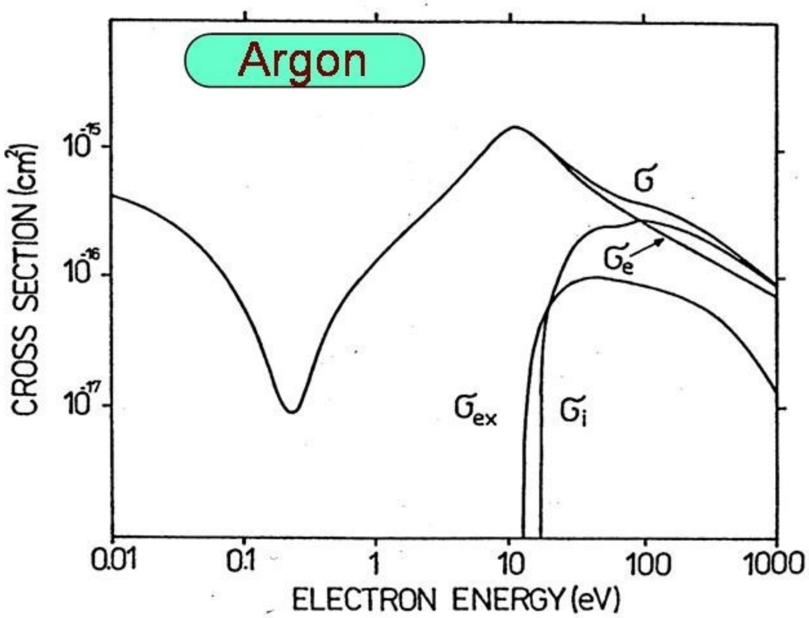
⇒ **Very high field close to the anode wire**

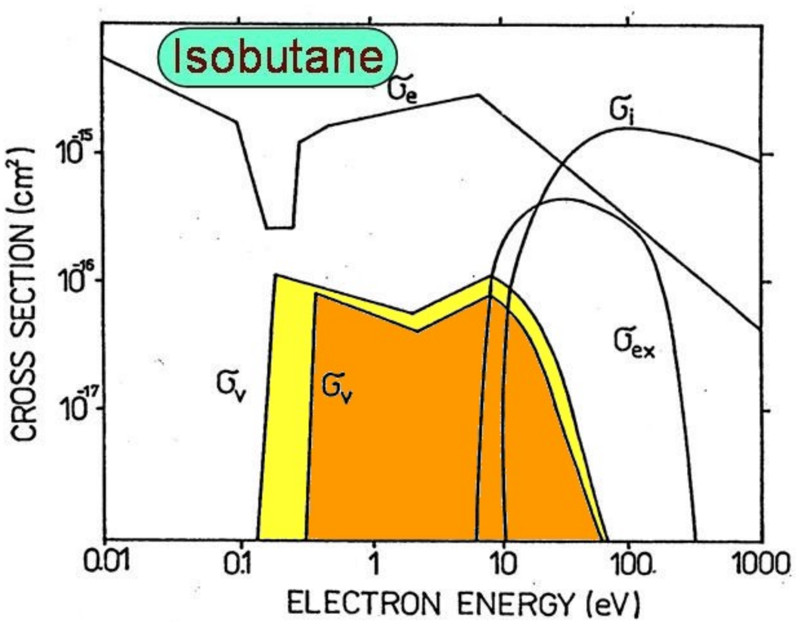
⇒ **Creation af an avalanche around the anode**

⇒ **Slow motion of the ions**

⇒ **The gas is at the same time the detecting and amplifying material**

The role of the gas





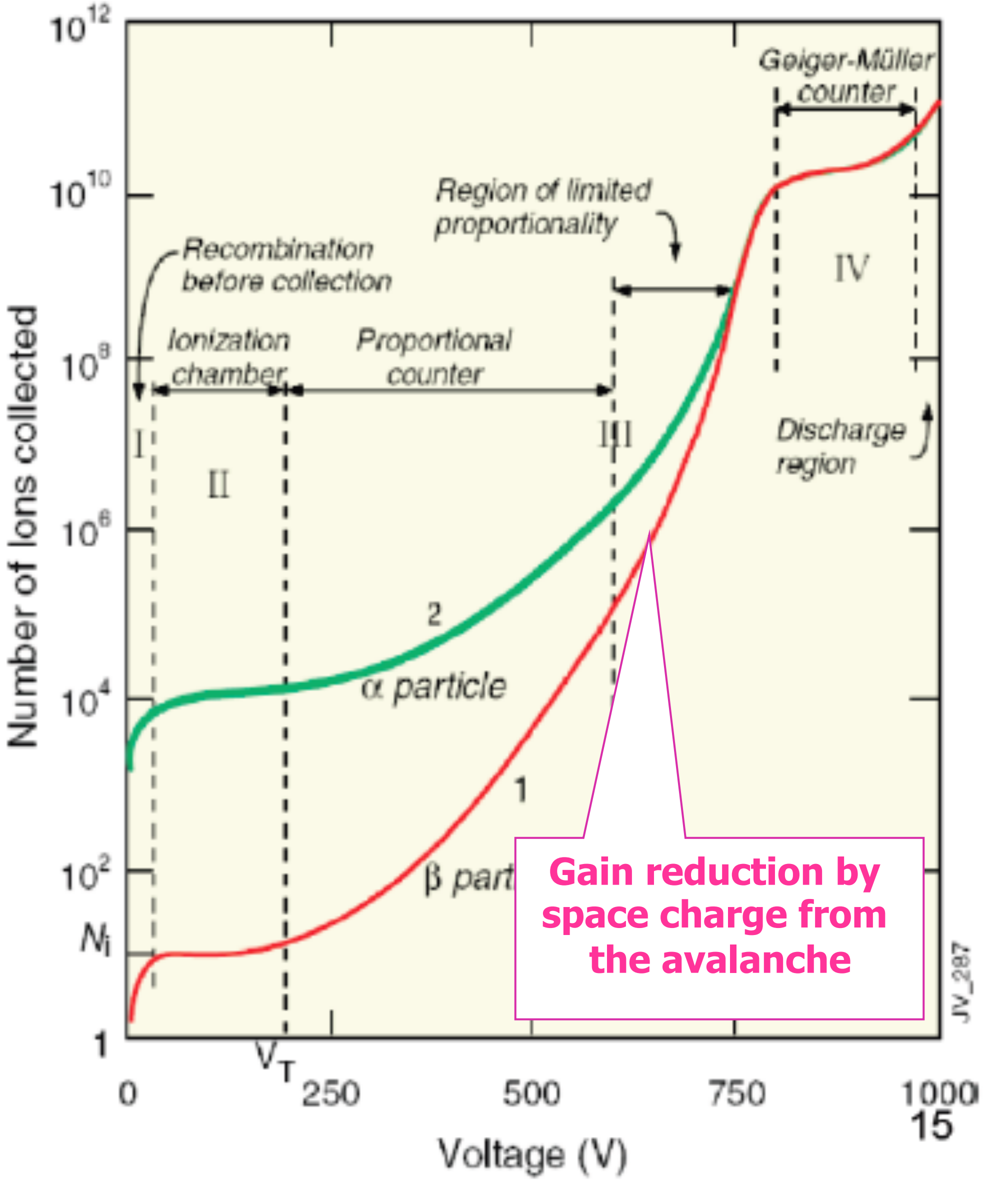
In practice one uses a mixture of gases, a noble gas and a molecular gas:

Noble gas: Ar, He, neon, xenon, krypton to favour ionisation.

High excitation energies, the photons from the de-excitation can generate new electrons by photoelectric effect on the cathode, which will provoke a second avalanche and so on. The detector is not stable

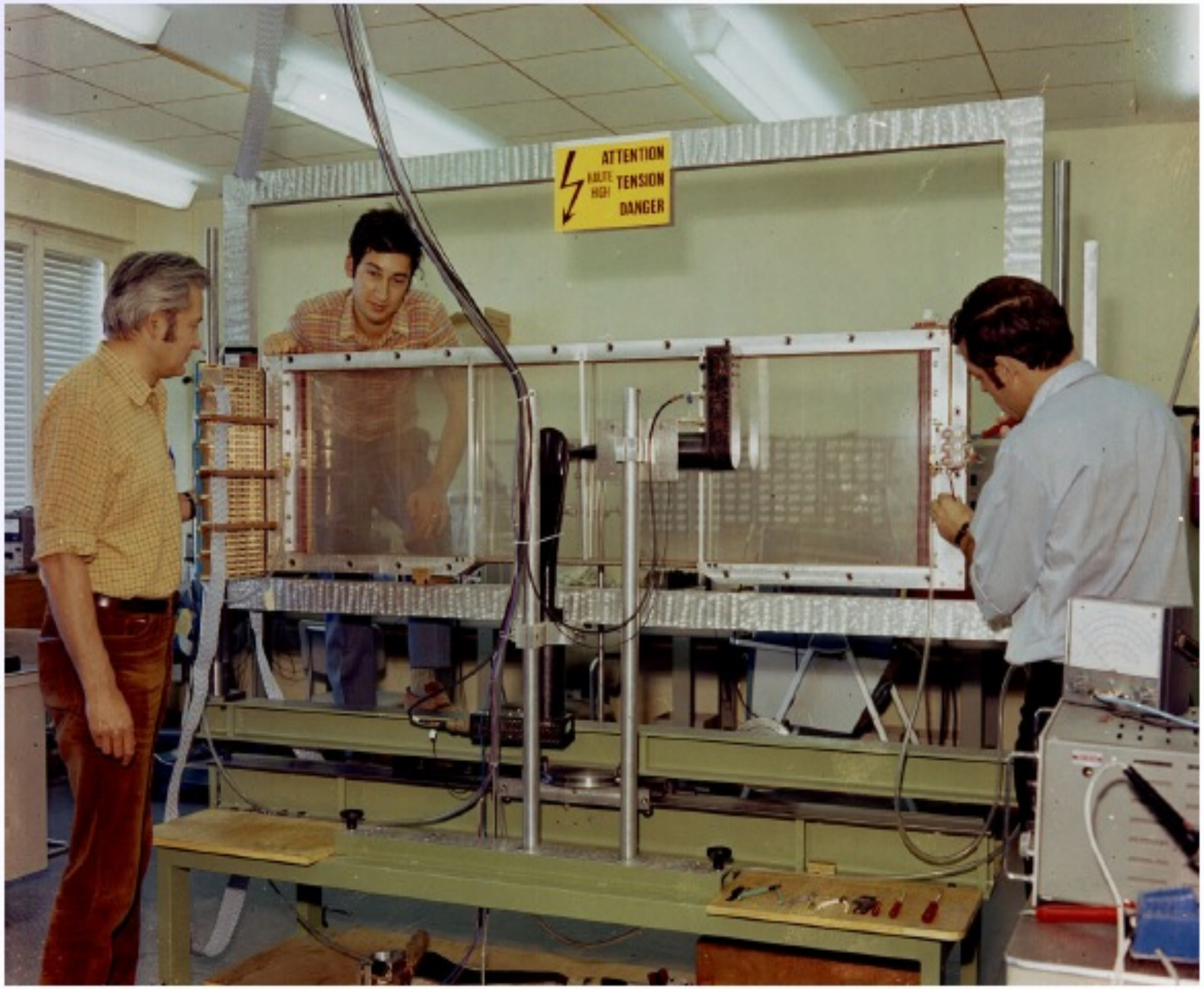
A molecular gas: CO_2, CH_4, C_2H_6, C_4H_{10}, have a lot of vibrational and rotational degrees of freedom. These exitations can absorbe some of these photons.

Simplified scheme of different regimes of gas counters



- **I.** ionization mode: full charge collection, but no multiplication;
- **II.** proportional mode: multiplication of ionization; detected signal proportional to original ionization → possible energy measurement (dE/dx); secondary avalanches are quenched; gain ~ $10^4 - 10^5$
- **III.** limited proportional mode (saturated, streamer) strong photoemission; secondary avalanches merging with original avalanche; requires strong quenchers or pulsed HV; large signals → simple electronics; gain ~ 10^{10}
- **IV.** Geiger mode – massive photoemission; full length of the anode wire affected; discharge stopped by HV cut; strong quenchers needed as well

CERN Academic Training Programme 2004/2005



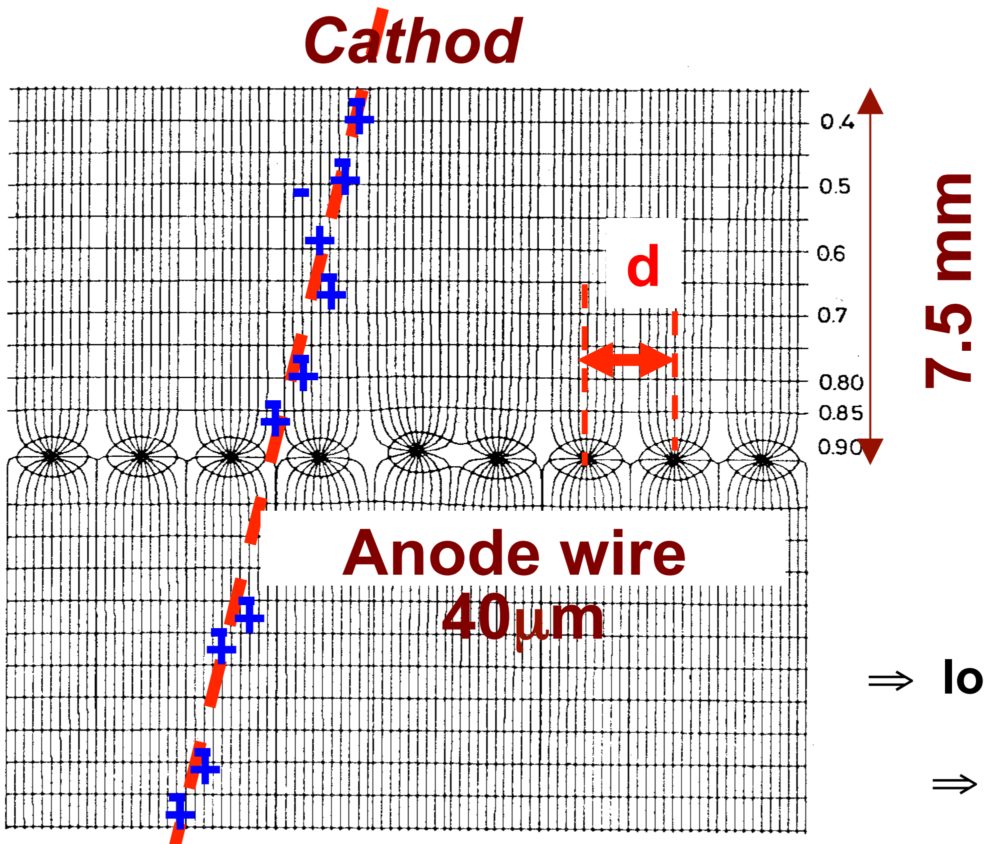
G. Charpak, F. Sauli and J.C. Santiard

1970

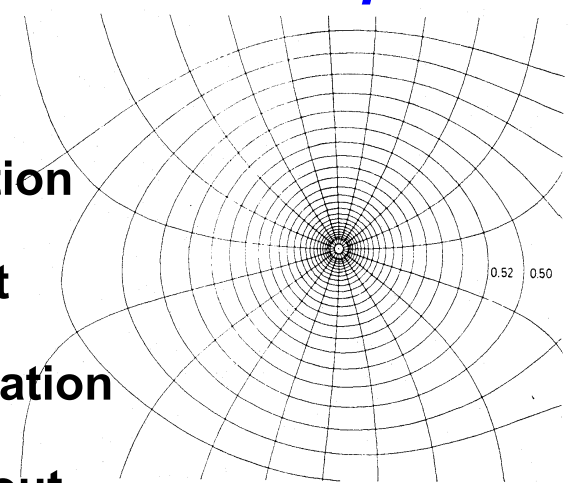
Multi Wire Proportional Chamber (MWPC)

Proposed by G. Charpak in 1967

- ***Wire:*** *tungsten 30-50µm,*
- ***Surface :*** *10x10cm² → 4×4m²,*
  t= *100ns*
- ***Counting:*** *10^5/fil,* ***signal:*** *qq mV,*
- ***gas:*** *argon+n-pentane.*
- ***Each wire is connected to an amplifier***



(a)



(b)

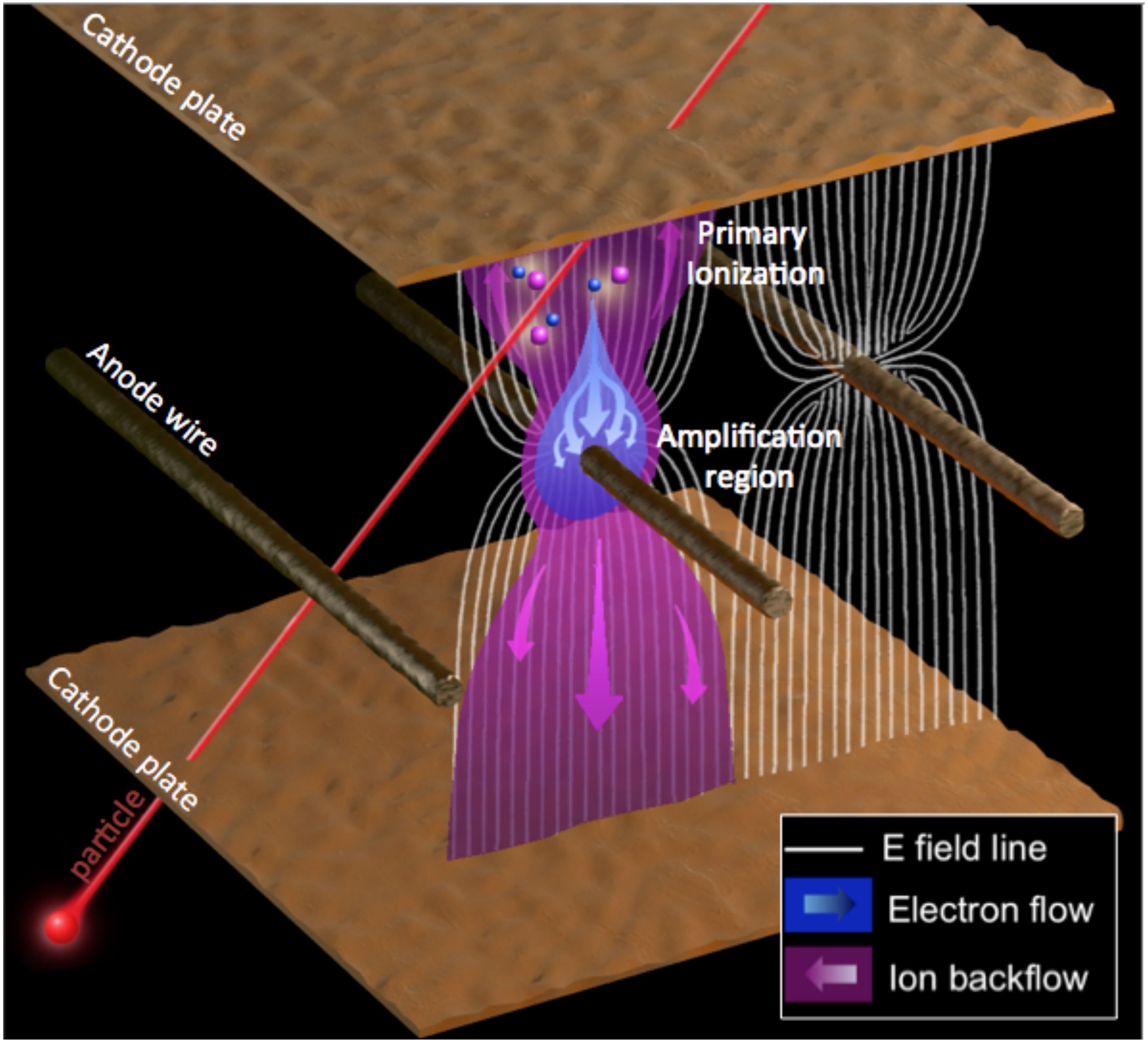
⇒ **Ionisation**

⇒ **Drift**

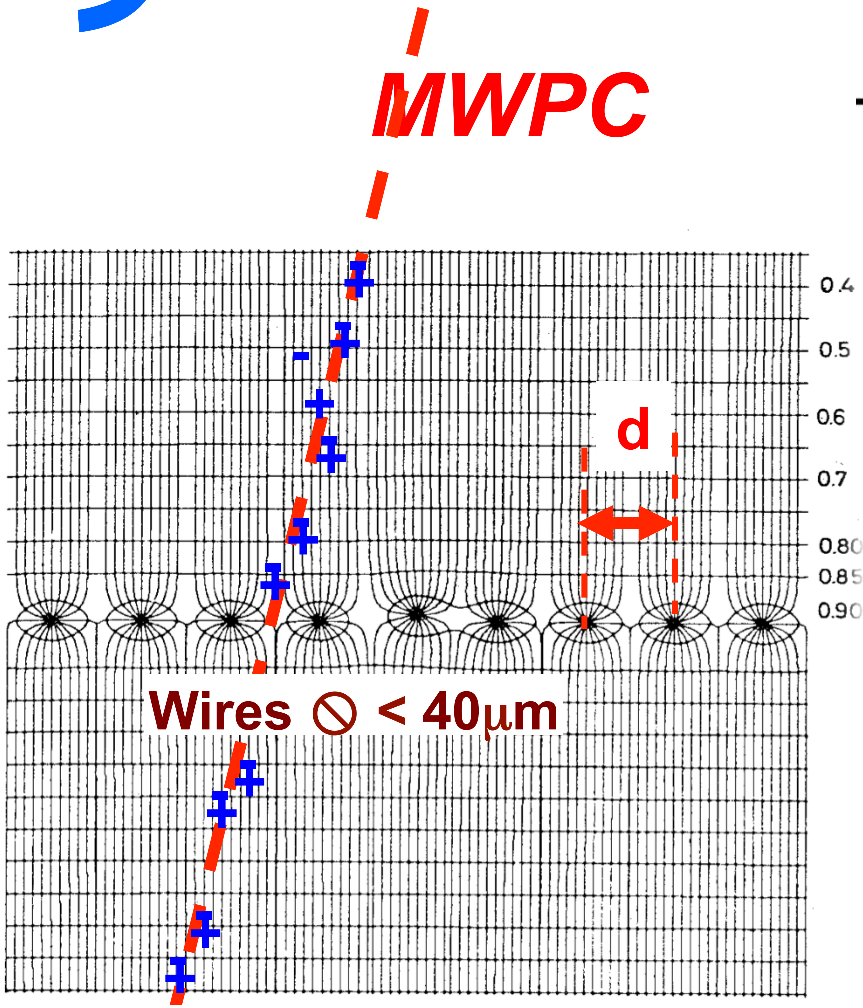
⇒ **Amplification**

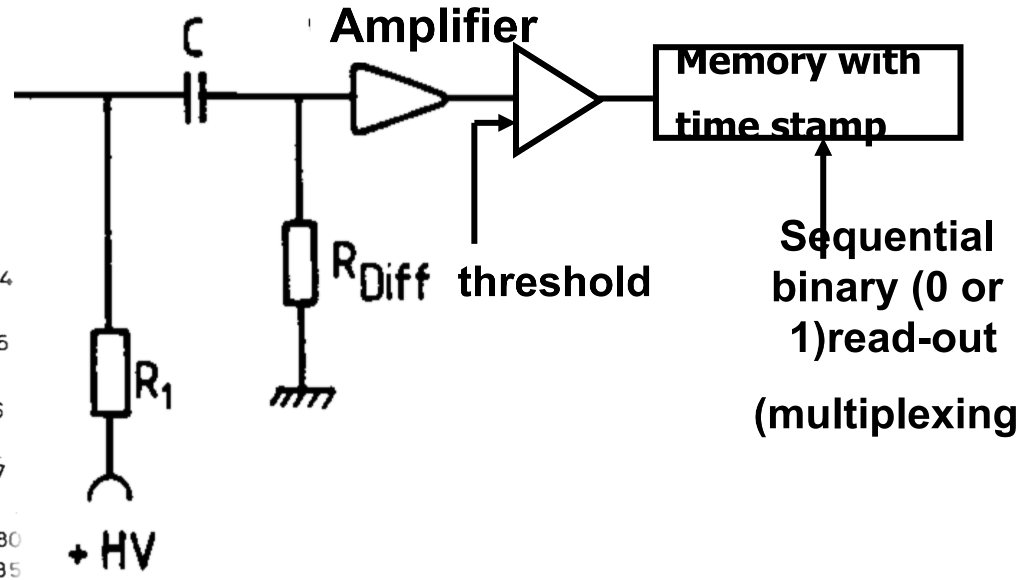
⇒ **Read-out**

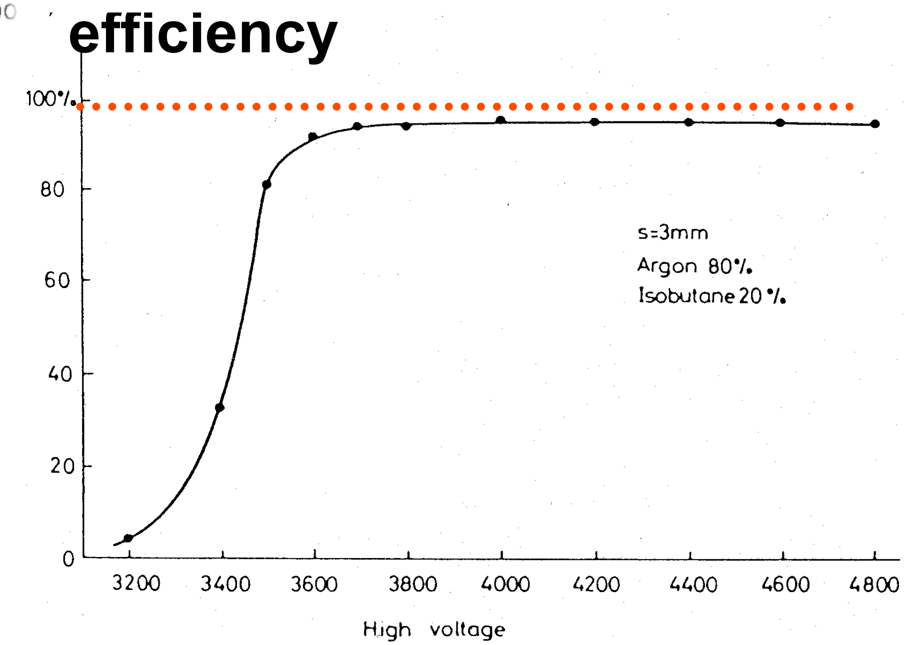
Spacial Resolution: d/√12


Cathode plate
Primary
Ionization
Anode wire
Amplification
region
Cathode plate
particle
E field line
Electron flow
Ion backflow

MWPC







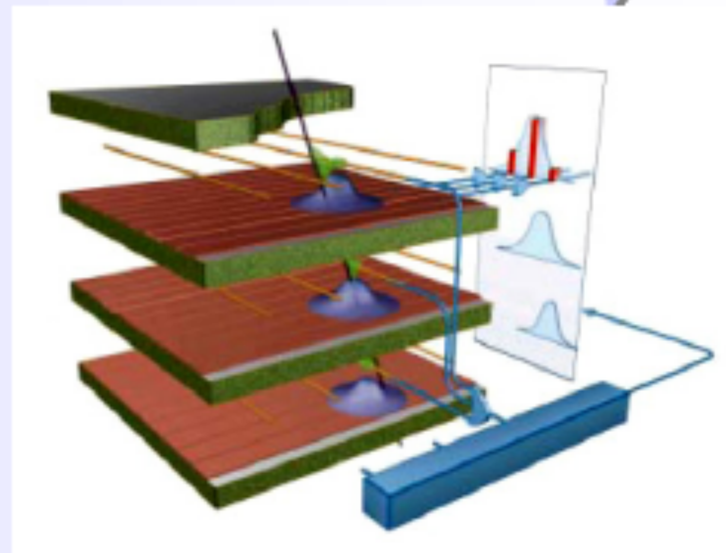
Binary read-out :

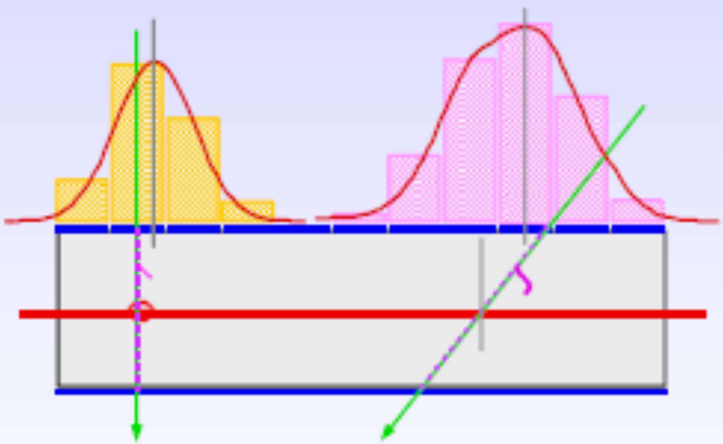
Resolution:

d/√12; d=2mm → σ ≈ 0,6 mm

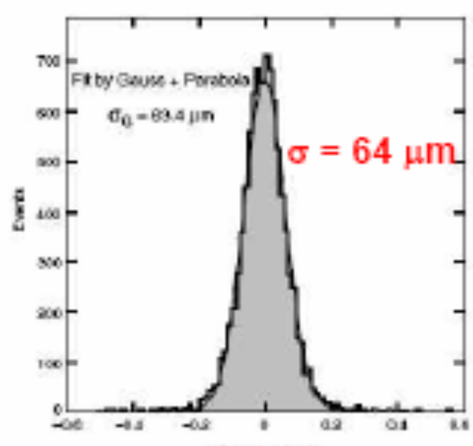
CSC – Cathode Strip Chamber

Precise measurement of the second coordinate by interpolation of the signal induced on pads.
Closely spaced wires makes CSC fast detector.





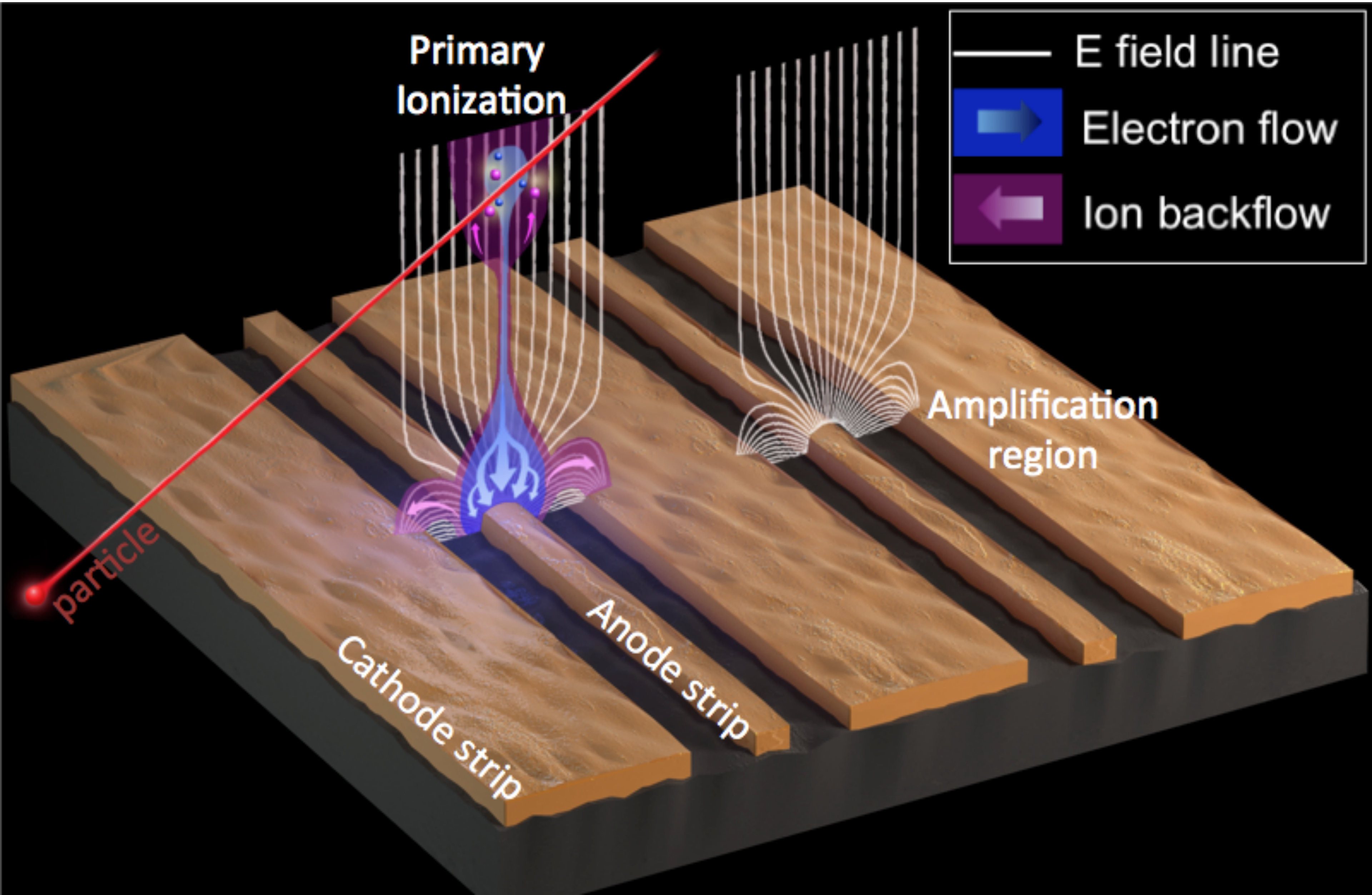
Center of gravity of induced signal method.



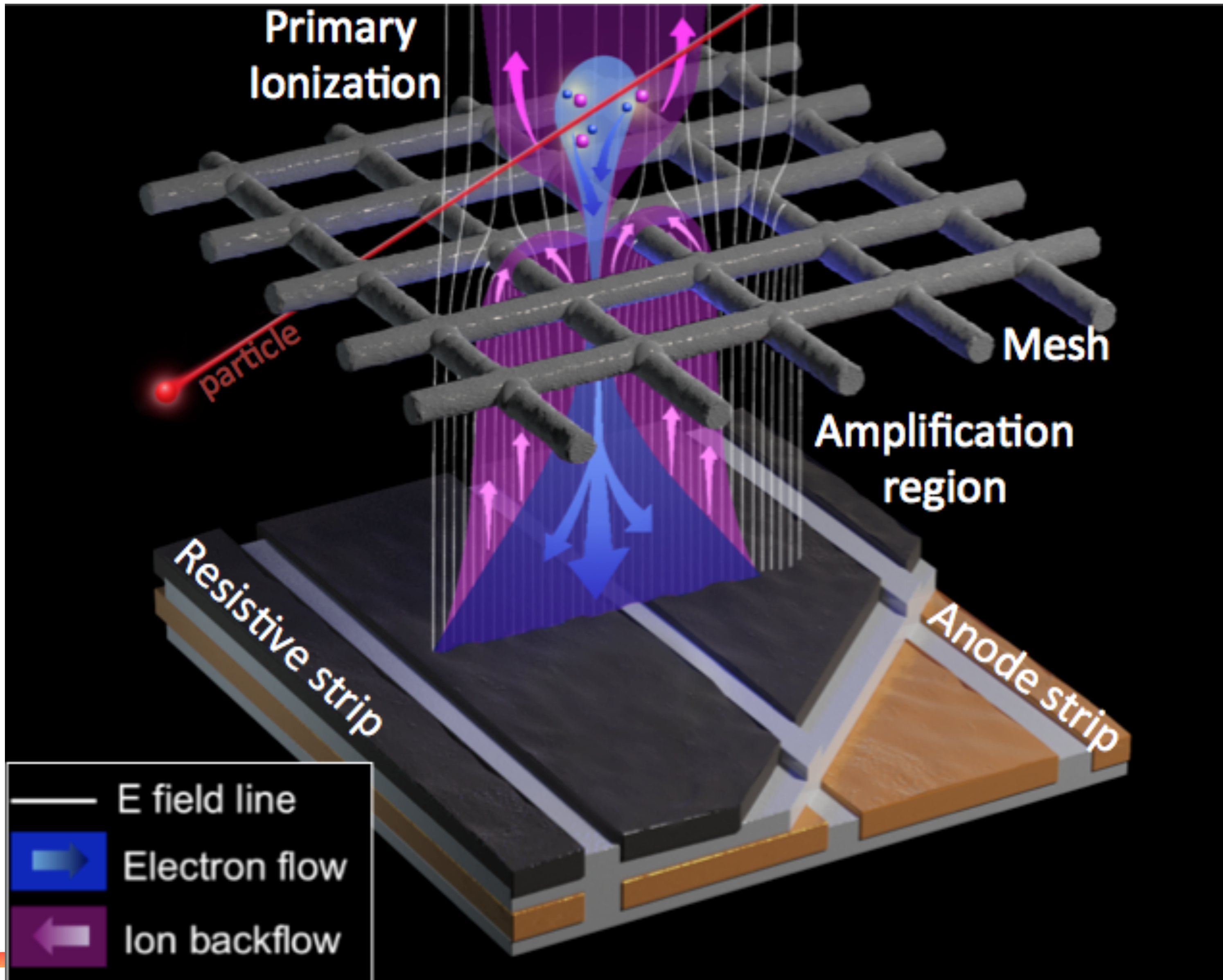
Space resolution

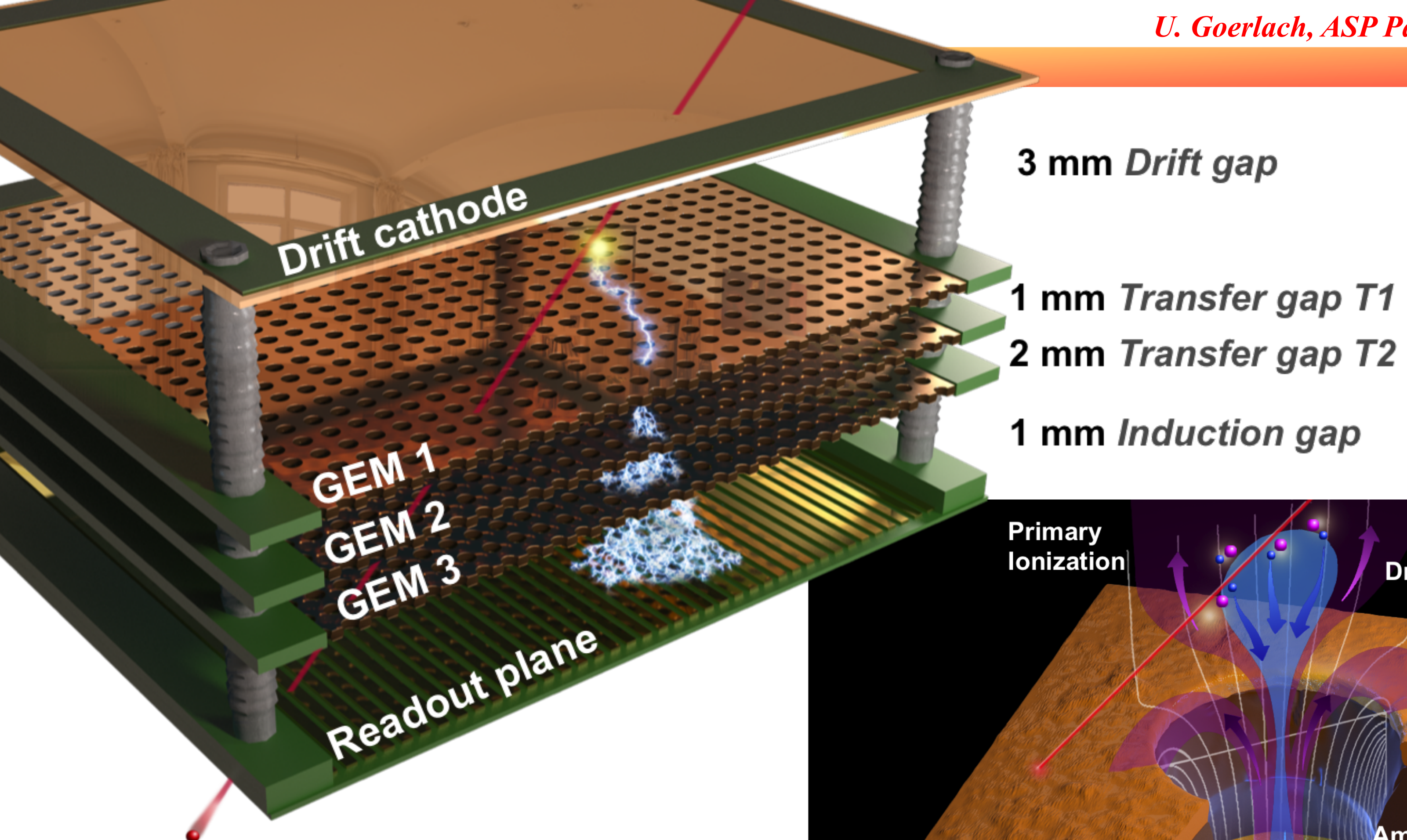
CMS

Micro-Strip-Gas-Chambers

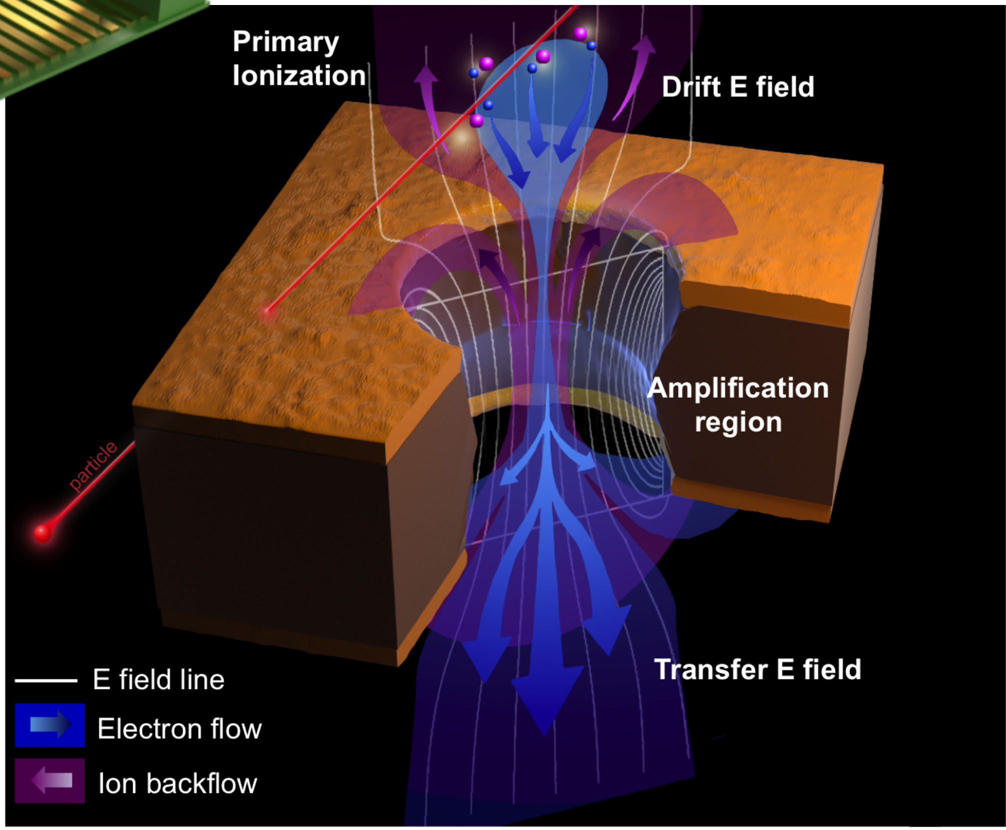


Micro MEshGAs Structure (Micromegas)





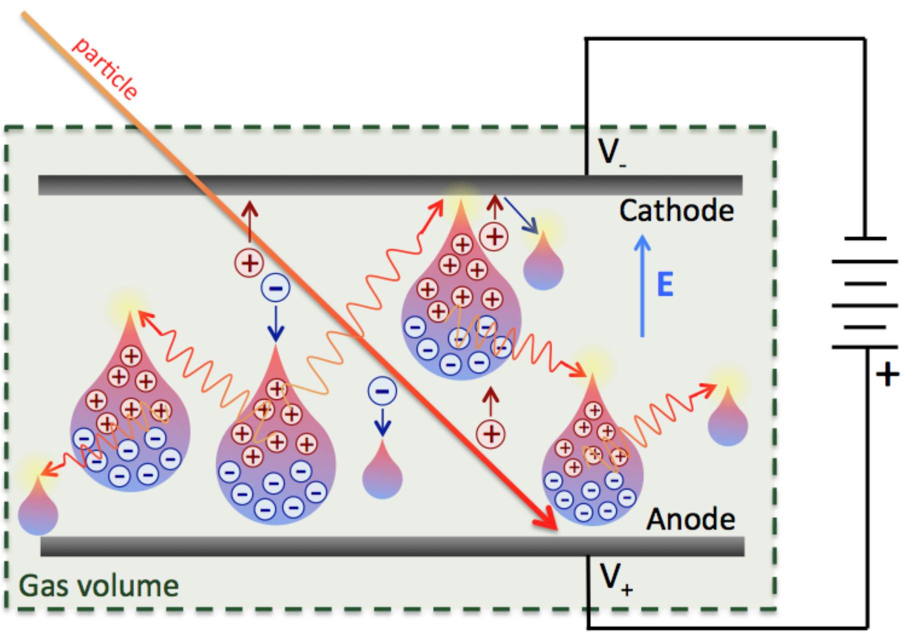
Gas-Electron-Multiplier (GEM)



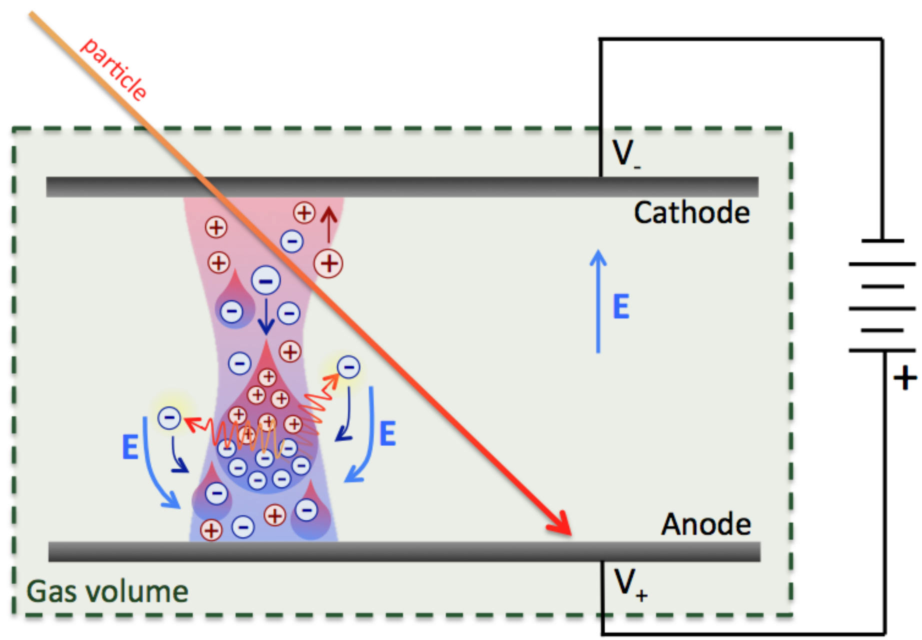
Proportional detectors

Geiger-Müller and Streamer modes

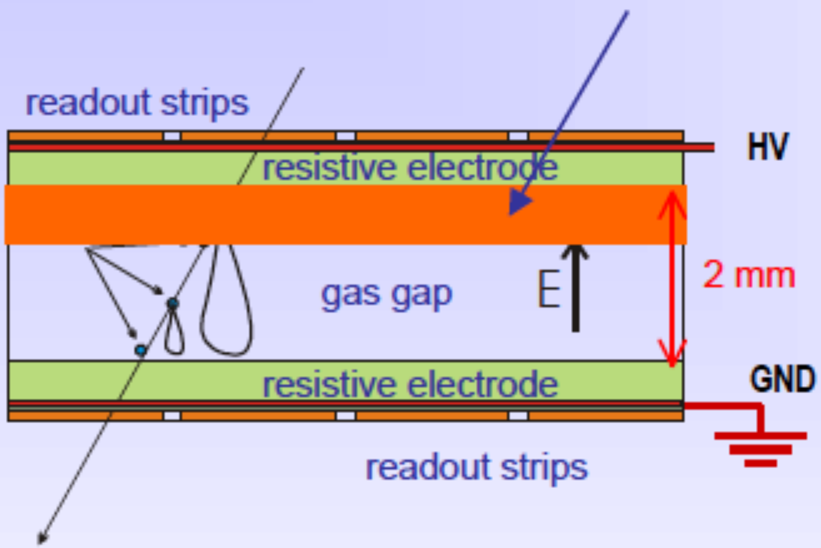
Schematic representation of Geiger-Muller counters.



Schematic representation of a Streamer in parallel plate detectors



RPC – Resistive Plate Chamber

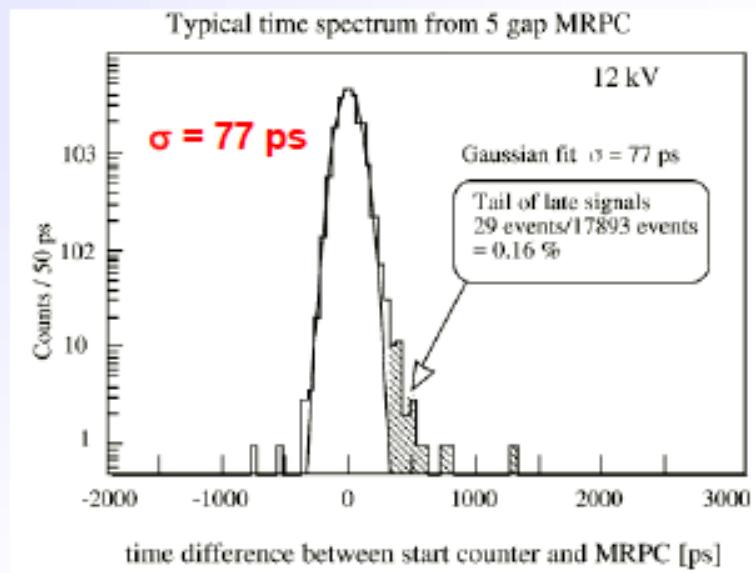


Rate capability strong function of the resistivity of electrodes in streamer mode.

MRPC

Multigap RPC - exceptional time resolution suited for the trigger applications

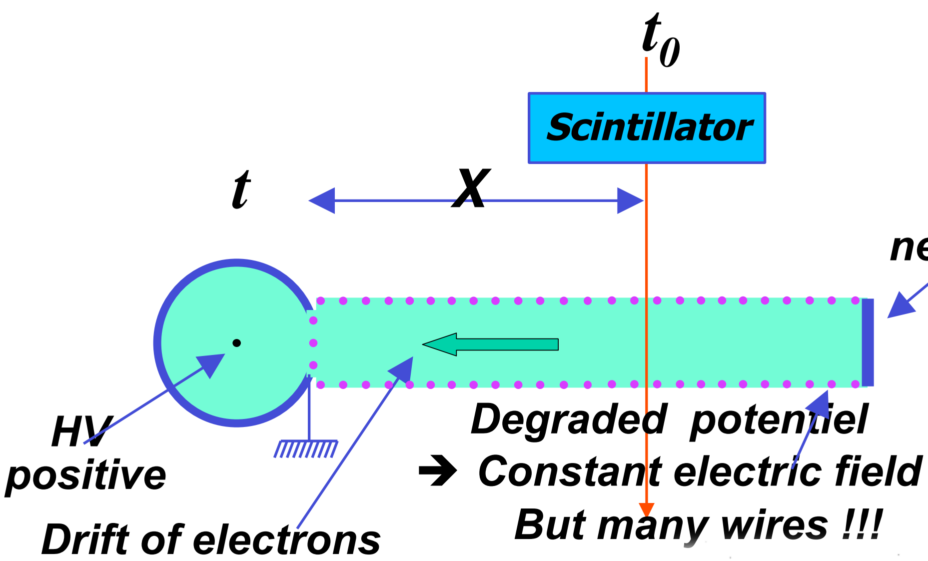
A. Akindinov et al., NIM A456(2000)16



Time resolution

CERN Academic Training Programme 2004/2005

Classical Drift Chambers

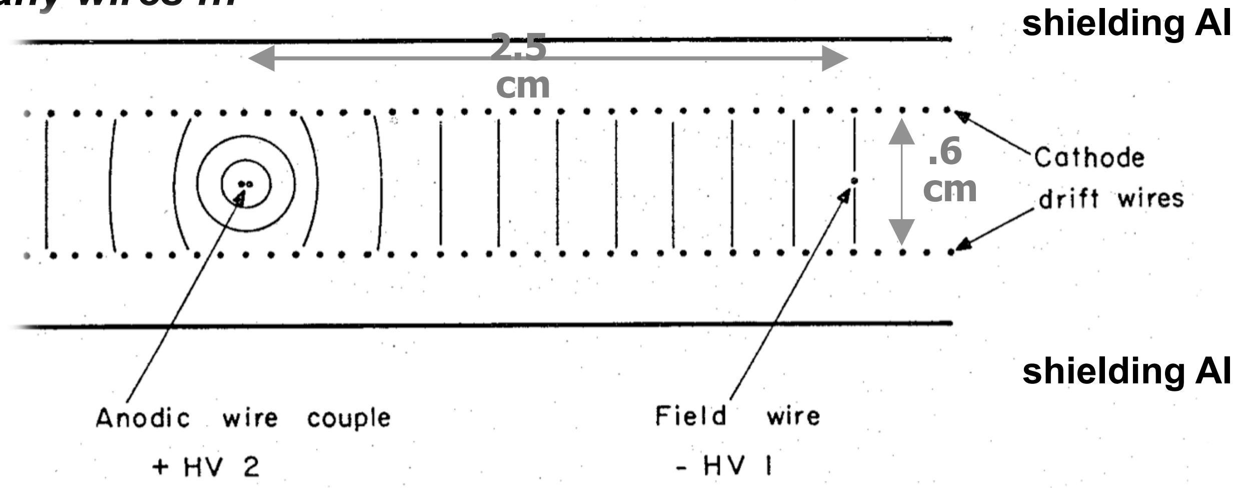


Drift velocity of electrons:

50 μm/ns

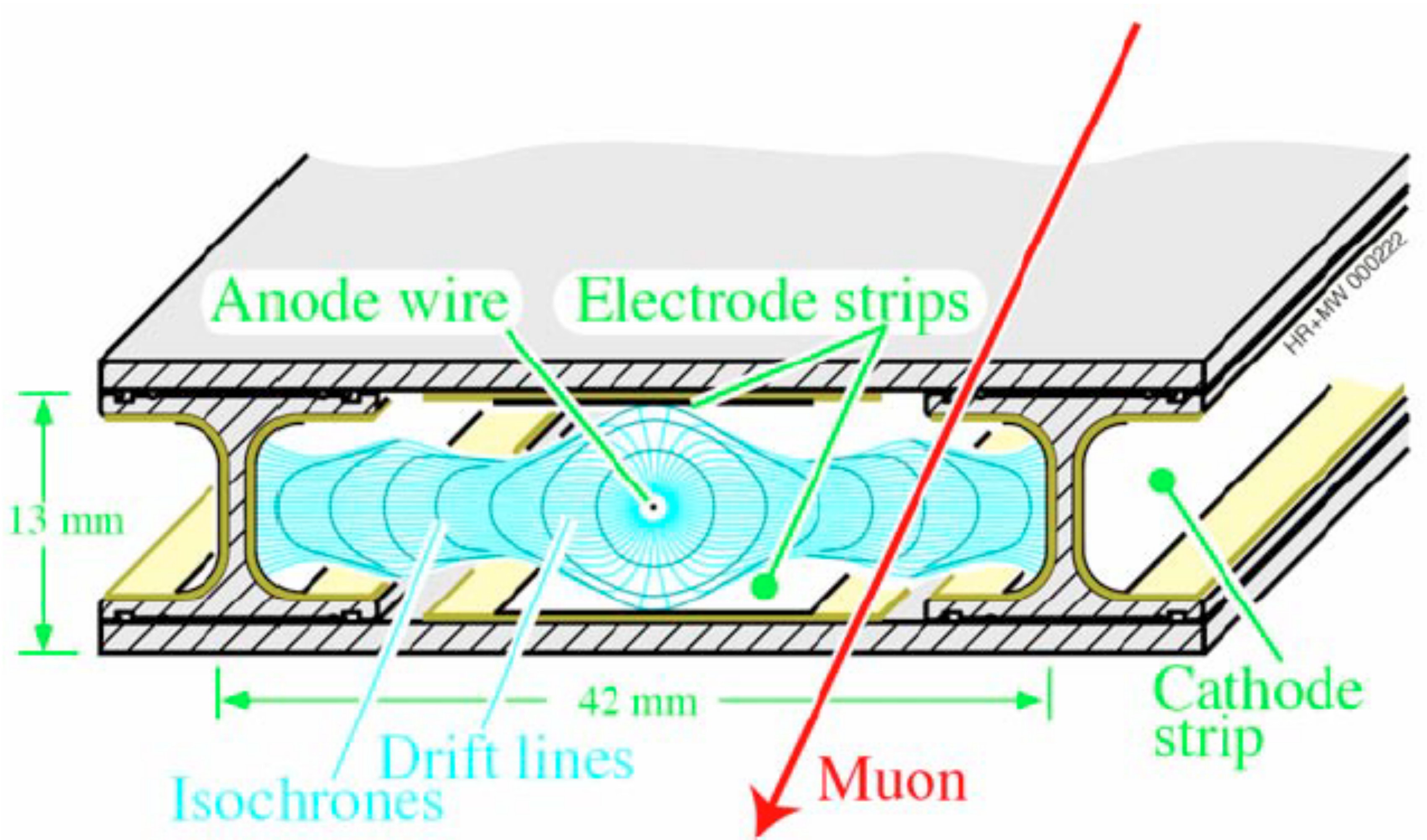
If the drift time is measured one can calculate the drift distance

Spacial resolution 100-200 μm

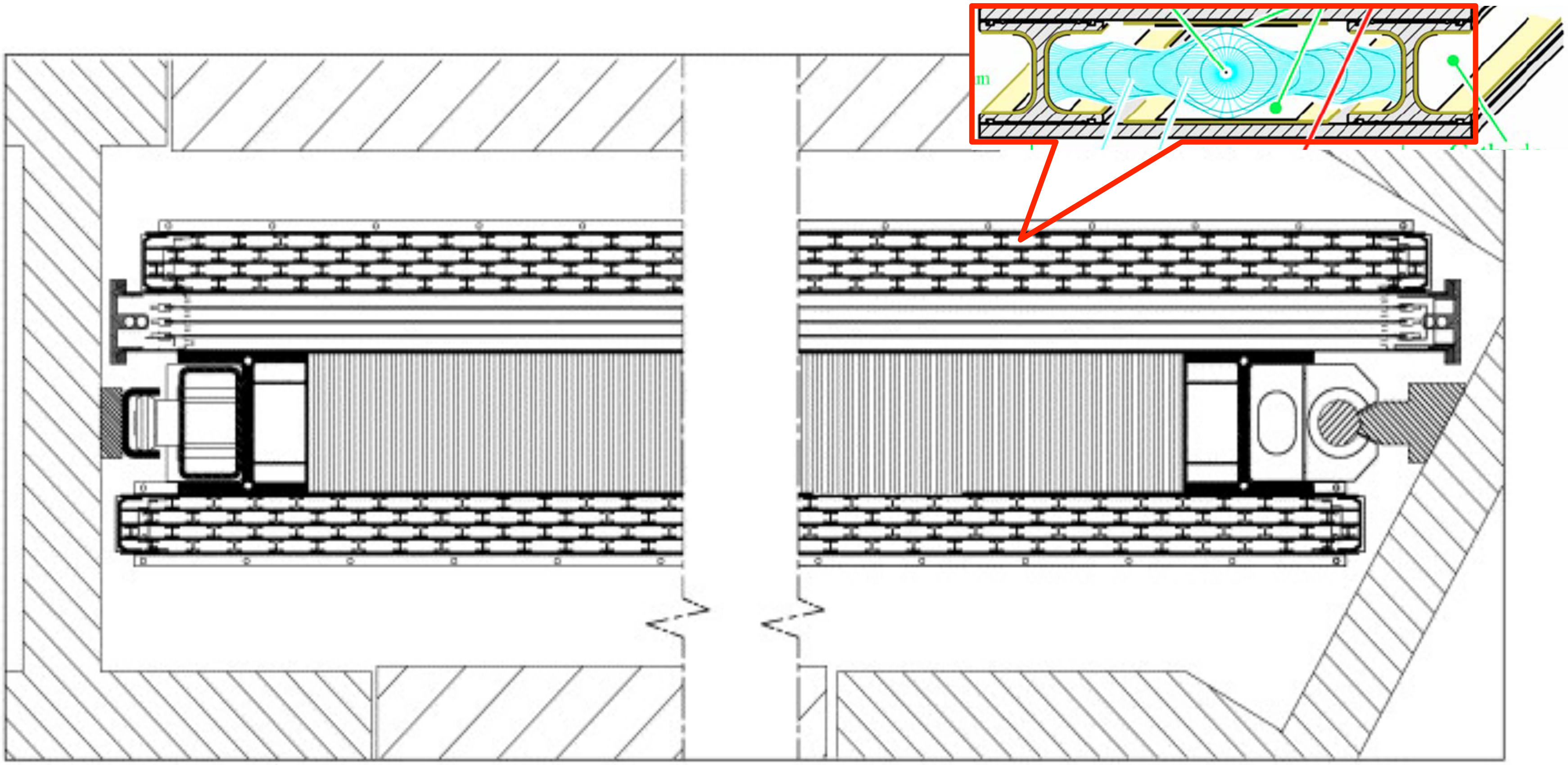


A. Breskin et al Nucl. Instr. Meth.A124 (1975) 189

Chambre_a_derive_2.pct

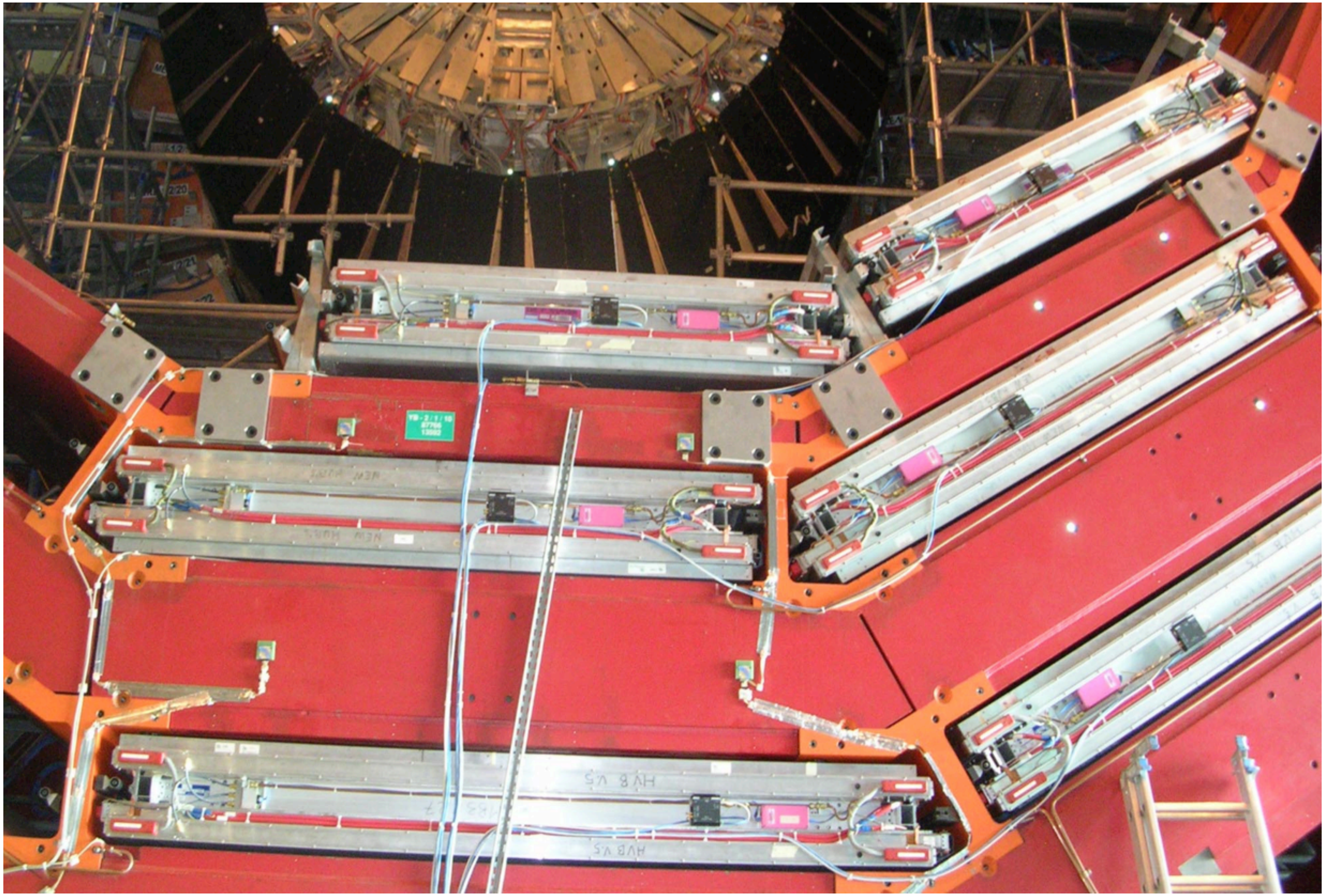

Anode wire
Electrode strips
HR+MW 000222
13 mm
42 mm
Cathode strip
Drift lines
Isochrones
Muon

CMS Muon chambers



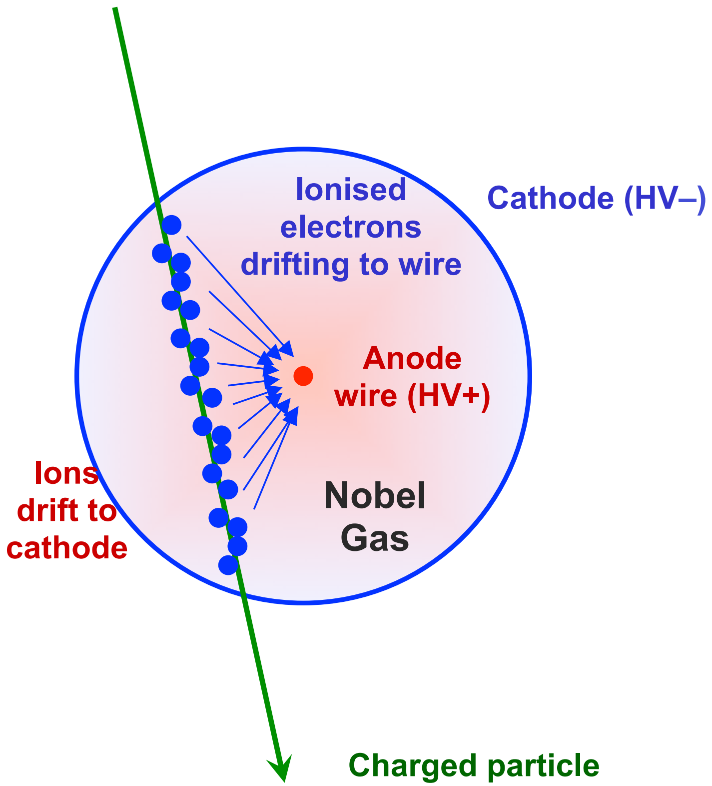
Cut view of a drift tube chamber in its final position inside the CMS iron yoke. Two superlayers with wires along the beam direction and a third crossed one can be seen as well as the honeycomb panel providing rigidity to the chamber.

CMS Muon chambers



Drift Tubes (DT) in ATLAS: inner detector and muon spectrometer

- Classical detection technique for charged particles based on gas ionisation and drift time measurement



- DTs used in muon systems and ATLAS TRT
- Primary electrons drift towards thin anode wire
- Charge amplification during drift ($\gtrsim 10^4$) in high E field in vicinity of wire: $E(r) \propto U_0 / r$
- Signal rises with number of primary e's (dE/dx) [signal dominated by ions → need differentiator]
- Macroscopic drift time: v_D / c ~10^{-4} → ~30 ns / mm
- Determine v_D from difference between DT signal peaking time and expected particle passage

➡ Spatial resolution of $O(100\ \mu m)$

TRT: Kapton tubes,	∅ = 4 mm
MDT: Aluminium tubes,	∅ = 30 mm

From D. Froidevaux, ASP 2010

The ATLAS Muon Spectrometer

Big wheel, Feb 2007

From D. Froidevaux, ASP 2010

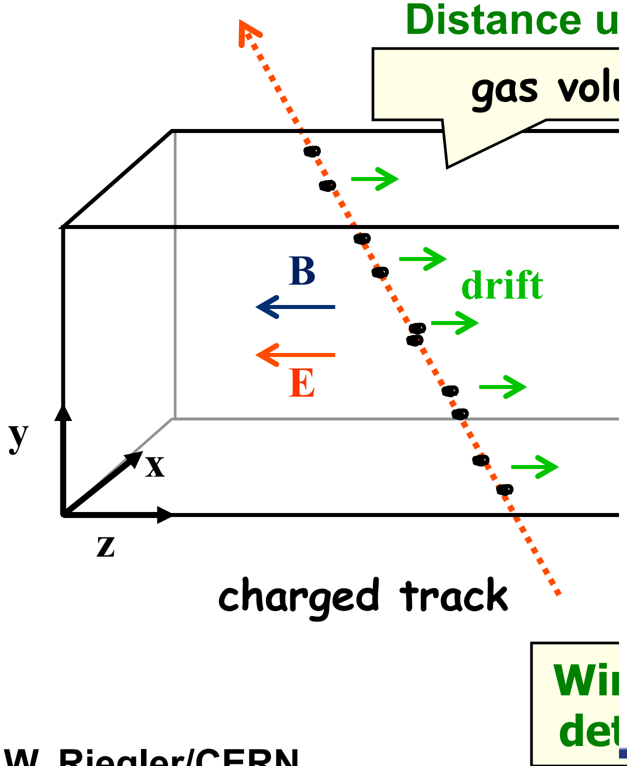
Time Projection (

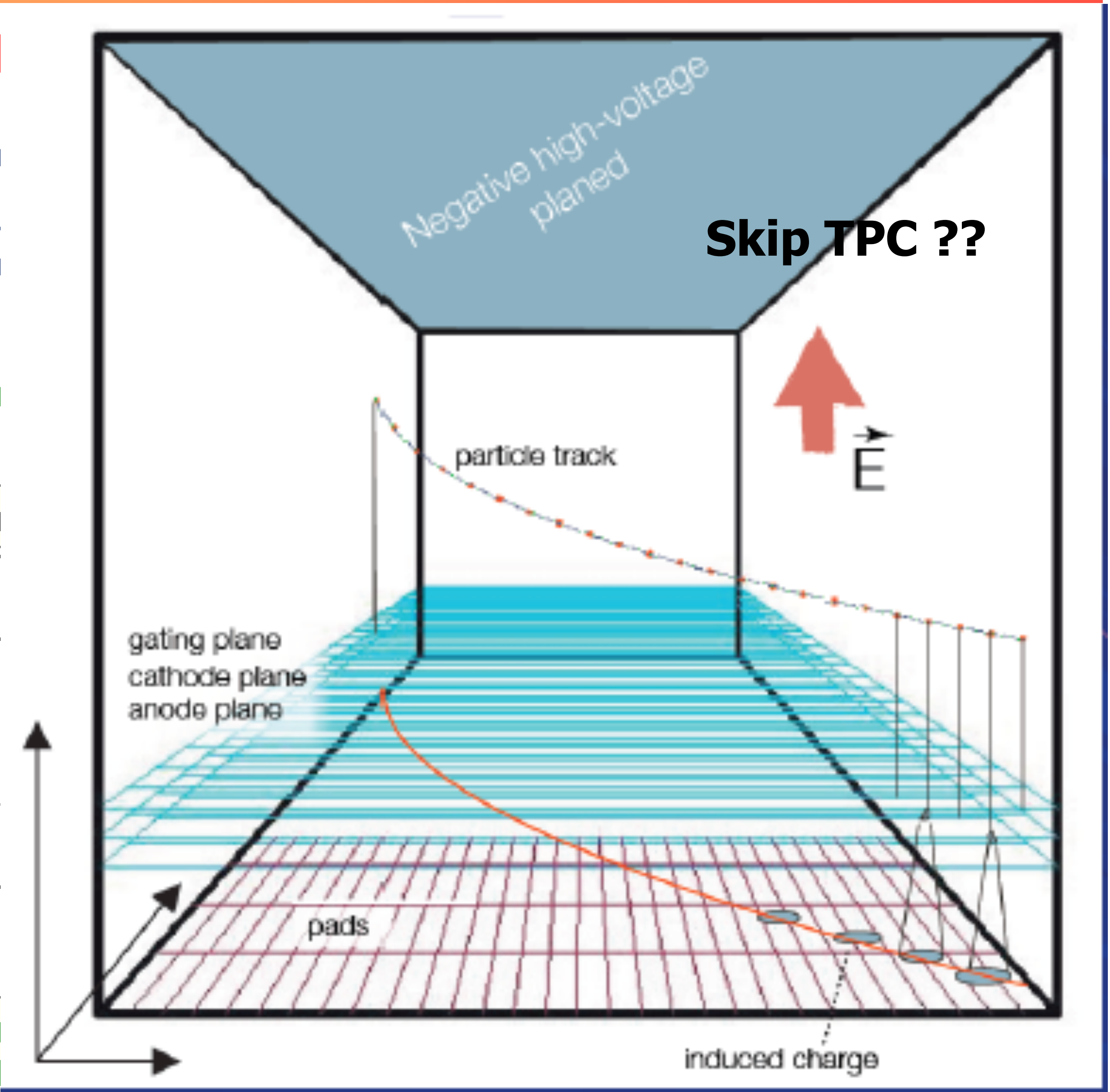
Gas volume with pa

B for momentum measu
Diffusion is strongly reduc

Drift Fields 100-400V/cn

Distance u





W. Riegler/CERN

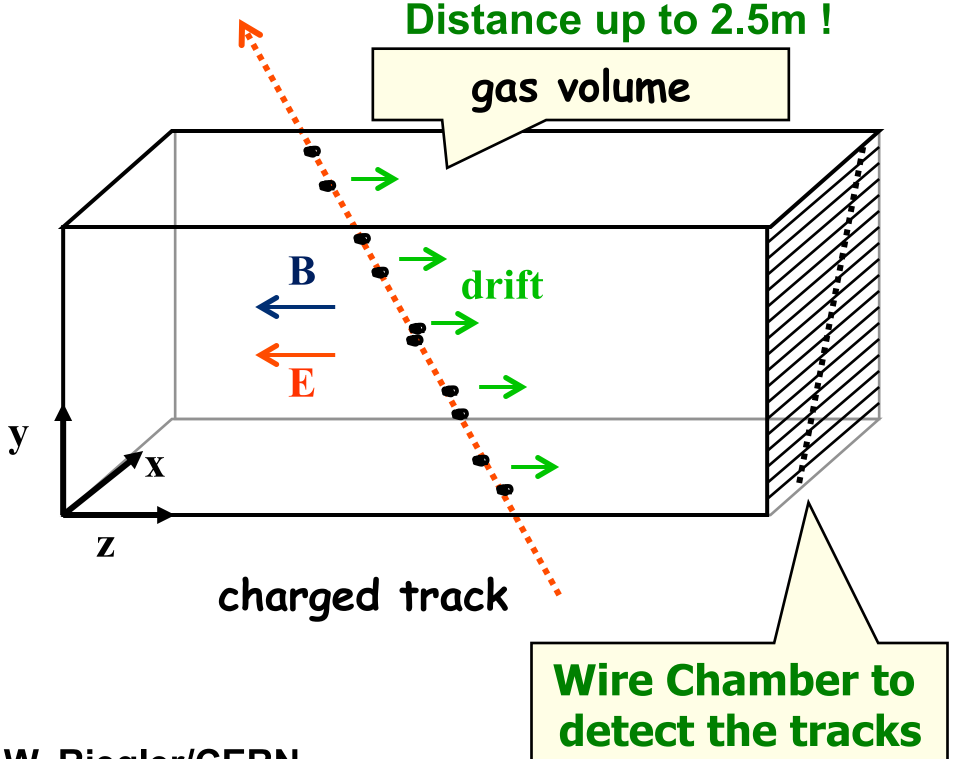
Time Projection Chamber (TPC):

Gas volume with parallel E and B Field.

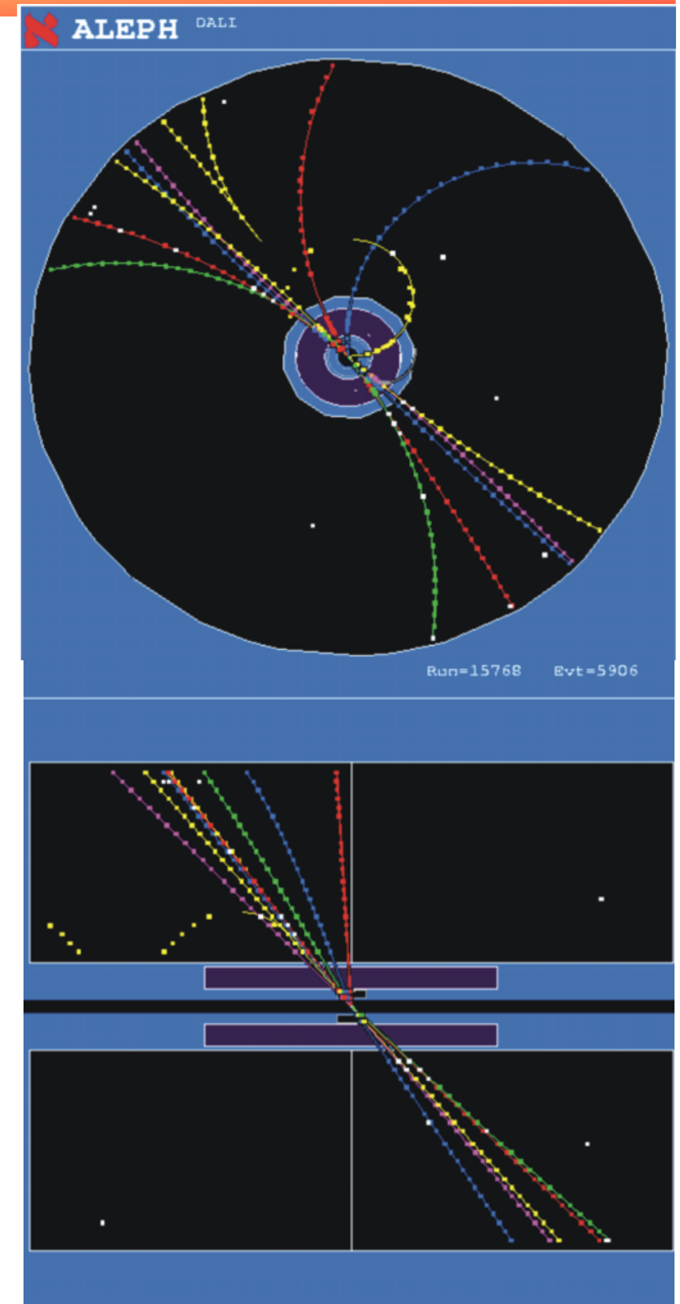
**B for momentum measurement. Positive effect:
Diffusion is strongly reduced by E//B (up to a factor 5).**

Drift Fields 100-400V/cm. Drift times 10-100 μs.

Distance up to 2.5m !



W. Riegler/CERN



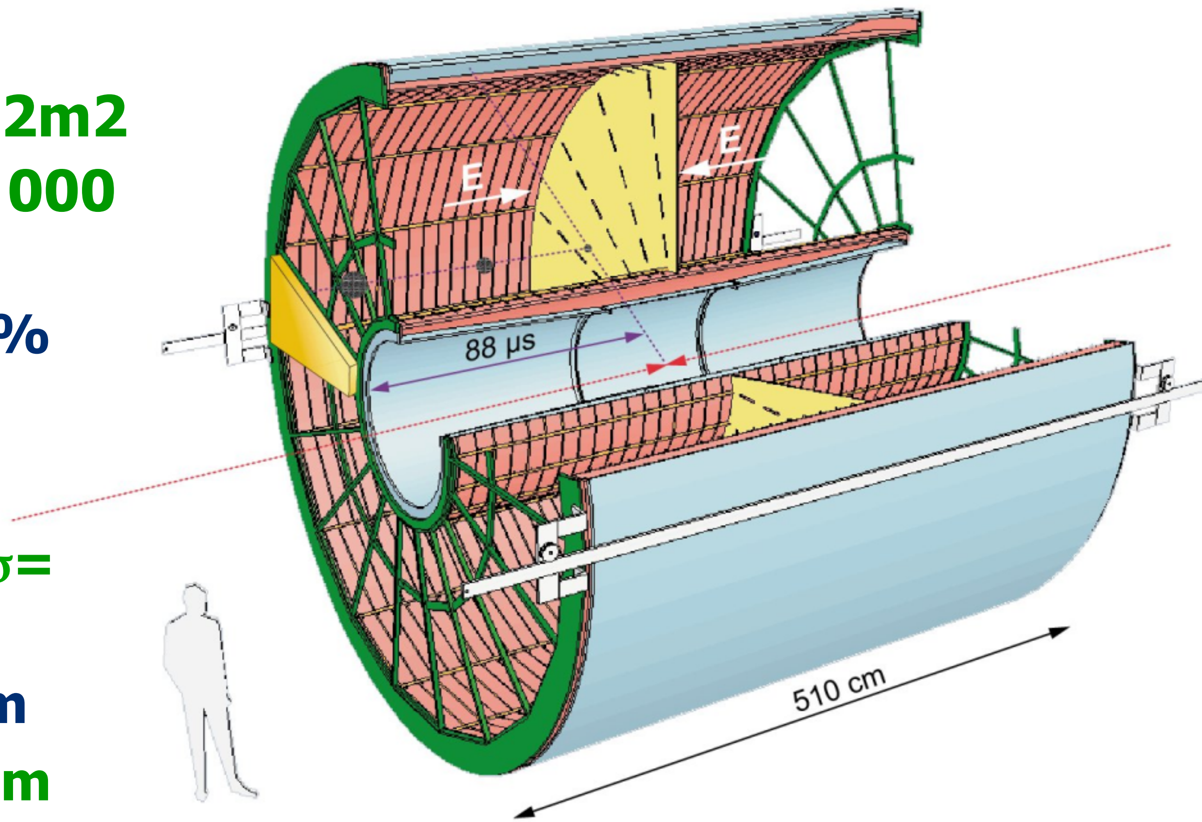
O.Ullaland CERN 2005

ALICE TPC: Detector Parameters

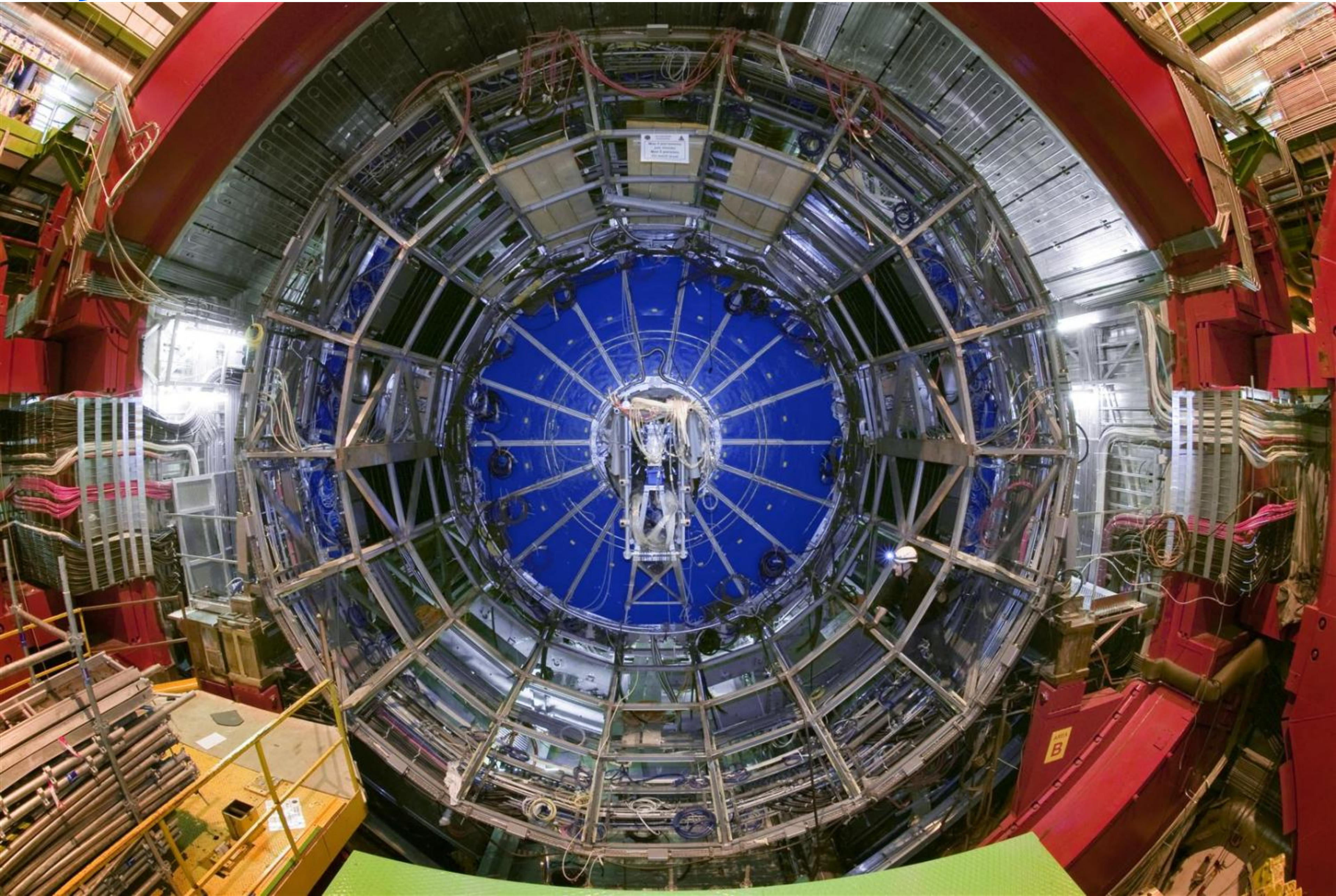
Largest TPC:

- Length 5m
- Diameter 5m
- Volume 88m3
- Detector area 32m2
- Channels ~570 000

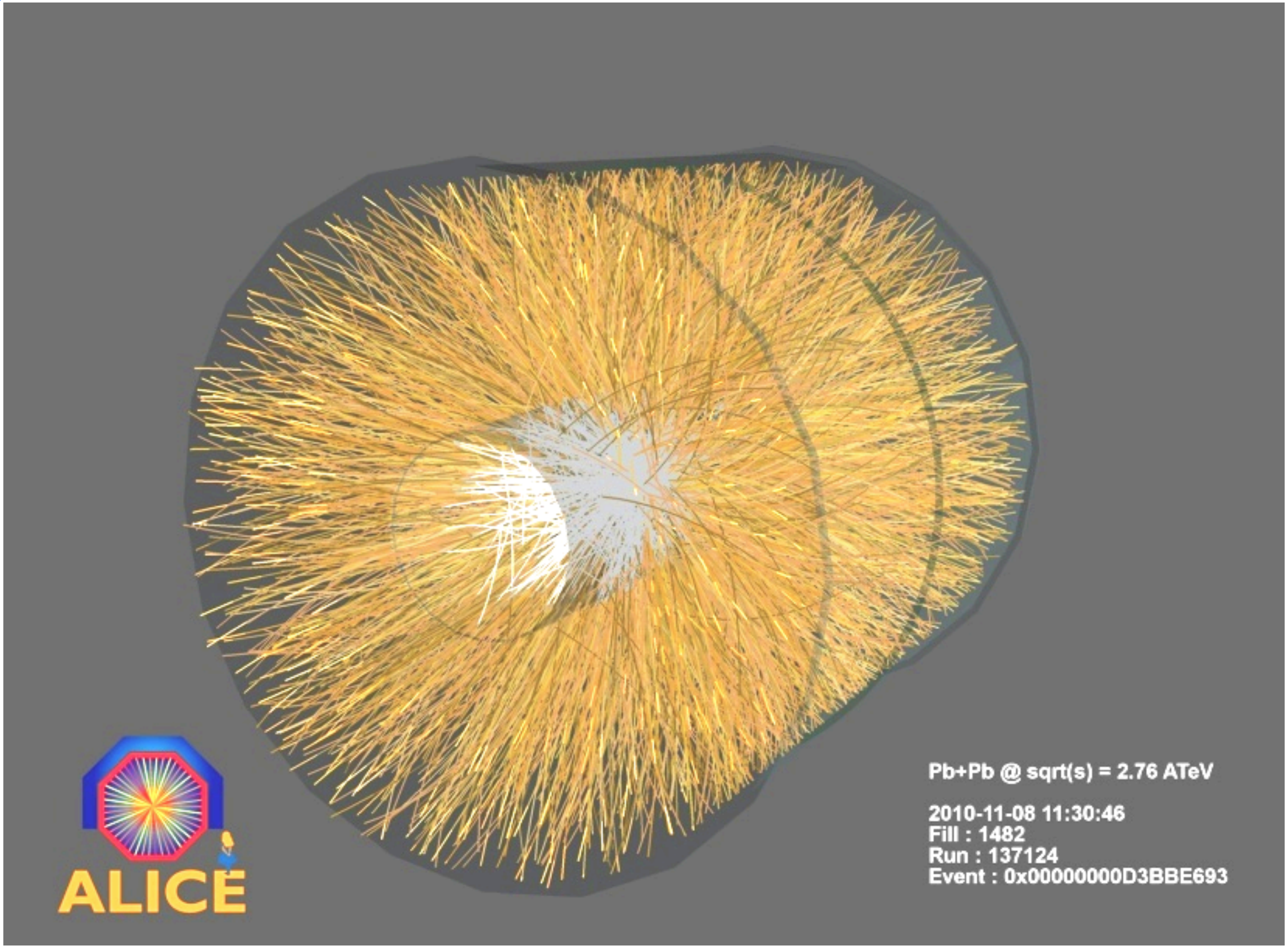
- Gas Ne/ CO_2 90/10%
- Field 400V/cm
- Gas gain $>10^4$
- Position resolution σ= 0.25mm
- Diffusion: σ_t= 250μm
- Pads inside: 4x7.5mm
- Pads outside: 6x15mm
- B-field: 0.5T



TPC installed in the ALICE Experiment



First Pb Pb Collisions in the ALICE TPC in Nov 2010 !

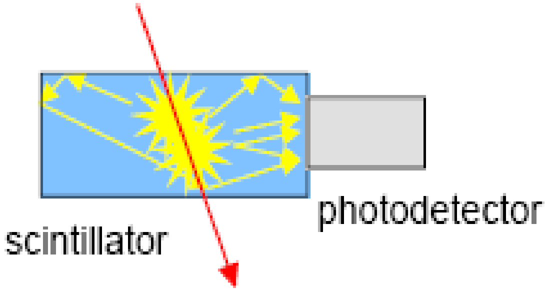


04/08/2016

Limitations of Gas Chambers

- **Operation stability**
  - Gas control
  - HV / pressure and temperature control
- **Rate capabilities**
  - Limited by the drift time of the positive ions from the avalanche to the cathode
- **Aging in high rate environment**

Scintillators

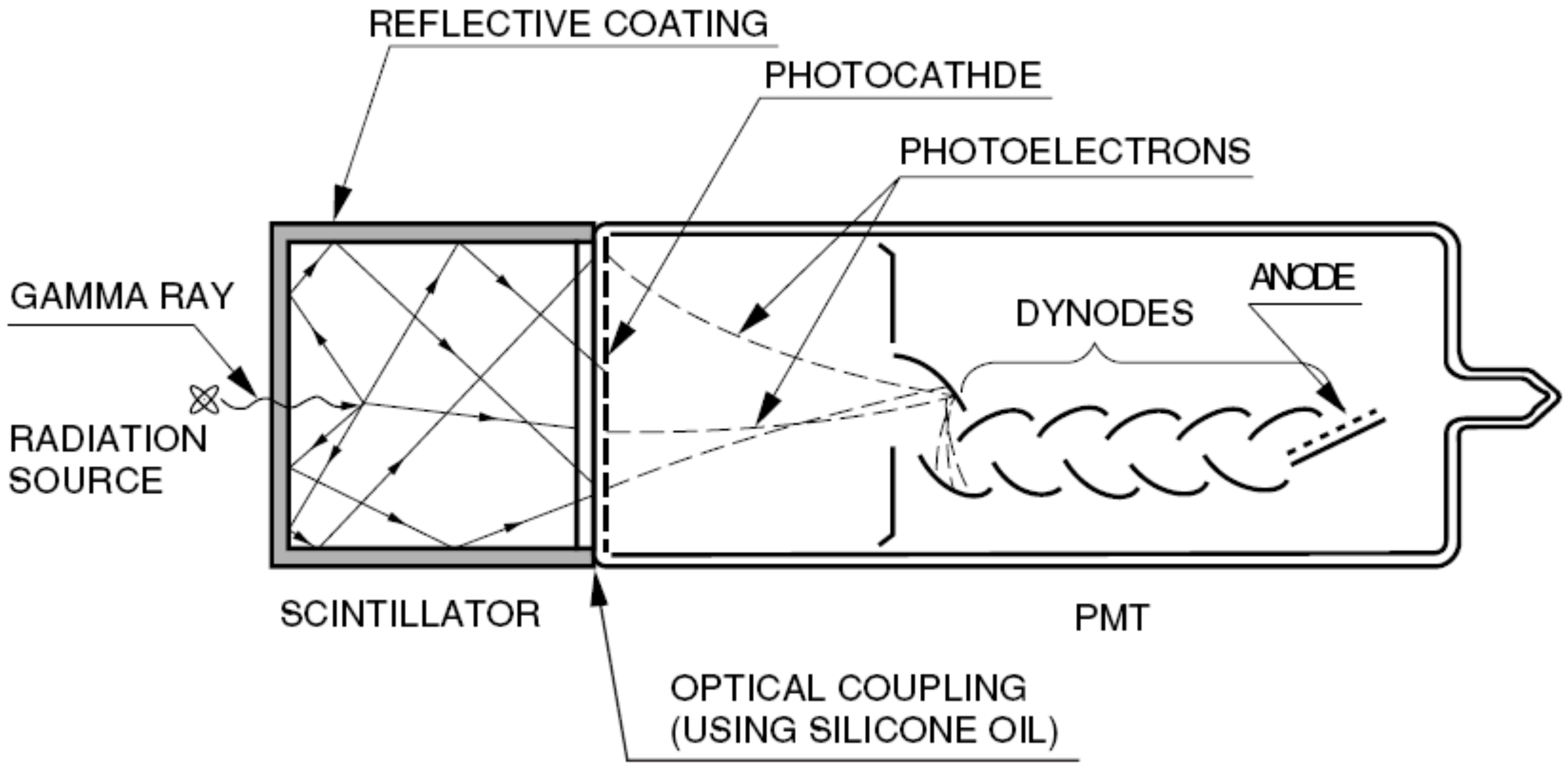


- Organic scintillators (molecules)
- Inorganic scintillators (crystals)
- Gas scintillators (atoms)

A good scintillator :

1. Number of produced photons should be high
2. And should be proportional to the deposited energy.
3. Transparent.
4. Short signals.
5. Good optical properties.
6. Refraction close to 1.5 .

Photomultiplier



The gain

$$G = \eta \cdot \delta^N$$

Dynode Number vs PMT Gain

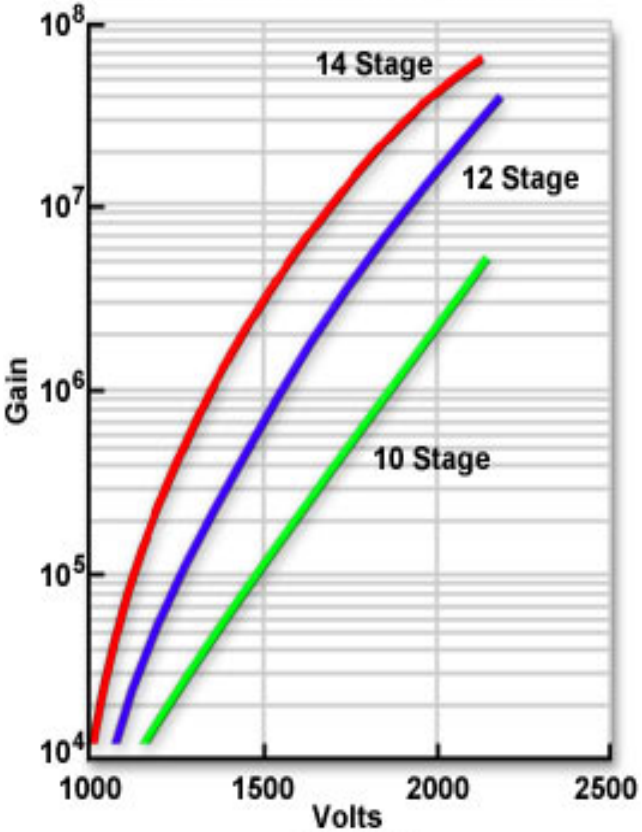
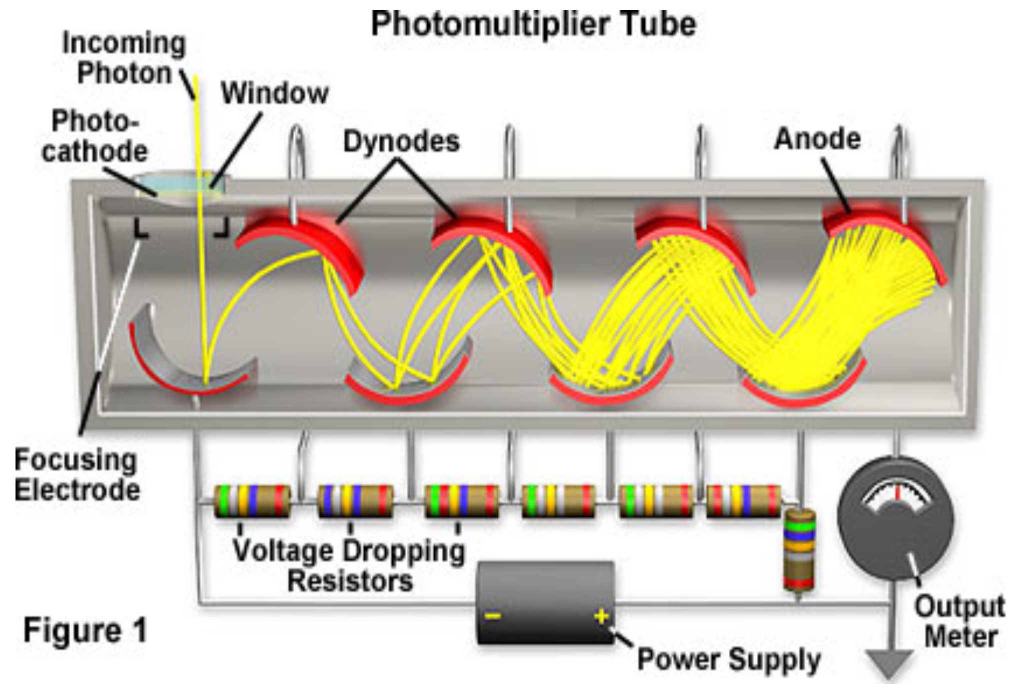
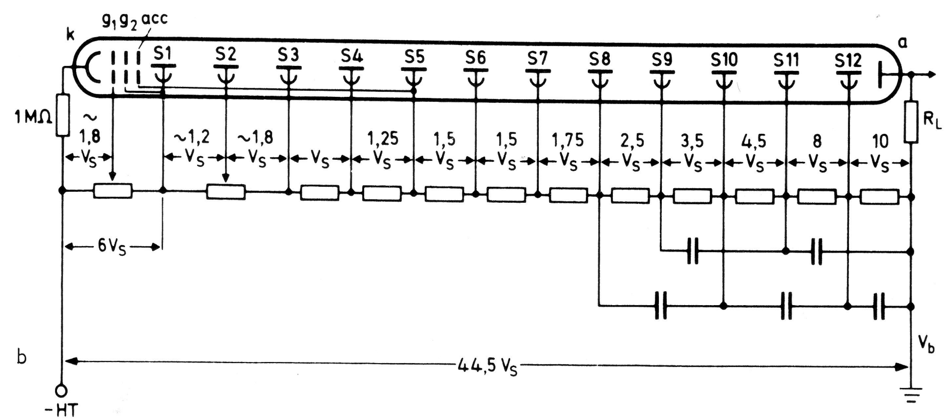


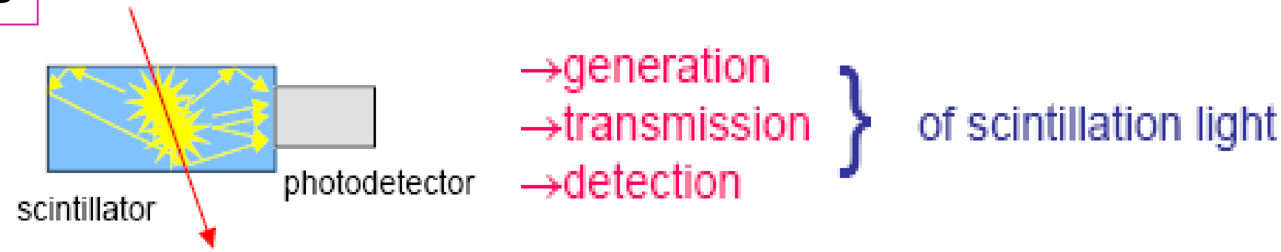
Figure 1





Fluorescence : < 10 ns
Phosphorescence >> 10 ns

Scintillators



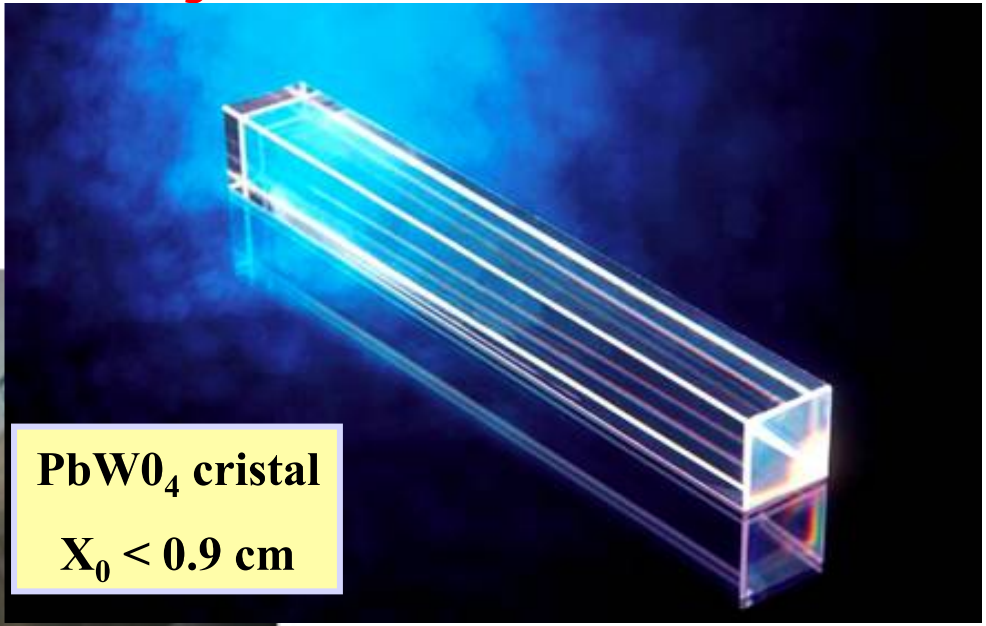
- **Inorganic Scintillators**
  Crystal structure
  - → 40 000 *hν*/MeV
  - High Z material,
  - High density
  - Time constants of ns - µs
  - High price!
  - ~ radiation hard

  Used for
  - Gamma detection
  - Medical imaging
  - Electromagnetic calorimeters

- **Organic scintillator**
  plastic or liquid
  - → 10 000 *hν*/MeV
  - low *Z*,
  - Low density ≈ 1g/cm^3
  - Large choice of emission spectra
  - Time constants of typically ns
  - "low" price
  - Sensitive to radiation

  Used for
  - Charged particle detection
  - TOF, Veto counters, calorimeters

Scintillator crystal



$PbW0_4$ cristal

$X_0 < 0.9$ cm

CMS

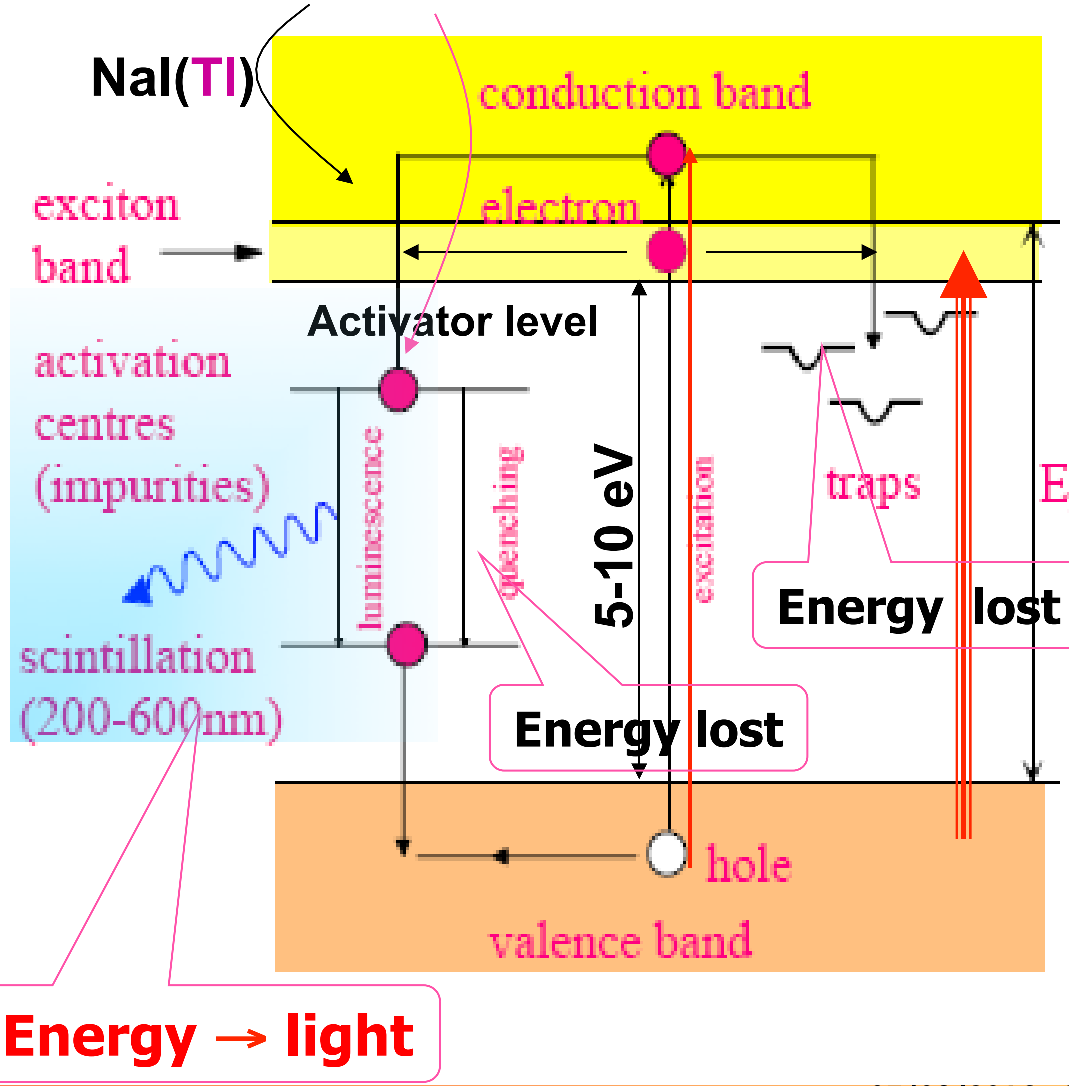
UNIVERSITÉ DE STRASBOURG

Scintillator - crystals

Three steps!
1. Absorption ⇒excitons/ionisation
2. Transfer to activator
3. Fluorescence of the activator

Excitons:
Pairs (e-,hole) (⇒ band below conduction band), but mobile within the crystal, will hit the activator atoms :

Transfer of energy
→ Excitation of activator atom
→ Radiative transition: light
→ Non-radiative transitions: vibrations (phonons) of the whole crystal, (energy loss)



Light emission of energy $E = h\nu$

$$E = h\nu < E_{gap};\ \tau_d = 0.02 - 1\ \mu s$$

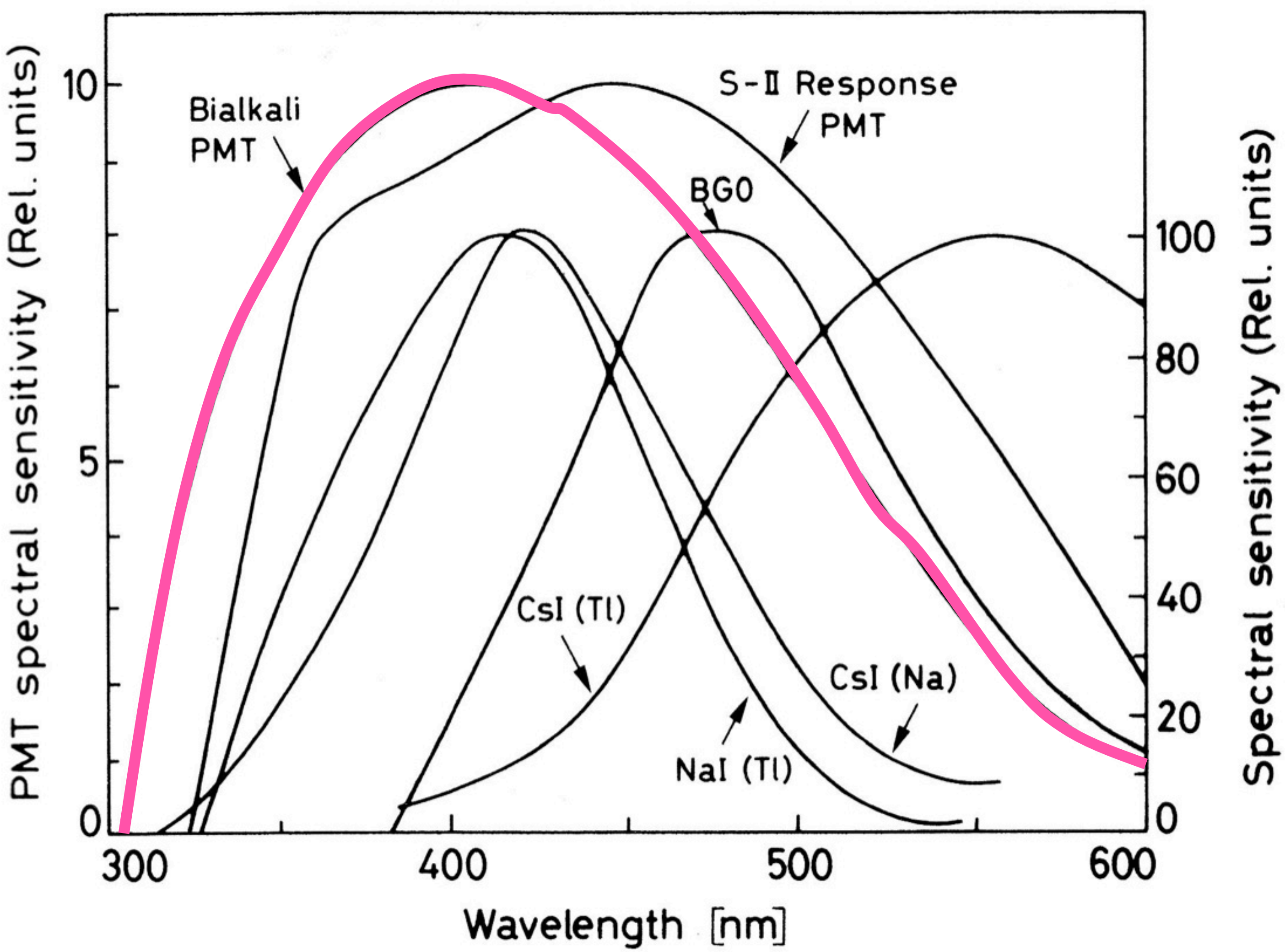
$$\frac{dN(t)}{dt} = \frac{N_0}{\tau_d}\exp\left(-t/\tau_d\right)$$

$$\lambda_{max} \approx 410 - 600\ \text{nm}$$

Scintillator composition	Density (g/cm^3)	Index of refraction	Wavelength of max.Em. (nm)	Decay time Constant (µs)	Scinti Pulse height[1)]	**Photons per Mev**
NaI(Tl)	3.67	1.9	410	0.25	100	38 000
CsI	4.51	1.8	310	0.01	6	
CsI(Tl)	4.51	1.8	565	1.0	45	52 000
CaF_2(Eu)	3.19	1.4	435	0.9	50	24 000
BaF_2	4.88	1.5	190/220 310	0,0006 0.63	5 15	10 000
BGO	7.13	2.2	480	0.30	10	8 200
$CdW0_4$	7.90	2.3	540	5.0	40	
$PbWO_4$	8.28	2.1	440	0.020	0.1	1 900
CeF_3	6.16	1.7	300 340	0.005 0.020	5	
GSO	6.71	1.9	430	0.060	40	
LSO	7	1.8	420	0.040	75	
YAP	5.50	1.9	370	0.030	70	

1) Relative to NaI(Tl) in %; 2) Hygroscopic; 3) Water soluble

Emission spectra of inorganic scintillators



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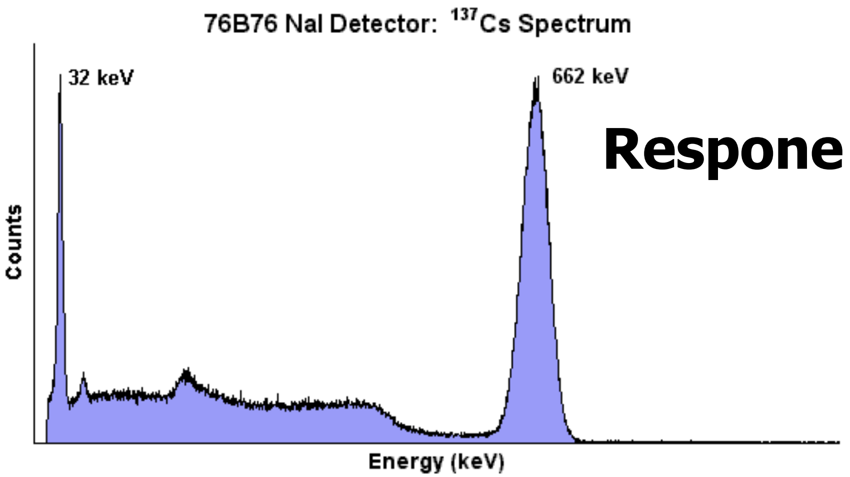
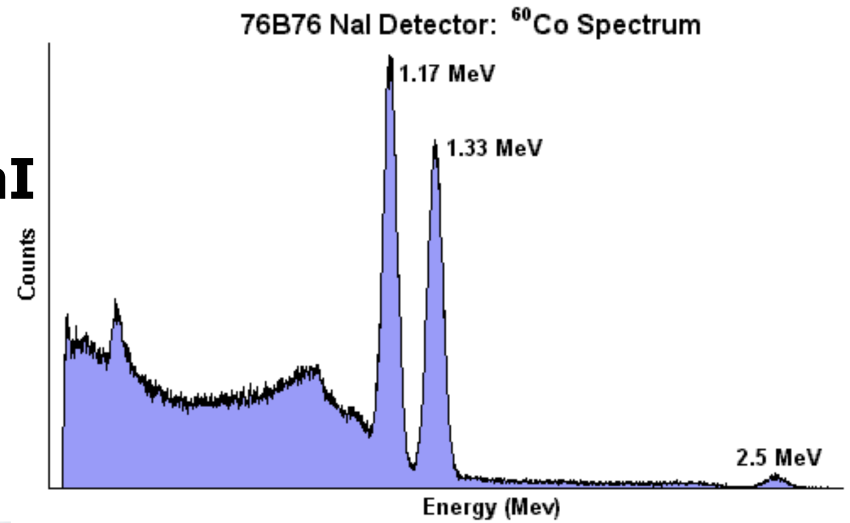
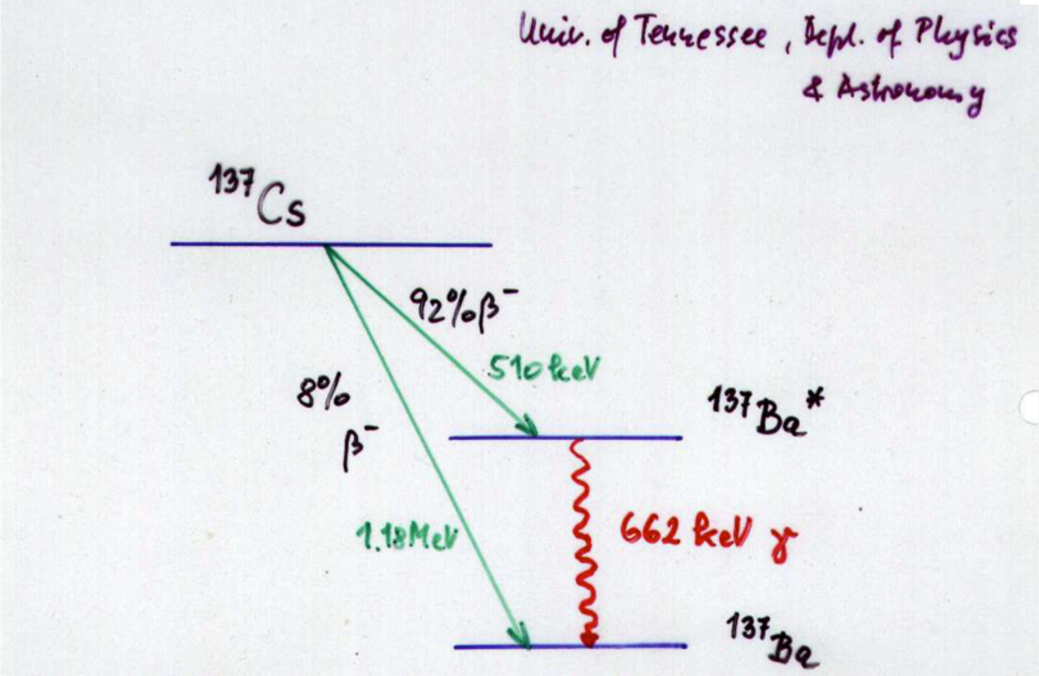
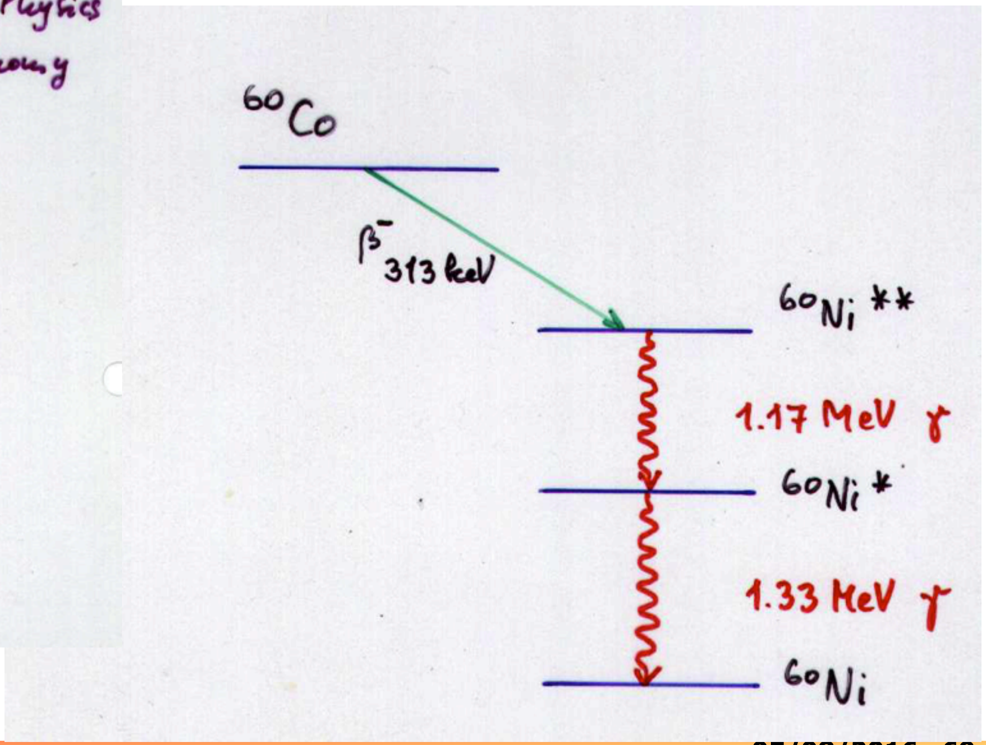
Respone of NaI





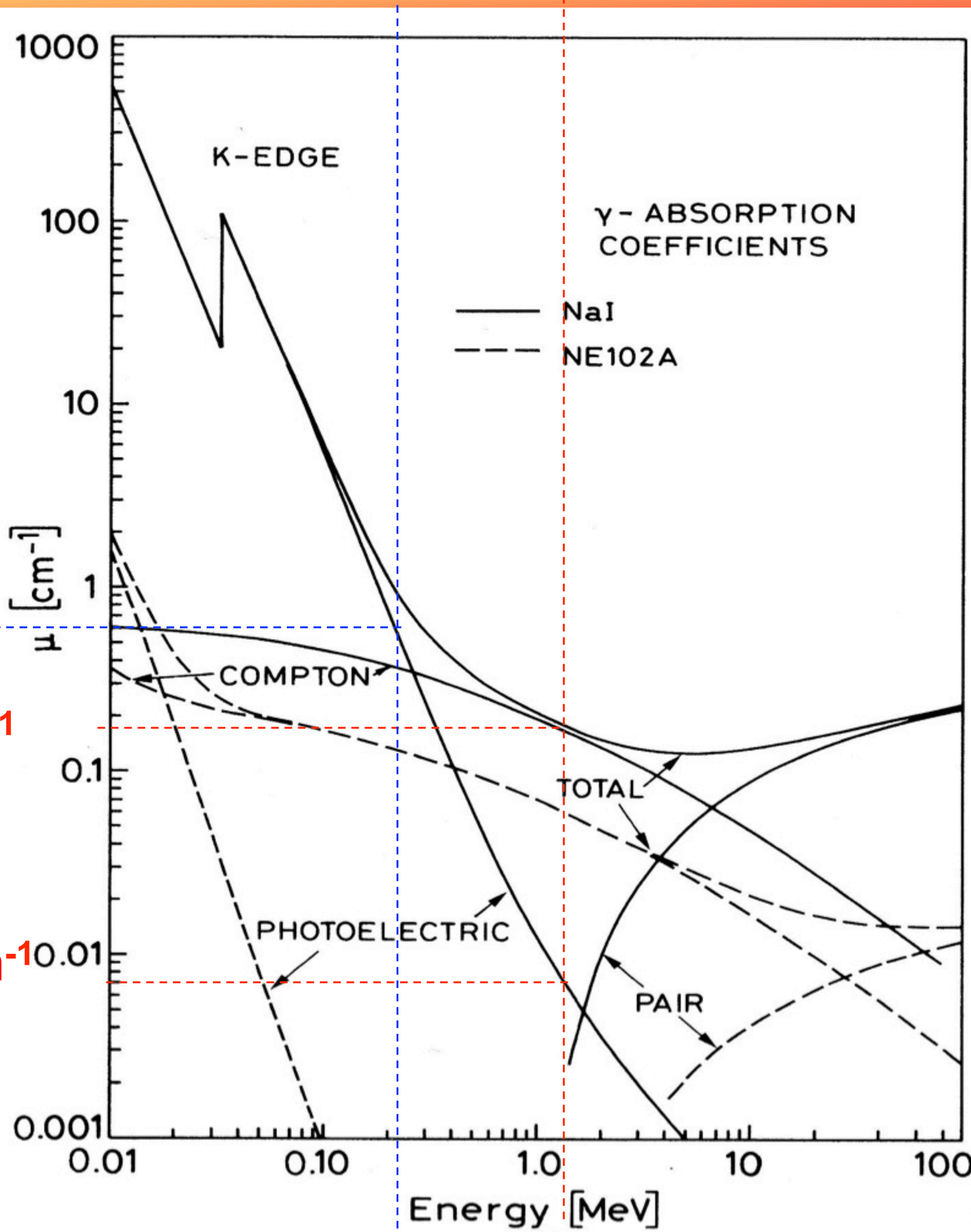




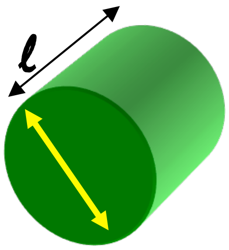
$\mu = 0.6\ cm^{-1}$

$\mu = 0.18\ cm^{-1}$

$\mu = 0.007\ cm^{-1}$



NaI (Tl)



- Reference/standard of efficiency: $\varepsilon = 1{,}22\times10^{-3}$
  - Cylindrical detector NaI(Tl), 7,62(∅) x 7,62(ℓ) cm^3
  - Source of ^{60}Co (1,33 MeV) at 25 cm

Properties of NaI:

- Z = 53 high ⇒ good efficiency
- Relatively short decay time (230 ns)
- intense signal
- Relative good energy resolution
- But NaI is very hygroscopic!!

Exercise : verify efficiency!

Efficiency of a detector

(valid in general!!)

Absolute or total efficiency

$$\varepsilon_{tot} = \frac{(\text{particles or gammas})\ \text{registered}}{(\text{particles or gammas})\ \text{emmitted}}$$

- This depends on the geometry between the source and the detector (its distance and opening, its solid angle)

$$\varepsilon_{tot} = \underbrace{\left[1 - \exp\left(\frac{-D}{\lambda}\right)\right]}_{\text{probability of an interaction}} \times \underbrace{\frac{\Delta\Omega}{4\pi}}_{\substack{\text{probability of an emmission}\\ \text{in the solid angle of the detector}}}$$

$$\varepsilon_{tot} \cong \varepsilon_{\text{int}} \times \varepsilon_{geom}$$

$$\lambda = \text{attenuation length;} \left\{\frac{1}{\lambda} = \sigma \cdot n_b\right\}; \ D = \text{Depth of the detector}$$

Intrinsic efficiency

$$\varepsilon_{\text{int}} = \frac{(\text{particles or gammas})\ \text{"registered"}}{(\text{particles or gammas})\ \text{in the acceptance of the detector}}$$

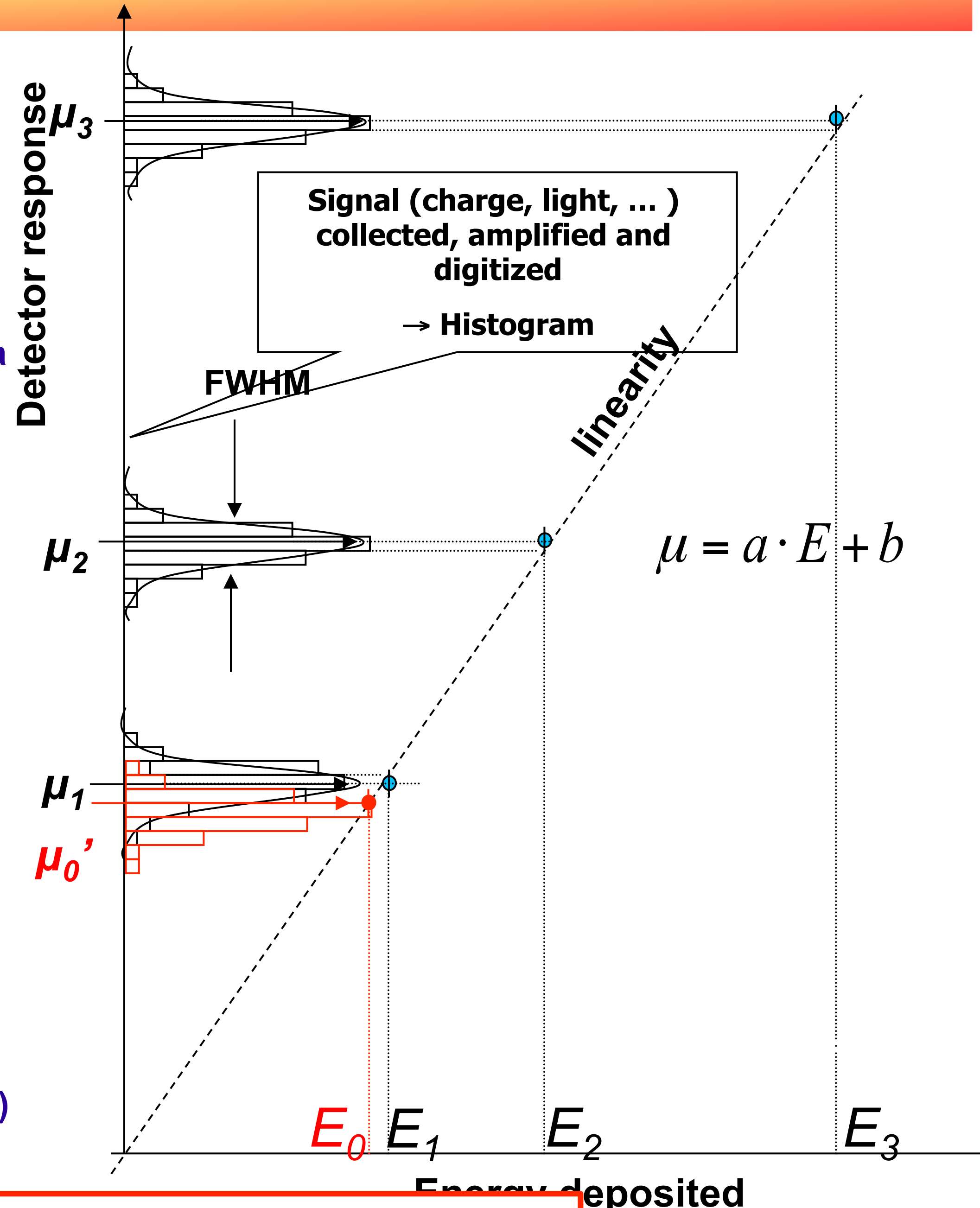
Energy Resolution

Detector response :

- For a fixed energy the detector will respond each time slightly different (also around the photo peak)
- All measurements will be distributed around a mean value with a certain width
- This distribution can be approximated by a Gaussian with
  - Mean μ and
  - A width FWHM
- The resolution *R* is defined by

$$R := \frac{\mathrm{FWHM}}{\mu} = 2.35\frac{\sigma}{\mu}$$

μ, σ^2 = mean and variance of the distribution



However, please note :

very often people talk about the resolution of their detector and what they (including myself) really mean or quote is σ / μ and NOT "*R*"

You cannot distinguish two energies closer than the FWHM

Gaussien or normal distribution

±1σ = 68.3% confidence level

±2σ = 95.5%

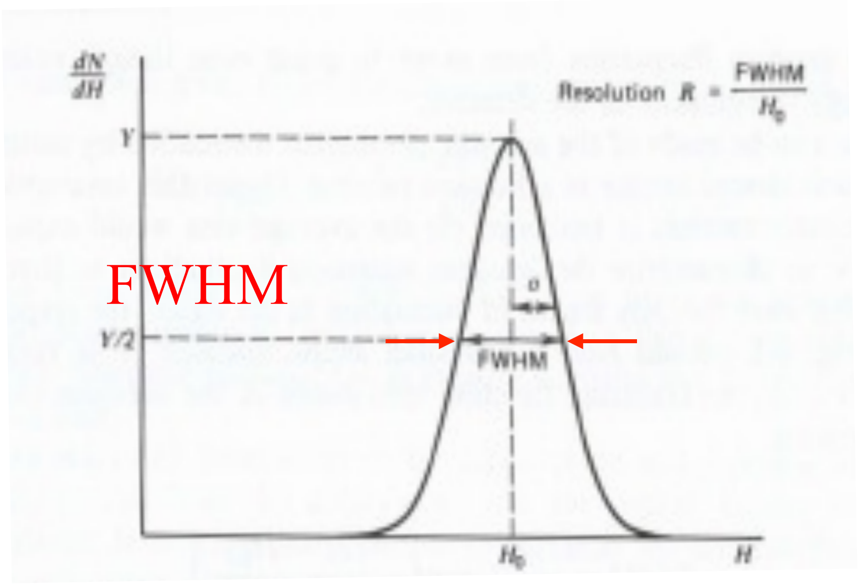
±3σ = 99.7%

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right);$$

μ = *mean*

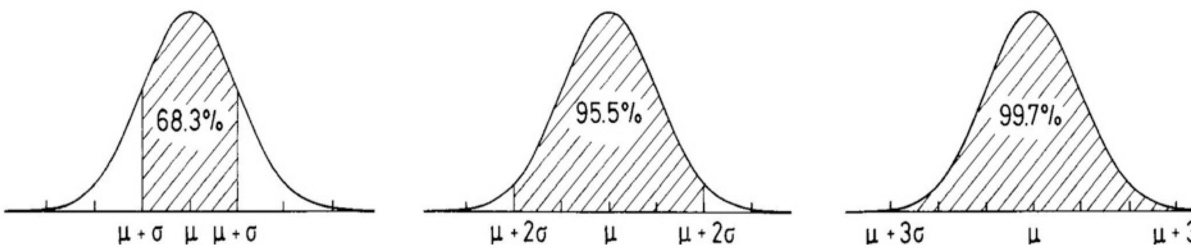
σ^2 = variance;

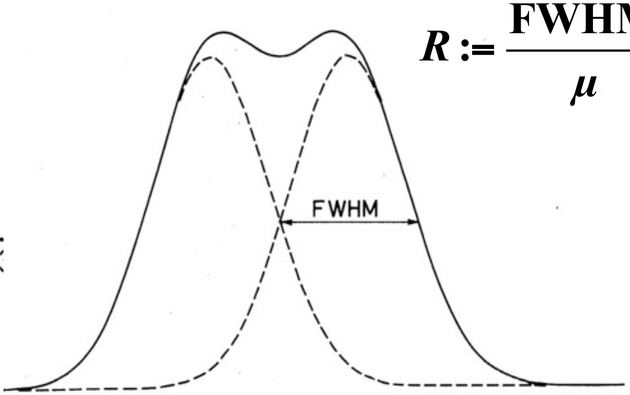
FWHM = 2.35 σ



Resolution

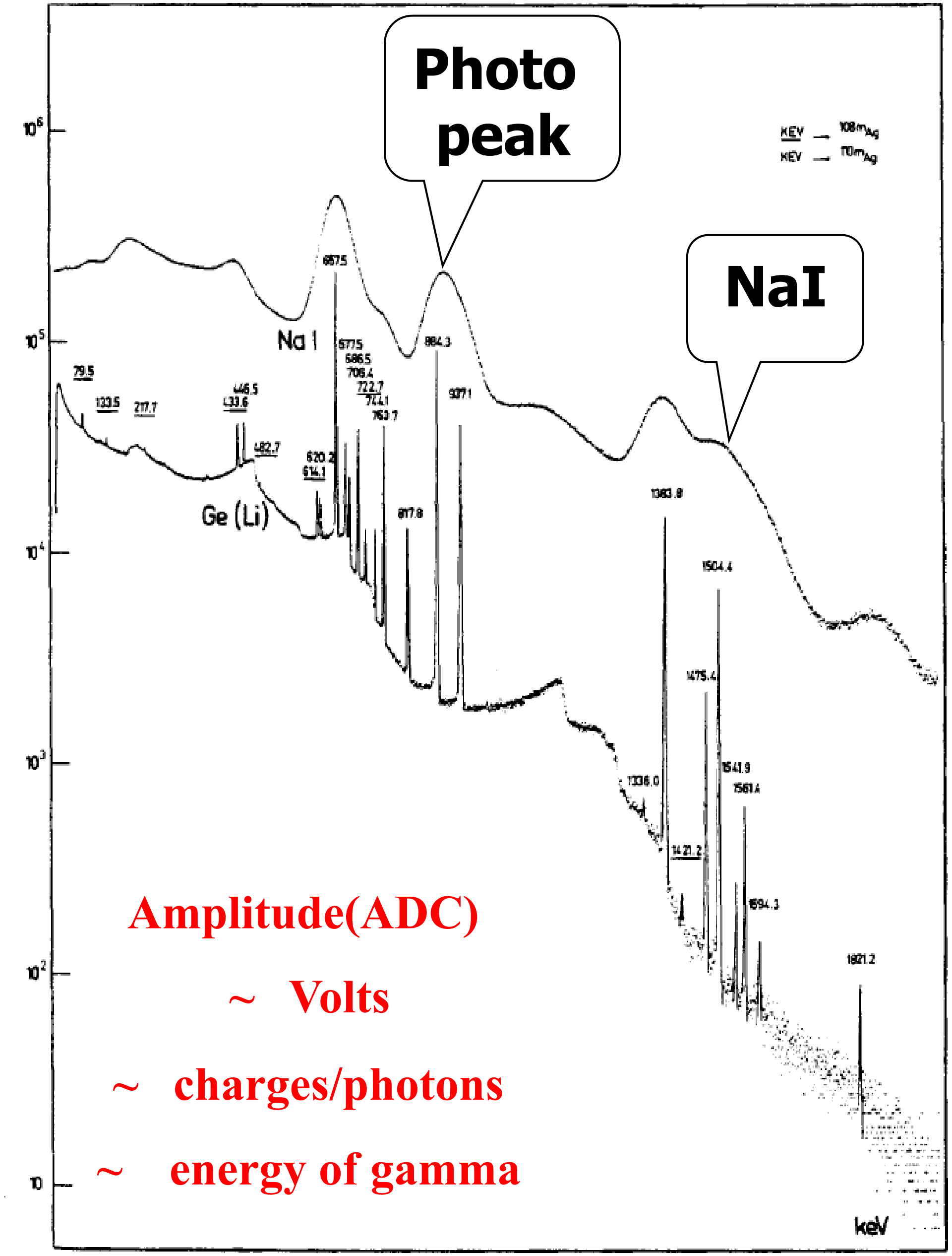
$$R := \frac{\text{FWHM}}{\mu}$$





Impossible to separate two signals closer than FWHM

NaI-Resolution



Amplitude(ADC)

~ Volts

~ charges/photons

~ energy of gamma

$$N_{h\nu} = \frac{E}{w};\ dN_{h\nu} = \sqrt{N_{h\nu}} = \sqrt{\frac{E}{w}}$$

Statistics strictly Poisson $\Rightarrow \sigma^2 = \mu;$

$$dE/E = dN_{h\nu}/N_{h\nu} \sim \frac{1}{\sqrt{N_{h\nu}}}$$

$NaI: w \approx 25\,eV / photon_{\text{scint}} \Rightarrow 40000\,h\nu / MeV$

Incomplete collection of scintillation photons and finite quantum efficiency will reduce the mean number of photo-electrons

$$N_{pe} = N_{h\nu} \times \varepsilon_{collection} \cdot \varepsilon_{quantic};$$

$$dN_{pe} = \sqrt{N_{pe}} = \sqrt{N_{h\nu} \times \varepsilon_{coll.} \cdot \varepsilon_{quant.}}$$

$$\varepsilon_{coll.} \approx 0.2 - 0.8;\ \varepsilon_{quant.} \approx 0.2\,(PM)$$

$$dE/E = dN_{pe}/N_{pe} \cong \frac{1}{\sqrt{N_{pe}}} = \frac{1}{\sqrt{N_{h\nu} \times \varepsilon_{coll.} \cdot \varepsilon_{quant.}}}$$

$$F \approx 1;\ \varepsilon_{coll.} \approx 0.4;\ \varepsilon_{quant.} \approx 0.2\,(PM)$$

$$\Rightarrow dE/E = \sigma_E / E \approx 1.5\%\ \text{à}\ 1.333\ MeV$$

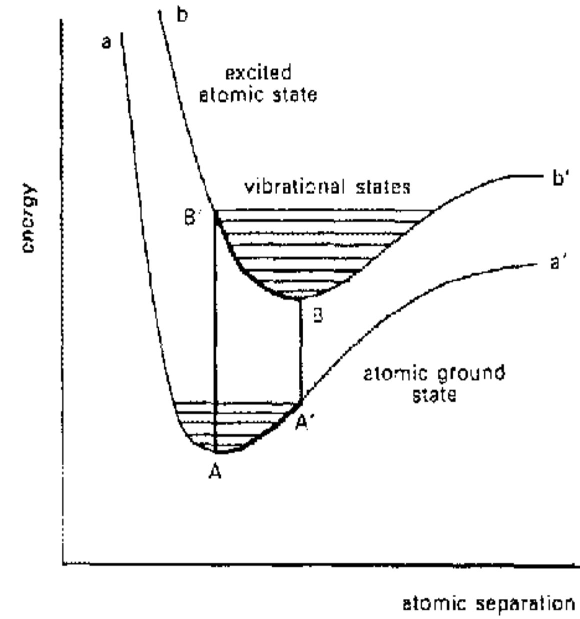
$$R = 2.35 \times 1.5\% = 3.6\% \xrightarrow{\text{experimental}} (5-8)\%$$

Organic scintillators

- Liquids and plastics
- Solvent which absorbs the energy
- The excitation energy of the solvent is transferred to the dopant
- Emission, reabsorption and re-emission of light
- Shift towards longer wave lengths
- Fast response, about 5ns
- Liquids :
  - Solvents liquids: xylene, tolene,benzene,phenylcyclohexane,triethylbenzene,decaline
  - Dopants for liquids: p-Terphenyl ($C_{18}H_{14}$), PBD($C_{20}H_{14}N_2O$), PPO($C_{15}H_{11}NO$), POPOP($C_{24}H_{16}N_2O_2$), ≈ 3g/l
- Solids:
  - Solvents plastics polyvinyltoluene, polyphenilbenzene, polystyrene.
  - Primary dopants for plastics : PBD, p-Terphenyl, PBO, 10g/l
  - Secondary dopant POPOP to shift the light to longer wavelengths.
- Quality depends largely on low level of impurities

Organic Scintillators

- fluorescence (durée ∼ ns-μs)
- phosphorescence (durée ∼ μs-min)

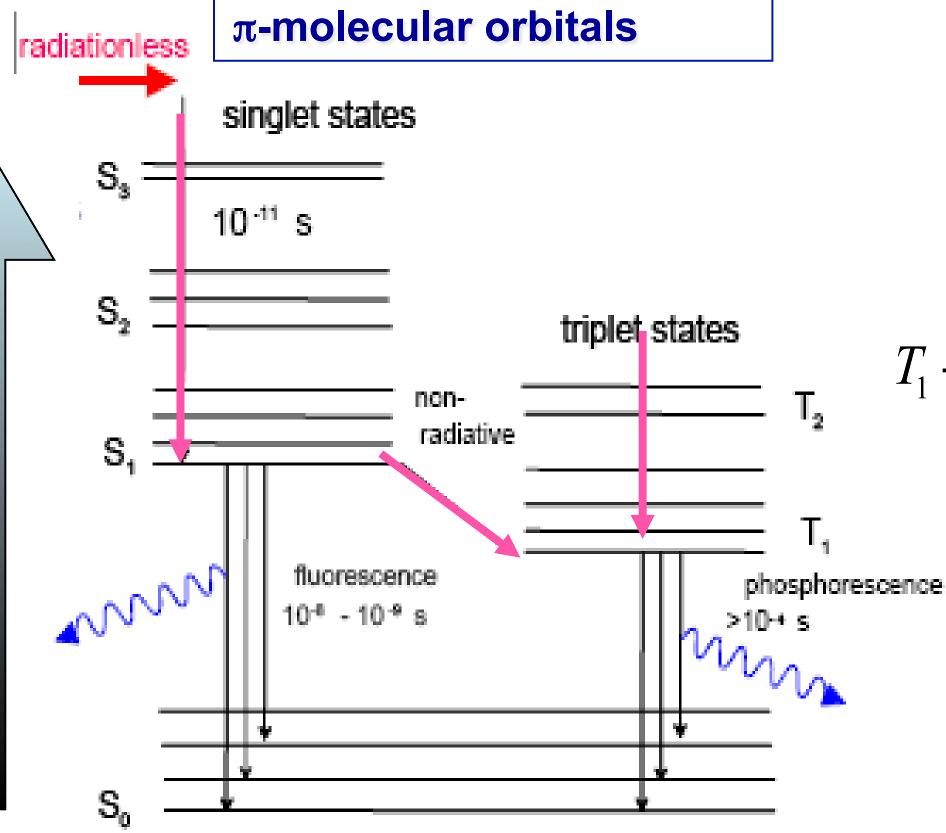


Valence electrons of the π-molecular orbitals

Radiation less transitions

(Förster)

The energy absorbed by the solvent is transferred to the dopant without radiation



$$T_1 + T_1 \rightarrow S_0 + S_1 + phonons$$

Phosphorescence : Slow emission

Organic Scintillators

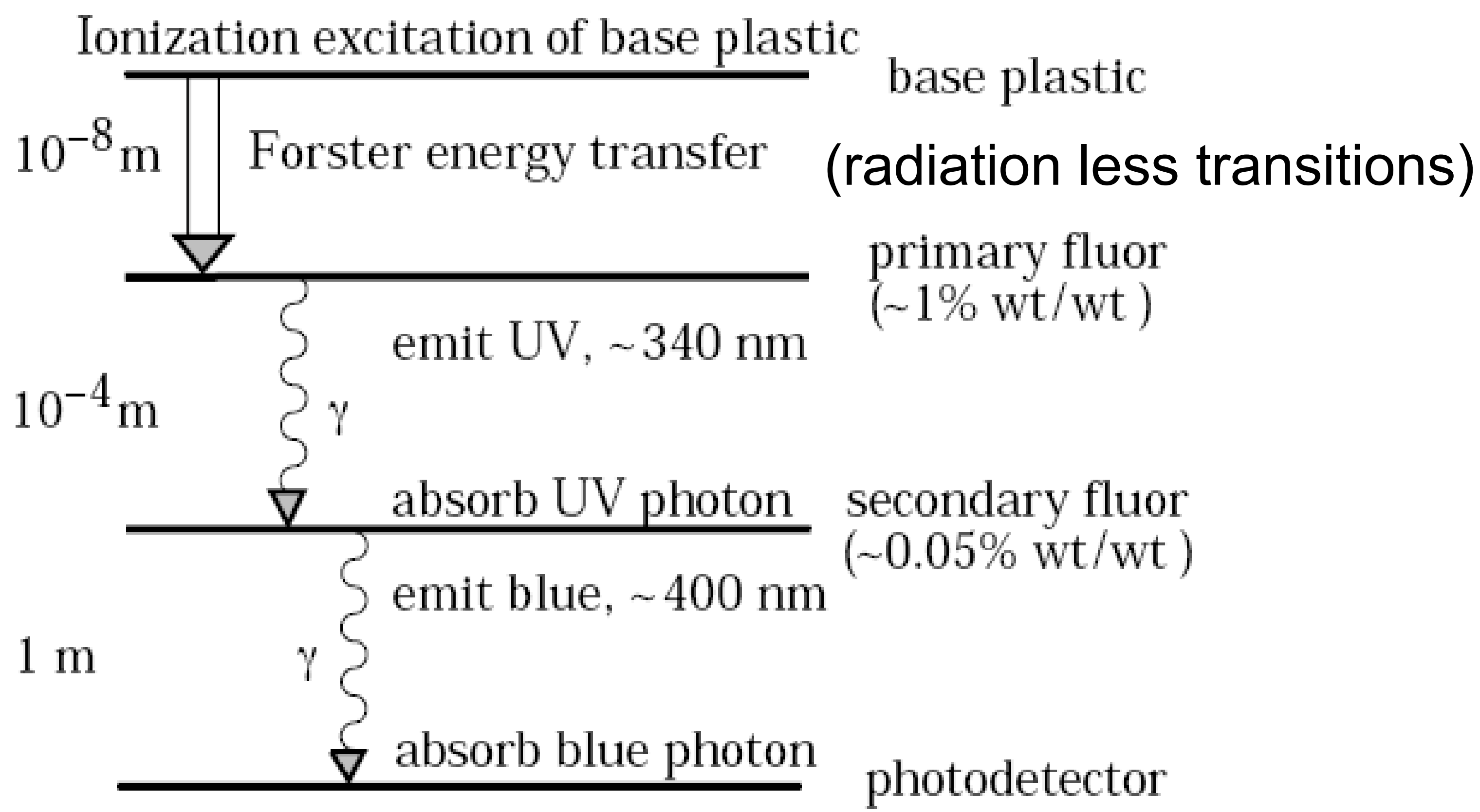
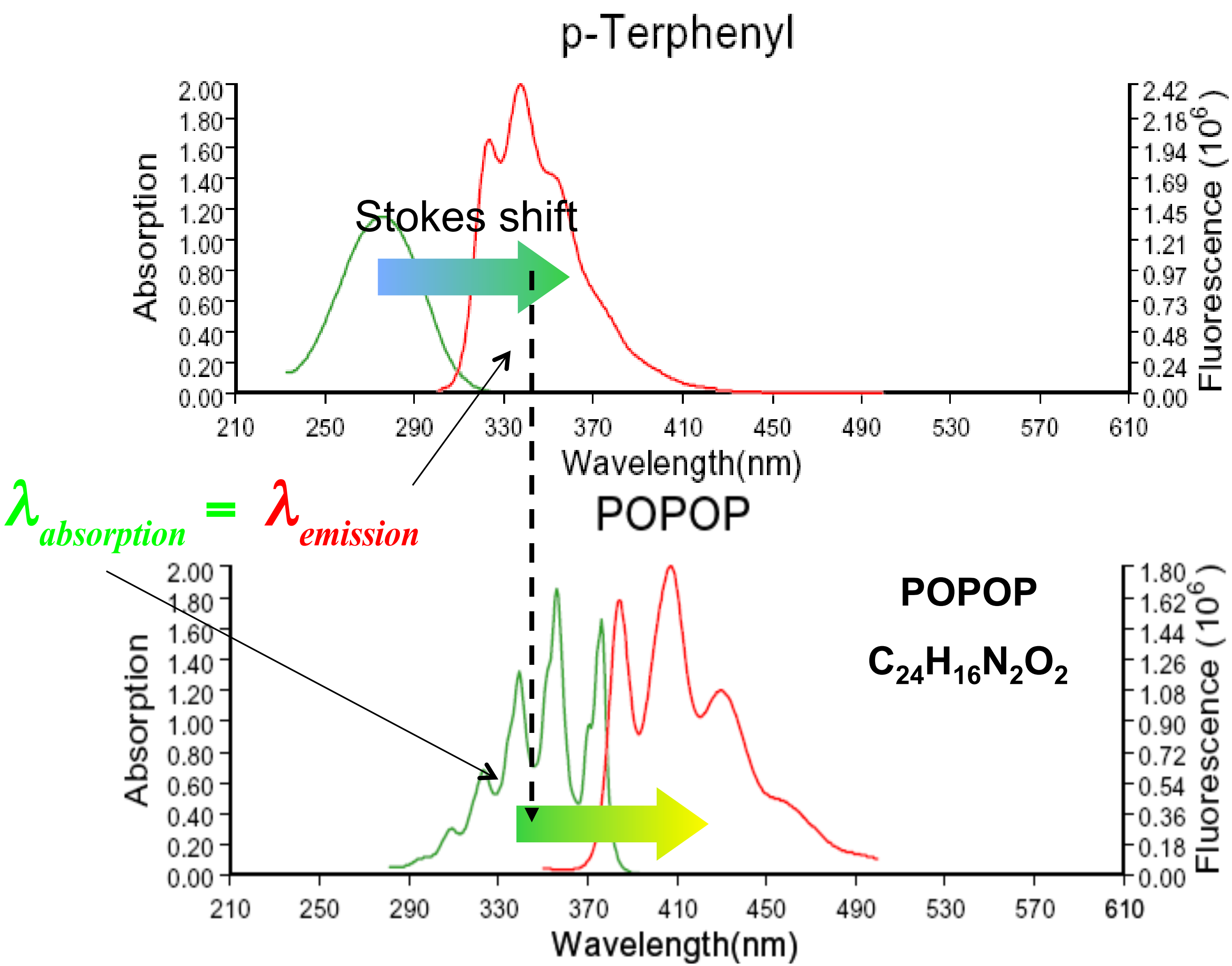


Figure 28.1: Cartoon of scintillation "ladder" depicting the operating mechanism of plastic scintillator. Approximate fluor concentrations and energy transfer distances for the separate sub-processes are shown.

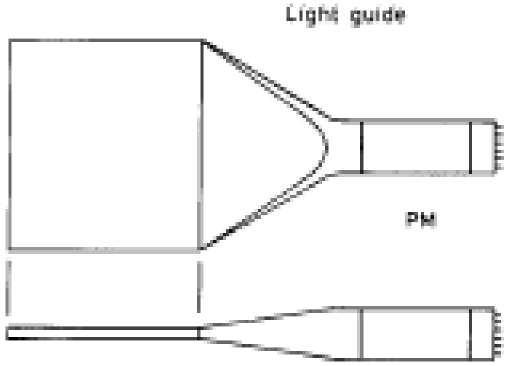
Absorption and emission



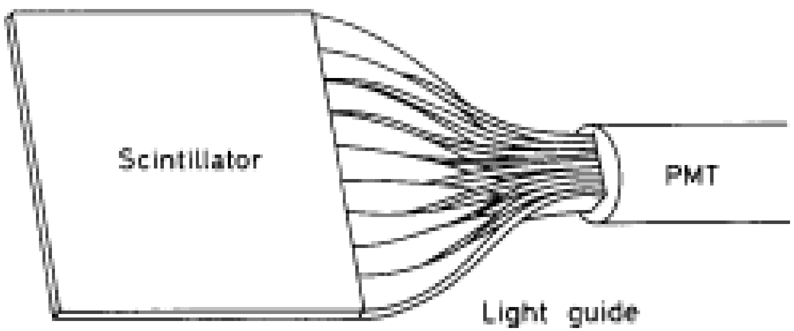
Light guides

Geometrical adaptation:

- Light guides: transfer by total internal reflection (+outer reflector)

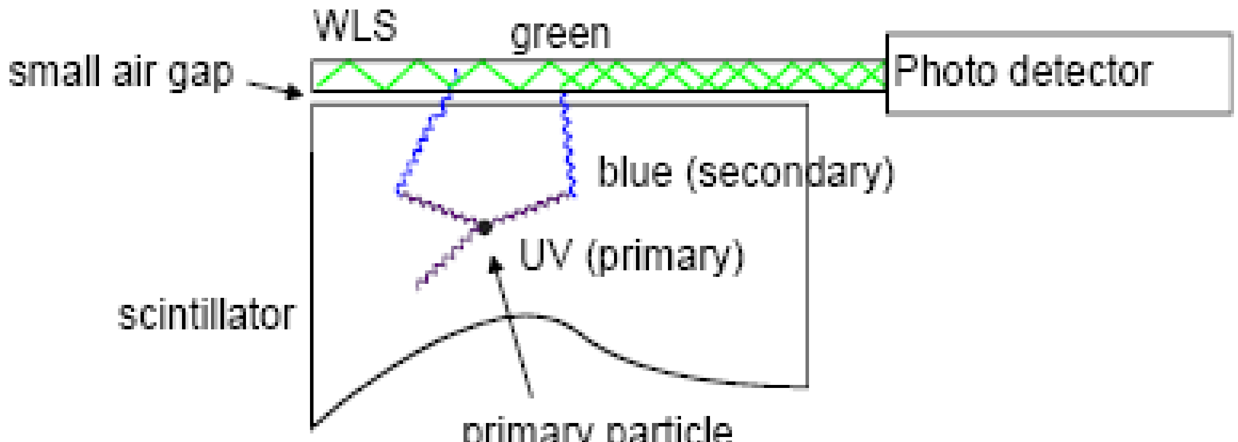


"fish tail"

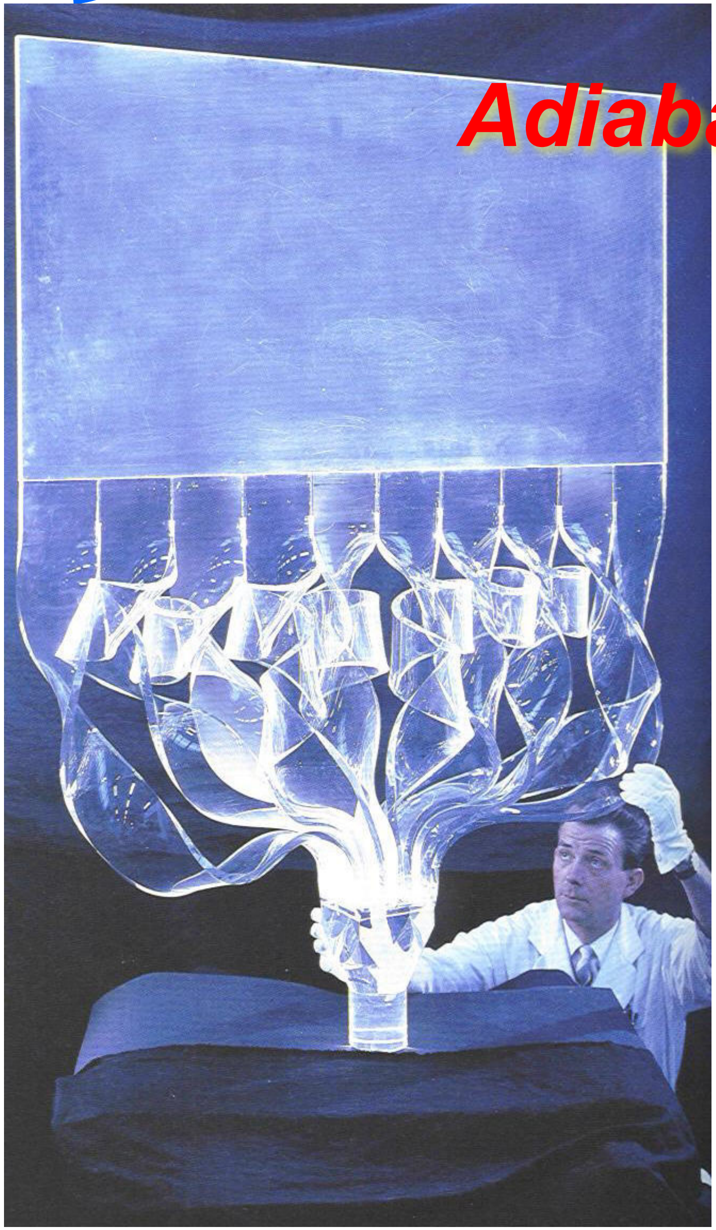


adiabatic

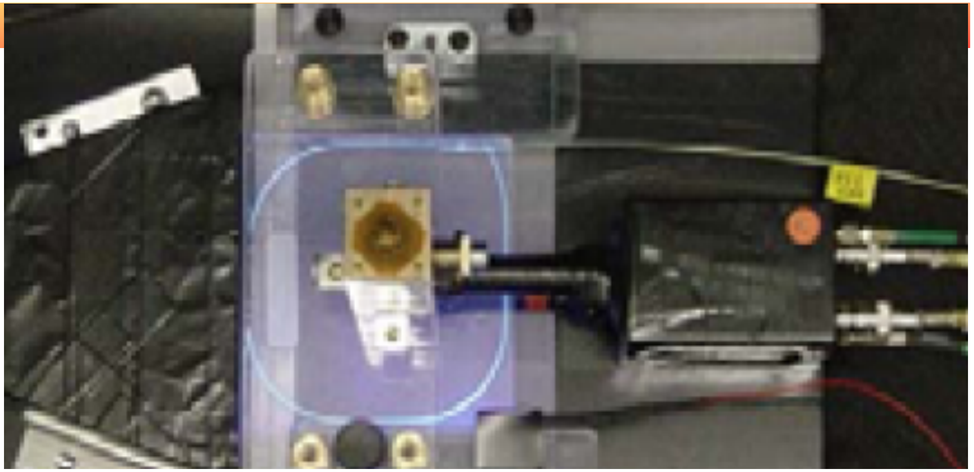
- wavelength shifter (WLS) bars

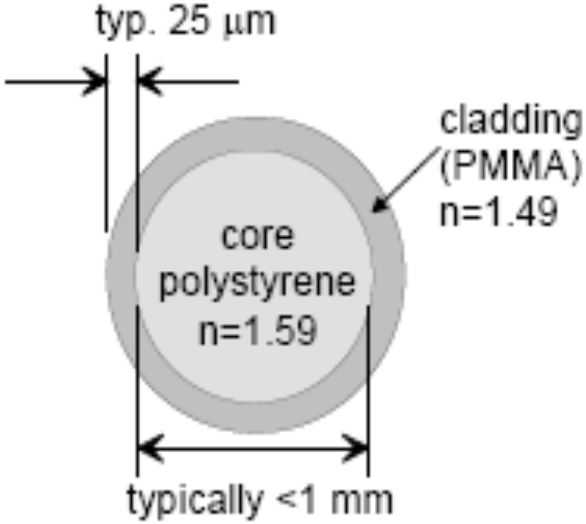


Adiabatic light guides

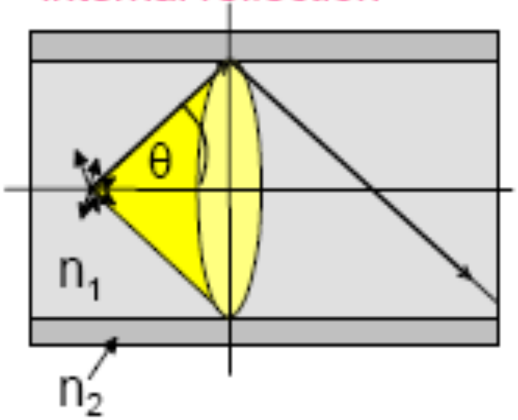


Scintillating fibers

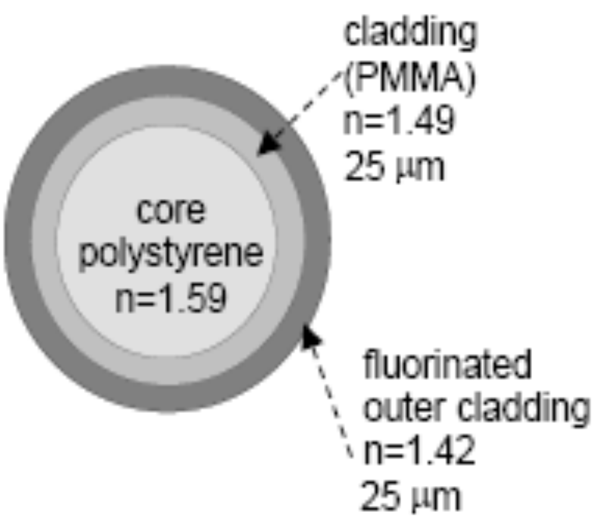




light transport by total internal reflection

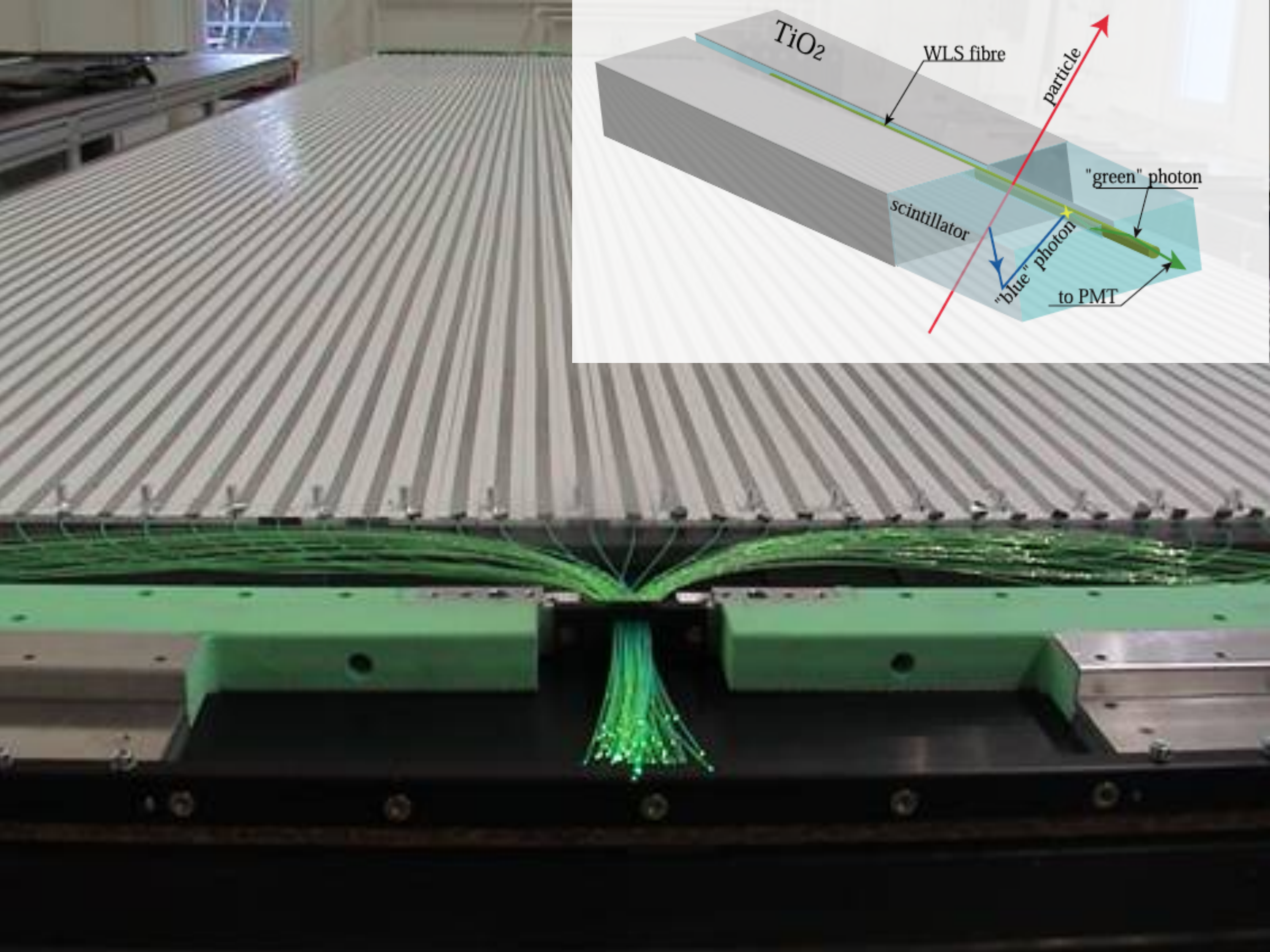


Double cladding system (developed by RD7)

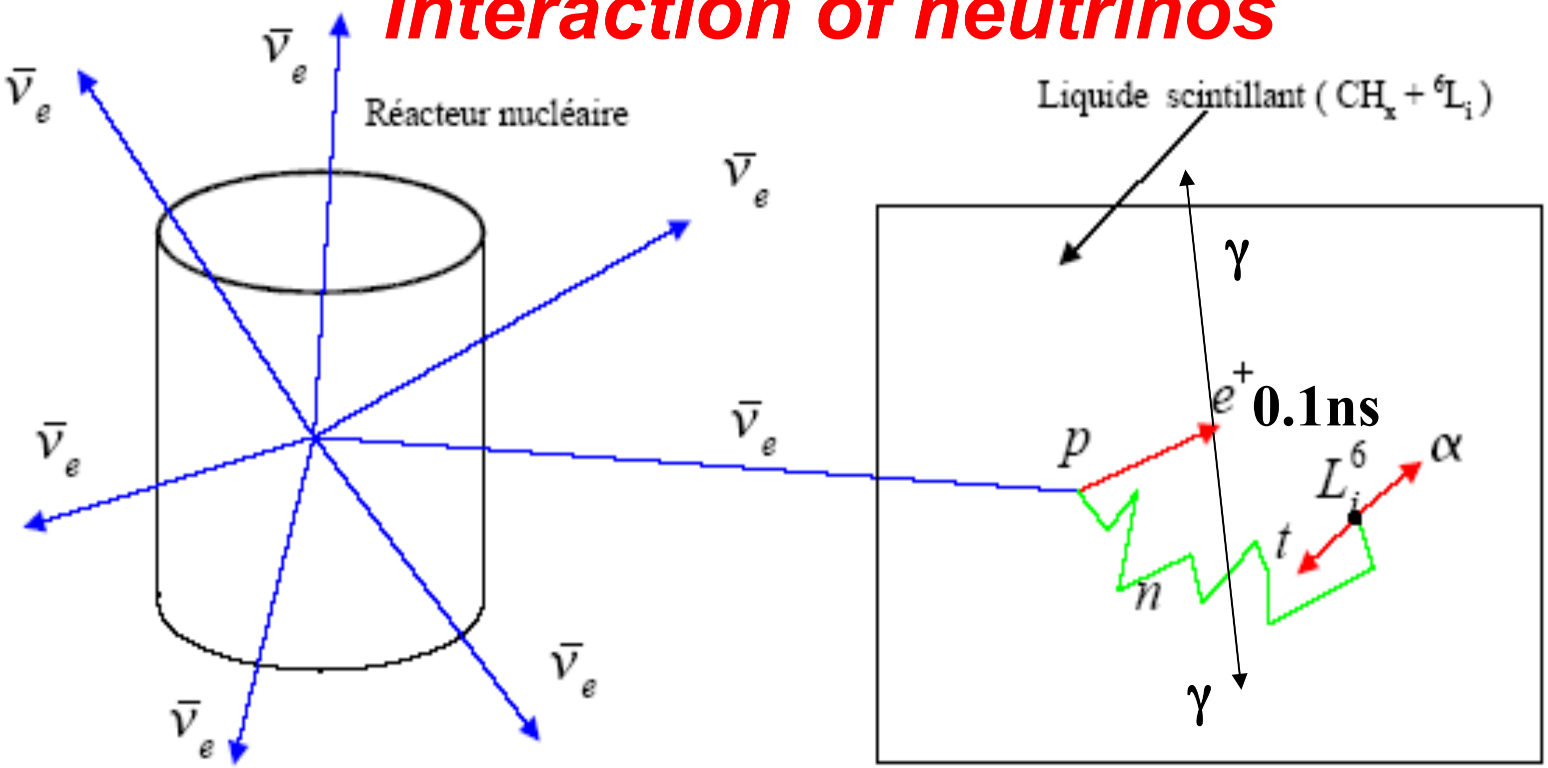


$$\cos\theta = \sin\alpha_1 = \frac{n_2}{n_1} = 0.937 \Rightarrow \theta = 20.5°; \quad \frac{d\Omega}{4\pi} = \tfrac{1}{2}\sin^2\theta = \tfrac{1}{2}\left(1-\cos^2\theta\right) = 0.06$$

$$\mathbf{\frac{n_2}{n_1} = 0.893 \quad \Rightarrow \theta = 26.7°; \quad \frac{d\Omega}{4\pi} = 0.10}$$


TiO2
WLS fibre
particle
"green" photon
scintillator
"blue" photon
to PMT

Interaction of neutrinos

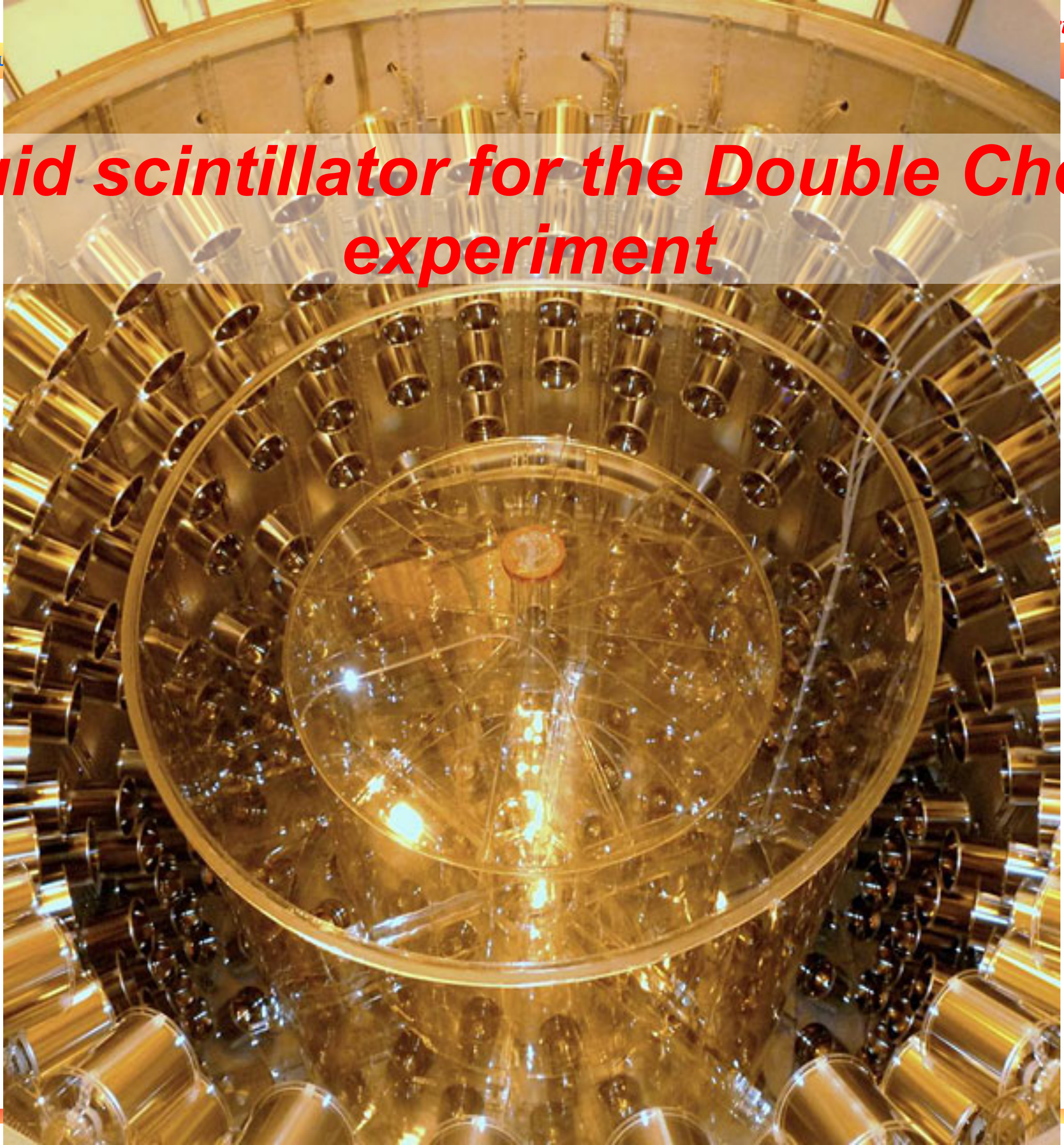


Reines & Cowan 1959

$\epsilon_\nu \sim 0$

La réaction de détection est : $\bar{\nu}_e + p \rightarrow n + e^+$, qui est rapidement (100 µs) suivie de la capture du neutron sur un noyau de L_i^6 selon la réaction : $n_{th} + L_i^6 \rightarrow \alpha + t + 4{,}8\,MeV$. Les particules chargées produisent des impulsions de scintillation en coïncidence . La signature de détection d'un neutrino correspond à l'enregistrement de deux impulsions lumineuses induites par le positon et la paire $\alpha - t$.

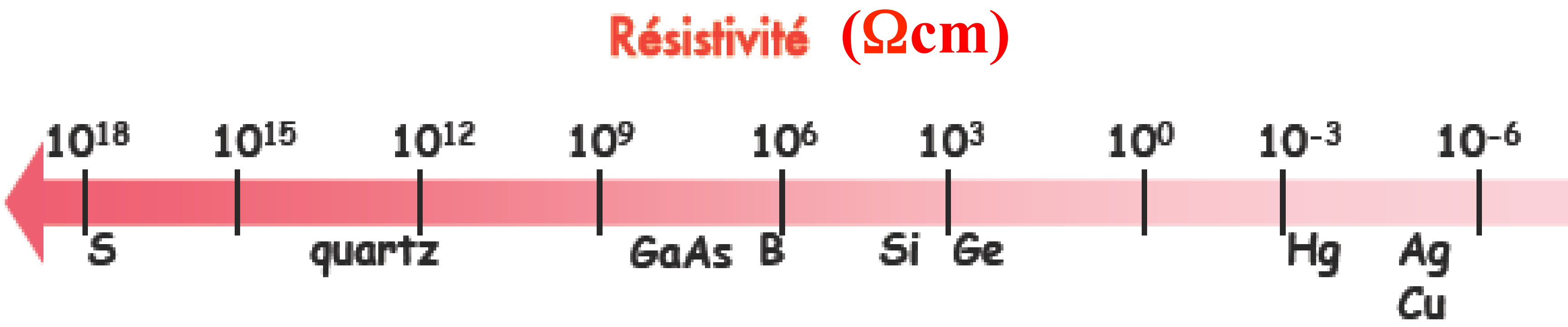
Liquid scintillator for the Double Chooz experiment

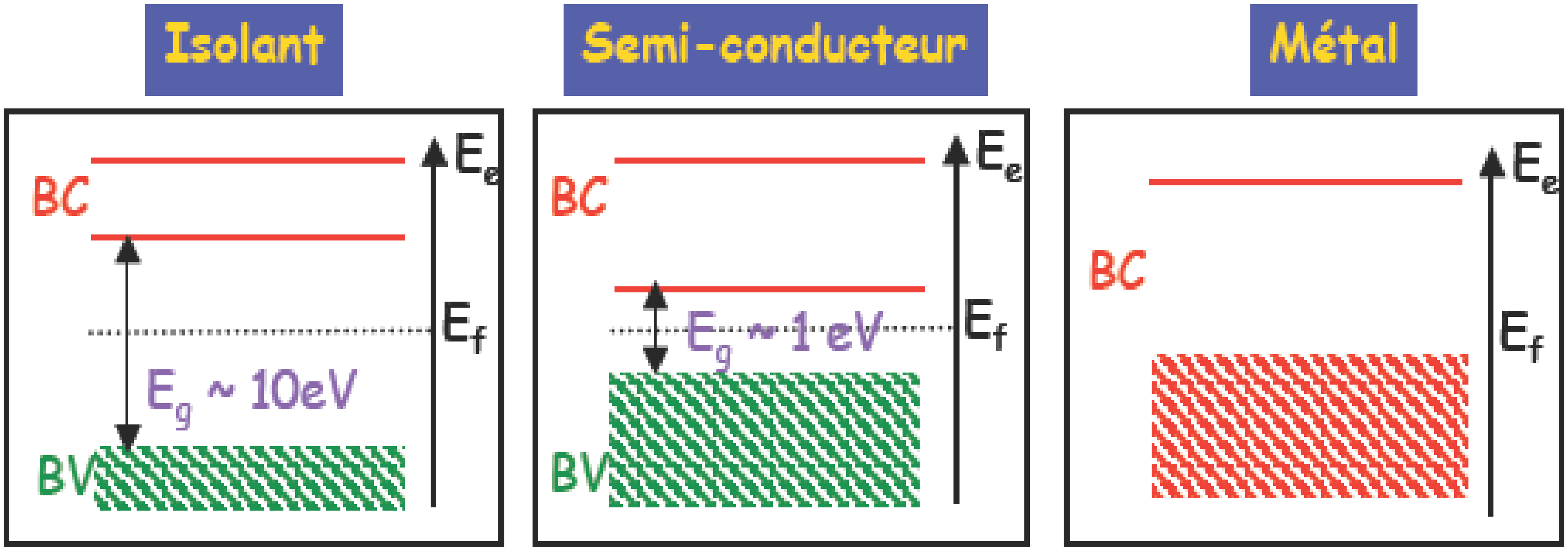


Semiconductor detectors

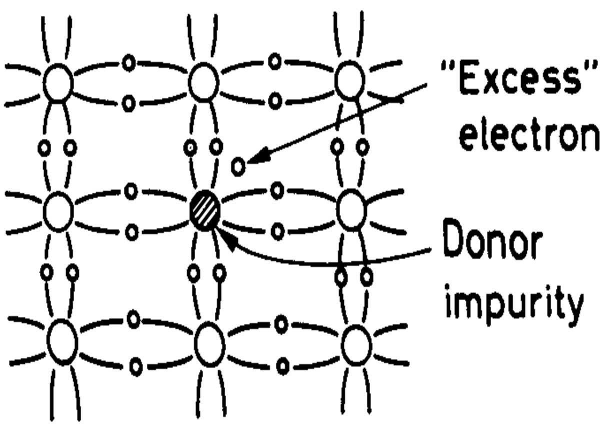
- Tracking detectors in High Energy Physics
- Energy measurement of charged particles and gammas in nuclear physics

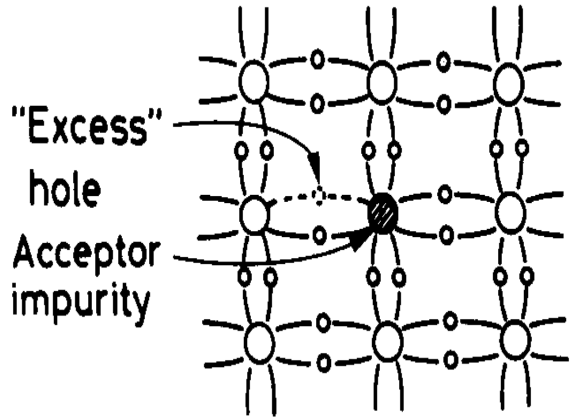
Semi-conductors

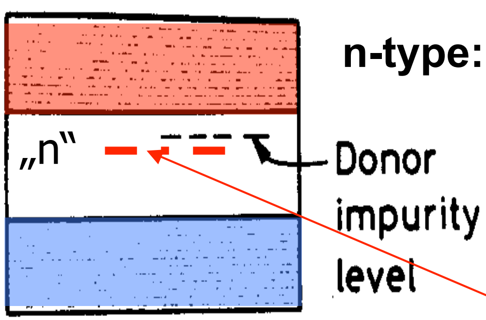




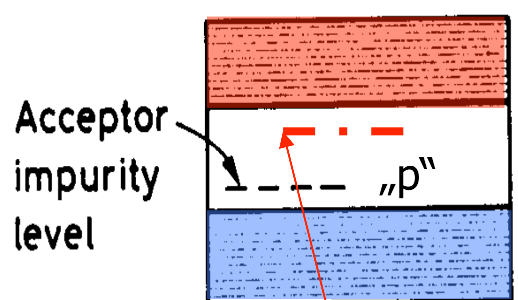
„Doped“ Semi-conductors



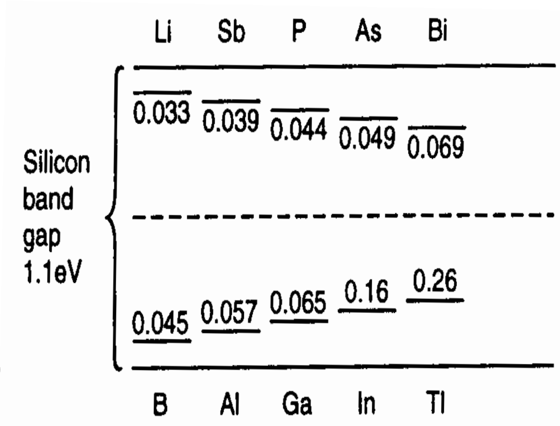




n-type: $N_D > N_A \approx 0$



p-type: $N_A > N_D \approx 0$



Energy levels within the band gap corresponding to various n- and p-type dopants [6]

Intrinsic: $1.5\ 10^{10}/cm^3$ ($N_A = 6.022\ 10^{23}/cm^3$!!)
n, p : $10^{13}/cm^3$
n^+, p^+ : $10^{20}/cm^3$

Impurities
- traps
- recombination

W.Dulinski

Semi-conductor detectors

Material	E_g [eV]	w [eV]	Mobility (velocity/E)		τ_e [s]	τ_h [s]	density	Z [a.m.u]
			μ_e [cm^2/Vs]	μ_h [cm^2/Vs]			g/cm^3	
C (diamond)	5.5	13	1800	1200	2 10^{-9}	2 10^{-9}	3.515	6
Si	1.12	3.61	1350	480	5 10^{-3}	5 10^{-3}	2.33	14
Ge	0.67	2.98	3900	1900	2 10^{-5}	2 10^{-5}	5.32	32
GaAs	1.42	4.70	8500	450	5 10^{-8}	5 10^{-8}	5.32	31,33
CdTe	1.56	4.43	1050	100	1 10^{-6}	1 10^{-6}		48,52
HgI_2	2.13	4.20	100	_	1 10^{-6}	2 10^{-6}		53,80

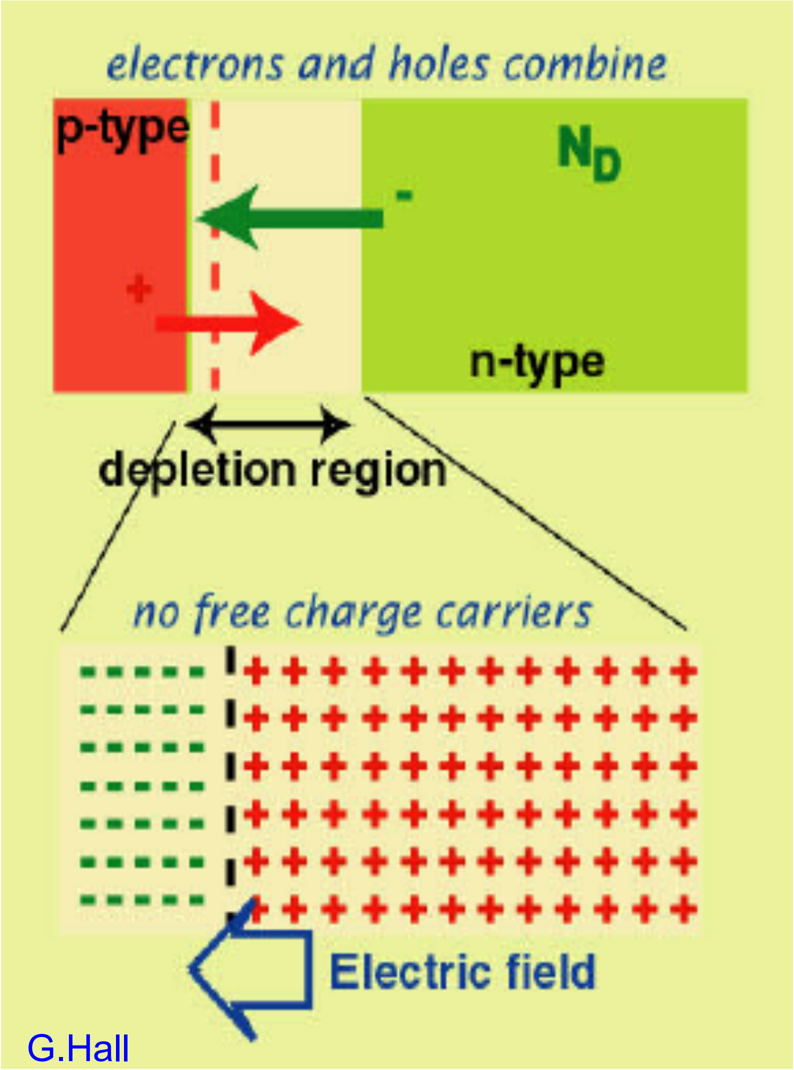
$$\frac{dN}{N} = \frac{1}{\sqrt{N}} \;;\quad E \sim N; \qquad N = \text{numb. of (e,h))}$$

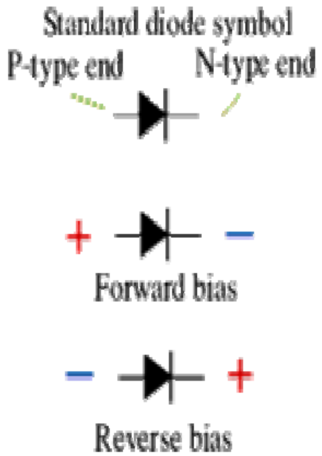
Parameters Values for Materials Used in Fabricating Semiconductor Radiation Sensors [3]

W.Dulinski

Junction p-n

Formation of a depletion zone



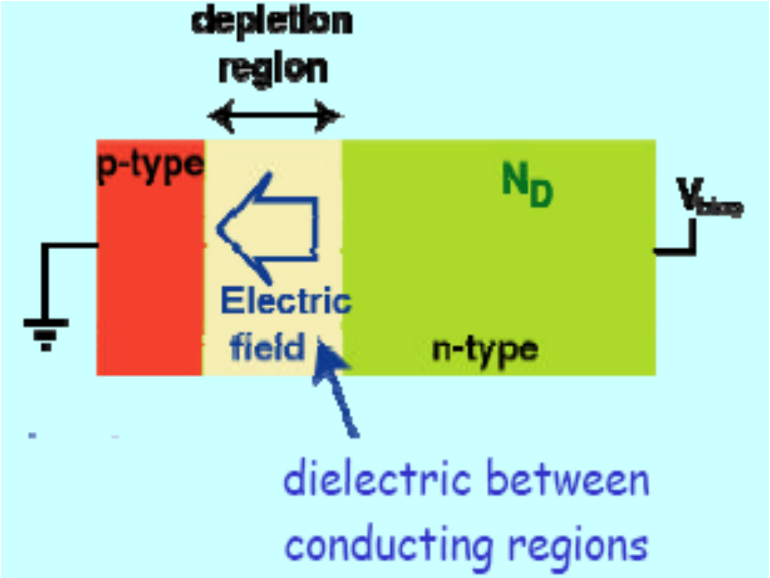


Direct Polarisation

- **conduction**
- $I \sim I_0[\exp(qV/kT) - 1]$

Inverse Polarisation

- **increase of depletion zone**
- **reduction of capacitance**



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Inverse Polarisation

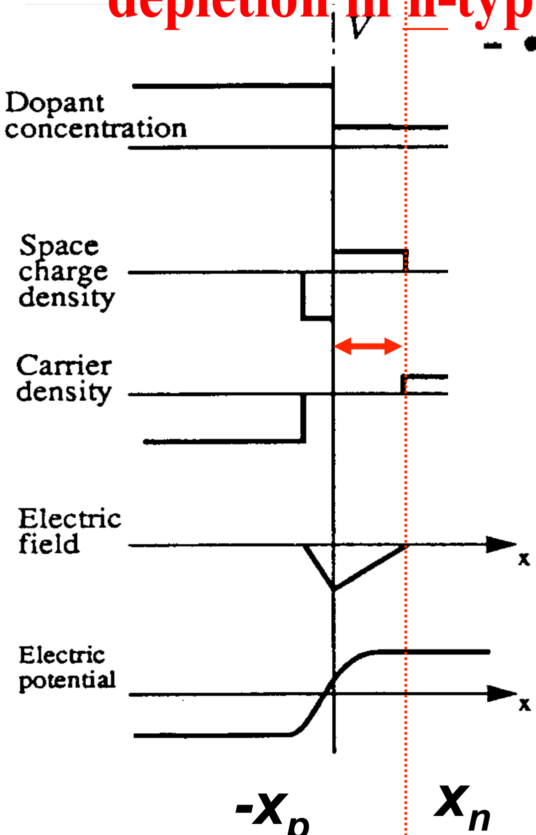
$$d\big|_{V_{bias}} = x_n + x_p = \sqrt{\frac{2\varepsilon\left(\phi_0 + V_{bias}\right)}{e}\,\frac{\left(N_A + N_D\right)}{N_A N_D}}$$

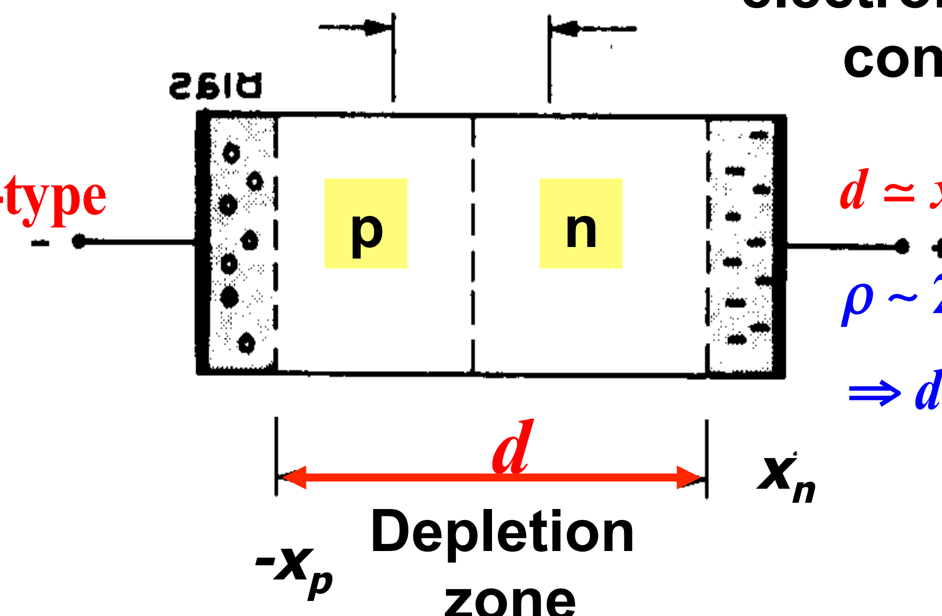
Holes move to « - »

electrons move to contact "+"

$$N_A \gg N_D$$

depletion in n-type

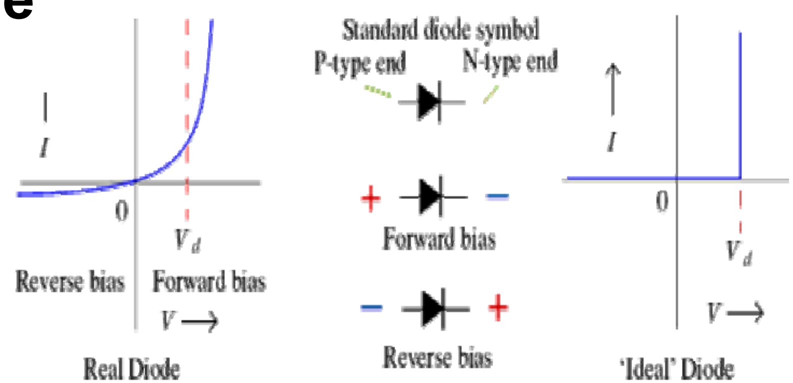




$$d \simeq x_n \approx 0.53\sqrt{\rho_n \phi_0}\ \mu m$$

$$\rho \sim 2\cdot 10^4\,\Omega cm,\ \phi_0 \sim 1V$$

$$\Rightarrow d \sim 75\,\mu m$$



Junction p-n

0.1-2µm ⇒ perte d'énergie

Diffused or Ion implanted

Diffused & Ion implanted

oxide window

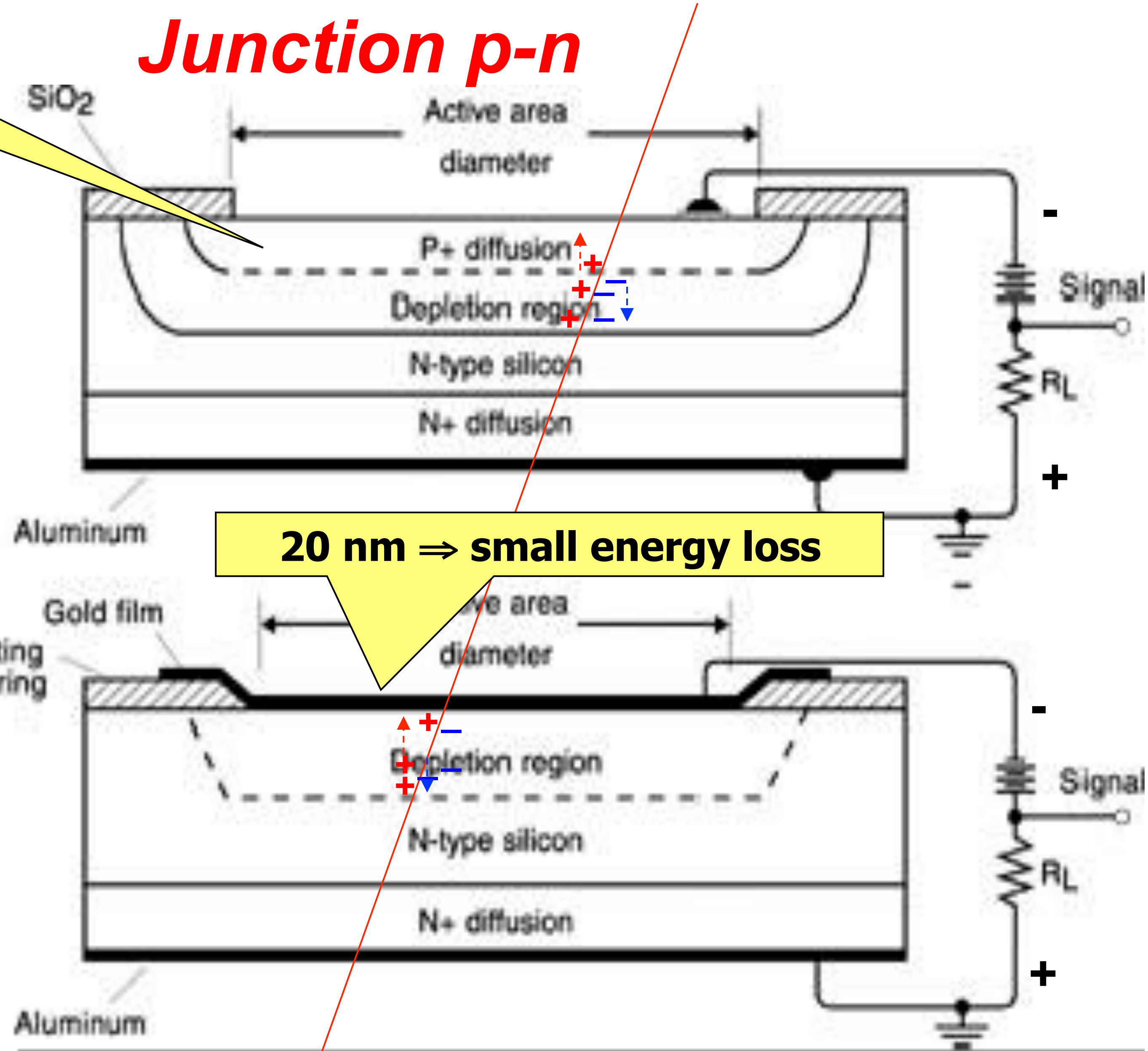
robust, flexible geometry

Shottky barrier

Shottky barrier

metal-silicon junction

thin metal contact more fragile



G.Hall

Surface barrier detectors

Interaction of charged particles in silicon

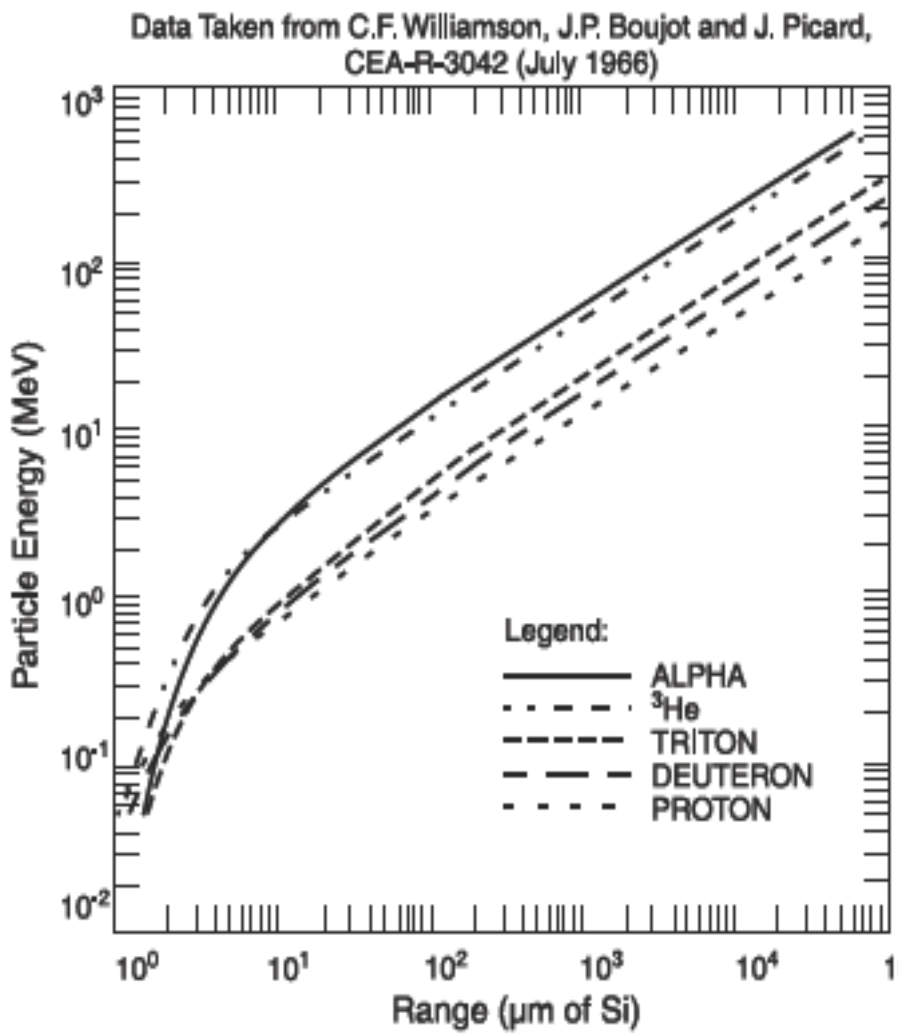
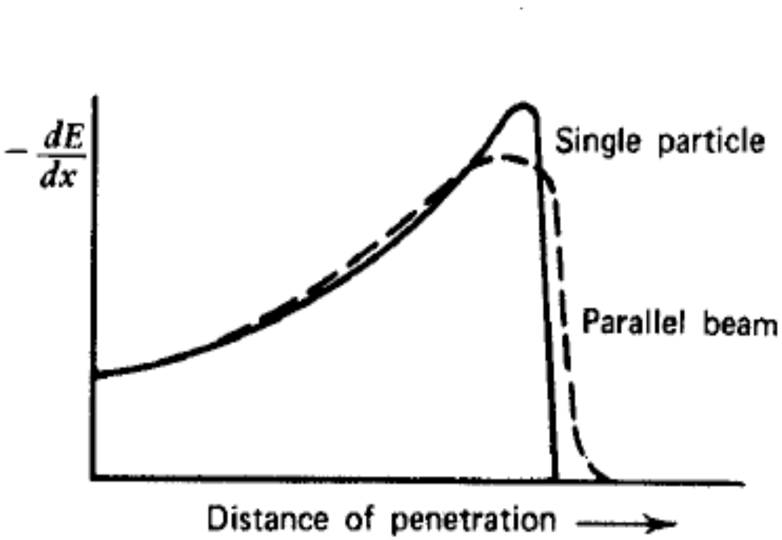
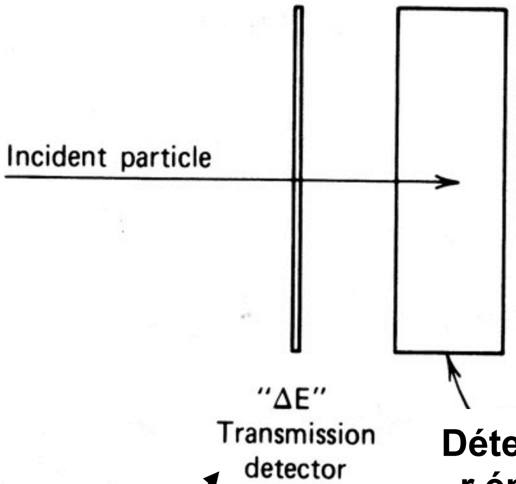


Figure 1.10 Range-Energy Curves in Silicon



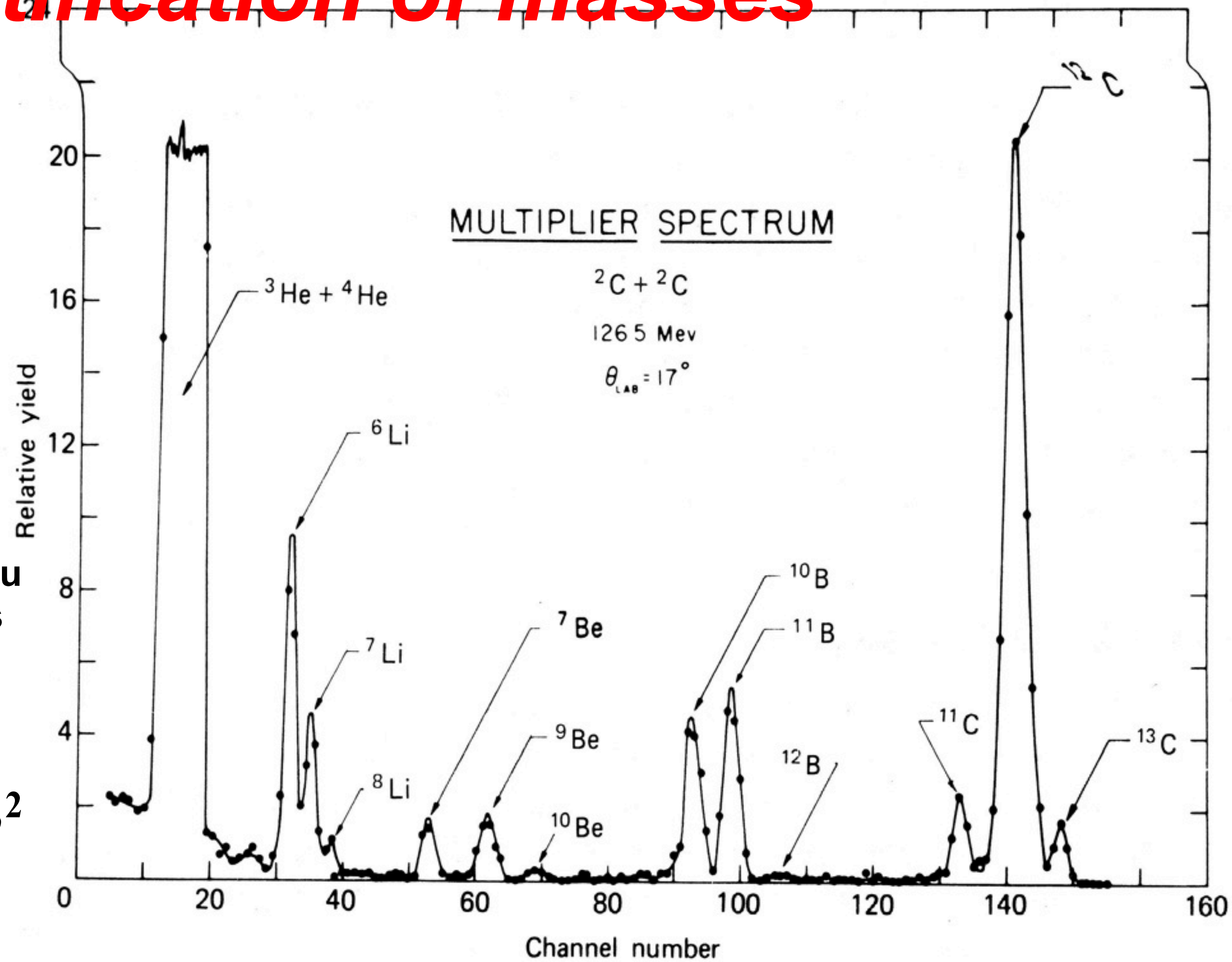
Identification of masses



Détecteur épais

E

(a)



(b)

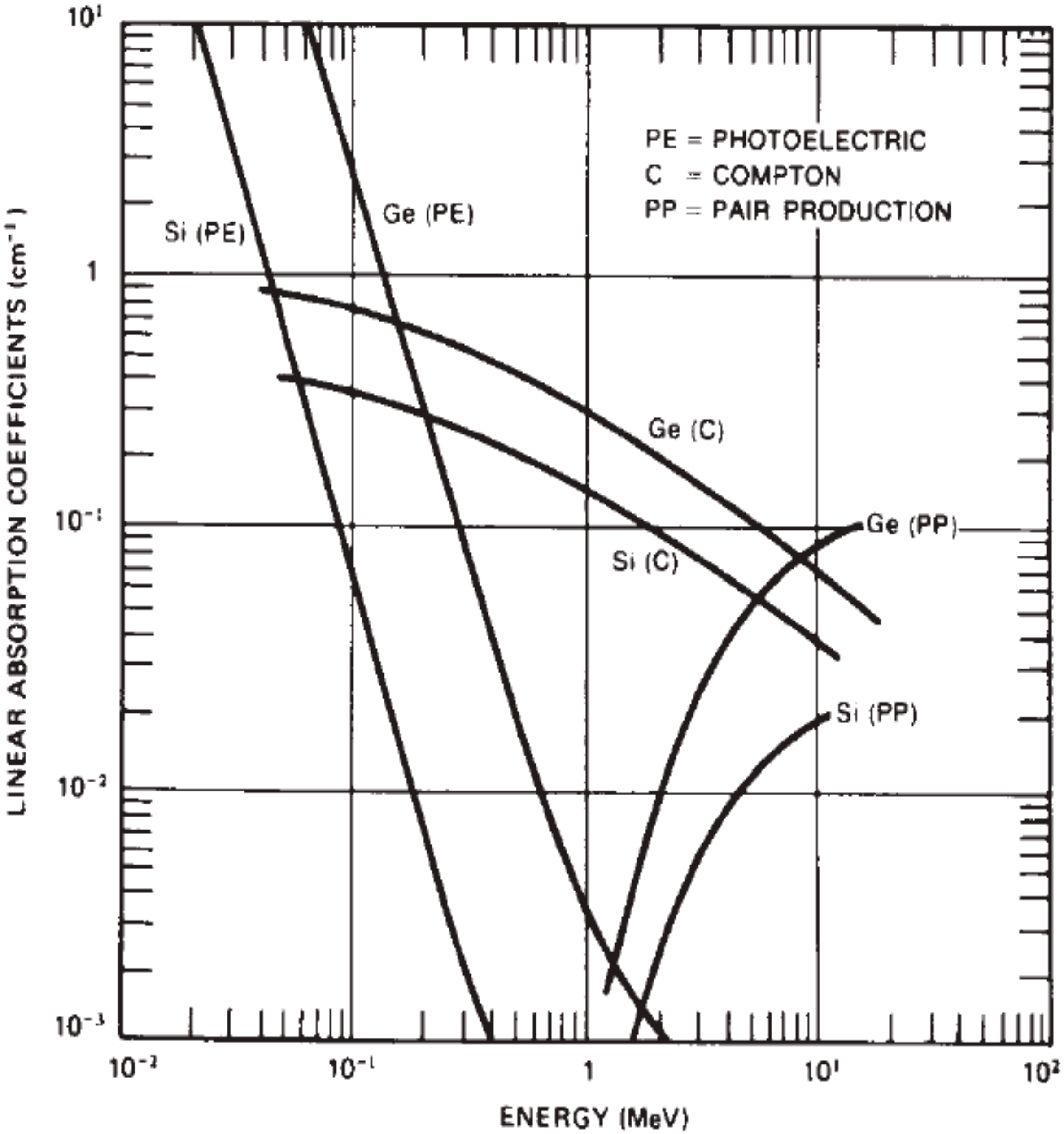
$$\frac{dE}{dx} \propto \frac{1}{v^2}; \quad E_{cin} = \frac{1}{2} m v^2$$

$$\Rightarrow$$

$$\frac{dE}{dx} \times E_{cin} \propto m$$

Figure 11-16 (a) A particle identifier arrangement consisting of tandem ΔE and E detectors operated in coincidence. (b) Experimental spectrum obtained for the $\Delta E \cdot E$ signal product for a mixture of different ions. (From Bromley.[90])

Detection of nuclear gammas



High Purity Germanium

Energy measurement of gammas

($|N_A - N_D| \cong 10^{10}$ cm^{-3}):

- E_{gap} = 0.74 eV ⇒ operation temperature : T= 77K
- w_{eh}=2.98 eV ⇒excellent resolution
  - E_γ = 1 MeV, dE ≅ 1 keV
  - "High" photo peak efficiency

Large volume detectors

- **Depletion zone :**

$$d\Big|_{V_{bias}} = x_n + x_p = \sqrt{\frac{2\varepsilon\left(\phi_0 + V_{bias}\right)}{e}\frac{\left(N_A + N_D\right)}{N_A N_D}}$$

$$N = N_A \ll N_D;\ \ \phi_0 \ll V_{bias}$$

$$d\Big|_{V_{bias}} = \sqrt{\frac{2\varepsilon V_{bias}}{eN}}\ ;\ N = N_A \text{ ou } N_D = \text{net impurity of material}$$

$$N = 10^{+13}\, atoms / cm^3;\ V_{bias} = 3000\, Volt;$$

$$d\Big|_{V_{bias}=3000\,Volt} = 2.2\, mm$$

- **High purity :**

$$N_A\, ou\ \ N_D = 10^{+10}\, atoms / cm^3;\ V_{bias} = 1000\, Volt;\ \varepsilon = 16\cdot\varepsilon_0;$$

$$\varepsilon_0 = 8.85\cdot 10^{-12}\, F / m;\ F = Coulomb / Volt\ ;\ e = 1.6\cdot 10^{-19}\, Coulomb$$

$$d\Big|_{V_{bias}=1000\,Volt} = 1.8\, cm$$

$$d\Big|_{V_{bias}=2000\,Volt} = 2.5\, cm$$

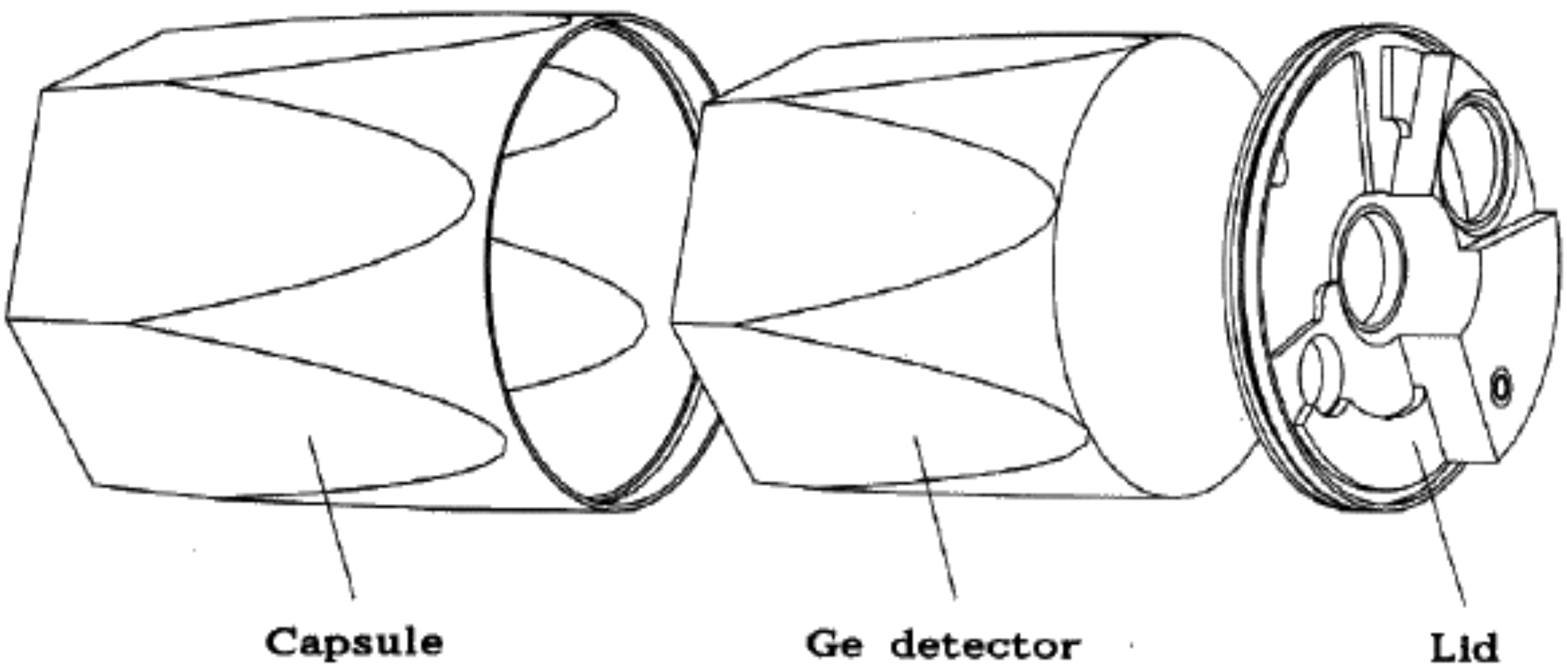
$$d\Big|_{V_{bias}=3000\,Volt} = 3.1\, cm$$

Germanium detectors

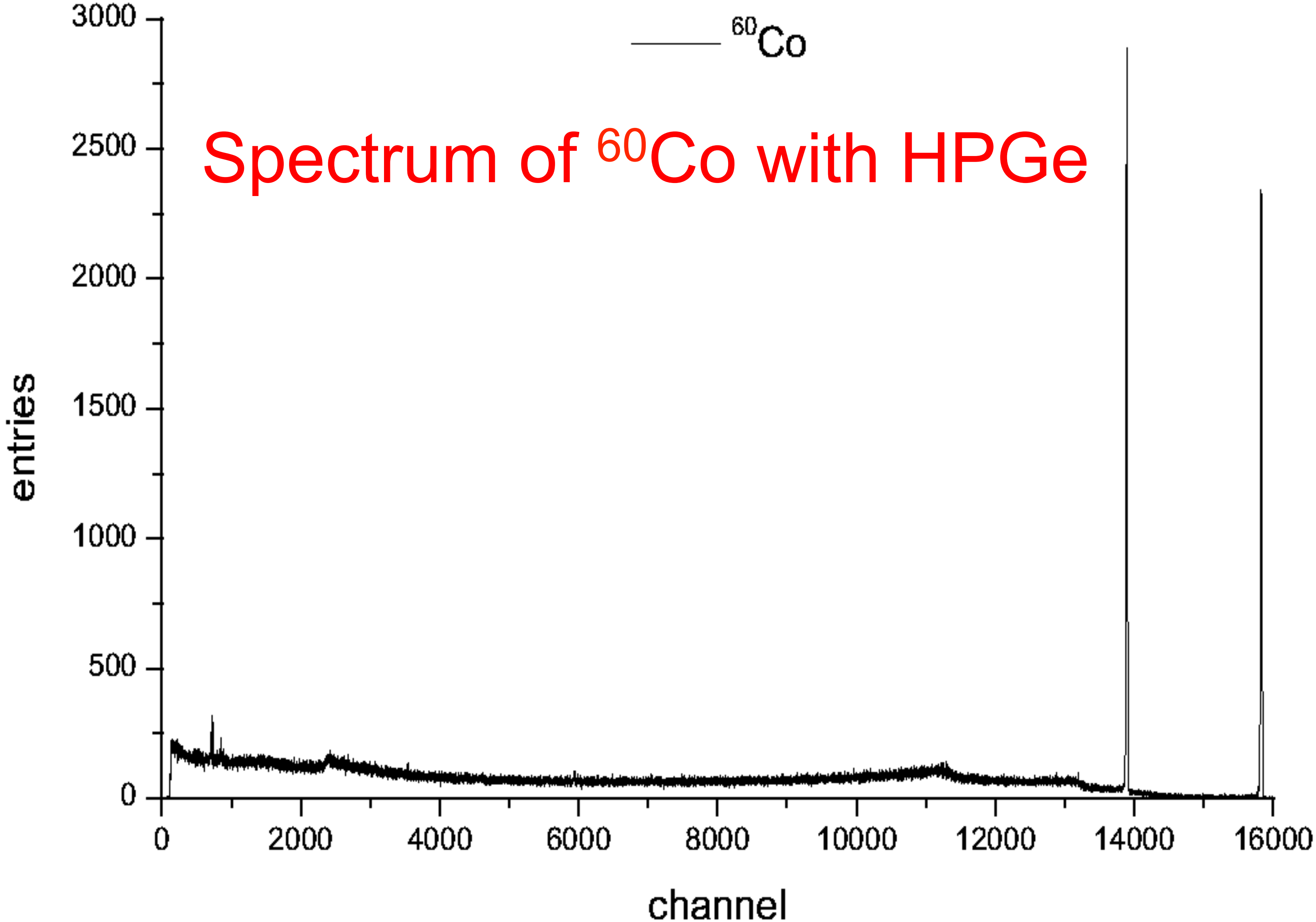
Operation temperature: T= 77K (Liquid Nitrogen)

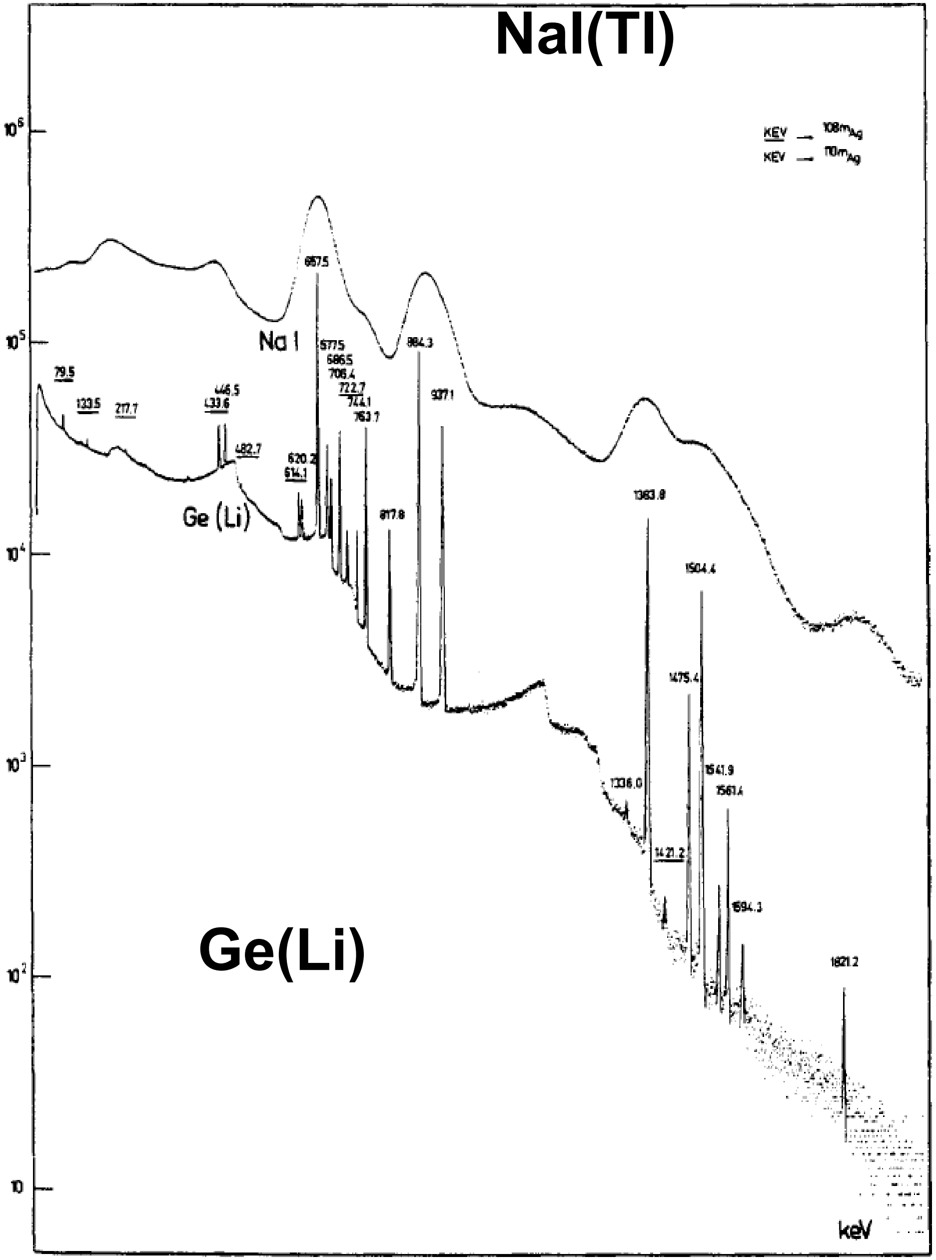
Configuration : co-axial

Electronics is mounted very close to the Crystal



Spectrum of ^{60}Co with HPGe





$$N_{eh} = \frac{E}{w}\varepsilon_{collection}$$

$$dN_{eh} = \sqrt{N_{eh}} = \sqrt{\frac{E}{w}\varepsilon_{collection}}$$

Statistics : Poisson

$\Rightarrow \sigma^2 = \mu; \quad \mu = \text{mean}; \sigma^2 = \text{variance}$

$$dE/E = dN_{eh}/N_{eh} \sim \frac{1}{\sqrt{N_{eh}}} = \frac{1}{\sqrt{\frac{E}{w}\varepsilon_{collection}}}$$

$\varepsilon_{collection} \approx 100\%; \; w = 2.98\,eV \quad E = 1\,MeV$

$\Rightarrow dE/E \approx 0.0017;$ Resolution $R = 2.35 \times dE/E = 0.4\%$

Fano factor:

$\sigma^2 = F_{ano}\mu;$

$F_{ano} \simeq 0.12\,(Ge, Si); \quad \sqrt{0.12} = 1/2.9$

$$dE/E = dN_{eh}/N_{eh} \sim \frac{\sqrt{F}}{\sqrt{N_{eh}}} = \frac{1}{\sqrt{\frac{E}{wF}\varepsilon_{collection}}}$$

$dE/E = 0.0006;$ Resolution $R = 2.35 \times dE/E = 0.14\%$

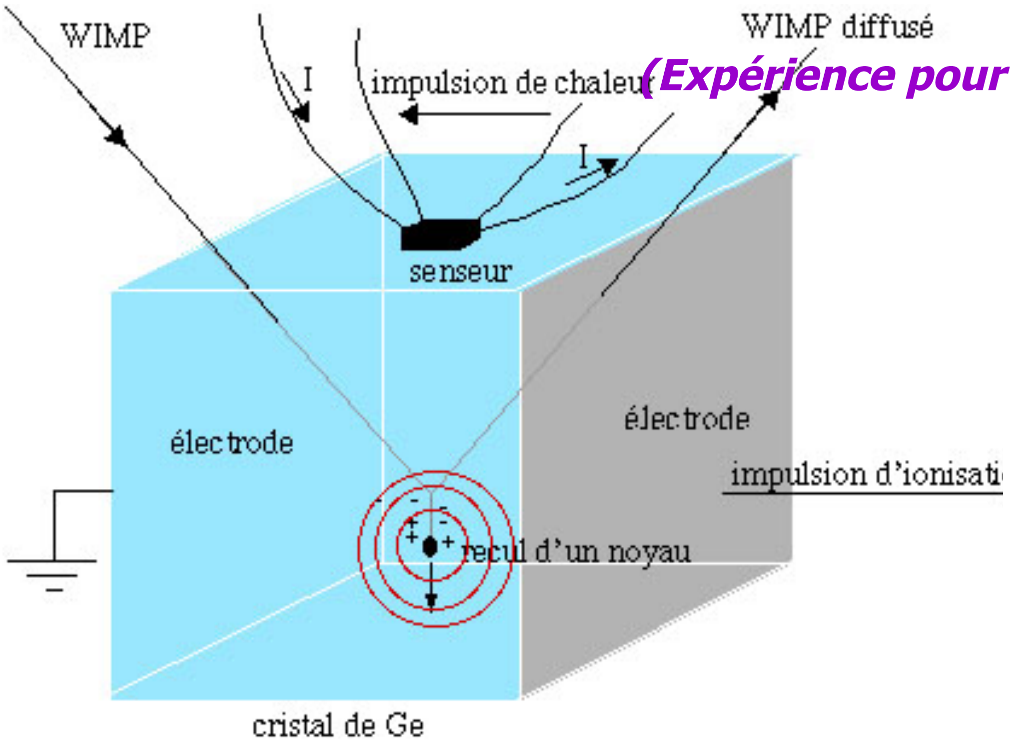
NaI:

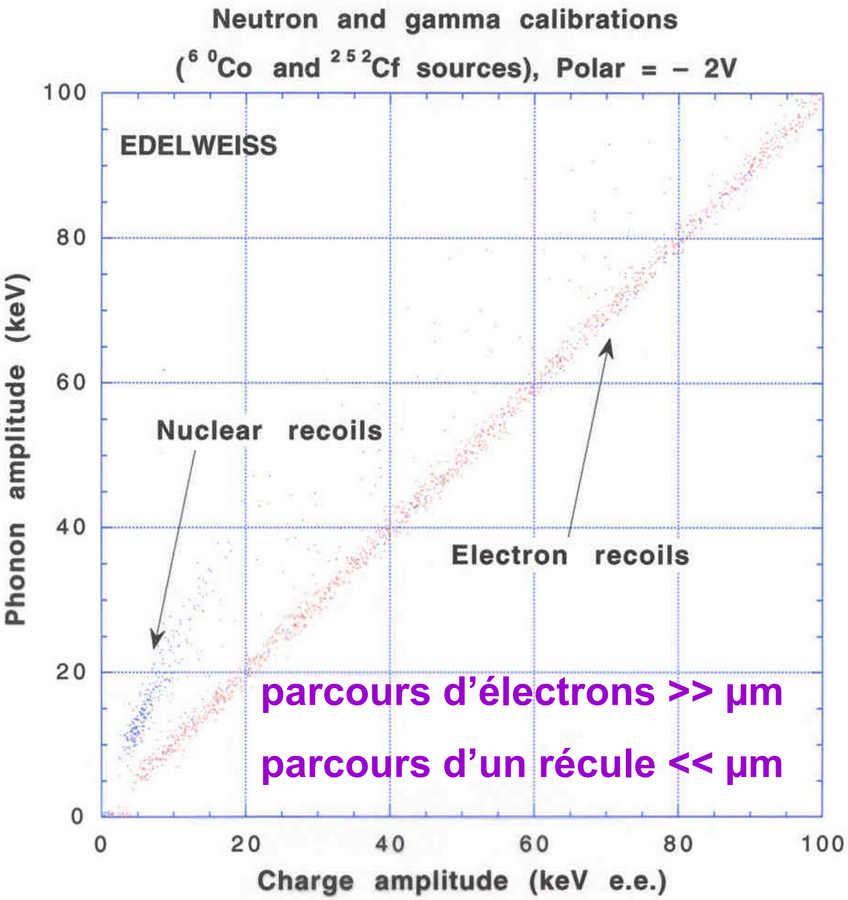
$w = 25\,eV/photon_{scint}$ Light collection: 0.5 PM : $Q.E. \approx 0.20$

$dE/E \approx 1.6\%$ Resolution $R = 2.35 \times dE/E = 3{,}7\%$ à $1\,MeV$

EDELWEISS

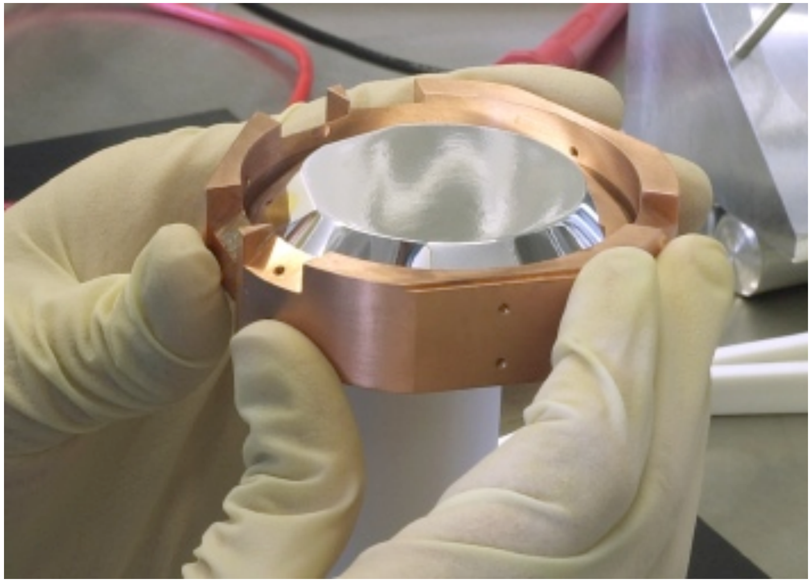
(Expérience pour Détecter Les Wimps en Site Souterrain)

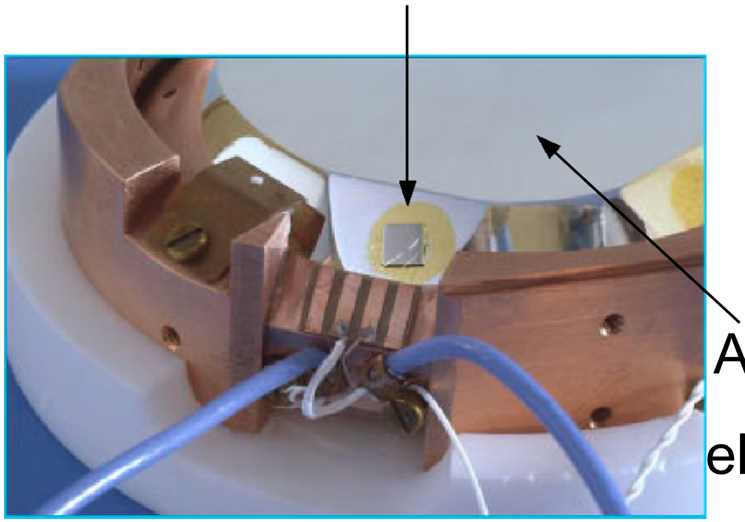




- **Cristal of very pure "Ge" 1Kg,**
- **Very rare events 1 event/Kg/year !!**
- **Ionisation**
  - **some keV**
- **Heat/ mechanical vibration of cristal**
  - **$\Delta T \approx$ 10-6 mK => cryostat(^{3}He-^{4}He) à 10 milli-Kelvin**

Ge ionization – phonon detectors I





- bolometer mass: 320 g
- 100nm sputtered Al layer as electrode (center + guard ring)
- 60nm Ge(Si) amorphous layer below electrode
- NTD sensor glued on sputtered gold pad on guard ring electrode
- electrical contacts/heat links via gold wire bonding (Ø=25μm)
- **operating temperature T=17.00±0.01mK**

High energies

- **SIlicon Tracking Detectors**

CMS Tracker

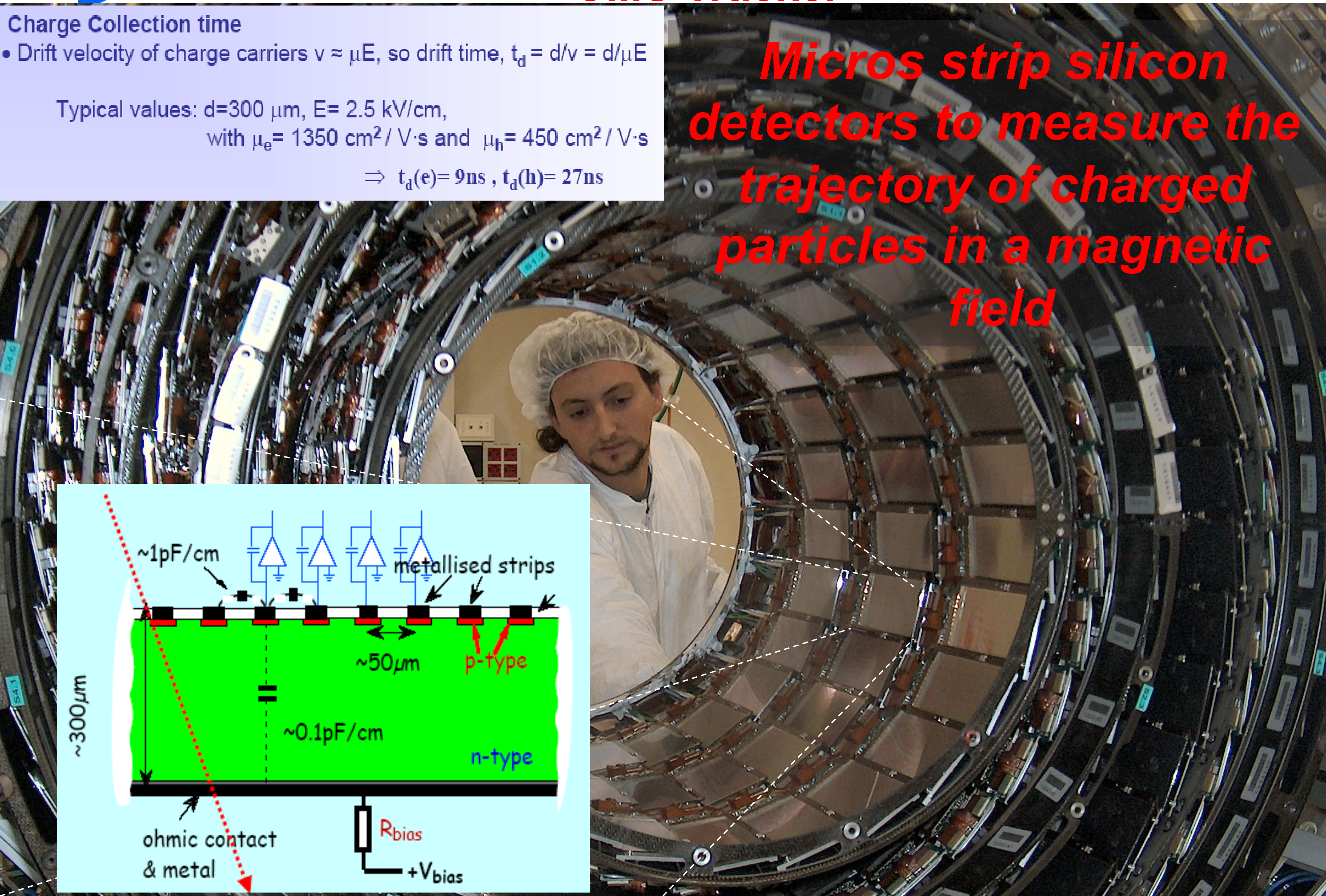
Charge Collection time

- Drift velocity of charge carriers $v \approx \mu E$, so drift time, $t_d = d/v = d/\mu E$

Typical values: d=300 μm, E= 2.5 kV/cm,
with μ_e= 1350 cm^2 / V·s and μ_h= 450 cm^2 / V·s

$\Rightarrow$ $t_d(e)$= 9ns , $t_d(h)$= 27ns

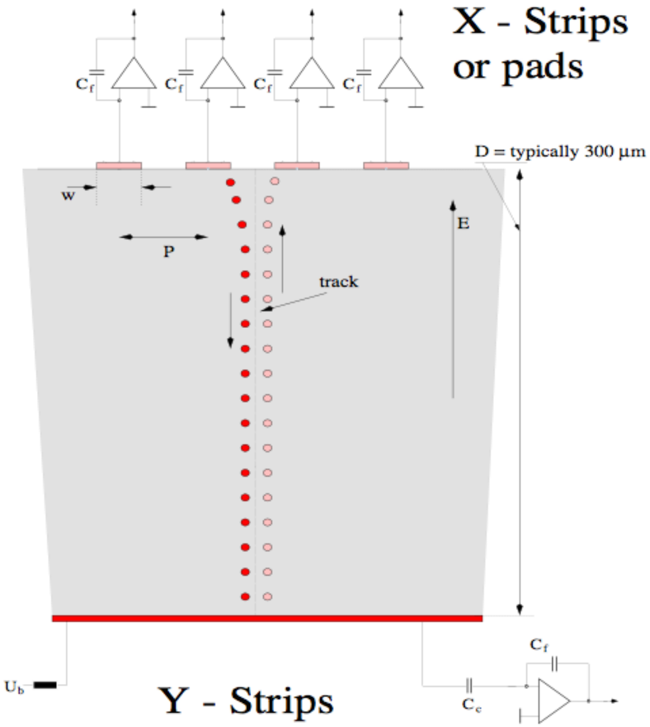
Micros strip silicon detectors to measure the trajectory of charged particles in a magnetic field



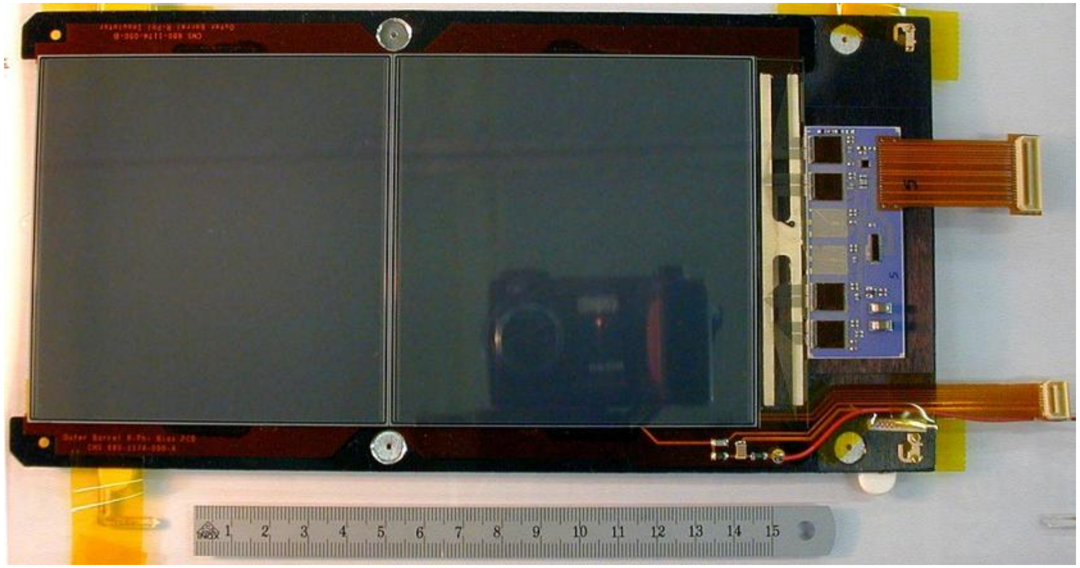
Silicon Detector

Every electrode is connected to an amplifier →

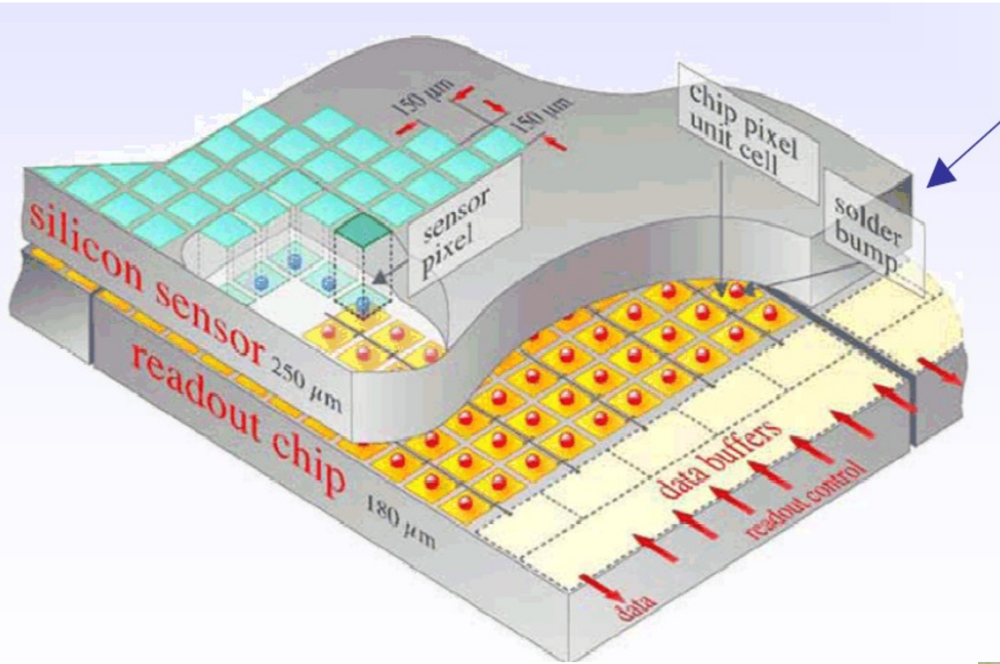
Highly integrated readout electronics.

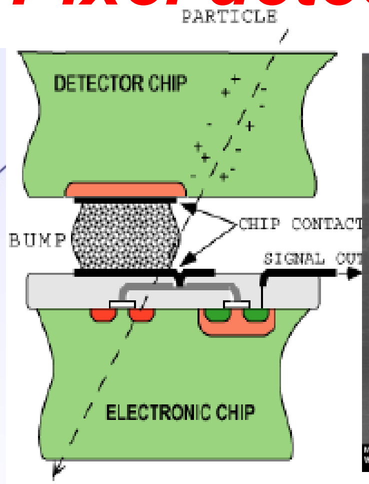


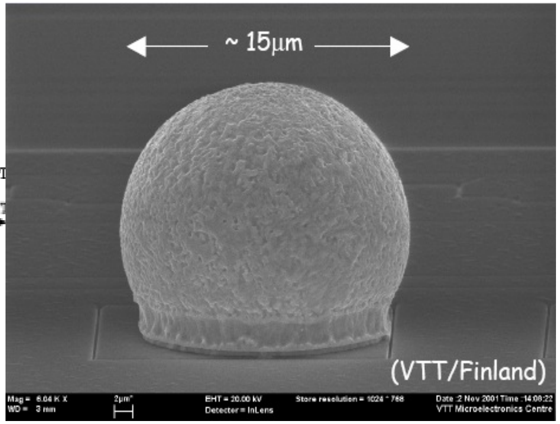
CMS Outer Barrel Module

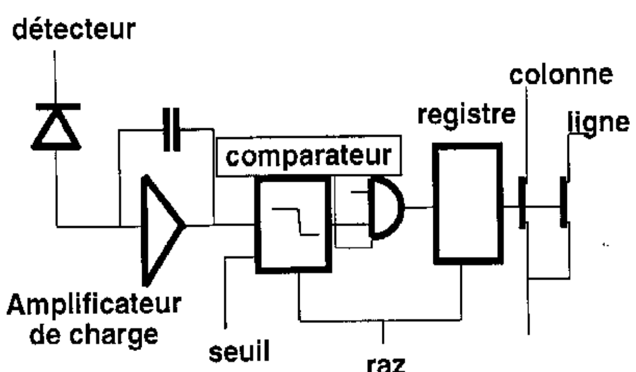


Pixel detectors

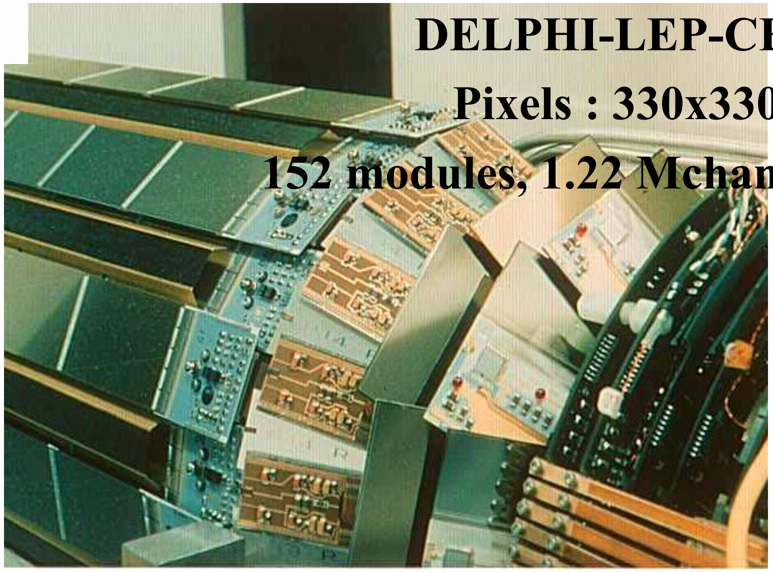








Pixel electronics: complex!



DELPHI-LEP-CERN

Pixels : 330x330 µm

152 modules, 1.22 Mchannels

High energy Calorimetry

Calorimeters at high energy

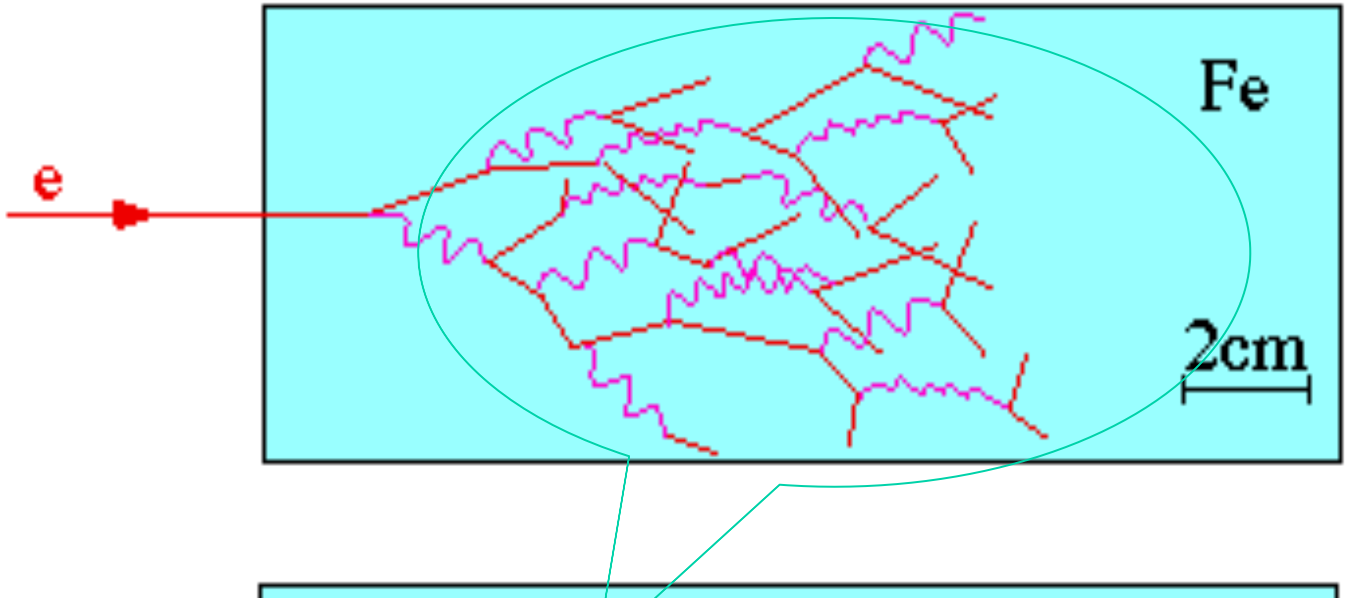
- At very high energies the momentum resolution of any magnetic spectrometer will deteriorate rapidly
- Calorimeters measure the energy of the particles

  The energy of the incident particle is transformed into a large number of secondary particles which can be measured

  The number of secondary's is proportional to the energy

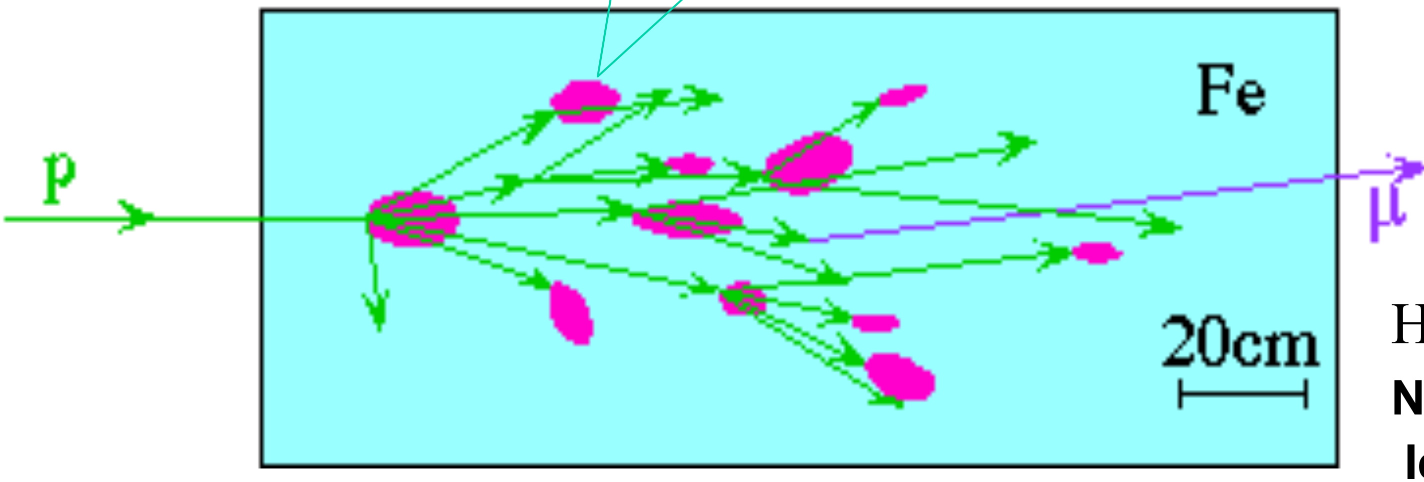
  Ionisation, scintillation Cerenkov…
  - Electromagnetic showers (electrons, gammas, π^0…
  - Hadronic showers, all hadrons!
- Electromagnetic showers :
  - Conversion of photons into e^+e^- and Bremsstrahlung
- Hadronic showers:
  - nuclear interactions, fragmentation of nuclei

Showers in calorimeters



Electromagnetic shower

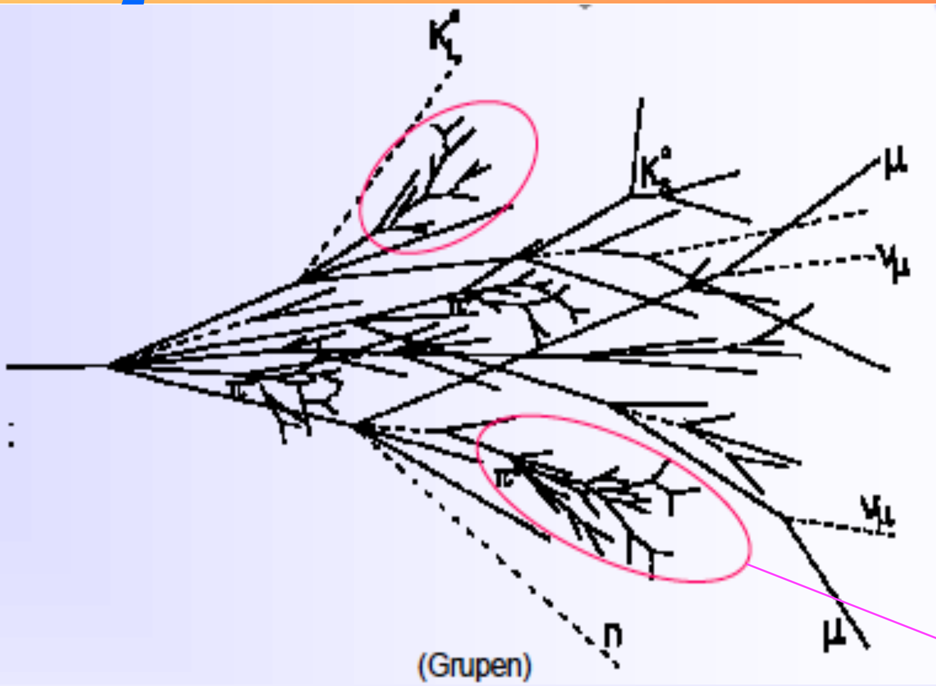
radiation length X_0



Hadronic shower

Nuclear interaction length Λ

Hadronic showers



hadronic + electromagnetic

- charged hadrons p, $\pi^{\pm}$, $K^{\pm}$,
- nuclear fragmets ….
- breaking up of nuclei (binding energy)
- neutrons, neutrinos, soft γ's, muons

neutral pions $\rightarrow 2\gamma$

$\rightarrow$ electromagnetic cascades

$$n(\pi^0) \approx \ln E(GeV) - 4.6$$

example $E = 100$ GeV: $n(\pi^0) \approx 18$

invisible energy $\rightarrow$ large energy fluctuations $\rightarrow$ limited energy resolution

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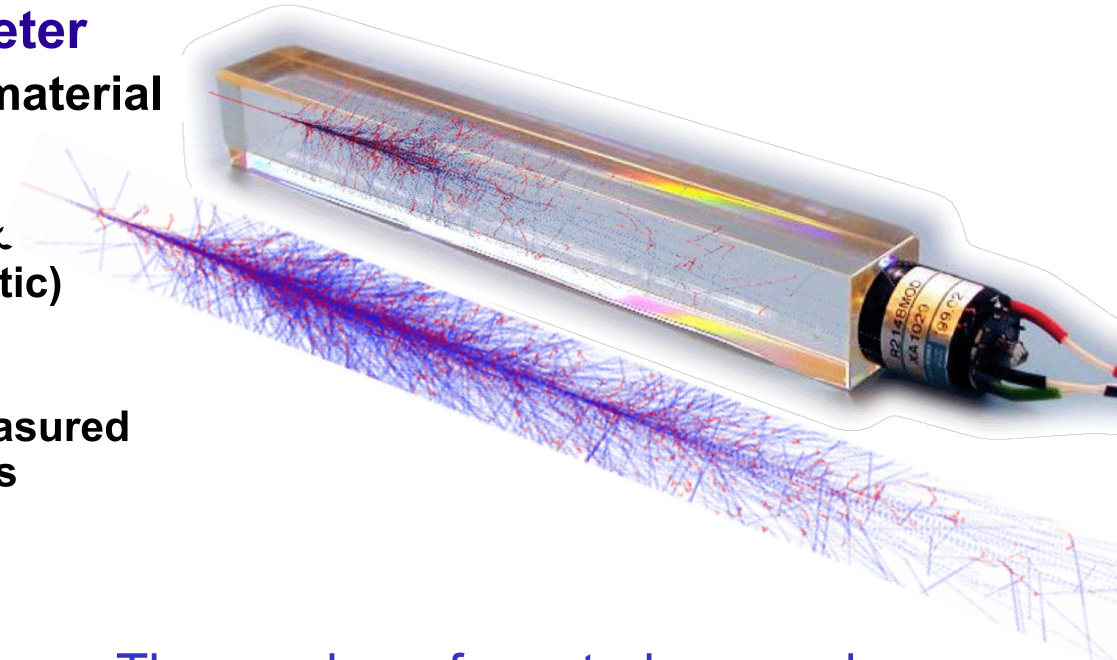
CMS homogeneous elm Calorimeter

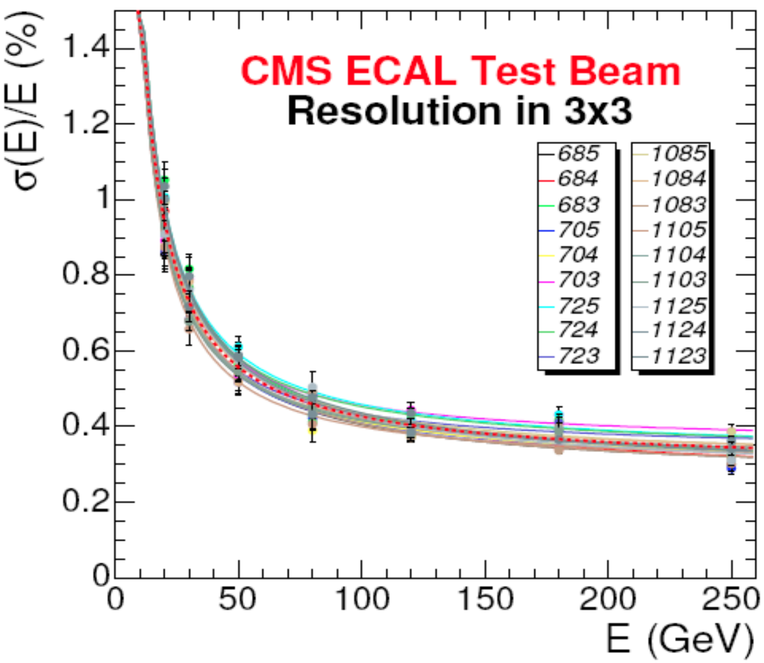
$PbWO_4$ Scint. Crystal Calorimeter

Entire shower in active detector material
- High density crystals (28 X_0)
- Transparent, high light yield
- No particles lost in passive absorb
- High resolution: ~3%/√*E* (stochastic)

Granularity
- Barrel: $\Delta\eta \times \Delta\phi = 0.017^2$ rad
- Longitudinal shower shape unmeasured

Read out with avalanche photo diodes





The number of created secondary particles is proportional to the energy $E \sim N$, $\sigma_{RMS} \sim \sqrt{N} \sim \sqrt{E}$

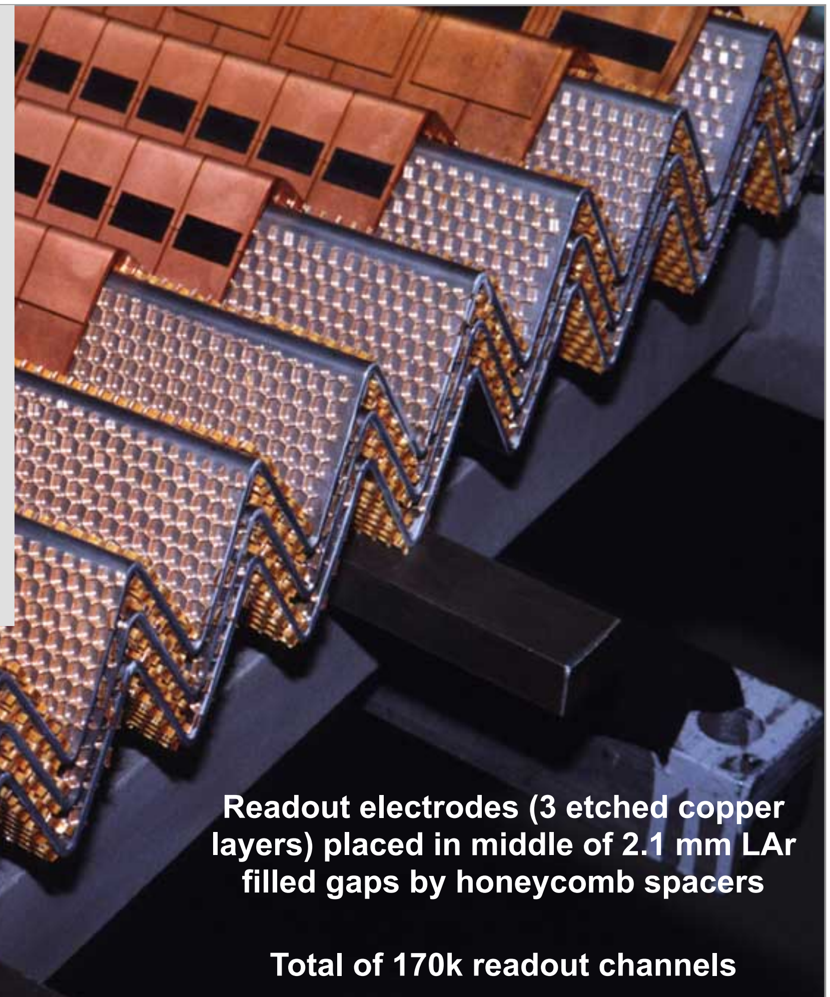
$$\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E\,(\mathrm{GeV})}} \oplus \frac{0.128}{E\,(\mathrm{GeV})} \oplus 0.3\%$$

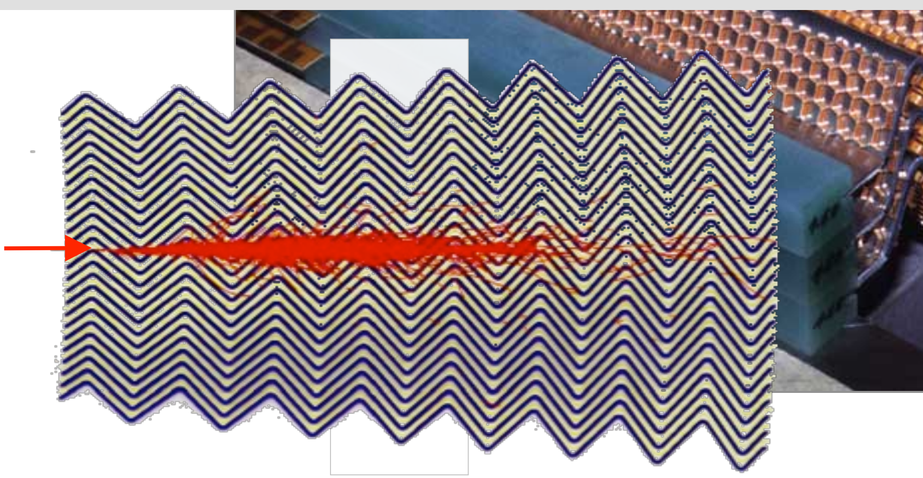
The Electromagnetic Calorimeter - ECAL

ATLAS Liquid Argon EM Calorimeter

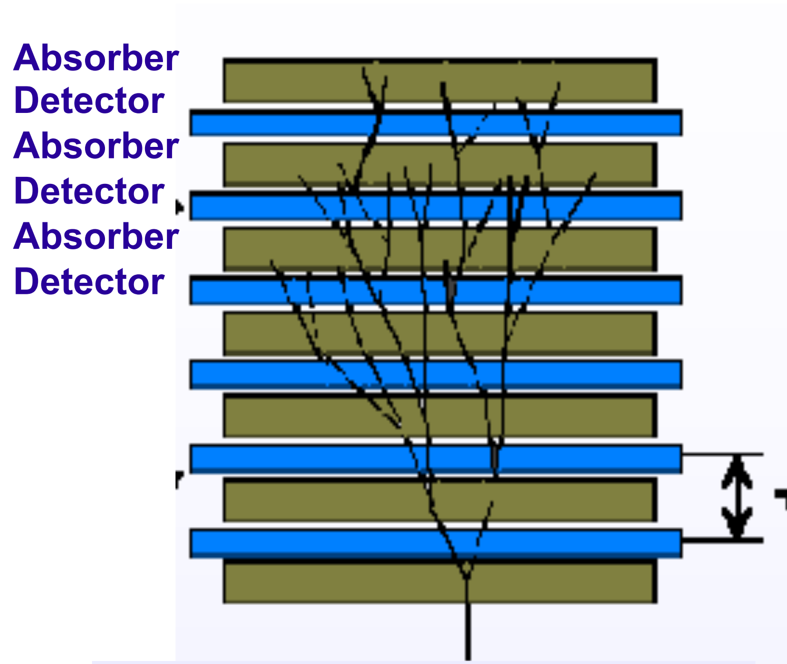
LAr Sampling Calorimeter

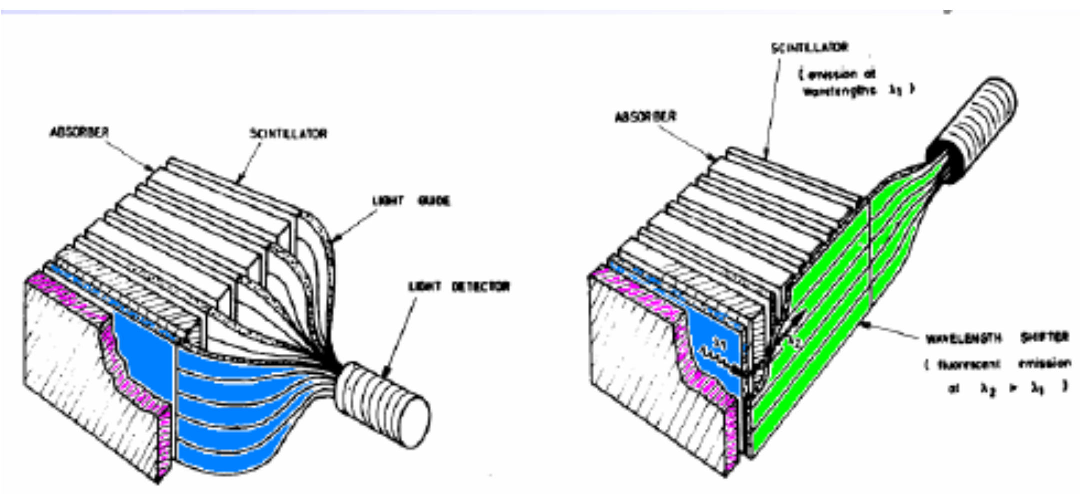
- Passive, heavy absorber (Pb, 1.1–1.5 mm thick [barrel]) inter-leaved with active detector material (liquid argon)
  - Overall 22 X_0
  - Accordion structure for full ϕ coverage
  - Resolution: ~10% / $\sqrt{E}$ (stochastic)
- Granularity
  - Barrel: $\Delta\eta \times \Delta\phi = 0.025^2$ rad (main layer)
  - Longitudinal segmentation (3 layers)

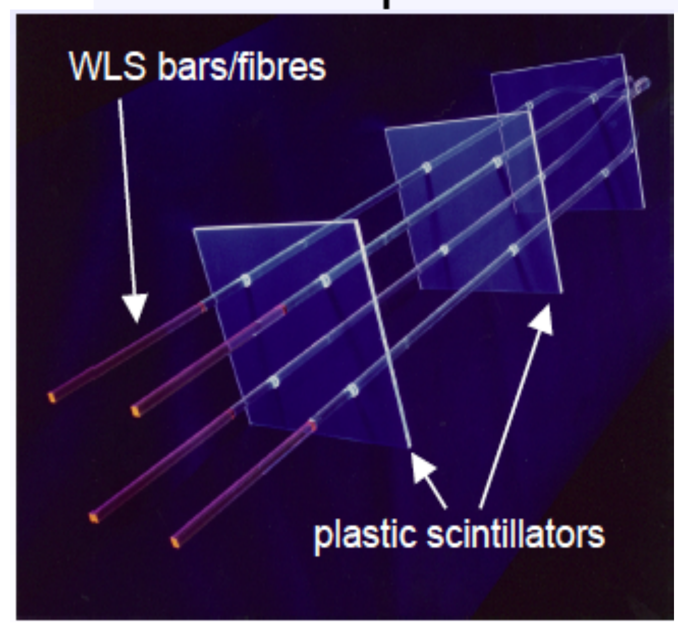




Sampling calorimeters





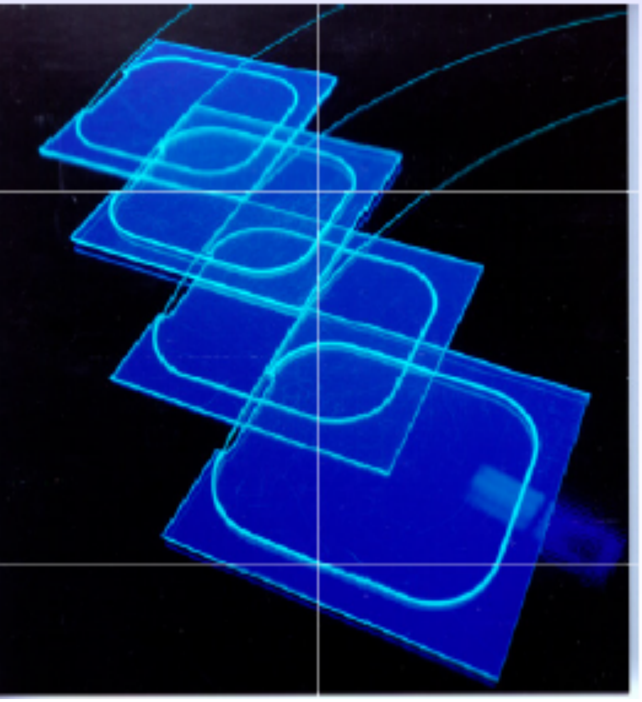


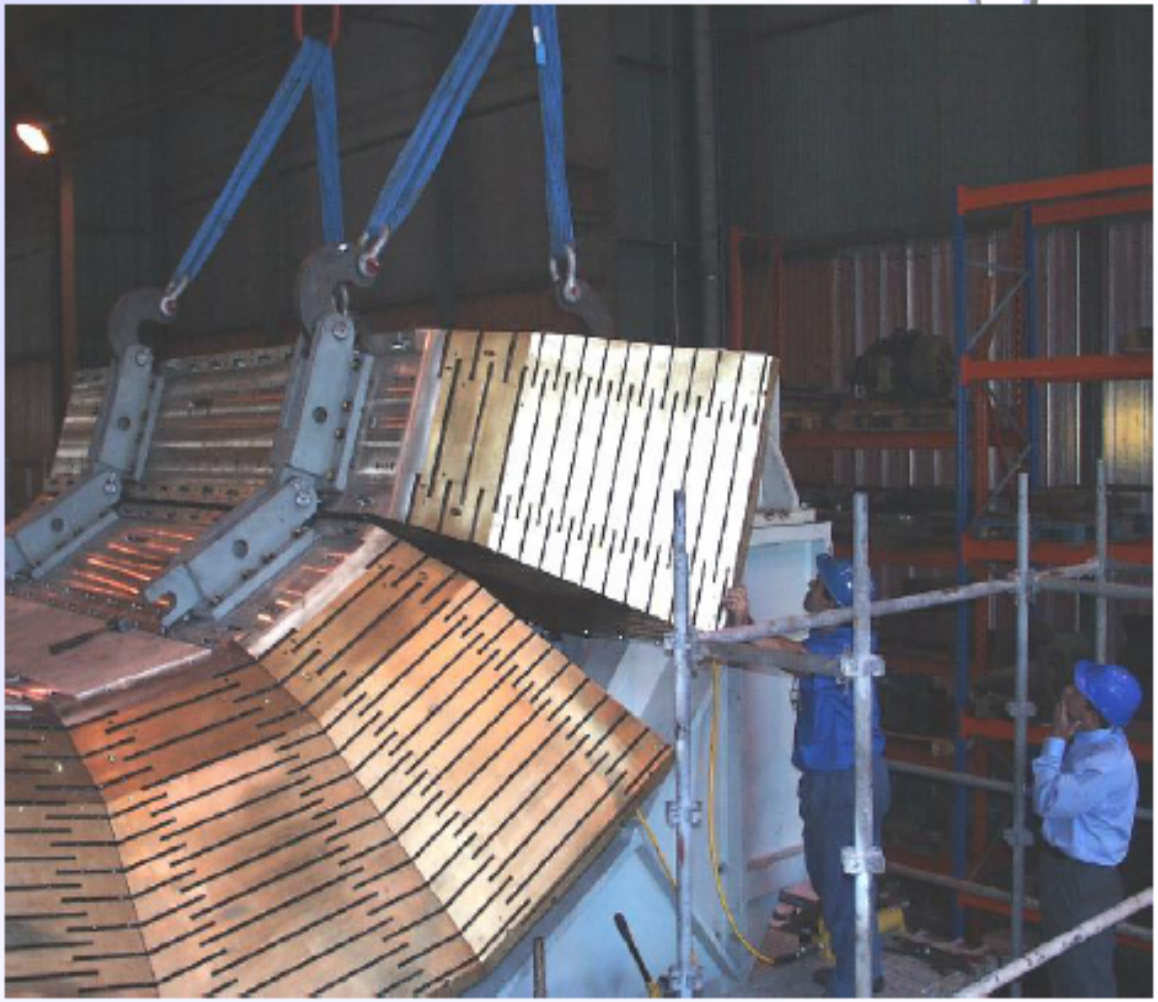
CMS Hadron calorimeter

Brass absorber + plastic scintillators

2 x 18 wedges (barrel)
+ 2 x 18 wedges (endcap)
~ 1500 T absorber
5.8 λ_i at $\eta = 0$.

Scintillators fill slots and are read out via WLS fibres by HPDs (B = 4T!)

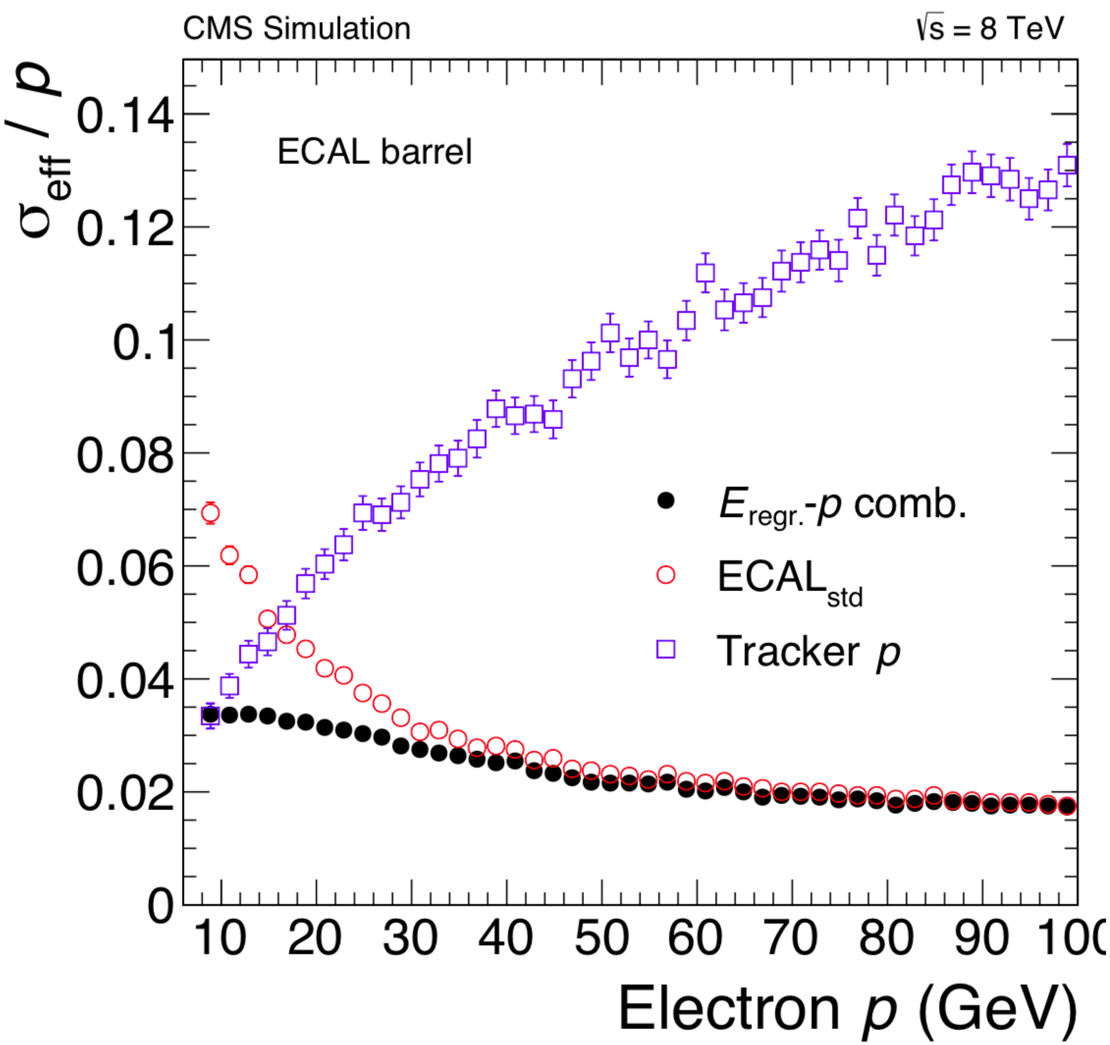




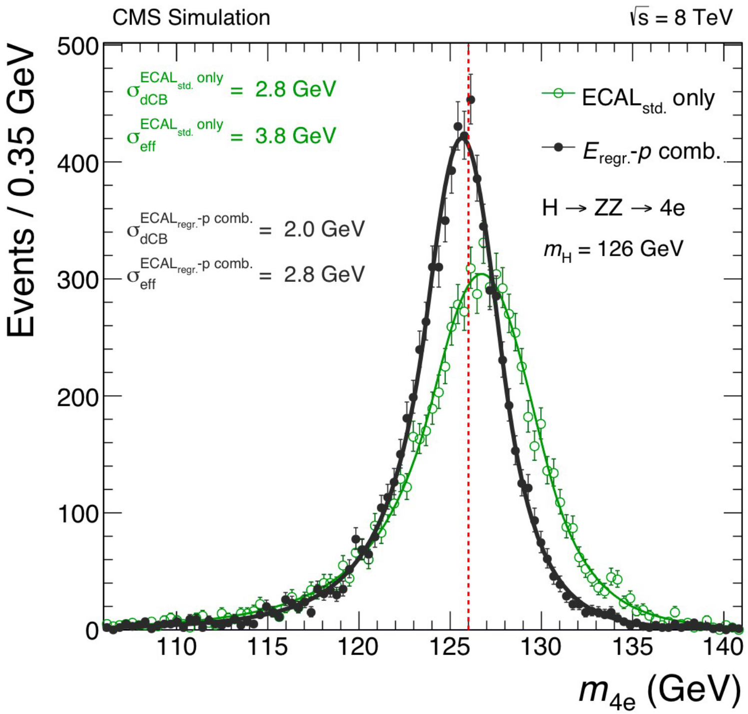
Test beam resolution for single hadrons

$$\frac{\sigma_E}{E} = \frac{65\%}{\sqrt{E}} \oplus 5\%$$

Energy / momentum resolution



$$\frac{dE}{E} \sim \frac{1}{\sqrt{E}}; \quad \frac{dp_T}{p_T} \sim \frac{\Delta s}{BL^2} p_T$$



(Simple?) Particle Identification, (PID)

- PID: charge, masse, leptons or hadrons, muons
- Measure dE/dx (β) and momentum (B-field)
- Photon vs neutral hadron
- Electron vs hadron
- Hadrons vs muons
- Cerenkov (β) or Transition radiation (γ)
- Time of flight (TOF)

$$\frac{dE}{ds}!!!$$

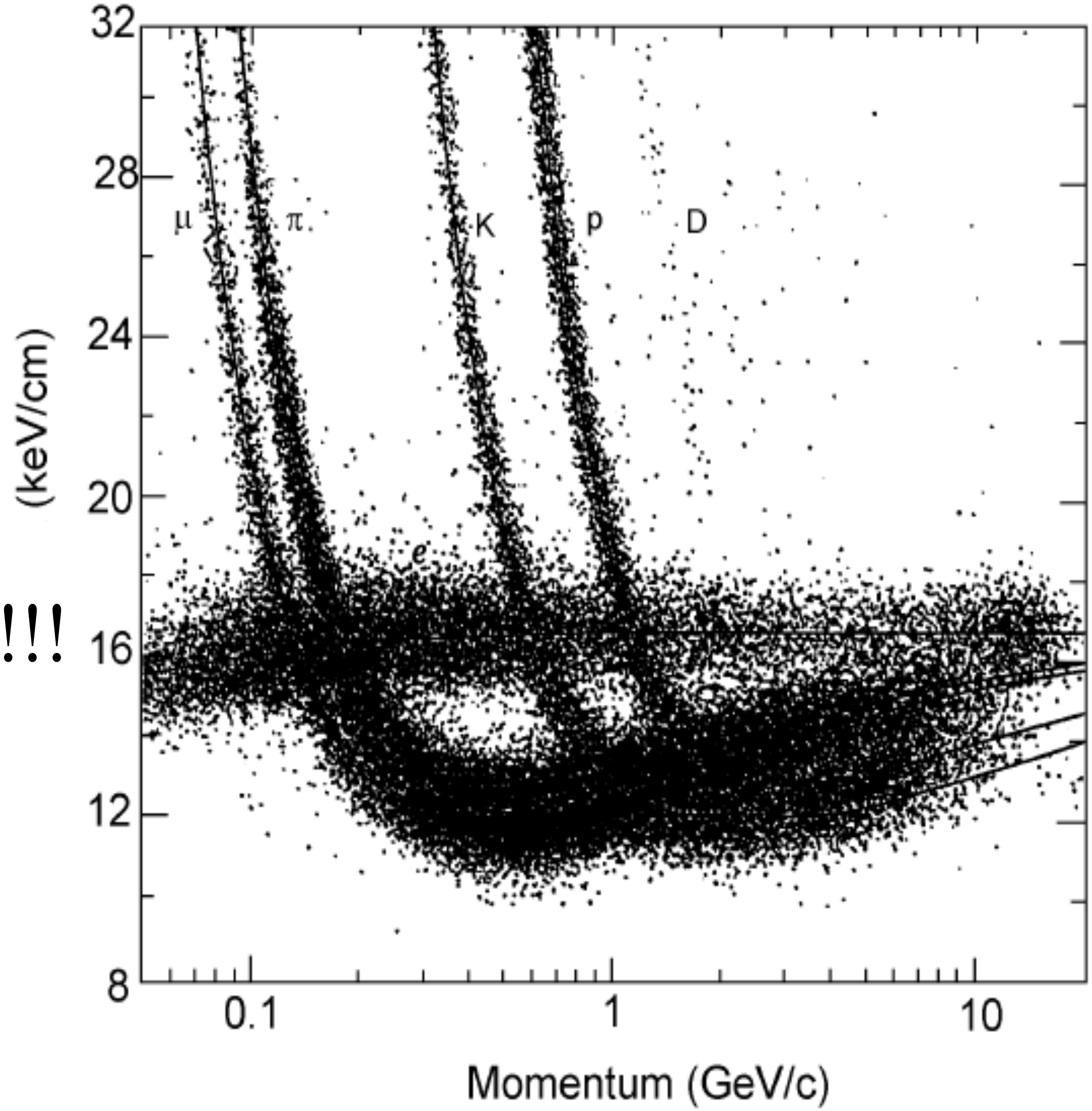
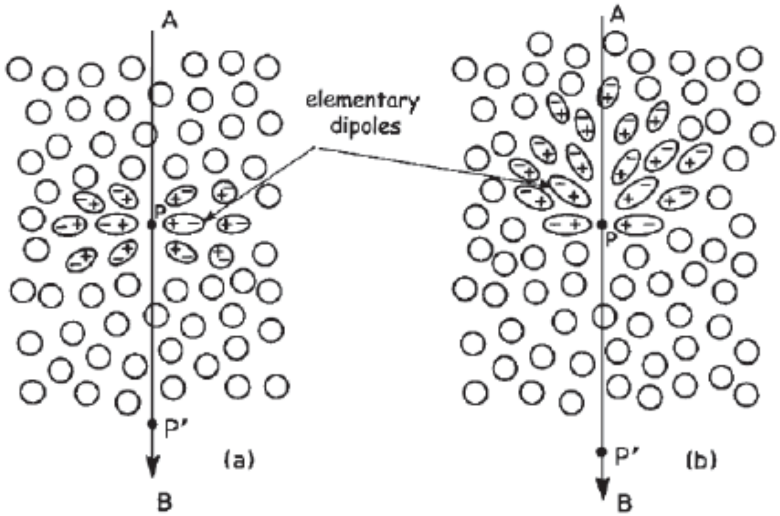
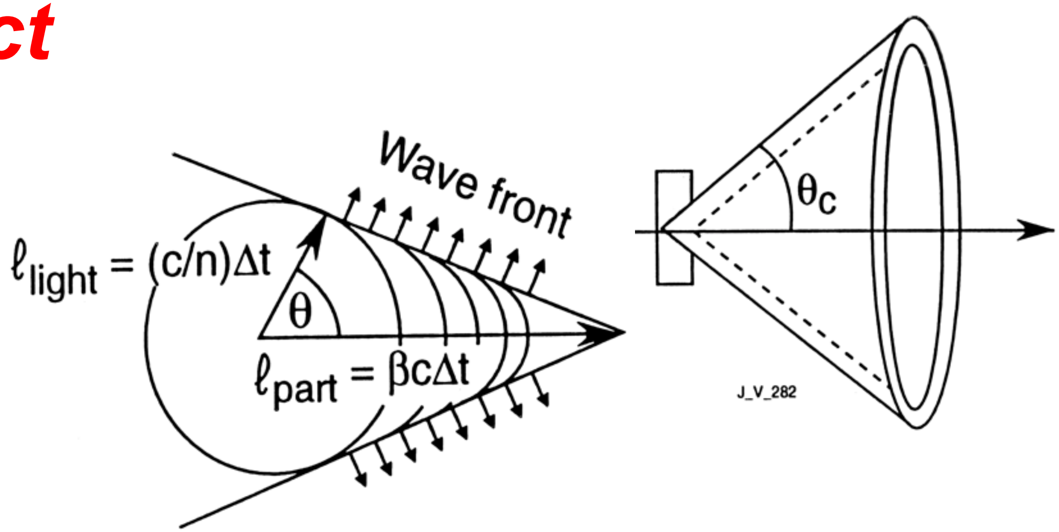


FIGURE 7. Measured ionization energy loss of electrons, muons, pions, kaons, protons and deuterons in the PEP4/9-TPC ($Ar–CH_4 = 80 : 20$ at 8.5 atm) [13]

Cerenkov effect



$v_p/c < c/n(\lambda)$ $v_p/c > c/n(\lambda)$



$$v = \beta c > c / n$$

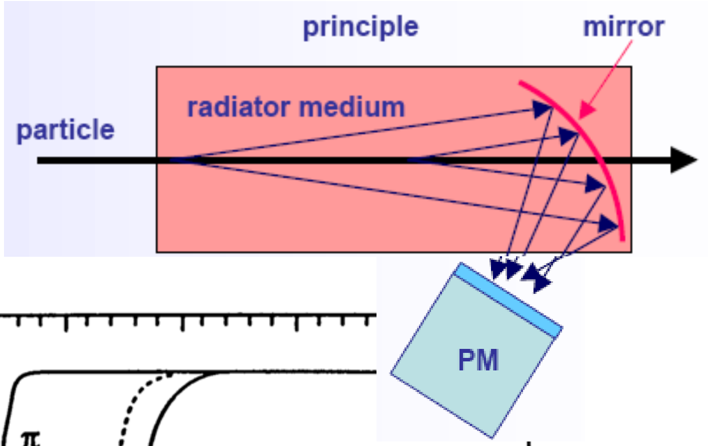
$$\cos\theta_C = \frac{c \cdot \Delta t / n}{\beta c \cdot \Delta t} = \frac{1}{\beta n}$$

$$\Rightarrow \beta > \frac{1}{n} \; ; \cos\theta_c^{max} = \frac{1}{n}$$

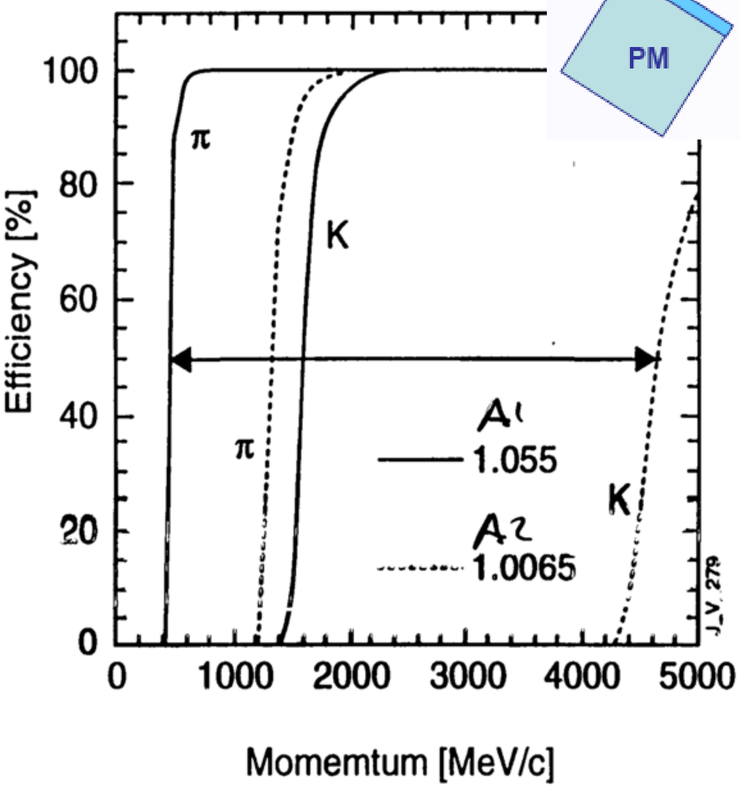
$$\lambda_{photons} \approx 200 - 700\, nm$$

- **Coherent superposition of the radiation of the atoms**
- **Mainly blue light**
- **Very few photons**
- **Very small energy loss**
- **Identification of particles!**

Cerenkov Detectors

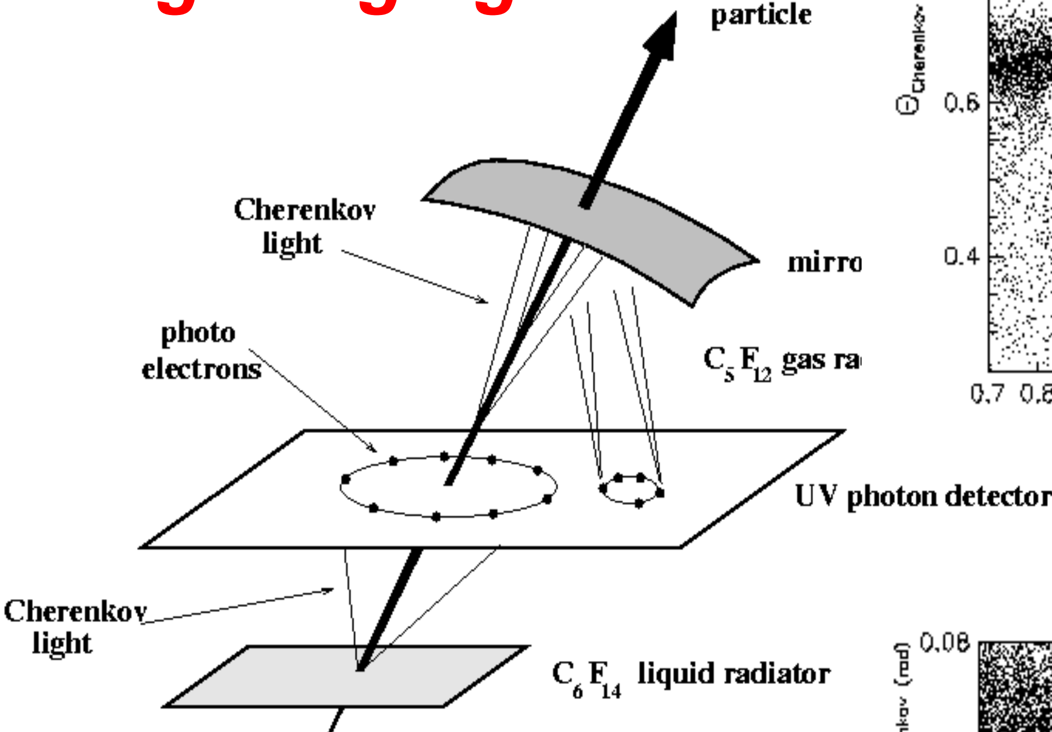


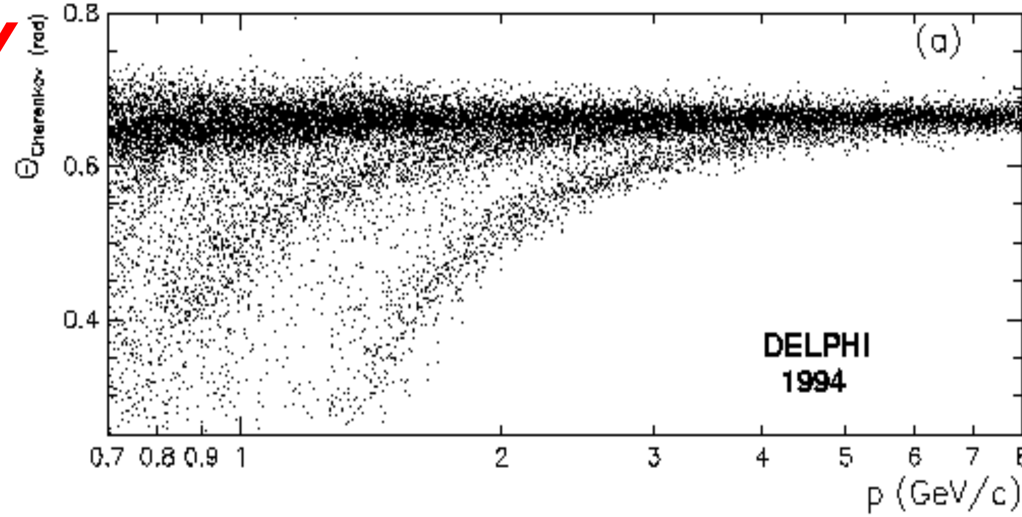
medium	n	θ_{max} (deg.)	N_{ph} (eV^{-1} cm^{-1})
air*	1.000283	1.36	0.208
isobutane*	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4

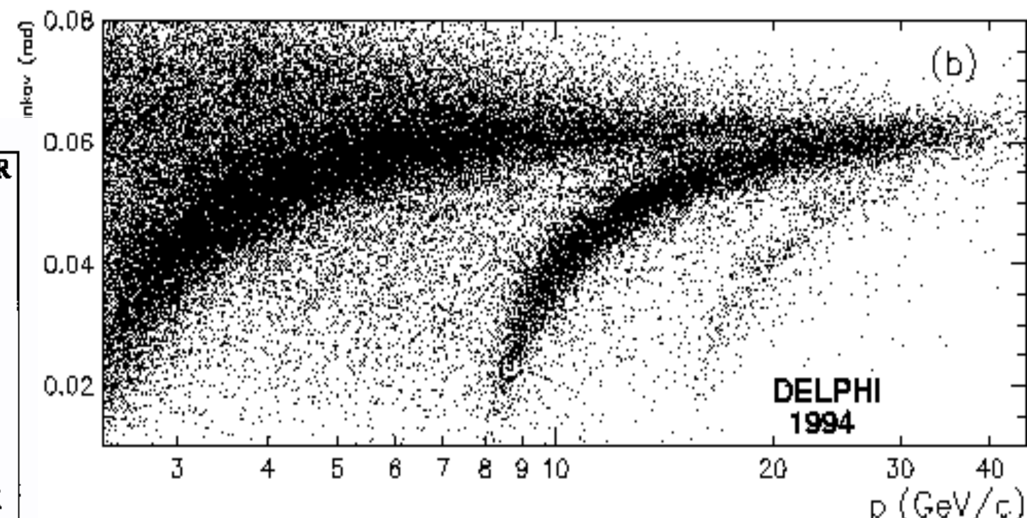


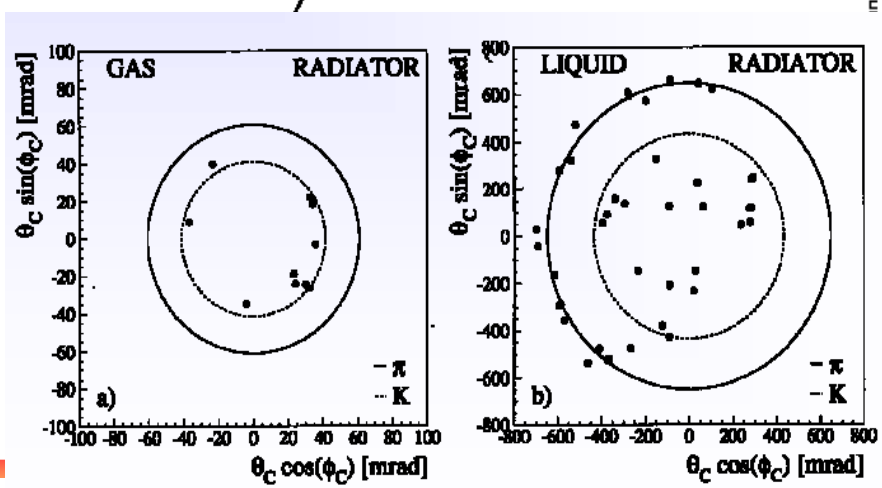
$$N_{ph} \approx 1 - \frac{1}{n^2\beta^2} = 1 - \frac{1}{n^2}\cdot\left(1 + m^2/p^2\right)$$

Ring Imaging Cerenkov





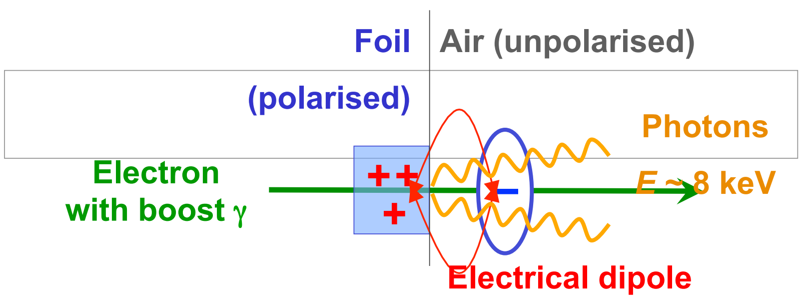




Transition radiation

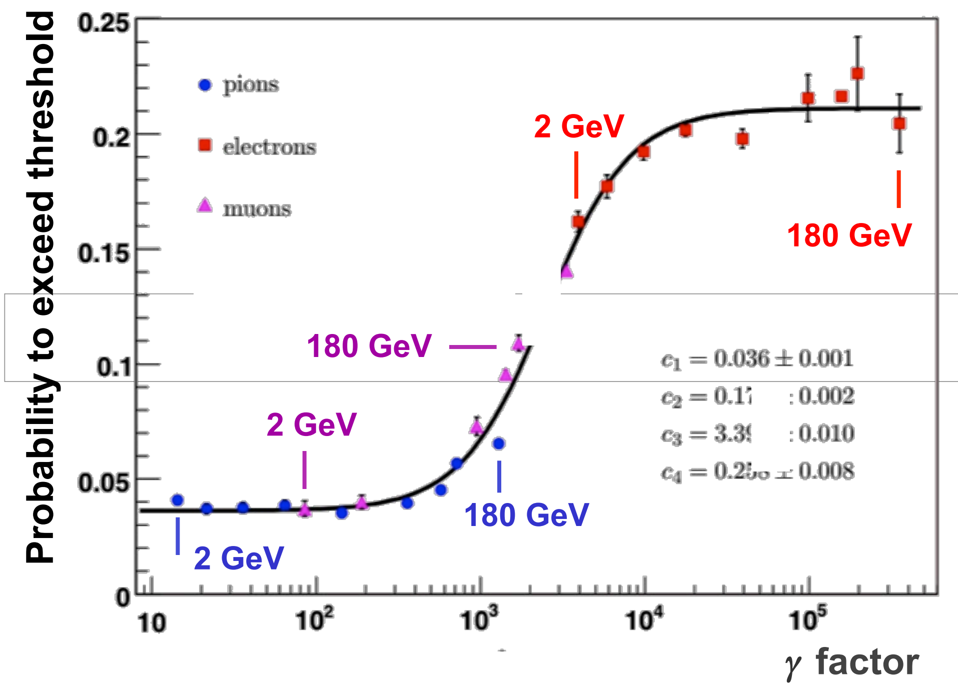
- Effect can be explained by re-arrangement of electric field
- A charged particle approaching a boundary creates a electric dipole with its mirror charge
- The time-dependent dipole field causes the emission of electromagnetic radiation

Photon radiation when charged ultra-relativistic particles traverse the boundary of two different dielectric media (foil & air)



➡ **Significant radiation for γ > 1000**

and > 100 boundaries



From D. Froidevaux, ASP 2010

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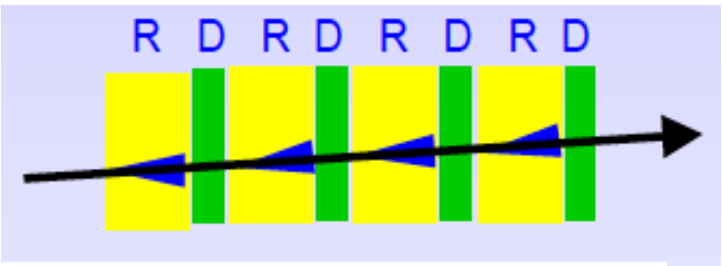
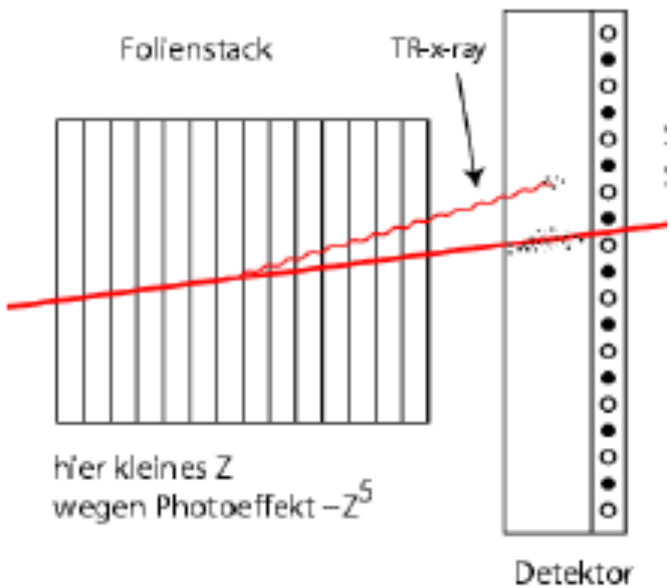
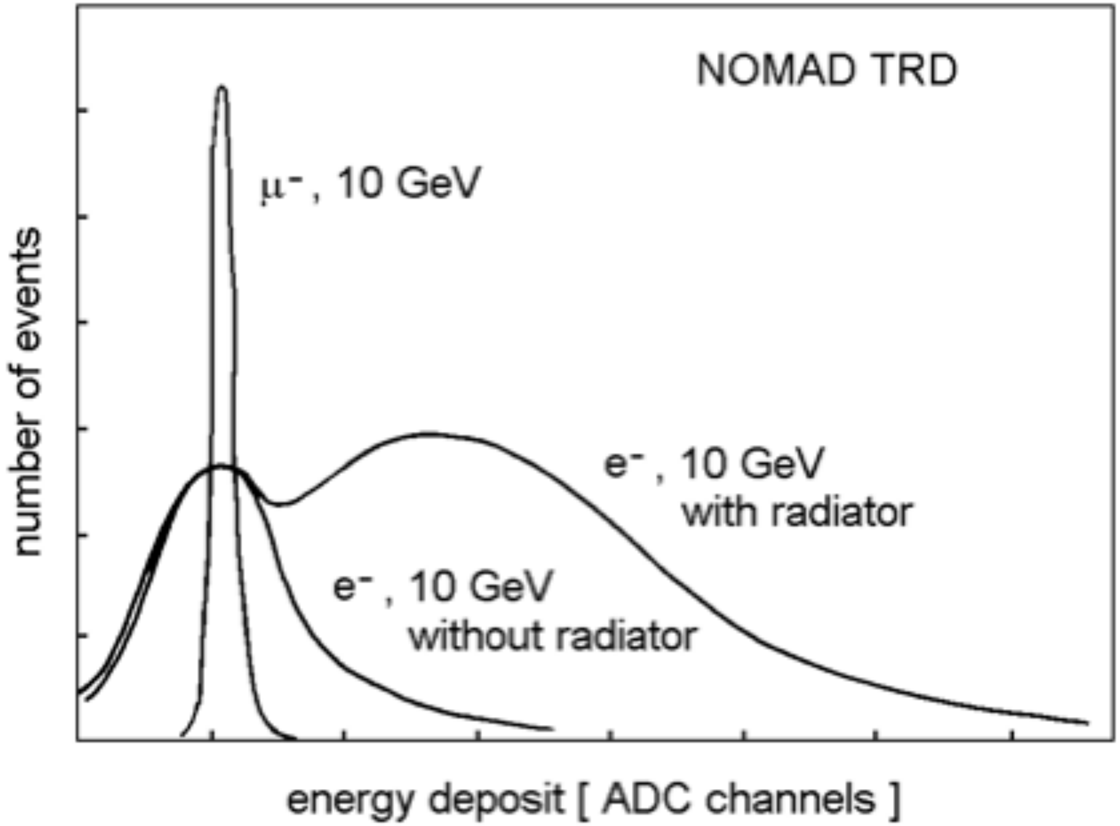
Transition Radiation Detectors







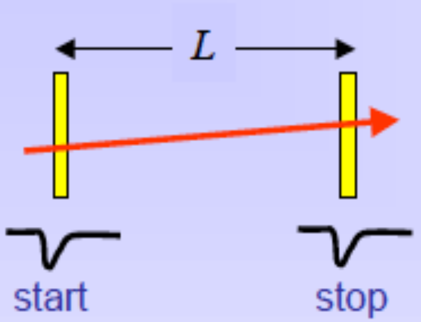
$$W = \tfrac{1}{3}\alpha\hbar\omega_{pl}\gamma \approx \gamma \;\; !!$$

$$N_{ph} \approx \frac{W}{\hbar\omega} \sim \alpha \approx \frac{1}{137}; \;\Rightarrow\; \textit{many layers}$$

$$\hbar\omega \approx \tfrac{1}{4}\hbar\omega_{pl}\gamma \;\;\rightarrow\;\; keV \;\; range$$

$$\theta_{X-ray} \sim 1/\gamma$$

Particle ID using Time Of Flight (TOF)



$$t = \frac{L}{\beta c} \longrightarrow \beta = \frac{L}{tc}$$

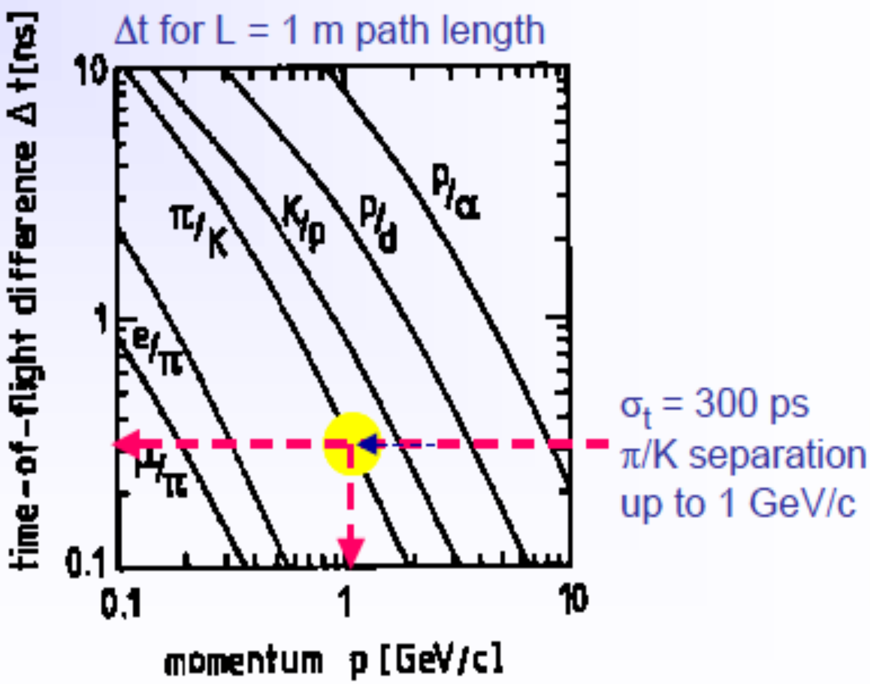
Combine TOF with momentum measurement

$$p = m_0 \beta\gamma \longrightarrow m_0 = p\sqrt{\frac{c^2 t^2}{L^2} - 1}$$

Mass resolution $$\frac{dm}{m} = \frac{dp}{p} + \gamma^2\left(\frac{dt}{t} + \frac{dL}{L}\right)$$

TOF difference of 2 particles as *f(p)*

$$\Delta t = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right)$$
$$= \frac{L}{c}\left(\sqrt{1 + m_1^2 c^2 / p^2} - \sqrt{1 + m_2^2 c^2 / p^2}\right)$$
$$\approx \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$



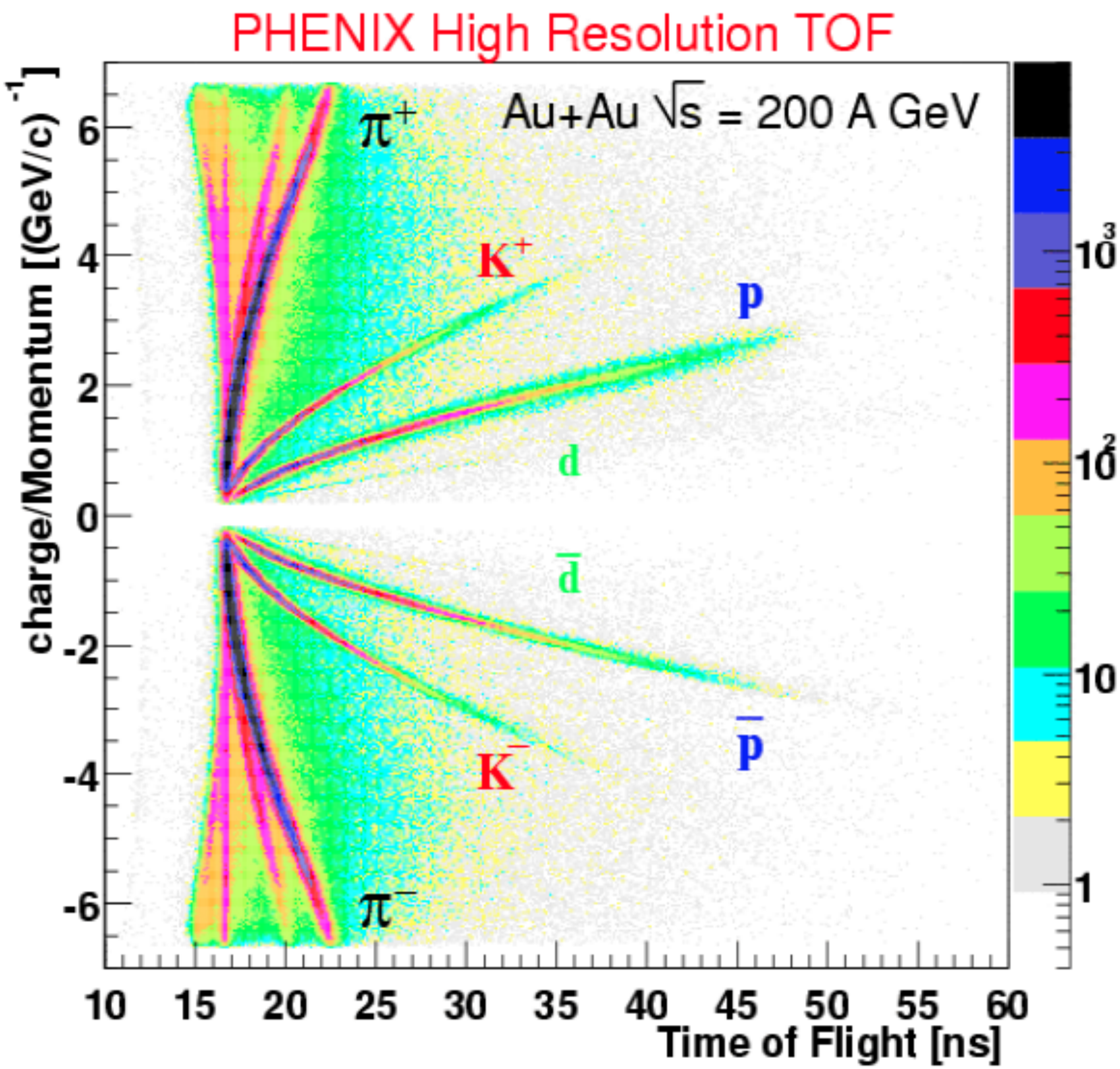


Figure 7. TOF-PID plot from PHENIX based on an Au-Au run in 2002.

Conclusions

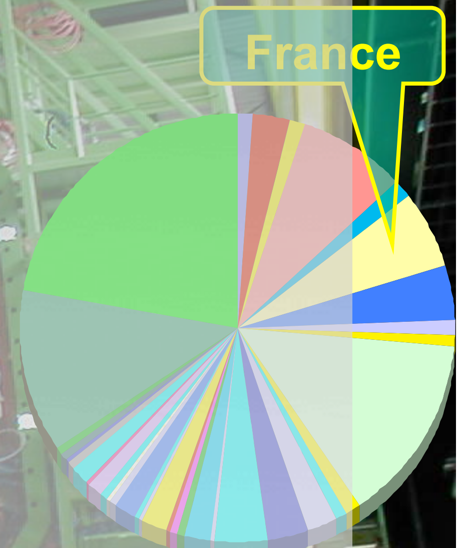
- All particle detectors in nuclear, particle and astroparticle physics are based on the physics of the interaction of particles and radiation with matter
- It is possible to measure and reconstruct the interaction of elementary particles also in the very difficult environments of proton proton collisions at the LHC
- Many of the experiments today are large and complex, both in their concept and in the new technologies employed
- They are run by very large collaborations of scientists, engineers and also of students over periods of 10-20 years
- We live in exciting times and there is a lot more ahead of us, many opportunities for students

Message to students

- It is fun to work on these experiments and their data

Large colaborations: Where are the students?

- Sub divided in smaller groups
  - Detector, subdetector
  - Analysis: different topics
  - Students belong to instituts
- International environment
  - Communication skills !
  - Mobility
  - Good students become well known in the collaboration very fast!
- Management
  - Physicists are (generally) not trained for that changes with time...
  - Sometimes there are problems, one has to sort them out..
- Students are an extremely important factor
- job opportunities outside particle physics



3300 Physicists and Engineers

39 Countries

172 Institutions

ATLAS and CMS EM Calorimeters

CMS: $PbWO_4$ Scint. Crystal Calorimeter

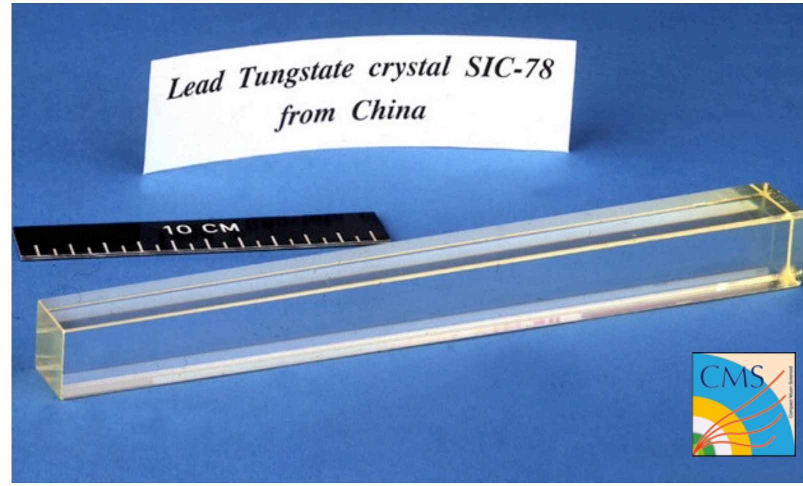
Entire shower in active detector material

- High density crystals (28 X_0)
- Transparent, high light yield
- No particles lost in passive absorber
- High resolution: ~3% / $\sqrt{E}$ (stochastic)

Granularity

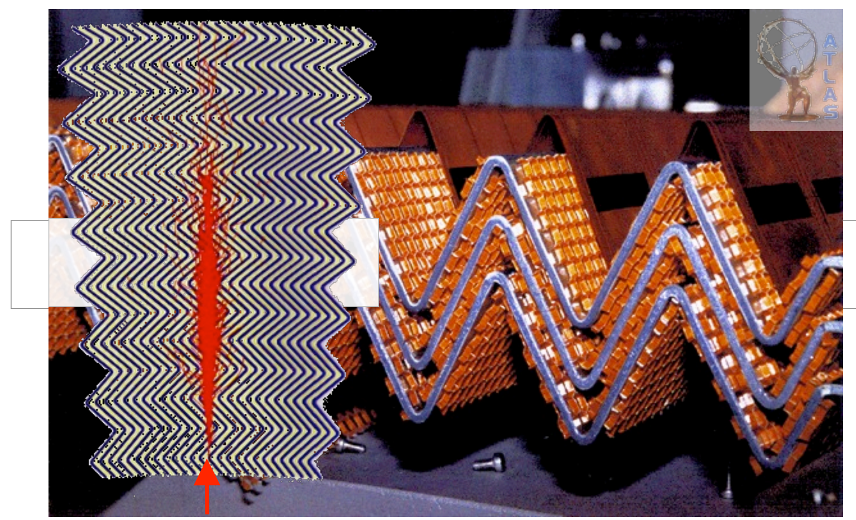
- Barrel: $\Delta\eta \times \Delta\phi = 0.017^2$ rad
- Longitudinal shower shape unmeasured

Read out with avalanche photo diodes



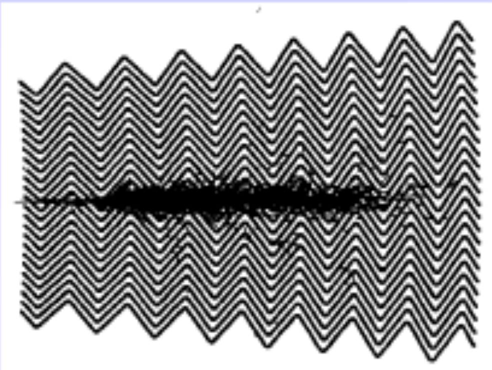
ATLAS: LAr Sampling Calorimeter

- Passive, heavy absorber (Pb, 1.1–1.5 mm thick [barrel]) inter-leaved with active detector material (liquid argon)
  - Overall 22 X_0
  - Accordion structure for full ϕ coverage
  - Resolution: ~10% / $\sqrt{E}$ (stochastic)
- Granularity
  - Barrel: $\Delta\eta \times \Delta\phi = 0.025^2$ rad (main layer)
  - Longitudinal segmentation (3 layers)



ATLAS electromagnetic Calorimeter

Accordion geometry absorbers immersed in Liquid Argon



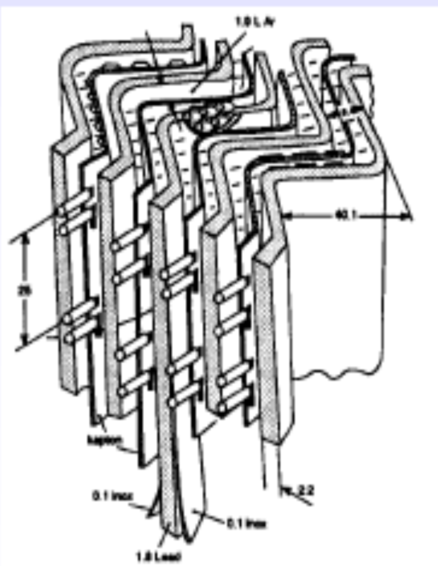
Liquid Argon (90K)

+ lead-steal absorbers (1-2 mm)

+ multilayer copper-polyimide readout boards

→ Ionization chamber.

1 GeV E-deposit → 5 x10^6 e^-



- Accordion geometry minimizes dead zones.
- Liquid Ar is intrinsically radiation hard.
- Readout board allows fine segmentation (azimuth, pseudo-rapidity and longitudinal) acc. to physics needs

Test beam results $\sigma(E)/E = 9.24\%/\sqrt{E} \oplus 0.23\%$

Spatial resolution ≈ 5 mm / √E

Two-dimensional read-out via cathodes

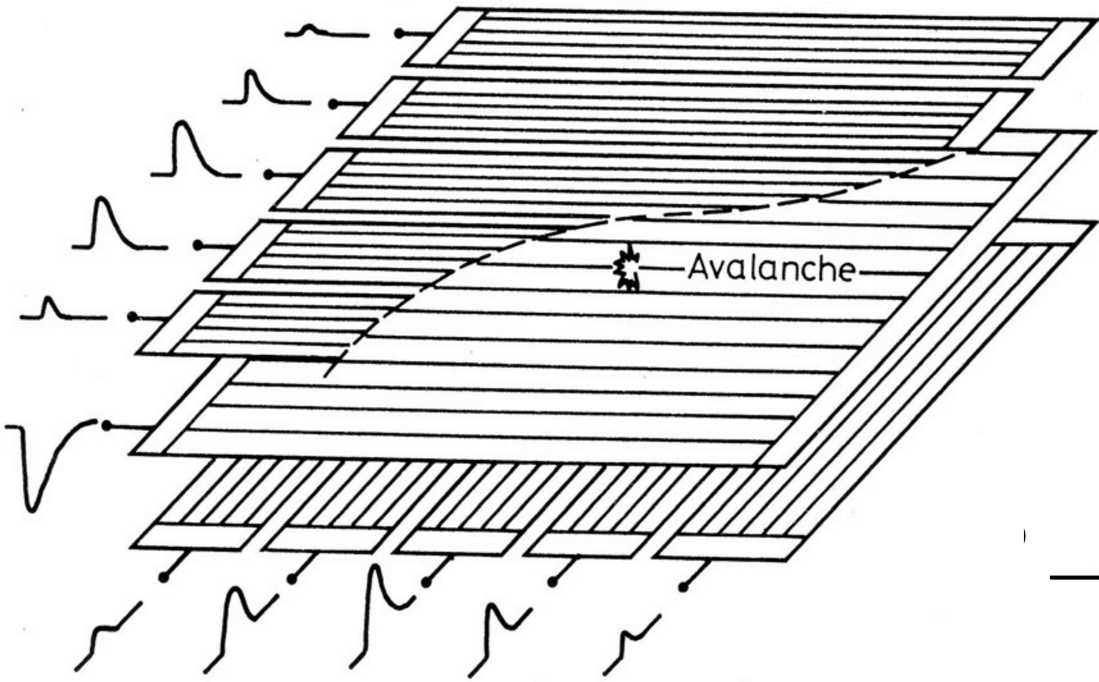
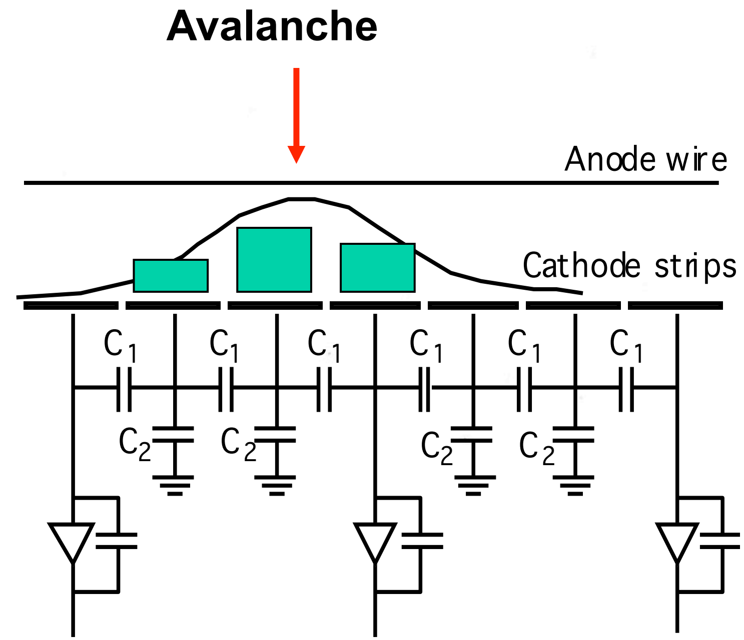


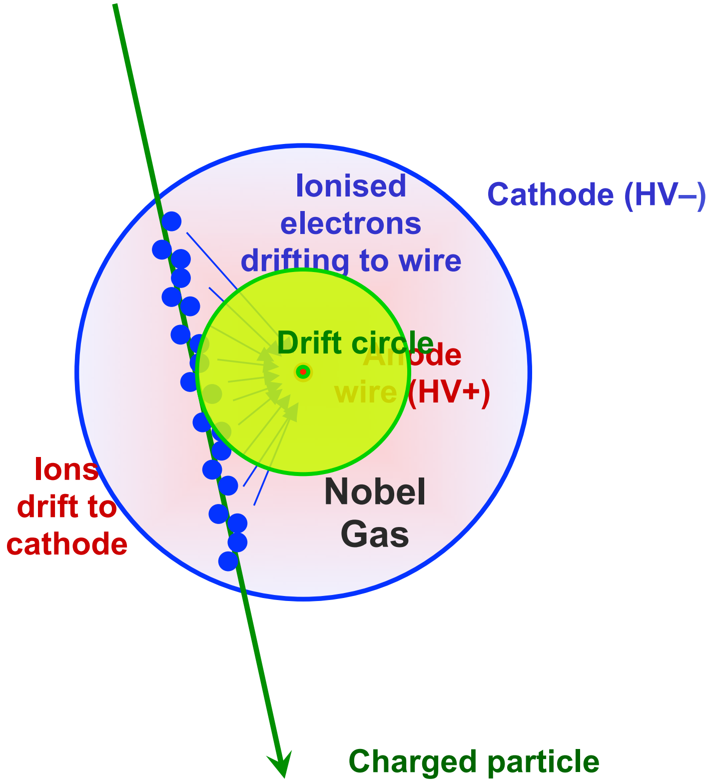
Fig. 6.11. Bidimensional readout using cathode strips (from *Breskin* et al. [6.18]). The signals from each strip are stored and the center of gravity of the distribution calculated to yield the position of the avalanche

$$y = \frac{\sum (Q_i - b) y_i}{\sum (Q_i - b)},$$

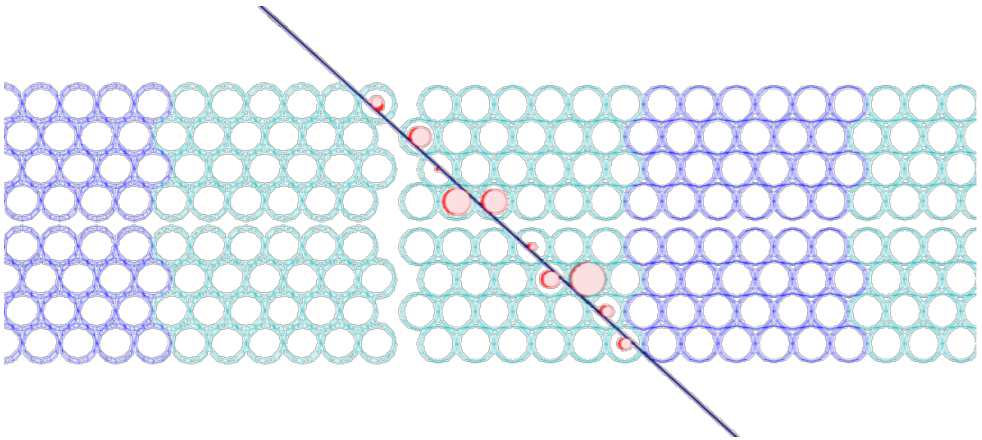


Drift Tubes (DT) in ATLAS: inner detector and muon spectrometer

- **Classical detection technique for charged particles based on gas ionisation and drift time measurement**



Example: muon in MDTs (aligned !)



TRT: Kapton tubes,	∅ =	4 mm
MDT: Aluminium tubes,	∅ =	30 mm

From D. Froidevaux, ASP 2010