

Particle Detectors

Lecture 16

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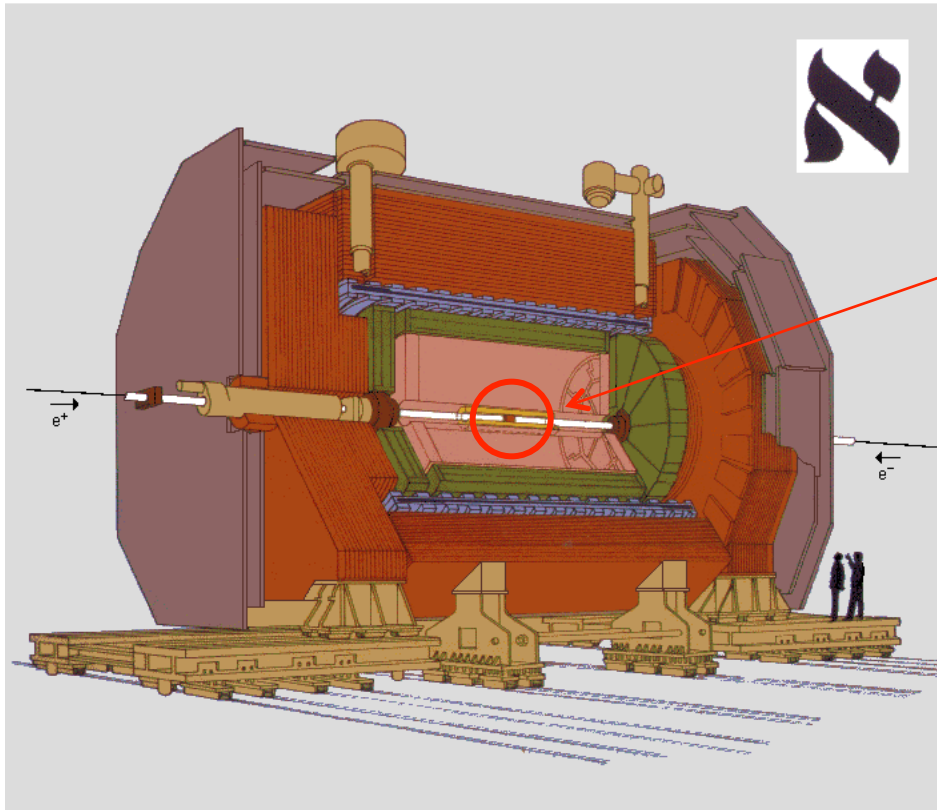
Rivelatori a stato solido

In fisica subnucleare si sono iniziati ad usare come rivelatori di posizione da meta' degli anni '80 circa.

Con camere a deriva a gas è possibile misurare posizioni con la precisione di $\sim 100 \mu\text{m}$ nel caso di traccia isolata (peggiore nel caso di tracce molto vicine) nel piano perpendicolare ai fili, mentre si hanno mm o peggio lungo la direzione del filo.

Con i rivelatori a stato solido si si possono raggiungere granularità (cioe' la segmentazione degli anodi e catodi di raccolta di carica) di pochi μm → possibile raggiungere precisioni di pochi μm richieste per la determinazione di vertici secondari e/o parametri d'impatto o per misure precise di impulso.

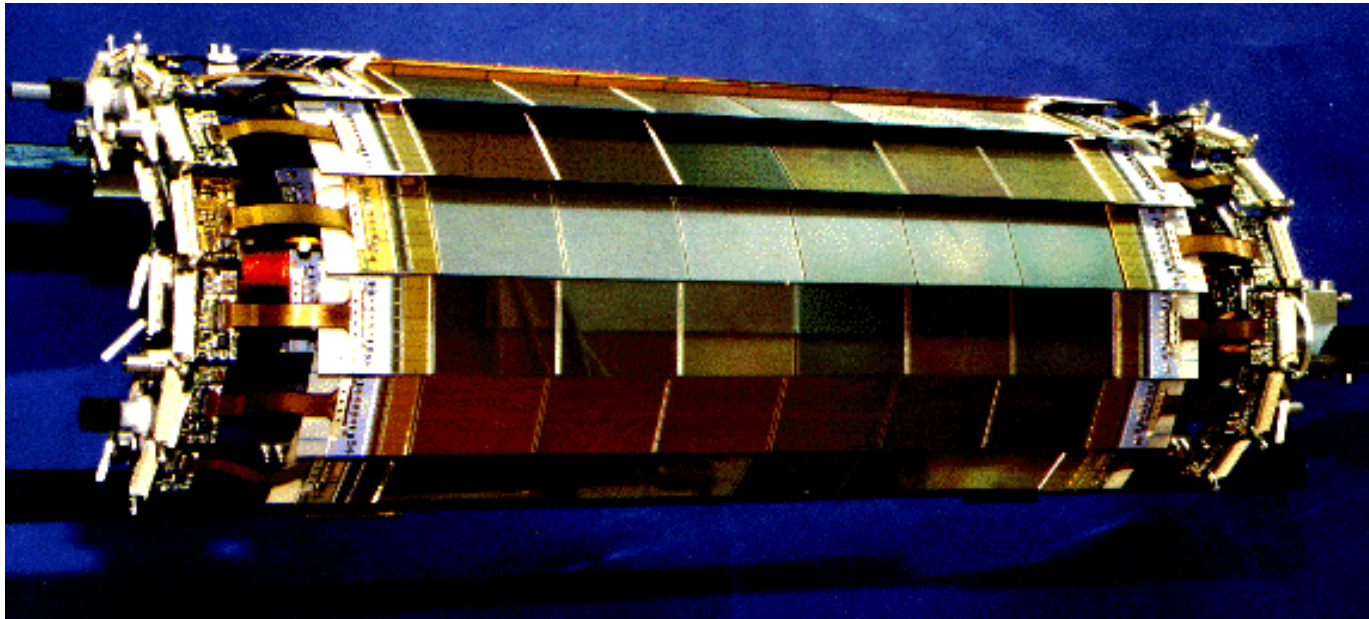
ALEPH



Gli esperimenti a LEP (Aleph, Delphi, Opal ed L3) furono i primi a essere equipaggiati con rivelatori a microstriscie di silicio.

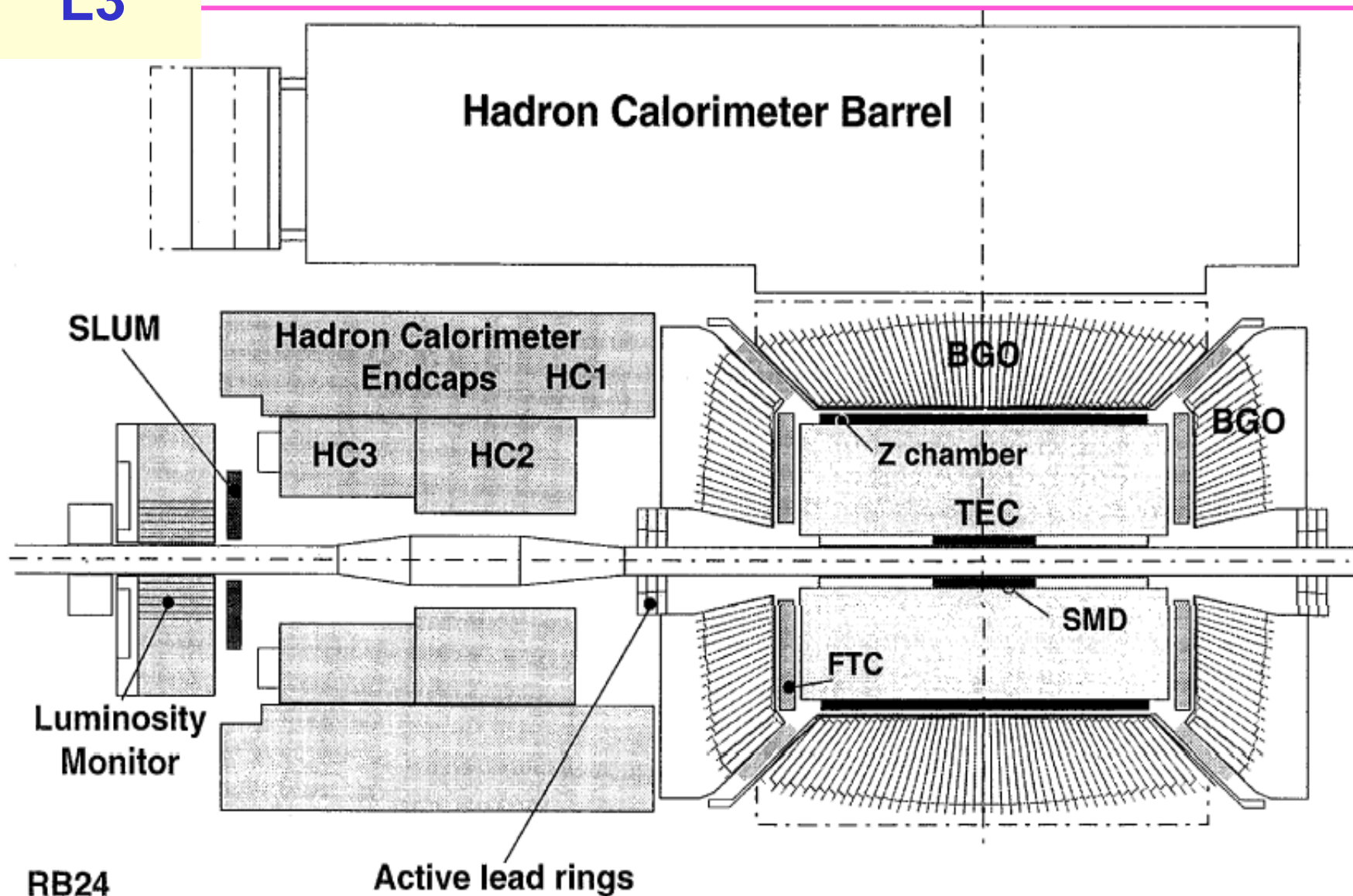
The ALEPH Detector

ALPEH – VDET (the upgrade)



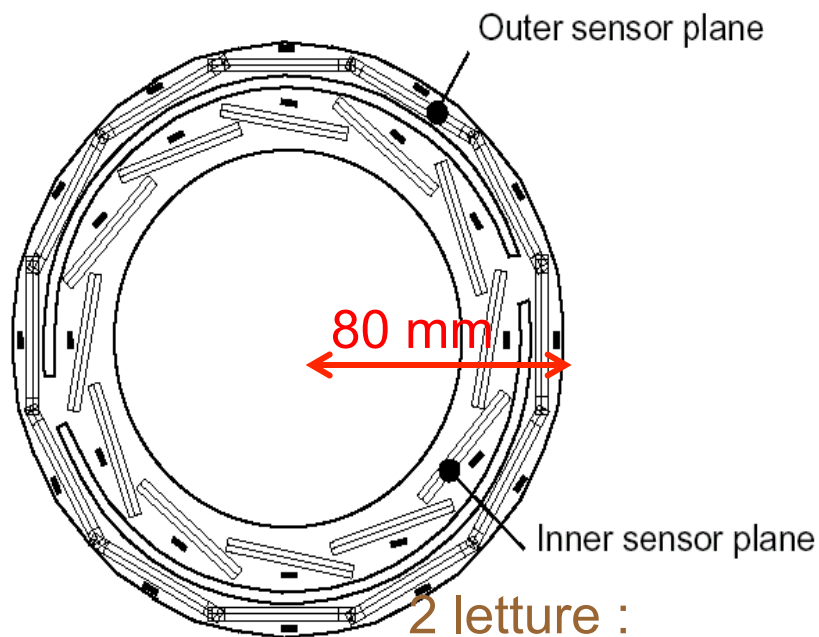
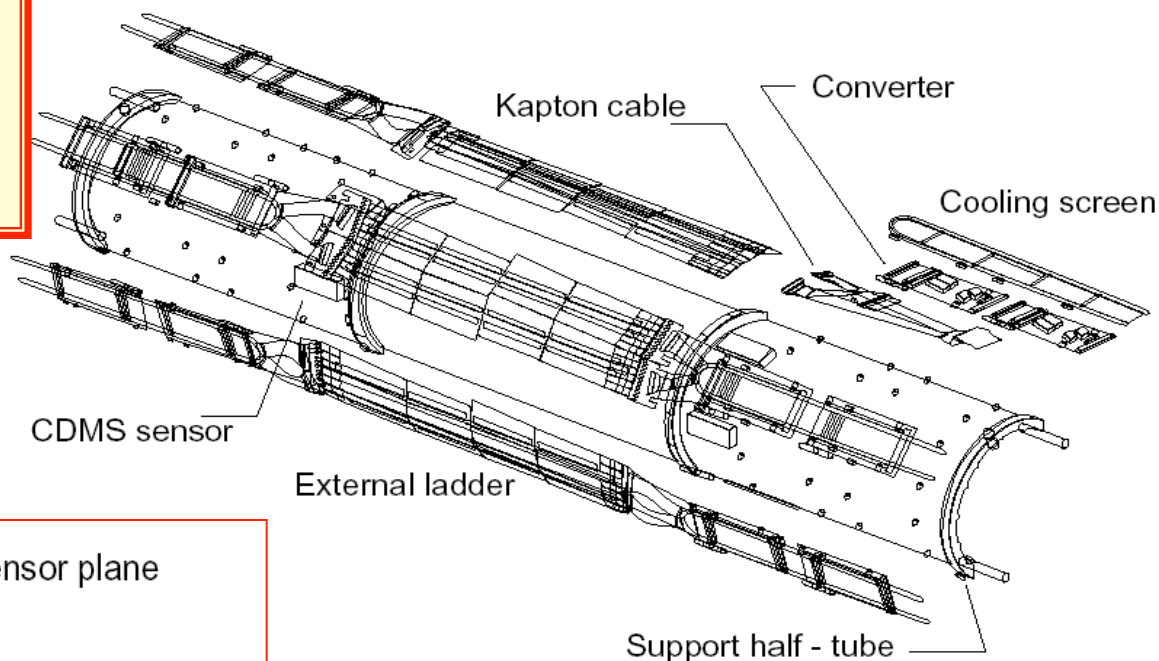
- 2 silicon layers, 40cm long, inner radius 6.3cm, outer radius 11cm
- 300 μm Silicon wafers giving thickness of only $0.015X_0$
- S/N $r\Phi = 28:1$; $z = 17:1$
- $\sigma_{r\phi} = 12\mu\text{m}$; $\sigma_z = 14\mu\text{m}$

L3



SMD : silicon μ -vertex detector - 1

96 tavolette di silicio
70 mm $\times$ 40 mm $\times$ 300 μ m



2 letture :

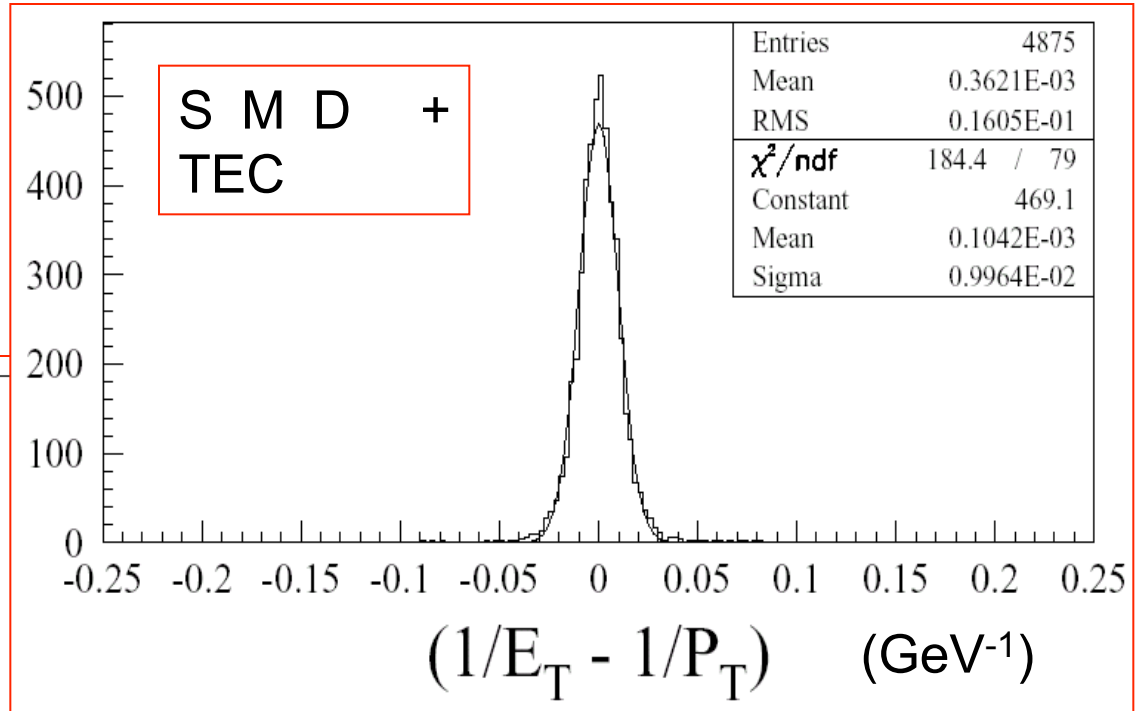
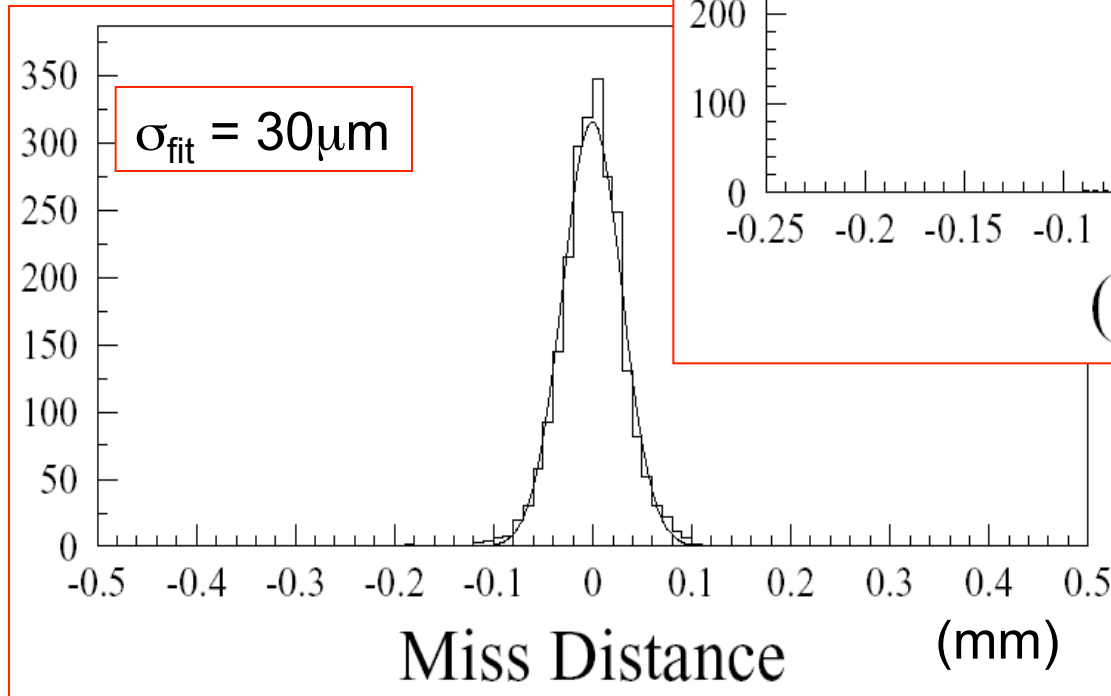
- 50 μ m in $r\phi$;
- 150÷200 μ m in z

Il primo rivelatore costruito a Pg, insieme a molti altri colleghi (bilei, santocchia, bertucci, ambrosi, servoli, pauluzzi, mantovani, alpat,...).

Tutta la tradizione "silicio" di perugia inizia da li'

Potete vederlo esposto nel pianerottolo al II piano del dipartimento

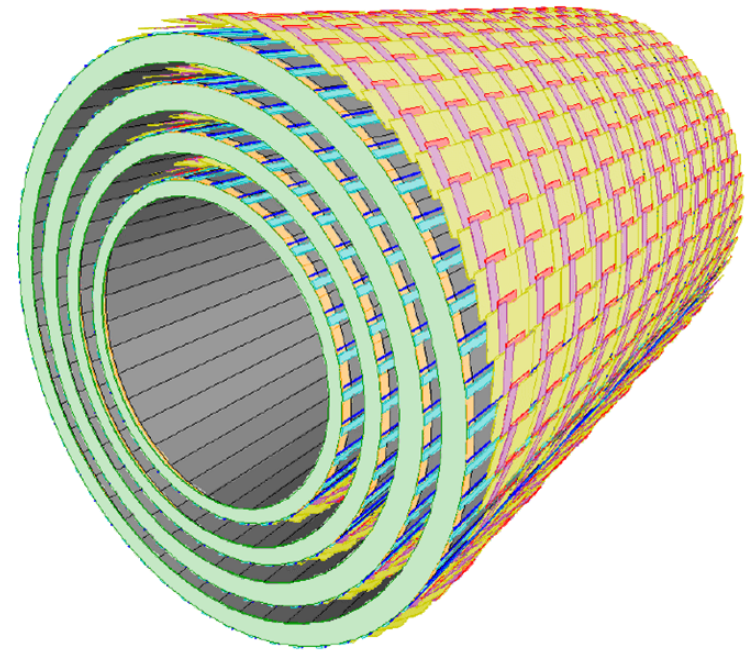
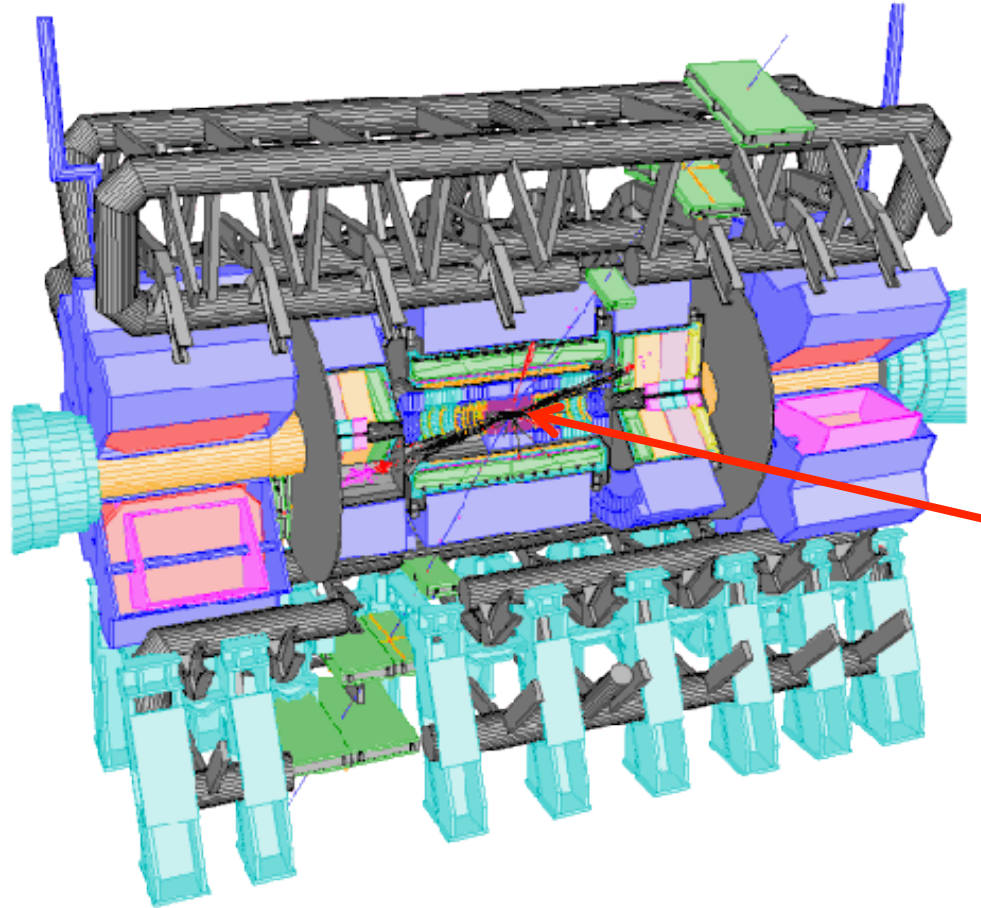
SMD : silicon μ -vertex detector - 2



per la rivelazione dei vertici secondari, vedi LHC.

ATLAS

■ A monster !



- 2112 Barrel modules mounted on 4 carbon fibre concentric Barrels, 12 in each row
- 1976 End-cap modules mounted on 9 disks at each end of the barrel region

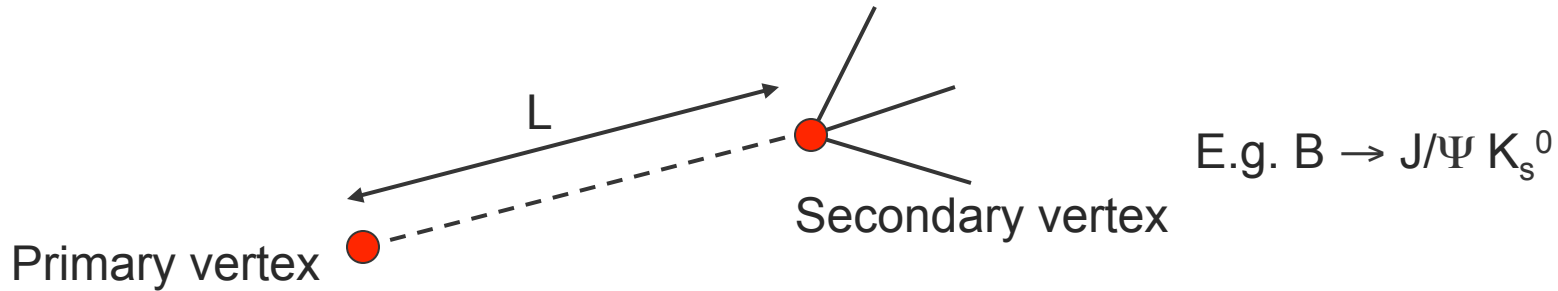
What is measured

- Measure space points of the passage of particles
- Deduce
 - Vertex location
 - Decay lengths
 - Impact parameters

Signature of Heavy Flavours

Stable particles $\tau > 10^{-6} \text{ s}$		$c\tau$
n		2.66km
μ		658m
Very long lived particles $\tau > 10^{-10} \text{ s}$		
$\pi, K^\pm, K_L^0$	2.6×10^{-8}	7.8m
$K_S^0, E^\pm, \Delta^0$	2.6×10^{-10}	7.9cm
Long lived particles $\tau > 10^{-13} \text{ s}$		
$\tau^\pm$	0.3×10^{-12}	91 μm
B_d^0, B_s^0, Δ_b	1.2×10^{-12}	350 μm
Short lived particles		
π^0, η^0	8.4×10^{-17}	0.025 μm
ρ, ω	4×10^{-23}	10 ⁻⁹ $\mu\text{m}!!$

Decay lengths



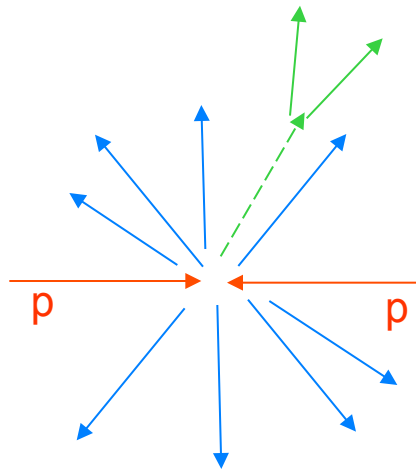
$$L = p\tau/m = E\tau/mc$$

- By measuring the decay length, L , **and** the momentum, p , or energy E **and** the mass the lifetime τ of the particle can be determined
- Need spatial accuracy on both production and decay point

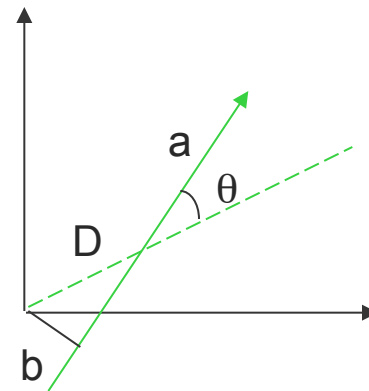
Rivelatori a stato solido

Parametro d'impatto (a un collider): distanza di min avvicinamento della estrapolazione di una traccia al vertice primario dell'interazione

A titolo di esempio consideriamo una particella neutra a breve vita media ed alta massa, prodotta ad un collider (e.g. un **D0**, **vita media $\sim 0.5-1 \times 10^{-12}$ e $c\tau = 315 \mu\text{m}$**) che decade in 2 particelle cariche (es. un K^- e un π^+), che per semplicità considereremo di massa trascurabile rispetto alla massa del D (**$m=1.85 \text{ GeV}$**). Essendo la particella in questione neutra l'unico modo di rivelarla è tramite il **parametro d'impatto**, ovvero lo spostamento del vertice secondario (di decadimento) dal vertice primario (di produzione).



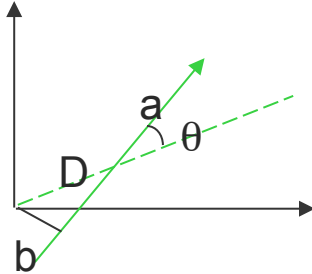
$$D \rightarrow a + x$$



D è la particella che decade in **a** che ha un parametro d'impatto **b** + un' altra (x) non indicata.

Rivelatori a stato solido

Il parametro d'impatto b è proporzionale al percorso di D e all'angolo θ . Ma:



$$D = \gamma_D (c\tau_D)$$

$$b \cong D\vartheta$$

$$\vartheta = \frac{p_T^a}{p^a} \Rightarrow b \sim \frac{p_T^a}{p^a} \gamma_D (c\tau_D)$$

Se il decadimento è a 2 corpi $D \rightarrow a + x$ e posso trascurare le masse di a e x (rispetto alla massa del D) $\rightarrow$

$$p_T^a \sim M_D/2$$

$$p^a \sim p_D/2$$

$$\vartheta \sim \frac{M_D}{p_D} \sim \frac{1}{\gamma_D}$$

ponendo $\beta=1$ e $p/M=\beta\gamma$

$\rightarrow$ il parametro d'impatto è indipendente dall'impulso $b \sim (c\tau)_D$.

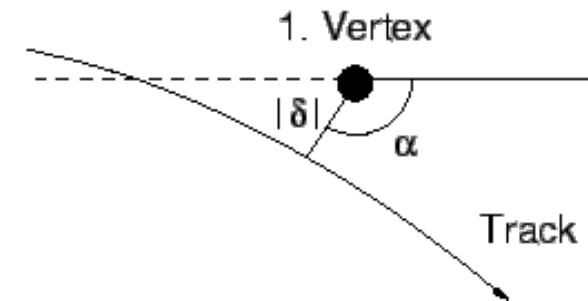
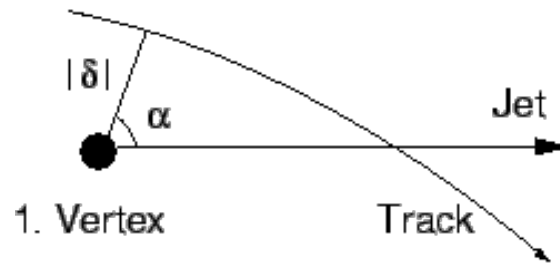
$db/b = d\tau/\tau \rightarrow$ se voglio un errore del 10% su τ , devo misurare b al 10%

Se la particella ha una vita media di $\sim 10^{-12}$ s $\rightarrow$ devo determinare distanze dell'ordine di ~ 300 μm $\rightarrow$ mi servono risoluzioni sul punto di max avvicinamento al vertice primario di ~ 30 μm $\rightarrow$ stato solido va bene

$$\alpha < \pi/2 \rightarrow \delta = +|\delta|$$

$$\alpha > \pi/2 \rightarrow \delta = -|\delta|$$

The impact parameter of a track is defined as the transverse distance of closest approach (DCA) of the track to the primary vertex point with a sign.

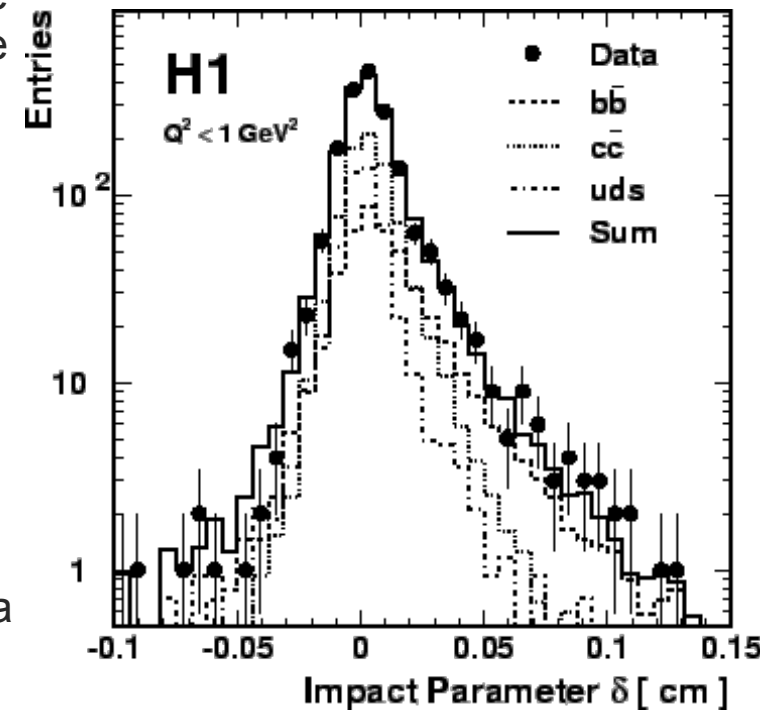


The signed impact parameter is defined by reference to the direction of the reconstructed particle or the jet to which the track is associated.

The signed impact parameter of a track is defined as positive if the angle between the jet direction and the line joining the primary vertex to the point of DCA $< 90^\circ$ and it is defined as negative otherwise.

The sign allows to statistically disentangle detector resolution effects and effects from the decay lifetime of the heavy hadron.

Tracks from the decays of long lived particles will have positive impact parameters, if resolution effects are neglected. Tracks produced at the primary vertex result in a symmetric distribution around 0, i.e. negative impact parameters predominantly result from detector resolution effects.



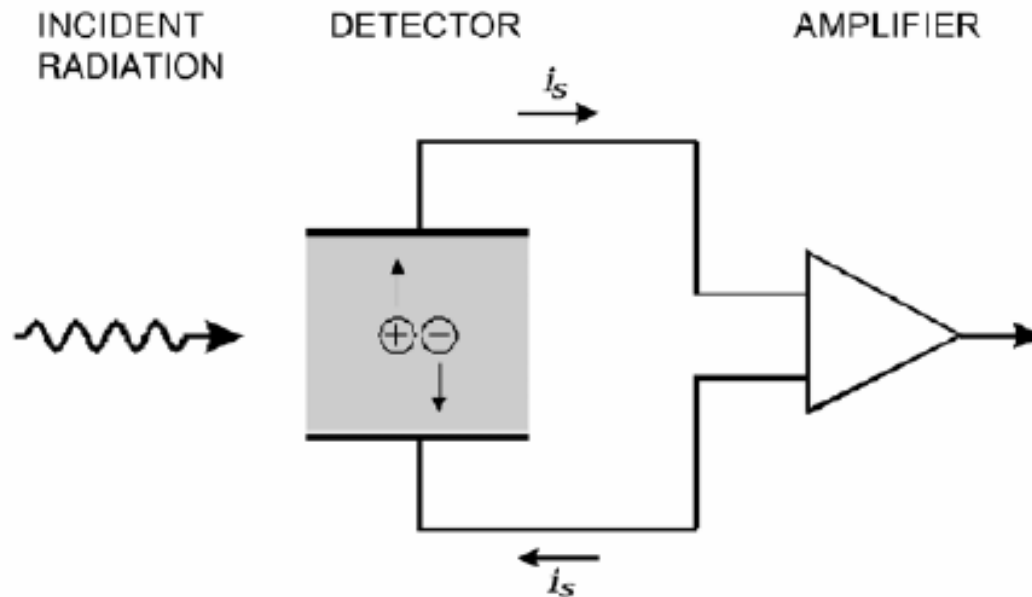
Semiconductor Detectors

Generally, Two kinds of solid state detectors can be distinguished:

- Photo resistors: Resistance changes with irradiation
- Photo diode: Depleted semiconductor layer with typically large electric field used as active zone

→ionization chamber

There is not charge multiplication, only charges due to ionization are collected



Semiconductor Detectors

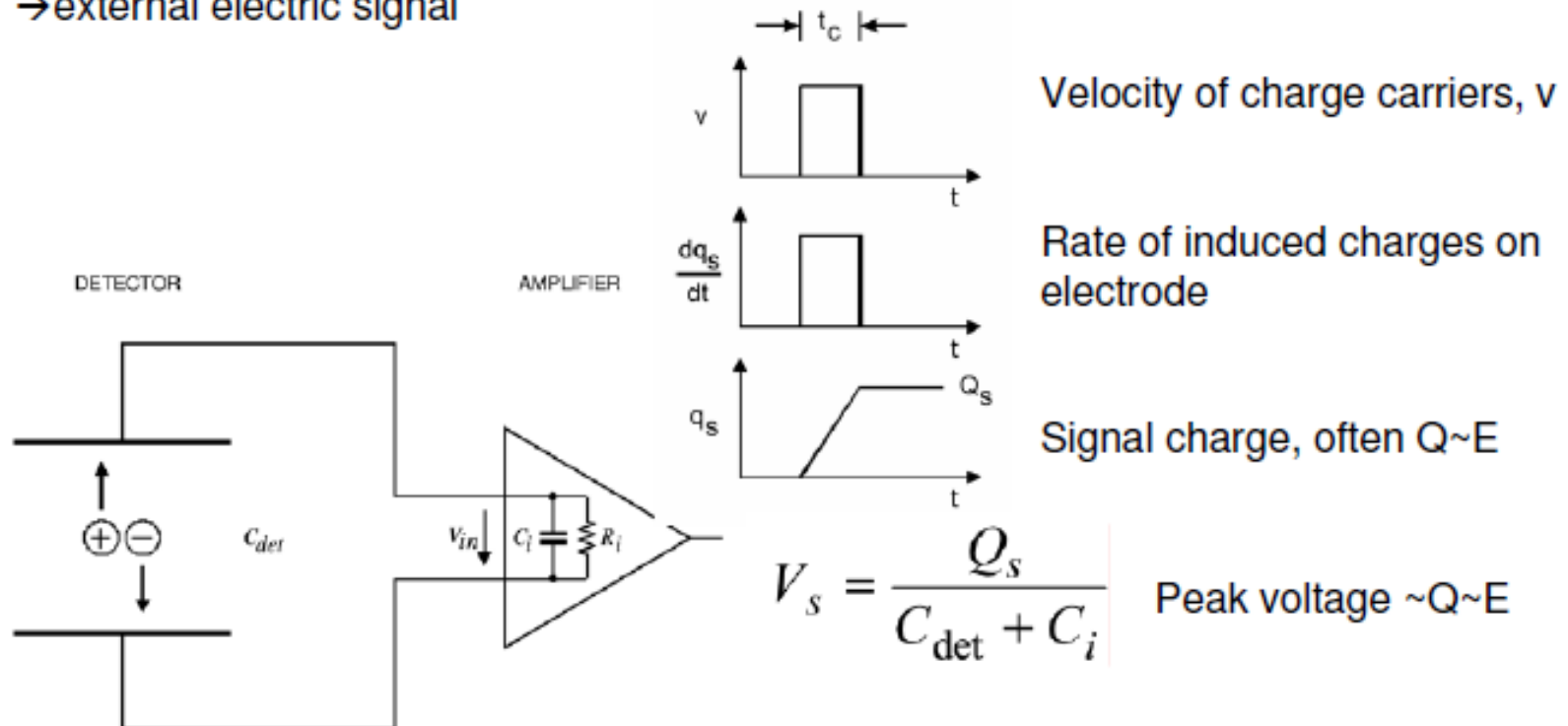
The same considerations made for gas ionization chambers apply for charge collection in semiconductor detectors

Detection volume with electric field

Charge carrier pairs generated via ionization

Charges drift in the electric field

→ external electric signal



Choice of material

$$Q_{\text{dep}} = e(dE/dx)(X/w)$$

$$\rightarrow y = x/X_0$$

$$= ey [(dE/dy)/w]$$

For Ionization chambers, in principle any material could be used that allows for charge collection at a pair of electrodes.

	Gas	liquid	solid
Density	low	moderate	high
Z	low	moderate	moderate
Ionization energy ϵ_i	moderate	moderate	small
Signal velocity	moderate	moderate	fast

Ideal material for "high" Q_{dep} and low σ_Q

- high specific E loss dE/dy
- low effective ionisation energy w
- Thickness y compromise for high Q collected and low multiple scattering (typically $< 1\% X_0$)

High electric field

→ fast response

in detection volume

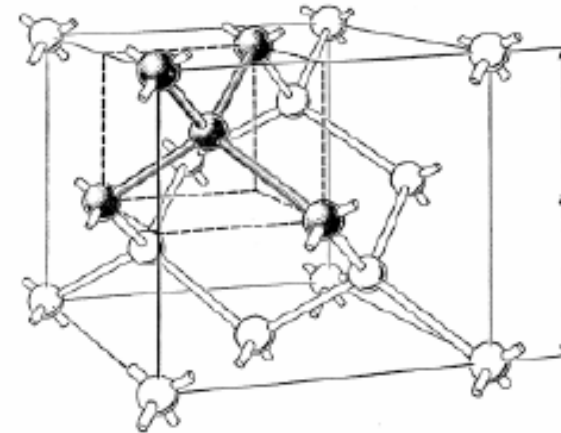
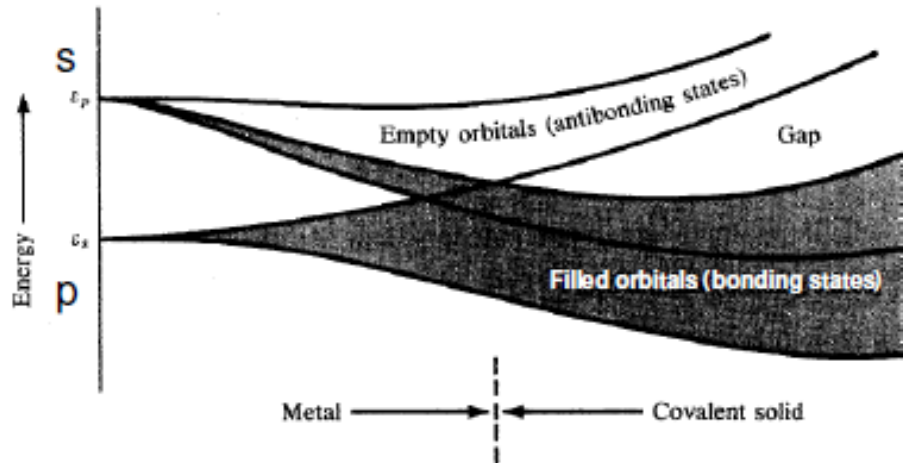
better charge collection efficiency

Rivelatori di Particelle

Rivelatori a stato solido

When atoms are joined to form a crystal lattice, the discrete energy levels are distorted and form continuous energy bands.

All atoms contribute.



Crystal structure of Si, Ge, diamond: Each atom shares four electrons with its four neighbors.

Bound states generate filled energy bands.

Anti-bound states generate empty bands.

Rivelatori a stato solido

In un metallo banda di conduzione e di valenza sono sovrapposte. →

molte elettroni liberi e alta conducibilità.
($n \sim 10^{28}$ elettroni/m³)

In un semiconduttore la banda di valenza e quella di conduzione non sono sovrapposte. La banda di valenza è **quasi** piena e quella di conduzione **quasi** vuota. La **GAP** fra le due bande è ~ 1.1 eV nel silicio →

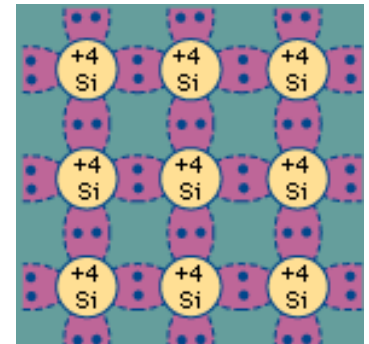
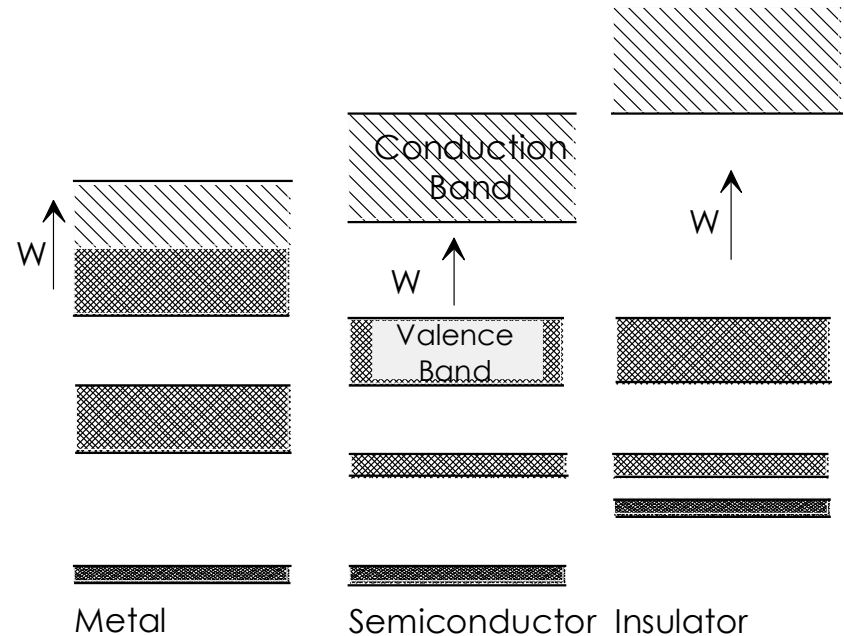
La conducibilità dipende dalla temperatura, cresce al crescere della temperatura.

In un isolante banda di conduzione e di valenza sono separate da una gap grossa (~ 8 eV in SiO₂ e ~ 5 eV nel diamante) →

Bassa conducibilità ($n \sim 10^7$ elettroni/m³).

Il silicio ha in totale 14 elettroni di cui 4 di valenza → il nucleo ionico ha carica +4.

Siccome gli elettroni di valenza servono ad unire gli atomi adiacenti, sono strettamente legati al nucleo a 0 K → bassa conducibilità.

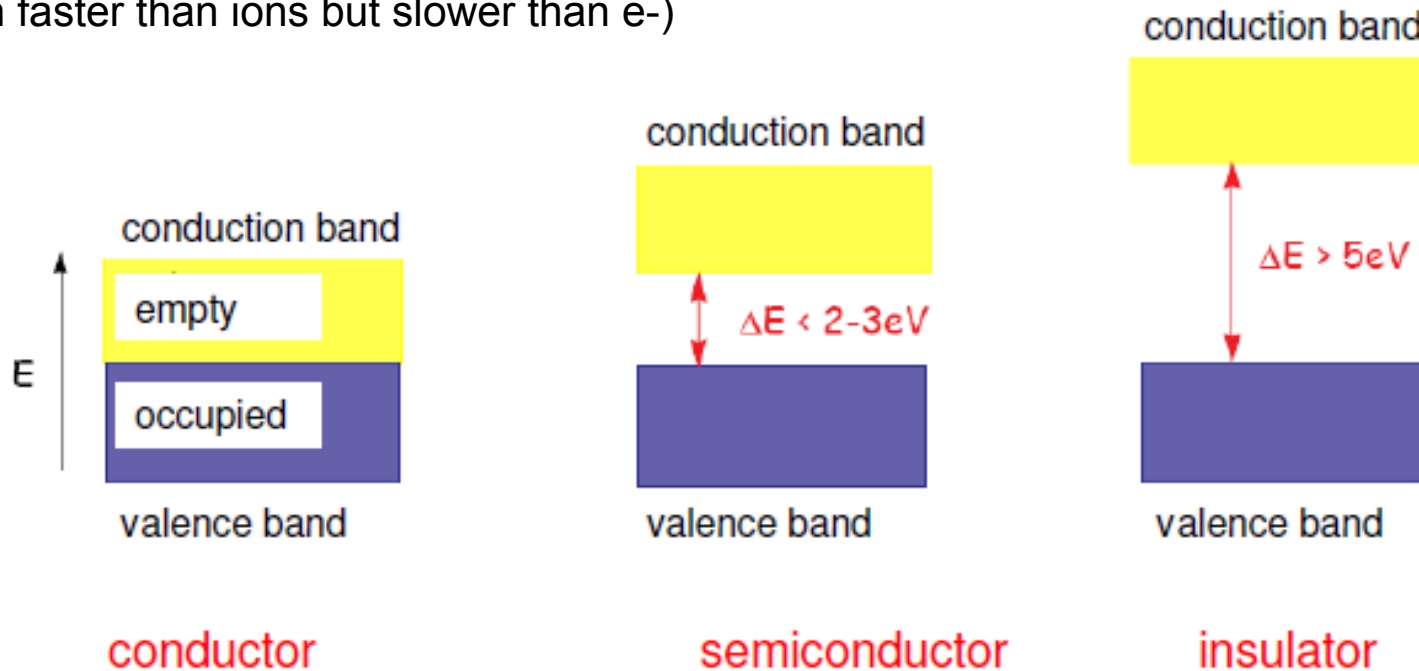


Conductivity

In semiconductors there are 2 charge carrier types: electrons and holes.

Holes are e- vacancies which behave as positive charges.

Holes "play" the same role of ions in gas but they are much faster → contribute to signal
(nb: much faster than ions but slower than e-)



The probability that an electron occupies a certain energy level is given by the Fermi-Dirac-Distribution:

$$f_e(E) = \frac{1}{e^{(E-E_F)/kT} + 1} \quad \text{and for holes} \quad f_h(E) = 1 - f_e(E) = \frac{1}{e^{(E_F-E)/kT} + 1}$$

For intrinsic semiconductors (e and h concentration equal): $E_F = E_{\text{gap}}/2$

For particles with $(E-E_F) \gg kT$, Maxwell Boltzmann statistics apply

Rivelatori a stato solido

Energy required for creation of an electron-hole pair

Ionization Energy > Band Gap

Formation of e-h pair requires both ...

1. Conservation of energy
 2. Conservation of momentum
- ⇒ additional energy excites phonons

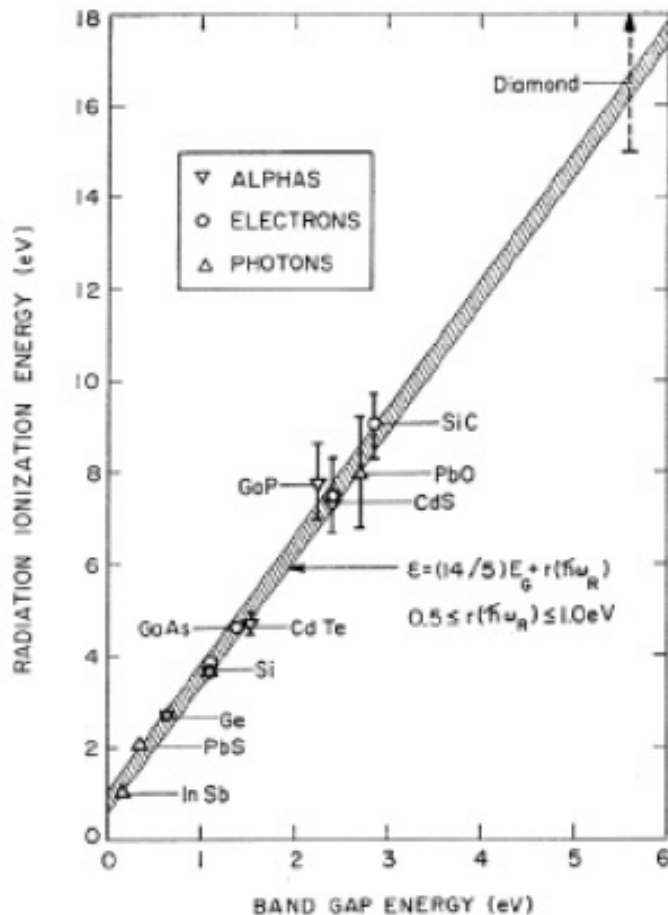
Ratio E_{ion}/E_{Gap} independent of

- material
- type of radiation

Reason: Fraction of energy going into phonons (momentum transfer) is approximately the same for all semiconductors.

Compare with gas: $w_{gas} \sim 30$ eV

Small w_i means large number of pairs:
no amplification required for the signal



Rivelatori a stato solido

Un breve riassunto sui semiconduttori.

- In un semiconduttore intrinseco (e.g. il Silicio, IV gruppo) ci sono 4 elettroni nella banda di valenza.
- A temperatura ambiente, la distribuzione dell'energia termica (Maxwell-Boltzman) fa sì che una frazione degli elettroni sia in banda di conduzione, cioè liberi di muoversi nel volume del solido.
- Il legame vacante (cioè l'assenza di un elettrone) si comporta come una carica positiva, detta lacuna, che si “sposta” quando viene riempita da un elettrone
- Quindi in un semiconduttore esistono due portatori di carica, analoghi alle coppie e- ione dei gas.
- La concentrazione intrinseca all'equilibrio è $n_i = p = n$ ed anche $np = n_i^2 = N_c N_v e^{-E_g/kT}$ con N_c ed N_v densità dei portatori di carica nella banda di conduzione e di valenza, rispettivamente. L'ultima relazione è valida per qualsiasi materiale semiconduttore anche drogato.
- Nel silicio puro $E_g = E_c - E_v = 1.12 \text{ eV}$ ed $n_i = 1.45 \times 10^{10} \text{ cm}^{-3}$ a temperatura ambiente.

Semiconductor Detectors

Property		Si	Ge	GaAs	Diamond
Z		14	32	31/33	6
A		28.1	72.6	144.6	12.0
Band gap	[eV]	1.12	0.66	1.42	5.5
radiation length X_0	[cm]	9.4	2.3	2.3	18.8
mean energy to generate eh pair	[eV]	3.6	2.9	4.1	~ 13
mean E-loss dE/dx	[MeV/cm]	3.9	7.5	7.7	3.8
mean signal produced	[$e^-/\mu\text{m}$]	110	260	173	~ 50
intrinsic charge carrier concentration n_i	[cm^{-3}]	$1.5 \cdot 10^{10}$	$2.4 \cdot 10^{13}$	$1.8 \cdot 10^6$	$< 10^3$
electron mobility	[cm^2/Vs]	1500	3900	8500	1800
hole mobility	[cm^2/Vs]	450	1900	400	1200

Si

- currently best compromise for strip detectors

Ge

- small band gap $\rightarrow$ high amount of charge produced $\rightarrow$ good for energy measurements
- high intrinsic charge carrier concentration $\rightarrow$ has to be cooled (liquid N_2)

GaAs

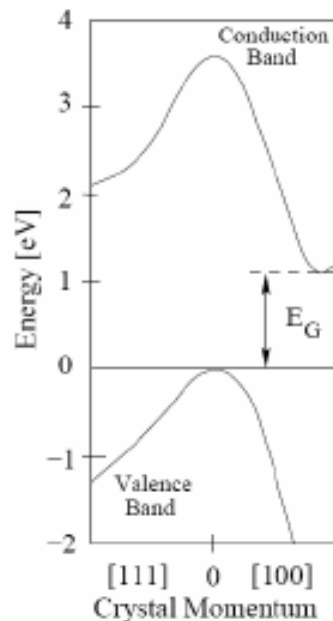
- good ratio generated charge/ noise
- but: charge collection efficiency strongly dependent on purity and composition

- radiation hard

Diamond

- radiation hard, but still quite expensive
- charge collection length $\sim 80\mu\text{m}$

Semiconductors: Silicon



- indirect band gap $\delta E = 1.12 \text{ eV}$

compare to $kT = 0.026 \text{ eV}$ at room temp. $\rightarrow$ dark current under control

(indirect: maximum of valence band and minimum of conduction band at different crystal momenta $\rightarrow E$ and p can only be conserved if additional phonons are excited)

- energy per electron-hole pair: 3.6 eV

(rest in phonons, compared to $\sim 30 \text{ eV}$ for noble gases)

- high density compared to gases: $\rho = 2.33 \text{ g/cm}^3$

- with $dE/dx|_{\min} = 1.664 \text{ MeV/g cm}^2$:

$$N = 1.664 \text{ MeV/g cm}^2 \times 2.33 \text{ g/cm}^3 / 3.6 \text{ eV}$$

$\rightarrow \sim 32000 \text{ electron-hole pairs in } 300 \mu\text{m (MIP)}$

- good mechanical stability $\rightarrow$ possible to produce mechanically stable layers of this thickness

- large charge carrier mobility

$\rightarrow$ fast charge collection $\delta t \sim 10 \text{ ns}$

Rivelatori a stato solido

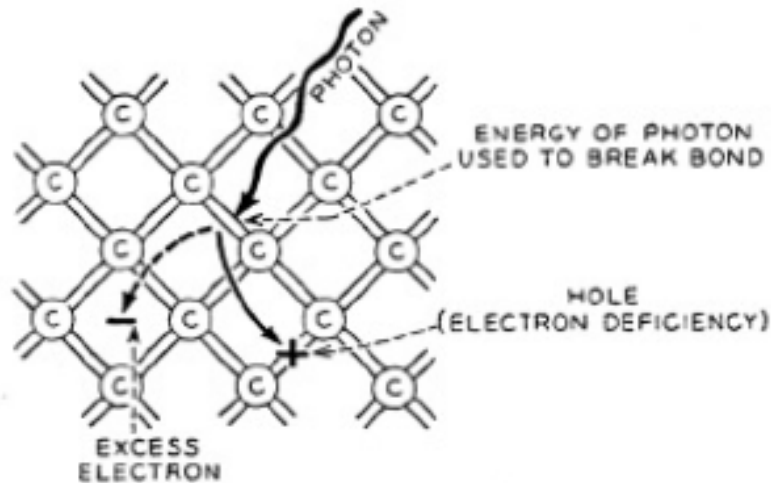
Proprietà del silicio

- ✎ Larghezza della gap $E_g = 1.12 \text{ eV}$ → Energia per creare una coppia elettrone-lacuna = 3.6 eV , ($\sim 30 \text{ eV}$ per gli apparati a gas)
- ✎ Alta densità specifica (2.33 g/cm^3) → $dE/(\text{lunghezza di traccia})$ per M.I.P. : $390 \text{ eV}/\mu\text{m} \approx 108 \text{ e-h}/\mu\text{m}$ (in media), circa $80 \text{ e-h}/\mu\text{m}$ come valore più probabile
- ✎ Alta mobilità : $\mu_n = 1450 \text{ cm}^2/\text{Vs}$, $\mu_p = 450 \text{ cm}^2/\text{Vs}$ → rapida raccolta della carica rilasciata ($< 10 \text{ ns}$).
- ✎ Produzione dell'apparato tramite tecniche micro-elettroniche → piccole dimensioni
- ✎ Rigidità del silicio permette strutture sottili. Spessori tipici $300 \mu\text{m}$ → $\approx 3.2 \cdot 10^4 \text{ e-h}$ (in media)

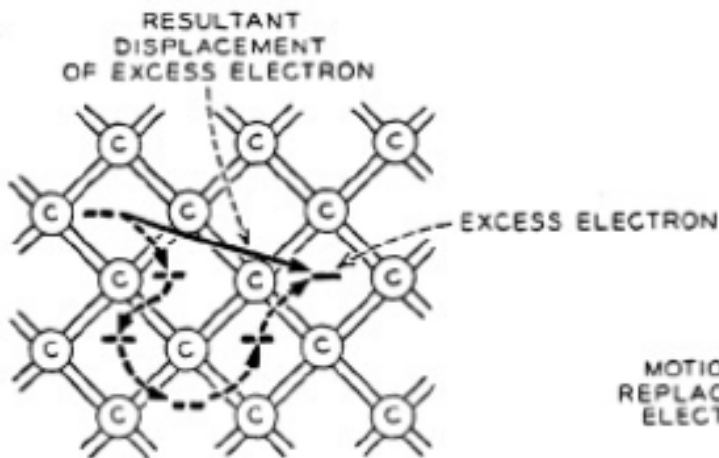
Semiconductors General

Material	Z	Bandgap [eV]	Mobility [cm ² /Vs]		Density g/cm ³
			electrons	holes	
Si	14	1.1	1350	480	2.3
Ge	32	0.7	3800	1800	5.3
Diamond	6	5.5	1800	1200	3.5
GaAs	31-33	1.5	8600	400	5.4
AlSb	13-51	1.6	200	700	4.3
GaSe	31-34	2.0	60	250	4.6
CdSe	48-34	1.7	50	50	
CdS	48-16	2.4	300	15	4.8
InP	49-15	1.4	4800	150	
ZnTe	30-52	2.3	350	110	
WSe ₂	74-34	1.4	100	80	
BiI ₃	83-53	1.7	680	20	
Bi ₂ S ₃	83-16	1.3	1100	200	6.7
Cs ₃ Sb	55-51	1.6	500	10	
PbI ₂	82-53	2.6	8	2	6.2
HgI ₂	89-53	2.1	100	4	6.3
CdTe	48-52	1.5	1100	100	6.1
CdZnTe	48-30-52	1.5-2.4			

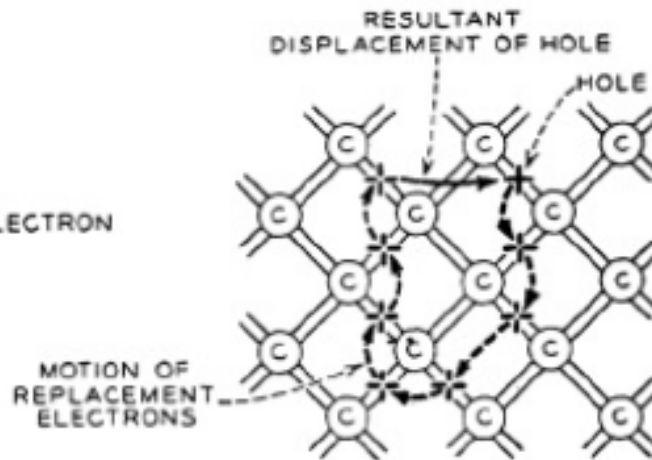
Charge transport



(a) PRODUCTION OF A HOLE-ELECTRON PAIR BY A PHOTON



(c) RANDOM MOTION OF AN EXCESS ELECTRON



(d) RANDOM MOTION OF A HOLE

Charge transport is different for electrons and holes: electrons scatter and drift in the crystal lattice as single particles. Holes move via successive replacements by electrons → their transport properties are determined by the collective motion of electrons. Motion of holes is slower than for electrons. Electrons and holes have different mobilities and diffusion coefficients

Drift velocity in Silicon

$$v_N = -\frac{q\tau_c}{m_N} E = -\mu_N E$$

$$v_p = \frac{q\tau_c}{m_p} E = \mu_p E$$

with $\tau_c = 10^{-12}$ s being the average time between collisions with irregularities in the crystal lattice due to thermal vibrations, impurities and defects.

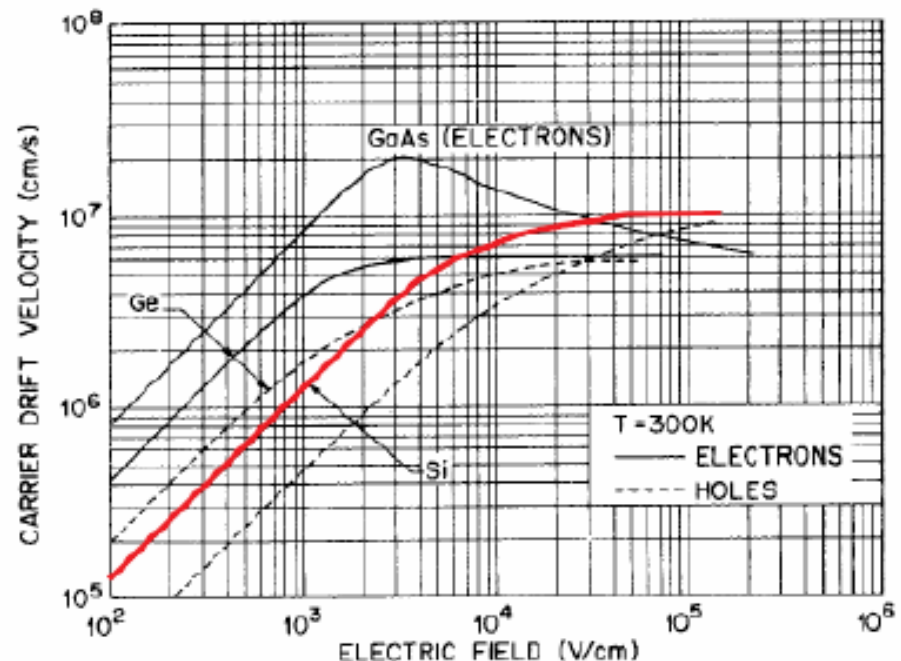
m_N, m_p effective mass of the electrons, holes: Inverse of the 2. derivative of the energy with respect to the momentum at the minimum of the conduction band (e), and the maximum of the valence band (p), respectively.

Only valid for sufficiently small field strength.

- $\rightarrow$ mobility $\mu = 1450 \text{ cm}^2/\text{Vs}$ for electrons and $450 \text{ cm}^2/\text{Vs}$ for holes.
- For larger field strengths: Saturation of drift velocities.
- Typical fields in Si with $V_{\text{bias}} = 100 \text{ V}$, $d = 300 \text{ }\mu\text{m}$:

$$E = 100 \text{ V} / 300 \mu\text{m} = 3.3 \times 10^3 \text{ V/cm}$$

$$\text{charge collection time } t = \frac{d}{v_{\text{Drift}}} \approx 3 - 15 \text{ ns}$$



Rivelatori a stato solido

Resistività.

La resistività ρ (inverso della conducibilità) del materiale è connessa alla densità dei portatori di carica ed alla mobilità:

$$\rho = \frac{1}{q(\mu_n n + \mu_p p)}$$

Deriva immediatamente dalla legge di Ohm:

$$\mathbf{j} = \mathbf{E}/\rho$$

e dalla definizione di densità di corrente

$$\mathbf{j} = en\mathbf{v}_D = en\mu\mathbf{E}$$

dove $q=1.6 \times 10^{-19} \text{ C}$ è la carica dell'elettrone.

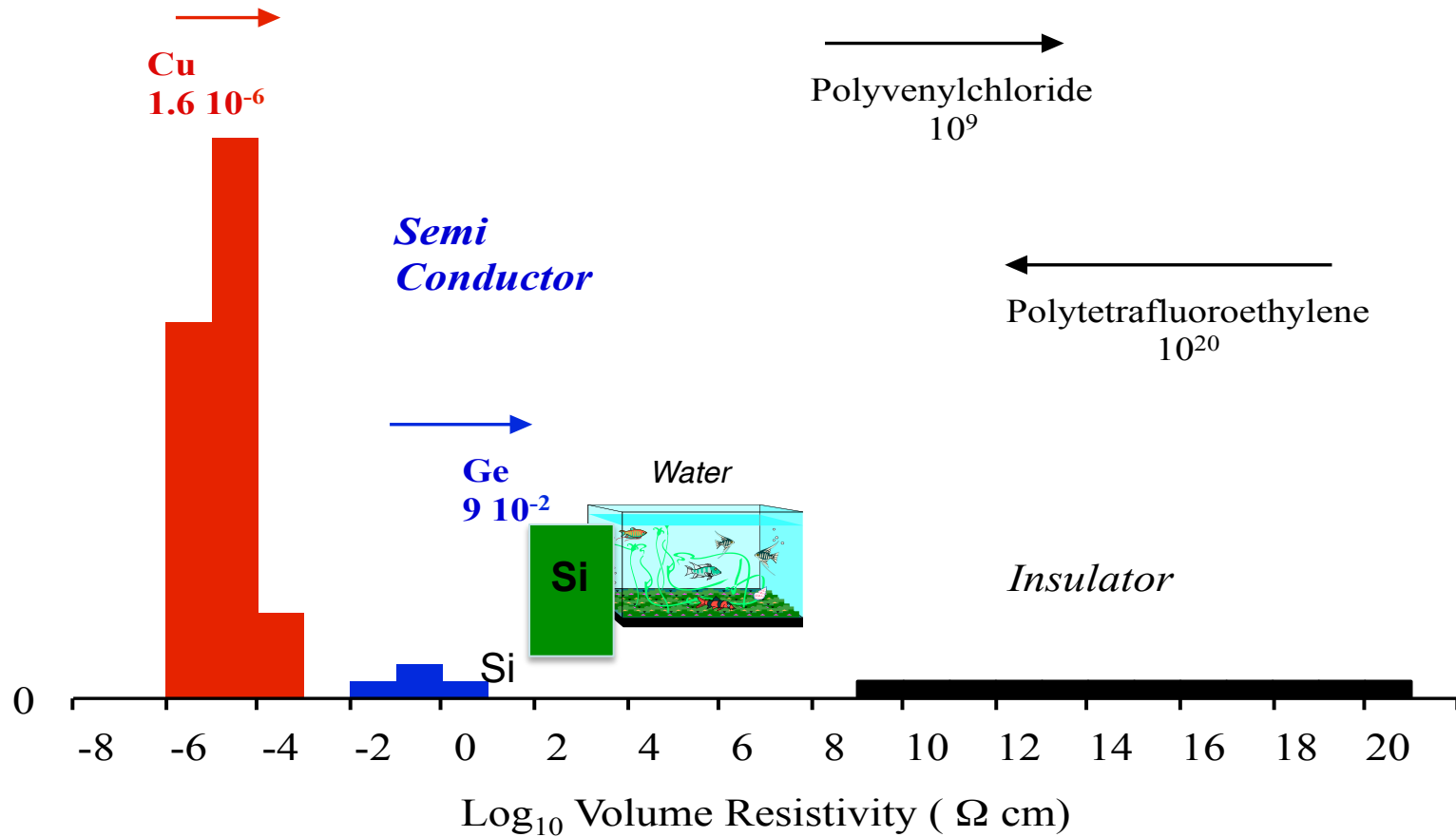
Per il silicio intrinseco $\rho=235 \text{ K}\Omega/\text{cm}$.

Per il silicio drogato è minore in quanto ci sono più portatori di carica.

Parametro operativo importante di un rivelatore perché determina correnti, tensione di lavoro,...

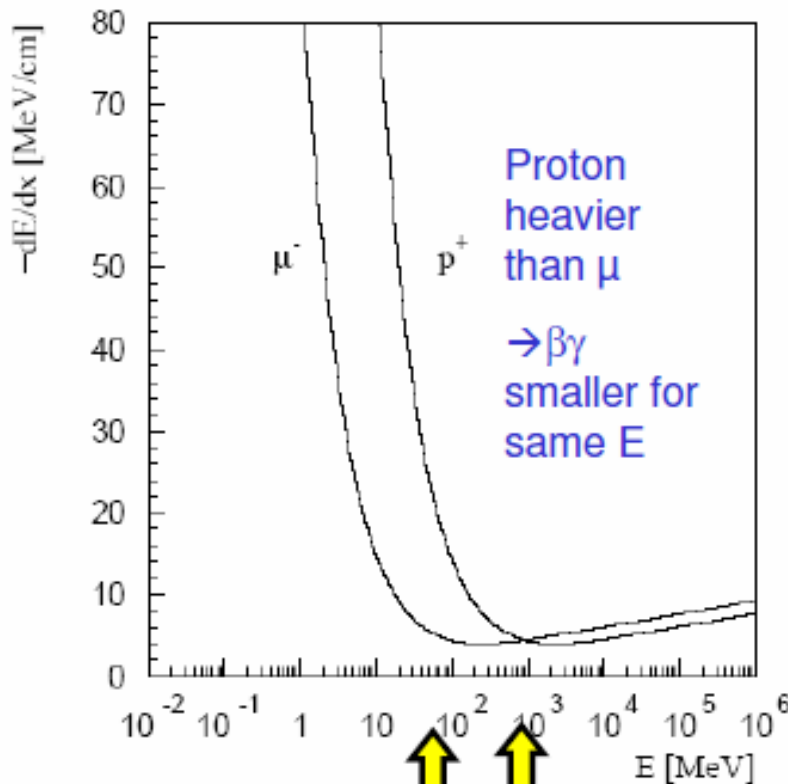
Rivelatori a stato solido

Conductor



Rivelatori di Particelle

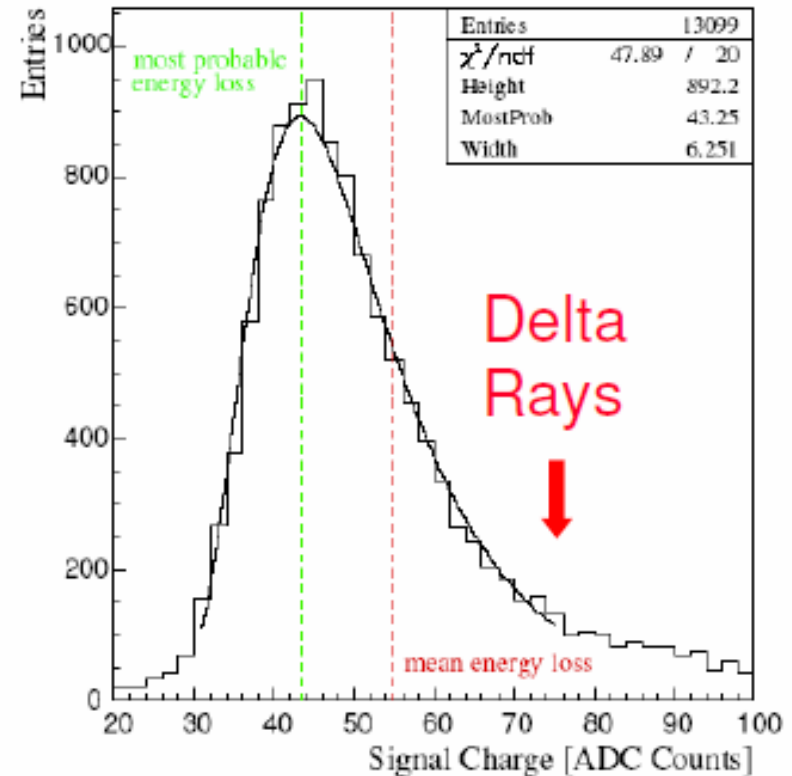
Number of pairs in Silicon



Minimal ionizing

Bethe-Bloch Formula

24000 most probable



1 Mip = on average 32500 e-hole pairs in 300 μ m silicon

Landau distribution

Signal in Silicon

- Conduction band really empty only at $T=0$
- Distribution according Fermi-Dirac Statistics
- Number of electrons in conduction band at room temp.:

$$n_1 = \sqrt{n_V n_C} \cdot \exp\left(-\frac{E_{Gap}}{2kT}\right) = 1.5 \times 10^{10} \text{ cm}^{-3}$$

→ Ratio of electrons in conduction band 10^{-12}
(Silicon $\sim 5 \times 10^{22}$ Atoms/cm³)

- A volume of **intrinsic Si** of 1 cm x 1 cm x 300 μm contains $\sim 4.5 \times 10^8$ free charge carriers at RT compared to only 2.3×10^4 electron-hole pairs for a MIP.

→ To detect this signal, the number of free charge carriers has to be reduced drastically.

Possibilities are:

- cooling
- pn-junction in reverse bias

