Particle Detectors

Lecture 18
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Rivelatori a stato solido

- ★ **The signal** generated in a silicon detector depends essentially only on the thickness of the depletion zone and on the dE/dx of the particle.

- ★ **The noise** in a silicon detector system depends on various parameters: geometry of the detector, the biasing scheme, the readout electronics, etc.

- ★ Noise is typically given as "equivalent noise charge" ENC. This is the noise at the input of the amplifier in elementary charges.

The Charge Signal

- **Collected Charge for a Minimum Ionizing Particle (MIP)** **$N = (dE/dx)(x/w)$**

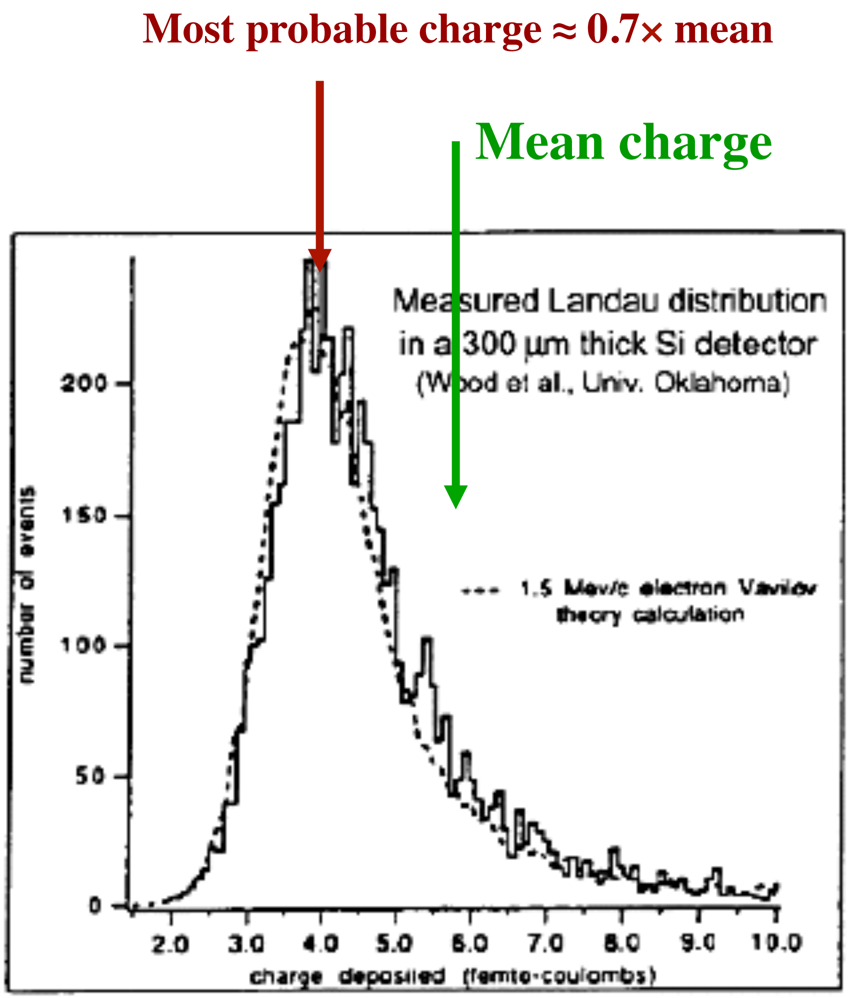
- **Mean energy loss**
  dE/dx (Si) = 3.88 MeV/cm
  ⇒ 116 keV for 300μm thickness

- **Most probable energy loss**
  ≈ 0.7 ×mean
  ⇒ 81 keV

- **3.6 eV to create an e-h pair**
  ⇒ 72 e-h / μm (most probable)
  ⇒ 108 e-h / μm (mean)

- **Most probable charge** (300 μm)

  ≈ 22500 e ≈ 3.6 fC



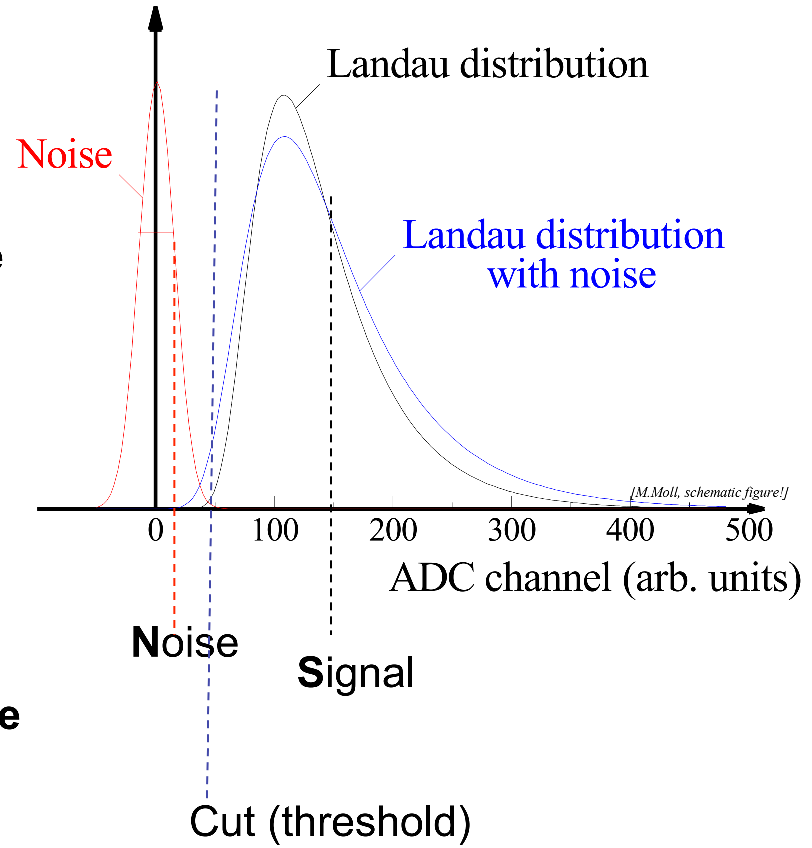
Signal to noise ratio (S/N)

- **Landau distribution** has a low energy tail
  - becomes even lower by noise broadening

- **Good hits selected by requiring N_{ADC} > noise tail**
  If cut too high ⇒ efficiency loss
  If cut too low ⇒ noise occupancy

- **Figure of Merit: Signal-to-Noise Ratio S/N**

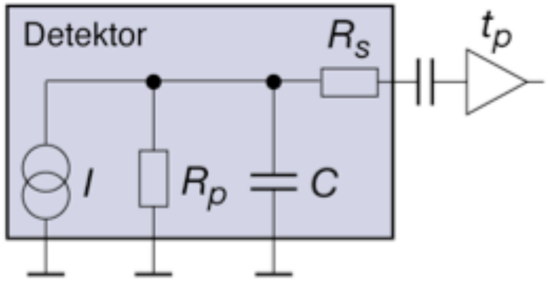
- **Typical values >10-15, people get nervous below 10.**
  Radiation damage severely degrades the S/N.



Rivelatori a semiconduttore

The most important noise contributions are:

1. Leakage current (ENC_I)
2. Detector capacity (ENC_C)
3. Det. parallel resistor (ENC_{Rp})
4. Det. series resistor (ENC_{Rs})



Alternate circuit diagram of a silicon detector.

The overall noise is the quadratic sum of all contributions:

$$ENC = \sqrt{ENC_C^2 + ENC_I^2 + ENC_{Rp}^2 + ENC_{Rs}^2}$$

Shot noise

- The detector leakage current comes from thermally generated electron holes pairs within the depletion region. These charges are seperated by the electric field and generate the leakage current. The fluctuations of this current are the source of noise.

  In a typical detector system (good detector quality, no irradiation damage) the leakage current noise is usually negligible.

  Assuming an amplifier with an integration time ("peaking time") t_p followed by a CR-RC filter the noise contribution by the leakage current I can be written as:

$$\mathrm{ENC}_I = \frac{e}{2}\sqrt{\frac{I t_p}{e}}$$

e .... Euler number (2.718...)
e ... Electron charge

  Using the physical constants, the leakage current in units of nA and the integration time in μs the formula can be simplified to:

$$\mathrm{ENC}_I \approx 107\sqrt{I t_p} \qquad [I \text{ in nA}, \; t_p \text{ in } \mu s]$$

  To minimize this noise contribution the detector should be of high quality with small leakage current and the integration time should be short.

Capacitance noise

The detector capacity at the input of a charge sensitive amplifier is usually the dominant noise source in the detector system.

This noise term can be written as:

$$\mathrm{ENC}_C = a + b \cdot C$$

The parameter *a* and *b* are given by the design of the (pre)-amplifier. *C* is the detector capacitance at the input of the amplifier channel.

Typical values are (amplifier with ~ 1 μs integration time):

$$a \approx 160 \text{ e und } b \approx 12 \text{ e/pF}$$

To reduce this noise component segmented detectors with short strip or pixel structures are preferred.

Parallel resistor noise

The parallel resistor R_p in the alternate circuit diagram is the bias resistor. The noise term can be written as:

$$ENC_{Rp} = \frac{e}{e}\sqrt{\frac{kTt_p}{2R_p}}$$

e .... Euler number (2.718...)
e ... Electron charge

Assuming a temperature of T=300K, t_p in μs and R_p in MΩ the formula can be simplified to:

$$ENC_{Rp} \approx 772\sqrt{\frac{t_p}{R_p}} \qquad \left[R_p \text{ in M}\Omega,\ t_p \text{ in } \mu\text{s}\right]$$

To achieve low noise the parallel (bias) resistor should be large!

However the value is limited by the production process and the voltage drop across the resistor (high in irradiated detectors).

Serie resistor noise

The series resistor R_s in the alternate circuit diagram is given by the resistance of the connection between strips and amplifier input (e.g. aluminum readout lines, hybrid connections, etc.). It can be written as:

$$\mathrm{ENC}_{Rs} \approx 0.395\, C \sqrt{\frac{R_s}{t_p}}$$

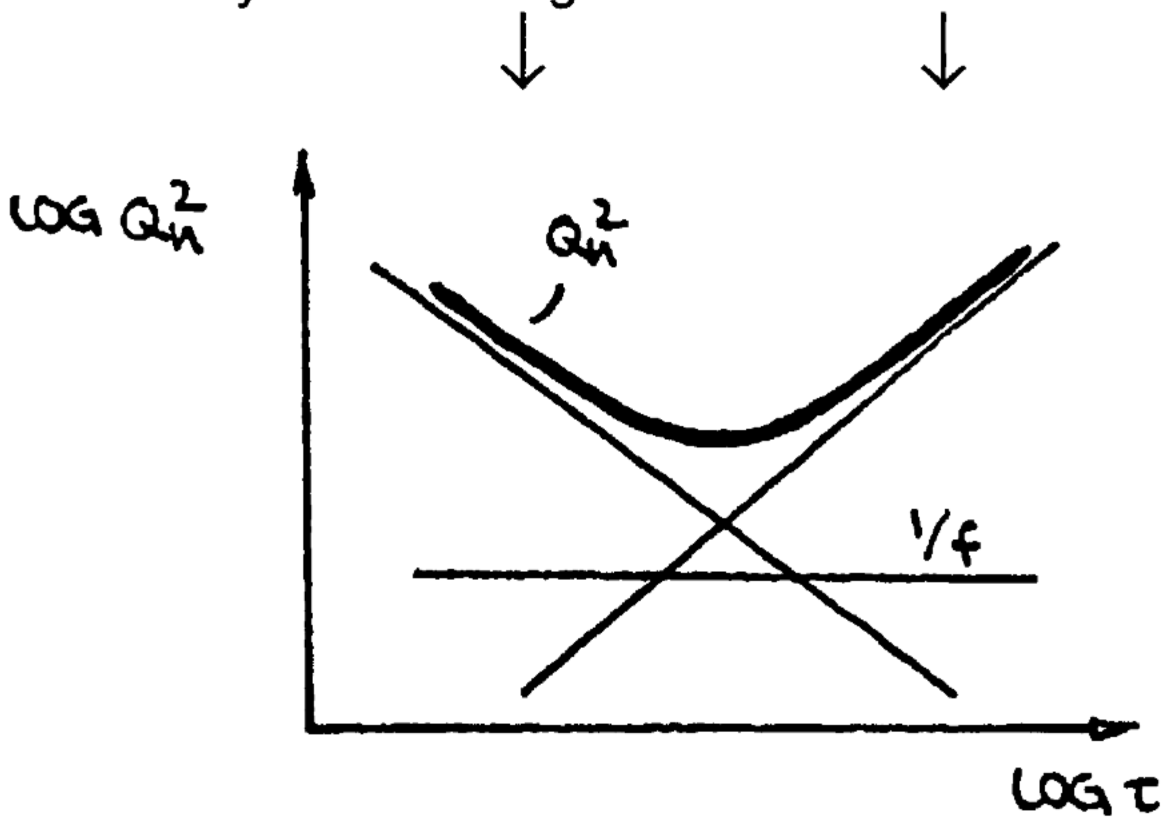
C .... Detector capacity on pF
t_p ... Integration time in μs
R_s ... Series resistor in Ω

Note that, in this noise contribution t_p is inverse, hence a long t_p reduces the noise. The detector capacitance is again responsible for larger noise.

To avoid excess noise the aluminum lines should have low resistance (e.g. thick aluminum layer) and all other connections as short as possible.

Q_n assumes a minimum when the current and voltage noise contributions are equal.

dominated by voltage current noise



To achieve a high signal to noise ratio in a silicon detector system the following conditions are important:

- ★ Low detector capacity (i.e. small element size)
- ★ Low leakage current
- ★ Large bias resistor
- ★ Short and low resistance connection to the amplifier
- ★ Usually long integration time

Obviously some of the conditions are contradictory. Detector and front end electronics have to be designed as one system. The optimal design depends on the application.

DELPHI Microvertex:

- ★ readout chip (MX6):
  $a = 325$ e, $b = 23$ e/pF, $t_p = 1.8\ \mu s$
- ★ 2 detectors in series each 6 cm long strips, $C = 9$ pF
  ➔ $ENC_C = 532$ e
- ★ typ. leakage current/strip: $I \approx 0.3$ nA
  ➔ $ENC_I = 78$ e
- ★ bias resistor $R_p = 36\ M\Omega$
  ➔ $ENC_{Rp} = 169$ e
- ★ series resistor = 25 Ω
  ➔ $ENC_{Rs} = 13$ e

➔ **Total noise: ENC = 564 e (SNR 40:1)**

CMS Tracker:

- ★ readout chip (APV25, deconvolution):
  $a = 400$ e, $b = 60$ e/pF, $t_p = 50$ ns
- ★ 2 detectors in series each 10 cm long strips, $C = 18$ pF
  ➔ $ENC_C = 1480$ e
- ★ max. leakage current/strip: $I \approx 100$ nA
  ➔ $ENC_I = 103$ e
- ★ bias resistor $R_p = 1.5\ M\Omega$
  ➔ $ENC_{Rp} = 60$ e
- ★ series resistor = 50 Ω
  ➔ $ENC_{Rs} = 345$ e

➔ **Total noise: ENC = 1524 e (SNR 15:1)**

Calculated for the signal of a minimum ionizing particle (mip) of 22500 e.

Si detectors: typical noise performance

- Example of noise
  - Some typical values for LEP silicon strip modules (OPAL):
    - ENC = 500 + 15 $\cdot C_d$
    - Typical strip capacitance is about 1.5pF/cm, strip length of 18cm so C_d=27pF

so ENC = 900e. Remember S=22500e

$\Rightarrow$ S/N $\approx$ 25/1

- Some typical values for LHC silicon strip modules
    - ENC = 425 + 64 $\cdot C_d$
  - Typical strip capacitance is about 1.2pF/cm, strip length of 12cm so C_d=14pF

so ENC = 1300e

$\Rightarrow$ S/N $\approx$ 17/1

Capacitive term is much worse for LHC in large part due to very fast shaping time needed (bunch crossing of 25ns vs 22μs for LEP)

Risoluzione spaziale

The position resolution – the main parameter of a position detector – depends on various factors, some due to physics constraints and some due to the design of the system (external parameters).

★ Physics processes:

- Statistical fluctuations of the energy loss
- Diffusion of charge carriers

★ External parameter:

- Binary readout (thresh hold counter) or read out of analogue signal value
- Distance between strips (strip pitch)
- Signal to noise ratio

Risoluzione spaziale

★ Silicon position detectors are thin (300–500 μm) and absorb only a small fraction of the total energy of through going particles.

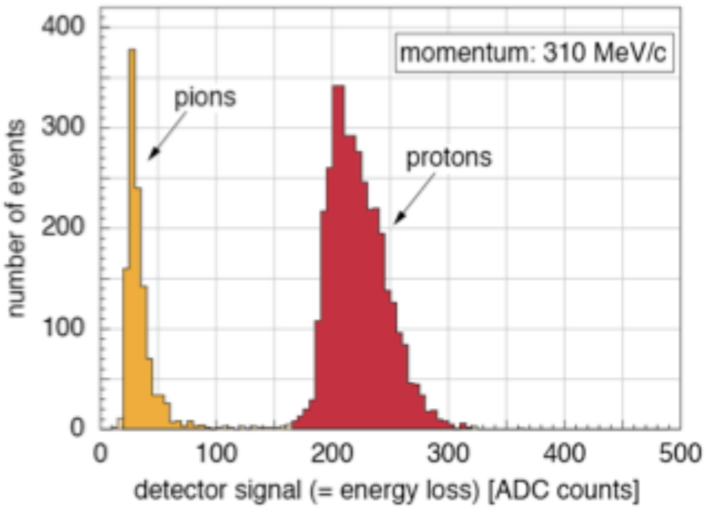
★ The energy loss *dE/dx* follows a Landau distribution, an asymmetric probability function with a long "tail" to large energy deposits.

★ Example of a mip measured in a 300 μm thick silicon detector:

- Most probable energy loss (Maximum of the distribution): 78 keV in 300 μm ➔ ≈ 72 e^-h^+ pairs per μm

- Mean of the energy loss: 116 keV in 300 μm ➔ ≈ 108 e^-h^+ pairs per μm

Pions and Protons:



W. Adam et al., CMS note 1998/092 (1998)

Risoluzione spaziale

Long tail in energy loss distribution is due to δ-electrons.
δ-electrons have a high energy (keV) and are produced by rare, hard collisions between incident particle and electrons from the detector material.

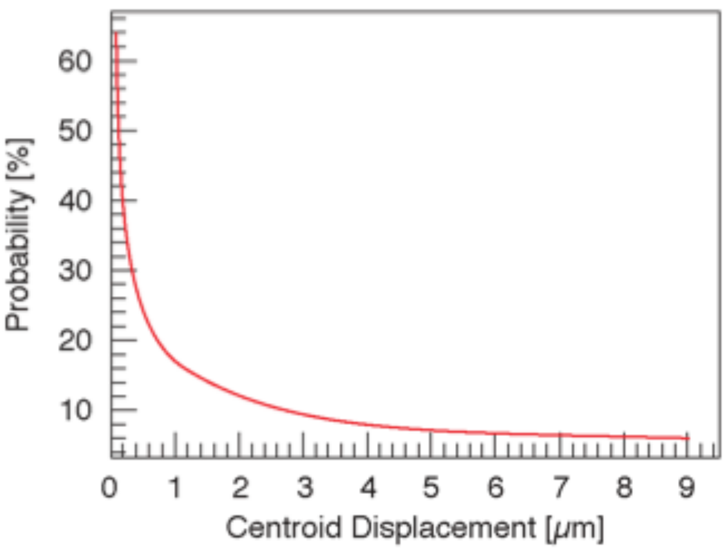
★ The probability to produce a δ-electrons is small.

★ δ-electrons have a long track length in the detector material and may produce e^+h^- pairs along the track.

➔ Dislocate the measured track

➔ Measurement errors in the order of μm unavoidable

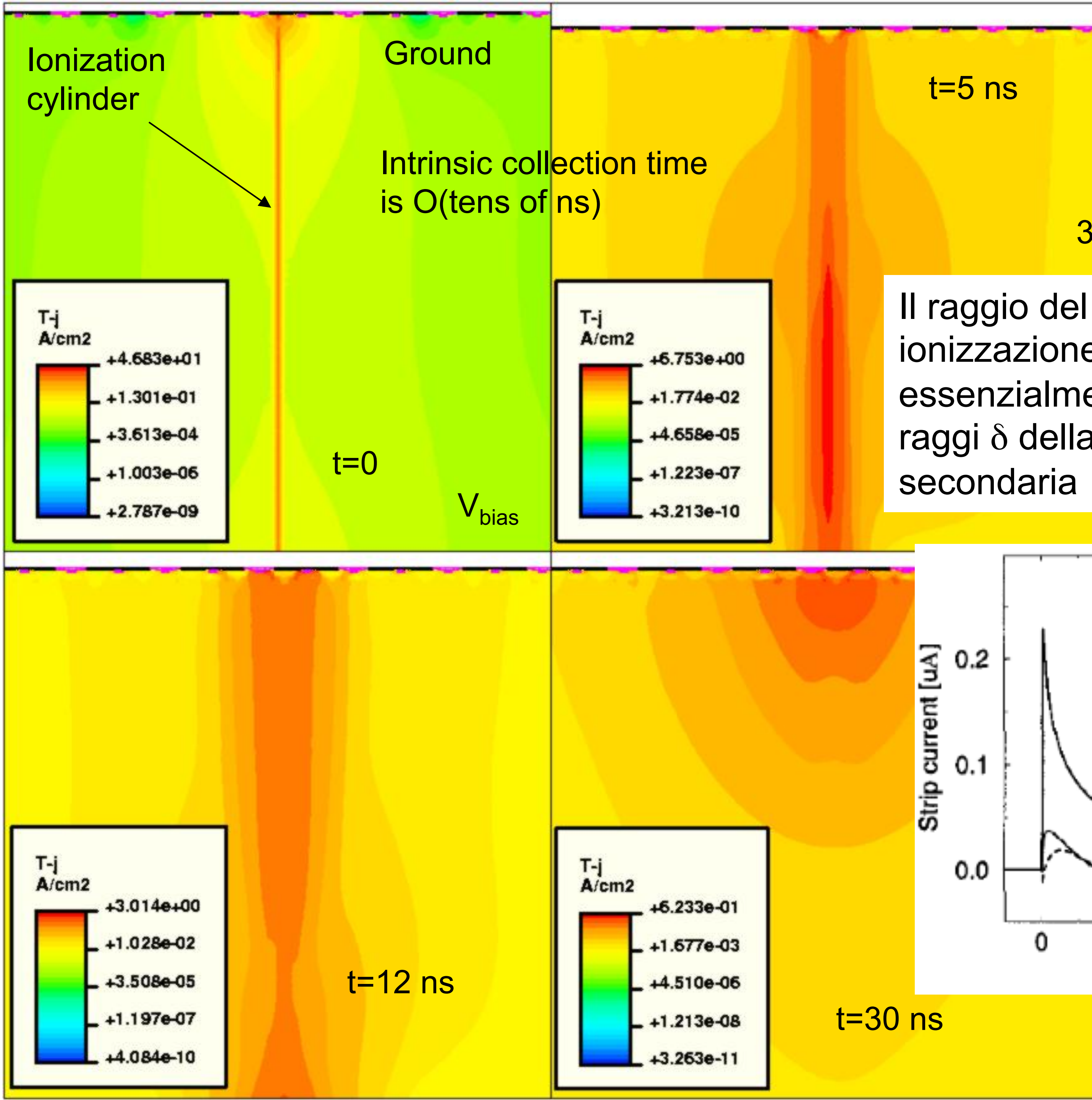
Displacement probability (calculation) of the charge center of gravity due to δ-electrons:



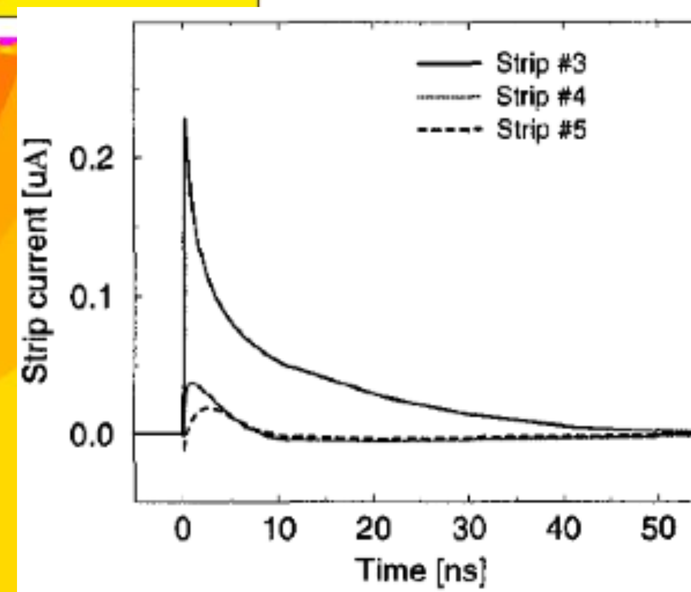
A. Peisert, *Silicon Microstrip Detectors*, DELPHI 92-143 MVX 2, CERN, 1992

Time evolution of current

300 um Silicon layer



Il raggio del cilindro di ionizzazione e' fissato essenzialmente dal range dei raggi δ della ionizzazione secondaria



Equazione di diffusione

The convection–diffusion equation can be derived in a straightforward way from the continuity equation, which states that the rate of change dn/dt for a scalar quantity in a differential control volume is given by flow and diffusion into and out of that part of the system along with any generation or destruction inside the control volume:

$$\frac{\partial n}{\partial t} + \nabla \cdot \vec{j} = R,$$

where is the total flux and *R* is a net volumetric source for n There are two sources of flux in this situation. First, **diffusive flux** arises due to diffusion. This is typically approximated by Fick's first law:

$$\vec{j}_{\text{diffusion}} = -D \nabla n$$

i.e., the flux of the diffusing material (relative to the bulk motion) in any part of the system is proportional to the local concentration gradient. Second, when there is overall convection or flow, there is an associated flux called **advective flux**: $\vec{j}_{\text{advective}} = \vec{v}\, n$

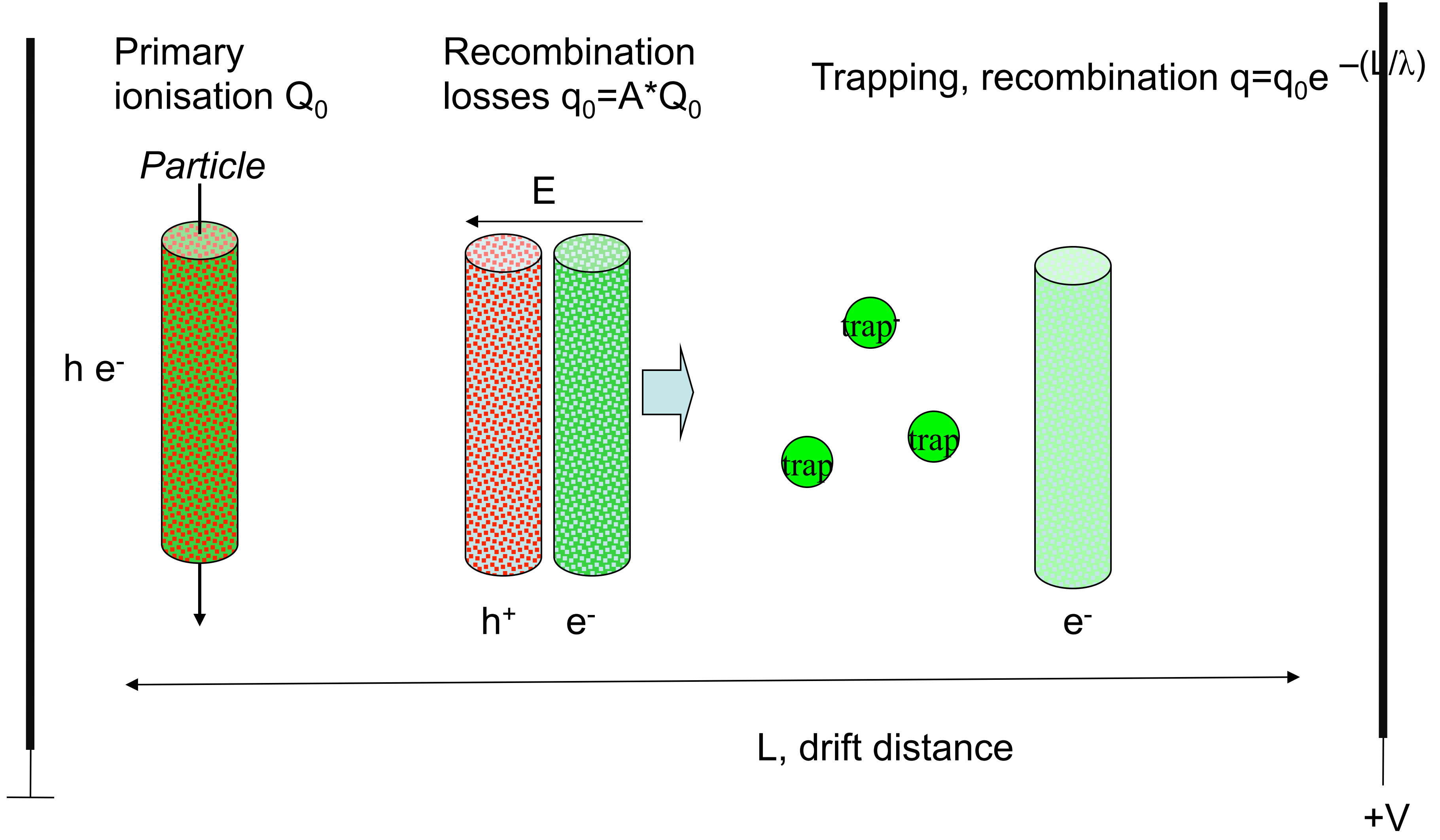
The total flux is given by the sum of these two: $\vec{j} = \vec{j}_{\text{diffusion}} + \vec{j}_{\text{advective}} = -D \nabla n + \vec{v}\, n$

$$\frac{\partial n}{\partial t} + \nabla \cdot \left(-D \nabla n + \vec{v}\, n \right) = R.$$

As for gas: initial volume recomb and Q loss during their travel to electrodes

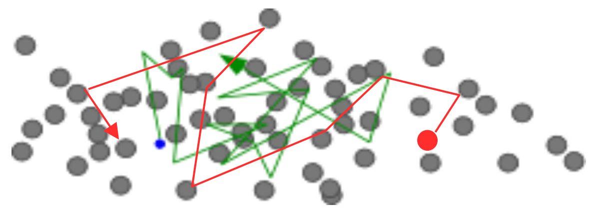
Response to a primary ionization

$$\frac{\partial n}{\partial t} + \nabla \cdot \left(-D \vec{\nabla} n + \vec{v} n\right) = R.$$

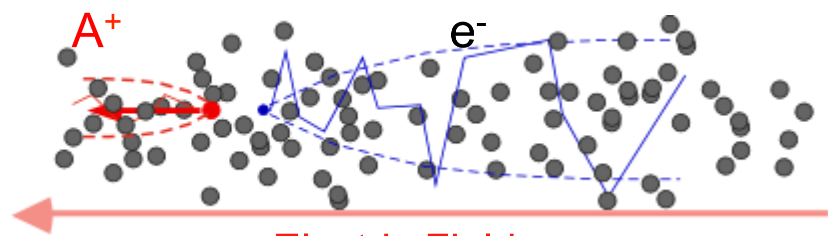


Drift and Diffusion in Presence of E field

E=0 thermal diffusion $\langle v \rangle_t = 0$



E>0 charge transport and diffusion $\langle v \rangle_t = v_D$



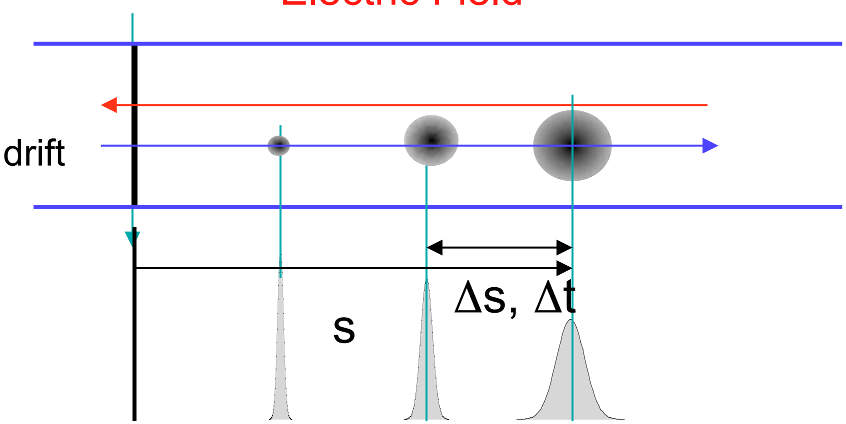
The solution of diffusion-transport eqn is then

$$N(x,t) = \frac{N_0}{\sqrt{4\pi D t}} e^{-\frac{(x - v_D t)^2}{4Dt}}$$

Electron swarm drift

Drift velocity

Diffusion



$v_D = \mu E$

drift + diffusion motion: the average position of the charge swarm moves as x = vt, while the width increases in time

Charge Collection time and diffusion

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

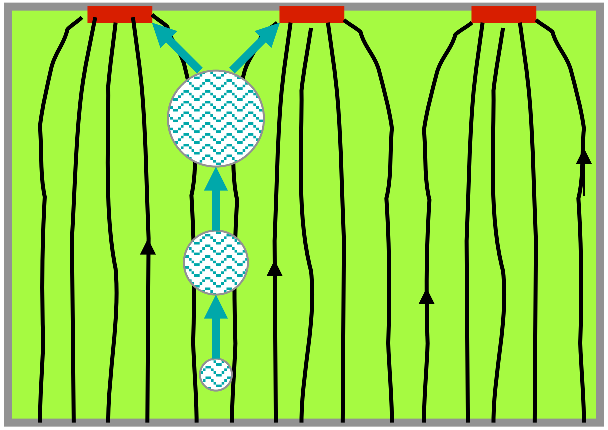
    Typical values: $d=300\ \mu m$, $E= 2.5\ kV/cm$,
    with $\mu_e= 1350\ cm^2/V\cdot s$ and $\mu_h= 450\ cm^2/V\cdot s$

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

- **Diffusion**
  - Diffusion of charge "cloud" caused by scattering of drifting charge carriers, radius of distribution after time td:

$$\sigma = \sqrt{2Dt_d}$$ with diffusion constant $$D = \mu \frac{kT}{q}$$

- Same radius for e and h since $t_d \propto 1/\mu$
  Typical charge radius: $\sigma \approx 6\mu m$, could exploit this to get better position resolution due to charge sharing between adjacent strips (using centroid finding), but need to keep drift times long (low field).

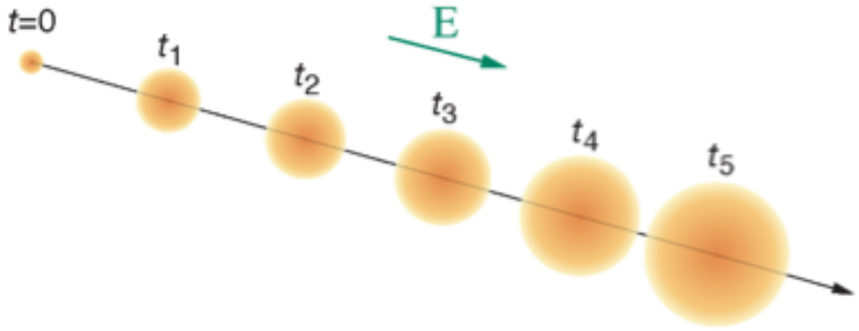


Risoluzione spaziale

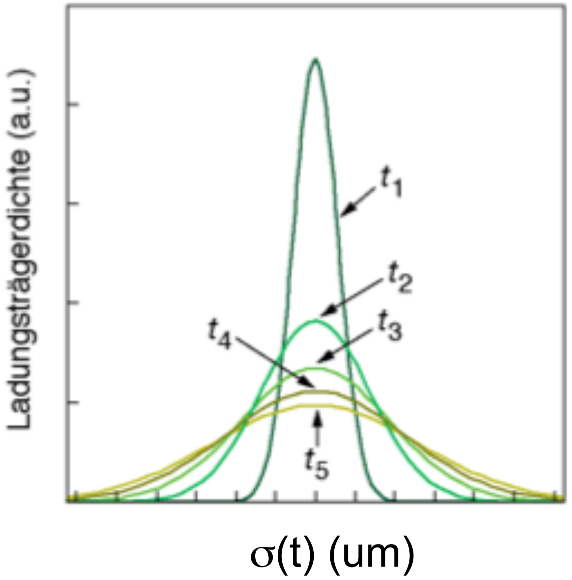
★ h^+ created close to the anode (i.e. the n^+ backplane) and e^- created close to he cathode (i.e. the p^+ strips or pixels) have the longest drift path. As a consequence the diffusion acts much longer on them compared to e^- h^+ with short track paths.

➔ The signal measured comes from many overlapping Gaussian distributions.

Drift and diffusion acts on charge carriers:



Charge density distribution for 5 equidistant time intervalls:



Risoluzione spaziale

- ★ Diffusion widens the charge cloud. However, this has an positive effect on the position resolution!

  ➔ charge is distributed over more than one strip, with interpolation (calculation of the charge center of gravity) a better position measurement is achievable.

- ★ This is only possible if analogue read out of the signal is implemented.
- ★ Interpolation is more precise the larger the signal to noise ratio is.

  ➔ Strip pitch and signal to noise ratio determine the position resolution.

- ★ Larger charge sharing can also be achieved by tilting the detector.

Risoluzione spaziale

★ Threshold readout (one strip signal):

→ position: $x = \text{strip position}$

→ resolution:

$$\sigma_x \approx \frac{p}{\sqrt{12}}$$

p … distance between strips (readout pitch)

x … position of particle track

★ charge center of gravity (signal on two strips):

→ position:

$$x = x_1 + \frac{h_2}{h_1 + h_2}(x_2 - x_1) = \frac{h_1 x_1 + h_2 x_2}{h_1 + h_2}$$

→ resolution:

$$\sigma_x \propto \frac{p}{SNR}$$

x_1, x_2 … position of 1st and 2nd strip

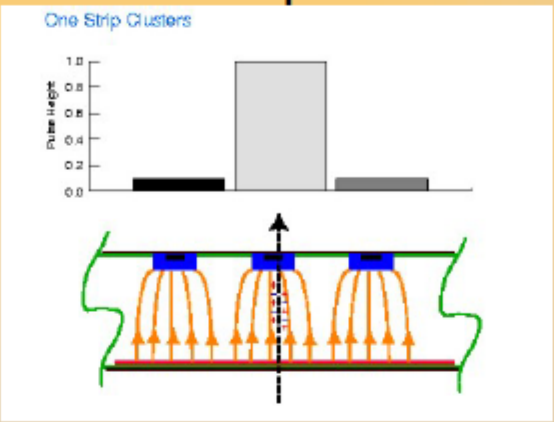
h_1, h_2 … signal on 1st and 2nd strip

SNR … signal to noise ratio

Si strip detectors: spatial resolution

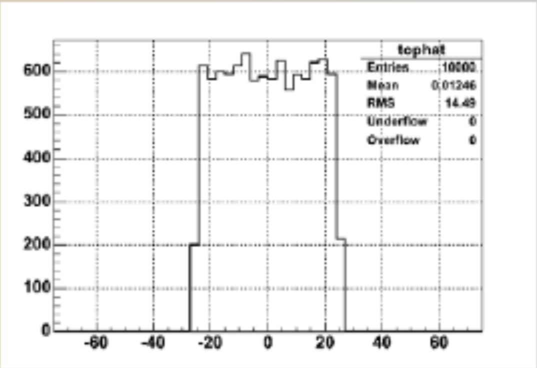
Resolution is the spread of the reconstructed position minus the true position

For one strip clusters

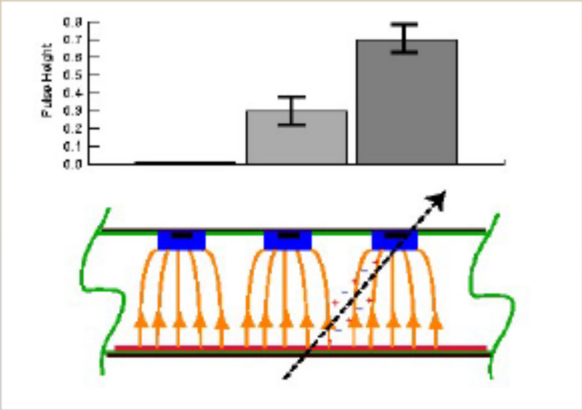


$$\sigma = \frac{pitch}{\sqrt{12}}$$

"top hat" residuals

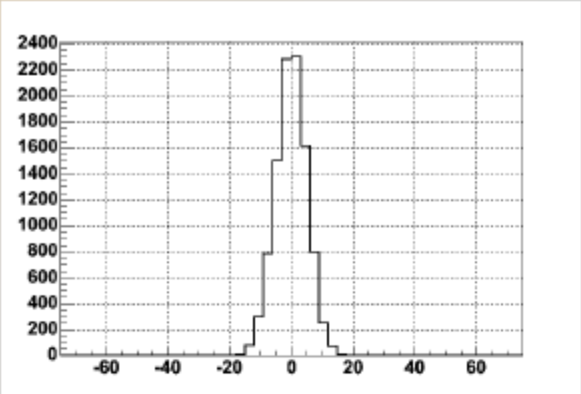


For two strip clusters



$$\sigma \approx \frac{pitch}{1.5 * (S/N)}$$

"gaussian" residuals



Risoluzione spaziale

★ The strip pitch determines to a large extend the position resolution. With small strip pitch a better position resolution is achievable.

But the signal-to-noise ratio plays an essential role

- ➔ small strip pitch requires large number of electronic channels
- ➔ cost increase
- ➔ power dissipation increase

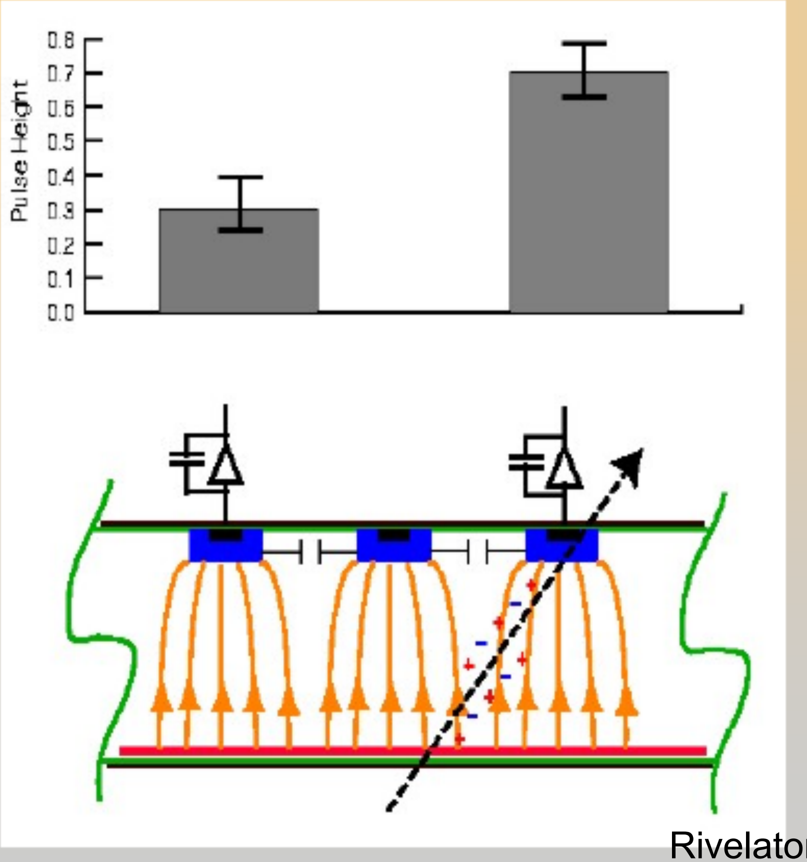
★ A possible solution is the implementation of intermediate strips. These are strips not connected to the readout electronics located between readout strips.

The signal from these intermediate strips is transferred by capacitive coupling to the readout strips.

- ➔ more hits with signals on more than one strip
- ➔ Improved resolution with smaller number of readout channels.

Si strip detectors: spatial resolution

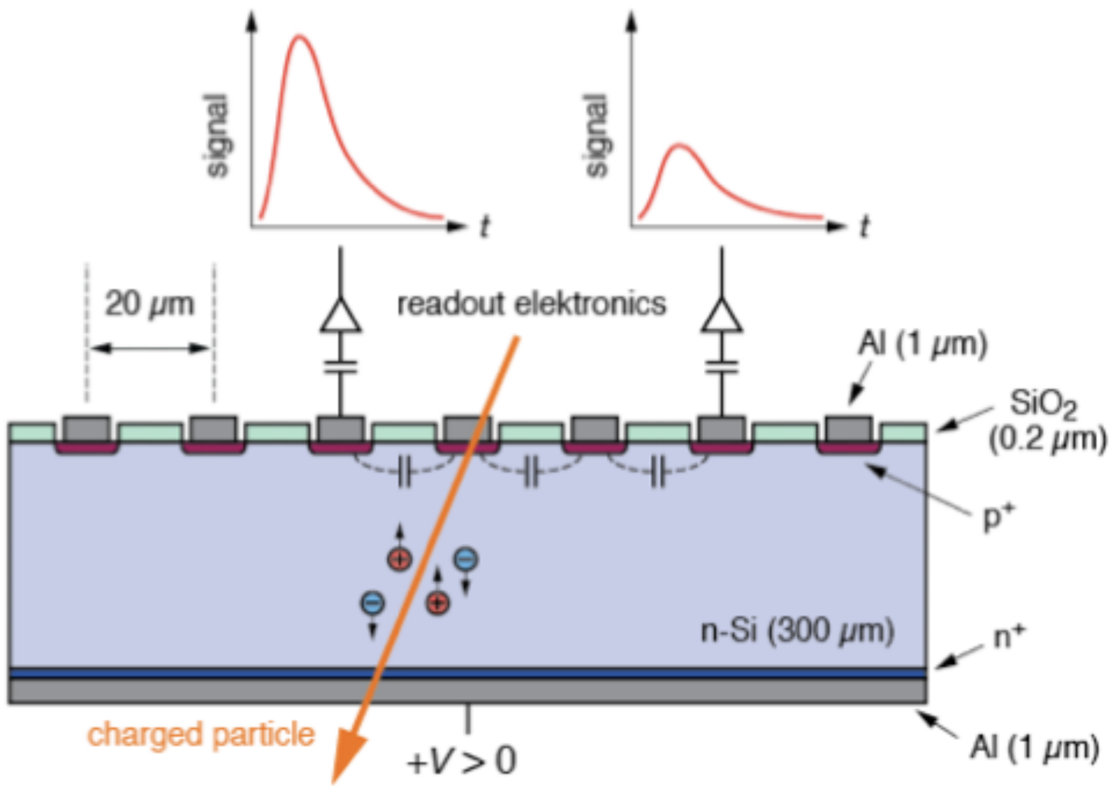
Fine pitch is good… but there is a price to pay! $$$$$
The floating strip solution can help



- The charge is shared to the neighboring strips via capacitative coupling. We don't have to read out every strip but we still get great resolution
- This is a very popular solution. ALEPH for instance obtain $\sigma \approx 12\ \mu m$ using a readout pitch of 100 μm and an implant pitch of 25 μm
- But you can't have everything for nothing! You can lose charge from the floating strips to the backplane, so you must start with a good signal to noise

Risoluzione spaziale

Scheme of a detector with two intermediate strips. Only every 3rd strip is connected to an electronics channel. The charge from the intermediate strips is capacitive coupled to the neighbor strips.

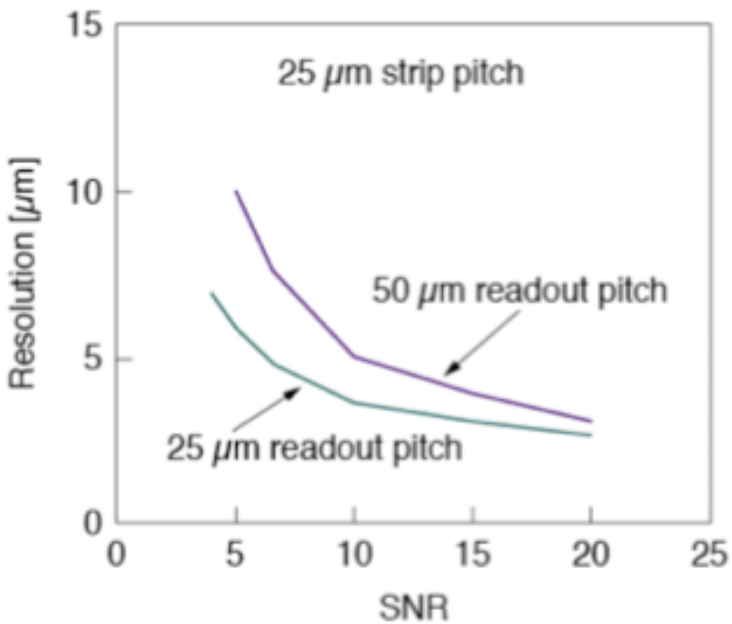


Risoluzione spaziale

Example of a detector with strip pith of 25 μm and analogue readout.
The position resolution is plotted as a function of the SNR.

Bottom curve: every strip is connected to the readout electronics

Top curve: every 2nd strip is connected, one intermediate strip



A. Peisert, *Silicon Microstrip Detectors*, DELPHI 92-143 MVX 2, CERN, 1992

To benefit from intermediate strips large SNR is required!

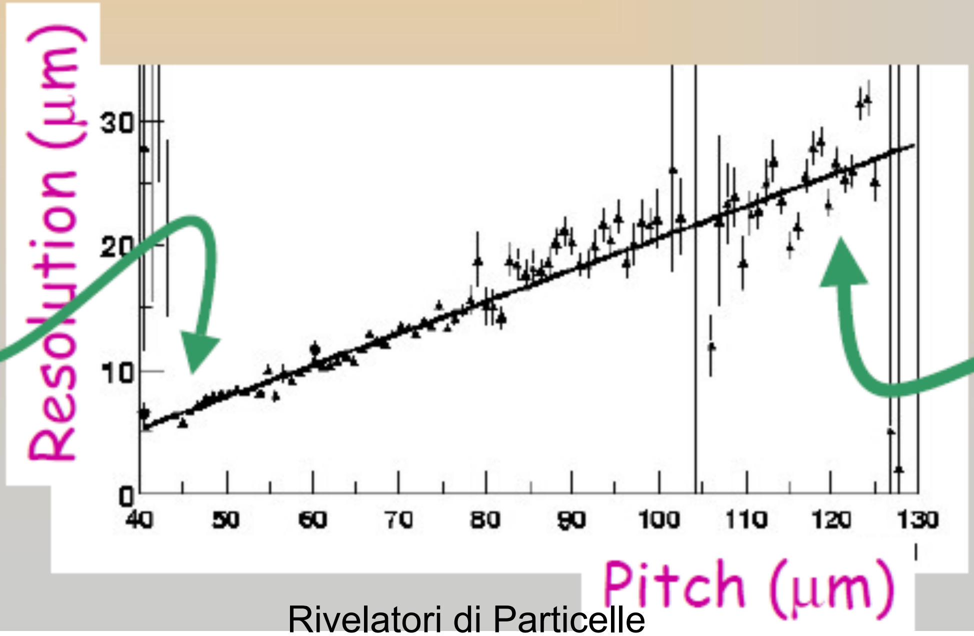
Si strip detectors: spatial resolution

In real life, position resolution is degraded by many factors

- ➢relationship of strip pitch and diffusion width (typically 25-150 μm and 5-10 μm)
- ➢Statistical fluctuations on the energy deposition

Typical real life values for a 300μm thick sensor with S/N=20

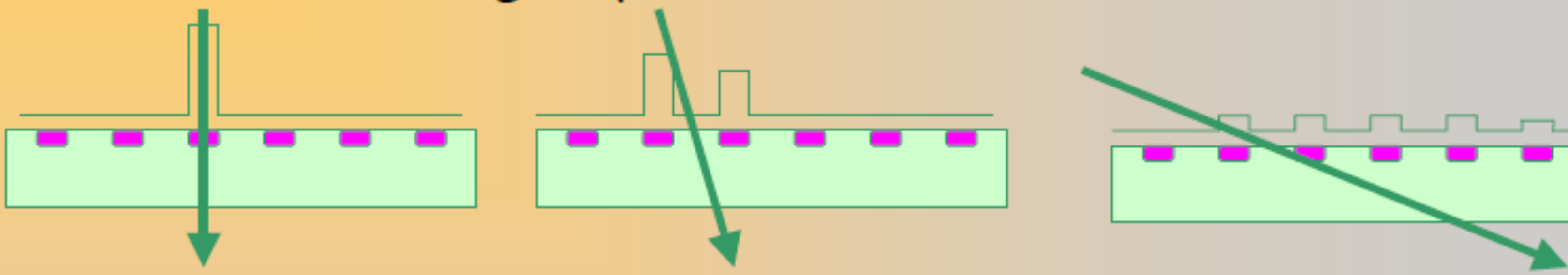
Here charge sharing dominates

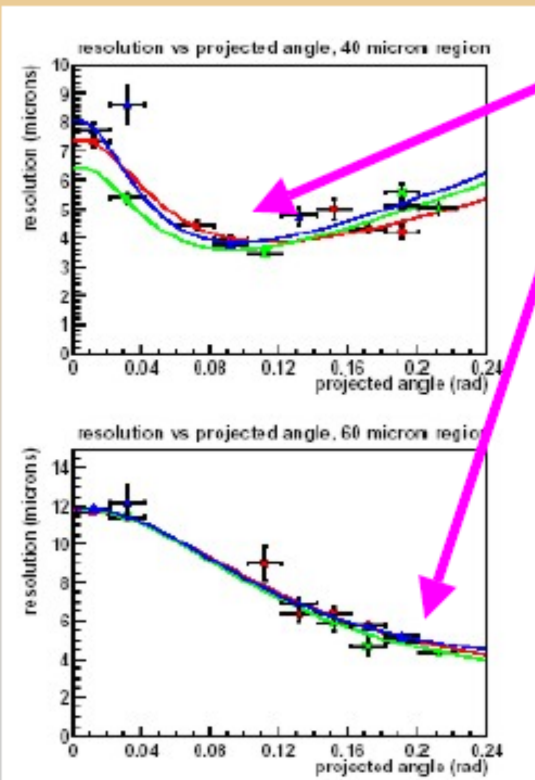


Here single strips dominate

Si strip detectors: spatial resolution

There is also a strong dependence on the track incidence angle





At small angles you win

At large angles you lose
(but a good clustering
algorithm can help)

Optimum is at

$$\tan^{-1}\frac{\text{pitch}}{\text{width}}$$