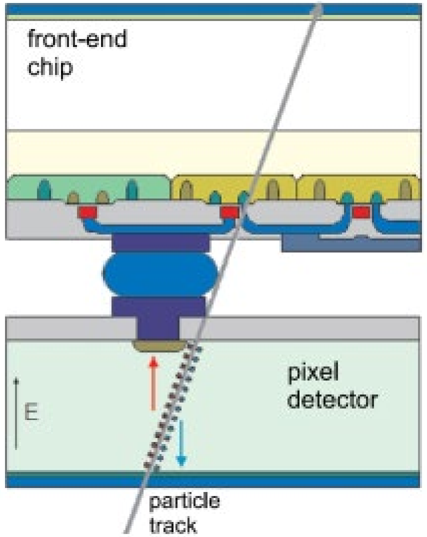
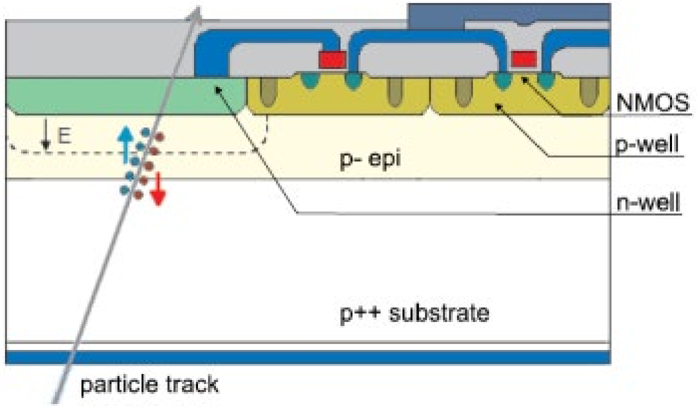
Rivelatori e Apparati

Slides_9 – MAPS, DMAPS, LGAD

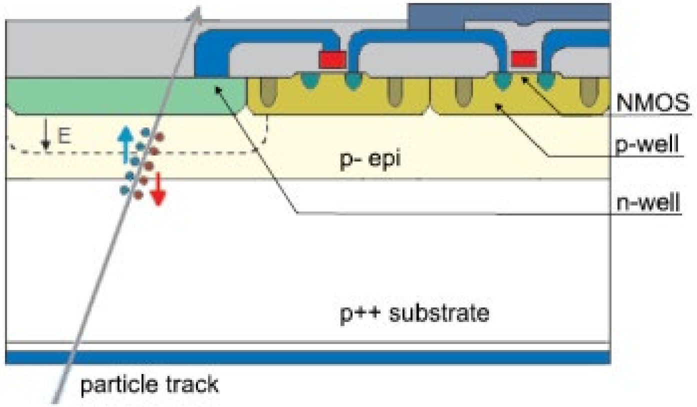
Hybrid Pixel Detectors



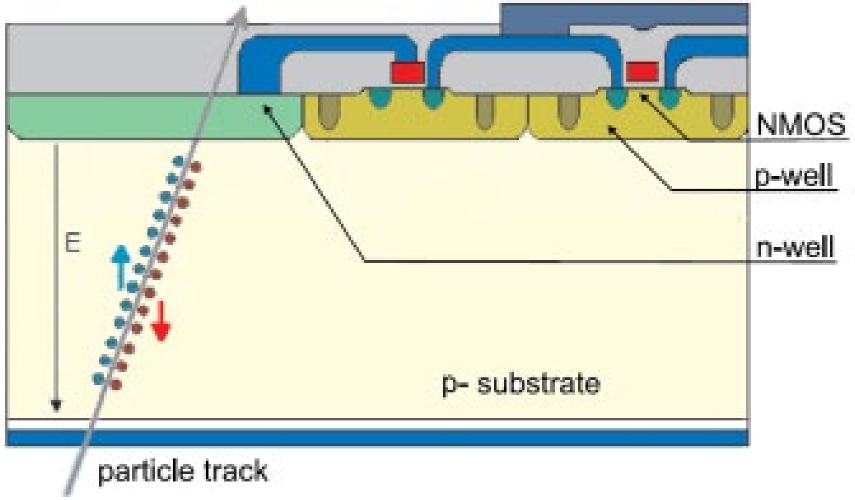
Monolithic Pixels



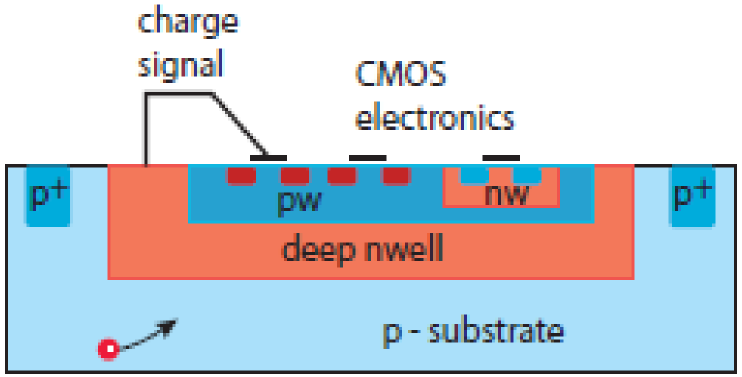
Monolithic Pixels



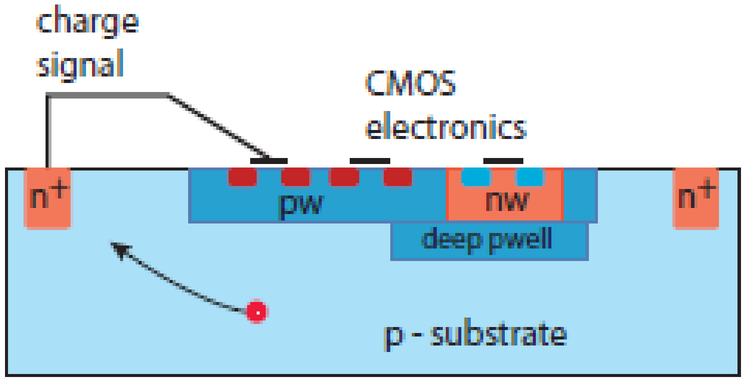
Depleted Monolithic Pixels



Fill factor

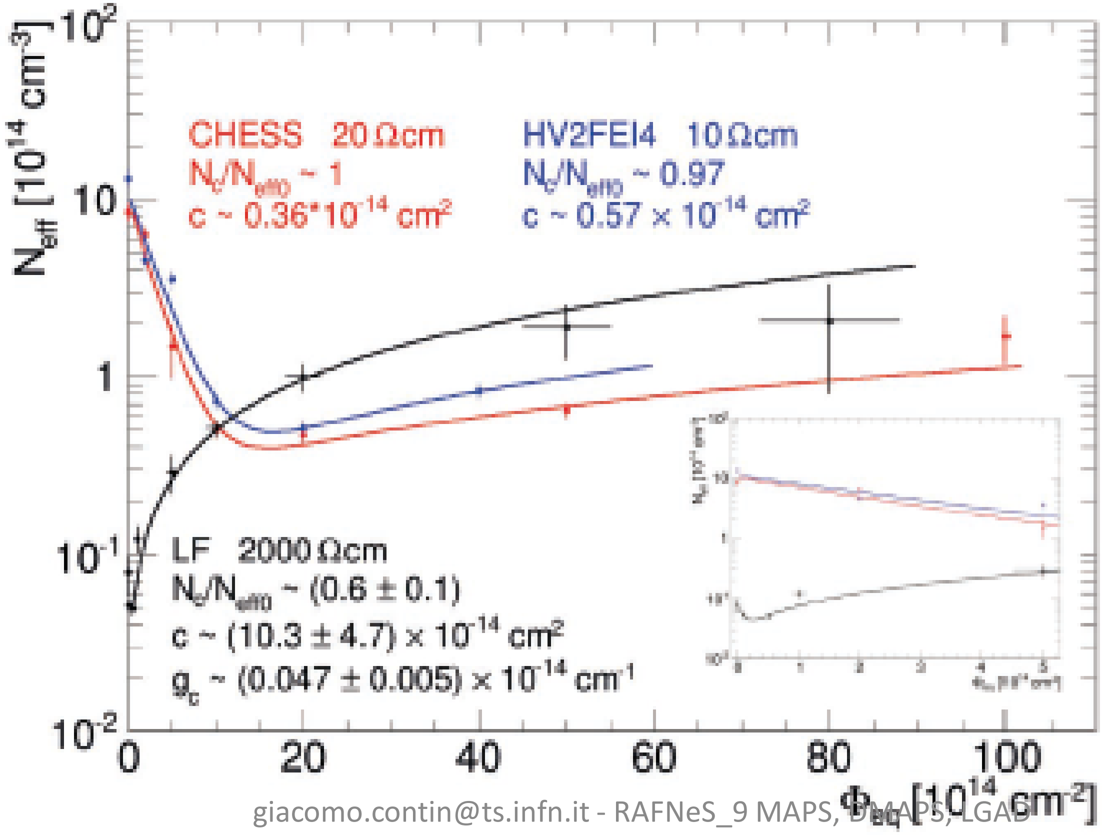


(a) Large fill-factor



(b) Small fill-factor

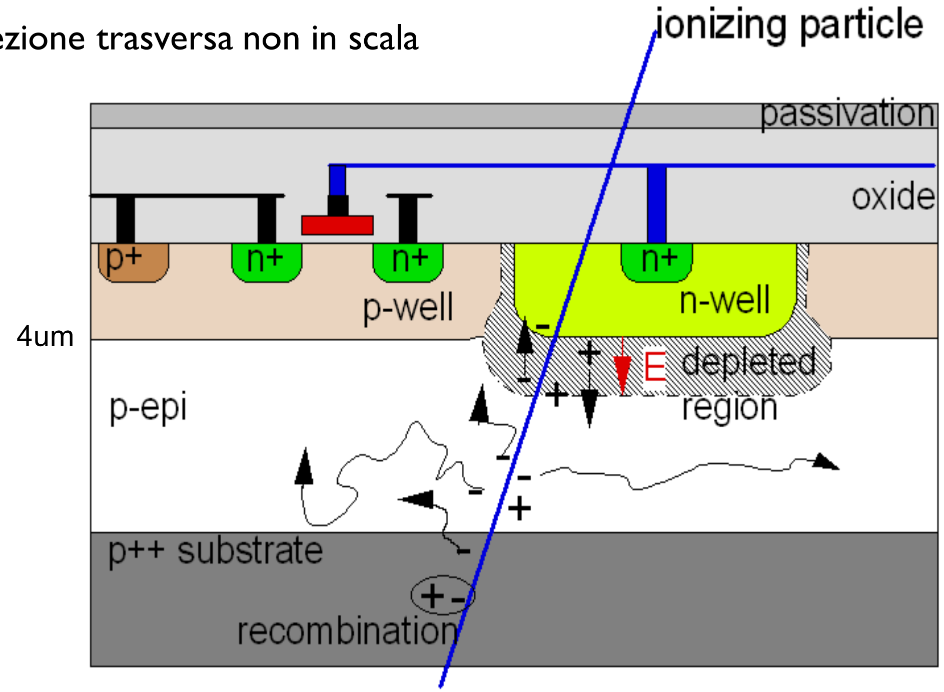
Resistivita' substrato



La tecnologia MAPS

Volume sensibile e logica CMOS di prima elaborazione del segnale nello stesso cristallo di silicio

Sezione trasversa non in scala

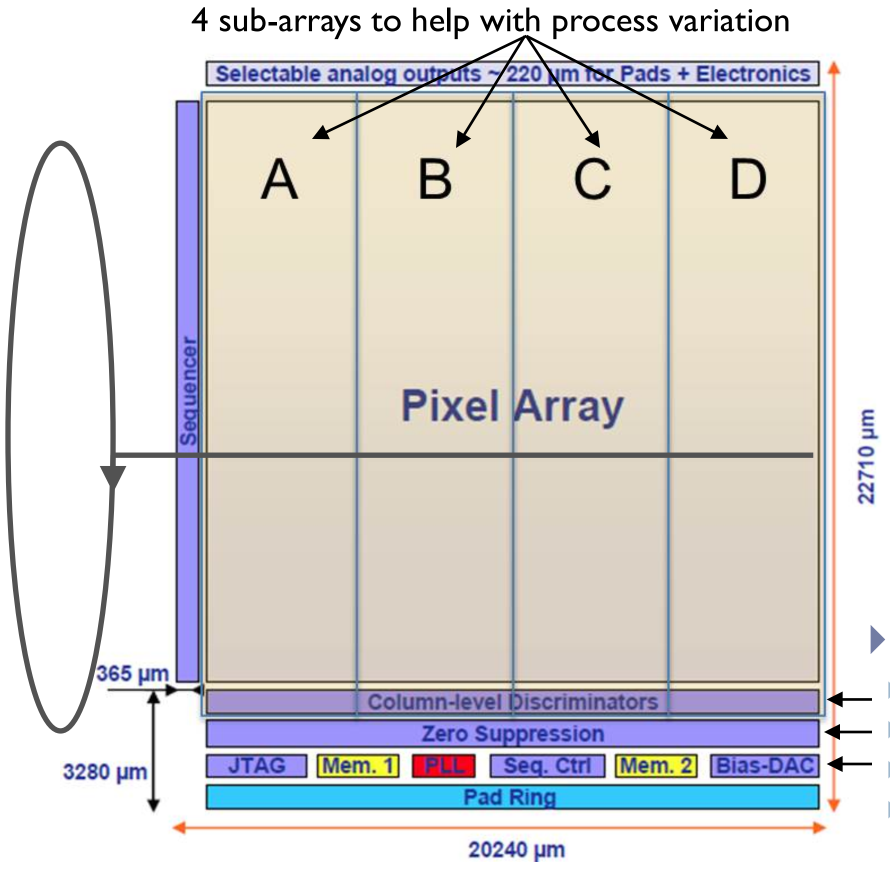


- Monolithic Active Pixel Sensor
- Tecnologia industriale standard CMOS
- **Room temperature** operation
- Sensore e processazione del segnale integrati nello stesso silicio
- Il segnale e' creato nell'epitassiale (tipicamente ~10-15 μm) a basso drogaggio → segnale di un MIP limitato a <1000 elettroni
- La raccolta di carica avviene soprattutto per diffusione termica (lenta, ~100 ns), anche grazie ai confini "riflettenti reflective boundaries at p-well and substrate.
- Epitassiali ad alta resistivita' per ottenere zone svuotate piu' spesse → raccolta della carica piu' efficiente, piu' tollerante alle radiazioni
- 100% fill-factor

STAR HFT PXL sensor: Ultimate-2

- *Ultimate-2:* third generation sensor developed for PXL by the PICSEL group of IPHC, Strasbourg
- *Monolithic Active Pixel Sensor* technology, MIMOSA series

- High resistivity p-epi layer
  - Reduced charge collection time
  - Improved radiation hardness
- S/N ~ 30
- MIP Signal ~ 1000 e-
- **Rolling-shutter readout**
  - A row is selected
  - For each column, a pixel is connected to discriminator
  - Discriminator detects possible hit
  - Move to next row
- 185.6 μs integration time
- ~170 mW/cm² power dissipation



Pixel matrix

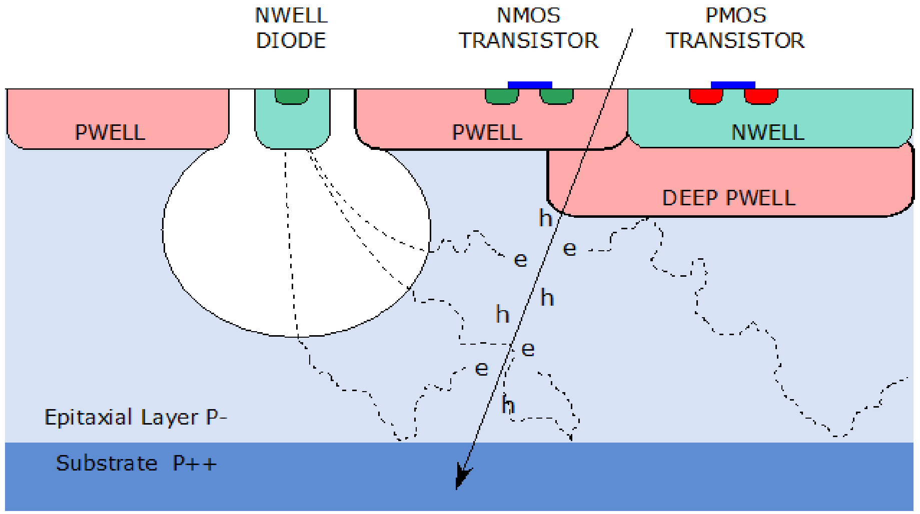
- 928 rows * 960 columns = ~1M pixel
- In-pixel amplifier
- In-pixel Correlated Double Sampling (CDS)

Digital section

- End-of-column discriminators
- Integrated zero suppression (up to 9 hits/row)
- Ping-pong memory for frame readout (~1500 w)
- 2 LVDS data outputs @ 160 MHz

ITS Pixel Chip – technology choice

CMOS Pixel Sensor using TowerJazz 0.18μm CMOS Imaging Process



ALPIDE sensor *(developed within ALICE)*

- ~28 μm pitch
- Integration time: < 20 μs
- Trigger rate: 100 kHz
- Read out up to 1.2 Gbit/s
- Power: 40 mW/cm^2
- Priority encoder - sparsified readout
- Rad. Tolerant: 700krad -10^{14} 1MeV n_{eq}/cm^2

- High-resistivity (> 1kΩ cm) p-type epitaxial layer (20μm - 40μm thick) on p-type substrate
- Small n-well diode (2-3 μm diameter), ~100 times smaller than pixel => low capacitance
- Application of (moderate) reverse bias voltage to substrate can be used to increase depletion zone around NWELL collection diode
- Quadruple well process: deep PWELL shields NWELL of PMOS transistors, allowing for full CMOS circuitry within active area

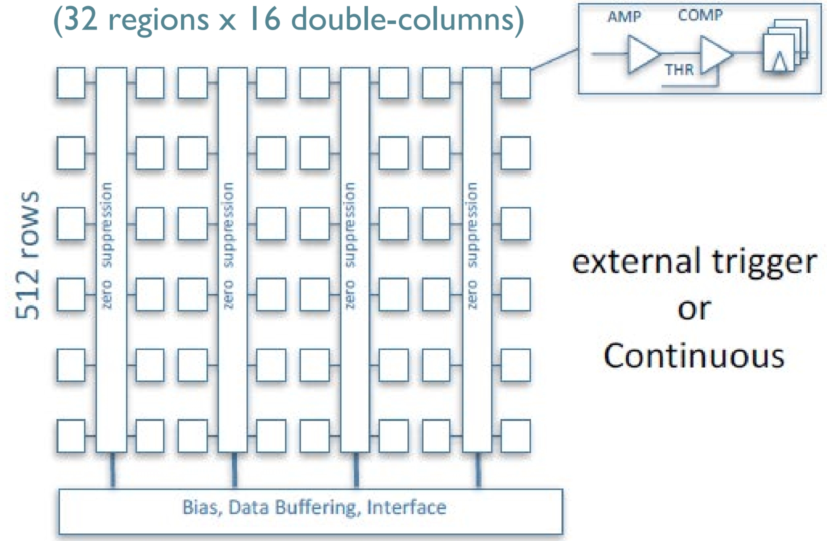
ALICE ITS Upgrade sensor: ALPIDE

Priority Encoder (AE-RD)

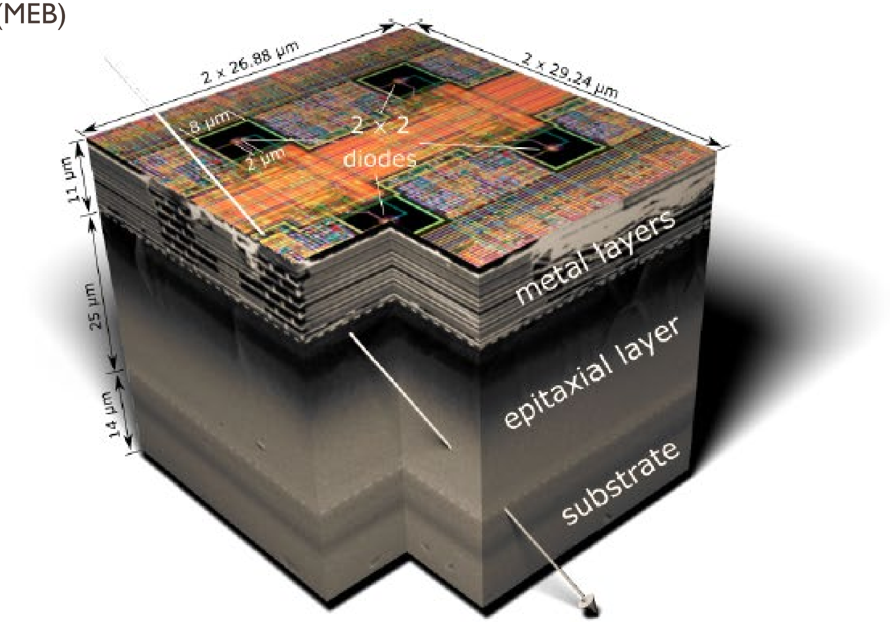
1024 pixel columns

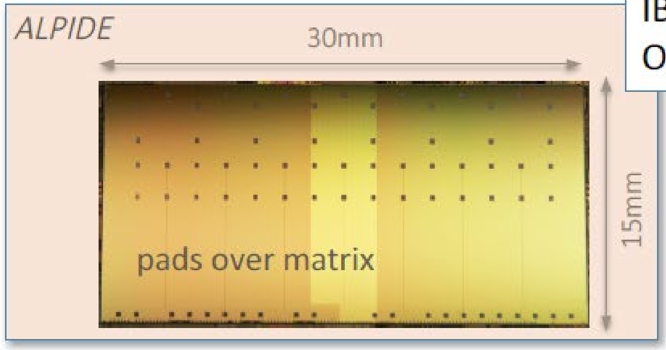
(32 regions x 16 double-columns)

In pixel:
- Amplification
- Discrimination
- 3 hit storage registers (MEB)



external trigger
or
Continuous





IB: 50µm thick
OB: 100µm thick

Power: 40 mW/cm^2
Trigger rate: 100 kHz
Integration time: < 20 µs
Read out up to 1.2 Gbit/s.

130,000 pixels / cm^2 27x29x25 µm^3

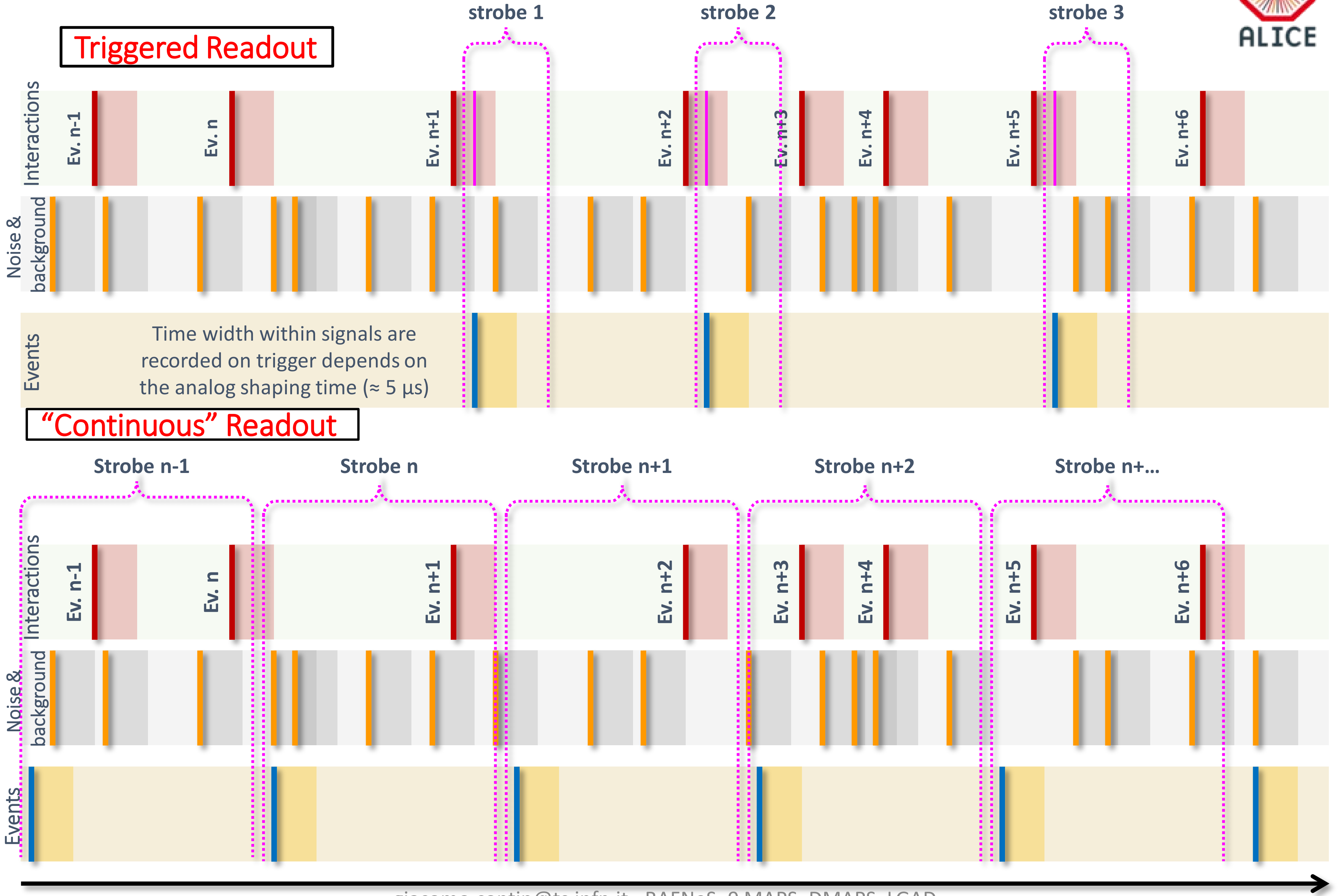
spatial resolution: ~ 5 µm (3-D)

Max particle rate: 100 MHz / cm^2

fake-hit rate: ~ 10^{-10} pixel / event

power : ~ 300 nW /pixel

ALPIDE Timing: Triggered & “Continuous” Readout

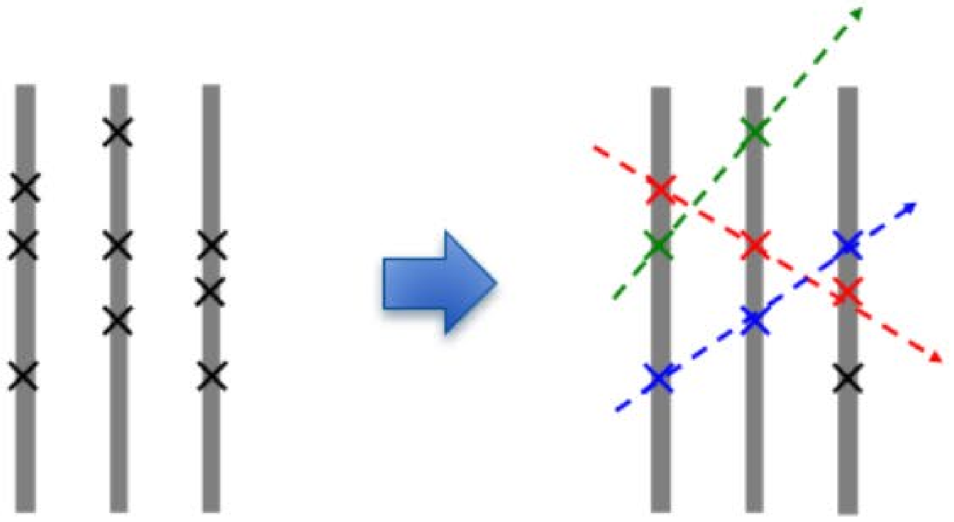


Rivelatori al silicio per misure di tempo

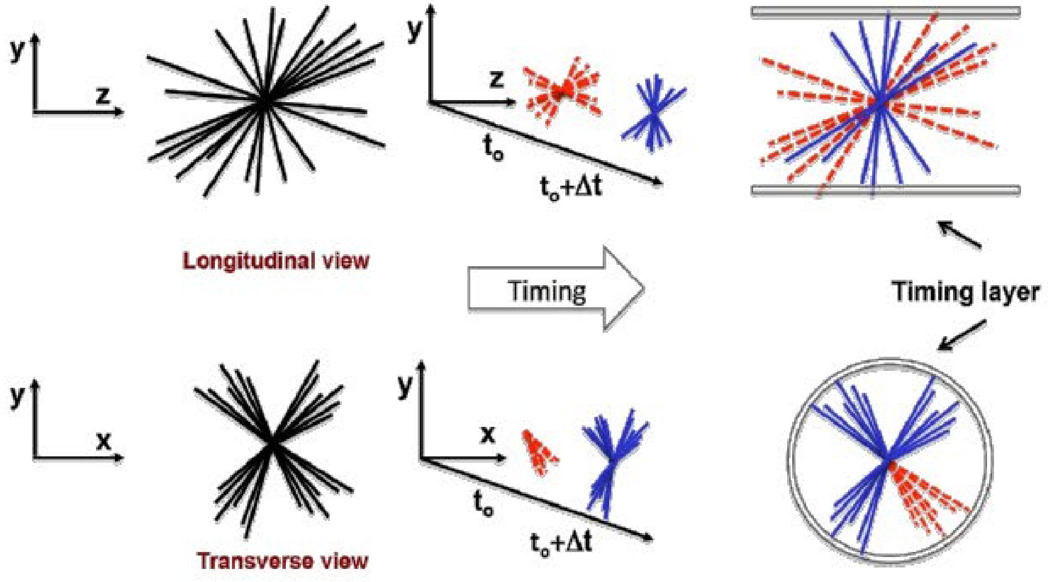
- Low Gain Avalanche Detectors (LGAD):
  - Rivelatori a valanga a basso guadagno
- SPAD
  - Single-photon avalanche photodiode: fotodiodo usato in regime valanga, come un interruttore seguito da una resistenza di quenching che spegne la valanga
- SiPM
  - Silicon Photo-Multiplier: matrici di SPAD in parallelo, non usato per imagine perche somma i segnali dalle diverse celle

Acquisition of timing information

- Time tagging at each point
  - LHCb Upgrade II (Run 5 ~2030)

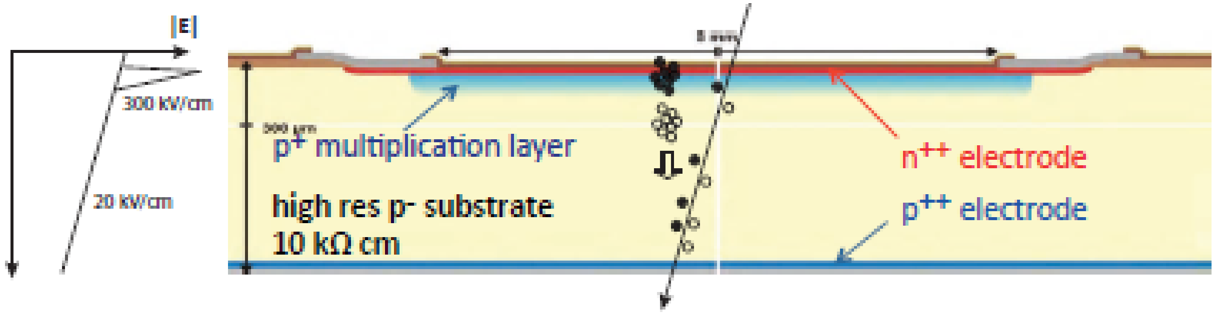


- Timing in the event reconstruction
  - HL-LHC: ATLAS and CMS

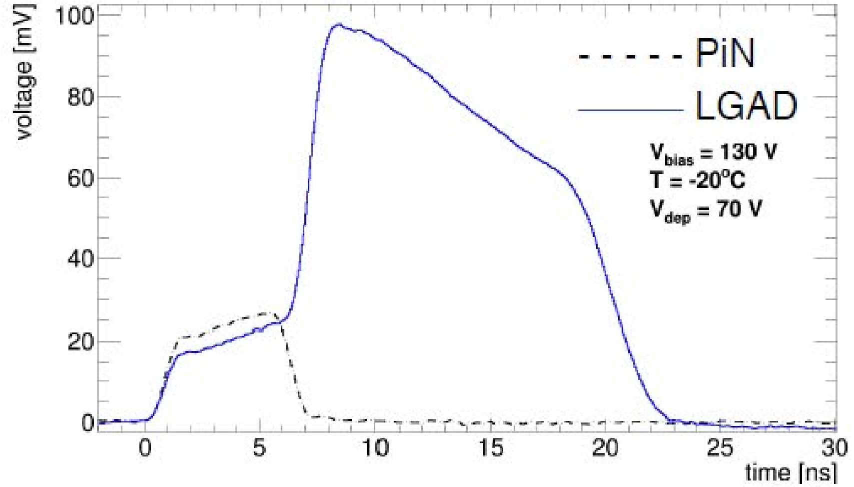


Gain mechanism in LGADs

- Planar silicon sensors (n+/p/p-)
  - n+ implant, p substrate
  - p-type multiplication layer

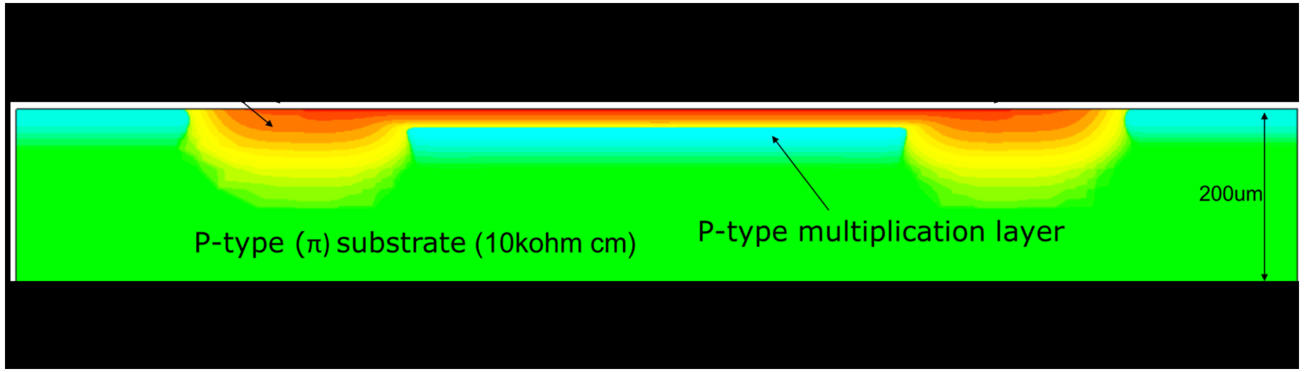


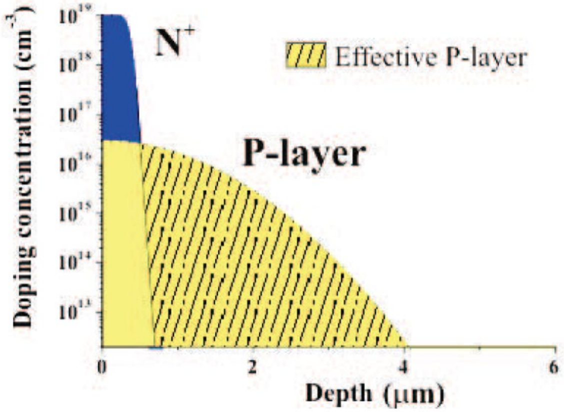
- **High electric field region in the multiplication layer**
  - Charges undergo impact ionisation
  - Gain depends on:
    - multiplication layer doping
    - bias voltage
    - temperature

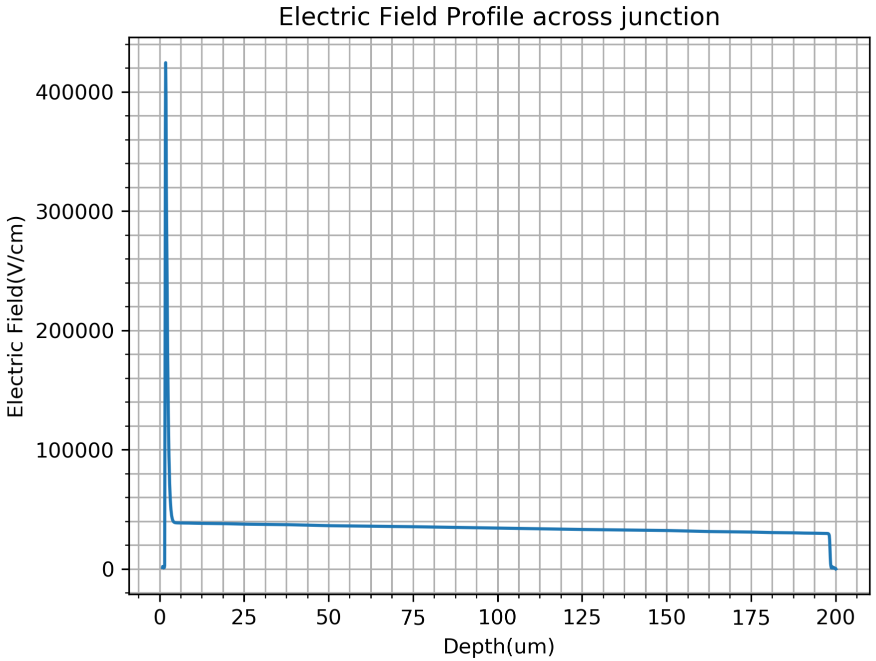


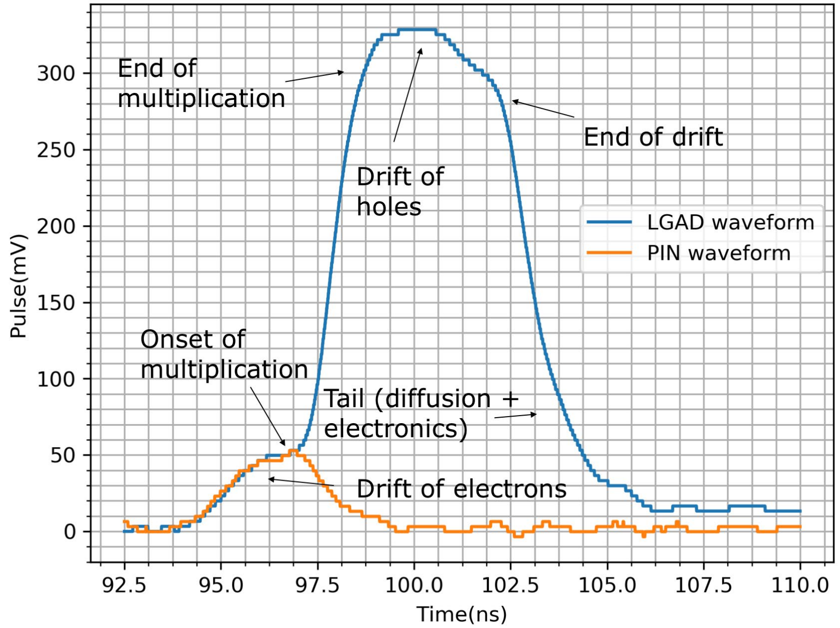
S. Otero Ugobono *et al.*, IEEE TNS (2018) vol. 6, no. 8, pp. 1667-1675

LGAD: simulazioni



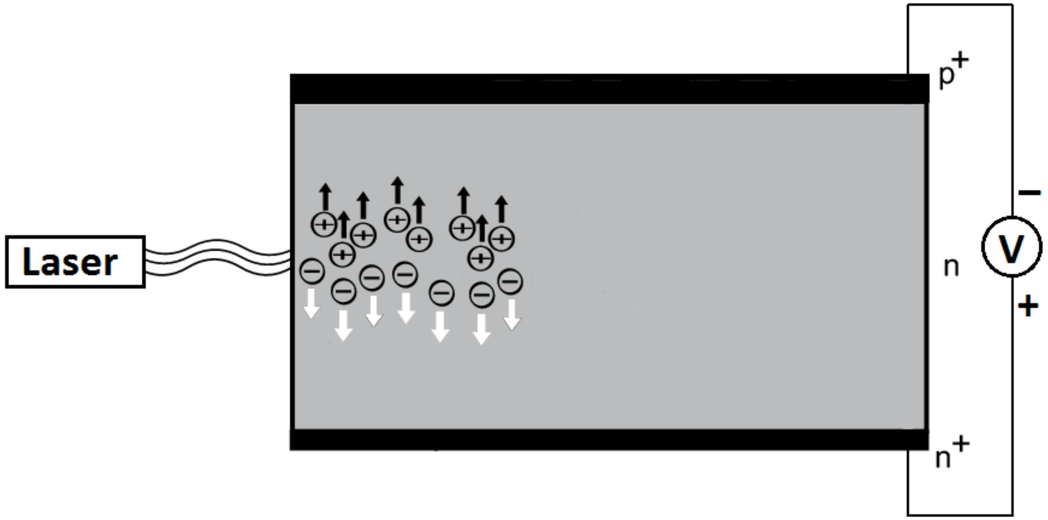




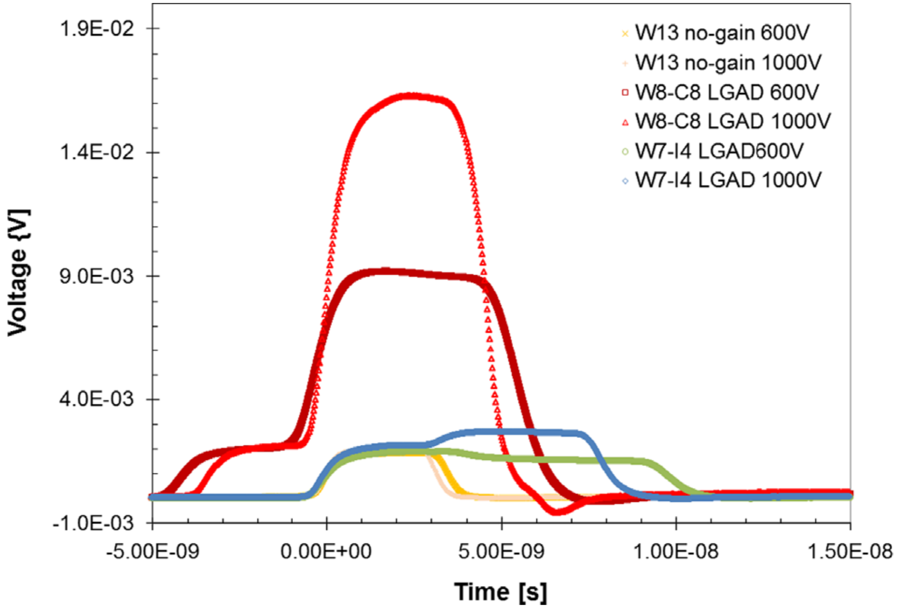


LGAD: misure TCT

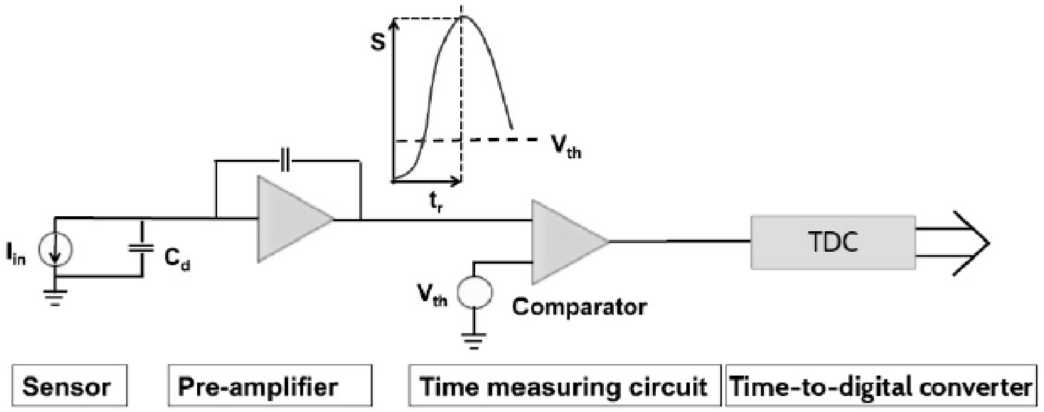
- Principio di funzionamento (Edge-)Transient Current Technique



- Misura TCT su LGAD con diversi Guadagni e a diverse Vbias



Time resolution



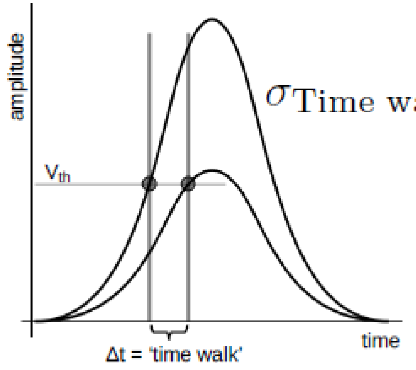
$$\sigma_t^2 = \sigma^2_{\text{Time walk}} + \sigma^2_{\text{Landau noise}} + \sigma^2_{\text{Jitter}} + \sigma^2_{\text{Distortion}} + \sigma^2_{\text{TDC}}$$

Time resolution is affected by:

- each step in the read-out process
- any effect that changes the shape of the signal

Time resolution

$$\sigma_t^2 = \sigma^2_{\text{Time walk}} + \sigma^2_{\text{Landau noise}} + \sigma^2_{\text{Jitter}} + \sigma^2_{\text{Distortion}} + \sigma^2_{\text{TDC}}$$



$$\sigma_{\text{Time walk}} \propto \left[\frac{N\sigma_n}{\text{dV/dt}}\right]_{RMS}$$

- Variation in time of arrival due to different signal amplitudes
- Can be compensated by electronics

- Caused by inhomogeneous:
  - drift velocity
  - weighting field
- Solutions:
  - saturated drift velocity
  - optimised geometry

TDC: time-to-digital converter

$$\sigma_{\text{TDC}} = \Delta T/\sqrt{12}$$

comparator time bin width

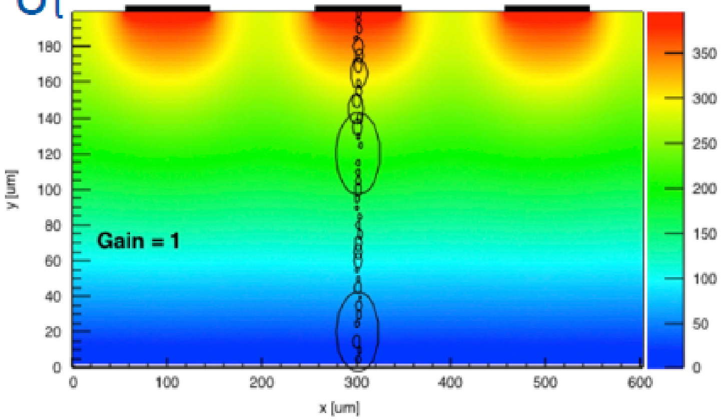
- Sub-picosecond ⇒ negligible

- V_{th}: threshold voltage to determine the time of arrival
- $N\sigma_n$: the threshold is usually expressed in multiples of the system noise

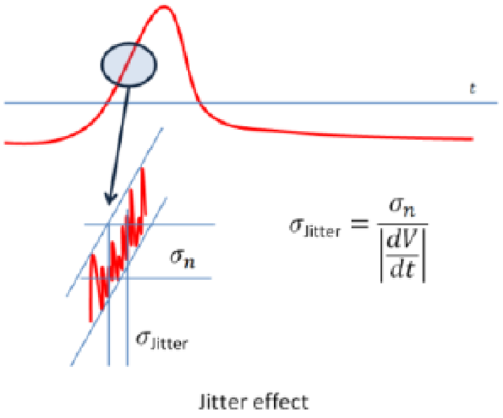
Time resolution

$$\sigma_t^2 = \sigma_{\text{Time walk}}^2 + \sigma_{\text{Landau noise}}^2 + \sigma_{\text{Jitter}}^2 + \sigma_{\text{Distortion}}^2 + \sigma_{\text{TDC}}^2$$

- Signal shape variations for MIPs
  - Non-uniform energy deposition per unit length
- Sets a physical limit to σ_t
- Can be minimised by:
  - setting a low V_{th}
  - using thin devices



- Variations in time of arrival due to signal noise



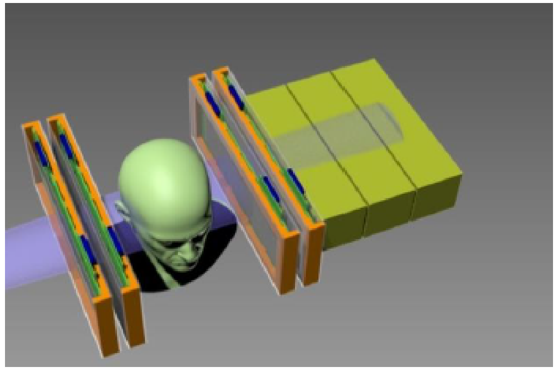
- Can be minimised with:
  - low noise sensors
  - low noise electronics
  - fast slew rates

- V_{th}: threshold voltage to determine the time of arrival

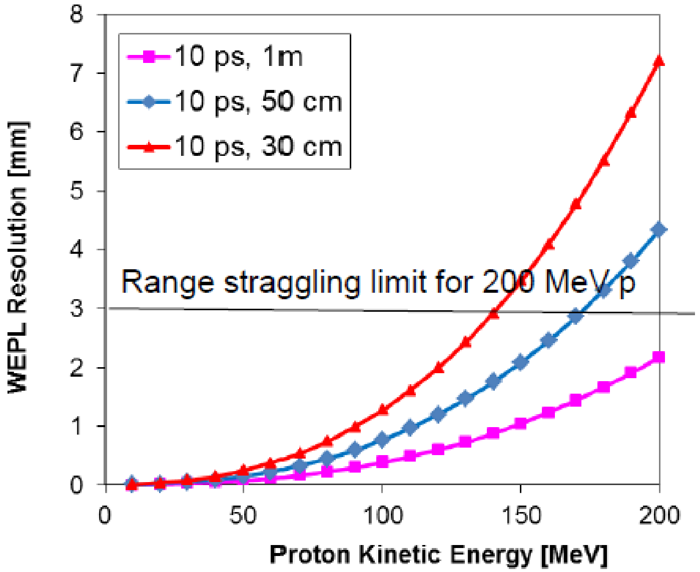
4-D Ultra-Fast Si Detectors in pCT

In support of Hadron Therapy, the relative stopping power (RSP) is being reconstructed in 3D.
The UCSC-LLU pCT scanner uses Si strip sensors to locate the proton and heavy scintillator stages to measure its energy loss (WEPL).

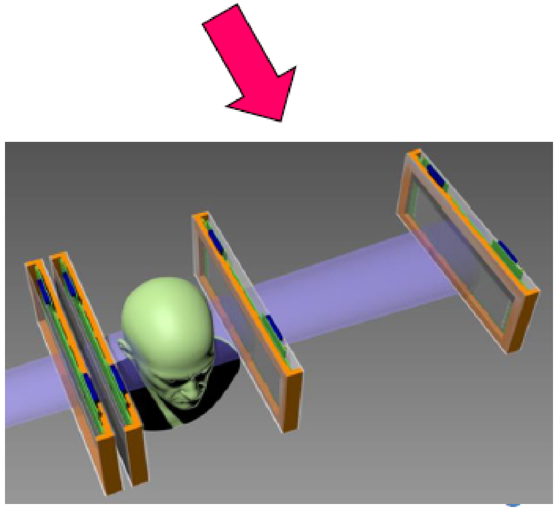
Protons of 200 MeV have a range of ~ 30 cm in plastic scintillator. The resulting straggling limits the WEPL resolution.



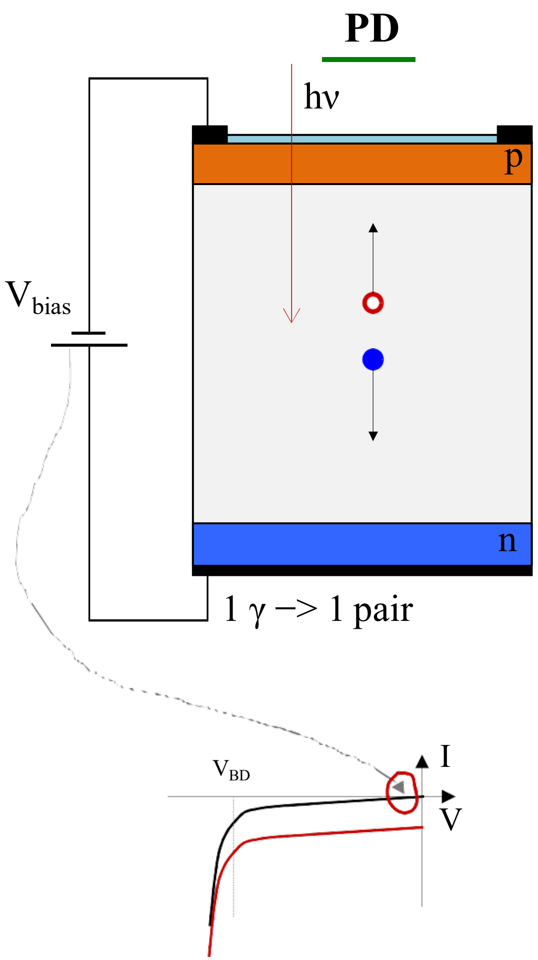
Replace calorimeter/range counter by UFSD:
Combine tracking with WEPL measurement where the ToF of the proton measures the residual energy., with comparable or better resolution than the scintillator.

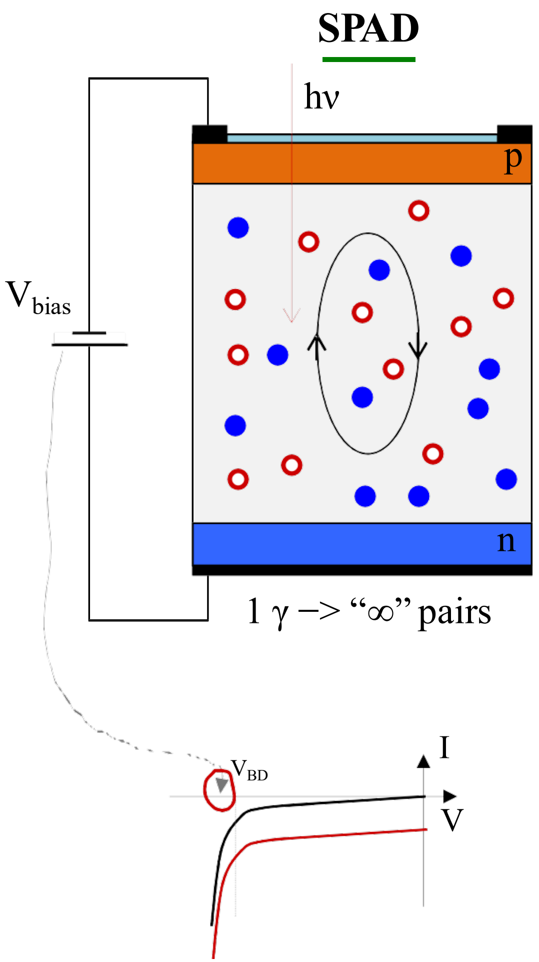


Light-weight, all silicon construction ideal for installation Into the gantry

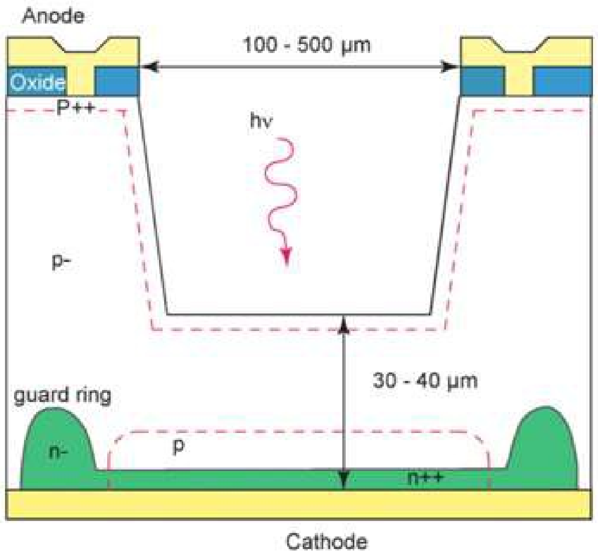


PD and SPAD

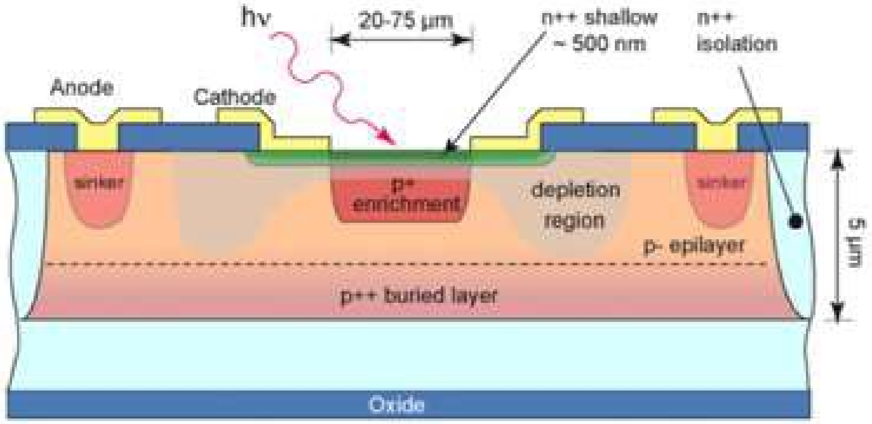




Structure of a SPAD



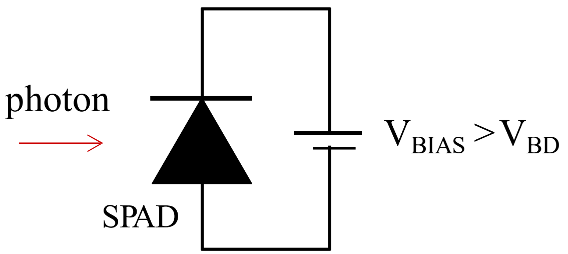
Structure of a *thick* SPAD

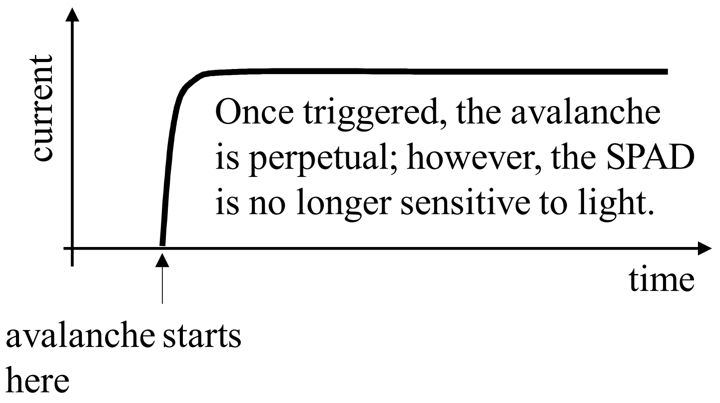


Structure of a *thin* SPAD. This structure is used in SPAD arrays.

Figures from Zappa et al. 2007

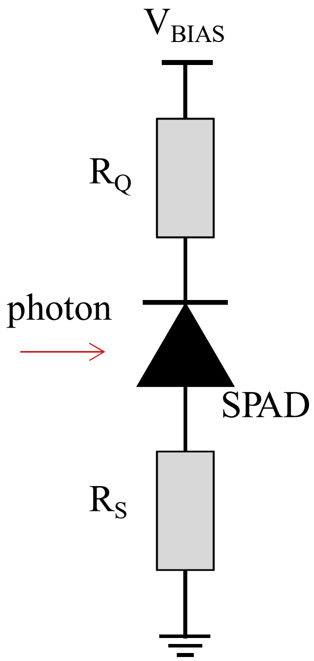
Operation of a SPAD



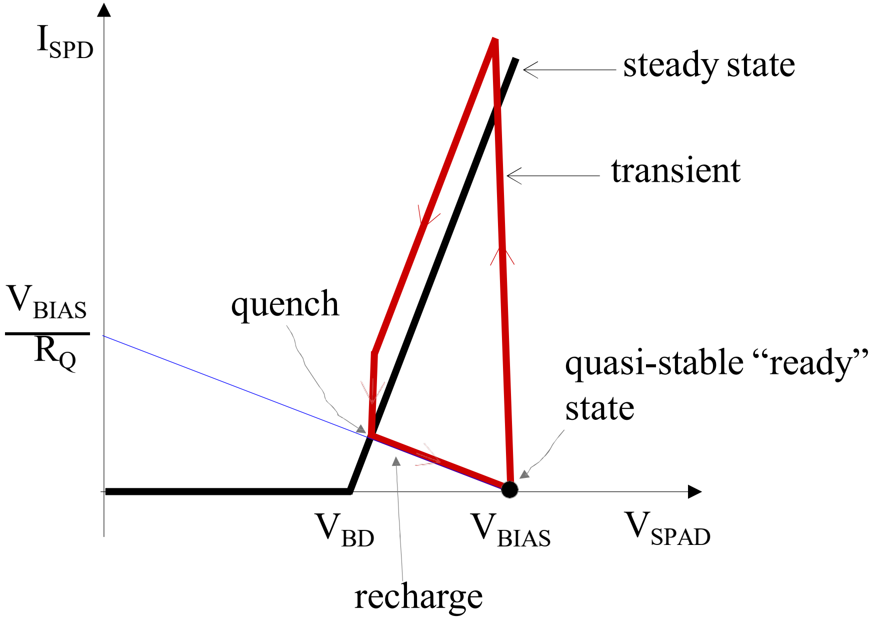


Without quenching, SPAD operates as a light switch.

Operation of a SPAD (passive quenching)

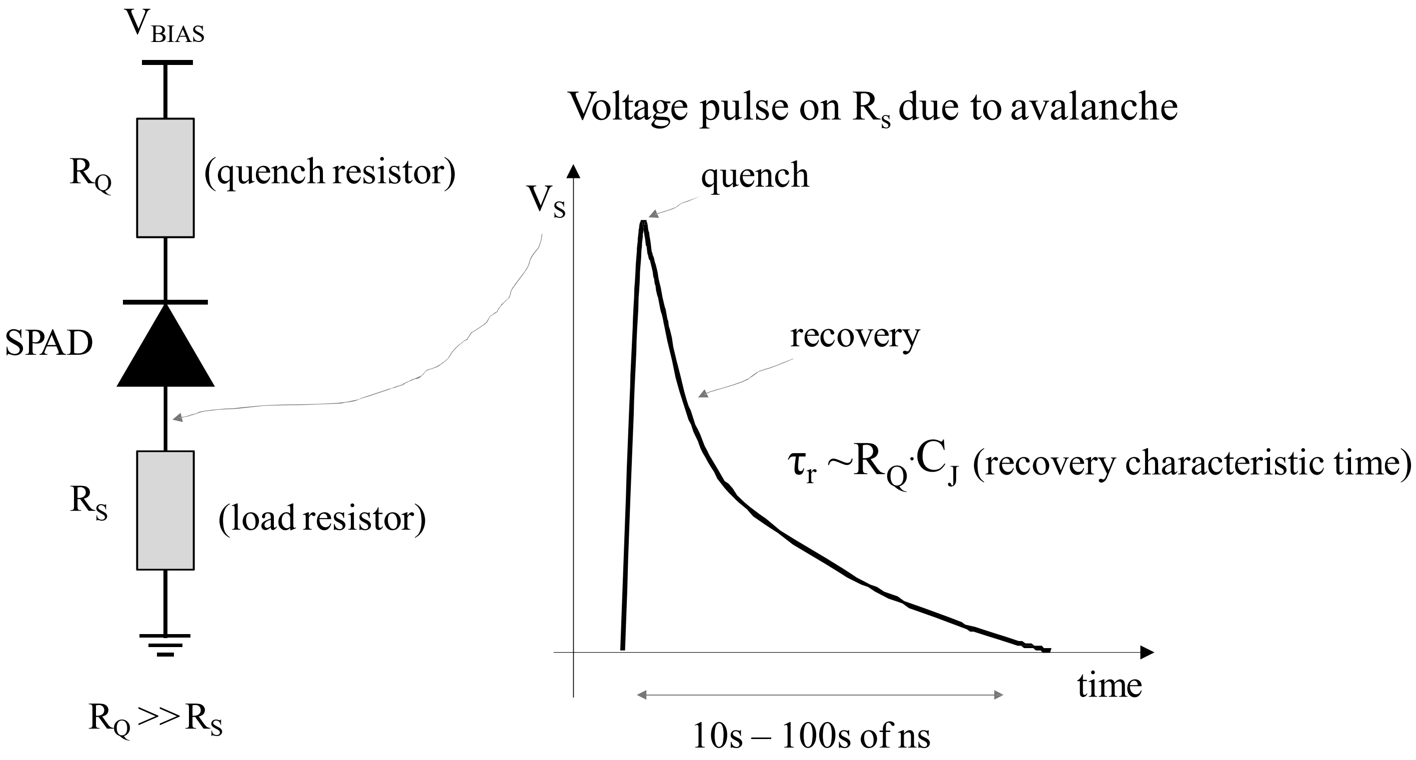


$R_Q >> R_S$

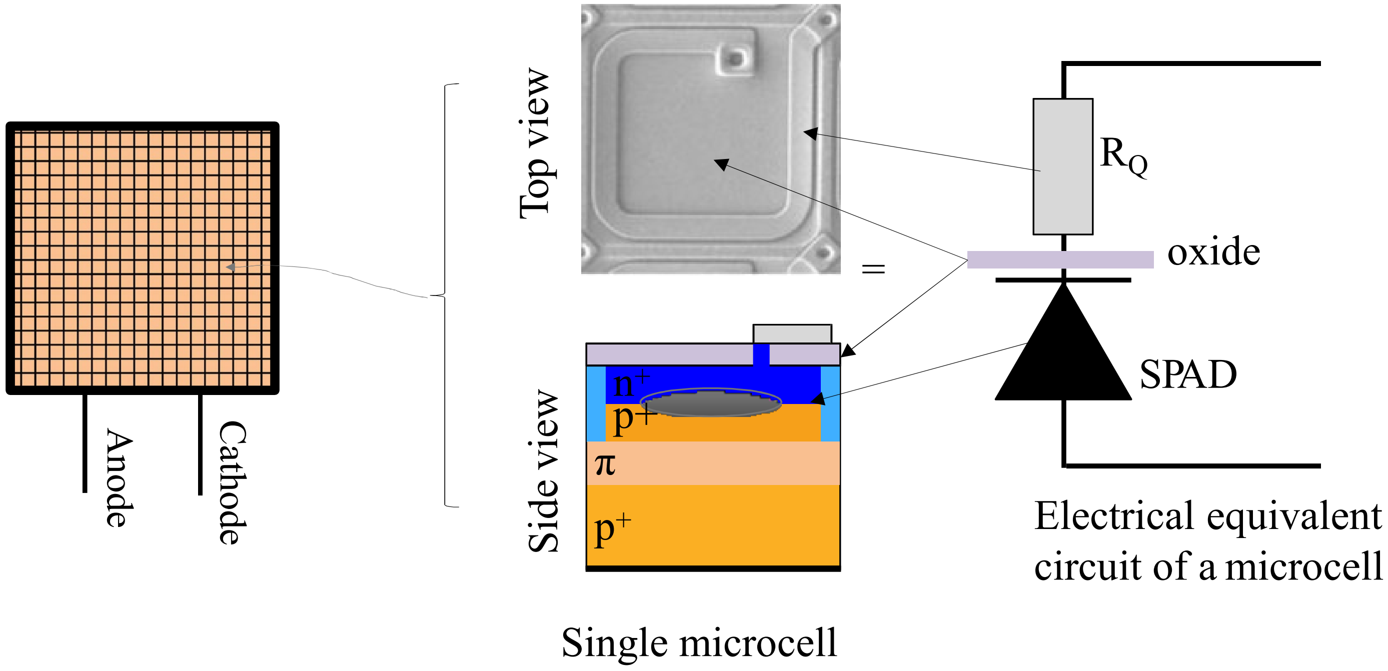


R_Q must be large enough to ensure quenching.

Operation of SPAD (passive quenching)

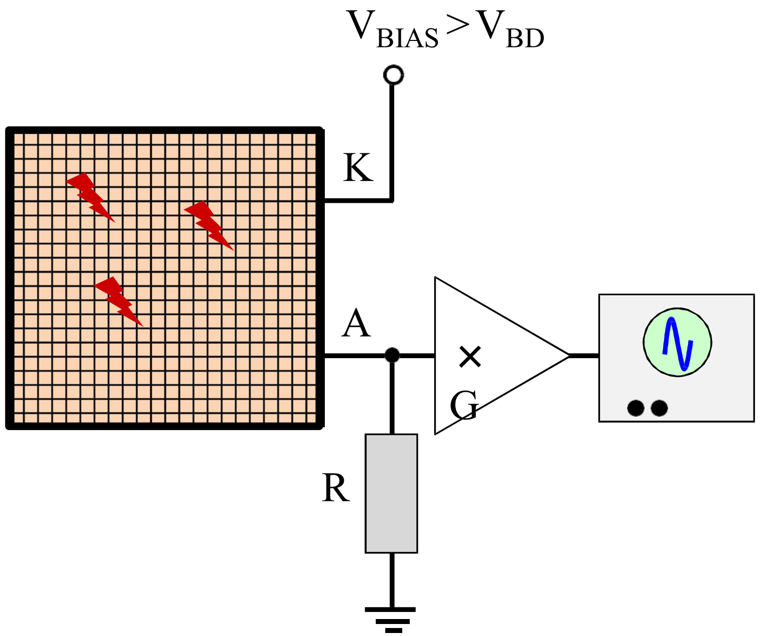


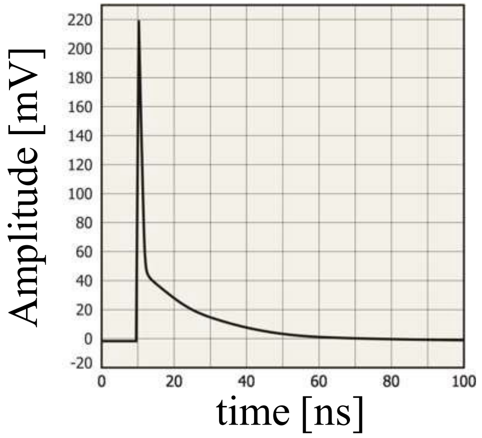
Si-PM Silicon photomultiplier: structure



Each microcell is a SPAD in series with a quench resistor. All microcells are connected in parallel. SiPM is **not** an imaging device because all microcells share a common current summing node.

Silicon photomultiplier: operation



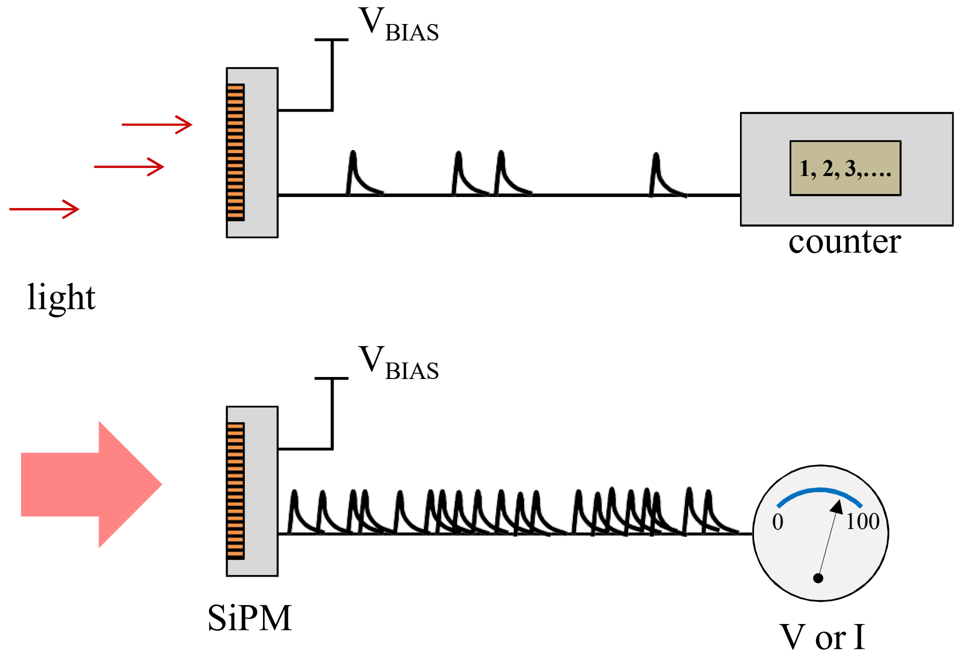


Example of single-photoelectron waveform (1 p.e.)

Gain = area under the curve in electrons

Overvoltage, $\Delta V = V_{BIAS} - V_{BD}$

Silicon photomultiplier: modes of operation



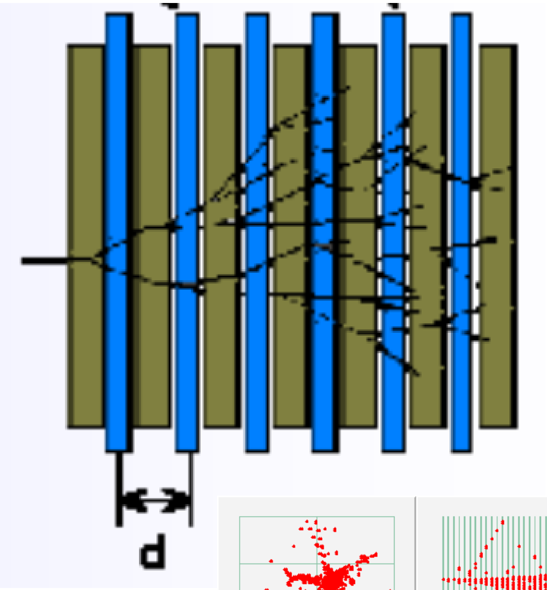
If the pulses are distinguishable, SiPM can be operated in a **photon counting** mode.

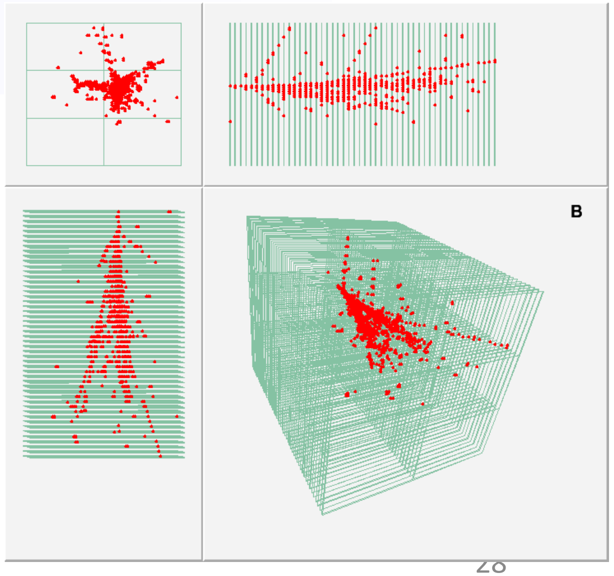
If the pulses overlap, the SiPM can be operated in an **analog mode**. The measured output is voltage or current.

- Applicazione rivelatori al silicio in calorimetria:
  - Calorimetri a campionamento

Sampling calorimeters

- Use different media
  - High density absorber
  - Interleaved with active readout devices
  - Most commonly used: sandwich structures ➔
  - But also: embedded fibres, ….
- Sampling fraction
  - $f_{sampl} = E_{visible} / E_{total\ deposited}$
- Advantages:
  - Cost, transverse and longitudinal segmentation
- Disadvantages:
  - Only part of shower seen, less precise

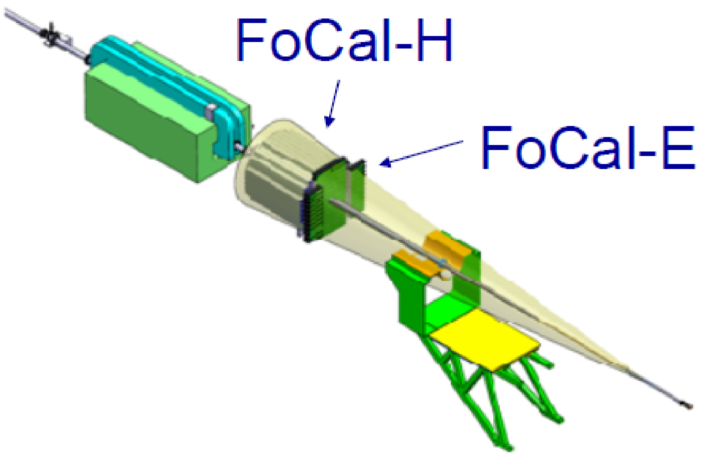




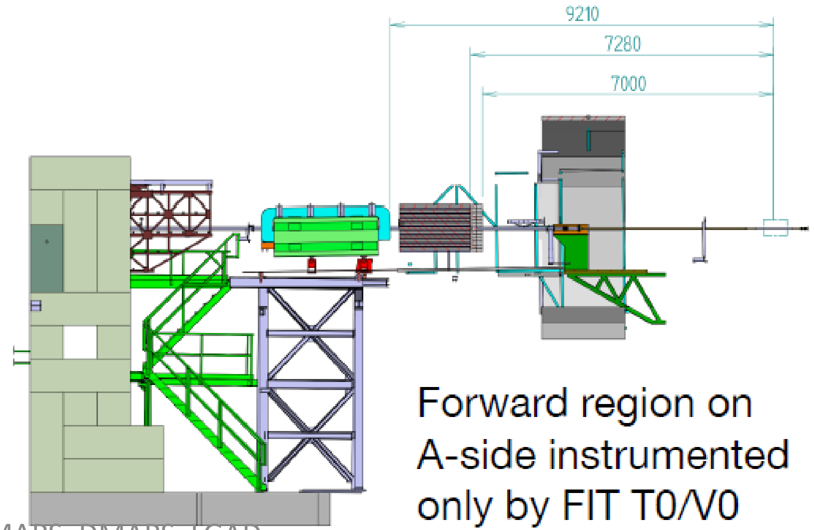
The FoCal proposal

$3.2 < \eta < 5.8$
(baseline design @ 7m)

FoCal-E: high-granularity Si-W sampling calorimeter for photons and π^0
FoCal-H: conventional Cu-Sc sampling calorimeter for photon isolation and jets

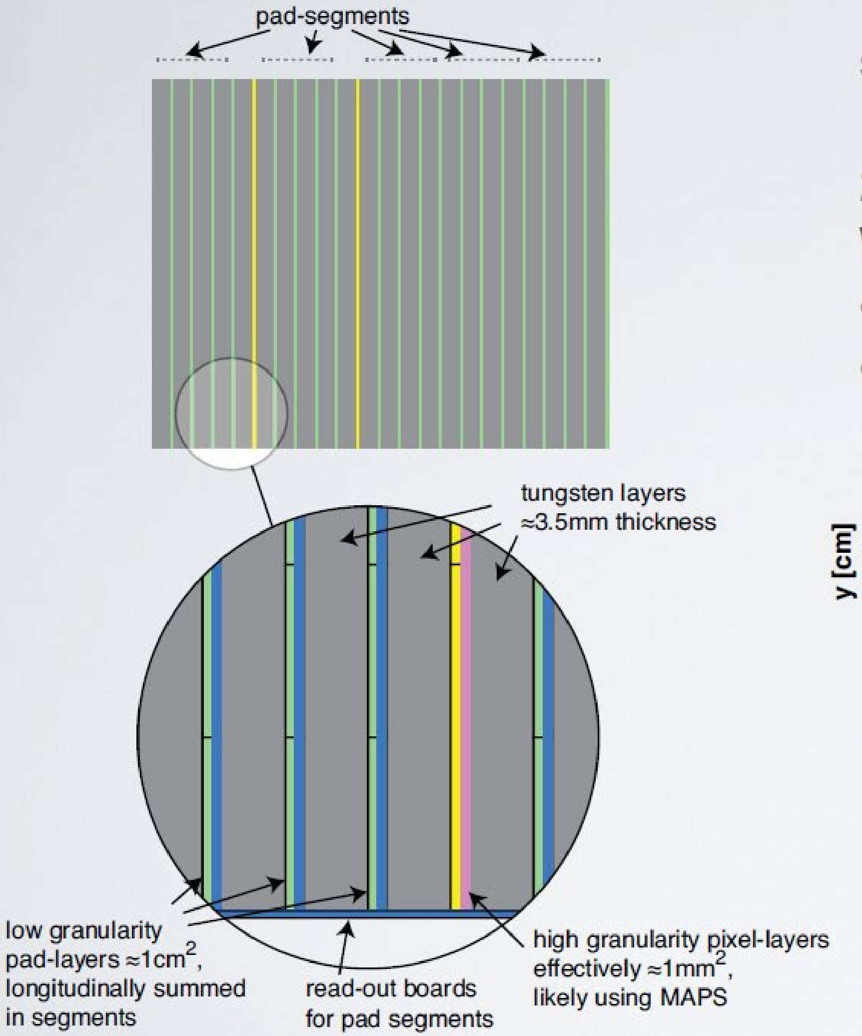


Observables:
- π^0 (and other neutral mesons)
- Isolated photons
- Jets (and di-jets)
- J/ψ (Υ) in UPC
- W, Z
- Event plane and centrality



Forward region on A-side instrumented only by FIT T0/V0

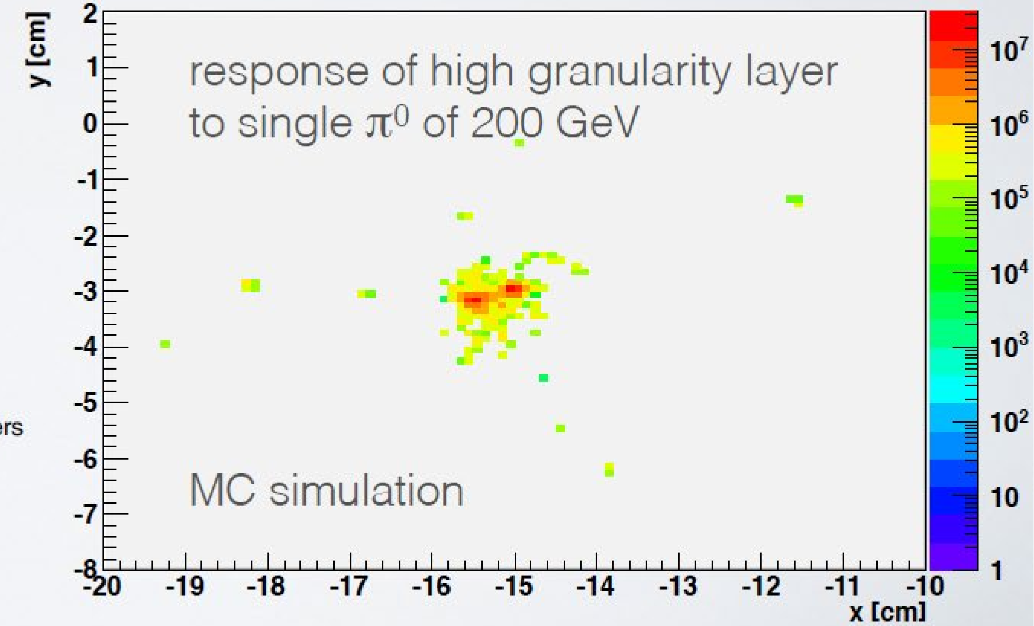
Strawman Design



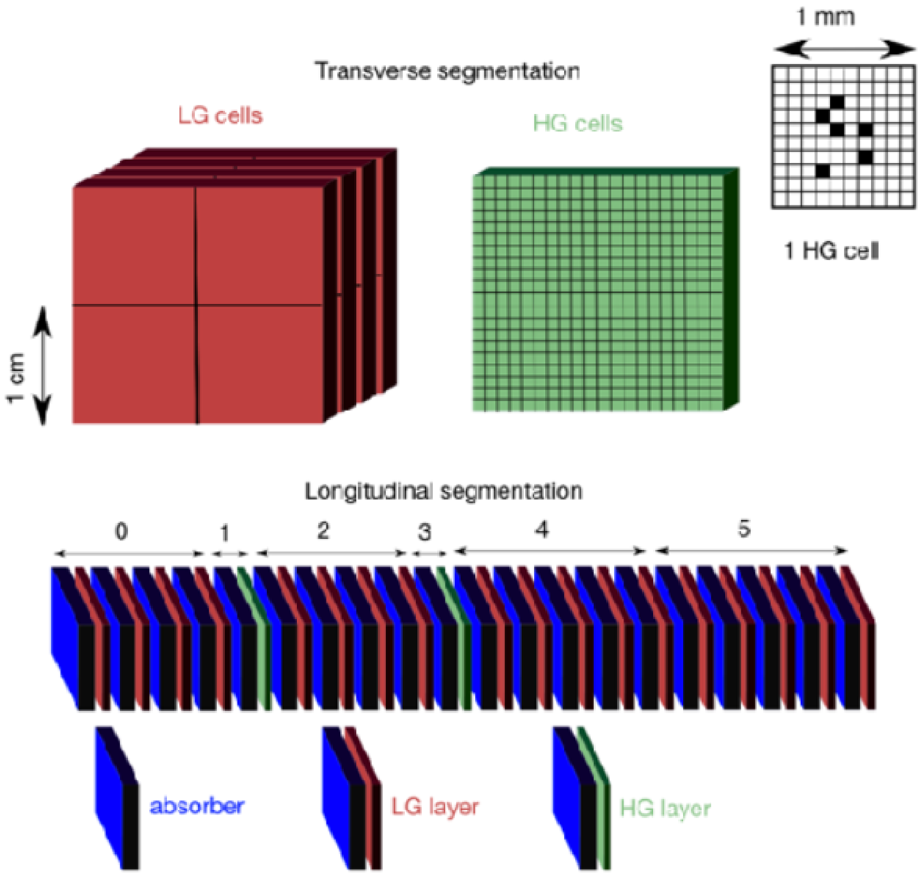
studied in performance simulations:

24 layers:
W (3.5mm ≈ 1 X_0) + Si-sensors (2 types)

- low granularity (≈ 1 cm^2), Si-pads
- high granularity (≈ 1 mm^2), obtained with pixels (e.g. CMOS-MAPS)



FoCal-E design



Studied in simulations 20 layers:
W(3.5 mm ≈ $1X_0$) + silicon sensors
Two types: Pads (LG) and Pixels (HG)

- Pad layers provide shower profile and total energy
- Pixel layers provide position resolution to resolve overlapping showers

Optimizations in progress:

- Number of pixel layers and location
- Number of pad layers
- Maximum separation between layers

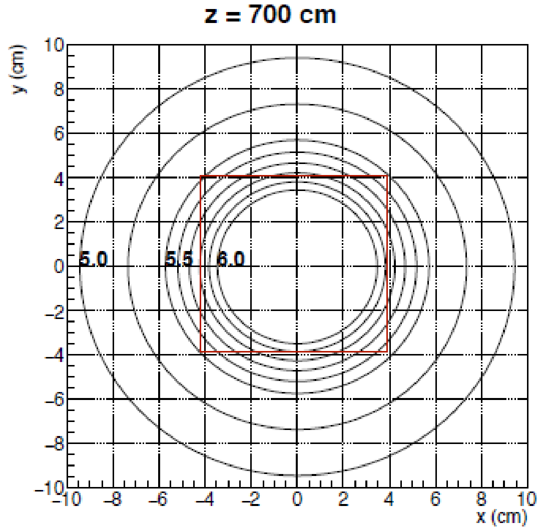
- Main challenge: Separate γ/π^0 at high energy
  - Two photon separation from π^0 decay (p_T=10 GeV, η=4.5) ~5mm
  - Requires small Molière radius and high granularity readout
  - Si-W calorimeter with effective granularity ≈ 1mm^2

Rapidity coverage and efficiency

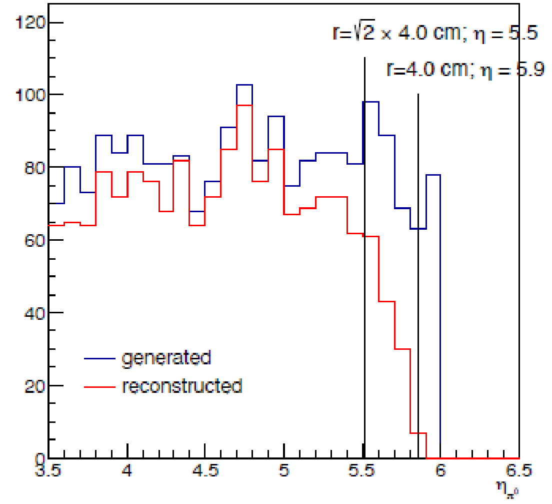
position z = 7m
beam pipe radius 3.5cm

8x8cm square around beam:
maximum rapidity 5.5-5.8

2-gamma distance gets small beyond η=5.5:
→ sharp drop at R_{min} plus effect of circle vs square

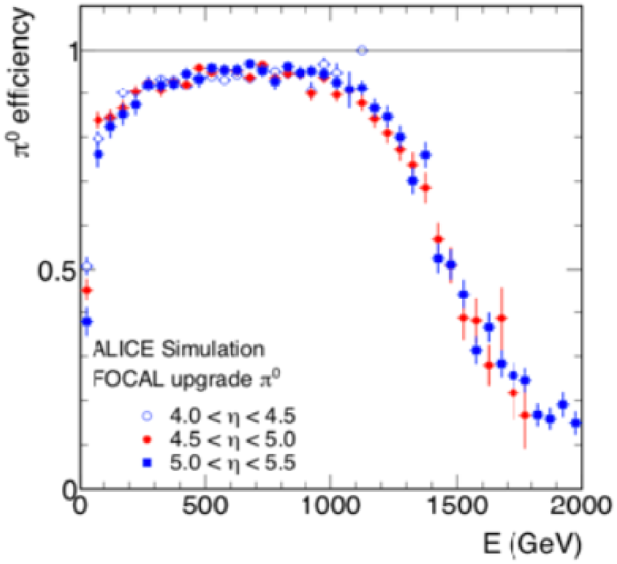


π^0 rapidity distribution



Very good π^0 efficiency up to η = 5.5
(falls off above p_T = 10 GeV due to 2-gamma distance)

Single π^0 efficiency vs E



Single π^0 efficiency vs p_T