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VIENNA CONFERENCE ON INSTRUMENTATION

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Optimisation of CMOS pixel sensors for high performance vertexing and tracking

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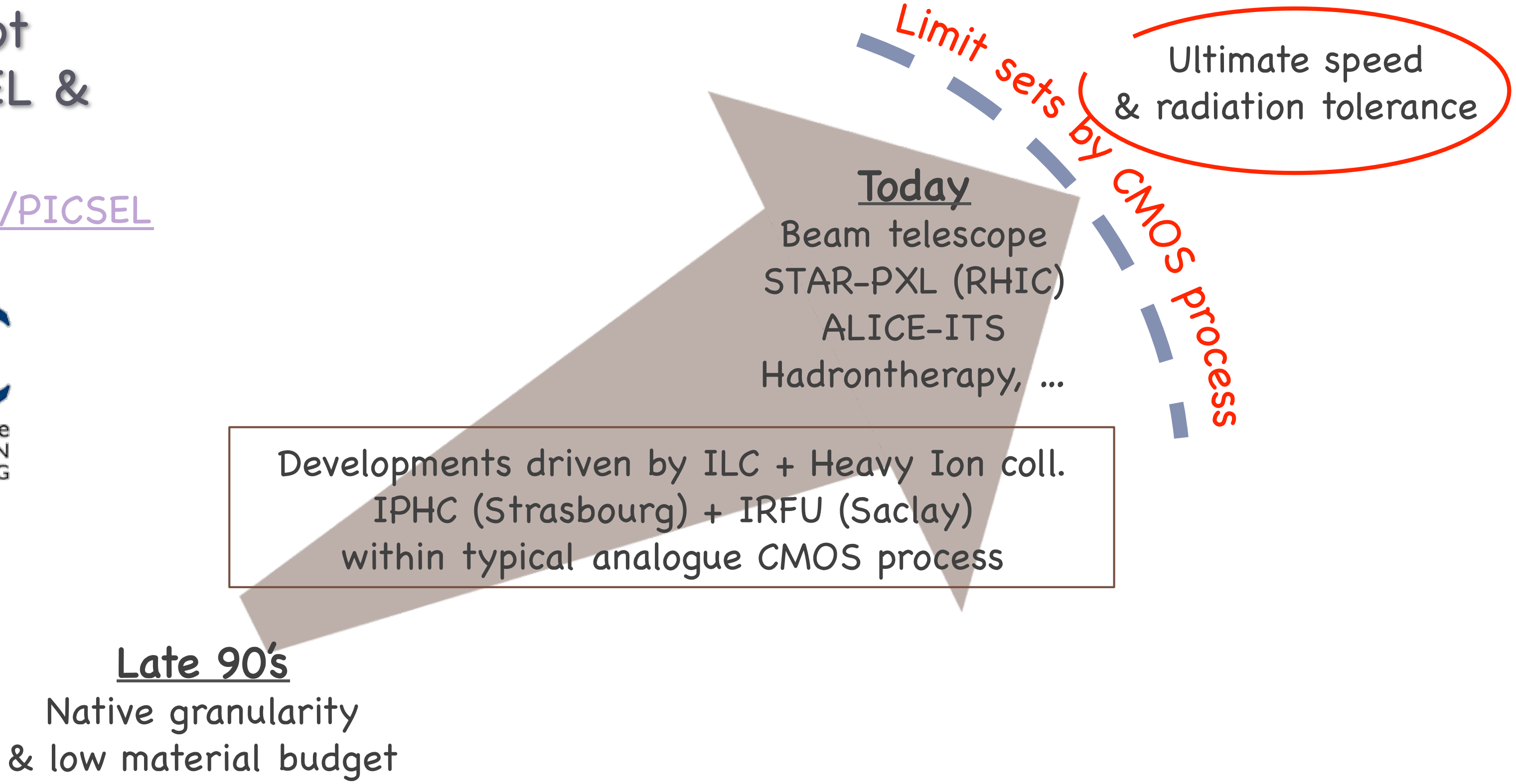


PICSEL GROUP

PHYSICS WITH INTEGRATED CMOS SENSORS AND ELECTRON MACHINES

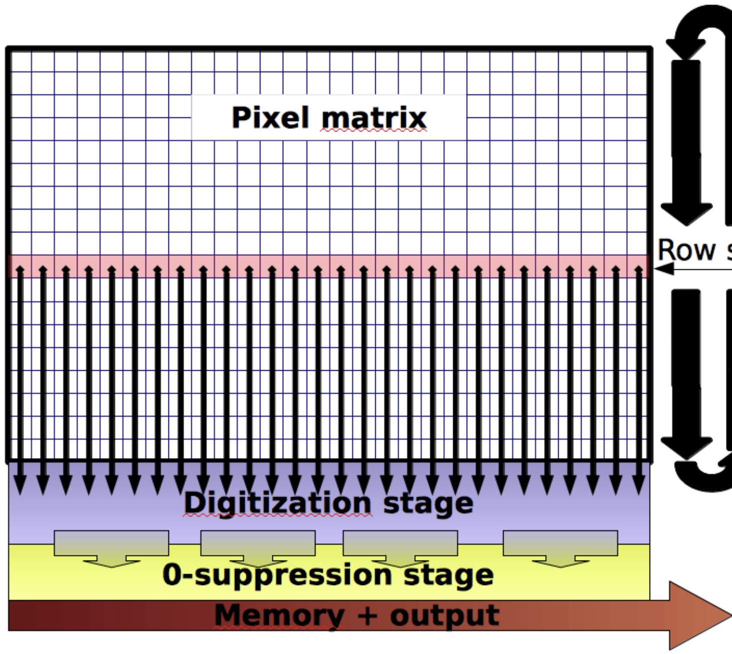
Outline

- Motivation for technology upgrade
- Prototypes in 0.18 µm technology
- Test beam characterisation
- Summary & outlooks to final detector

State-of-the-art

- CMOS Pixel Sensor (CPS)
  - Monolithic ⟺ full detector system on sensor
  - ➞ Optimisation required / 3 functionalities
    - Sensor: sensing node
    - FEE: analogue amplification
    - Acquisition board: digital treatment

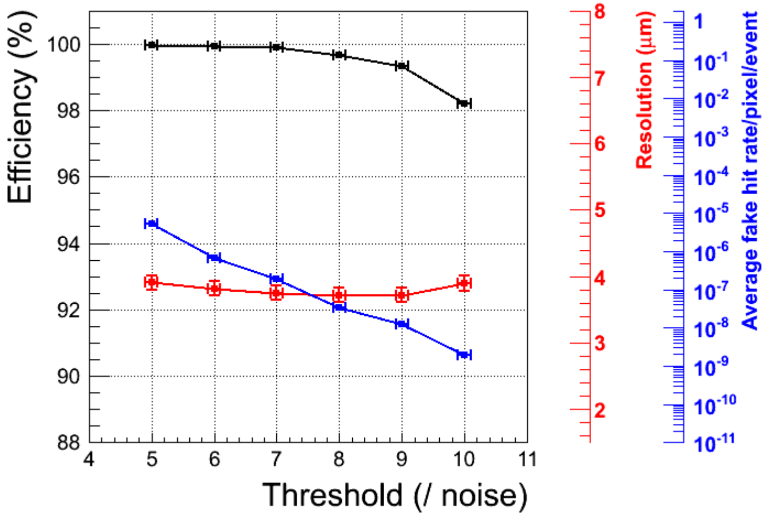
- MIMOSA architecture
  - In-pixel correlated double sampling (CDS)
    - Requires pre-amplification in pixel
  - Column parallel Rolling-shutter read-out
    - Integration time = matrix read-out time = # rows × row r.o. time
  - Limits power dissipation
    - Hence material budget
  - Allows high counting rate
    - Data compression ⬅ zero-suppression
  - Preserves main CMOS pixel sensor advantages
    - Granularity ⬅ small feature size
    - Small thickness ⬅ sensitive layer 10-20 µm



Current applications

- MIMOSA series: technology 0.35 μm OPTO process
  - Epitaxial layer resistivity ~400 Ω.cm
  - Row read-out time ~ 200 ns

- EUDET beam telescope
  - MIMOSA 26: 100 μs integration time
  - Operating since 2008
- STAR experiment PXL detector
  - ULTIMATE sensor (400 needed)
  - counting rate > 10^6 part/cm²/s
  - Power ≲ 150 mW/cm²
  - Ladder material budget: 0.37 % X_0
    - sensors thinned to 50 μm
  - Operating conditions @ 30°C
    - Total Ionising Dose = 150 kRad,
    - Fluece = 3.10^{12} n_{eq}/cm^2
  - Detector (1/3) commissioning in spring 201



Next frontier

	Single point res.	Integra. time	TID	Fluence n_{eq}/cm^2	Temp.
STAR - PXL	~ 5 µm	≲ 200 µs	150 kRad	3.10^{12}	30 °C
ALICE - ITS	~ 5µm	10-30 µs	700 kRad	1.10^{13}	30 °C
CBM - MVD	~ 5 µm	10-30 µs	≲ 10 MRad	1.10^{14}	≪0 °C
ILD - VXD	≲ 3 µm	≲ 10 µs	$\mathcal{O}$(100 kRad)	$\mathcal{O}(10^{11})$	≲ 30 °C
Super Flavor Factory	≲ 10 µm	≲ 2 µs	5 Mrad/year x safety f.	5.10^{12} /year x safety f.	≳ 10 °C

- **Accelerating the rolling-shutter read-out**
  - Less pixels for same surface → elongated pixel decreases #rows
  - Higher level of parallelisation → 2 to 4 rows read in parallel → 4 to 8 sub-arrays read in parallel
  - Faster row read-out with binary signal transmission → In-pixel digitisation (discri or 3-bits ADC)
- **Enhancing radiation tolerance**
  - Ionising dose → small feature size
  - Non-ionising fluence → high resistive sensing layer

➡ more complex µ-circuits

- **Preserve granularity & power budget**

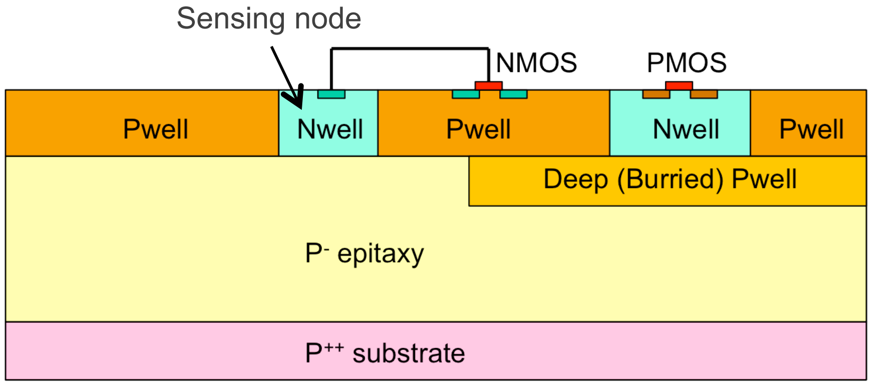
  → limits pixel size & parallelisation

➡ CMOS technology upgrade & architecture optimisation

Upgrading the technology

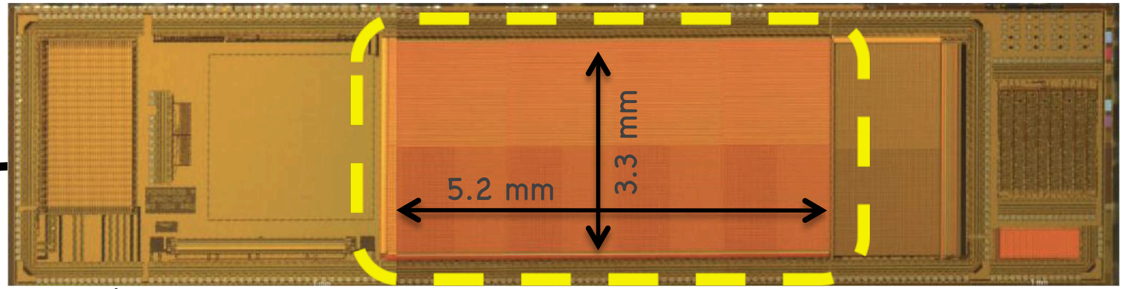
- Remark on CPS development
  - q-collection properties poorly predictable
    - Frequent prototyping desirable
  - ➡ Choice of cost-effective technologies

- TowerJazz® 0.18 μm process options
  - CMOS Image Sensor (CIS) process
  - Up to 6 metal layers
  - Metal-Insulator-Metal (MIM) capacitor
  - Quadruple well
    - both NMOS & PMOS type transistors possible in pixel
  - Pinned collection diode
    - Decouple collection & transmission node
  - Highly resistive epitaxial layer: 1-5 kΩ.cm
    - thickness 18 μm standard (could reach 40 μm)
  - Stitching



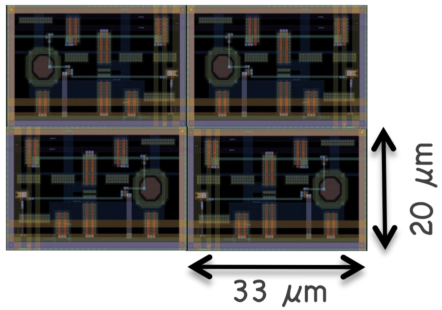
Prototypes in 0.18 μm technology

- **Common features**
  - Same footprint
  - 32 small matrices:
    - 16 × 16/32/64 pixels
    - Simple analogue readout (2MHz clock) → Integration time = 32 μs
    - Pixels without amplification & pixels with amplification
  - Matrix combined with column-level discriminator (IRFU design)
  - Matrix with in-pixel discriminator



- **MIMOSA 32**
  - Fabricated Q1/2012
  - Sensing element
    - Pixel pitch: 20 × 20/40/80 μm
    - Collection diode: various area & numbers
  - In-pixel amplification (for CDS)
    - NMOS and PMOS based
  - First results presented at RESMDD'12 (S.Senyukov) and NSS'12 (M.Winter)

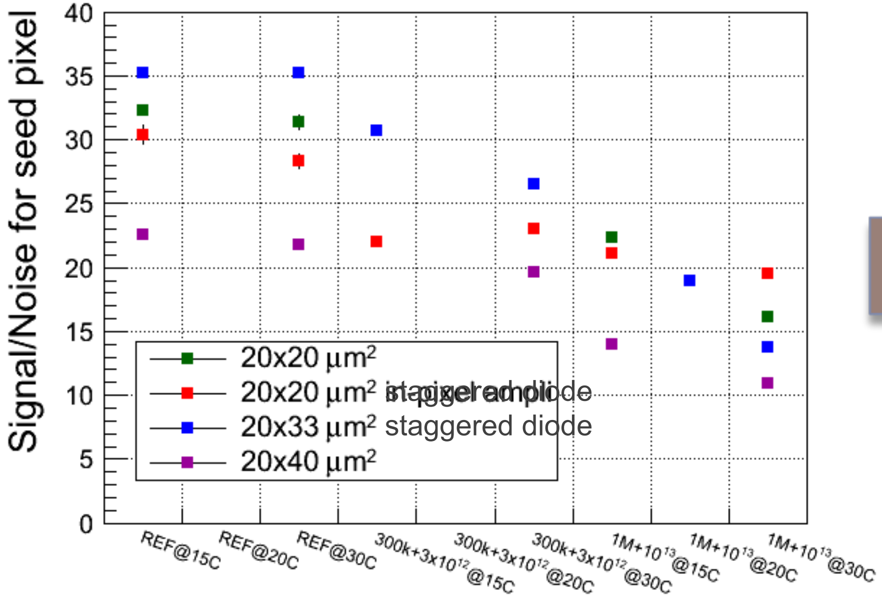
- **MIMOSA 32ter**
  - Fabricated in Q4/2012
  - Complements & corrections / Mimosa 32
    - Near ALICE-nominal pitch 20x33 μm^2

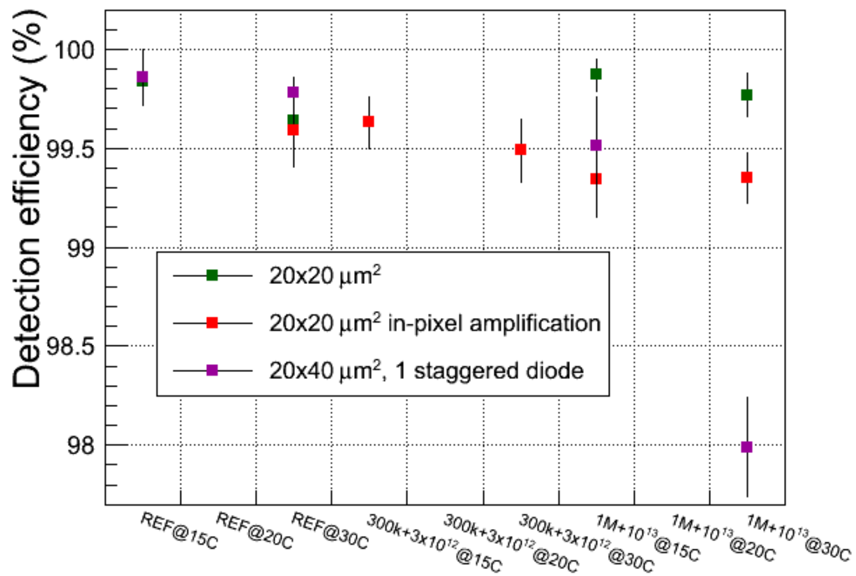


Evaluation method

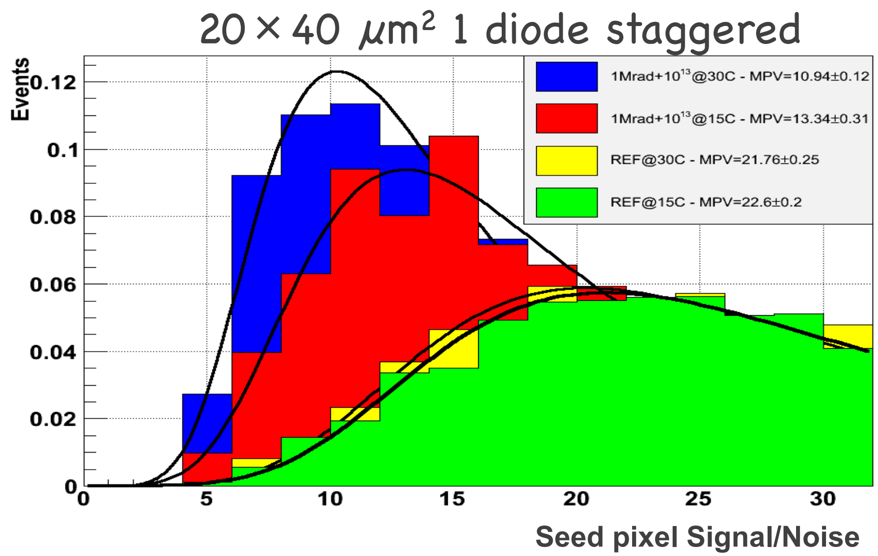
- **Irradiation**
  - Neutron fluence: 1/3/10 $.10^{12}$ n_{eq}/cm^2
  - Total ionising dose: 0.3 / 1 / 3 MRad
  - Combinations
    - TID = 0.3 MRad + fluence = 3.10^{12} n_{eq}/cm^2
    - TID = 1 MRad + fluence = 1.10^{13} n_{eq}/cm^2
- **Operating conditions**
  - Coolant temperatures: 15 / 20 / 30°C
    - Sensor typically +5°C warmer
- **Beam (2012 campaigns)**
  - CERN-SPS: π 20 to 120 GeV (mostly 80 & 120 GeV)
  - Beam telescope with either strip or pixel detectors
  - About 90 irradiation-temperature measurement points
    - 1500 to 3000 tracks per point

Basic feature: SNR



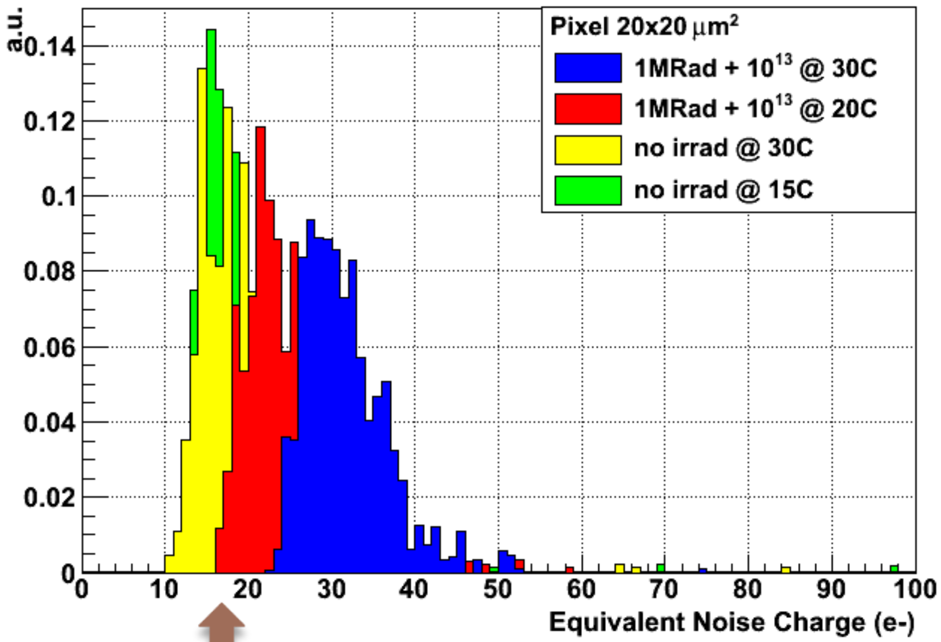


- Detection efficiency > 99 % for all conditions
  - Except 20x40 pixel at highest load and 30C (98 %)
- Validation of
  - Radiation tolerance
  - Elongated pixel

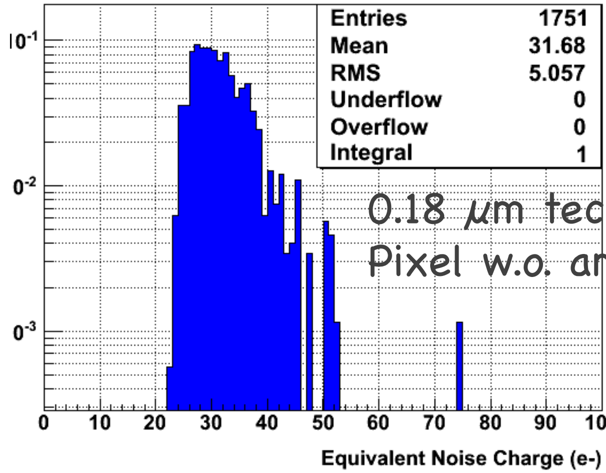


Basic feature: Noise

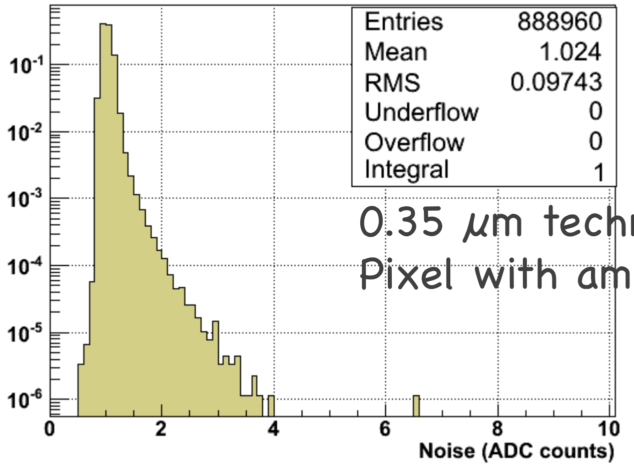
$20 \times 20\ \mu m^2$



Noise level of $20 \times 20\ \mu m^2$ with in-pixel amplification



0.18 μm techno.
Pixel w.o. ampli



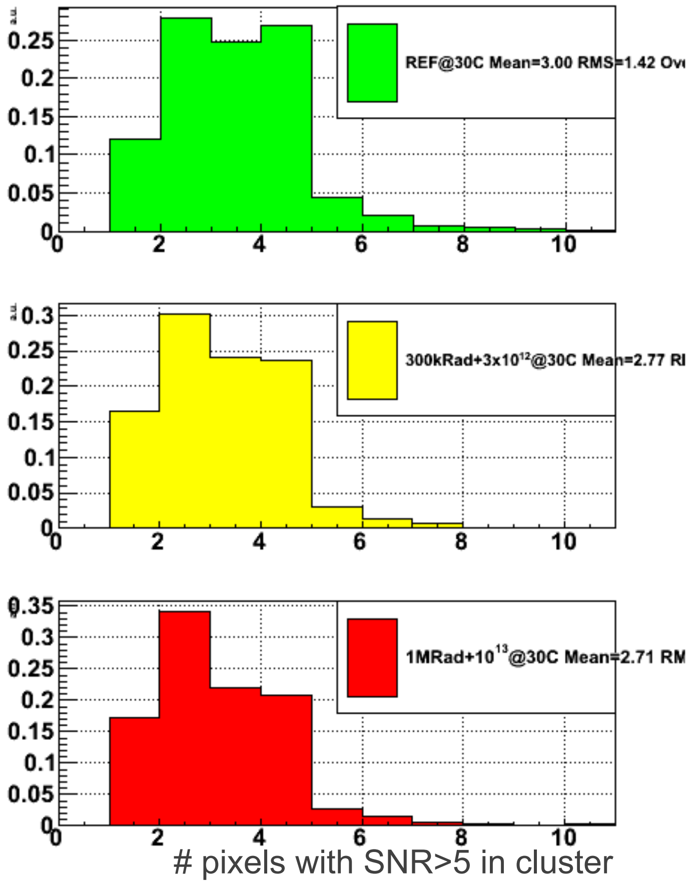
0.35 μm techno.
Pixel with ampli

- Noise increase with radiation level mainly explains SNR degradation
- Distribution of noise over pixels much larger

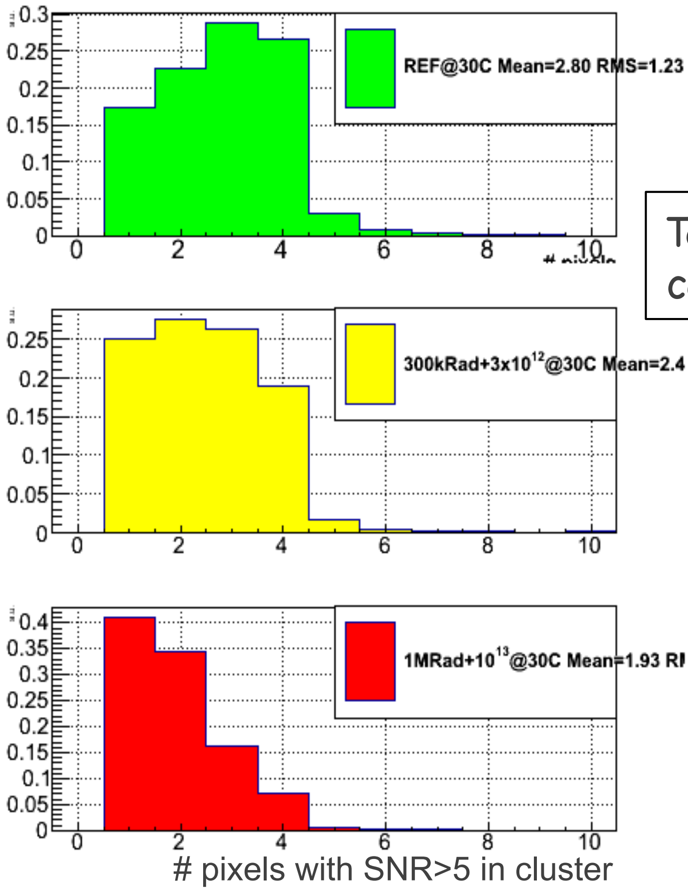
➡ non-yet optimised transistors geometry for 0.18 μm process

Basic feature: cluster size

$20 \times 20\ \mu m^2$ with amplification



$20 \times 33\ \mu m^2$ staggered diode

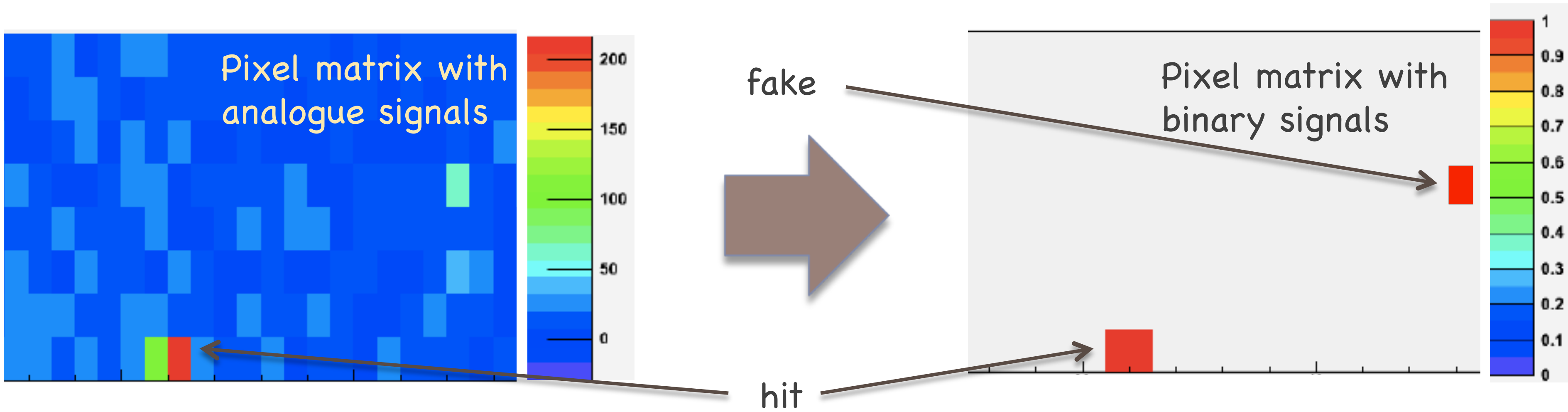


Total cluster charge collected within $\lesssim$ 5 pixels

- Decrease of cluster size (SNR>5) related to increase of noise with irradiation load
- Impact of high resistive sensitive layer assessed

Digitisation emulation

- Apply same threshold to all pixels
  - → binary output
  - Equivalent to zero-suppression in rolling-shutter read-out
- Cluster characteristics
  - Size = #pixels
  - Position = average (weight=1) over pixel positions
- Fake hits
  - Noise fluctuation of single pixels over threshold

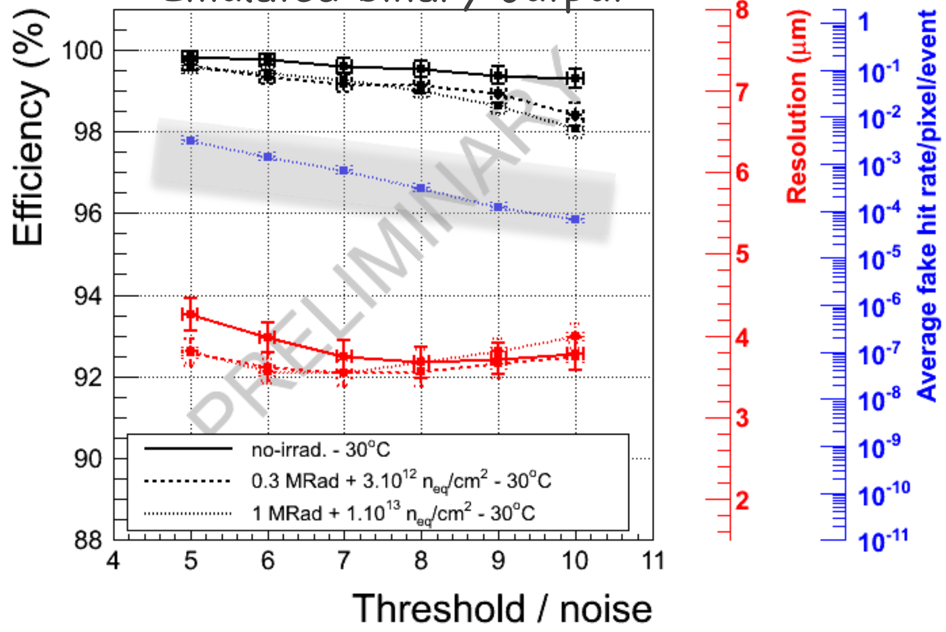


Square pixel digitisation

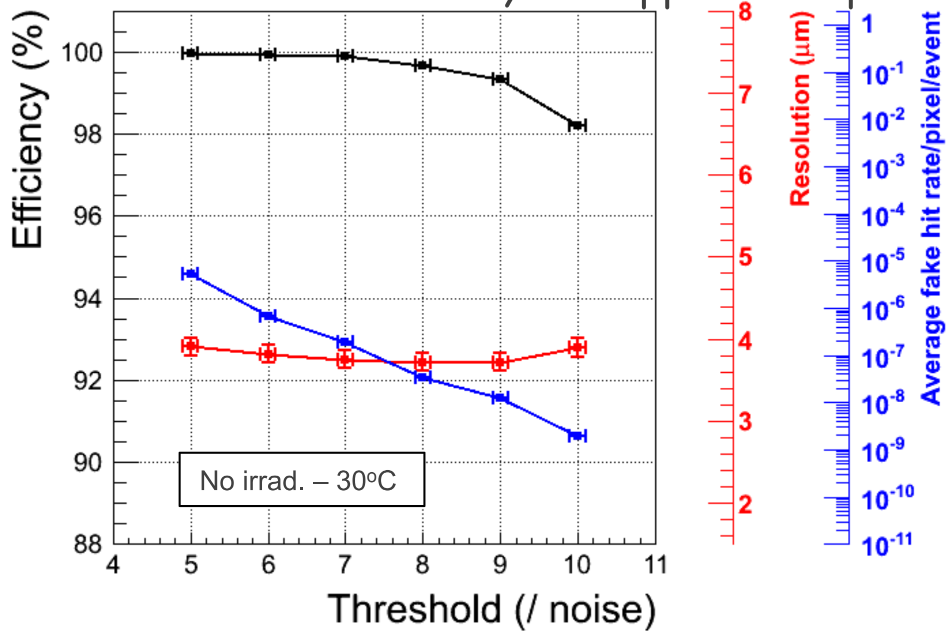
MIMOSA 32ter, 0.18 μm process, 18 μm >1 kΩ.cm epi.
pitch 20x20 μm^2

MIMOSA 28, 0.35 μm process, 20 μm <1 kΩ.cm epi.
pitch 20.7x20.7 μm^2, meas. binary+0-supress output

Emulated binary output



Measurements for binary+0-suppress output



- clear efficiency plateau near 100 % → potential operating thresholds = 5-7 x noise
- fake hit rate high → coherent with current noise performances
  - ➡ will get down with transistors adapted to 0.18 μm process
- single point resolution in expected range (3.5 μm)
  - detailed behaviour related to #pixels/cluster (average ranges from 3.5 ↘ 2)

Summary

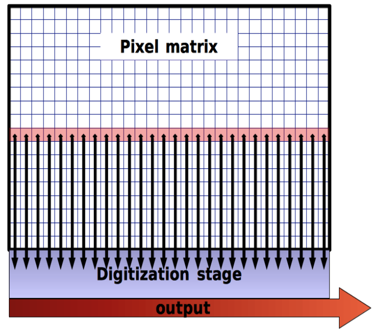
- Elements validated in the 0.18 μm process
  - Baseline sensing node & in-pixel preamplifier
  - Elongated pixel pitch (ALICE near-baseline: 20x33 μm^2)
  - Radiation tolerance with TID=1MRad & fluence 10^{13} n_{eq}/cm^2

☛ First successful step to go beyond state-of-the-art

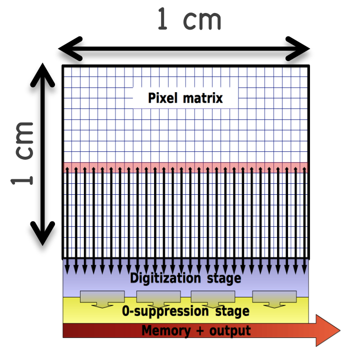
- Further steps
  - Optimisation: noise (transistors), q-collection (diode)
  - Complete read-out architectures on full-scale sensors

Outlooks…ALICE-ITS

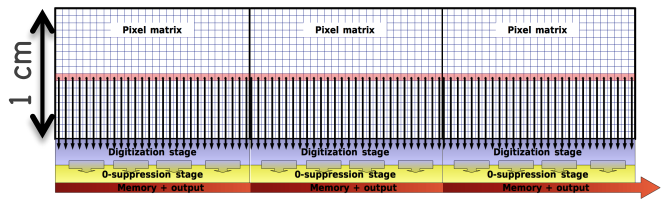
- **Q1/2013**
  - MIMOSA-32/34: further optimisation of q-collection, noise, ampli.
  - MIMOSA-22-THR: pixel matrix + col-level discriminators
    - single and double rows read-out
  - SUZE-02: zero-suppression circuitry
  - AROM-0: matrix with in-pixel discriminator
  - MIMADC: matrix with in-pixel 3-bits ADC



- **Full Scale Basic Blocs (FSBB)**
  - = complete functionality over ~1 cm^2
  - Q4/2013: col-level discri. approach (→MISTRAL)
  - Q4/2015: in-pixel discri. approach (→ASTRAL)

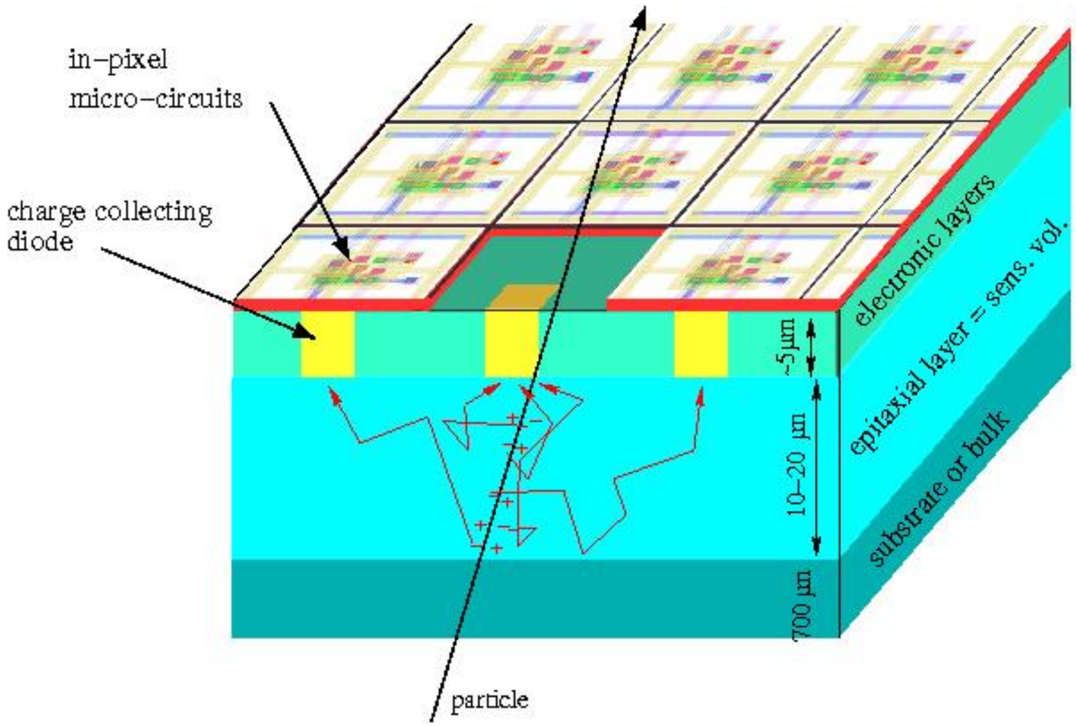


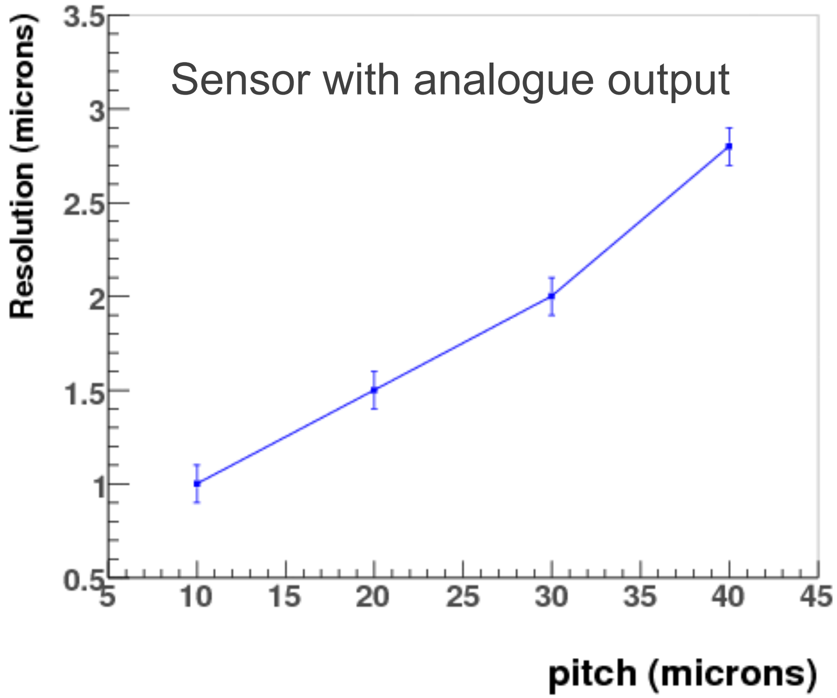
- **Final sensors**
  - Q4/2014: MISTRAL 22x33 μm2 pitch
    with 30 μs integration time (15 μs possible)
  - Q4/2016: ASTRAL 15 μs integration time (2 μs possible)
  - 2015(?): AIDA large area (4 × 6 cm2) beam telescope sensor



ADDITIONAL SLIDES

Basic principle of CPS

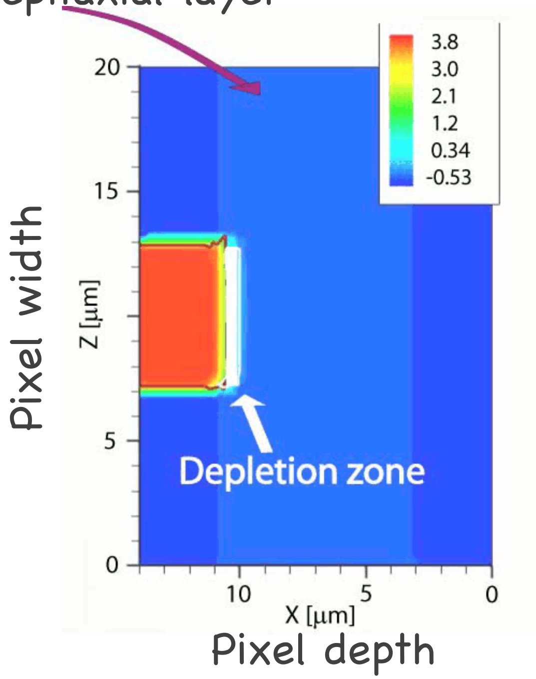




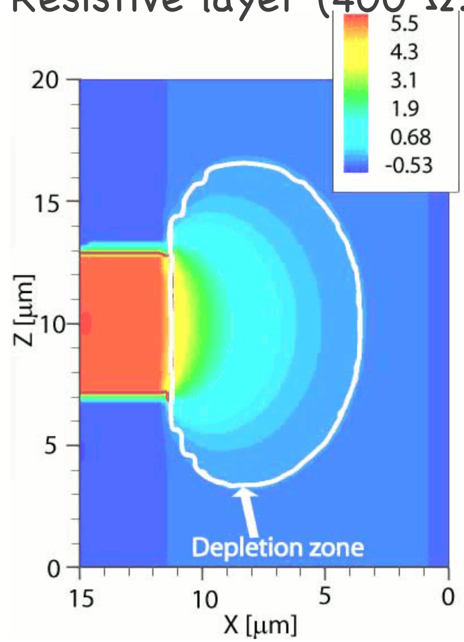
High resistive layer and depletion

TCAD simulations for 0.35 μm process

Standard epitaxial layer

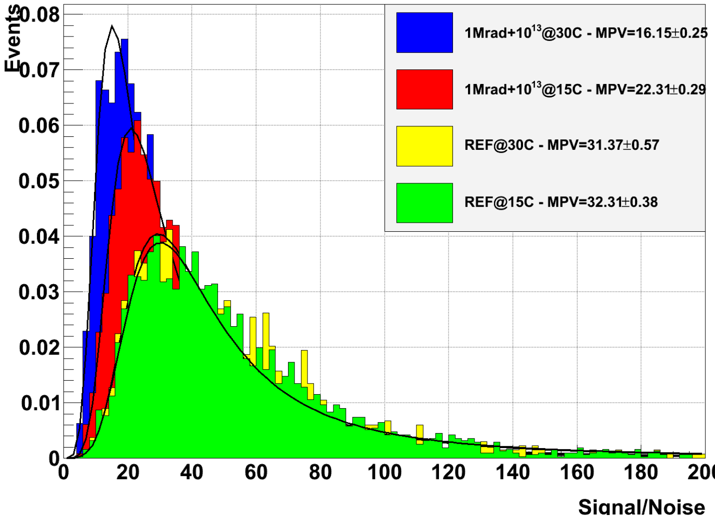


High Resistive layer (400 Ω.cm)

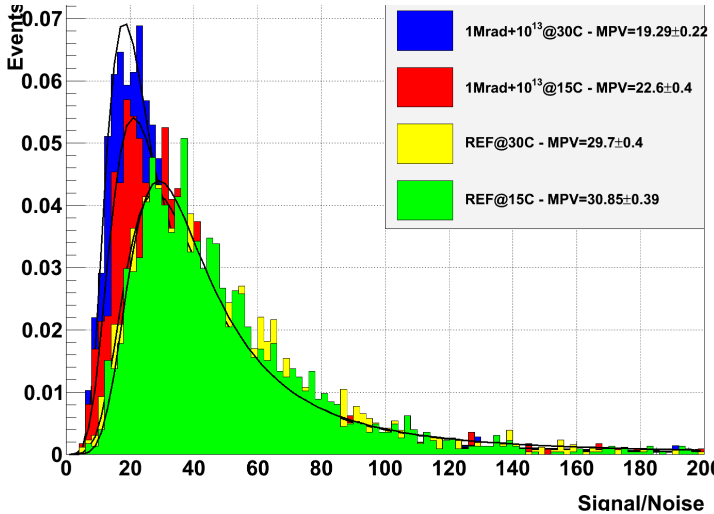


Seed pixel SNR distributions

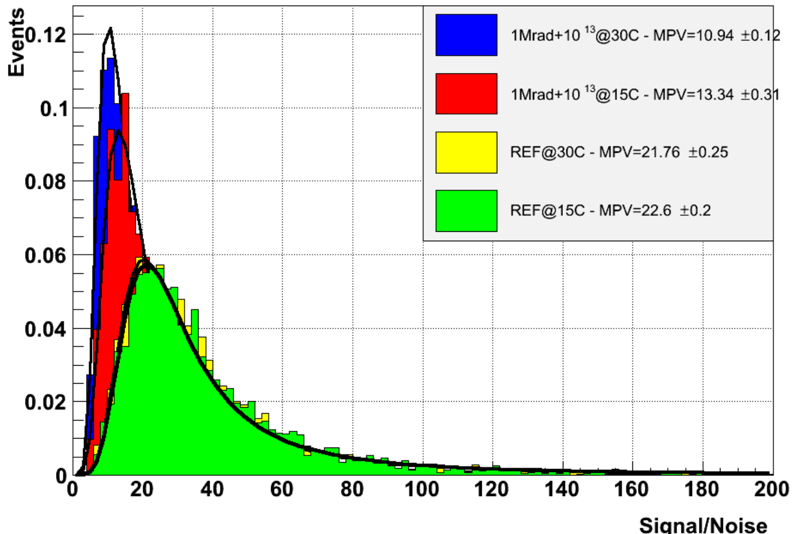
20 × 20 μm^2



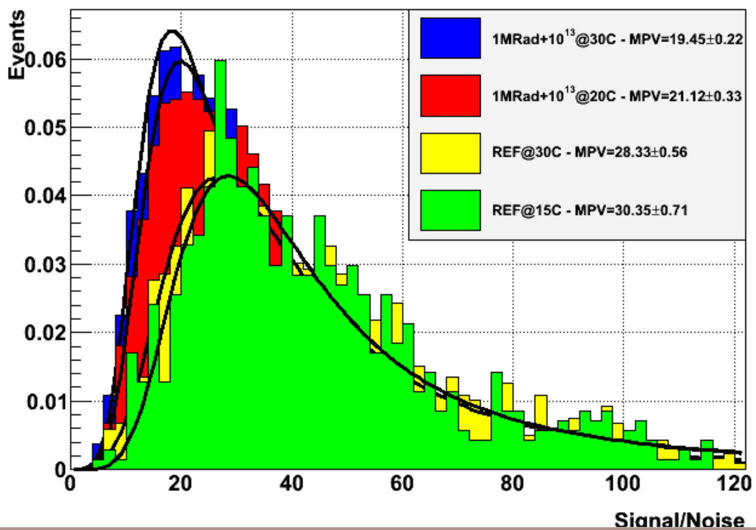
20 × 20 μm^2 with in-pixel PMOS transistor



20 × 40 μm^2 1 diode staggered



20 × 20 μm^2 with in-pixel amplification



Number of significant pixels / cluster