4th Beam Telescopes and Test Beams Workshop – Feb. 3 – 5 2016

DAΦNE Beam Test Facility and Performances Assessment of Large Pixels CMOS Sensors

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PICSEL GROUP
PHYSICS WITH INTEGRATED CMOS SENSORS AND ELECTRON MACHINES

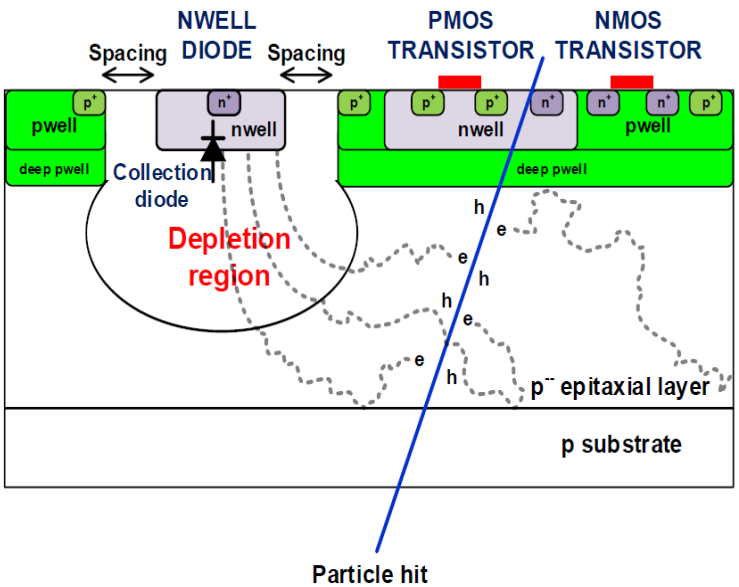
Outline

- **Introduction to CMOS Pixel Sensors (CPS)**
- **The DAΦNE Beam Test Facility (BTF)**
- **Larger Pixels Performances Assessment @ DAΦNE BTF: May – June 2015**
  - Motivations
  - Telescope & DUT
  - Experimental Set-up
  - Data Analysis Results
  - Simulation for interpretation
- **Summary and Outlook**

Introduction to CPS

Introduction to CPS

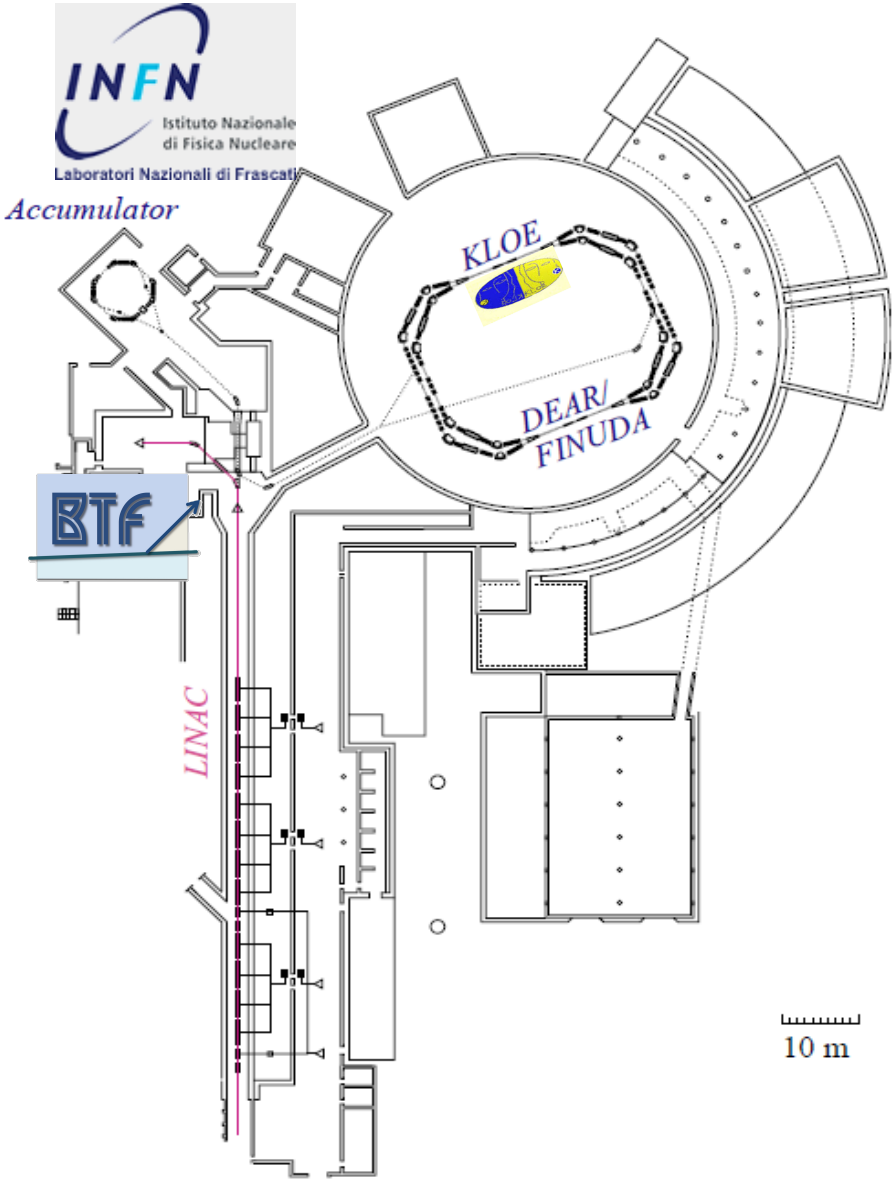
- **Assets of CPS**
  - Signal processing integrated on sensor substrate
    ⇒ downstream electronics & syst. Integration
  - Standard fabrication process
    ⇒ low cost & easy prototyping, many vendors, …
  - High granularity ⇒ excellent spatial resolution (O(μm))
  - Signal generated in thin (10-40μm) epi-layer
    ⇒ usual thinning up to 50 μm total thickness



- **Several applications**
  - High resolution Telescope: EUDET-BT @ DESY (few GeV e^- beam) (Mimosa26 sensor)
    - 6 copies around the globe: DESY, CERN-SPS, SLAC (USA), TRIUMF (Canada), ...
  - Hadron physics experiment: STAR-PXL @ RHIC (Mimosa28 sensor)
  - Hadron-therapy database: FIRST (Mimosa26 sensor)
  - Large area & high resolution Telescope: AIDA-BT (SALAT) (Mimosa28 sensor)
  - Upgraded ALICE Inner Tracking System: 7 layers with full CPS (ongoing R&D)
  - Machine Backgrounds @ Belle II (Beast2): Double-sided ladders (6 Mimosa26 sensors/side)

The DAΦNE BTF

DAΦNE BTF



- **DAΦNE LINAC main parameters**
  - Energy range: (50 – 800)/(50 - 550) MeV e^-/e^+
  - Energy spread @ 510 MeV: 1%/2% e^-/e^+
  - Macro bunch duration (Δt): 10 ns
  - Repetition rate: 10 – 50 Hz
  - Max. current: 500 (100) mA/bunch for e^- (e^+)
  - Min. current: ~1 mA/bunch

    $\Rightarrow$ ~6×10^7 $e^\pm$

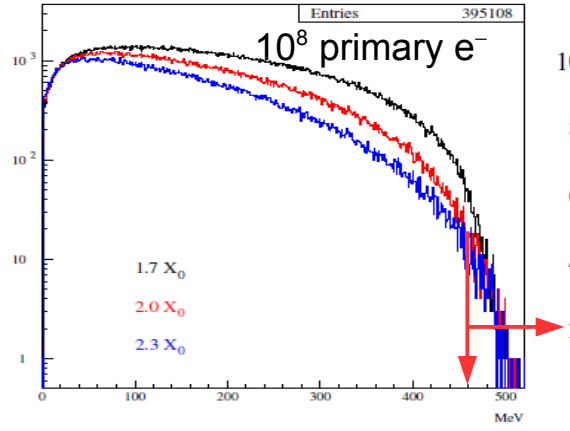
    $\Rightarrow$ Need strong reduction of number of primaries to reach the few particles range

- **Beam Test Facility (BTF)**
  - Transfer line optimized for producing e^-/e^+ beams in wide range of multiplicities, down to single-$e^\pm$
  - Operating since Nov. 2003

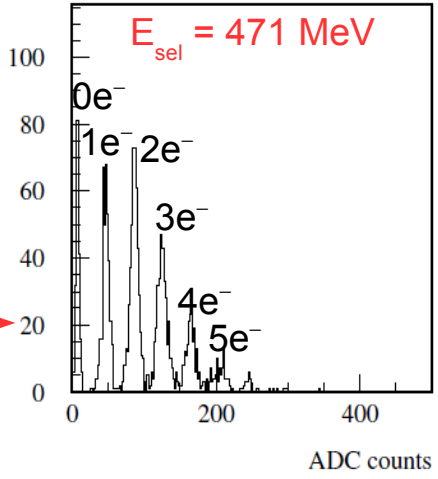
BTF: From 10^7 to few $e^{\pm}$

- **Starting from ~10^8 $e^{\pm}$ from LINAC, two modes of operation**
  - High intensity: primary beam directly driven to BTF experimental hall, 250 – 800 MeV, tuned with collimators
  - Single-$e^{\pm}$/bunch (Poisson distributed): created by intersecting beam with Cu target ⇒ select energy and collimating
  - Intermediate intensity ($10^5 e^{\pm}$/bunch): hit target with low-E beam

GEANT Simulation

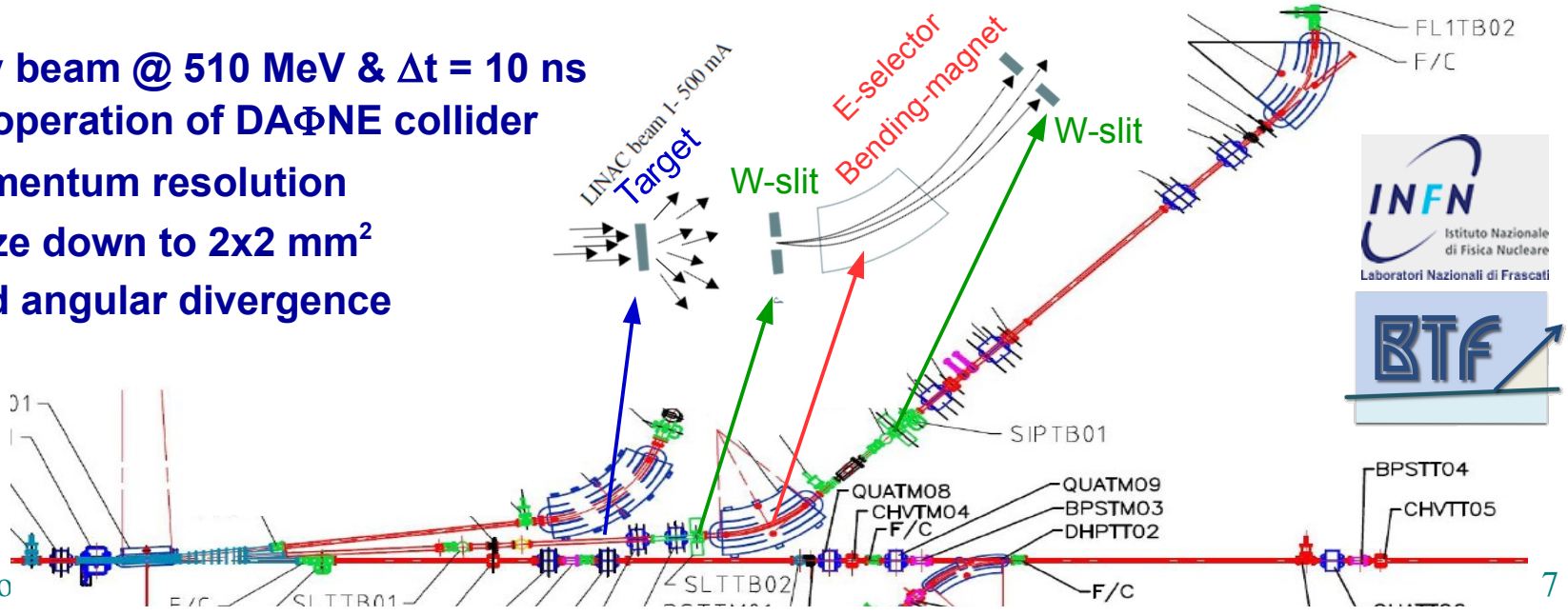


Calibrated calorimeter



- **Primary beam @ 510 MeV & Δt = 10 ns during operation of DAΦNE collider**
- **1% momentum resolution**
- **Spot size down to 2x2 mm²**
- **~2 mrad angular divergence**

BTF experimental hall

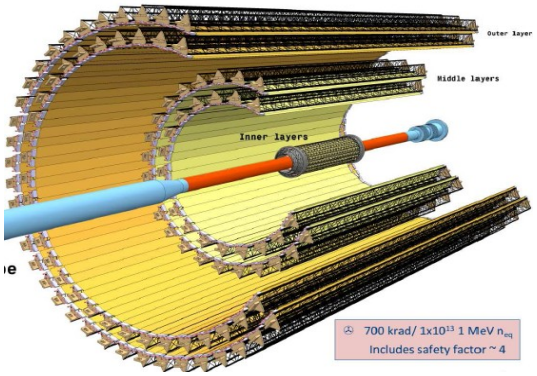


Beam Test @ BTF

Beam Test @ BTF: Motivation

- **Upgraded ITS entirely based on CPS**
  - **Present detector:** 2xHPD/2xDrift-Si/2xSi-strips
  - **Future detector:** 7-layers with CPS (25-30k chips)

    ⇒ 1st large tracker (~ 10 m^2) using CPS
  - ITS-TDR approved on March 2014 (Pub. In J.Phys. G41 (2014) 087002)

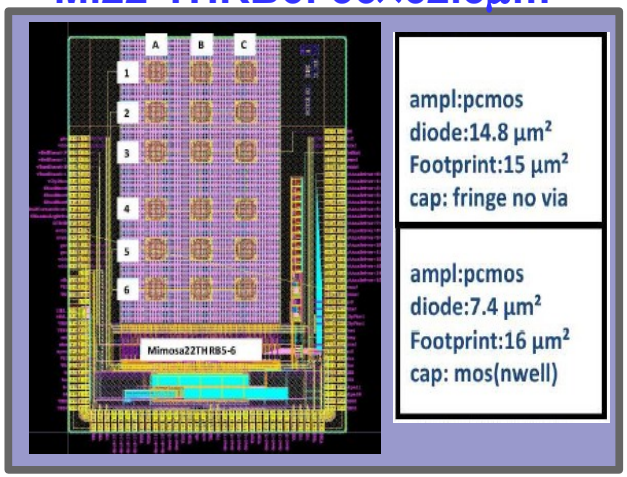


- **New ALICE-ITS requirements**

	σ_{sp}	$t_{r.o.}$	Dose	Fluency	T_{op}	Power	Active area
STAR-PXL	$< 4\ \mu m$	$< 200\ \mu s$	150 kRad	$3 \cdot 10^{12}$ n_{eq}/cm^2	30-35°C	160 mW/cm^2	0.15 m^2
ITS-in	$\lesssim 5\ \mu m$	$\lesssim 30\ \mu s$	**2.7 MRad**	**$1.7 \cdot 10^{13}$ n_{eq}/cm^2**	30°C	< 300 mW/cm^2	0.17 m^2
ITS-out	$\lesssim 10\ \mu m$	$\lesssim 30\ \mu s$	100 kRad	$1 \cdot 10^{12}$ n_{eq}/cm^2	30°C	**< 100 mW/cm^2**	**~ 10 m^2**

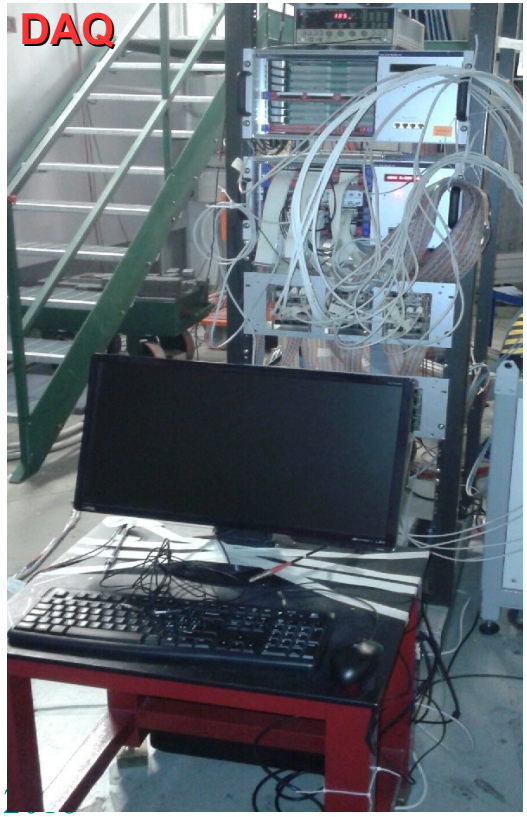
- **Large-pixel prototype (MIMOSA-22THRb)**
  - Two slightly different large pixels
    - 36x62.5 μm^2 and 39x50.8 μm^2 (staggered layout)
  - Pads over pixel array (3ML used for in-pixel circuitry)
  - Double-row r.o. with no-sparsification ($t_{r.o.}$ ~ 5 μs)
  - Fabricated with 18 μm thick high-ρ epi-layer
  - **BUT:** only < 10 mm^2, 4k pixels & no sparsification
  - **Validation of large pixel detection performances**

Mi22-THRB6: 36×62.5μm^2

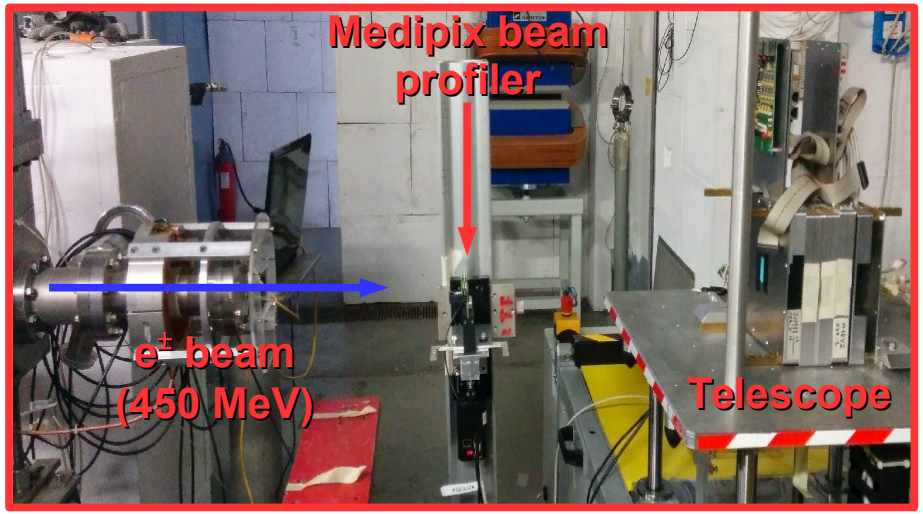


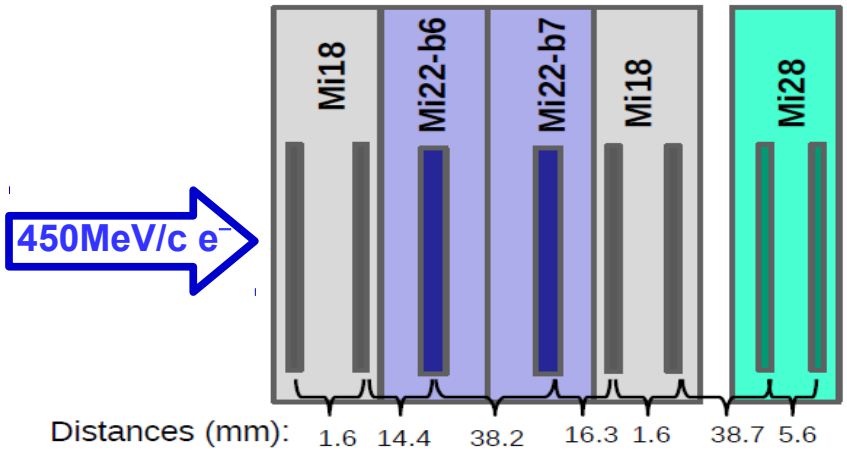
Beam Test @ BTF: Experimental Set-up

- **Beam test period**
  - May 25th - June 1st 2015
- **Partnership**
  - Strasbourg,
  - Frascati,
  - Catania,
  - Torino



Beam Test @ BTF: Experimental Set-up

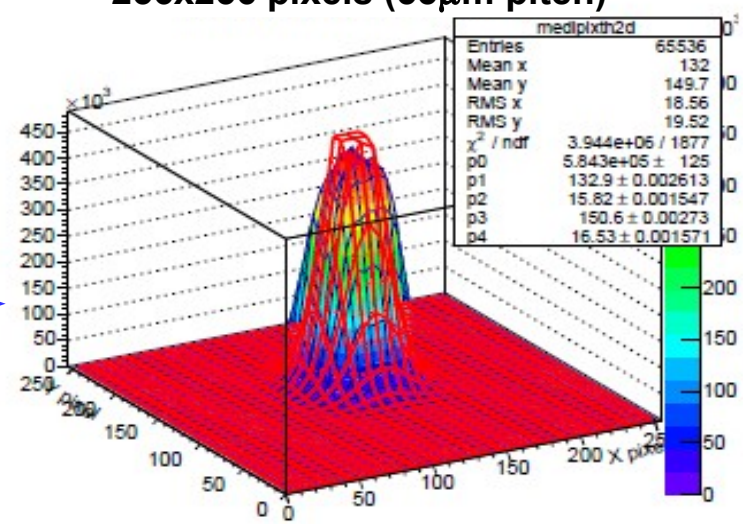




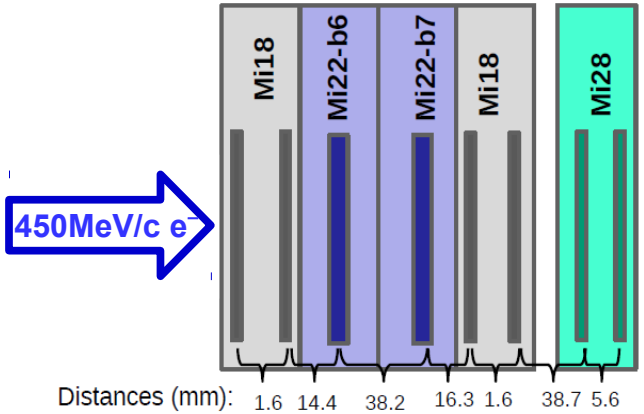
- **Running conditions**
  - Beam energy (E_{sel}): 450 MeV
    ⇒ 10 – 20 e^-/bunch
  - Average spills rate: 25 Hz
  - Δt = 10 ns ⇒ Beam trigger sent to DAQ
  - Beam spot size: ~ 1.7×1.8 mm^2
  - Hall temperature: 20ºC
    ⇒ 25 – 30ºC @ sensors

Medipix beam profiler

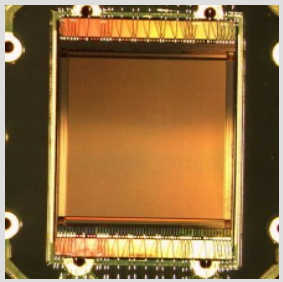
256x256 pixels (55µm pitch)



BTF @ LNF: Telescope & DUT

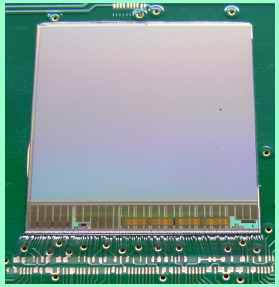


Mimosa18



512×512 pixels
10 μm pitch
5x5 mm^2 active area
Analog output
$t_{r.o.}$ = 6.4 ms
σ_{sp} = 1 – 2 μm

Mimosa28



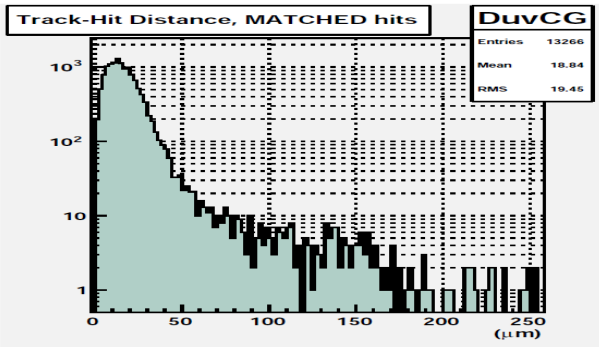
960×928 pixels
20.7 μm pitch
2x2 cm^2 active area
Digital output
$t_{r.o.}$ = ~200 μs
σ_{sp} ~ 3.5 μm

- **Telescope & DUT Set-up (**all sensors thinned up to 50 μm**)**
  - Reference planes (Telescope): 2 station of 2 Mi18 & 1 station of 2 Mi28
  - DUTs (Mimosa22-THRb): 2 DUTs in-between the Mi18 stations but only one is readout
    ⇒ the other sensor only contributes to multiple scattering (MS)
  - DAQ (developed by E. Spiriti)
    - Beam trigger sent to all modules (Δt = 10 ns)
      ⇒ synchronization granted for very different $t_{r.o.}$ (5 μs, 200 μs & 6.4 ms)
    - DAQ rate ~3 Hz, beam efficiency ~ 100 % & tracks/acquisition = 2 – 20
  - Data collected
    - ~630k triggers with beam ⇒ ~800k rec. tracks for performances assessment

Data Analysis

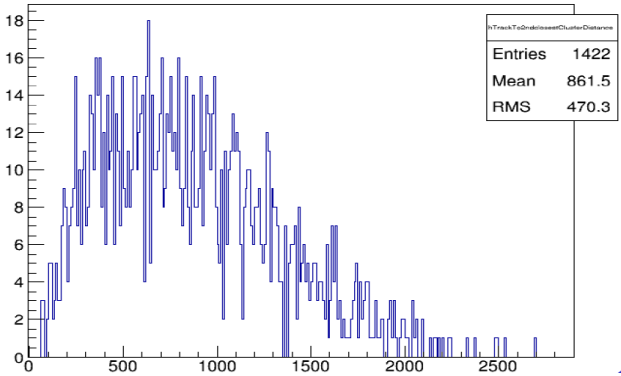
Analysis strategy & Efficiency correction

- **Analysis framework:** TAF (iphc.cnrs.fr/TAF)
- **Analysis strategy**
  - Reconstruct tracks in telescope and extrapolate @ DUT
  - Associate track to DUT hits within some track-hit distance
  - Evaluate DUT ε_{det} and σ_{sp}

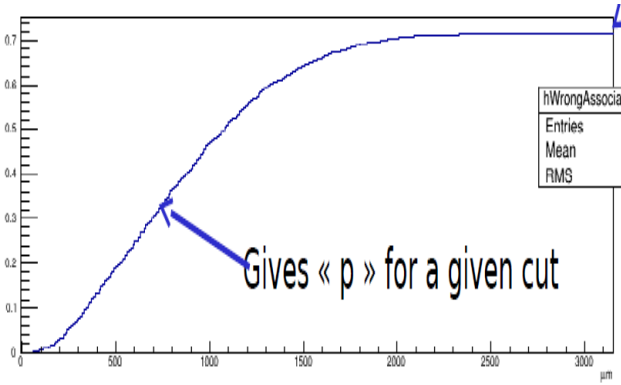


- **Efficiency Correction:** $\varepsilon_{det}^{corr} = (\varepsilon_{det}^{raw} - p)/(1 - p)$
  - Due to MS some track-hit distances seems quite large (few 100 μm)
    - Enlarging the track-hit distance cut has 2 consequences for non-efficient events
      - Increases probability (**p**) to get a fake hit
      - Increases probability (**p**) to associate a real hit from another track
  - Correction method
    - Use efficient events to get the distribution of the 2nd closest hit to the track
    - Use normalized cumulated distribution to estimate **p**

Track - hit distance of the 2nd closest hit

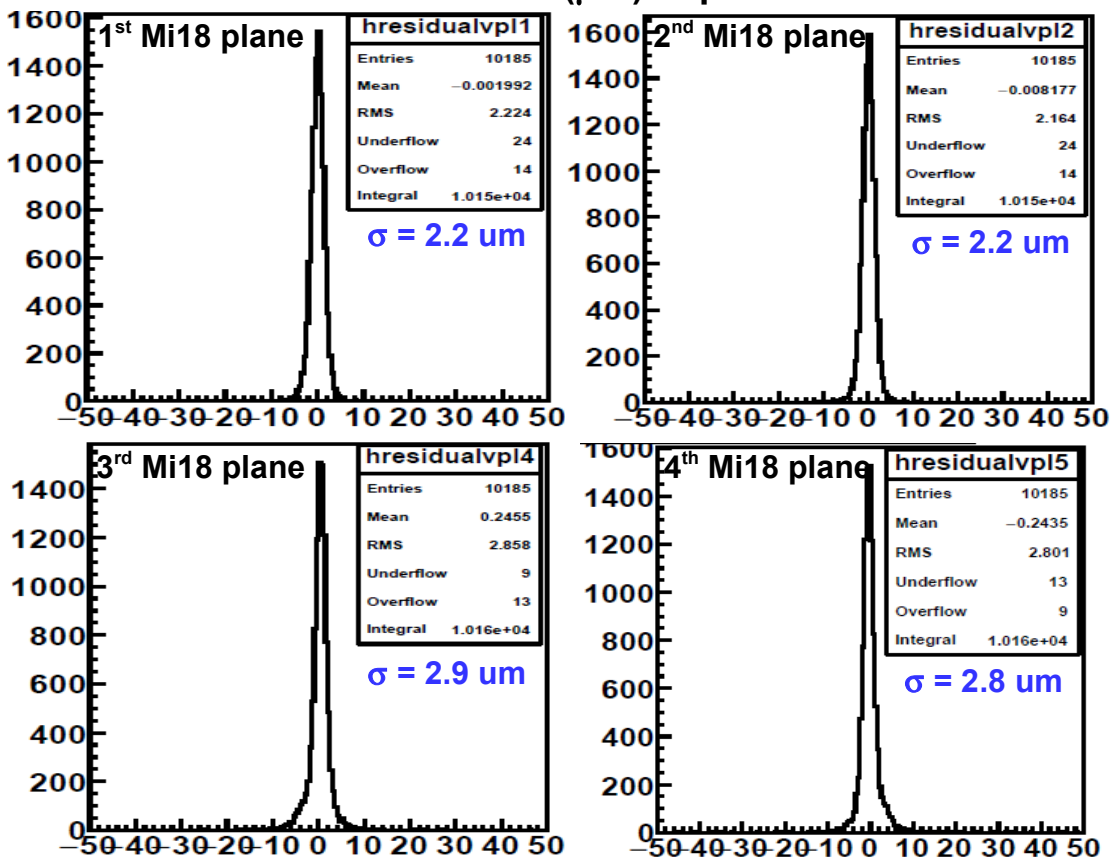


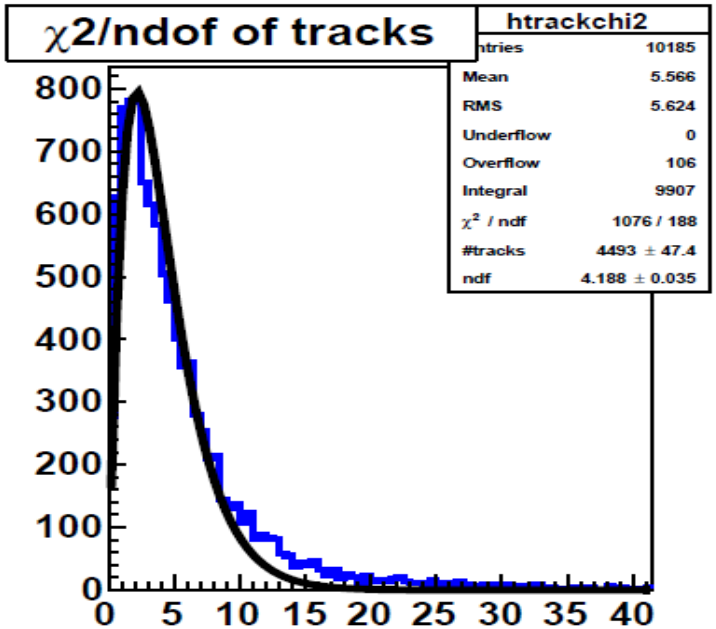
Norm. cumulated distribution



Telescope Alignment

Biased Track Residues (μm): 4 points tracks





- **Sub-micron alignment precision of the reference planes**
- **χ^2 track fitting not including MS contributions** ⇒ bias of χ^2/nof distribution
- **Still good enough tracks for DUT performances assessment**

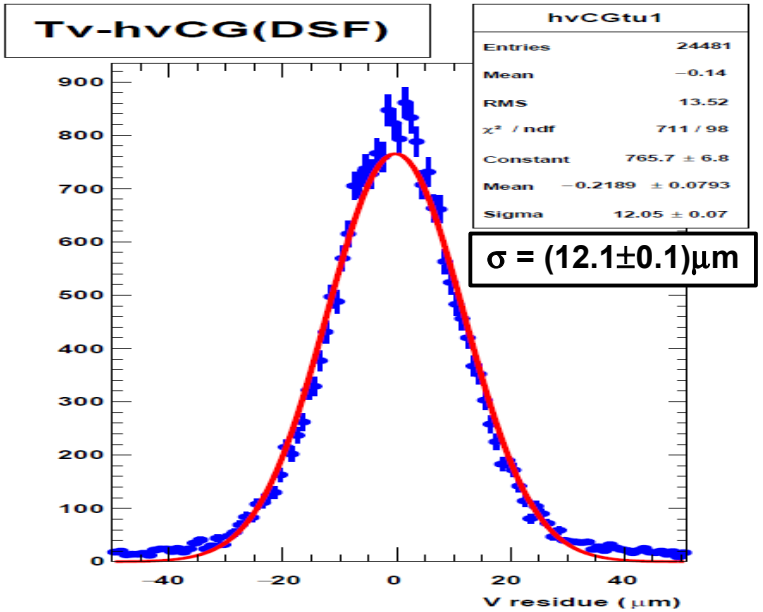
Measurements on Mimosa22-THRb sensors (DUT)

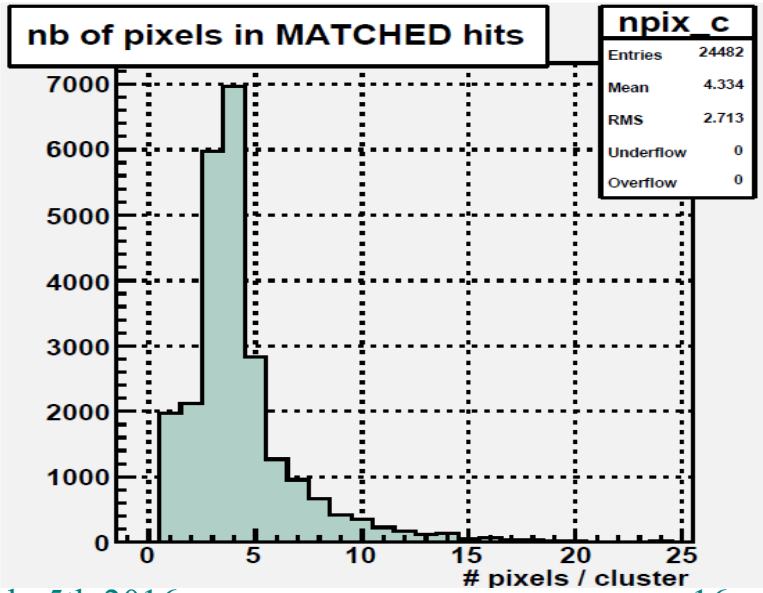
- **Measurements vs discriminator Threshold**
  - Detection efficiency (ε_{det}) vs fake rate
  - σ_{sp} associated with binary encoding of large pixels
  - Rad. tolerance (30ºC): 150kRad $\oplus$ $1.5\times10^{12} n_{eq}/cm^2$

- **Example for one threshold measurement**
  - Discriminator threshold = 4.0mV (~7.3 $\times$ noise)
  - Good DUT alignment w.r.t telescope
  - 24k tracks @ DUT
  - ε_{det} = (99.99 $\pm$ 0.01) %
  - $\sigma_{residue}$ = (12.1 $\pm$ 0.1) µm
  - Average cluster pixel multiplicity ~ 4.3

- **In order to obtain DUT's σ_{sp} need to evaluate telescope pointing resolution (σ_{Tel})**

  ⇒ **Simulation**





BTF Simulation: Strategy

- **Motivation:** σ_{Tel} @ DUT (significant MS)

- **Several simulation tools implemented in TAF**
  - **Toy simulation:** 2 configurations
    - Gaussian MS modelled with the formula $\theta_{rms}^{proj} = \sqrt{\langle \theta^2 \rangle} = \frac{13.6\,MeV}{\beta c p} z \sqrt{\frac{x}{X_0}} [1 + 0.038 \ln(x/X_0)]$
    - Include non-Gaussian tails of MS as described in *PRD Vol89, Number 6, March 15, 1953*
  - **GEANT4-based simulation** (in principle more realistic MS model)

- **Simulation principle**
  - Set a geometry description of the experimental environment
  - Generate tracks with a given angular dispersion (set by user)
  - Transport tracks through geometry to get intersections with Telescope & DUT planes
  - Gaussian smearing of the intersection position applied according to plane σ_{sp}

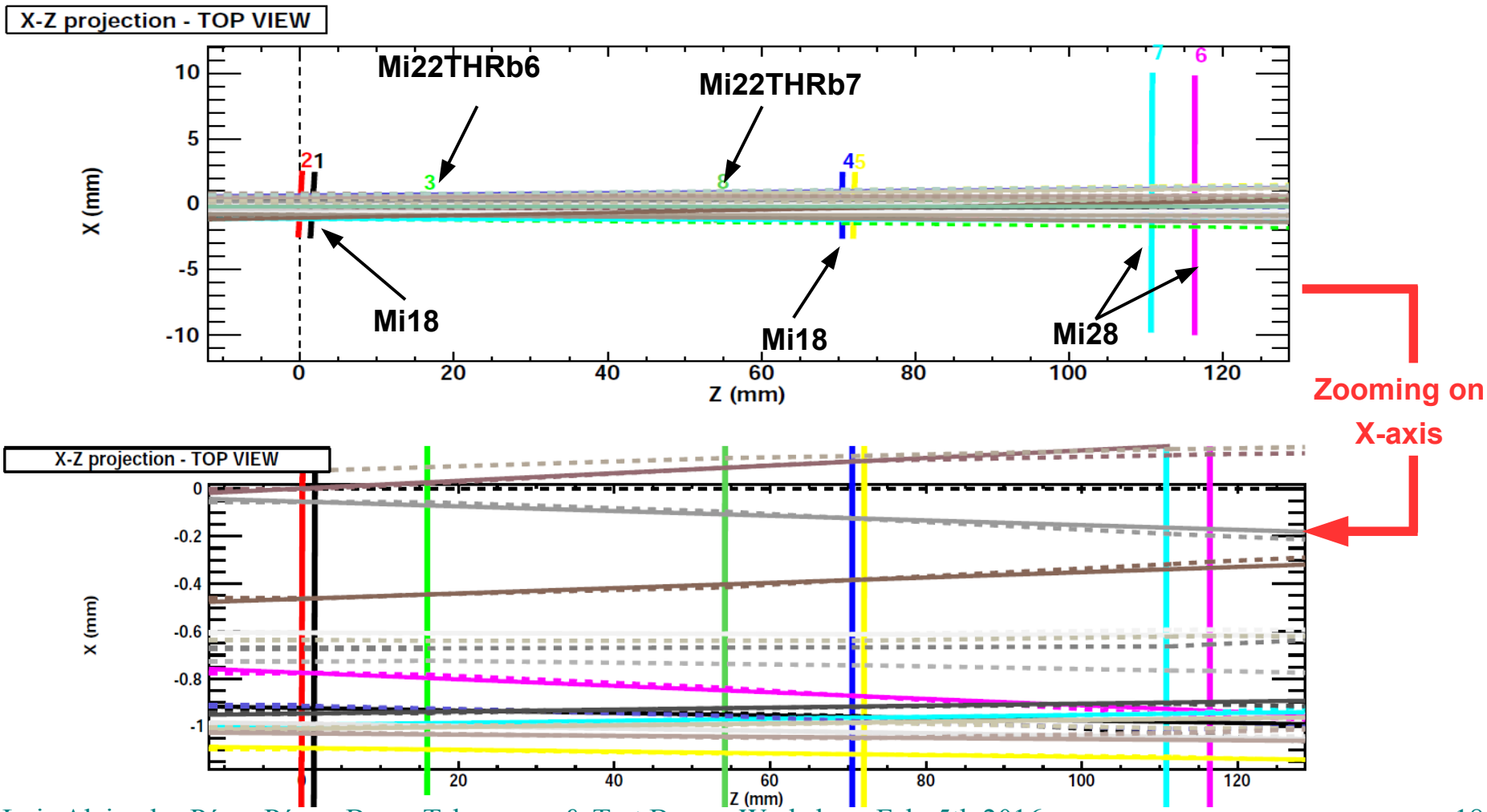
  ⇒ Hit generation

- **The list of generated hits are then passed to the analysis framework**

  ⇒ use same pattern recognition and track-fitting algorithms as in regular analysis

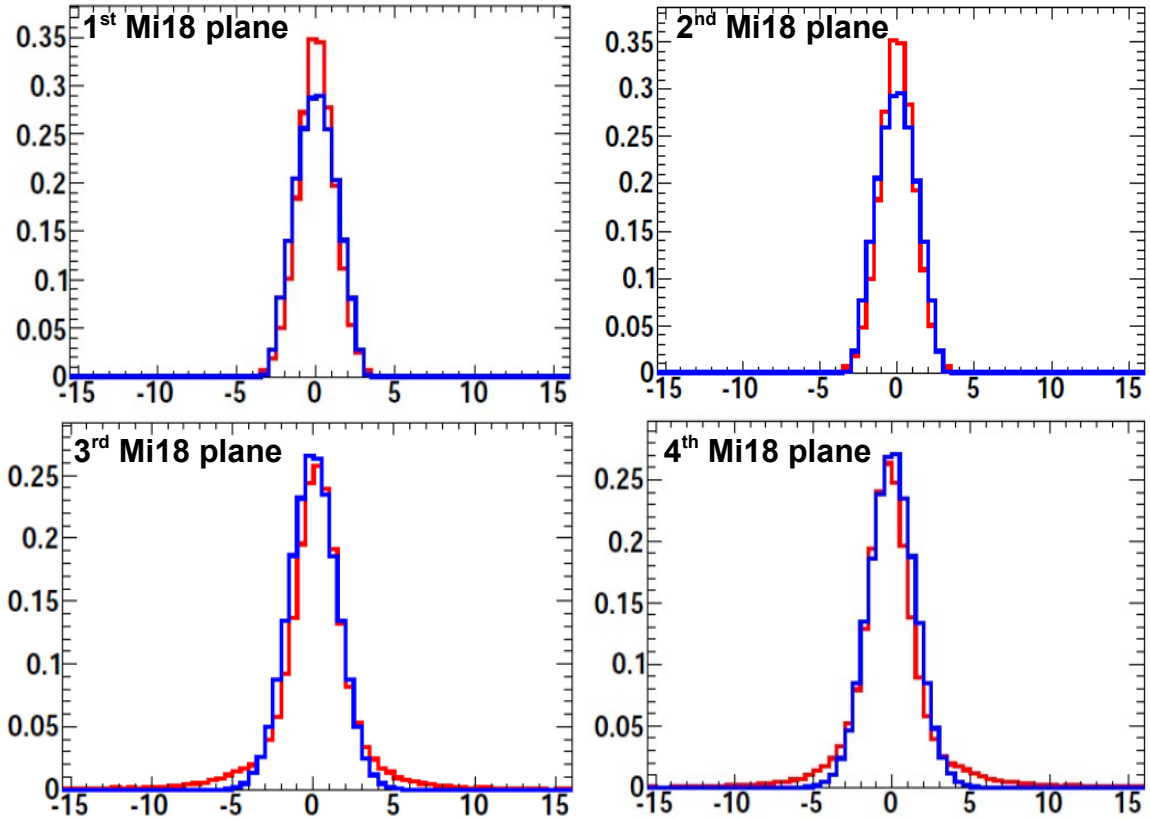
BTF Simulation: Visualization

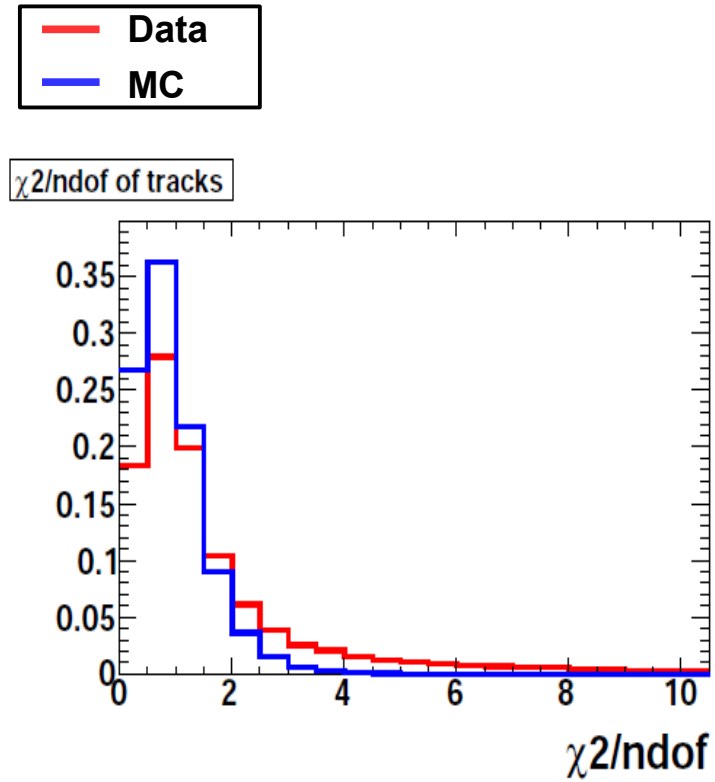
- **Beam:** e^- with p = 450 MeV/c
- **Dotted/Solid-line:** generated/reconstructed tracks



BTF Simulation: Data/MC comparison

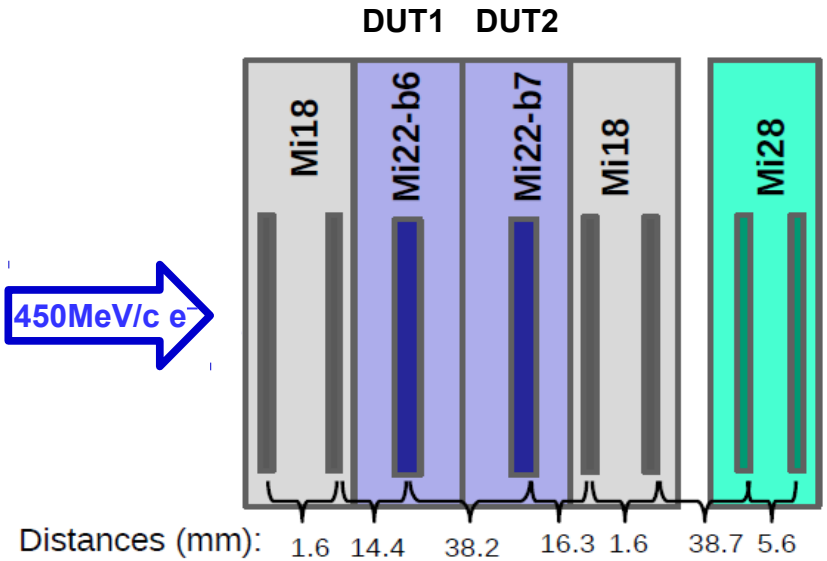
Biased Track Residues (μm): 4 points tracks





- **Quite good agreement between Data and Simulation**
- **Small disagreement due to:** geometry model + DAQ synchronization effects
- **Assign 0.2 μm systematic error on σ_{Tel} from previous test with DUT of know σ_{sp}**

BTF Simulation: σ_{Tel} @ DUT position

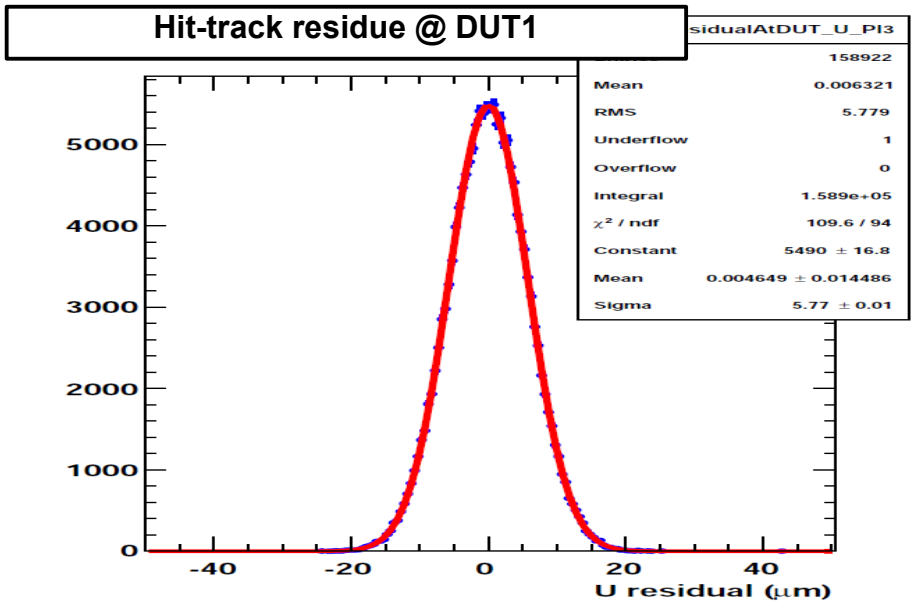


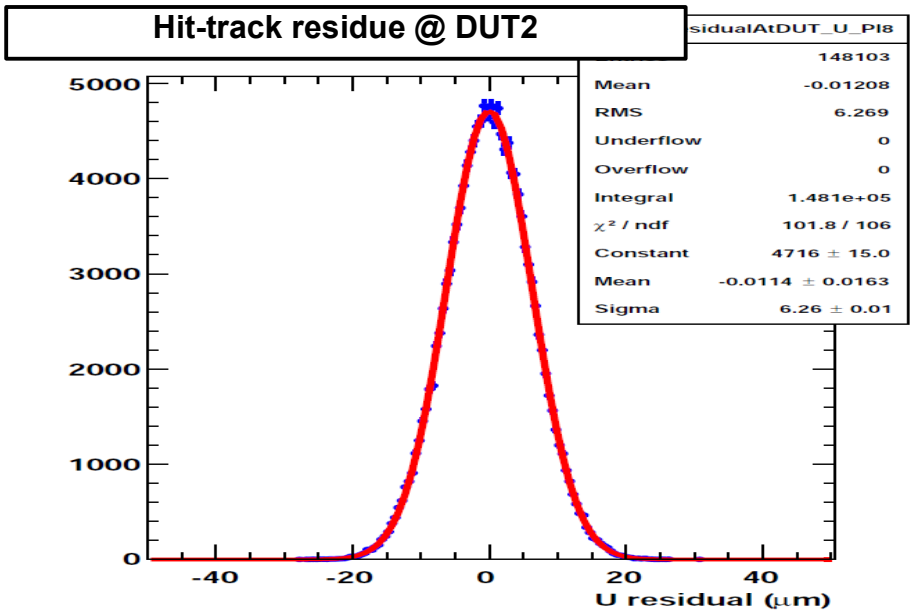
Telescope resolution @ DUT position

(both DUTs thinned to 50μm)

DUT1: $\sigma_{Tel} = (5.77 \pm 0.01_{stat} \pm 0.20_{syst})\ \mu m$

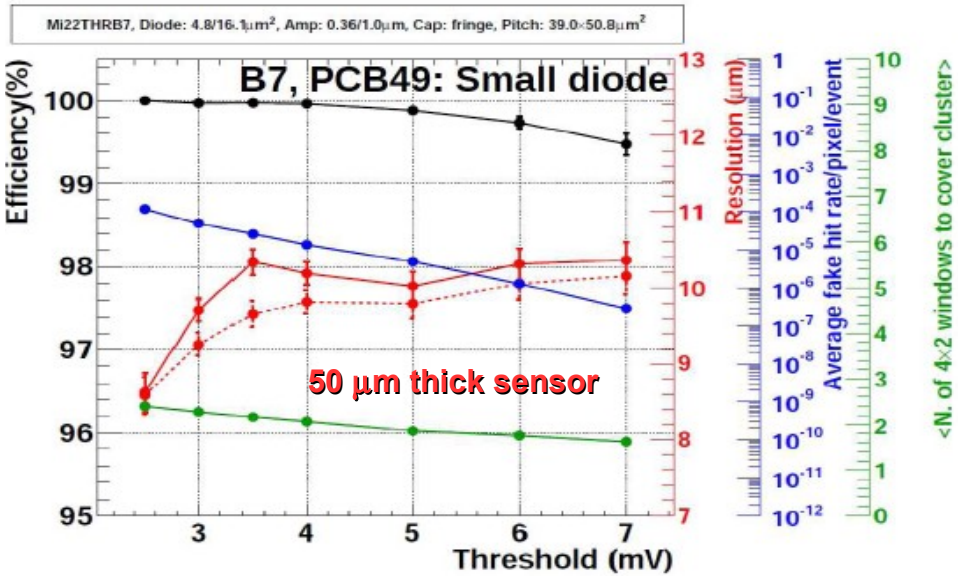
DUT2: $\sigma_{Tel} = (6.26 \pm 0.01_{stat} \pm 0.20_{syst})\ \mu m$



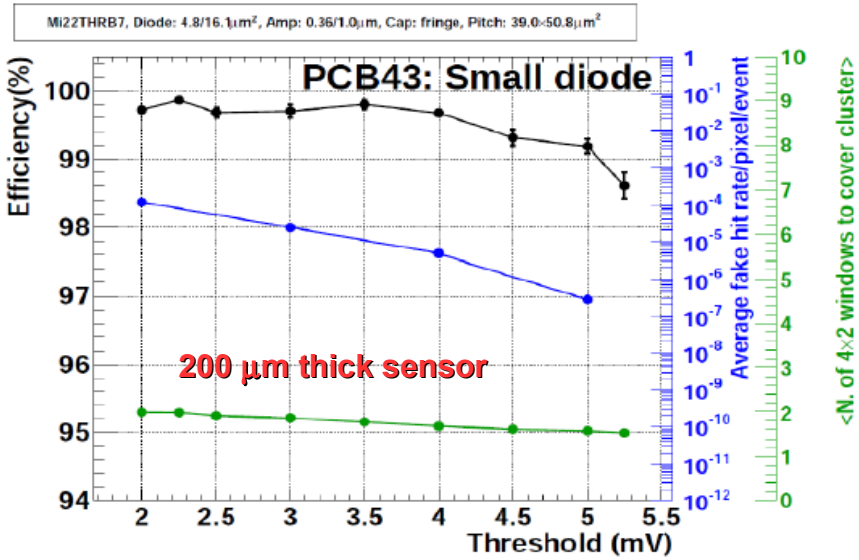


Main MIMOSA-22THRb detection performances

Pixel type	Pixel dim.	Diode/Footprint	Pre-Amp T.	Clamping capa.	Integ. time
MIMOSA-22THRb7	39 μm x 50.8 μm	5/16 μm^2	N-MOS	MOS (N-well)	5 μs



No Irradiation



150 kRad ⊕ 1.5×10^{12} n_{eq}/cm^2

- **Excellent detection performances**
  - ε_{det} > 99% & σ_{sp} ~ 10 μm (as expected)
  - Good performances for radiation load relevant for outer ALICE-ITS

Efficiency
U residue
V residue
Fake rate
<# Suze Windows>

- **Validation of large pixel design for the outer layers of the ALICE-ITS!**

Summary and Outlook

Summary and Outlook

- **DAΦNE BTF provides an environment for testing particle detectors**
  - Small bunch duration (Δt = 10 ns) ⇒ synchronization and possible timing measurements
  - Wide range of particle multiplicities: up to single-particle

- **Testing of position sensitive detectors @ BTF**
  - Low-energy particle beam (~ 500 MeV $e^{\pm}$) ⇒ significant MS effects
  - Need high-precision & low material beam telescope ⇒ Mimosa CMOS sensors
  - Able to measure MIP detection efficiency: even for relatively thick sensors (~200 μm)
  - Spatial resolution: only possible for thin and relatively high σ_{sp} ($\gtrsim$ 10 μm) sensors
  - Allowed validation of large pixel CMOS sensors adapted for outer layers of new ALICE-ITS

- **Outlook**
  - Geometry: as compact as possible to reduce MS (smaller lever arm from sensor to sensor)
  - DAQ readout speed: up to spill rate ⇒ increase statistics
  - Mimosa28-based Telescope ⇒ foreseen to become part of available on-site equipment

Back up Slides