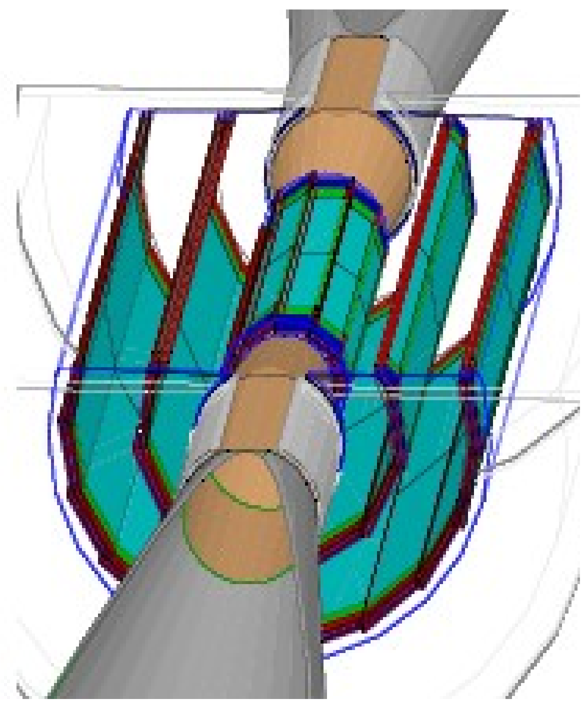
4ème Journées Collisionneur Linéaire, 24 Mar. 2016

CMOS Pixel Technologies: Prospects for a VTX detector @ ILC

Alejandro Pérez Pérez

IPHC – CNRS Strasbourg

On behalf of the PICSEL team of IPHC



CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

IPHC Institut Pluridisciplinaire Hubert Curien STRASBOURG

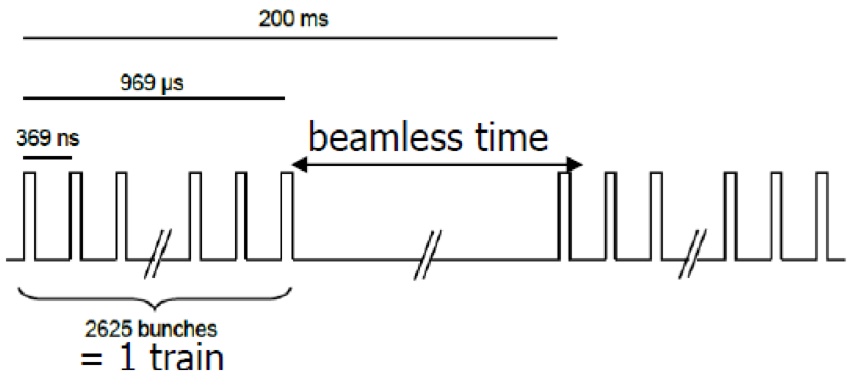
PICSEL GROUP

Outline

- ILC-VTX: experimental conditions & requirements
- R&D roadmap for a VTX detector for ILC
- Summary and outlook

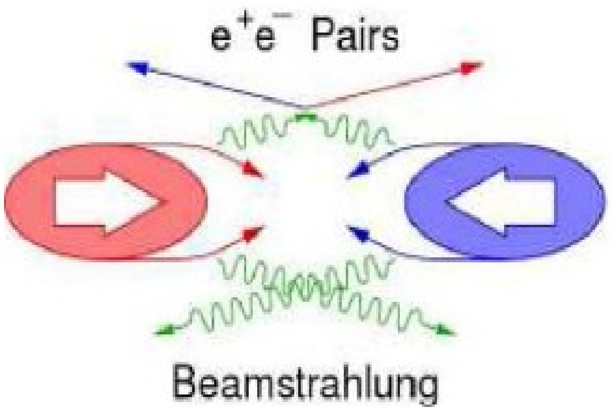
ILC-VTX: experimental conditions

- **Beam structure**
  - Trains of ~2600 bunches every 200 ms
  - Operation strategies
    - Full detector readout (r.o.) ⇒ triggerless
    - Power pulsing ⇒ reduced power



- **Beam induced background**
  - Radiation level: ~100kRad ⊕ 10^{11} n_{eq}/cm^2

    (LHC: ~1GRad ⊕ 10^{16} n_{eq}/cm^2)
  - Beamstrahlung is main source of occupancy
    - ~5 hits/cm^2/BX @ $\sqrt{s}$ = 500 GeV (high systematics)
    - Drives VTX readout speed & minimum radius



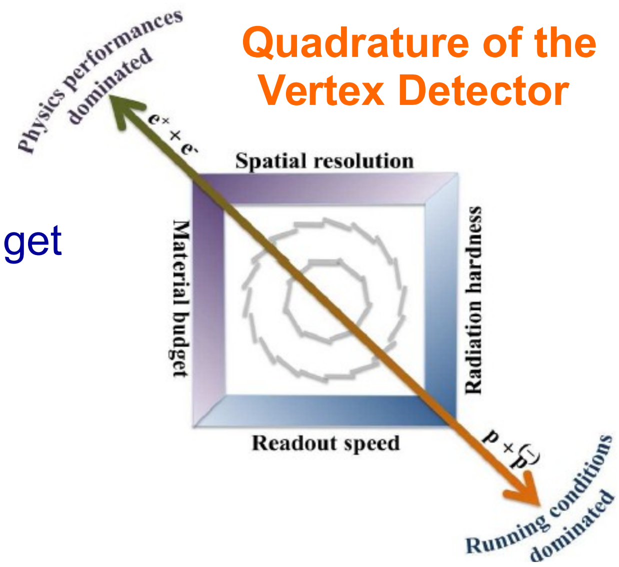
- **Possible readout architecture**
  - Integrate few bunches
  - Readout between trains with time-stamping ⇒ chronopixels
  - Readout between trains without time-stamping ⇒ very high granularity

ILC-VTX: requirements & design

- **Linear e^+e^- collider**
  - Exhibit milder running conditions than pp/LHC
    - Relaxed readout-speed & radiation tolerance
  - Favours technologies focusing on resolution & material budget

  ⇒ **CMOS Pixel Sensors (CPS)**

Quadrature of the Vertex Detector



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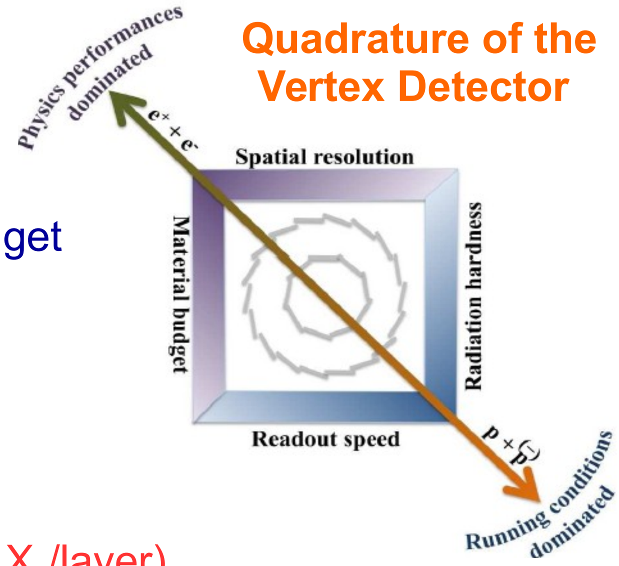

- **ILC-VTX requirements**
  - Physics performances: $\sigma_b < 5 \oplus 10/p\beta \sin^{3/2}\theta$ µm

    ⇒ σ_{sp} ~3 µm (~17 µm pitch) & low material budget (~0.15% X_0/layer)
  - Occupancy ⇔ readout-speed: few % occupancy (~5 hits/cm^2/BX)
  - Moderate radiation tolerance (/year): ~100kRad ⊕ 10^{11} n_{eq}/cm^2

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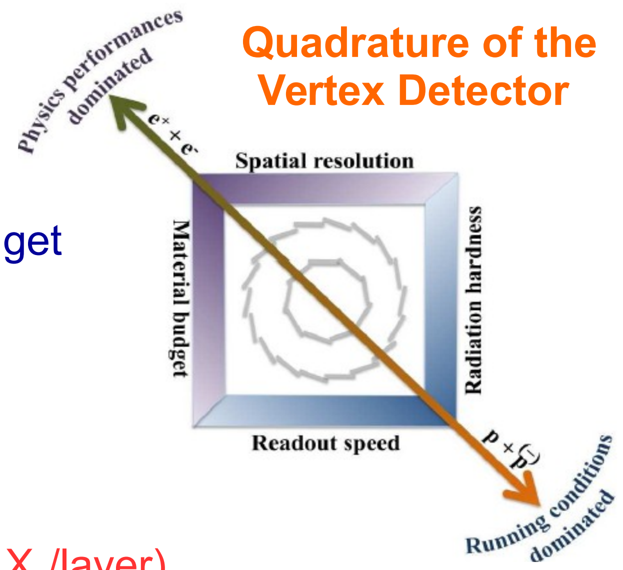

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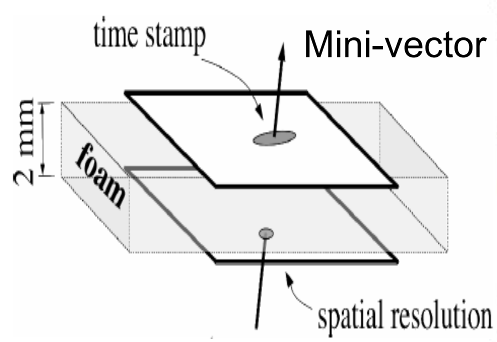
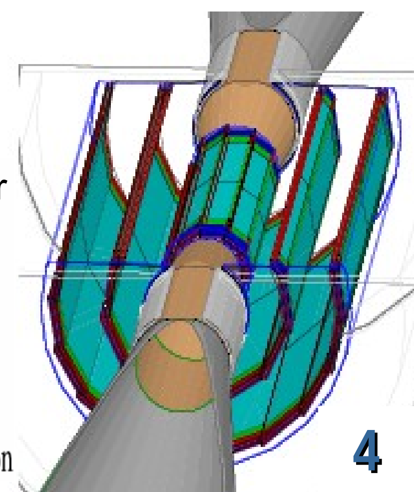
- **ILD-VTX design:** 3 x double-sided ladders
  - Alignment & tracking improvement (pointing)
  - 1 support/2-layers ⇒ lower material budget
  - Background rejection capabilities?





CPS State-of-the-Art in operation: STAR-PXL detector

STAR-PXL @ RHIC

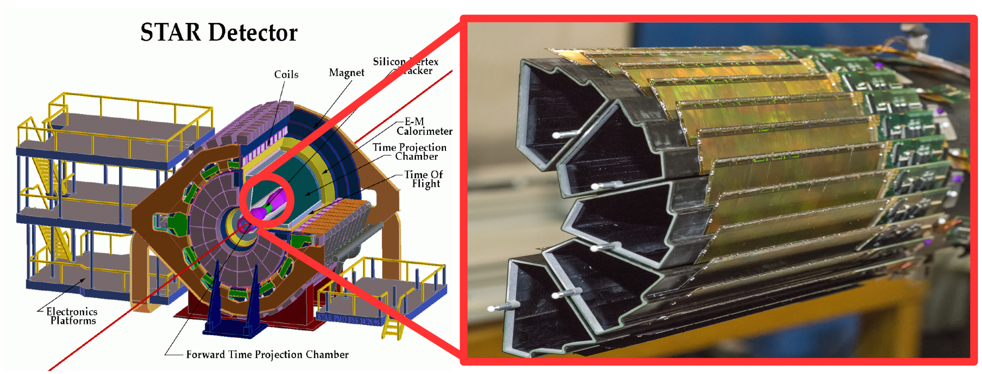
1st CPS @ a collider experiment!

ULTIMATE Sensor (Mimosa28)

- Rolling shutter r.o. ($t_{r.o.} \lesssim 200\ \mu s$)
- $T_{operation} = 30 – 35^{o}C$
- $\varepsilon_{det} \gtrsim 99.9\%$ $\sigma_{sp} \gtrsim 3.5\ \mu m$ & $f_{rate} \lesssim 10^{-5}$
- Rad. Hard: $\gtrsim$ 150kRad $\oplus$ $3\times10^{12} n_{eq}/cm^2$

STAR-PXL HALF-BARREL (180M pixels)

- 2 layers @ r = 2.8, 8 cm
- 20 ladders (10 sensors/ladder) (0.37% X_0)



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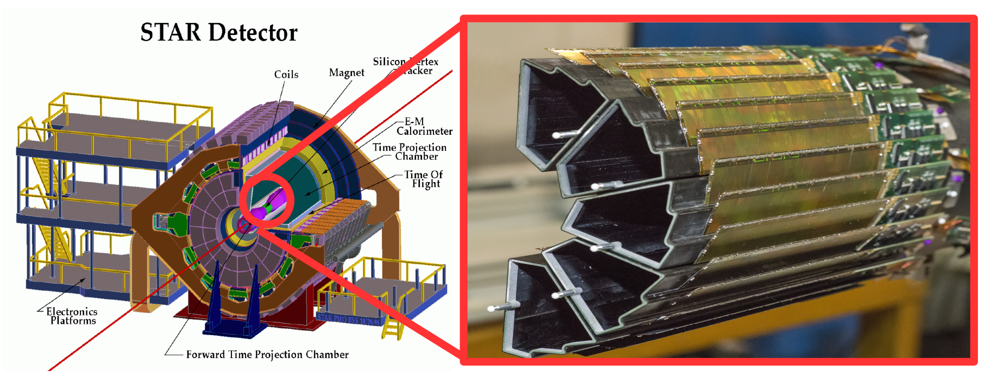

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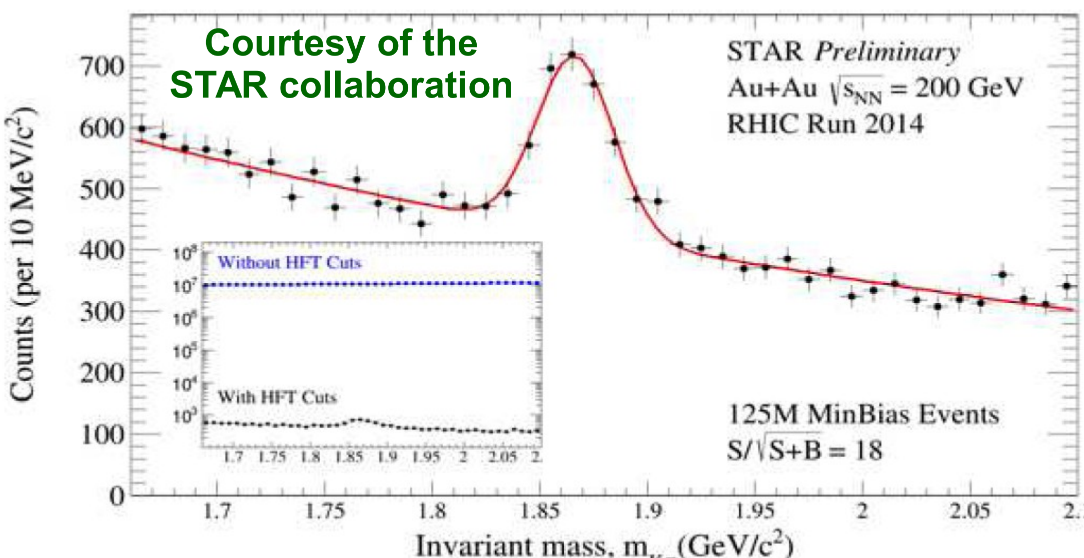


Several Physics-runs

- 1st /2nd run in 2014/2015
- Currently 3rd run (Since Jan. 2016)
- $\sigma_{ip}(p_T)$ matching requirements

  ~40 μm @ 750 MeV/c for $K^{\pm}$

Observation of D^0 production

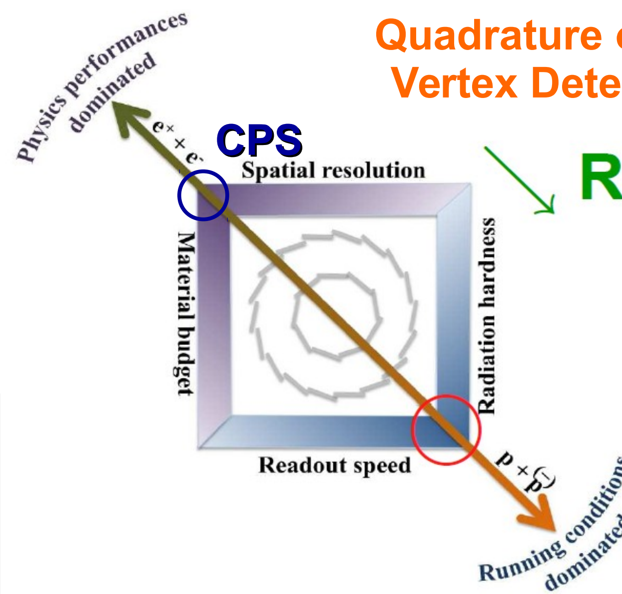
- **STAR:** peak significance = 18
- **ALICE:** peak significance = 5

CPS @ PICSEL - IPHC: A long term R&D

How to improve r.o. speed and rad. tolerance while preserving σ_{sp} (3-5 μm) and material budget (< 0.1% X_0)?

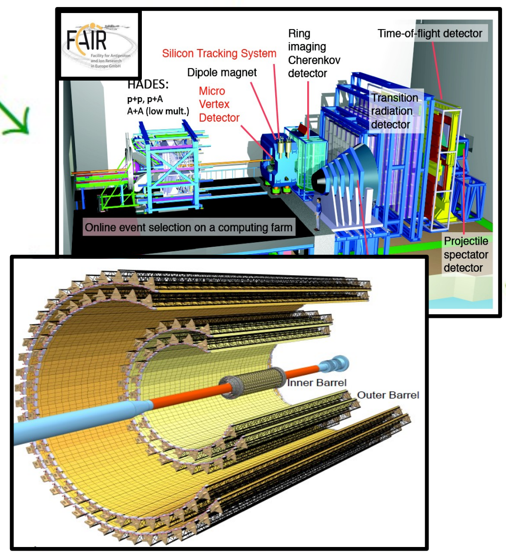
Quadrature of the Vertex Detector

R&D

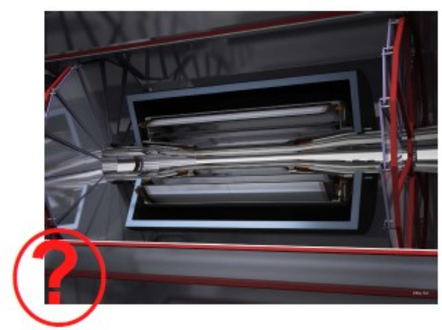


O(10^2) μs

O(10) μs



O(1) μs



EUDET/STAR	⟼	ALICE/CBM	⟼	?X?/ILC
2010/14	⟼	2015/2019	⟼	$\gtrsim$ 2020

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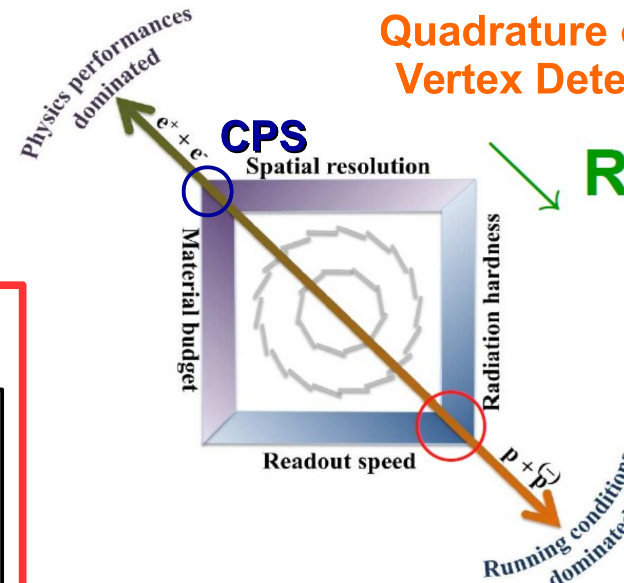
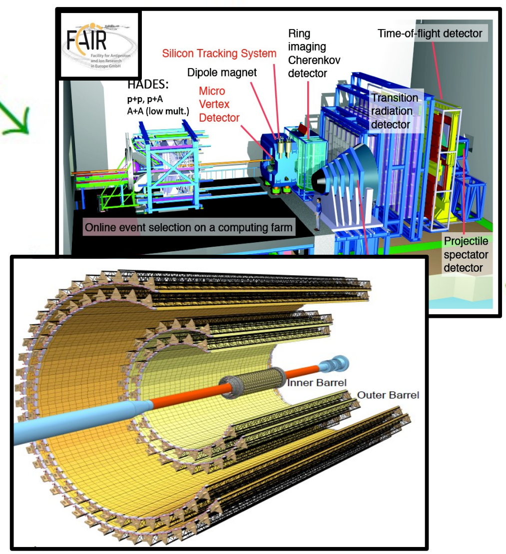


R&D

$O(10^2)\ \mu s$

We are currently here!

$O(10)\ \mu s$



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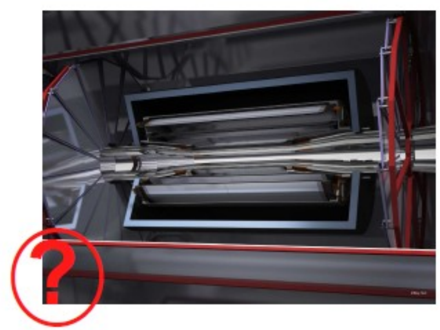
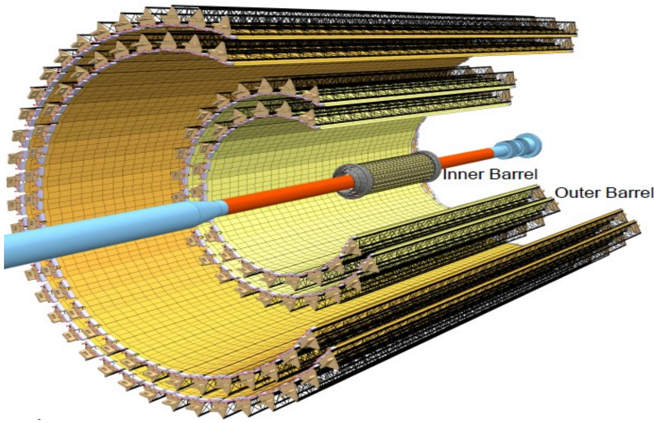


EUDET/STAR		ALICE/CBM		?X?/ILC
2010/14	→	2015/2019	→	$\gtrsim$ 2020

Next challenge: ALICE-ITS upgrade

- **Upgraded ALICE-ITS (**Installation during LS2**)**
  - **Present detector:** 2xHPD/2xDrift-Si/2xSi-strips
  - **Future detector:** 7-layers with CPS (25k sensors)

    ⇒ 1^{st} large tracker entirely based on CPS (~ 10 m^2)



Requirements for ITS inner & outer layers (comparison with STAR-PXL chip)

	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** μs	**2.7 MRad**	$\mathbf{1.7{\cdot}10^{13}\ n_{eq}/cm^2}$	30°C	$< 300\ mW/cm^2$	0.17 m^2
ITS-out	$\lesssim 10\ \mu m$	$\lesssim$ **30** μs	100 kRad	$1{\cdot}10^{12}\ n_{eq}/cm^2$	30°C	$<$ **100 mW/cm²**	$\sim$ **10 m²**

⇒ **0.35 µm CMOS process (STAR-PXL) marginally suited to r.o. speed & radiation hardness**

- **Transition to new CMOS process for improving readout speed and radiation hardness**

  ⇒ **Tower-Jazz 0.18 µm CIS**

ALICE-ITS upgrade: 2 r.o. architectures R&D

MISTRAL-O

Pixel pitch: 36x64 μm^2

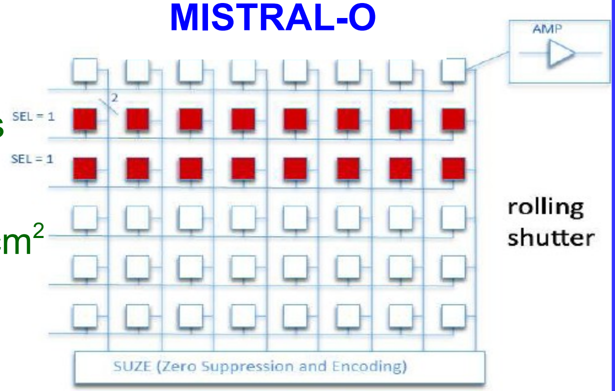
Time resolution: ~ 20 μs

W: 80 mW/cm^2

Max hit rate: ~0.8 MHz/cm^2

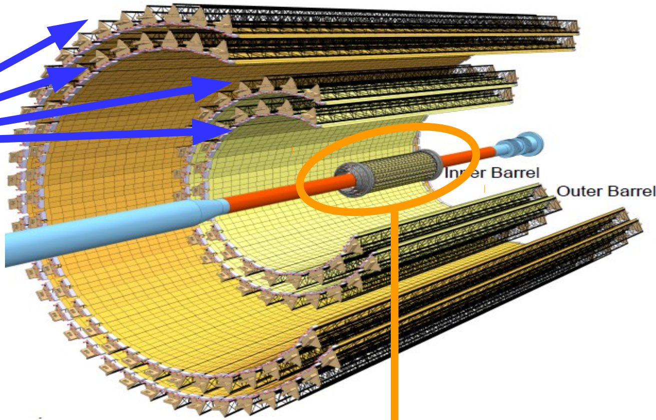
Dimension: 15 x30 mm^2

Dead area: 1.5x30 mm^2

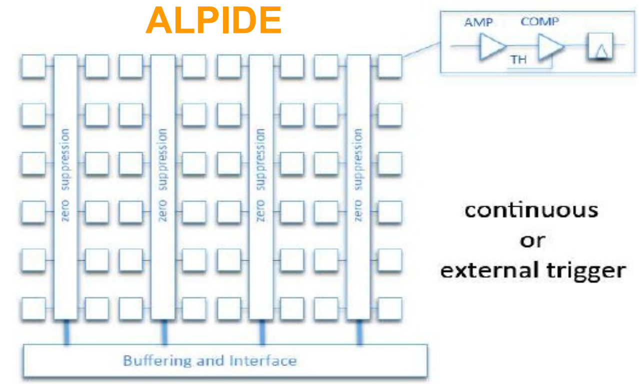


Goal: early available & reliable solution

- **Conservative design based on STAR-PXL**
- Big pixels ⇒ lower power & higher speed
- Moderate rad. hardness & σ_{sp} ~10 μm ⇒ OK



ALPIDE



Pixel pitch: 28x28 μm^2

Time resolution: ≲ 5 – 10 μs

W: 39 mW/cm^2

Max hit rate: ~ 3 MHz/cm^2

Dimension: 15 x30 mm^2

Dead area: 1.1x30 mm^2

Goal: high performance, accept risks

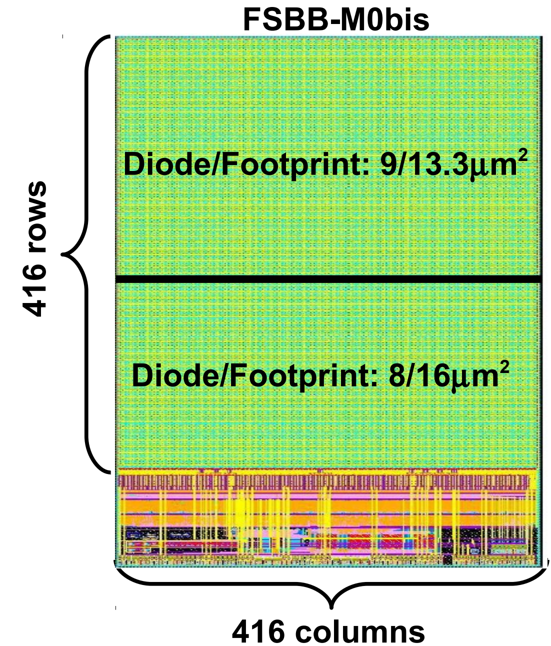
- **Aggressive design**
- In-pixel discrimination
- Asynchronous r.o. (priority encoder)

- **Both chips have same physical & electrical interfaces**
- **Base-line solution: ALPIDE for all ITS layers**

MISTRAL-O: prototypes tested on beam

Full Scale Building Block (FSBB) sensor

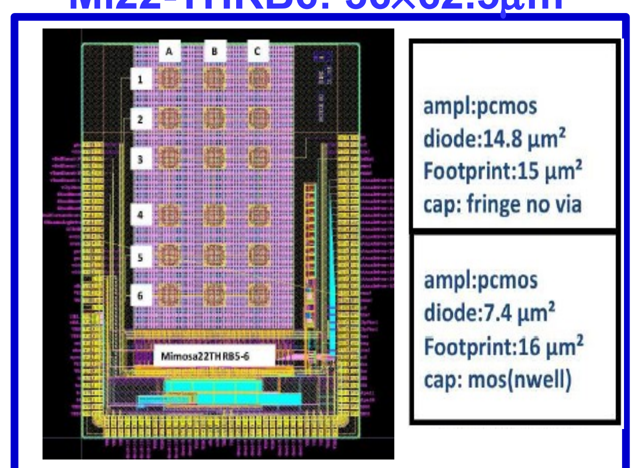
- Full 2-row r.o. chain & 2D sparsification $t_{r.o.} = 40\ \mu s$
- Sensitive area (~1 cm^2) ≈ final building bock
- Similar Nb of pixels (~170k) to final chip
- Epi-layer: high-ρ 18 μm thick
- **BUT:** small pixels (22x32.5 μm^2) & sparsification circuitry is oversized (power!)
- **Tested in 2015 @ DESY (3-6 GeV/c e$^-$) & CERN (120GeV/c π^-)**



Large-pixel prototype (MIMOSA-22THRb)

- Two slightly different large pixels
  - 36x62.5 μm^2 & 39x50.8 μm^2
- Pads over pixel (3ML used for in-pixel circuitry)
- Epi-layer: high-ρ 18 μm thick
- **BUT:** only ≲ 10 mm^2, 4k pixels & no sparsification
- **Tested @ Frascati (450 MeV/c e$^-$) March 2015**

Mi22-THRB6: 36×62.5µm^2



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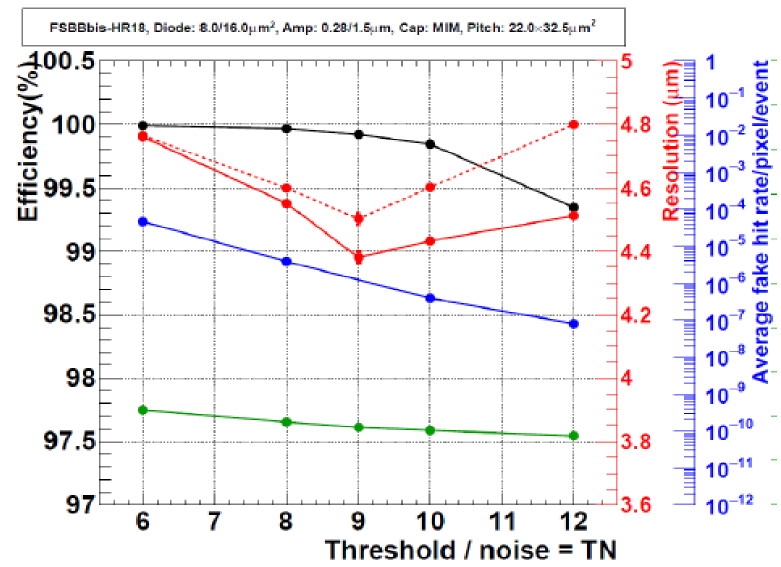

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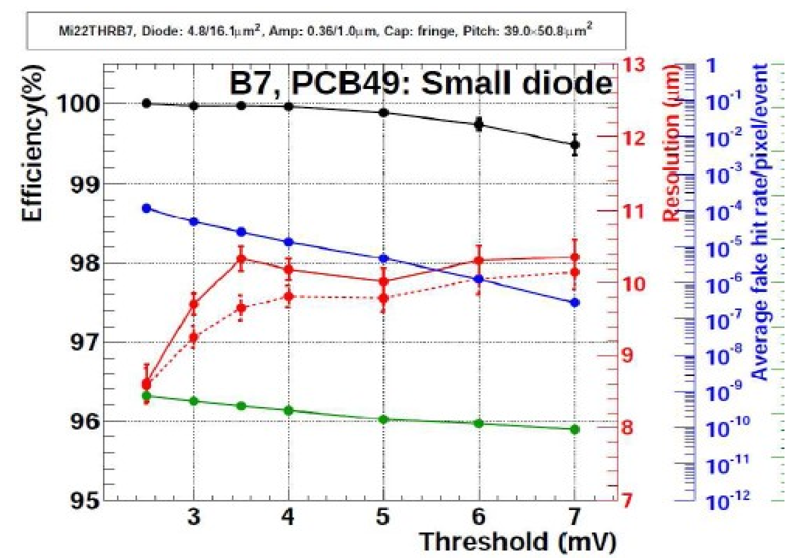
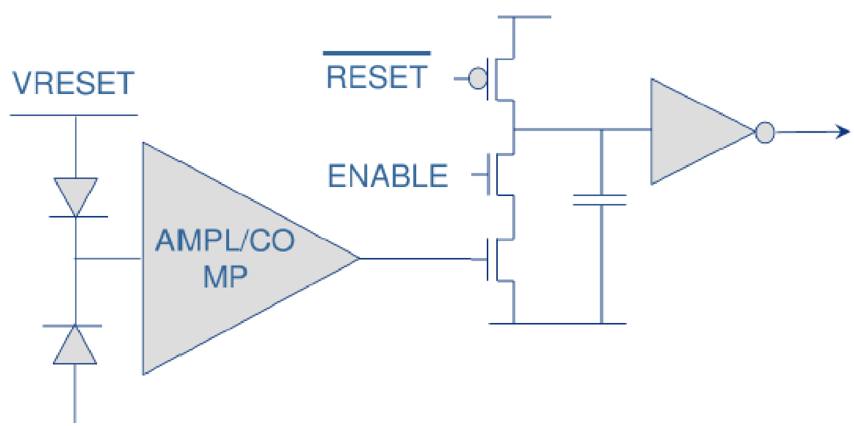


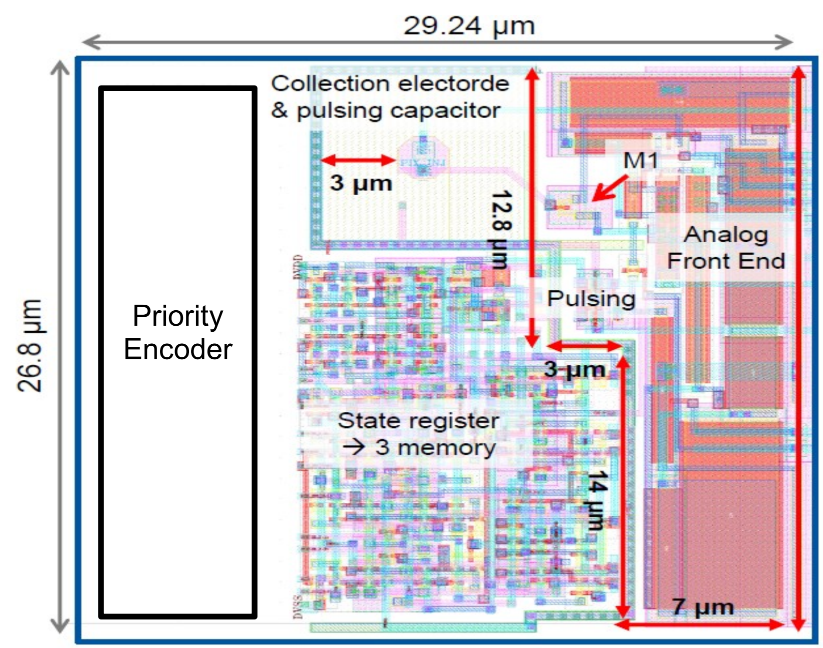
Asynchronous r.o. architecture: ALPIDE

- Concept similar to hybrid pixel r.o. architecture
- Continuously power active in each pixel
  - FEE: single stage amplifier (~100) + shaping (~5 µs) / current comparator
  - Dynamic memory cell, ~80fF storage capacitor which is discharged by an NMOS controlled by the FE
- Data driven readout ⇒ only zero-suppressed data transferred to periphery

Pixel FEE

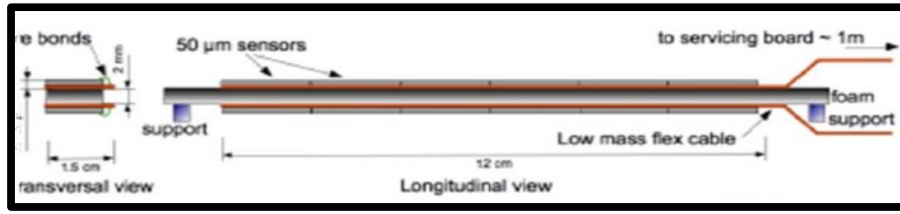


pALPIDE-3 pixel layout

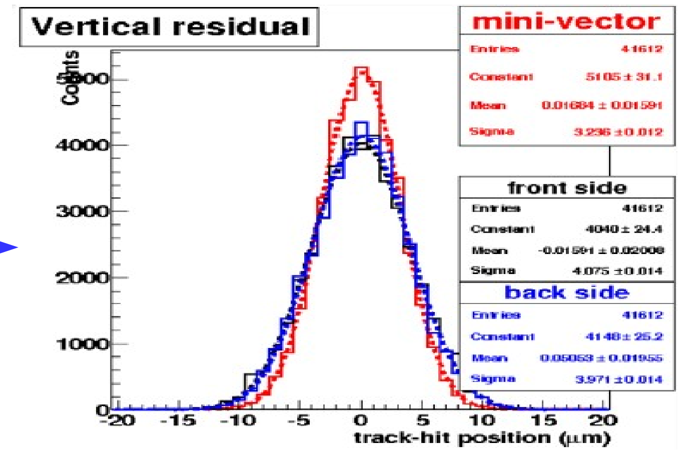


Sensor Integration in Ultra-Light devices

- **PLUME collaboration (Britol, DESY, IPHC)**

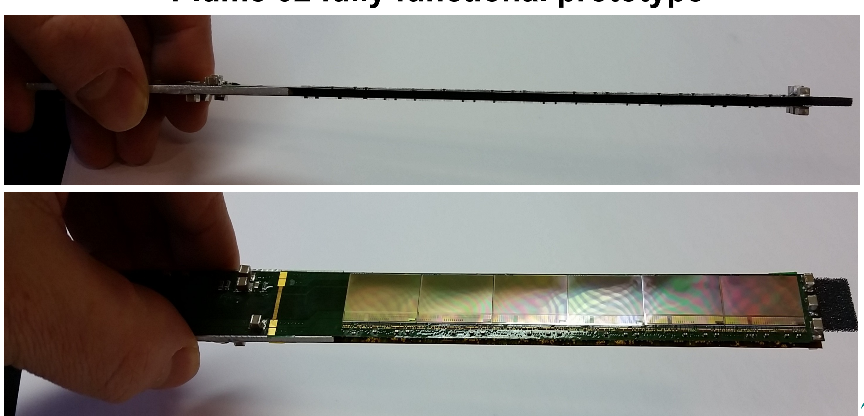


- **Plume 01 prototype** (fabricated in 2012**)**
  - 2x6 Mi26 sensors on 2 mm thick foam SiC (0.6% X_0)
  - Air cooling
  - Validated in beam @ CERN (2011) →
  - New test-beam @ DESY in April 2016



- **Plume 02 prototype:** 6 ladders for 2016
  - Reduced material budget: → 0.35/0.42 % X_0 (Al/Cu flex PCB)

Plume 02 fully functional prototype

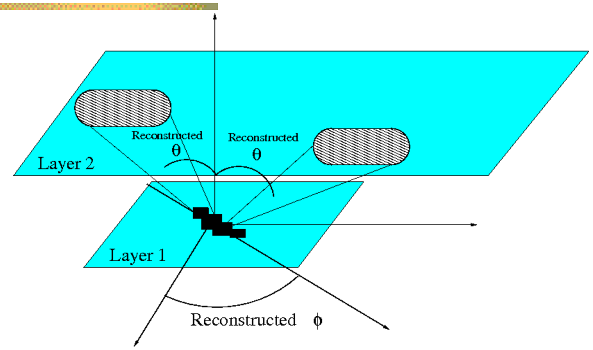


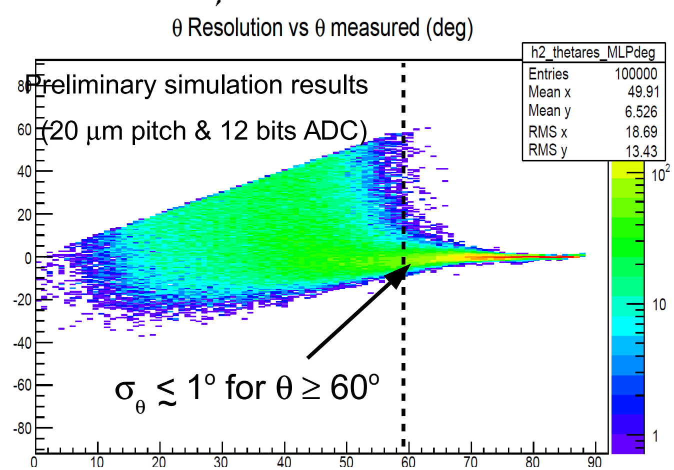
Application @ SuperKEK-B

- Beam-background measurement @ Belle II
- 2 Plume 02 ladders will be installed inside Belle II inner volume in 2017
- MIBEL project (ANR-2016): 1st stage cleared
  - PI: Isabelle Ripp-Baudot (IPHC)

On-chip background rejection with Neural Network

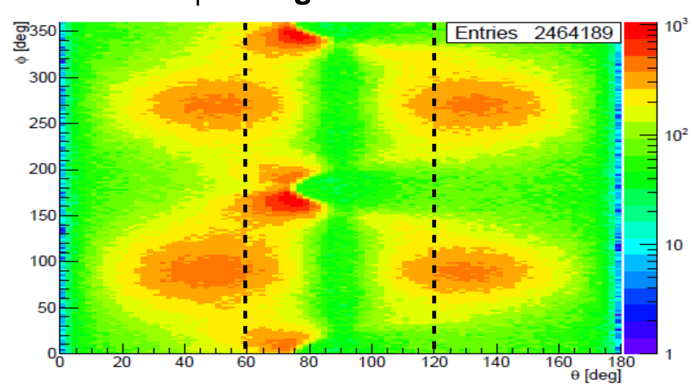
- **Small feature size (0.18 μm) & new imaging algorithms**
  - Neural Network (NN) on chip
- **NN advantages**
  - Reconstruction of particle incident angles (θ & ϕ)
  - Potential reduction of bandwidth & power
- **NN application @ ILC**
  - Filter beam-background hits in VTX
  - Improve double-sided ladder hit association





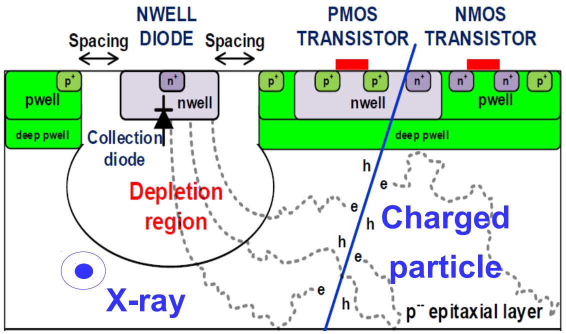
- **CIRENE (Défi instrumentation aux limites 2016 CNRS)**
  - PI: Auguste Besson (IPHC)
  - Success (with Bourgogne University)
  - 2016
    - NN proof of principle (implemented in FPGA)
    - Data taking with different sources (lases, $\beta^{\pm}$, ...)
  - 2017: summit a dedicated chip

θ vs ϕ Background distribution

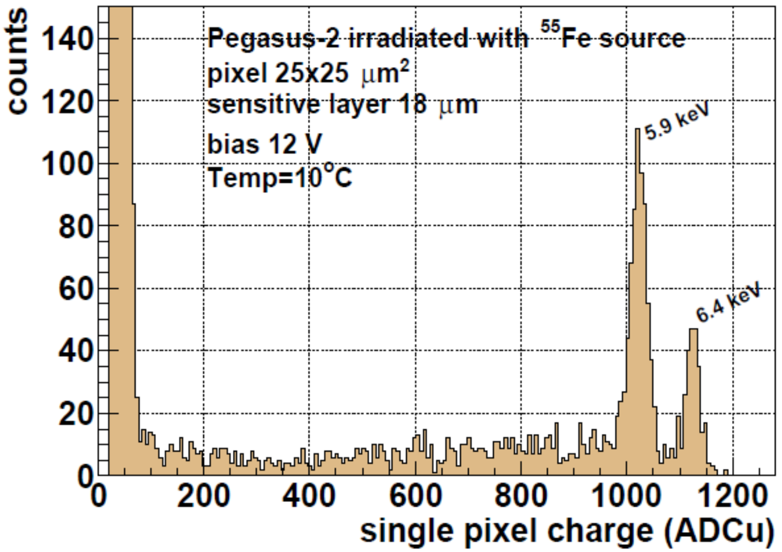


Improving epitaxial-layer depletion

- **Motivations**
  - **HEP:** faster signal ⇒ better tolerance to NIEL
  - **X-Ray detection:** thicker sensitive volume



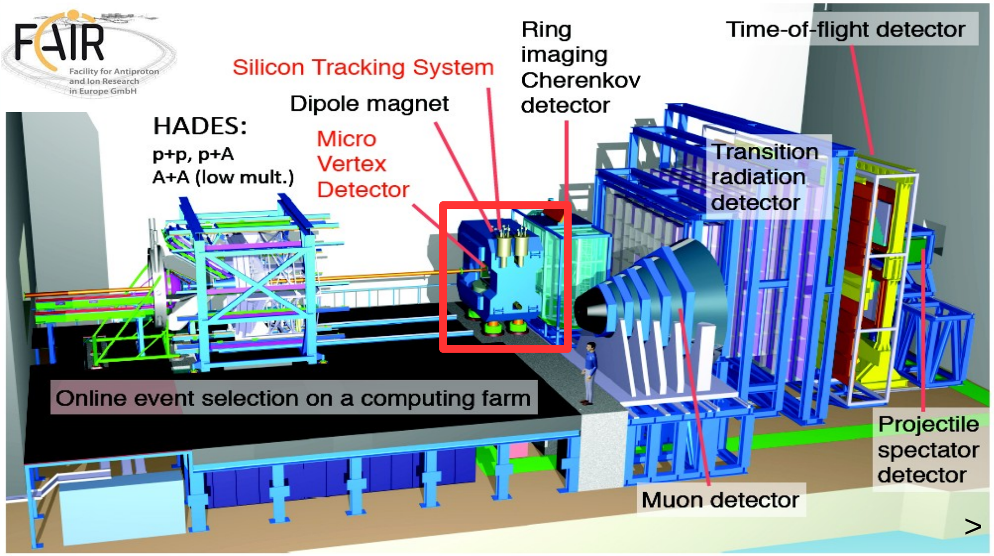
- **Beam-test @ SOLEIL (Mi26 sensor)**
  - Validation of rolling shutter architecture
- **Pegasus-1/2 prototypes (**Tower/Jazz 0.18 μm CIS**)**
  - V_{Bias} = 0 – 30 V + AC-coupling to Pre-Amp
  - 56 x 8 pixels (25 μm pitch)
  - Epi-layer: 18 μm & 1 kΩ cm
  - TN ≈ 16 ± 1 e^- ENC @ 10°C



SYNAPS project partnership with SOLEIL SYNCHROTRON

- High granularity/counting-rate CPS for soft X-ray detection (0.1 – 5 keV)
- SYNAPS project (ANR-2016): 1st stage cleared
  - PI: Jérôme Baudot (IPHC)

Next-to-next challenge: MVD of CBM @ SIS100



Micro Vertex Detector (MVD)

- **Layout:** 4 planes of pixels sensors
- Factor 10 improvement in rad. Hardness
- Vacuum compatible
- Operation @ negative T

Sensor properties	FSBB	MIMOSIS-100 (preliminary)
Active surface (mm^2)	9.2 × 13.7	~10 × 30
# pixels (cols × rows)	416 × 416 (173k)	1500 × 300 (450k)
Pixel pitch (μm)	22 × 33	22 × 33
Integration time (μs)	40	30
Data rate (Mbps)	2 × 320	> 6 × 320
NEIL ($10^3 n_{eq}/cm^2$)	$\gtrsim$ 1 →	3 (*)
TID (MRad)	$\gtrsim$ 1.6 →	3 (*)
$T_{opetation}$ (°C)	+30 →	-20

(*) per year of operation

Summary and outlook

- **CPS with rolling shutter r.o. (mainly AMS-0.35 μm process) in use for several years**
  - High precision beam-telescopes: multi-GeV → sub-GeV beams (CERN, DESY, LNF)
  - Vertex detectors for flavour tagging (STAR-PXL, FIRST)
- **Ultra-light double-sided ladders**
  - Added value for tracking & alignment (studies showed in previous meetings)
  - Ultra-light ladder assembly validated & getting improved ⇒ PLUME collaboration
  - Spin-off (MIBEL): beam-background measurement @ SuperKEKB/Belle II
- **Tower-Jazz 0.18 um CIS technology validated for future projects**
  - STAR-PXL chip successfully translated ⇒ 2-4 faster & ≳ 10 times more rad. tolerant
  - Asynchronous r.o. progressing towards $t_{r.o.} < 10$ μs (ALPIDE)
  - ALICE-ITS: 1st large tracker fully based on CPS
- **Outlook**
  - Depleted epitaxy CPS under study ⇒ SYNAPS project
  - Few μs asynchronous r.o. CPS for CBM @ FAIR & ILC @ Japan

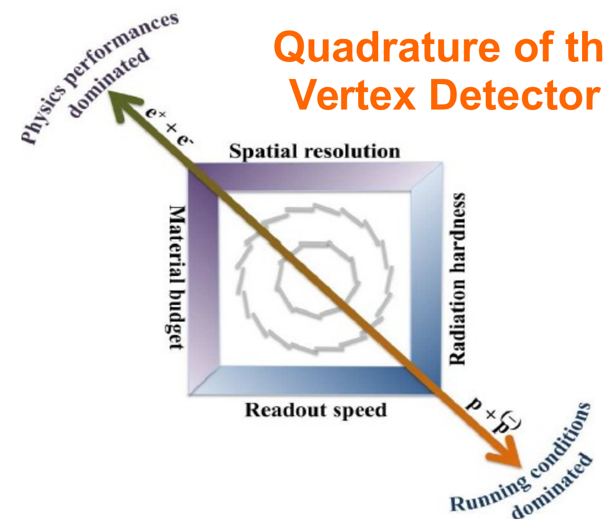
Backup

CPS: Development motivation

- **CPS triggered by the need of very granular and low material budget sensors**

- **CPS applications exhibit milder running conditions than at pp/LHC**
  - Relaxed readout (r.o.) speed & rad. tolerance

Quadrature of the Vertex Detector



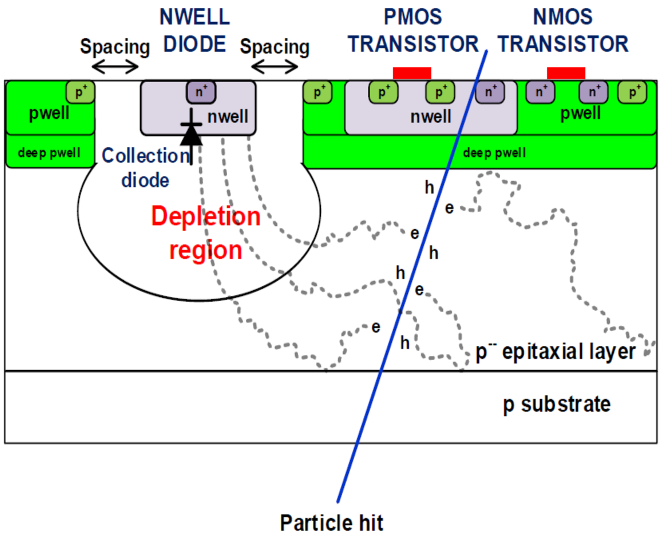
- **Application domain widens continuously (existing/foreseen/potential)**
  - **Heavy-ion collisions**
    - STAR-PXL, ALICE-ITS, CBM-MVD, NA61…
  - **e^+e^- collisions**
    - BES-III, ILC, Belle II (BEAST II)
  - **Non-collider experiments**
    - FIRST, NA63, Mu2e, PANDA, …
  - **High-precision beam-telescopes (**adapted to medium/low energy e^+ beams**)**
    - Few µm resolution @ DUT achievable with EUDET-BT (DESY), BTF-BT (Frascati)

CPS: Main features

The basic working principle

- Secondary charges generated in epi-layer by ionization
  - Signal proportional to epi-thickness
- Charges transport driven by 3 potentials
  - P-well/coll. node/P++ (usually GND/few volts/GND)
- Epi-layer not fully depleted: $d_{dep} \sim 0.3 \sqrt{\rho_{sub} \times U_{bias}}$

  $\Rightarrow$ transport is mix of thermal diffusion & drift



Prominent features

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

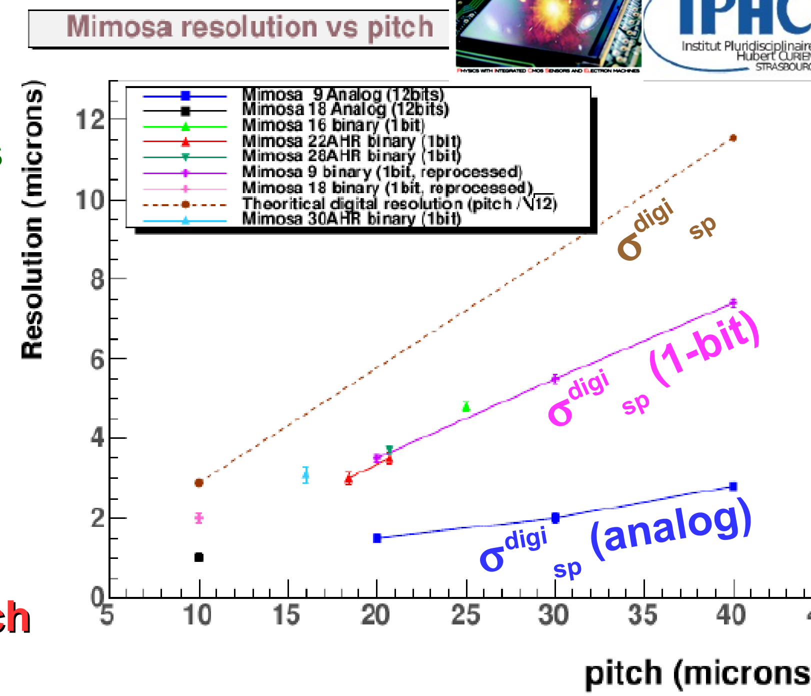
CPS technology developments

- Mainly driven by commercial applications $\Rightarrow$ Not fully optimized for particle detection
- R&D largely consists in exploiting as much as accessible industrial processes

CPS performances: Spatial Resolution (σ_{sp})

- **Several parameters govern σ_{sp}**
  - **Pixel pitch**
  - **Epi-layer:** thickness & ρ
  - **Sensing node:** geometry & electrical properties
  - **Signal-encoding resolution:** Nb of bits
  - **σ_{sp} function of:**

    pitch ⊕ SNR ⊕ charge-sharing ⊕ ADCu ⊕ ...



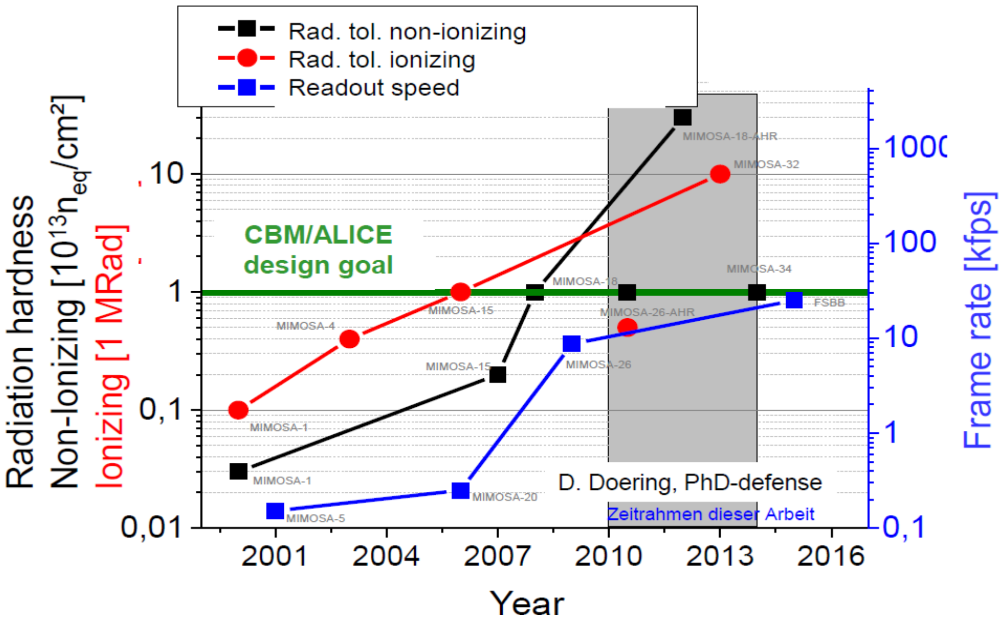
- **Pixel-pitch impact (analogue output)**
  - Pitch = 10 (40) µm ⇒ σ_{sp} ~ 1 µm (≲ 3 µm)
  - **Nearly linear improvement in σ_{sp} vs pixel pitch**

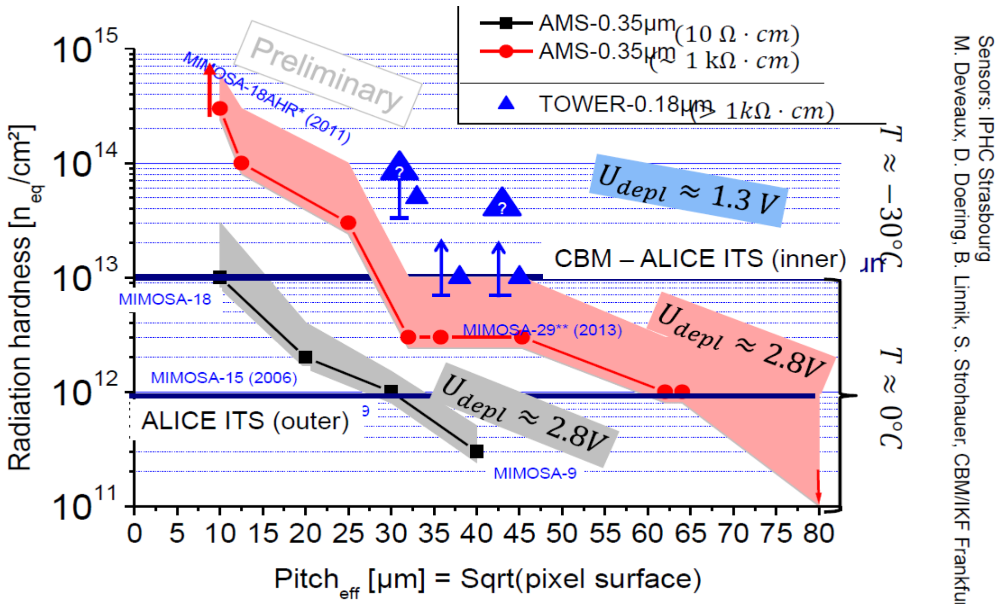
- **Signal-encoding impact (digital output)**
  - σ^{digi}_{sp} = pitch/(12)$^{1/2}$

    ⇒ e.g. σ^{digi}_{sp} ~ 5.7 µm for 20 µm pitch
  - **Significant improvement in σ_{sp} by increasing signal encoding resolution**

Nb of bits	12	3-4	1
Data	*measured*	*reprocessed*	*measured*
σ_{sp}	$\lesssim 1.5\mu m$	$\lesssim 2\mu m$	$\lesssim 3.5\mu m$

CPS performances: r.o. speed & rad. hardness





PICSEL GROUP

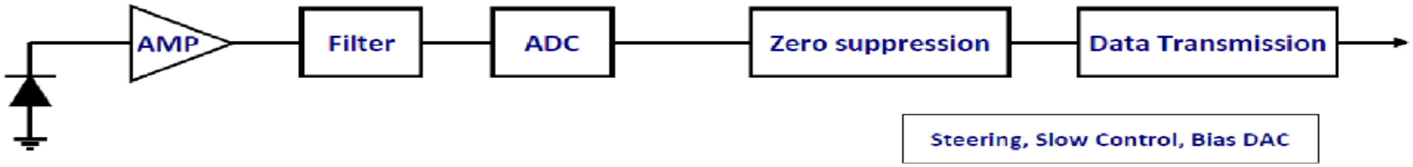
ADvanced MOnolithic Sensors for FAIR

- **15 years of experience of PICSEL group in developing CPS**
- **Strong collaboration with ADMOS group at Frankfurt**

- **r.o. speed evolution**
  - Two orders of magnitude improvement in 15 years of research

- **Radiation tolerance**
  - Significant improvement with time
  - Sensor validation up to 10 MRad ⊗ $10^{14} n_{eq}/cm^2$
  - Adequacy to ALICE-ITS and CBM applications

ALICE-ITS: Readout chain components



Typical readout components

- **AMP:** in-pixel low noise pre-amplifier
- **Filter:** in-pixel filter
- **ADC** (1-bit ≡ discriminator): may be implemented at end-of-column or pixel level
- **Zero suppression** (SUZE): only hit pixel info is retained and transferred
  - Implemented at sensor periphery (usual) or inside pixel array
- **Data transmission:** O(Gbps) link implemented at sensor periphery

r.o. alternatives

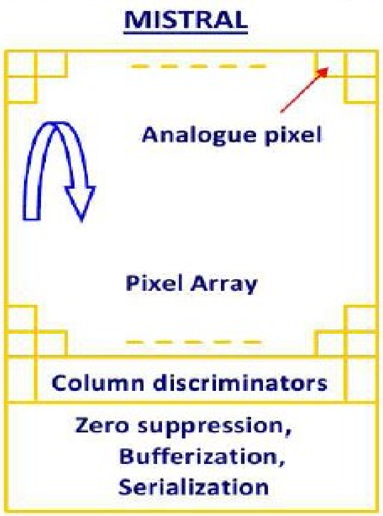
- data-driven (asynchronous): only hit pixels are output upon request (priority encoding)
- Rolling shutter (synchronous): || column r.o. reading N-lines at the time (usually N = 1-2)
  - Best approach for twin-well process

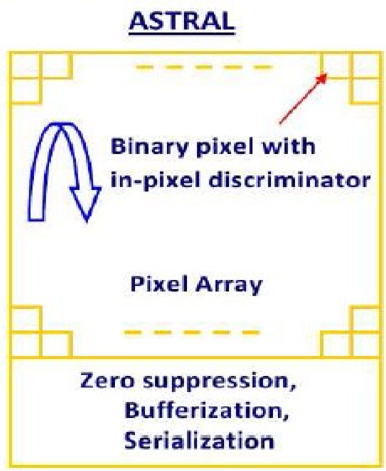
    ⇒ trade-off between performance, design complexity, pixel dimensions, power

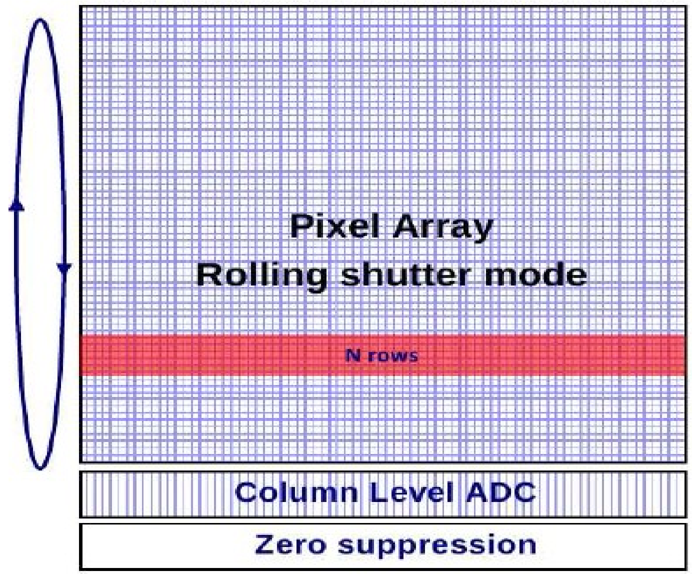
    e.g.: Mimosa-26 (EUDET-BT), Mimosa-28 (STAR-PXL)

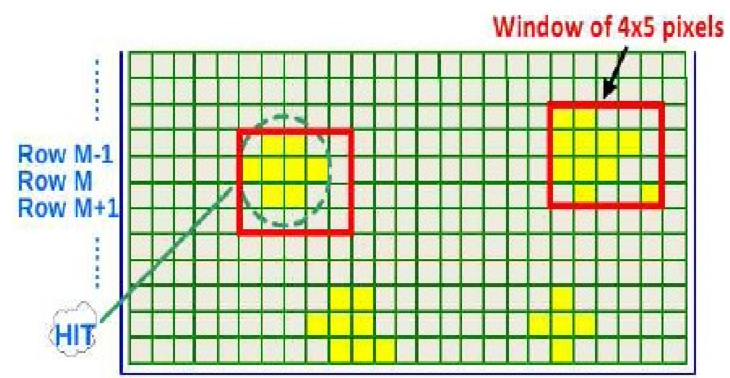
Synchronous readout Architecture: Rolling Shutter Mode

- Design addresses 3 issues
  - Increasing S/N at pixel-level
  - Analogue to Digital Conversion
    - At end of column ⇒ **MISTRAL**
    - Inside pixel ⇒ **ASTRAL**
  - Zero suppression (SUZE) at chip edge









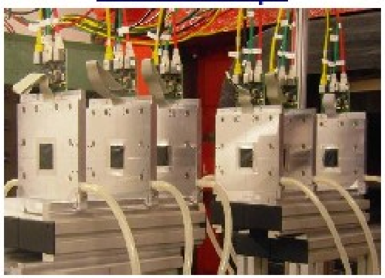
- Power vs Speed
  - Power: only the selected rows (N=1,2,3 …) to be readout
  - Speed: N rows of pixels are readout in ||
    - Integration-time (t_{int}) = frame readout time ⇒ $t_{\text{int}} = \frac{(Row\ readout\ time)\times(No.\ of\ Rows)}{N}$

CPS @ PICSEL - IPHC: A long term R&D

- ***Ultimate objective: ILC, with staged performances***
  - *CPS applied to other experiments with intermediate requirements*

running

EUDET 2006/2010
Beam Telescope

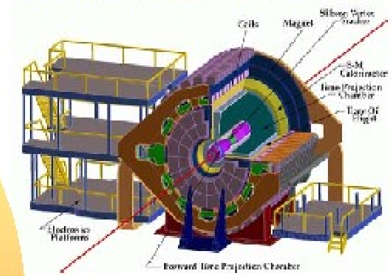


ILC >2020
International Linear Collider

EUDET (R&D for ILC, EU project)
STAR (Heavy Ion physics)
CBM (Heavy Ion physics)
ILC (Particle physics)
HadronPhysics2 (generic R&D, EU project)
AIDA (generic R&D, EU project)
FIRST (Hadron therapy)
ALICE/LHC (Heavy Ion physics)
EIC (Hadron physics)
CLIC (Particle physics)
BESIII (Particle physics)
...

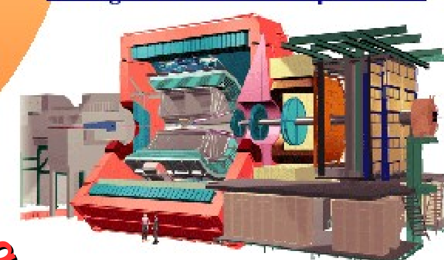
running

STAR 2013
Solenoidal Tracker at RHIC



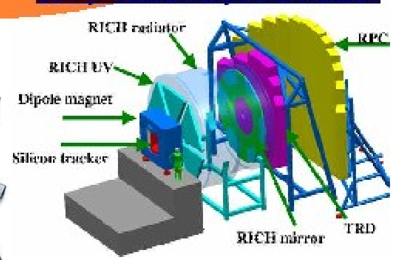
On-going R&D

ALICE 2018
A Large Ion Collider Experiment



On-going R&D

CBM >2018
Compressed Baryonic Matter



On-going R&D

SOLEIL SYNCHROTRON

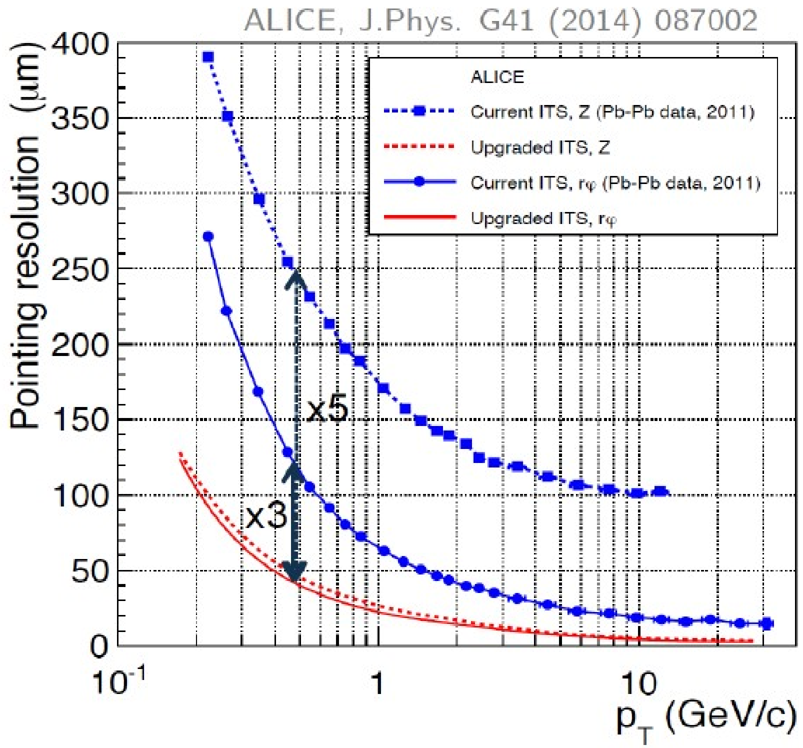
HR-CMOS for X-rays (2018)

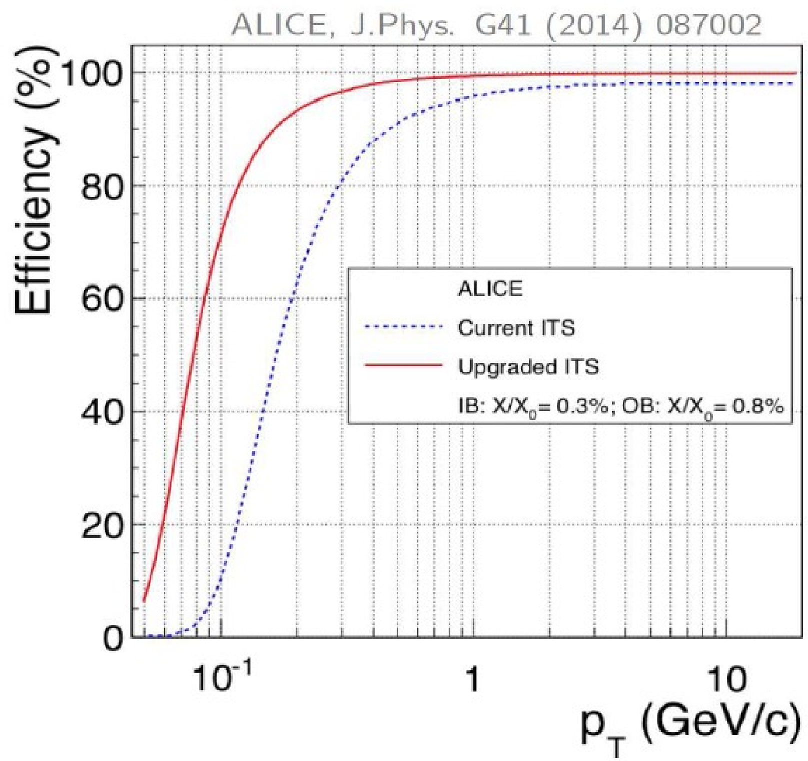
Example of Application : Upgrade of ALICE-ITS

- **ALICE Inner Tracking System (ITS) foreseen to be replaced during LS2/LHC**

  ⟶ higher luminosity (≡ collision rate), improved charm tagging

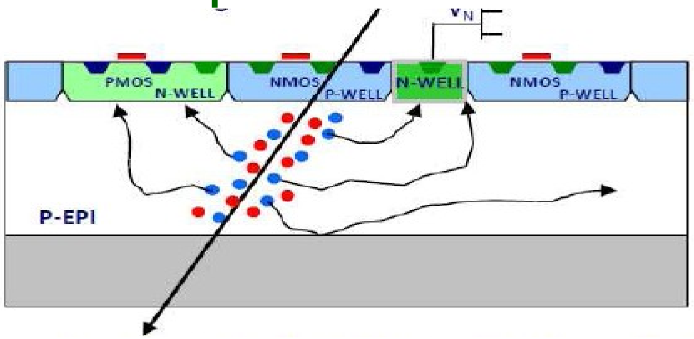
- **Expected improvement in pointing resolution and tracking efficiency**



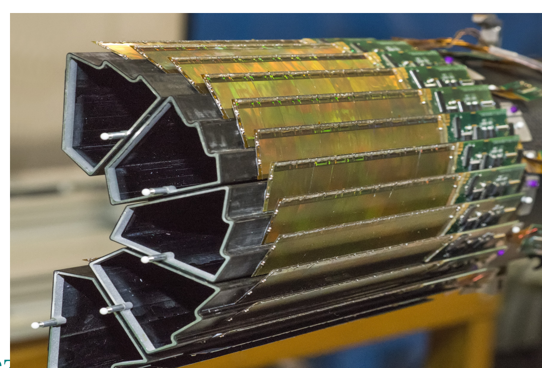


CMOS Process Transition: STAR-PXL → ALICE-ITS

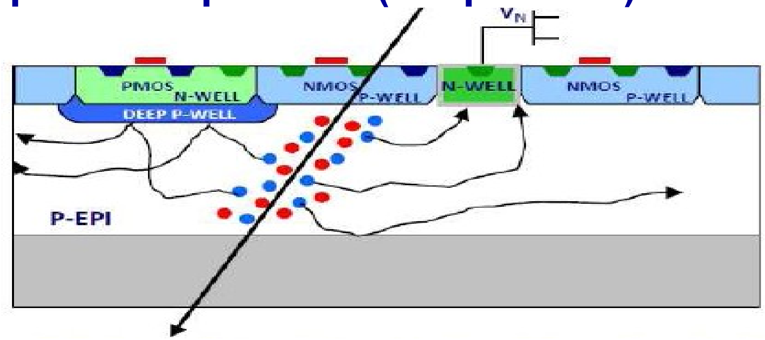
Twin well process: 0.6-0.35 um



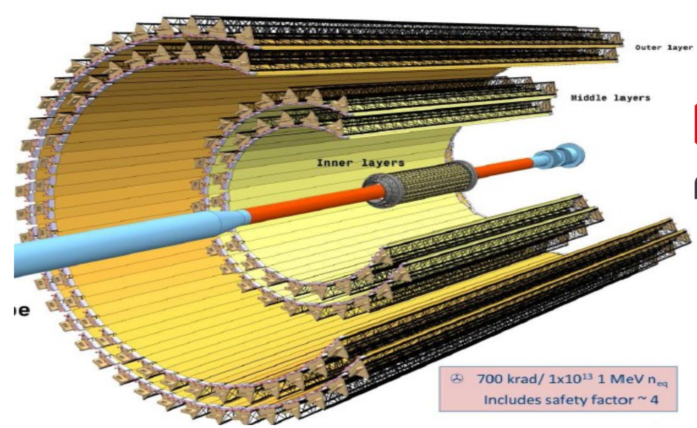
- Use of PMOS in pixel array not allowed
  ⇒ parasitic q-collection of additional N-well
- Limits choice of readout architecture strategy
- Already demonstrated excellent performances
  - **STAR-PXL:** Mi-28 (AMS 0.35 μm process)
    ⇒ $\varepsilon_{det} > 99.5\%$, $\sigma_{sp} < 4\mu m$
  - 1st CPS detector @ collider experiment



Quadrupole well process (deep P-well): 0.18 um



- N-well of PMOS transistors shielded by deep P-well
  ⇒ both types of transistors can be used
- Widens choice of readout architecture strategies
  - **New ALICE-ITS:** 2 sensors R&D in || using TowerJazz CIS 0.18 um process (quadru. well)
    - **Synchronous Readout R&D:** proven architecture ⇒ safety
    - **Asynchronous Readout R&D:** challenging



ALICE

ALICE-ITS: Boundaries of the CPS Development

- **New fabrication process (TowerJazz CIS 0.18 μm)**
  - Expected to be ration tolerant enough
  - Expected to allow for fast enough readout
  - Larger reticule: ~ 25 x 32 mm^2

STAR-PXL	ALICE-ITS	added-value
0.35 μm	0.18 μm	speed, TID, power
4 ML	6 ML	speed. power
twin-well	quadruple-well	speed, power
EPI 14/20 μm	EPI 18/40 μm	SNR
EPI $\gtrsim$ 0.4 k$\Omega \cdot cm$	EPI $\sim$ 1 - 8 k$\Omega \cdot cm$	SNR, NITD

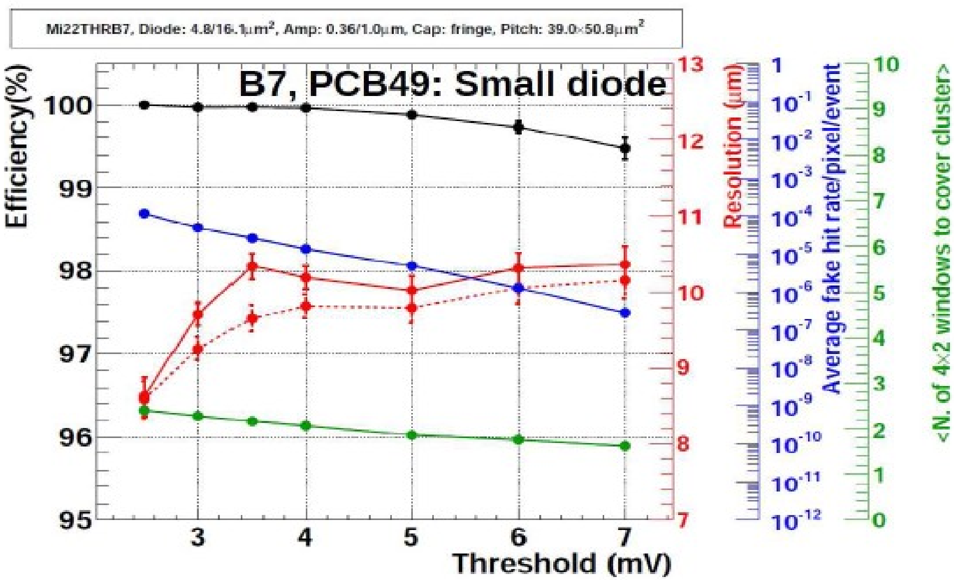
- **Drawback of smaller feature size**
  - 1.8 V operative voltage (instead of 3.3 V)

    ⇒ reduced dynamics in signal processing circuit & epi-layer depletion voltage
  - Increase risk of Random Telegraph Signal (RTS) noise

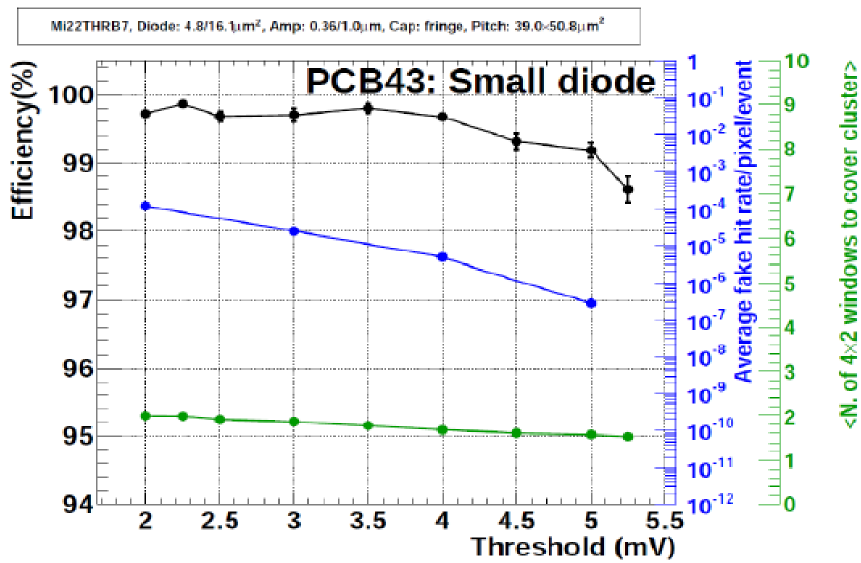
- **Requirements of the larger surface to cover: Mainly outer layers**
  - Good fabrication yield ⇒ sensor design robustness
  - Mitigate noisy pixels
  - Sensor operation stable along 1.5 m ladder (voltage drop)
  - Minimize material budget
    - Minimize power consumption
    - Minimal connexions to the outside

Main MIMOSA-22THRb detection performances (1/2)

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

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

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

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

Main FSBB-M0 detection performances (1/3)

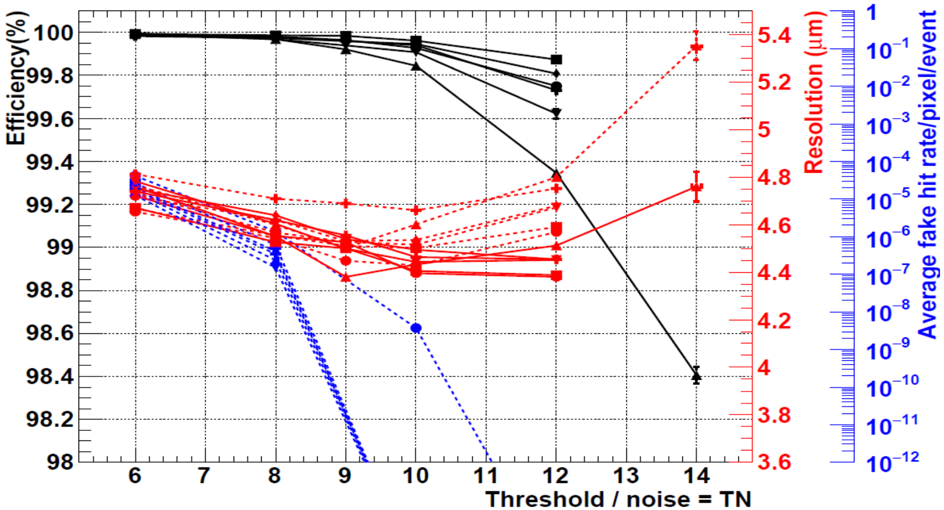
All the 6 sensor performances on the same plot

- Efficiency
- U residue
- V residue
- Fake rate @ 10^{-3} masking

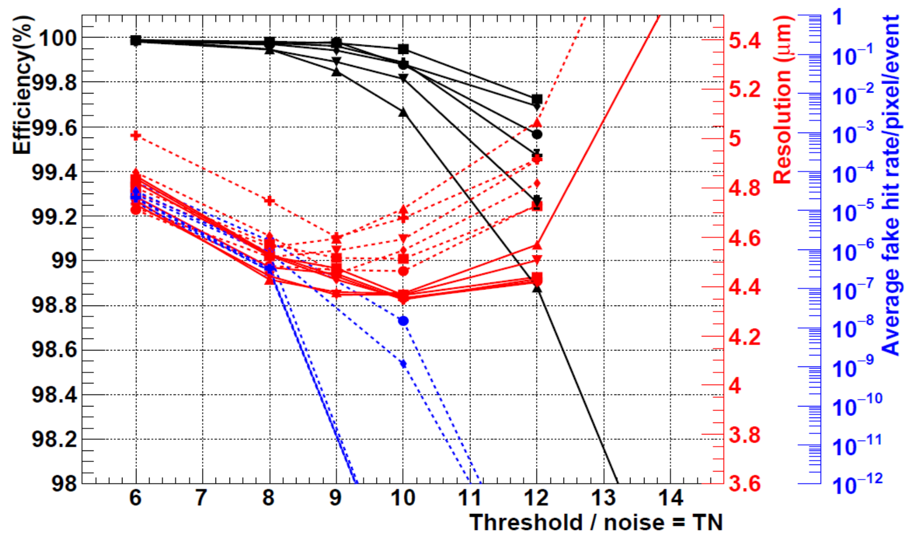
Excellent and uniform performances among sensors (thr < 10xNoise)

- detection efficiency: > 99%
- spatial resolution: < 5µm
- Fake rate: < 10^{-6} with moderate (10^{-3}) hot pixels masking

Diode/Footprint: 8/16 µm²



Diode/Footprint: 9/13.3 µm²



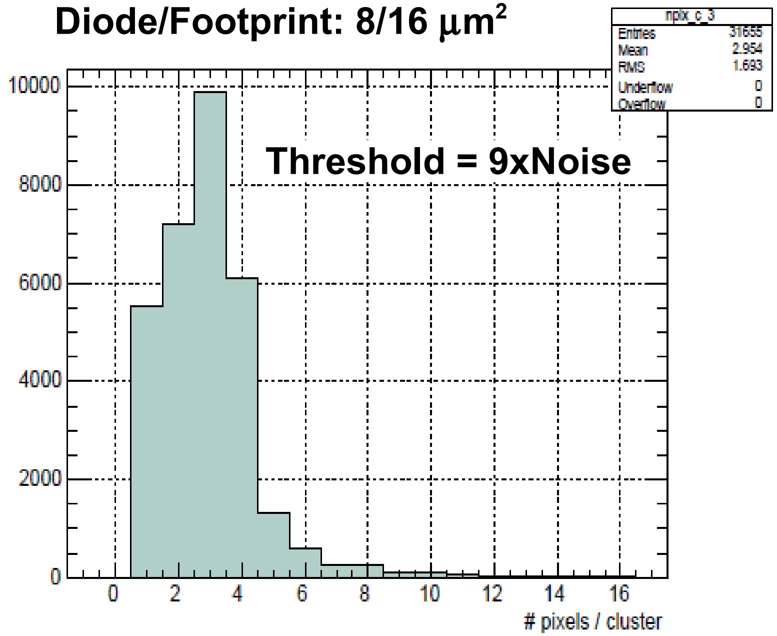
Detection performances stability

- Same results obtained @ DESY (4.5 GeV/c e^-) and CERN-SPS (120 GeV/c π^-)
- Same results for different particles rates: 1 – 25 hits/frame
- Robust performances in terms of operation parameters

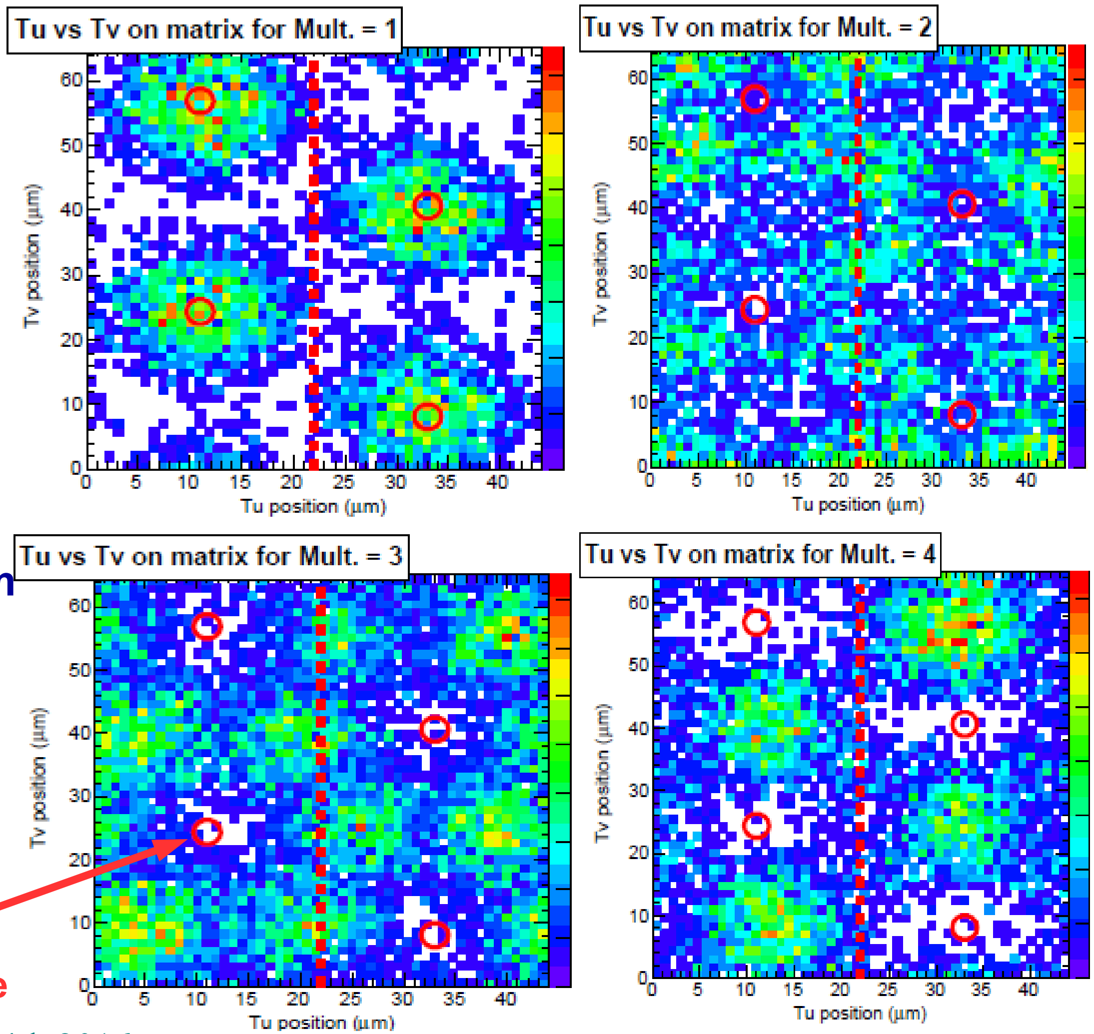
Main FSBB-M0 detection performances (2/3)

- **Spatial resolution vs cluster pixel size**

Diode/Footprint: 8/16 μm^2



Track position @ DUT w.r.t closest set of collection diodes as a function of cluster pixel multiplicity



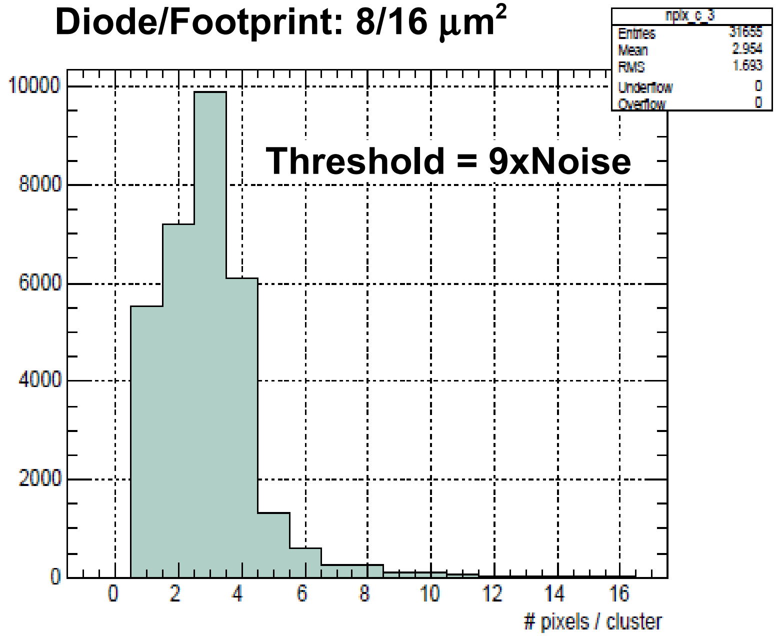
- **Telescope pointing resolution ~2 µm**
- **Charge sharing depends on track impinging position w.r.t coll. diode**

Collection diode

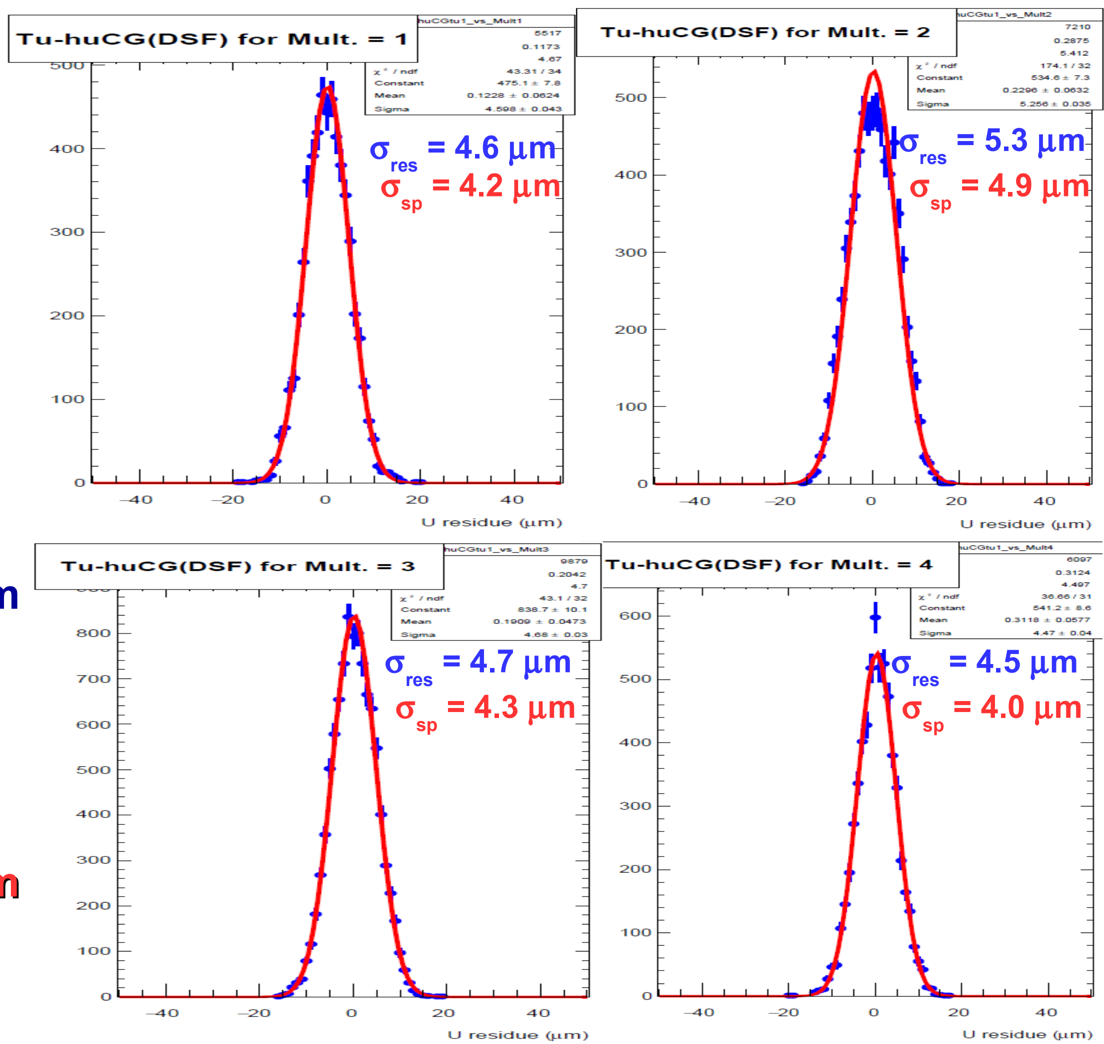
Main FSBB-M0 detection performances (2/3)

Spatial resolution vs cluster pixel size

Diode/Footprint: 8/16 μm^2



Residue distribution in the raw parallel direction as a function of cluster pixel multiplicity

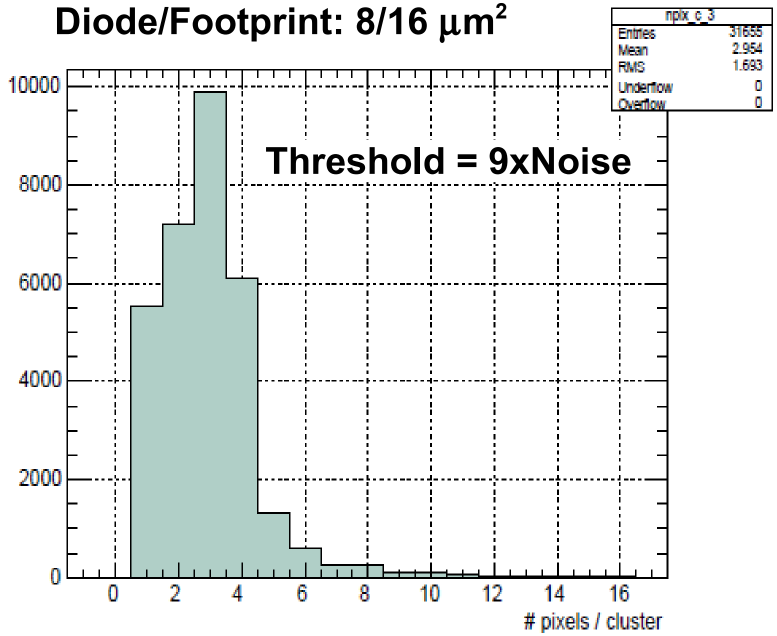


- **Telescope pointing resolution ~2 μm**
- **Charge sharing depends on track impinging position w.r.t coll. diode**
- **Spatial resolution is mostly dependent on # pixels/cluster**
- **σ_{sp}(Mult=1) ~ 4.2 μm < σ^{digi}_{sp} ~ 7.8 μm**

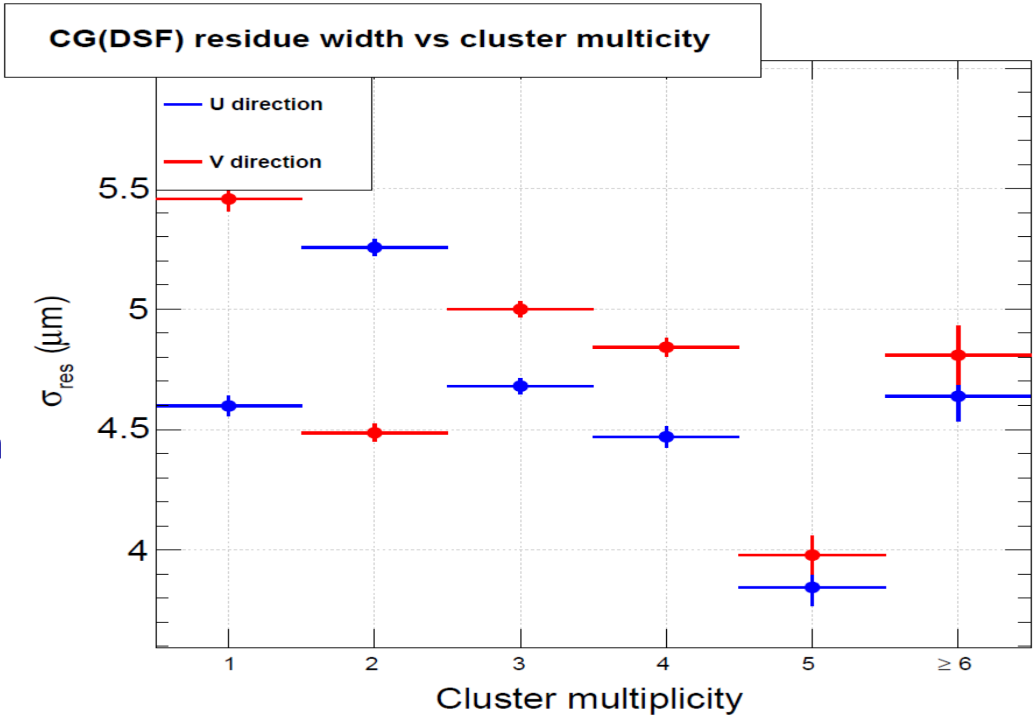
Main FSBB-M0 detection performances (2/3)

- **Spatial resolution vs cluster pixel size**

Diode/Footprint: 8/16 µm^2



Residue RMS in the raw/column parallel direction as a function of cluster pixel multiplicity



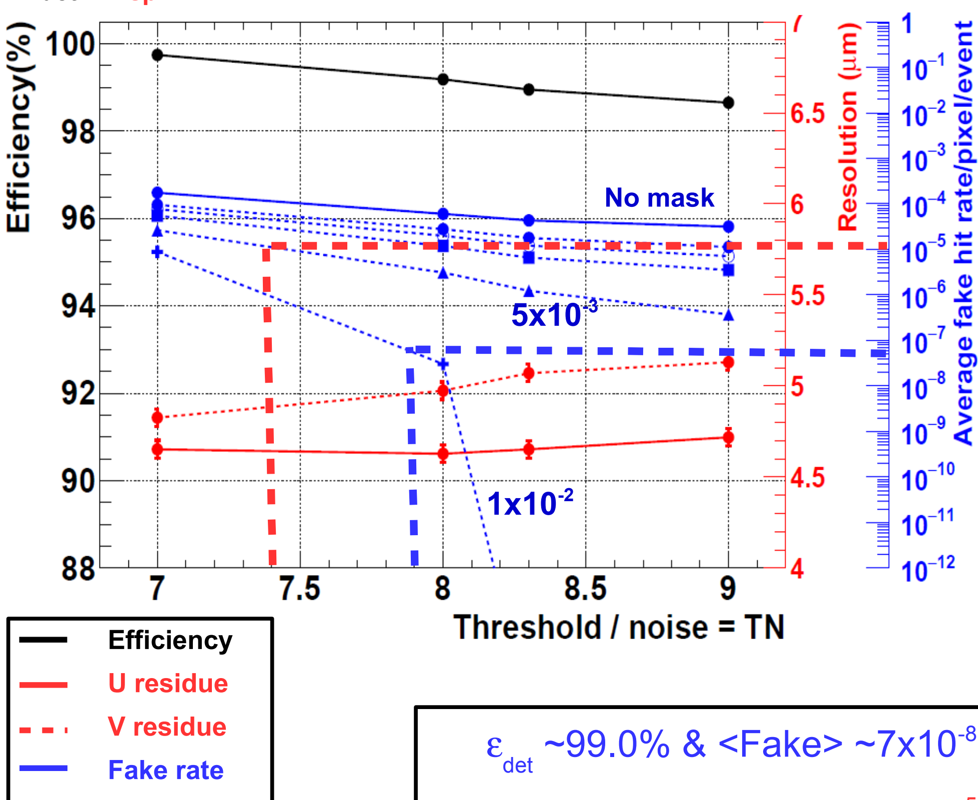
- **Telescope pointing resolution ~2 µm**
- **Charge sharing depends on track impinging position w.r.t coll. diode**
- **Spatial resolution is mostly dependent on # pixels/cluster**
- **σ_{sp}(Mult=1) ~ 4.2 µm < σ^{digi}_{sp} ~ 7.8 µm**
- **Staggering mitigates σ_{sp} difference in raw/column directions**

Main FSBB-M0 detection performances (3/3)

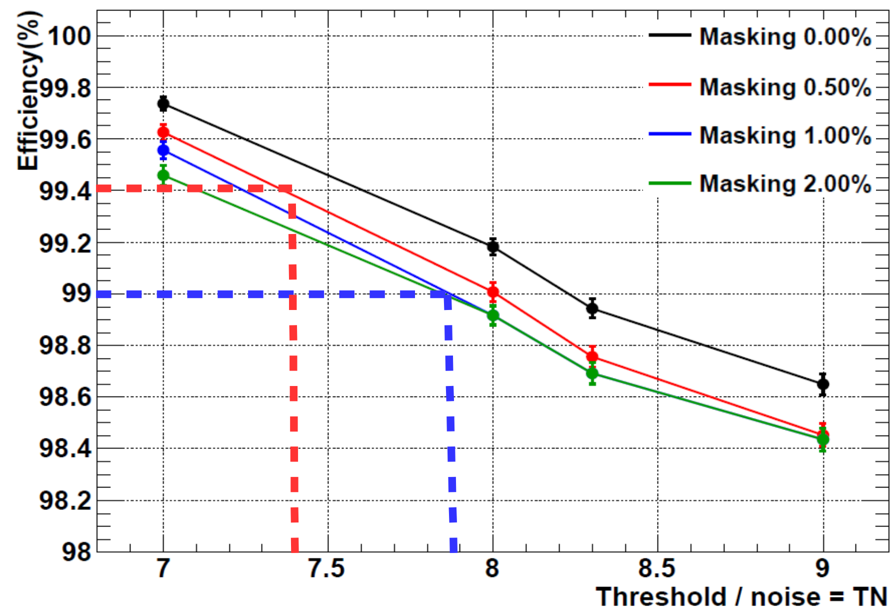
- **Study of rad. tolerance @ T $\gtrsim$ 30 °C:** loads relevant to ALICE-ITS inner layers
  - **Load:** 1.6 MRad ⊕ $10^{13} n_{eq}/cm^2$

Diode/Footprint: 9/13.3 μm^2

ε_{det}, σ_{sp} & fake-rate vs Discr. Threshold



ε_{det} vs Discr. Threshold vs pixel masking

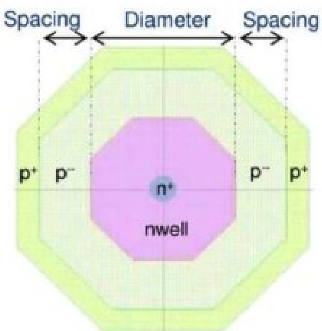


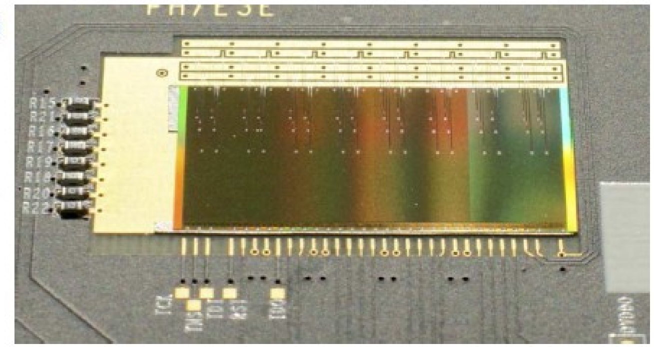
ε_{det} ~99.0% & <Fake> ~7×10^{-8} (1.0% masking) @ Thr = $7.9\times\sigma_{TN}$

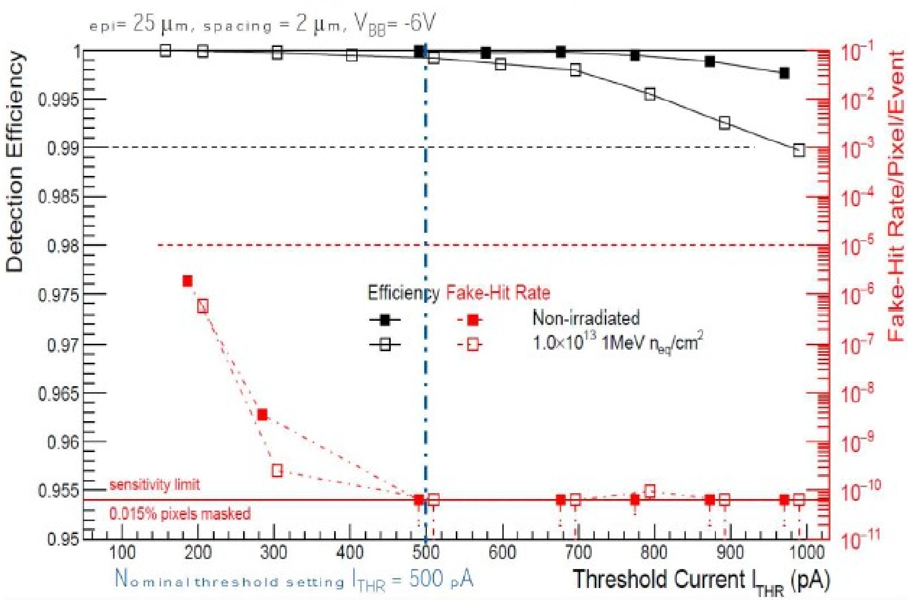
ε_{det} ~99.4% & <Fake> ~1×10^{-5} (0.5% masking) @ Thr = $7.4\times\sigma_{TN}$

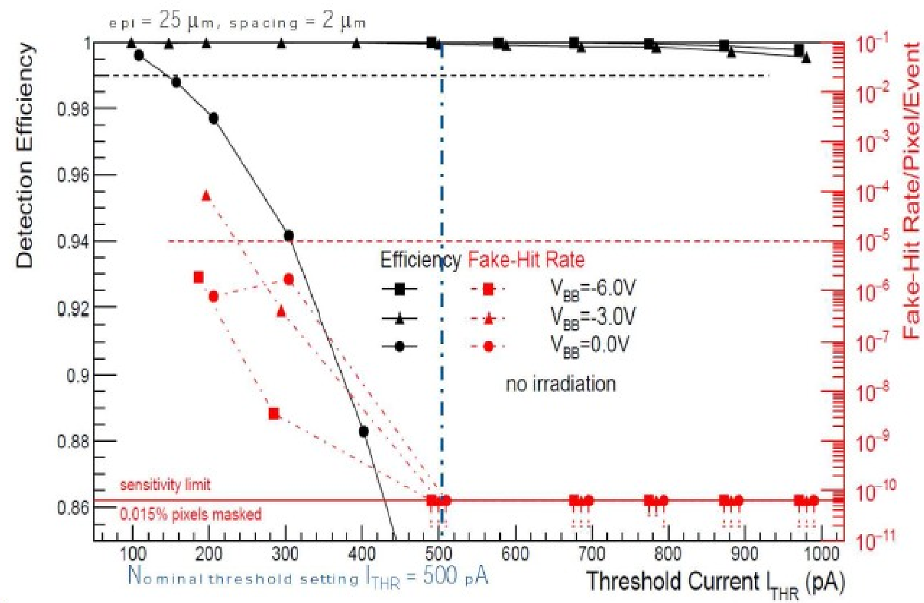
ALPIDE Detection Performance Assessment

- **ALPIDE-2 beam tests :**
  - Final sensor dimensions : 15 mm $\times$ 30 mm
  - About 0.5 M pixels of 27 μm $\times$ 29 μm
  - Various sensing node geometries studied
  - Substrate reverse biased for the sake of SNR
    - $\hookrightarrow$ default : - 6 V
  - Possibility to mask pixels (fake rate mitigation)
    - $\hookrightarrow$ default : $\lesssim$ O(10^{-3}) masked pixels

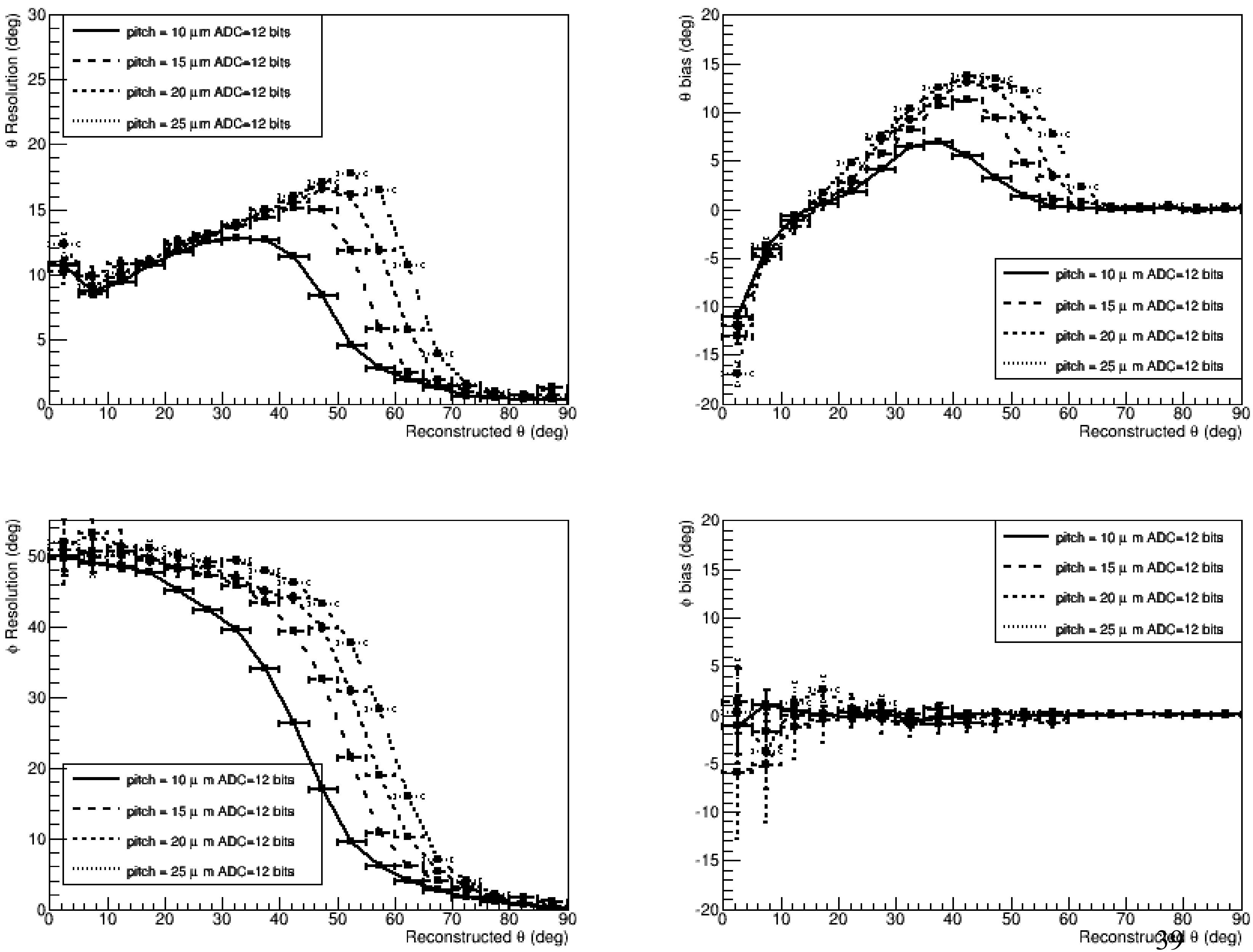




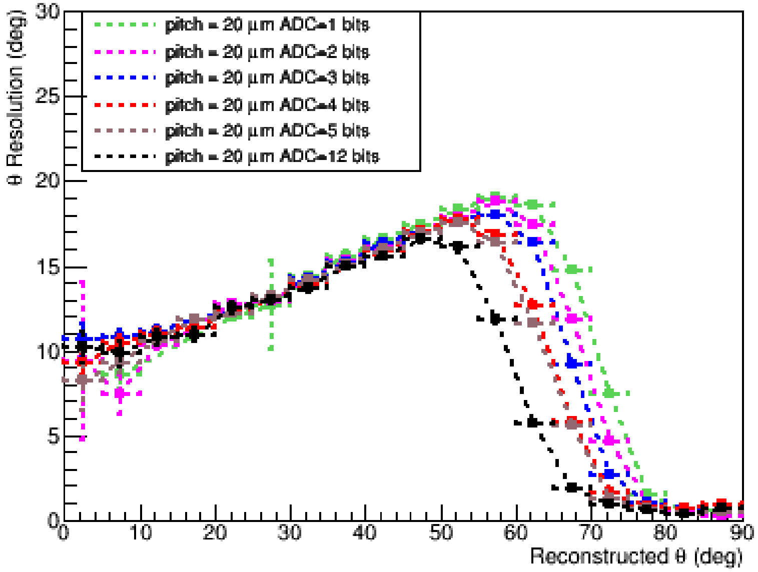


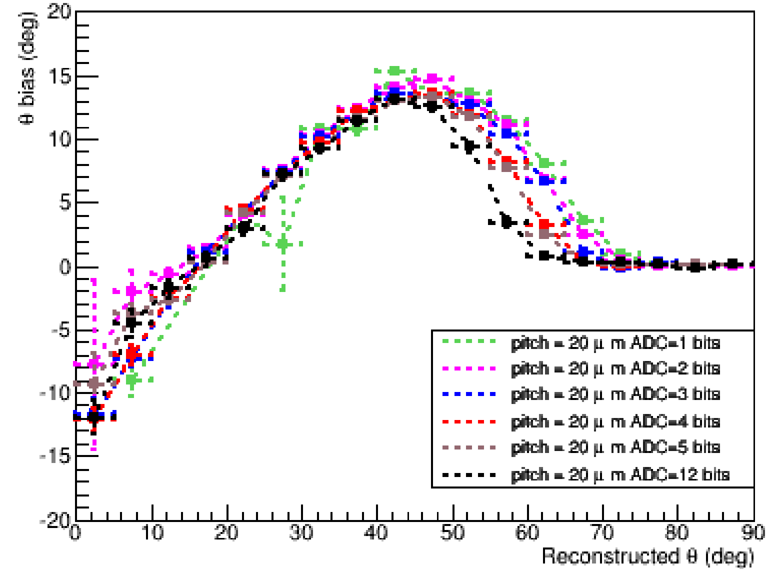


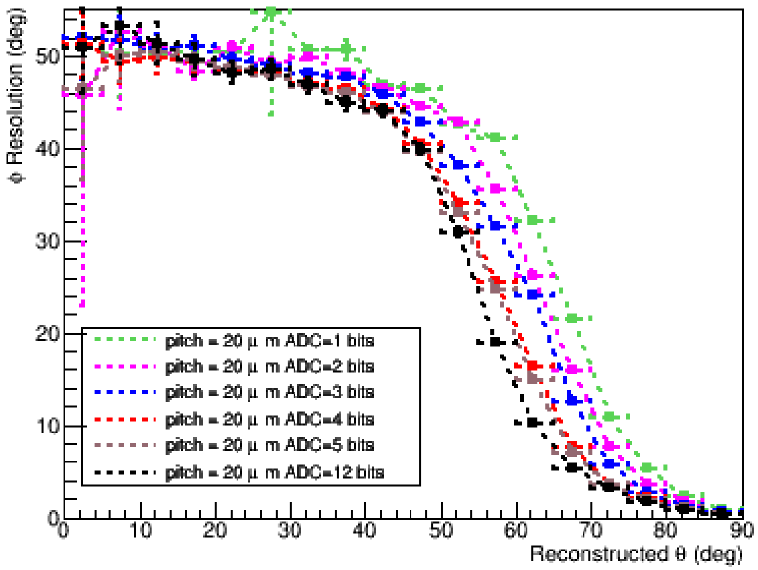
Performances vs pitch (simulations)

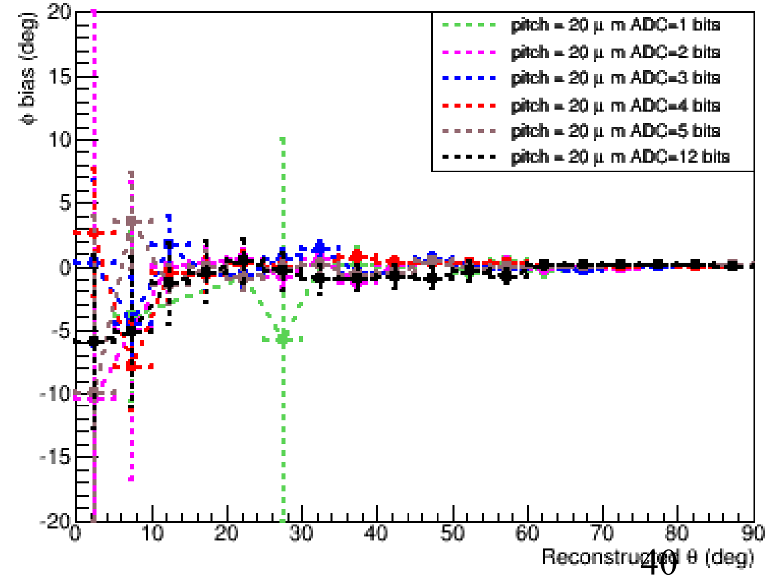


Performances vs ADC (for pitch = 20 µm)

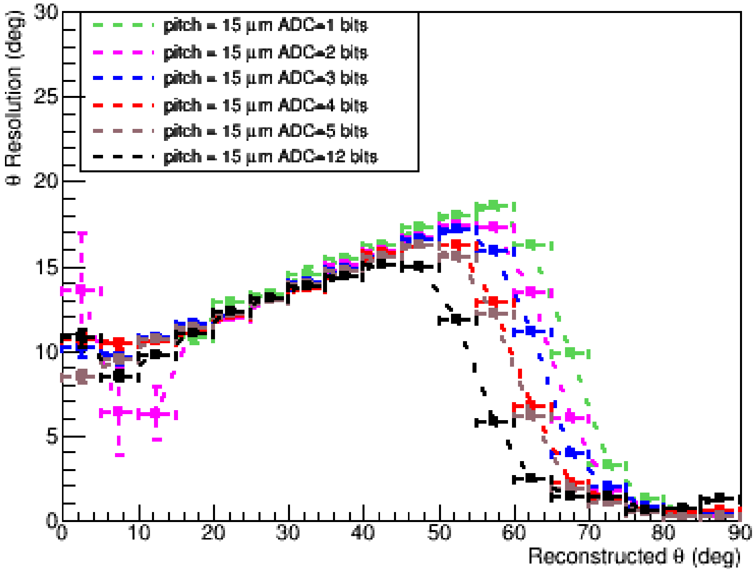


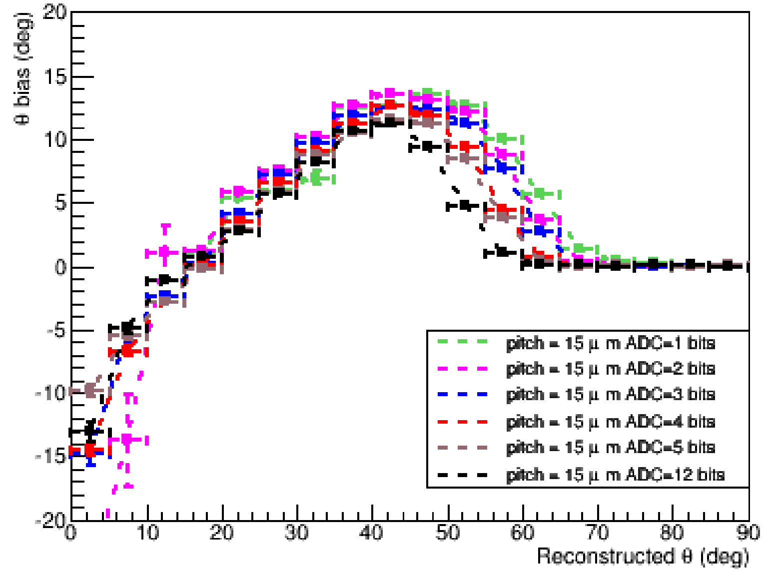


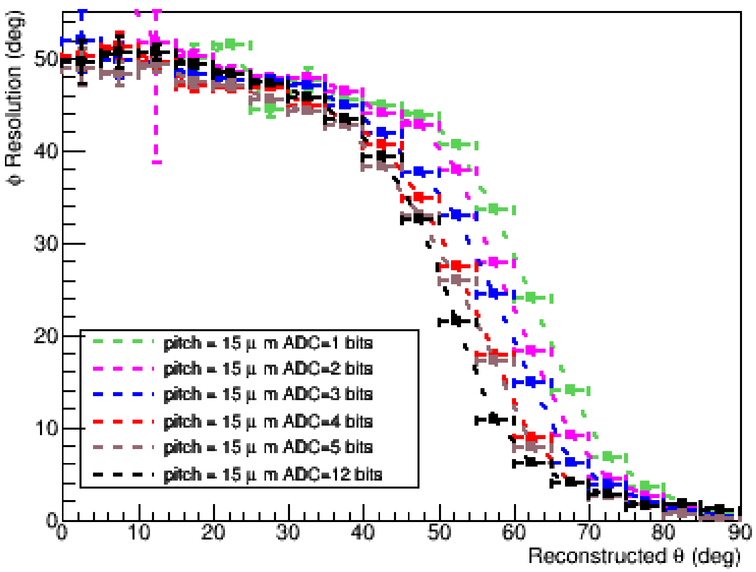


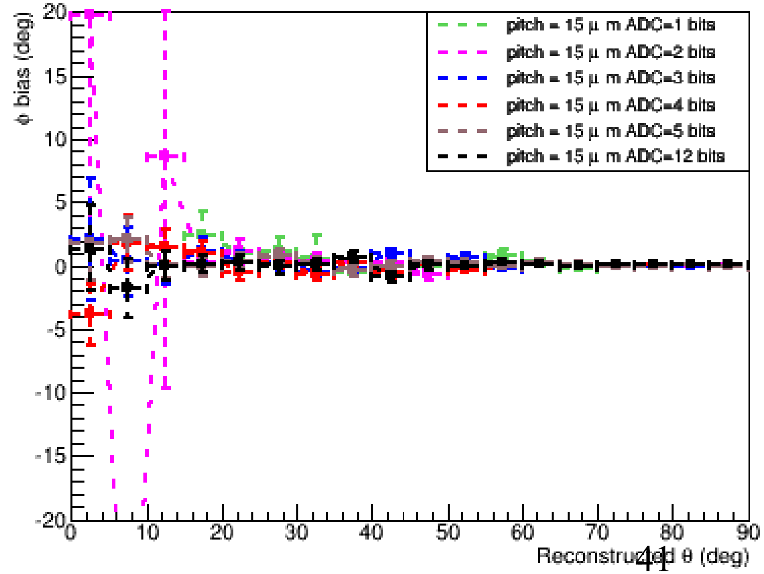


Performances vs ADC (for pitch = 15 µm)



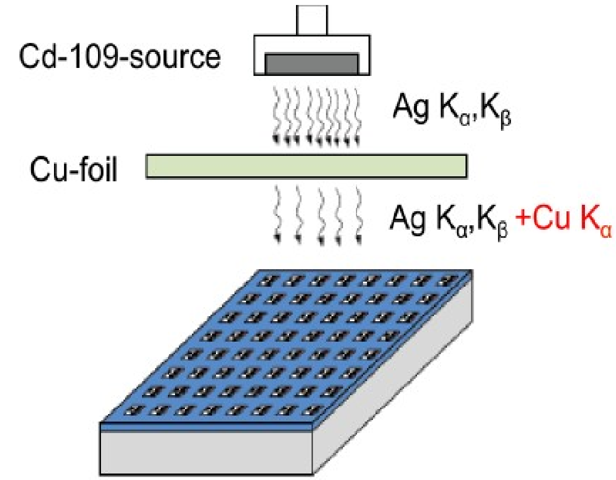


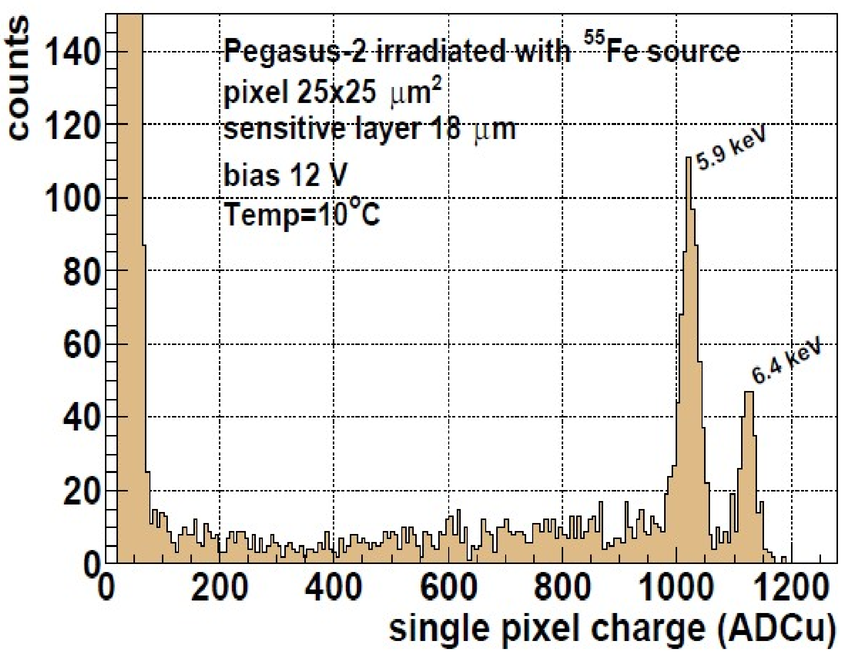


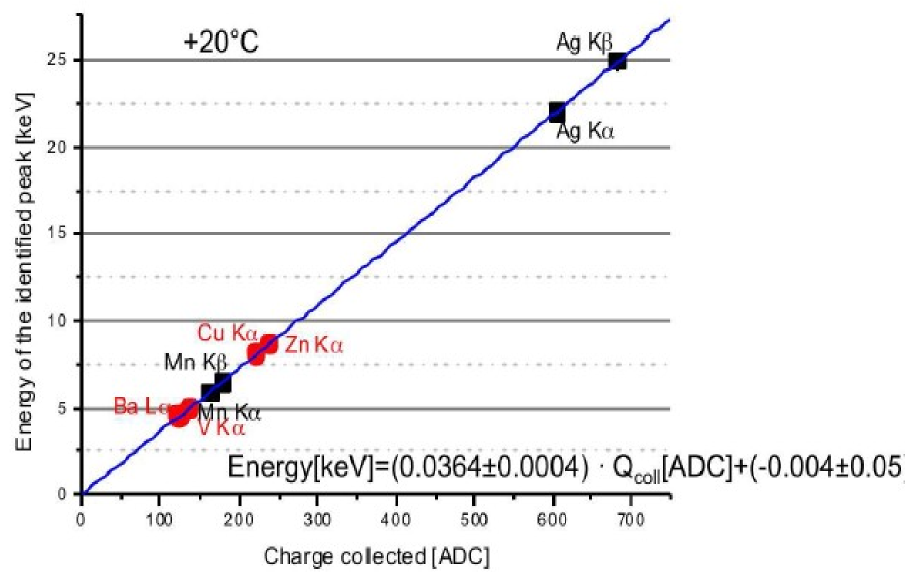


Improving epitaxial-layer depletion: via sensing diode

- **Pegasus-2 sensor:**
  - Tower-Jazz 0.18 CIS process
  - 56 x 8 pixels (25 μm pitch)
  - Epitaxy: 18 μm, 1 k$\Omega \cdot cm$ predominantly depleted
  - TN $\simeq$ 16 $\pm$ 1 e^-ENC at 10°C

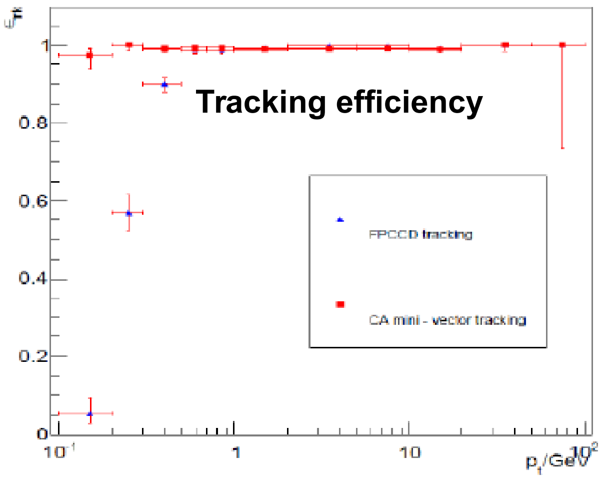


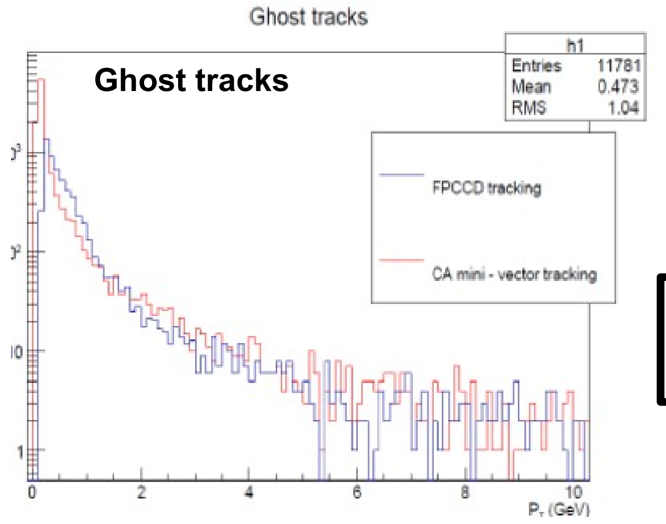




Vertexing, tracking and alignment studies

- **Tracking with mivi-vectors (G. Voutsinas PhD thesis, now @ DESY)**





Sample: ttbar, √s = 500 GeV, fast CMOS VXD, pair bkg overlayed

- **Alignment with mini-vectors (L. Cousin PhD Thesis, defended in 2015)**
  - Use beam-backgrounds particles
    ⇒ low momentum tracks (p $\gtrsim$ few 100 MeV/c)
  - Quick alignment (~10k tracks/hour)
  - Expect a sub-micron precision