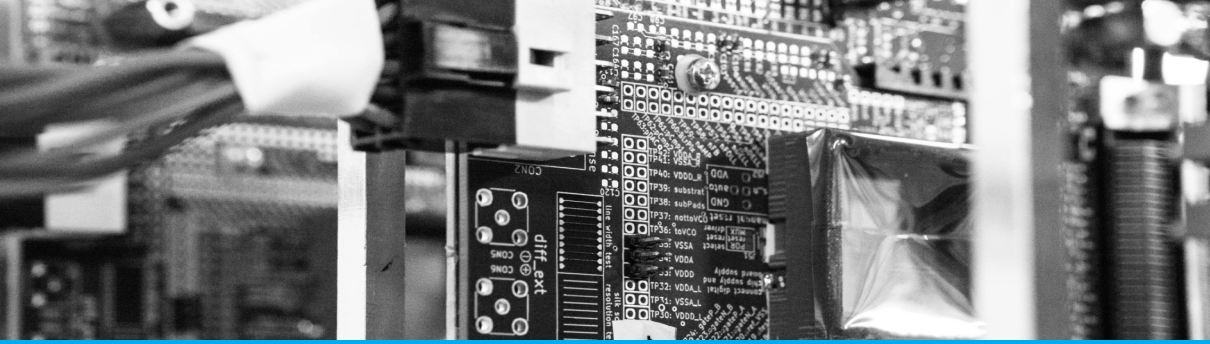


MuPix10: An Unexpected Journey

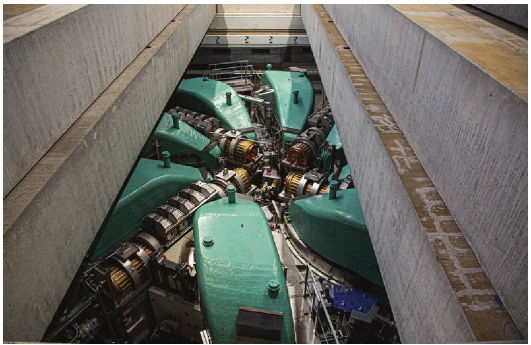
David Maximilian Immig

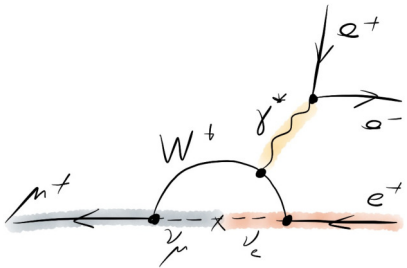
30.03.2022

Bundesministerium
für Bildung
und Forschung

Searching for $\mu^+ \to e^+e^-e^+$ (Mu3e)

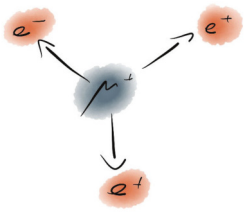
- charged lepton flavor violating decay heavily suppressed to a BR $\leq 10^{-54}$
- excellent probes for new physics
- current upper limit set by SINDRUM (1988) to $\leq 10^{-12}$ [doi.org/10.1016/0550-3213(88)90462-2]





- Mu3e: aimed sensitivity of 1 in $10^{15(16)}$ decays in Phase-I(II)
- high intensity muon beam of $10^9\,\mu^+/s$ provided by Paul-Scherrer Institut (PSI) in form of the "High Intensity Muon Beam" (HIMB)

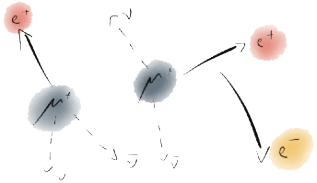
Signal & Background



Signal decay:

- $\mu^+ \rightarrow e^+e^-e^+$ at rest
- share same vertex
- $\sum p_e = m_\mu$

$\rightarrow$ $p_e \leq \frac{1}{2} m_\mu \approx 53\,\mathrm{MeV/c}$



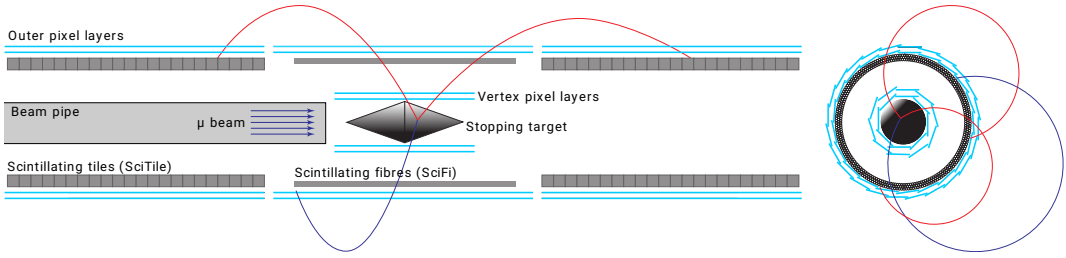
Accidental Background:

- composition of multiple muon decays
- demands good vertex and time resolution

Internal Conversion

- $\mu^+ \rightarrow e^+e^-e^+\nu\bar{\nu}$
- demands excellent momentum reconstruction to detect missing energy carried by neutrinos

The Mu3e Detector (Phase-I)



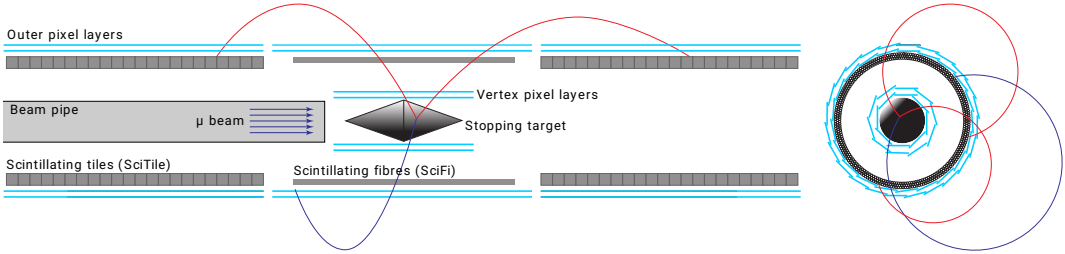
[F. Meier Aeschbacher et al. arXiv:2003.11077]

- muons stopped at mylar target and decay at rest within $1\,\mathrm{T}$ solenoid field
- helium atmosphere for cooling and material minimisation

$\rightarrow$ scattering $\sim \frac{1}{p}\sqrt{\frac{x}{X_0}}$

- ultra thin layers of pixel sensors ($x/X_0 \approx 0.1\,\%$) $\rightarrow$ HV-MAPS
- scintillating fiber and tile detector for precise timing information
- recurl stations for precise momentum reconstruction

The Mu3e Detector (Phase-I)



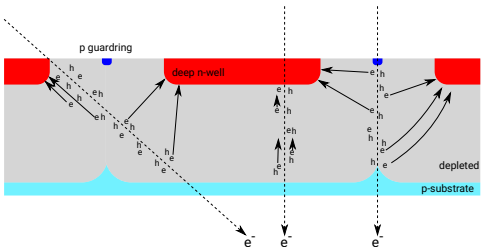
[F. Meier Aeschbacher et al. arXiv:2003.11077]

Mu3e pixel sensor specifications [Mu3e TDR Phase-I arXiv:2009.11690]:

pixel size [μm^2]	80×80
sensor size [mm^2]	20×23
active area [mm^2]	20×20
sensor thickness [μm]	50
maximum bandwidth [Gbit/s]	3×1.6

spatial resolution [μm]	$\leq$ 30
time resolution [ns]	$\leq$ 20
efficiency [%]	$\geq$ 99
noise rate [$Hz/Pixel$]	$\leq$ 20
power consumption [mW/cm^2]	$\leq$ 350

High-**V**oltage **M**onolithic **A**ctive **P**ixel **S**ensor (**HV-MAPS**)



Monolithic design:

- active matrix & readout in one entity
- in-pixel eletronics

Commercially available processes:

- HV-CMOS processes up to 120 V
- AMS 180 nm & TSI 180 nm

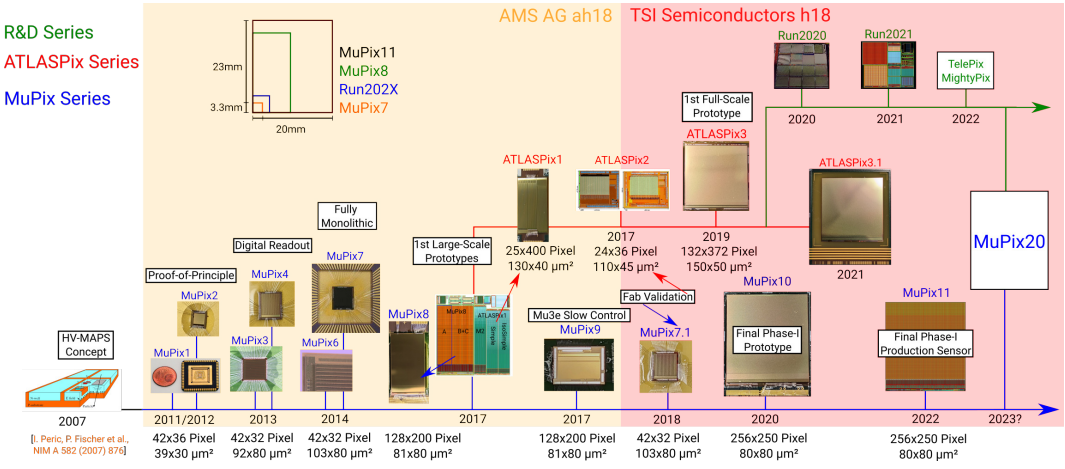
Characteristics:

- low-ohmic substrate (10-200 Ω cm)
- deep n-well diode is reversely biased

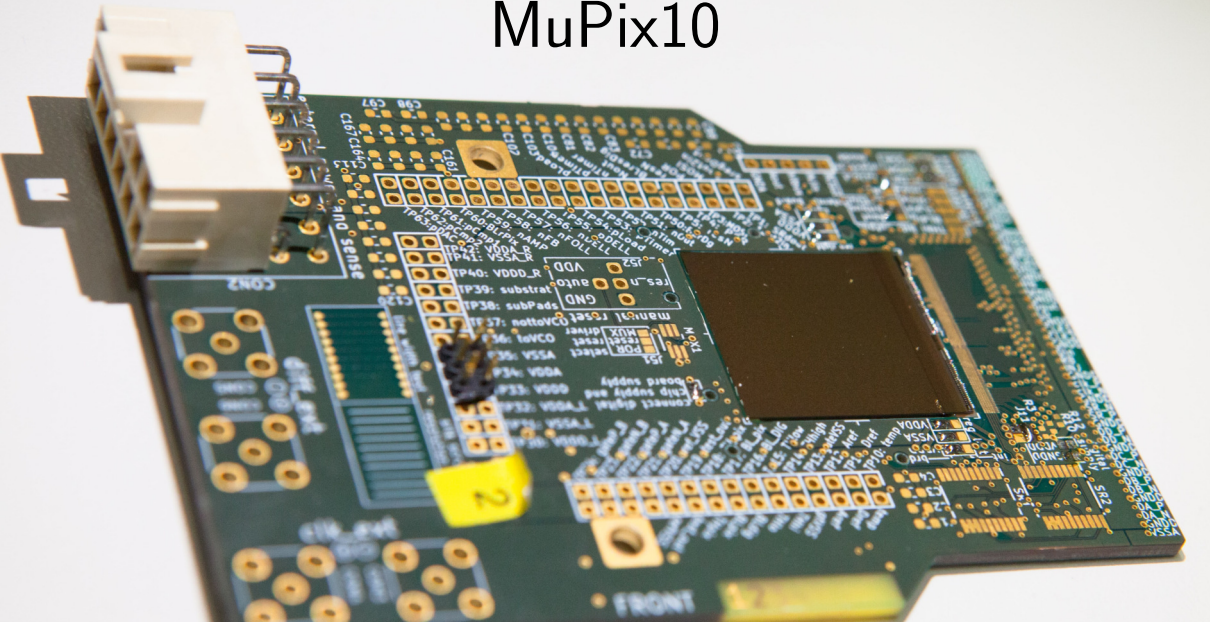
→ ∼10-30 µm depletion zone allows fast charge collection via drift

- chips can be thinned to 50 µm

HV-MAPS Roadmap

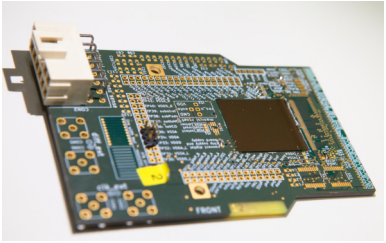


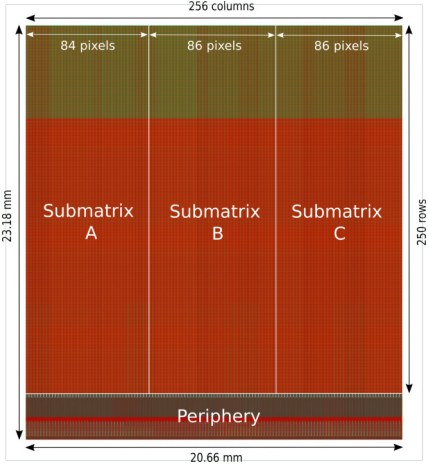
MuPix10



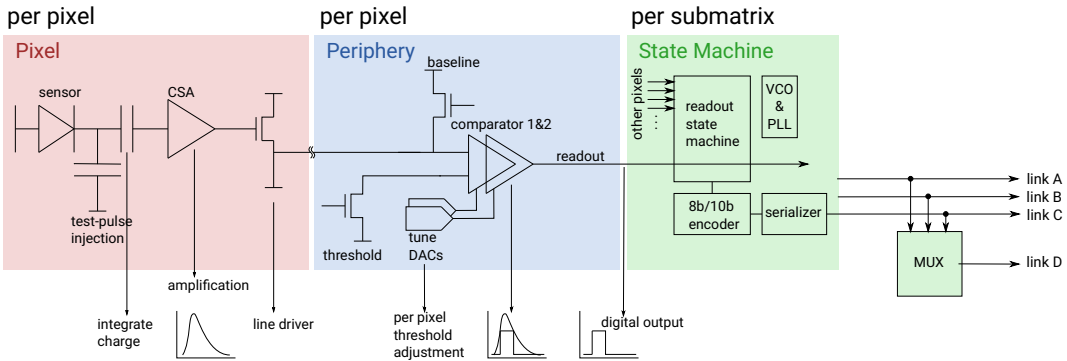
MuPix10 Specification

Substrate [$\Omega\,\mathrm{cm}$]	20, 200
Thickness [µm]	50-70, 100, 650
Matrix [pixel]	256×250
Pixel size [$\mu\mathrm{m}^2$]	80×80
Active area [mm^2]	20.48×20.0
ToA+ToT [bits]	11+5
Tuning+Masking [bits]	2x3+1
LVDS links	3+1



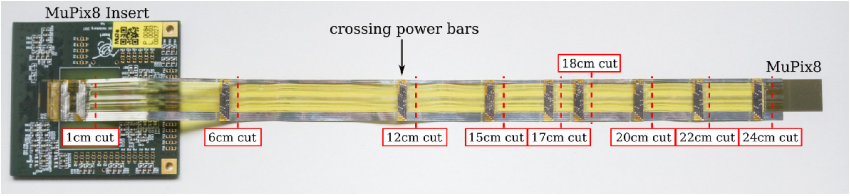


Readout Structure: MuPix10



[H. Augustin arXiv:2012.05868]

High Density Interconnects (HDI) Flexprints

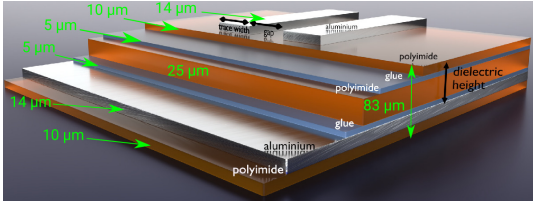


[F. Meier Aeschbacher et al. arXiv:2003.11077]

- provides all electrical connections

→ SpTa-bonded to Sensors

- provides HV, bias voltage, clock, differential input & output links for up to 6(18) sensors in the inner(outer) layers



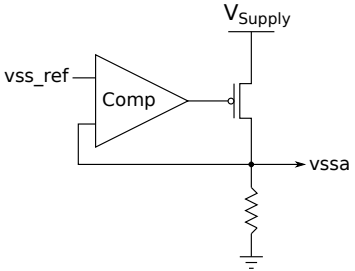
[L.O.S. Noehte Master Thesis] (modified)

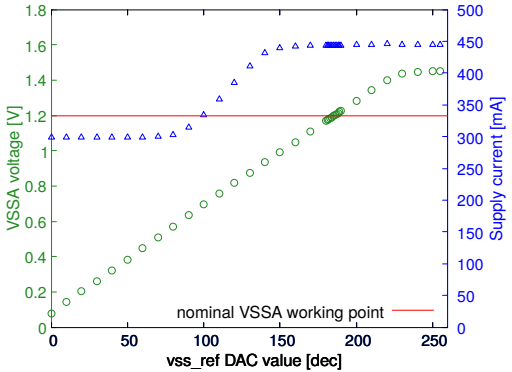
VSSA Regulator: Powering of the CSA

- linear series regulator with differential amplifier for level adjustments (see [PhD Thesis A. Weber])

→ configurable by the reference value vss_ref

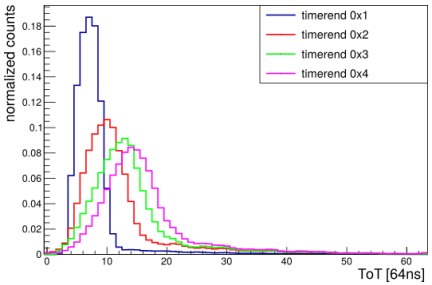
⇒ MuPix10 operational via 1 supply voltage (+HV)



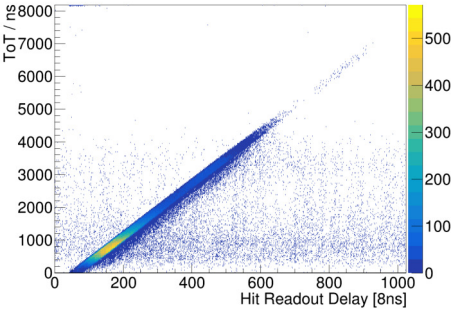


[H. Augustin arXiv:2012.05868]

Time-over-Threshold (ToT) Sampling



[J. Hammerich Master Thesis]



- MuPix8: Falling Edge Timestamp (TS2) is sampled when hit is read out

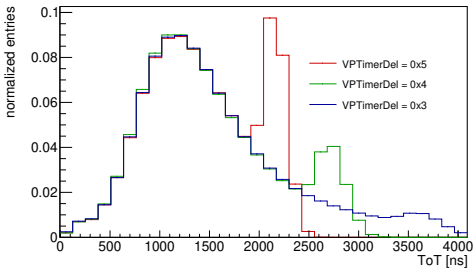
⇒ affacted by speed of state machine (decreases readout Speed)

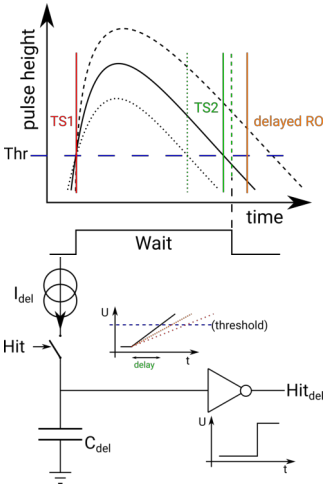
- ATLASPix3: Hit read out after TS2 sampling

⇒ readout latency of hit depends on ToT (disturbs data chronology)

ToT Sampling: Maintain Data Chronology & RO-Speed

1. hit is registered and its readout is withhold
2. current source (adjustable by 6 bit DAC: VPTimerDel) charges a capacitance
3. discriminating element enables RO if rising voltage crosses threshold (ToT is sampled now at the latest)



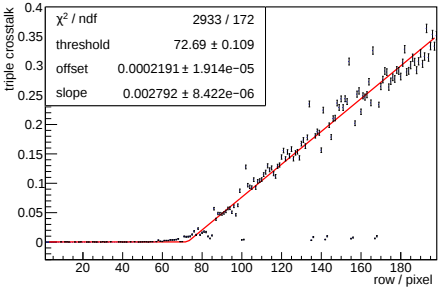


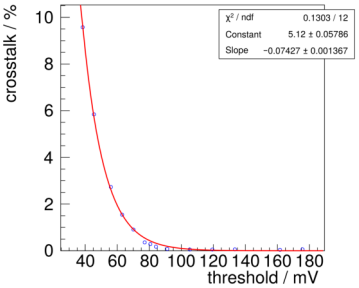
[H. Augustin arXiv:2012.05868]

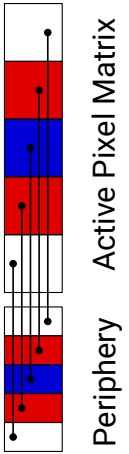
Signal Line Crosstalk MuPix8

- neighbouring lines form parallel plate capacitor → scales with adjacent length

⇒ a signal can create cross talk pulses in neighbouring signal lines



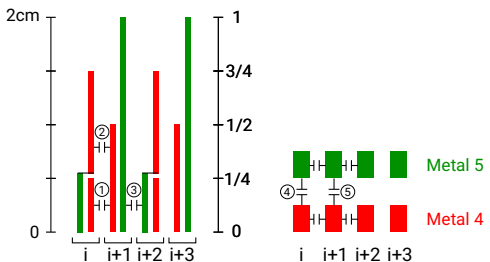




[L. Huth doi:10.11588/heidok.00025785]

Minimise Signal Line Crosstalk for MuPix10

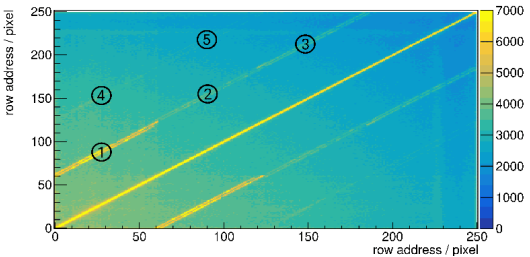
2 metal layers: each 125 lines/column

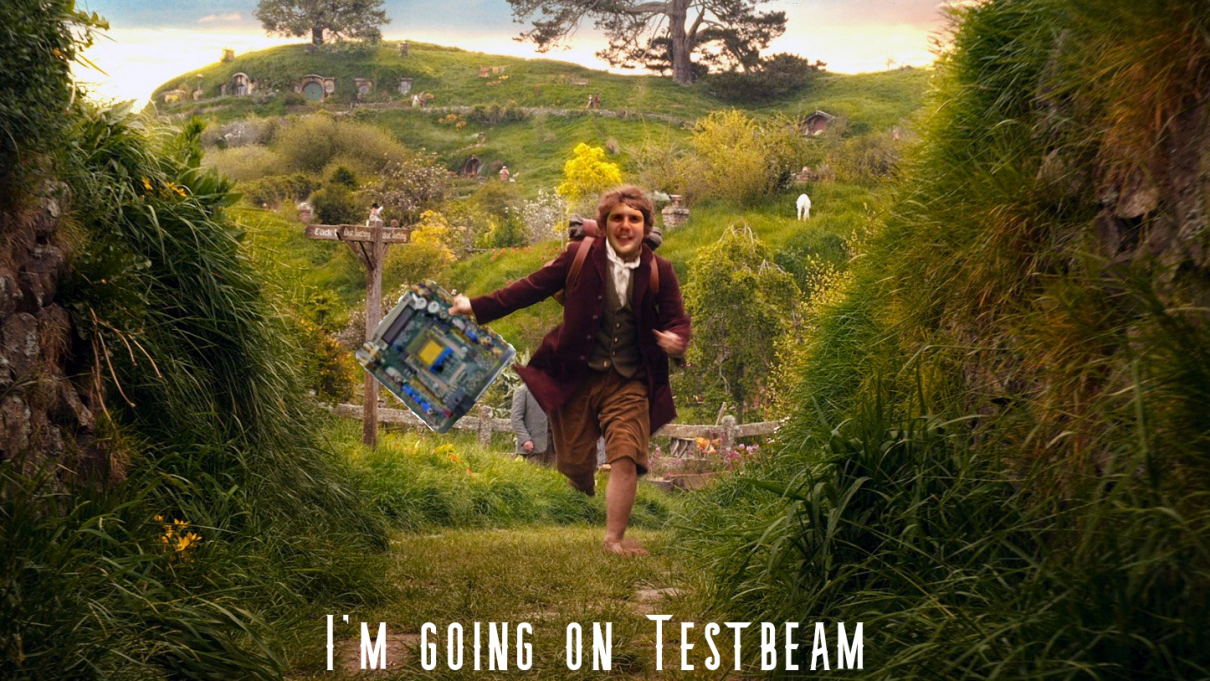


[H. Augustin arXiv:2012.05868]

1. reduce neighbouring line length (1/4 of maximal length)
2. distinguish cross talk hits with recognisable patterns
   - off diagonal correlation → cross talk

⇒ Estimated crosstalk probability <1.5 %

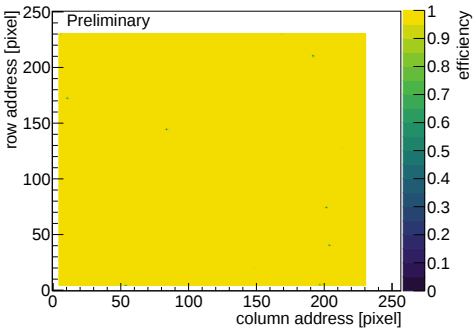


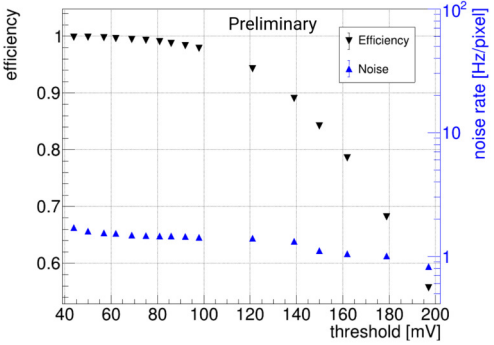

I'm going on Testbeam

First Results of MuPix10 (100 µm, 200 Ω cm) [Oct. 2020]

- 1 external supply voltage (usage of VSSA regulator) + HV
- w/o threshold tuning or pixel masking

Efficiency	$> 99\,\%$
Noise Rate	$< 2\,\mathrm{Hz/Pixel}$
Power Consumption	$< 200\,\mathrm{mW/cm^2}$



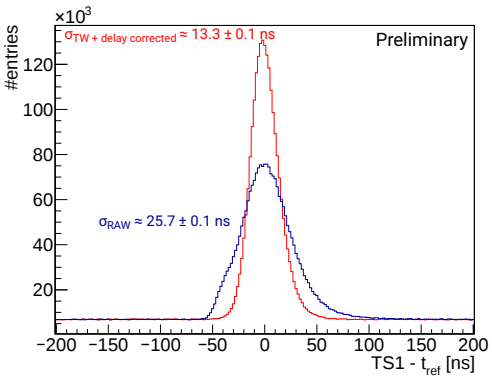


First Results of MuPix10 (100 µm, 200 Ω cm) [Oct. 2020]

Efficiency	$> 99\,\%$
Noise Rate	$< 2\,\mathrm{Hz/Pixel}$
Power Consumption	$< 200\,\mathrm{mW/cm^2}$
Time resolution RAW	$25.7\,\mathrm{ns}$
Time Resolution corrected	$13.3\,\mathrm{ns}$

- the measured time resolution on test beam is worse than expected

→ MuPix8:
time resolution raw $\mathcal{O}(11\,\mathrm{ns})$
time resolution corrected $\mathcal{O}(7\,\mathrm{ns})$
[J. Hammerich, Master Thesis]

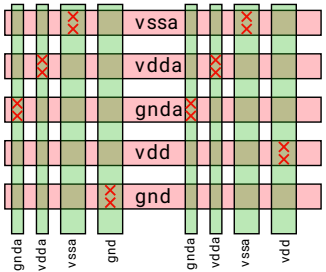


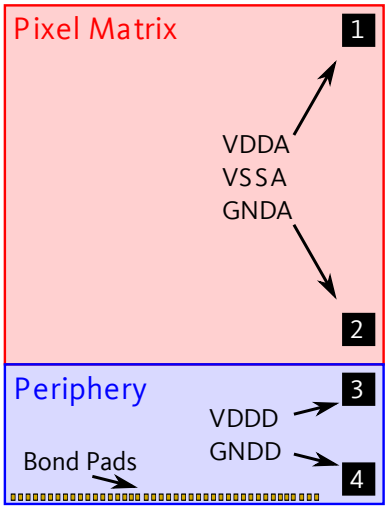
On-Chip Voltage Drop Observation

- test outputs for internal voltages levels at different points on the chip

→ negligible voltage drops within power grid: $\mathcal{O}(1 - 4\,\mathrm{mV})$

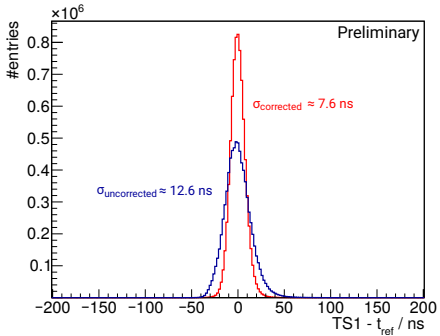
→ significant voltage drop from bond pads to power grid: $\mathcal{O}(200\,\mathrm{mV})$

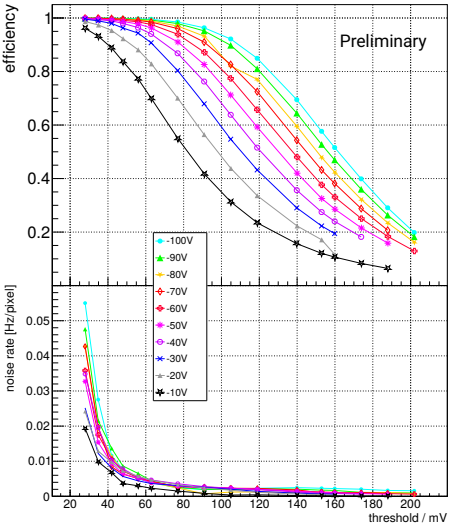




Updated Results of MuPix10 (100 µm, 200 Ω cm) [April 2021]

Efficiency	$> 99\,\%$
Noise Rate	$< 2\,\mathrm{Hz/Pixel}$
Power Consumption	$< 350\,\mathrm{mW/cm^2}$
Time Resolution uncorrected	$\mathcal{O}(13\,\mathrm{ns})$
Time Resolution corrected	$\mathcal{O}(8\,\mathrm{ns})$





What happens if the Depletion Zone reaches the Backside?

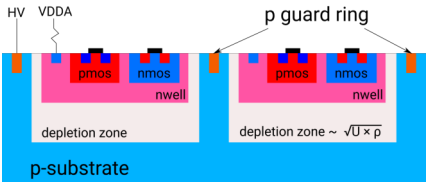
- MuPix10: breakdown voltage for sensors $\geqq 100\,\mu\mathrm{m}$ is $\approx -110\,\mathrm{V}$

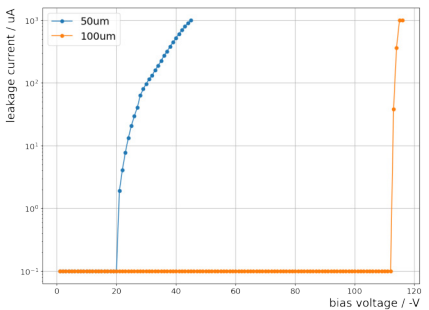
$\rightarrow$ breakdown at pixel guard ring

- for $200\,\Omega\,\mathrm{cm}$ MuPix10 a full depletion for $50\,\mu\mathrm{m}$ was expected at $\approx -50\,\mathrm{V}$

$\rightarrow$ MuPix10 ($200\,\Omega\,\mathrm{cm}$, $50\,\mu\mathrm{m}$) has a breakdown at $\approx -20\,\mathrm{V}$

- Hypothesis: subtrate resistivity is $\approx 400\,\Omega\,\mathrm{cm}$





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$\rightarrow$ MuPix10 ($200\,\Omega\,\mathrm{cm}$, $50\,\mu\mathrm{m}$) has a breakdown at $\approx -20\,\mathrm{V}$

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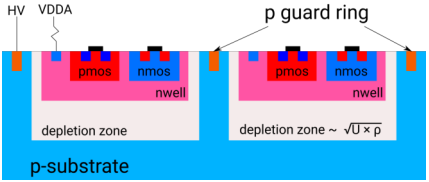
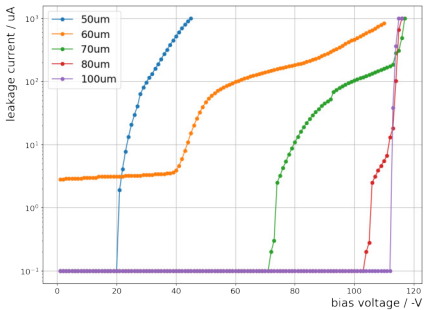
$\rightarrow$ supported by IV-Data





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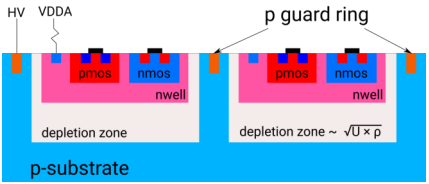
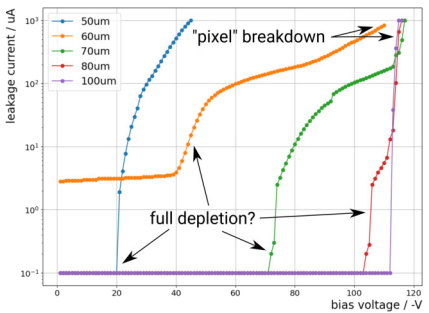
- Hypothesis: subtrate resistivity is $\approx 400\,\Omega\,\mathrm{cm}$

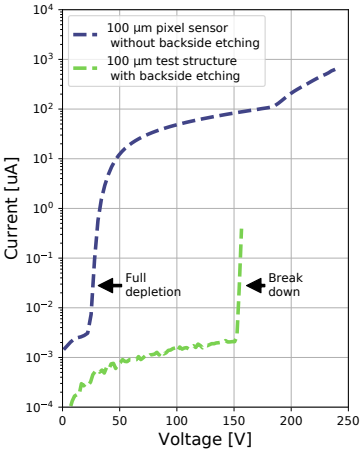
$\rightarrow$ supported by IV-Data

$\Rightarrow$ supplier provided us a substrate resistivity measurement of $370 \pm 20\,\Omega\,\mathrm{cm}$





Observation with LFoundry passive CMOS Sensor Prototypes

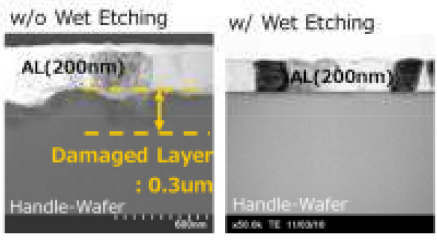


[PhD Thesis David-Leon Pohl]

- 100 µm, 5.5 kΩ cm: an increased leakage current when full-depletion is reached (23 V)

→ caused by damaged layer of silicon after grinding

⇒ solution: "The 0.3um-thick damaged layer can be removed by wet etching. In this case, it is confirmed the abnormal leakage current can be suppressed." [arXiv:1511.05224]

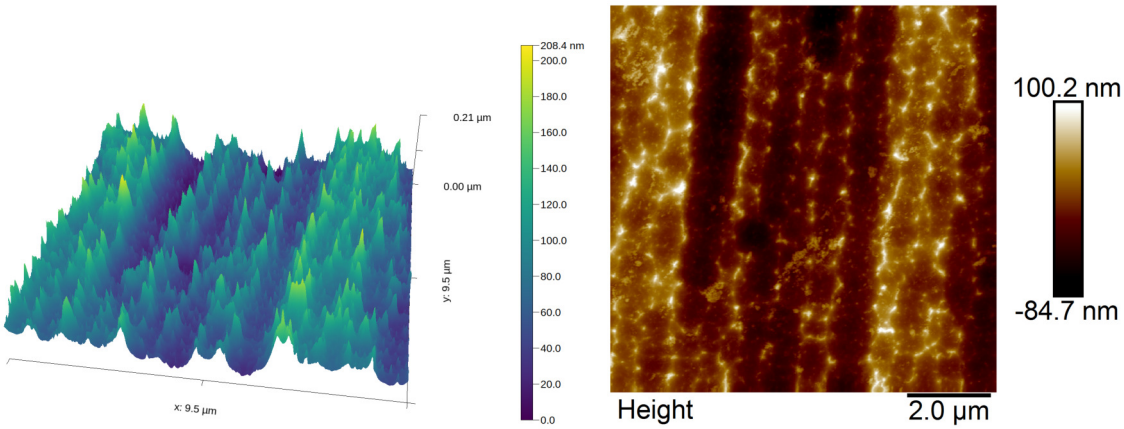


Atomic **F**orce **M**icroscopy Measurement of 50 µm MuPix10

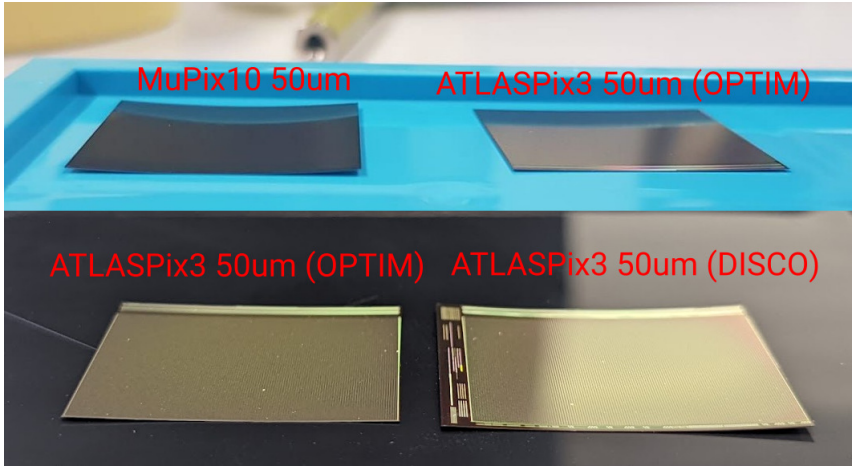
- Prof. Dr. ir. Martijn Kemerink (CAM, Uni Heidelberg) was so nice to help out
- together with Priya Mariam Viji (PhD Student), an AFM measurement of a 50 µm MuPix10 was performed

→ clear structures from grinding already visible under the microscope

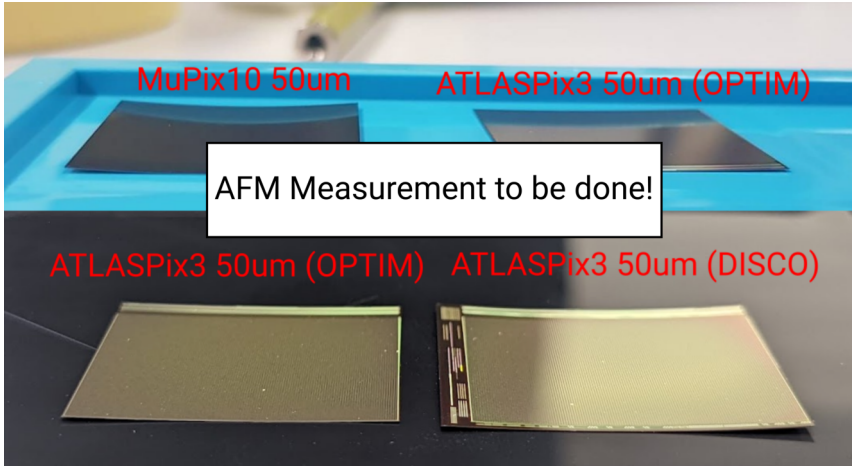
Atomic **F**orce **M**icroscopy Measurement of 50 µm MuPix10



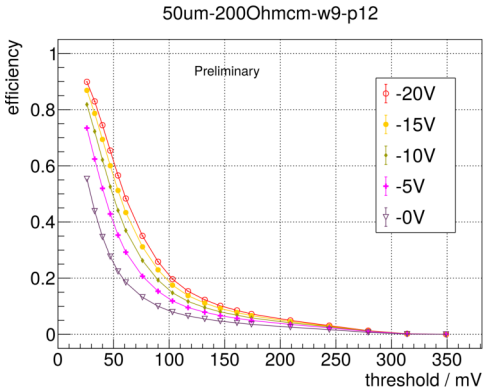
Thinning Large Silicon Sensors to 50 µm

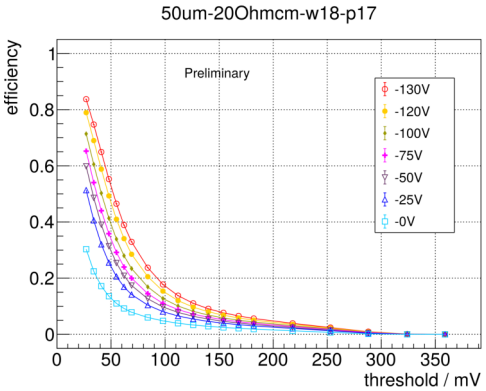


Thinning Large Silicon Sensors to 50 µm



Efficiency Study of 50 µm MuPix10 [Aug. 2021]





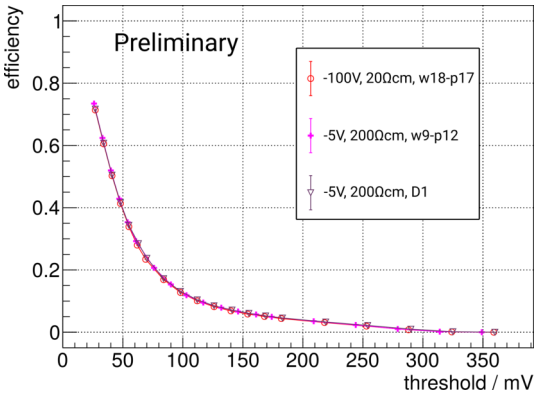
- measurement campaign at PSI with varying sensor thickness & (high) bias voltage performed (analysis on-going)
- both substrates of 20&200 Ω cm for 50 µm did not reach acceptable efficiencies!!

Efficiency Study of 50 µm MuPix10 [Aug. 2021]

- provided substrate resistivity statements:
  $20\,\Omega\,\mathrm{cm} \approx$ 10-20 $\Omega\,\mathrm{cm}$
  $200\,\Omega\,\mathrm{cm} \approx 370 \pm 20\,\Omega\,\mathrm{cm}$

$\rightarrow$ depletion: $w \sim \sqrt{U \times \rho}$ (ρ: resistivity)

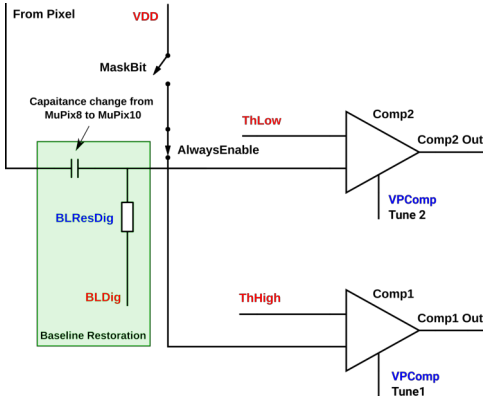
$\Rightarrow$ "same" efficiency curve at:
$20\,\Omega\,\mathrm{cm}$: U $\approx -100\,\mathrm{V}$
$370\,\Omega\,\mathrm{cm}$: U $\approx -5\,\mathrm{V}$



Digital Cell MuPix10

- capacitance change of baseline restoration, which acts as high-pass filter, from MuPix8 to MuPix10

→ shaping element for the analog pulse coming from the pixel



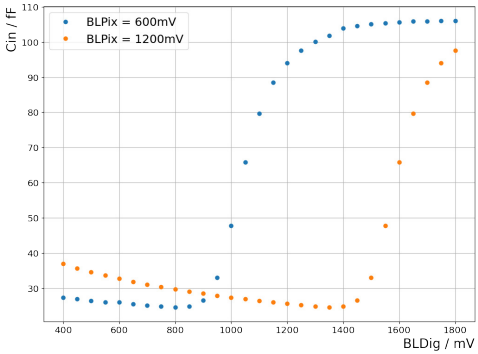
Digital Cell MuPix10

- capacitance change of baseline restoration, which acts as high-pass filter, from MuPix8 to MuPix10

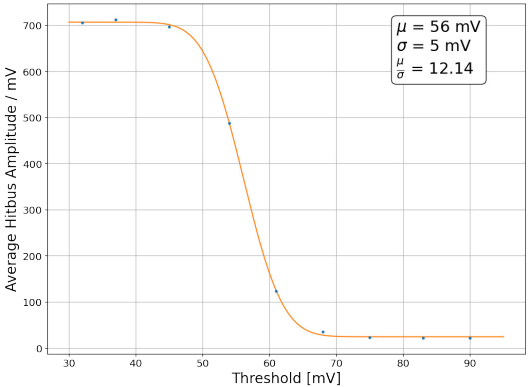
$\rightarrow$ shaping element for the analog pulse coming from the pixel

- capacitance depends on the levels of the analog & digital baseline (initially too small)

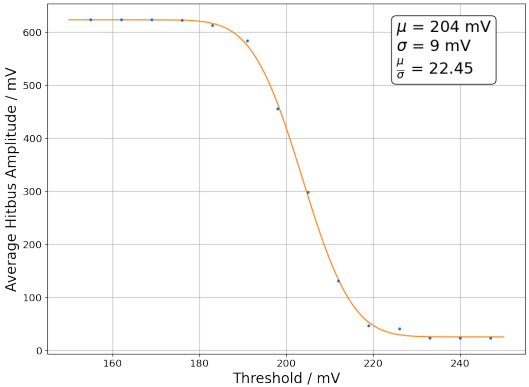
$\Rightarrow$ for now new operational setting has to be found to bypass this problem



Signal-to-Noise Ratio (SNR) Comparison

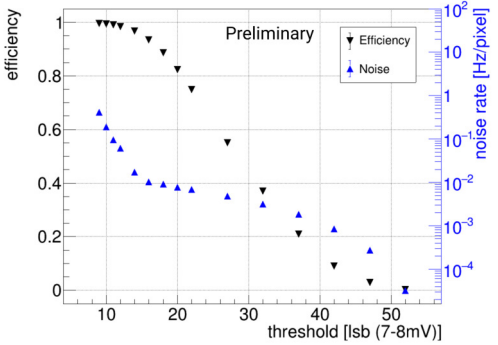


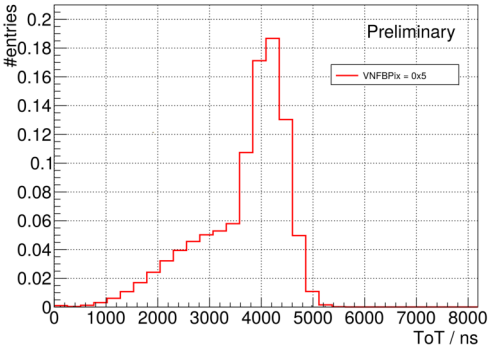
old setting



new setting

Efficiency Scans of 50 µm MuPix10 (200 Ω cm) [Dec. 2021]

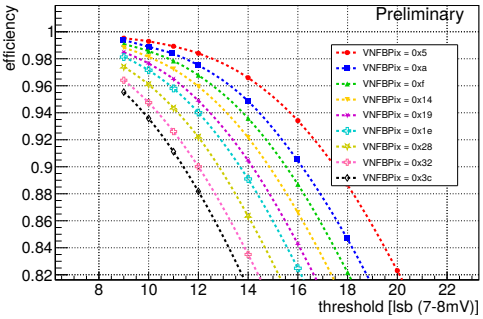


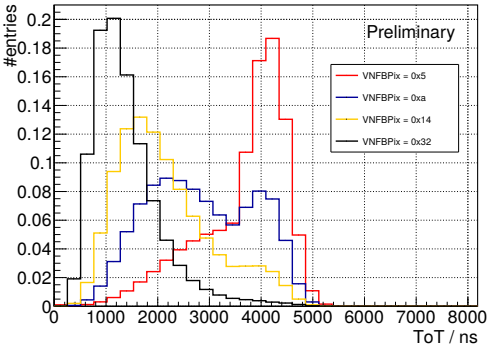


- sufficient efficiency can be reached with 200 Ω cm, 50 µm

→ too long pulse length to fit into ToT window, which detoriates the TW-correction

Efficiency Scans of 50 µm MuPix10 (200 Ω cm) [Dec. 2021]



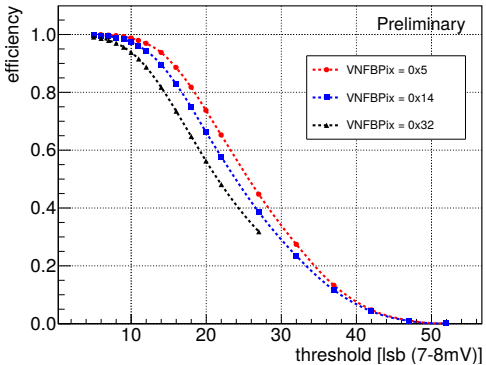


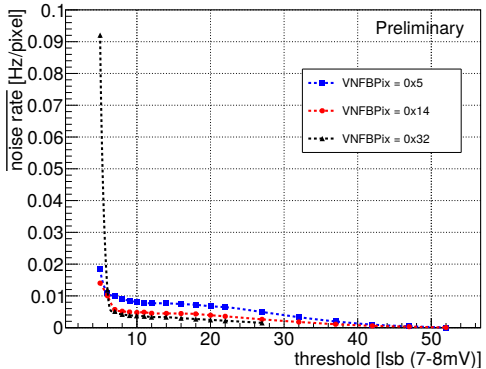
- sufficient efficiency can be reached with 200 Ω cm, 50 µm

→ too long pulse length to fit into ToT window, which detoriates the TW-correction

⇒ shorter pulses (= stronger feedback) require lower threshold levels (via tuning!)

Tuned Efficiency Scans of 50 µm MuPix10 (200 Ω cm) [Dec. 2021]

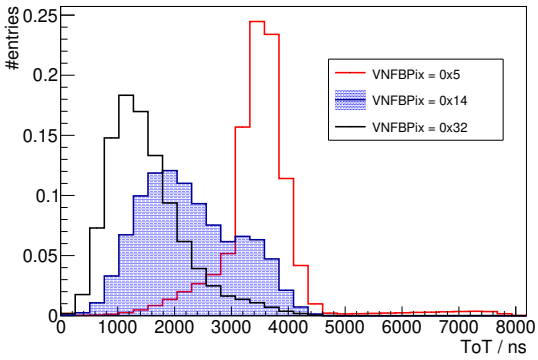


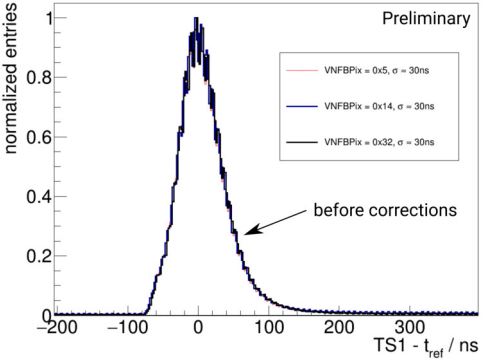


- even for strongest feedback (VNFBPix = 0x32) an efficiency of above 99 % is achieved (only lowest threshold)

→ the efficiency is recovered and the plateau increased

Tuned ToT Spectra & Time Resolution [Dec. 2021]

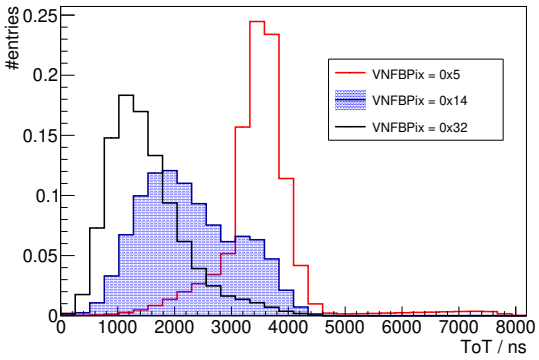


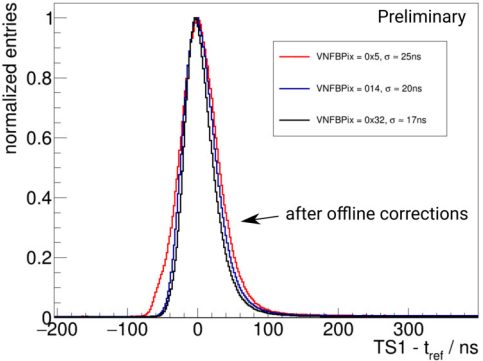


- the observable ToT spectra significantly affacts the time walk correction

→ after offline corrections the Mu3e Phase-I requirements can be achieved

Tuned ToT Spectra & Time Resolution [Dec. 2021]





- the observable ToT spectra significantly affacts the time walk correction

→ after offline corrections the Mu3e Phase-I requirements can be achieved

Summary

- MuPix10 has some problems, but temporary solutions could be found for them

→ solution for aforementioned problems are implemented in MuPix11

- with MuPix10 it is demonstrated that the this technology can fulfill the requirements for Mu3e Phase-I

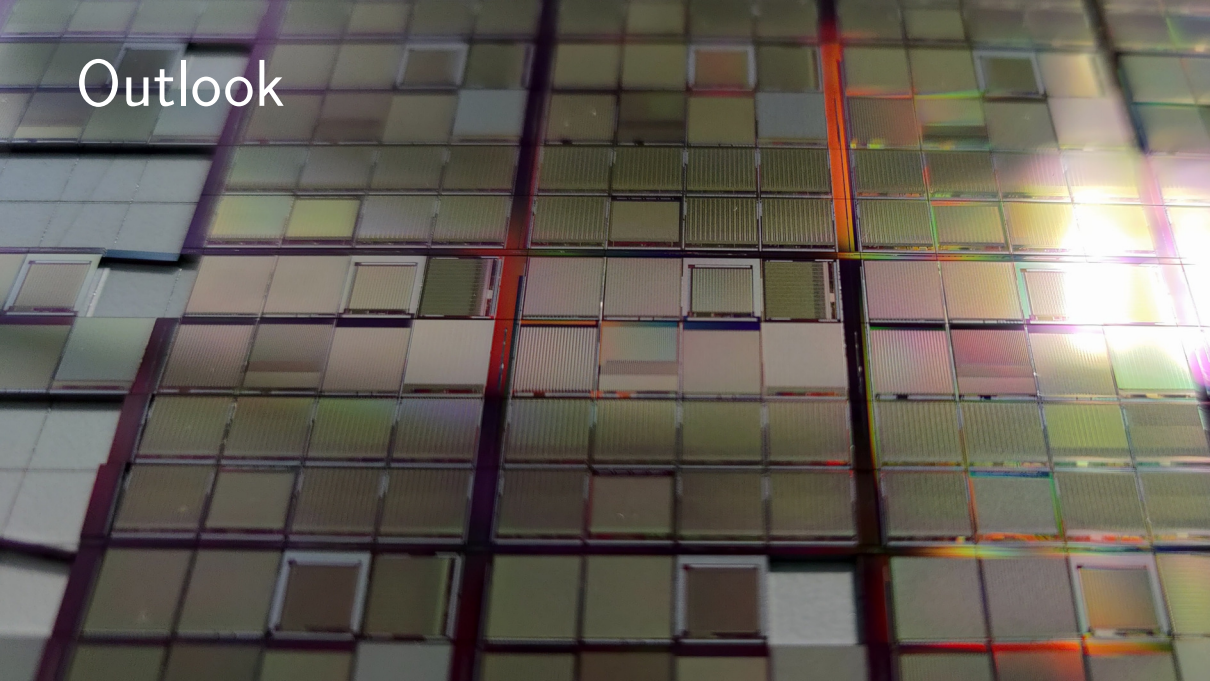
→ better time resolution is expected by using the 2-Threshold method (analysis on-going)

	sensor thickness [µm]	efficiency [%]	noise rate [Hz/pixel]	time resolution [ns]	power consumption [mW/cm^2]
Requirement	50	≥ 99	≤ 20	≤ 20	≤ 350
MuPix10	50 ✓	> 99 ✓	≤ 2 ✓	$\approx 17 - 20^{\ddagger}$ ✓	≤ 250 ✓

‡after offline corrections: study for FPGA-based online implemention on-going

MuPix11 submitted in January 2022 → expected return this Summer

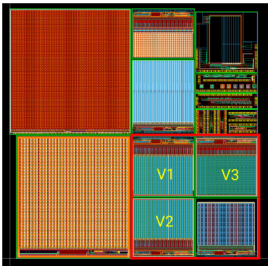
Outlook

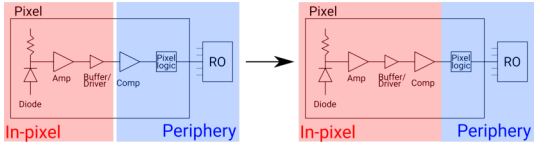


R&D Series: Run2021

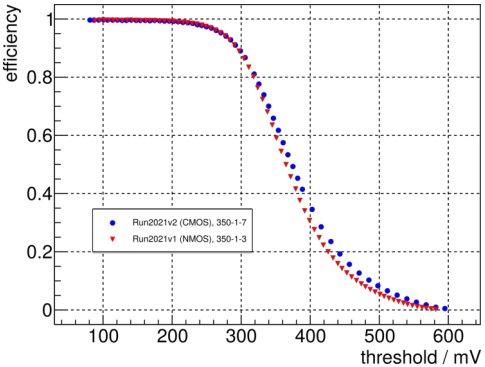
Version	Matrix [pixel]	Pixel size [μm^2]	Substrate [Ω cm]	Amplifier Type[‡]	Comparator	ToA+ToT [bits]	LVDS links
Run2021v1	29×124	165×25	20, 200-400, 5k	NMOS	CMOS	2x10[†]+10	1
Run2021v2	29×124	165×25	20, 200-400, 5k	CMOS	CMOS	2x10[†]+10	1
Run2021v3	29×62	165×50	20, 200-400, 5k	NMOS	Distributed	2x10[†]+10	1

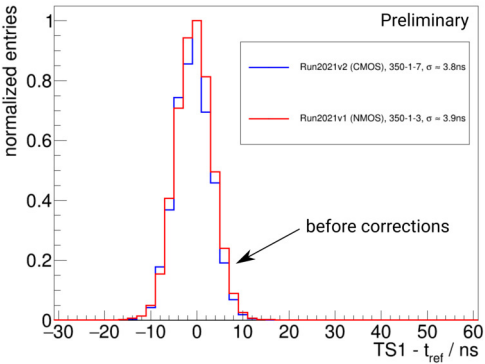
[‡] Amplifier naming scheme refers to the type of the input transistor [†] ToA is sampled on the rising (10 b) and falling (10 b) clock edges





Preliminary Results of Run2021 ($200\,\Omega\,\mathrm{cm}$, $100\,\mu\mathrm{m}$) [Feb. 2022]

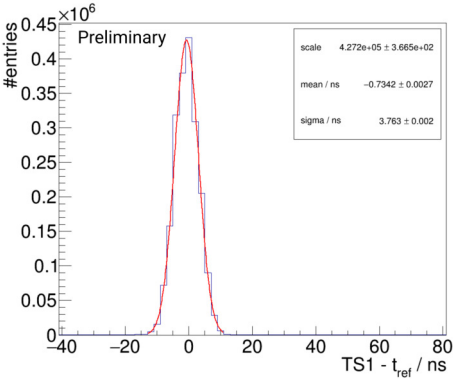


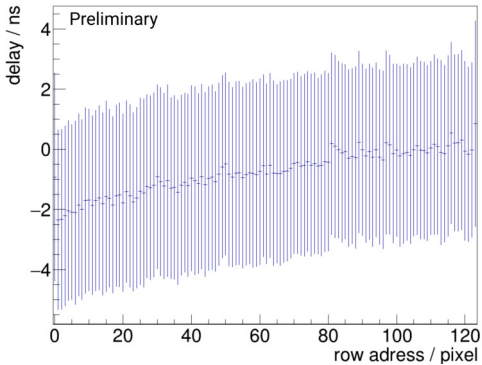


- both sensors show very promising results from the comissioning testbeam

→ a large efficiency ($\geq 99\,\%$ plateau is observable for both sensors while keeping the noise below $1\,\mathrm{Hz/pixel}$ (not shown)

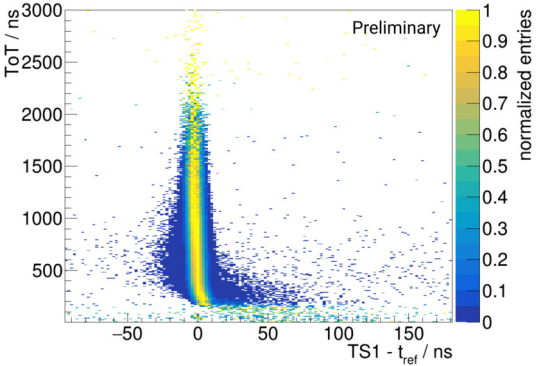
Time Resolution of CMOS Type (Run2021v2) [Feb. 2022]

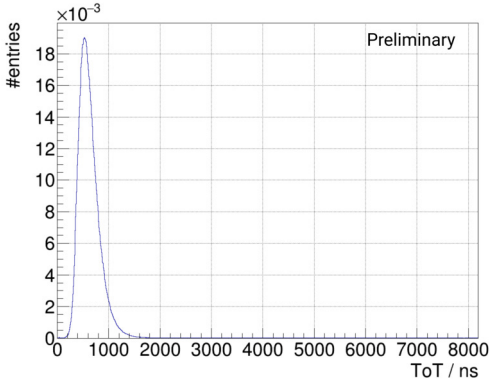




- with 8 ns binnning and w/o any offline corrections a time resolution below 4 ns can be achieved
- at the same time the average pulse length can be shorten to ≈ 500 ns

Time Resolution of CMOS Type (Run2021v2) [Feb. 2022]





- with 8 ns binnning and w/o any offline corrections a time resolution below 4 ns can be achieved
- at the same time the average pulse length can be shorten to ≈ 500 ns

Take-Away Message

- the 200 $\Omega\,\mathrm{cm}$, 100 $\mu\mathrm{m}$ Run2021 sensors show promising results in terms of efficiency and time resolution

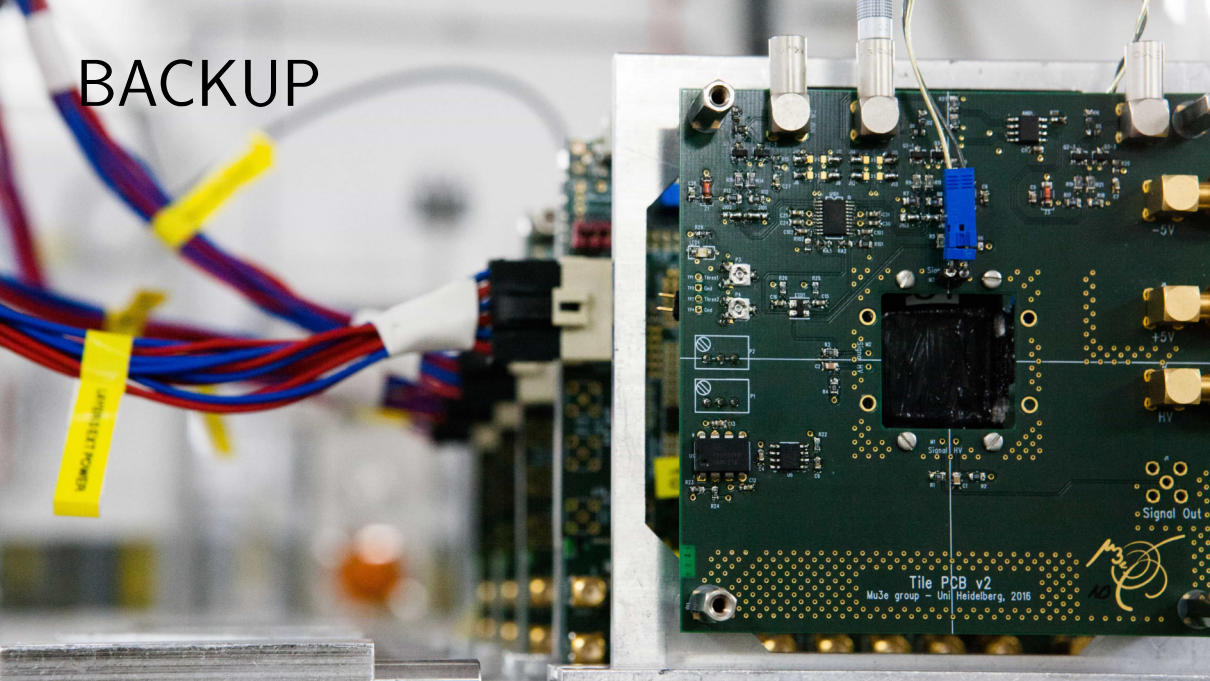
$\rightarrow$ a detailed study of different thicknesses and substrate resistivities is planned for up-coming april/may

Version	Amplifier Type	efficiency [%]	noise rate [Hz/pixel]	time resolution [ns]
Run2021v1	NMOS	≥ 99	≤ 1	$\approx 3.9\,\mathrm{ns}$
Run2021v1	CMOS	≥ 99	≤ 1	$\approx 3.8\,\mathrm{ns}$

- take note that these sensors are still small scale and later large scale prototypes have to proof similar performance!!

$\Rightarrow$ combining these with the features of MuPix10/11 will lead to the development of MuPix20

BACKUP


-5V
+5V
HV
Signal Out
Tile PCB v2
MuJe group – Uni Heidelberg, 2016

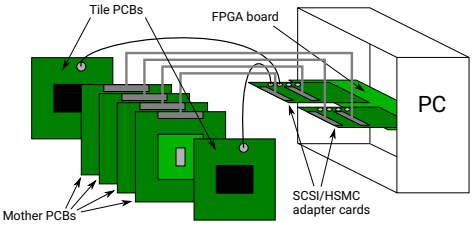
MuPix10 Performance Measurements at DESY

DESY Testbeam Facility:

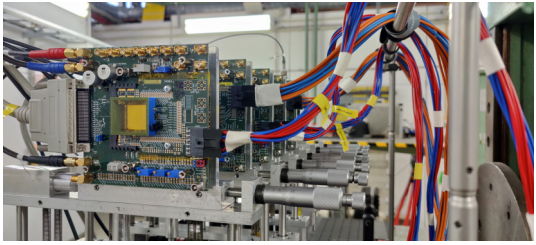
- electron beam with 1 to 6 GeV

$\rightarrow$ measurements performed at 4 GeV

$\Rightarrow$ trade-off between rate and scattering

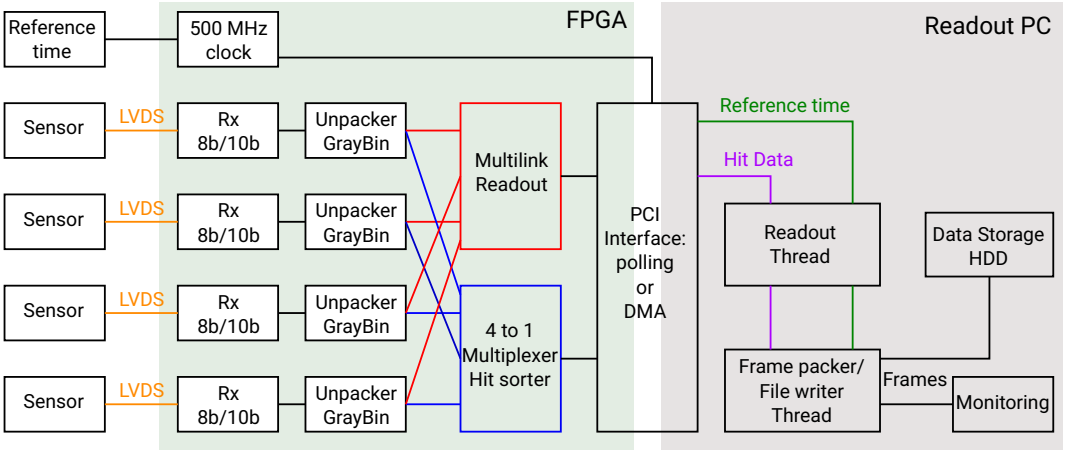


[A.Herkert doi:10.11588/heidok.00027893]



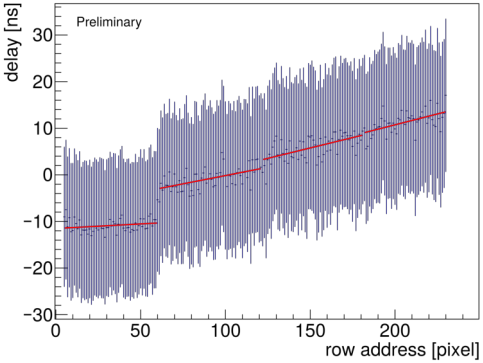
- study of several HV-MAPS prototypes
- 4-8 layers + 2 scintillating tiles for time reference

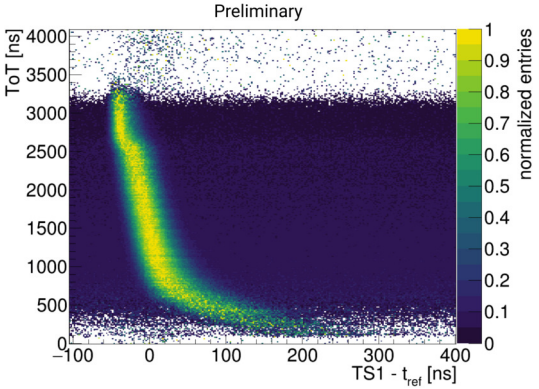
Readout: From Sensor to Disc



[L. Huth doi:10.11588/heidok.00025785] (modified)

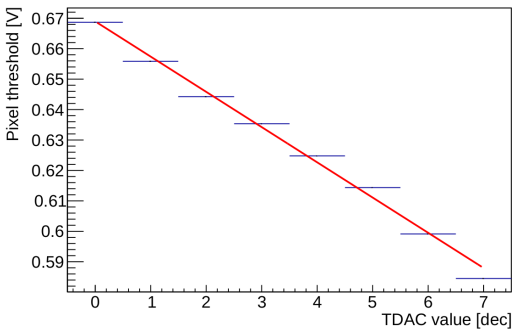
MuPix10 Signal Line Delay & Time Walk





MuPix10 Threshold Tuning Example

- globally applied threshold to 2 comparators
- 3 bit DAC/comparator for threshold tuning + 1 bit to "mute" pixel

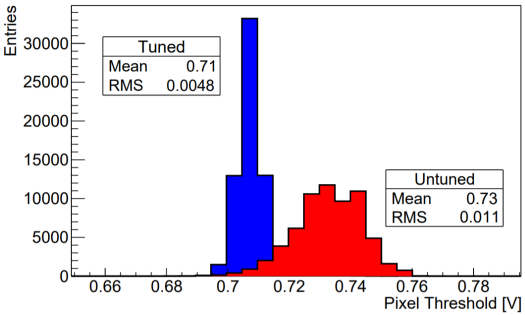


[H. Augustin arXiv:2012.05868]

MuPix10 Threshold Tuning Example

- globally applied threshold to 2 comparators
- $3\,\mathrm{bit}$ DAC/comparator for threshold tuning $+\ 1\,\mathrm{bit}$ to "mute" pixel
- threshold dispersion minimized from $11\,\mathrm{mV}$ ($240\,\mathrm{e^-}$) to $4.8\,\mathrm{mV}$ ($79\,\mathrm{e^-}$)

$\rightarrow$ effect to be studied on future test beam



[H. Augustin arXiv:2012.05868]