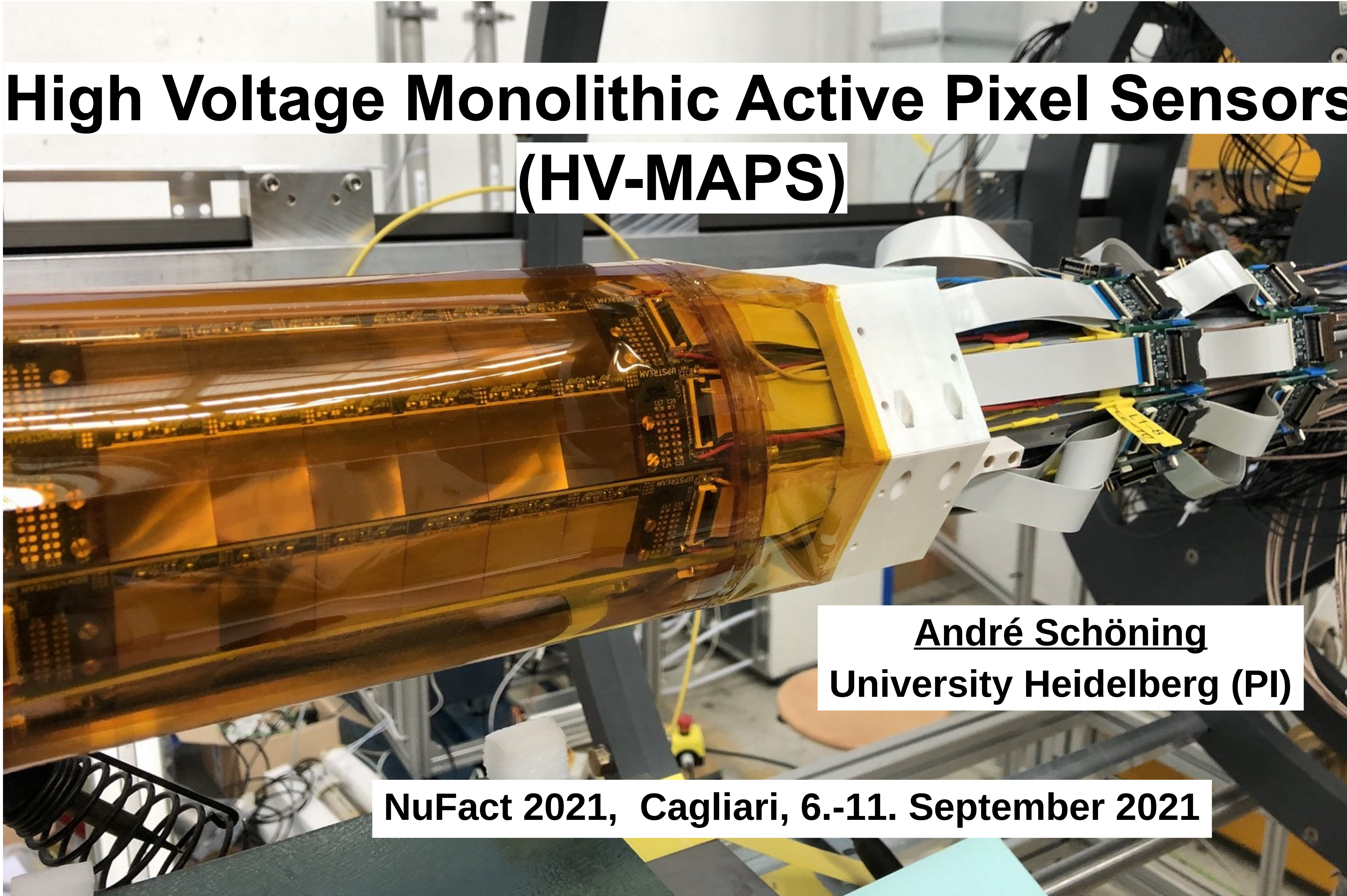


High Voltage Monolithic Active Pixel Sensors (HV-MAPS)

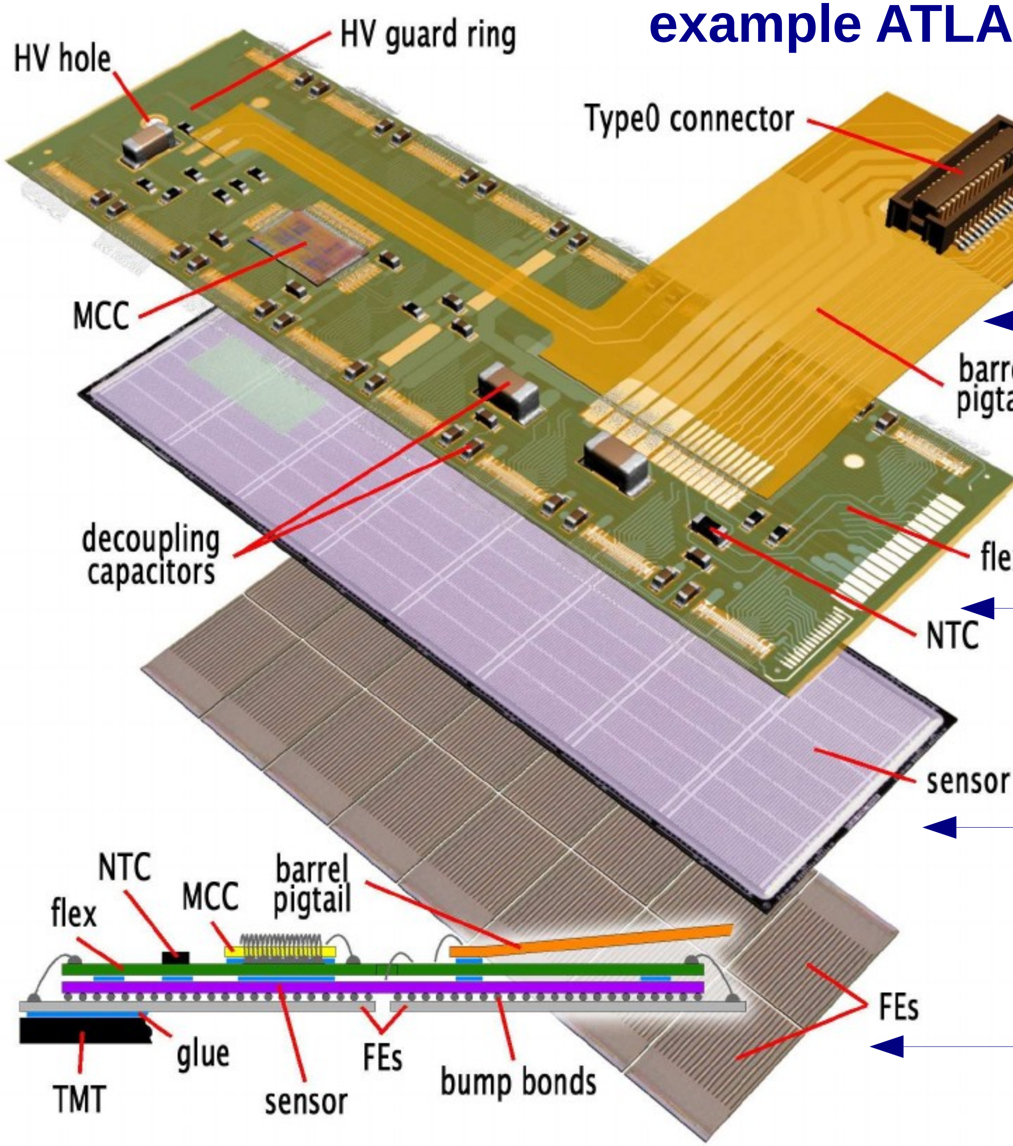
André Schöning
University Heidelberg (PI)

NuFact 2021, Cagliari, 6.-11. September 2021

Hybrid Pixel Sensors

Monolithic Sensors

example ATLAS@LHC



connectivity

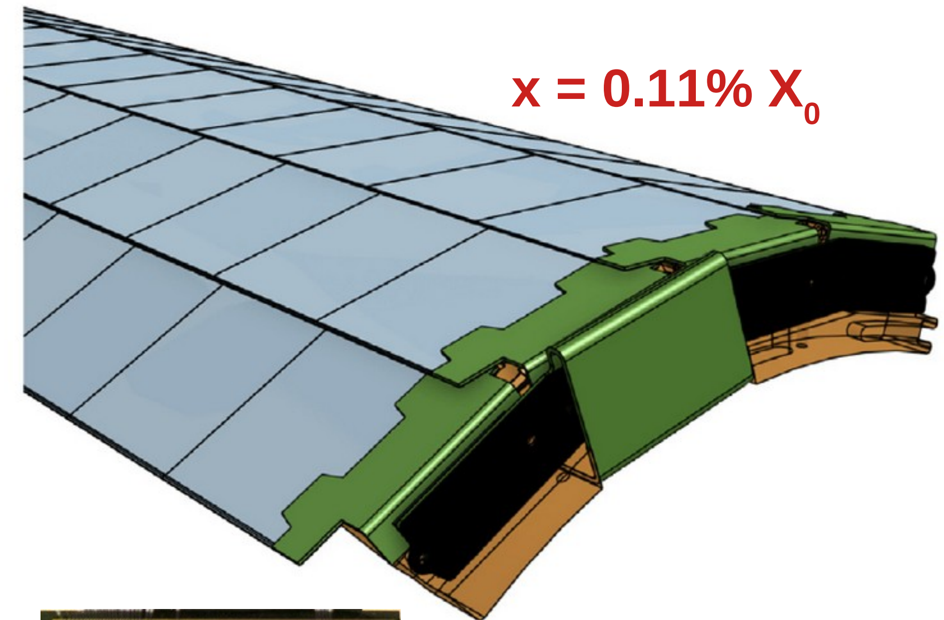
flexprint & services

sensor

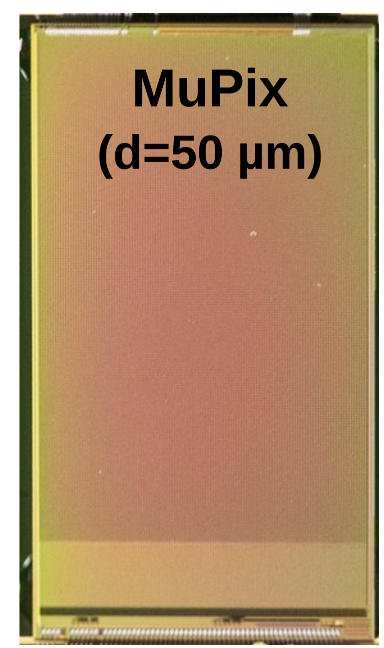
digitisation & readout

x = 2.5% X_0

example Mu3e@PSI



x = 0.11% X_0



active matrix

periphery & pads

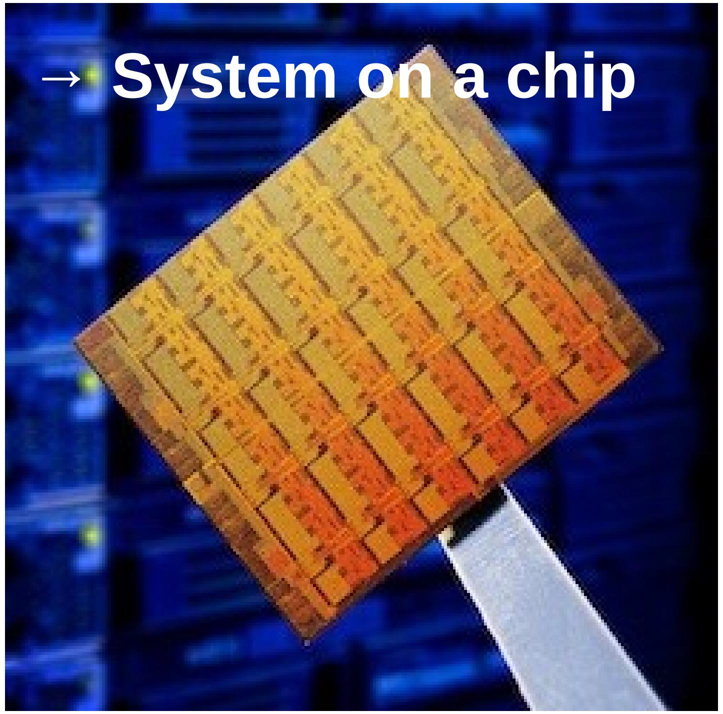
Monolithic Active Pixel Sensors (MAPS)

- **silicon pixel sensors allow for very high particle rates**
  (in contrast to gaseous tacking devices)
- **monolithic sensors allow for the construction of ultra-light tracking detectors**

➔ **MAPS are interesting for particle physics experiments at “low energy” (sub-GeV regime)**

MAPS are usually produced in an industrial **CMOS** process. Benefits:

- standardised design and simulation tools
- profits from process miniaturisation
- high level of integration possible
  → system on a chip or “smart sensor”



Charge Collection in MAPS

Drift-Diffusion Equation: $\vec{j} = q D \nabla n + q n \mu \vec{E}$

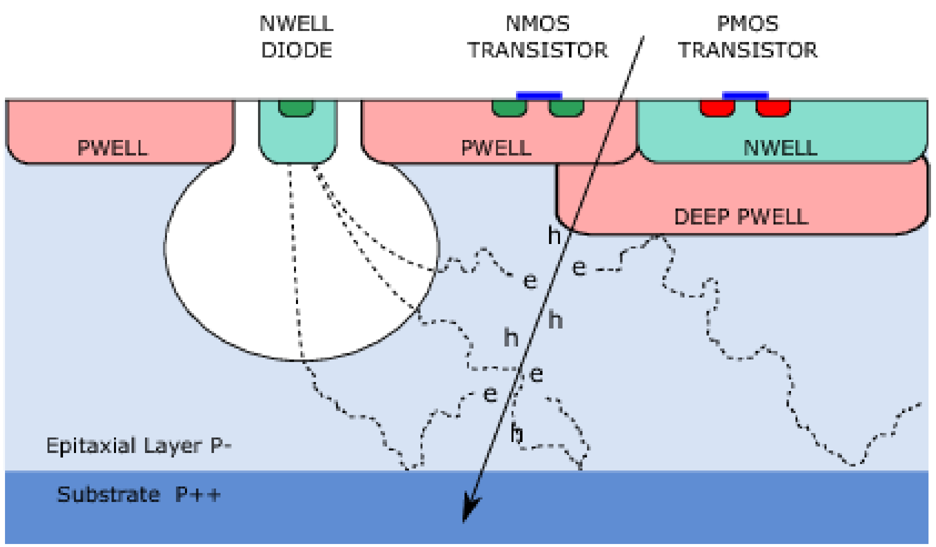
D=diffusion constant, μ=mobility, n=charge density

$$\tau_{collection}^{-1} = \tau_{diffusion}^{-1} + \tau_{drift}^{-1}$$

(depends on substrate, temperature, pixel geometry, electric field, ...)

Standard MAPS

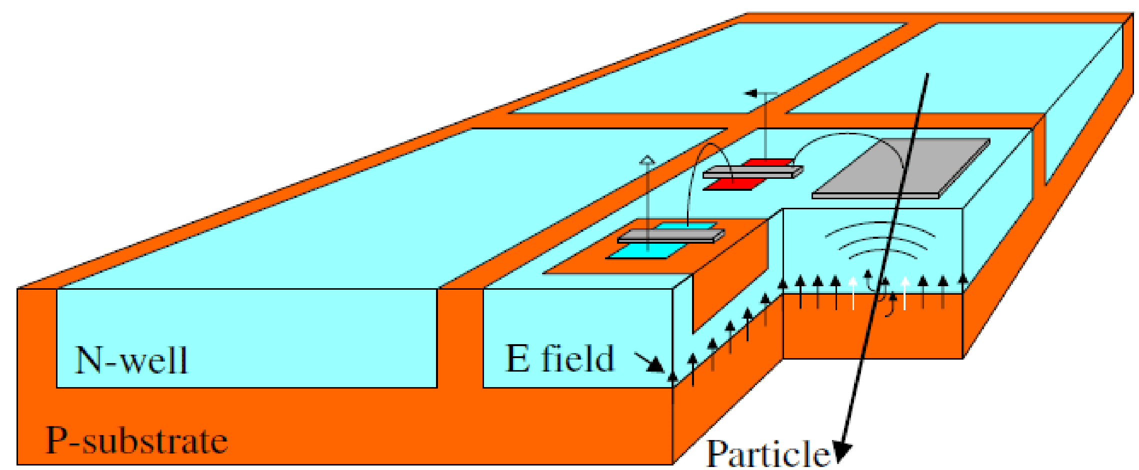
$\tau_{diffusion}^{-1} \approx 10-1000\,\text{ns}$



(from Besson et al. 2016)

Depleted MAPS

$\tau_{drift}^{-1} \approx 10-100\,\text{ps}$

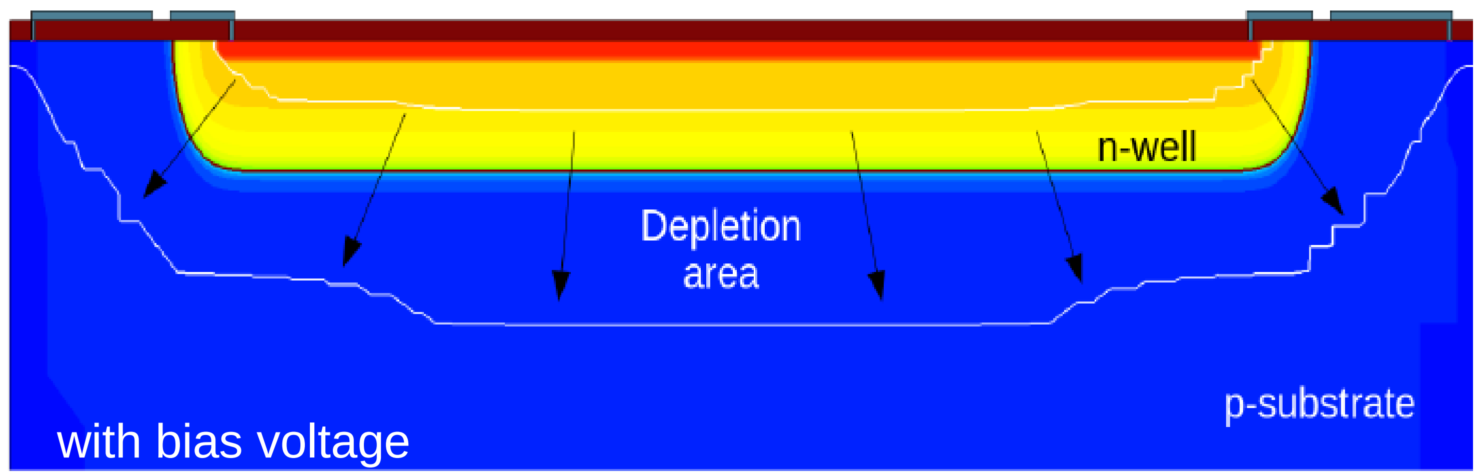


e.g. High Voltage – Monolithic Active Pixel Sensor

(I. Peric et al., NIM A 582 (2007) 876)

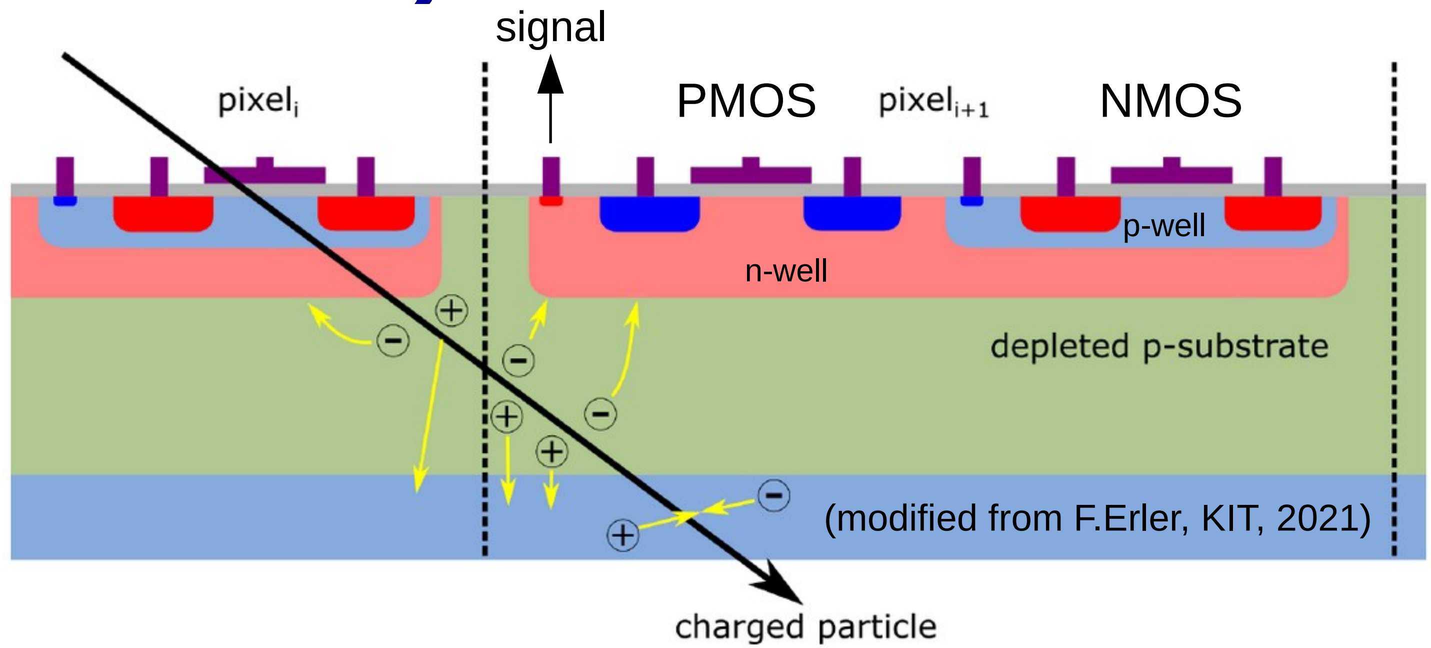
HV-MAPS Charge Collection

electrical field
up 10^5 V/cm



“depleted MAPS”

High Voltage - Monolithic Active Pixel Sensors (HV-MAPS)



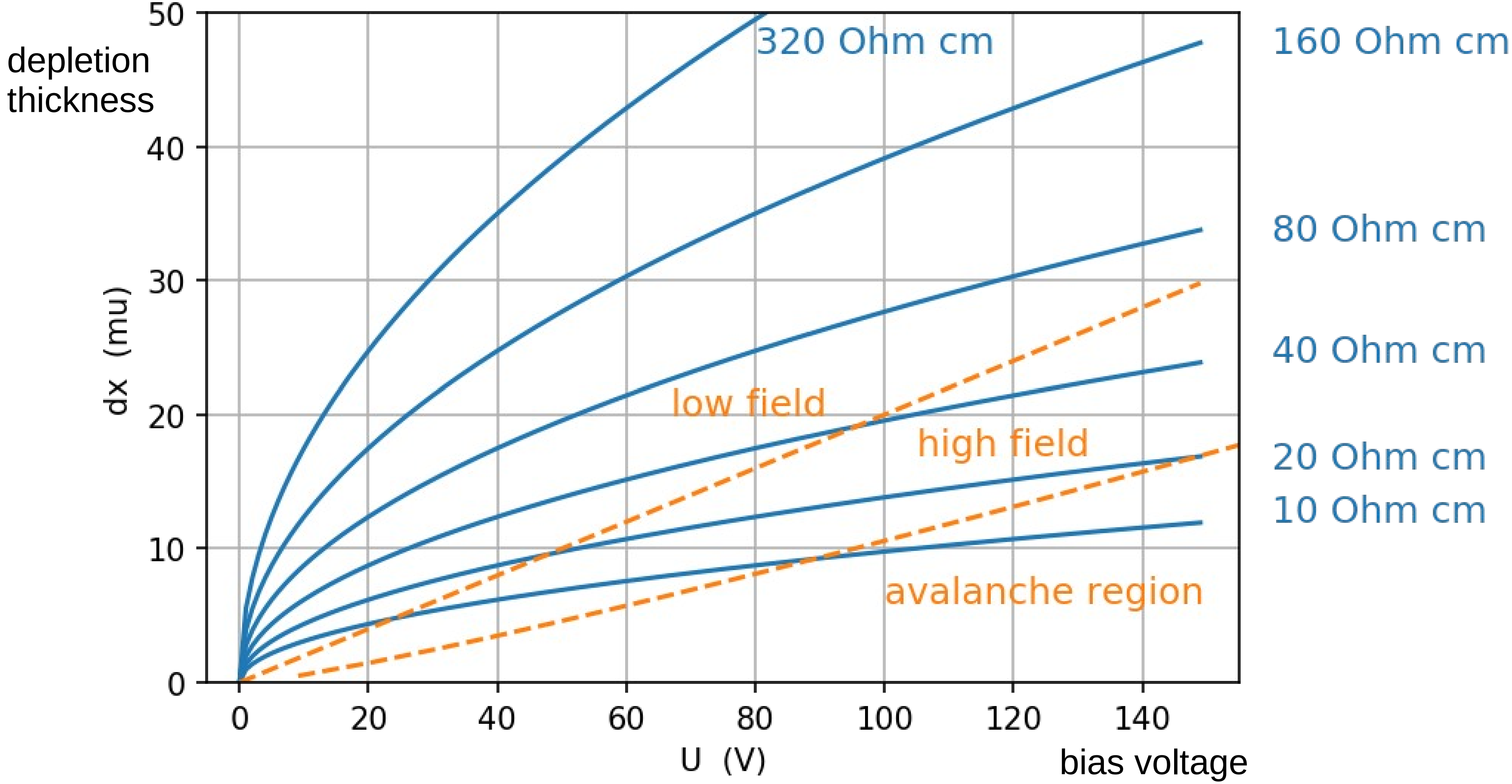
Commercial HV-CMOS process

- foundries: AMS or **TSI**
- design rules for up to **120V**
- triple and **quad well** possible
- reticle sizes of about **4-5 cm²**
- standard substrate 10-20 Ω cm (can be changed)

Main Features

- **depletion thickness** determined by substrate resistivity and bias voltage: $d \propto \sqrt{\rho \cdot V}$
- HV-MAPS concept allows for **high fill-factors** (all pixel electronics is inside the diode and floats)
- **digital CMOS** (PMOS) circuits can be placed over the active depletion region by isolating the PMOS transistors from the charge collecting pn-diode with an **iso-p-well**
- **noise** is typically **80 -100 e$^-$**
- **MIP signal** is **~800 e$^-$** per **10 µm** depletion

Depletion and Bias Voltage Relation

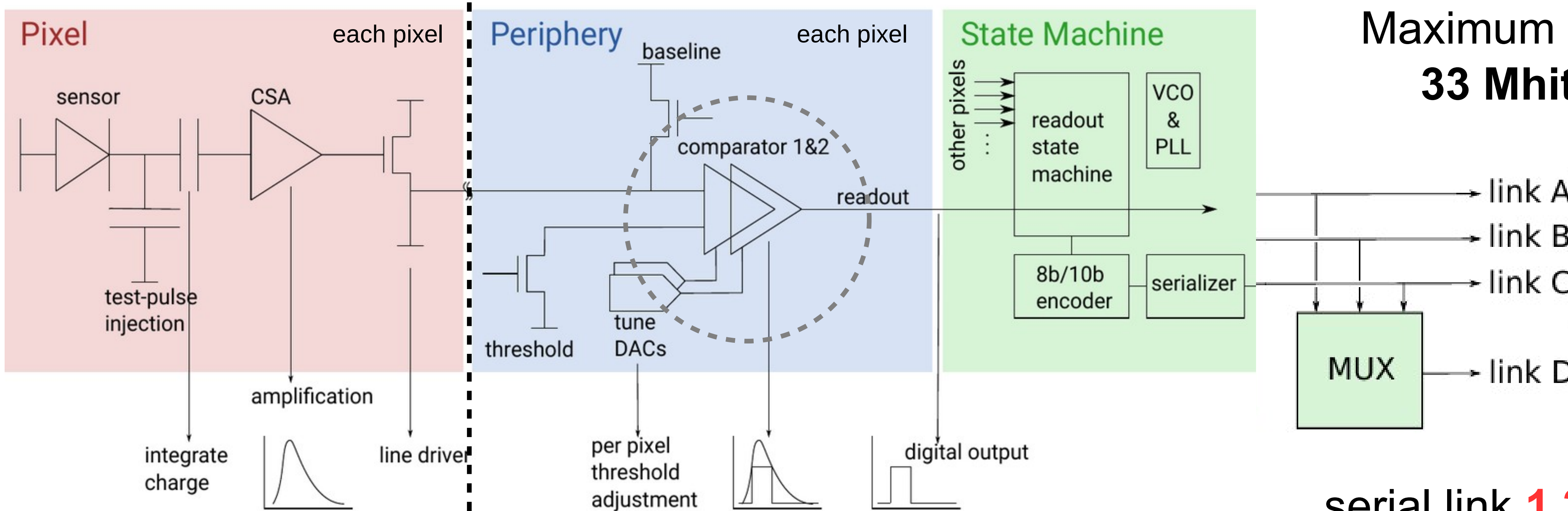


Low resistivity substrates provide high charge collection fields and small depletion

→ allows for thin sensors

High Rate & Continuous Readout

MuPix



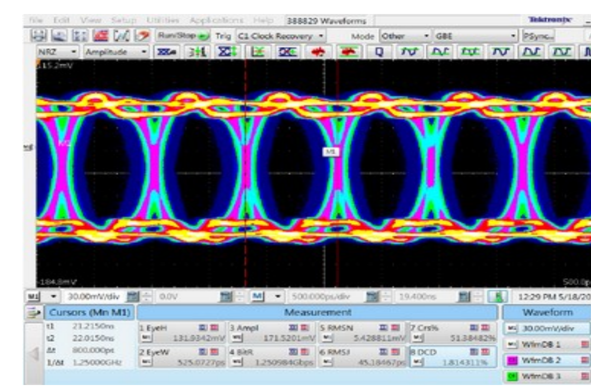
Maximum readout rate is **33 Mhits/s** per link

serial link **1.25 -1.6 Gbit/s**

MuPix8 sensor

periphery & SM

eye diagram

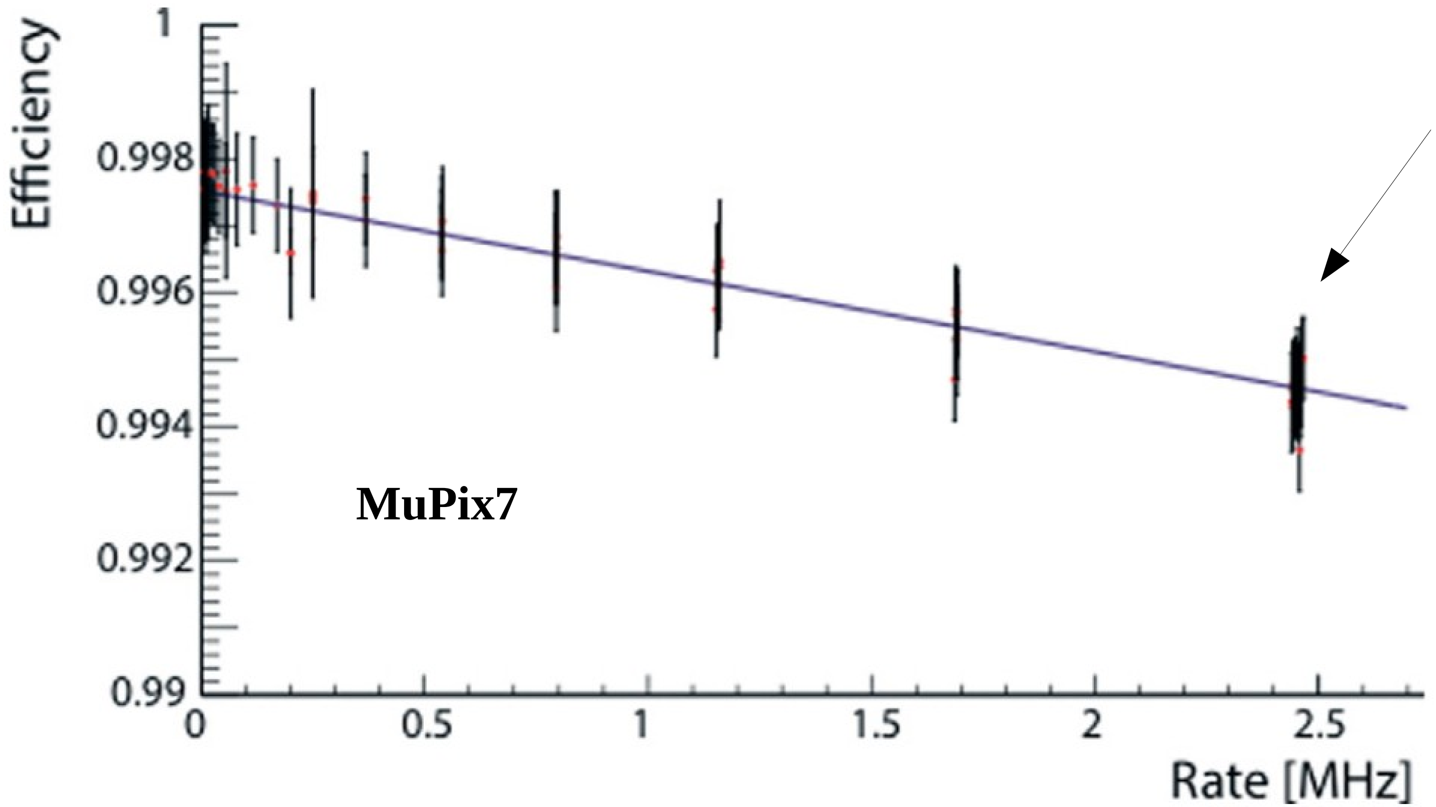


MuPix series is the first monolithic pixel sensor with continuous sampling and readout!

High Rate Characterisation Studies (MuPix)

Single hit efficiency measured in the highly focused e^- beam at MAMI (Mainz)

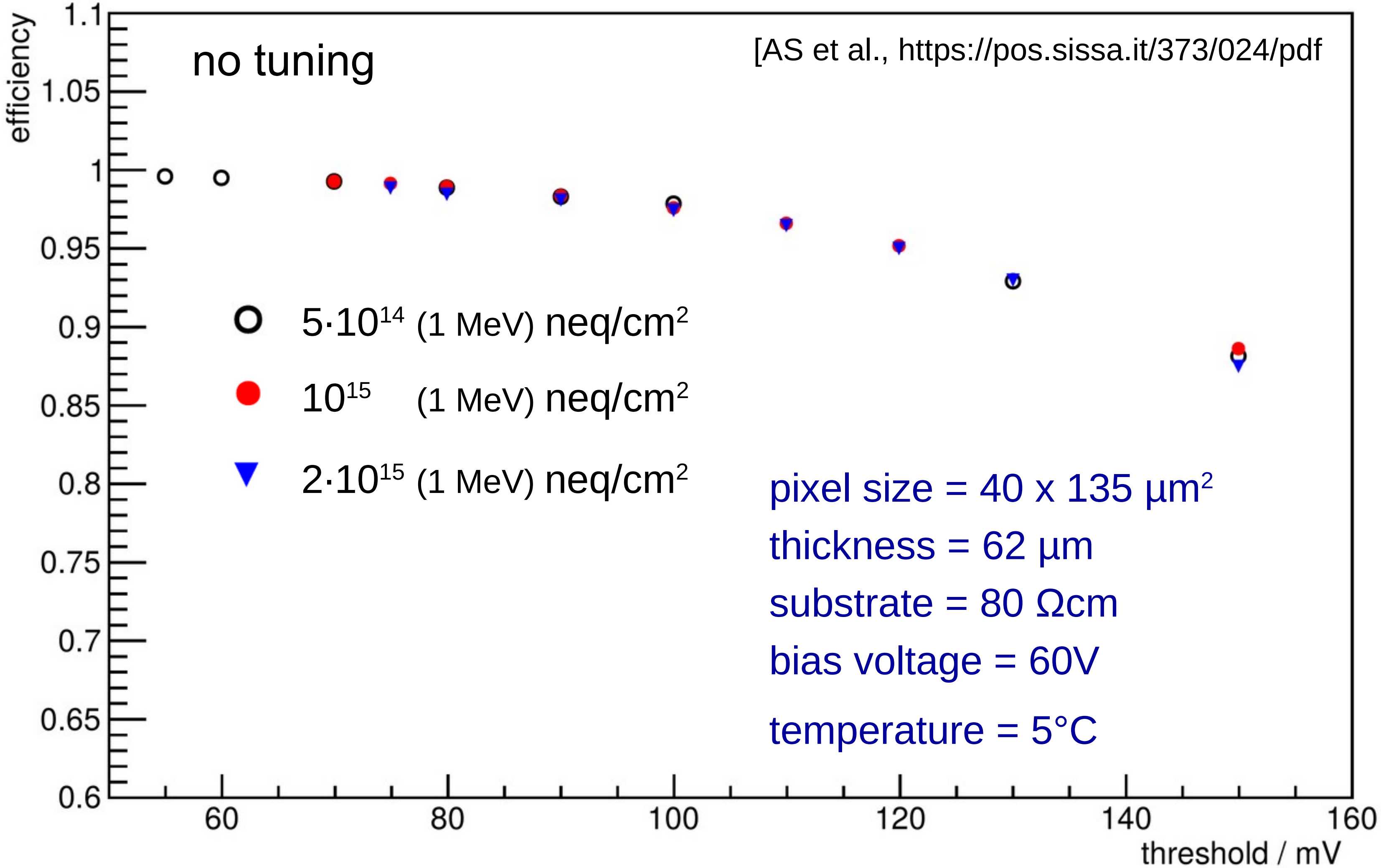
- E_e = 875 MeV
- Beam spot size σ ~ 0.5 mm



corresponds to
~ 10^9 particles/cm^2

small decrease of single hit efficiency due to in-pixel deadtime (electronics)

Neutron Irradiated ATLASpix1 (HVMAPS) sensor



- fluence of 10^{15} neq/cm^2 corresponds to ATLAS @ High Luminosity LHC at radius of ~R=30cm
- similar results for proton irradiation [https://pos.sissa.it/373/024/pdf]

➔ 180nm HV-CMOS process is very radiation hard (→ trapping in the bulk is negligible)

First HV-MAPS Summary

- 180nm HV-CMOS process has a high integration level (smart sensor), is relatively “cheap” and allows to construct large scale pixel detectors (>1m^2) at reasonable price
- sensors can be thinned to 50 μm (or even less) and are therefore suitable for particles physics experiments at low energy
- HV-MAPS have intrinsically an excellent timing resolution, provide high speed readout, are very radiation tolerant and ideal for high rate applications
- HV-MAPS can also be used for beam monitoring

Mu3e Experiment @ PSI

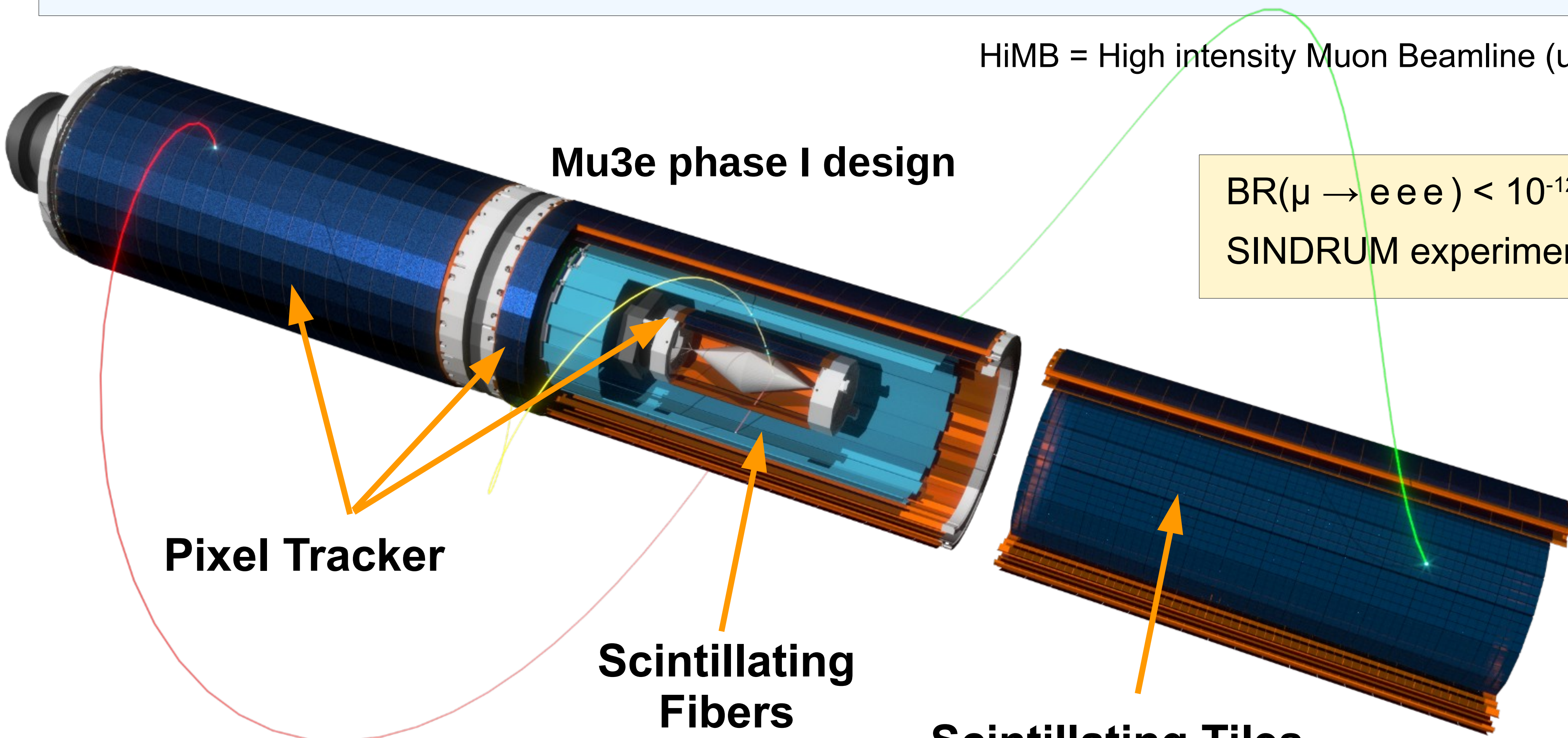
→ Alexandr Kozlinskiy (Mu3e Overview)
→ Marius Köppel (Integration Run, poster)

Aiming for a sensitivity (SES) requires:

$BR(\mu \rightarrow eee) < 2\cdot10^{-15}$	(phase I)	→	**10^8 muons/s (PiE5)**	**~next 5 years**
$BR(\mu \rightarrow eee) < 10^{-16}$	(phase II)	→	**$>10^9$ muons/s (HiMB)**	**R&D**

HiMB = High intensity Muon Beamline (under study)

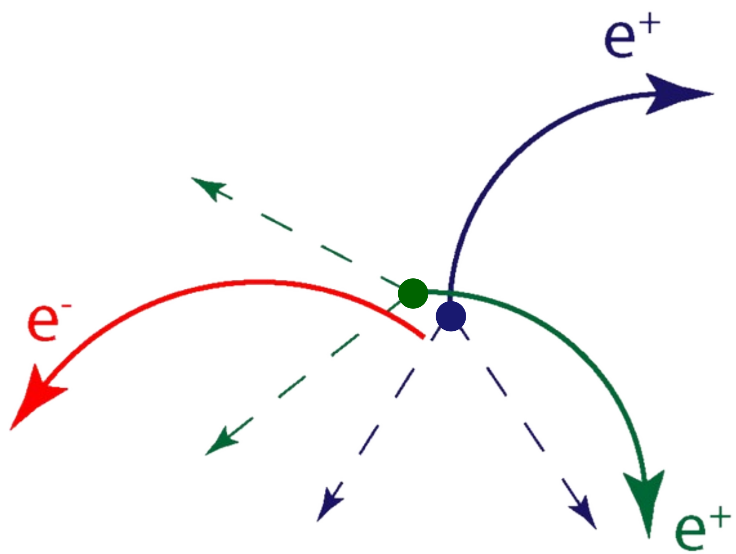
$BR(\mu \rightarrow eee) < 10^{-12}$ (90% CL)
SINDRUM experiment (1986)



Accidental Backgrounds

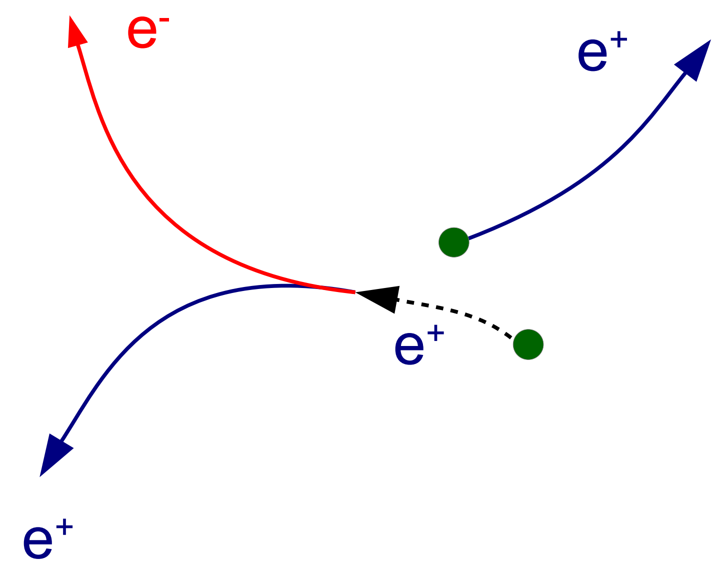
=> scale with muon rate

- **Overlays** of two ordinary **μ^+ decays** with a (fake) **electron (e^-)**
- Electrons from: **Bhabha** scattering, photon conversion, mis-reconstruction



Need excellent:

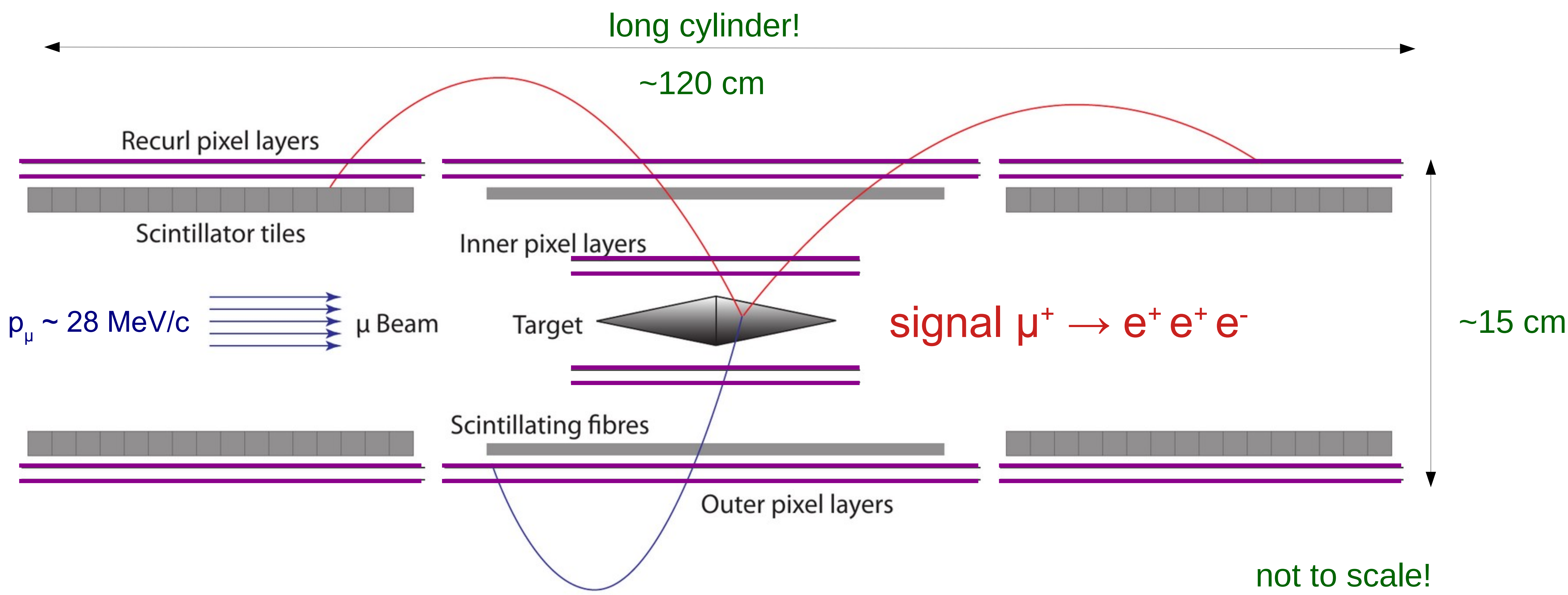
- **Vertex resolution**
- **Timing resolution**
- **Kinematic reconstruction**



example for Bhabha pileup

Mu3e Design (Phase I)

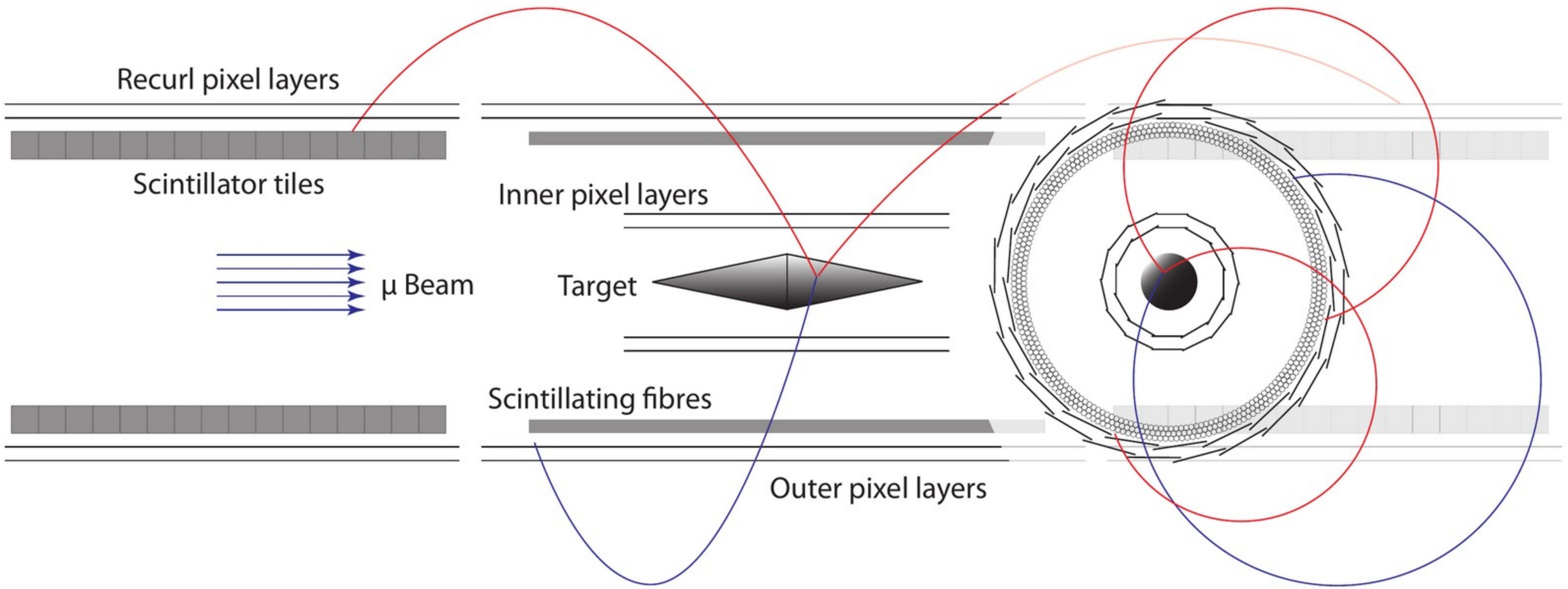
tracking of electrons (positrons) in low momentum range: **$p_e \leq 53$ MeV/c**



- **4 layers** of HVMAPS (MuPix) in **central** part
- **2 layers** of HV-MAPS (MuPix) **upstream** and **downstream** (recurl stations)
- pixel size **80 µm x 80 µm** → resolution **σ ~ 23 µm**

Mu3e Design (Phase I)

transverse view:

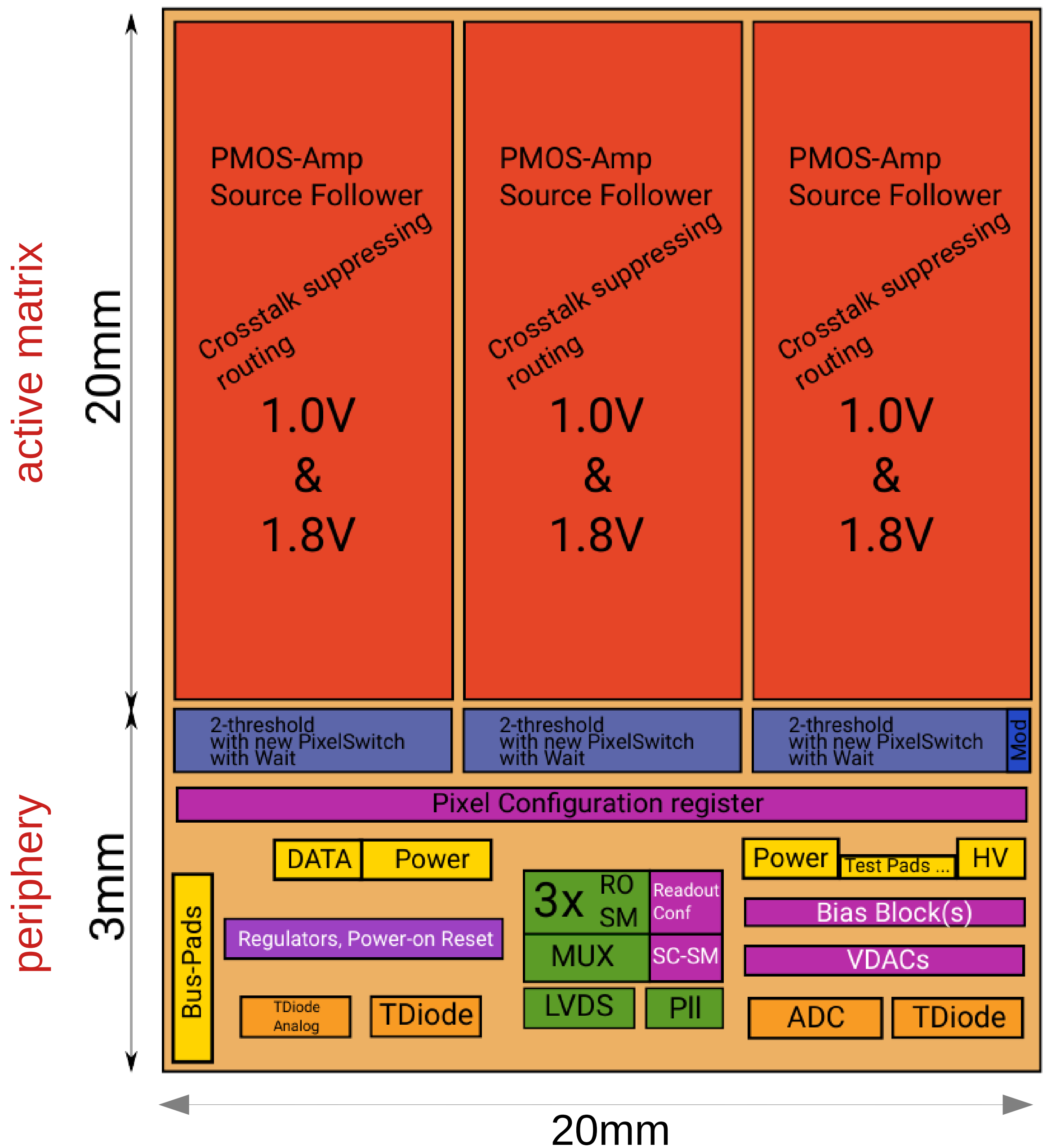


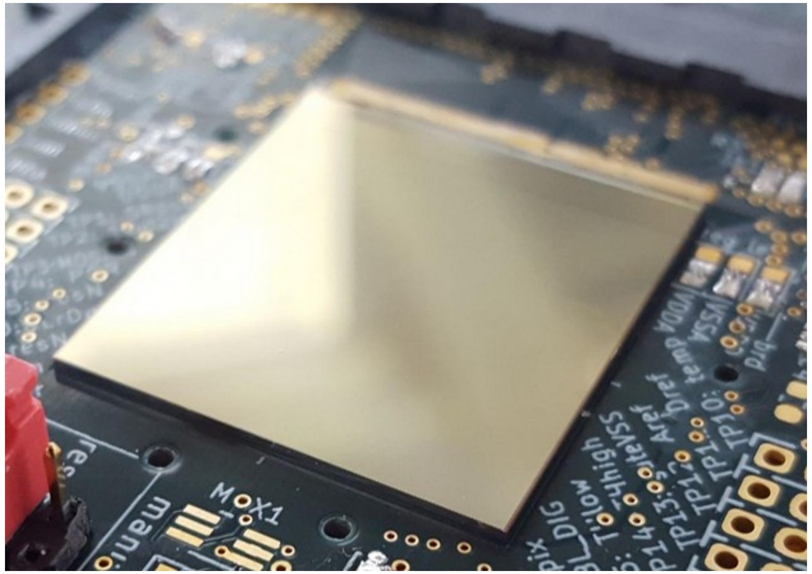
+ strong magnetic field (B=1T)

+ helium gas cooling

in helium atmosphere
→ low dE/dx

Mupix Design & Specifications

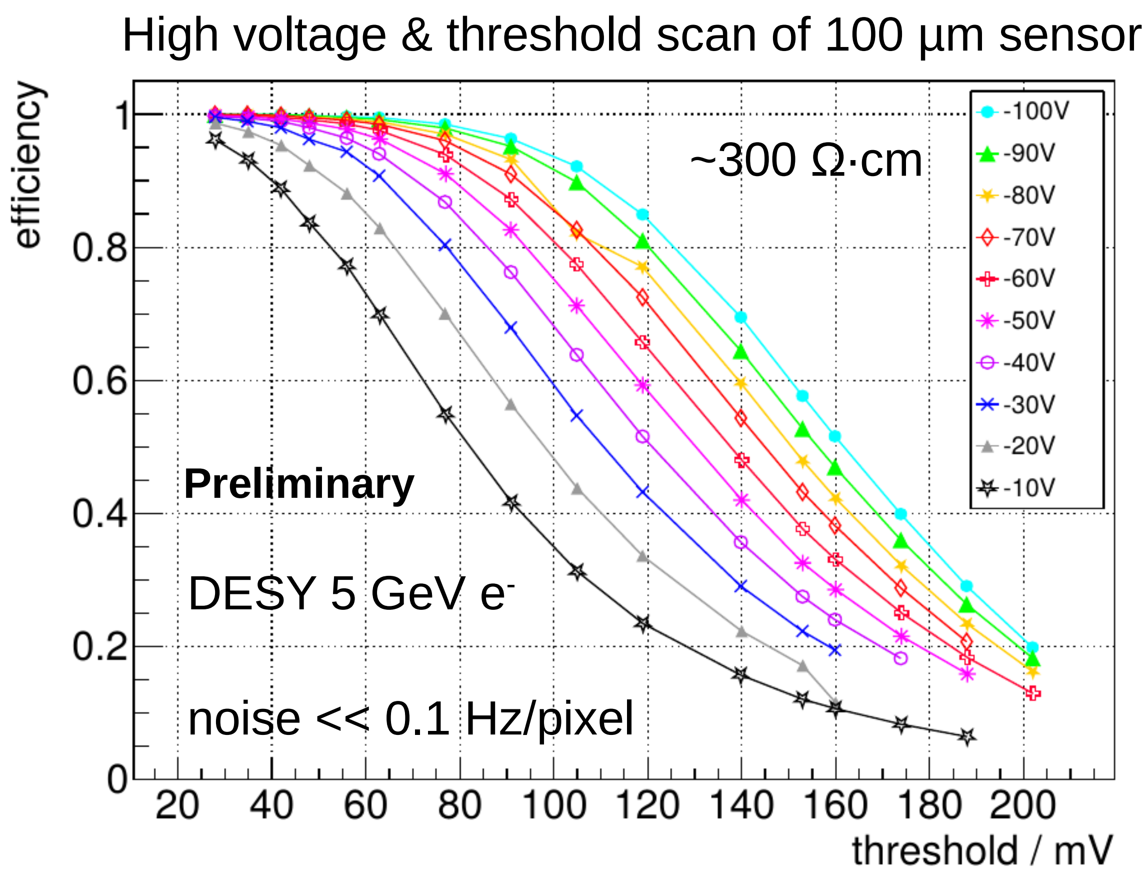


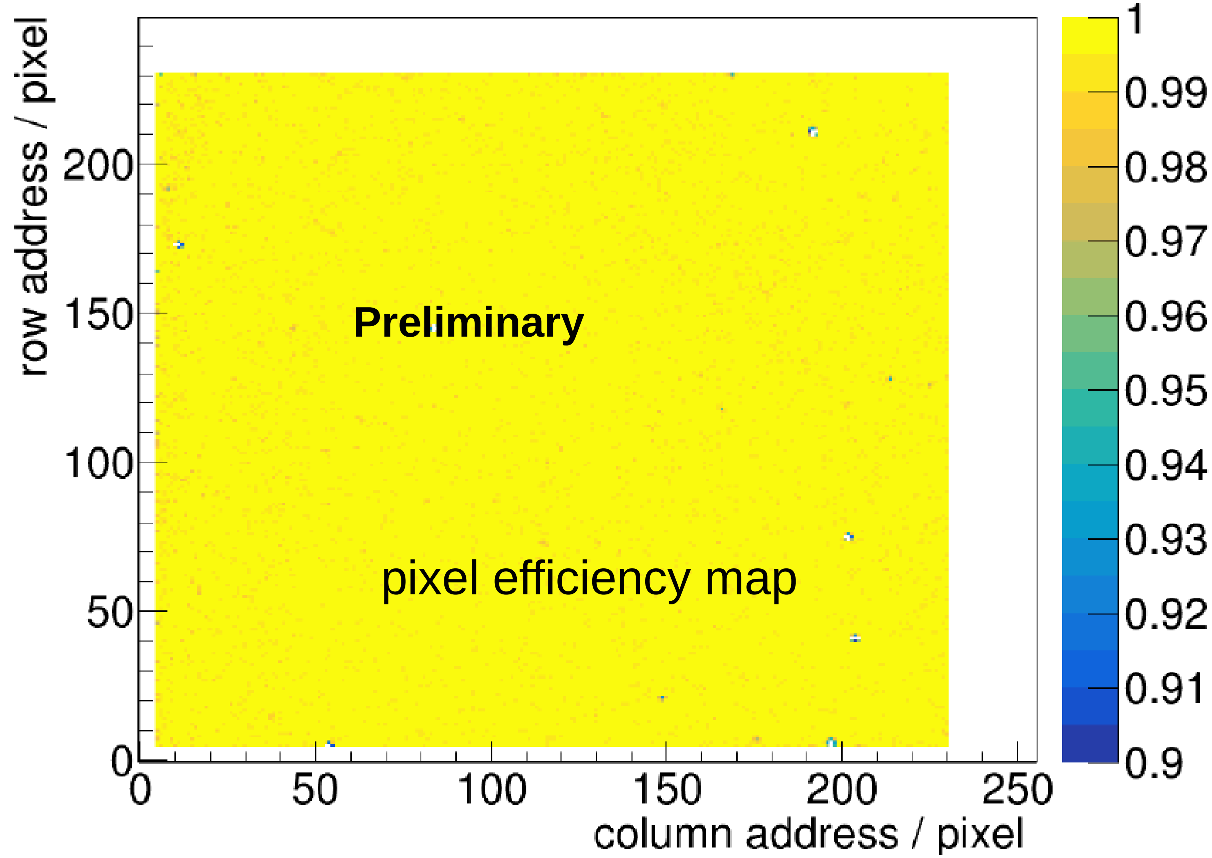


Specification from TDR

sensor dimensions [mm^2]	$\leq 21 \times 23$
sensor size (active) [mm^2]	$\approx 20 \times 20$
thickness [µm]	≤ 50
spatial resolution µm	≤ 30
time resolution [ns]	≤ 20
hit efficiency [%]	≥ 99
#LVDS links (inner layers)	1 (3)
bandwidth per link [Gbit/s]	≥ 1.25
power density of sensors [mW/cm^2]	≤ 350
operation temperature range [°C]	0 to 70

Mupix10 Performance (Preliminary)

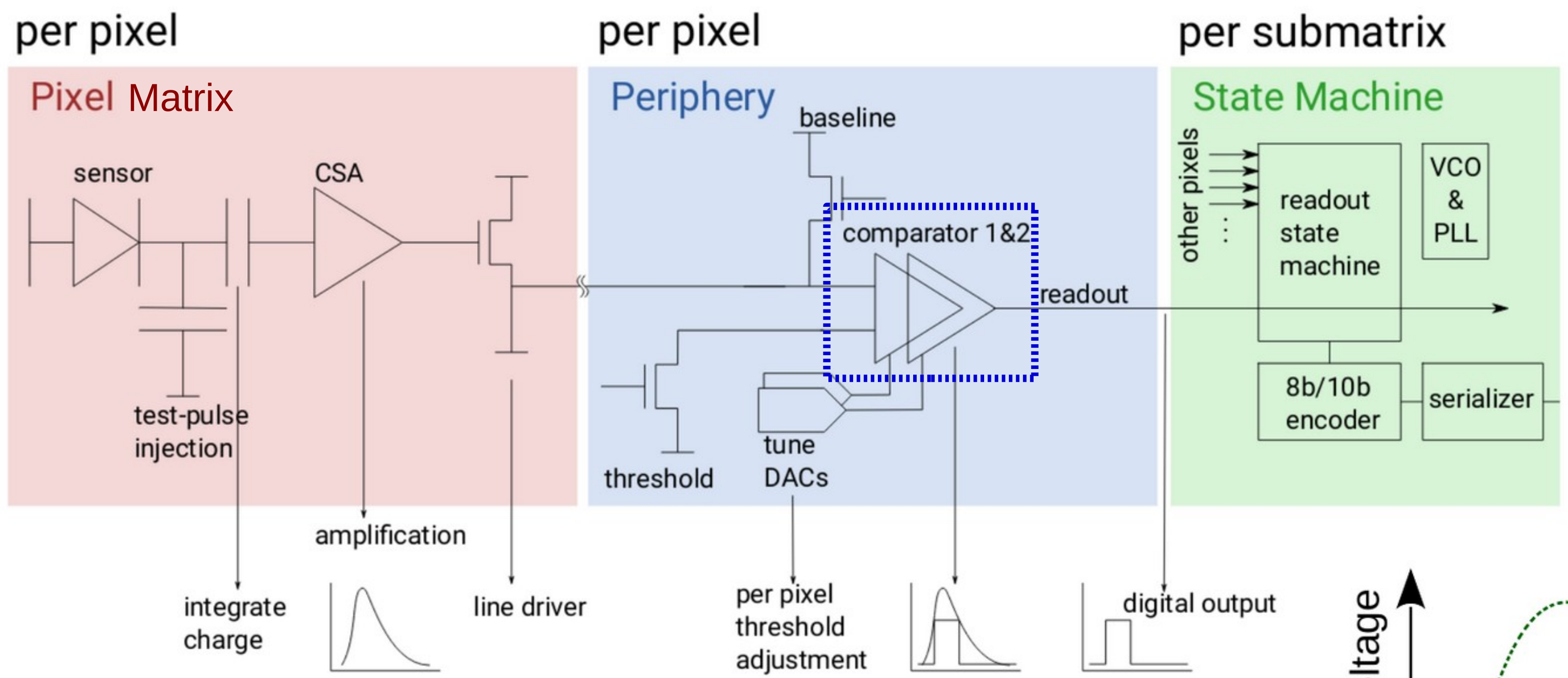




- threshold of 100 mV corresponds to about 1500 electrons
- efficiency increases with HV (depletion zone)

$$d \propto \sqrt{U\rho}$$

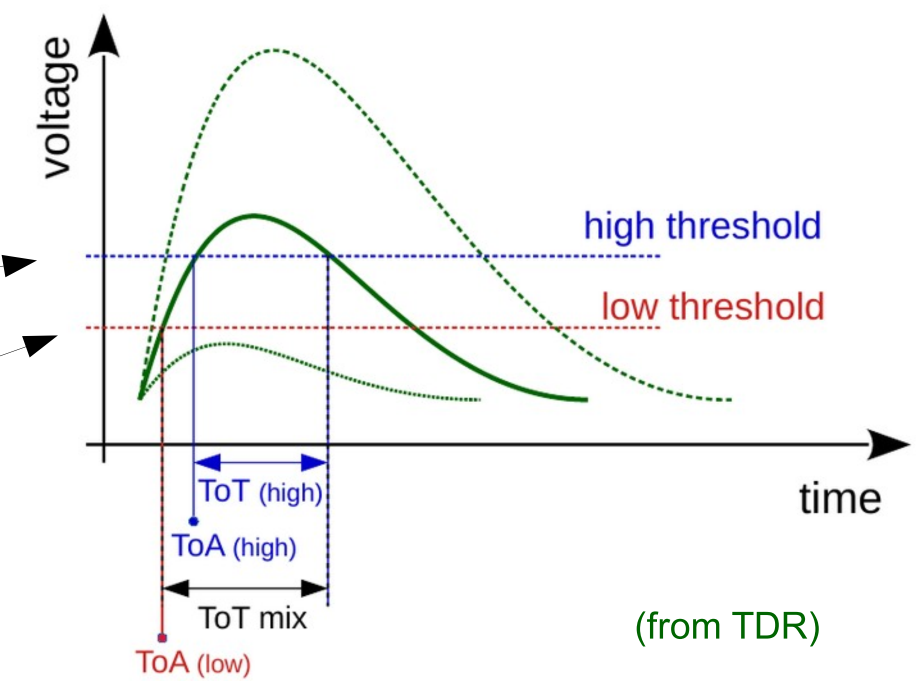
MuPix Two-Comparator Design



Motivation of 2-comparator design

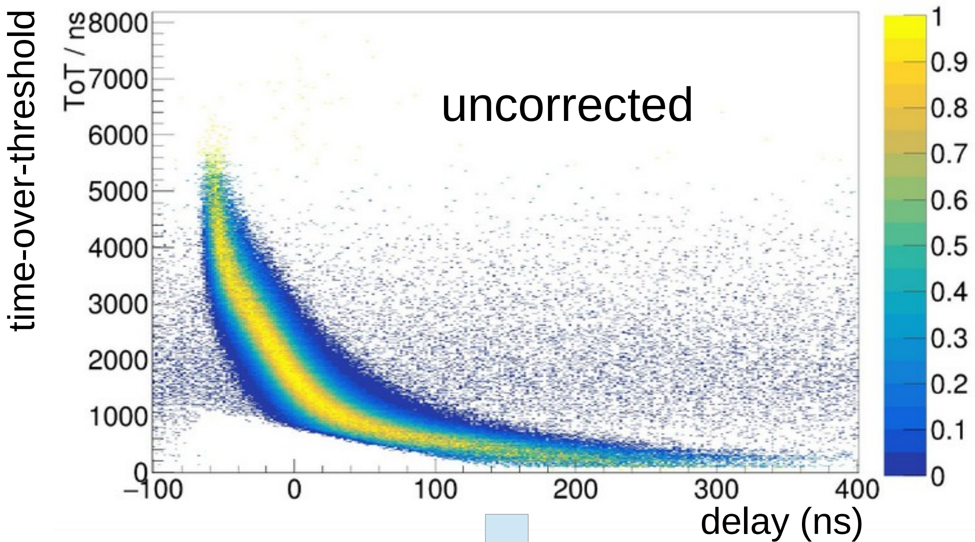
- use <u>higher</u> threshold for **hit validation**
- use <u>lower</u> threshold to reduce **time walk** (ToA)

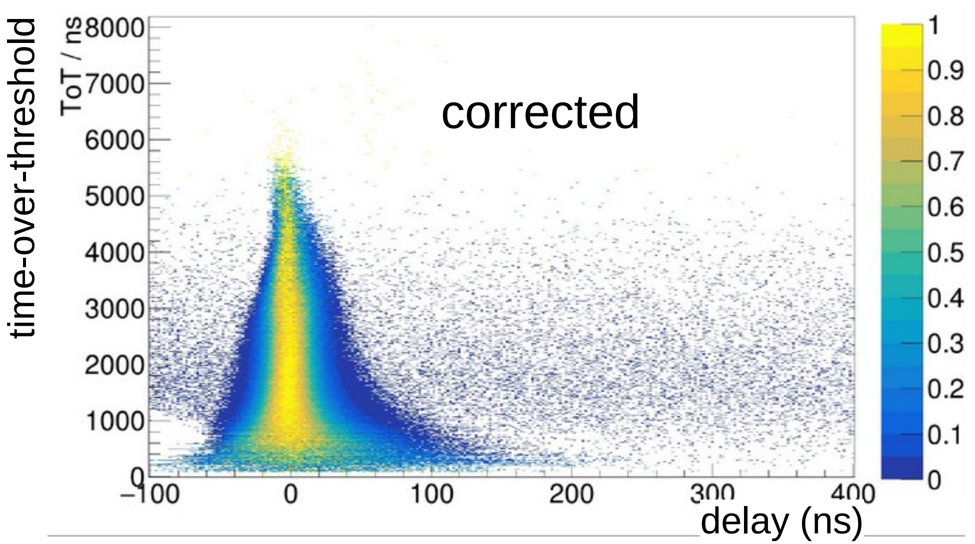
→ timewalk mitigation

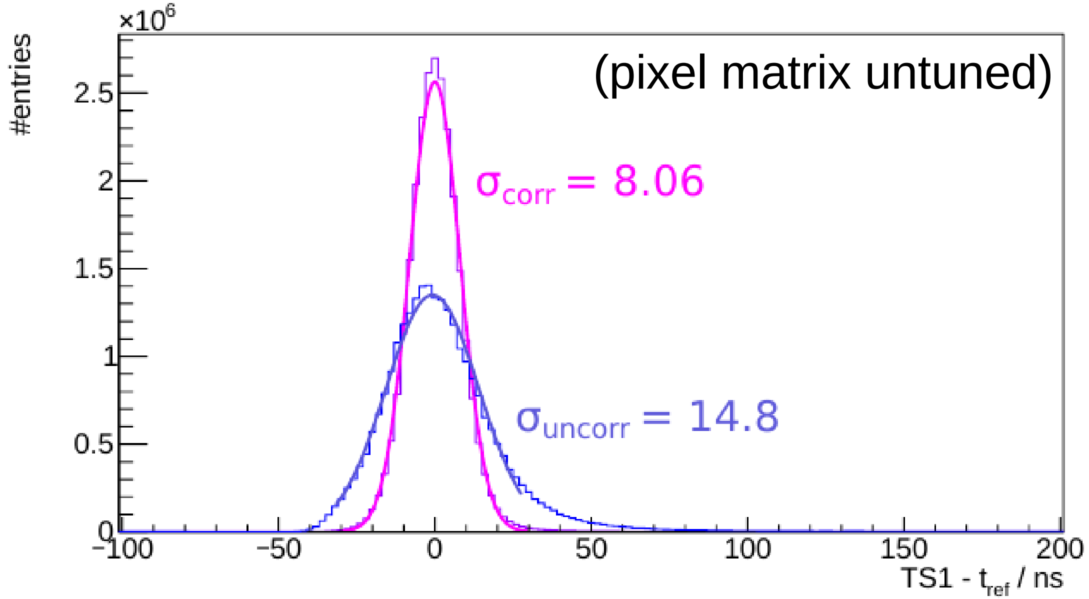


Timewalk Correction (MuPix10)

(bachelor thesis F.Frauen, Heidelberg)



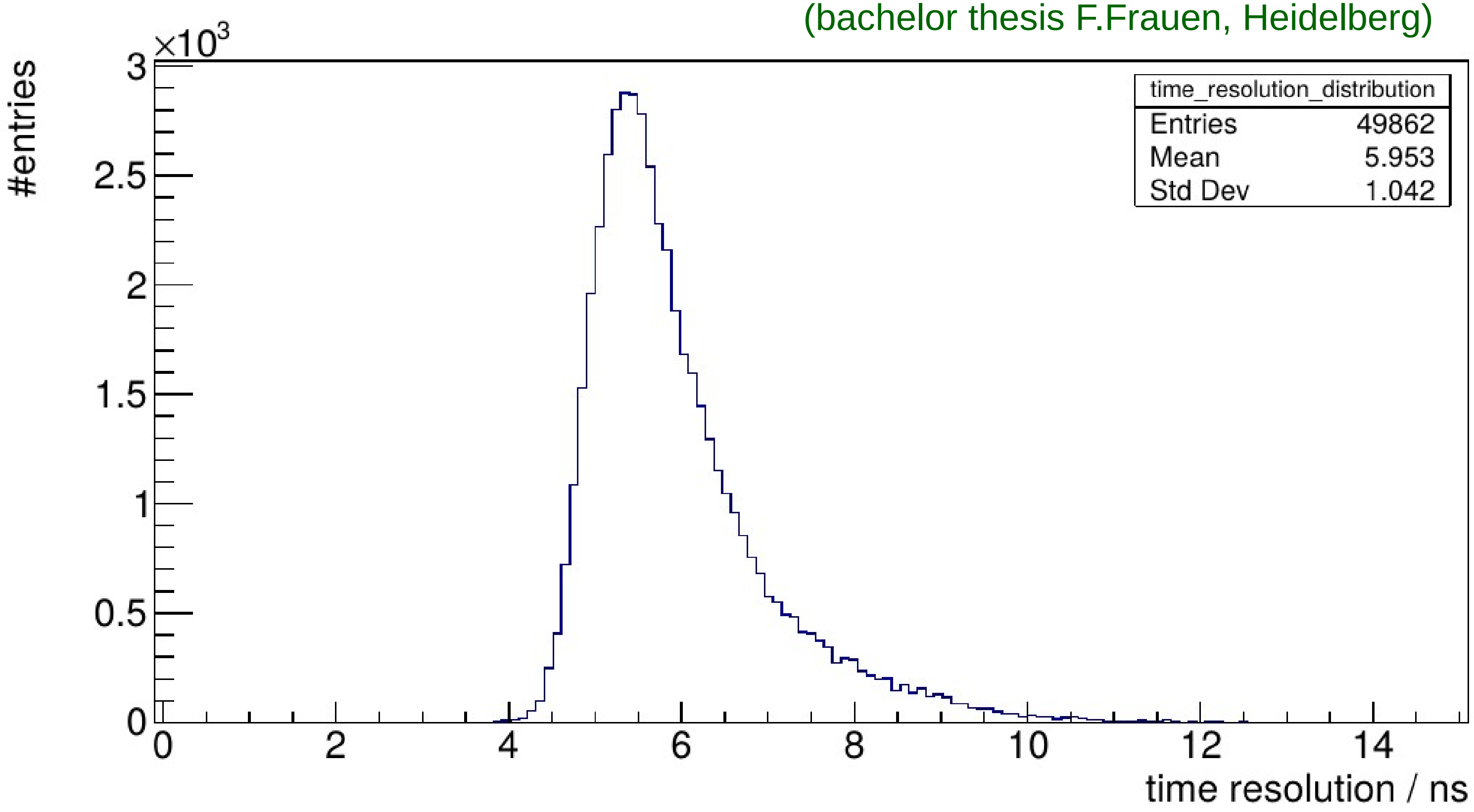




Time Resolution (MuPix10)

- contribution to overall time resolution from pixel-to-pixel variations if sensor is not tuned
- time resolution of single pixels **~ 6ns**:

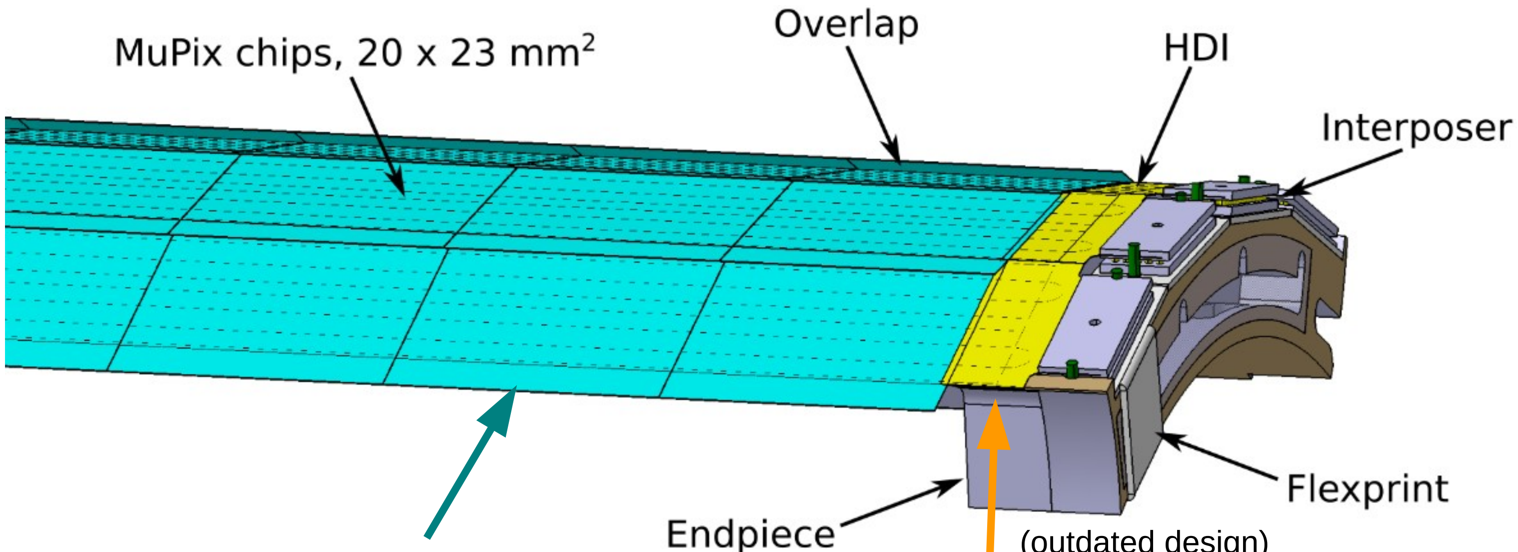
(bachelor thesis F.Frauen, Heidelberg)



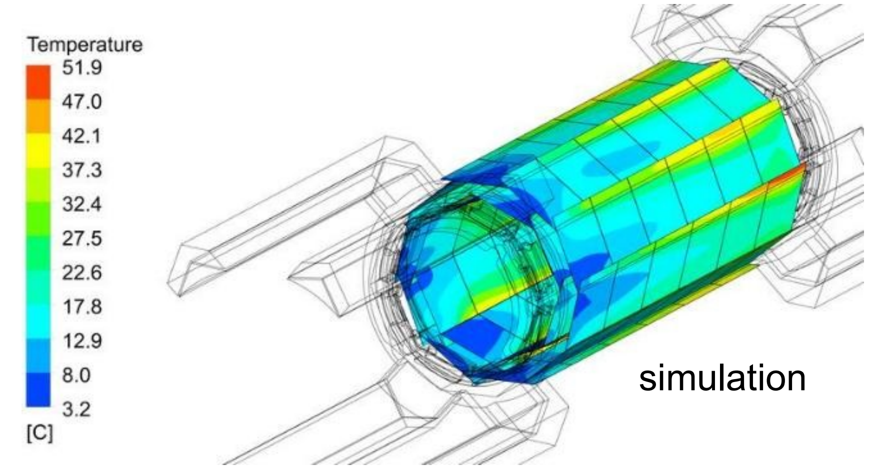
- further improvements possible by tuning each of the 64000 pixels individually (3-bit tune-DAQs)

Mu3e Pixel Tracking Detector

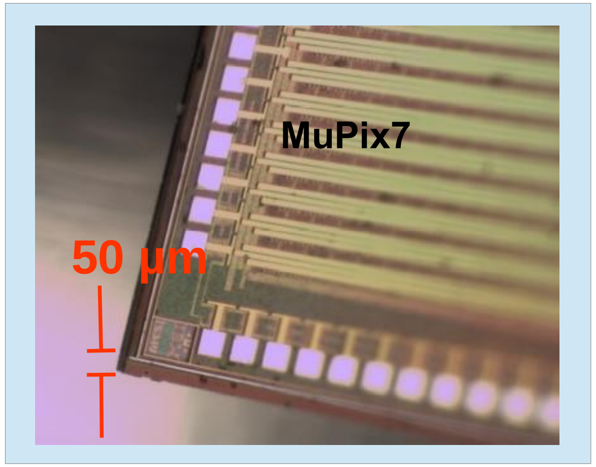
Ultra-thin pixel sensor modules (X/X_0 = 1.15 per mille)



Gaseous He-Cooling System

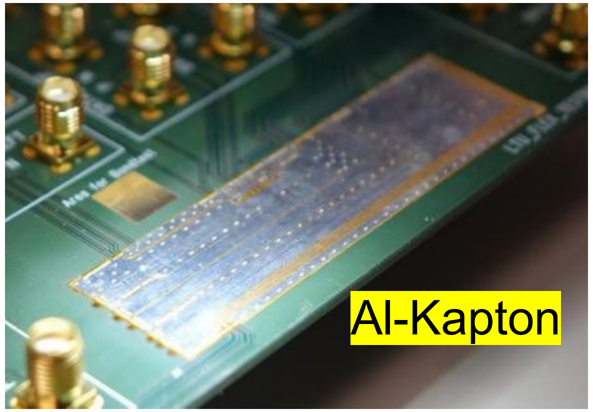


MuPix (HV-MAPS)

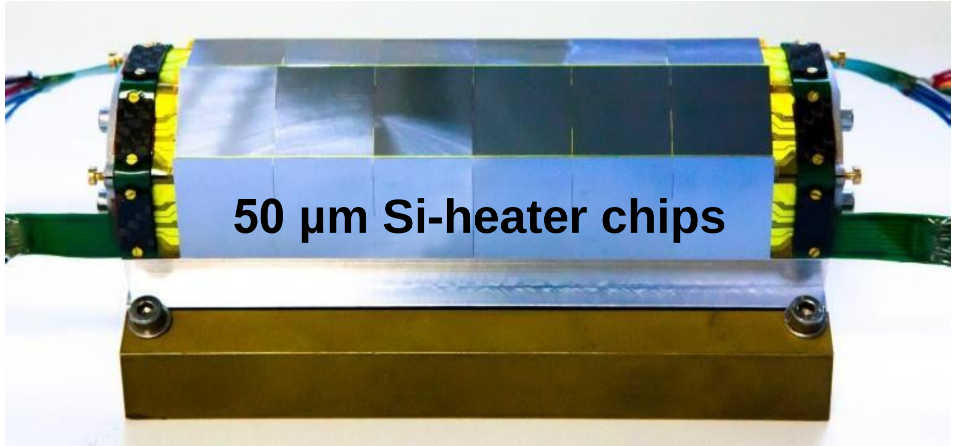


Monolithic pixel sensor in
180 nm HV-CMOS

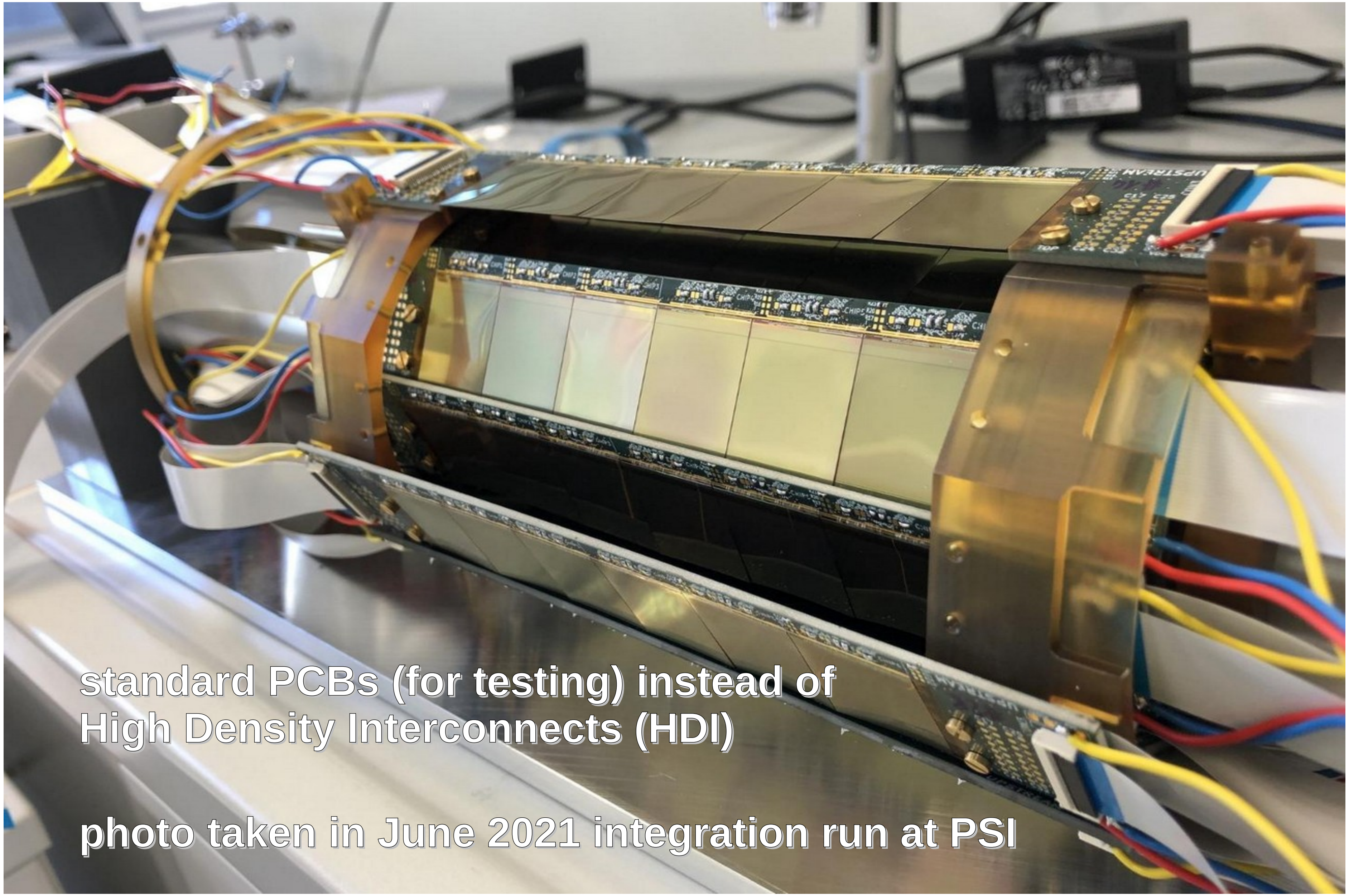
High Density Interconnect
d < 100 µm (LTU, Ukraine)



Thermo-Mechanical Mockup (vertex)



Pixel Tracking Detector Prototype



Comparison of Tracking Detectors

Pixel detectors

TRACKING DETECTOR	STAR PXL	BELLE II PXD	ALICE ITS II	**Mu3e PTD**
radiation length per layer in X_0	0.5%	0.2-0.5%	0.3-0.8%	**$\mathbf{0.11}$%**

Comparison of Tracking Detectors

Pixel detectors

TRACKING DETECTOR	STAR PXL	BELLE II PXD	ALICE ITS II	**Mu3e PTD**
radiation length per layer in X_0	0.5%	0.2-0.5%	0.3-0.8%	**0.11%**

SINDRUM (1988) – Mu3e comparison

PARAMETER		SINDRUM	**Mu3e**
rel. momentum resolution σ_p/p	$(p = 50\,\text{MeV/c})$	5.1%	0.8%
rel. momentum resolution σ_p/p	$(p = 20\,\text{MeV/c})$	3.6%	0.5%
polar angle σ_θ	$(p = 20\,\text{MeV/c})$	28 mrad	24 mrad
vertex resolution σ_{dca}		≈ 1 mm	280 µm
radiation length per layer in X_0		0.08% - 0.17%	0.11%

MPWC (gas) silicon pixel

Beam Position Monitoring with HV-MAPS for Particle Therapy

Heidelberg Ion Beam Therapy Center (HIT)

- ions: p, ^{4}He, ^{12}C, ^{16}O
- particle rates up to $4 \cdot 10^{10}$ per spill (5 sec)
- beam spot σ = 4 - 10mm
- beam energy up to 430 MeV/u

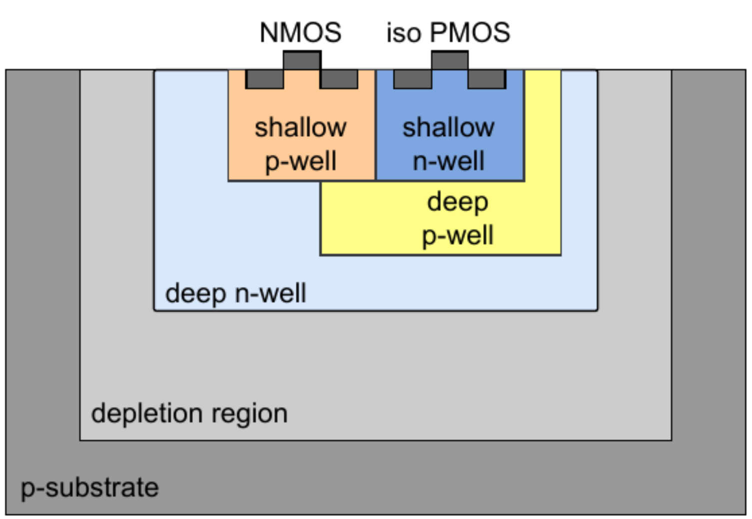
HitPix (Counter Chip) (A.Weber, thesis HD/KIT)

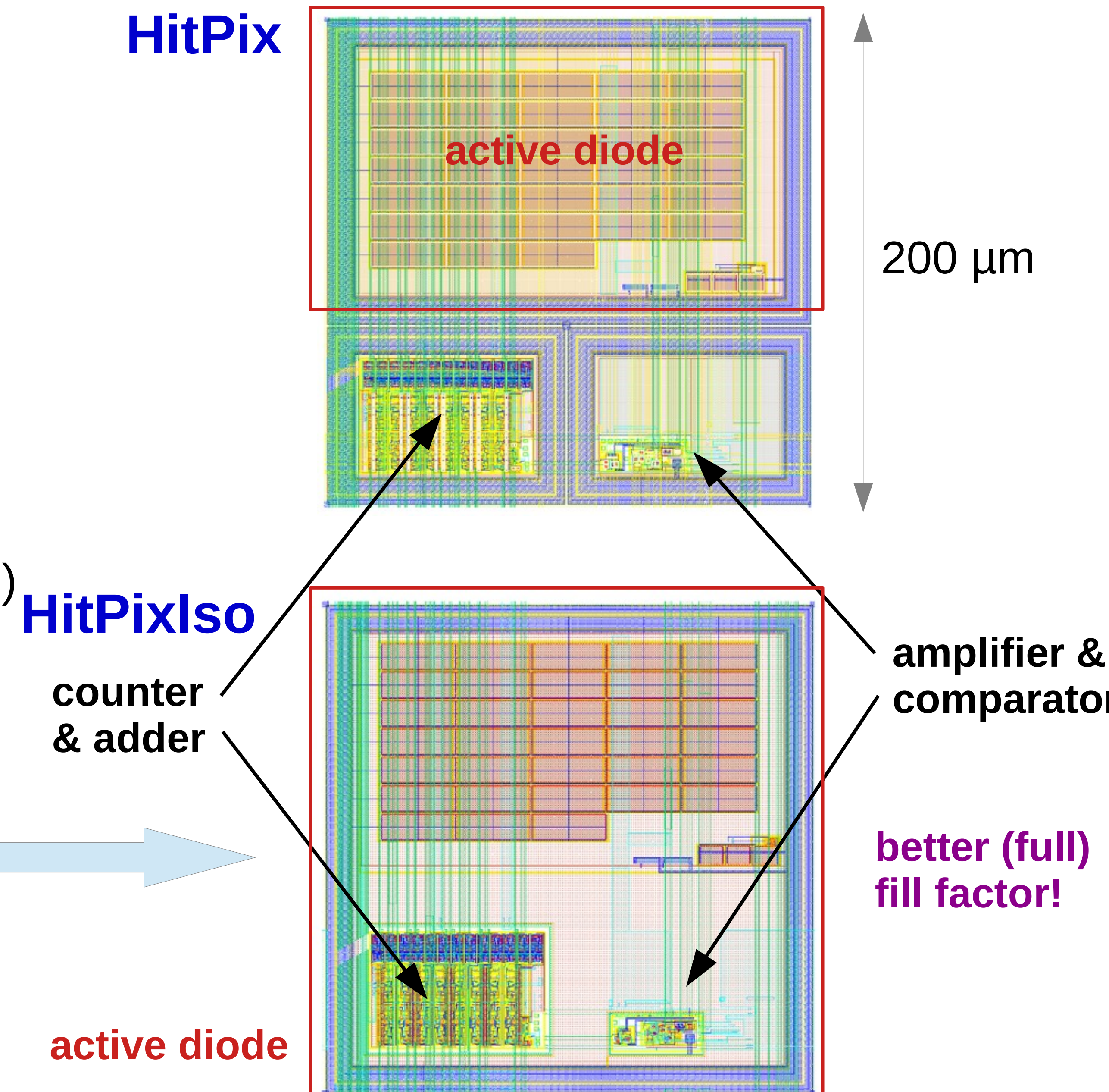
Main specification parameters

- counter in every **200 µm x 200 µm** pixel
- **adder** for measuring beam profile
- **online readout** during counting
- radiation hard design **~10^{15} (1 MeV) neq** (enclosed NMOS transistors)

ISO deep p-well process

- allows for implementing **CMOS circuitry** over **active structures** (charge collecting diode)



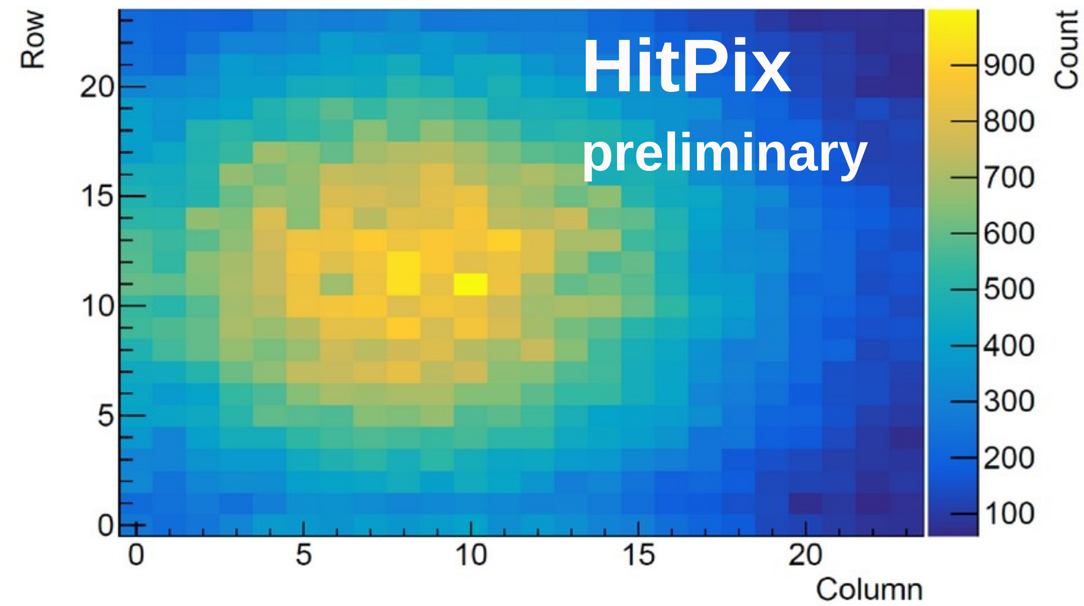


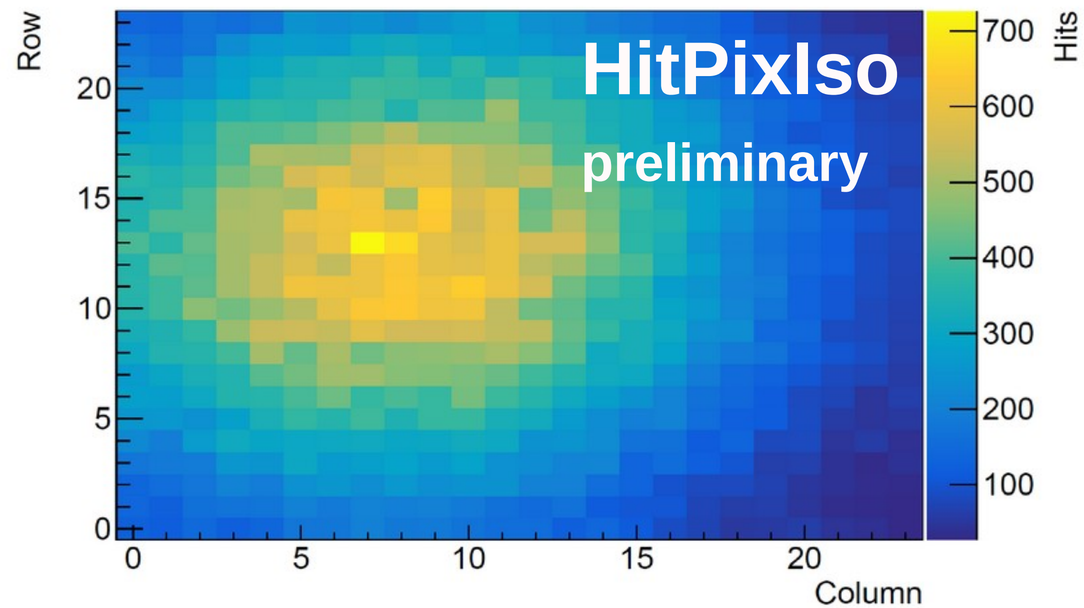
HitPix & HitPixIso Results (A.Weber, thesis HD/KIT)

Hit testbeam (2021)

- ion type = ^{12}C
- energy = 400 MeV/s
- rate = $2 \cdot 10^6$ ions per second

Both chip designs work perfectly and give consistent results!





Other HV-MAPS Activities for Particle Tracking

Low Energy

Sensors:

PandaPix → large dynamic ranged for dEdx

TelePix → high resolution timing reference layer for beam telescope at DESY

High Energy

ATLASpix → proposal for high luminosity ATLAS outer pixel layer (dismissed) → CEPC

CLICPix → high resolution pixel layer for CLIC

MightyPix → LHCb tracker upgrade for high rate

Projects:

P2 experiment @MESA (Weinberg angle)
→ tracking of scattered 150 MeV electrons

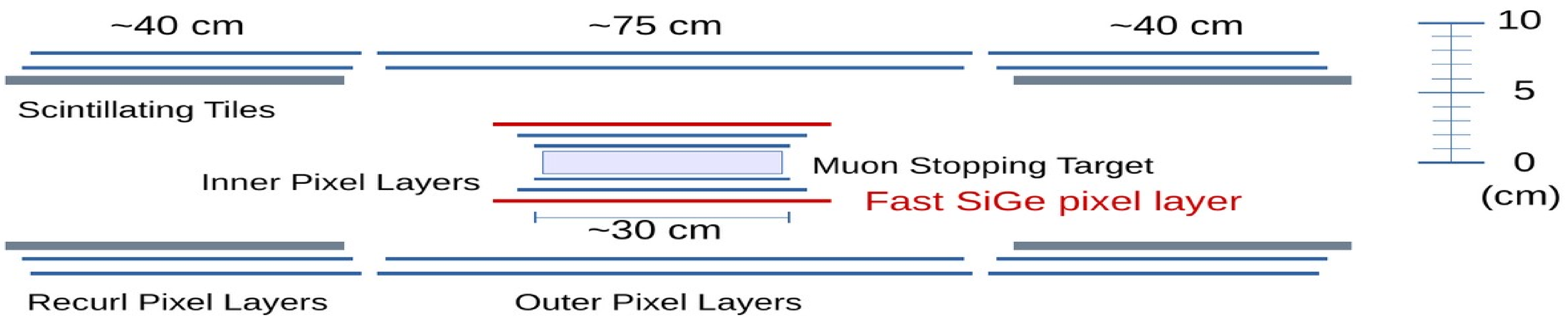
μSR @PSI: muon resonance spectroscopy for solid state physics applications
→ tracking of Michel electrons

Mu3e phase II and **MEG III** at new high intensity muon beamline (HIMB) @PSI → talk by Andreas Knecht

about 20x higher muon stopping rates → next slides

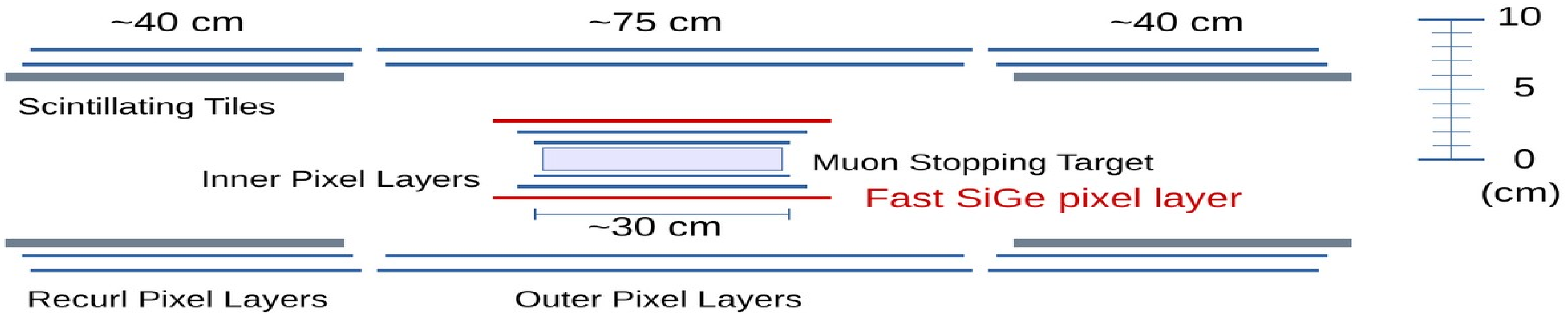
HV-MAPS for Mu3e Phase II at HIMB (PSI)

Design concept similar to phase I, but with longer muon stopping target and pixel modules:



HV-MAPS for Mu3e Phase II at HIMB (PSI)

Design concept similar to phase I, but with longer muon stopping target and pixel modules:



1. Development of new MuPix20 sensor:

- improved timing resolution of **~1ns** (~4ns already achieved with ATLASpix3)
- improved readout → **daisy chaining** of sensors
- smaller pixel size for vertex layers about **50 µm x 50 µm**

2. Development of new SiGe pixel/pad sensor with sub-nanosecond resolution (PicoPix):

- **130 nm SiGe BiCMOS** process provides fast bipolar transistors
- time resolution of **~100 ps** has been demonstrated for this process (L. Paolozzi et al, Geneva, 2021)

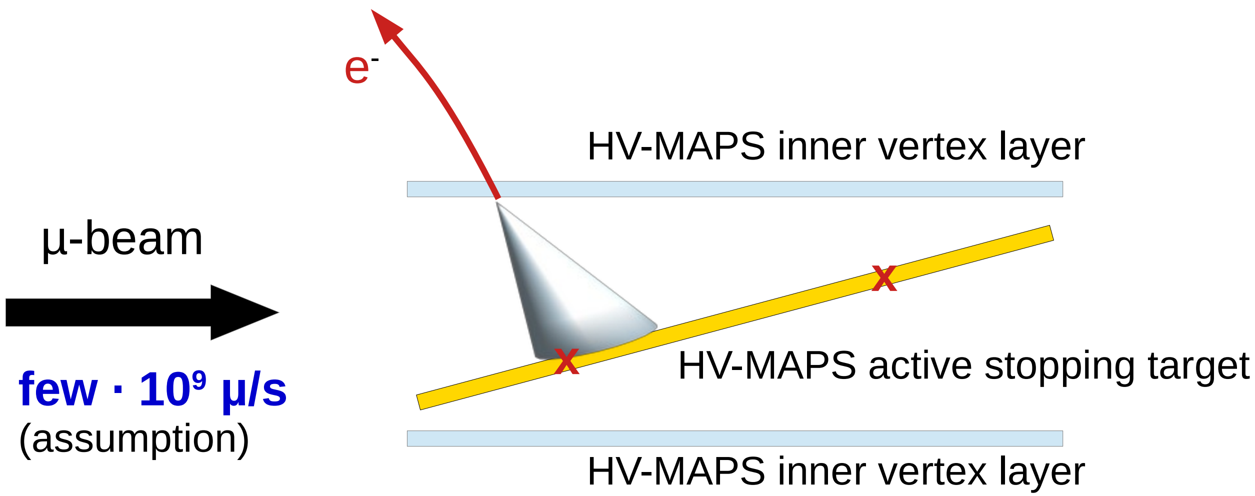
Goal is to reduce accidental background at ~20x increased muon stop rates

HV-MAPS for MEG III at HIMB (PSI)

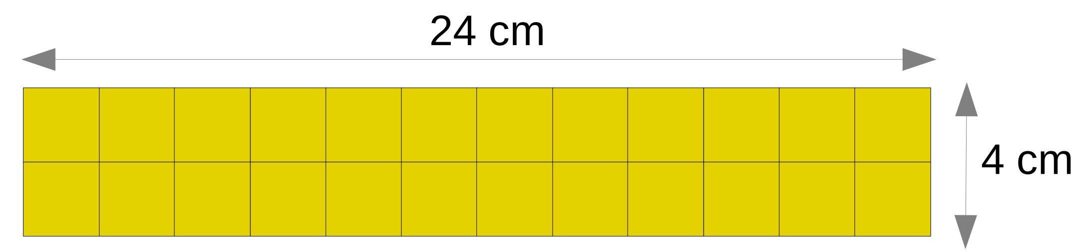
MEG III @ HIMB could possibly reach a sensitivity $BR(\mu \rightarrow e\gamma) < 10^{-14}$

Sensitivity given by: $B_{acc} \propto R_\mu \; \sigma(p_e) \; \sigma(E_\gamma)^2 \; \boxed{\sigma(\Theta_{e\gamma})^2}$

search for back-to-back topology



Example layout:

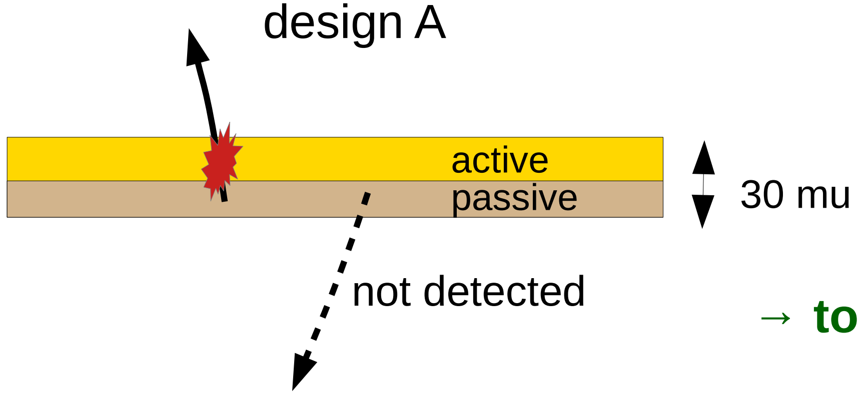


Idea: measure vertex precisey using an active stopping target (HV-MAPS)

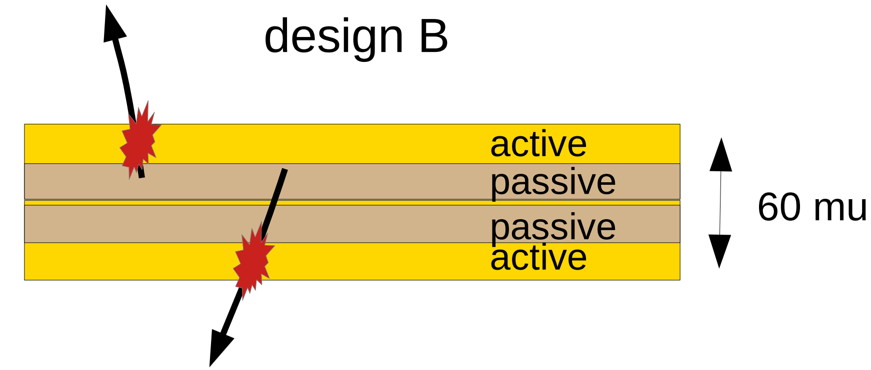
2 x 12 sensors a 2x2 cm^2

→ total stopping area ~**100 cm²**

design A



design B



→ **to be studied!**

Summary

High Voltage Monolithic Active Pixel Sensors represent an interesting technology

- small sensor thickness
- excellent performance
- good timing resolution
- fast readout
- radiation tolerant

Very active field!

- 180nm HV-CMOS process is baseline for several projects (Mu3e, MightyPix @LHCb, P2 @MESA)
- several engineering runs per year (2021: HitPix & others, Telepix & MightyPix, Mupix11)

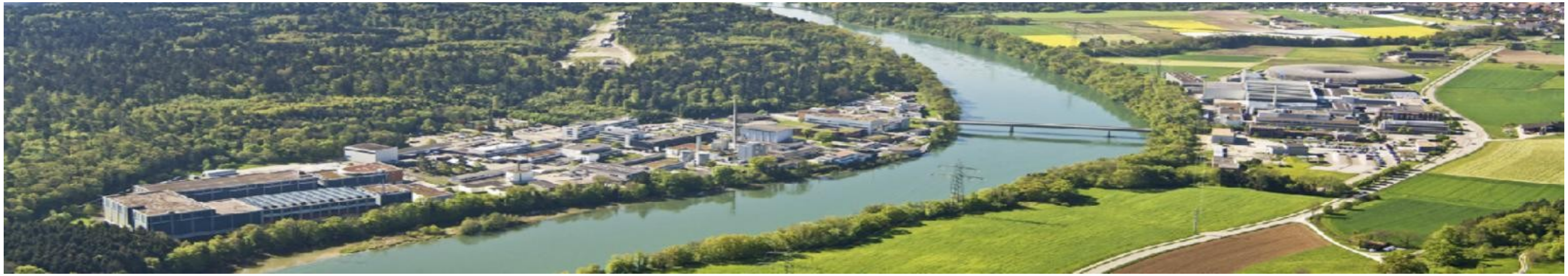
Future

- Expect further improvements concerning time and spatial resolution, and scalability
- 130nm SiGe process → sub-nanosecond timing
- active muon stopping target?

HV-MAPS are Ideal for particle tracking at low energy and high rate!

Backup

Paul-Scherrer Institut (Schweiz)



High intensity Proton Accelerator (HiPA) → 2.4 mA protons at 590 MeV (1.5 MW)

Muon Beam:

- World's most intense continuous muon beam
- Low momentum muons ~**28 MeV/c**
- PiE5 beamline shared between **MEGII** and **Mu3e**

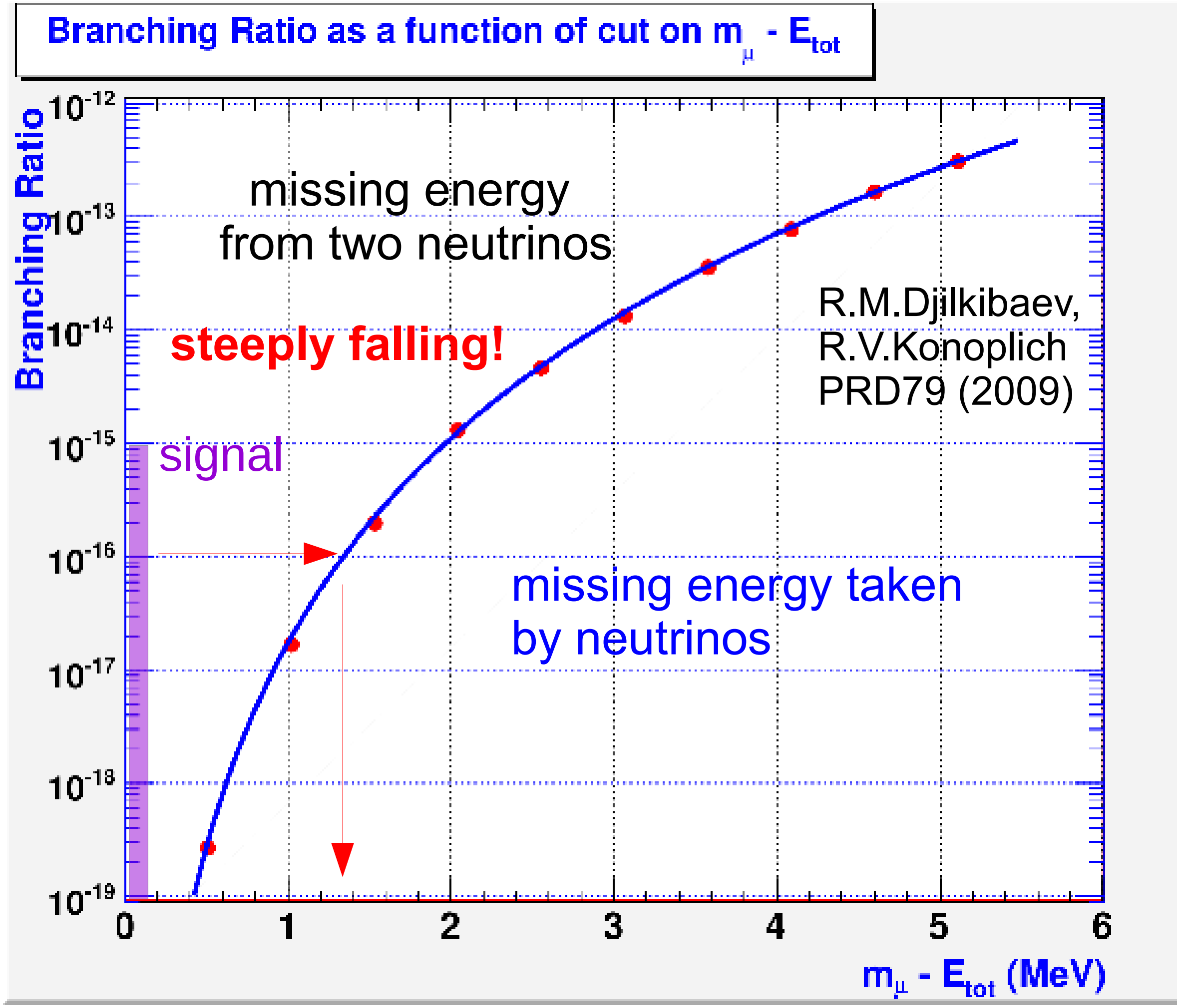
➢ **expect $1.4 \cdot 10^8$ μ^+/s at 2.4 mA**

➢ **about half is stopped on μ-stopping target**

→ **Mu3e Phase I**

PiE5: Compact Muon Beamline for Mu3e

Irreducible Background $\mu^+ \to e^+e^+e^- \nu\nu$ and Multiple Scattering



- Background scales with energy resolution:

$$\text{sensitivity} \propto \sigma(E)^6$$

- energy (momentum) resolution solely depends on multiple scattering:

$$\sigma(p) \propto \Theta_{MS}^{1-2}$$

- momentum resolution scales with material thickness:

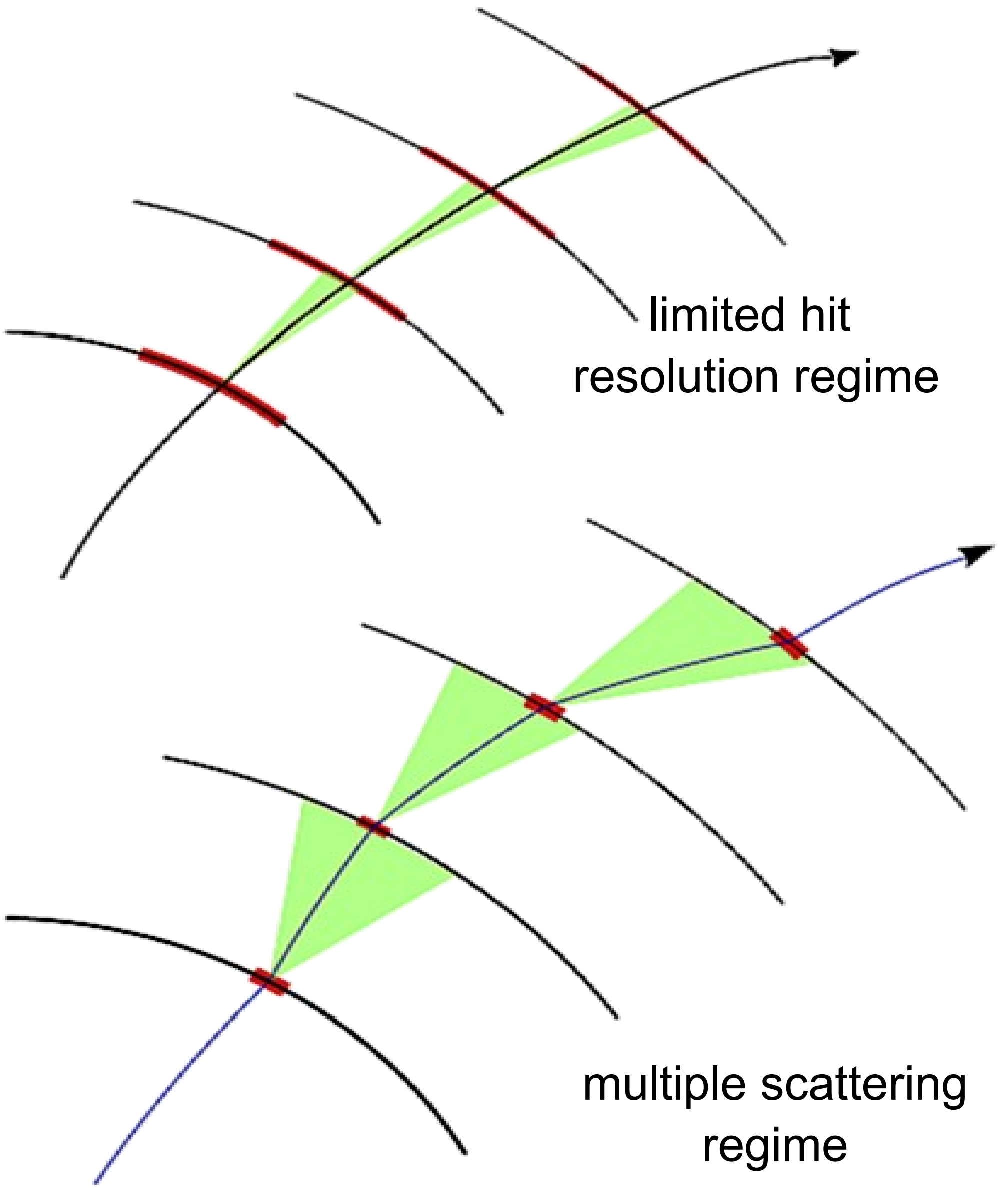
$$\Theta_{MS} \sim \frac{1}{P}\sqrt{X/X_0}$$

- in summary:

$$\text{sensitivity} \propto (X/X_0)^{3-6}$$

30% reduction of material results in at least a factor 3 increase in sensitivity

Tracking Resolution + Multiple Scattering



- Muon decay (m=105.6 MeV):

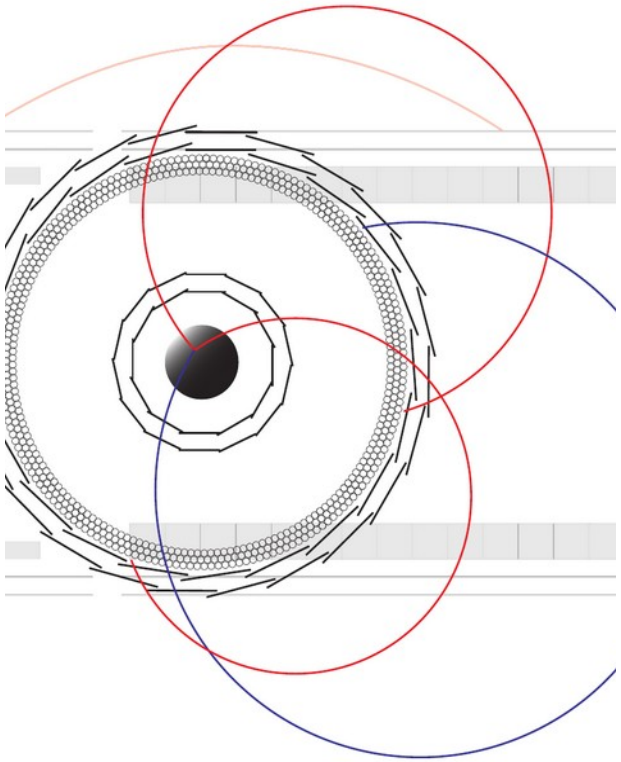
  → electrons in low momentum range
  p < 53 MeV/c

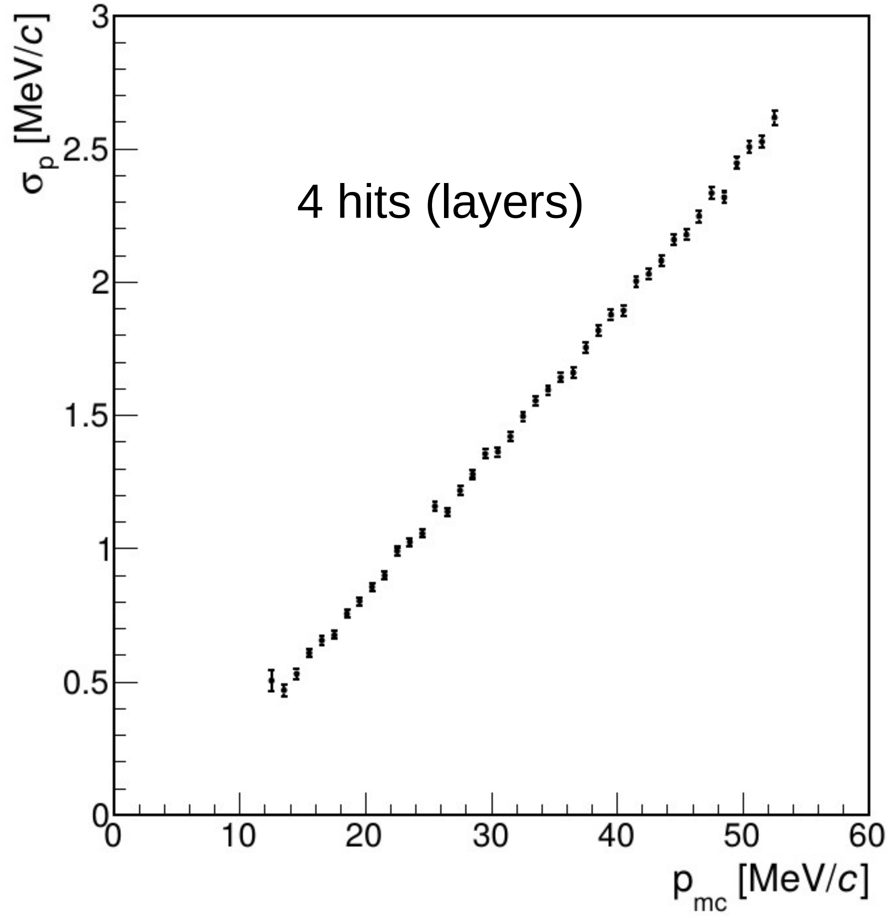
- Multiple scattering is dominant!

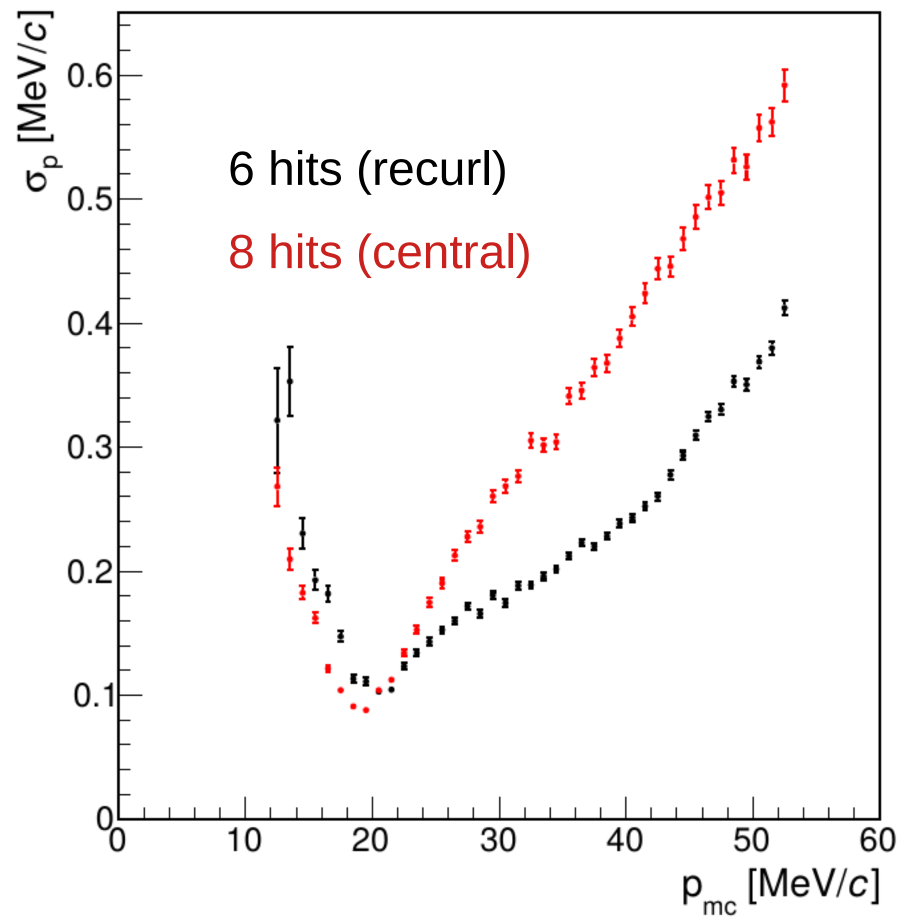
➔ **Need thin, fast and high resolution tracking detectors operated at high rate (>> 10^9 particles/s @ phase II)**

$$\Theta_{MS} \sim \frac{1}{P} \sqrt{X / X_0}$$

Momentum Resolution (Simulation)

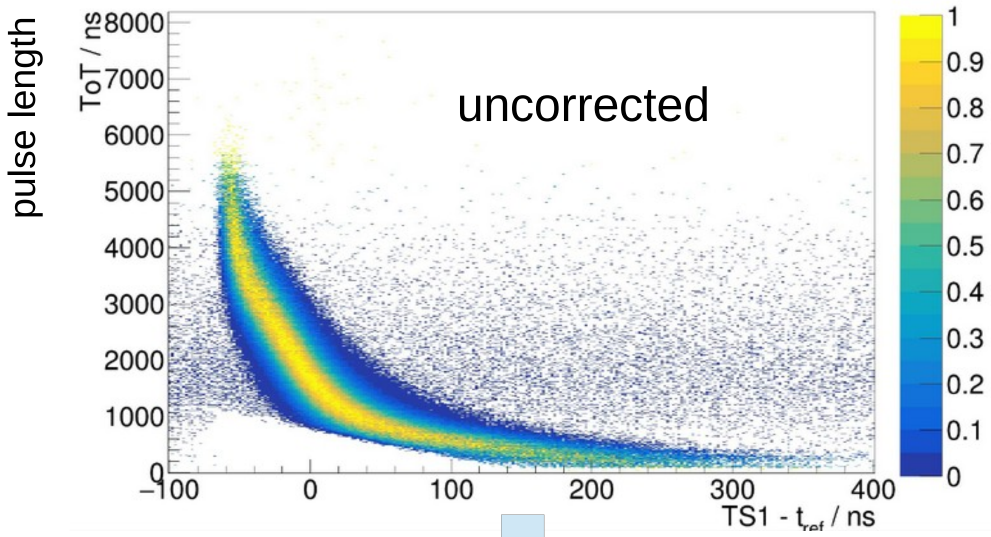


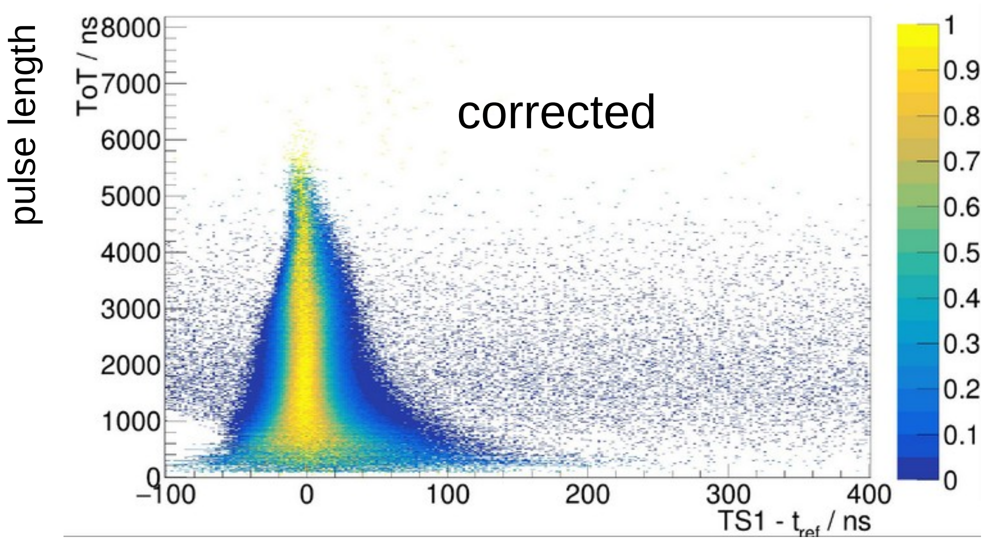


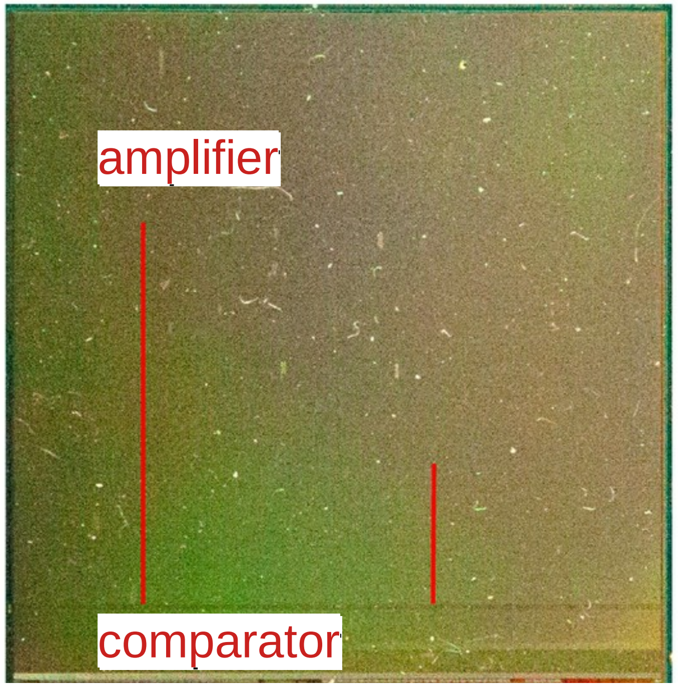


Timewalk in MuPix10

bachelor thesis F.Frauen, Heidelberg



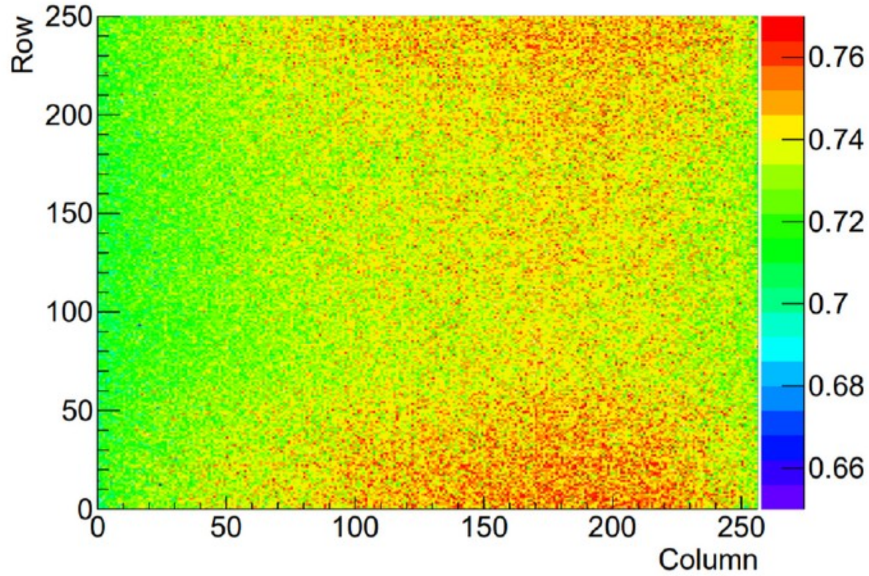




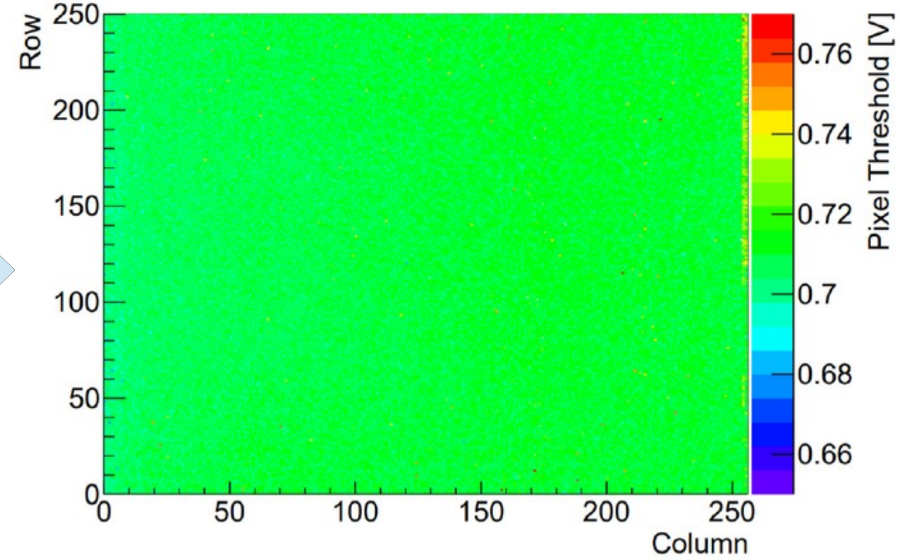
- timewalk effects from the long routing lines (analog signal) are large and row dependent
- correction possible with measured ToT
- **hit time resolution** after correction
  → **5-6 ns** (prel.)

Mupix10: Pixel Tuning of Comparator Threshold

(bachelor thesis M.Menzel, Heidelberg)

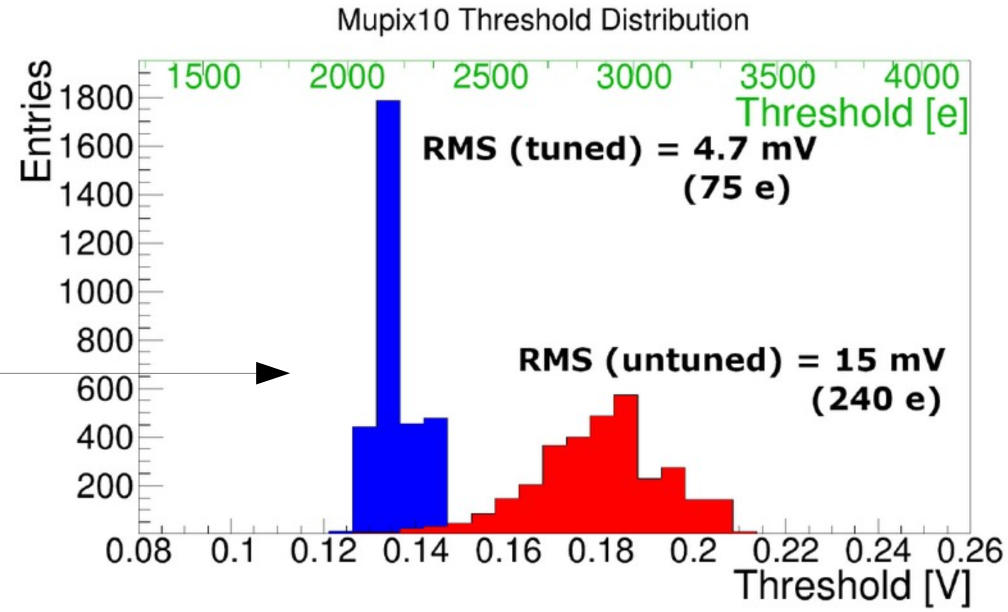


Untuned pixel threshold distribution.

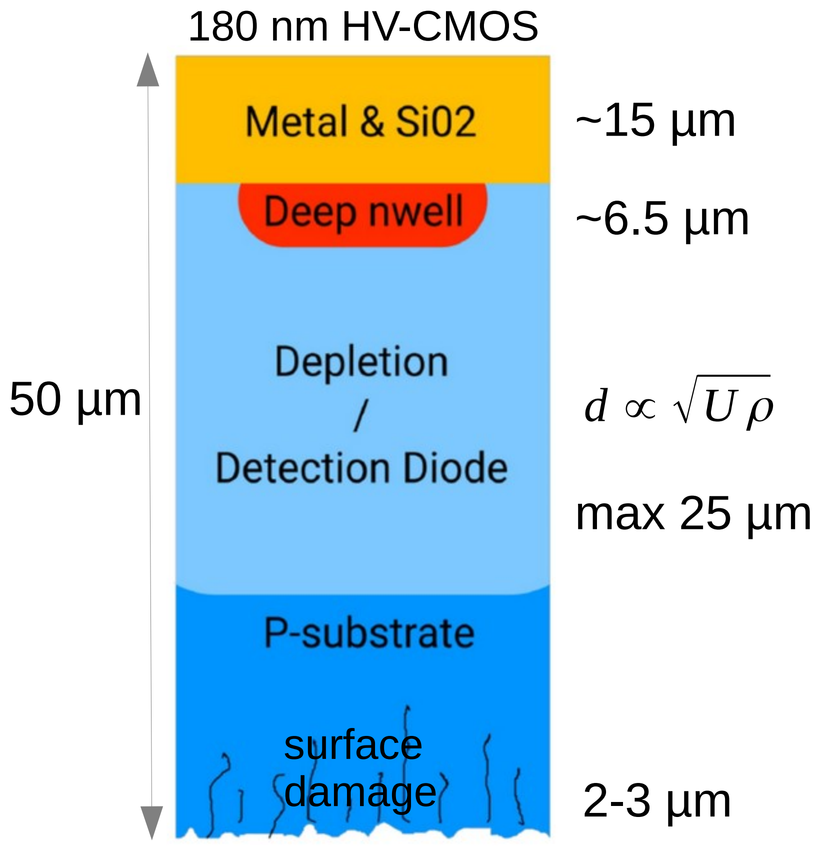


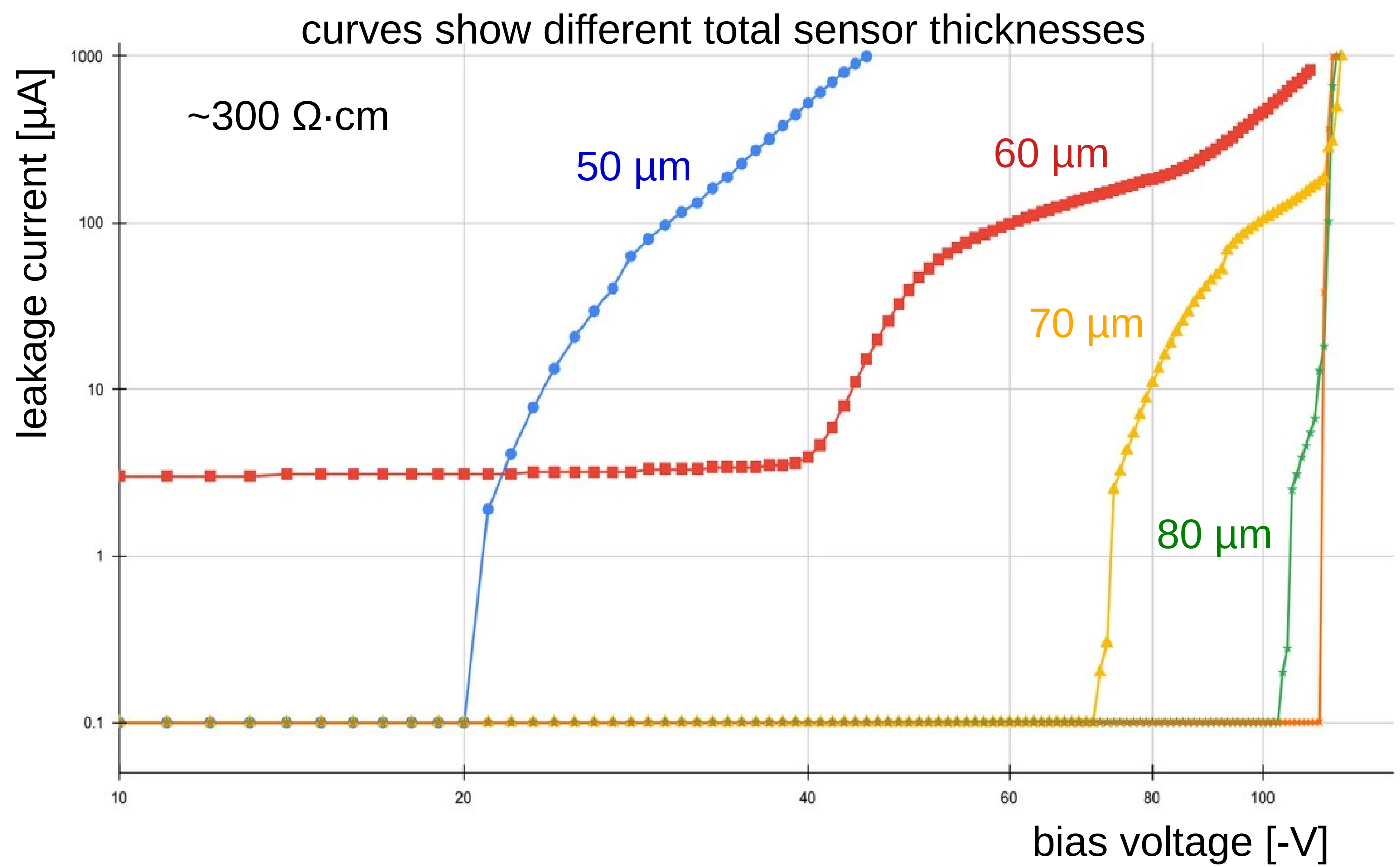
Tuned pixel threshold distribution.

- **3 bit tune** dac (digital-analog converter) per pixel
- tune with charge **injection**
- significant **dispersion reduction**



Depletion and Sensor Thickness





- depletion should be "alap" (as large as possible)
- maximum HV depends on full depletion limit

Measured leakage currents with MuPix10 and ~300 Ω·cm substrate