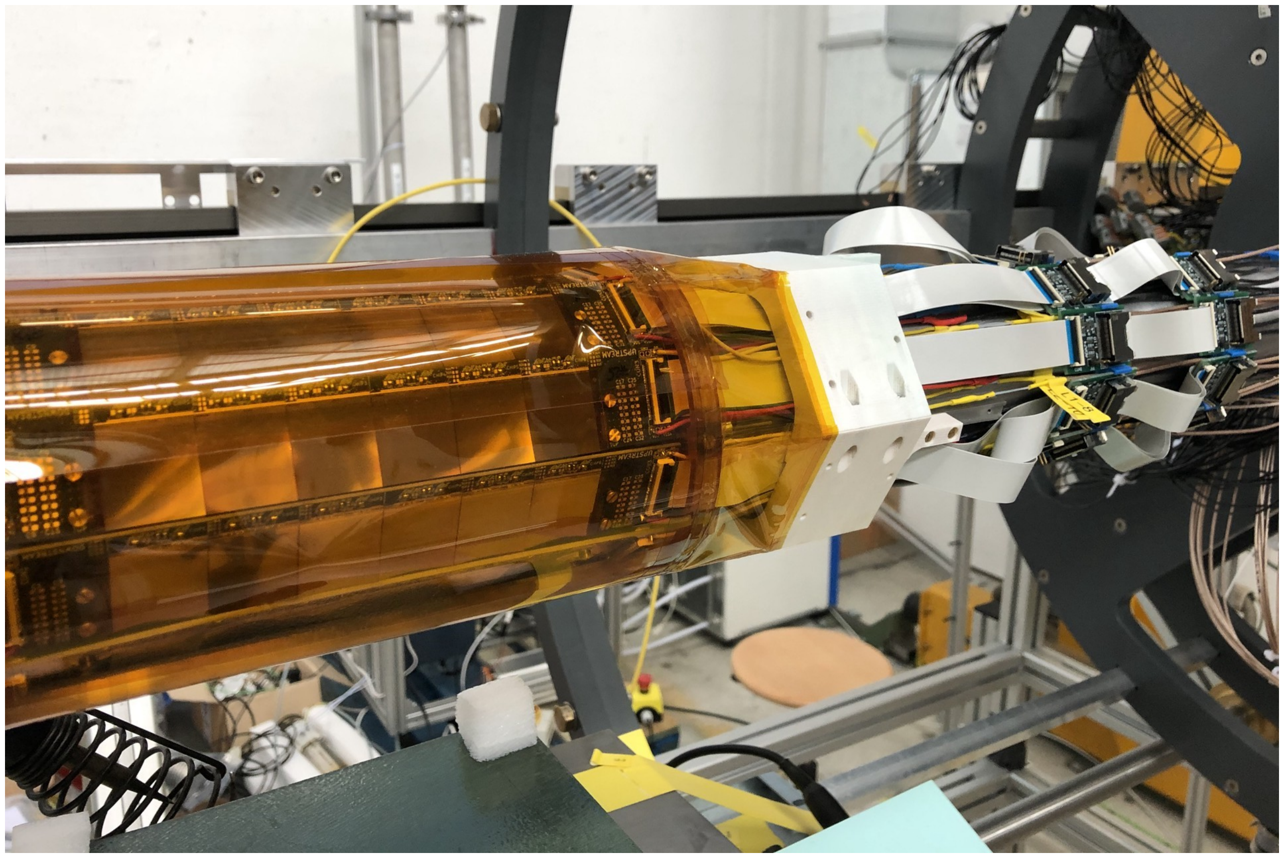
Mu3e silicon timing upgrade



Monolith Workshop

5.-6. September 2022

André Schöning

University Heidelberg (PI)

Search for the golden lepton flavor violating decay $\mu^+ \rightarrow e^+ e^+ e^-$

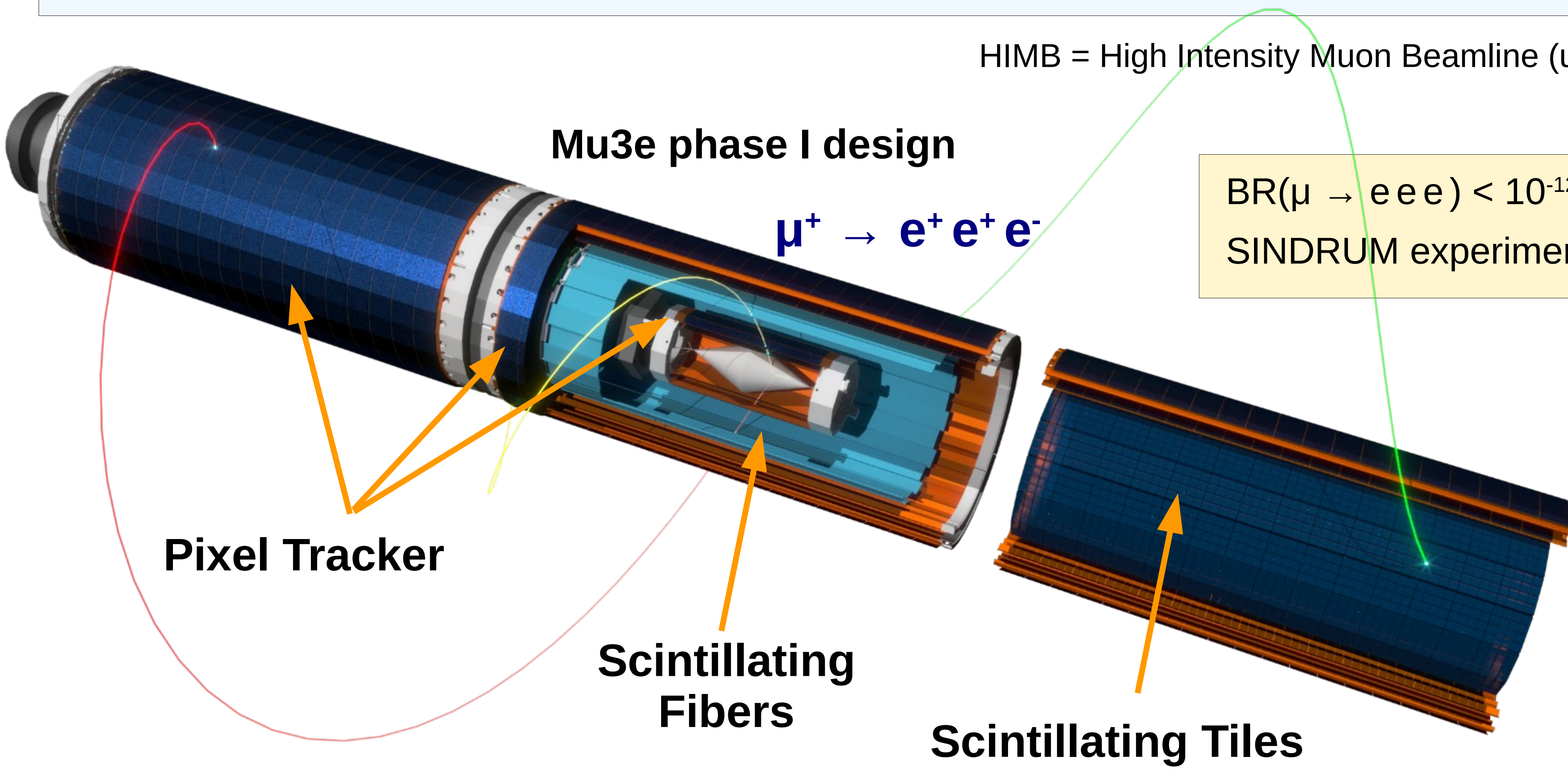
Mu3e Experiment @ PSI

<u>Aiming for a sensitivity (SES)</u> <u>requires:</u>

$BR(\mu \rightarrow eee) < 2\cdot 10^{-15}$	(phase I)	$\rightarrow$	10^8 muons/s (PiE5)	~until 2026
$BR(\mu \rightarrow eee) < 10^{-16}$	(phase II)	$\rightarrow$	$>10^9$ muons/s (HIMB)	R&D

HIMB = High Intensity Muon Beamline (under study)

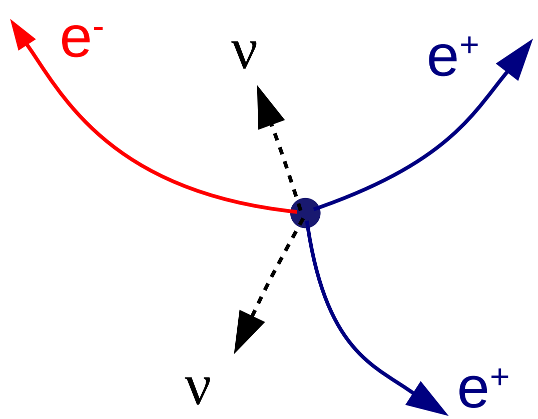
$BR(\mu \rightarrow eee) < 10^{-12}$ (90% CL)
SINDRUM experiment (1986)



Backgrounds & Requirements

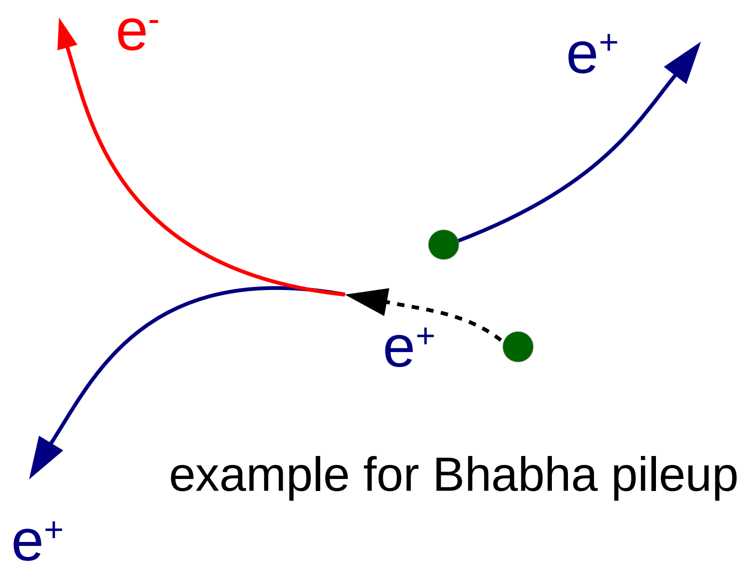
Irreducible BG

$B(\mu^+ \rightarrow e^+e^+e^- \nu\nu) = 3.4 \cdot 10^{-5}$



Accidental BG

→ **scales with muon rate**

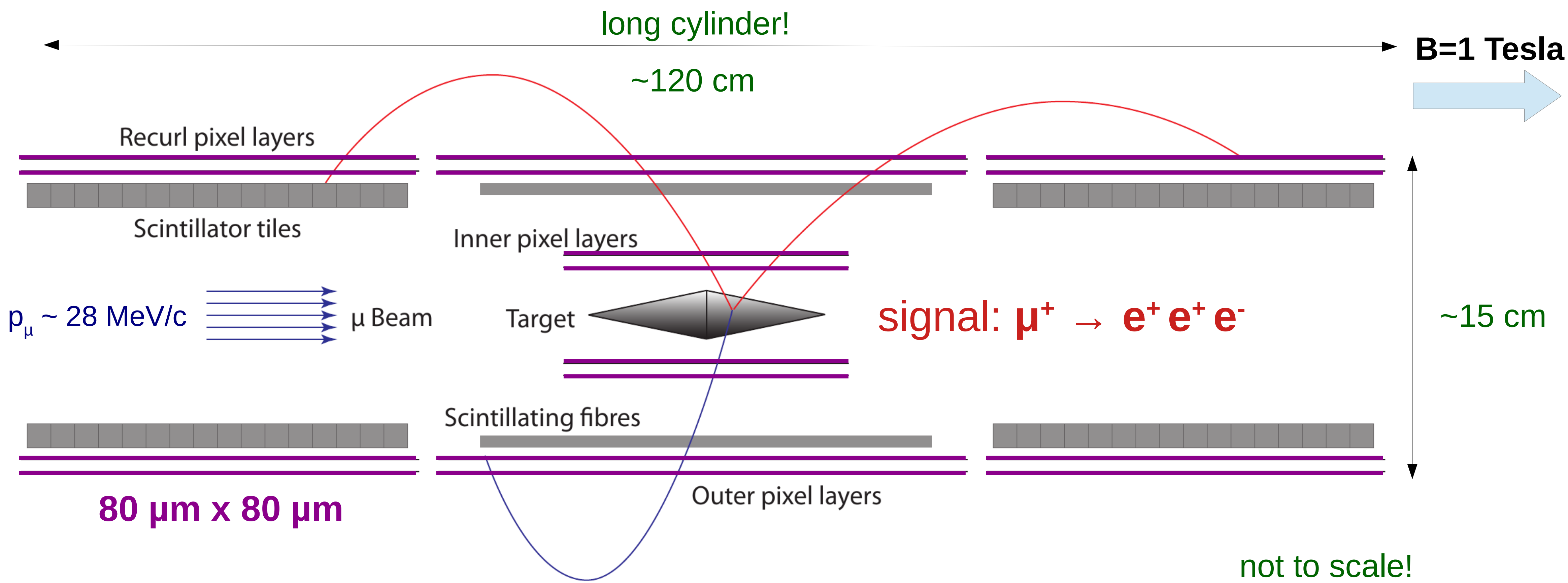


Need excellent:

- **vertex resolution** → **high granularity, low mass detector** (multiple scattering)
- **timing resolution** → **fast scintillator system in phase I (100-250 ps)**
- **kinematic reconstruction** → **low mass detector** (multiple scattering)

Mu3e Silicon Pixel Tracker Design (Phase I)

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

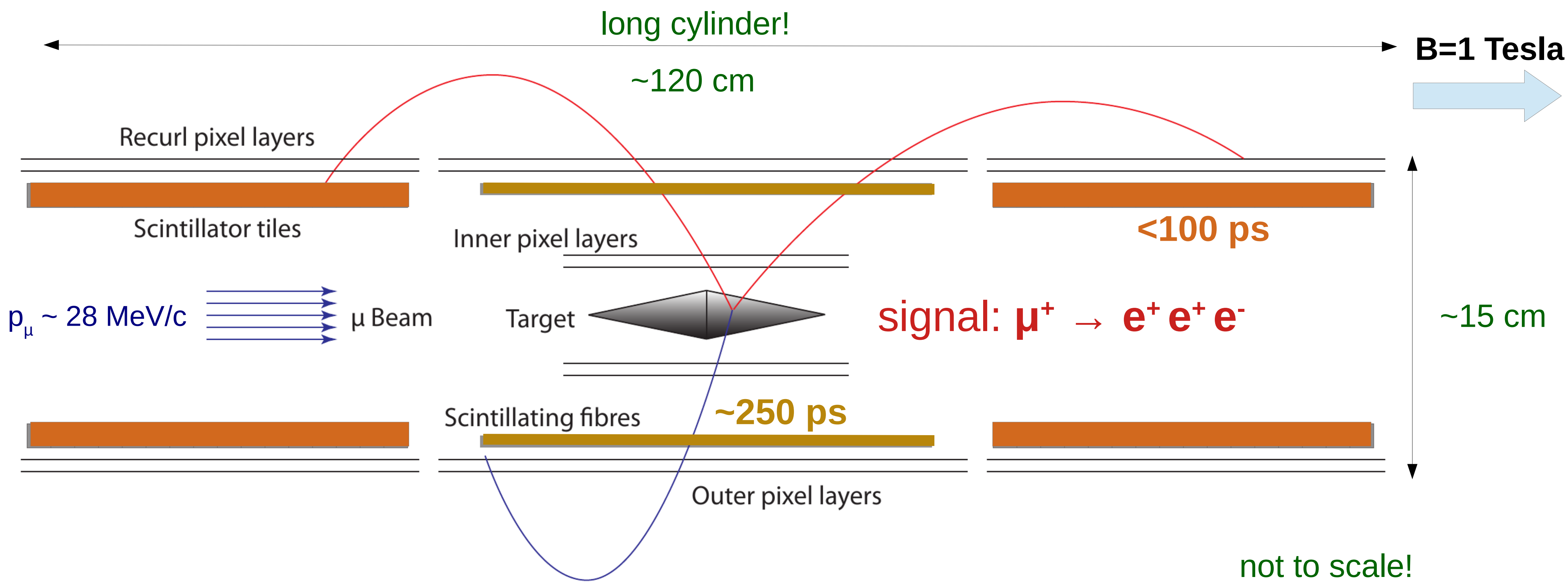


- **4 layers** of HVMAPS (MuPix) in **central** part **x/X_0 ~ 0.001 per layer**
- **2 layers** of HV-MAPS (MuPix) **upstream** and **downstream** (recurl stations)

- all layers cooled by **gaseous helium** (up to 400 mW/cm^2)

Mu3e Silicon Pixel Tracker Design (Phase I)

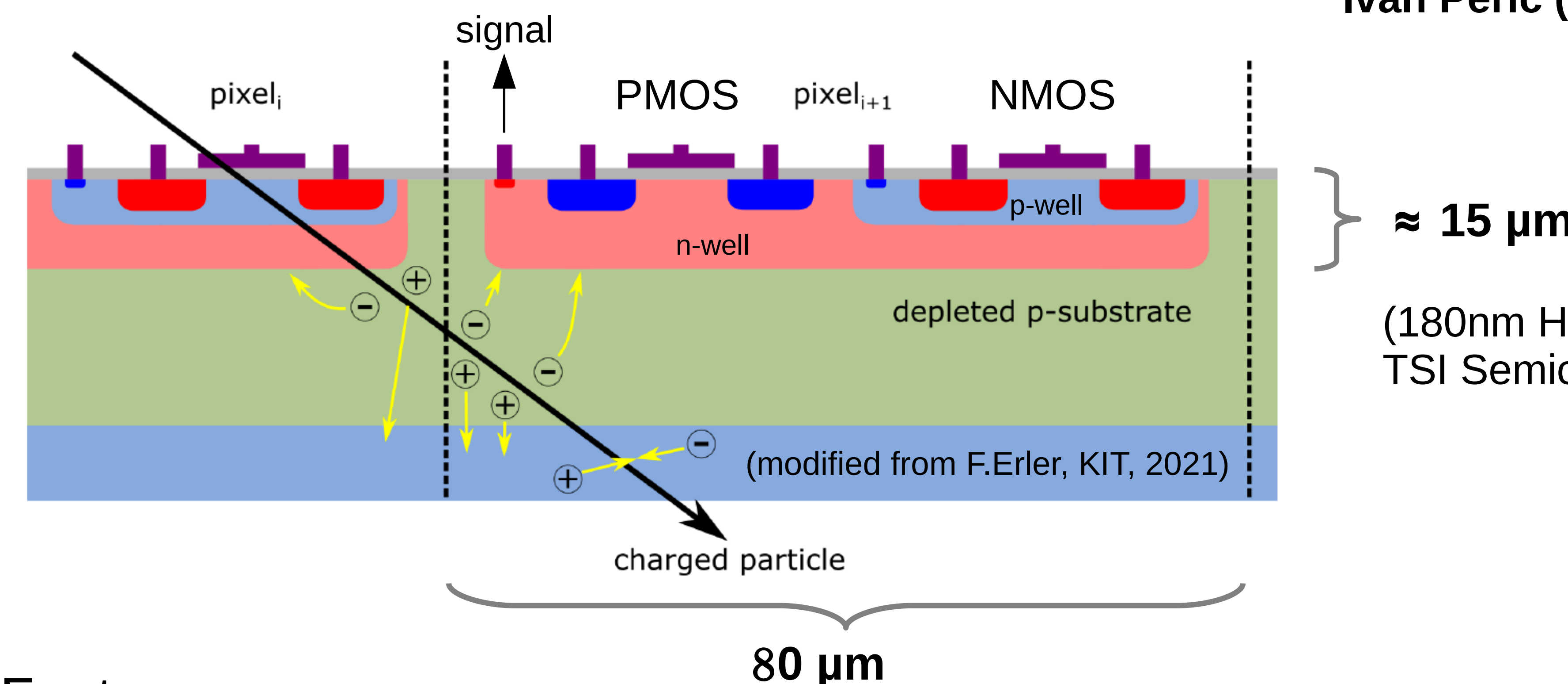
tracking of electrons (positrons) in low momentum range: $p_e \leq 53$ MeV/c



- **Scintillating fibre detector** (3 layers a 250 µm, timing resolution <**250 ps**) $x/X_0 \sim 0.002$
- **Scintillating tile detectors** (tile size 1 mm³, timing resolution <**100 ps**)

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

first published by
Ivan Peric (KIT) in 2007



(180nm HV-CMOS, TSI Semiconductors)

Main Features

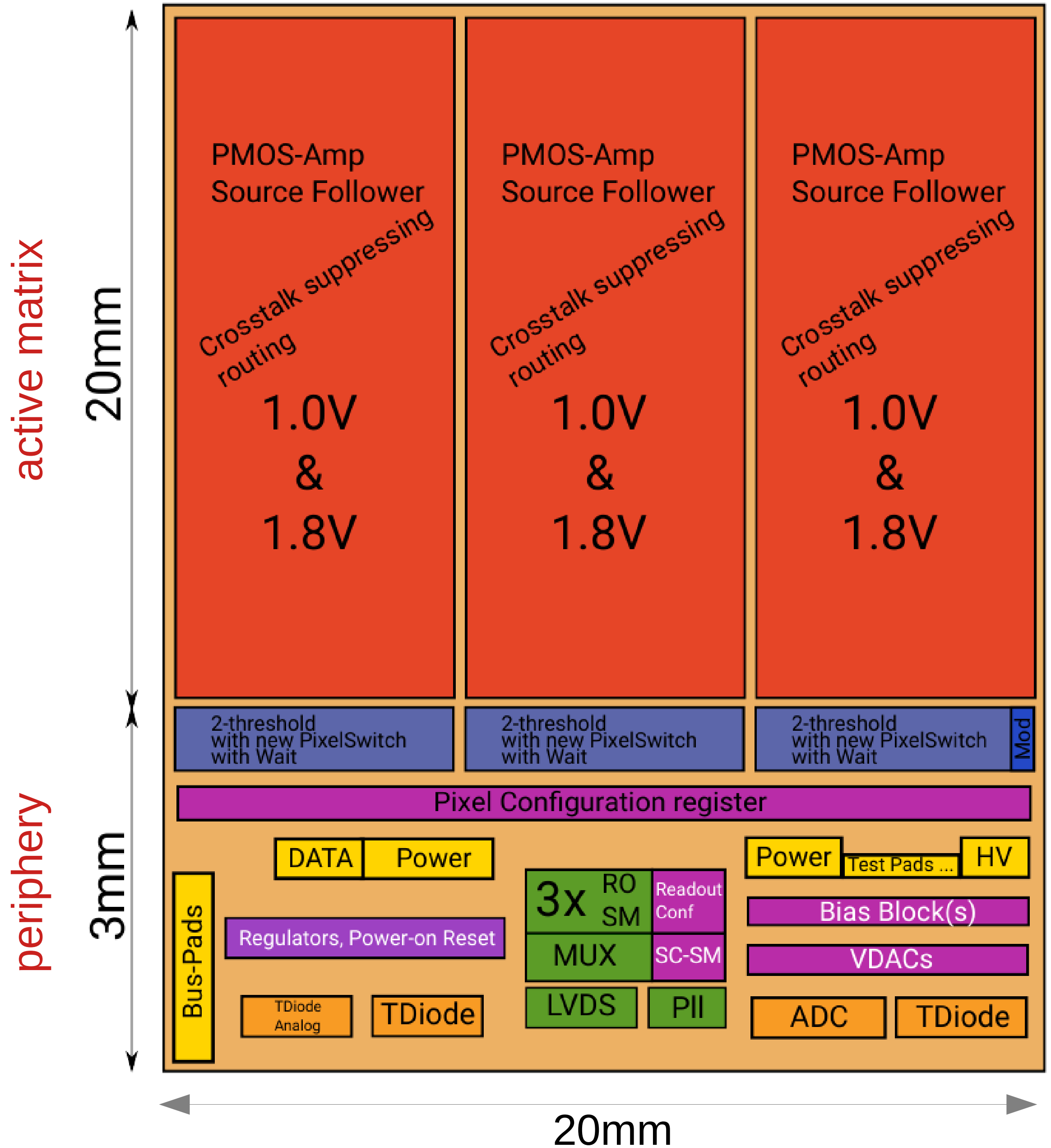
- **noise** is typically O(**100**) **e$^-$**
- **MIP signal** is **~800 e$^-$** / **10 µm** depletion
- (zero suppressed) **continuous readout**
- **sensor can be made very thin!** (Mu3e: 50 µm)

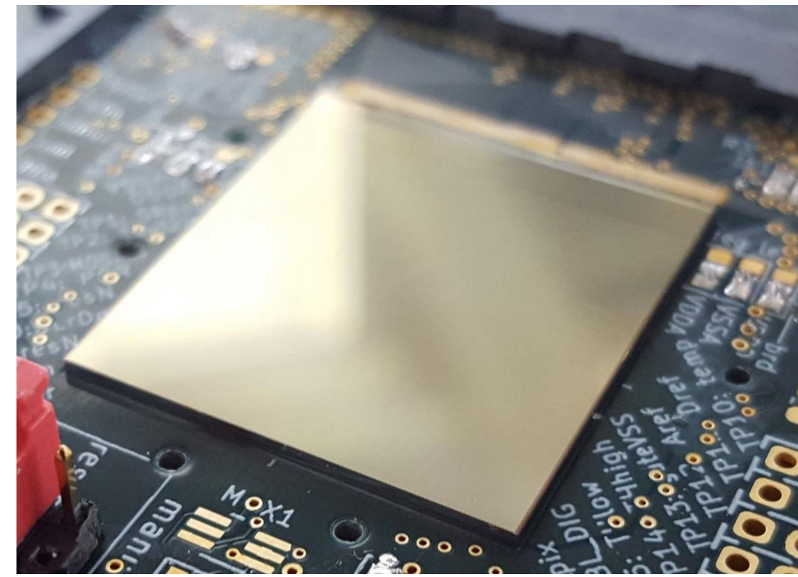
depletion depth: $d \propto \sqrt{\rho \cdot U}$

$$U = 20 - \mathbf{100}\, V$$

$$\rho = \mathbf{80} - 400\ \Omega \cdot cm$$

Mupix Design & Specifications (Phase I)



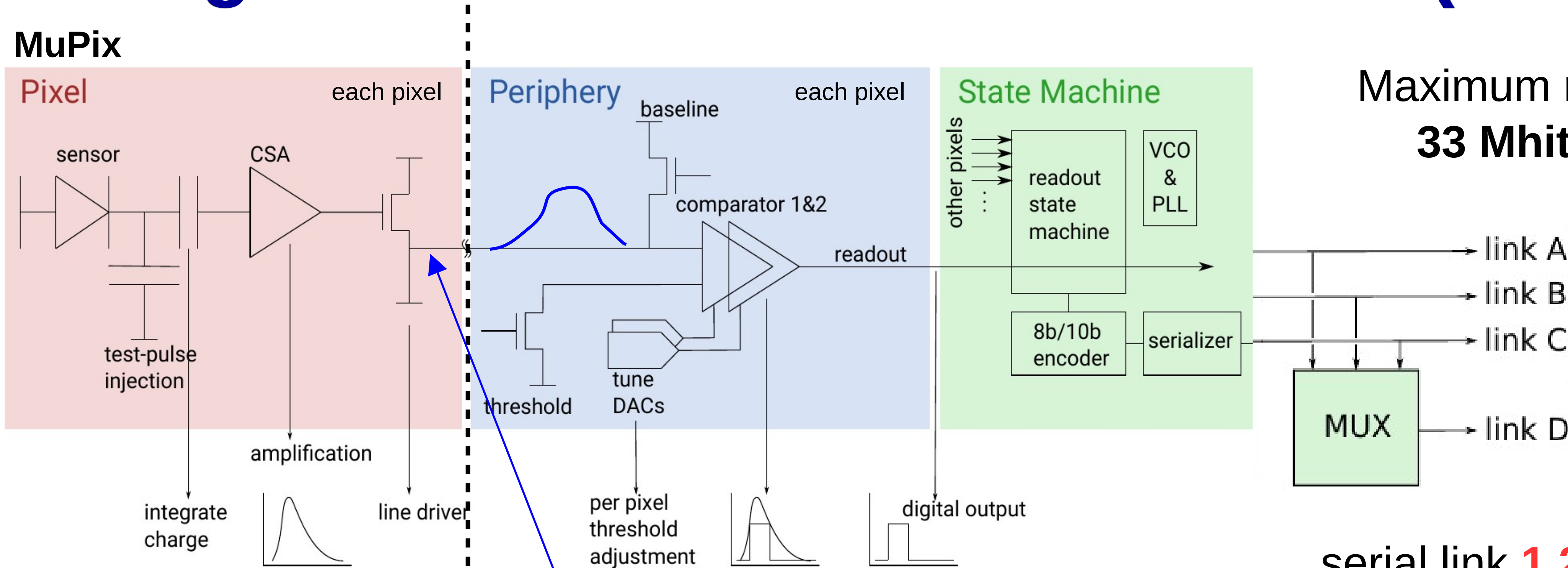


Specification from TDR

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

High Rate & Continuous Readout (MuPix)

MuPix

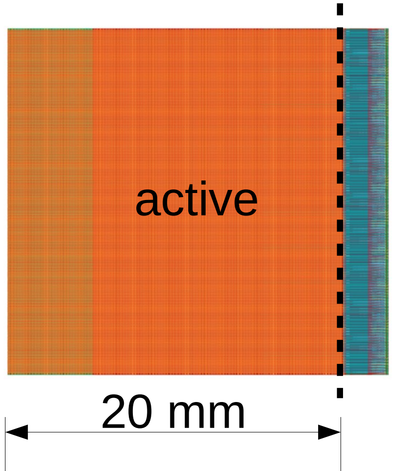


Maximum readout rate is **33 Mhits/s** per link

serial link 1.25 **(1.6) Gbit/s**

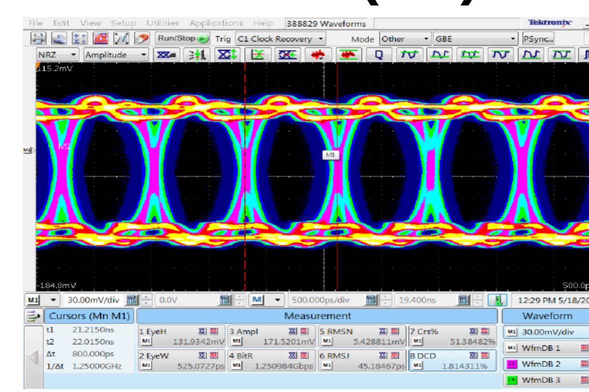
analog signals

MuPix sensor



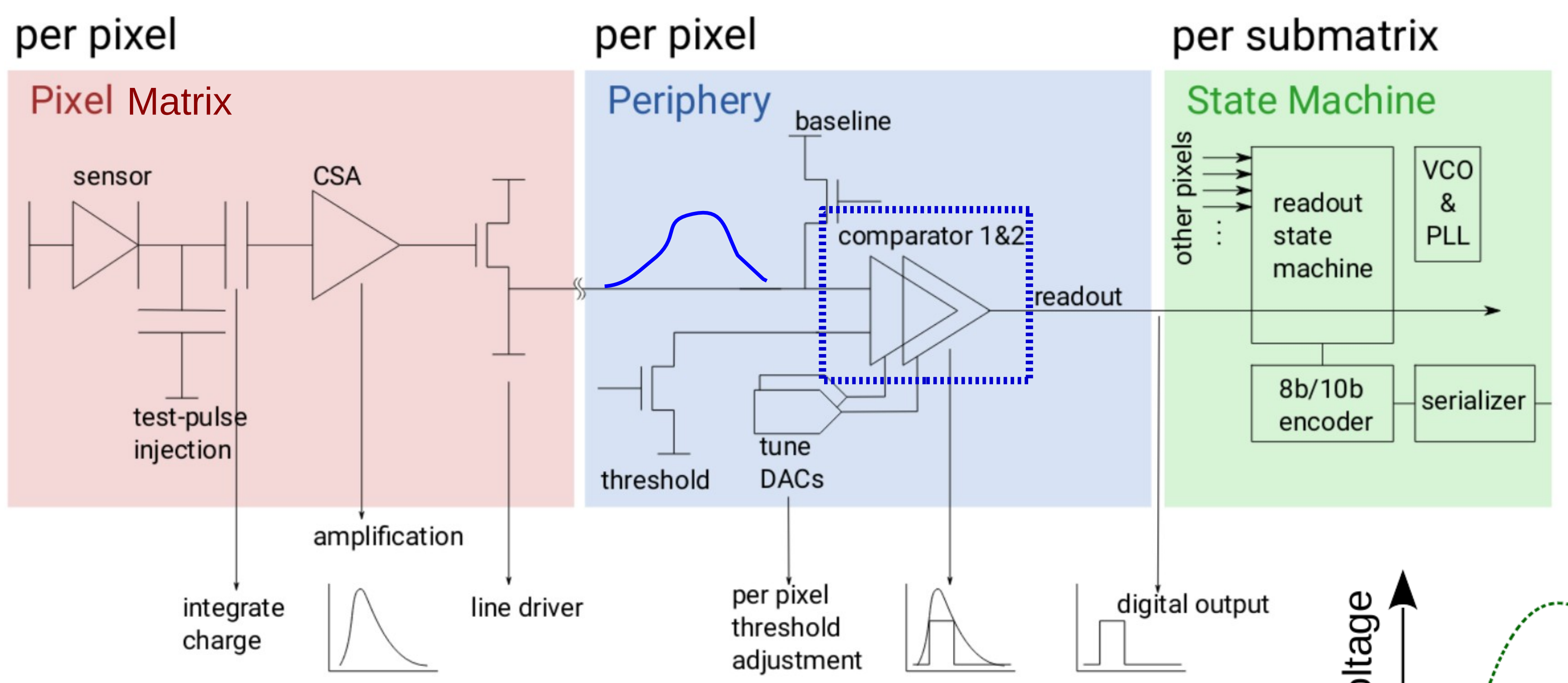
comparator & state machine

eye diagram



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

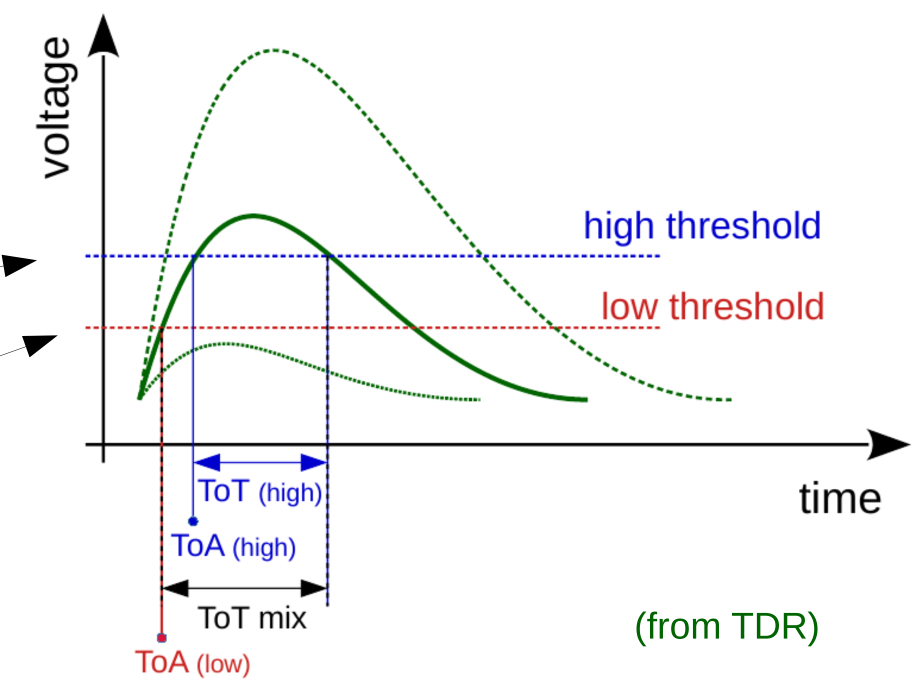
MuPix Two-Comparator Design



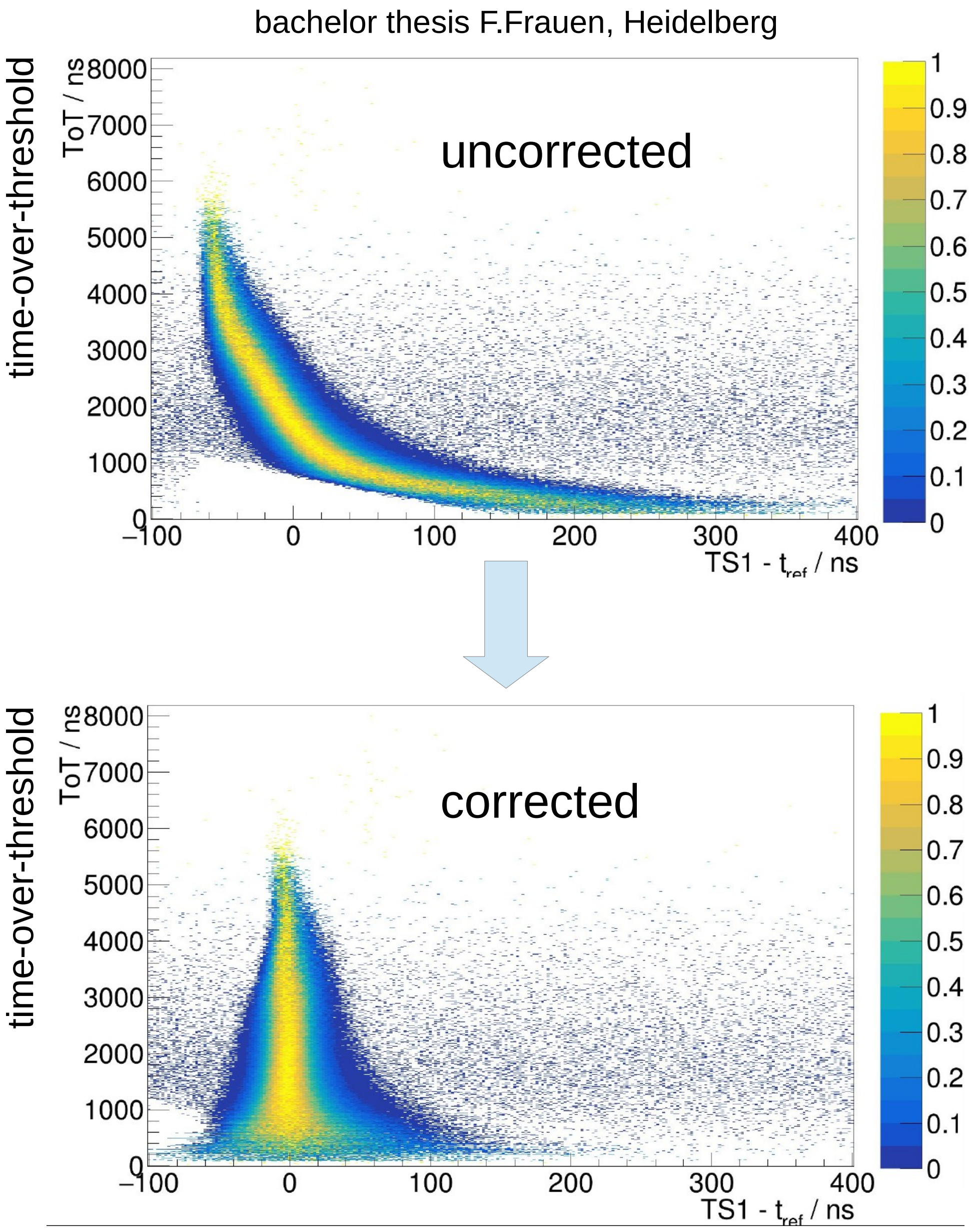
Two-comparator design

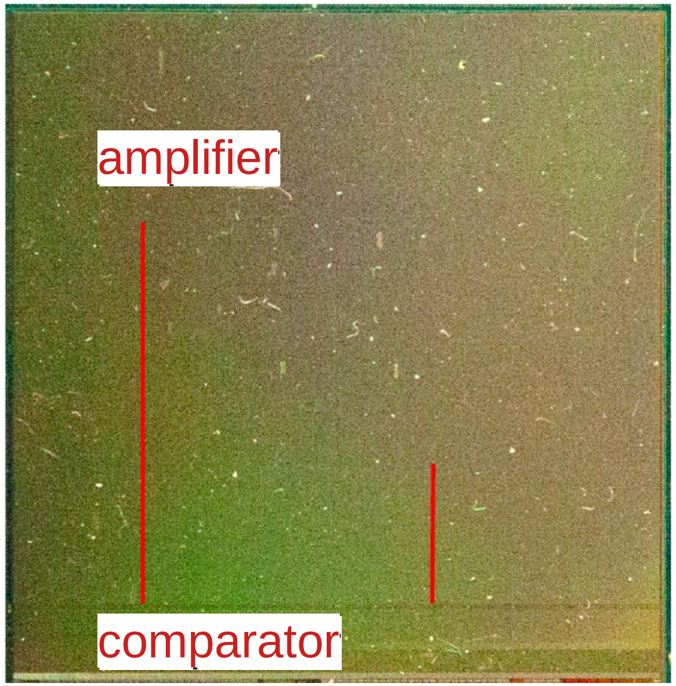
- use <u>higher</u> threshold for **hit validation**
- use <u>lower</u> threshold to reduce **time walk** (ToA)

→ timewalk mitigation



Timewalk in MuPix & Correction



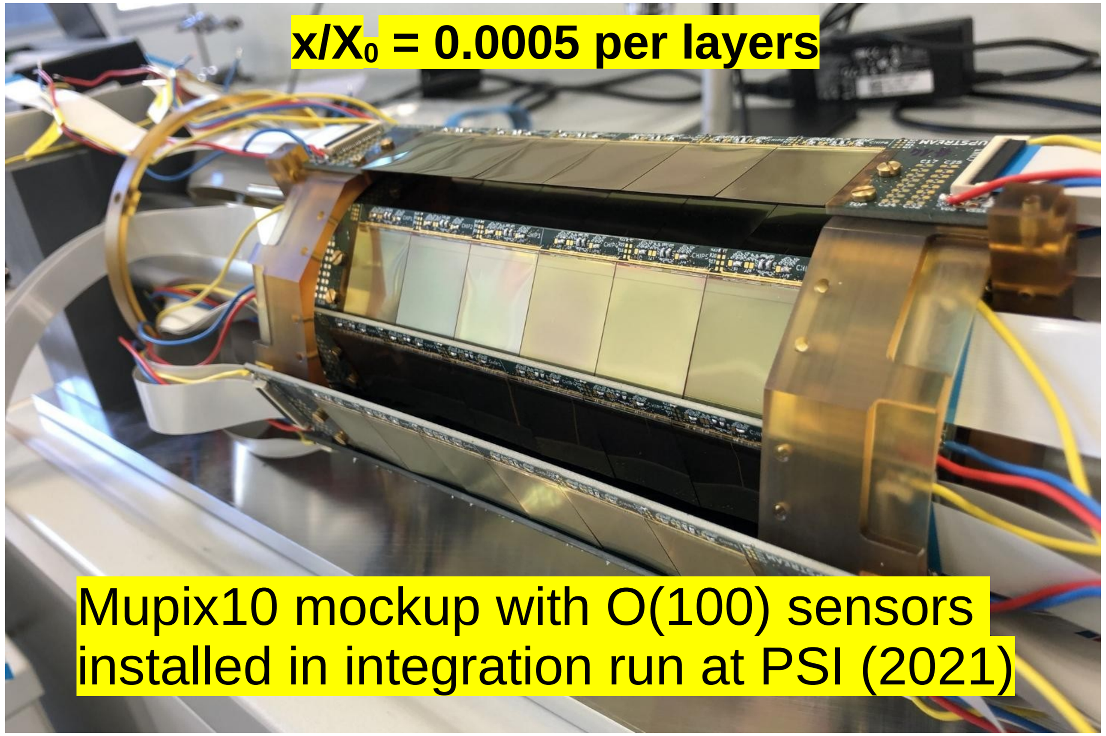


64000 pixel →
64000 RO lines
in parallel!

periphery

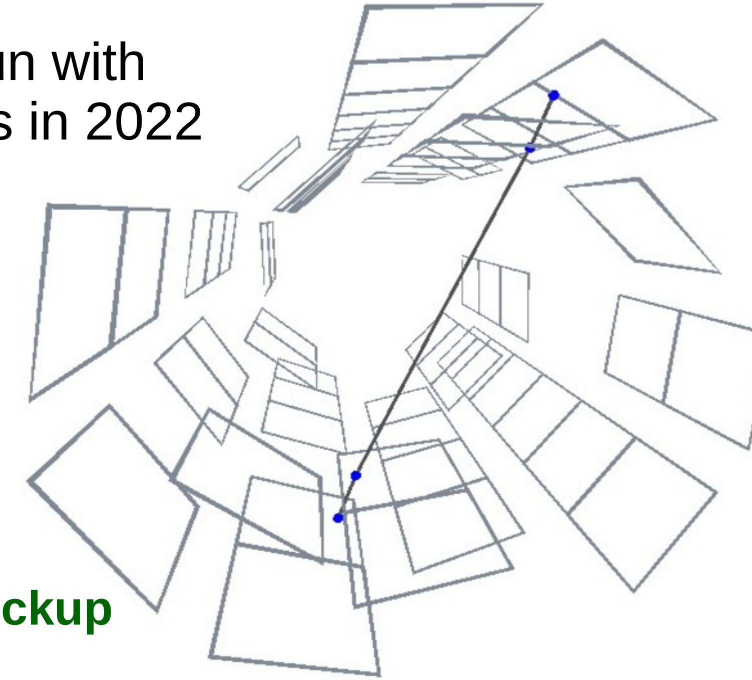
- timewalk effects from long routing lines (analog signal)
- correction possible by exploiting measured ToT
- **hit time resolution** after correction
  → **O(5 ns)** (digital RO over full sensor)
- good enough for **phase I rate** of **1 μ decay every 10ns**

MuPix Status

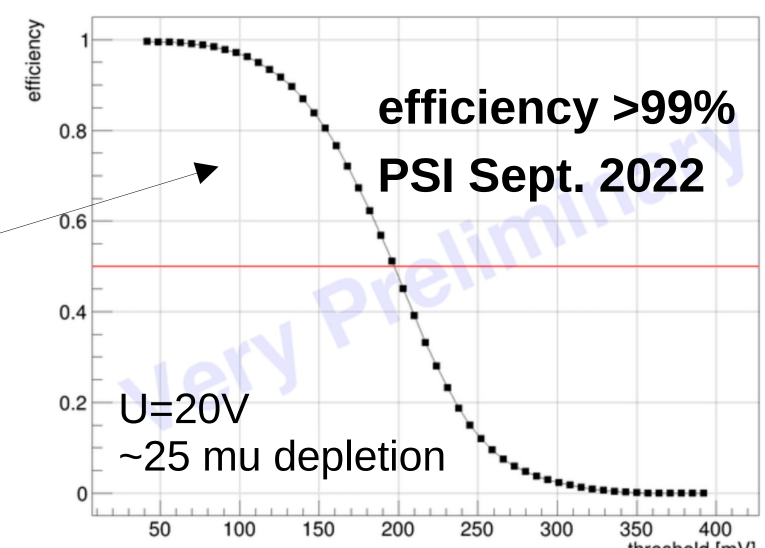


Integration Run with cosmic muons in 2022

4 out of 4 cosmic in Mu3e tracker mockup



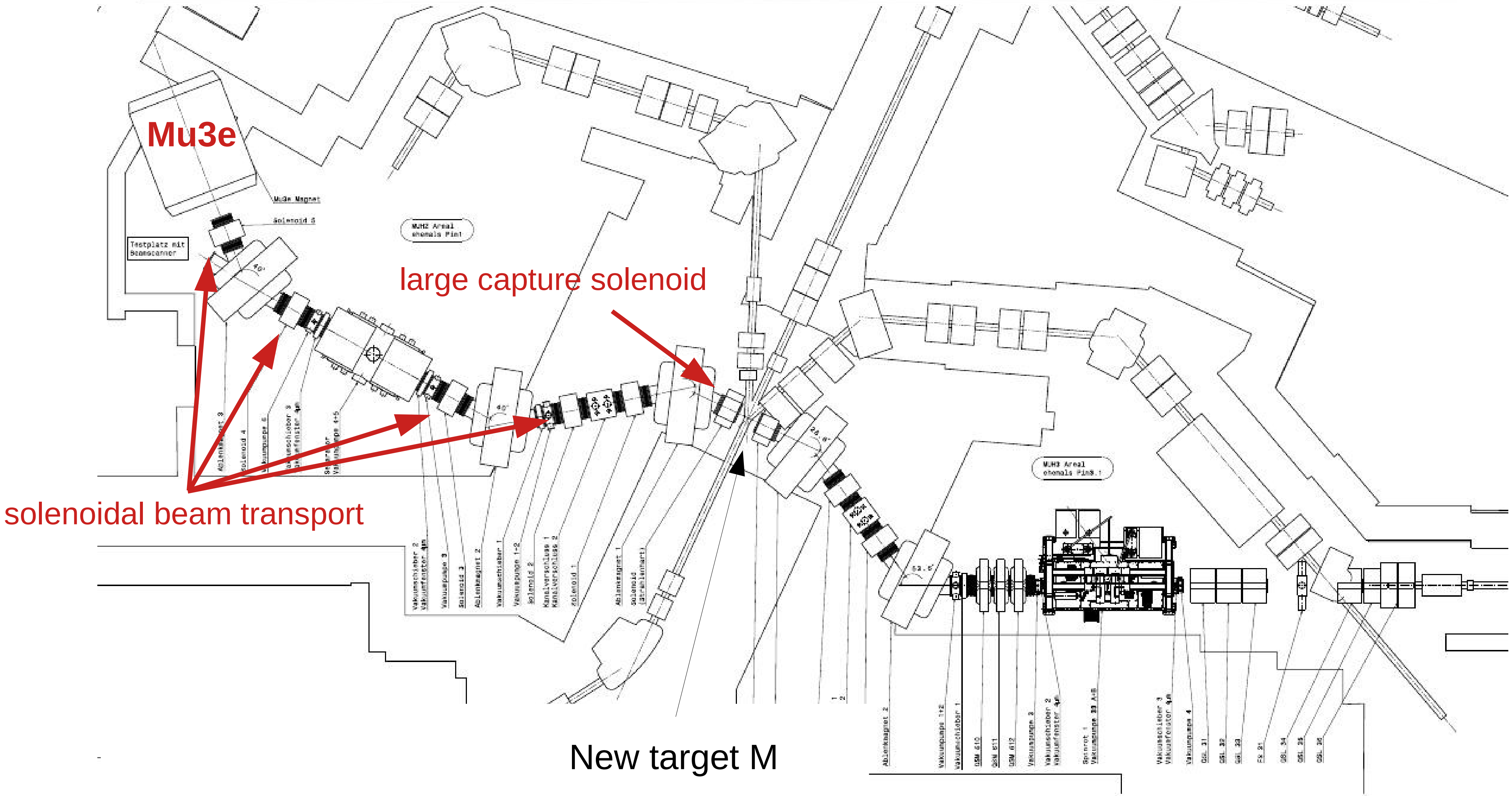
Threshold scan:



- MuPix11 engineering run Jan-August 2022
- First results in lab and in beam look promising
- Mupix11 production (6000 sensors) will start soon
- First data taking planned for 2024

Mu3e Phase II and High Intensity Muon Beamline (HIMB)

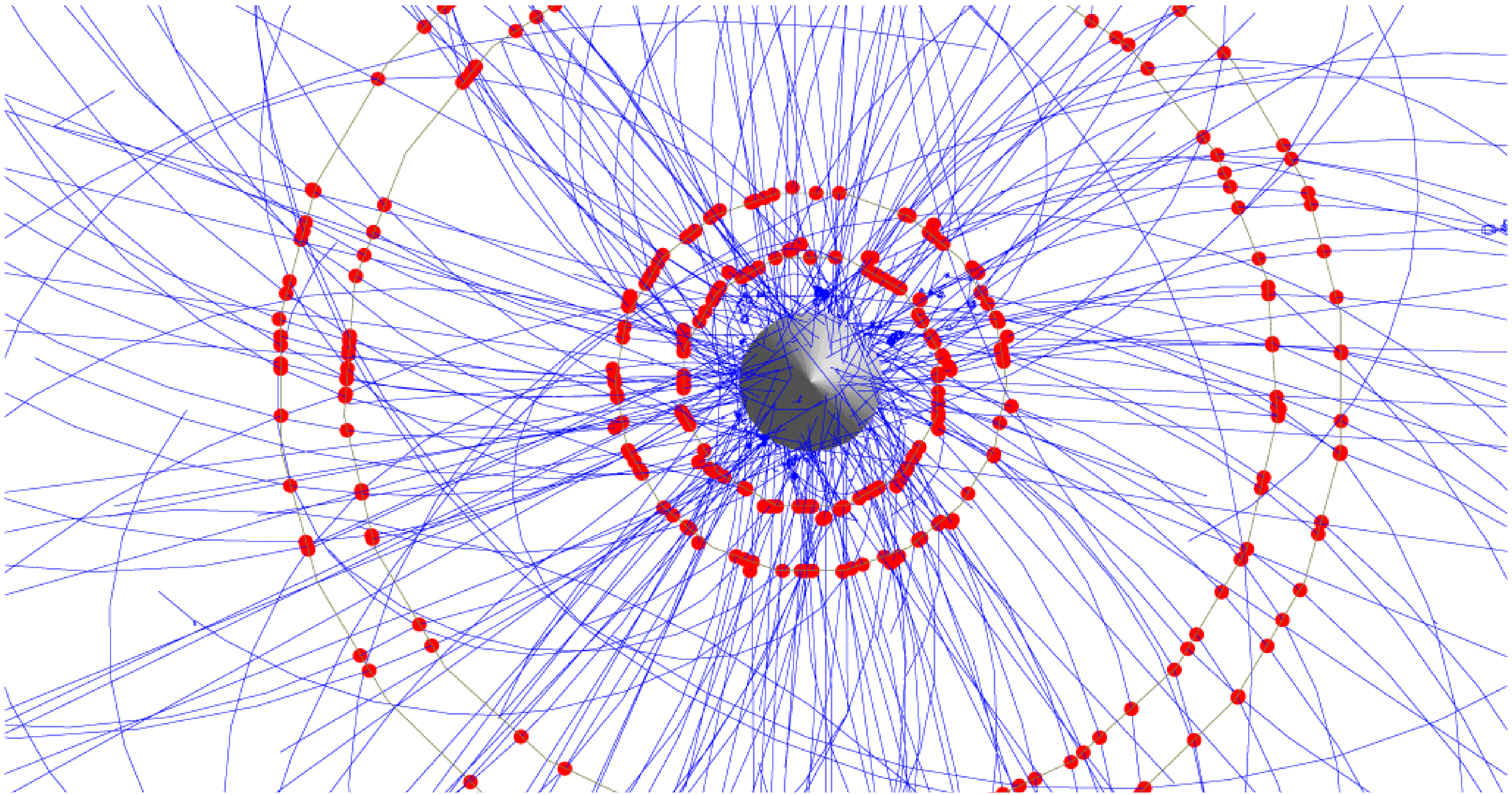
Goal: deliver up to **10^{10} muons/s** to two beamline experiments (Mu3e, muSR)



Construction 2026-2028

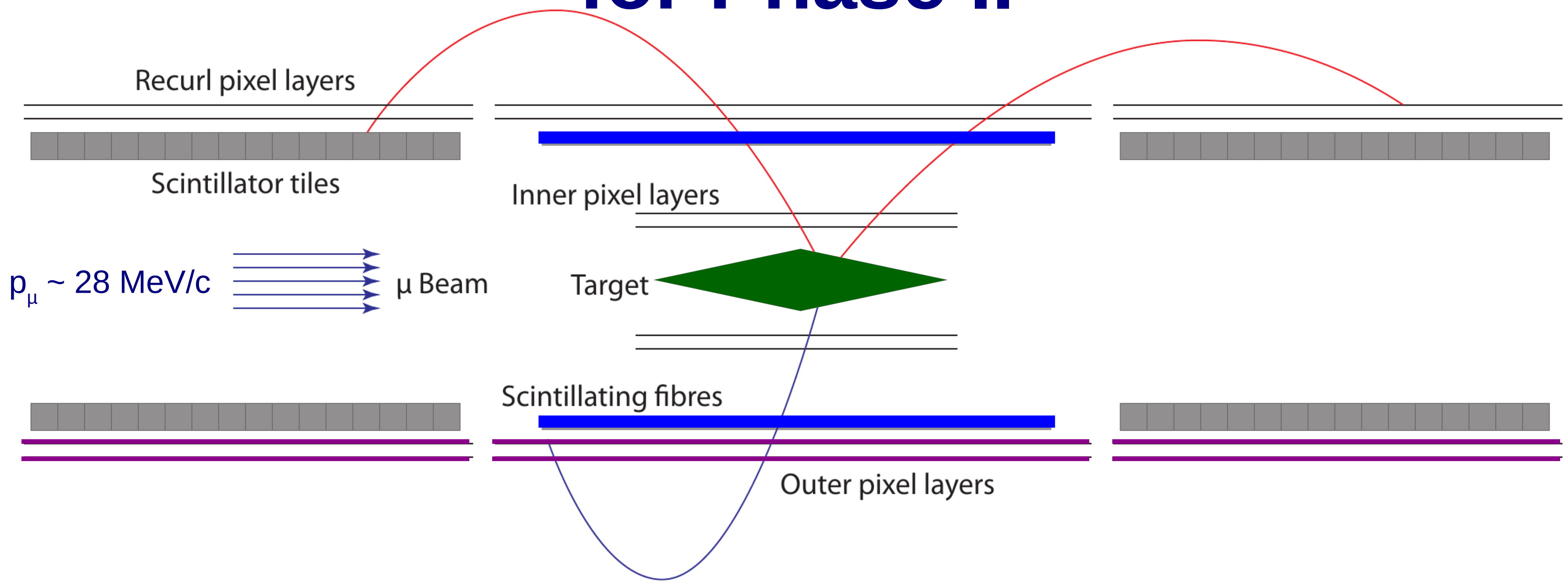
Projected Phase II Rate of ($2 \cdot 10^9$ muons/s)

50ns readout frame (100 muon decays):



Challenge: combinatorics and accidental background

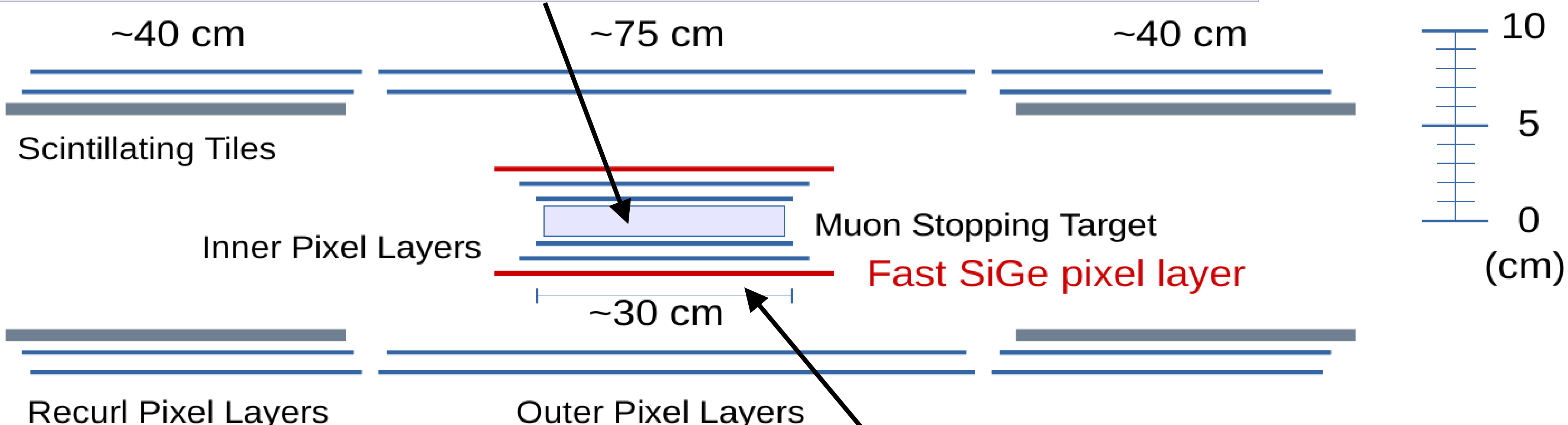
Improvements of the Mu3e Phase I Design for Phase II



- **Improve** timing of **MuPix pixel** tracker (1 m^2) : O(5 ns) → **O(1 ns)**
- **Replace Scintillating Fibres** with new monolithic pico-second timing silicon detector (→ project name: PicoPix)
- **Enlarge the size** of the **muon stopping target** to lower the hit occupancy in the inner detectors (→ **redesign** of experimental setup & **longer pixel modules**)

Tentative Phase II design (>2028)

Stop $2 \cdot 10^9$ muons on elongated mylar target or a special gas target (~30 cm long)



from https://arxiv.org/abs/2111.05788]

New Pixel MuPix Tracker → MuPix20:

- **~10 times** higher hit rate on **inner pixel** layers
- **~20 times** higher hit rate on **outer pixel** layers

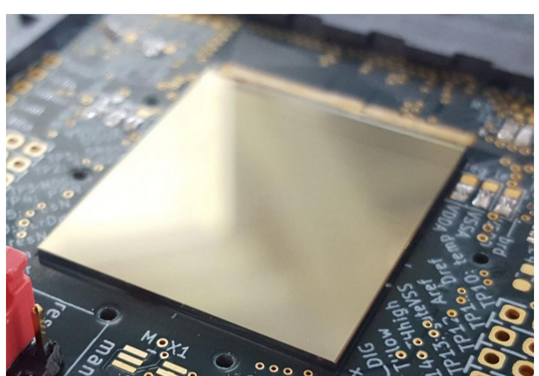
Fast SiGe pixel detector ("baseline")

- **radius 3-4 cm** ; **~40 cm long**: → **10^7 hits / (cm^2 s)**
- **100-250 ps** time resolution (not specified yet)

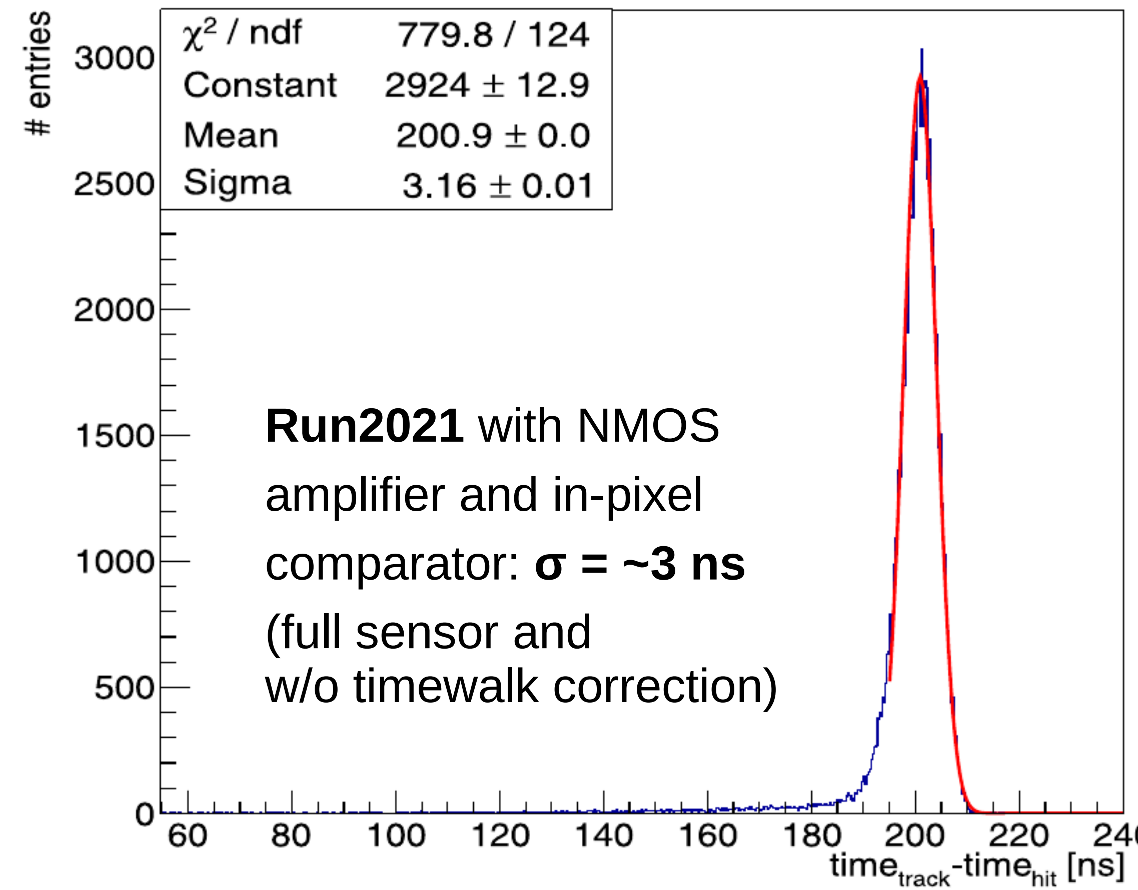
MuPix20 (next generation)

Planned changes with respect to Mupix11:

- **full CMOS** amplifier and comparator (TSI Semiconductors provides deep p-well)
- move hit **comparators** from periphery into pixel (like in MightyPix, TelePix)
  - → better time resolution **O(1 ns)**
  - → smaller periphery → reduced material
- **serial powering**
  - → reduction of power lines
- **daisy chained and faster readout**
  - → reduction of signal lines



MuPix20 will look like Mupix11



L. Huth et al. 2022

Fast Silicon Pixel Detector (Mu3e-Picopix)

Specification Requirements:

- radius 3-4 cm ; ~40 cm long → area 750-1000 cm^2
- monolithic design
- small sensor thickness: **x/X_0 <= 0.001**
- excellent time resolution **100-250 ps** (not specified yet)
- capable of high hit rates: → **10^7 hits / (cm^2 s)**
- fast readout links ~1 Gbit (cm^2 s)
- maximum pixel size 1 mm x 1mm
- sensor size 10-20mm x 20mm
- maximum power dissipation **250 mW / cm^2** (gaseous He cooling)

very challenging requirements

Considered Technologies

- IHP BiCMOS SiGe 130nm
- Monolothic sensor with gain layer in a modified industrial HV-CMOS process
- alternatives?

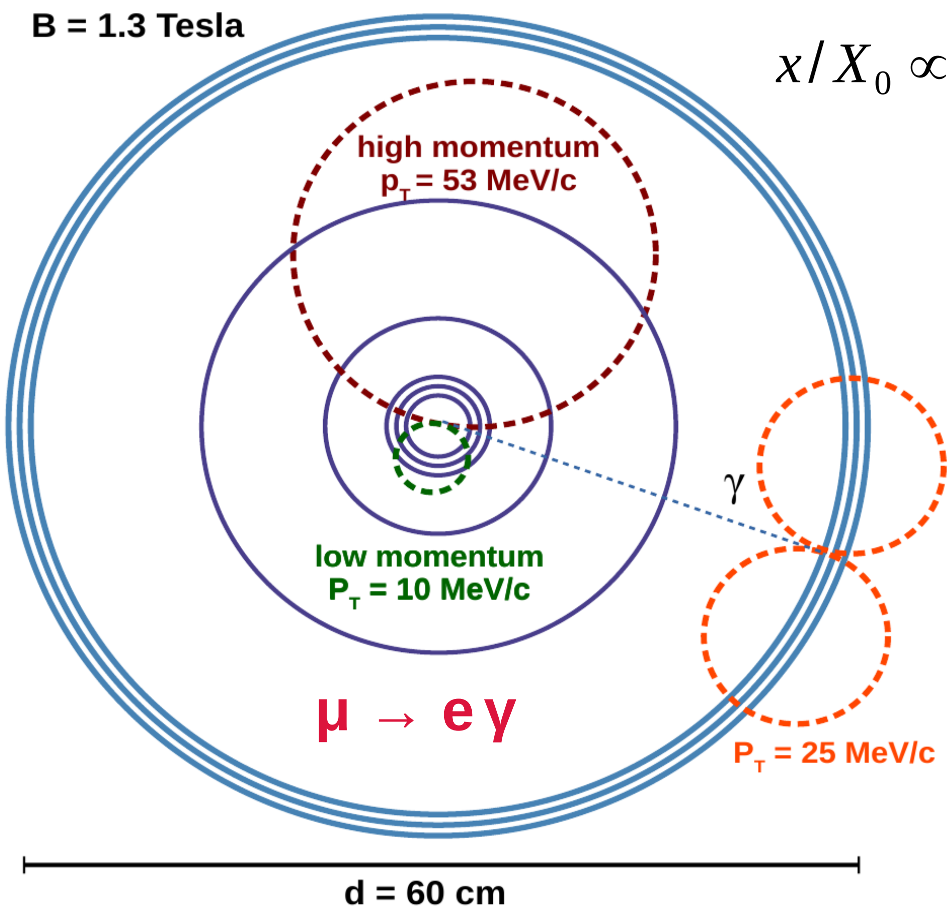
→ **only 5 years for R&D and production!**

another interesting idea

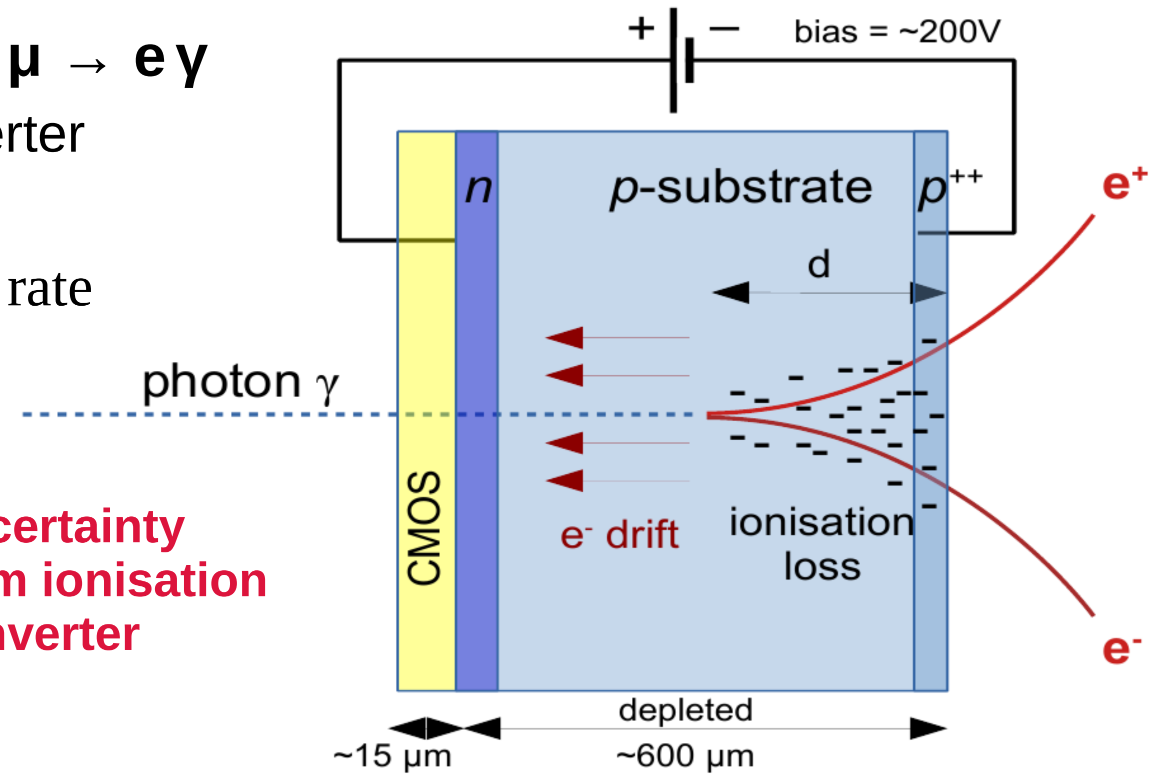
Mu3e-Gamma at HIMB with O(10^{10}) muon stops

Combine Mu3e **μ → e e e** and MEG experiments **μ → e γ**

- Gamma detection with a “thick” active photon converter



$x/X_0 \propto$ conversion rate



largest uncertainty comes from ionisation loss in converter

$$E_\gamma = p_{e^-} + p_{e^+} + \boxed{E_{ion}} + E_{brems}$$

Idea: measure ionisation loss directly

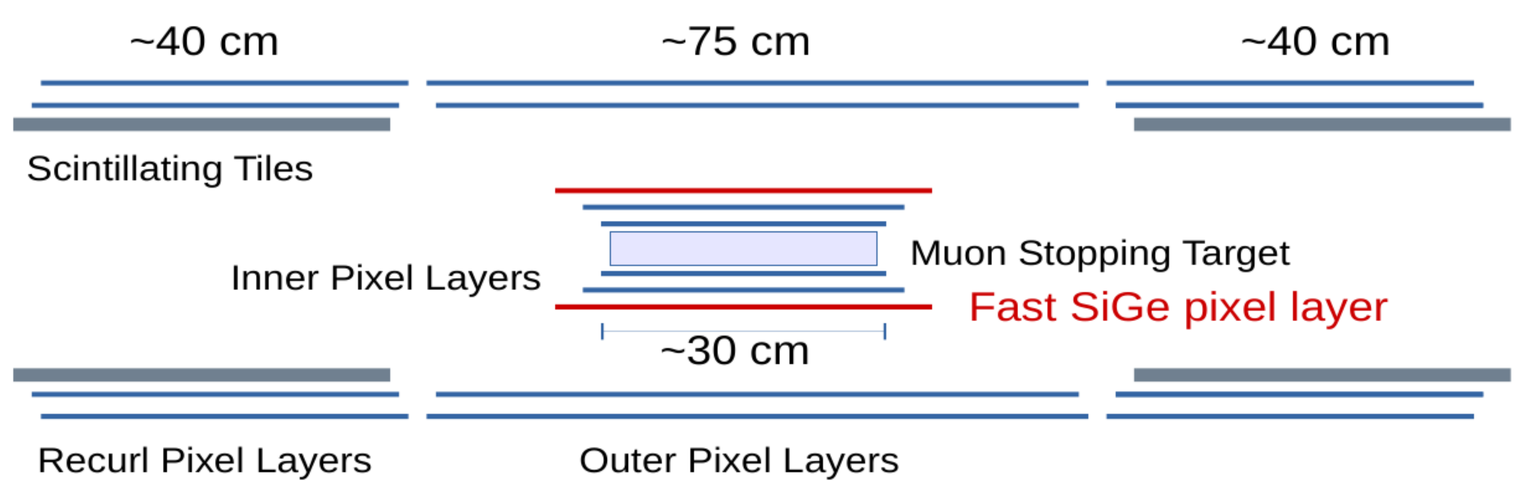
- more than 95% of the sensor are active!

First prototype (HVCMOS 180 nm, ~8 kΩ cm) with high dynamic range works (Run2021)

In addition, To suppress accidental BG a timing resolution of 50 ps is required. Add it to active converter?

Summary

- Mu3e is currently under construction
- **Phase I** data taking will **start in 2024**
- HIMB Upgrade will provide **20-100 times higher muon rates**
- Central scintillating fibre (timing) detector needs to be replaced by radiation harder technology providing
  - time resolution of **100-250 ps** (not yet specified)
  - **high rate** capability
  - extremely **low material** budget (monolithic)
- Consider SiGe BICMOS and alternatives
- **New groups and ideas** are highly welcome!

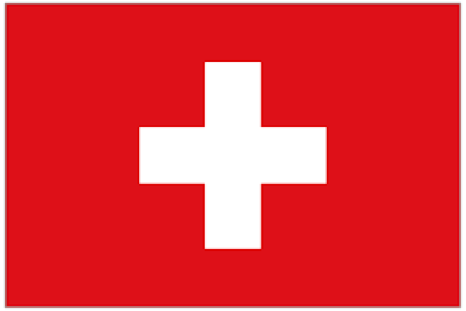


Backup

Mu3e Collaboration

Germany
- University Heidelberg (KIP)
- University Heidelberg (PI)
- Karlsruhe Institute of Technology
- University Mainz

Switzerland
- University of Geneva
- Paul Scherrer Institute
- ETH Zurich
- University Zurich
- [University of Applied Sciences Northwestern Switzerland]
  associated partner



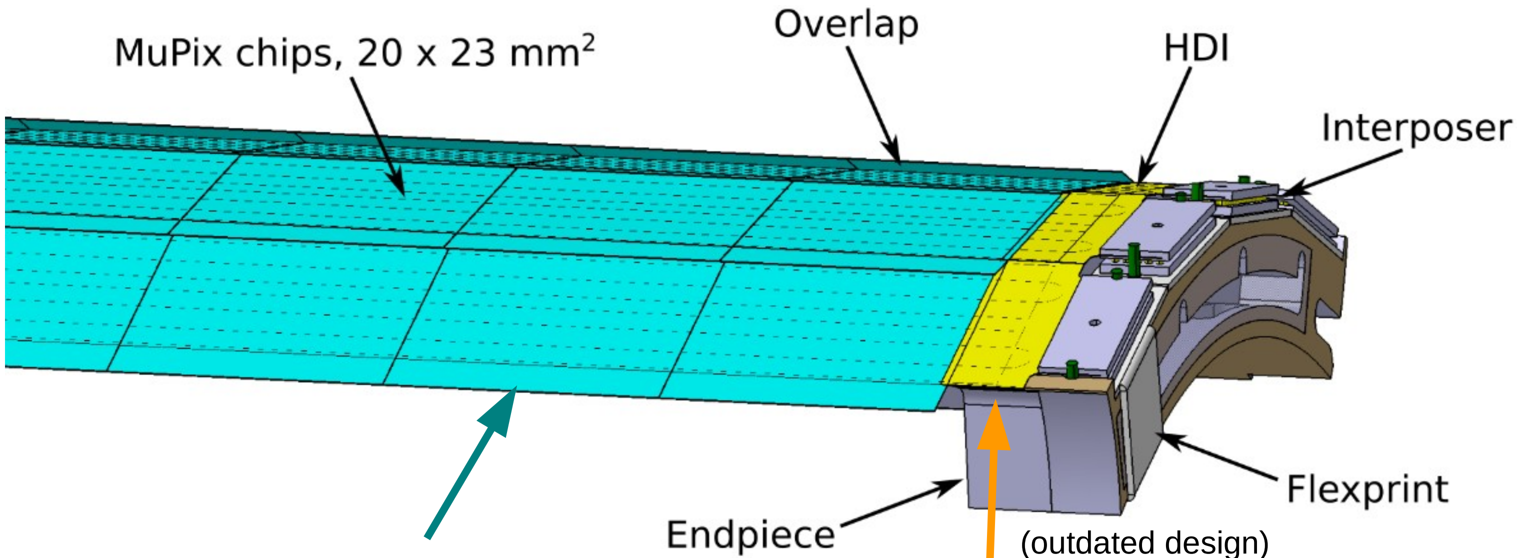
United Kingdom
- Bristol
- Liverpool
- Oxford
- UC London

about 70 members; ~15 PhD students

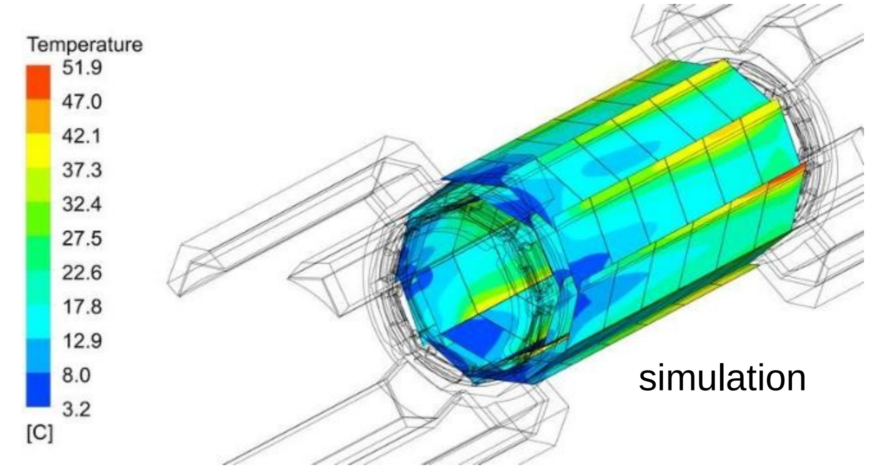
Mu3e Pixel Tracking Detector

→ very homogeneous material distribution

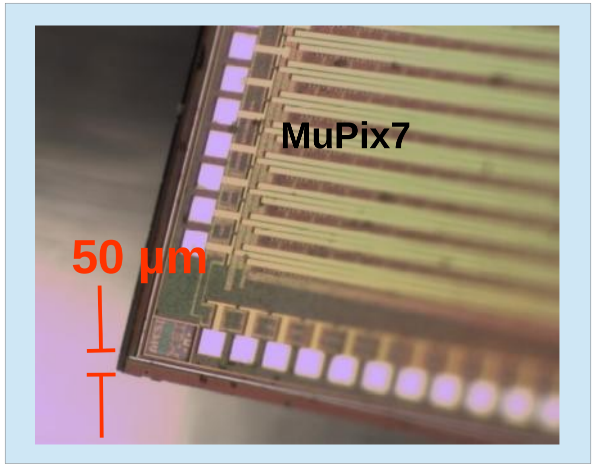
Ultra-thin pixel sensor modules (X/X_0 = 1.15 per mille)



Gaseous He-Cooling System

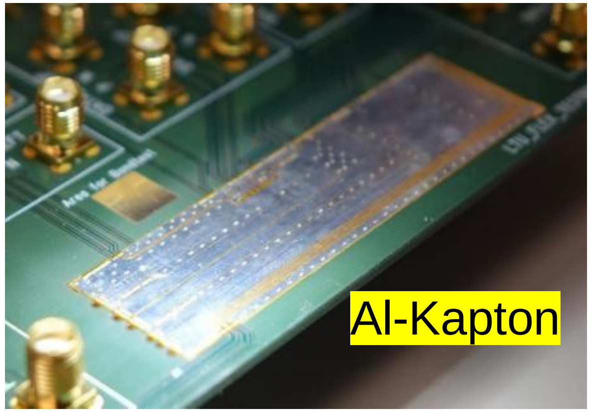


MuPix (HV-MAPS)

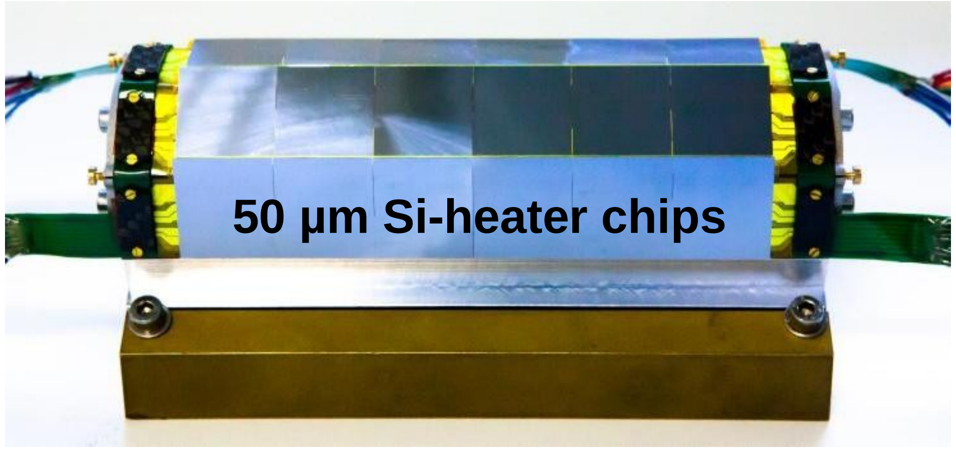


Monolithic pixel sensor in
180 nm HV-CMOS

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



Thermo-Mechanical Mockup (vertex)



Paul-Scherrer Institut (Schweiz)

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

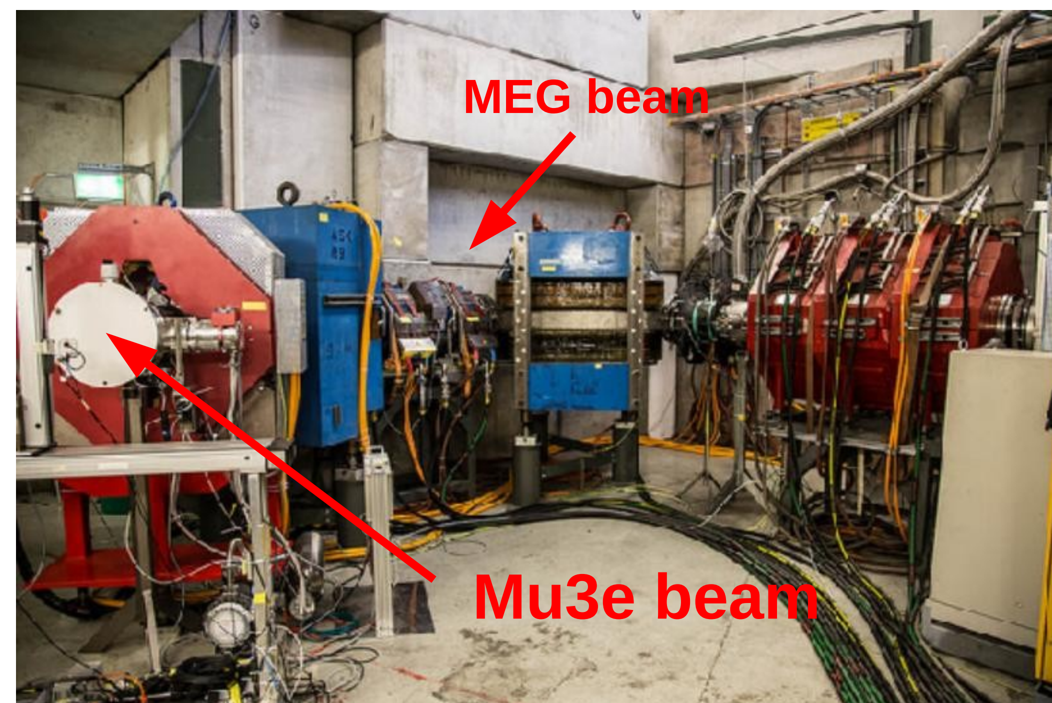
Muon Beam:

- 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**

PiE5: Compact Muon Beamline for Mu3e



Comparison of Tracking Detectors

Pixel detectors

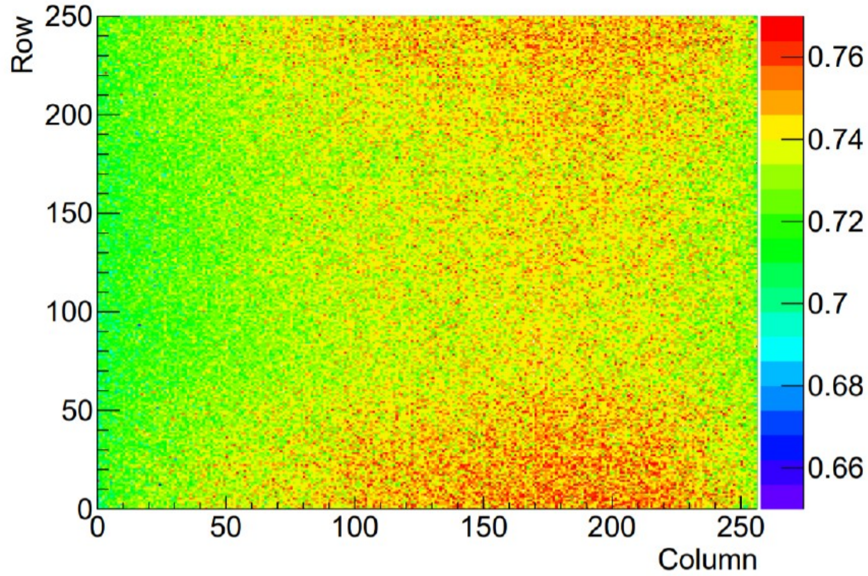
TRACKING DETECTOR	STAR PXL	BELLE II PXD	ALICE ITS II	**Mu3e PTD**
radiation length per layer in X_0	0.5%	$0.2\text{-}0.5\%$	$0.3\text{-}0.8\%$	$\mathbf{0.11\%}$

SINDRUM (1988) – Mu3e comparison

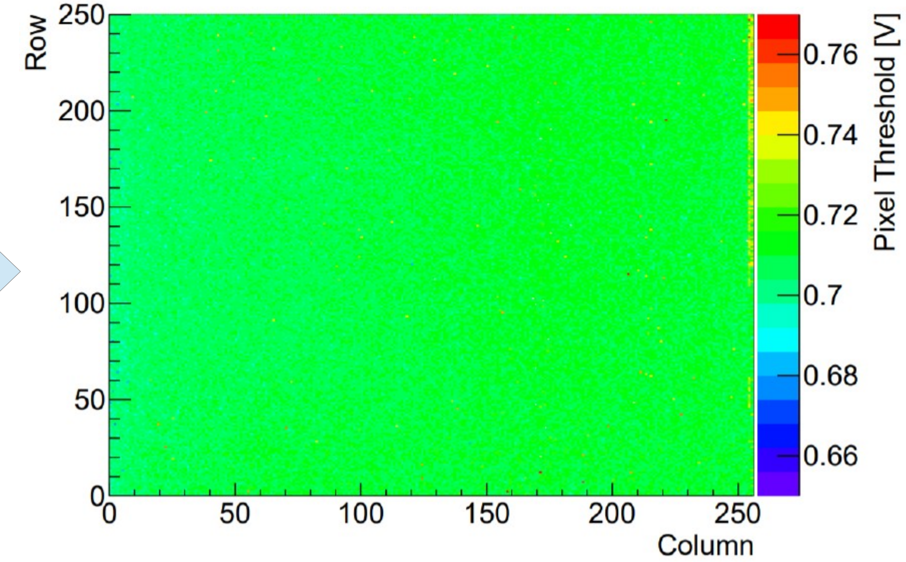
PARAMETER		SINDRUM	**Mu3e**
rel. momentum resolution σ_p/p	$(p = 50$ MeV/c)	5.1%	0.8%
rel. momentum resolution σ_p/p	$(p = 20$ MeV/c)	3.6%	0.5%
polar angle σ_θ	$(p = 20$ MeV/c)	28 mrad	24 mrad
vertex resolution σ_{dca}		≈ 1 mm	280 µm
radiation length per layer in X_0		0.08% - 0.17%	0.11%
		MPWC (gas)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

Mupix10: Pixel Tuning of Comparator Threshold

(bachelor thesis M.Menzel, Heidelberg)

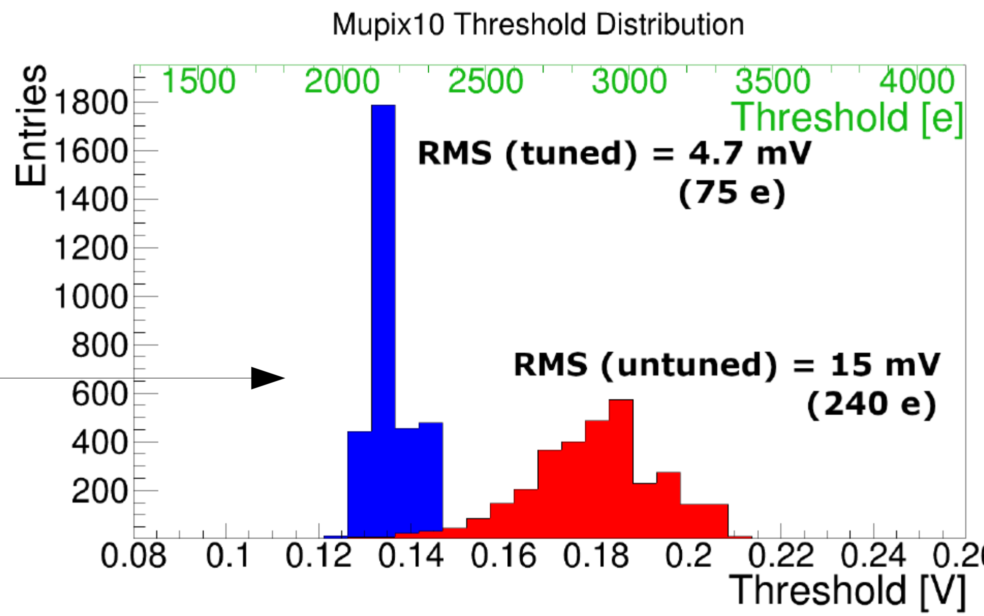


Untuned pixel threshold distribution.

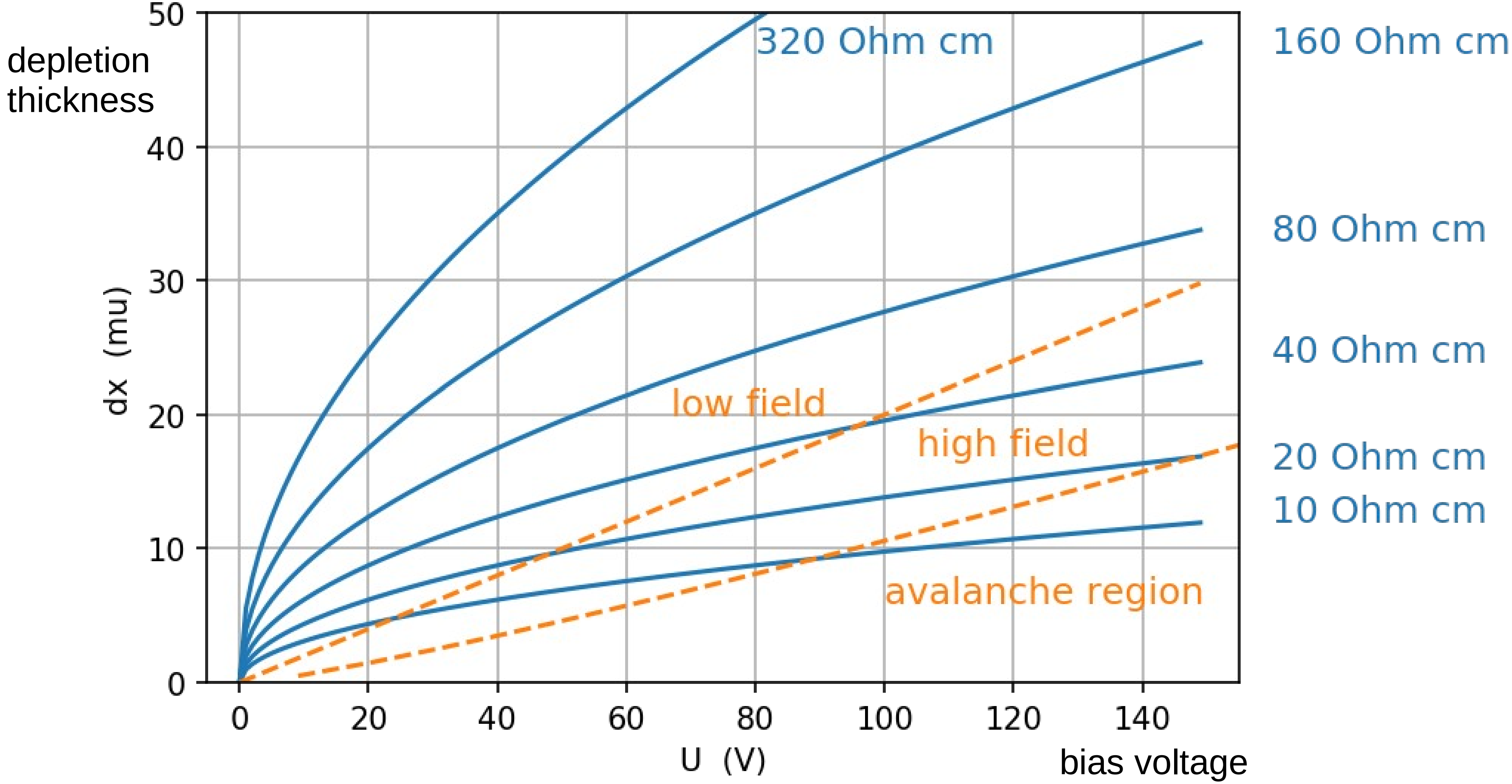


Tuned pixel threshold distribution.

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



Depletion and Bias Voltage Relation



Low resistivity substrates provide high charge collection fields and small depletion

→ allows for thin sensors