The Mu3e Pixel Detector

Vertex 2016, 26.-30. September, 2016

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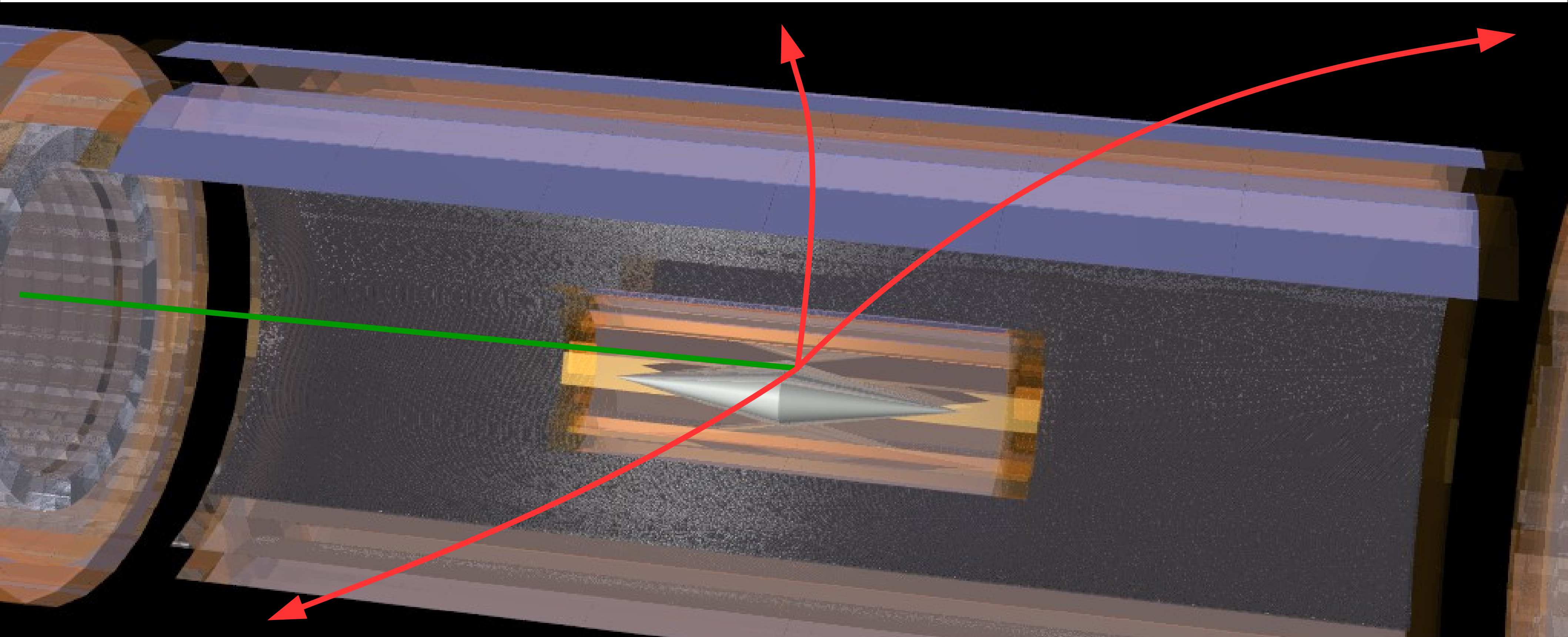


Overview

- Introduction (physics, backgrounds, requirements, recurlers)
- Mu3e detector and concept
- Pixel Tracker
  - Ultralight Mechanics
  - The MuPix Sensor (HV-MAPS)
  - Flexprint
  - Helium Gas Cooling
  - Readout and the MuPix telescope
- Outlook + Schedule
- Summary

Mu3e Experiment at PSI

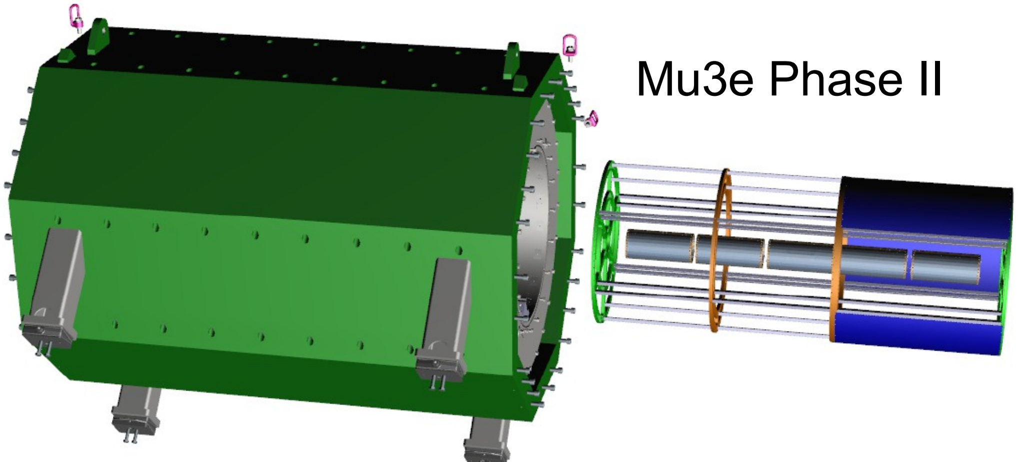
Mu3e Research Proposal, A.Blondel et al., arXiv:1301.6113

Search for lepton flavor violating decay

- $BR(\mu^+ \rightarrow e^+ e^+ e^-) < 10^{-12}$ (SINDRUM 1986)
- **$BR(\mu^+ \rightarrow e^+ e^+ e^-) < 10^{-15}$** (phase I, PiE5 beamline)
- $BR(\mu^+ \rightarrow e^+ e^+ e^-) < 10^{-16}$ (phase II, High Intensity Muon beamline)

→ high sensitivity to physics beyond the SM (complementary to LHC)

Mu3e Solenoid B=1 Tesla



Mu3e Phase II

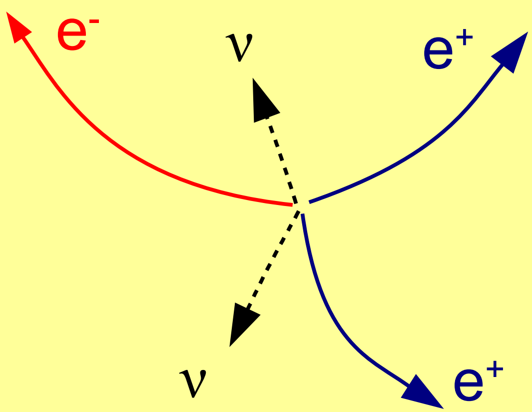
Requirements:

- $10^8 - 10^9$ muon stops / second
- electron energies < 53 MeV
  - multiple scattering dominated
- high precision silicon pixel tracker
  - relative momentum resolution < 1%
- scintillating timing detectors
  - 100-500 ps resolution

Backgrounds

Irreducible SM background

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



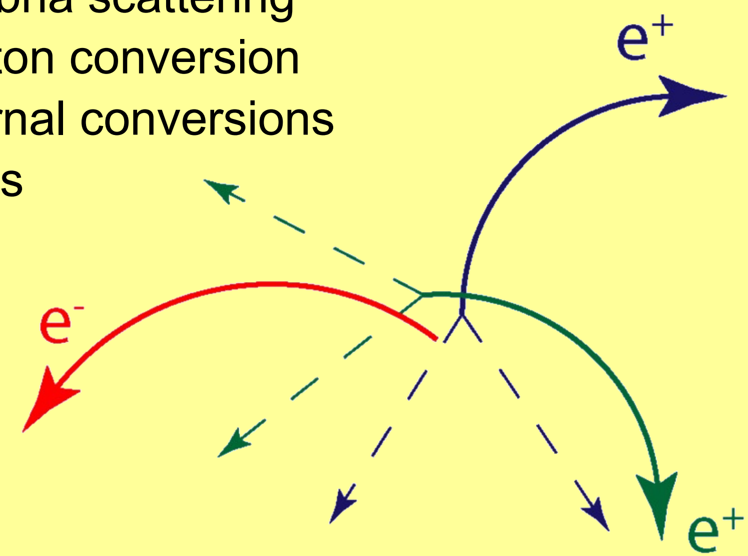
Requirements

- **O(0.5%) energy (momentum) resolution to reconstruct missing energy from neutrinos**

Accidental background

Main decay: $\mu^+ \to e^+ \nu\nu$

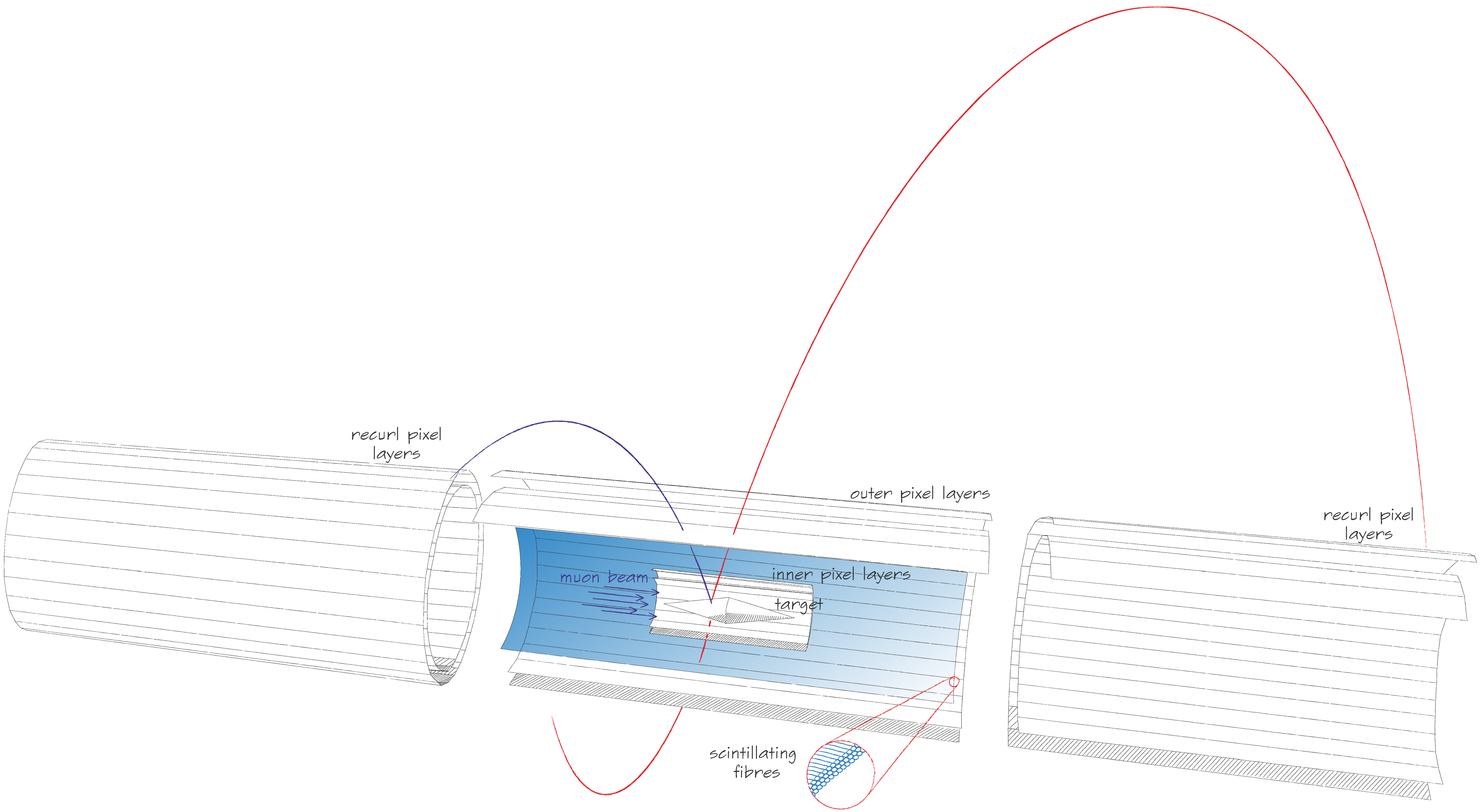
electrons from:
- Bhabha scattering
- photon conversion
- internal conversions
- fakes



Requirements:

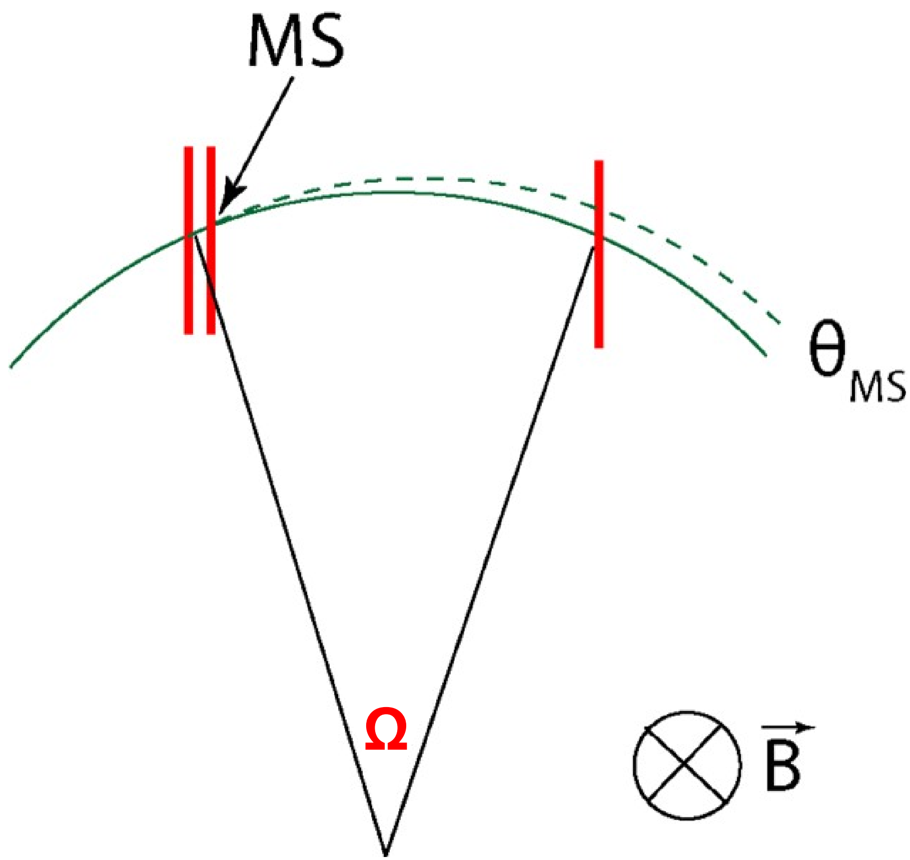
- **DC μ^+ beam**
- **good energy resolution**
- **good pointing (vertex) resolution**
- **good timing resolution**

Mu3e Detector Layout Concept



Momentum Resolution in MS Regime

- Muon decay: **p(electron) < 53 MeV/c → multiple scattering**
- Standard spectrometer:



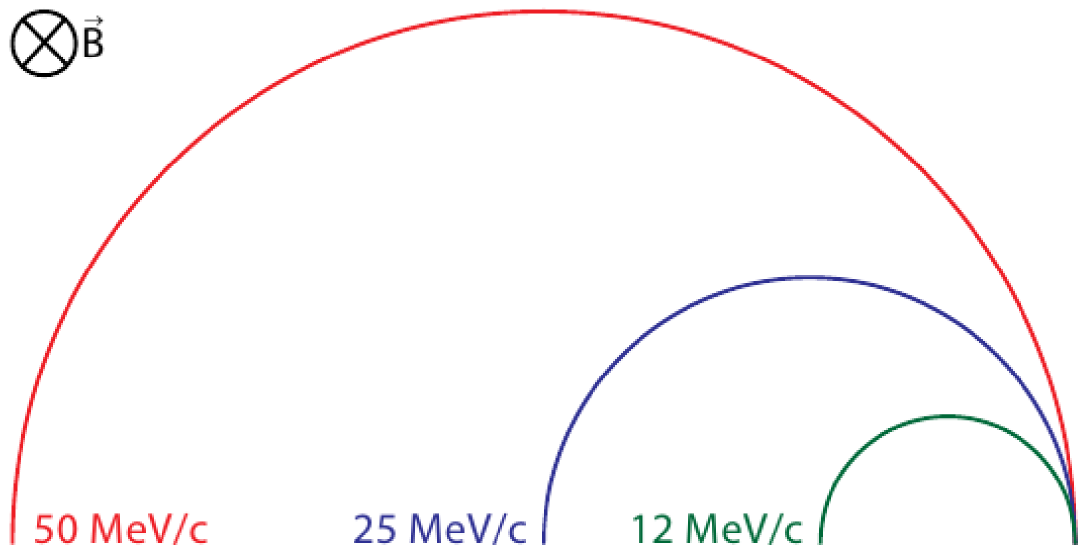
$$\Theta_{MS} \sim \frac{1}{P}\sqrt{X/X_0}$$

precision requires
→ little material X

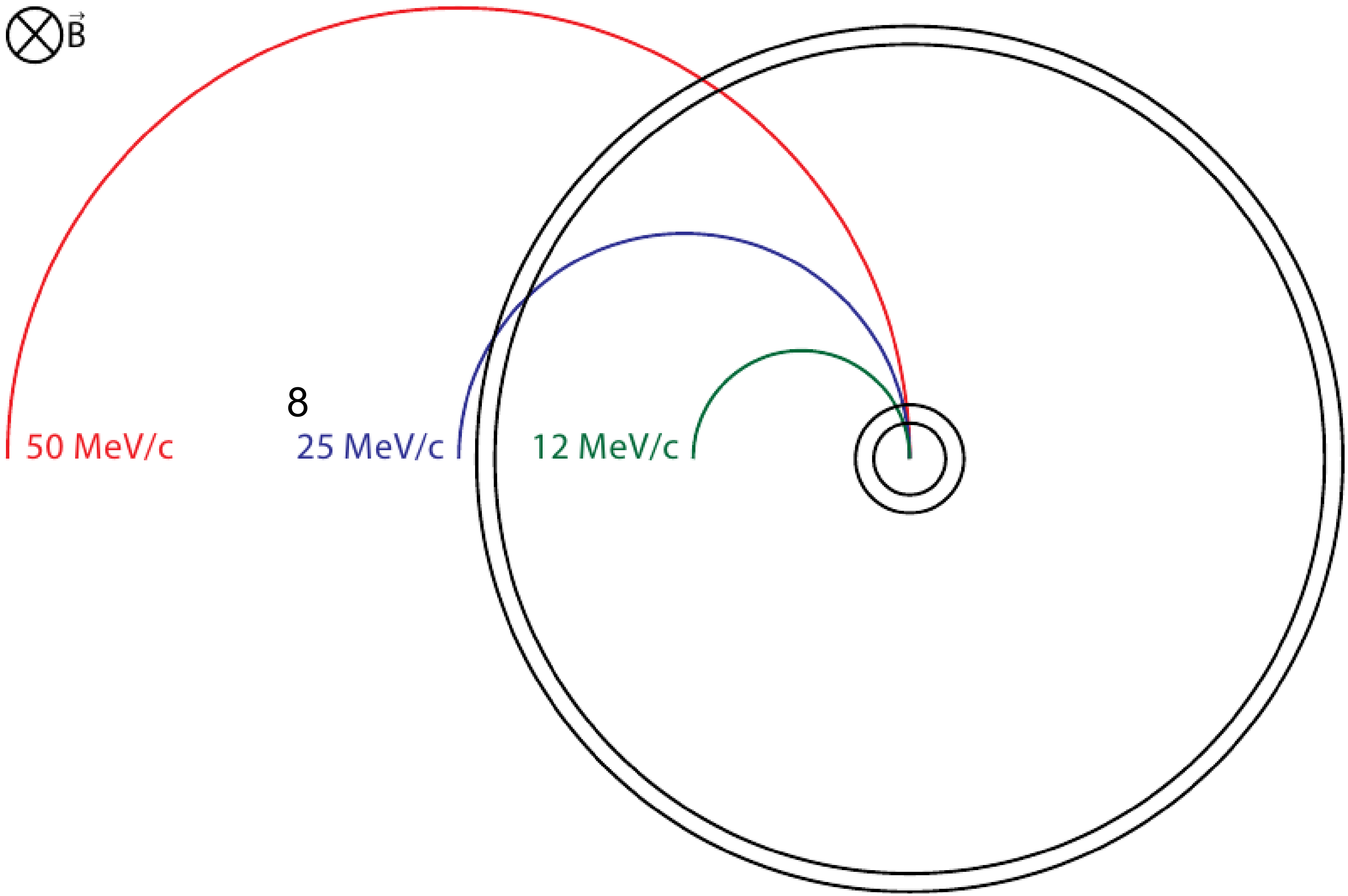
$$\frac{\sigma_p}{P} \sim \frac{\Theta_{MS}}{\Omega}$$ (linearised)

precision requires lever arm
→ large bending angle Ω

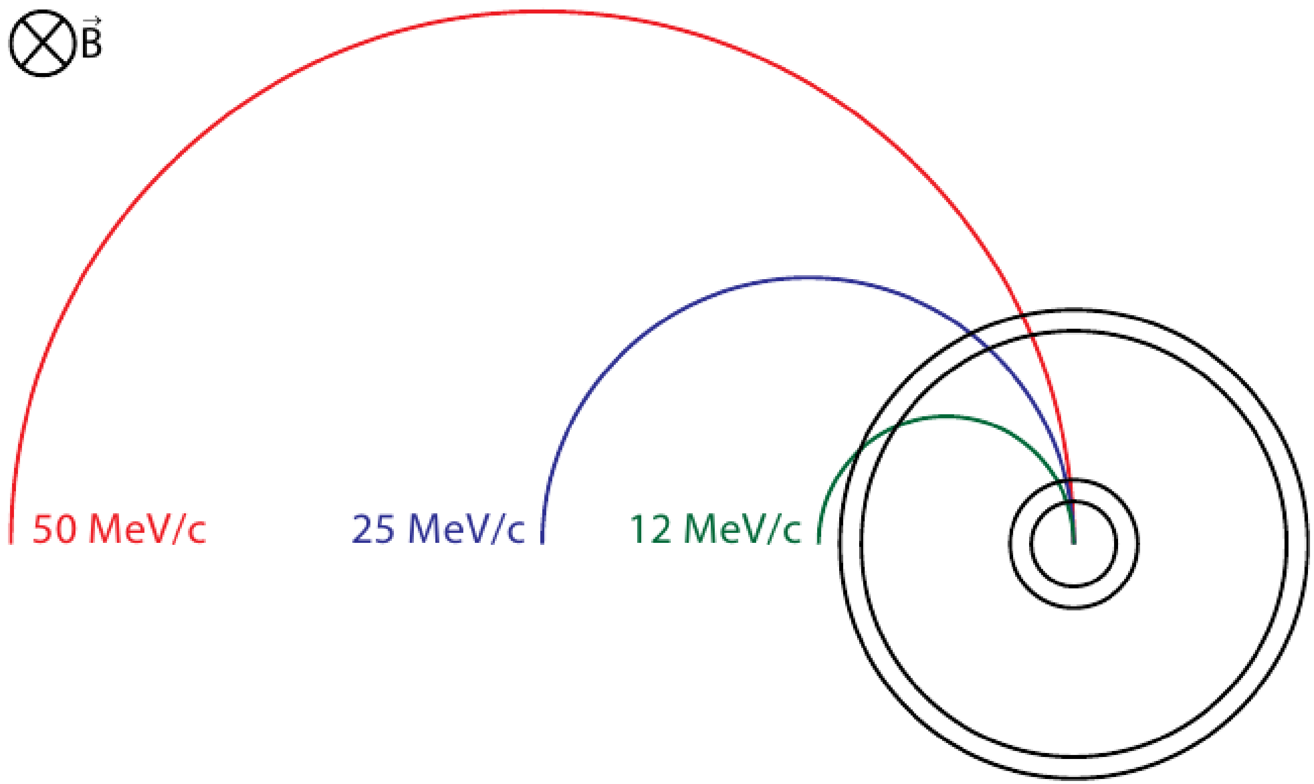
Tracking Design Considerations



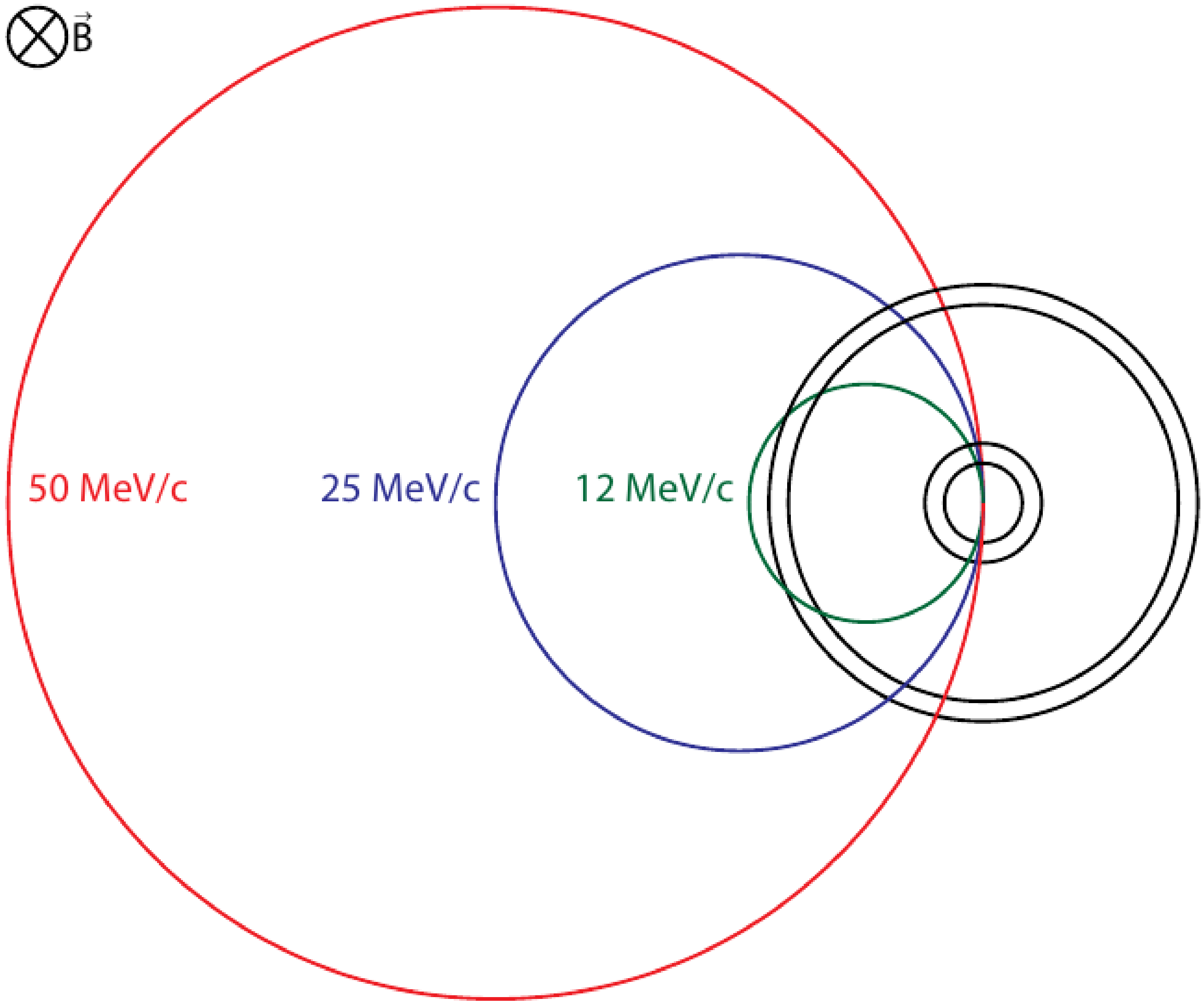
Tracking Design Considerations



Tracking Design Considerations

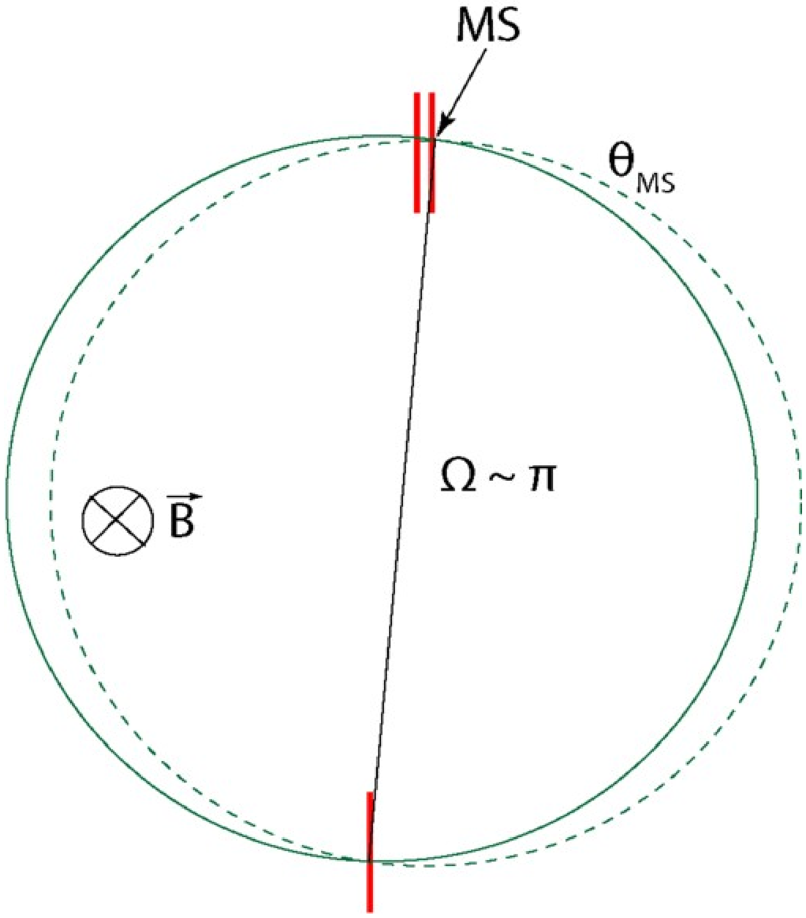


Tracking Design Considerations



Momentum Resolution in MS Regime

- "Half turn" spectrometer:



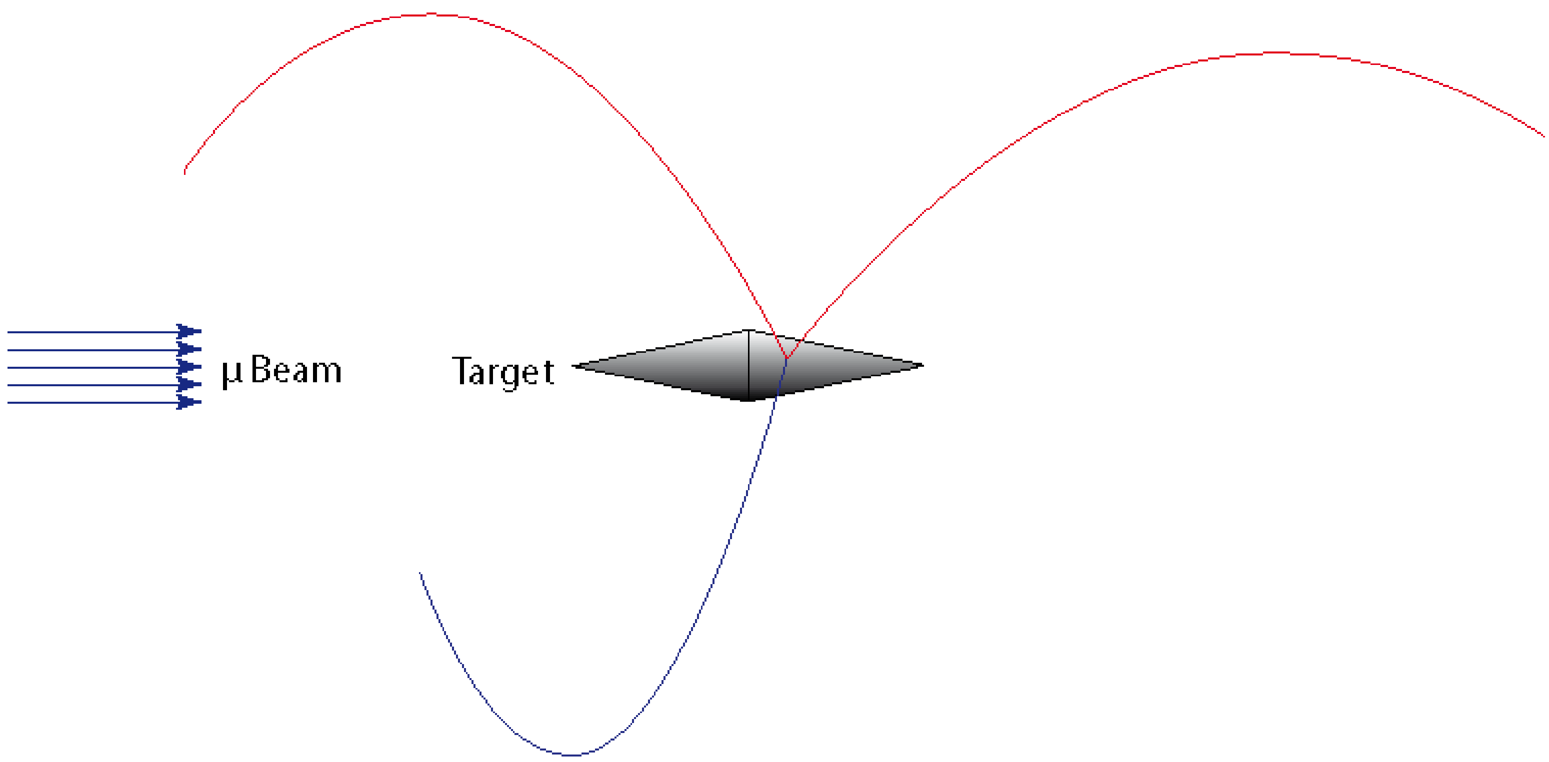
$$\frac{\sigma_p}{P} \sim O\left(\Theta_{MS}^2\right)$$

- best precision for **half turn** tracks
- measure **recurling tracks**

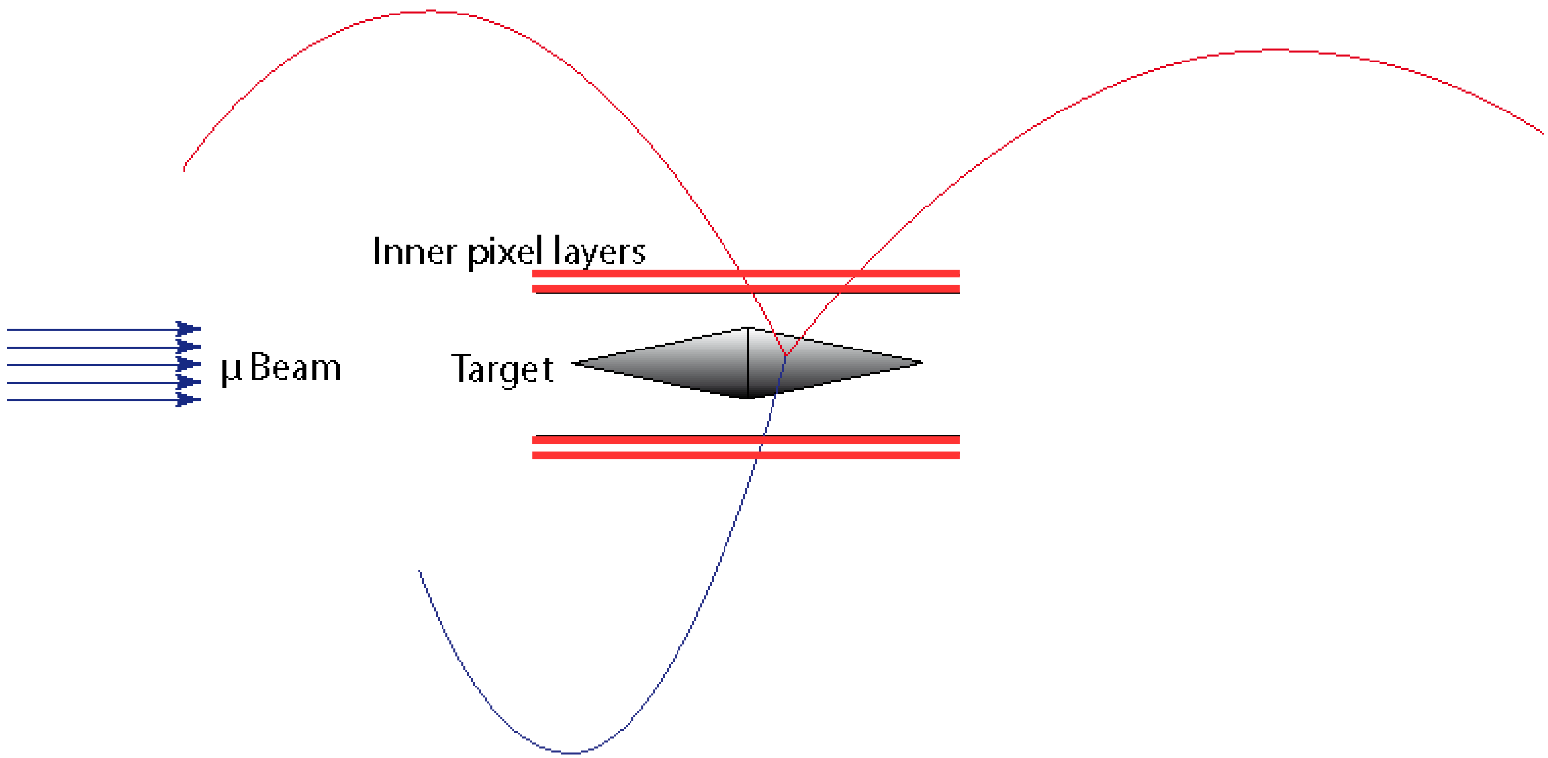
Mu3e Design

E_{kin}=28 MeV

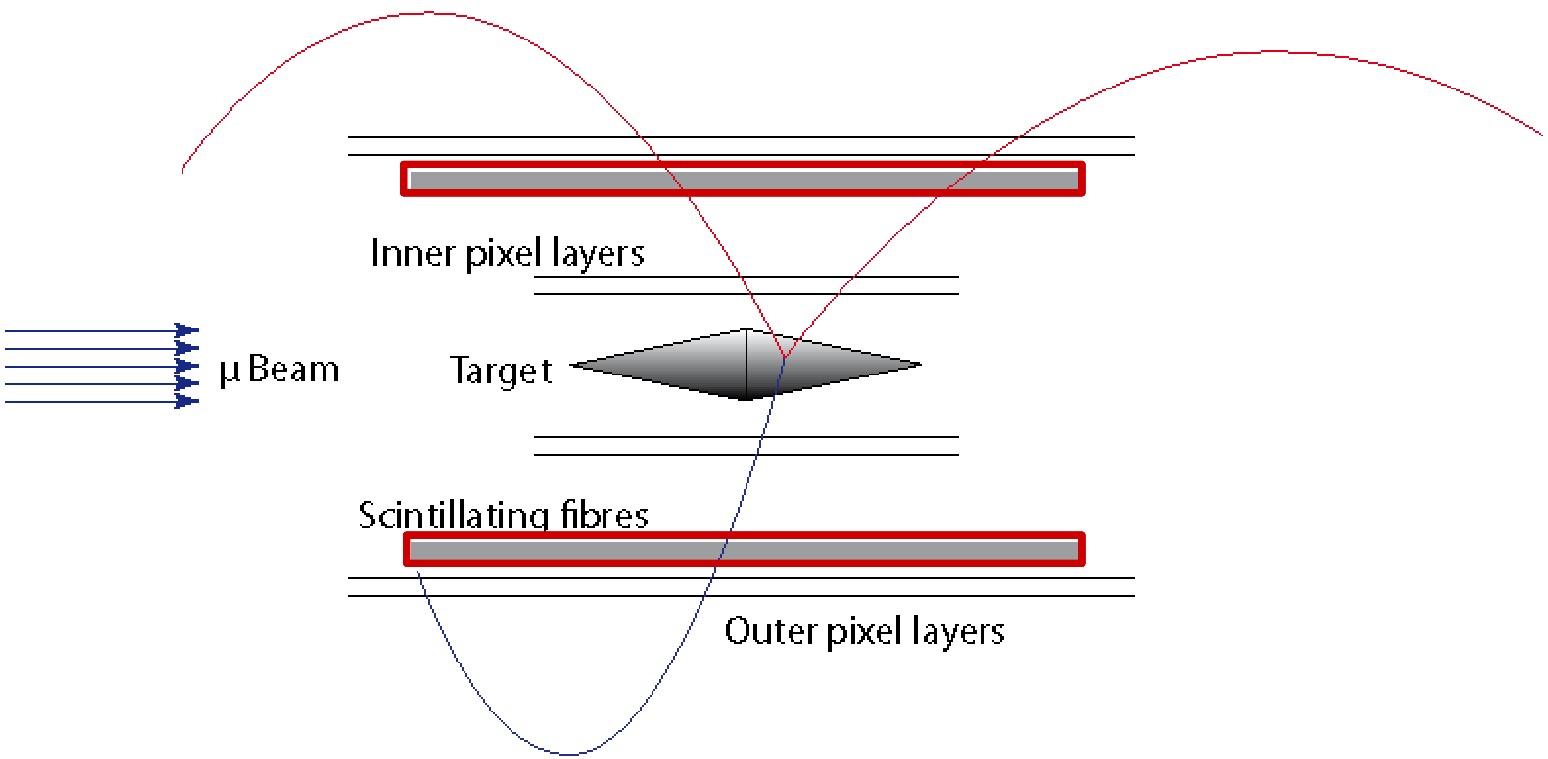
Mu3e Design



Mu3e Design

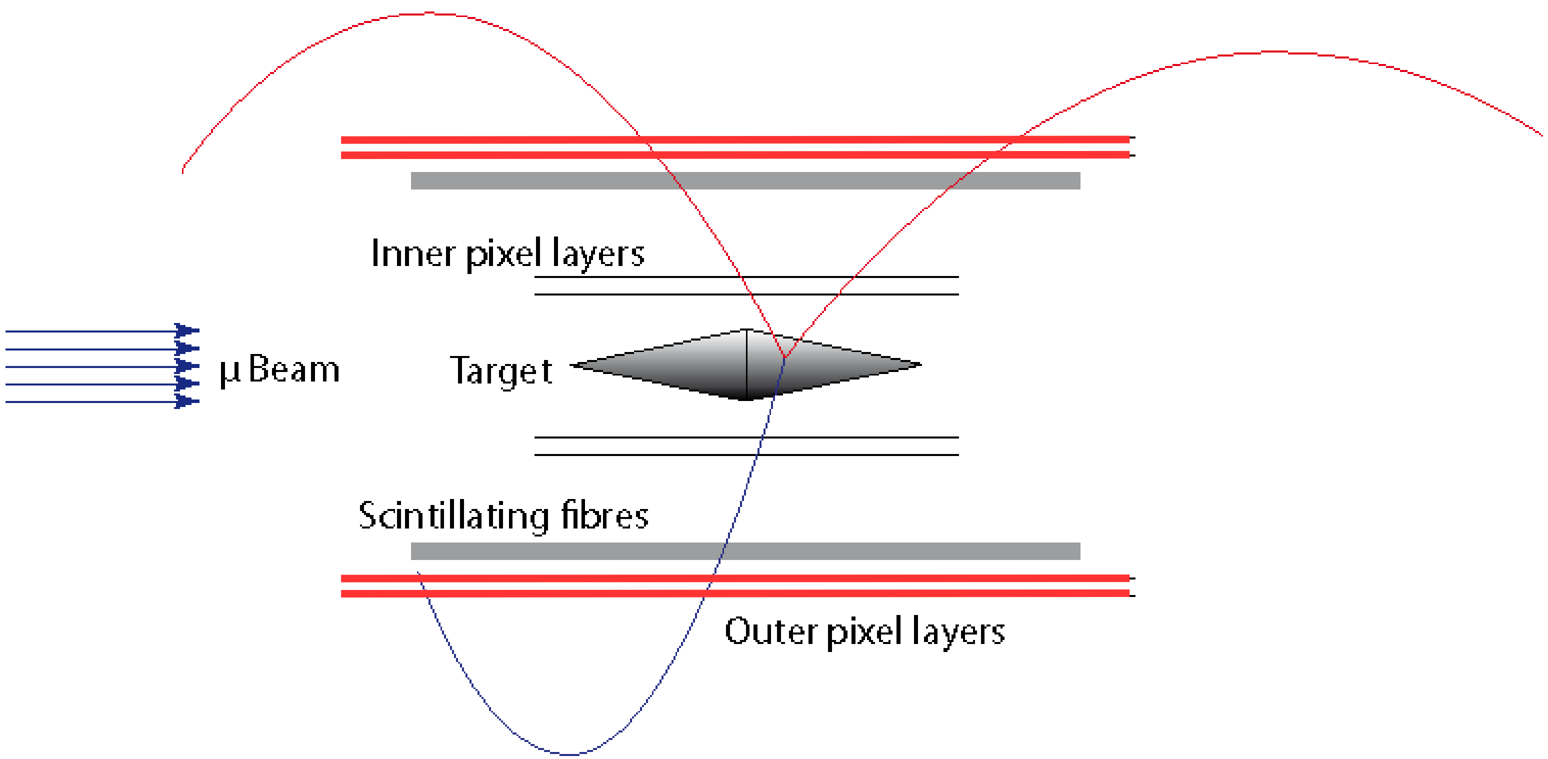


Mu3e Design



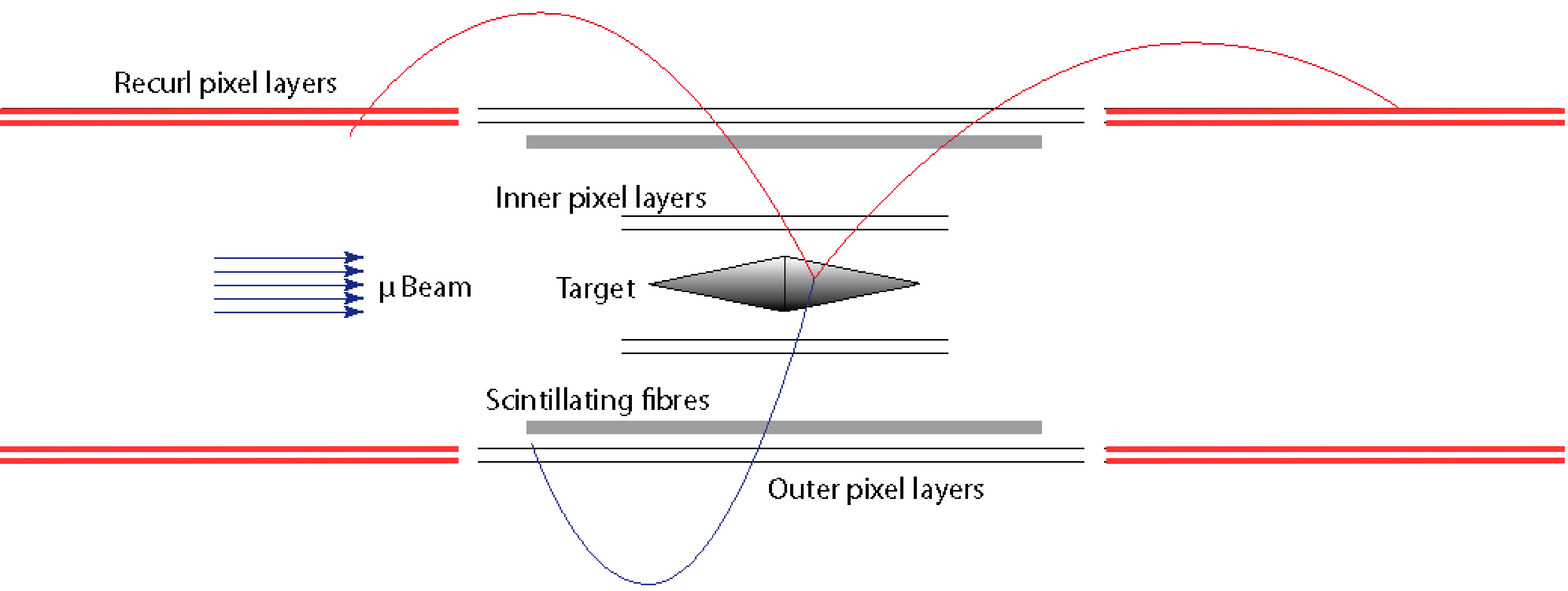
Inner pixel layers
μ Beam
Target
Scintillating fibres
Outer pixel layers

Mu3e Design

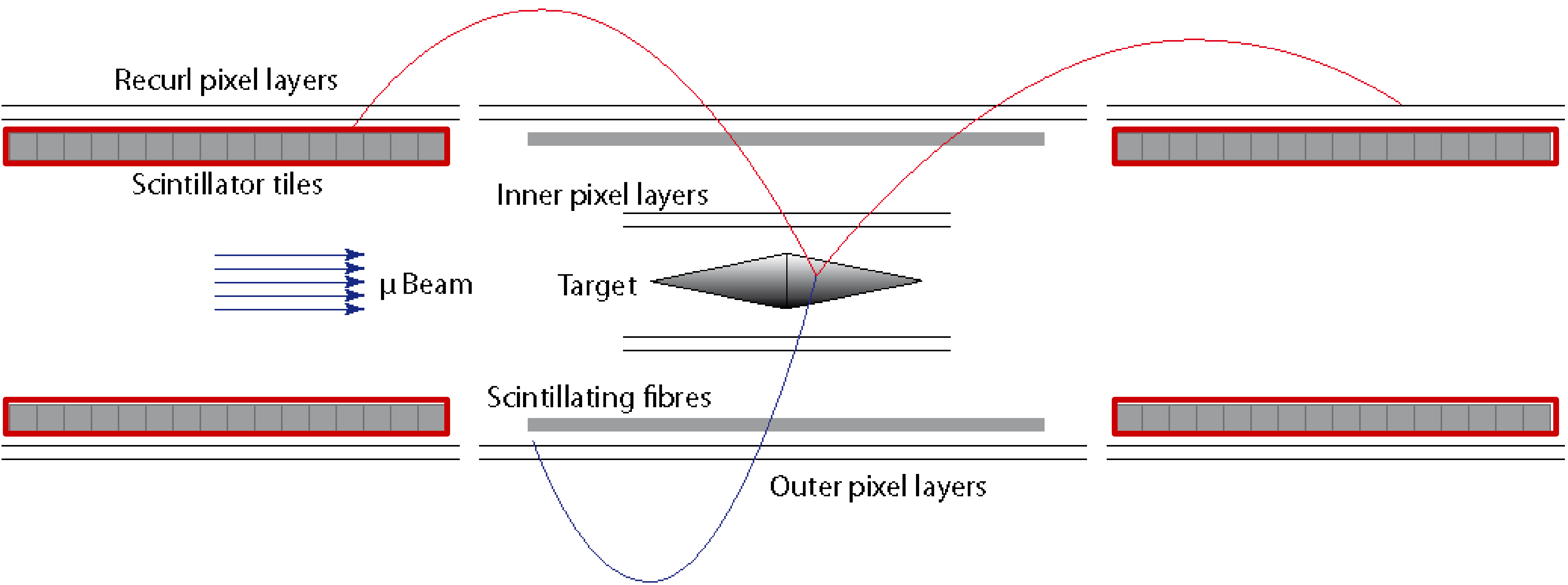


Inner pixel layers
μ Beam
Target
Scintillating fibres
Outer pixel layers

Mu3e Design

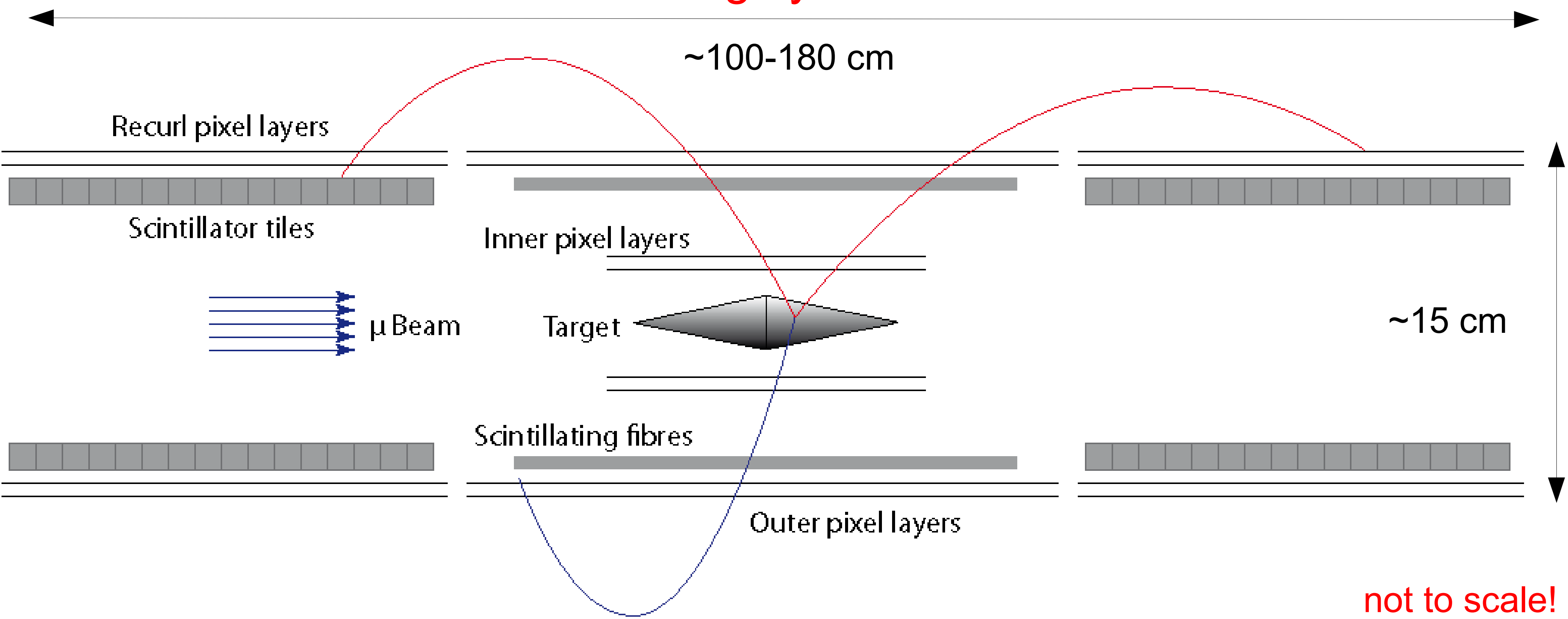

Recurl pixel layers
Inner pixel layers
μ Beam
Target
Scintillating fibres
Outer pixel layers

Mu3e Design


Recurl pixel layers
Scintillator tiles
Inner pixel layers
µ Beam
Target
Scintillating fibres
Outer pixel layers

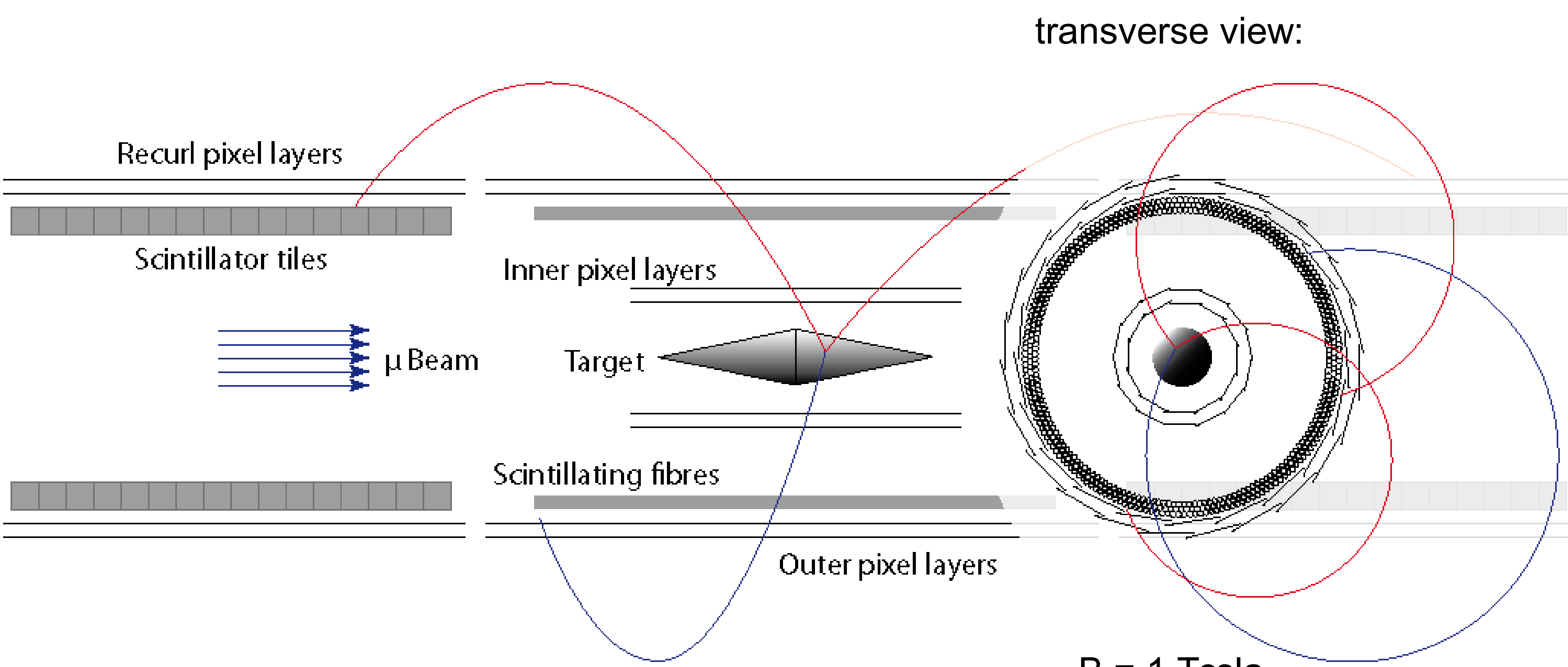
Mu3e Design

Long cylinder!



not to scale!

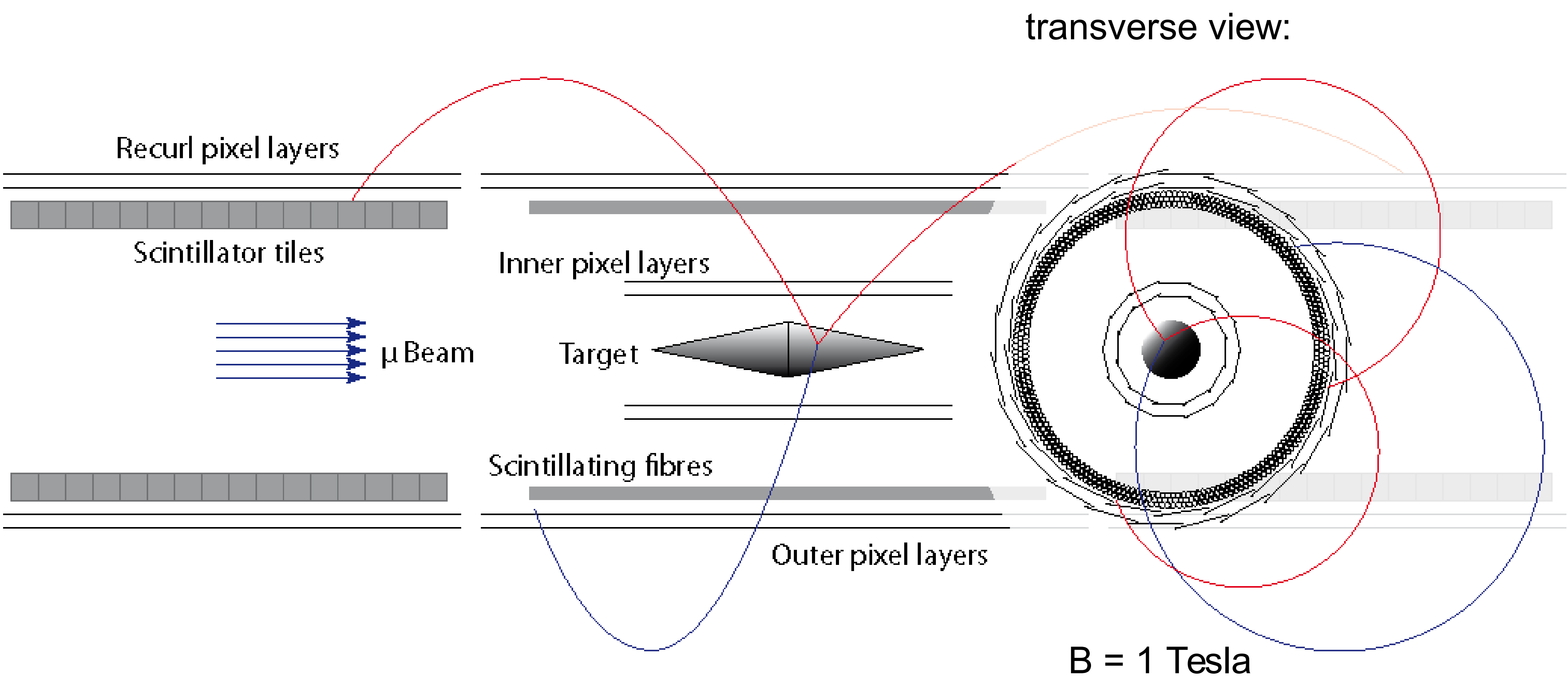
Mu3e Design



B = 1 Tesla

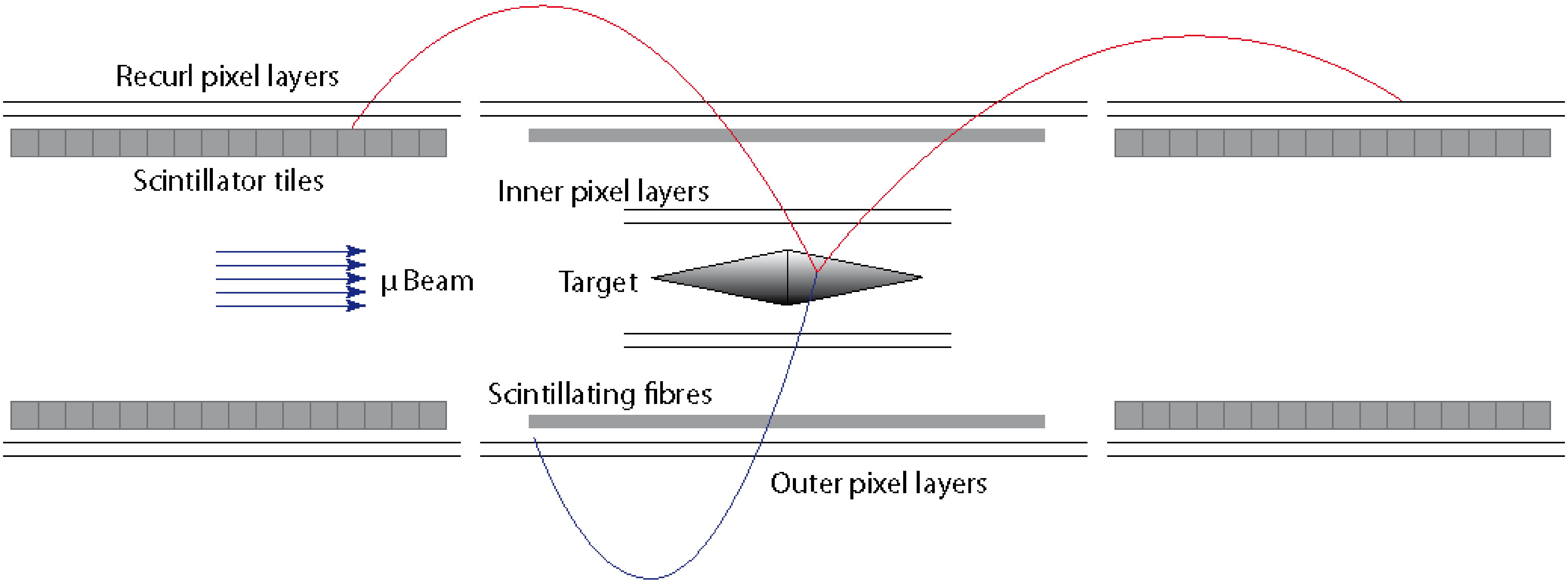
helium atmosphere

Mu3e Design



Geometrical acceptance **~70 %** for **$\mu^+ \rightarrow e^+e^+e^-$** decay

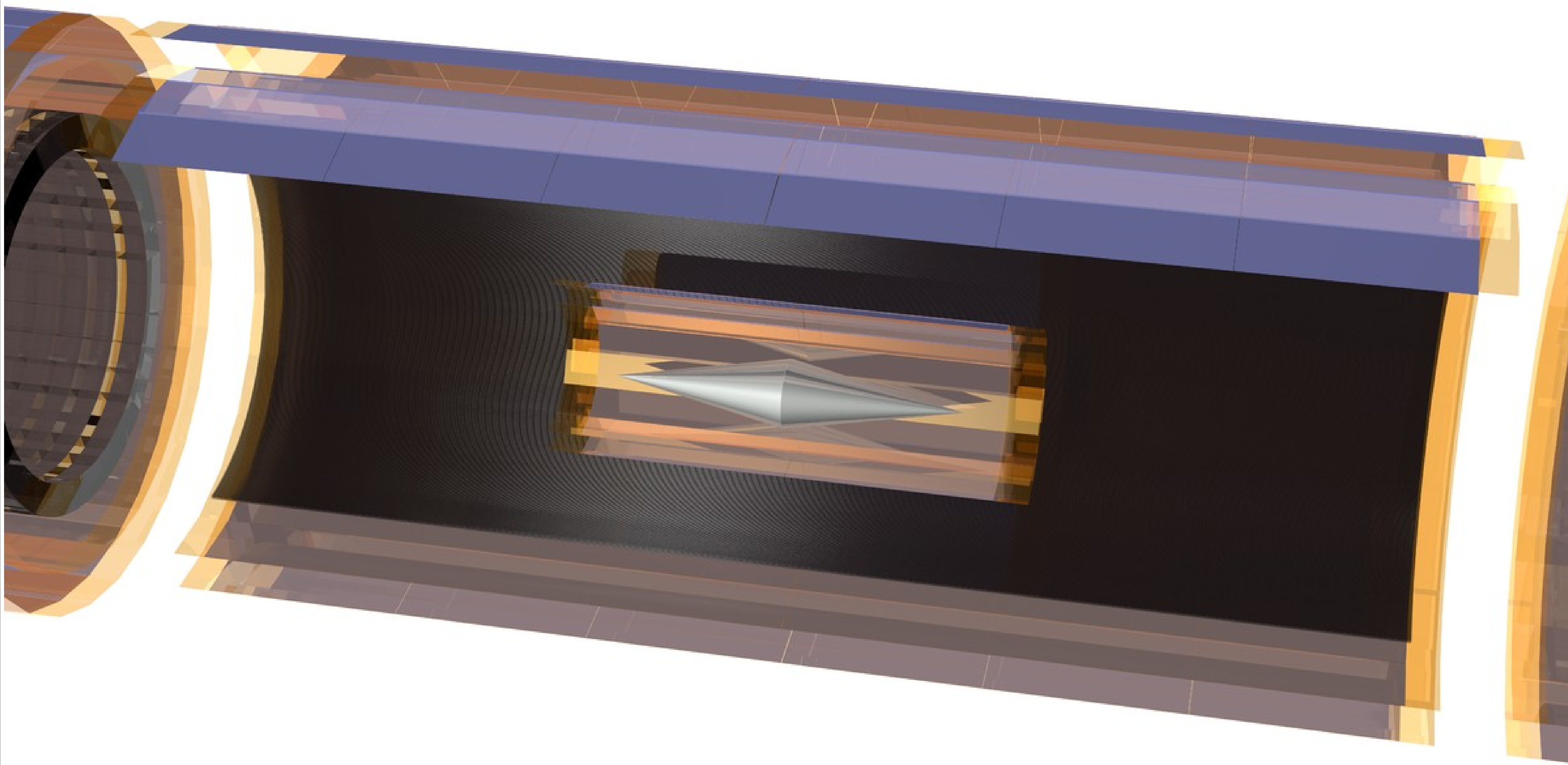
Mu3e Design



Main technological Challenges

- Large area O(1m^2) monolithic pixel detectors with X/X_0 = 0.1% per tracking layer
- Novel helium gas cooling concept
- Thin scintillating fiber detector with ≤ 1mm thickness
- Timing resolution 100-500 ps
- Filter farm reconstructing and processing 10^8-10^9 tracks per second

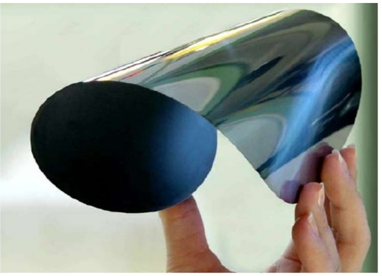
Mu3e Pixel Tracker



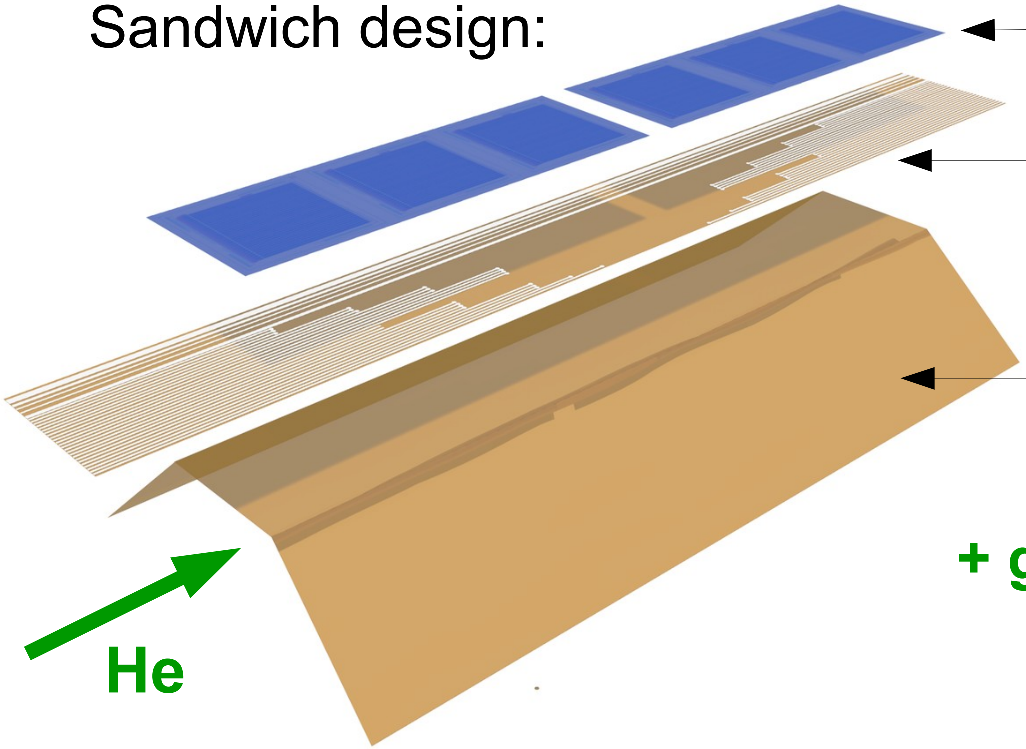
Mu3e Pixel Mechanics

Mu3e physics sensitivity: $\sim (X/X_0)^3$

Most challenging requirement: $X/X_0 \leq 0.1\%$



Sandwich design:



monolithic HV-CMOS sensor (50 µm)

thin aluminium / kapton flexprint

kapton support foil (25 µm)

+ gaseous helium cooling

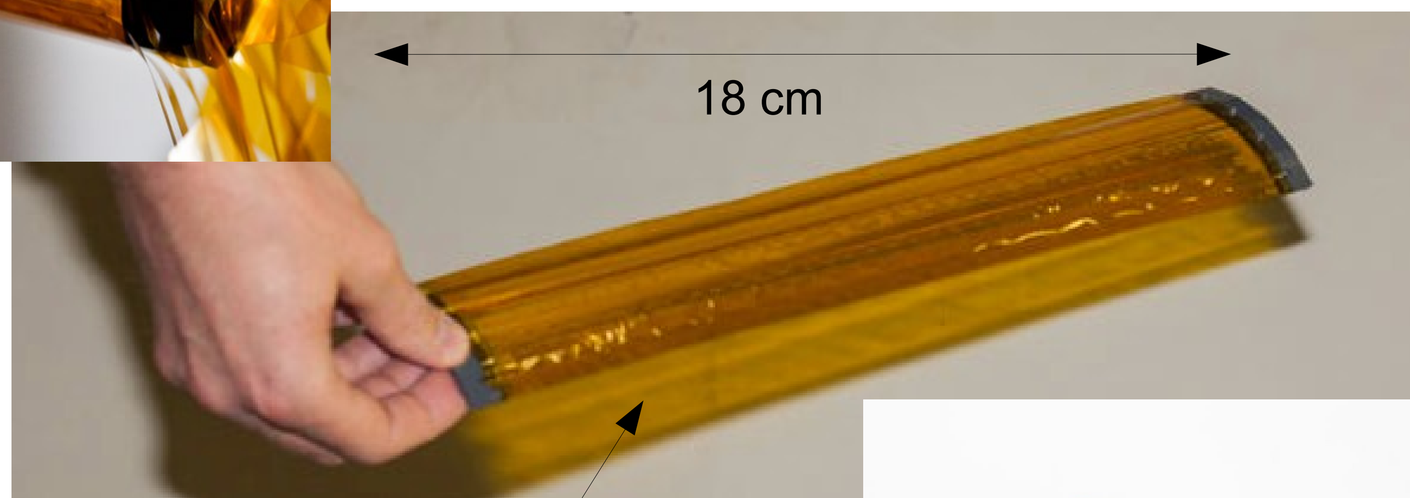
$X \leq 0.1\%\ X_0$ per layer possible

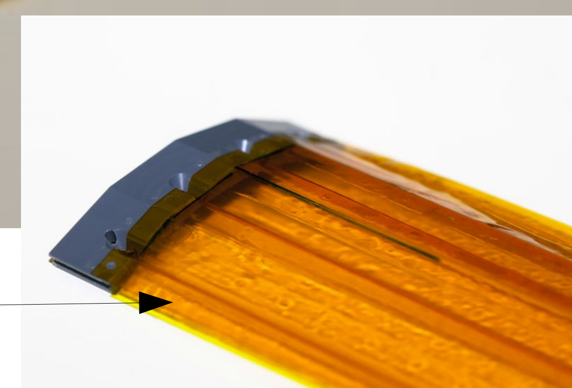
Mechanical Mockups

Ultra-thin mechanical mockup:

- sandwich of 25 µm Kapton®
- here 50 µm glass (instead of Si)

Even larger stable structures possible

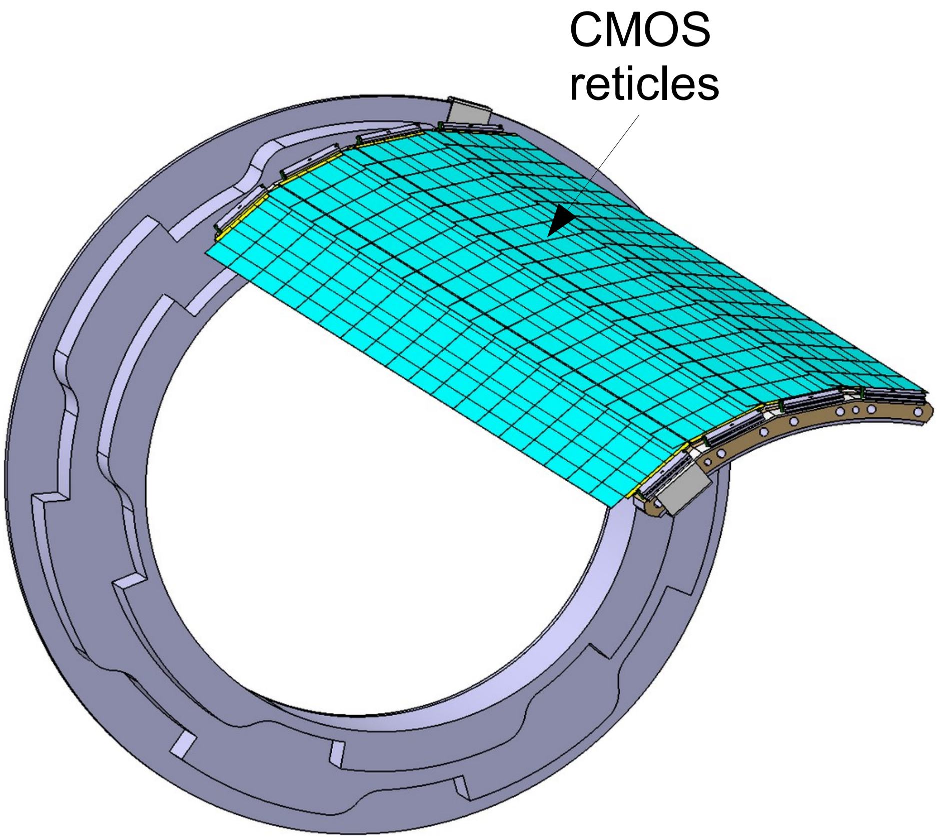


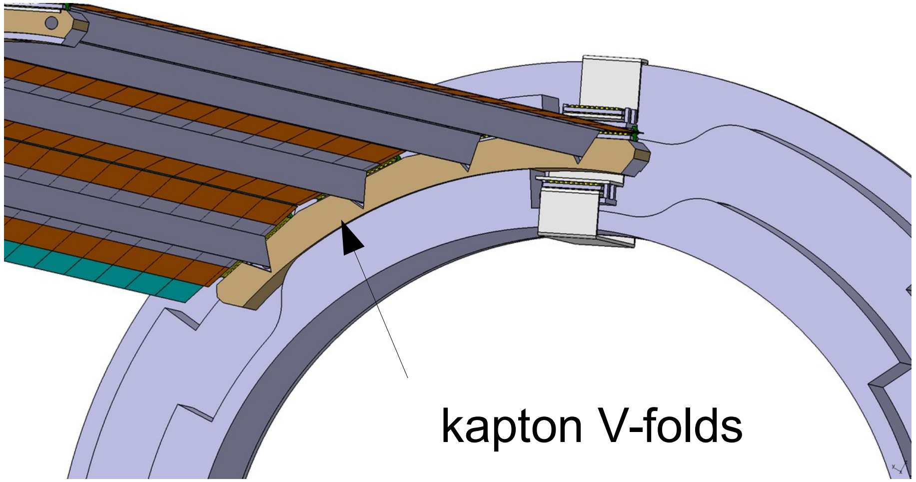


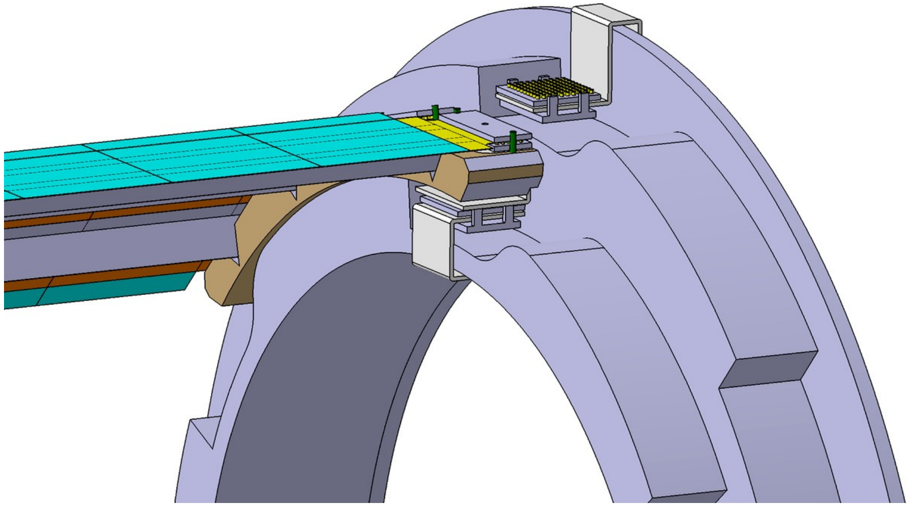
by using Kapton V-folds

Pixel Module Design

Outer pixel layers

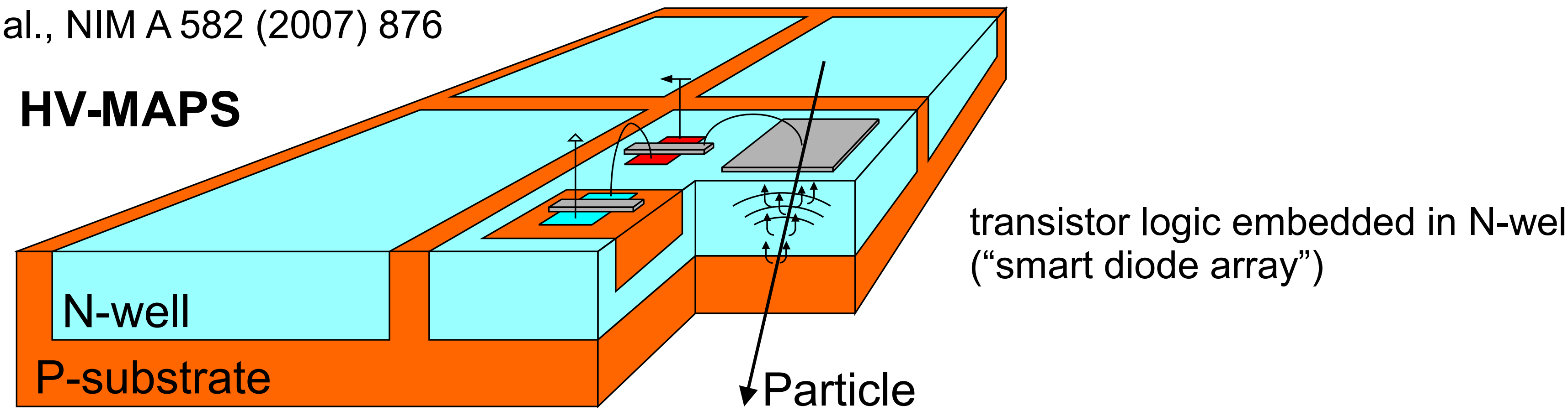






The MuPix Sensor for Mu3e

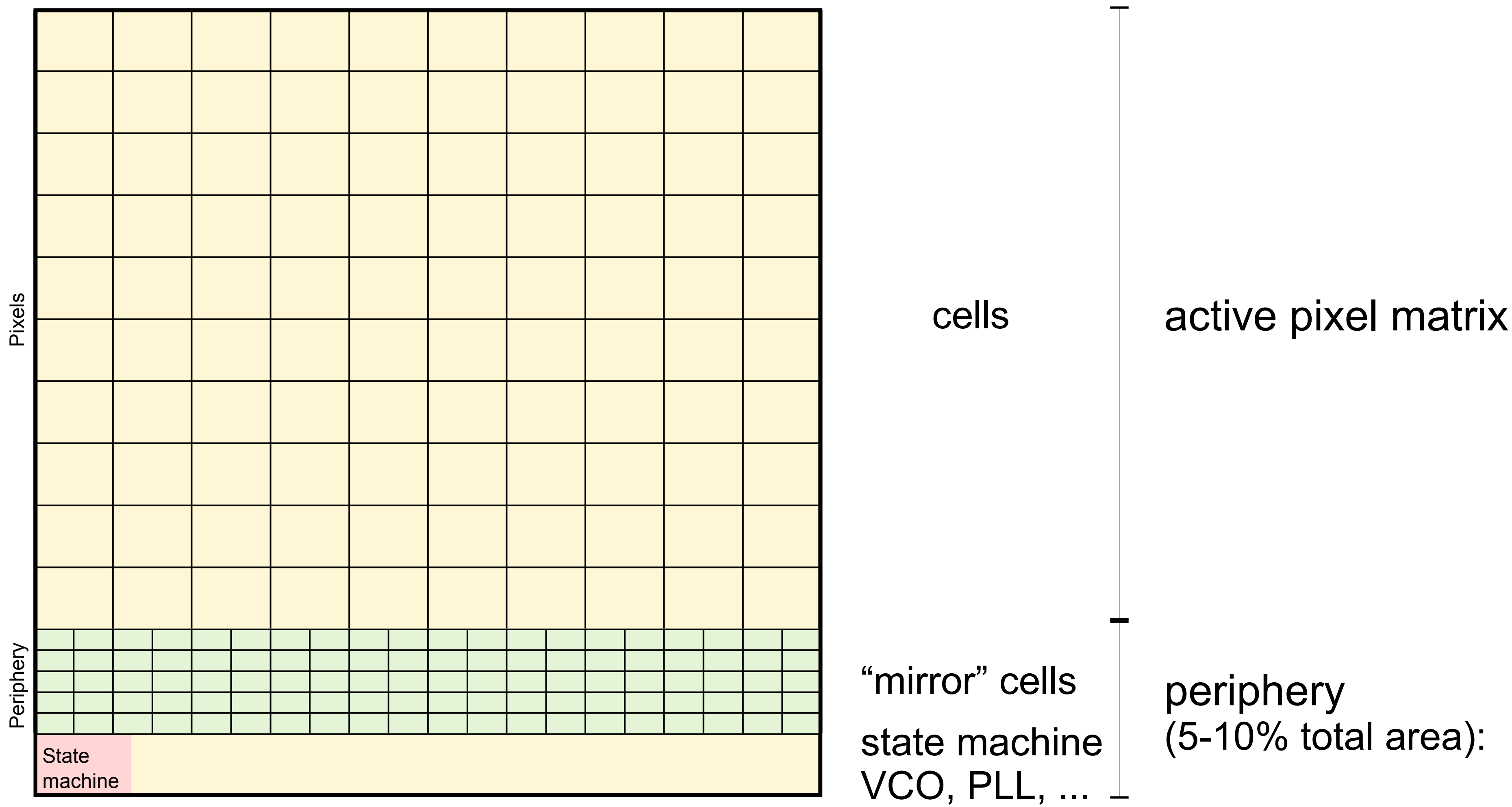
I.Peric, et al., NIM A 582 (2007) 876



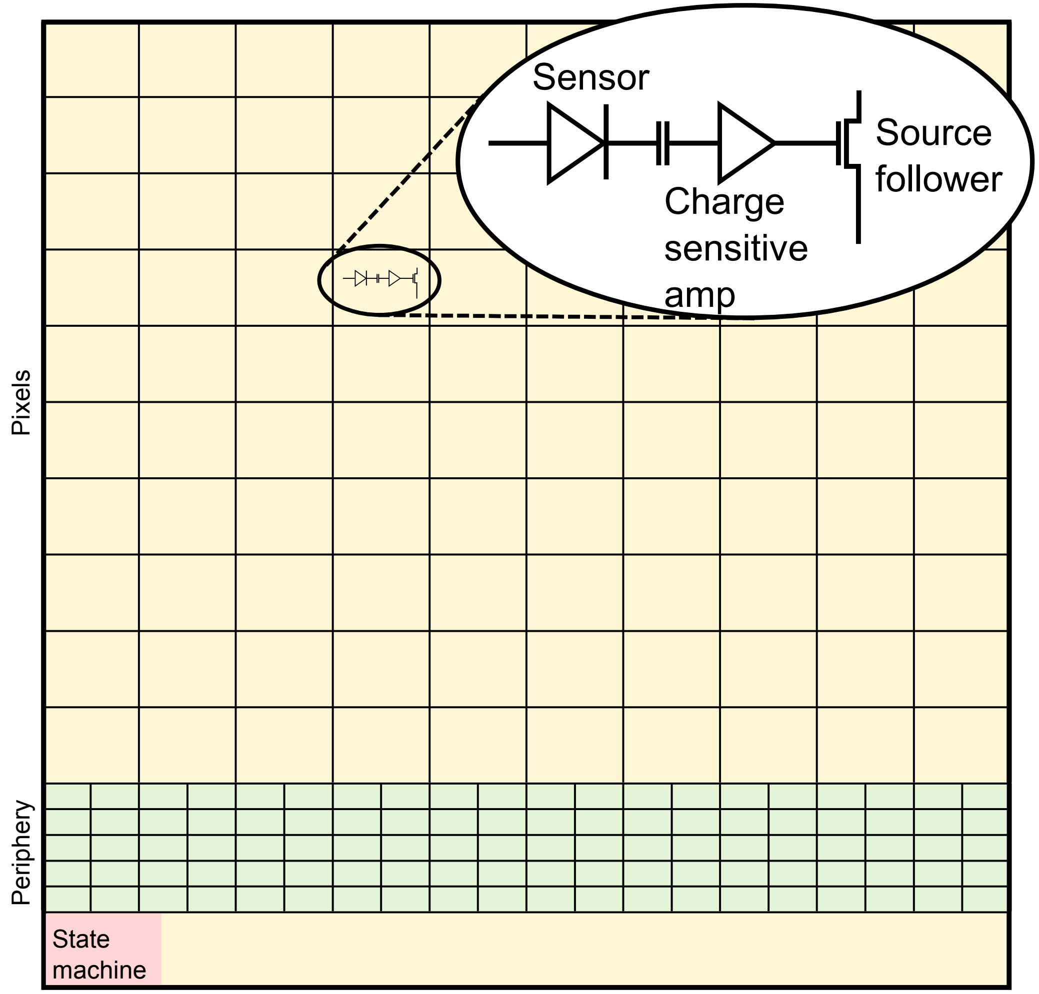
High Voltage - Monolithic Active Pixel Sensor (HV-MAPS)

- **active sensor → hit finding + digitisation + zero suppression + readout**
- high precision → pixels 80 x 80 μm^2
- low noise ~ 40 - 50e → low threshold
- small depletion region of ~ 10 µm → thin sensor ~50 µm (~ 0.0005 X_0)
- standard HV-CMOS process, 60 - 90 V → low production costs
- continuous and fast readout (serial link) → online reconstruction

MuPix Chip Design



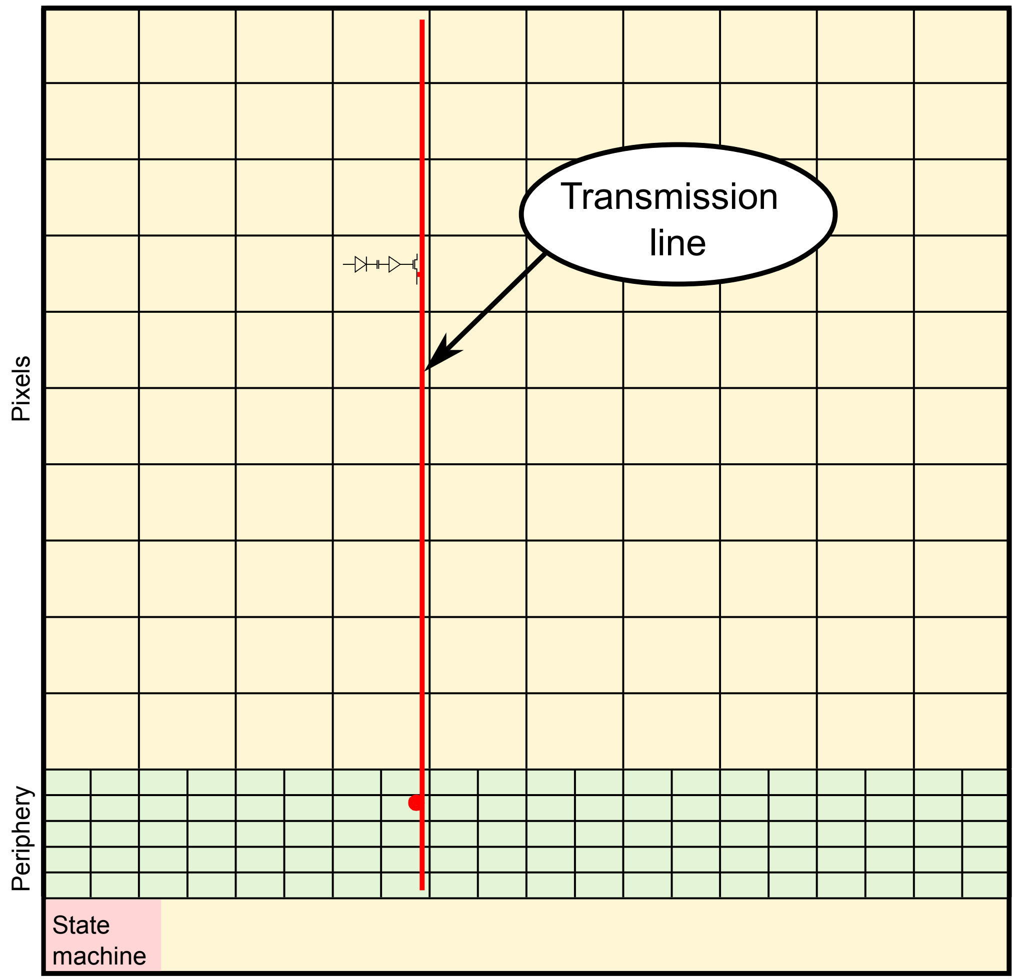
MuPix Chip Design



analog cell:

- reverse biased -85V
- charge sensitive amplifier
- source follower

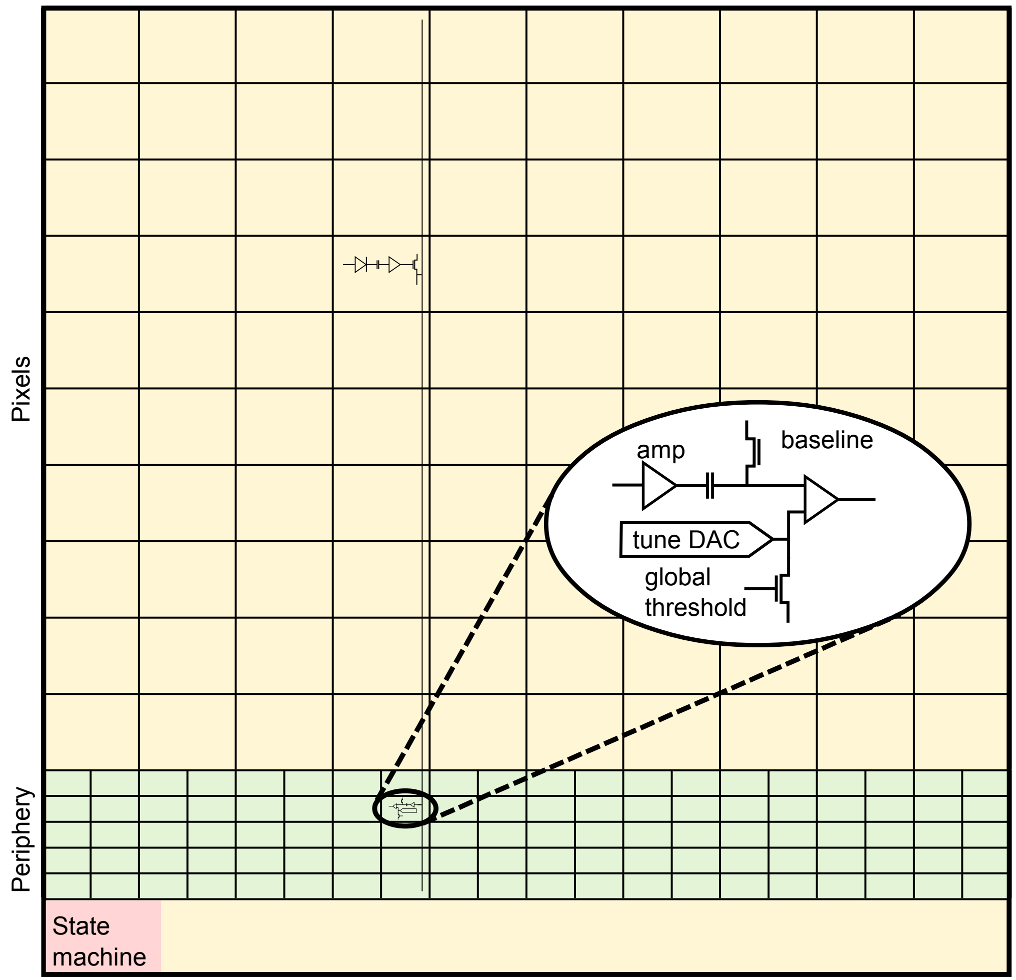
MuPix Chip Design



transmission line:

- send signal to corresponding mirror cell

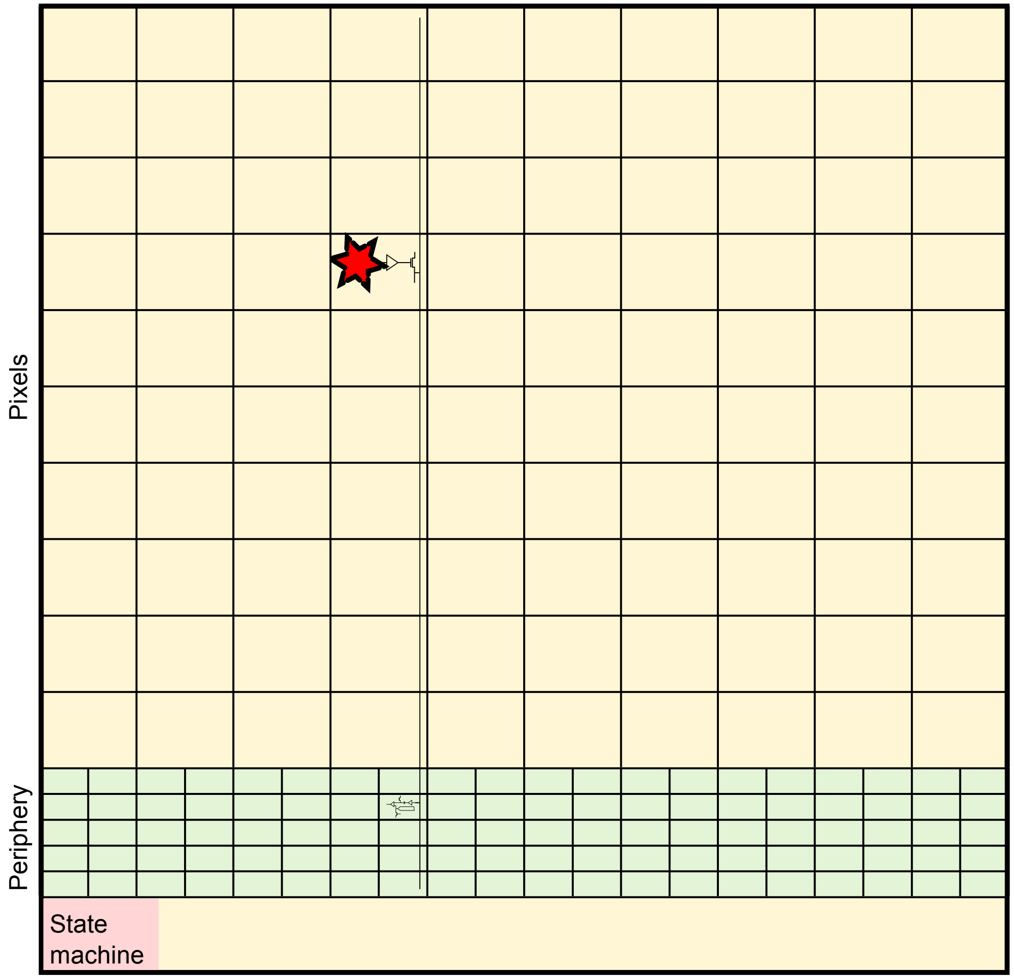
MuPix Chip Design



mirror cell:

- 2^{nd} amplifier
- comparator for discrimination
- threshold and baseline by tuning DACs

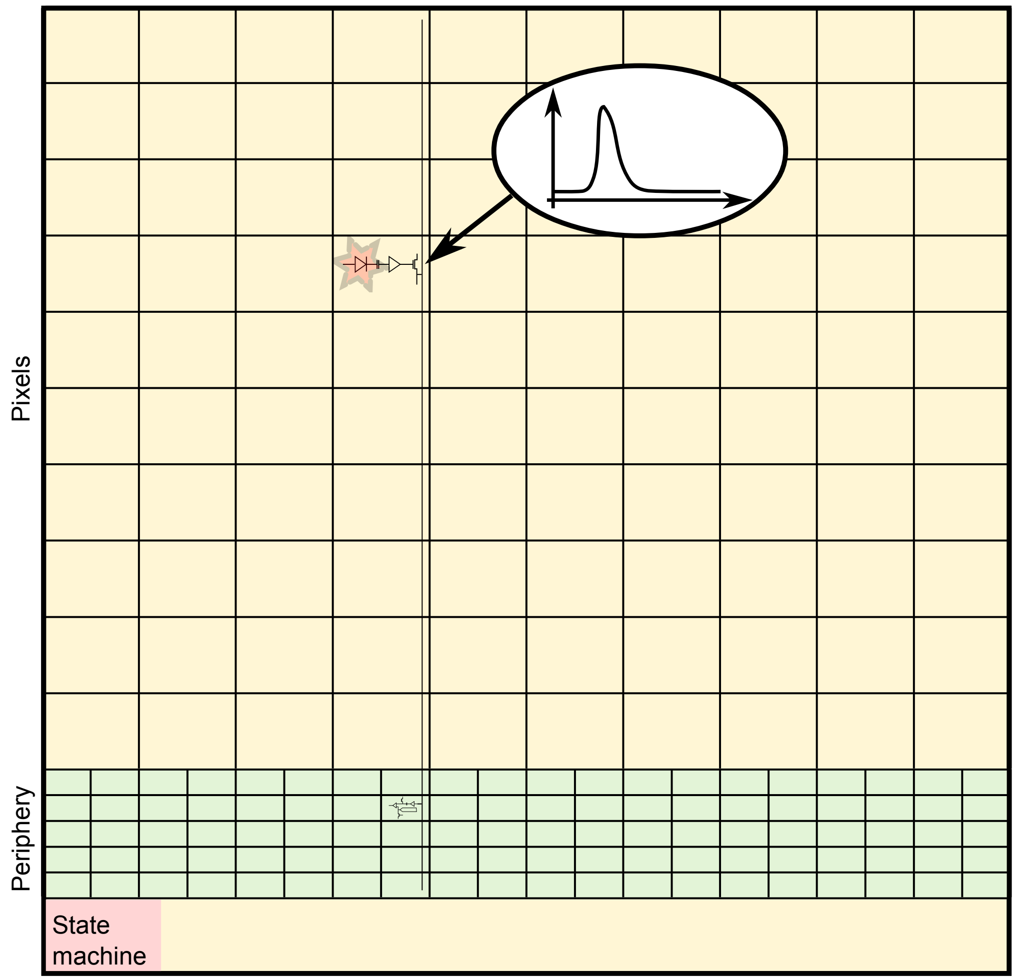
MuPix Hit Detection



hit sequence:

- signal generation

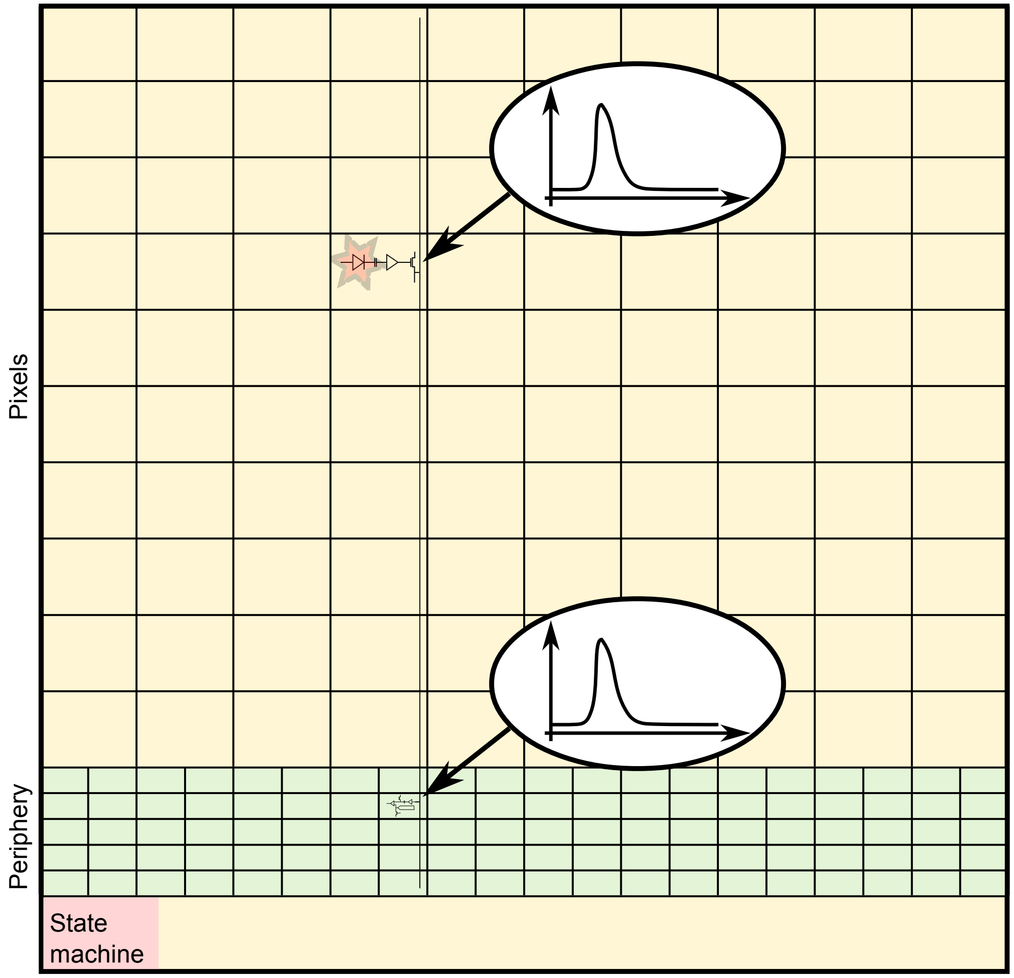
MuPix Hit Detection



hit sequence:

- signal generation
- amplification

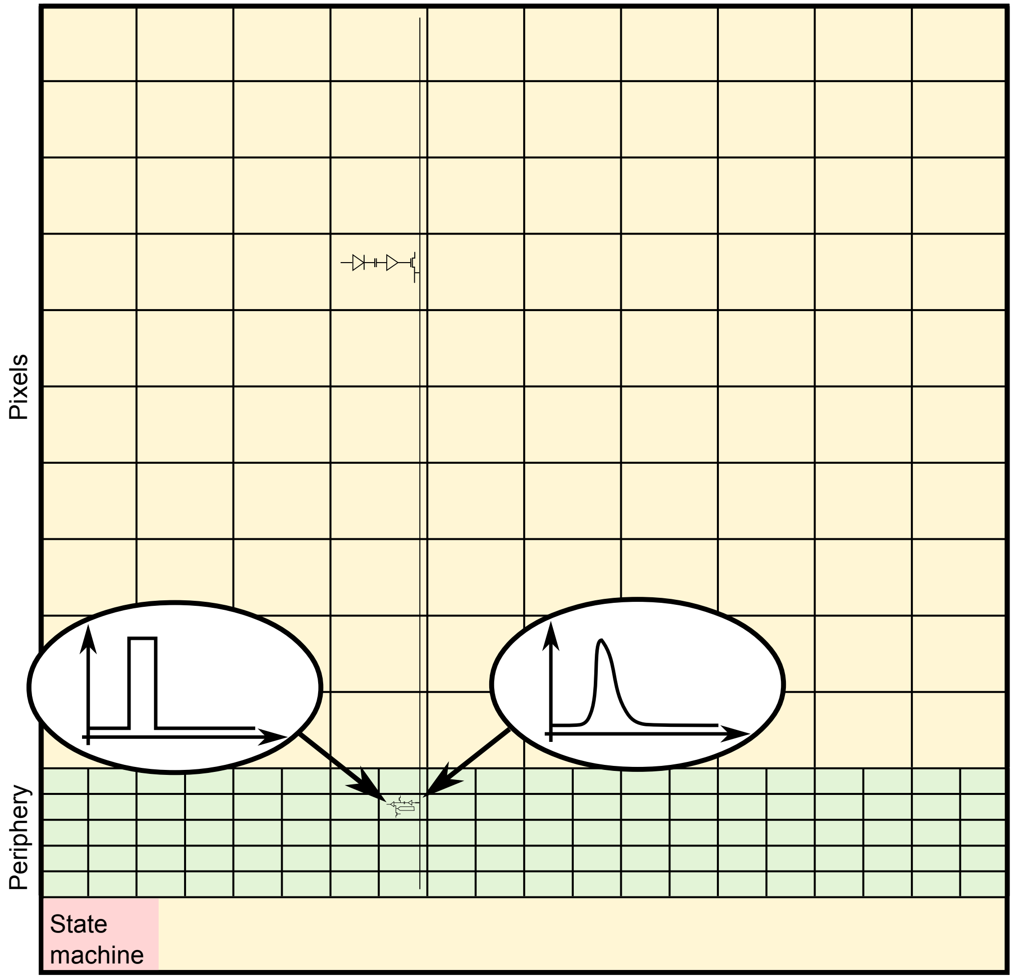
MuPix Hit Detection



hit sequence:

- signal is generated
- charge amplified
- received in mirror pixel

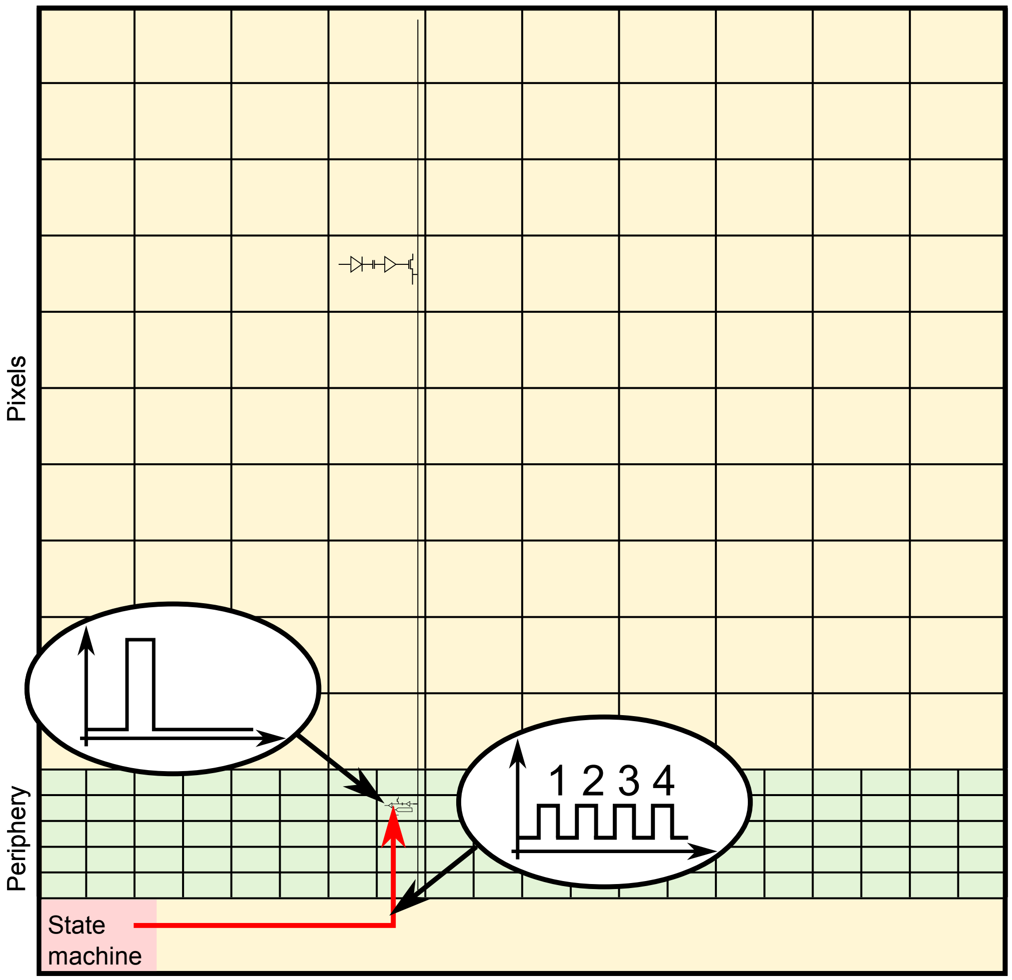
MuPix Hit Detection



hit sequence:

- signal is generated
- charge amplified
- received in mirror pixel
- discriminated

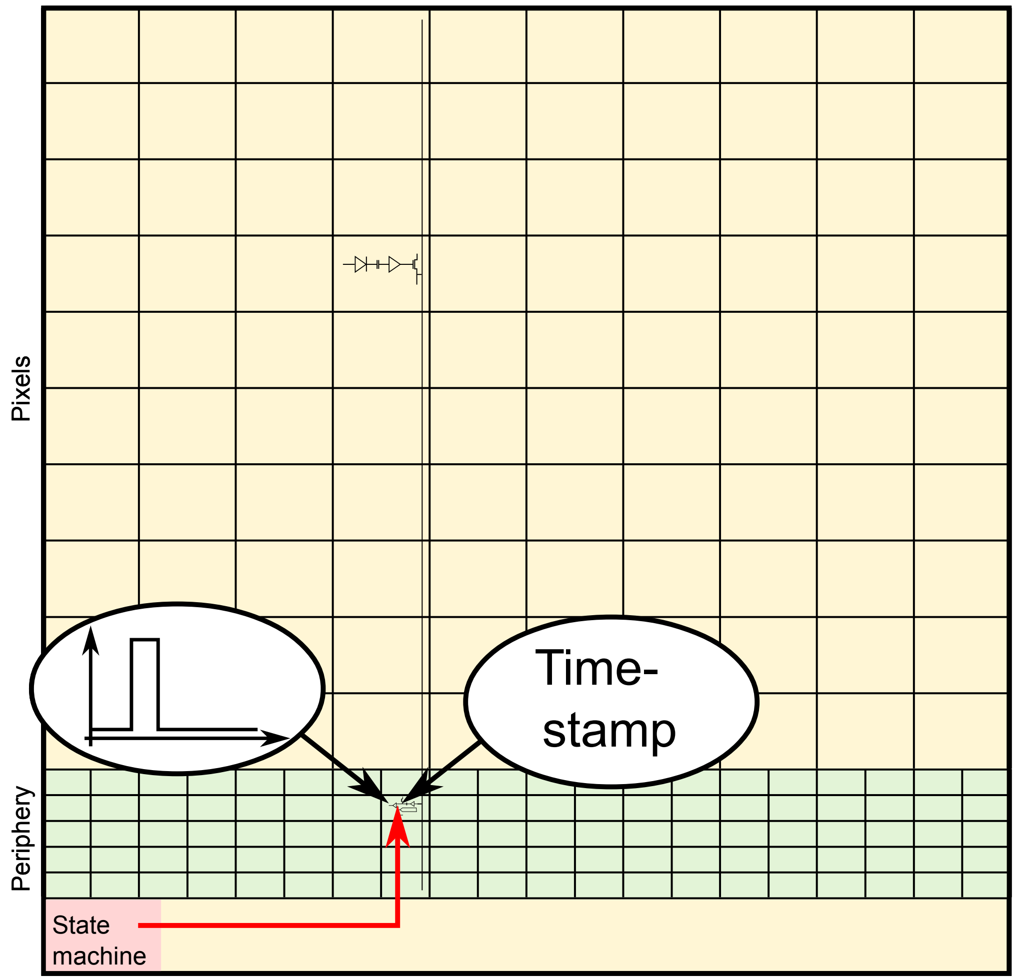
MuPix Hit Detection



hit sequence:

- signal is generated
- charge amplified
- received in mirror pixel
- discriminated
- scaler generated from clk

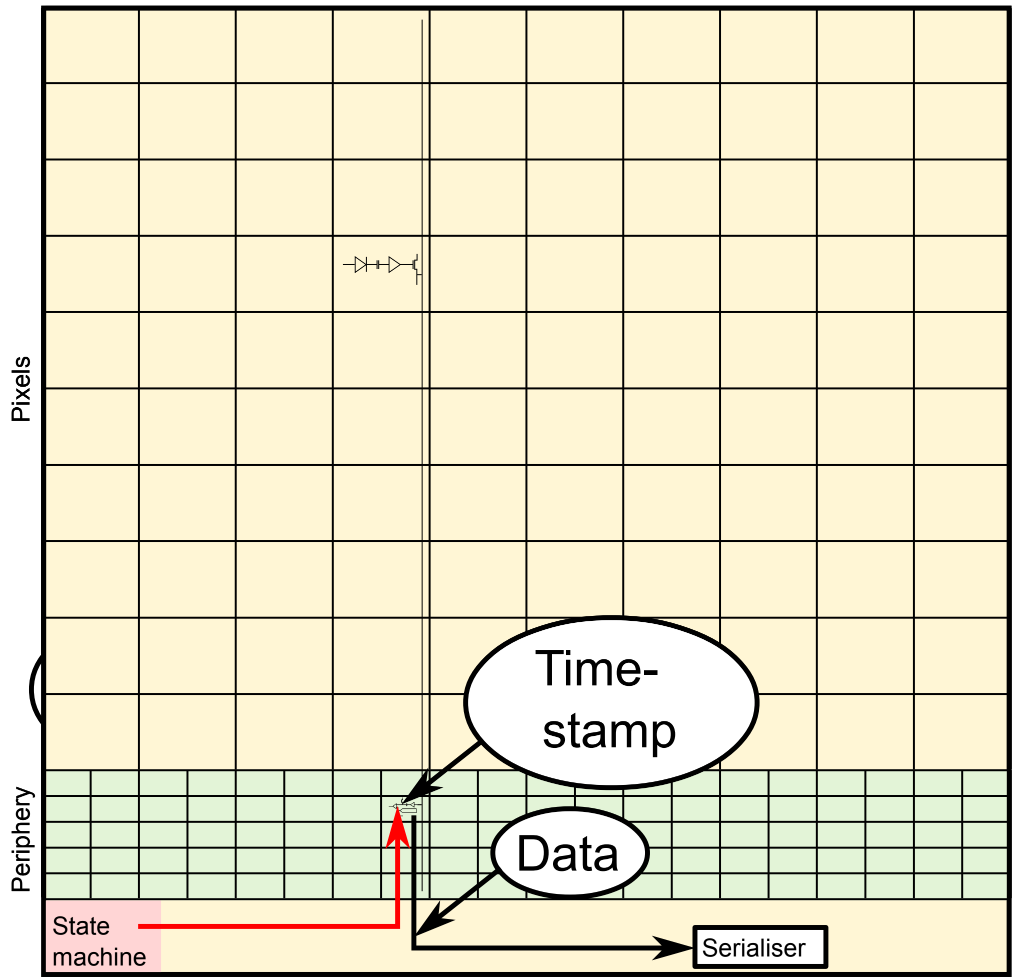
MuPix Hit Detection



hit sequence:

- signal is generated
- charge amplified
- received in mirror pixel
- discriminated
- scaler generated from clk
- timestamp generation

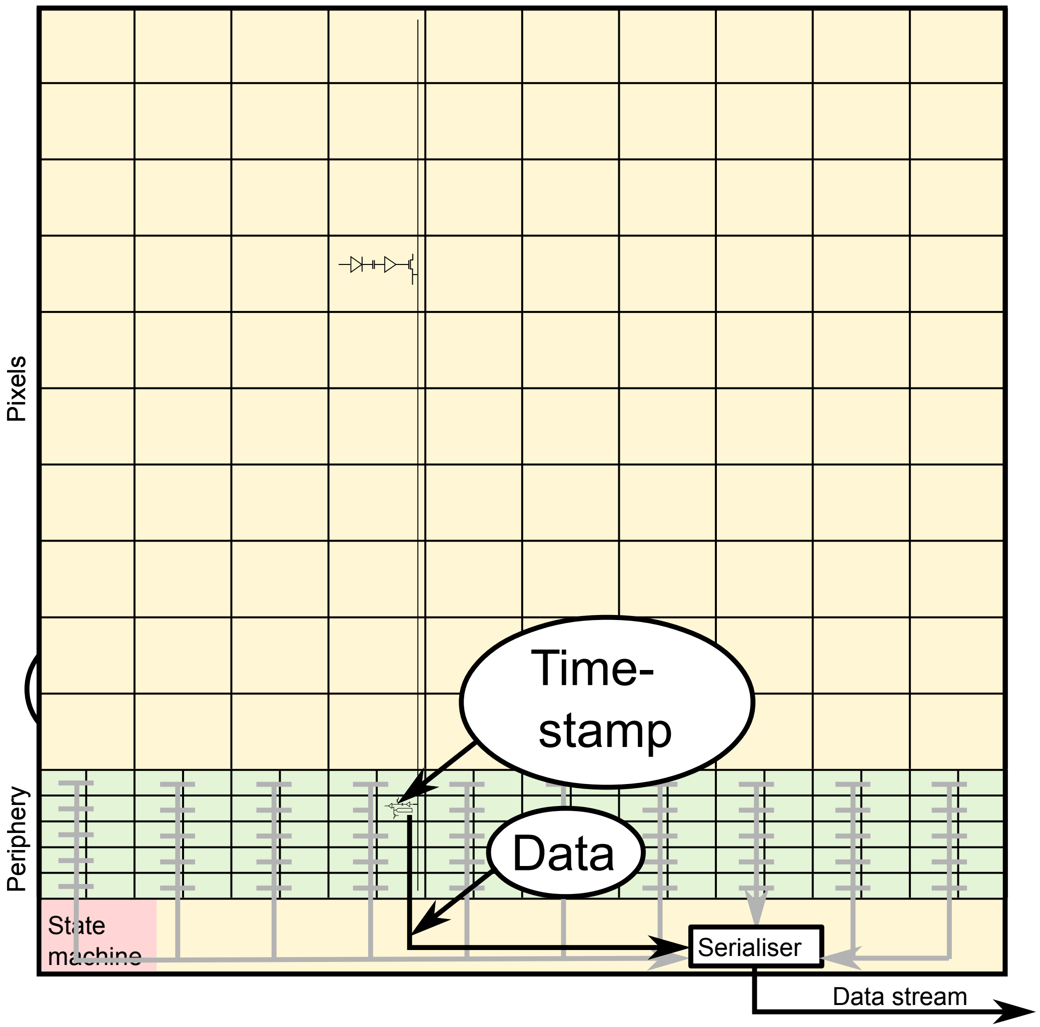
MuPix Hit Detection



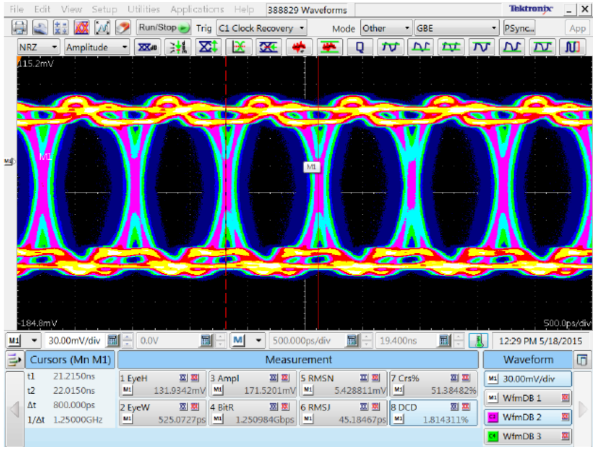
hit sequence:

- signal is generated
- charge amplified
- received in mirror pixel
- discriminated
- scaler generated from clk
- timestamp generation
- hit address and timestamp send to serializer

MuPix Hit Detection



Finally, **all detected hits** are sent out via a **1.25 Gbit/s** serial link

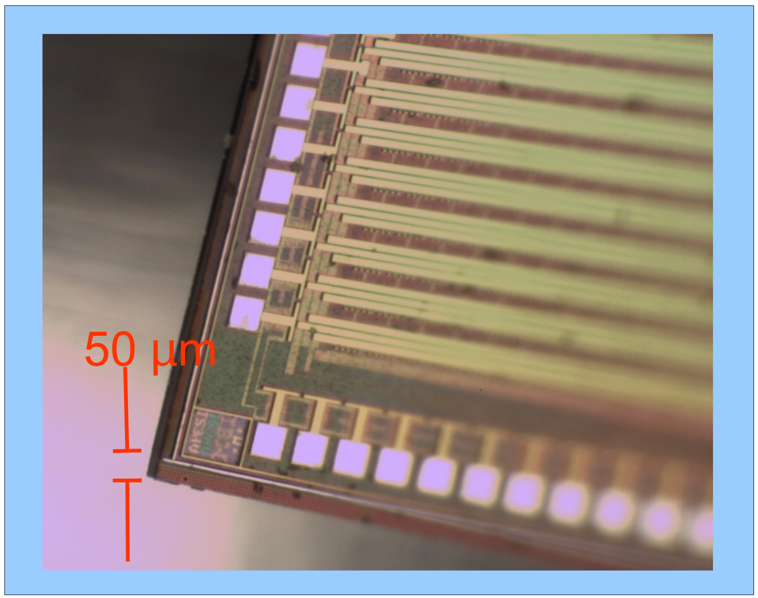


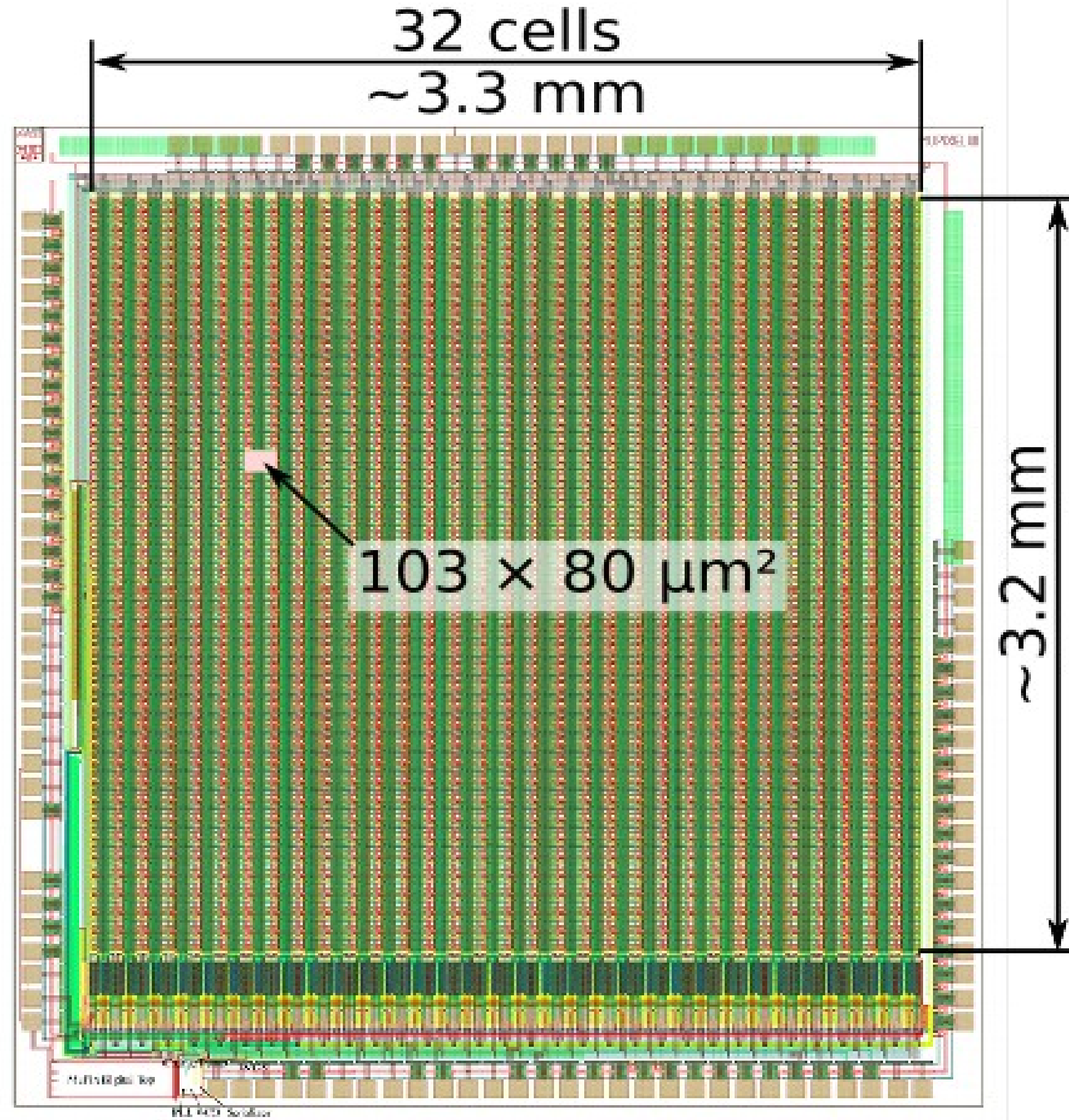
Eye diagram measured with Mupix7 prototype

Maximum readout rate is 33 Mhits/s per link

MuPix7 Prototype

Institutes: Heidelberg, Karlsruhe, Mainz



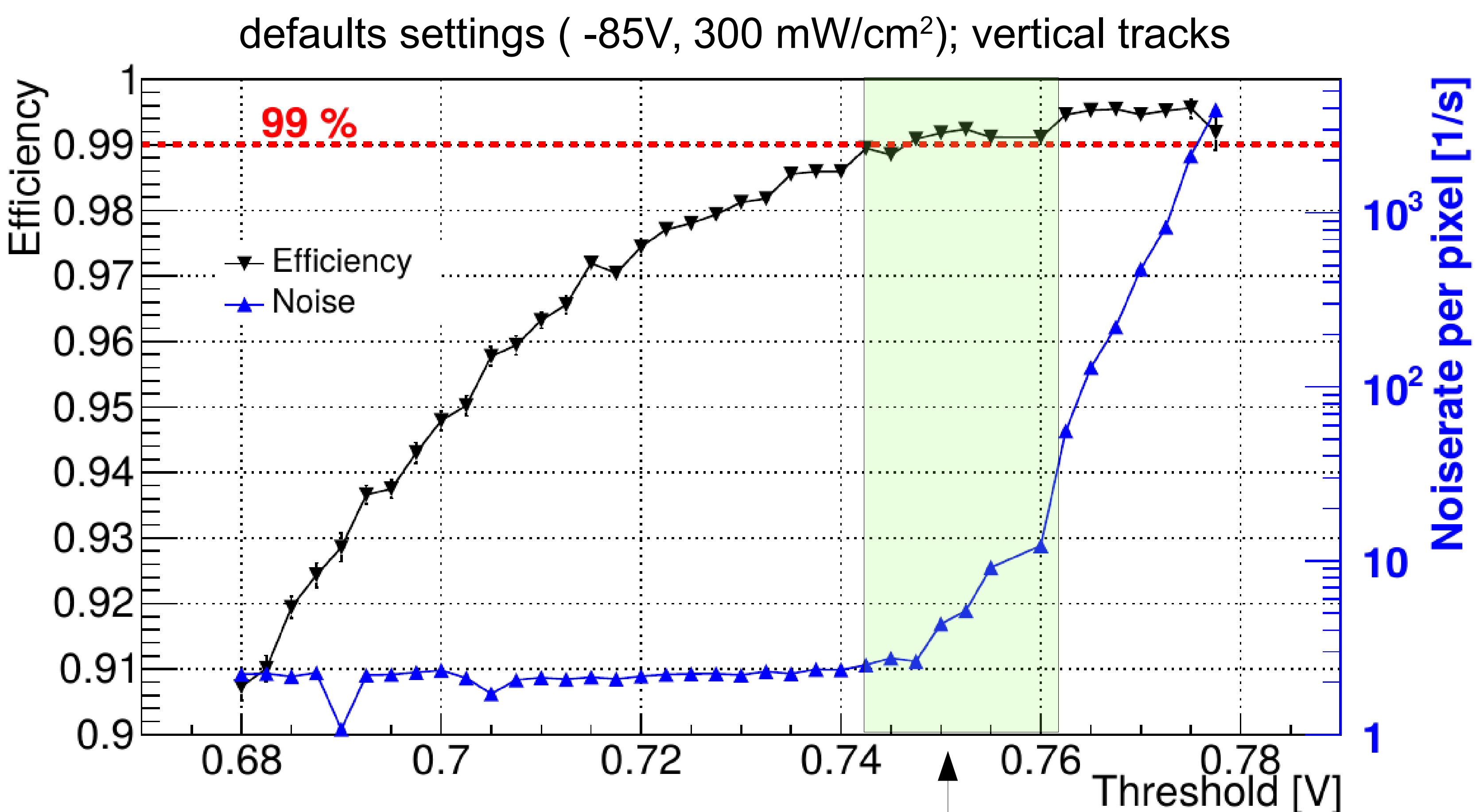


Austria Microsystems (AMS)
HV-CMOS 180 nm

20 Ωcm p-substrate

MuPix7 Efficiency and Noise

Data obtained from PSI beamtest (PiM1) using MuPix telescope

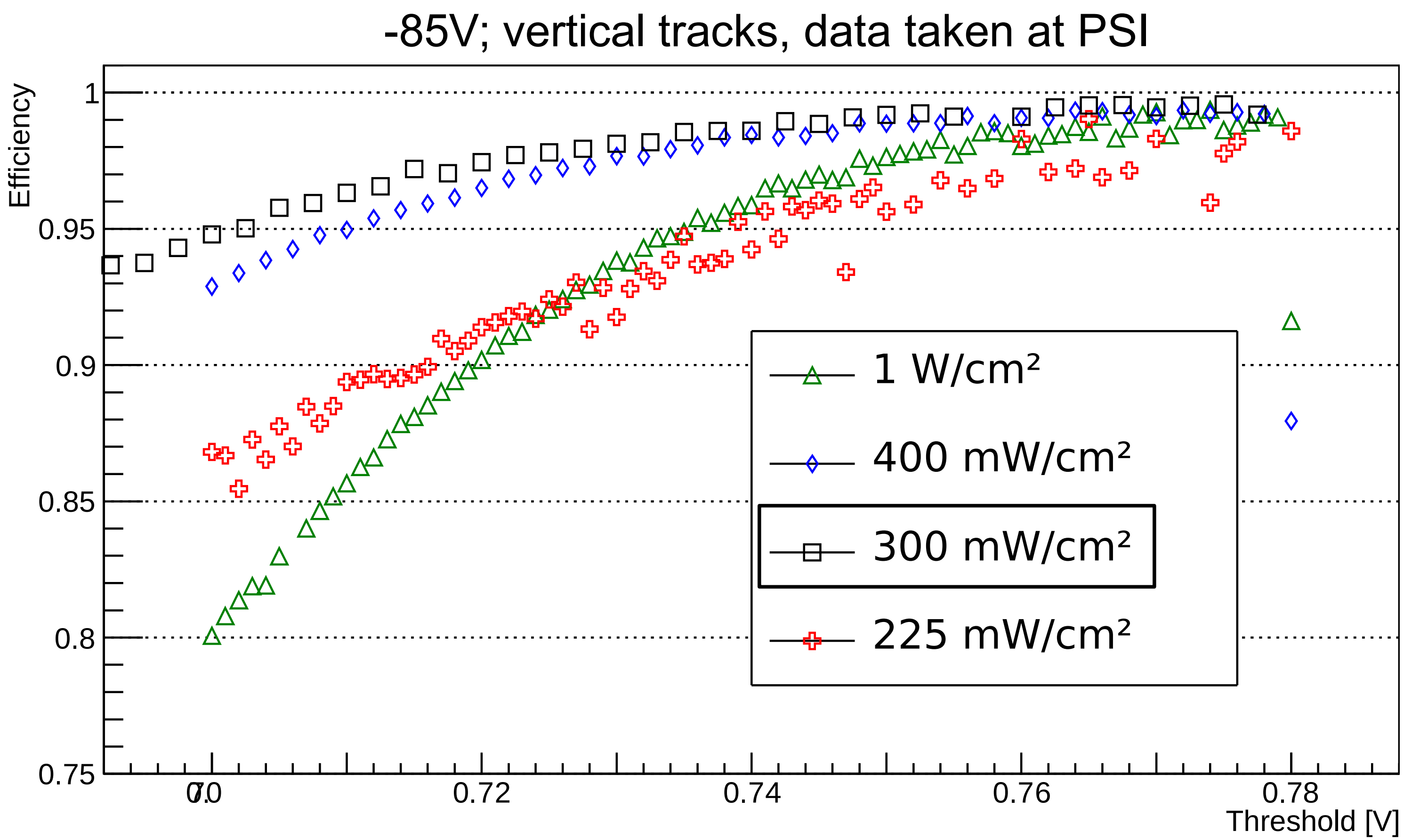


Mu3e noise limit $<10^{-6}$

operation region

MuPix7 Operation Parameters

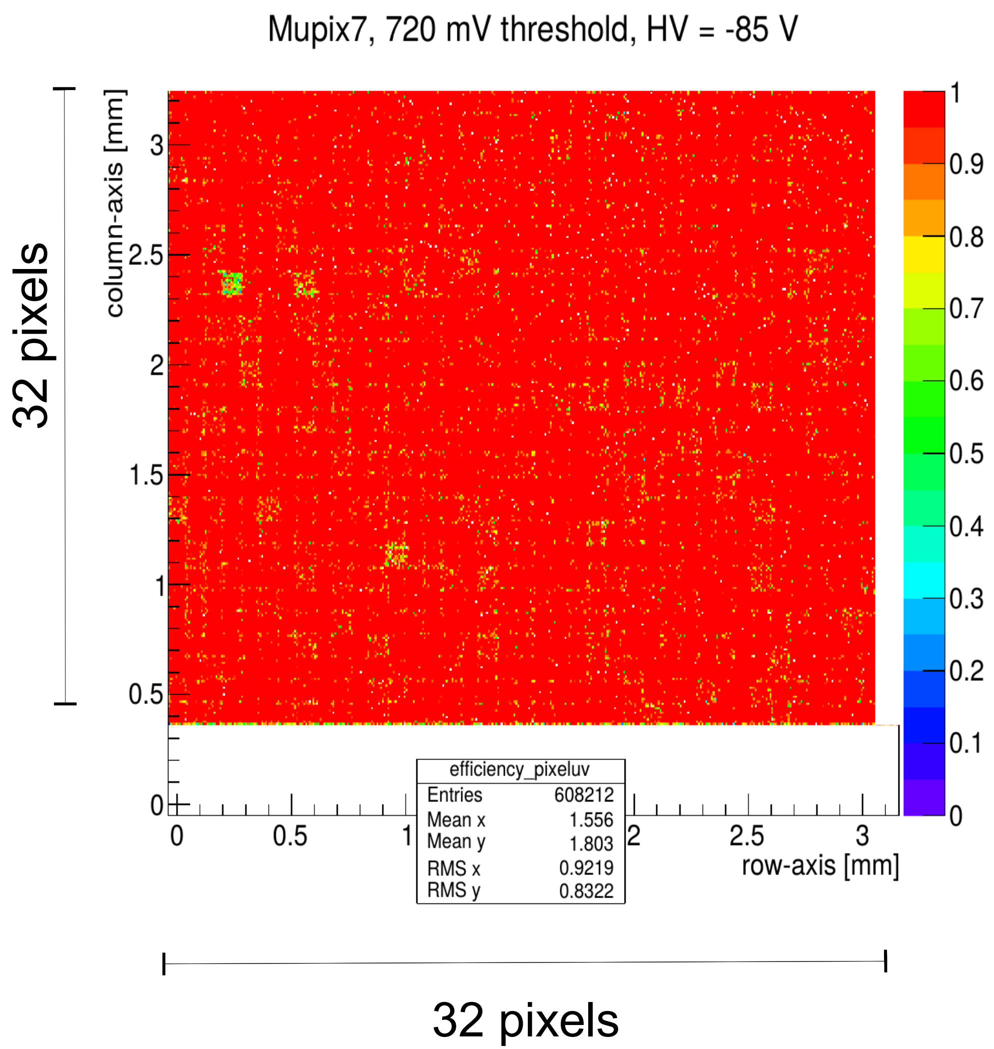
Operation point defined by 13 DAC settings → scan



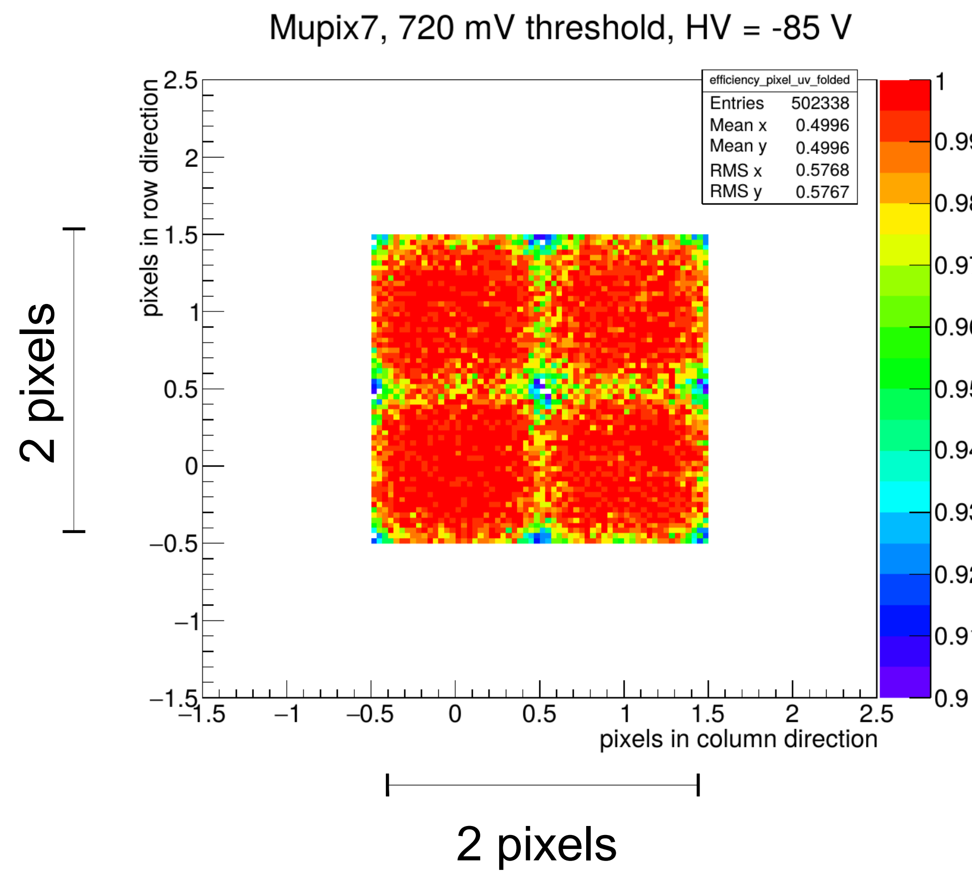
more power does not improve performance

MuPix7 (In-)Efficiency Investigations

Efficiency map with <u>increased</u> threshold



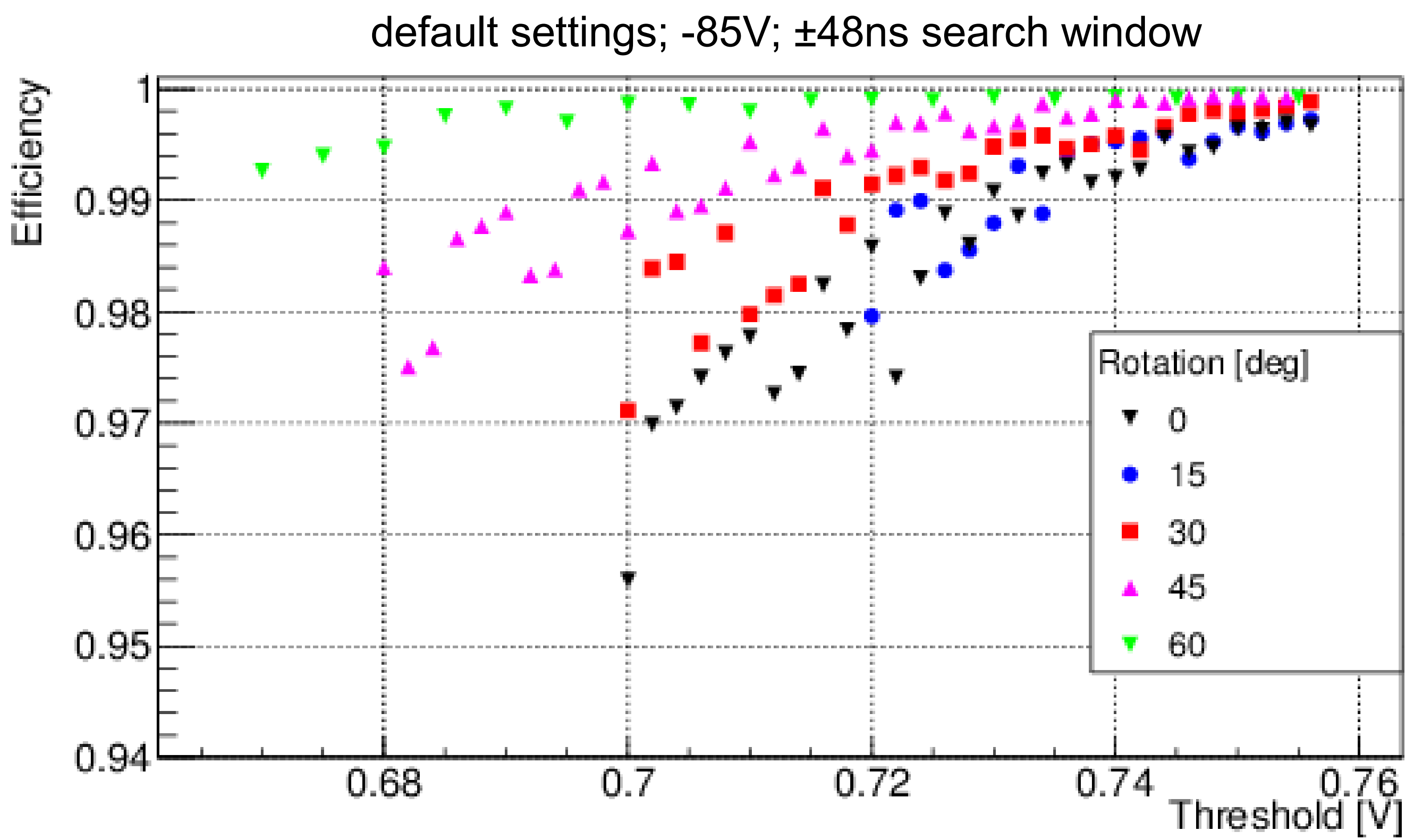
DESY testbeam with EUDET telescope



inefficiency due to charge sharing at edges and corners

Efficiency with Rotated Sensors

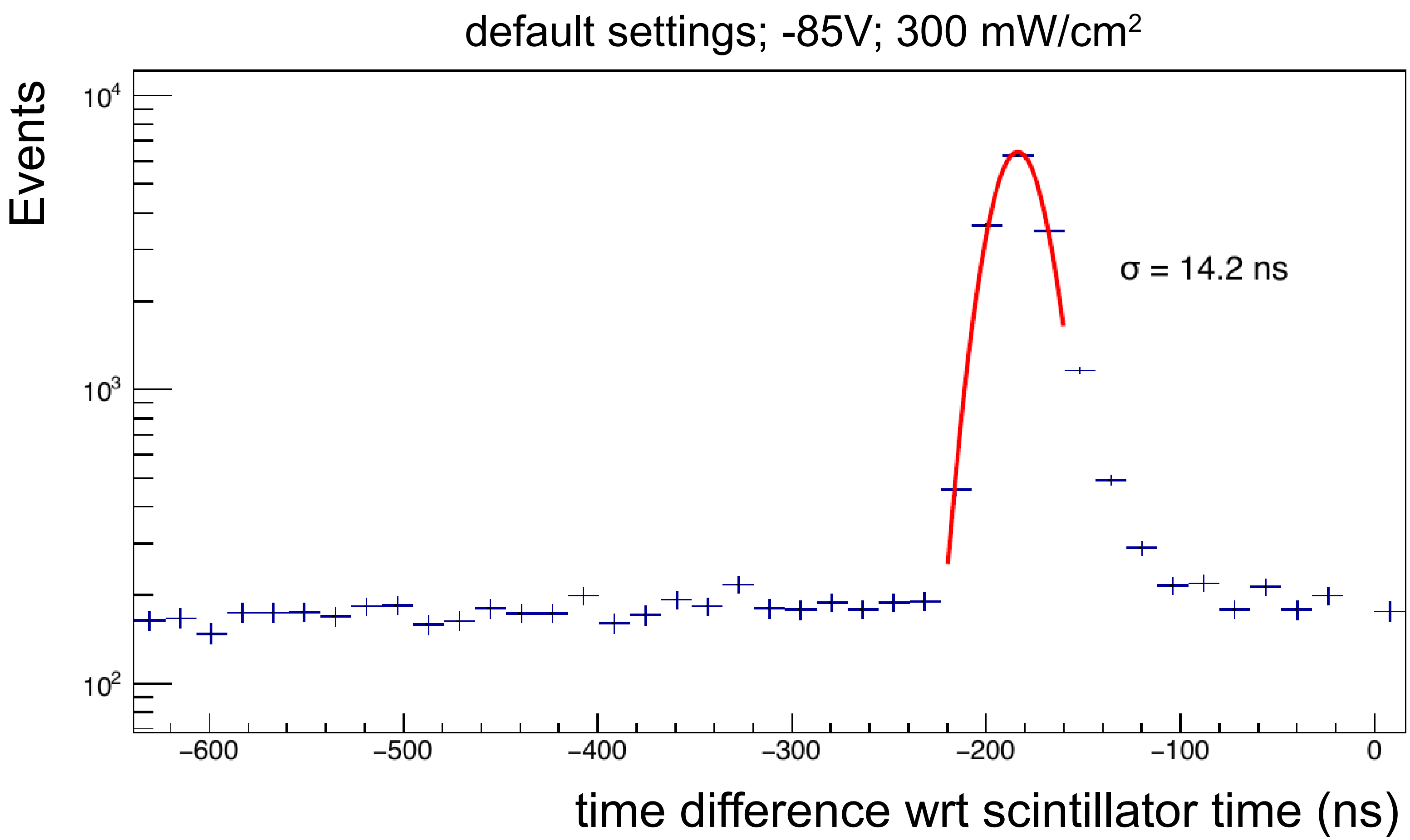
Increase deposited ionisation charge by using tilted sensor



with factor 2 more charge (rot=60°) → 100% efficiency

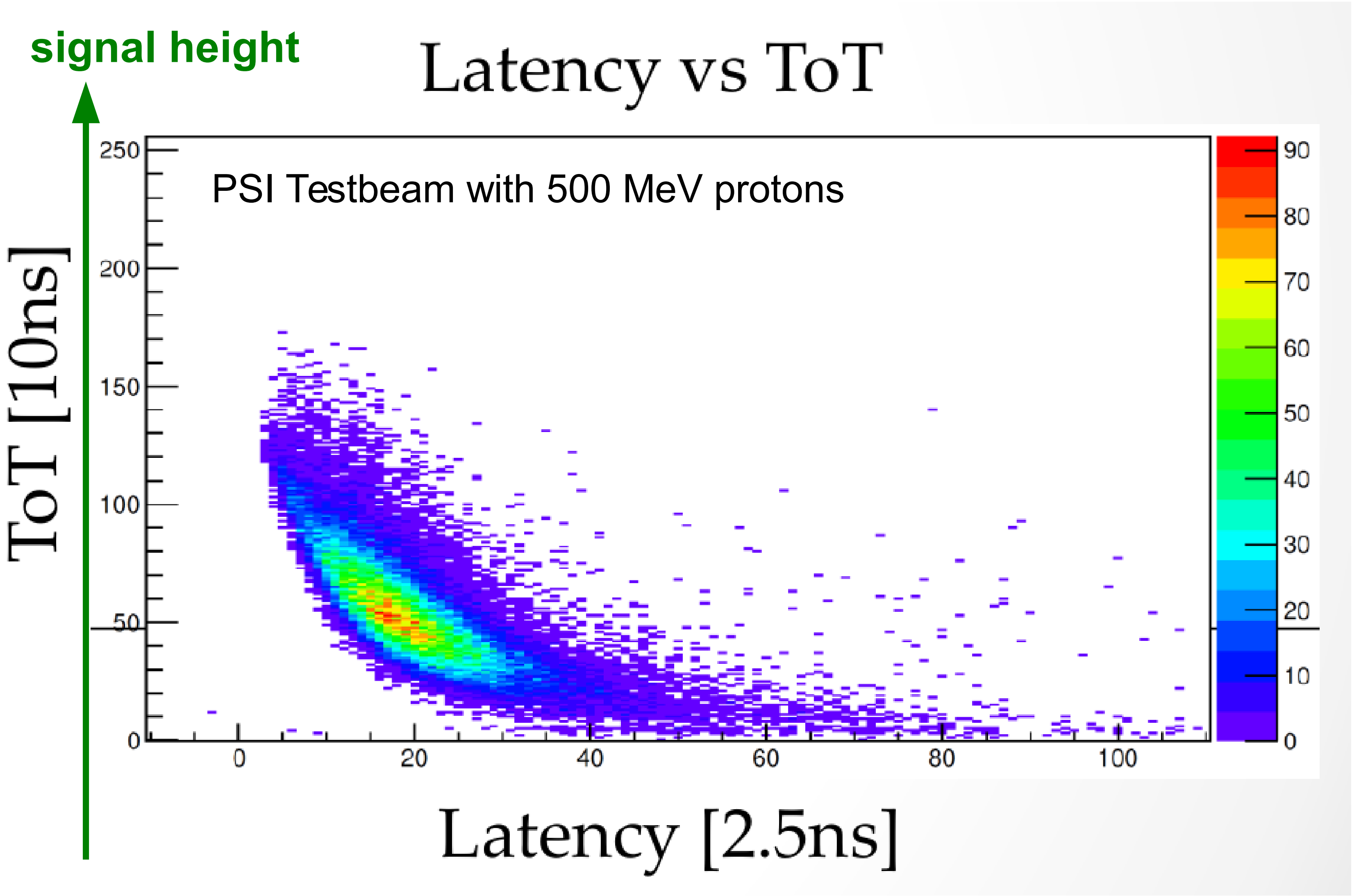
MuPix7 Time Resolution

MuPix telescope with scintillator as time reference:



Mu3e requirement sigma (t) < 20 ns fulfilled

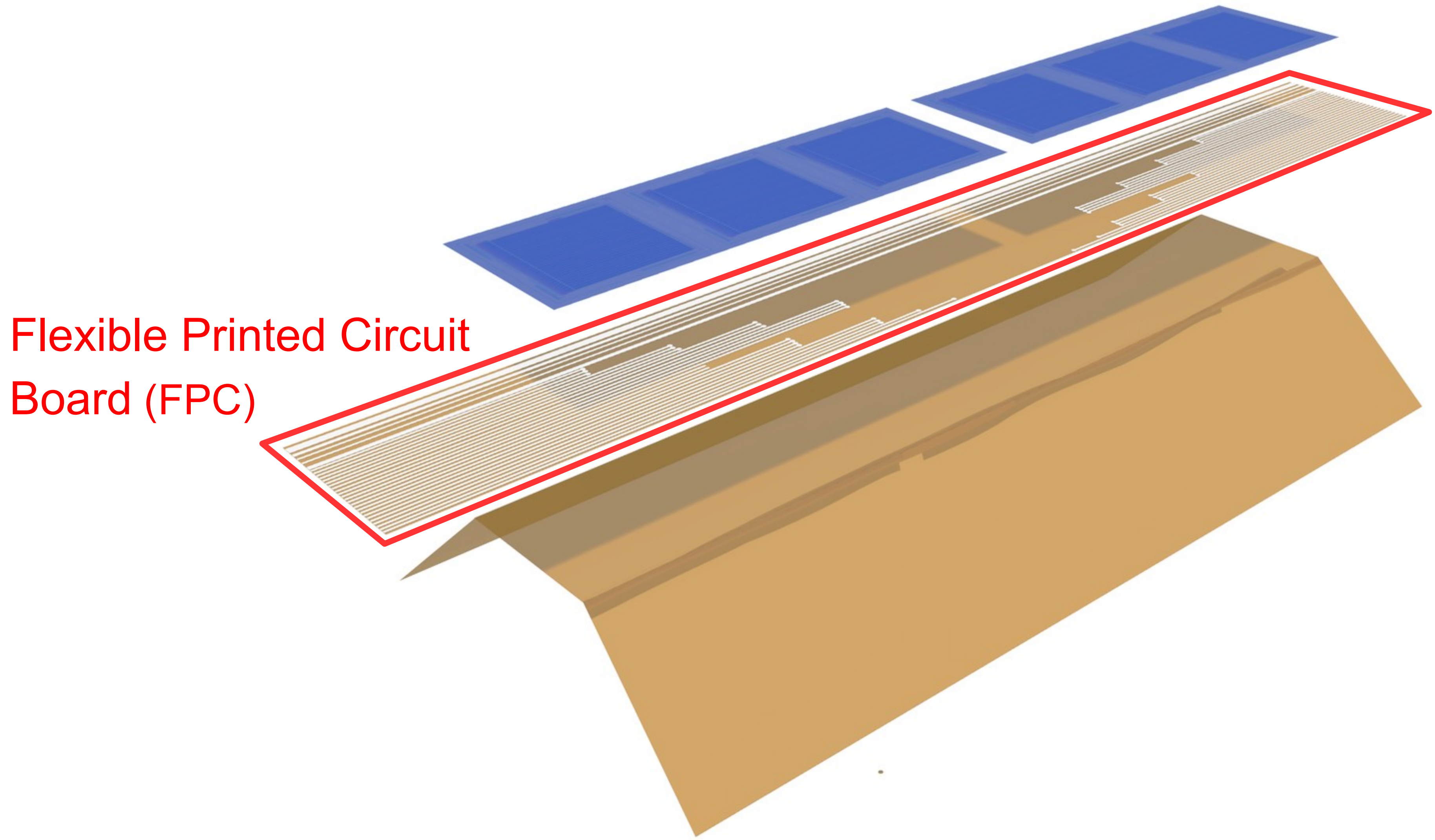
MuPix7 Time Resolution



→ timewalk correction possible

→ in test chips sigma(t) ~ 5 ns achieved (I. Peric et al. KIT)

Mu3e Flexprint



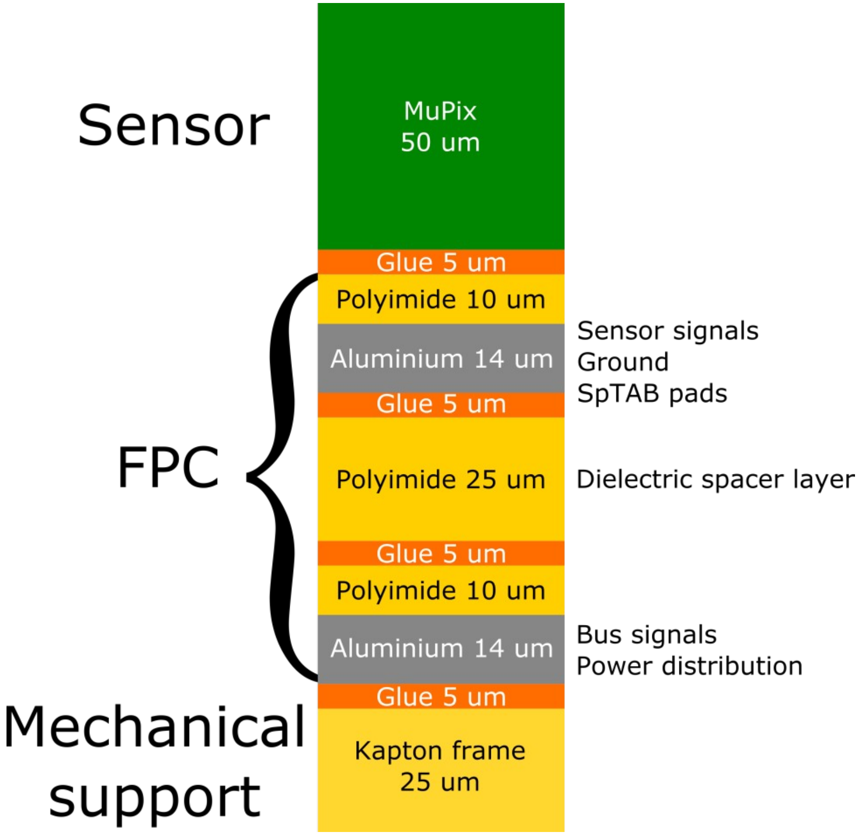
Mu3e Flexprint

Two layer aluminium (LTU Ltd.)

- 14μm Al + 10μm polyimide per layer
- Structure sizes ≥ 65μm
- Dielectric spacing 45μm

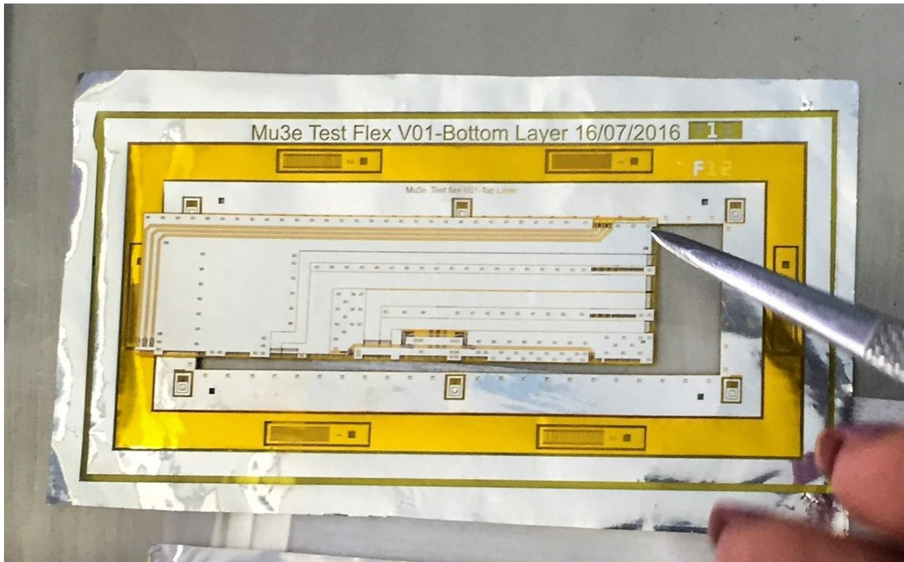
SpTAB technology

- Single point Tape Automated Bonding
- No additional (high Z) material for bonding!



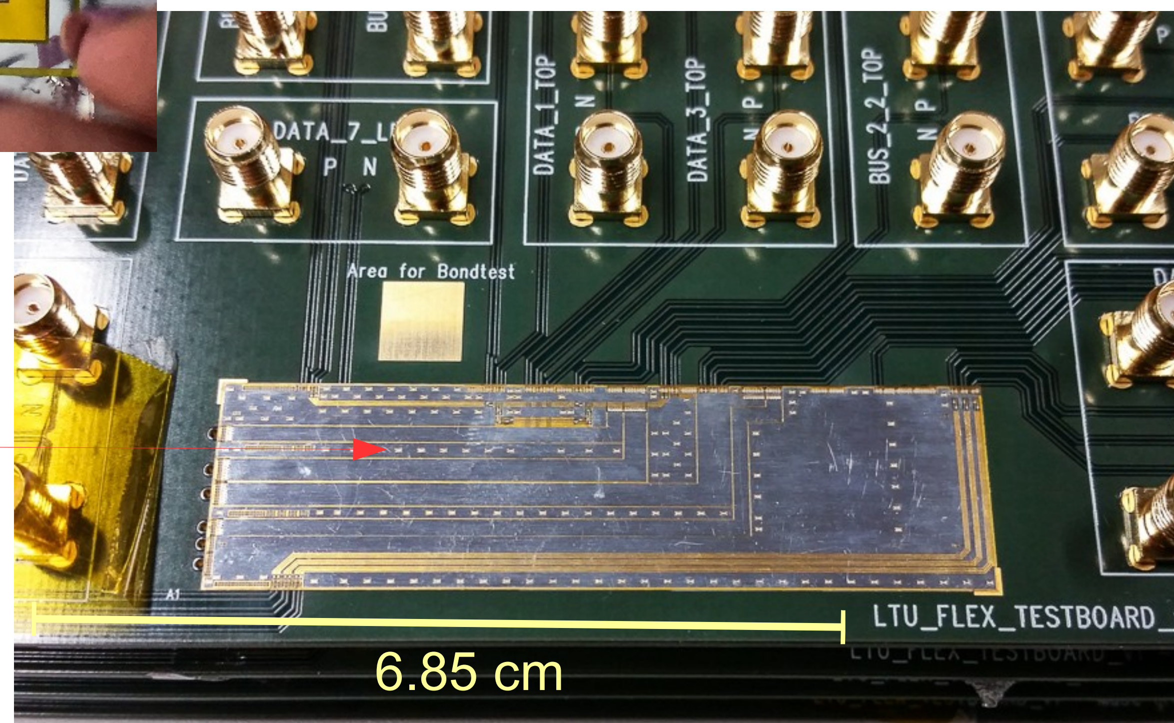
Flexprint Production and Bonding

FPC Production by LTU Ltd



→ bonding yield 100%

FPC SpTAB bonded on test board

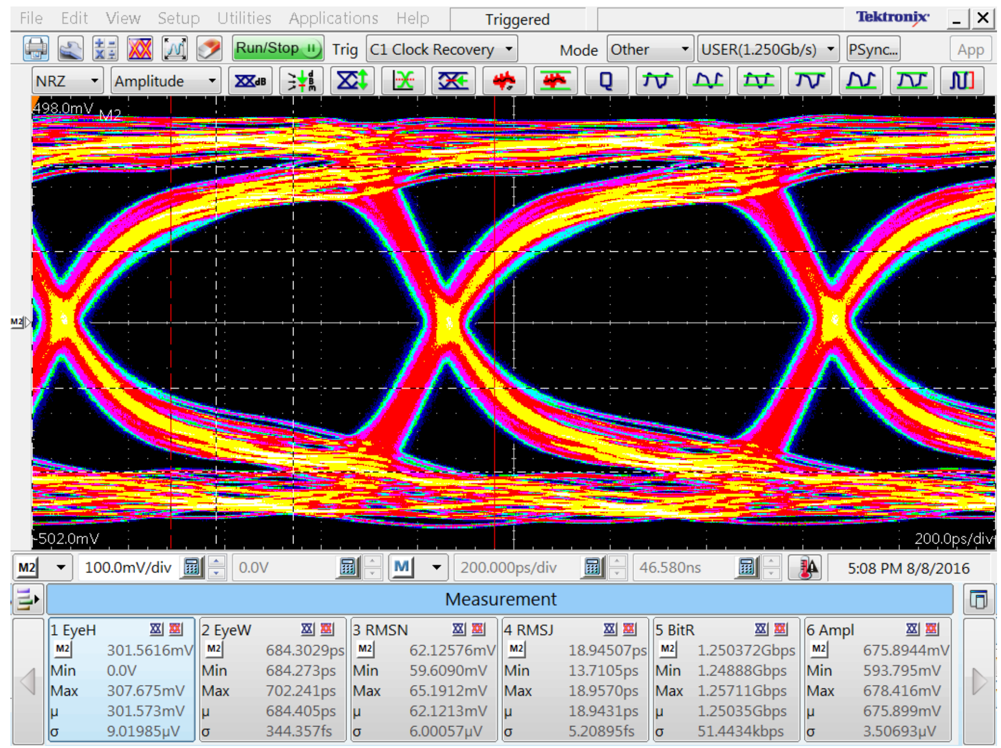


SpTAB bond zoomed in

Flexprint Test Results

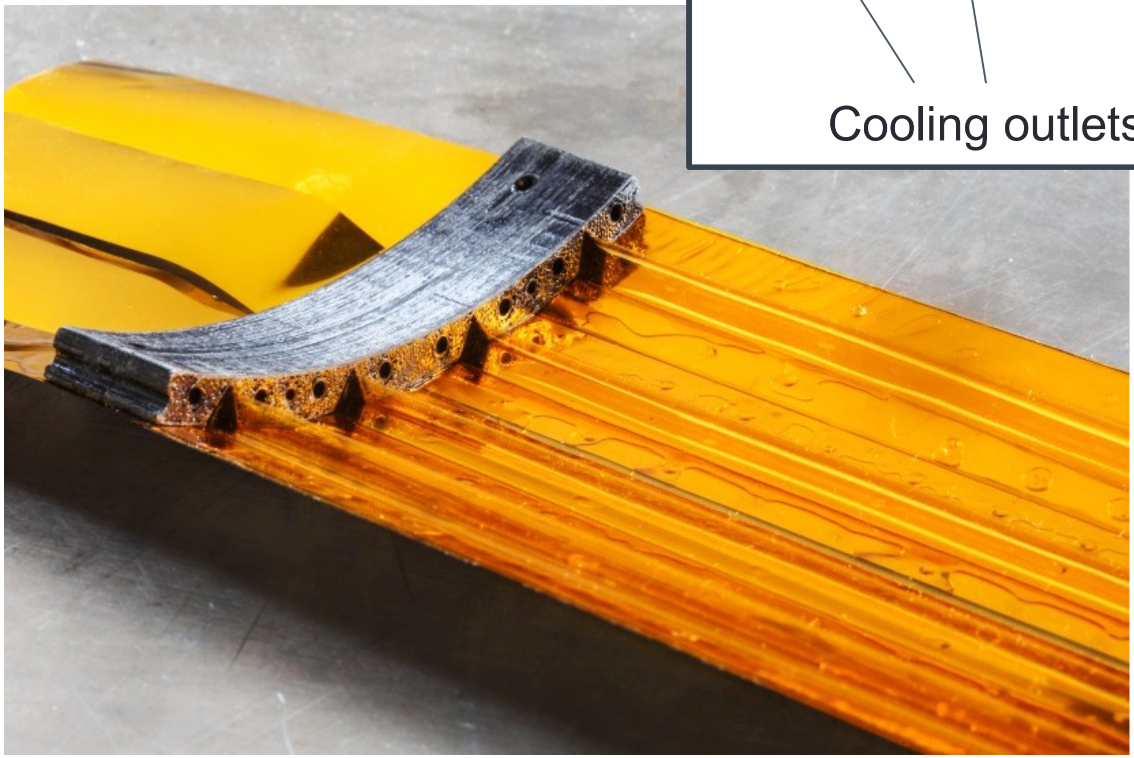
Bit error rate measurements

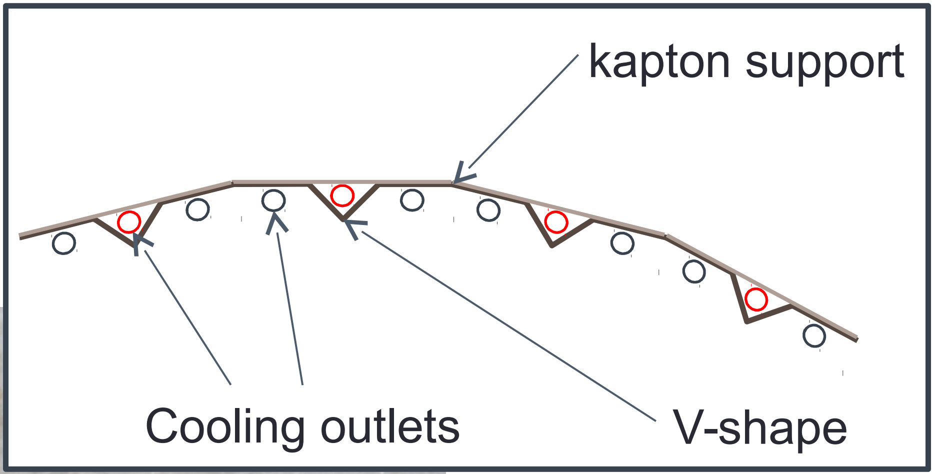
- 10 differential pairs
- No bit errors at 1.25 Gbit/s
  - ➔ BER < $2 \cdot 10^{-13}$ per pair
- No bit errors at 2.5 Gbit/s
  - ➔ BER < $3 \cdot 10^{-13}$ per pair



Mu3e Helium Gas Cooling Concept

V-shapes for local cooling channels



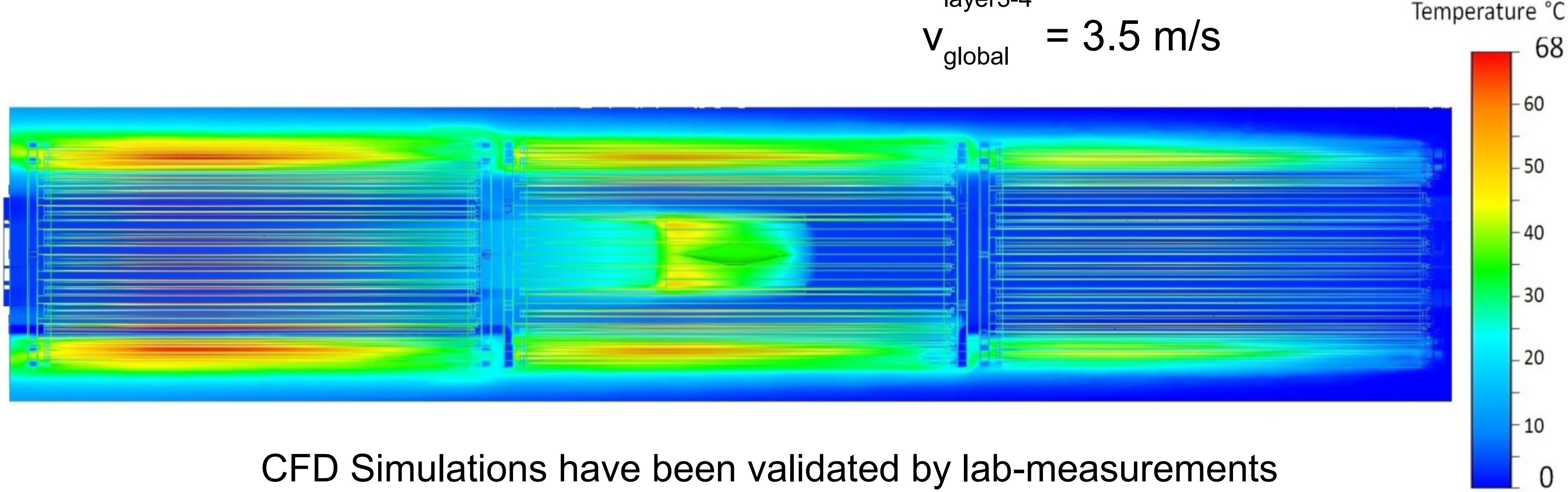


Helium cooling:
- global flow
- flow between layers
- flow in V-shapes

Mu3e Cooling Simulation

Helium input temperature T=0°C

v_{local} = 16 m/s (V-folds)
$v_{layer1-2}$ = 4 m/s
$v_{layer3-4}$ = 3.5 m/s
v_{global} = 3.5 m/s

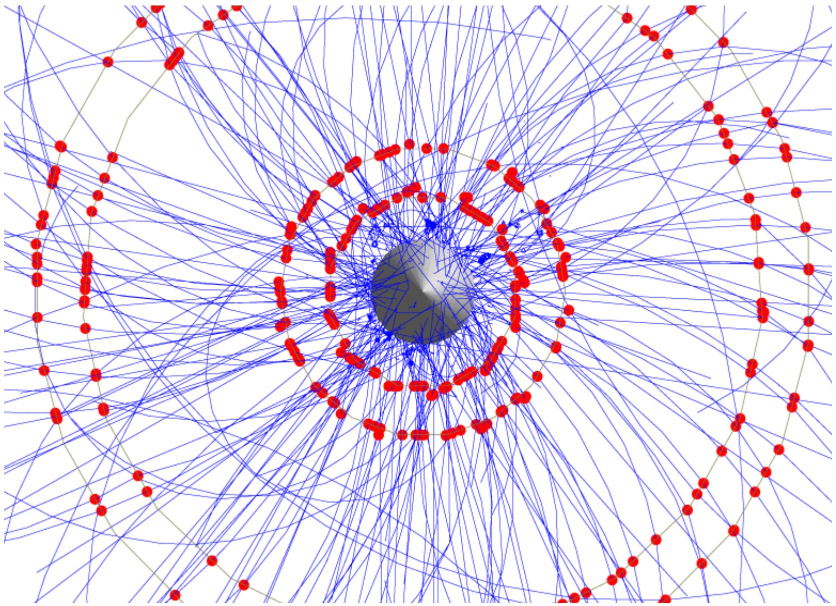


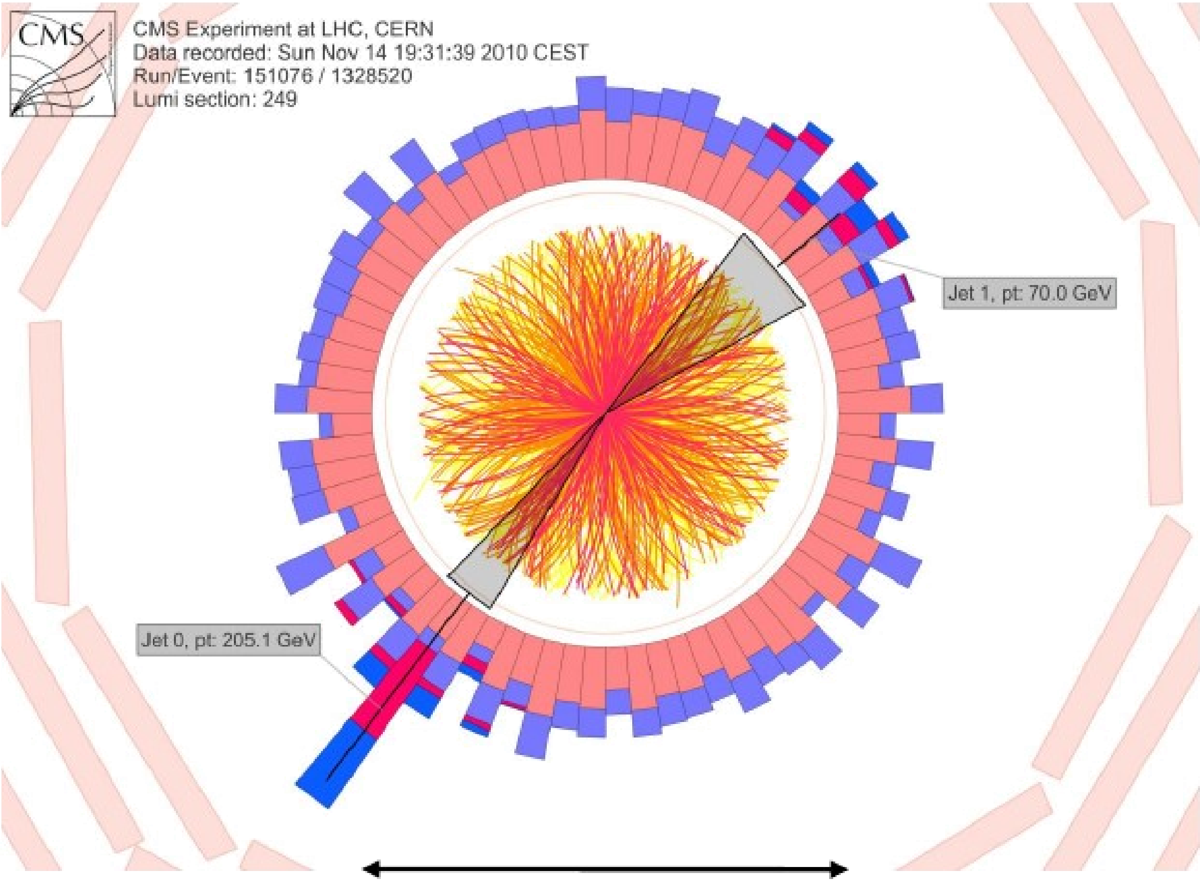
CFD Simulations have been validated by lab-measurements

- Target power consumption ($P=250\ mW/cm^2$) seems feasible
- Maximum power consumption ($P=400\ mW/cm^2$) requires higher flow velocities

Mu3e Readout

Mu3e reconstructed tracks

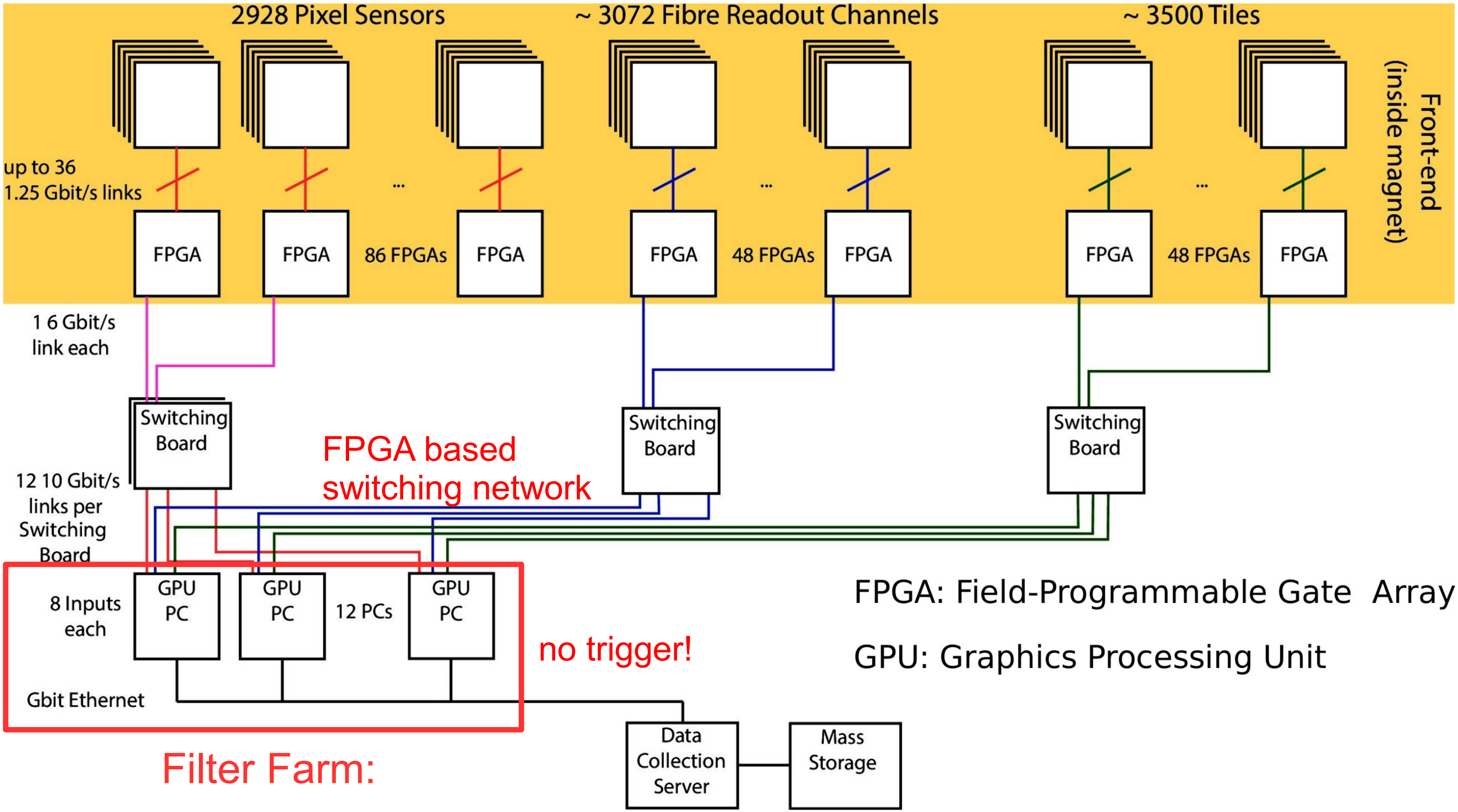




≈16 cm
Readout in frames of 50 ns
E ~ 10-50 MeV

≈2.5 m
Collision every 25 ns
E ~ 200 GeV

Mu3e Readout Concept



FPGA: Field-Programmable Gate Array

GPU: Graphics Processing Unit

Filter Farm:

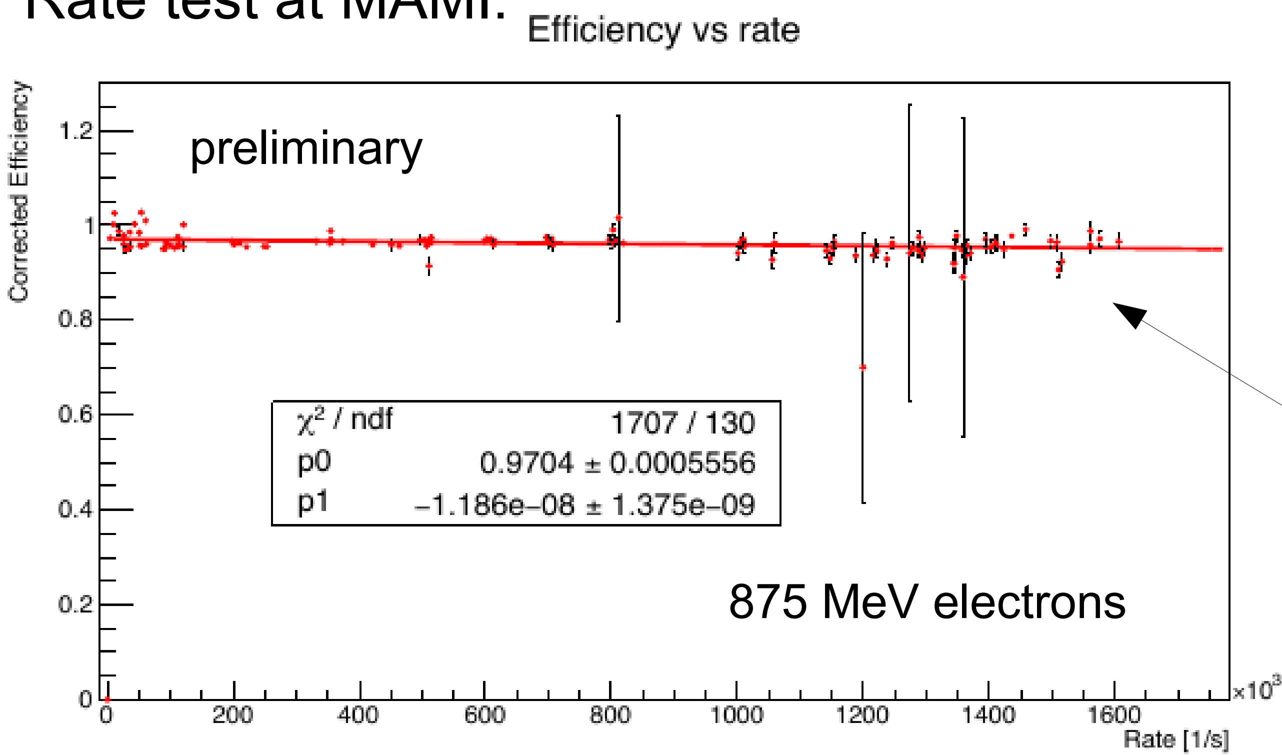
Online track reconstruction using fast algorithm → arXiv:1606.04990

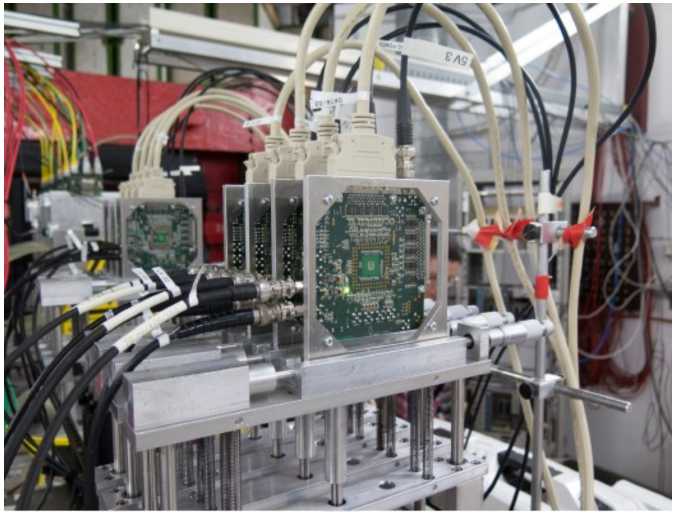
MuPix Telescopes + Rate Tests

Mu3e readout architecture (DMA transfer) implemented in beam telescopes

- one telescope with 8 stations
- two telescopes with 4 stations
- successfully used at CERN, DESY, MAMI, PSI

Rate test at MAMI:





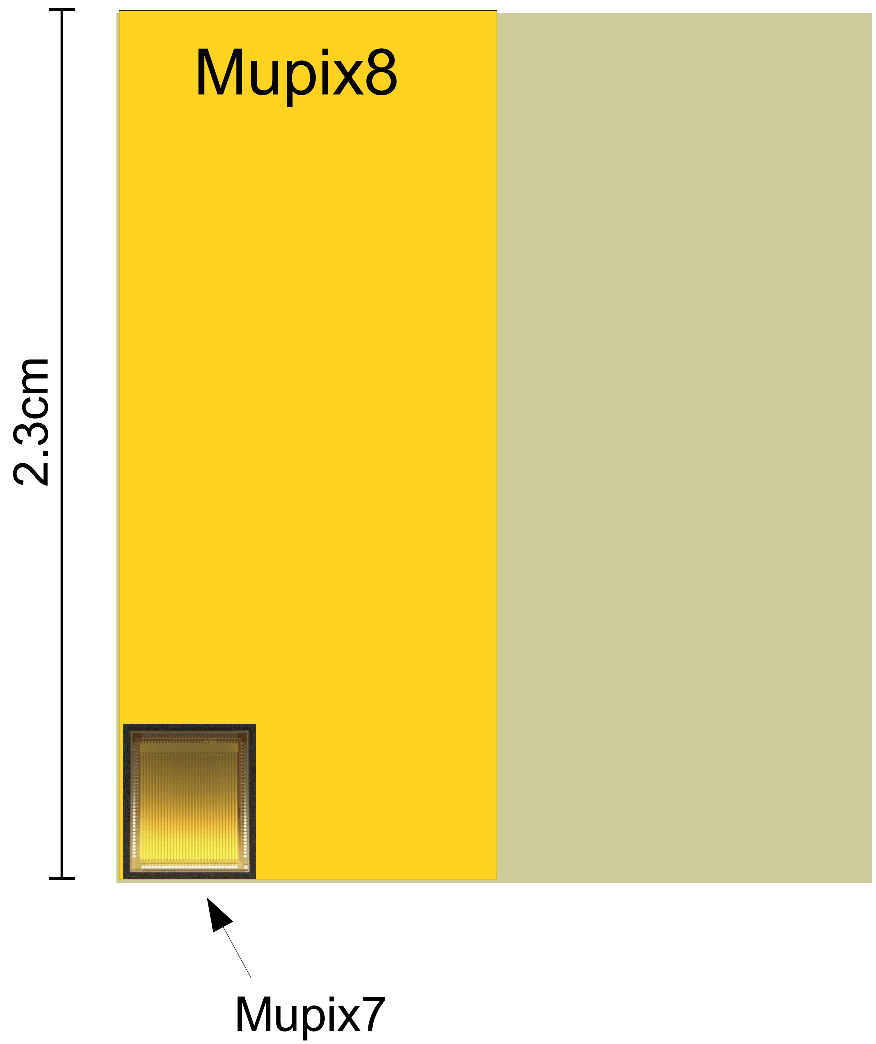
MAMI rate test

- **875 MeV e⁻**
- maximum rate rate of **1.6 MHz / 5x5 pixels**
- corresponds to **780 Mhits/cm²/s**

→ **very small rate dependence of efficiency!**

Outlook

Mupix8 submission in AMS HV 180nm in October 2016
(Heidelberg, Karlsruhe, Liverpool, Mainz)

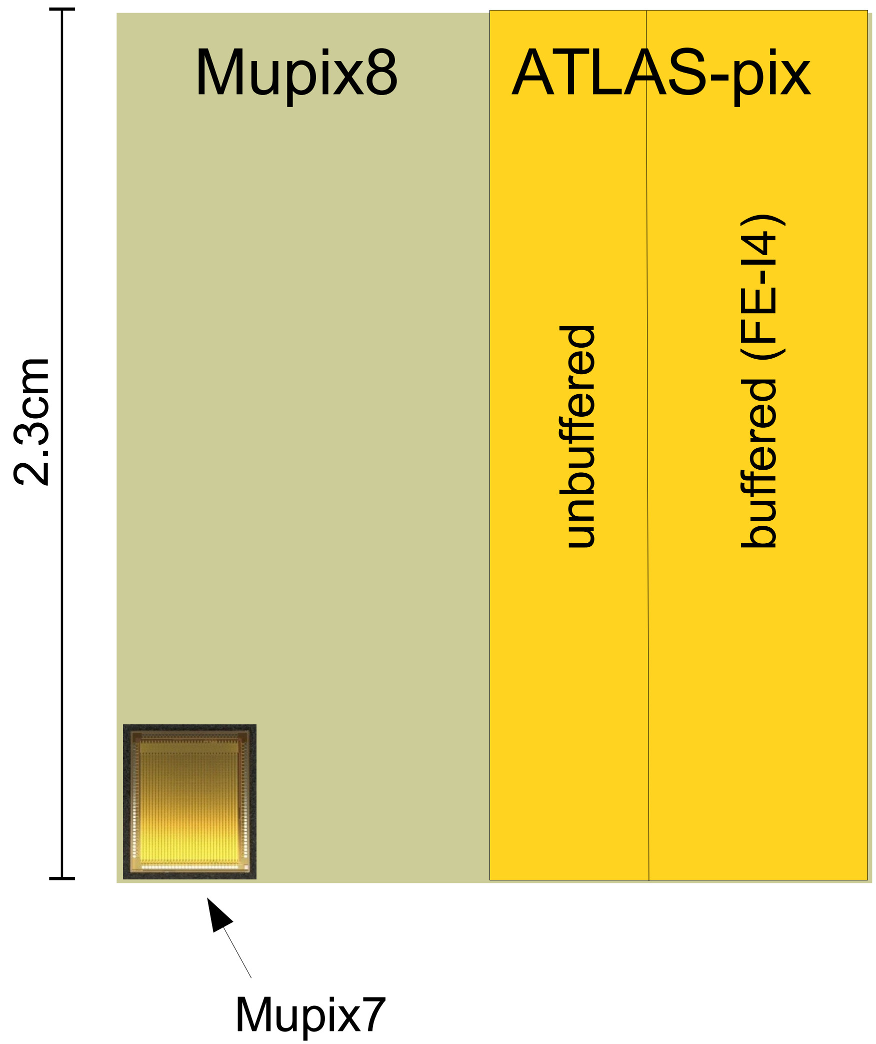


Features and main changes

- 31250 pixel of size 80 x 80 μm^2
- 36 bond-pads per chip (+ extra test pads)
- four serial links a 1.25 Gbps
- two time walk correction schemes
  - → two threshold method
  - → ToT with voltage ramp
- change substrate: 80 Ωcm (before 20 Ωcm)
  - → larger depletion
- current drivers for transmission lines
- some fixes and changes
  (cross talk, state machine, no 2nd amplifier...)

Outlook

ATLAS-pix submission in AMS HV 180nm in October 2016
(Bern, BNL, CPPM, Geneva, Heidelberg, Karlsruhe, Liverpool)



ATLAS-pix Features

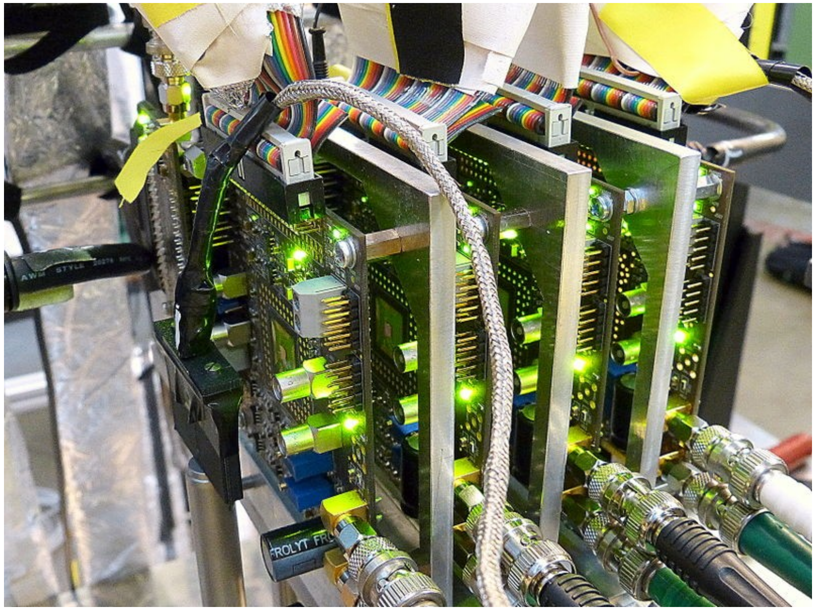
- monolithic design
- one half is unbuffered similar to MuPix
  - → allows for 40 MHz track trigger!
- → the other half with FE-I4 RO architecture
- digital cells (comparator in cell)
- Different substrates/process (std. 20 Ωcm):
  - → 80 Ωcm
  - → 200 Ωcm
  - → 200 Ωcm with deep P-well

AMS HV process is rather **radiation hard**
→ see talk be Fabian Huegging

Mu3e Experimental Status

- Technical Design Report for Phase almost ready
- Detector construction will start in 2017
- Commissioning of the two inner HV-MAPS pixel layers in 2018
- Delivery of solenoid magnet in 2018
- First data (Phase I) earliest in 2019

Mupix beam telecope
in July 2014 at PSI



Summary

Mu3e Pixel tracker with several innovations + challenges

- **recurler geometry**
- **ultralight mass design with 0.1% X_0 per layer**
- **pixel tracker based on HV-CMOS**
- **fast monolithic sensors with continuous readout**
- **helium gas cooling**
- **fast readout of all hits**

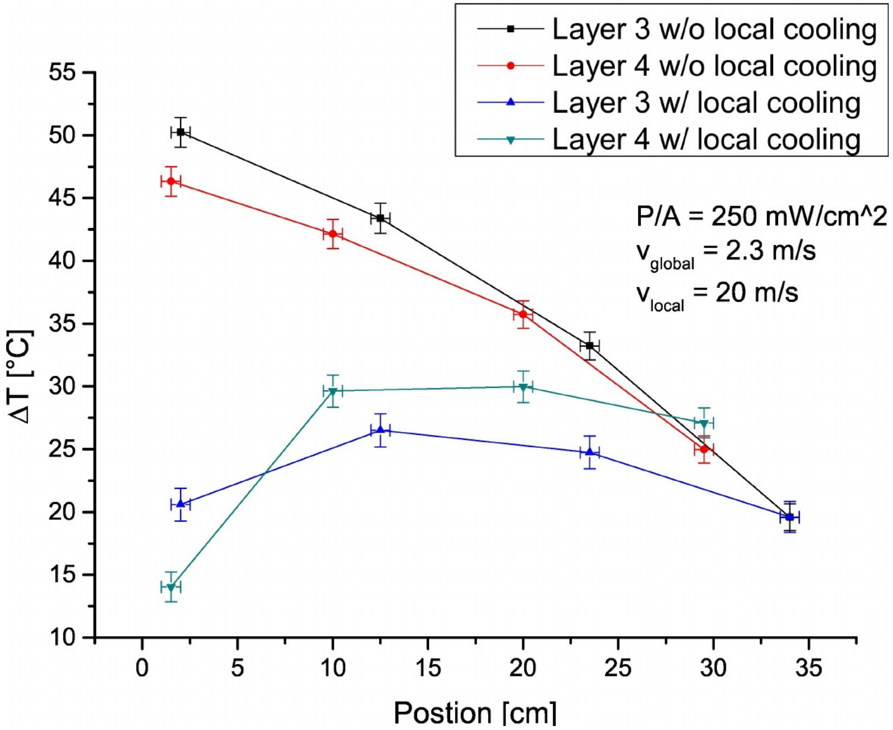
Backup

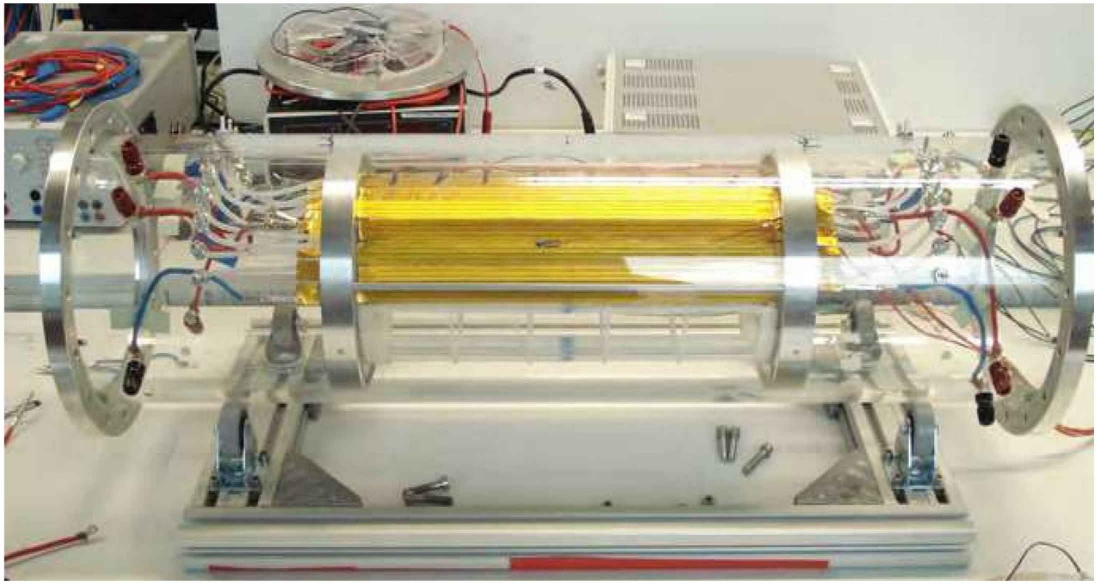
Mu3e Collaboration

- DPNC Geneva University
- Physics Institute, University Heidelberg
- Kirchhoff Institute, University Heidelberg
- IPE @ KIT, Karlsruhe
- Institute for Nuclear Physics, Mainz
- Paul Scherrer Institute
- Physics Institute, University Zurich
- Institute for Particle Physics, ETH Zurich
- University of Liverpool

Pixel Detector + Helium Gas Cooling

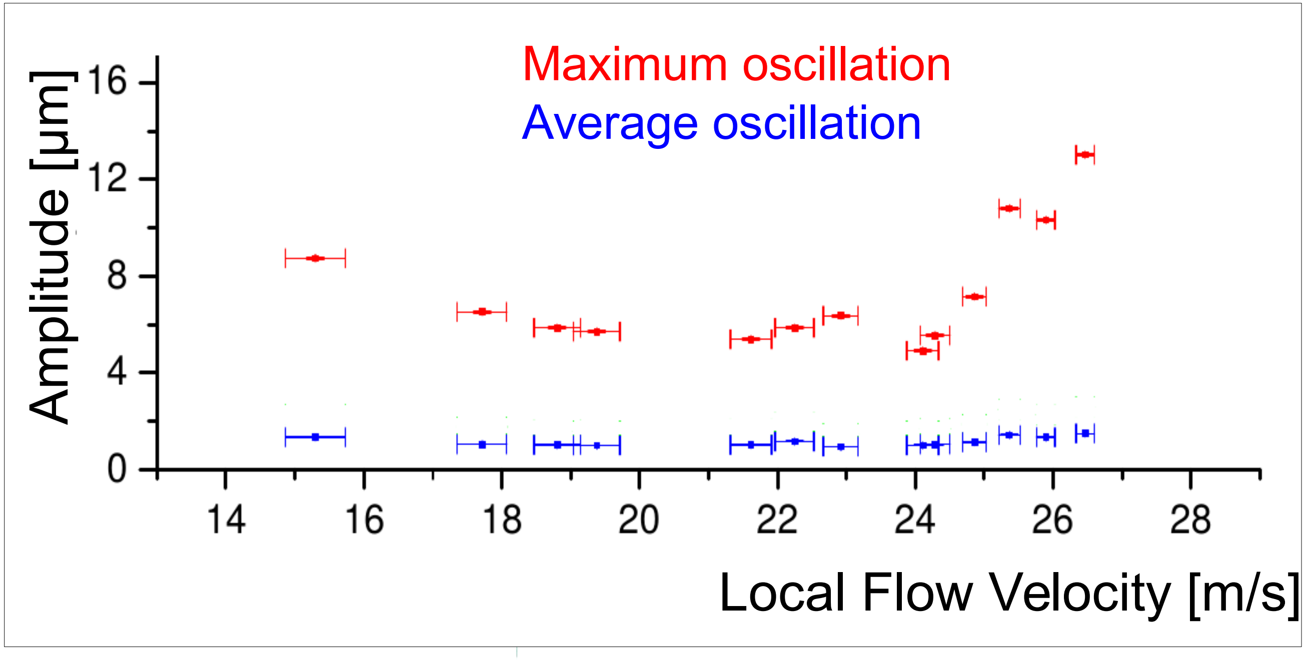
- Heatable module prototypes
- Temperature sensors
- Flow container
- Local and global helium flow

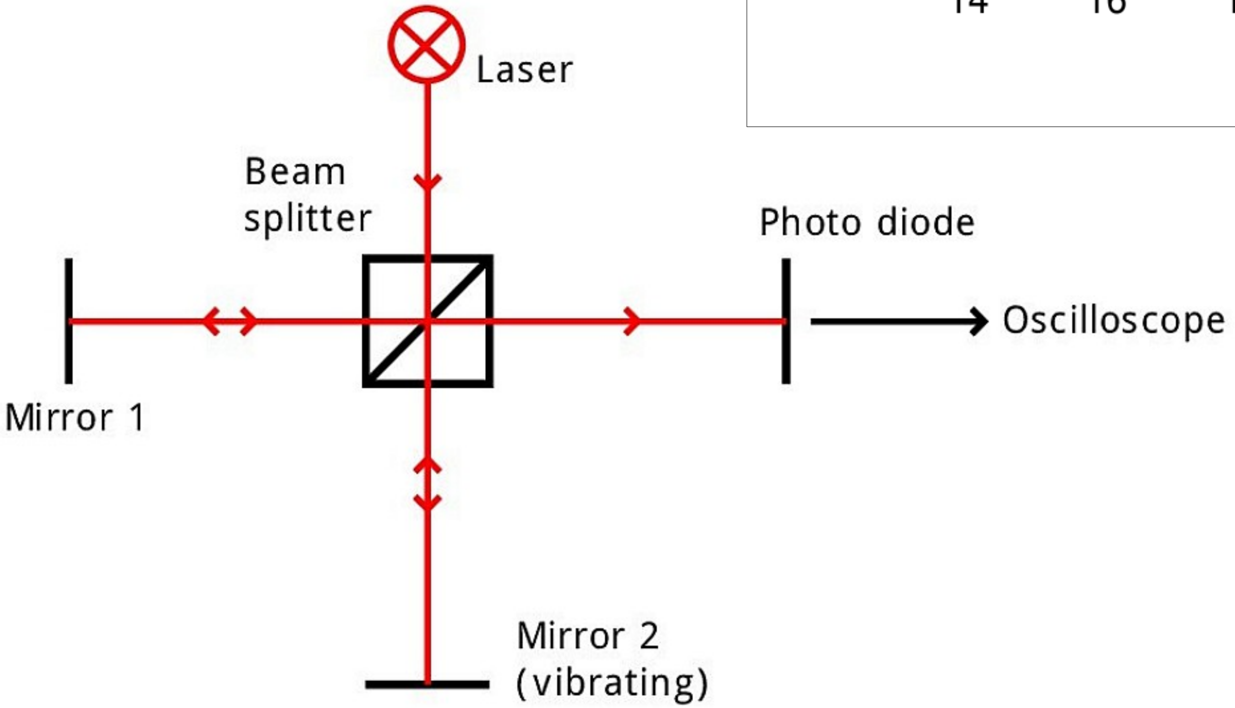




Vibration Measurements

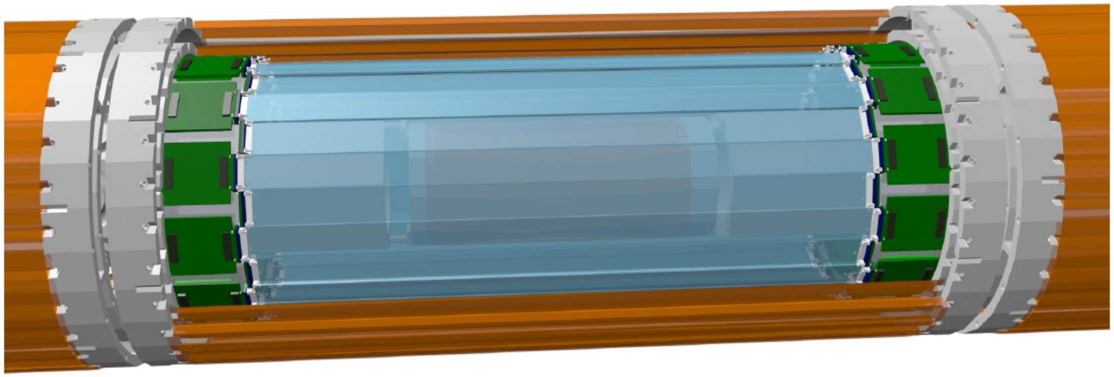
Measurement of flow-induced vibrations with Michelson interferometer

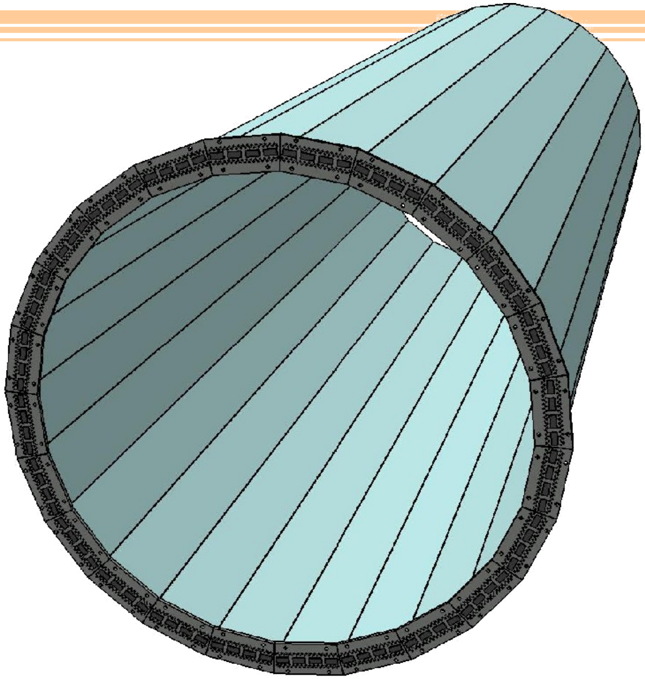




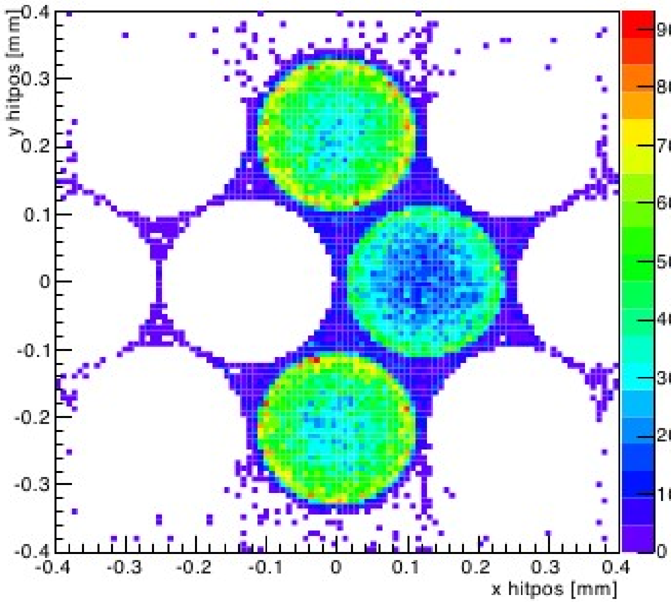
→ **maximum vibrations in tolerable range**

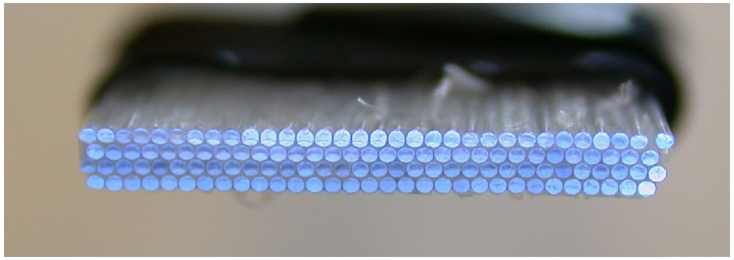
Scintillating Fiber Tracker





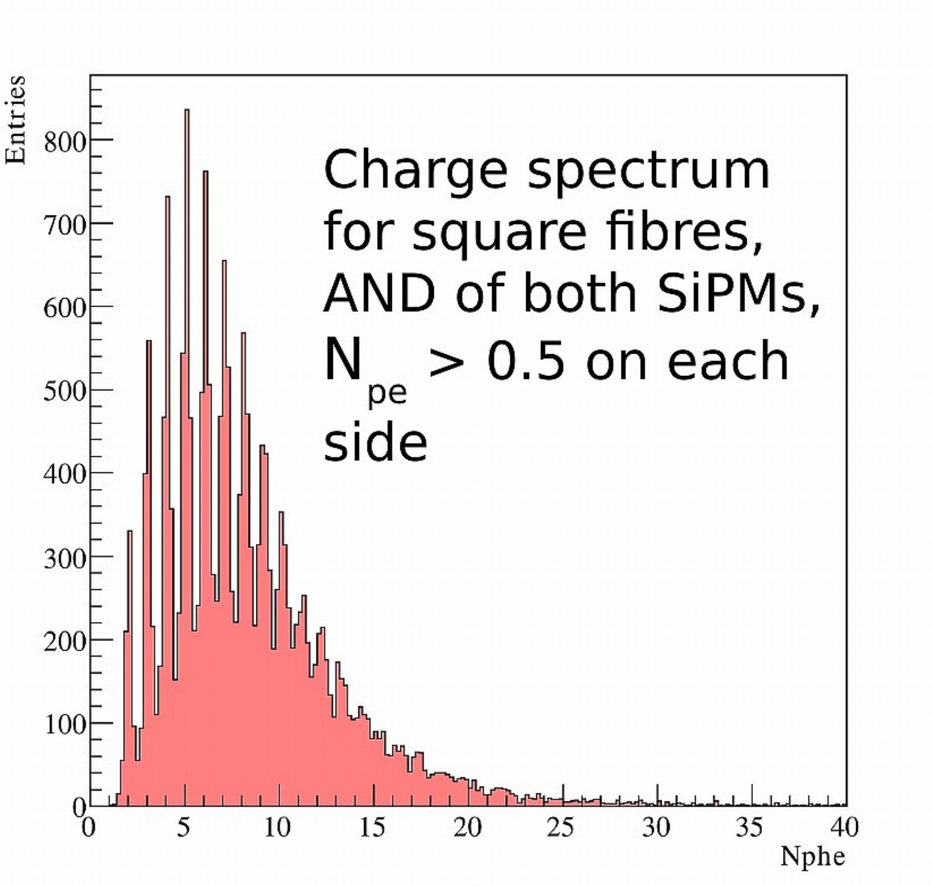
simulation





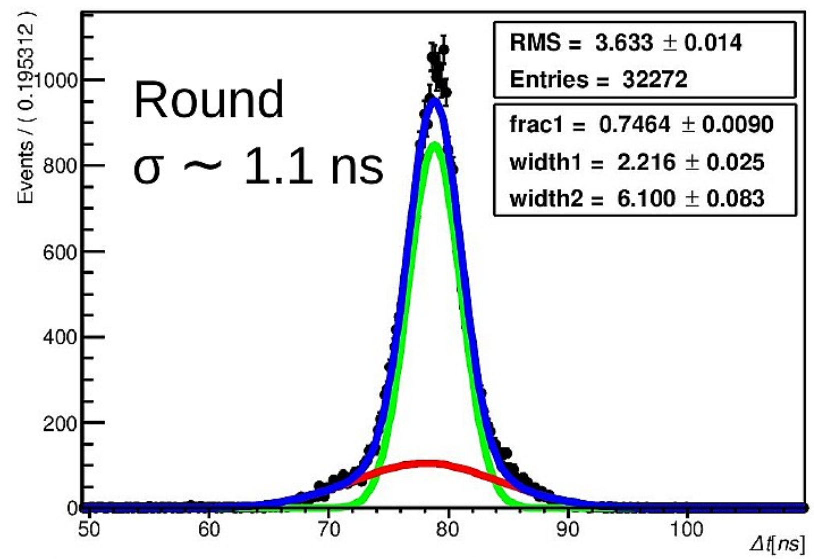
- 2-3 layers of scintillating fibers Ø = 250 µm
  - readout by silicon photomultipliers (SiPMs) and custom ASIC (MuSTic)
  - 100 nm Al coating by evaporation (instead of Ti)

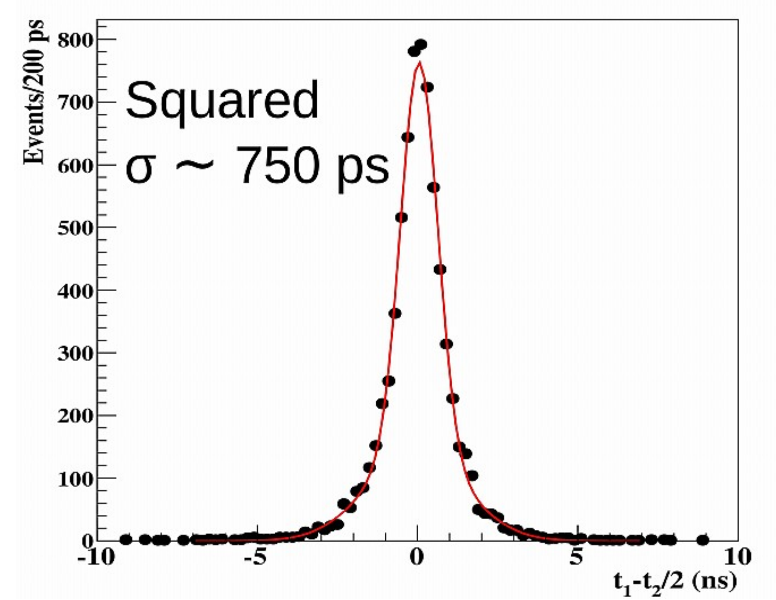
Sci-Fi Results from Prototypes



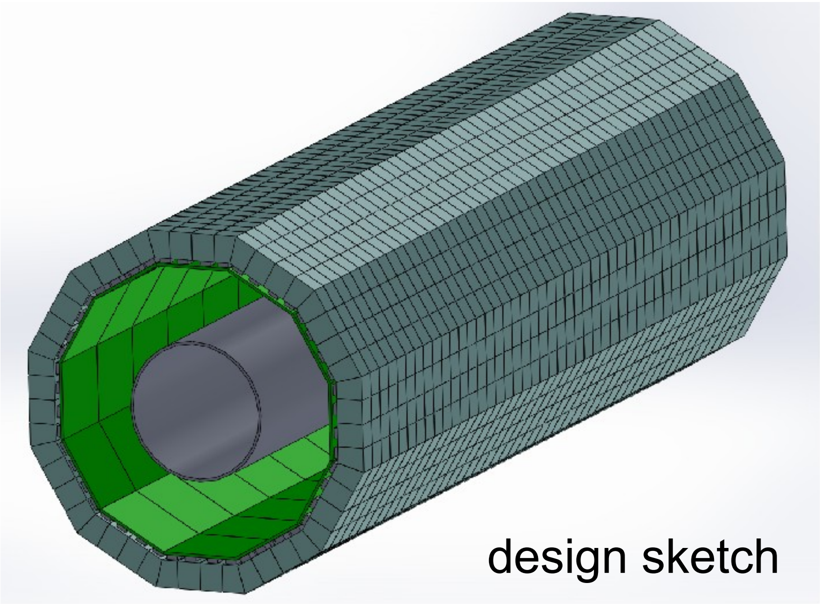
Double layer square fibres, AND configuration, $N_{pe} > 0.5$: 93 % efficiency

Single fiber time resolutions





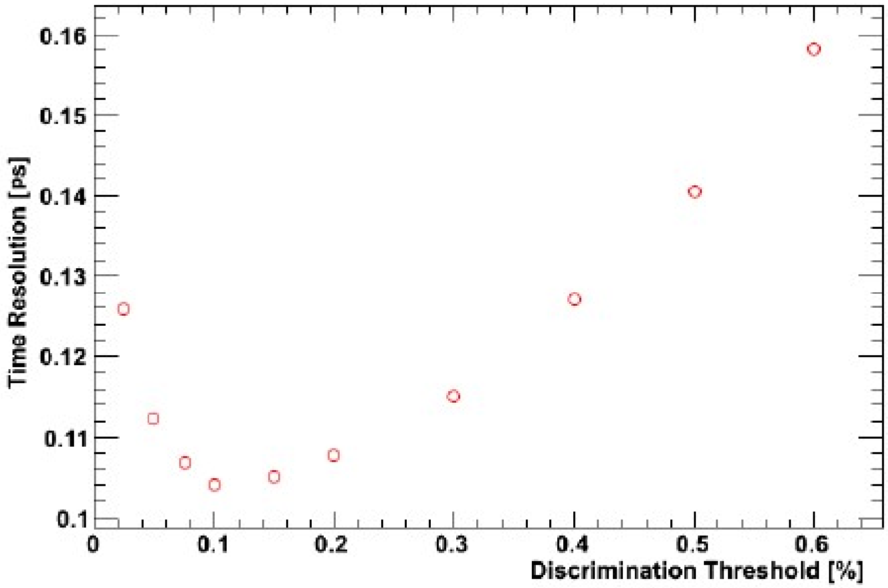
Scintillating Tile Detector



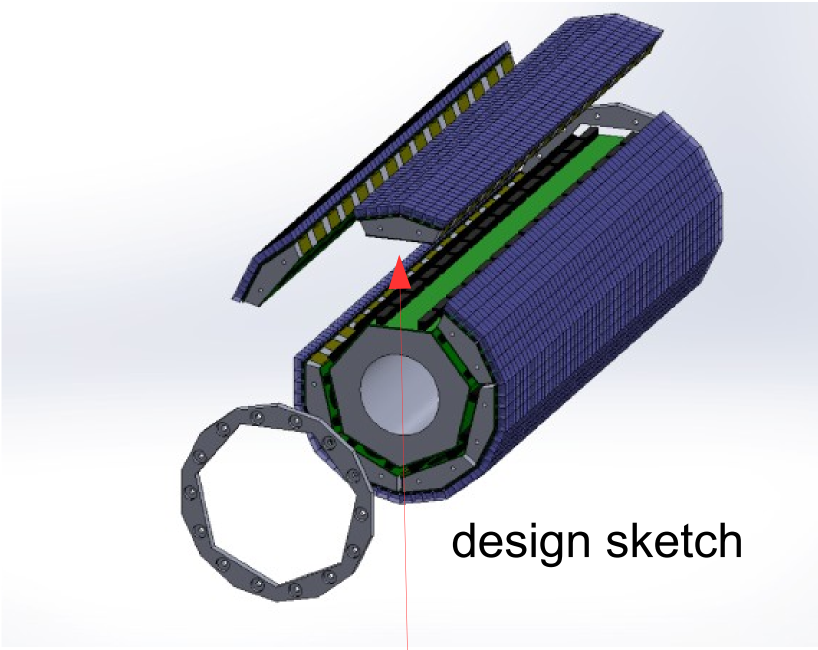
simulated (phase 2)

- scintillating tiles of size ~ 1 cm^2
- timing resolution of about 100 ps
- photosensors (SiPM) read-out by custom ASICs

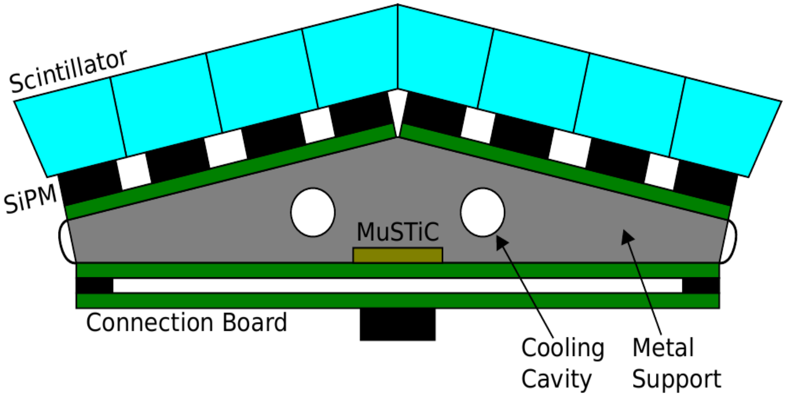
DESY beam test results (March 2013)



Scintillating Tile Detector

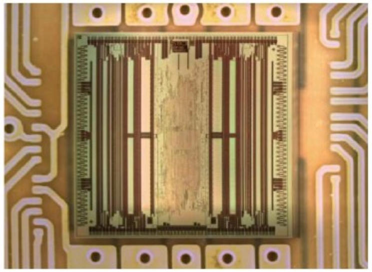


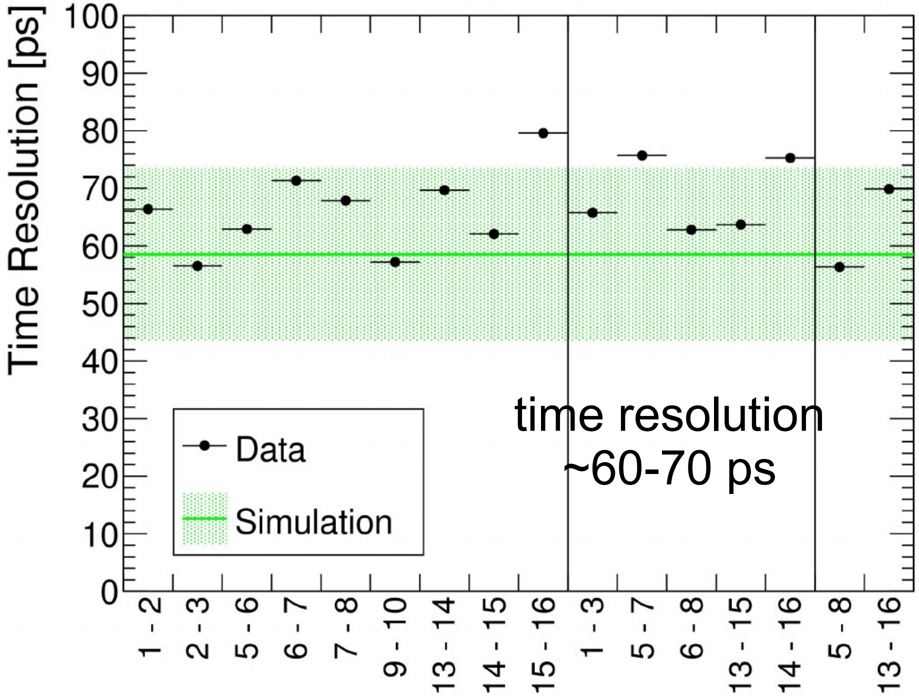
design sketch



- scintillating tiles of size ~ 1 cm^2
- timing resolution of about <100 ps
- photosensors (SiPM) readout by custom-made ASIC:

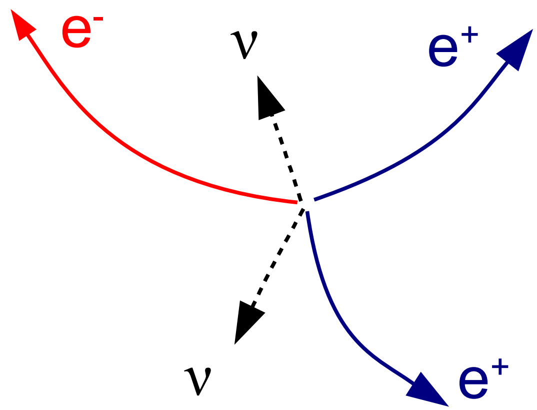
StiC 3.1



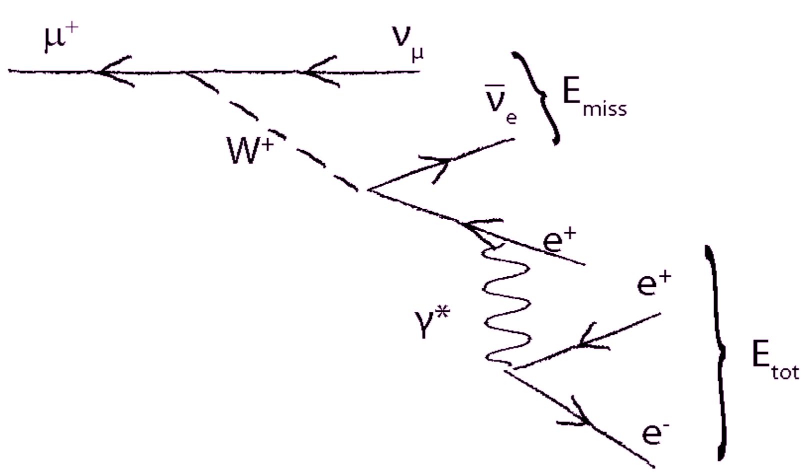


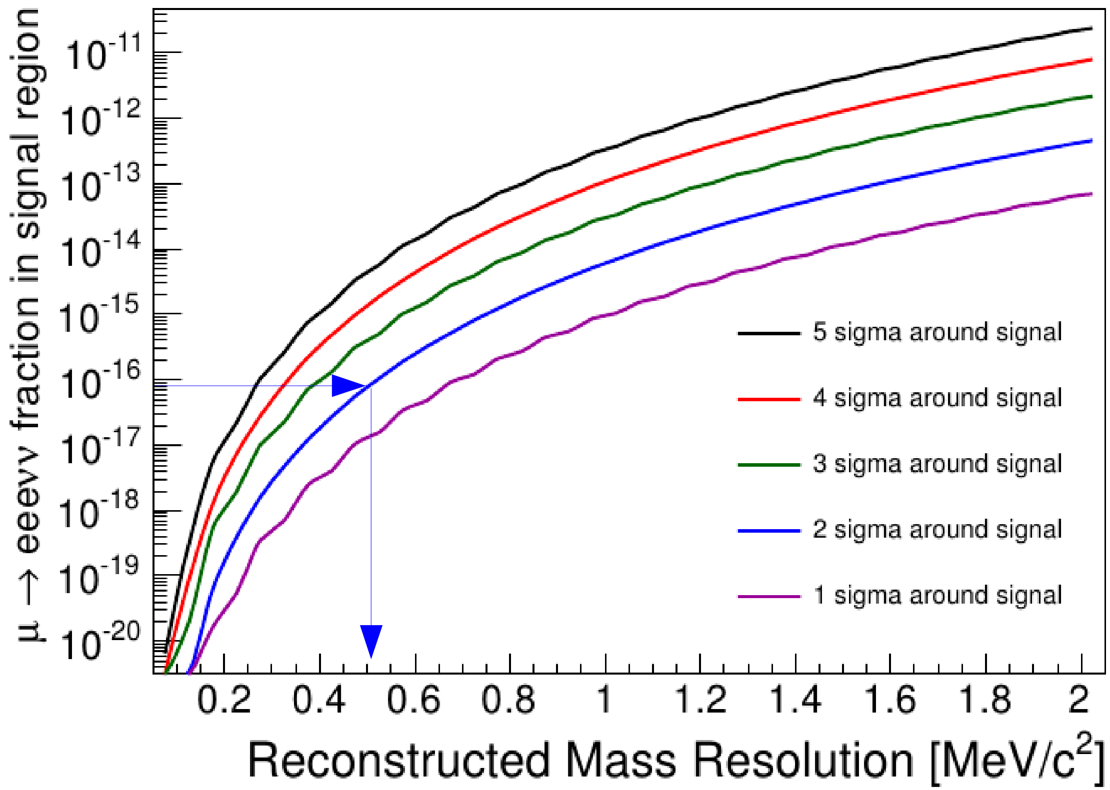
Backgrounds

Irreducible BG: radiative decay with internal conversion



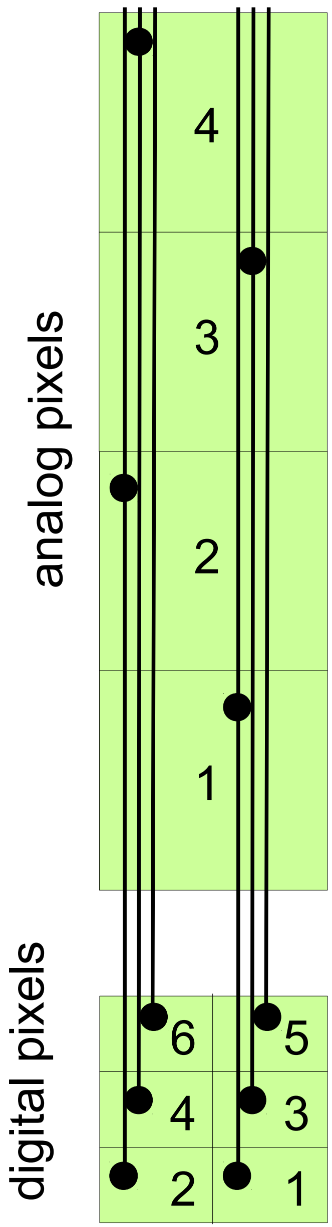
B($\mu^+ \rightarrow e^+e^+e^- \nu\nu$) = 3.4 ·10^-5





very good momentum +
total energy resolution required!

Cross Talk in Mupix7



transmission lines between matrix and periphery