The Mu3e Experiment: A new search for μ → eee with unprecedented sensitivity

CERN Detector Seminar, March 31st 2017

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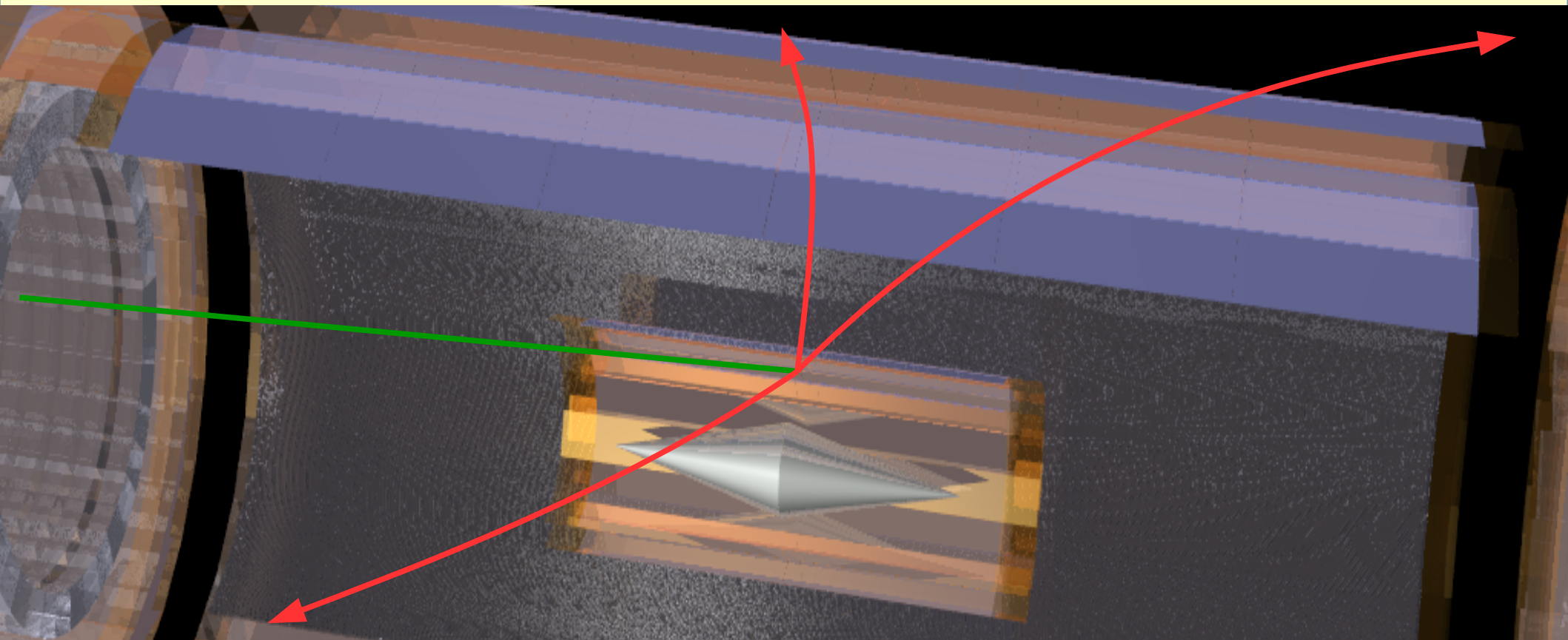
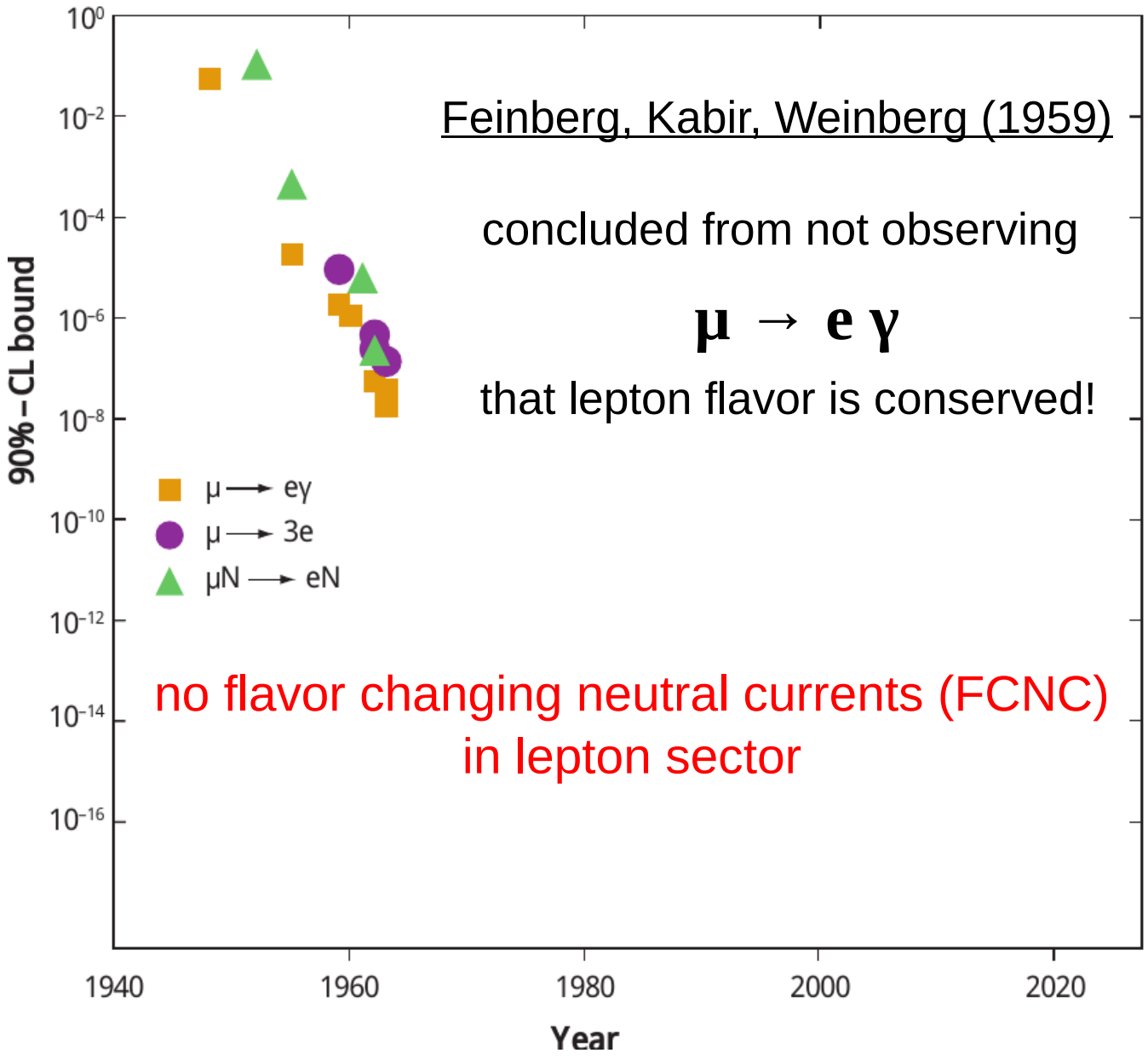


History of LFV Decay experiments



Feinberg, Kabir, Weinberg (1959)

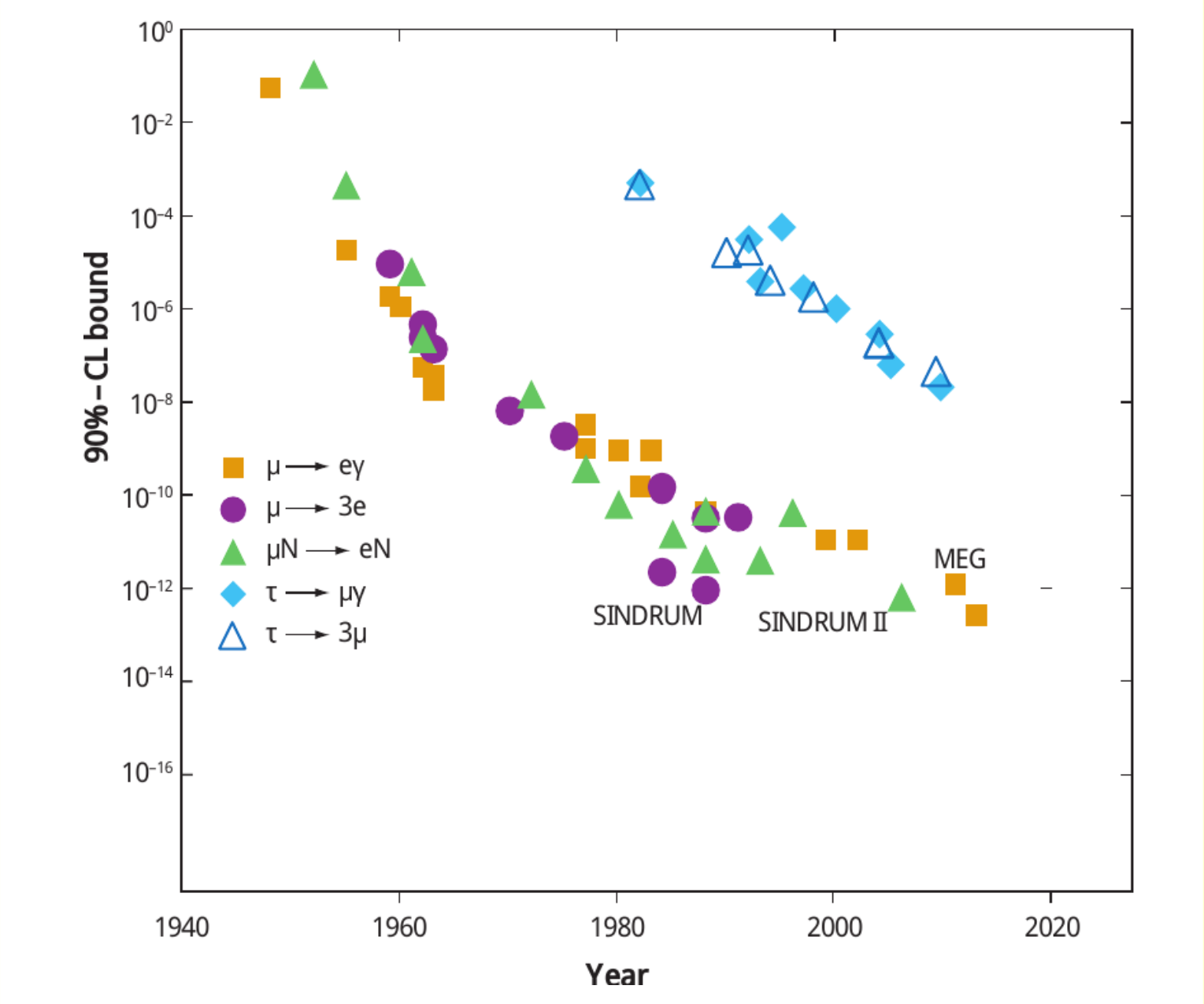
concluded from not observing

$\mu \rightarrow e\,\gamma$

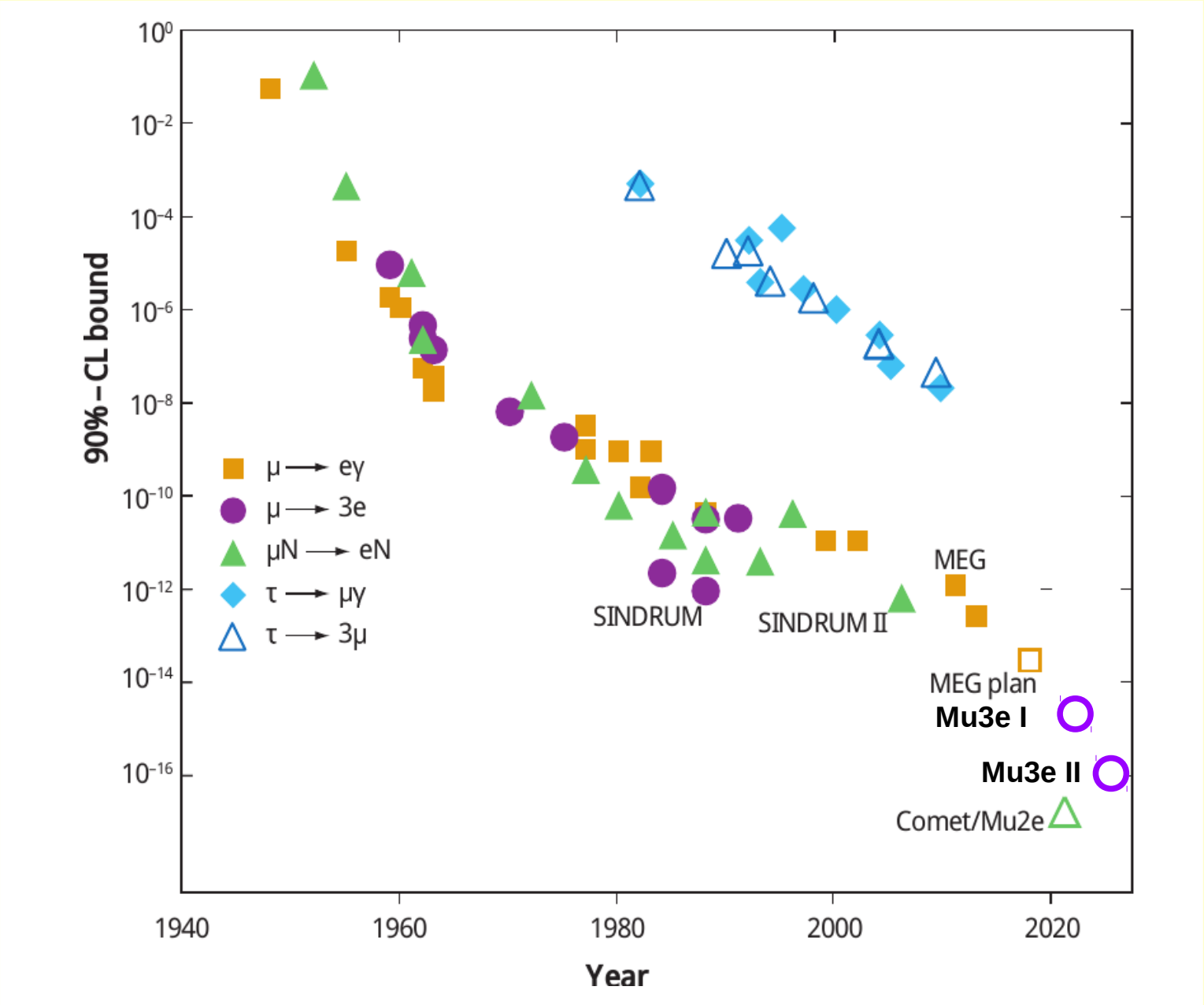
that lepton flavor is conserved!

no flavor changing neutral currents (FCNC) in lepton sector

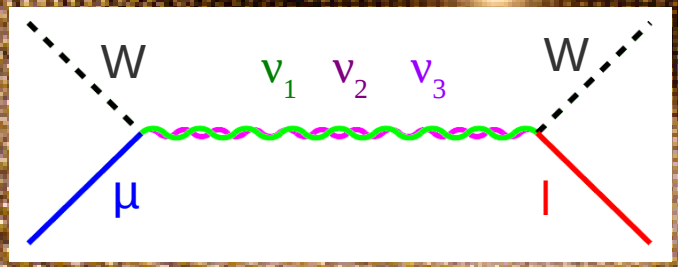
History of LFV Decay experiments



History of LFV Decay experiments

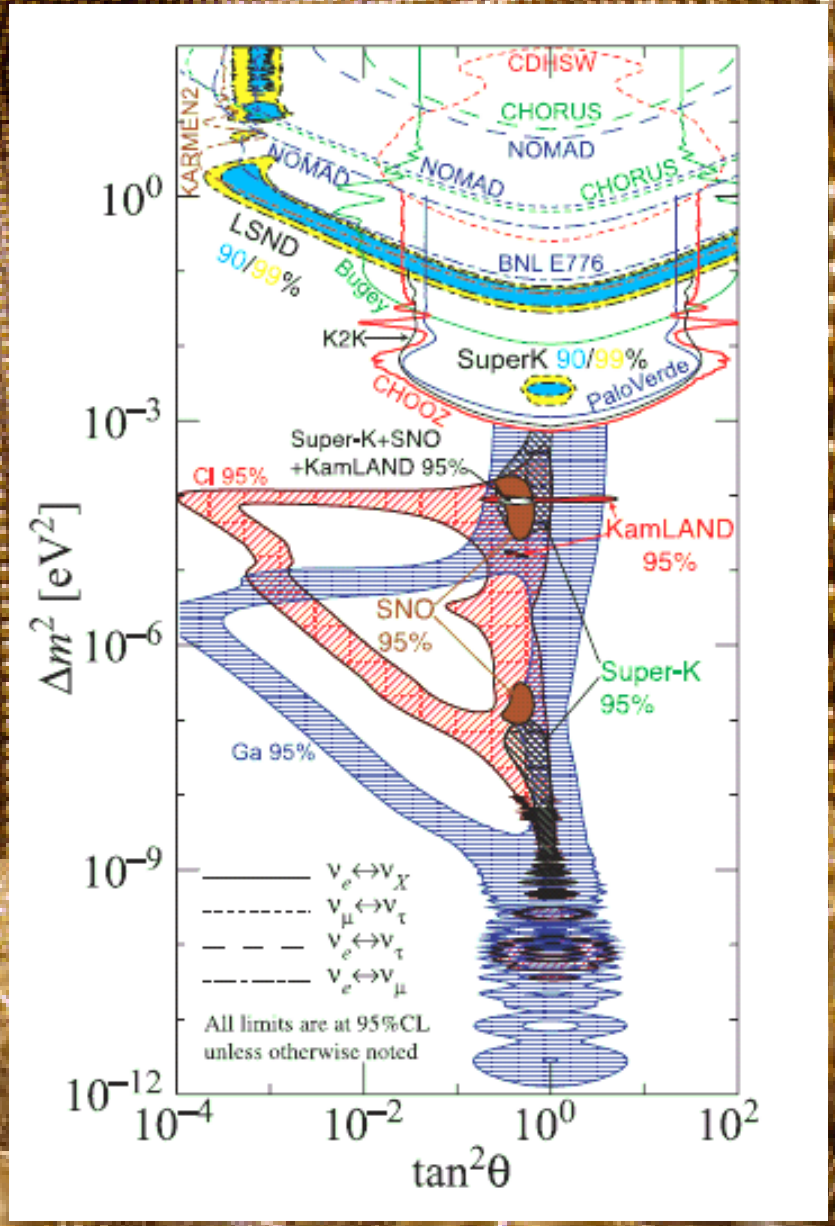


Discovery of Neutrino Oscillations

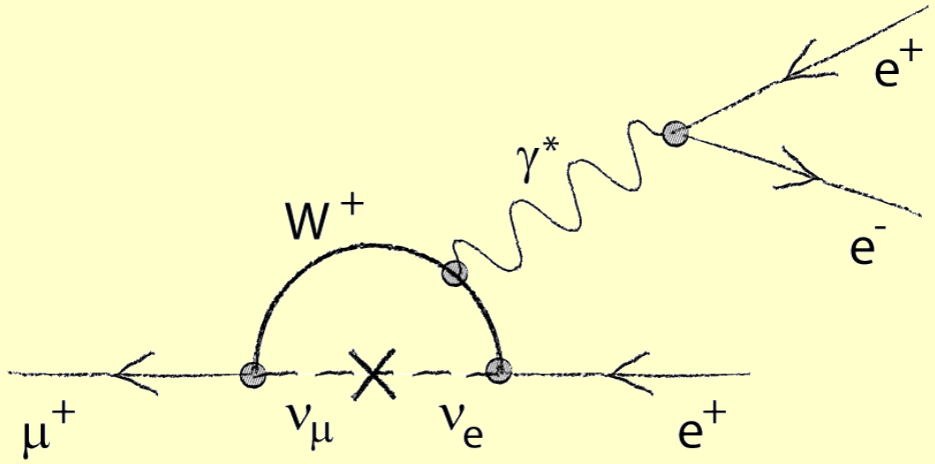


$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\Theta)\sin^2\left(\Delta m^2_{\alpha\beta}\frac{L}{E_\nu}\right)$$

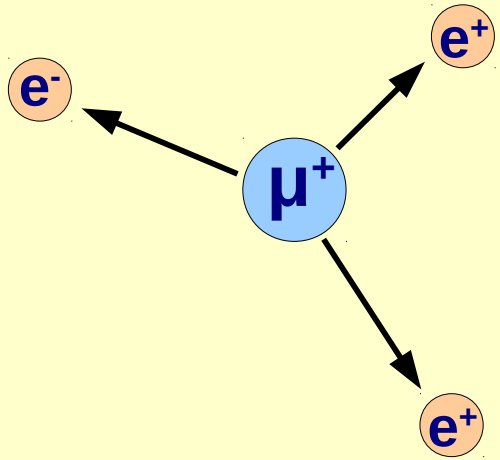
- Neutrino Oscillations:
  - solar neutrinos
  - reactor neutrinos
  - atmospheric neutrinos
  - neutrino beams



SM Loop Diagrams

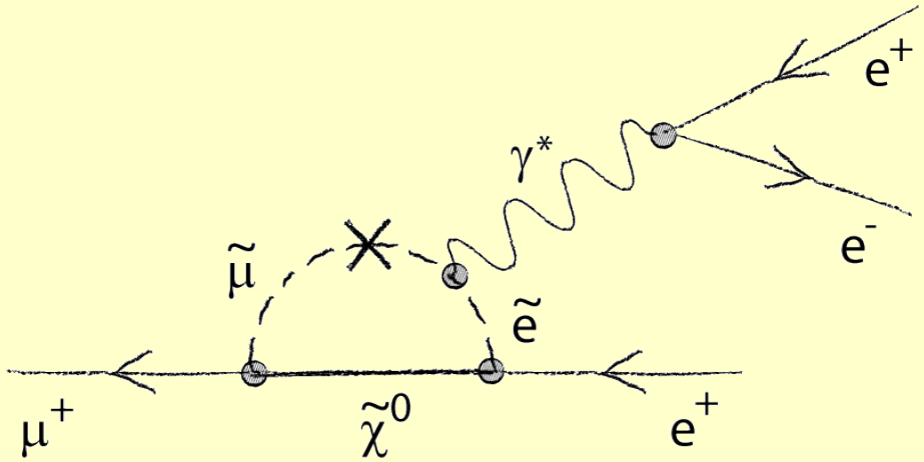


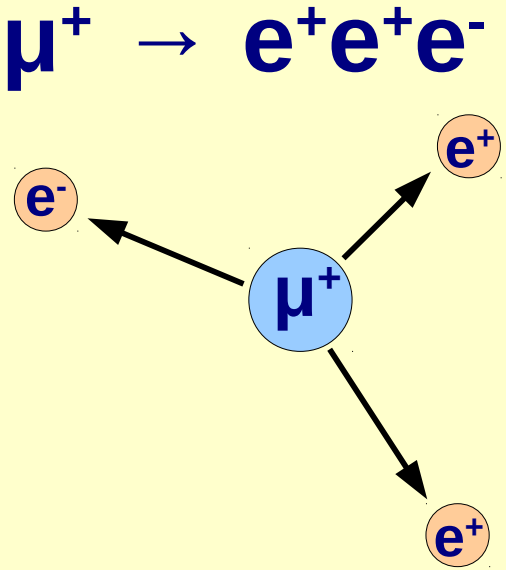
$\mu^+ \rightarrow e^+e^+e^-$



BR suppressed by $\propto \frac{(\Delta m_\nu^2)^2}{m_W^4} \approx 10^{-50}$

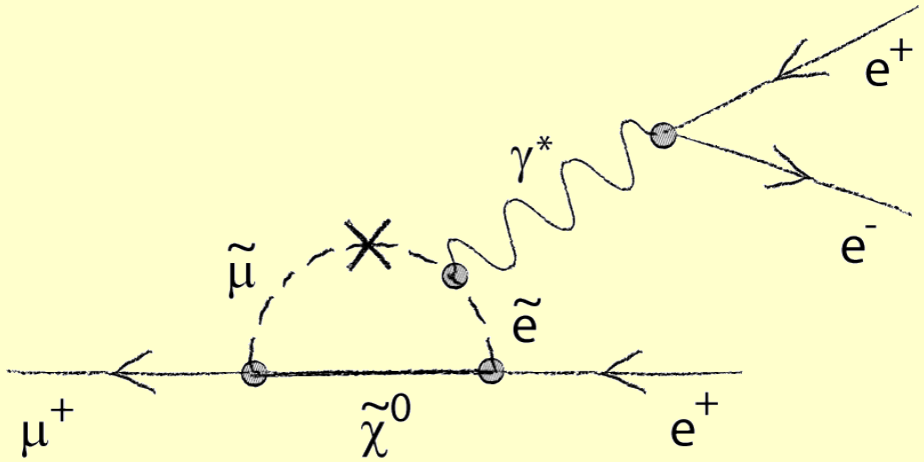
SUSY Loop Diagrams



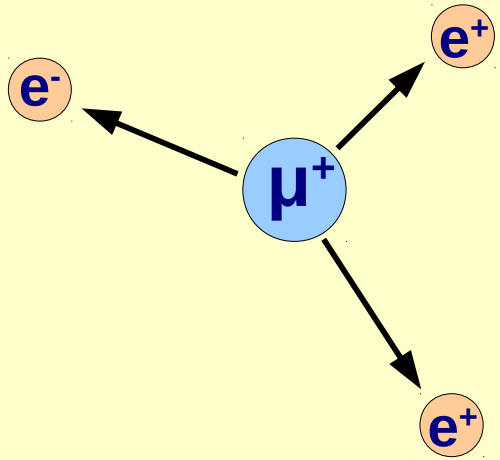


BR can be as large as $\approx 10^{-12}$

SM Loop Diagrams



$\mu^+ \rightarrow e^+e^+e^-$

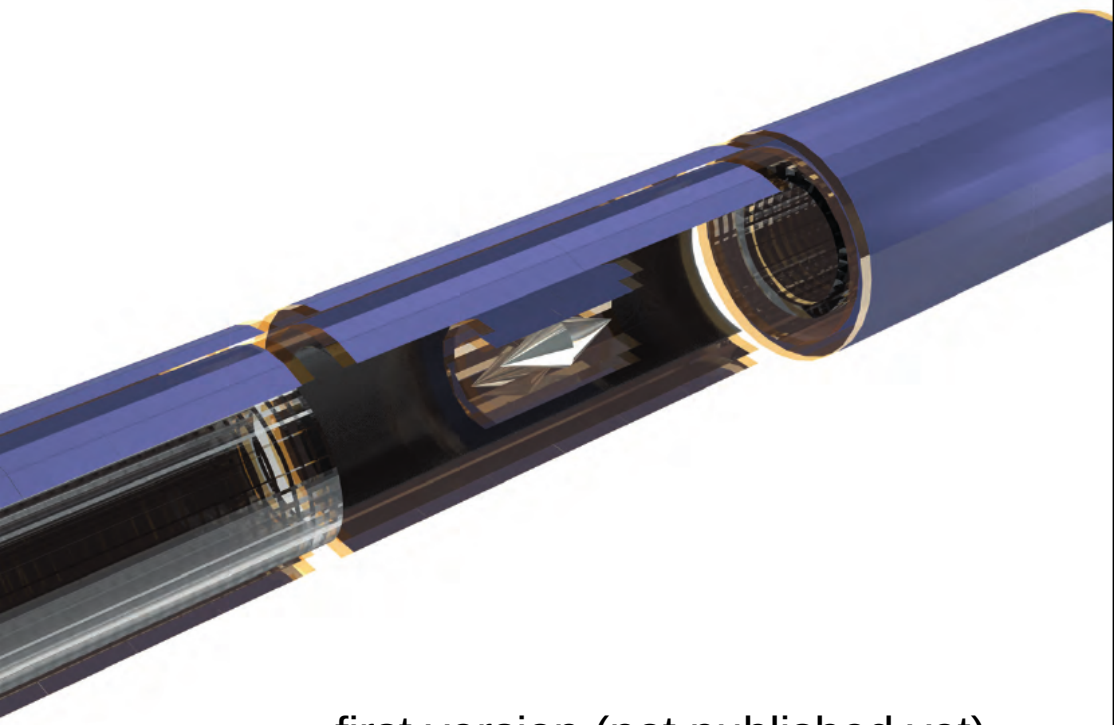


BR can be as large as $\approx 10^{-12}$

Most BSM models (e.g. SUSY) induce naturally LFV

Technical design of the Phase I

Mu3e Experiment



first version (not published yet)

Technical Design of the Phase I

Mu3e Experiment

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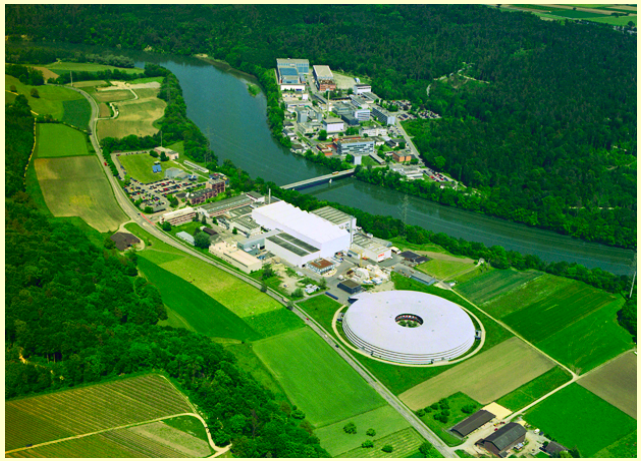
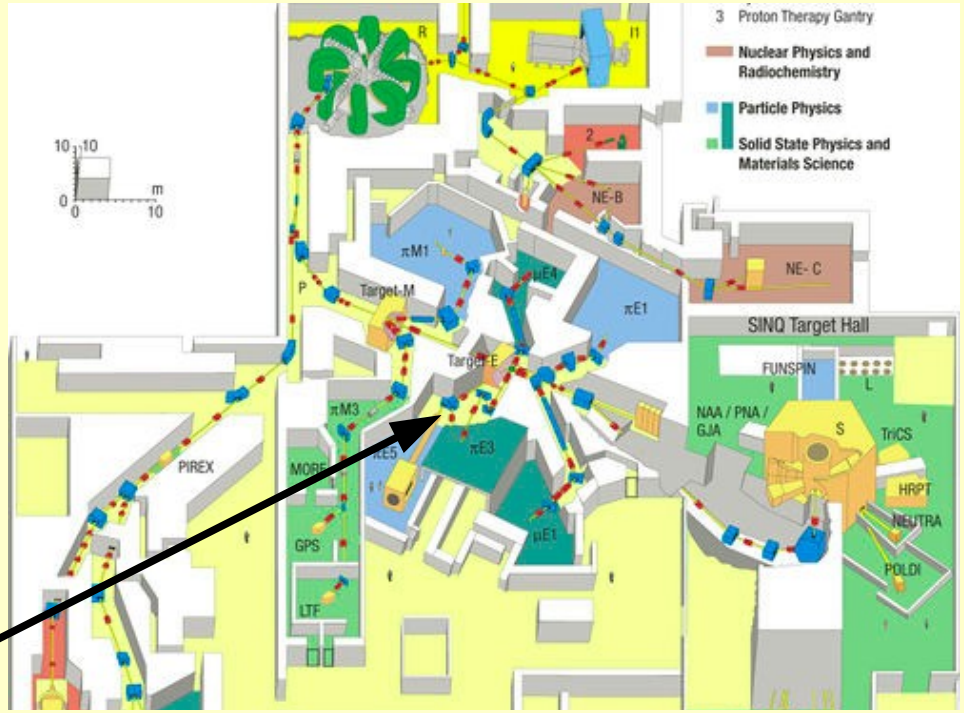
December 2016

Search for $\mu^+ \rightarrow e^+e^+e^-$ at PSI



project approved in Jan 2013

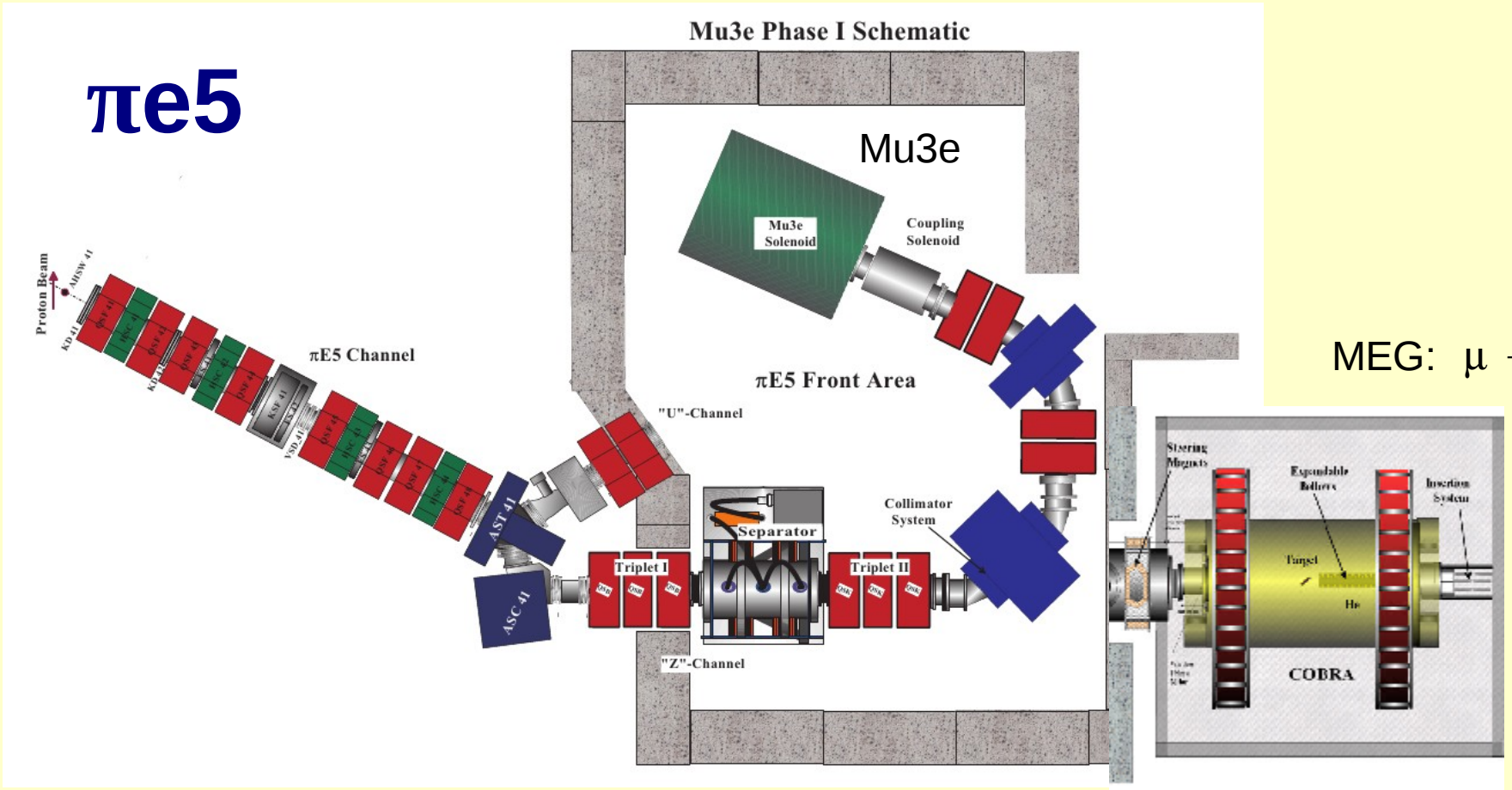


Aiming for a sensitivity of

$BR(\mu \rightarrow eee) < 10^{-15}$ (phase I)

$BR(\mu \rightarrow eee) < 10^{-16}$ (phase II at new High Intensity Beamline)

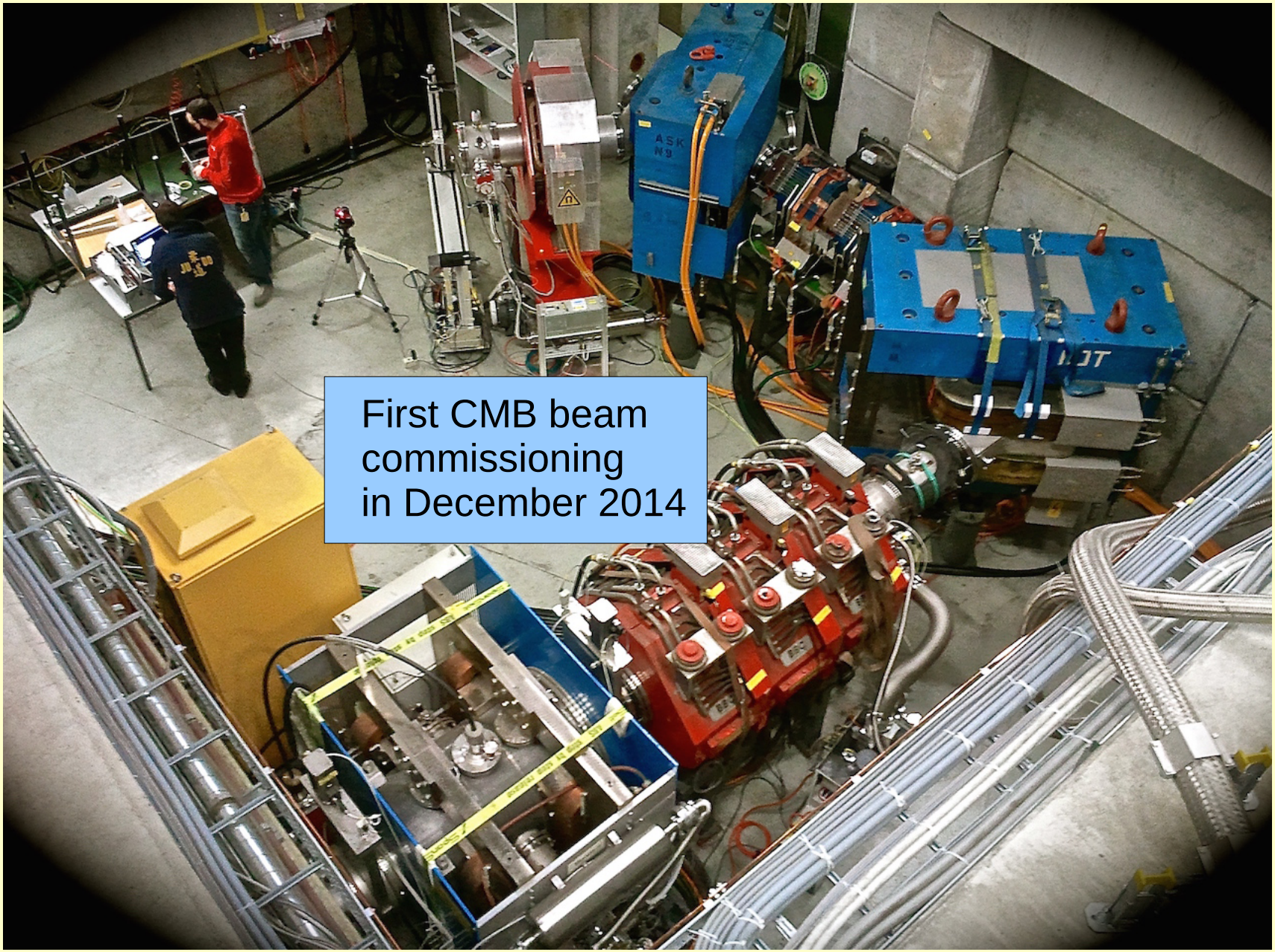
Compact Muon Beamline (Phase I)



MEG: $\mu \rightarrow e\,\gamma$

- muon rates of up to **$8.4 \cdot 10^7$/s** at **solenoid entrance** achieved in 2016
- further optimizations might be possible
- aiming for: → **10^8 muons/s on target**

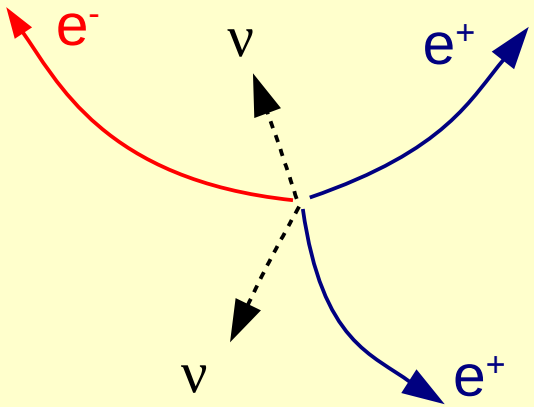
Compact Muon Beamline (CMB)



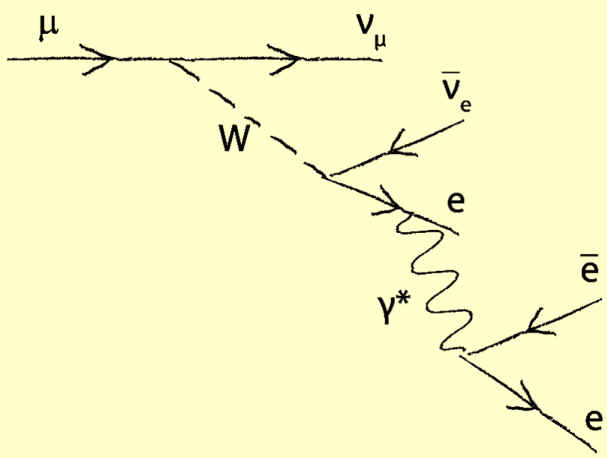
How Big is 10^{-16} ?

Backgrounds for Mu3e

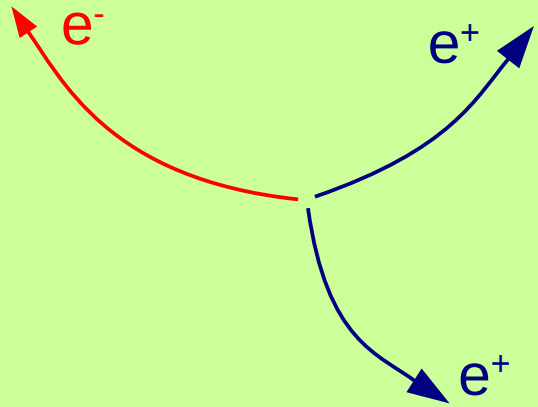
Irreducible BG: radiative decay with internal conversion (IC)



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



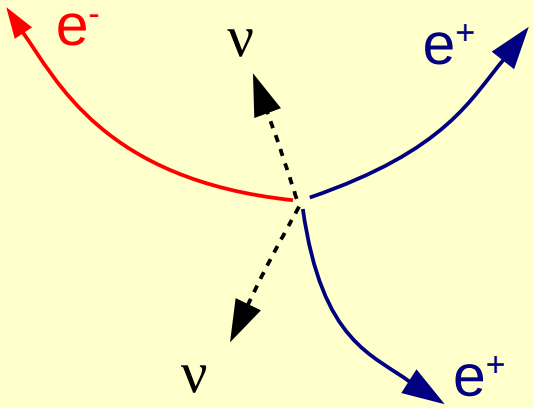
Signal: $B(\mu^+ \rightarrow e^+e^+e^-)$



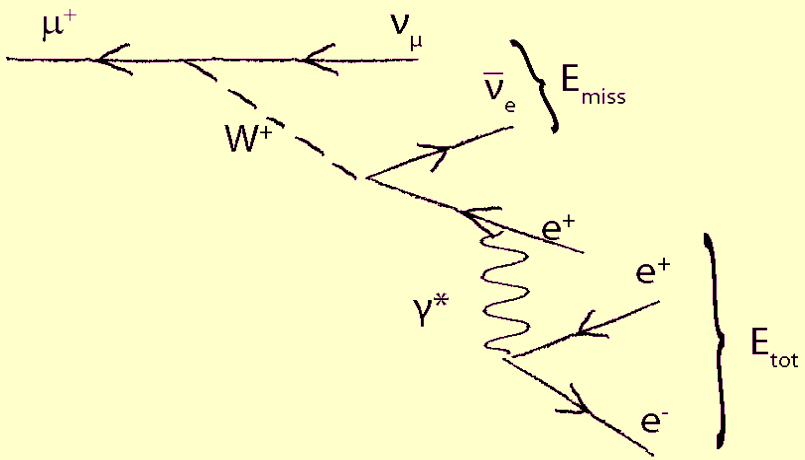
$$\sum_i E_i = m_\mu$$
$$\sum_i \vec{p}_i = 0$$

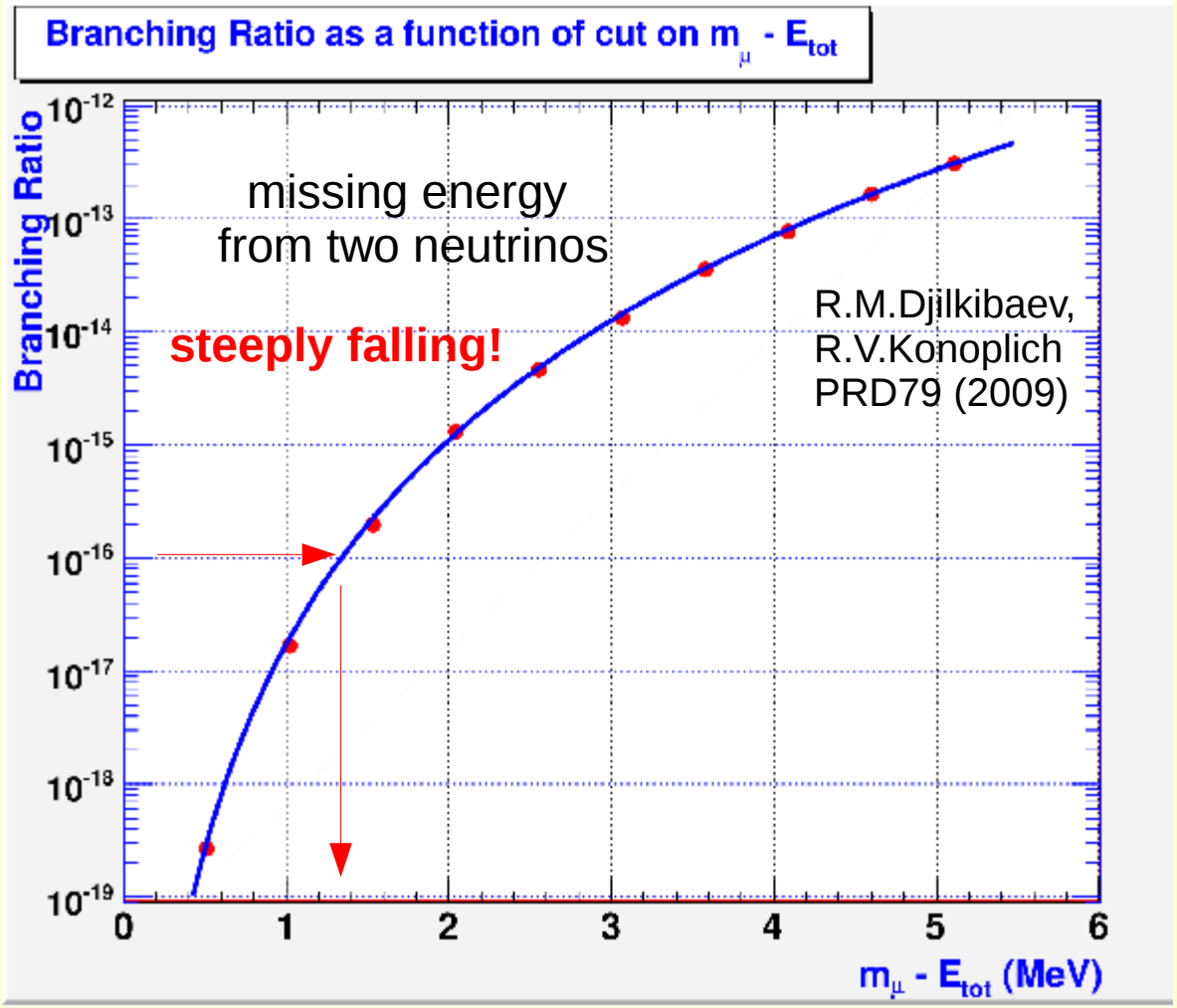
Backgrounds

Irreducible BG: radiative decay with internal conversion (IC)



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

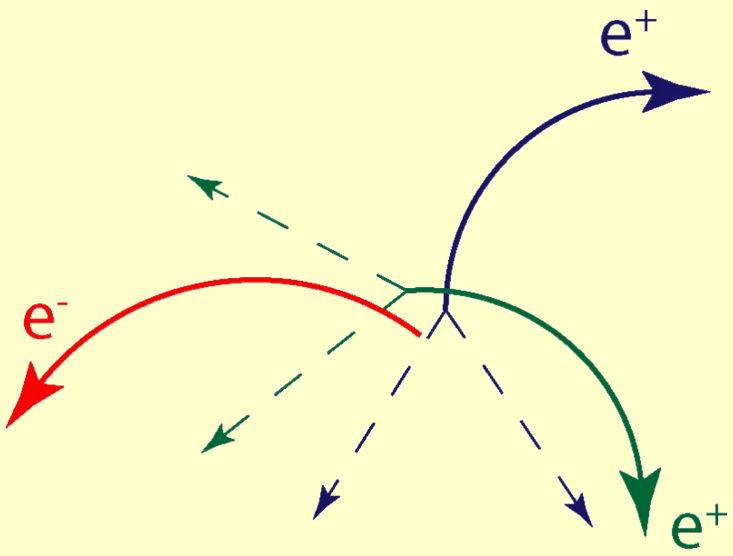


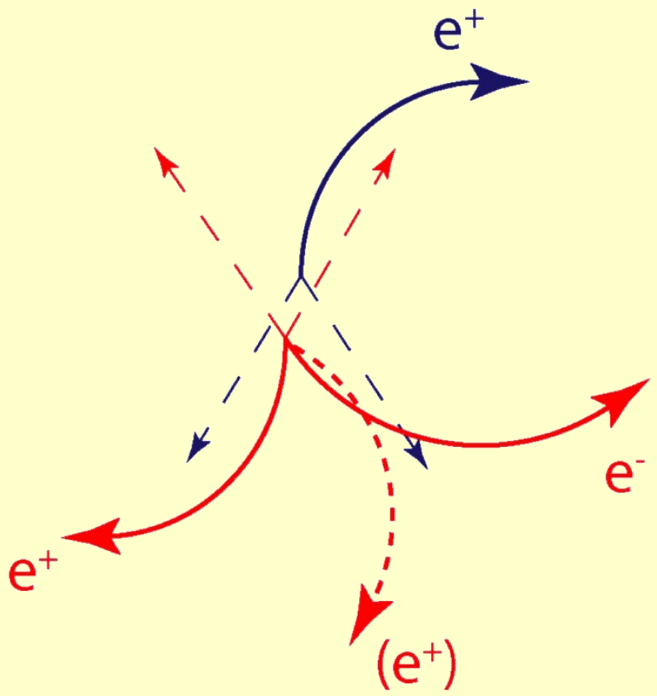


very good momentum / total energy resolution required!

Accidental Backgrounds

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

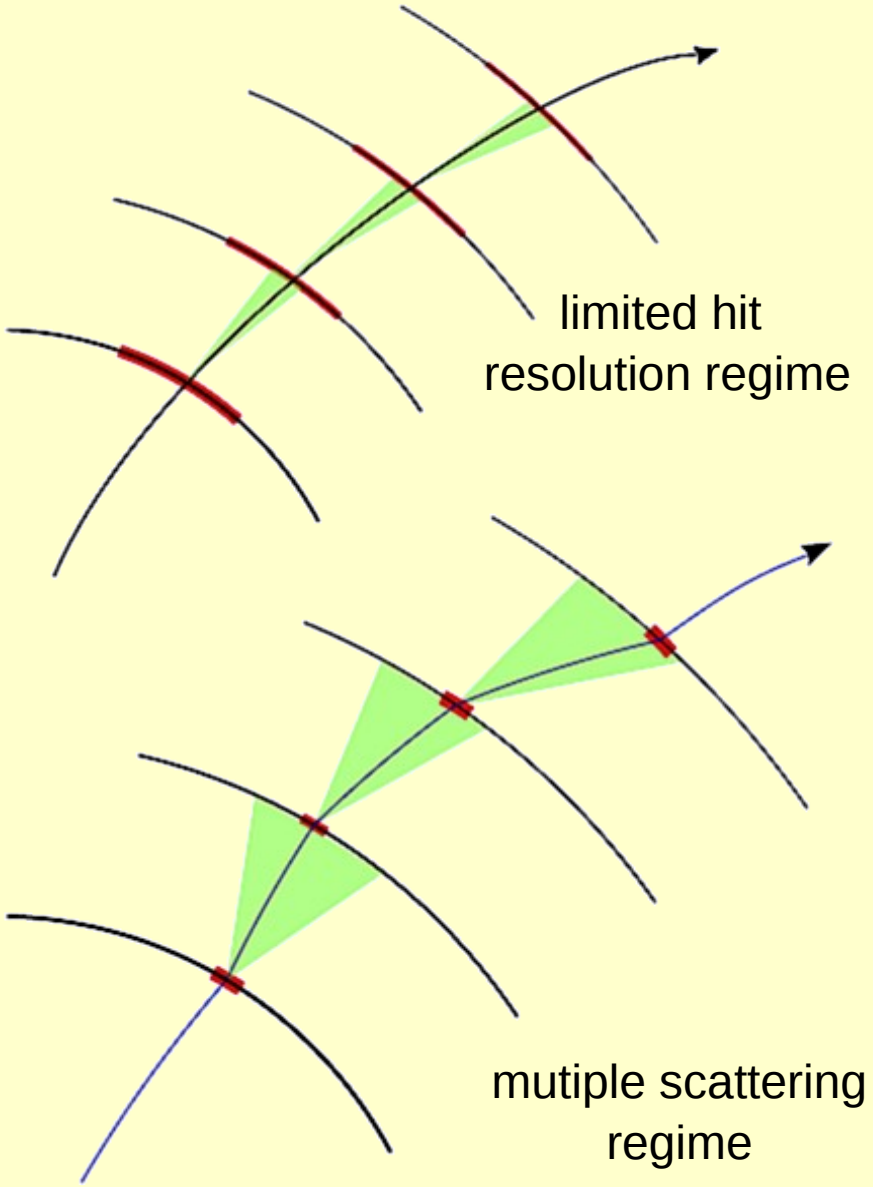




Detector requirements:

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

Tracking Resolution + Multiple Scattering



- Muon decay (m=105.6 MeV):

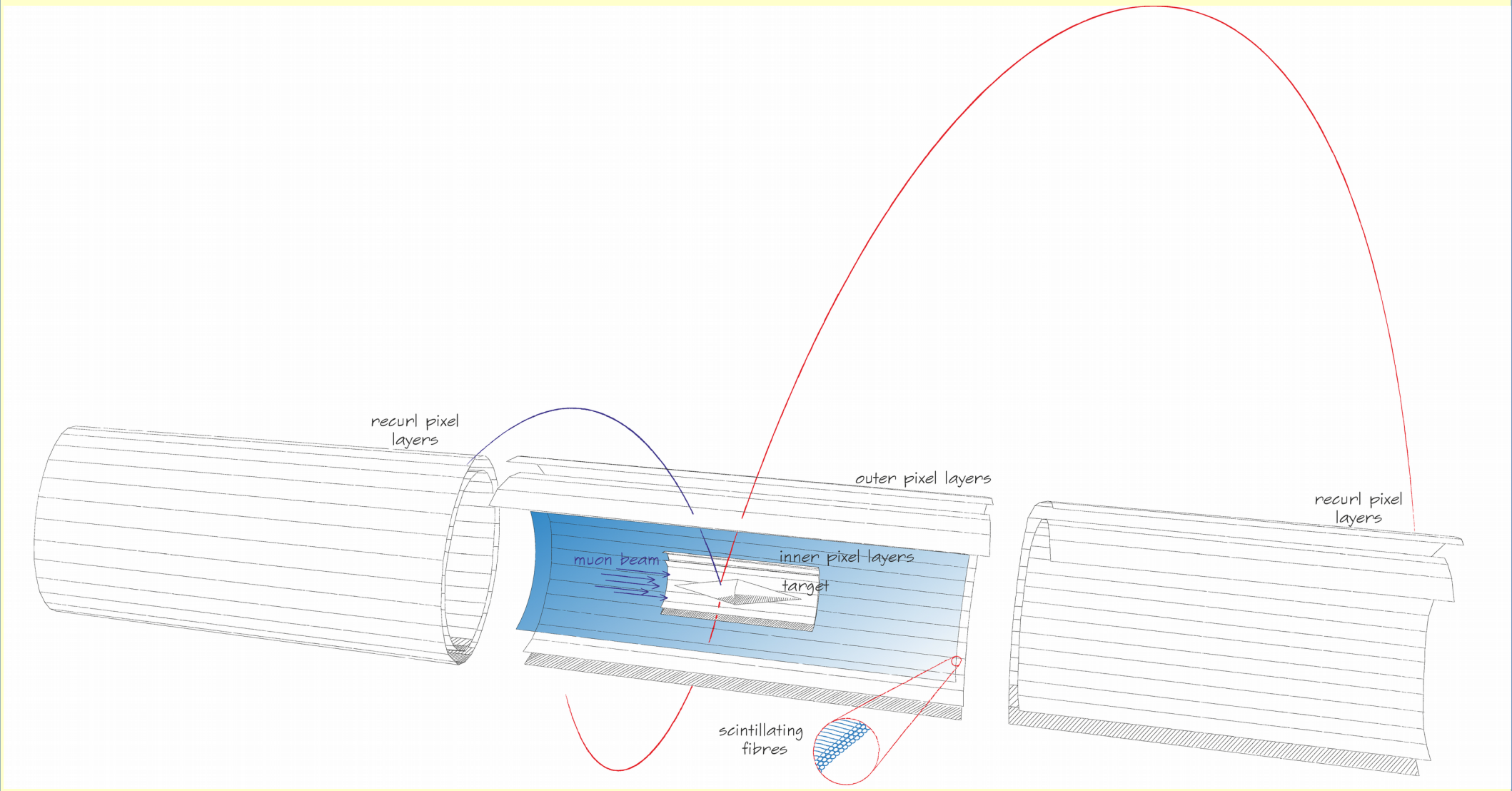
  → electrons in low momentum range
  p < 53 MeV/c

- Multiple scattering is dominant!

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

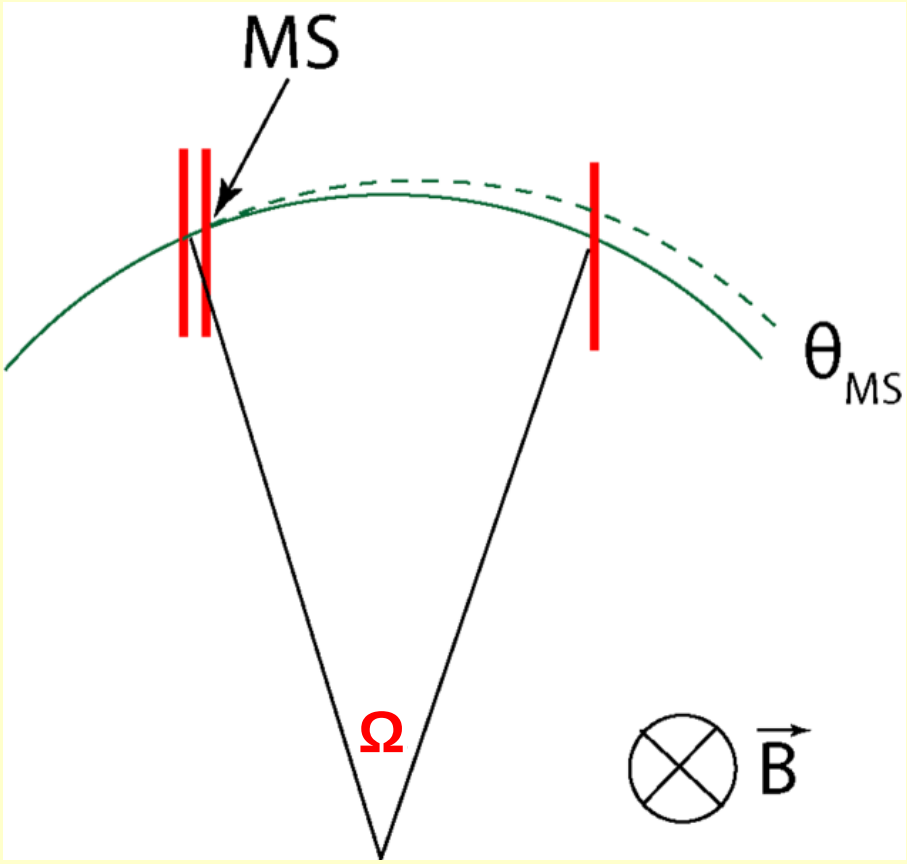
$$\Theta_{MS} \sim \frac{1}{P}\sqrt{X/X_0}$$

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

$$\frac{\sigma_p}{P} \sim \frac{\Theta_{MS}}{\Omega}$$

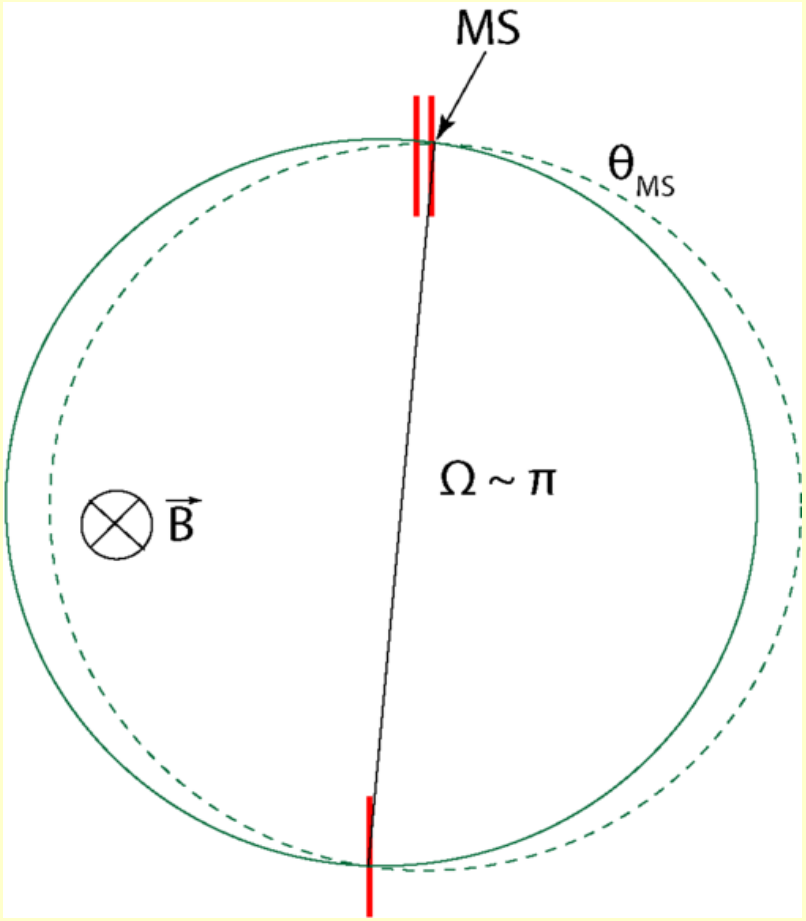
(linearised)

precision requires lever arm

→ large bending angle Ω

Momentum Resolution in MS Regime

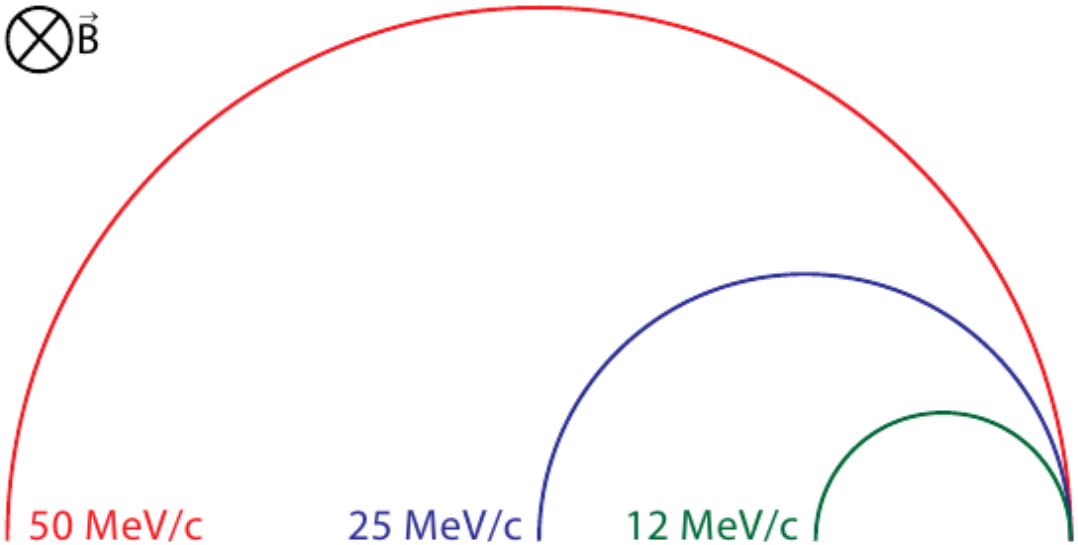
- "Half turn" spectrometer:



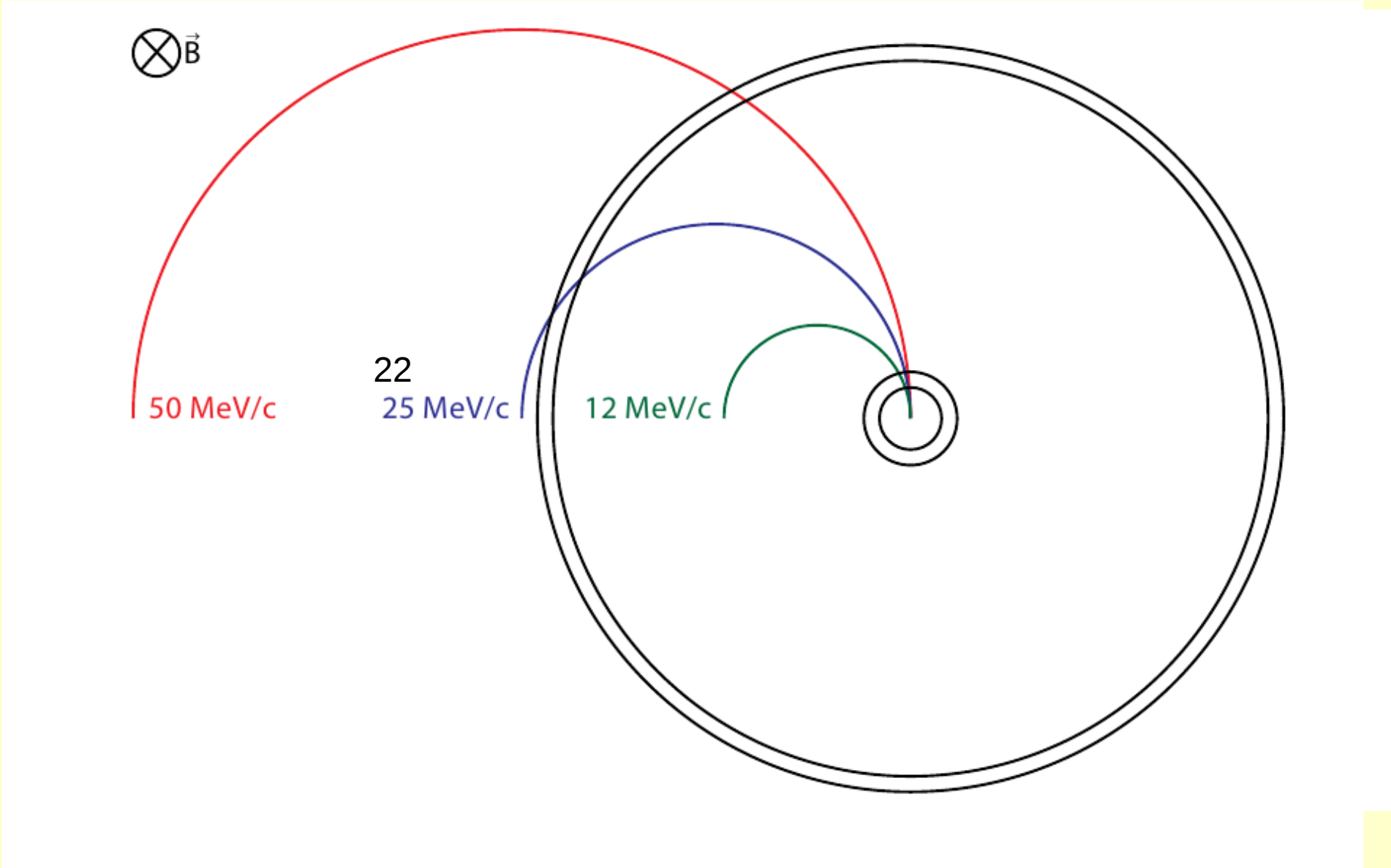
$$\frac{\sigma_p}{P} \sim O\left(\Theta^2_{MS}\right)$$

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

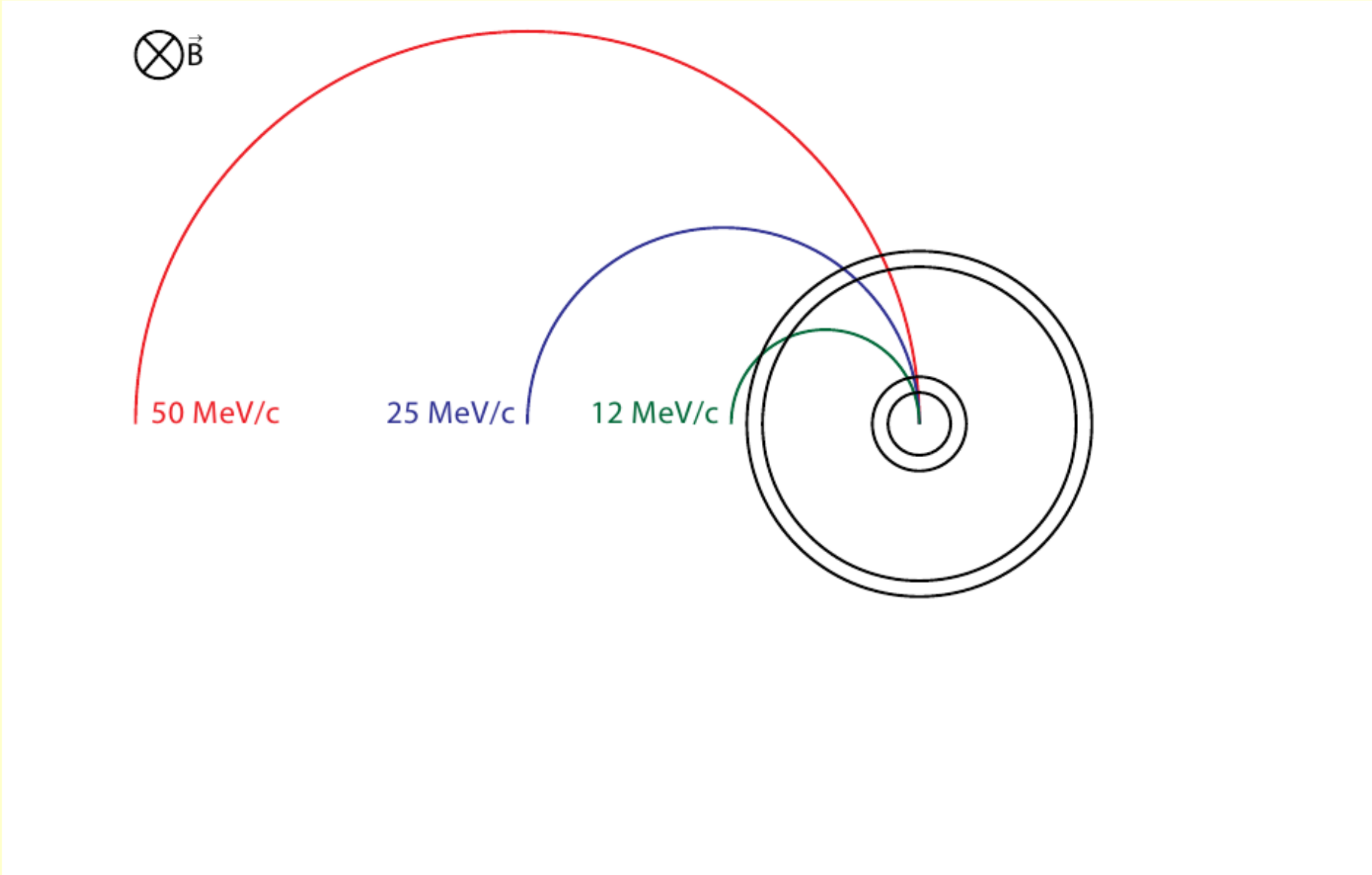
Tracking Design Considerations



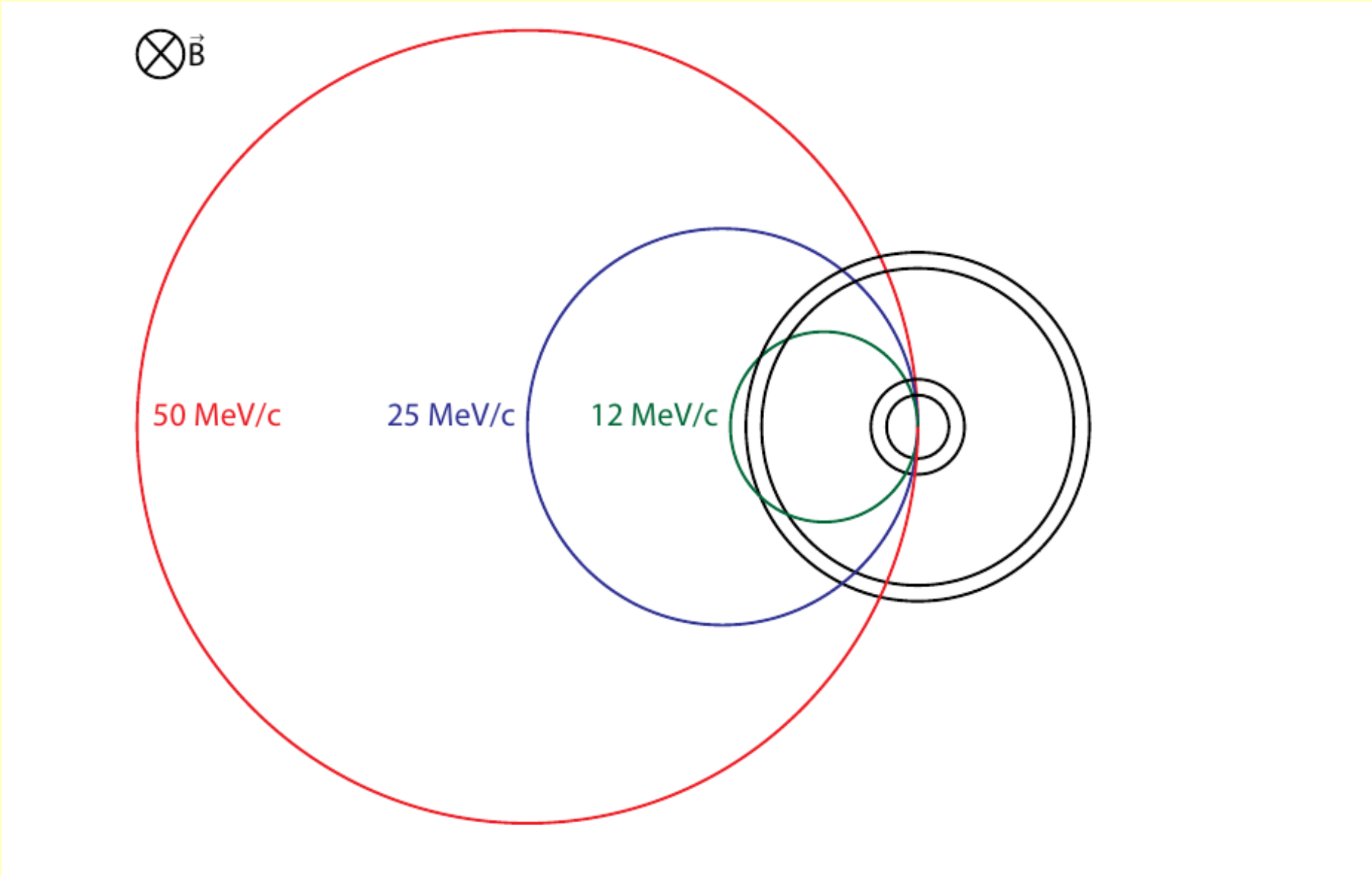
Tracking Design Considerations



Tracking Design Considerations



Tracking Design Considerations

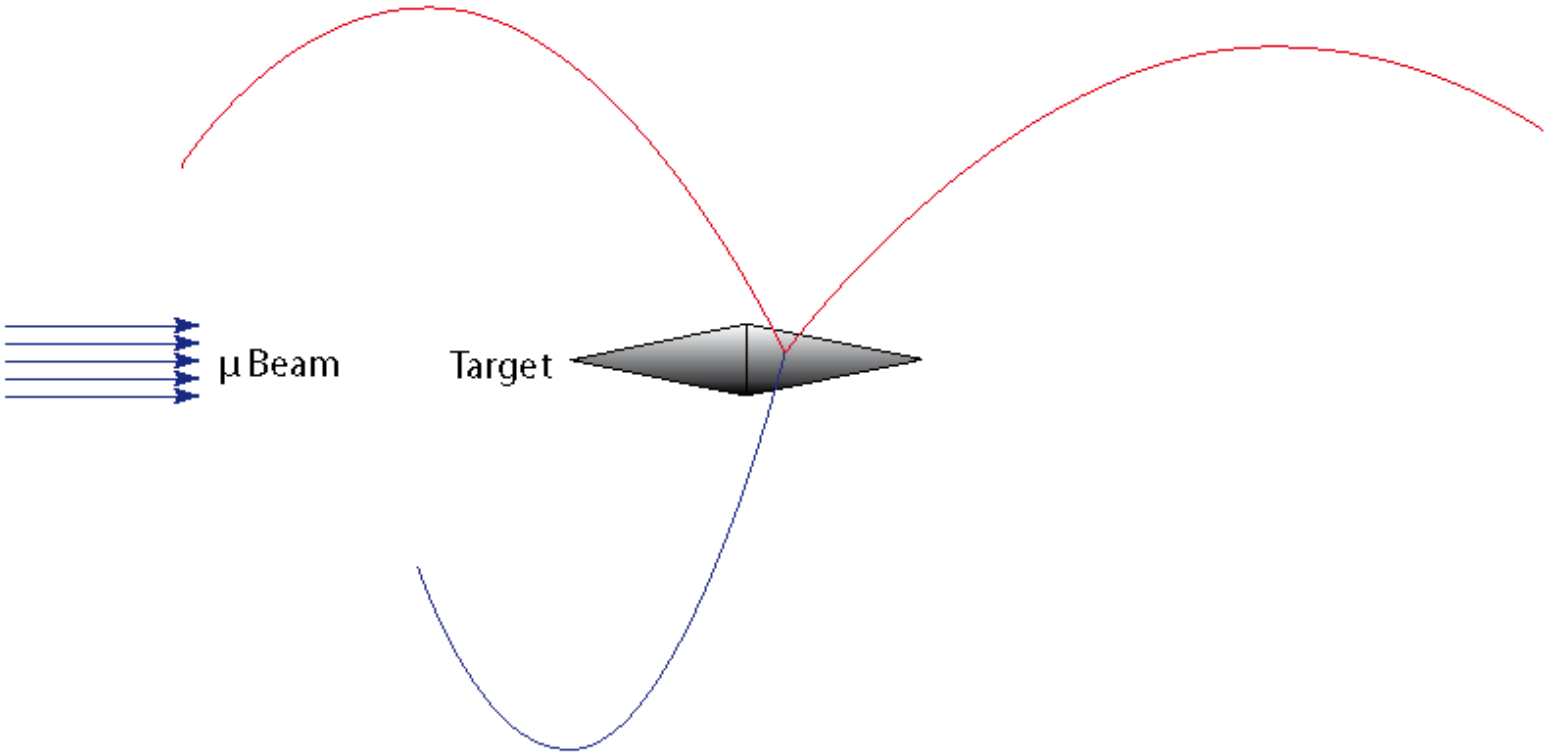


Mu3e Design

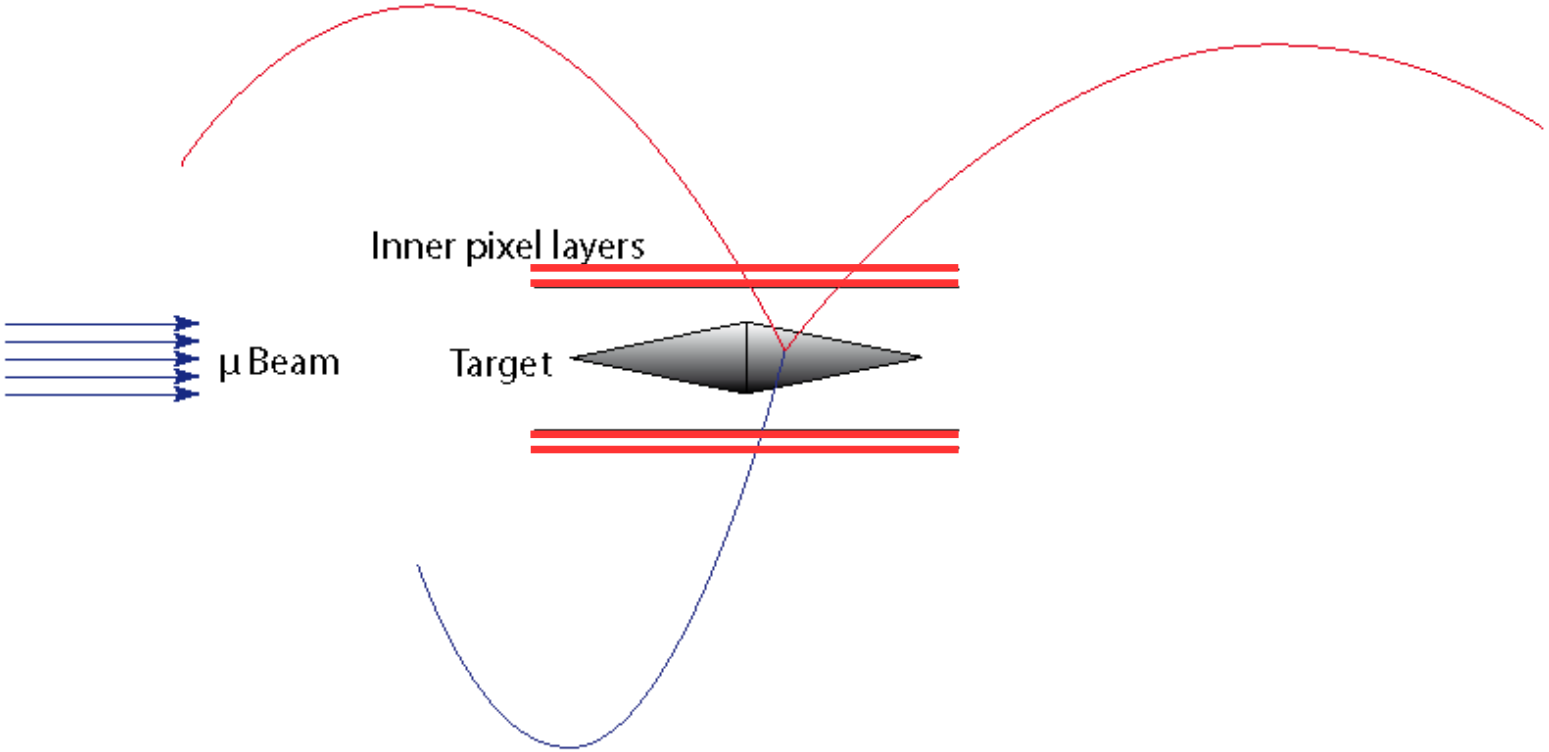
10^8 muons per second (phase I)

p = 28 MeV/c (E_{kin}=4.1 MeV)

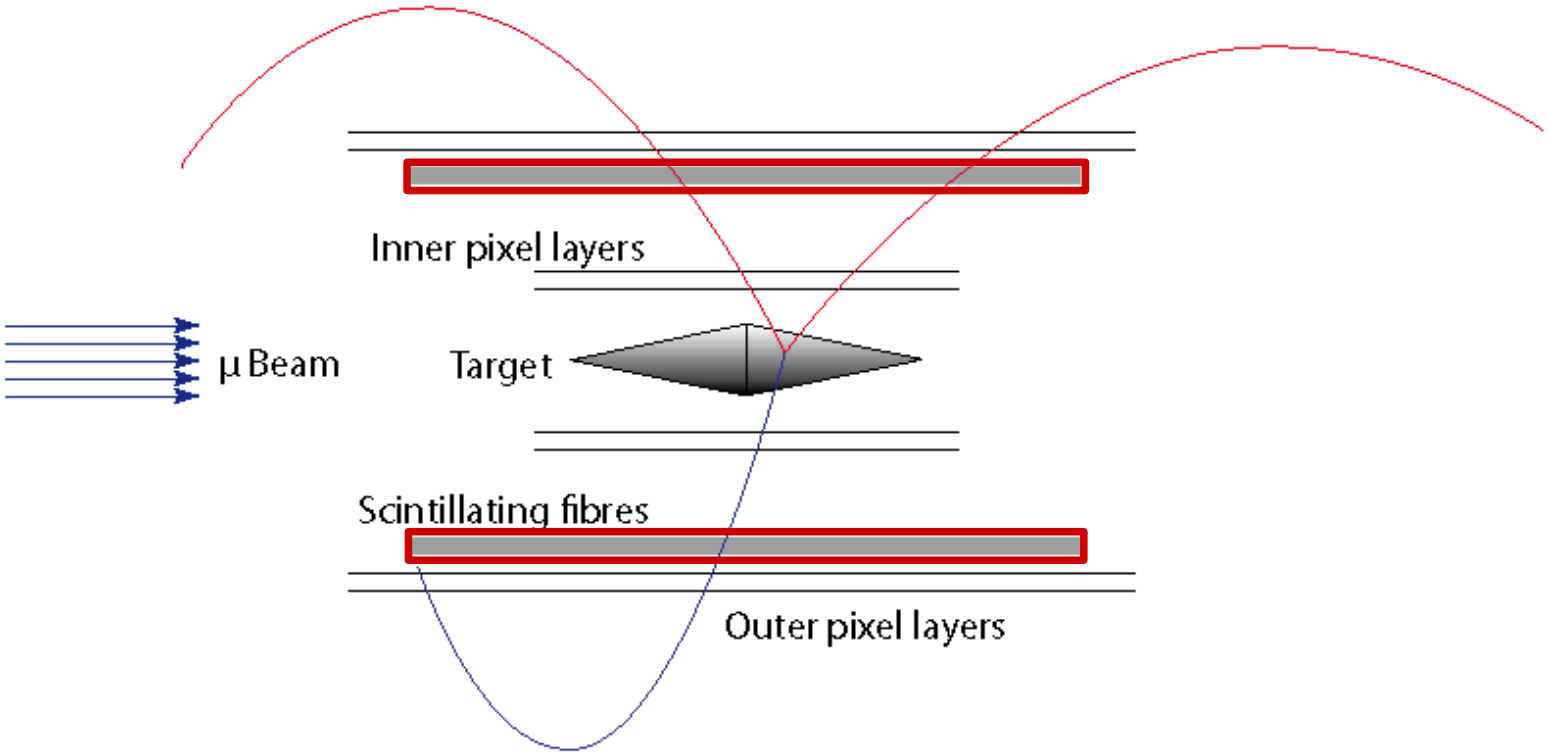
Mu3e Design



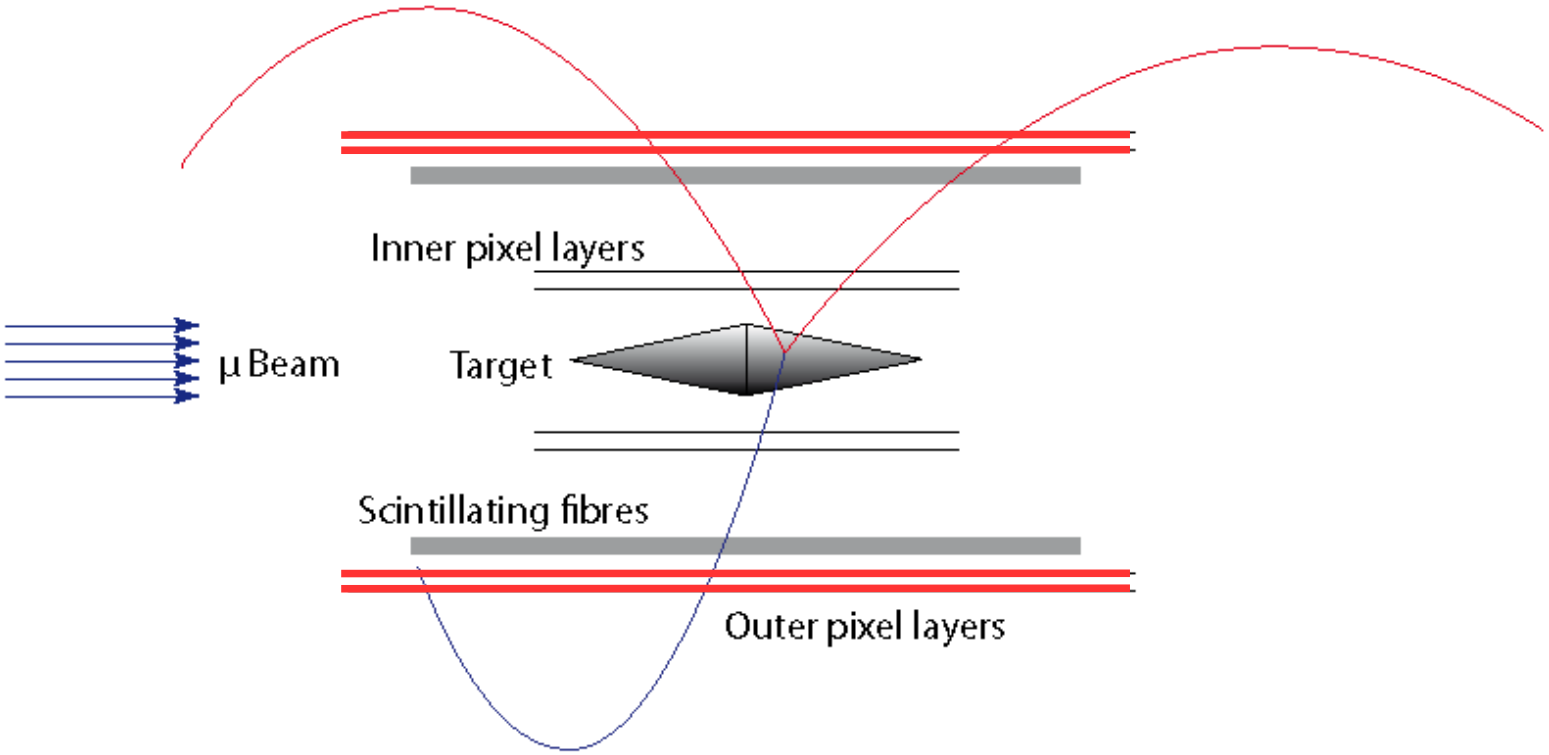
Mu3e Design



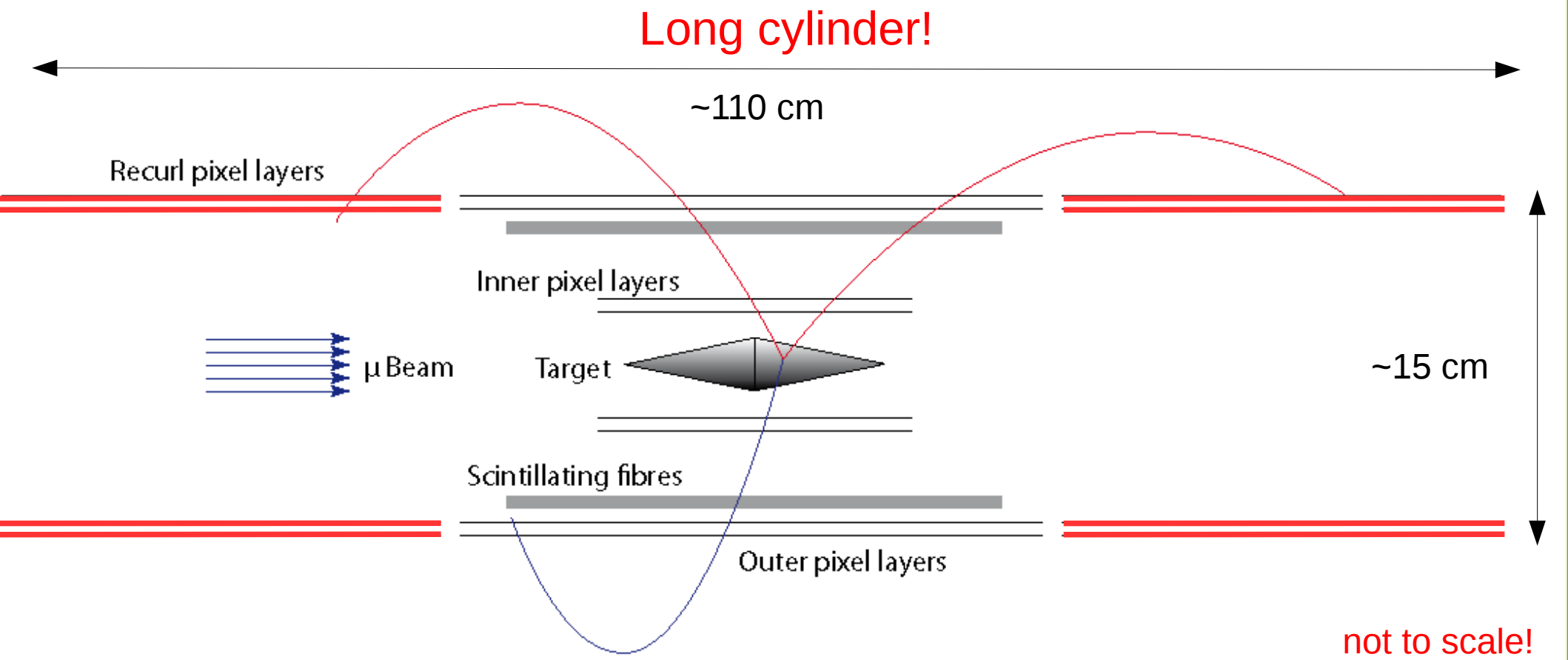
Mu3e Design


Inner pixel layers
μ Beam
Target
Scintillating fibres
Outer pixel layers

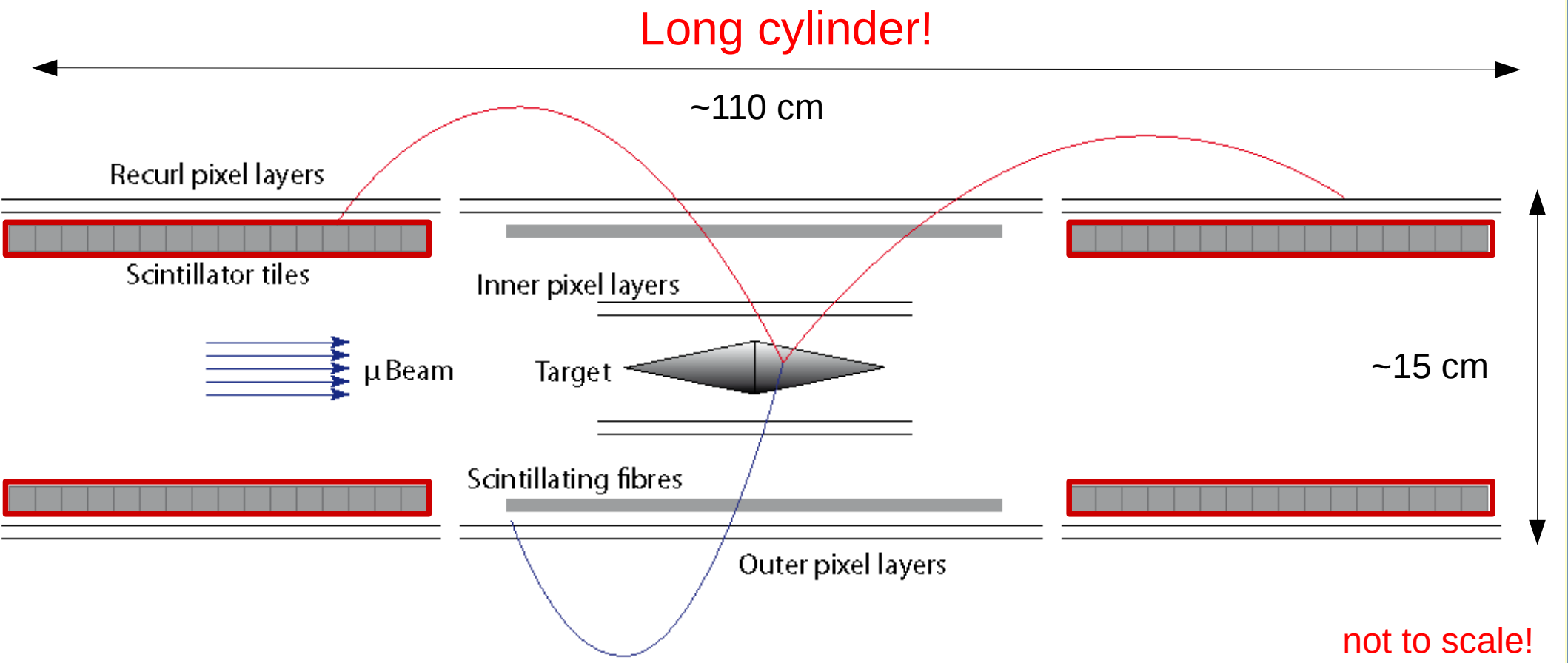
Mu3e Design


Inner pixel layers
μ Beam
Target
Scintillating fibres
Outer pixel layers

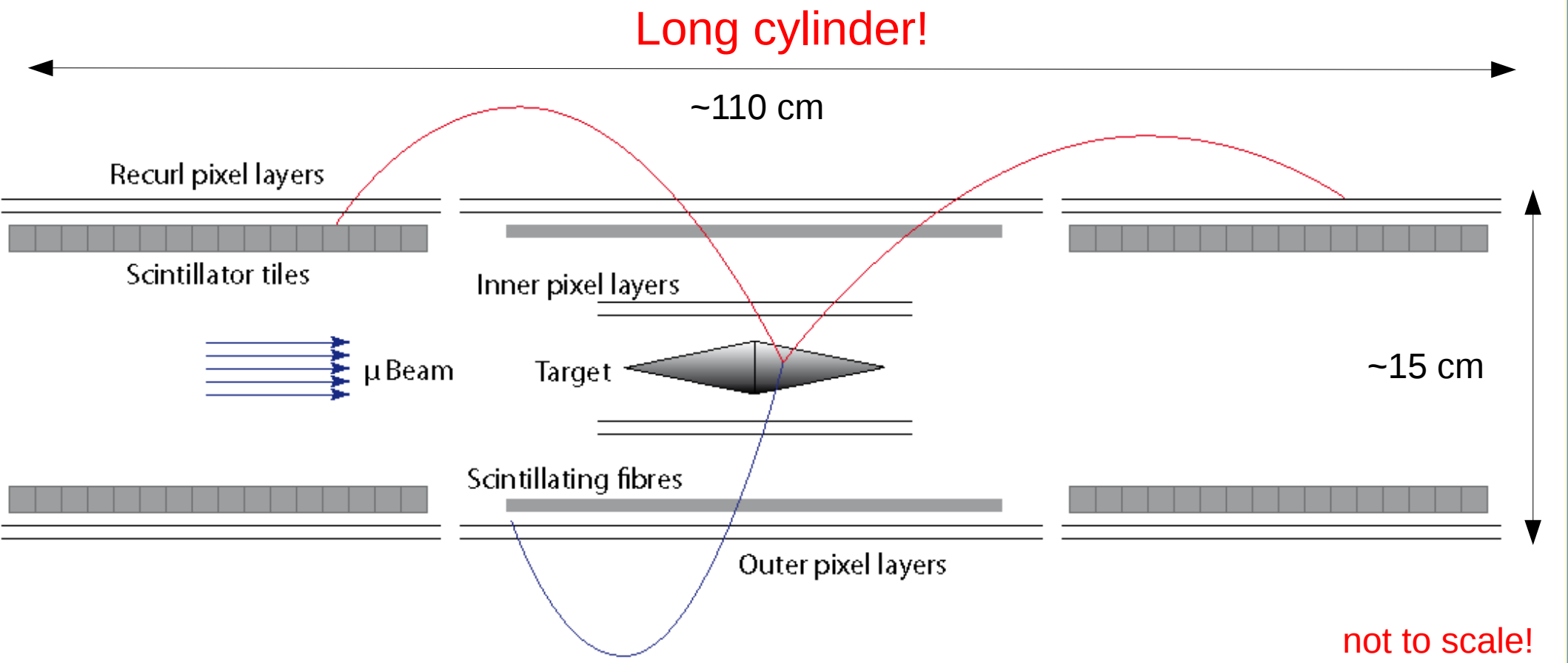
Mu3e Design


Long cylinder!
~110 cm
Recurl pixel layers
Inner pixel layers
μ Beam
Target
~15 cm
Scintillating fibres
Outer pixel layers
not to scale!

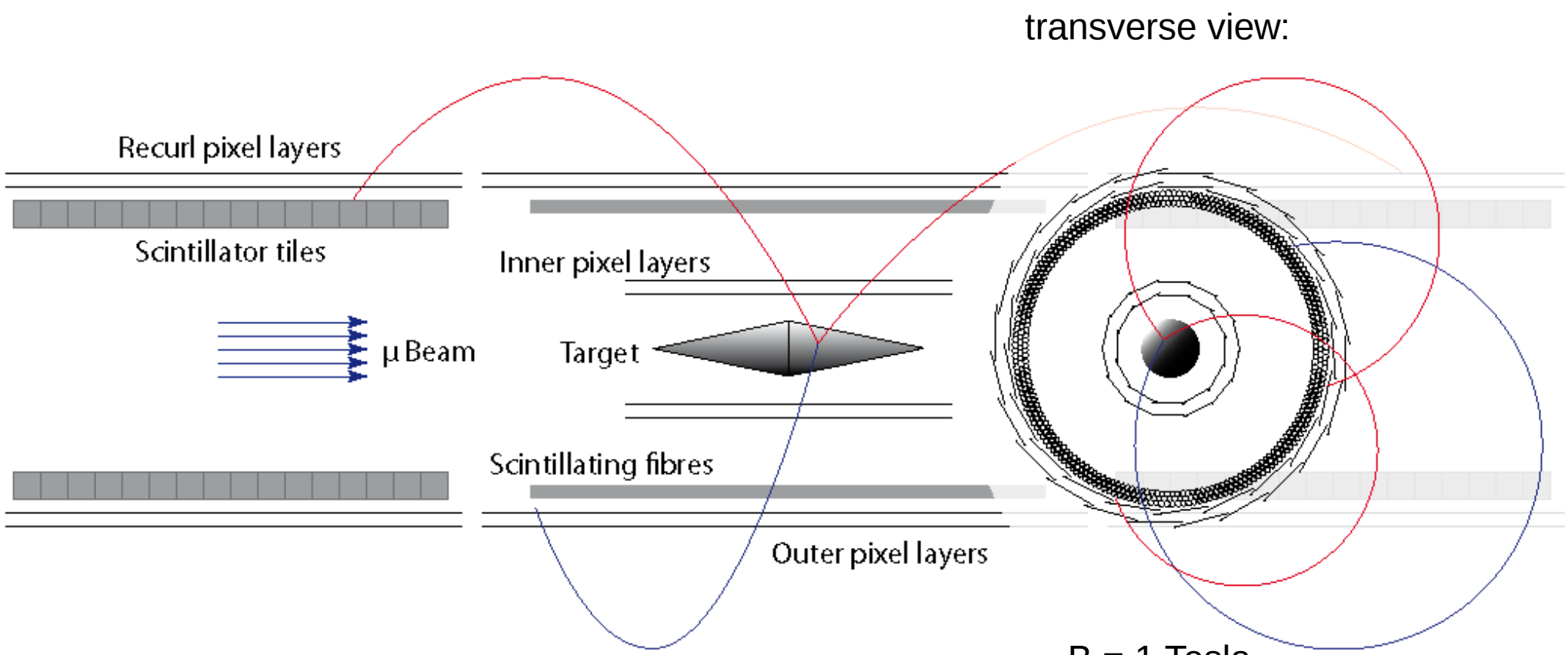
Mu3e Design


Long cylinder!
~110 cm
Recurl pixel layers
Scintillator tiles
Inner pixel layers
μ Beam
Target
~15 cm
Scintillating fibres
Outer pixel layers
not to scale!

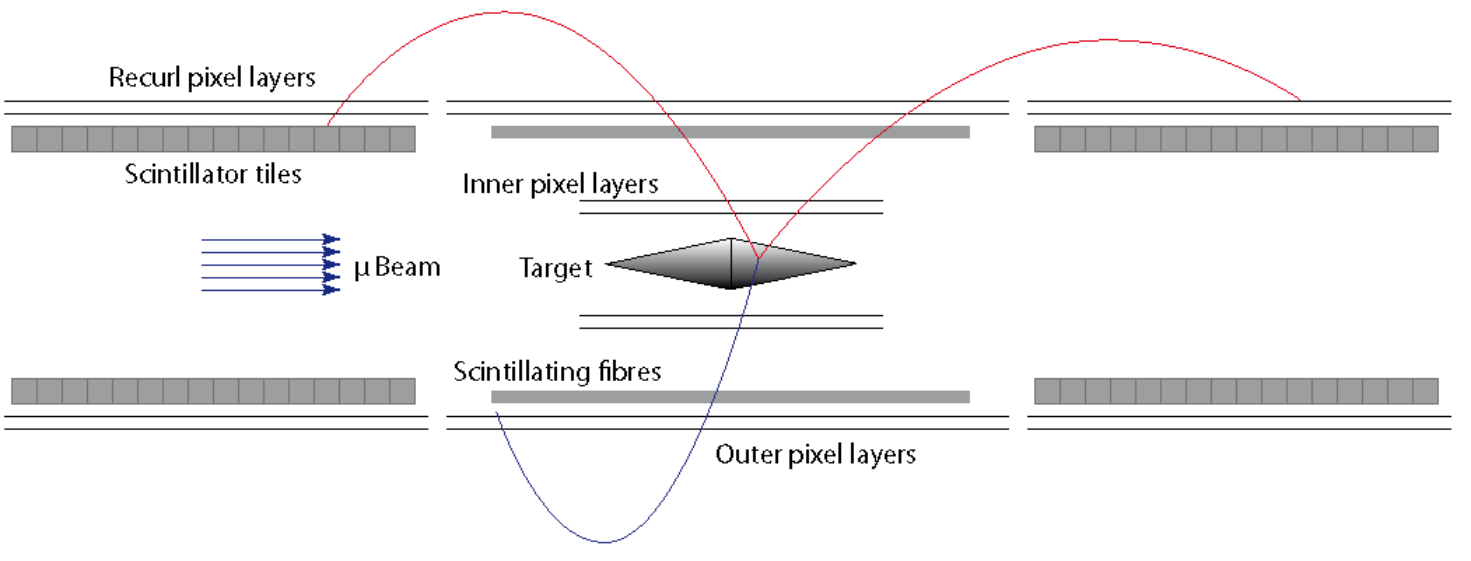
Mu3e Design


Long cylinder!
~110 cm
Recurl pixel layers
Scintillator tiles
Inner pixel layers
μ Beam
Target
~15 cm
Scintillating fibres
Outer pixel layers
not to scale!

Mu3e Design

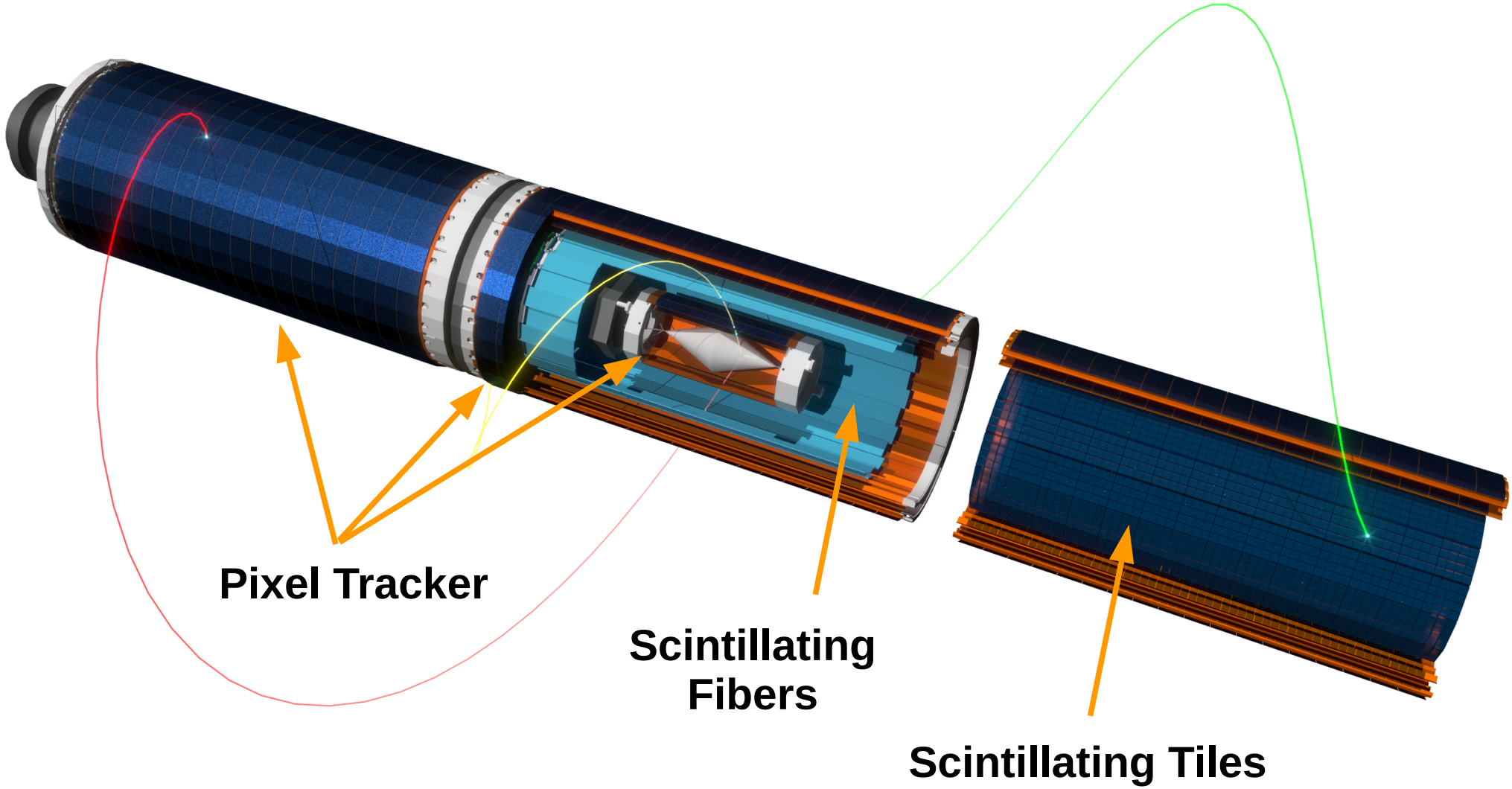

transverse view:
Recurl pixel layers
Scintillator tiles
Inner pixel layers
μ Beam
Target
Scintillating fibres
Outer pixel layers
B = 1 Tesla
helium atmosphere

Main Technological Challenges

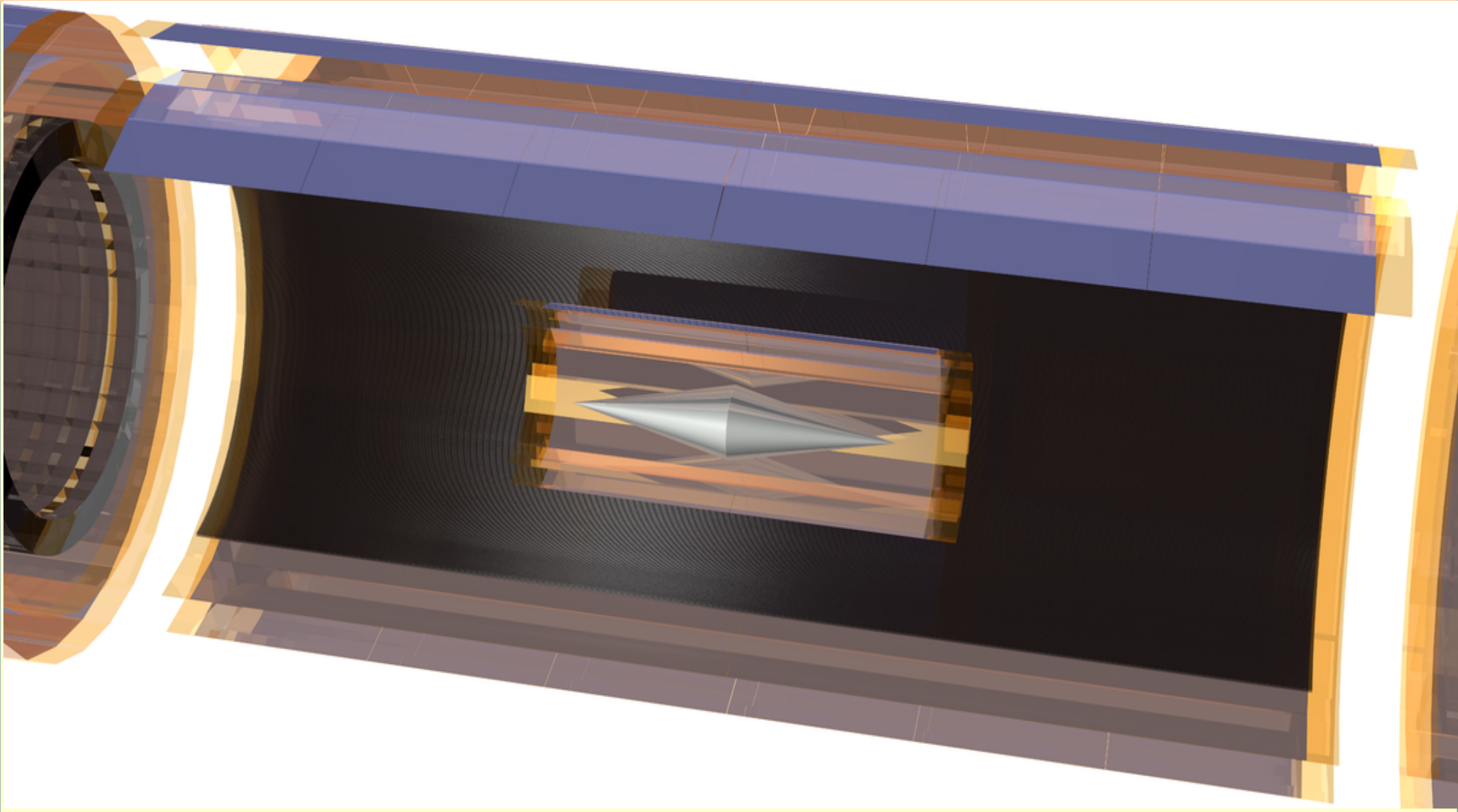


- Large area O(1m^2) fats monolithic pixel detectors with X/X_0 = 0.1% per tracking layer
- Novel helium gas cooling concept
- Thin scintillating fiber detector with ≤ 1mm thickness
- Timing resolution 100-500 ps
- Filter farm reconstructing and processing 10^8-10^9 tracks per second

Mu3e Detector



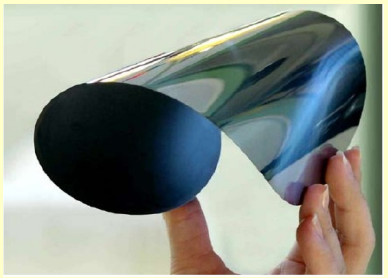
Mu3e Pixel Tracker



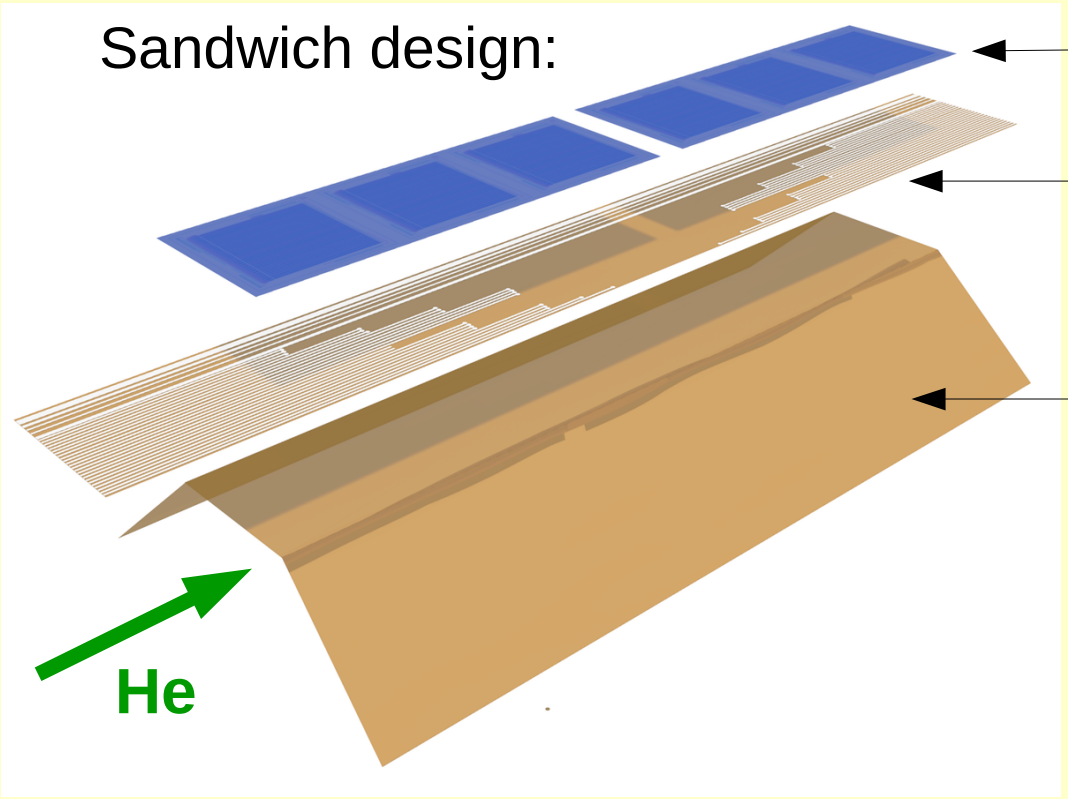
Mu3e Pixel Mechanics

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

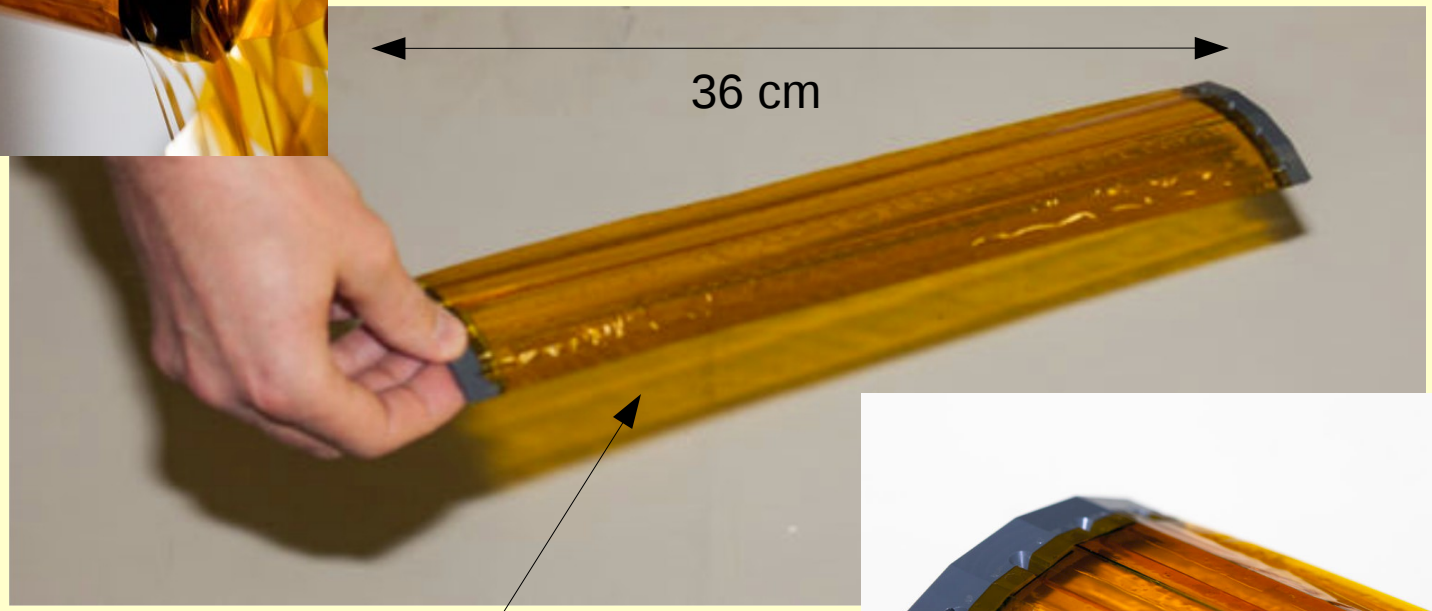
X ~ 0.1% X_0 per layer possible

Mechanical Mockups

Ultra-thin mechanical mockup:

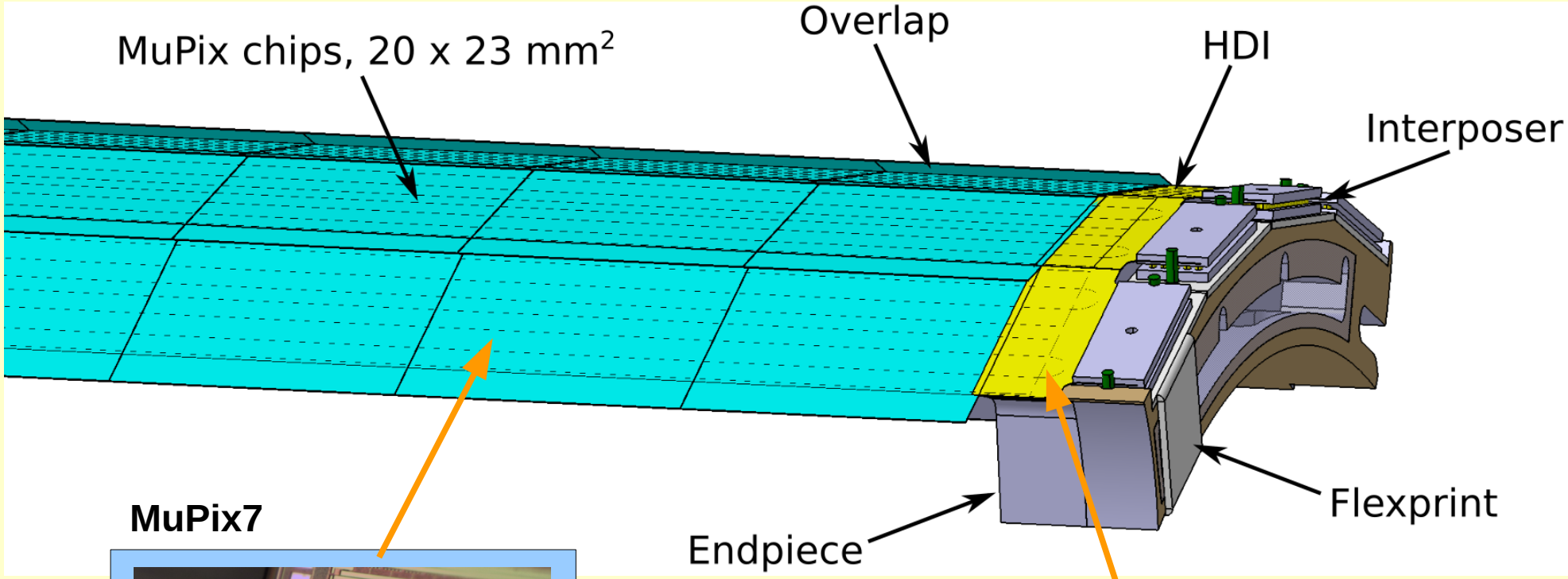
- sandwich of 25 µm Kapton®
- here 50 µm glass (instead of Si)

Even larger stable structures possible

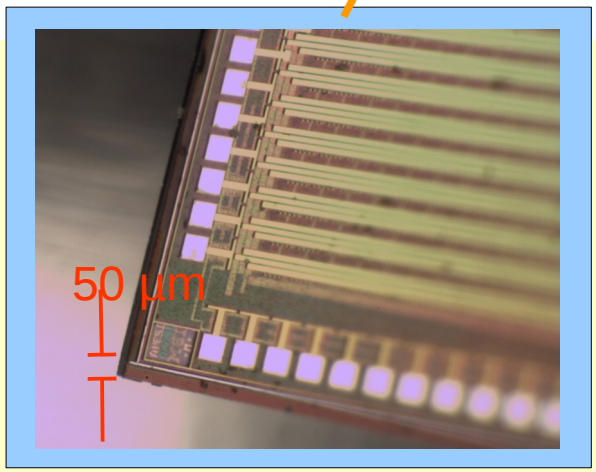


by using Kapton V-folds

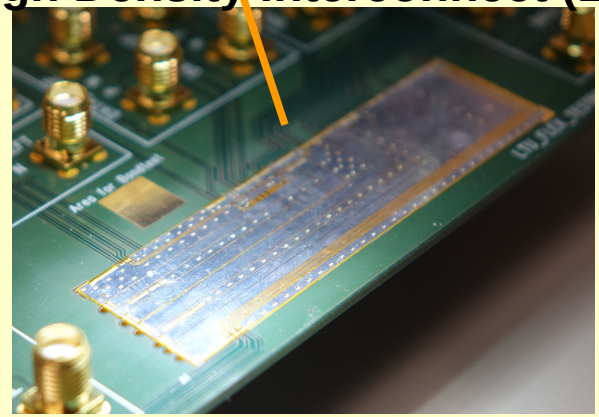
(Outer) Pixel Tracker Module



MuPix7

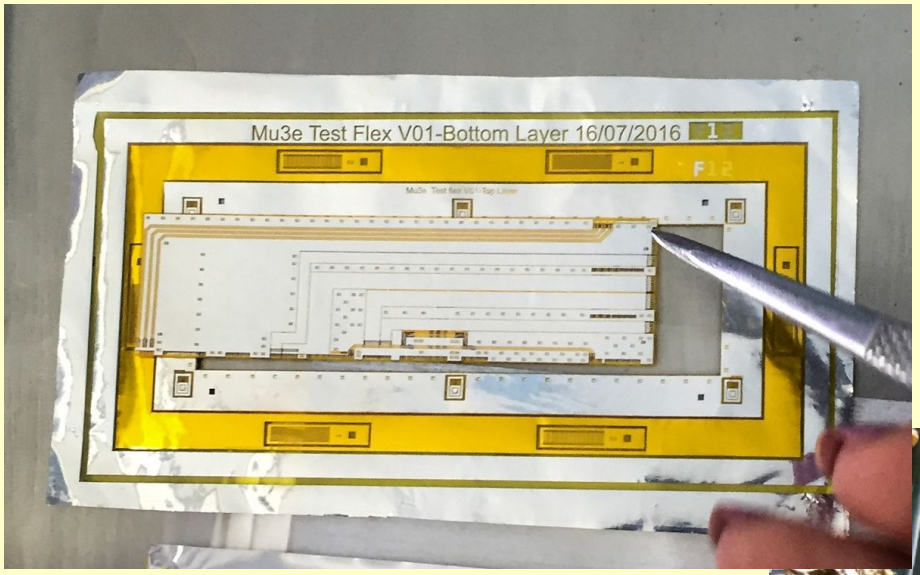


High Density Interconnect (LTU)



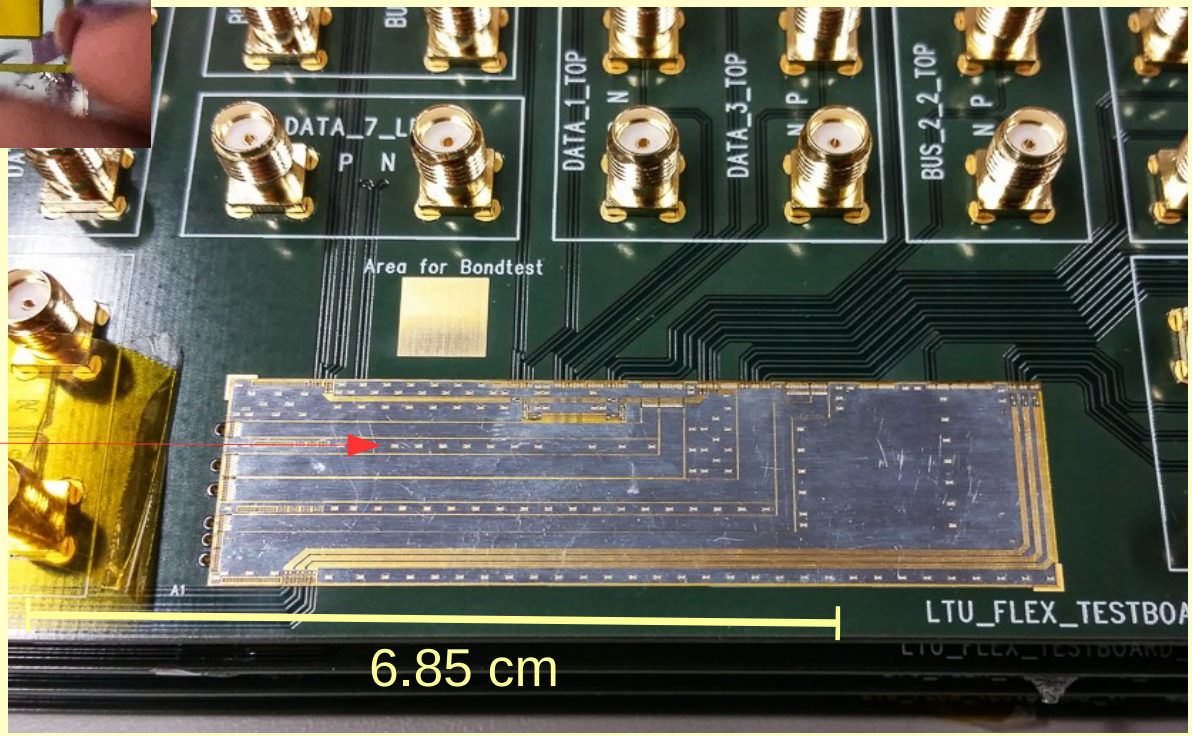
Flexprint Production and Bonding

FPC Production by LTU Ltd (Ukraine)

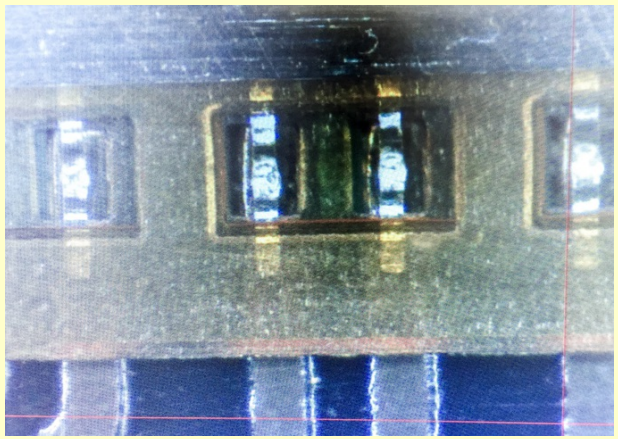


→ bonding yield 100%

FPC SpTAB bonded on test board

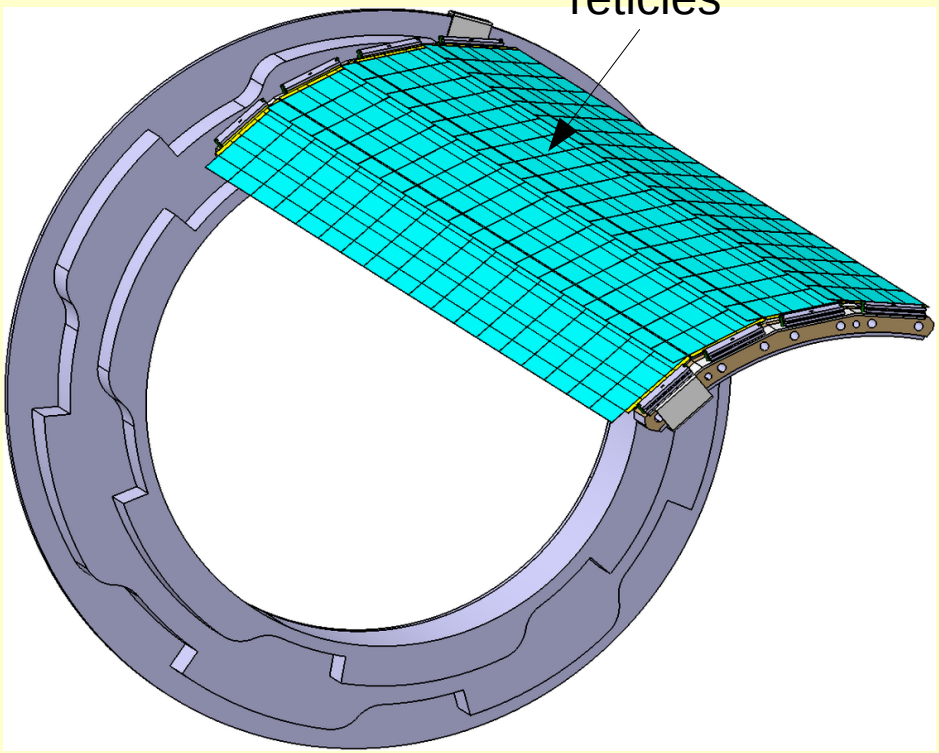


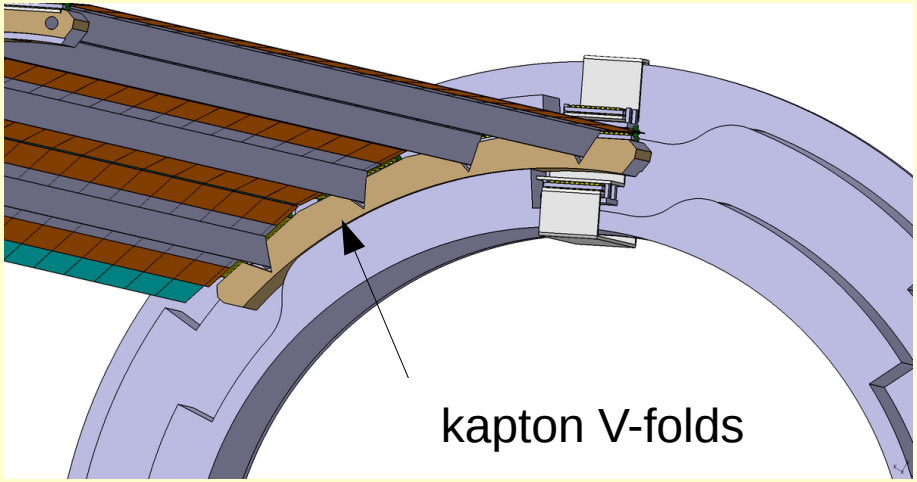
SpTAB bond zoomed in

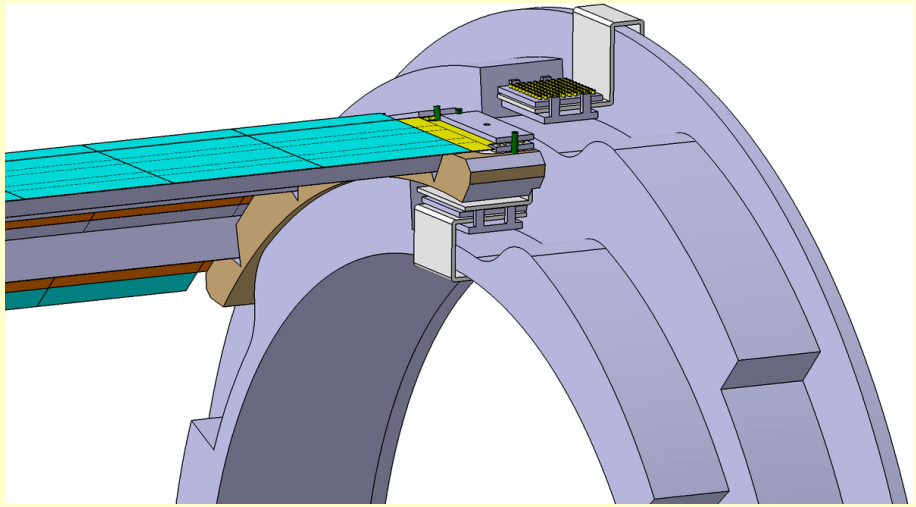


Pixel Module Design

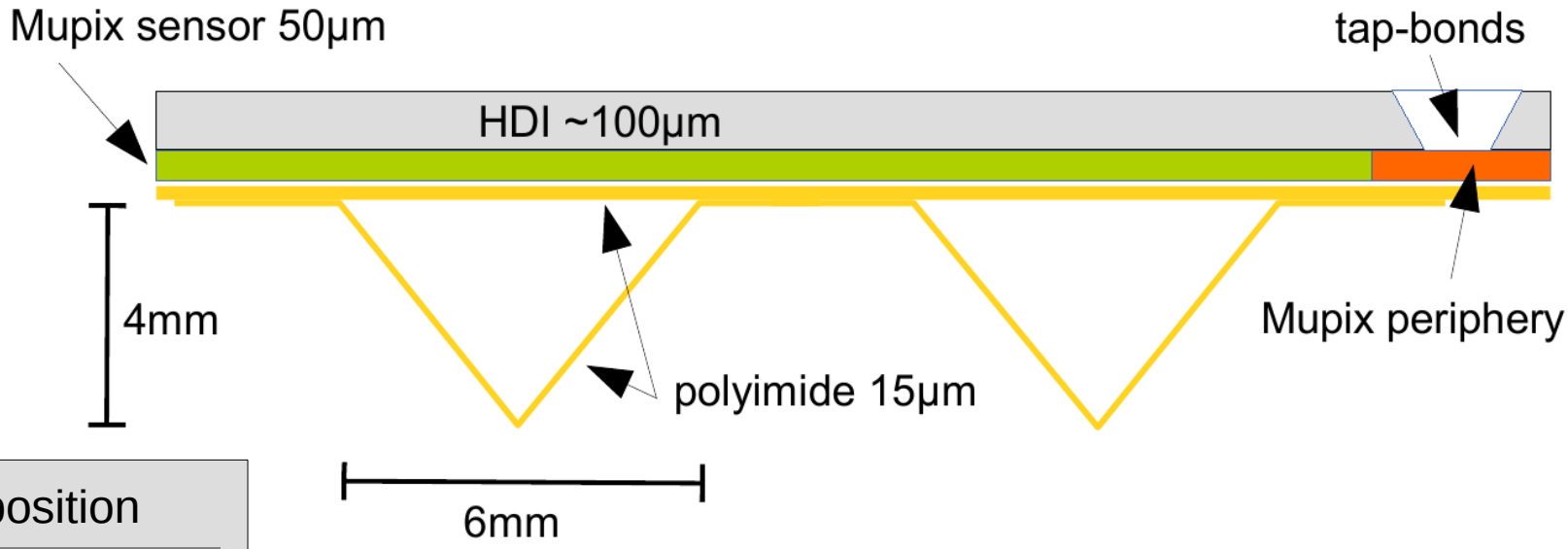
Outer pixel layers



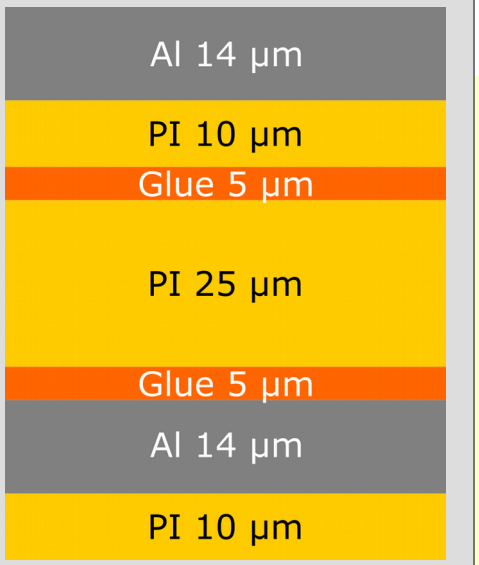




Ultralight Pixel Ladder



HDI composition



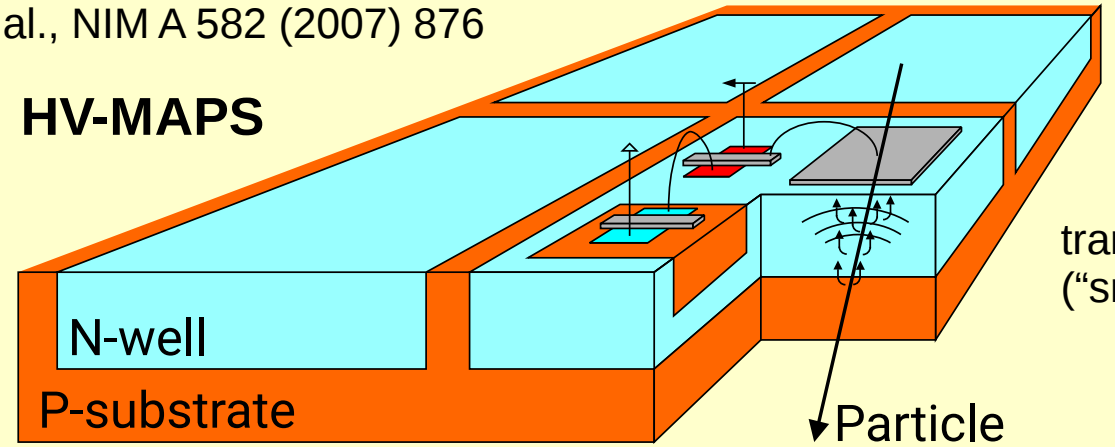
	Layer 1-2		Layer 3-4	
	thickness [µm]	X/X_0	thickness [µm]	X/X_0
MuPix Si	45	$0.48 \cdot 10^{-3}$	45	$0.48 \cdot 10^{-3}$
MuPix Al	5	$0.06 \cdot 10^{-3}$	5	$0.06 \cdot 10^{-3}$
HDI polyimide & glue	45	$0.18 \cdot 10^{-3}$	45	$0.18 \cdot 10^{-3}$
HDI Al	28	$0.31 \cdot 10^{-3}$	28	$0.31 \cdot 10^{-3}$
polyimide support	25	$0.09 \cdot 10^{-3}$	≈ 30	$0.10 \cdot 10^{-3}$
adhesives	10	$0.03 \cdot 10^{-3}$	10	$0.03 \cdot 10^{-3}$
total	158	$1.15 \cdot 10^{-3}$	163	$1.16 \cdot 10^{-3}$

module: ~ 1 per mill radiation length

The MuPix Sensor for Mu3e

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

HV-MAPS

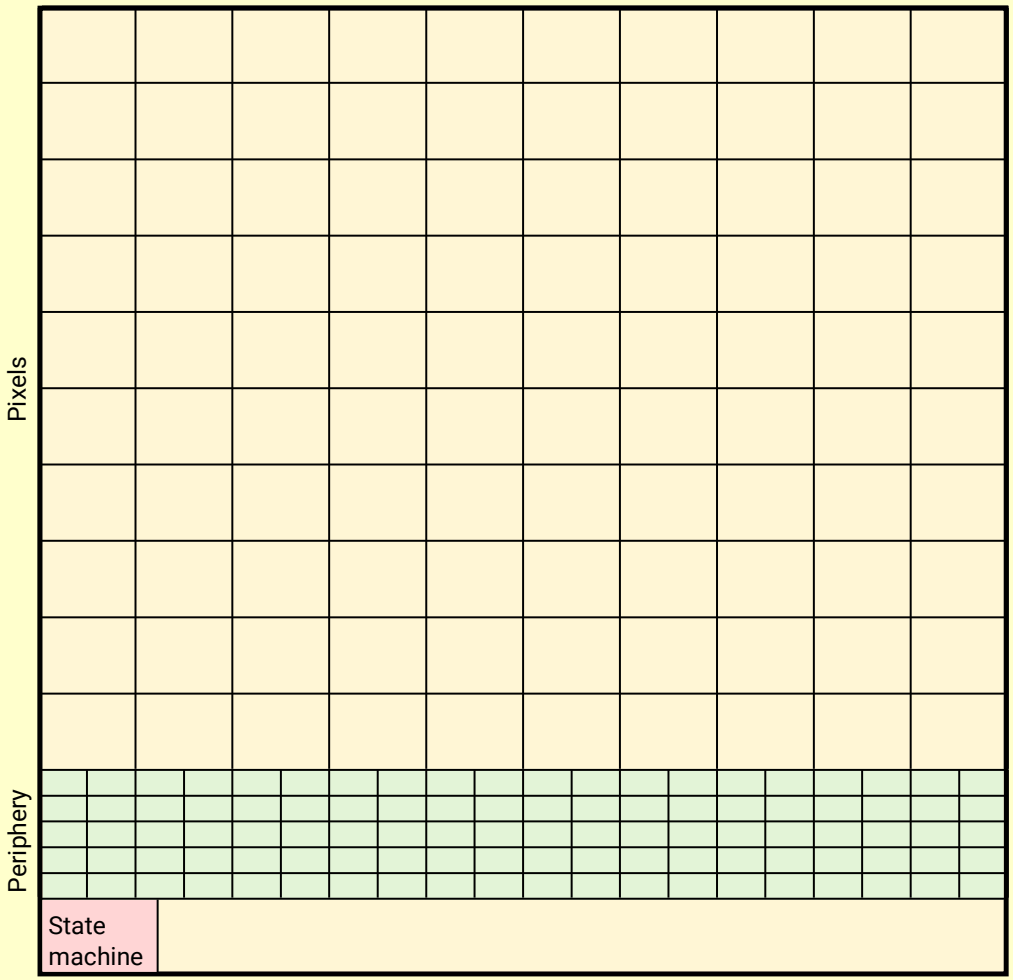


transistor logic embedded in N-well
("smart diode array")

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

- **active sensor → hit finding + digitisation + zero suppression + readout**
- high precision → pixels 80 x 80 μm²
- 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



cells

active pixel matrix

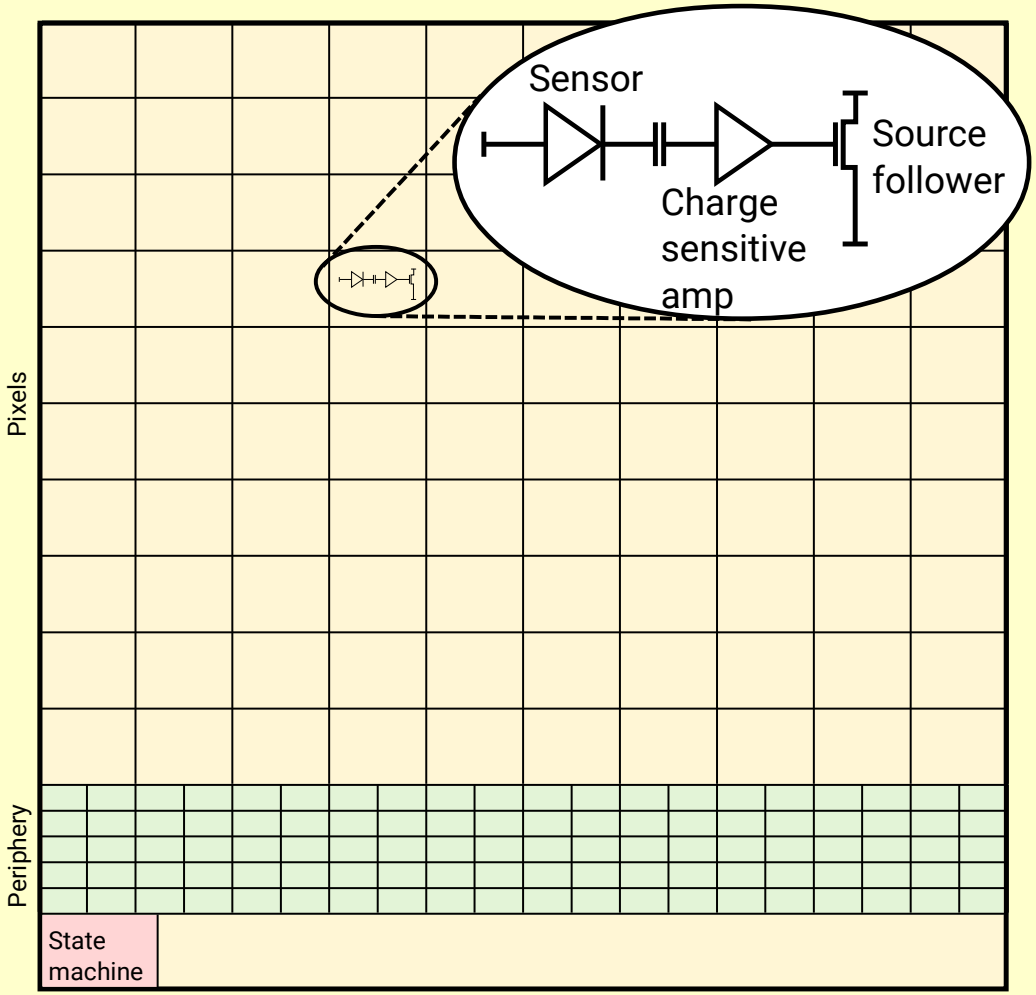
“mirror” cells

state machine

VCO, PLL, ...

periphery
(5-10% total area):

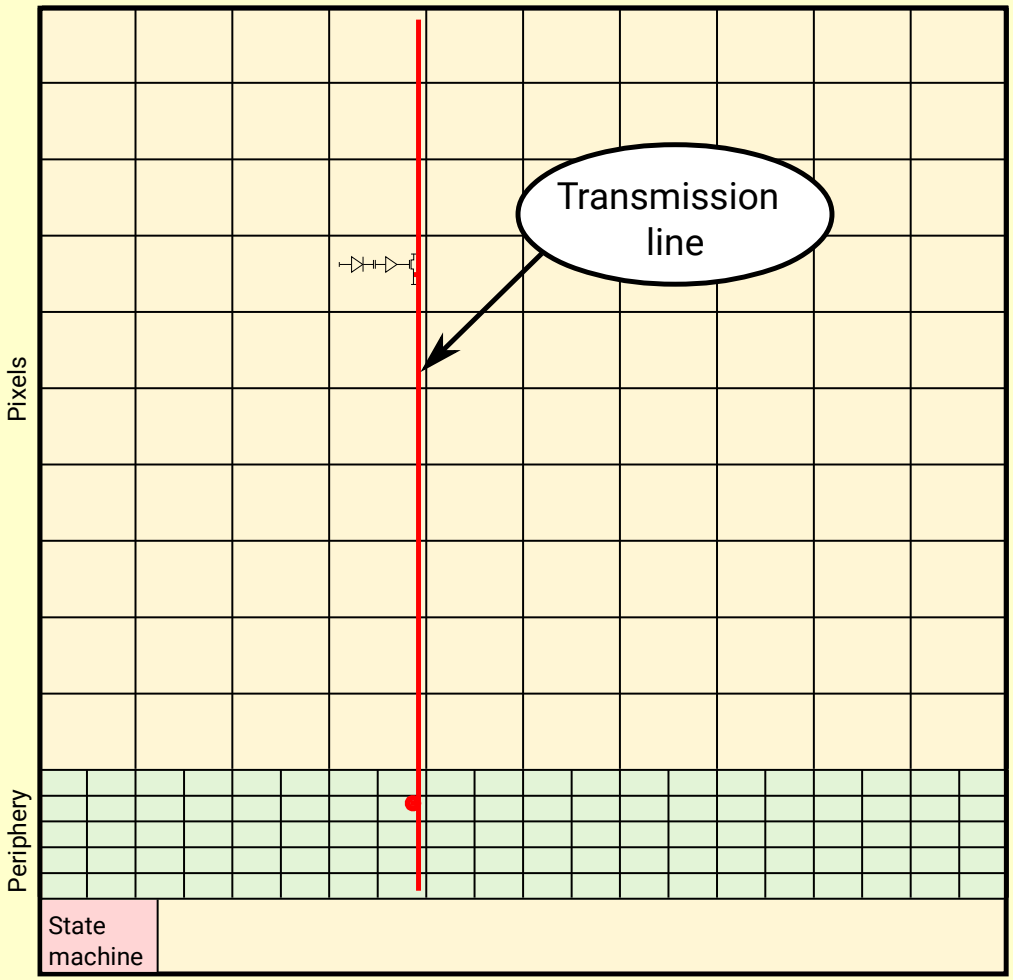
MuPix Chip Design



analog cell:

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

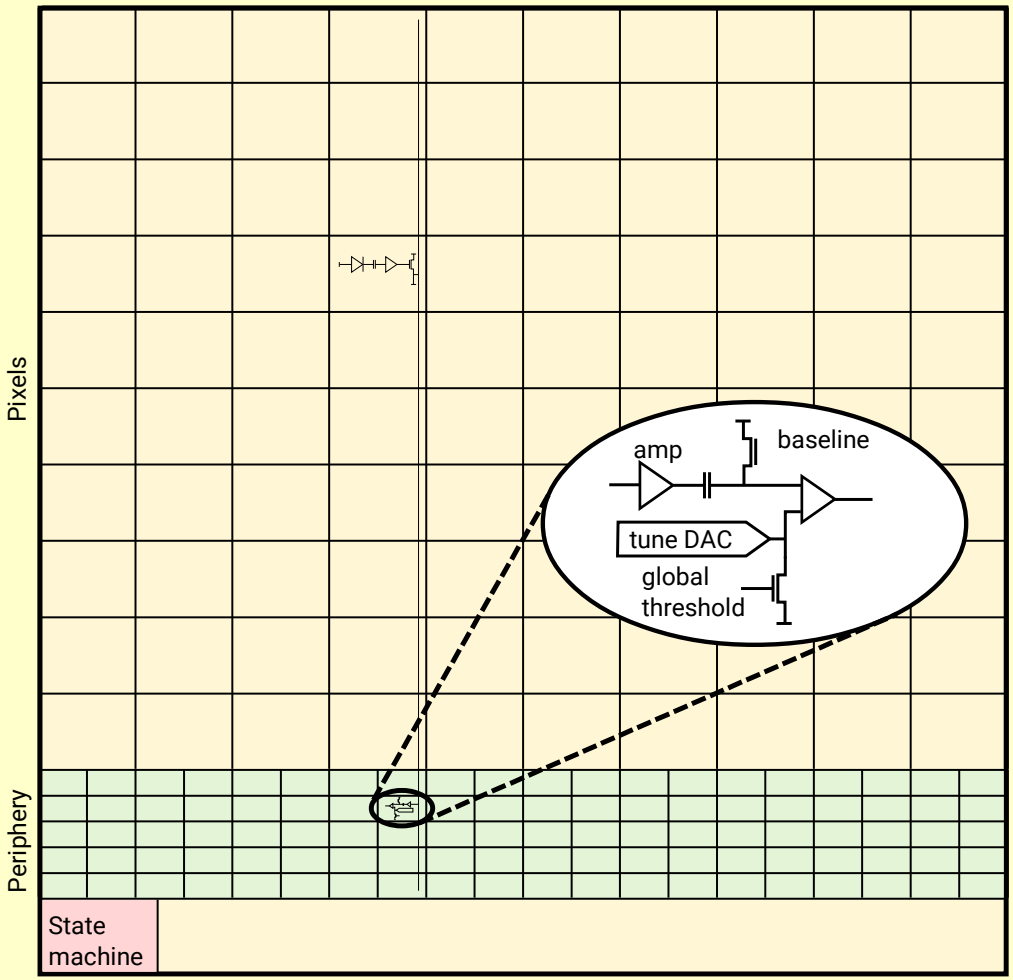
MuPix Chip Design



transmission line:

- send signal to corresponding mirror cell

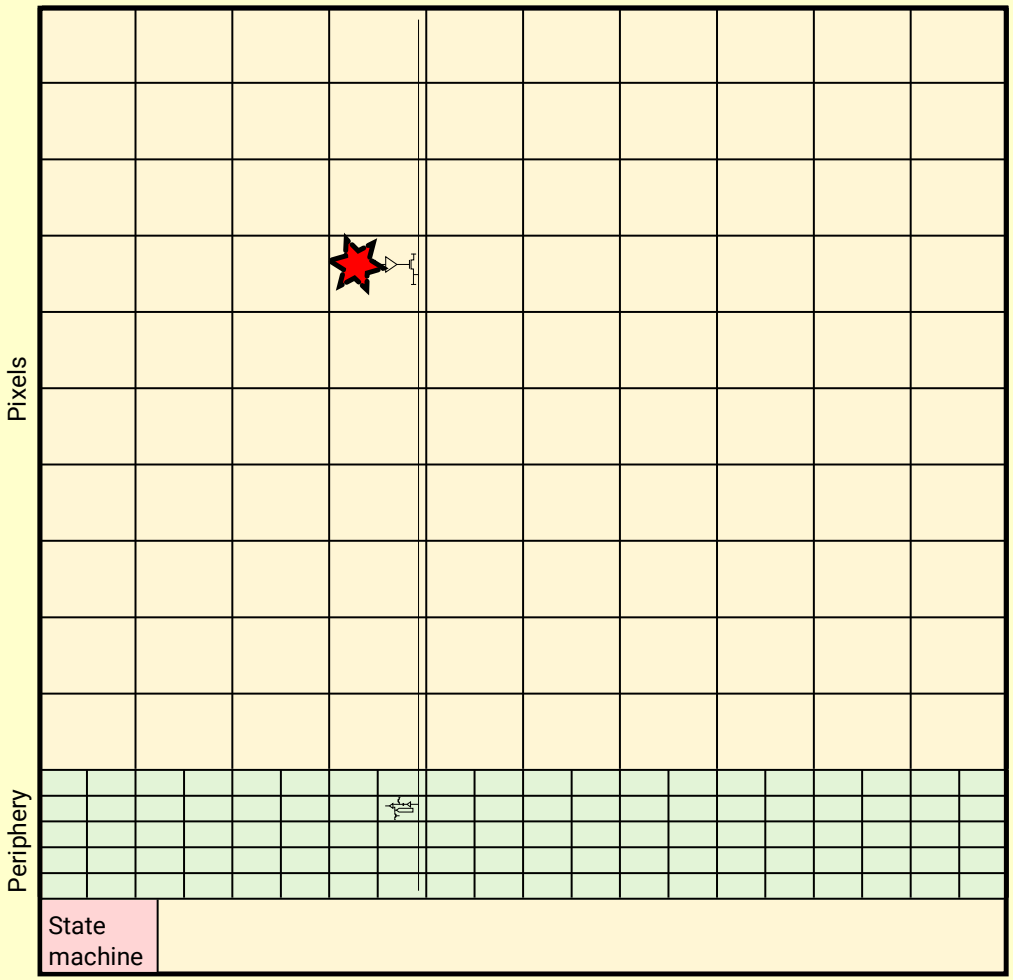
MuPix Chip Design



mirror cell:

- 2nd amplifier (Mupix7)
- comparator for discrimination
- threshold and baseline by tuning DACs

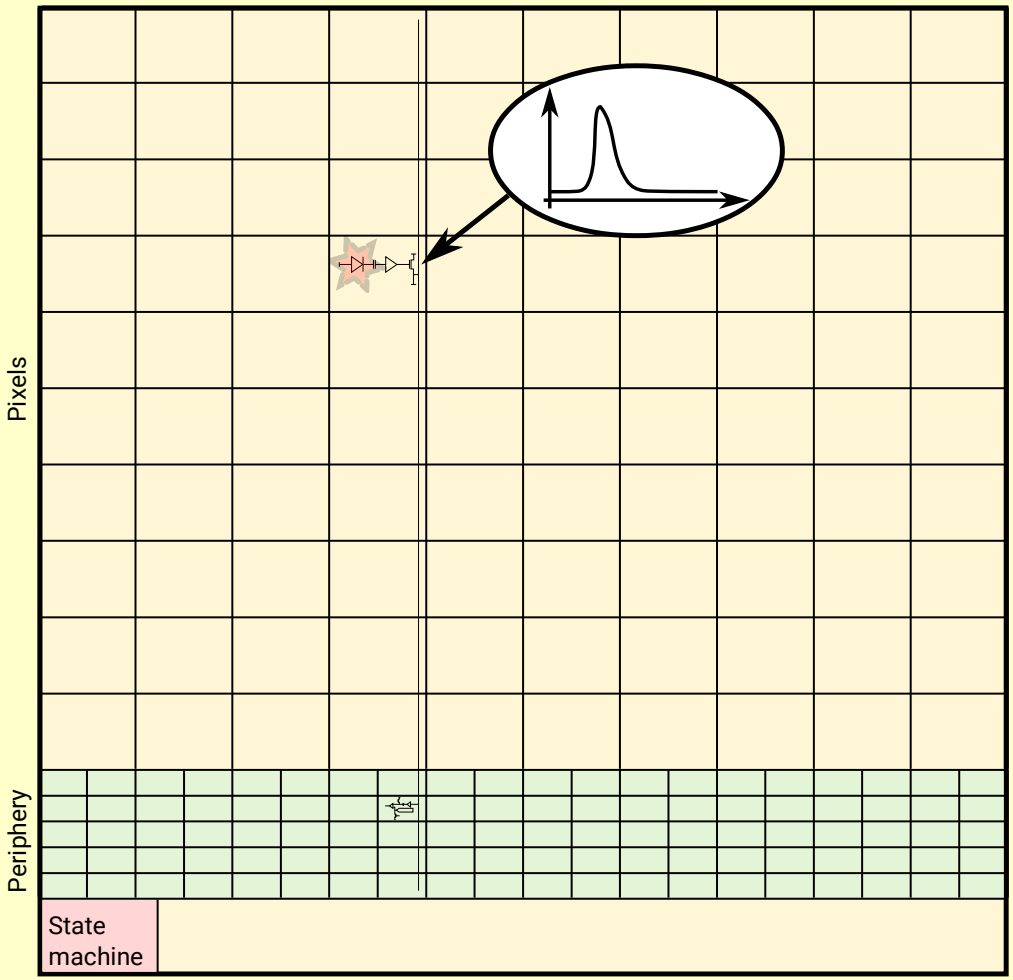
MuPix Hit Detection



hit sequence:

- signal generation

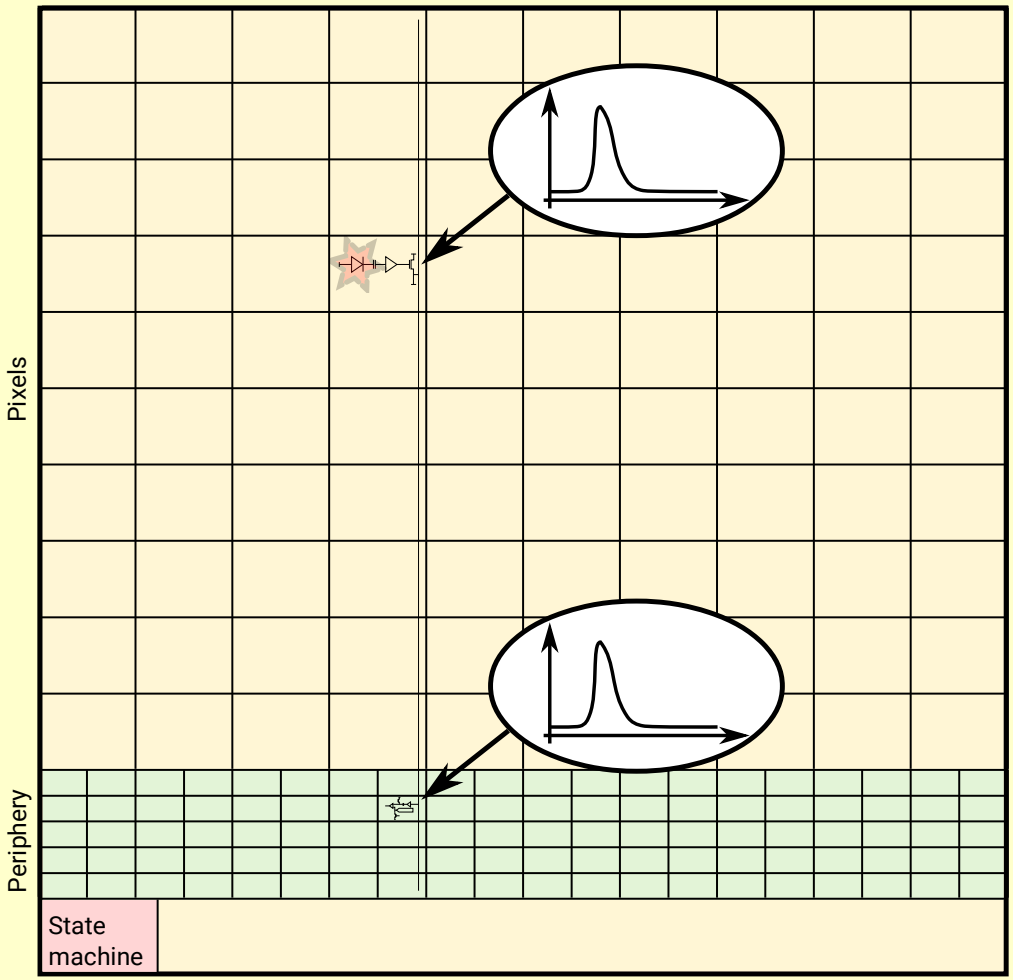
MuPix Hit Detection



hit sequence:

- signal generation
- amplification

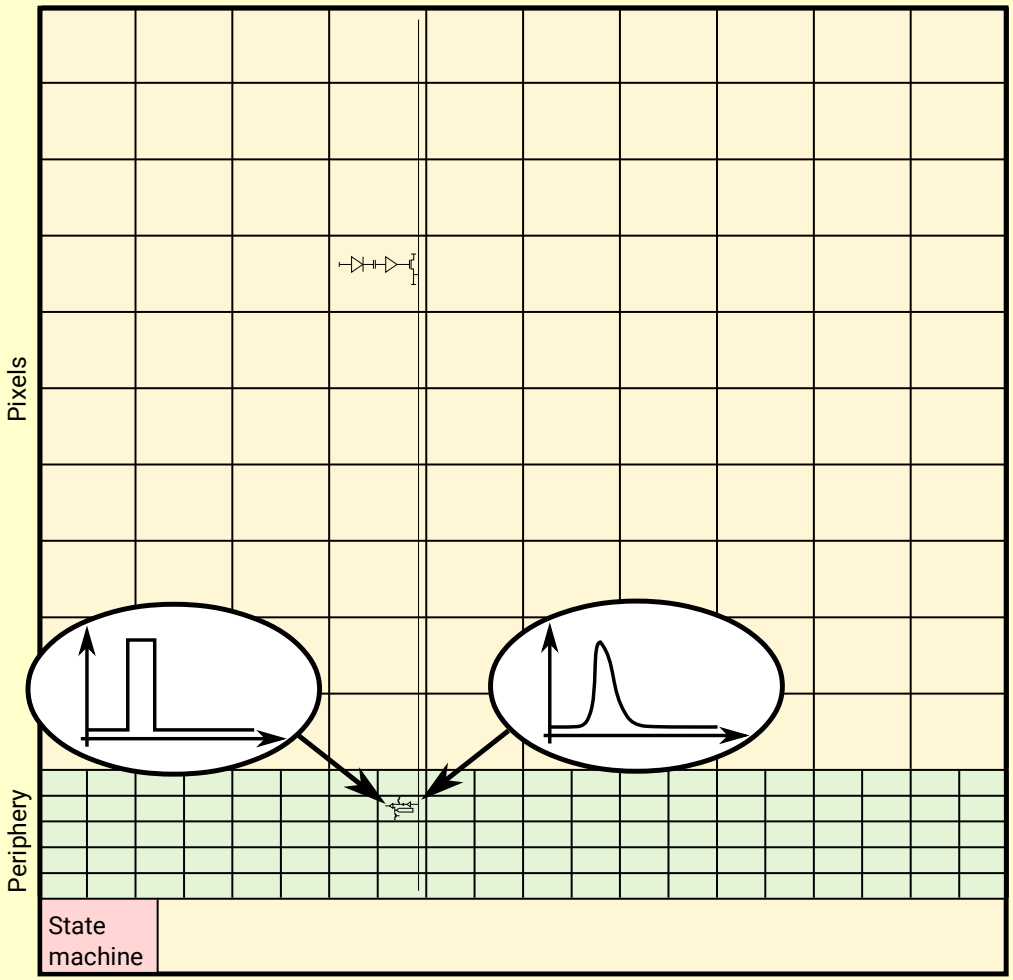
MuPix Hit Detection



hit sequence:

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

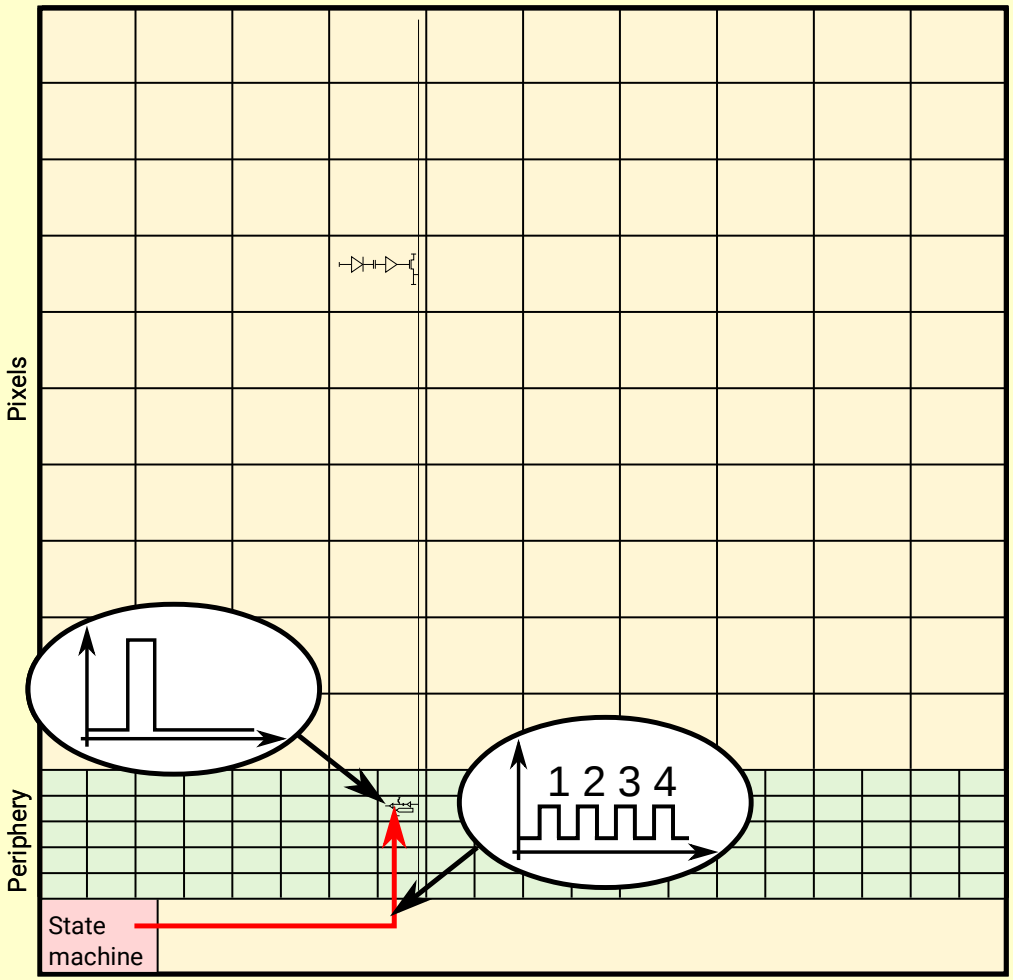
MuPix Hit Detection



hit sequence:

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

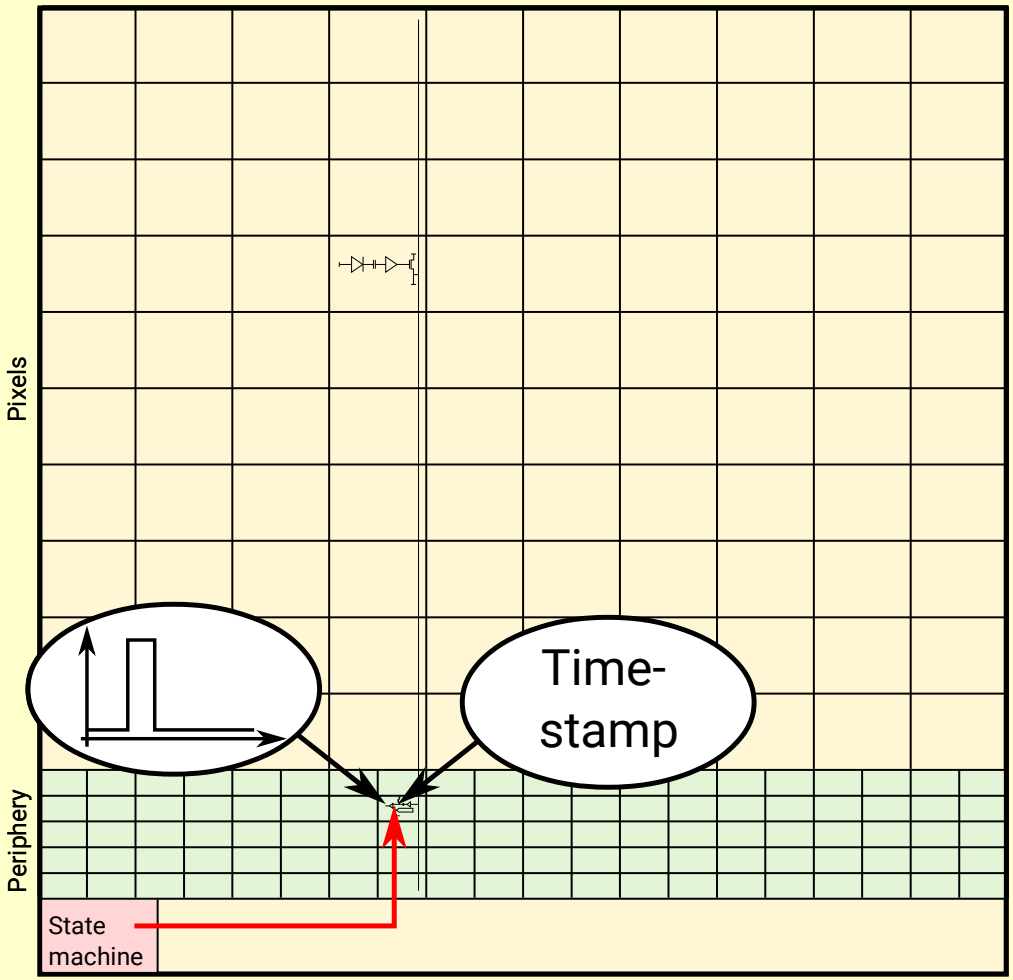
MuPix Hit Detection



hit sequence:

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

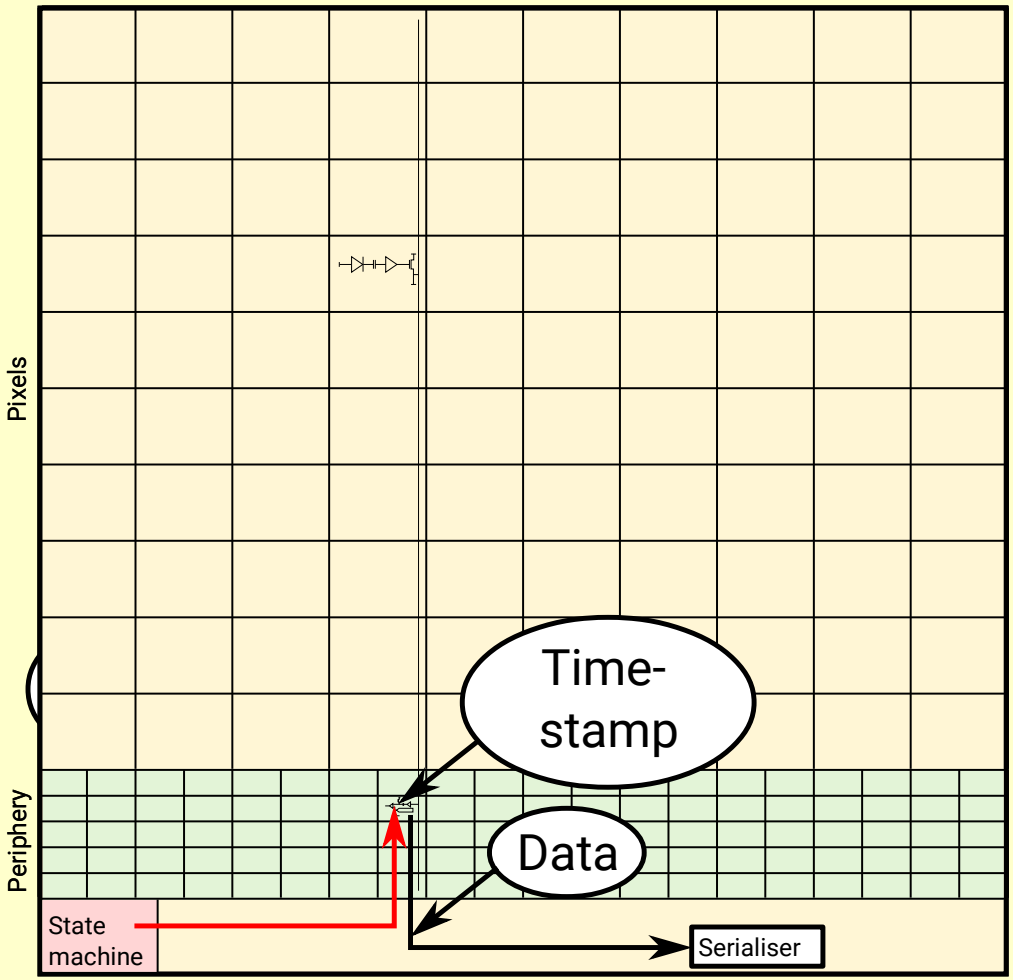
MuPix Hit Detection



hit sequence:

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

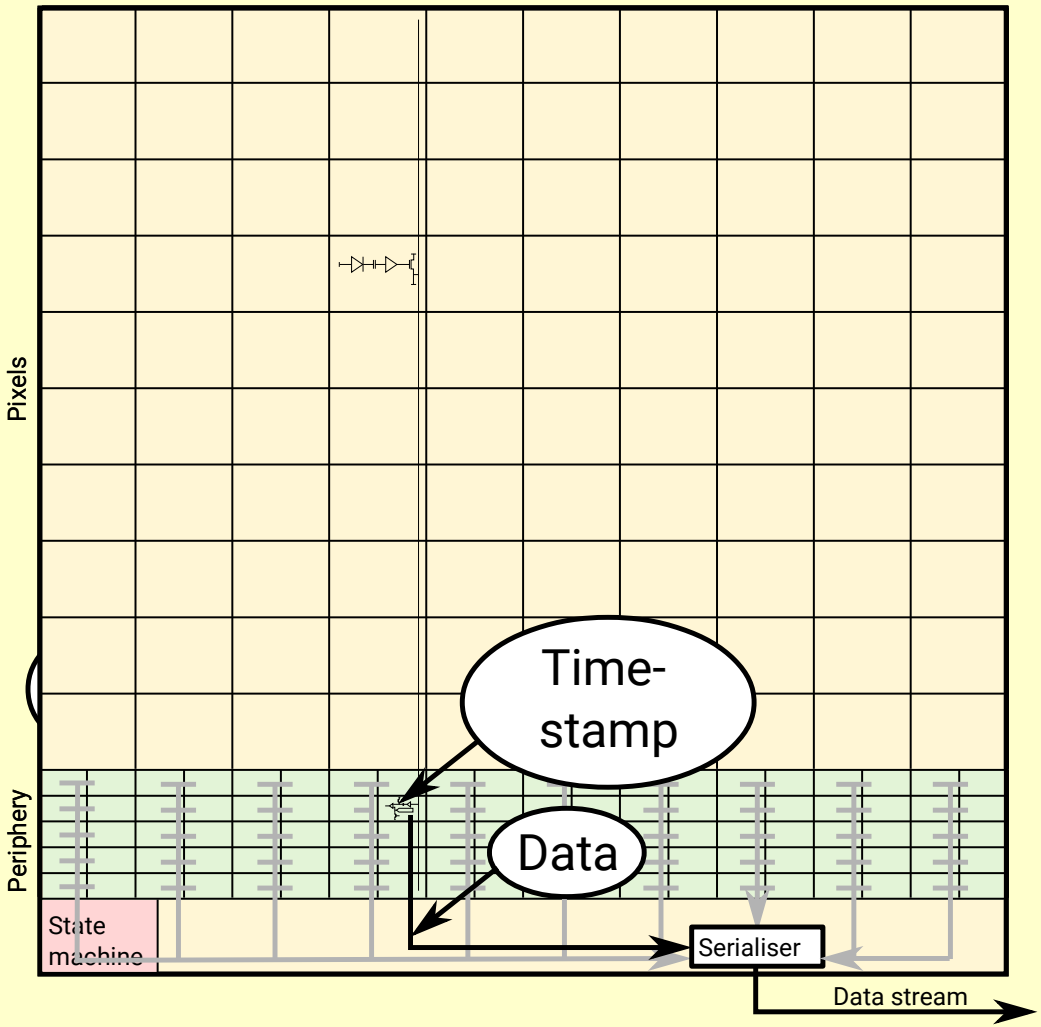
MuPix Hit Detection



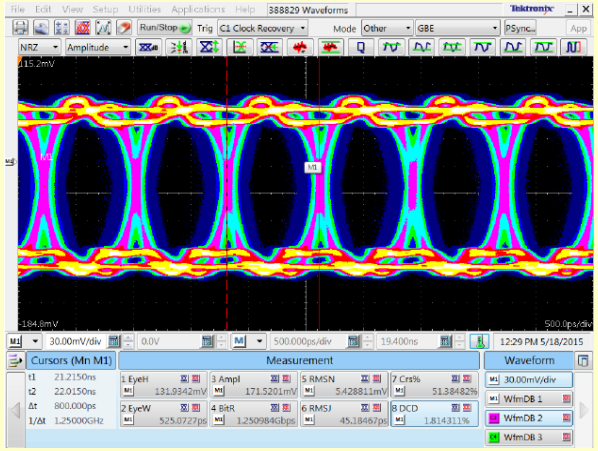
hit sequence:

- 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 (1.6) Gbit/s** serial link

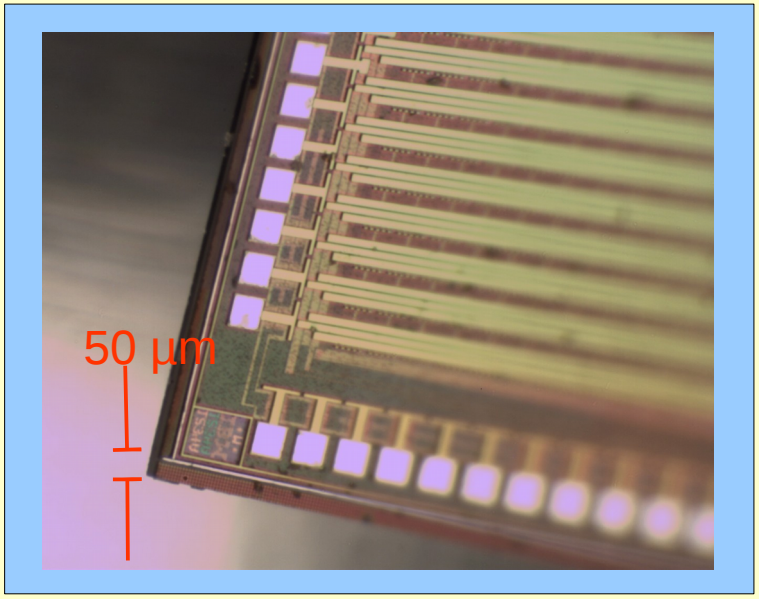


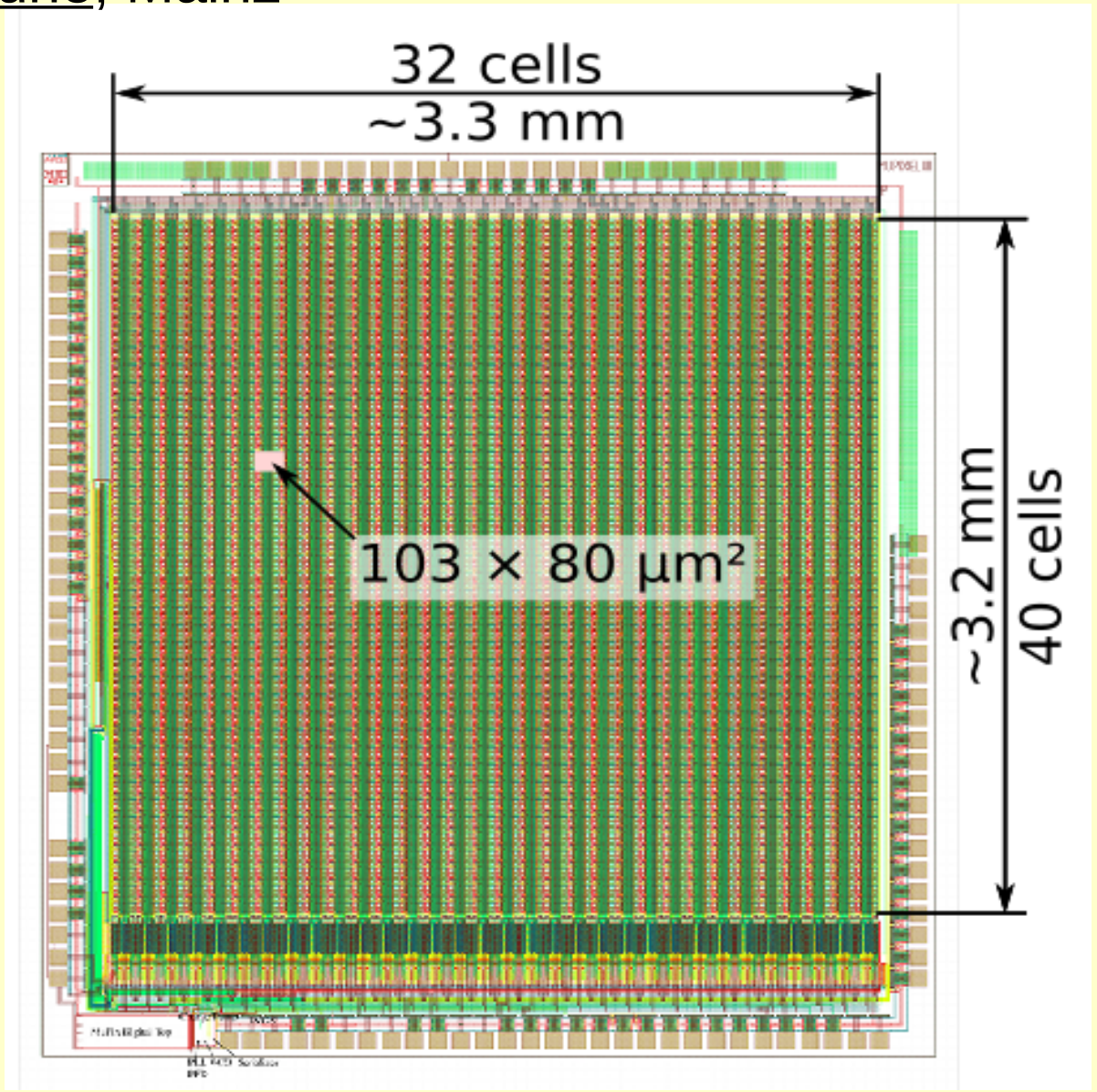
Eye diagram measured with Mupix7 prototype

Maximum readout rate is 33 Mhits/s per link

MuPix7 Prototype

Institutes: Heidelberg, Karlsruhe, Mainz





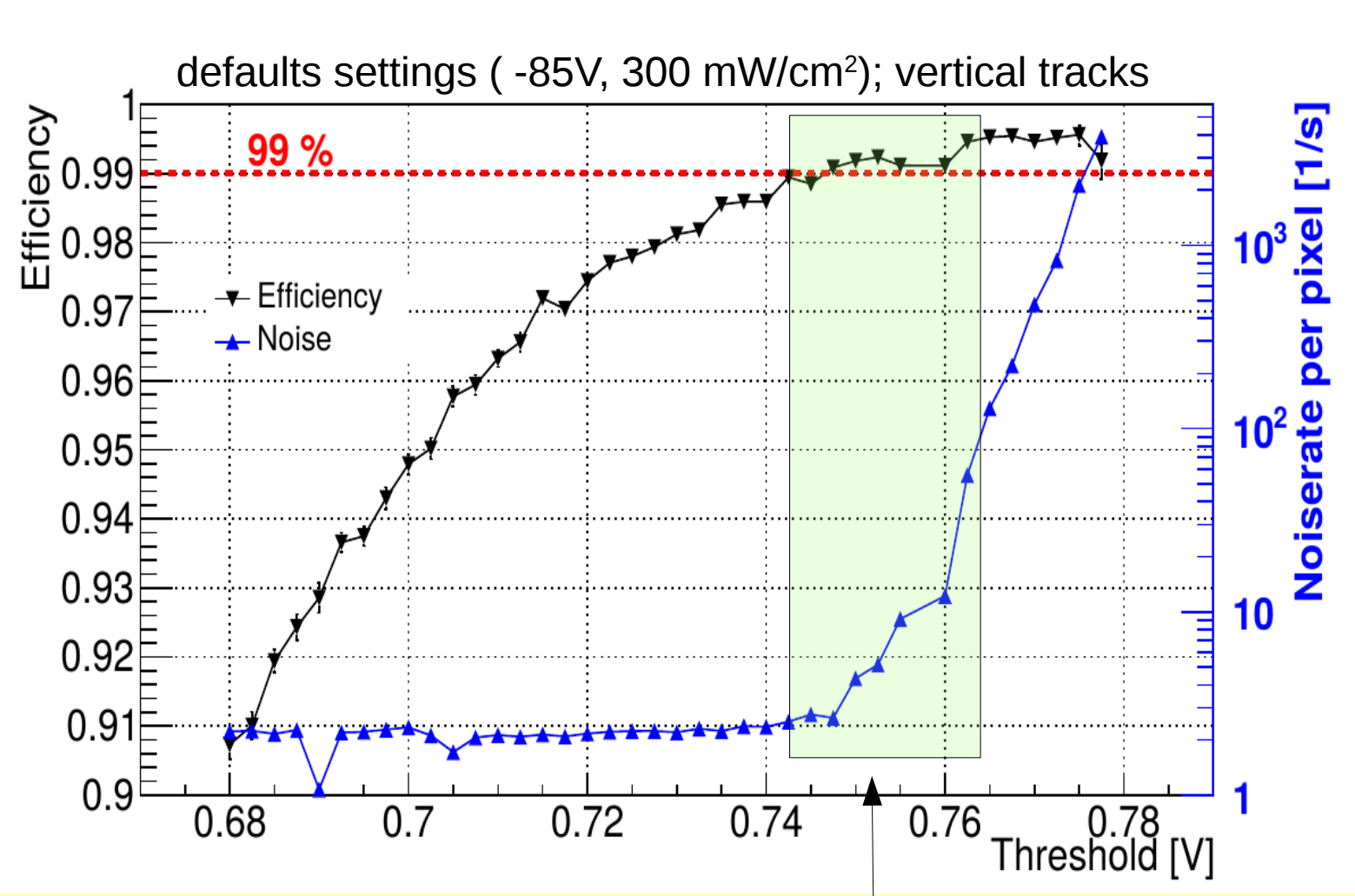
Austria Microsystems (AMS)

HV-CMOS 180 nm

20 Ωcm p-substrate

MuPix7 Efficiency and Noise

Data obtained from PSI beamtest (PiM1) using MuPix telescope

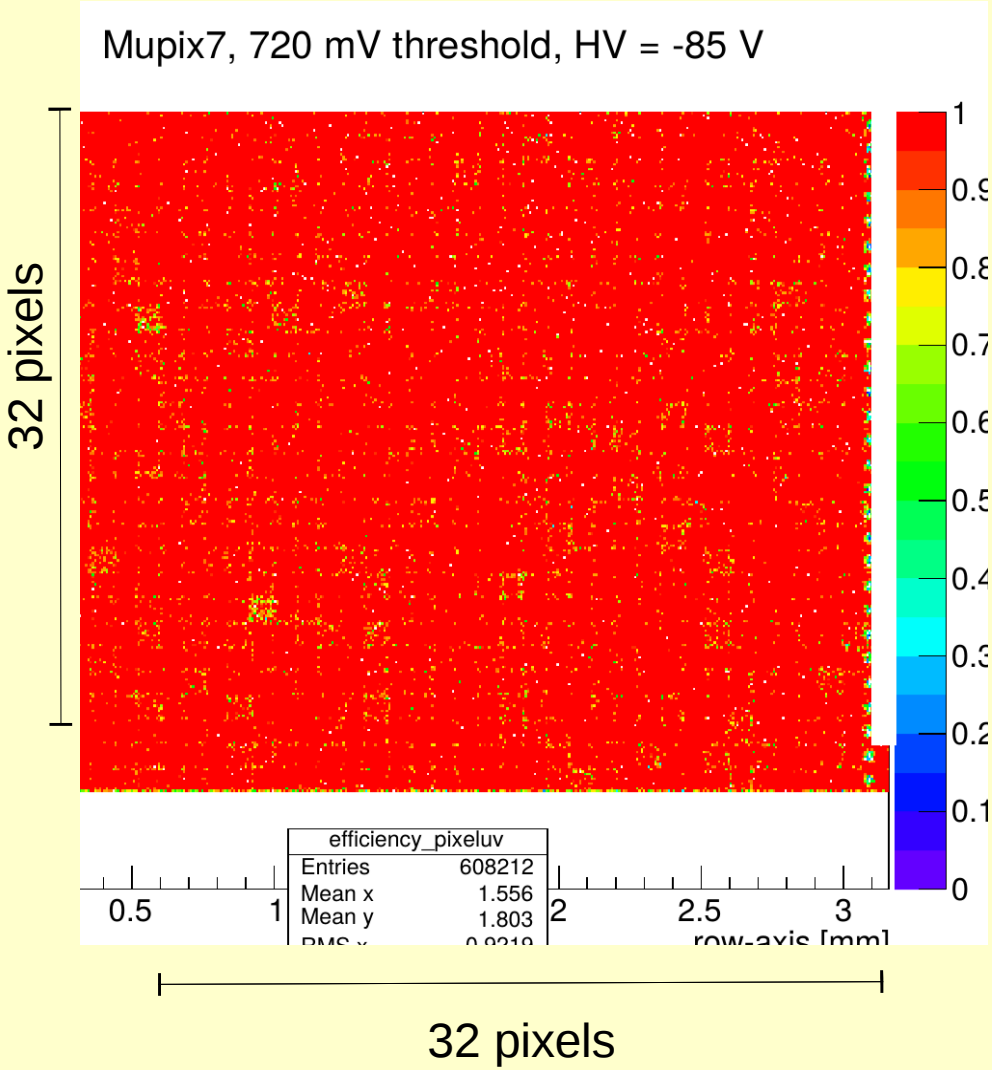


Mu3e noise limit $<10^{-6}$

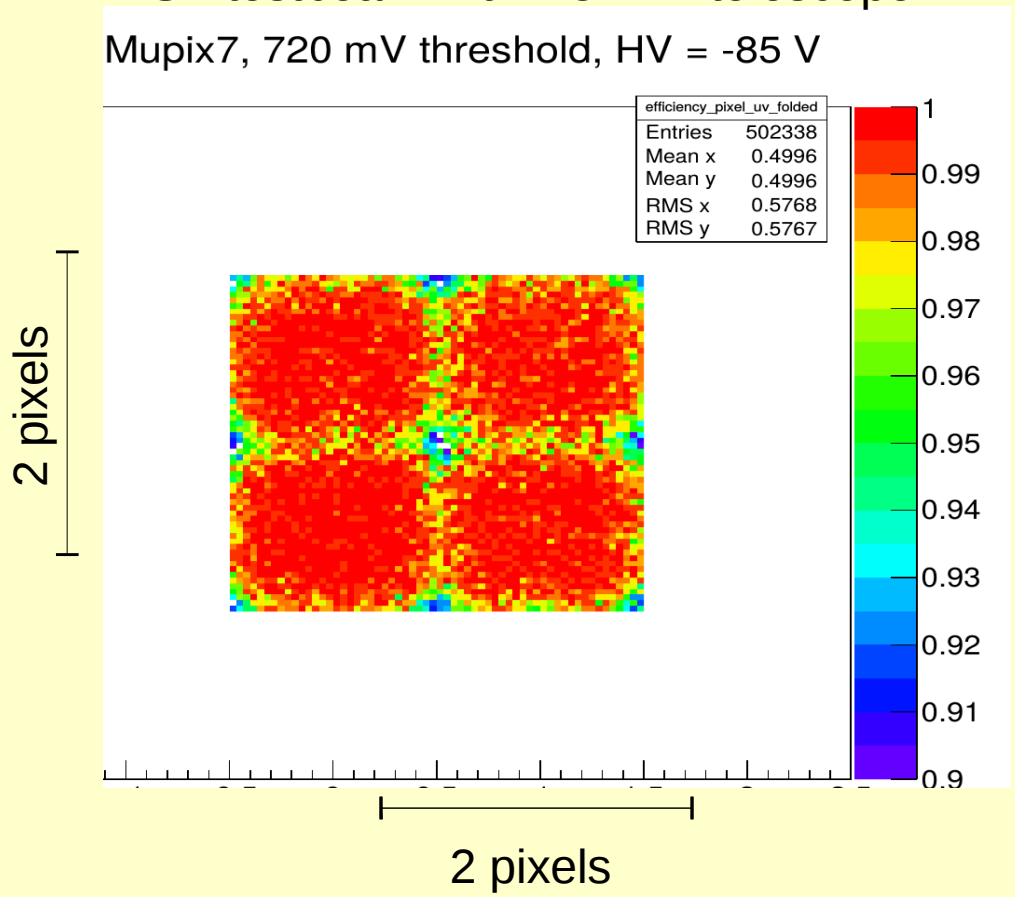
operation region

MuPix7 (In-)Efficiency Investigations

Efficiency map with increased threshold



DESY testbeam with EUDET telescope

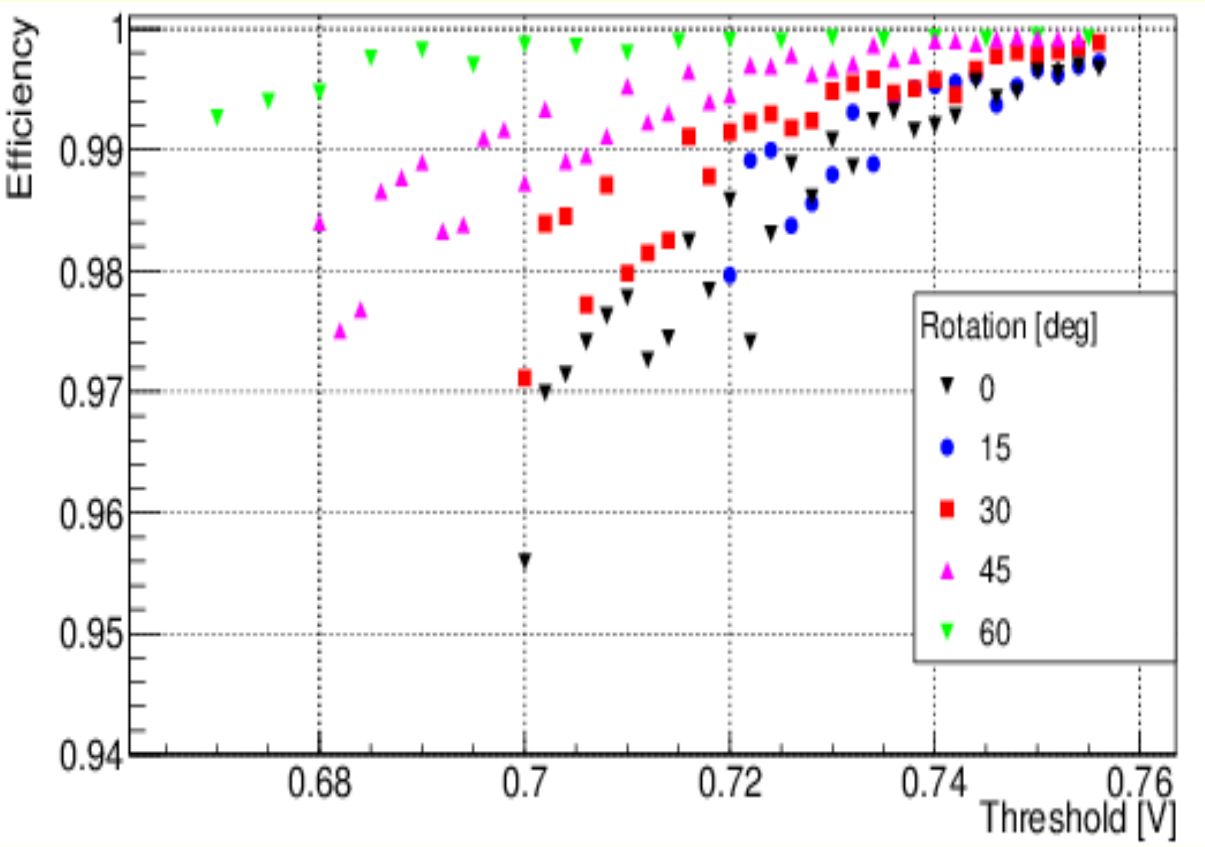


inefficiency due to charge sharing at edges and corners

Efficiency with Rotated Sensors

Increase deposited ionisation charge by using tilted sensor

default settings; -85V; ±48ns search window

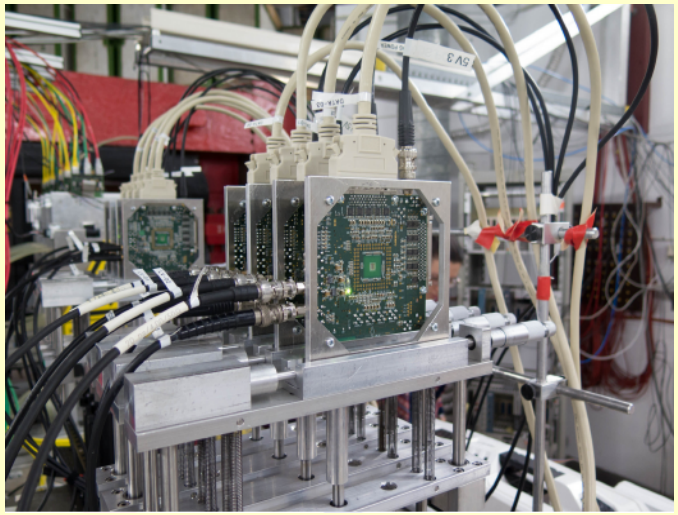


with factor 2 more charge (rot=60°) → ~100% efficiency

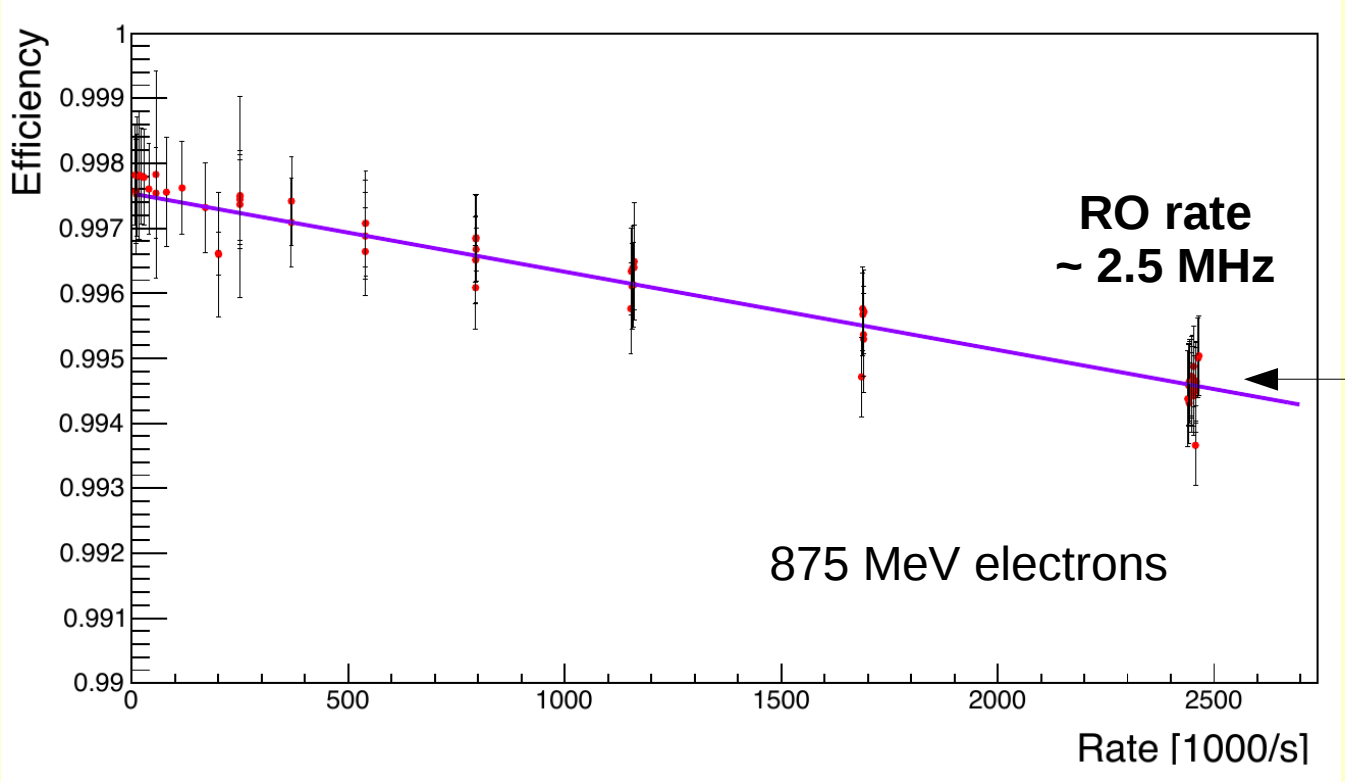
MuPix Telescopes + Rate Tests

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

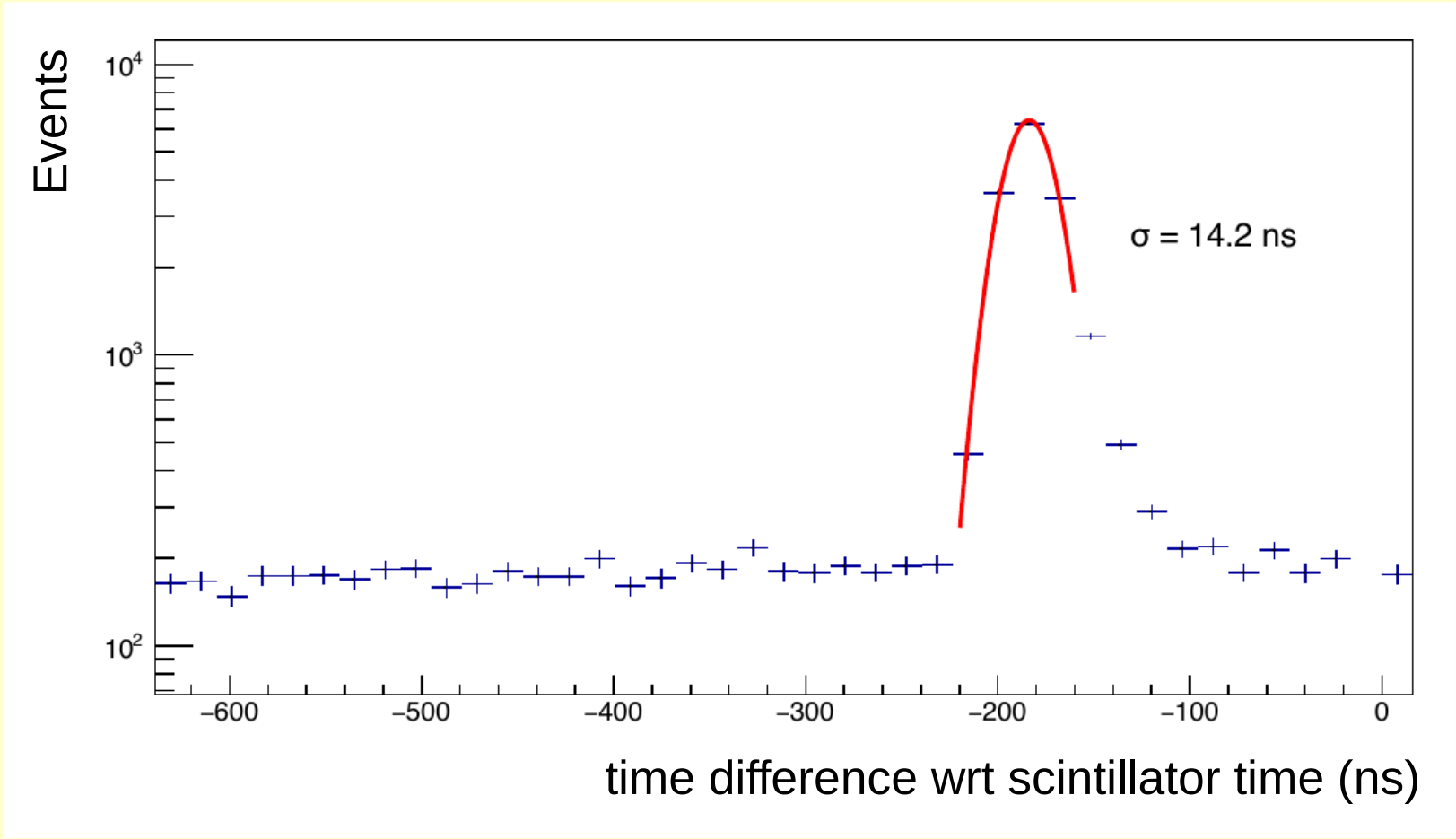
- **875 MeV e^-**
- maximum rate rate of **2.5 MHz / 5x5 pixels**
- corresponds to **780 Mhits/cm²/s**

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

MuPix7 Time Resolution

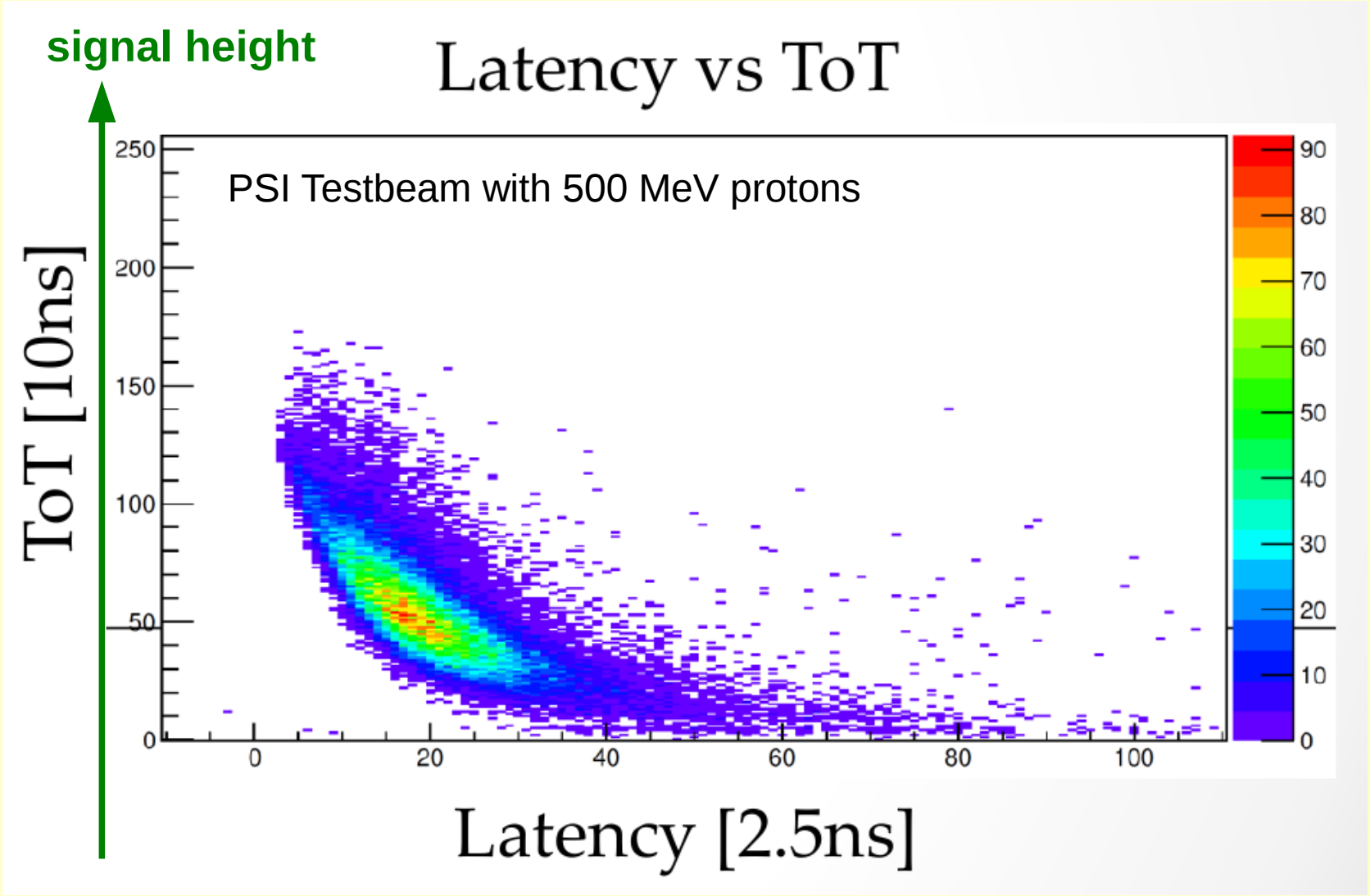
MuPix telescope with scintillator as time reference:

default settings; -85V; 300 mW/cm^2



Mu3e requirement sigma (t) < 20 ns fulfilled

MuPix7 Time Resolution

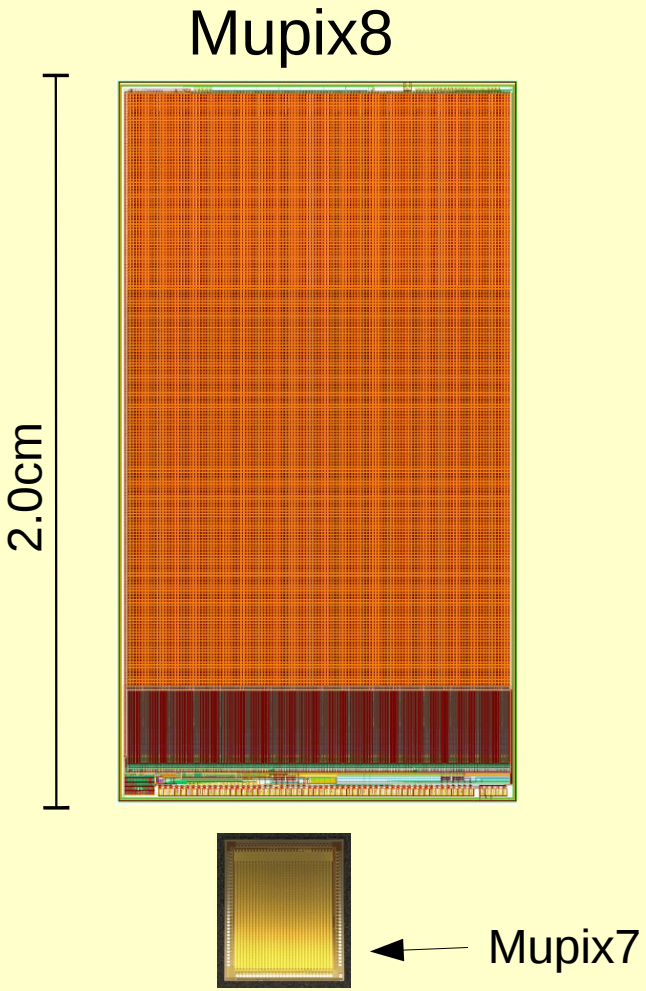


→ timewalk correction possible

→ in test chips: σ(t) ~ 5 ns (I. Peric et al., KIT)

Mupix8 Prototype

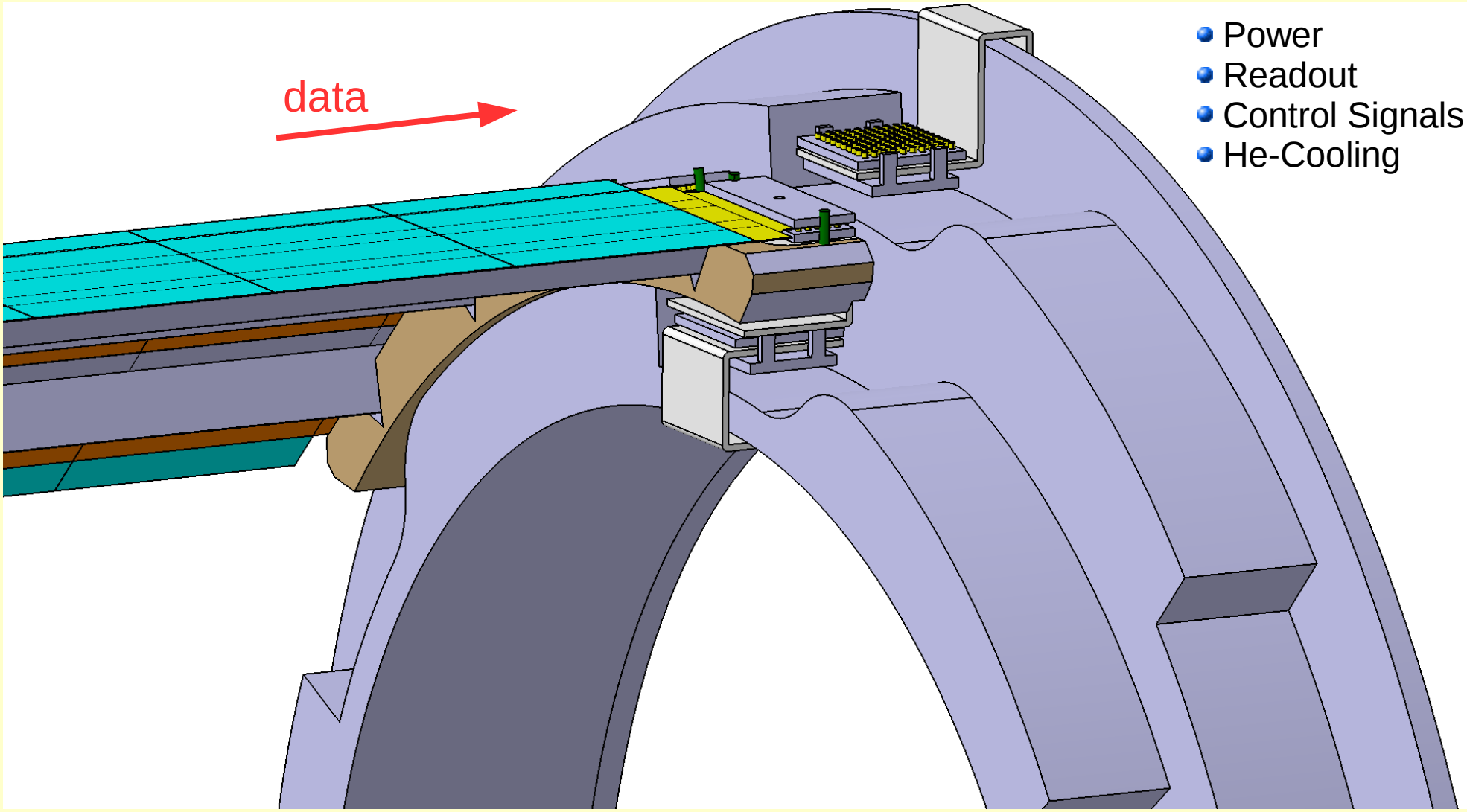
Mupix8 submission in AMS HV-CMOS 180nm (chips expected mid April)
(Heidelberg, Karlsruhe, Mainz)



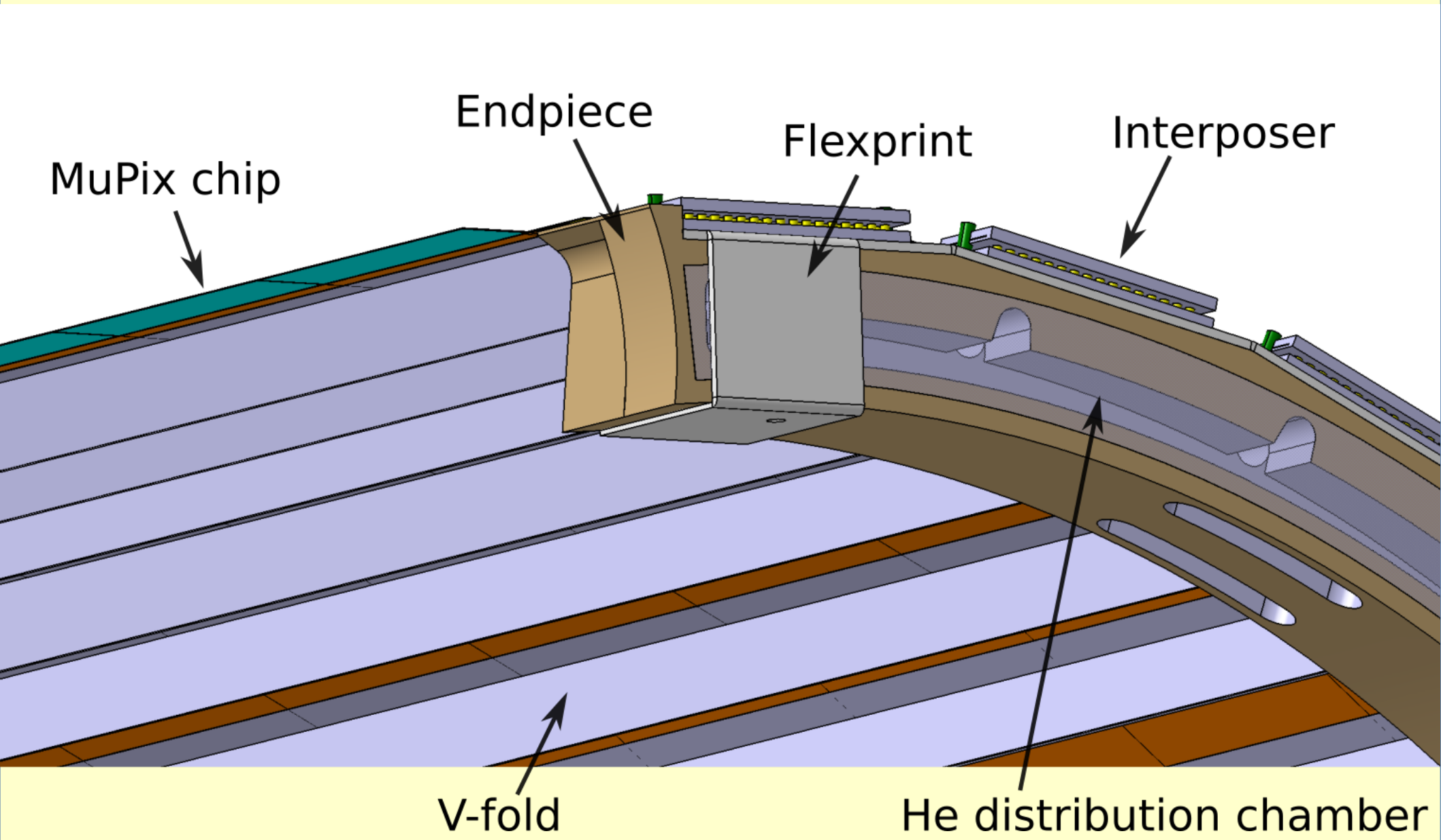
Features and improvements wrt Mupix7

- 31250 pixel of size 80 x 80 µm²
- only 36 bond-pads per chip (+ test pads)
- four serial links a 1.25 Gbps
- two time walk correction schemes
  - ➔ 2-thresholds method
  - ➔ ToT with voltage ramp
- substrate: 80 Ωcm (before 20 Ωcm)
  - ➔ larger depletion
- current drivers for transmission lines
- some fixes and changes:
  (cross talk, state machine, no 2nd amplifier...)

Pixel Tracker Endrings

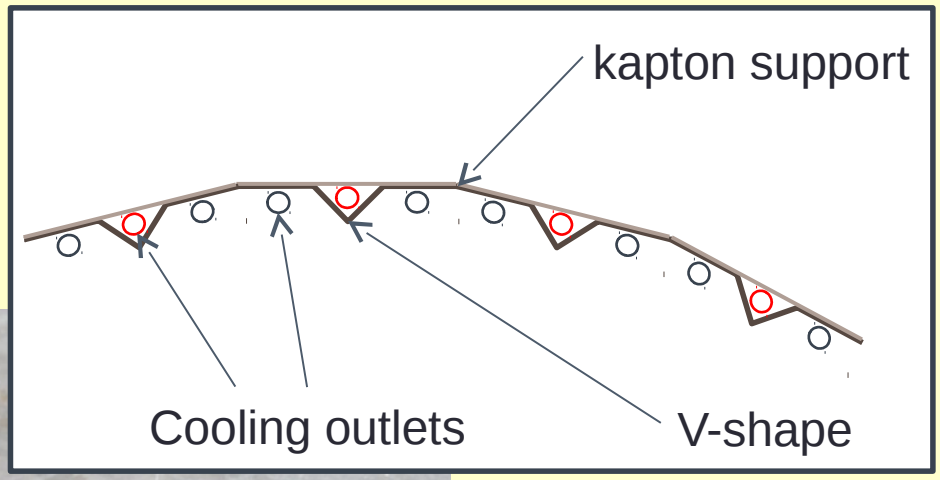


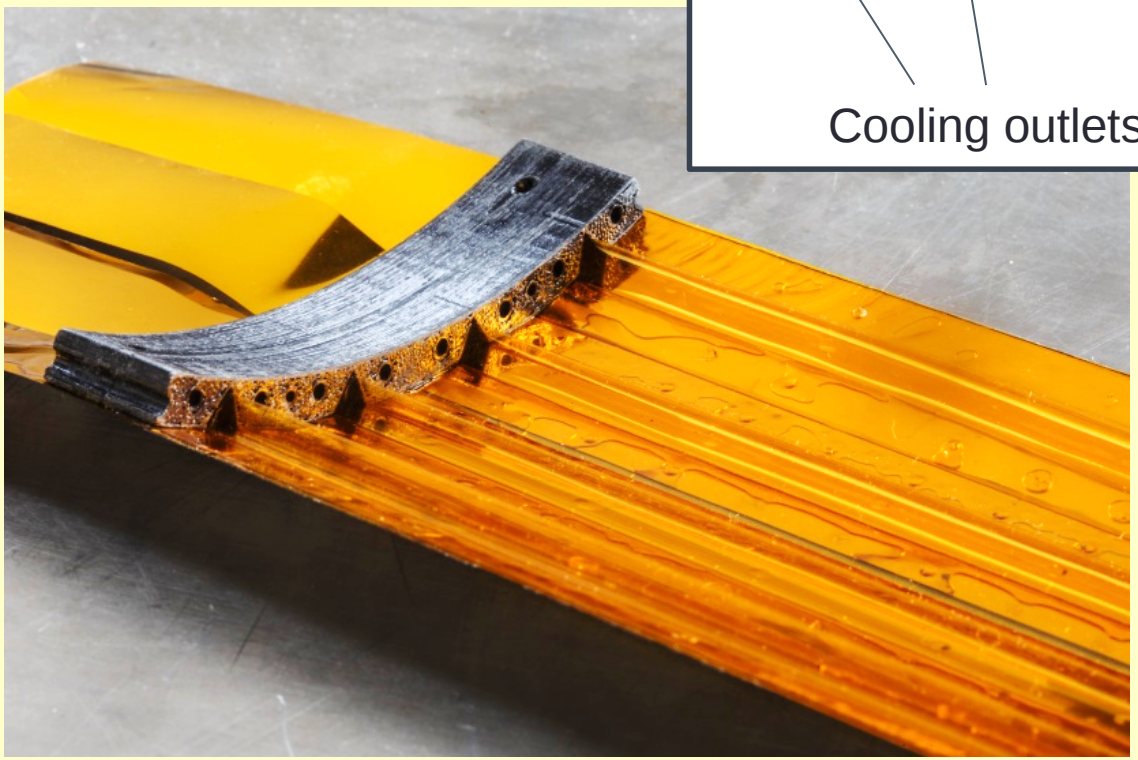
V-Fold Cooling Channels



Mu3e Helium Gas Cooling Concept

V-shapes for local cooling channels





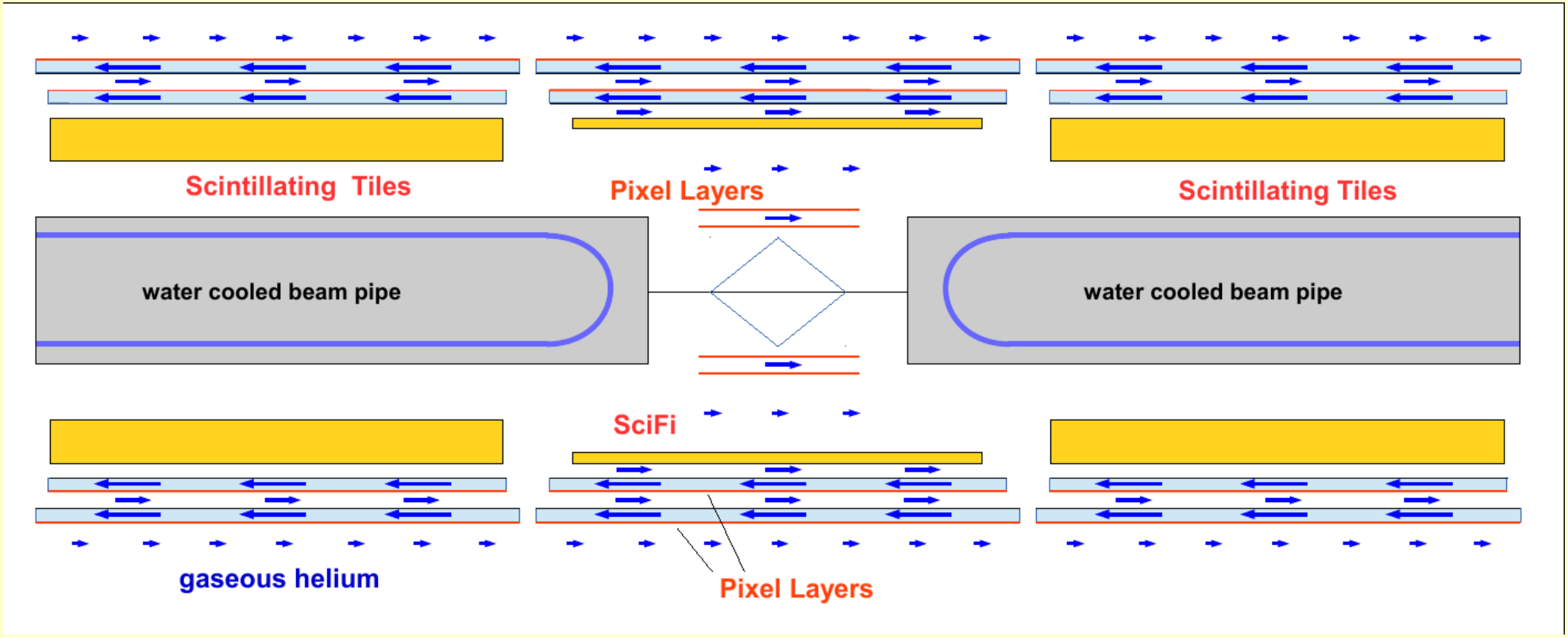
Helium cooling:

- global flow
- flow between layers
- flow in V-shapes

Mu3e Cooling System

Total Power Consumption: ~10 KW

- **Water cooling** system around beam pipe: DC-DC converters, electronics (~5KW)
- Novel **Helium gas cooling** system: pixel tracker modules (~5KW)
  - He flow in V-folds (channels) up to 20 m/s
  - He flow in gaps between layers up to 5 m/s
  - global He-flow

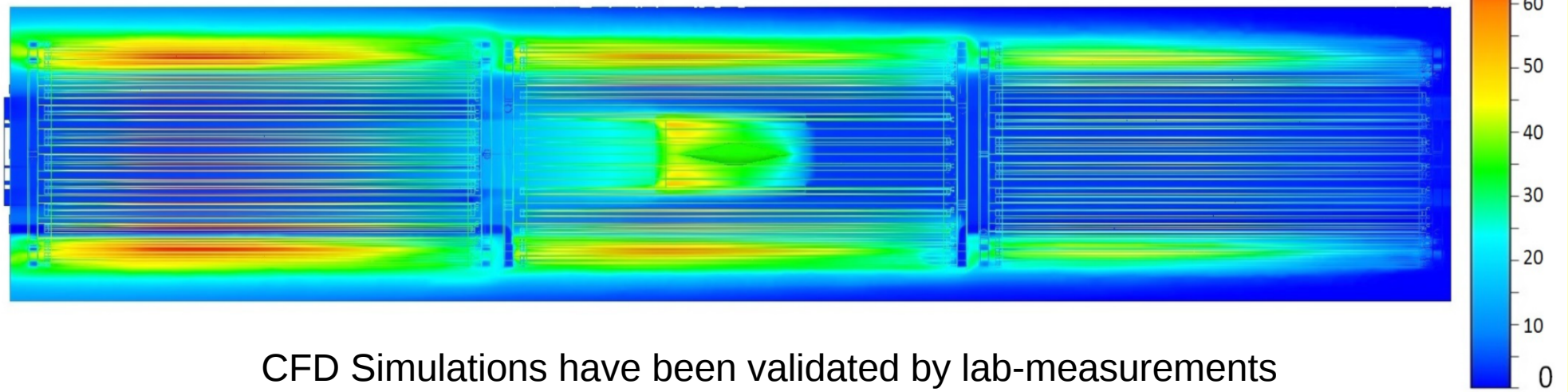


Mu3e Cooling Simulation

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

Simulation for 400mW/cm²



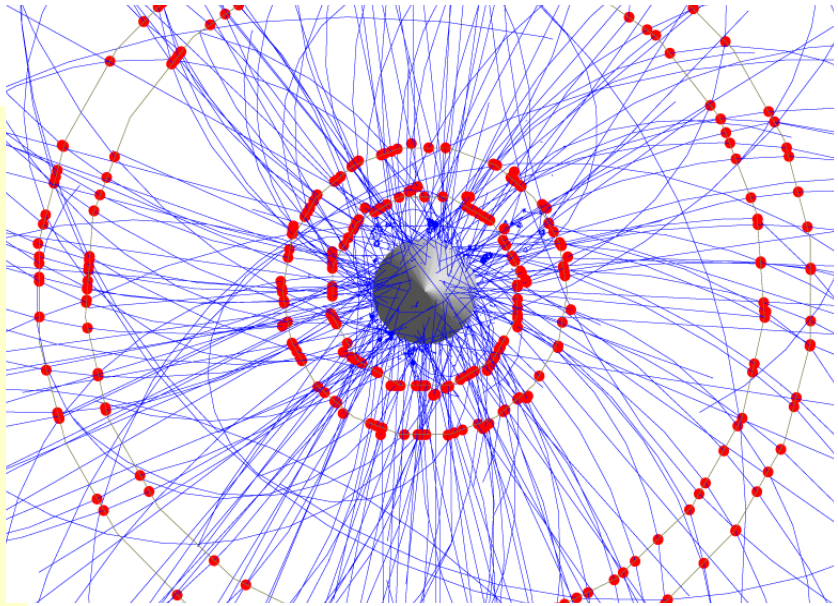
CFD Simulations have been validated by lab-measurements

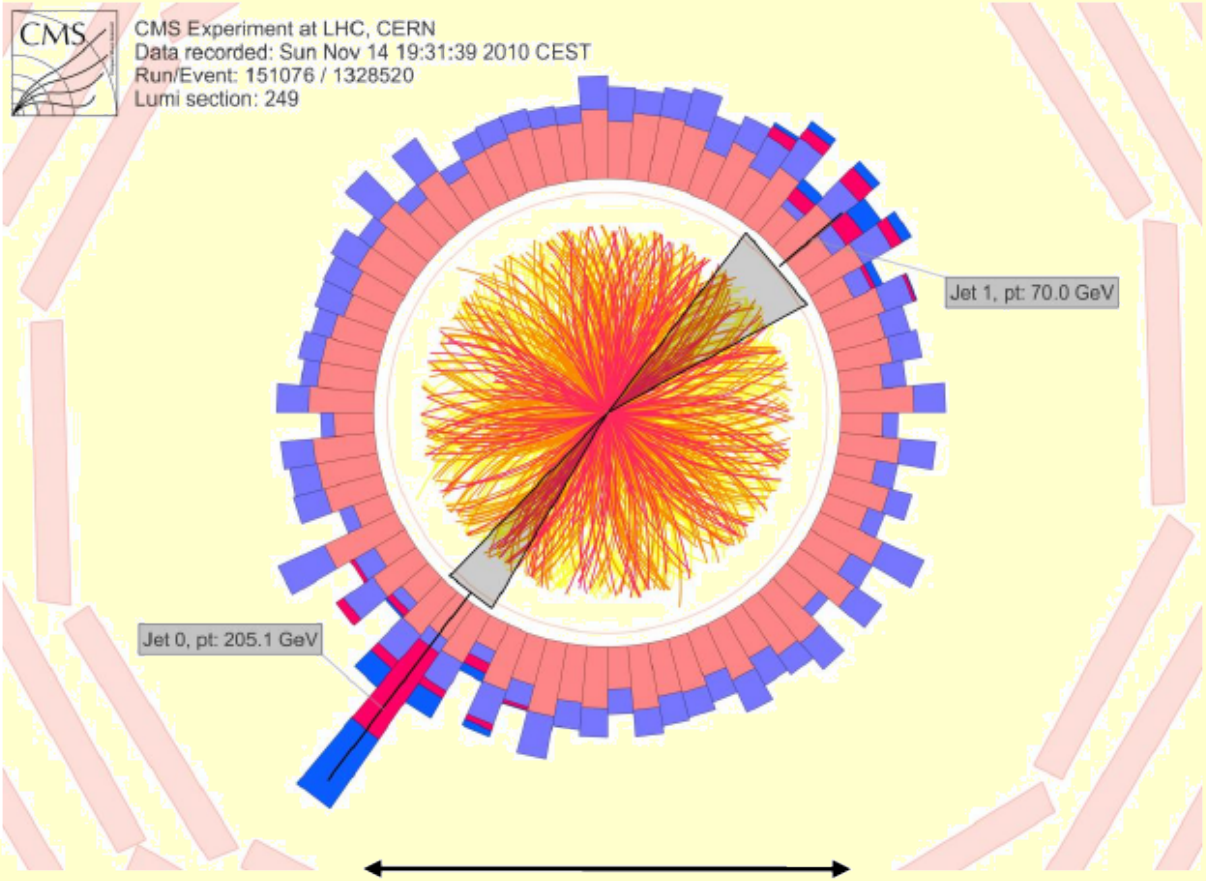
- Targeted power consumption (P=250 mW/cm²)
- Maximum allowed power consumption (P=400 mW/cm²)

Timing

Pileup

Mu3e reconstructed tracks



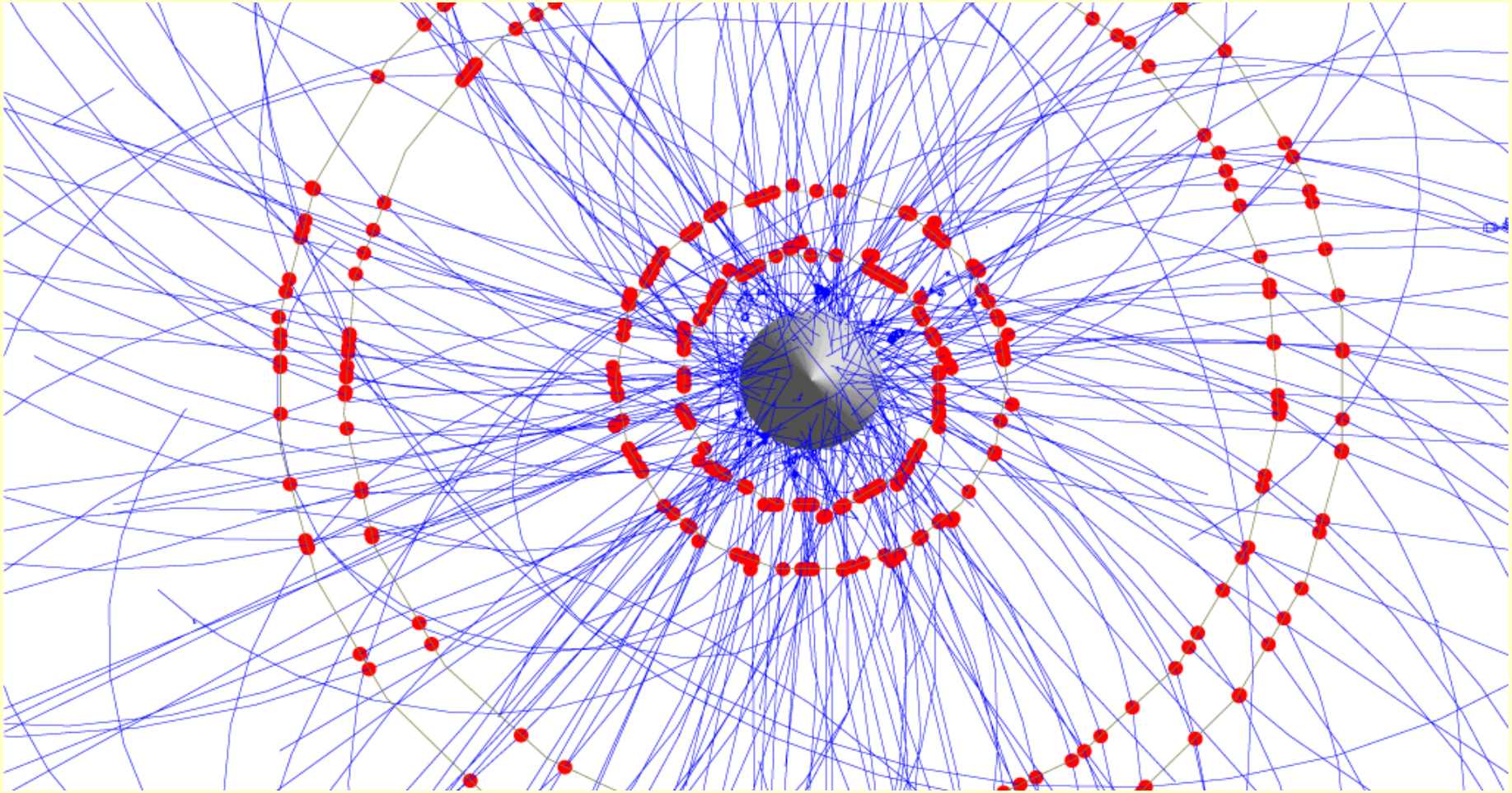


≈16 cm
Readout in frames of 50 ns
E ~ 10-50 MeV

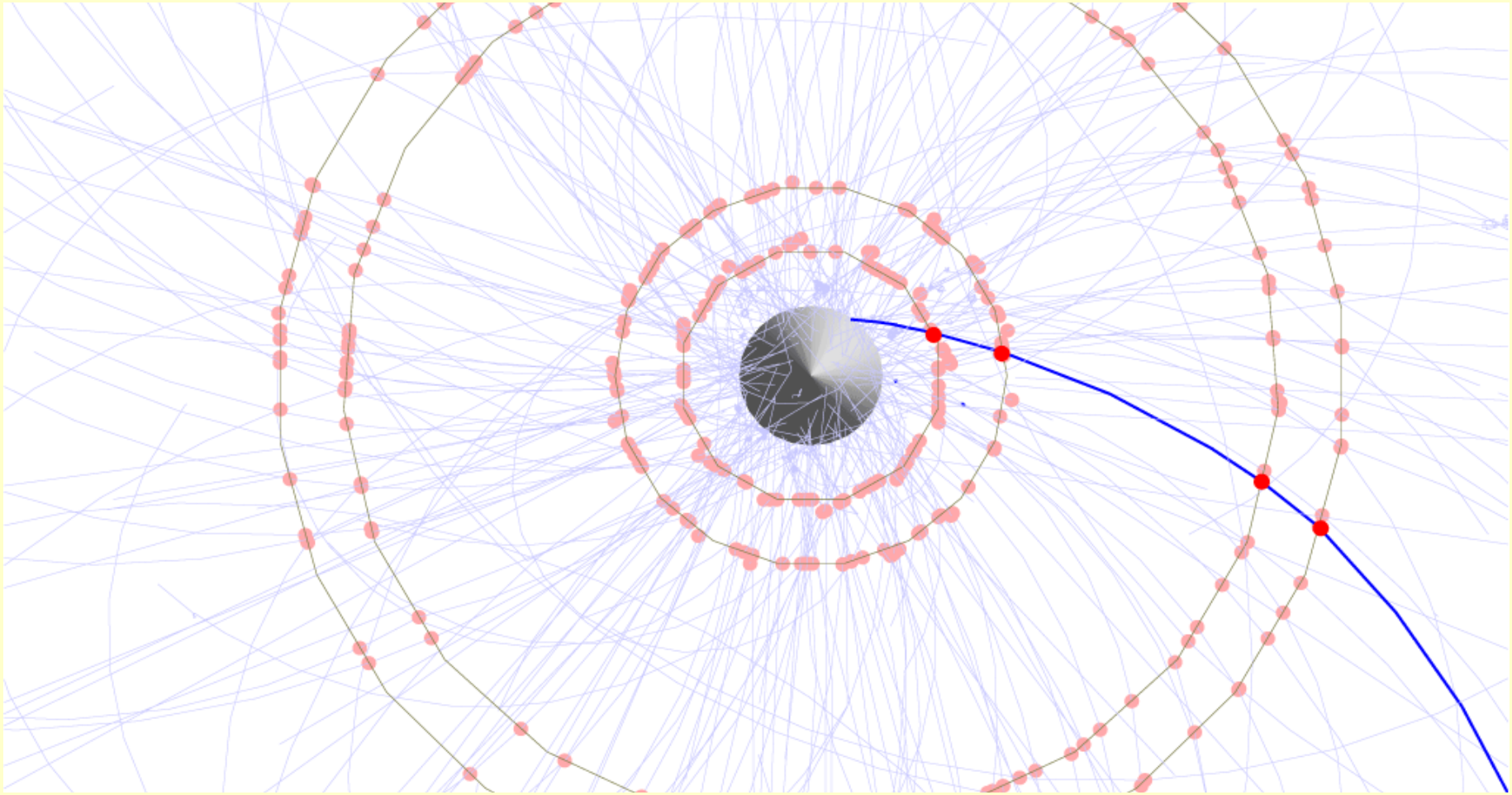
≈2.5 m
Collision every 25 ns
E ~ 200 GeV

Tracks in Pixel Detector

10^9 muon stops per second, 50ns readout frame

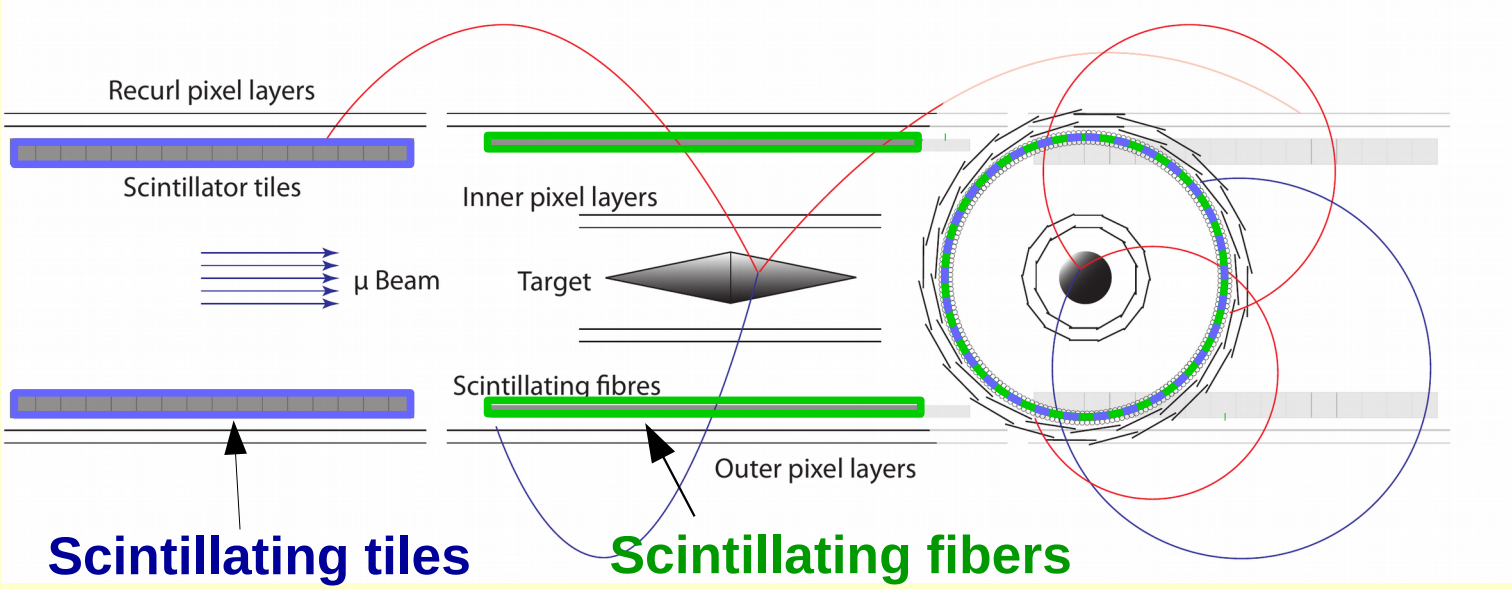


Tracks in Pixel Detector

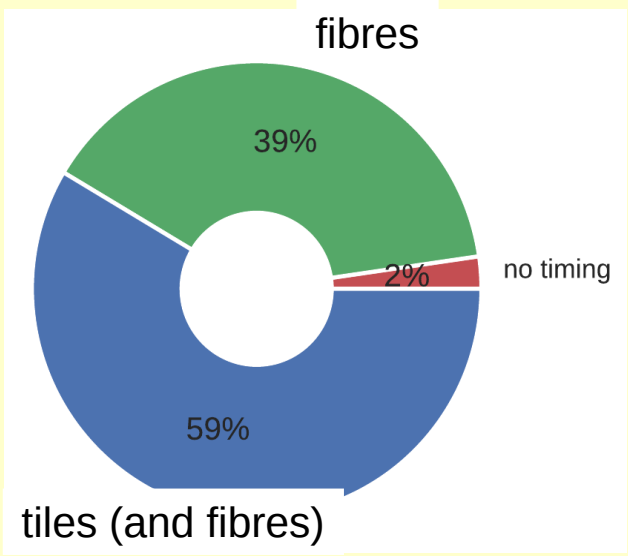


- additional timing detectors needed < 1ns

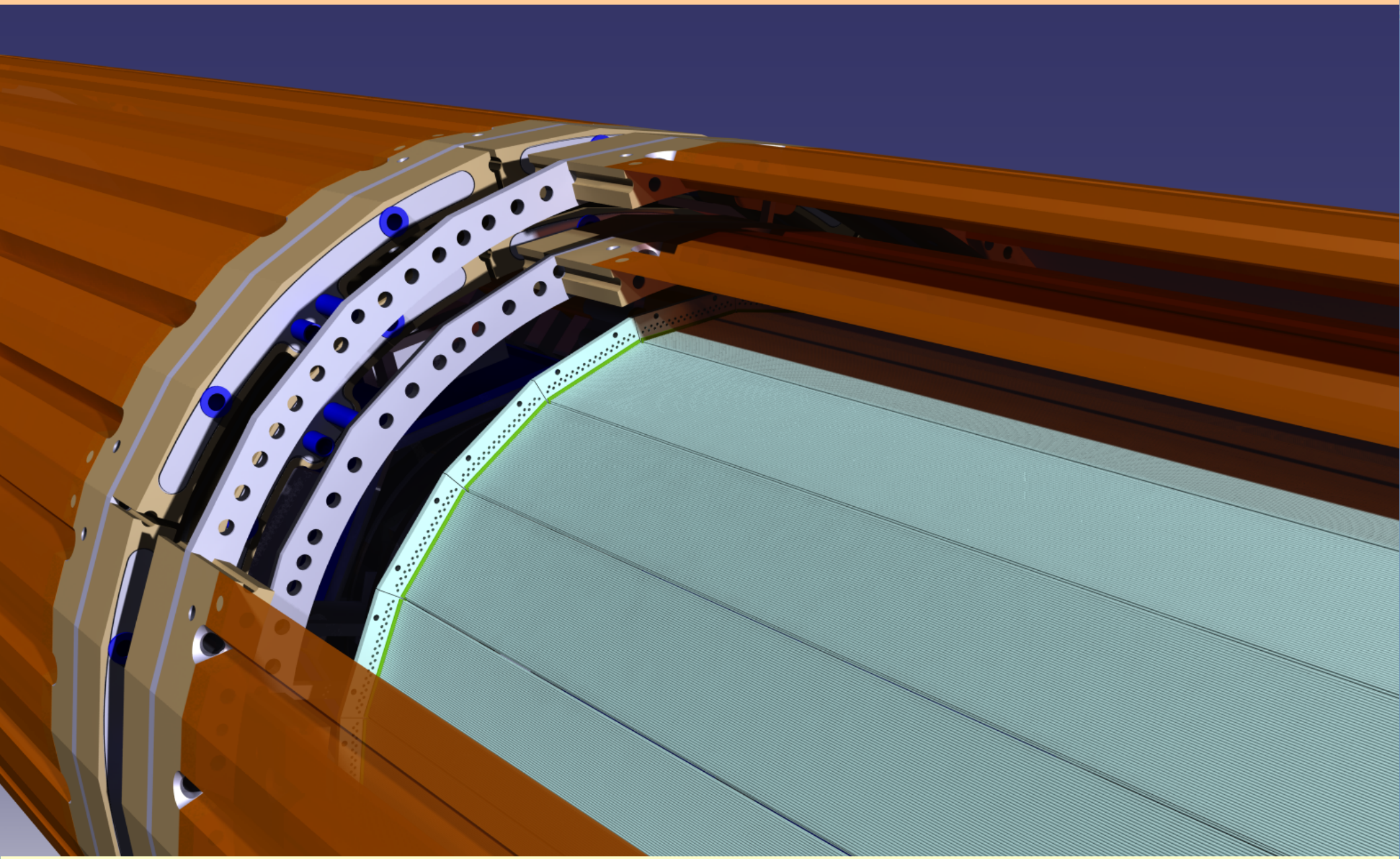
Mu3e Time Timing Detector



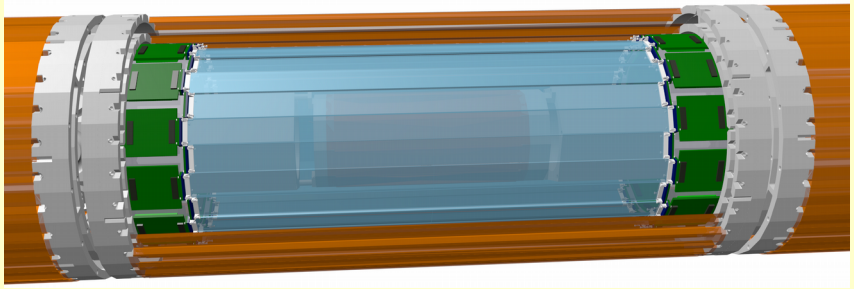
→ **background suppression factor of 100!**



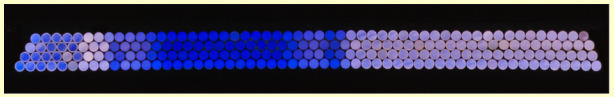
Scintillating Fibre Detector



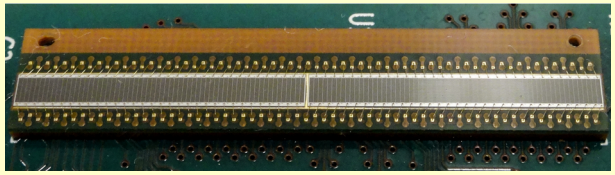
Scintillating Fibres



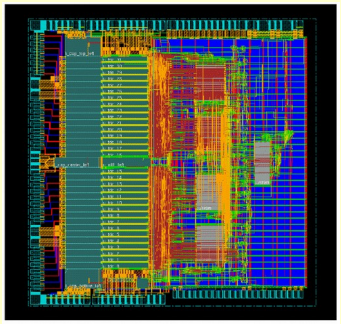
- Two types of scintillating 250µm fibres studied:
  - round (Kuraray SCSF-81M)
  - squared (Saint Gobain BC 418) (coated with Al)



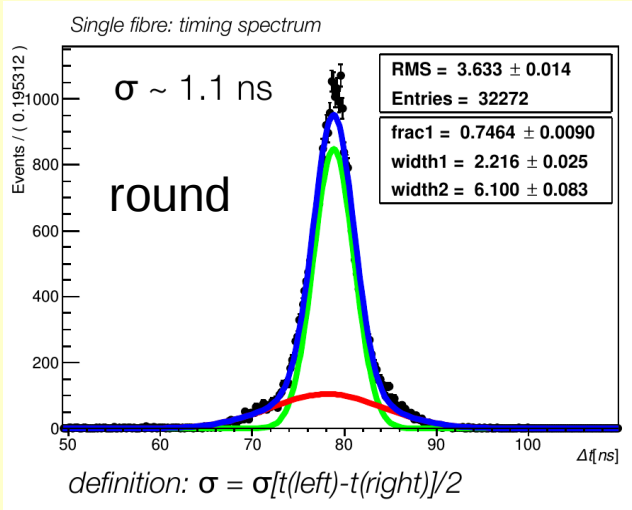
- SiPM: Hamatsu S12571-050P (LHCb)
  - SiPM array
  - 1 x 1 mm^2, 50 µm pitch

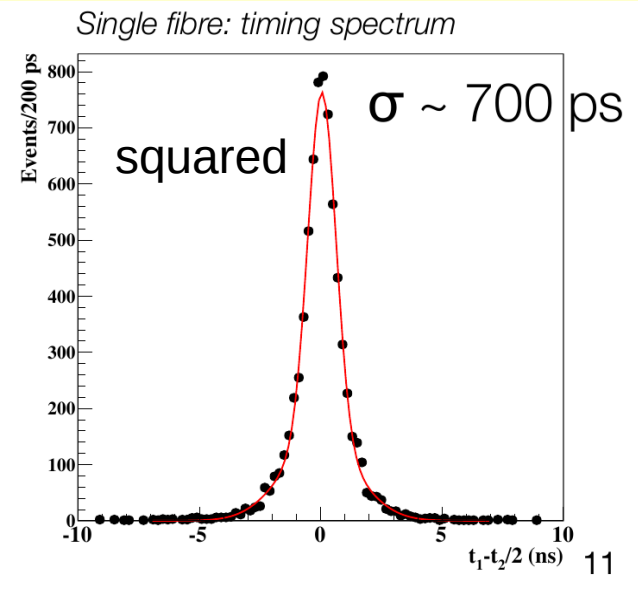


- MuTRig readout chip (KIP Heidelberg)
  - time resolution 50 ps
  - 32 channels
  - bandwidth 1.25 Gbit/s
  - chip received in January 2017

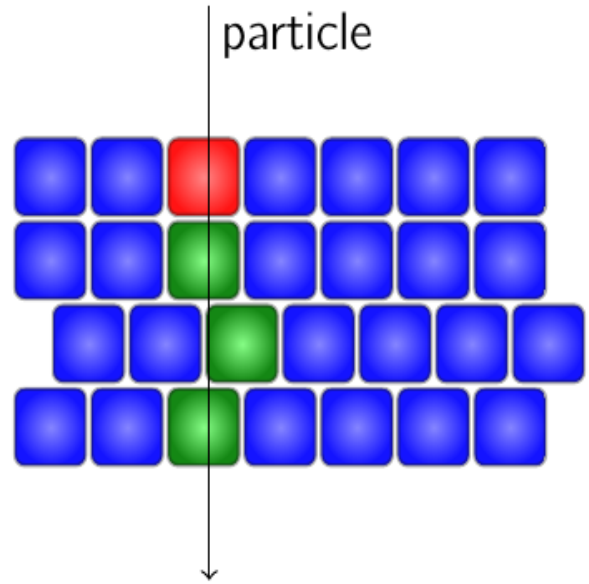


Single fibre time resolutions

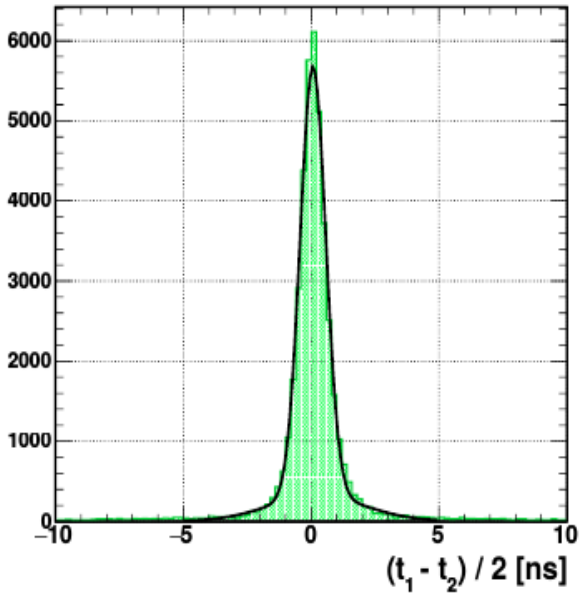




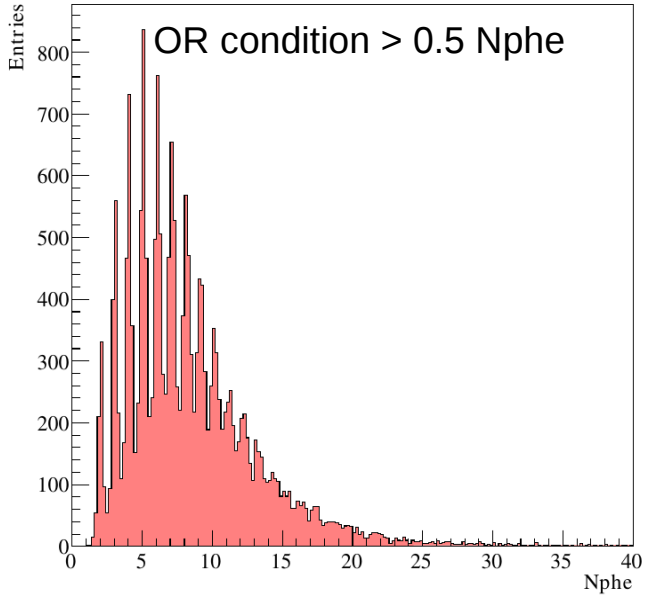
Scintillating Fibre Test Beams

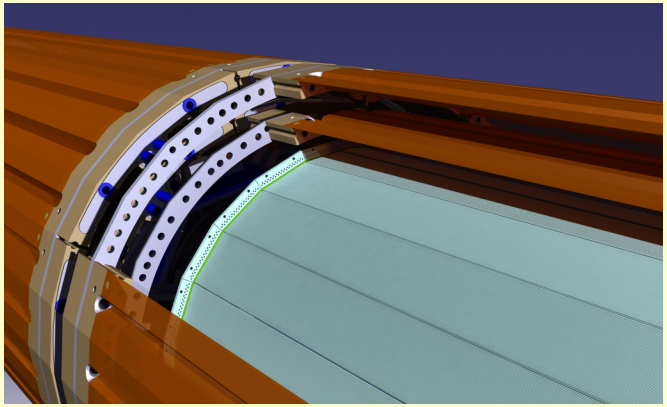


time resolution

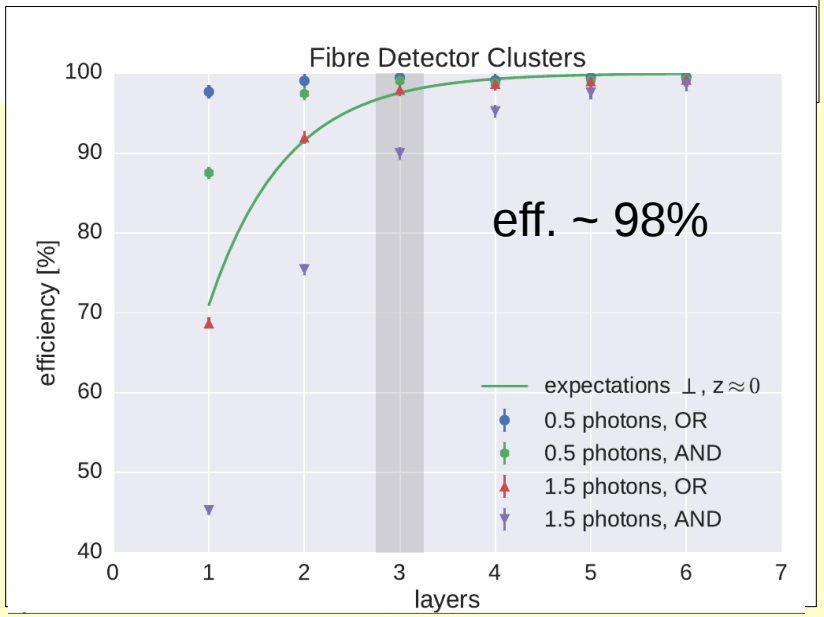


#electrons

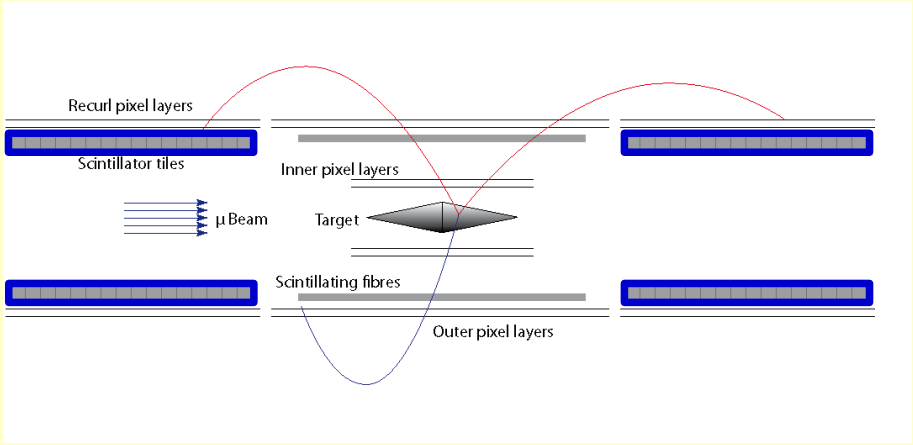


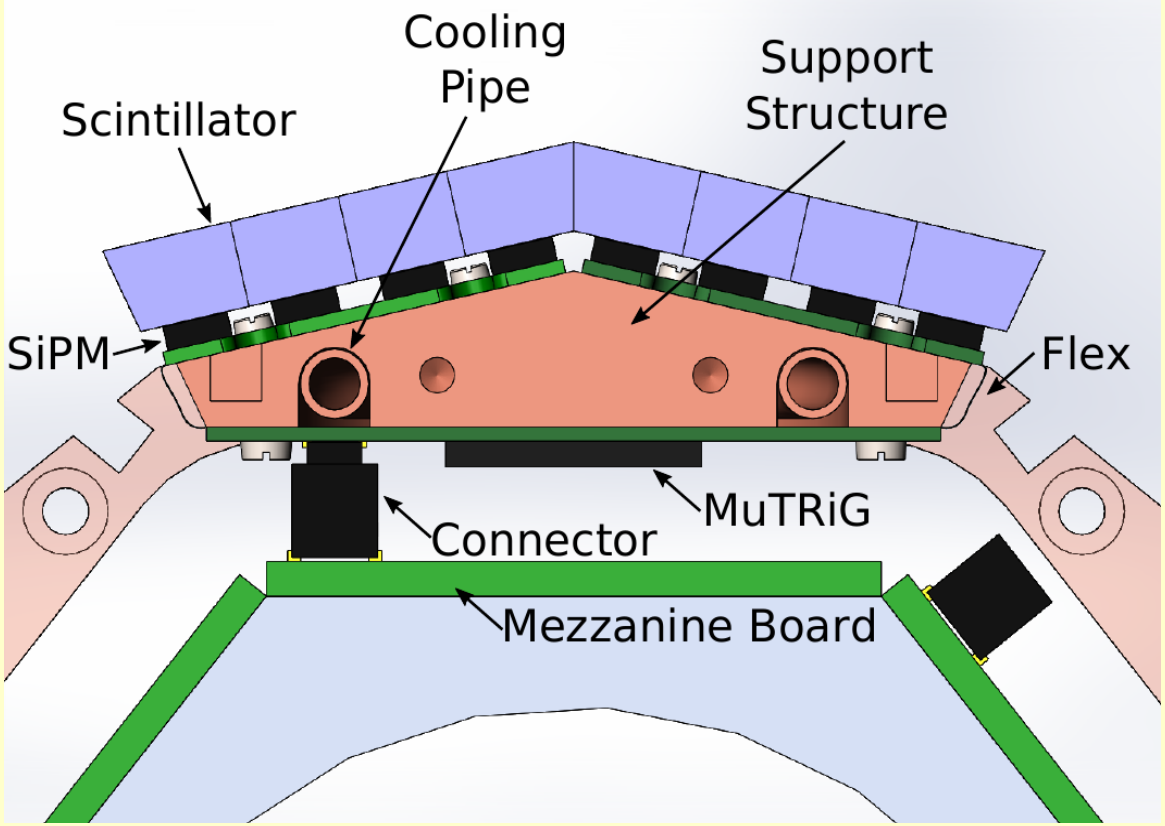


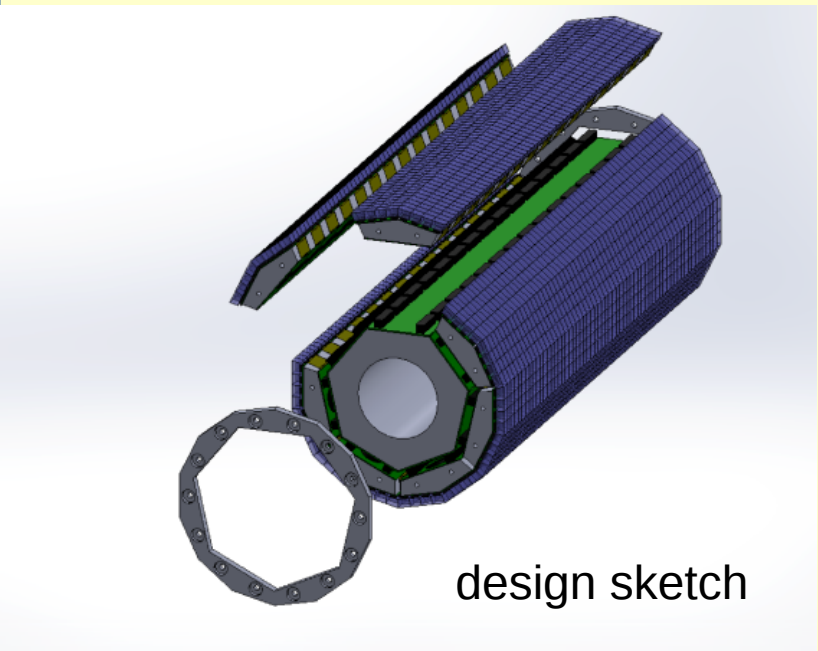
Requirements and expectations fulfilled in test beams!



Scintillating Tile Detector



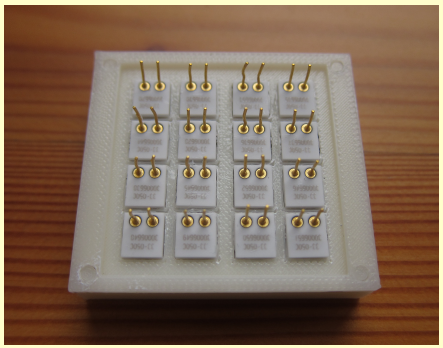


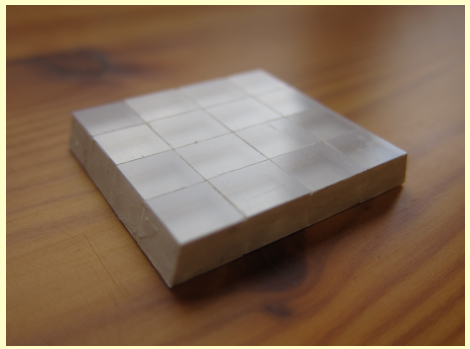


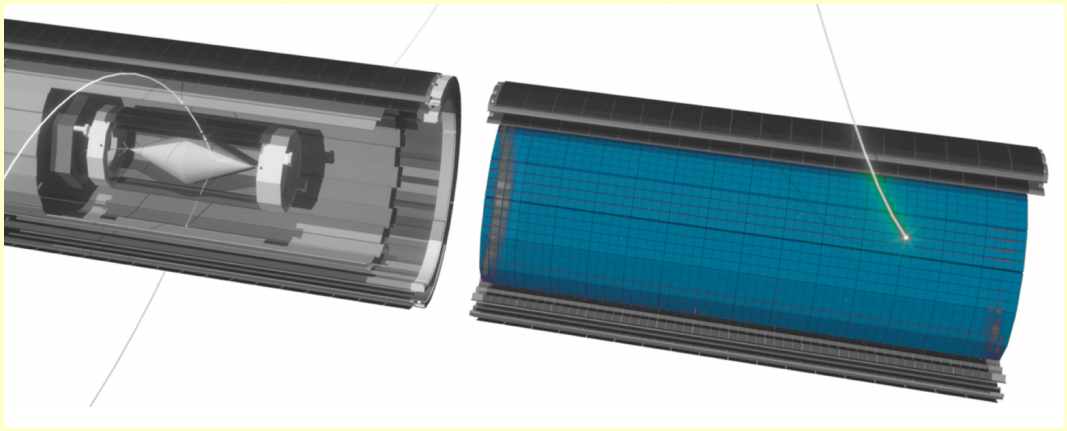
- 56 x 56 tiles (6.5 x 6.5 x 5.0 mm^3)
- 3 x 3 mm^2 single SiPM
- timing resolution of ≤ 100 ps
- mixed mode ASIC (MuTRig)

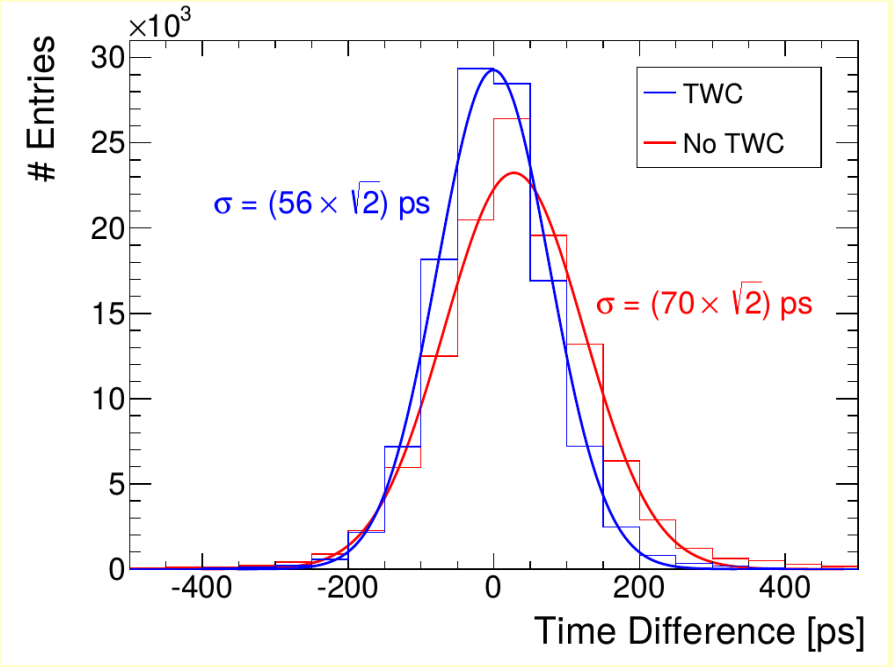
Scintillating Tile Detector

- Very promising results from test beam measurements (4 x 4 array)
- Time resolution **< 100 ps**
- Now testing new MuTRig readout ASIC

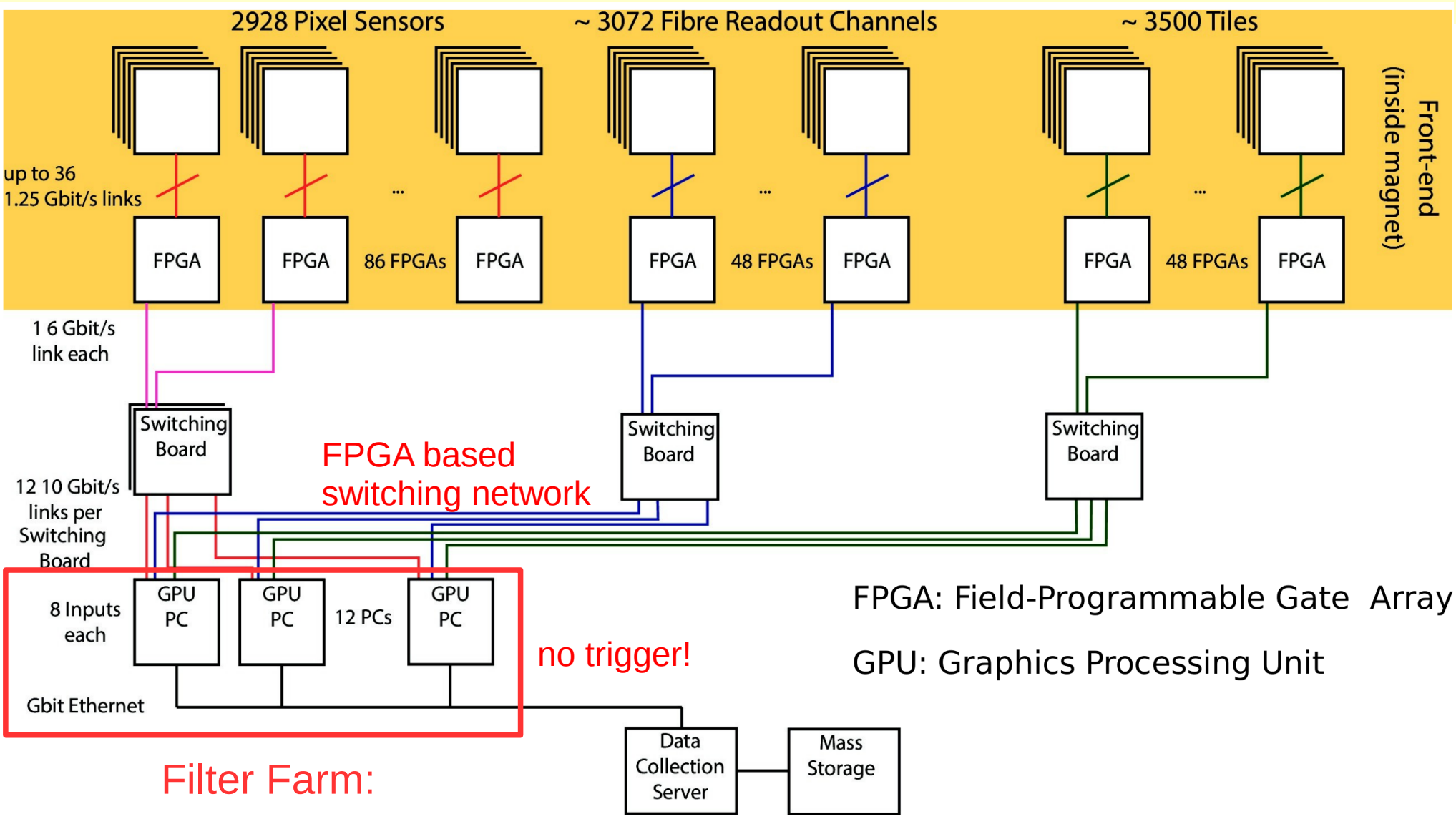




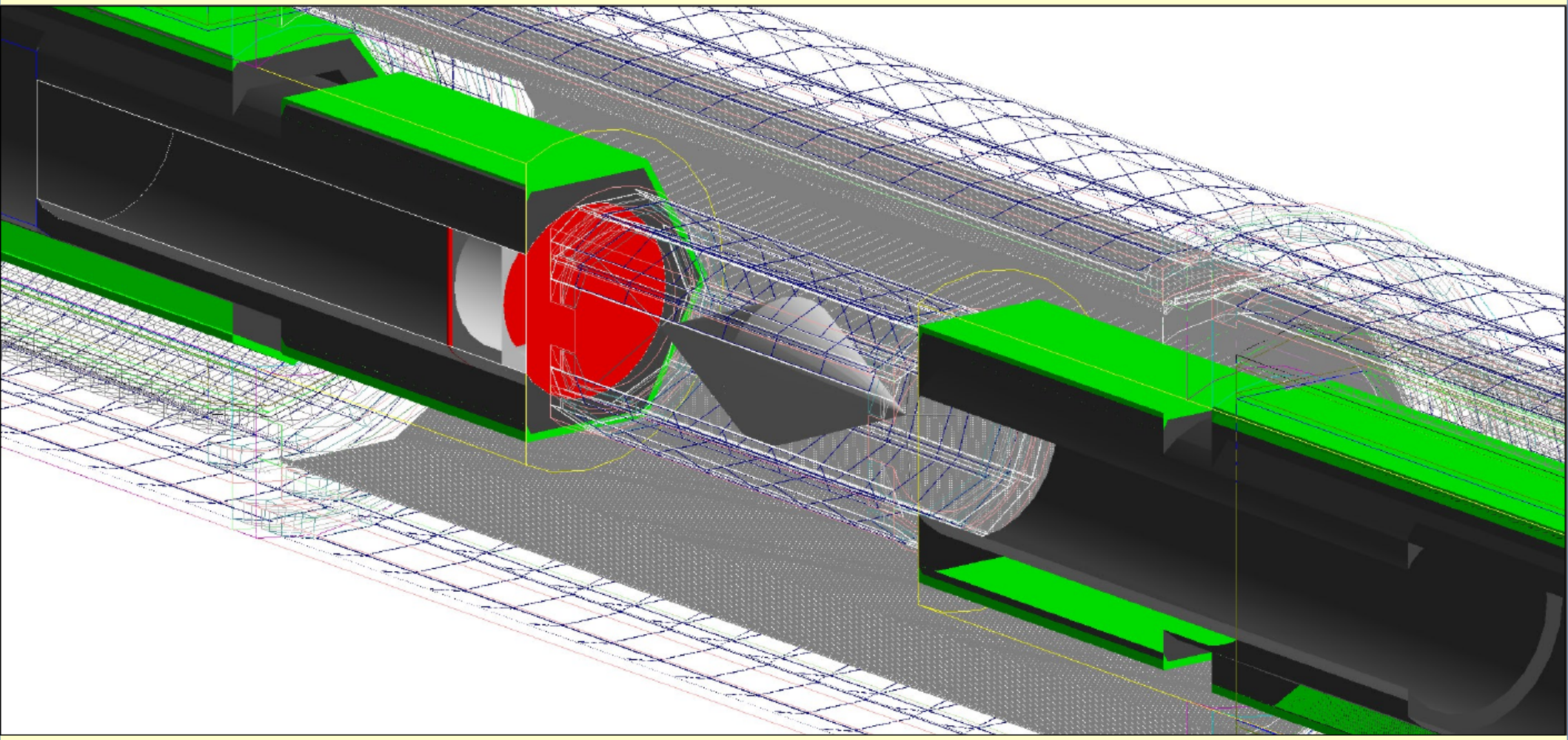




Mu3e Readout Concept

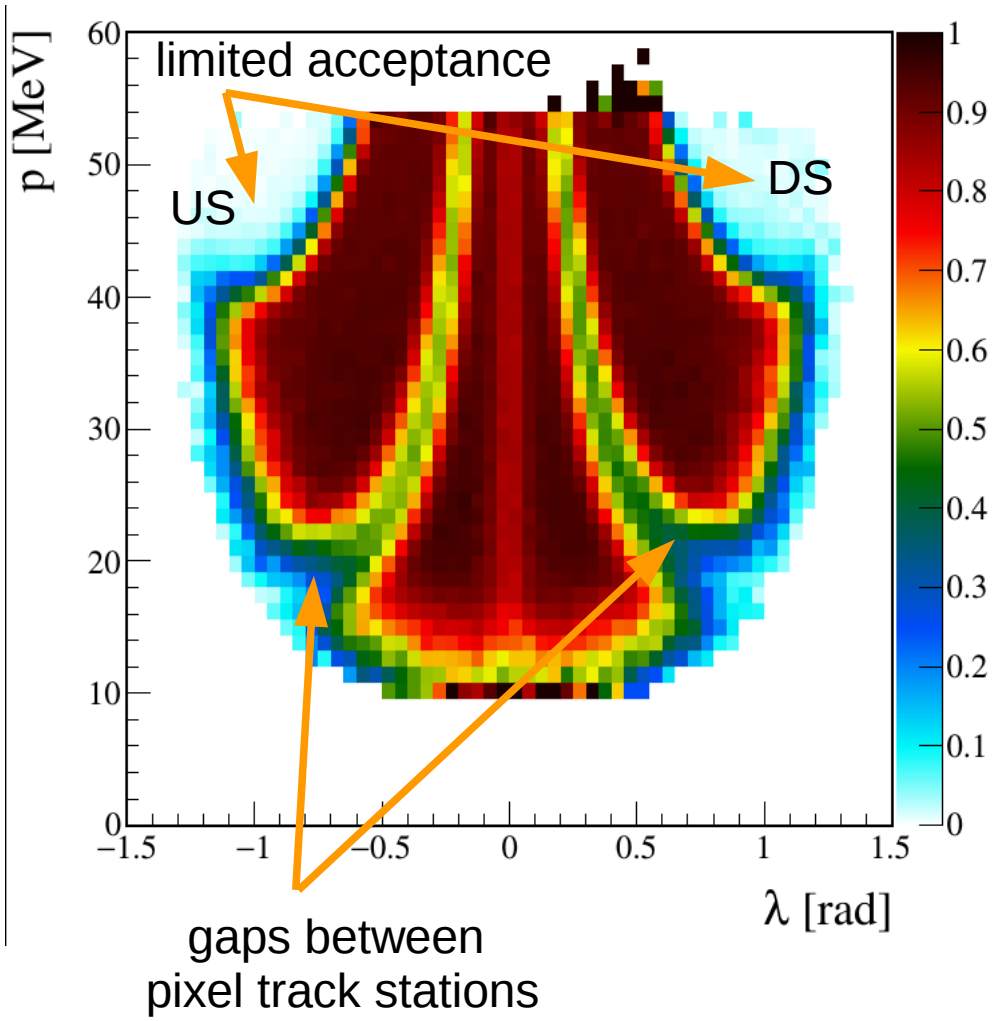


Simulation and Performance

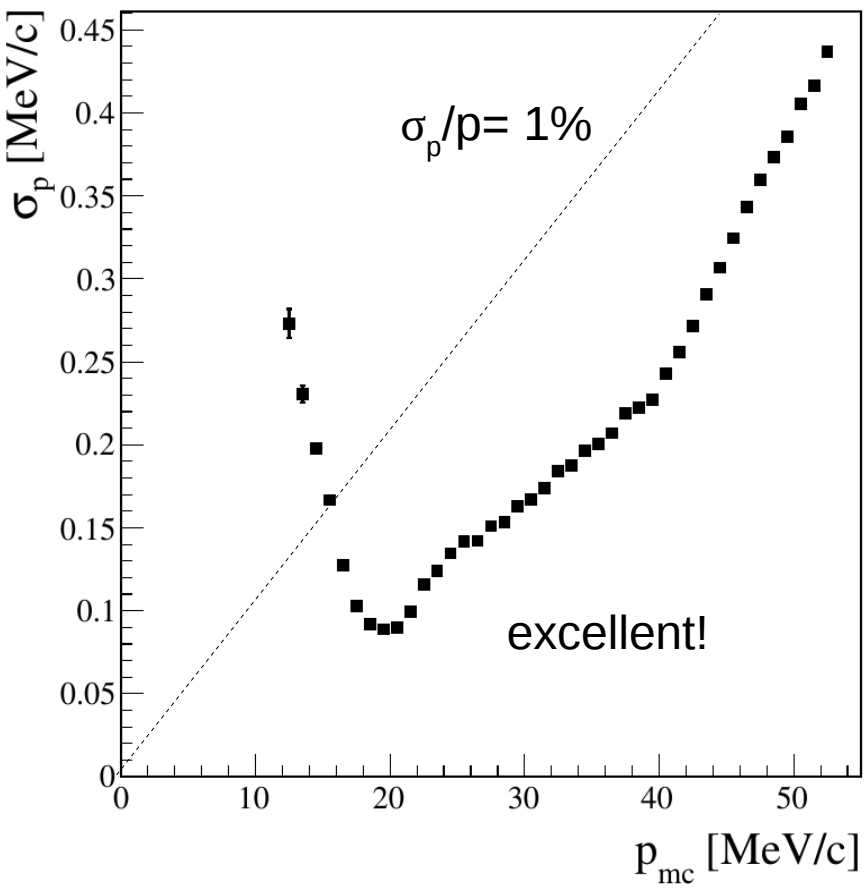


Simulation and Performance

Track Reconstruction Efficiency



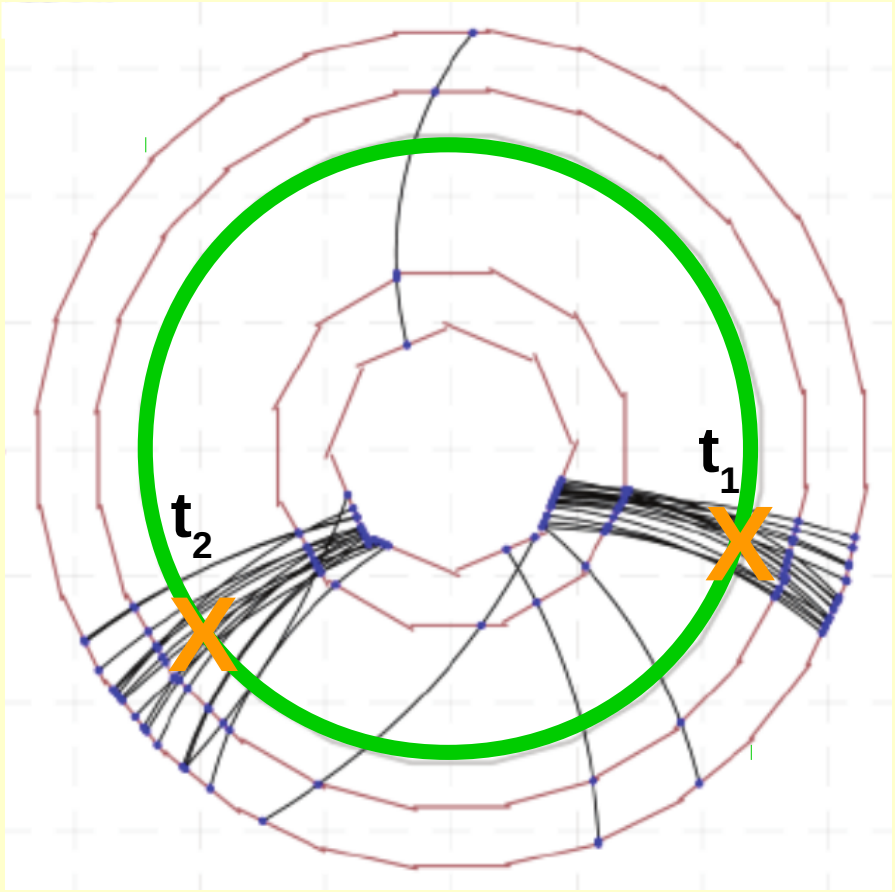
Track Momentum Resolution



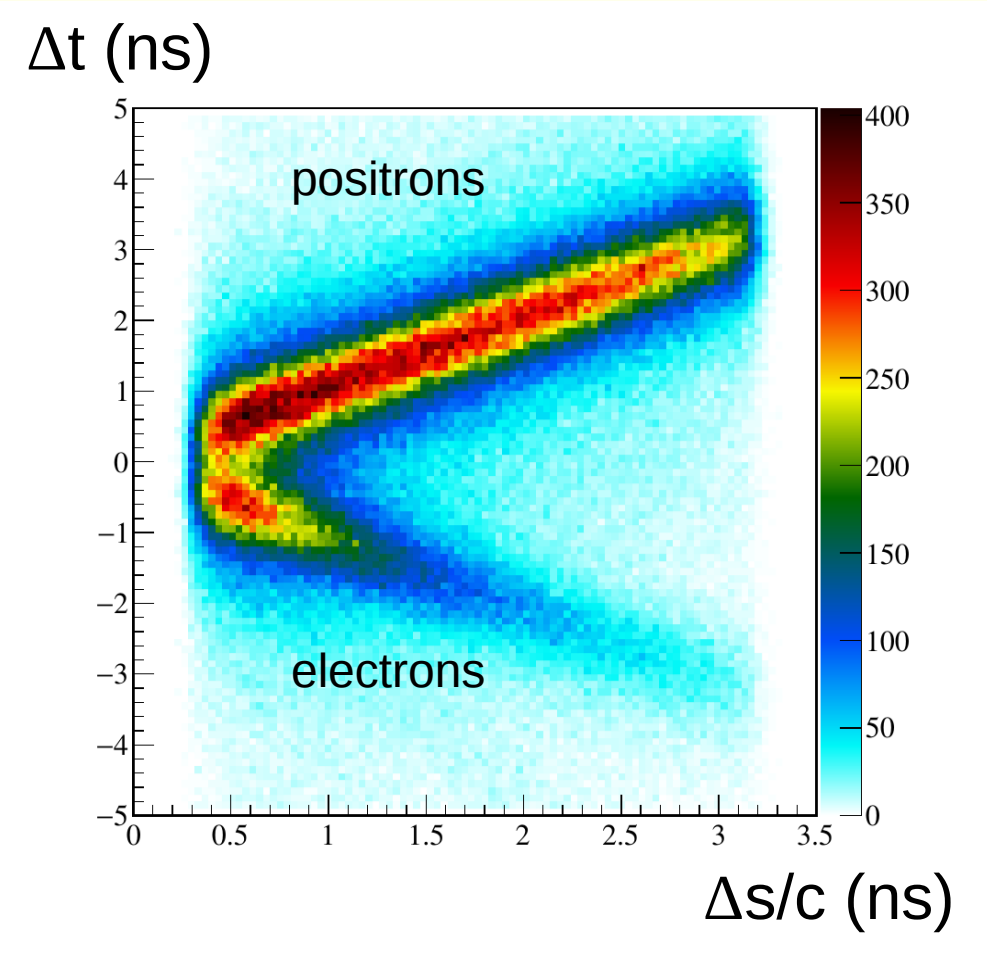
Charge Identification

Main process: $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

positron loopers → charge confusion

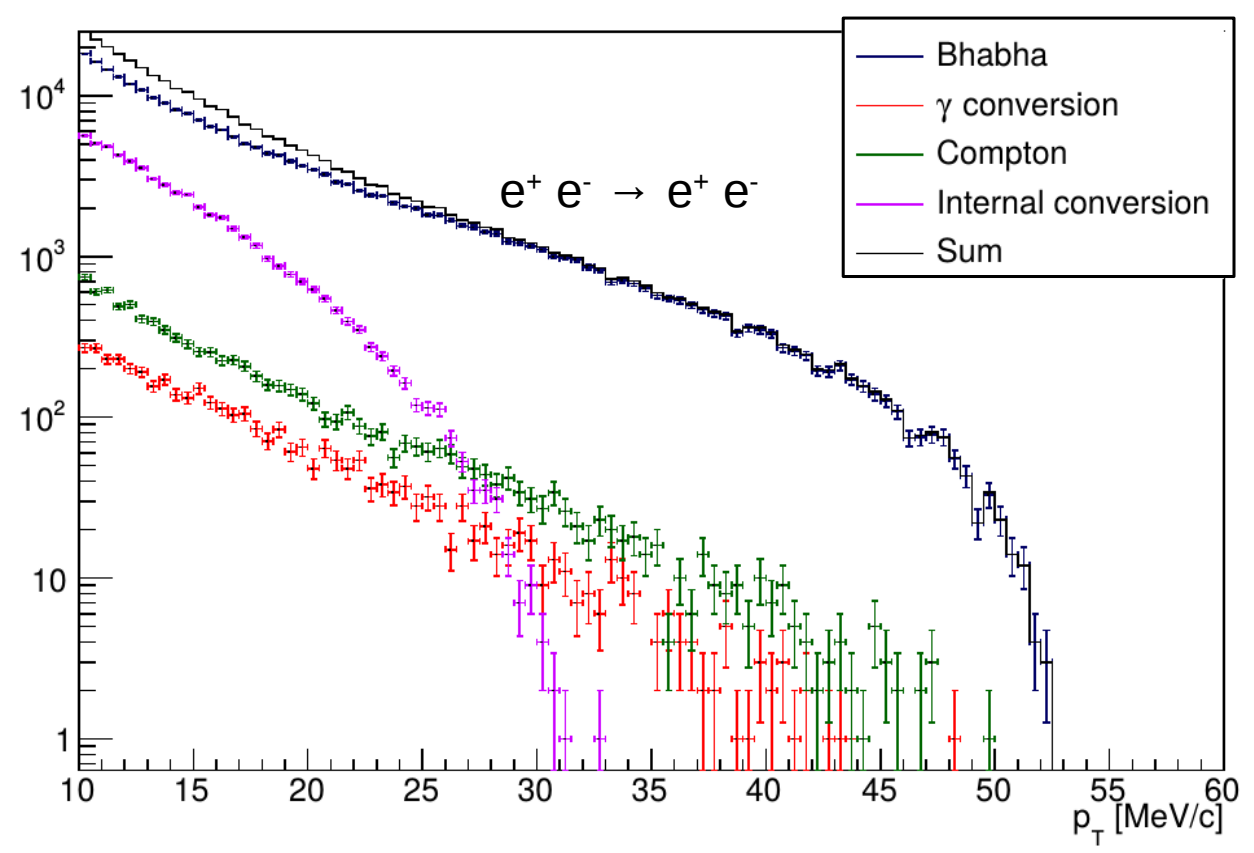


Time difference vs path length

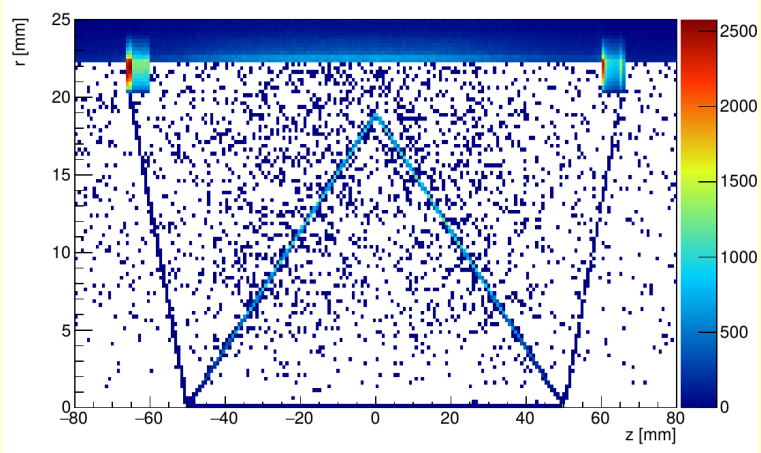


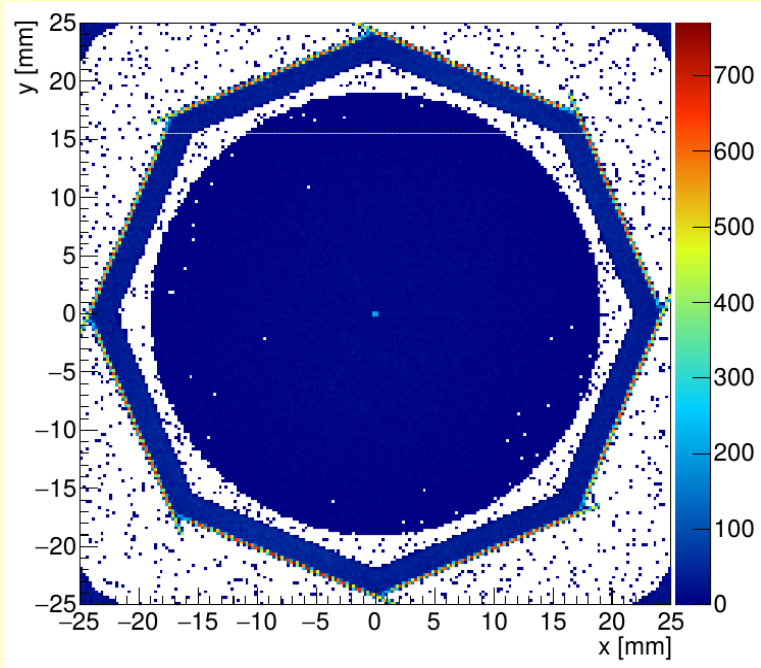
Significant reduction of BG for: $\mu^+ \rightarrow e^+ e^+ e^-$

Bhabha Scattering Background



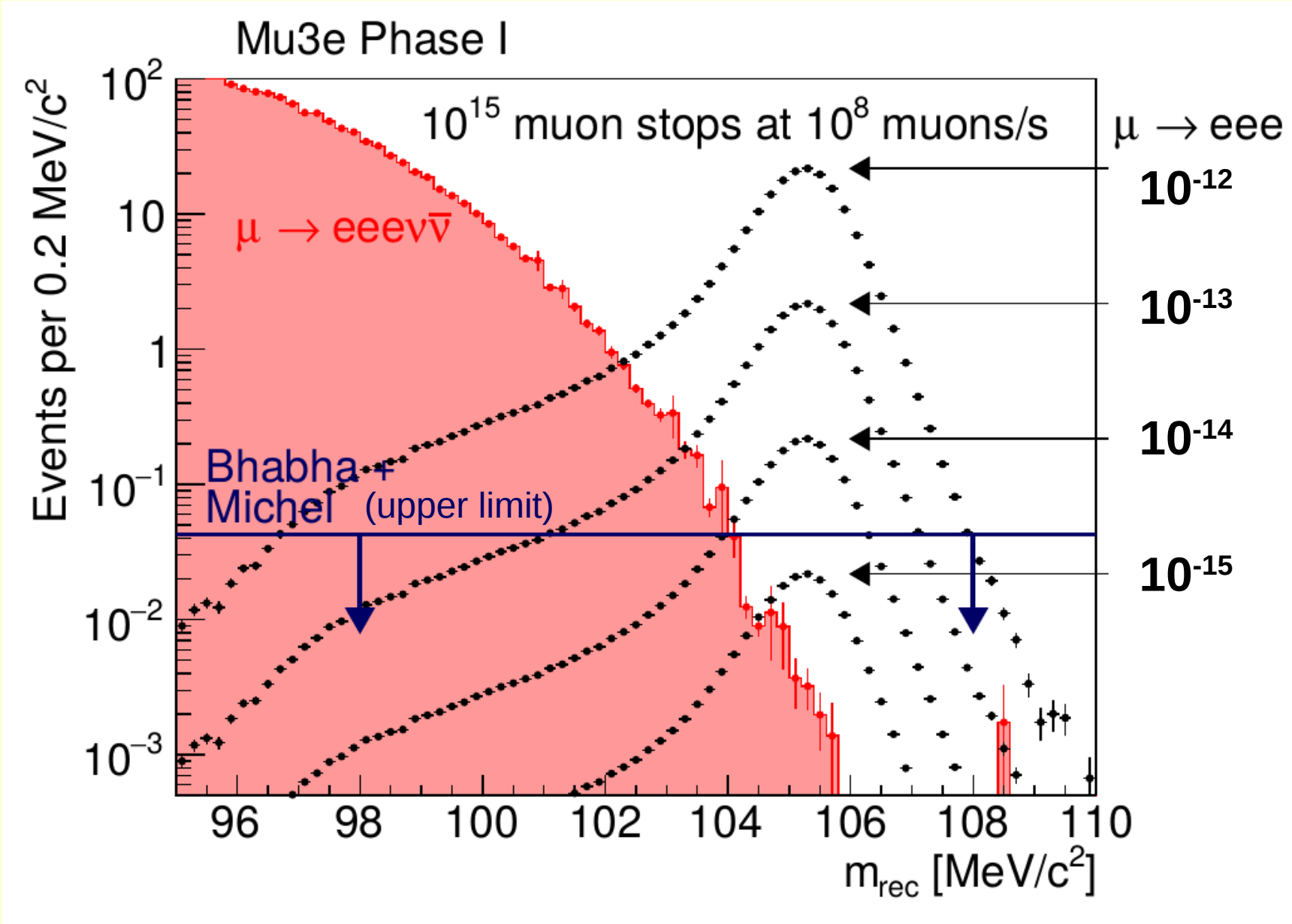
Bhabha vertices target region



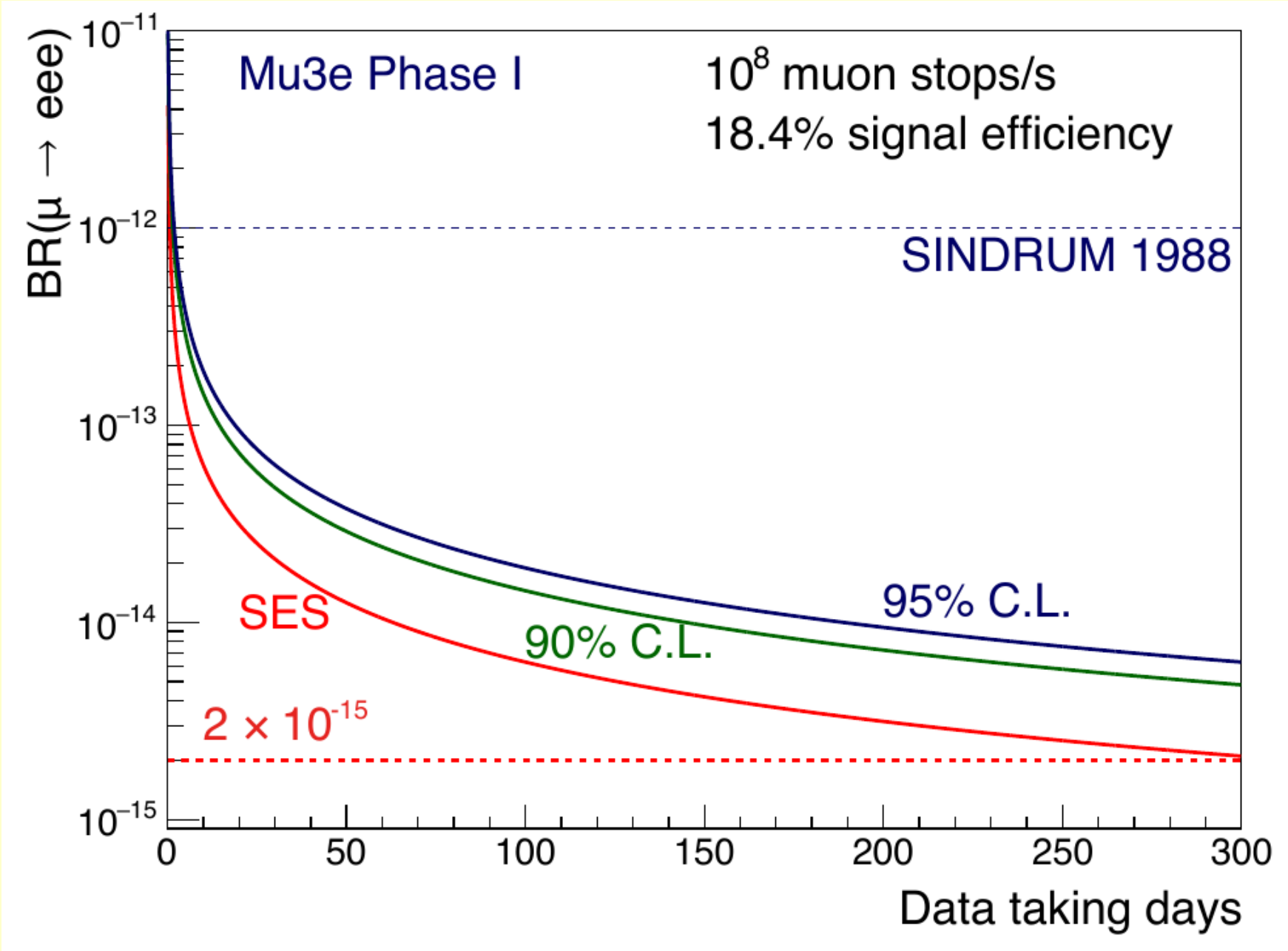


- Accidental background due to Bhabha scattering is difficult to simulate
- Bhabha's can be cut away with only small loss in signal efficiency

Mu3e Mass Plot



Sensitivity versus Time



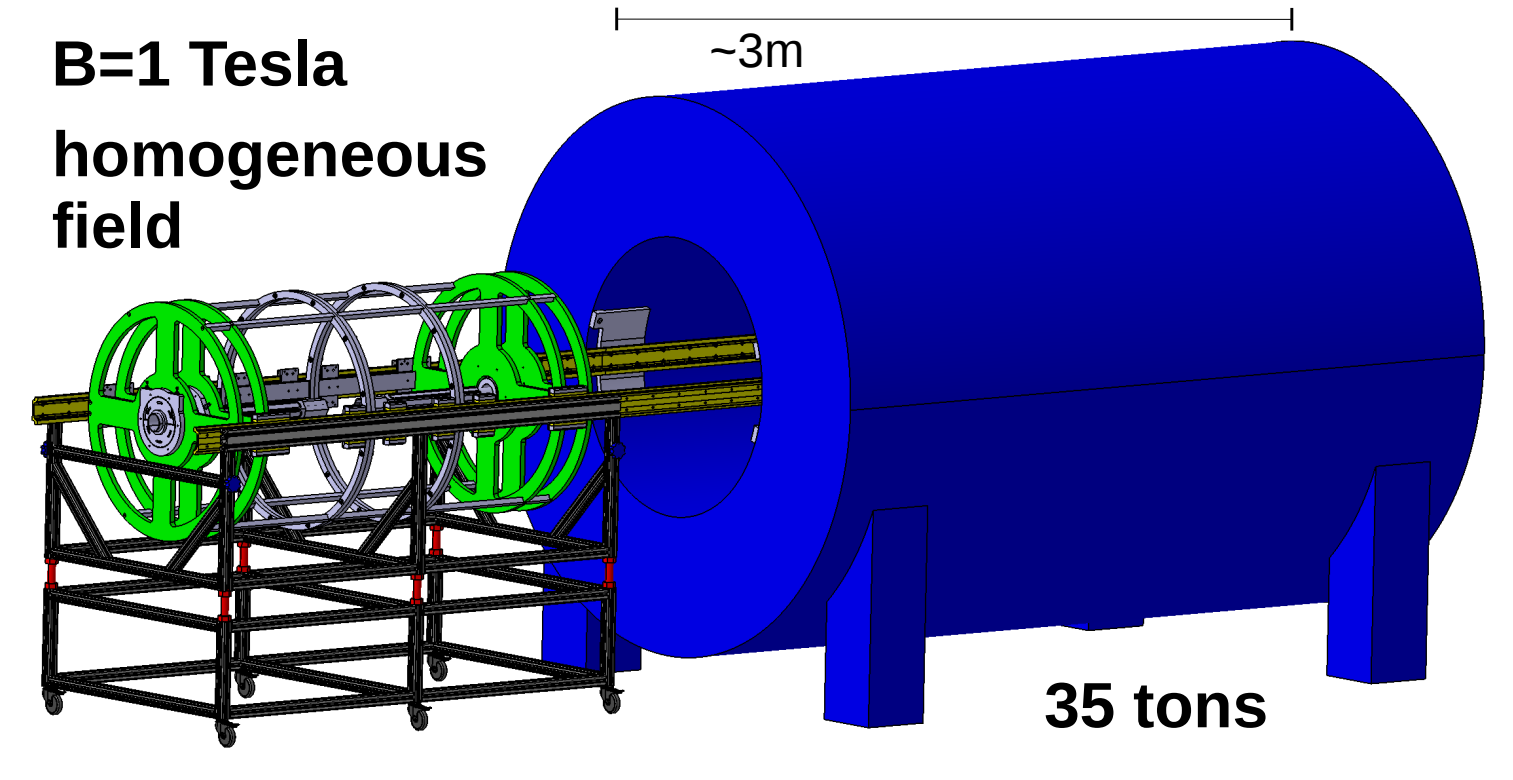
Mu3e Collaboration

- University of Geneva (CH)
- University Heidelberg (D)
- Karlsruhe Institute of Technology (D)
- University Mainz (D)
- Paul Scherrer Institute (CH)
- ETH Zurich (CH)
- University Zurich (CH)

Several UK institutes interested to join

- Bristol
- Liverpool
- Oxford
- UC London

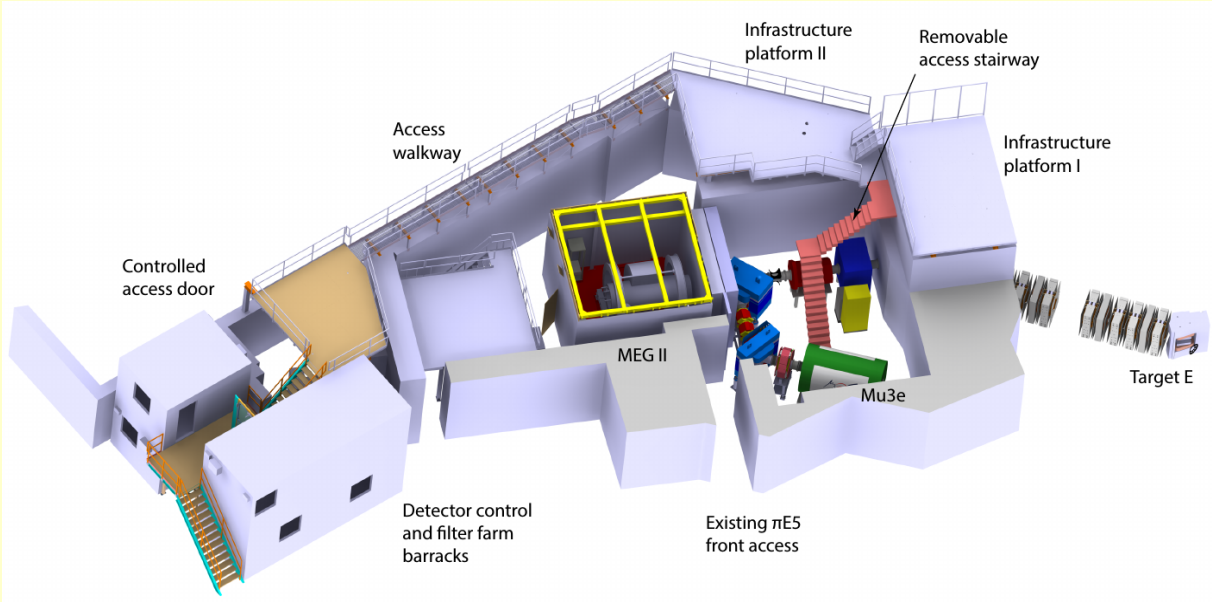
Mu3e Magnet



- First tendering process in 2015 → Danfysik (Denmark)
- Contract canceled in January 2017
- New tendering process is about to start
- Earliest possible delivery of magnet end of 2019

Mu3e Experimental Status

- Detector construction will start end of 2017
- Commissioning of the two inner HV-MAPS pixel layers in 2018
- Construction of outer pixel layers in 2019
- Timing detectors ready in 2019
- First physics results in 2020/21



Mu3e++ Workshop

Workshop in Wengen 13.2-16.2.2017

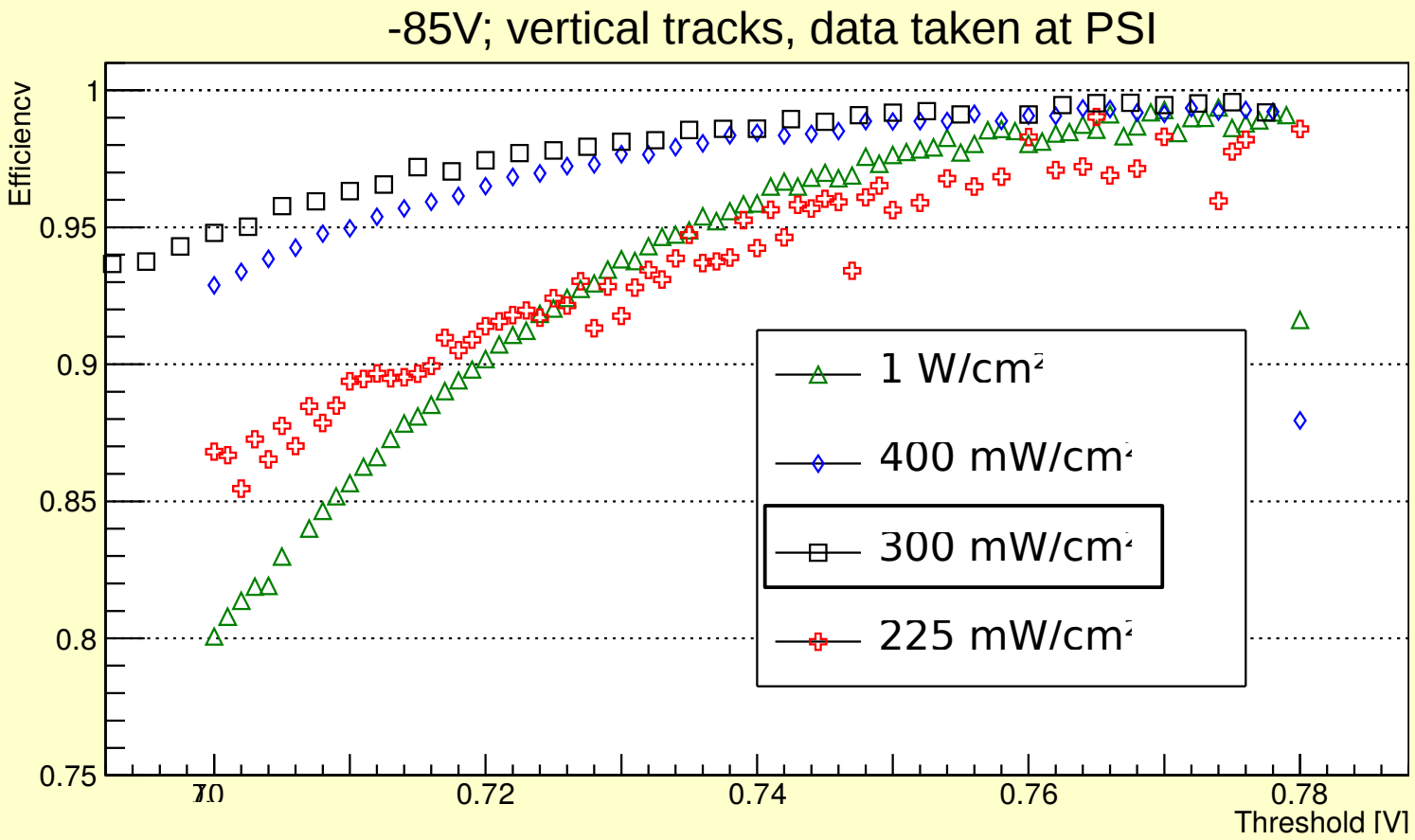
- B($\mu^+ \rightarrow e^+e^+e^-$) Phase II
- B($\mu^+ \rightarrow e\gamma$)
- Searches for familons, majorons, etc.
- Dark photons
- SM-tests

VERY SUCCESSFUL!

Backup

MuPix7 Operation Parameters

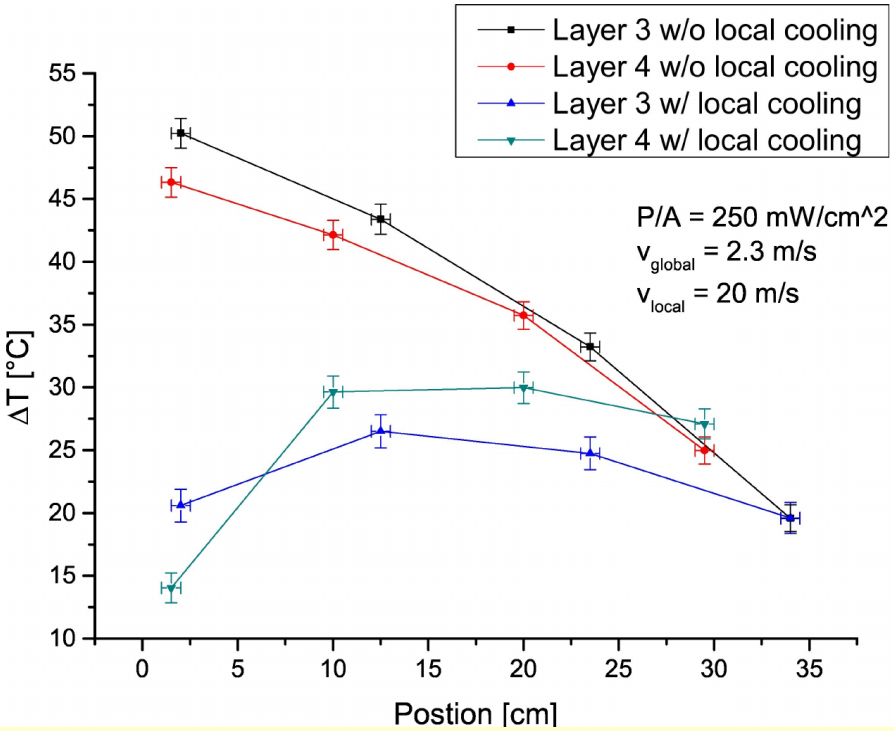
Operation point defined by 13 DAC settings → scan

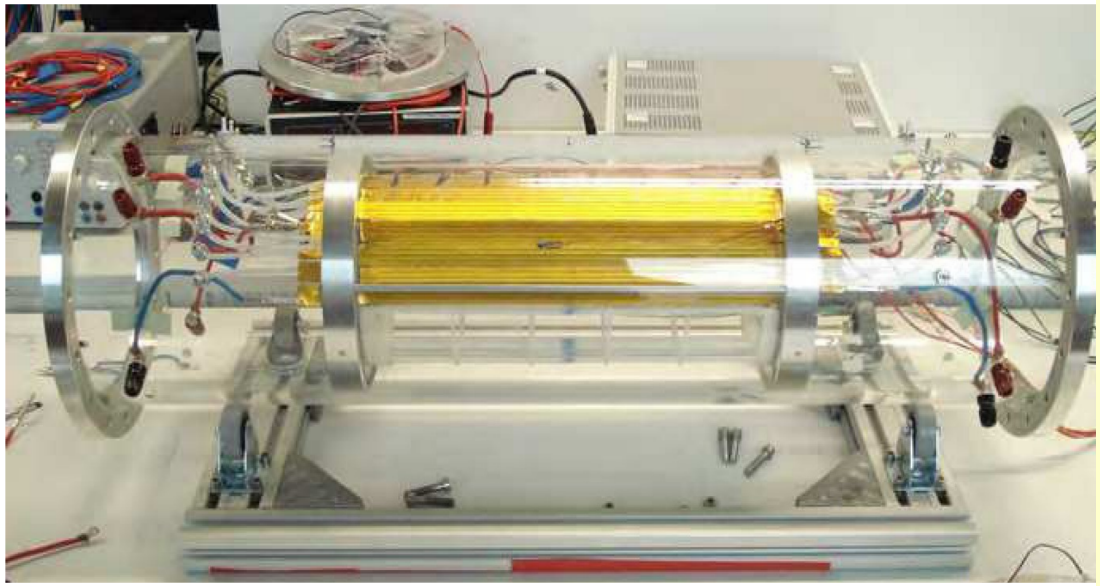


more power does not improve performance

Pixel Detector + Helium Gas Cooling

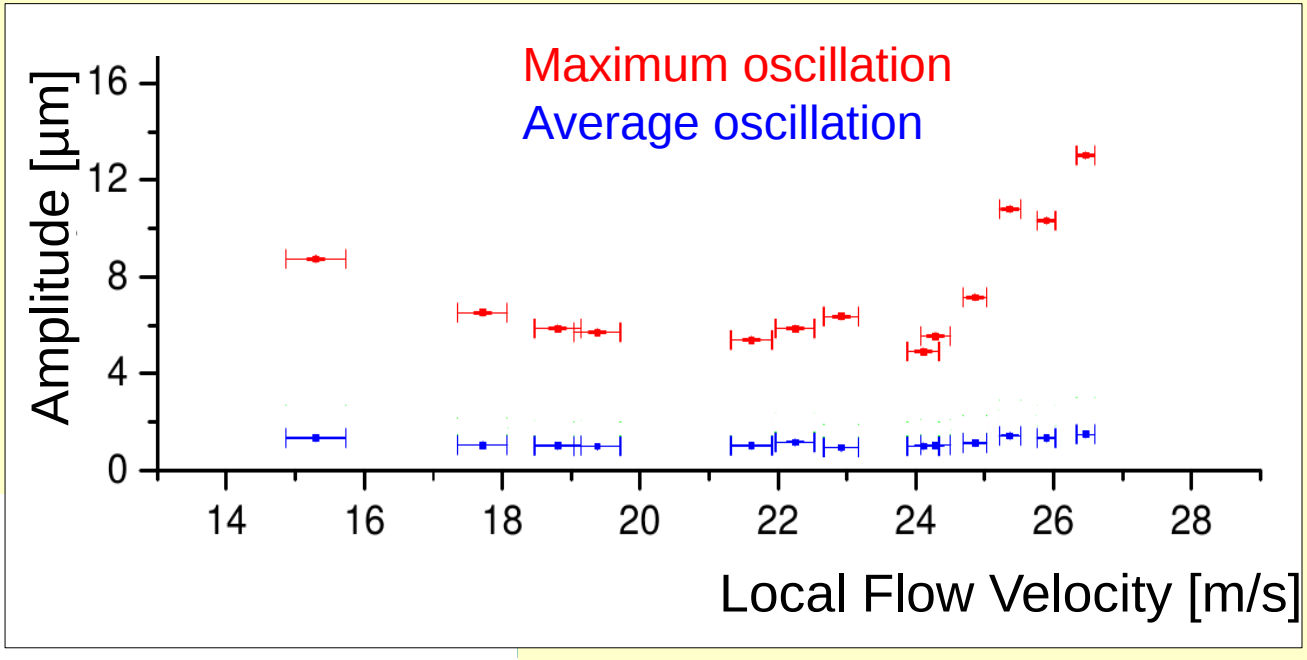
- Heatable module prototypes
- Temperature sensors
- Flow container
- Local and global helium flow

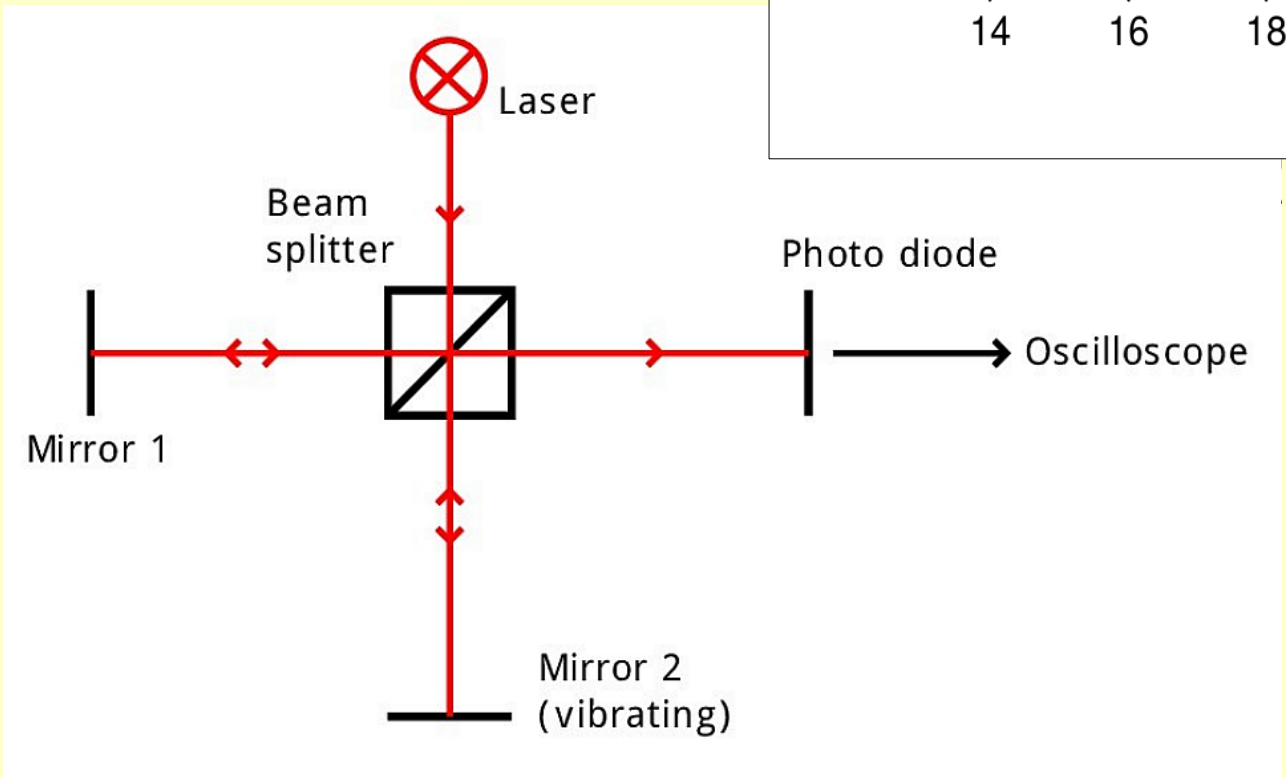




Vibration Measurements

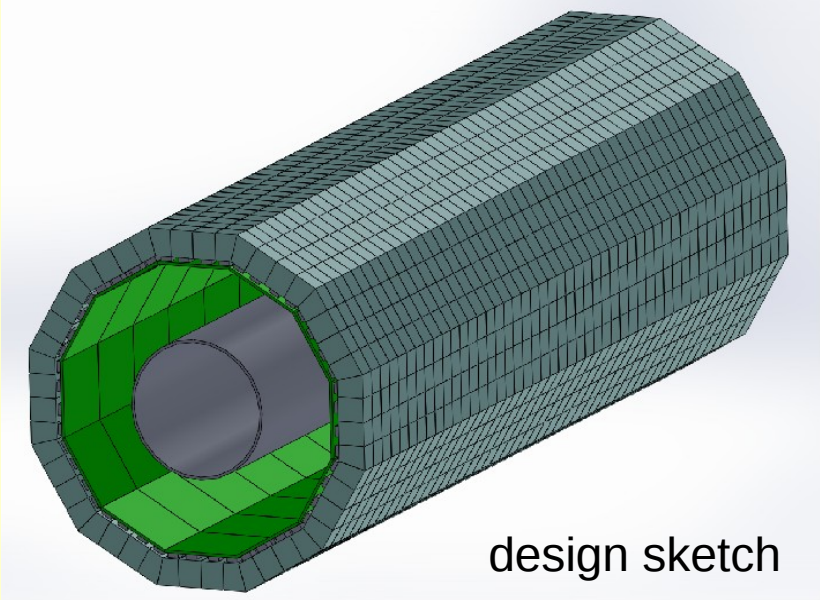
Measurement of flow-induced vibrations with Michelson interferometer



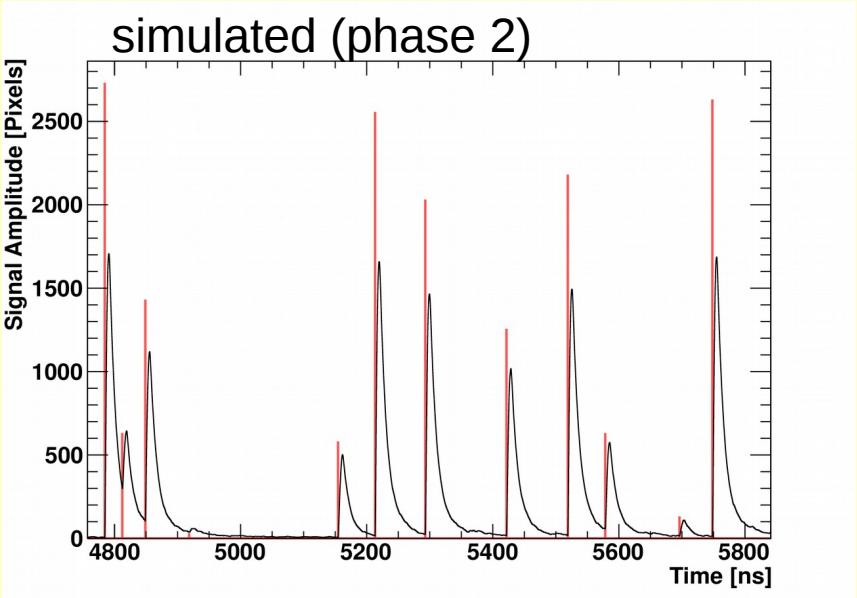


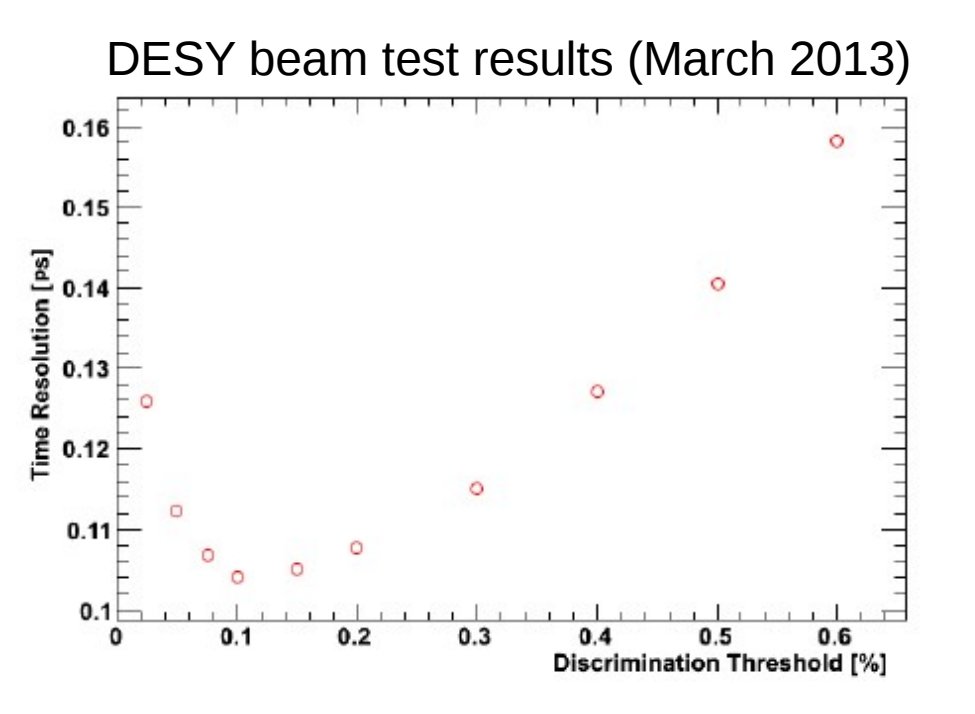
→ **maximum vibrations in tolerable range**

Scintillating Tile Detector



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





Cross Talk in Mupix7

transmission lines between matrix and periphery