The Mu3e Experiment

Searching for Lepton Flavour Violation

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BEYOND STANDARD MODEL

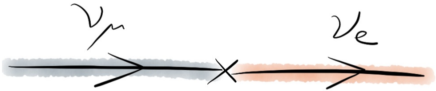
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

Charged Lepton Flavour Violation

Searching for New Physics in the Decay $\mu \rightarrow eee$

Lepton Flavour conserved in Standard Model

... but ν oscillations



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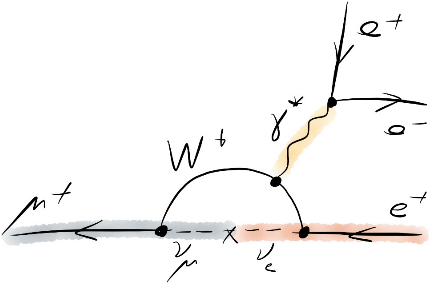


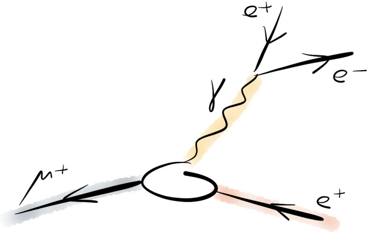
Expectation from lepton mixing: $\mathrm{BR}_{\mu \to eee} \sim \left(\frac{\Delta m_\nu^2}{m_W^2} \right)^2 < 10^{-54}$

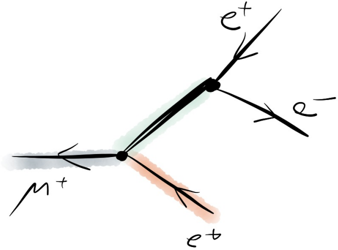
Charged Lepton Flavour Violation

Searching for New Physics in the Decay $\mu \to eee$

Observation of $\mu \to eee$ is a clear sign for New Physics

SUSY, GUTs, extended Higgs sector, ...



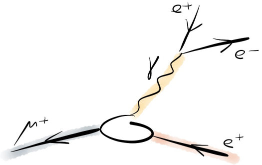


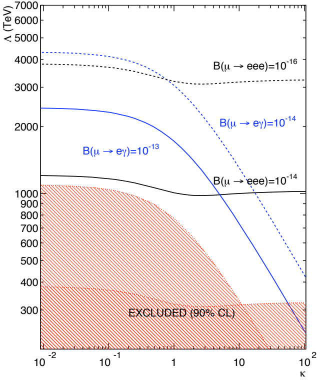
Current limit: $BR_{\mu \to eee} < 1.0 \cdot 10^{-12}$ at 90 % CL [SINDRUM, 1988]

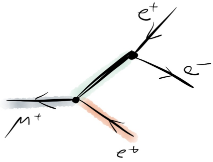
Mu3e: New experiment sensitive to BR's of 10^{-15} (10^{-16})

Charged Lepton Flavour Violation

Searching for New Physics in the Decay μ → eee





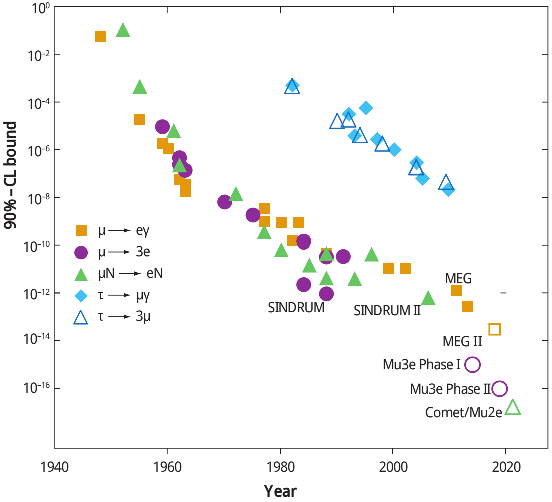


$$\mathcal{L}_{\text{CLFV}} = \left[\frac{m_\mu}{(\kappa+1)\Lambda^2}\overline{\mu_R}\sigma_{\mu\nu}e_L F^{\mu\nu}\right]_{\text{dipole-like}} + \left[\frac{\kappa}{(\kappa+1)\Lambda^2}(\overline{\mu_L}\gamma_\mu e_L)(\overline{e_L}\gamma^\mu e_L)\right]_{\text{four-fermion}}$$

A. Gouvêa, P. Vogel, Prog.Part.Nucl.Phys. 71 (2013)

Charged Lepton Flavour Violation

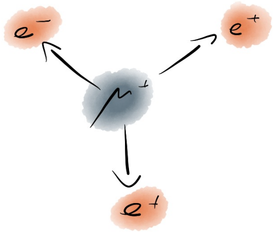
History of LFV Searches in μ and τ Decays



Adapted from Marciano et al. [Ann.Rev.Nucl.Part.Sci.58, 2008]

Signal and Background

Signal Decay $\mu \rightarrow eee$



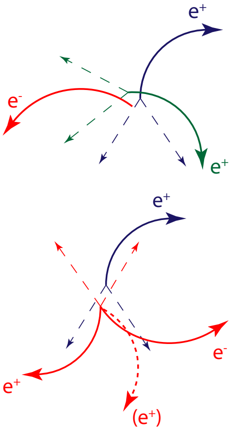
Signature for μ decay at rest

- Common vertex
- Coincident in time
- $\sum E_e = m_\mu c^2$
- $\sum \vec{p}_e = 0$
- All particles in one decay plane

- $E_e = (0 - 53)$ MeV
- Multiple Coulomb scattering limits momentum resolution

Signal and Background

Background: Combinatorial Background



Overlays of Michel decay $\mu \rightarrow e\nu\nu$, Bhabha scattering, photon conversion, . . .

No common vertex

Not coincident

$\sum E_e \neq m_\mu c^2$

$\sum \vec{p}_e \neq 0$

Increases with beam intensity

Signal and Background

Background: Radiative Decay with Internal Conversion $\mu \to ee e\nu\nu$

$BR_{\mu^+ \to e^+ e^- e^+ \overline{\nu}_\mu \nu_e} = (3.4 \pm 0.4) \cdot 10^{-5}$ [Nucl.Phys.B260, 1985]

Common vertex

Coincident in time

$\sum E_e < m_\mu c^2$

$\sum \vec{p}_e \neq 0$

→ Missing energy due to neutrinos

Need very good momentum resolution

Signal and Background

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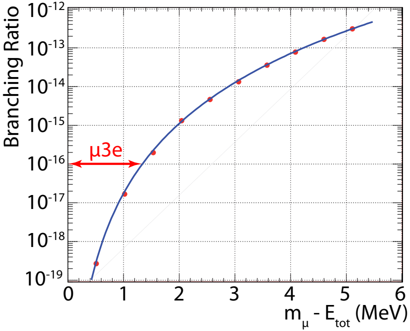

[Djilkibaev, Konoplich, Phys.Rev.D79, 2009]

Common vertex

Coincident in time

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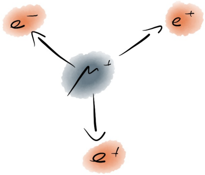
Need very good momentum resolution

Experimental Concept

Requirements

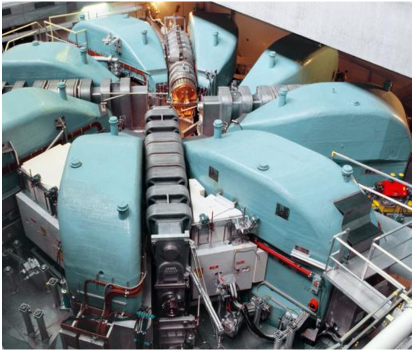


- High muon stopping rates: $10^8 \mu/s$ to $> 10^9 \mu/s$
- Very good vertex ($\sim 200\,\mu m$) and time resolution ($\sim 100\,ps$)
- Excellent momentum resolution ($\sim 0.5\,MeV$)
- Minimal material amount
- Triggerless data acquisition
- Fast online reconstruction for data rate reduction

Experimental Concept

Muon Beam

Paul-Scherrer Institute in Switzerland



2.2 mA proton beam with 590 MeV

Secondary beamlines: μ^+ with 28 MeV

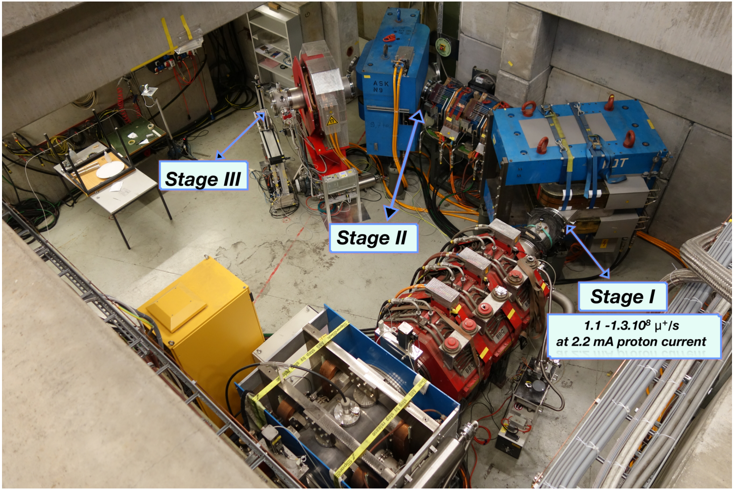
10^8 muons/s at existing beamline

10^9 muons/s at future beamline (under investigation)

Experimental Concept

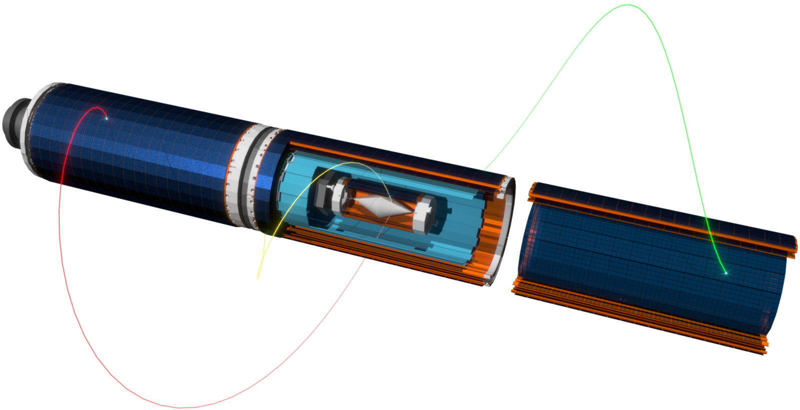
Muon Beam

Paul-Scherrer Institute in Switzerland



Experimental Concept

Detector

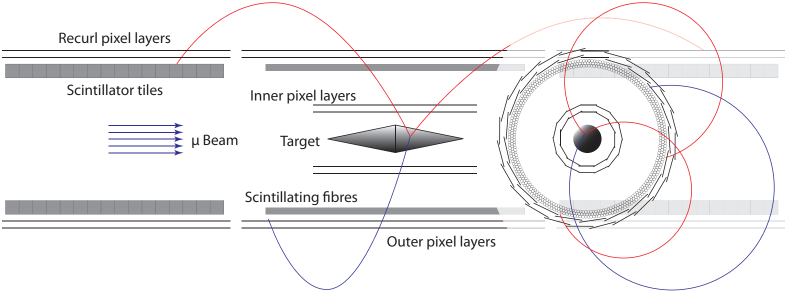


Tracking detector:
Thin Si pixel sensors (HV-MAPS)

+ Timing detector:
Scintillating fibres and tiles

Experimental Concept

Detector



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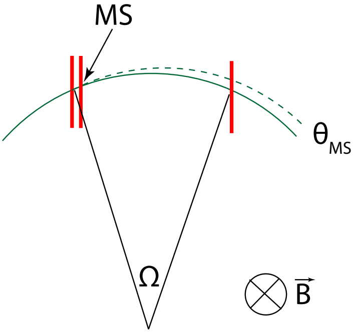
Experimental Concept

Multiple Coulomb Scattering



Decay electrons have low momentum < 53 MeV/c

Momentum resolution is dominated by multiple scattering

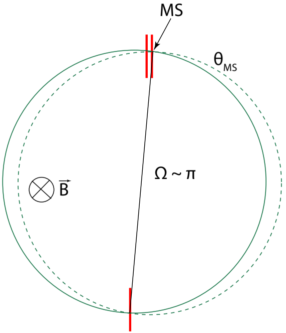
$$\frac{\sigma_p}{p} \sim \frac{\theta_{\mathsf{MS}}}{\Omega} \text{ with } \theta_{\mathsf{MS}} \propto \frac{1}{p}\sqrt{\frac{x}{X_0}}$$

→ reduce material thickness x

→ increase opening angle Ω

Experimental Concept

Multiple Coulomb Scattering



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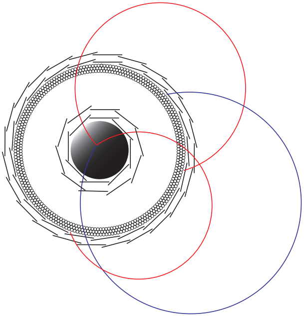
at $\Omega \approx \pi \Rightarrow \frac{\sigma_p}{p} \sim \mathcal{O}(\theta^2_{\mathrm{MS}})$

Experimental Concept

Multiple Coulomb Scattering



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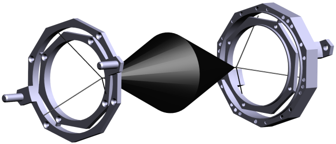
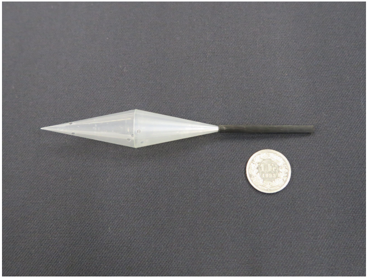
Experimental Concept

Target





- Extended hollow double-cone target made of mylar (~ 80 μm)
- Length 10 cm, diameter 3.9 cm

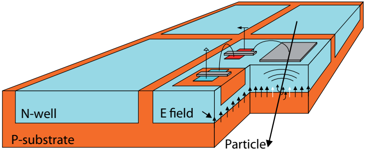
- High muon stopping fraction
- Vertex separation over a large surface
- Low distortion for 'escaping' electrons

Experimental Concept

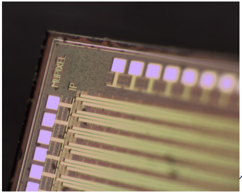
Pixel Sensors: HV-MAPS

High Voltage Monolithic Active Pixel Sensors

- 180 nm HV-CMOS process
- N-well in p-substrate
- Reverse bias of 60 to 90 V
  - Fast charge collection via drift
  - Depletion zone of ~ 10 μm
    Thinning possible (≲ 50 μm)
- Transistor logic embedded in N-well
  "smart diode array"
- Pixel size $80 \times 80 \mu m^2$
  Sensor size $2 \times 2 cm^2$



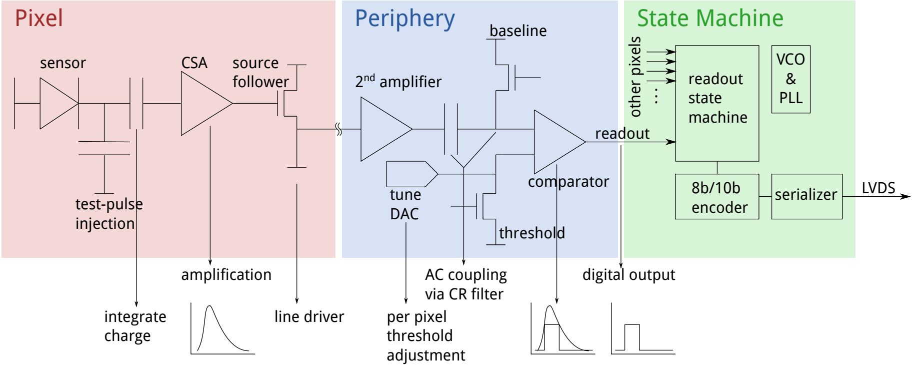
I. Perić, NIM A 582 (2007)



Thin and granular

Experimental Concept

Pixel Sensors: HV-MAPS

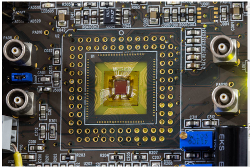


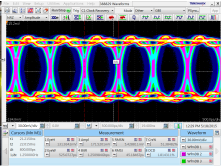
Hit finding, digitisation, zero-suppression and readout on-chip

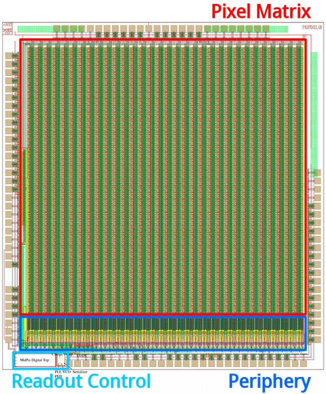
Continuous and fast readout at 1.25 Gbit/s

MuPix7 is the latest HV-MAPS prototype for Mu3e

- 32×40 pixels à $103 \times 80\mu m^2$
- $2.9 \times 3.2mm^2$ of active area
- 50 µm thin
- 'System-on-chip'
- Zero-suppressed hit addresses and timestamps



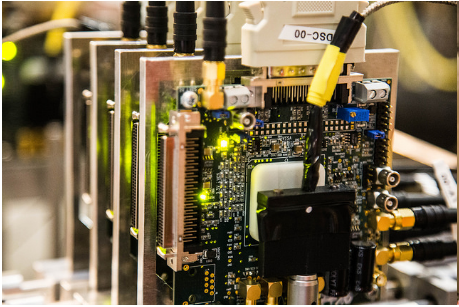


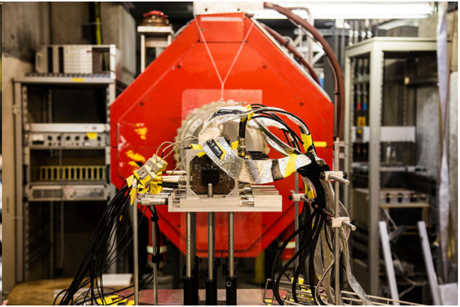


Experimental Concept

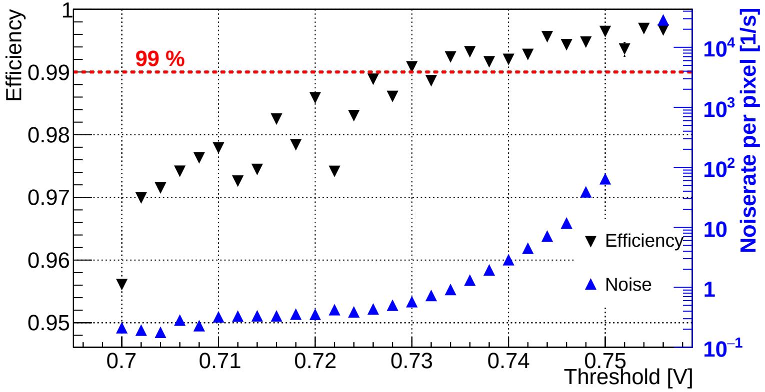
Pixel Sensors: MuPix Prototype

Beam telescope with 4 layers of MuPix7 and scintillating tiles
One MuPix layer used as DUT





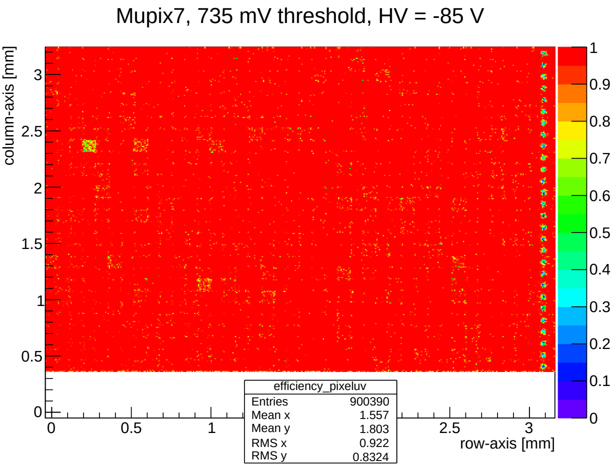
Testbeam at DESY: 4 GeV e^+ beam



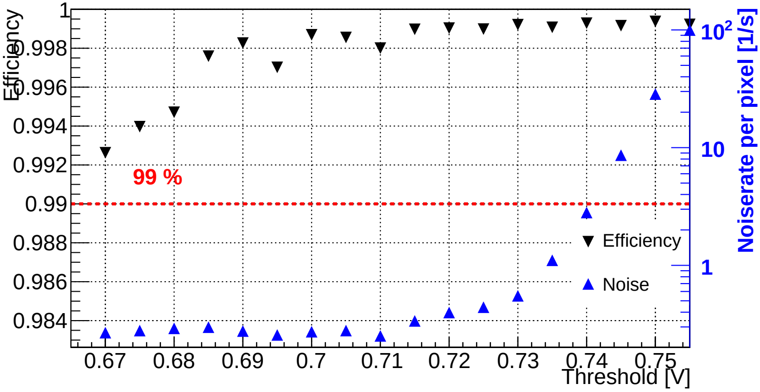
Experimental Concept

Pixel Sensors: MuPix Prototype

Testbeam at DESY: 4 GeV e^+ beam; using DESY Duranta telescope



Testbeam at DESY: 4 GeV e^+ beam; DUT rotated by 60° wrt to beam axis

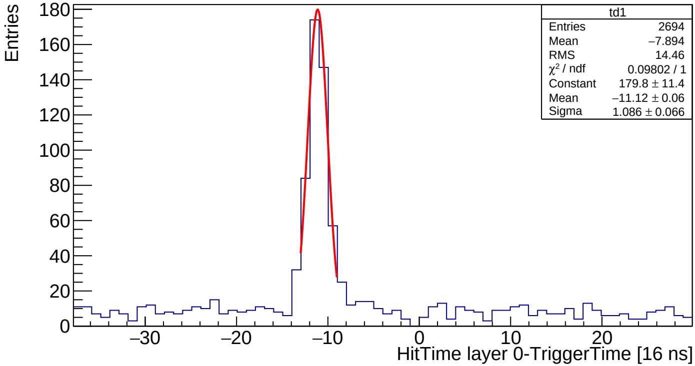


Experimental Concept

Pixel Sensors: MuPix Prototype

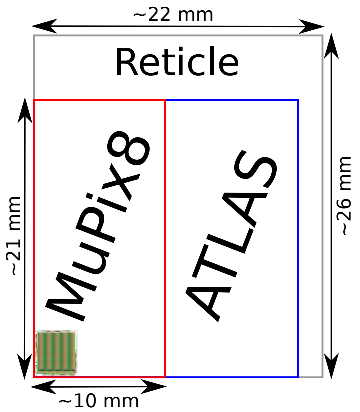
Testbeam at DESY: 4 GeV e^+ beam

Timing resolution of 17.4 ± 1.1ns



Experimental Concept

Pixel Sensors: MuPix Prototype



Next prototype: MuPix8

- First large MuPix sensor $2 \times 1\text{cm}^2$
- 4 serial links
- Time walk correction
- Different substrates $20\,\Omega\,\text{cm}$ and $80\,\Omega\,\text{cm}$

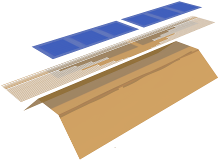
Submission in November

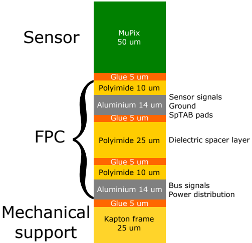
Experimental Concept

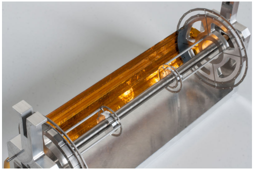
Pixel Detector: Lightweight Mechanics

- 50 µm silicon sensor
- 80 µm Flexible printed circuit board (FPC)
- 25 µm Kapton support structure

→ ~ 0.1 % of radiation length





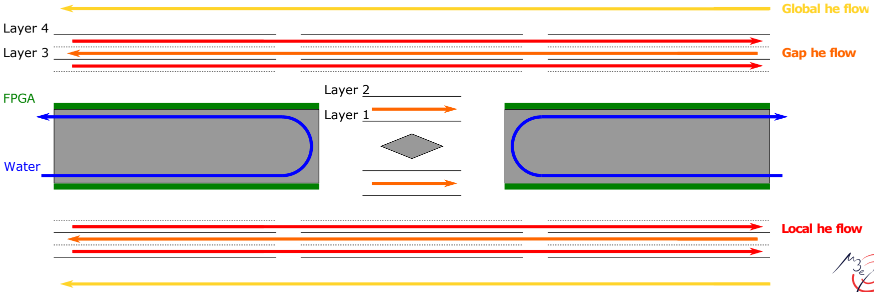


Experimental Concept

Cooling

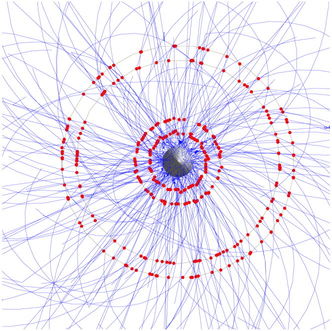
Cooling with gaseous helium

Power consumption of Si pixel sensors is $250\,\mathrm{mW/cm^2}$

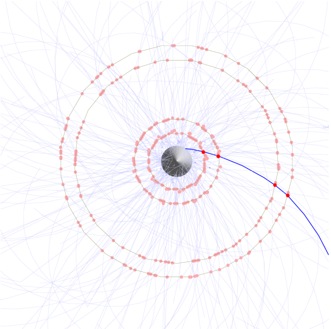


Experimental Concept

Time Measurement



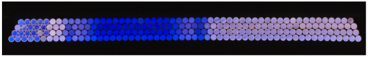
Tracks expected within readout frame of 50 ns

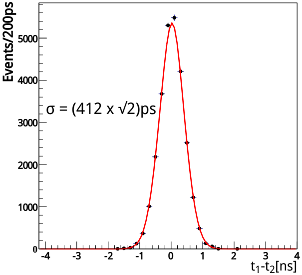


Matching with time information of scintillating fibres and tiles

Experimental Concept

Scintillating Fibres





Time resolution of squared fibres

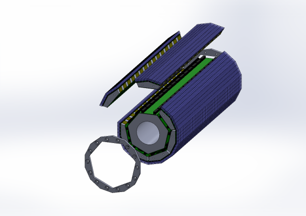
- 2 to 4 layers of fibres with ∅ ~ 250 µm
- Round and squared fibres under investigation
- Photon detection at both ends with SiPM array
- Readout with custom-designed STiC chip
- Time resolution:

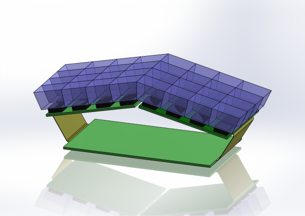
$$\frac{\sigma_{\text{round}}}{\sqrt{2}} \approx 1.5\,\text{ns}$$

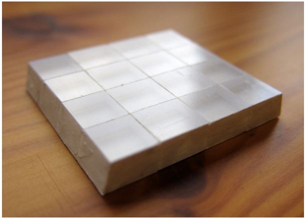
$$\frac{\sigma_{\text{squared}}}{\sqrt{2}} \leq 500\,\text{ps}$$

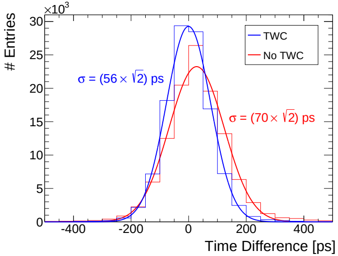
Experimental Concept

Scintillating Tiles





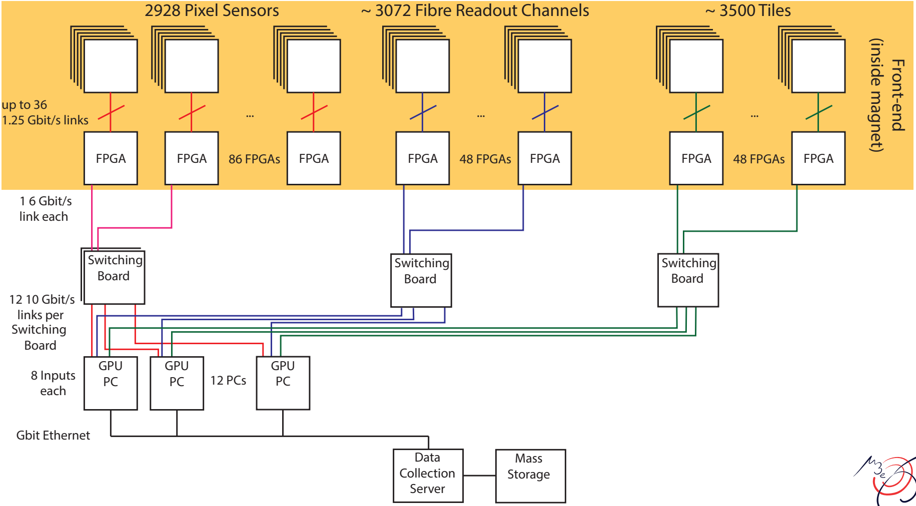




- Size ~ $1 \times 1 \times 1 \text{cm}^3$
- Each tile has a SiPM
- Readout with custom-designed STiC chip
- Time resolution $\lesssim 100\,\text{ps}$

Experimental Concept

Data Acquisition



Experimental Concept

Data Acquisition

Triggerless data acquisition

Front-end board

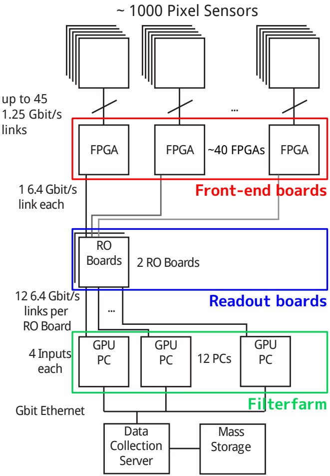
- Slow control
- Buffer and merge data
- Time-sorting

Readout board

- Switch between front-end and filterfarm
- Merge data of sub-detectors

GPU filterfarm

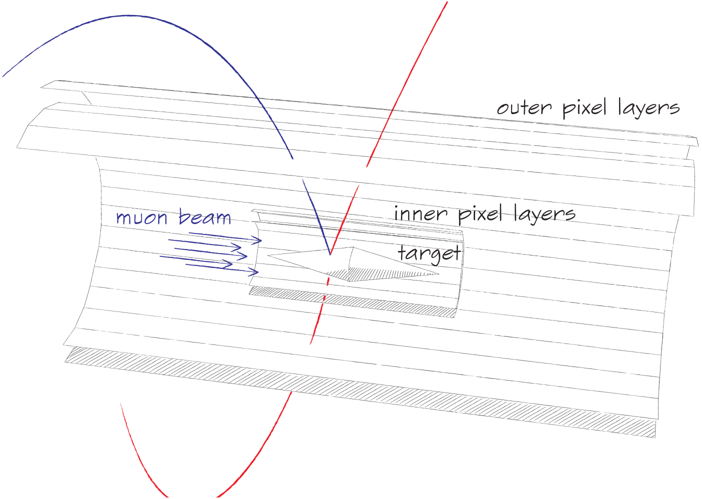
- Fast track finding and online reconstruction
- Reduce data rate from $\sim 1\,\text{Tbit/s}$ to $\sim 100\,\text{MB/s}$



Experimental Concept - Phase I

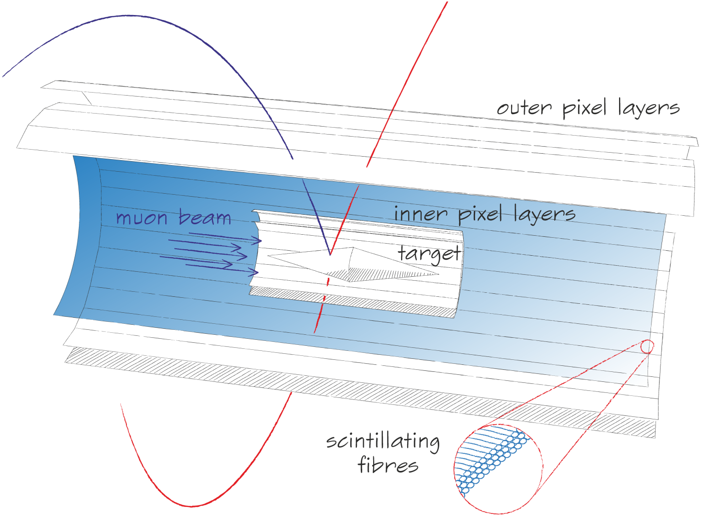
Detector construction in 2 phases

Starting with central Si pixel tracking detector $\rightarrow 10^7 \mu/s$



Experimental Concept - Phase I

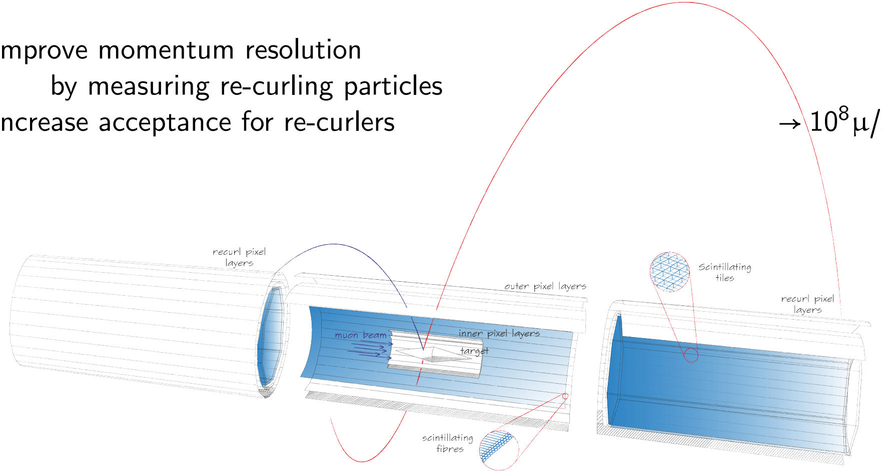
Improve time resolution with scintillators



Experimental Concept - Phase I

Improve momentum resolution
by measuring re-curling particles
Increase acceptance for re-curlers

$\rightarrow 10^8 \mu/s$

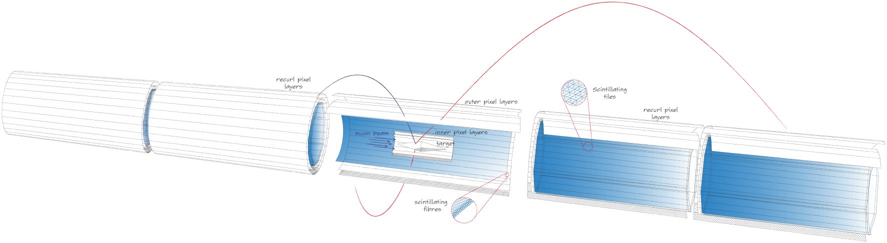


Experimental Concept - Phase II

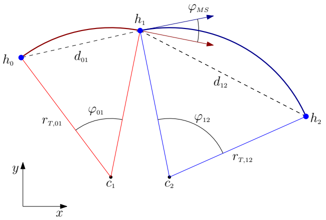
Full-size detector

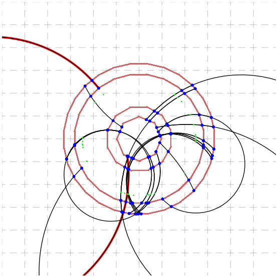
New beamline with $\sim 2 \cdot 10^9 \mu/s$

$\Rightarrow$ reach design sensitivity of $BR_{\mu \to eee} \simeq 10^{-16}$



Reconstruction





- 3D multiple scattering fit for track reconstruction
- Spatial uncertainties of hit positions are ignored as MS dominates

- Hits in 3 layers form a 'triplet'
- Join triplets by minimizing MS angles

- Subsequent vertex fit with 3 trajectories of correct charge

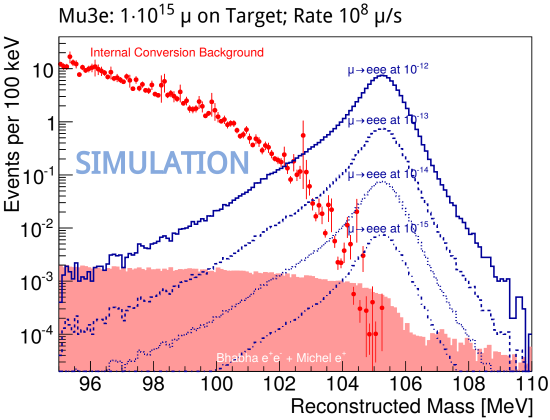
Simulation

Full Geant4-based detector simulation

Generators for SM and BSM decays

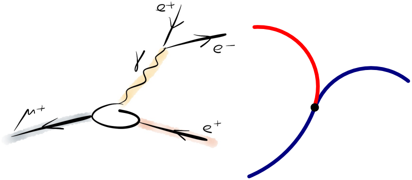
Track and vertex reconstruction

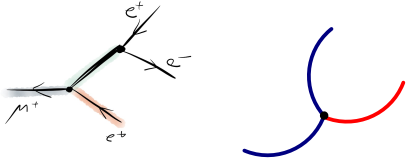
Analysis tools



Physics Prospects

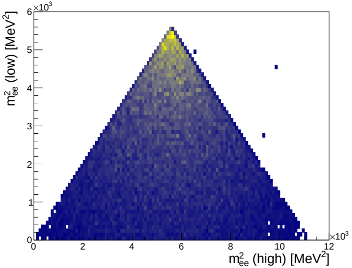
- μ → eee
  EFT approach with LFV dim6 operators
  $\mathcal{L} \supset \sum_i \frac{c_i}{\Lambda^2} O_i$
- Other LFV decays
  μ → eγ, μ → eX
- Searches for dark photons
  μ → eννA′ and A′ → ee





Physics Prospects

- $\mu \to eee$
  EFT approach with LFV dim6 operators
  $\mathcal{L} \supset \sum_i \frac{c_i}{\Lambda^2} O_i$
- Other LFV decays
  $\mu \to e\gamma$, $\mu \to eX$
- Searches for dark photons
  $\mu \to e\nu\nu A'$ and $A' \to ee$



Dalitz plot for 4-fermion operator

Physics Prospects

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  EFT approach with LFV dim6 operators
  $\mathcal{L} \supset \sum_i \frac{c_i}{\Lambda^2} O_i$
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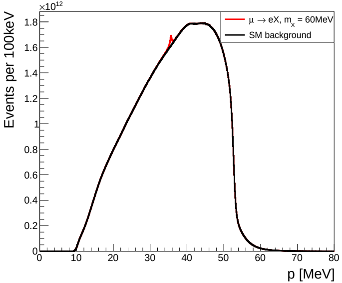
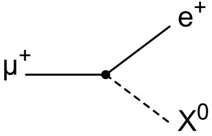




Mu3e Collaboration

DPNC, Geneva University

KIP, Heidelberg University

Physics Institute, Heidelberg University

IPE, Karlsruhe Institute of Technology

Institute for Nuclear Physics, JGU Mainz

Paul Scherrer Institute

Institute for Particle Physics, ETH Zürich

Physics Institute, Zürich University

Summary

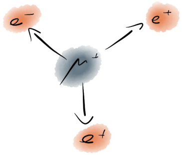
Mu3e Search for LFV decay $\mu \rightarrow eee$ with a sensitivity of $BR < 10^{-16}$ (90% CL)

Low-material tracking detector operated at high muon rates

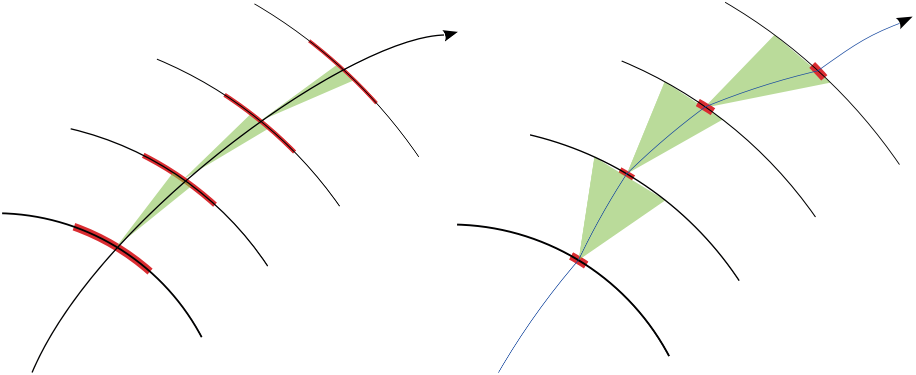
Status Research proposal approved in 2013

Research and development on subsystems

Preparation of detector construction

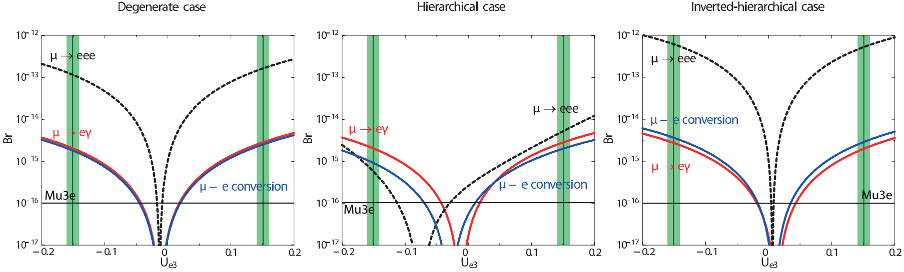


Tracking in MS-dominated Environment



LFV in Higgs Triplet Models

Models with Higgs triplet responsible for neutrino mass generation
Projections for LFV processes shown for different neutrino mass hierarchies

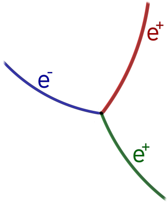


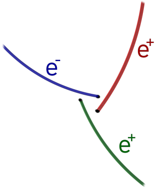
M. Kakizaki, Y. Ogura, F. Shima, Phys.Lett. B566 (2003)
(Plotted BR depens on mass scale M and can thus vary)

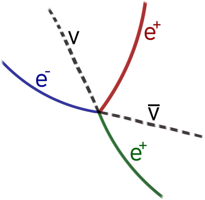
Signal and Background

Signal

Background







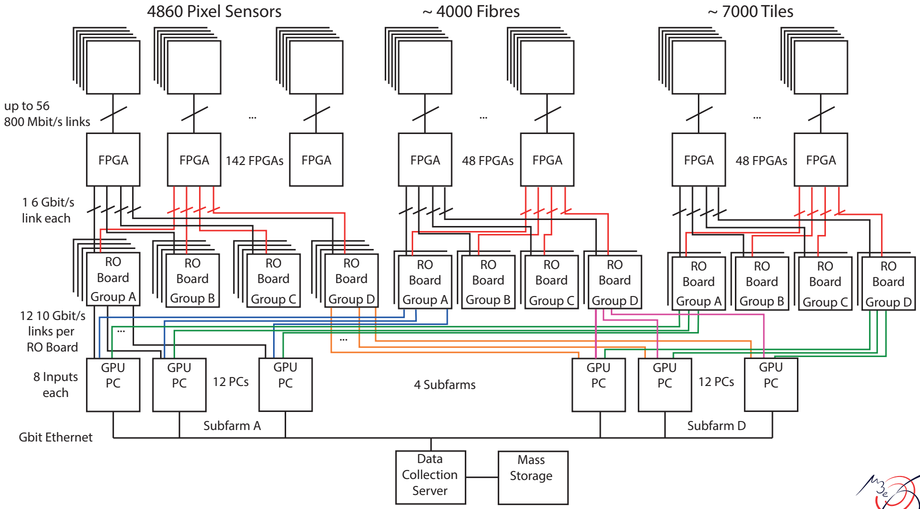
Signal $\mu^+ \rightarrow e^+e^-e^+$

Accidental combinations

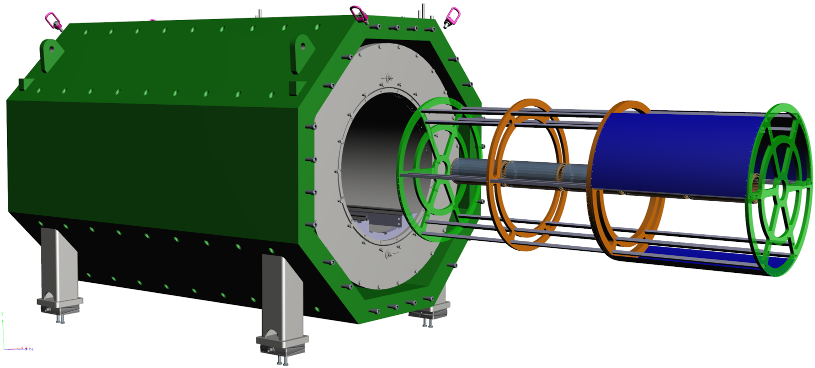
Internal conversion $\mu^+ \rightarrow e^+e^-e^+\overline{\nu}_\mu\nu_e$

Signal	Accidental combinations	Internal conversion
Common vertex	No common vertex	Common vertex
Coincident	Not coincident	Coincident
$\sum E_e = m_\mu$	$\sum E_e \neq m_\mu$	$\sum E_e < m_\mu$
$\sum \vec{p}_e = 0$	$\sum \vec{p}_e \neq 0$	$\sum \vec{p}_e \neq 0$

Full Readout Scheme

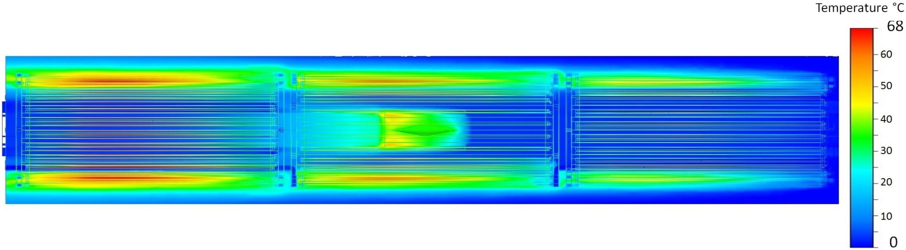


Experimental Concept



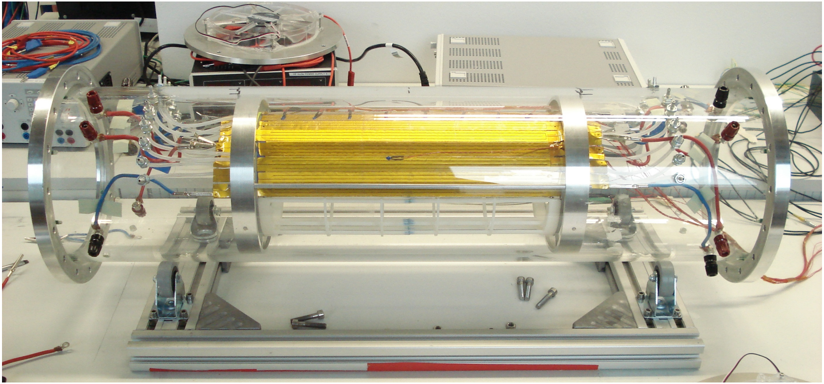
Experimental Concept
Cooling

Finite elements simulation of temperature distribution at 250 mW/cm^2

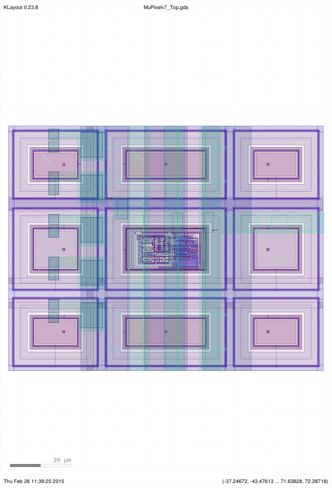


Experimental Concept

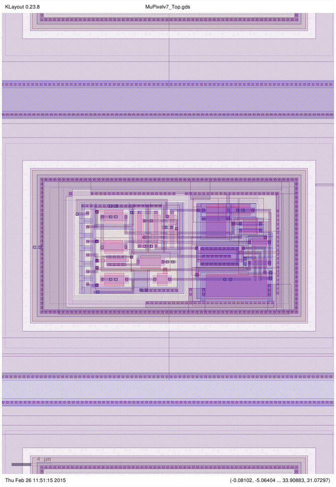
Cooling



MuPix: Pixel Layout



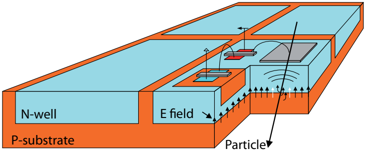
MuPix: Pixel Layout



MuPix7 Prototype

High Voltage Monolithic Active Pixel Sensor

- Integrated signal processing
  - Amplification and signal shaping
  - Hit detection
- Internal state machine
  - Column-wise readout
    time structure is 'lost'
  - 8b/10b encoded data:
    hit: time stamp, pixel address
    or counter
  - LVDS link at up to 1.25 Gbit/s
    up to 30 Mhits/s can be read out
    expected $\leq$ 8 Mhits/s on busiest sensor at 10^8 μ/s



I. Perić, NIM A 582 (2007)

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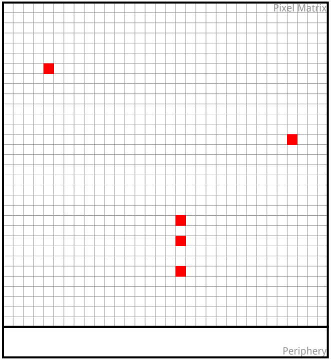

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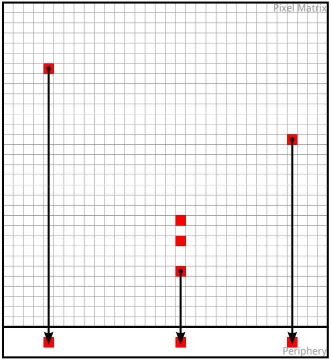

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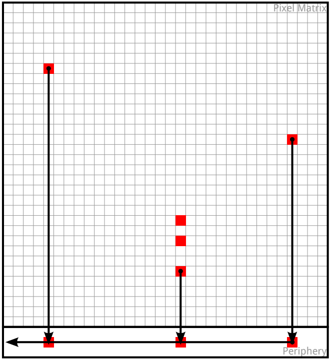

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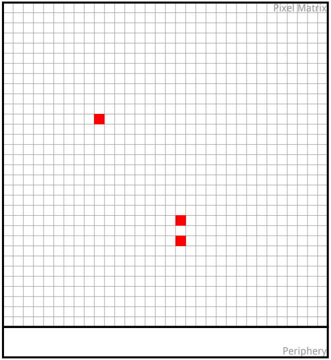

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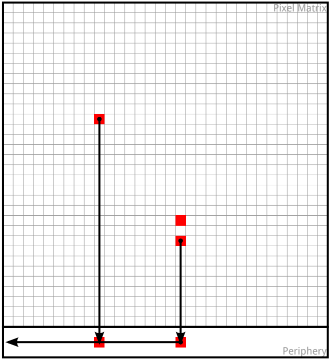

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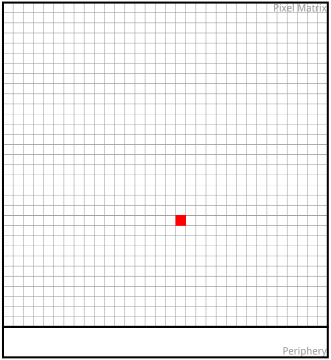

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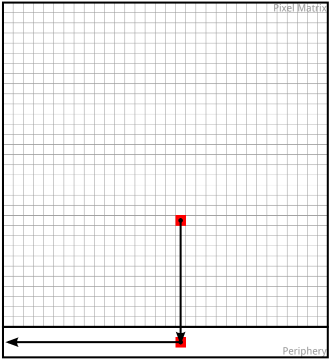

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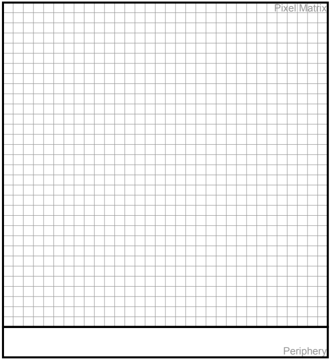
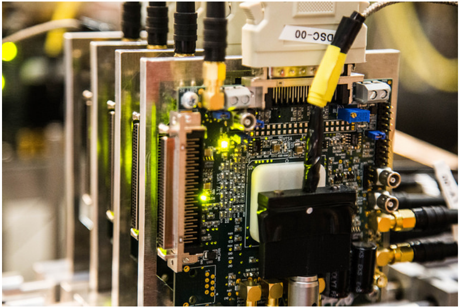


Front-End for the MuPix Telescope

MuPix telescope

- Tests of new prototypes and system integration
- 4 planes of MuPix7
- Readout via Altera Stratix IV development boards
- Test beam at DESY, PSI, SPS, MAMI in 2015



Front-End for the MuPix Telescope

Receiver

- Receive data via LVDS at 1.25 Gbit/s
- Align to word boundary using K-words
- 8b/10b decoding

"Unpacker"

- Disentangle hit and counter data
- Remove K-words

Hit sorter

- Merge data from 4 sensors to one datastream
- Sort hit data by time stamp

Data transfer to PC via PCIe