Searching for the Decay $\mu \rightarrow eee$
The Mu3e Experiment in Phase I

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VISTAS on Detector Physics
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The Mu3e Experiment

SINDRUM	$\mathcal{B}_{\mu \to eee} < 1.0 \cdot 10^{-12}$ at 90 % CL [1988]
Mu3e	Single-event sensitivity of $2 \cdot 10^{-15}$ in phase I *

Challenges

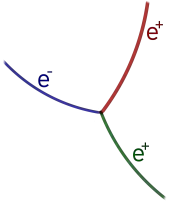
- Background-free operation
  - Very good vertex and time resolution
  - Excellent momentum resolution
- High muon stopping rates of $10^{8}\,\mu/\mathrm{s}$
  - Detectors and data acquisition need to cope with high rates

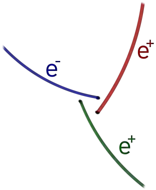
* [SES of $\sim 10^{-16}$ in phase II]

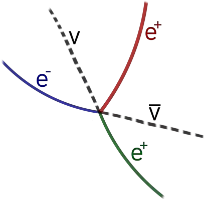
Signal and Background

Signal

Background







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

- Common vertex
- Coincident
- $\sum E_e = m_\mu$
- $\sum \vec{p}_e = 0$

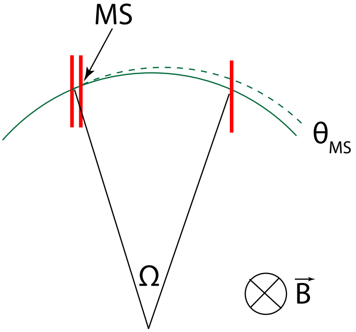
Accidental background

- No common vertex
- Not coincident
- $\sum E_e \neq m_\mu$
- $\sum \vec{p}_e \neq 0$

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

- Common vertex
- Coincident
- $\sum E_e < m_\mu$
- $\sum \vec{p}_e \neq 0$

Multiple Coulomb Scattering



- Decay electrons have low momentum $< 53\,\mathrm{MeV/c}$
- Momentum resolution is dominated by multiple scattering

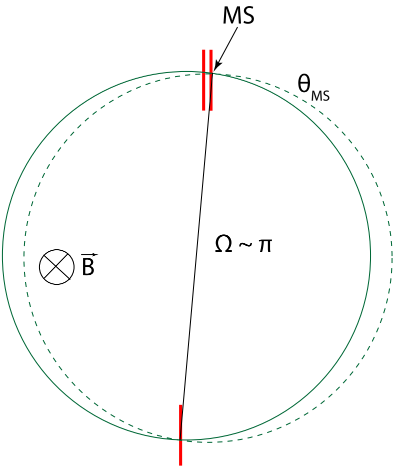
Scattering angle: $$\theta_{\mathsf{MS}} \propto \sqrt{\frac{x}{X_0}}$$

Resolution: $$\frac{\sigma_p}{p} \sim \frac{\theta_{\mathsf{MS}}}{\Omega}$$

→ Reduce material thickness x

→ Increase opening angle Ω

Multiple Coulomb Scattering



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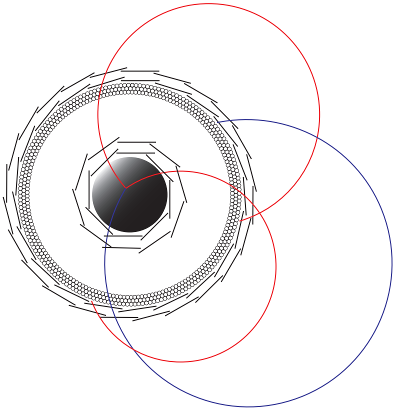

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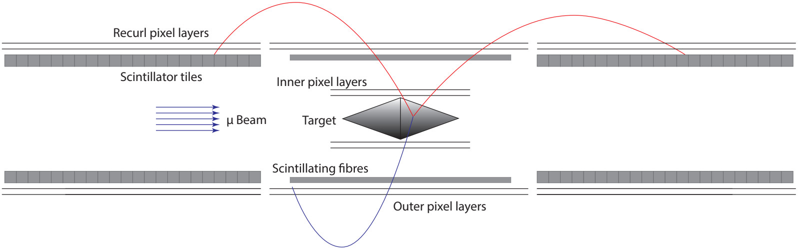
The Mu3e Detector



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

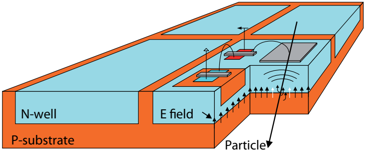
+ Timing detector:
Scintillating fibres and tiles

B-field: 1 T
Length: 110 cm
Diameter: 18 cm

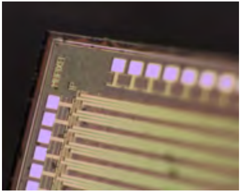
Pixel Sensors: HV-MAPS

High Voltage Monolithic Active Pixel Sensors

- AMS 180 nm HV-CMOS process
- N-well in p-substrate
- Reverse bias of ~ 80 V
  - Fast charge collection via drift
  - Depletion zone of a few 10 μm
    Thinning possible ($\lesssim$ 50 μm)
- Integrated readout electronics
- Pixel size $80 \times 80 \mu m^2$
  Sensor size $2 \times 2 cm^2$

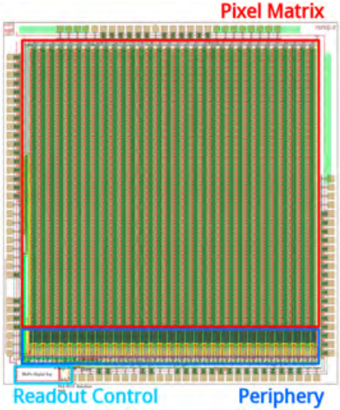


I. Perić, NIM A 582 (2007)



Pixel Sensors: MuPix7 Prototype

- Small-scale prototype
  - 32×40 pixels à $103 \times 80\mu m^2$
  - $2.9 \times 3.2 mm^2$ of active area
  - 50 µm thin
- Integrated signal processing
  - Amplification and signal shaping within the pixel
  - Hit detection and digitisation in periphery
  - Zero-suppressed data output: pixel address and time stamp
  - LVDS link at 1.25 Gbit/s



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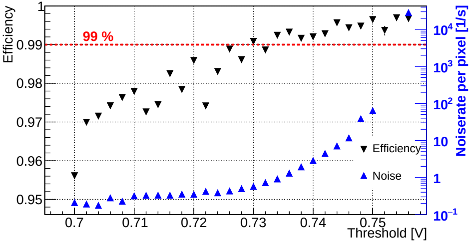
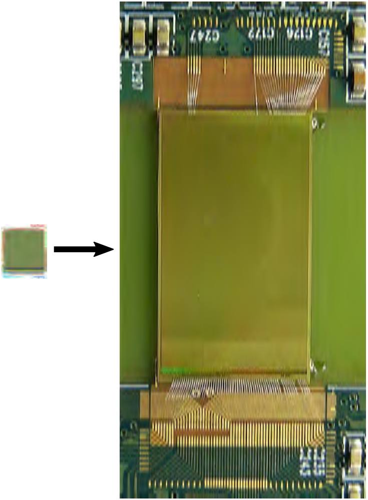
Efficiency $> 99\,\%$

at low noise rates

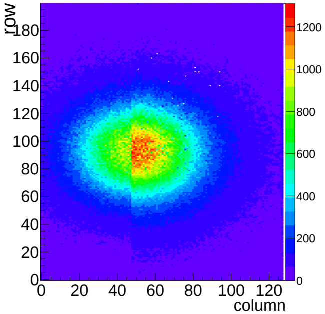


Pixel Sensors: MuPix8 Prototype



- First large MuPix sensor: $2 \times 1\text{cm}^2$
- 128×200 pixels à $81 \times 80\mu\text{m}^2$
- Two different approaches for the line driver
- Analogue pulse information for time walk correction
- Different substrates: $20\,\Omega\,\text{cm}$ and $80\,\Omega\,\text{cm}$

Pixel Sensors: MuPix8 Prototype



Preliminary hitmap of a Sr-90 source

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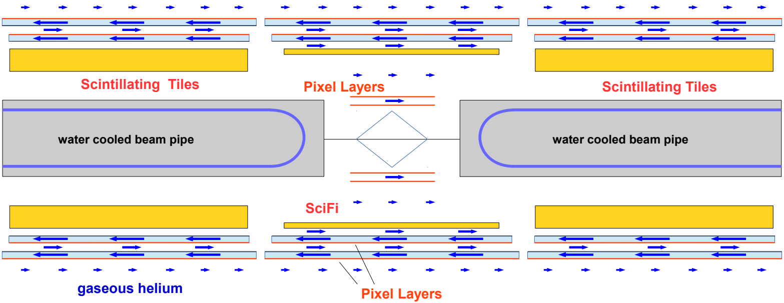
Pixel Sensors: Cooling

Cooling with gaseous helium

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



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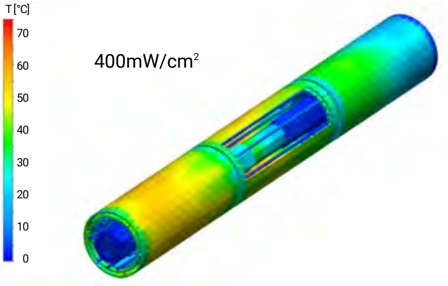
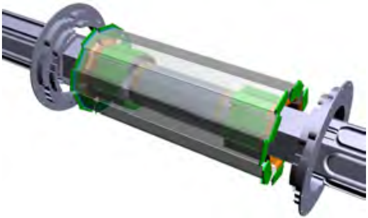
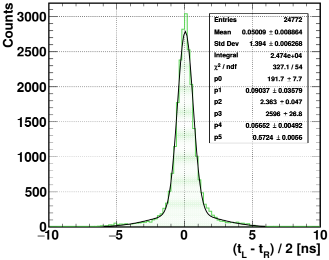


Timing Detector: Scintillating Fibres

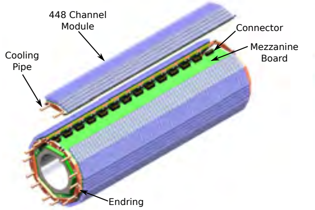


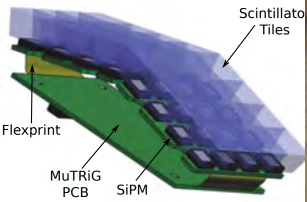


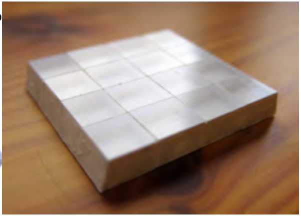
Time resolution of square fibres

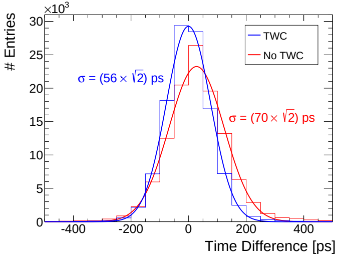
- 3 layers of fibres with $\varnothing \sim 250\,\mu\text{m}$ and length of 28 to 30 cm
- Photon detection at both ends with LHCb SiPM column array
- Readout with custom-designed MuTRiG
- Round and square fibres under investigation
- Prototype with 3 layers of square multiclad fibres: $\sigma_t = (572 \pm 6)\text{ps}$ and $\epsilon \gtrsim 95\,\%$

Timing Detector: Scintillating Tiles



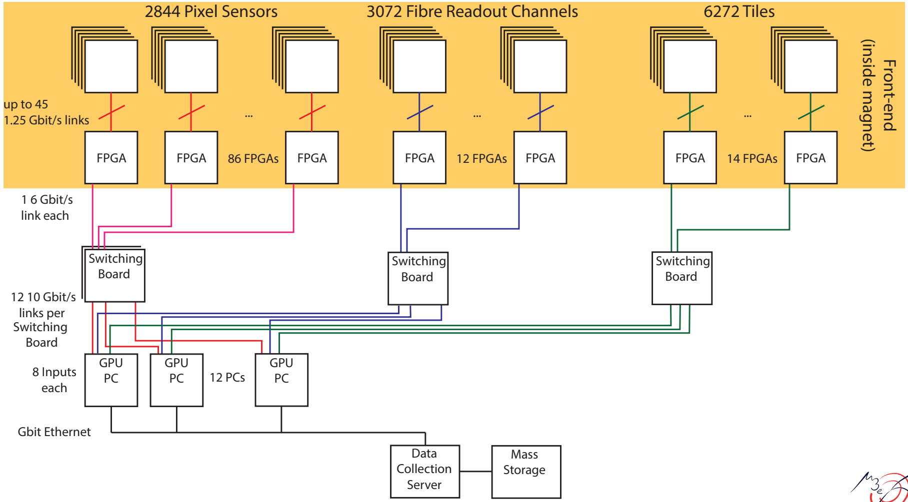






- $6.5 \times 6.5 \times 5.0\mathrm{mm}^3$ tiles with individual SiPMs
- Custom-designed MuTRiG: TDC ASIC for SiPM readout
- Prototype yields time resolution $\sim 70\,\mathrm{ps}$ and efficiency $\epsilon \gtrsim 99.7\,\%$

Data Acquisition



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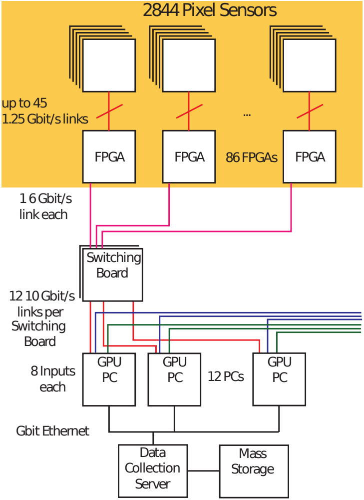


Triggerless data acquisition

Front-end board

- Decode and merge data of ~ 15 (36) sensors
- Time-sorting

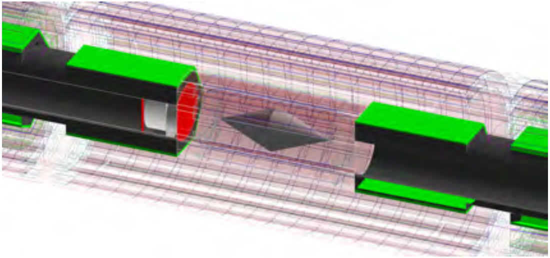
Switching board

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

GPU filterfarm

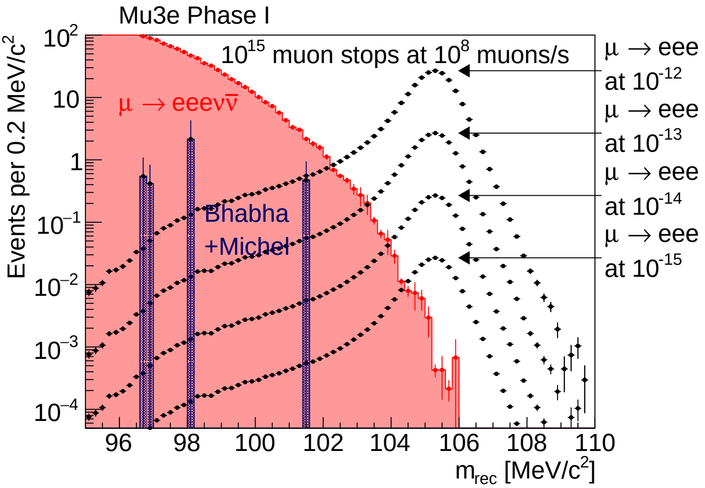
- Fast online track and vertex reconstruction
- Data rate reduction for mass storage from 60 Gbit/s to 100 MB/s

The Mu3e Simulation Framework



- Full Geant4-based detector simulation
- Detector geometry and beam
- Generators of physics processes
- Track reconstruction and vertex fit

Sensitivity Studies for $\mu \rightarrow eee$



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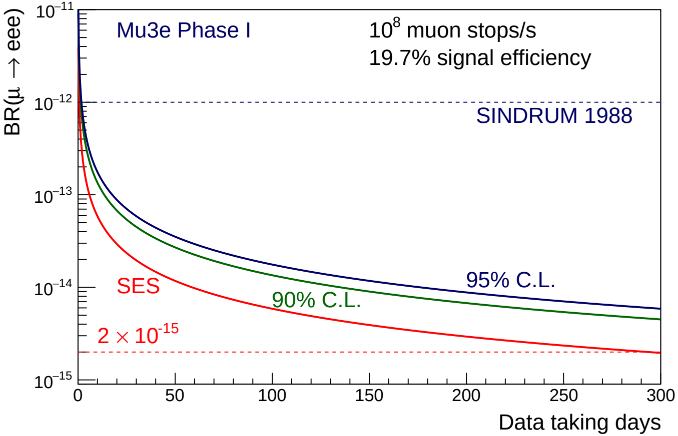


Summary

Mu3e Search for LFV decay $\mu \rightarrow eee$

Low-material tracking detector

- Thin Si pixel sensors
- Scintillating fibres and tiles

Triggerless data acquisition and online event filtering

Phase I Expected single-event sensitivity of $2 \cdot 10^{-15}$ in 300 days of data taking

Status Finalizing phase I detector design

Preparation for construction and commissioning

$\mu 3e$

Mu3e Collaboration

University of Geneva

Heidelberg University

Karlsruhe Institute of Technology

JGU Mainz

Paul Scherrer Institute

ETH Zürich

University of Zürich

University of Bristol

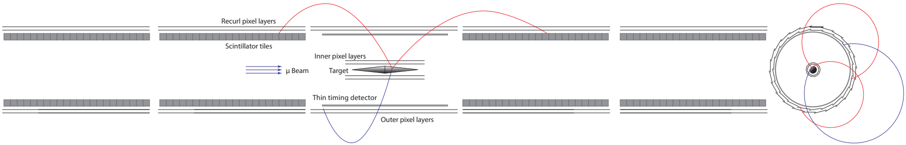
University of Liverpool

University College London

University of Oxford

The Phase II Detector

Final sensitivity of one in 10^{16} muon decays

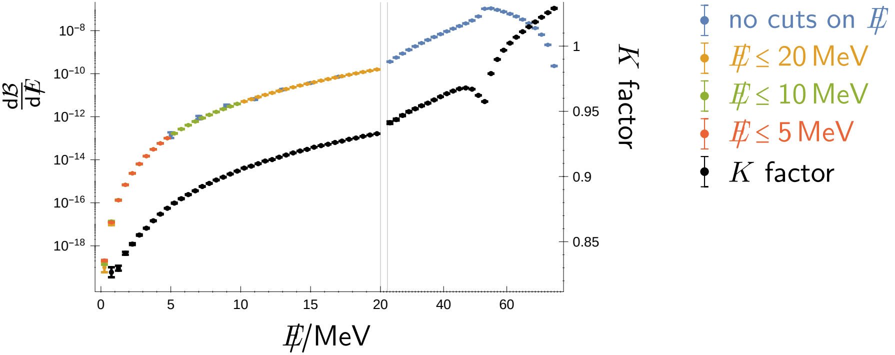


Increase muon stopping rate to $2 \cdot 10^9\ \mu/s$

Additional recurl stations increase acceptance for recurler

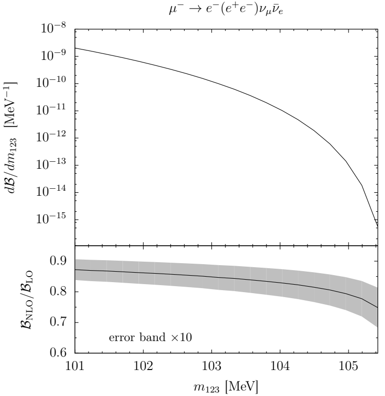
Smaller beam profile ⇒ smaller target radius

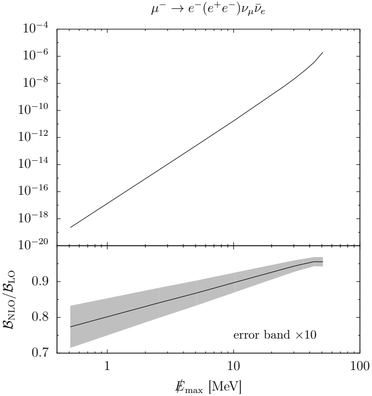
Background: $\mu \to ee e\nu\nu$



NLO calculations for $\mu \to eee\nu\nu$: Pruna, Signer, Ulrich [arXiv:1611.03617]

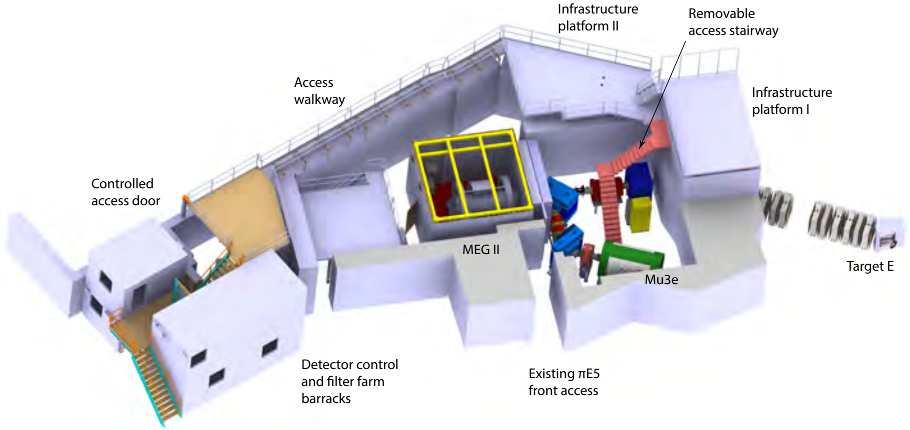
Background: $\mu \to ee e\nu\nu$





NLO calculations for $\mu \to eee\nu\nu$: Fael, Greub arXiv:[1611.03726]

Experimental Area



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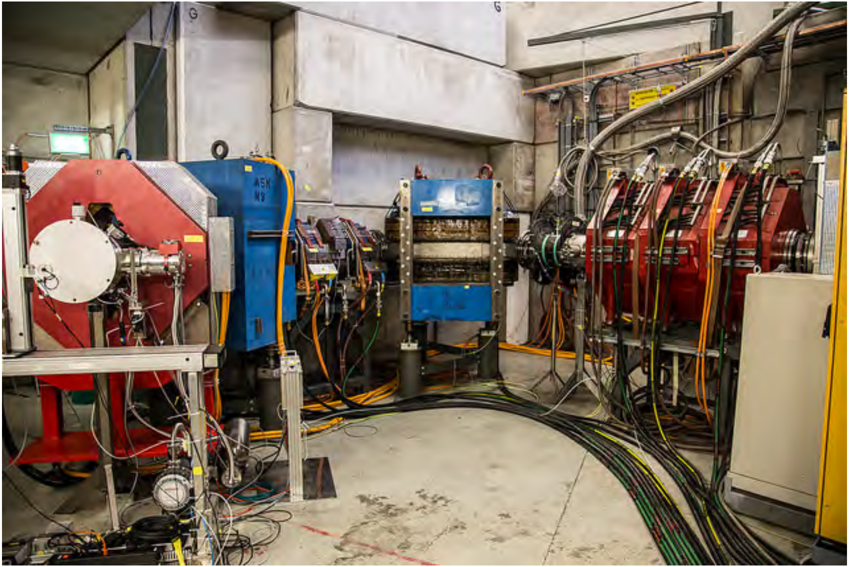
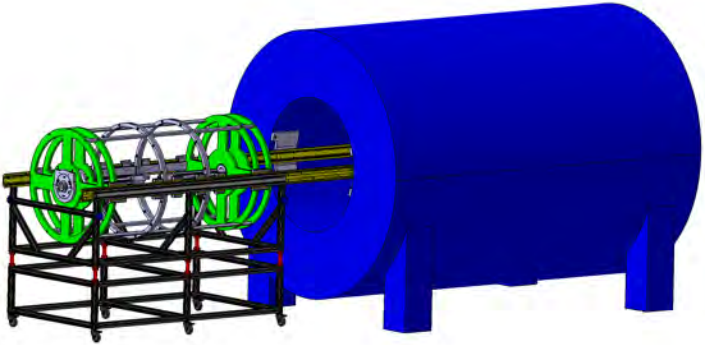
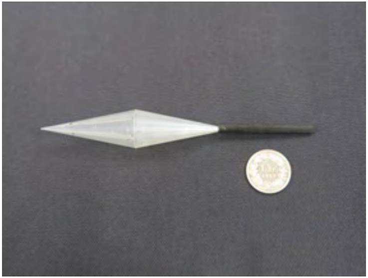


Magnet and Detector Cage



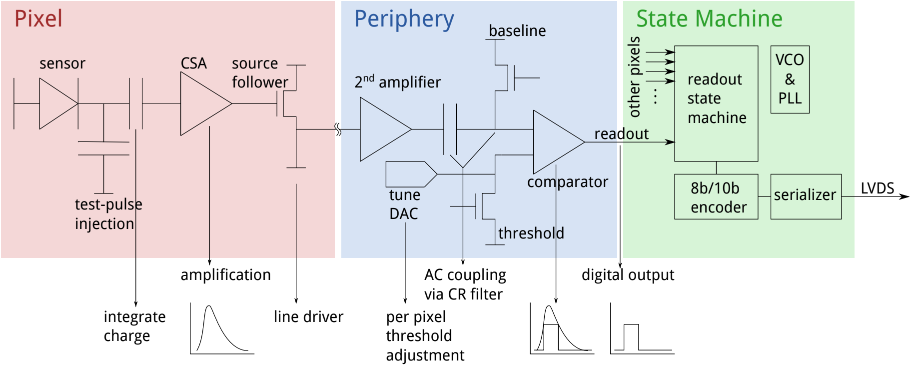
Target



- Extended hollow double-cone target made of ~ 80 µm mylar foil
- 10 cm long with a radius of 19 mm

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

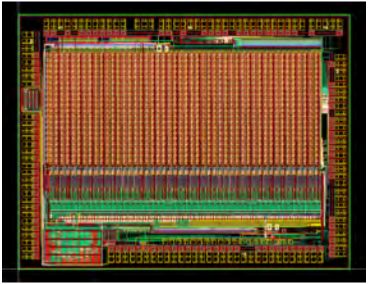
Pixel Sensors: HV-MAPS



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

Continuous and fast readout at 1.25 Gbit/s

Pixel Sensors: MuPix9 Prototype



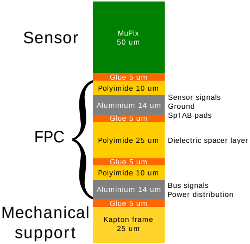
MuPix9 submitted in August

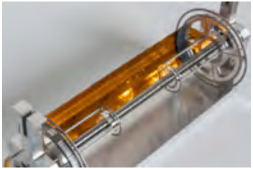
- Small-scale prototype
- Slow control
- Serial powering

Lightweight Mechanics

- $50\,\mu m$ silicon sensor
- $80\,\mu m$ Flexible printed circuit board (FPC)
- $25\,\mu m$ Kapton support structure

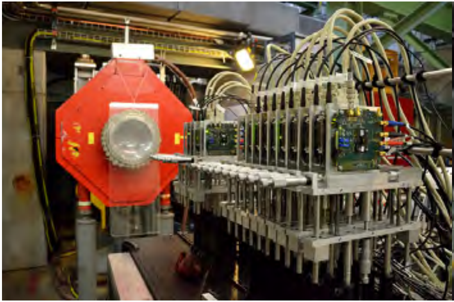
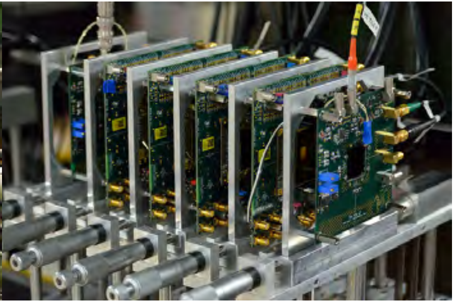
→ $\sim 0.1\,\%$ of radiation length





MuPix Telescope

- System integration test for pixel tracker front-end
- Characterisation of prototypes
- 4 or 8 planes of MuPix7 well established
- 4 planes of MuPix8 just commissioned

Data Acquisition at the MuPix Telescope

Receiver

- Receive and de-serialize data

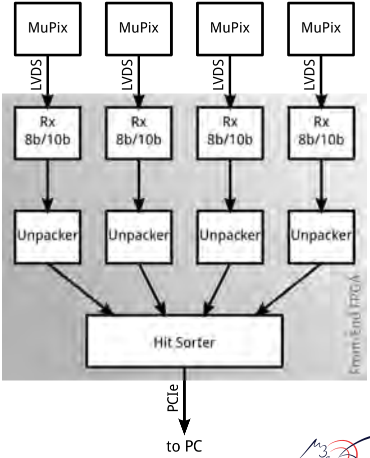
Unpacker

- Disentangle hit and status information

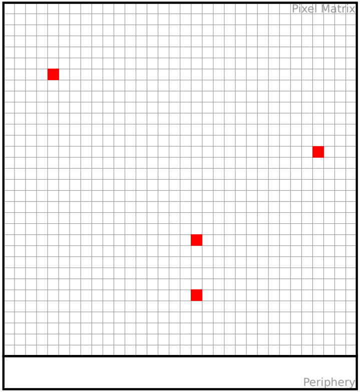
Hit sorter

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

Data transfer to PC



Sorting at the Pixel Tracker Front-End

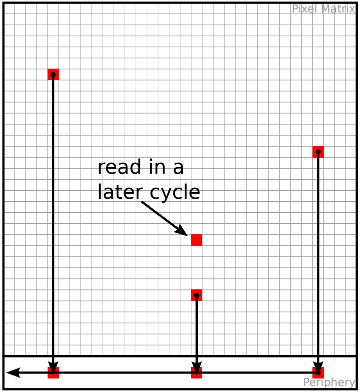


Readout scheme on MuPix

- Skip empty columns and rows
- Read only first hit in a column
- Hits that happened at the same time do not necessarily end up in the same readout cycle

⇒ Restore time structure at front-end using time stamp information

Sorting at the Pixel Tracker Front-End



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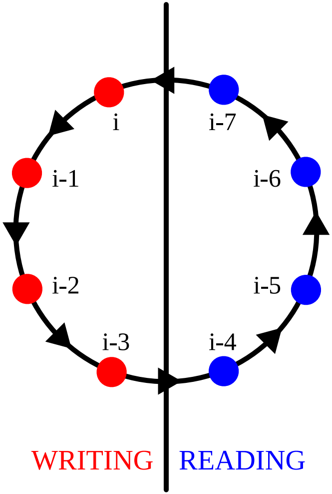


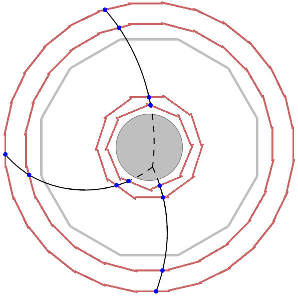
Sort hits by time stamp on FPGA

- Write hits in time-order to memory
  Address: time stamp + counter
- Dual-port RAM used as ring-buffer
- Divided into 8 blocks
  either accessible for writing or reading
- Skip addresses without data

Front-End Board

- MuPix telescope:
  Stratix IV development board
  plus custom PCBs
- First prototype of front-end board:
  Stratix IV, optical transceivers, ...
- Later prototypes will use Arria V

Reconstruction and Event Filtering



- Online reconstruction on GPU filter farm
  - Selection cuts
  - Fast 3D multiple scattering track fit
    - Triplet from three consecutive hits
    - Add fourth hit
  - Subsequent vertex fit with three trajectories of correct charge
  - Select $\mu \rightarrow eee$ candidates
  - Reduction of data rate from 60 Gbit/s to 100 MB/s
- Offline Reconstruction
  - Reconstruction of recurling tracks
  - Refined vertex fit