The Data Acquisition of the Mu3e Experiment

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Overview

Searching for charged lepton flavour violation:

- The Mu3e experiment

100 Gbit/s streaming readout:

- The Mu3e data acquisition

> $10^9$ track fits/s on GPUs:

- The Mu3e filter farm
Searching for $\mu^+ \to e^+e^-e^+$

- Lepton flavour violating muon decays
- Extremely low branching fractions in the Standard Model
- Excellent probes for new physics
- $\text{BR}(\mu^+ \to e^+e^-e^+) < 10^{-12}$ (SINDRUM, 1988)
Searching for $\mu^+ \rightarrow e^+e^-e^+$

- Lepton flavour violating muon decays
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- Mu3e aims for a sensitivity of 1 in $10^{16}$
- Very intense muon beam: Paul Scherrer Institute (PSI), Villigen, Switzerland
- $2 \times 10^{-15}$ in a first phase at an existing beam line with $10^8$ muons/s - this talk
- Plans for new high-intensity muon beam line (HiMB) with $> 10^9$ muons/s
Signal

- $\mu^+ \rightarrow e^+e^-e^+$ at rest
- Two positrons, one electron
- From same vertex
- Same time
- $\Sigma p_e = m_\mu$
- Maximum momentum: $\frac{1}{2} m_\mu = 53 \text{ MeV}/c$

Signal and Background
Signal and Background

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Accidental Background

- Several muon decays
- Plus an electron
- Need good vertexing
- Need good timing
Signal and Background

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**Accidental Background**
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- Need good timing

**Internal conversion decay**
- Allowed rare decay
- $\mu^+ \rightarrow e^+e^-\bar{\nu}\nu$
- Detect missing energy carried by neutrinos
- Need excellent momentum reconstruction
The Mu3e Detector

- 1 T solenoid field
- Helium atmosphere to reduce scattering and for cooling
- Minimize material to minimize scattering
- Ultra-thin layers of high-voltage monolithic active pixel sensors (HV-MAPS)
- Scintillating fibres and tiles for improved timing measurements
- Long lever arm of recurling tracks gives precise momentum measurement
Detector ASICs

**MuPix** High-Voltage Monolithic Active Pixel Sensor (TSI 180 nm HV-CMOS process)
- 2 x 2 cm², 80 x 80 μm² pixels, 50 μm thin
- Discriminator, address generation and time-stamping for each pixel
- Readout state-machine, serializer
- 1.25 Gbit/s LVDS 8bit/10bit encoded output

**MuTrig** TDC for Silicon Photomultiplier readout (UMC 180 nm CMOS process)
- 32 channels, 50 ps time bins
- Bias adjustment for the SiPMs
- Readout state-machine, serializer
- 1.25 Gbit/s LVDS 8bit/10bit encoded output
Requirements for the data acquisition

- Up to $10^8$ muon decays/s
- 2844 MuPix sensors with 182 million pixels
- 8896 SiPM readout channels - 278 MuTrig TDC ASICs
- ~100 Gbit/s data after zero suppression on ASICs
- Highly non-local signal signature
- Can write about 100 MB/s to mass storage
- Fully streaming DAQ
- Network of FPGAs and optical links
- Collect all data of a time slice on one PC
- Reconstruct tracks, then vertices on a GPU
- Write interesting events to disk
Front-end board

- Operates in magnet and helium atmosphere, space is tight
- Up to 45 1.25 GBit/s LVDS inputs from detector ASICs
- Intel Arria V A7 FPGA for time-sorting and clustering of hits
- Output to a 6 Gbit/s optical link on a Samtec Firefly Transceiver
- Two SiLabs 5345 jitter cleaners and clock multipliers provide FPGA and detector clocks
- Intel MAX10 FPGA for configuration and monitoring
- Air-coil DC/DC converters for powering
Switching board

• Operates in a PC case
• Up to 37 front-end board inputs (and control lines)
• Up to eight 10 Gbit/s outputs to filter farm
• Use PCIe40 board developed in Mar- seilles for LHCb and ALICE upgrades
• Intel Arria 10 - 115 FPGA
• Avago MiniPod Transmitters and Receivers
• Two 8-lane PCIe 3.0 interfaces (used for control and monitoring data)
Receiving board

- Operates in a PC case, together with a GPU
- 16 10 Gbit/s inputs and outputs (daisy chain)
- Use commercial DE5A NET board from Terasic Inc.
- Intel Arria 10 - 115 FPGA
- DDR 3/4 memory for buffering
- QSFP Transmitters and Receivers
- 8-lane PCIe 3.0 interface
- Buffer all incoming data in DDR memory
- Use subset from central detector for track and vertex finding on a GPU
- If interesting: Get full data from buffer, send to PC
- Up to 38 Gbit/s PCIe DMA transfers using custom firmware and driver
- After full reconstruction: Send off to mass storage
- Use the MIDAS software for data collection, detector control and monitoring etc. (see talk by Stefan Ritt)
GPU reconstruction

- GPU reconstruction on gaming cards
- Have achieved $>10^9$ track fits/s per GPUs (Nvidia GTX 980)
- Twelve GTX 1080Ti are sufficient for dealing with $10^8$ muon decays/s
- Excited about the possibilities with the latest cards...
System synchronization

- Produce 144 copies of the 125 MHz system clock
- Produce 144 copies of the 1.25 Gbit/s, 8bit/10bit encoded reset and state transition signal
- Digilent Genesys FPGA board
- Samtec Firefly optical transmitters
System synchronization

• Produce 144 copies of the 125 MHz system clock
• Produce 144 copies of the 1.25 Gbit/s, 8bit/10bit encoded reset and state transition signal
• Digilent Genesys FPGA board
• Samtec Firefly optical transmitters
• Less than 10 ps clock-to-clock jitter
Current status

- All commercial components available and tested
- All detectors have been read out via a prototype front-end board (see poster by Marius Köppel)
- Detector integration run inside magnet in December
- Full production of front-end boards and commissioning next year: Mu3e DAQ ready end of 2021
- Full detector ready end of 2022
Mu3e is searching for charged lepton flavour violation: Aiming for a sensitivity for $\mu \rightarrow eee$ of one decay in $10^{16}$.

**Mu3e Phase I:**
Search for $\mu \rightarrow eee$ with a sensitivity of $2 \times 10^{-15}$
- $10^8$ muons/s and 100 Gbit/s data

**Mu3e DAQ:**
Optical links and FPGAs for transporting and sorting data

**Mu3e filter farm:**
> $10^9$ tracks/s reconstructed on just a dozen GPUs

**For more:**
Backup
LFV Muon Decays

\[ \mu^+ \rightarrow e^+\gamma \quad \mu^- N \rightarrow e^- N \quad \mu^+ \rightarrow e^+e^-e^+ \]
LFV Muon Decays: Experimental Situation

\[ \mu^+ \rightarrow e^+ \gamma \]
\[ \mu^- N \rightarrow e^- N \]
\[ \mu^+ \rightarrow e^+ e^- e^+ \]

**MEG (PSI)**

\[ B(\mu^+ \rightarrow e^+ \gamma) < 4.2 \cdot 10^{-13} \]
(2016)

**SINDRUM II (PSI)**

\[ B(\mu^- Au \rightarrow e^- Au) < 7 \cdot 10^{-13} \]
(2006)

relative to nuclear capture

**SINDRUM (PSI)**

\[ B(\mu^+ \rightarrow e^+ e^- e^+) < 1.0 \cdot 10^{-12} \]
(1988)
LFV Muon Decays: Experimental signatures

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

Kinematics

- 2-body decay
- Monoenergetic $e^+, \gamma$
- Back-to-back
LFV Muon Decays: Experimental signatures

\[ \mu^+ \rightarrow e^+ \gamma \]
\[ \mu^- N \rightarrow e^- N \]
\[ \mu^+ \rightarrow e^+ e^- e^+ \]

Kinematics
- 2-body decay
- Monoenergetic \( e^+, \gamma \)
- Back-to-back

Background
- Accidental background
- Radiative decay
LFV Muon Decays: Experimental signatures

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**Kinematics**
- 2-body decay
- Monoenergetic e^+, γ
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**Background**
- Accidental background
- Radiative decay

**Kinematics**
- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected
LFV Muon Decays: Experimental signatures

Kinematics
- 2-body decay
- Monoenergetic $e^+$, $\gamma$
- Back-to-back

Background
- Accidental background
- Radiative decay

Kinematics
- Quasi 2-body decay
- Monoenergetic $e^-$
- Single particle detected

Background
- Decay in orbit
- Antiprotons, pions, cosmics
LFV Muon Decays: Experimental signatures

\[ \mu^+ \rightarrow e^+ \gamma \quad \mu^- N \rightarrow e^- N \quad \mu^+ \rightarrow e^+ e^- e^+ \]

**Kinematics**
- 2-body decay
- Monoenergetic \( e^+, \gamma \)
- Back-to-back

**Background**
- Accidental background
- Radiative decay

**Kinematics**
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- Single particle detected

**Background**
- Decay in orbit
- Antiprotons, pions, cosmics

**Kinematics**
- 3-body decay
- Invariant mass constraint
- \( \Sigma p_i = 0 \)

**Background**
- Internal conversion decay
- Accidental background
LFV Muon Decays: Experimental signatures

Kinematics
- 2-body decay
- Monoenergetic e⁺, γ
- Back-to-back

Background
- Accidental background
- Radiative decay

Kinematics
- Quasi 2-body decay
- Monoenergetic e⁻
- Single particle detected

Background
- Decay in orbit
- Antiprotons, pions, cosmics

Kinematics
- 3-body decay
- Invariant mass constraint
- Σ p_i = 0

Background
- Internal conversion decay
- Accidental background
LFV Muon Decays: Experimental signatures

Kinematics
- 2-body decay
- Monoenergetic e⁺, γ
- Back-to-back

Background
- Accidental background

Continuous Beam

Kinematics
- Quasi 2-body decay
- Monoenergetic e⁻
- Single particle detected

Background
- Decay in orbit
- Antiprotons, pions

Pulsed Beam

Kinematics
- 3-body decay
- Invariant mass constraint
- Σ p_i = 0

Background
- Radiative decay
- Accidental background

Continuous Beam

Niklaus Berger – RealTime 2020 – Slide 30
Very thin and fast silicon pixel sensors: HV-MAPS
Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)
Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift
Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

• Use a high voltage commercial process (automotive industry)
• Small active region, fast charge collection via drift

• Implement logic directly in N-well in the pixel - smart diode array
• Can be thinned down to < 50 μm

(I. Perić, NIM A 582 (2007) 876)
The MuPix Prototypes

Developed a series of HV-MAPS prototypes

- Goal: Detection and signal processing with just 50 μm silicon

- 6th chip, MuPix7, was the first full system-on-a-chip

- Going “big” 2 x 1 cm\(^2\) MuPix8 with 80 by 80 μm pixels also working nicely - some growing pains fixed

- Now: MuPix10, 2 x 2 cm\(^2\), integration ready - under test
MuPix8: Results

Time resolution of < 6 ns σ reached

80 Ω cm

100mV ~ 1300 e⁻
Integration with Flexprint

Operate MuPix on an aluminium-kapton flexprint without decoupling capacitors

- Low noise
- No transmission errors
- Longer than needed for Mu3e
Better timing: Scintillating fibres and tiles
Timing Detector: Scintillating Fibres

- 3 layers of 250 μm scintillating fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (MuTRiG)

Timing resolution < 400 ps including ASIC
Timing Detector: Scintillating tiles

- ~ 0.5 cm$^3$ scintillating tiles
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (MuTRiG)

![Graph showing time difference and timing resolution](image)

- Test beam with tiles, SiPMs and readout ASIC
- Timing resolution better 80 ps
Front-end board

- Mounted in quarter-circular crates inside the 1 m diameter solenoid
- Backplane for control connections and connection to detector
- Adaptors on back of backplane for detector specific cabling
- Aluminium cooling plates connected to water-cooled crate with heat pipes
- ~1000 multi-mode optical fibres to the outside world