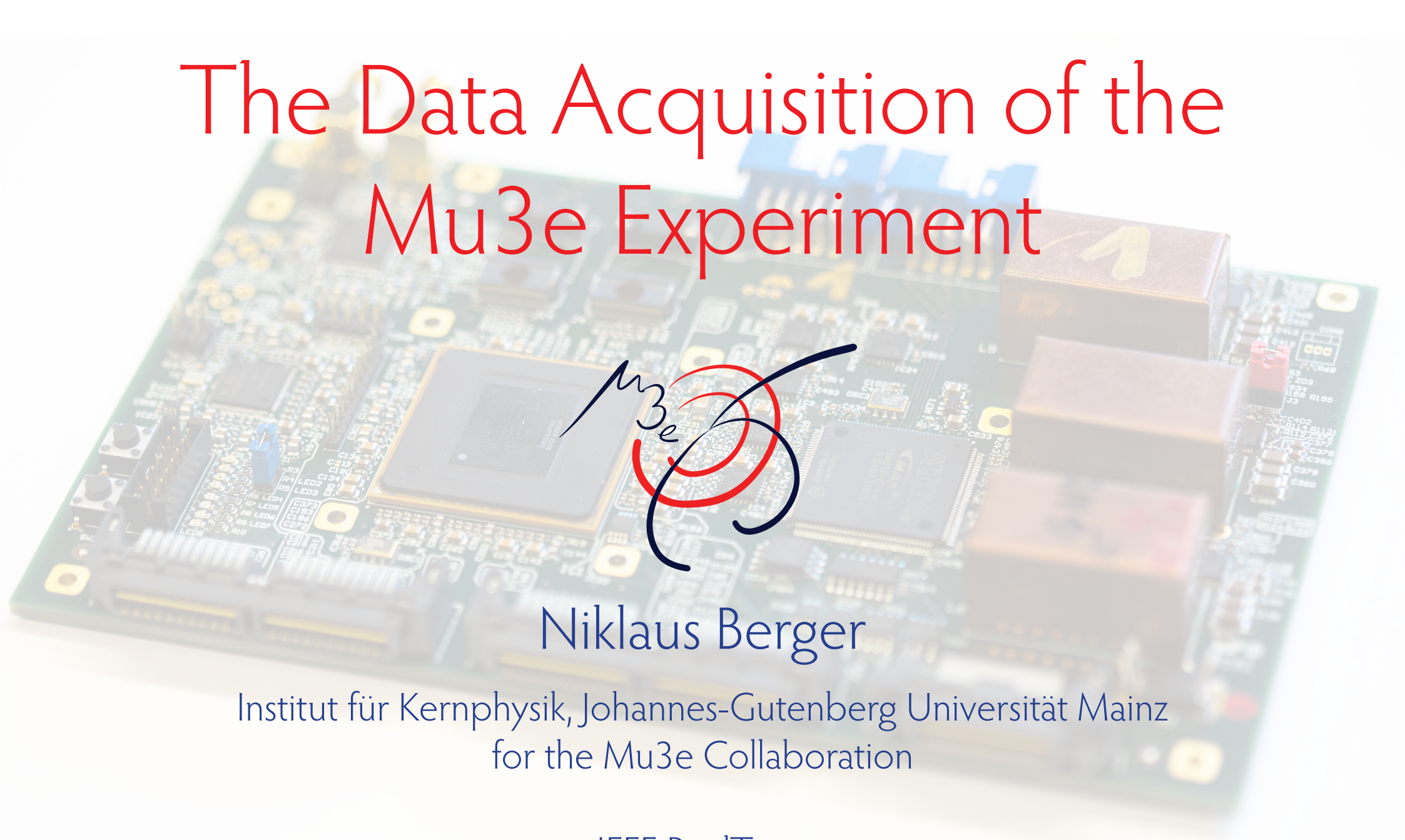
The Data Acquisition of the Mu3e Experiment



Niklaus Berger

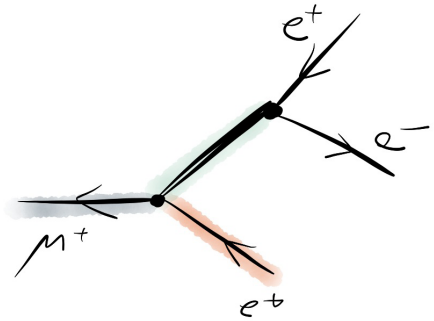
Institut für Kernphysik, Johannes-Gutenberg Universität Mainz
for the Mu3e Collaboration

IEEE RealTime
October 2020

JG|U

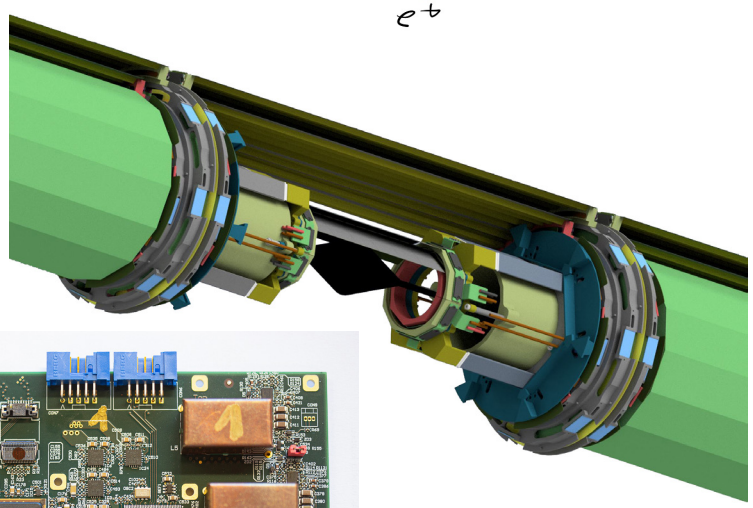
PRISMA+

Overview



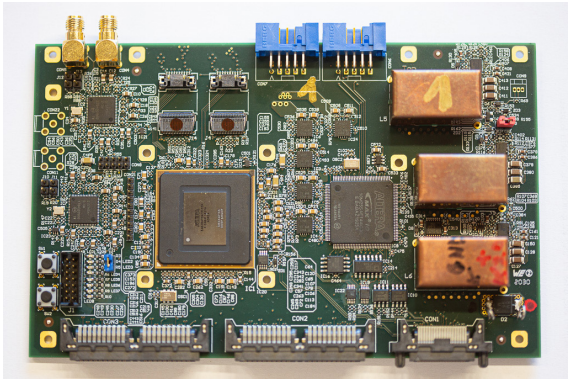
Searching for charged lepton flavour violation:

- The Mu3e experiment



100 Gbit/s streaming readout:

- The Mu3e data acquisition



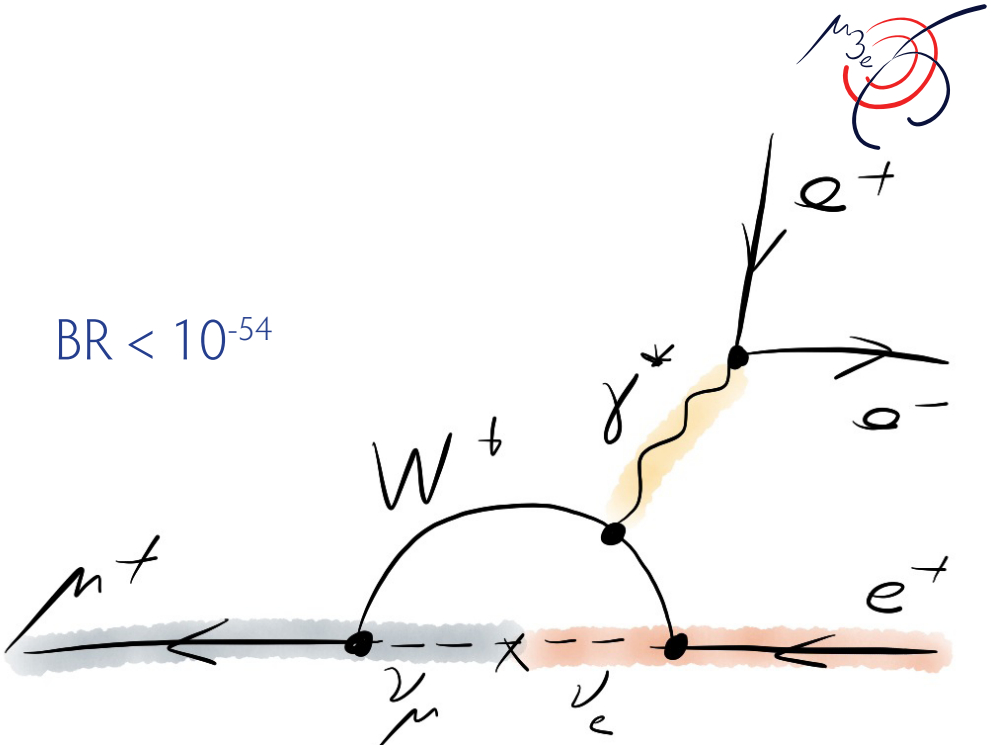
> 10^9 track fits/s on GPUs:

- The Mu3e filter farm

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

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

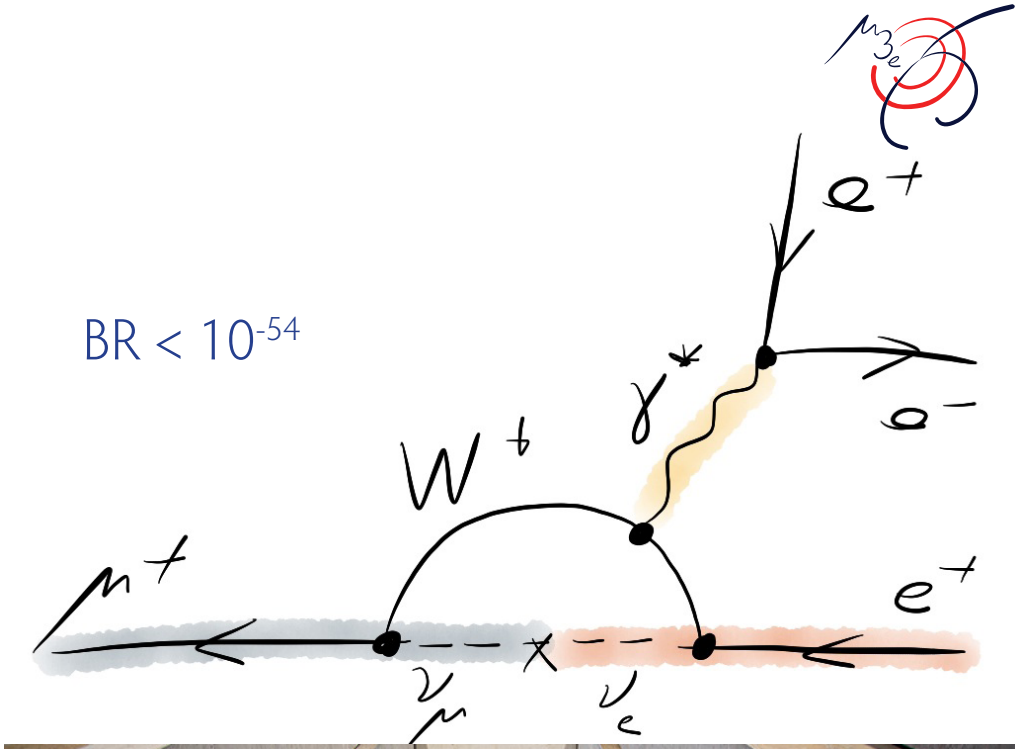
$BR < 10^{-54}$

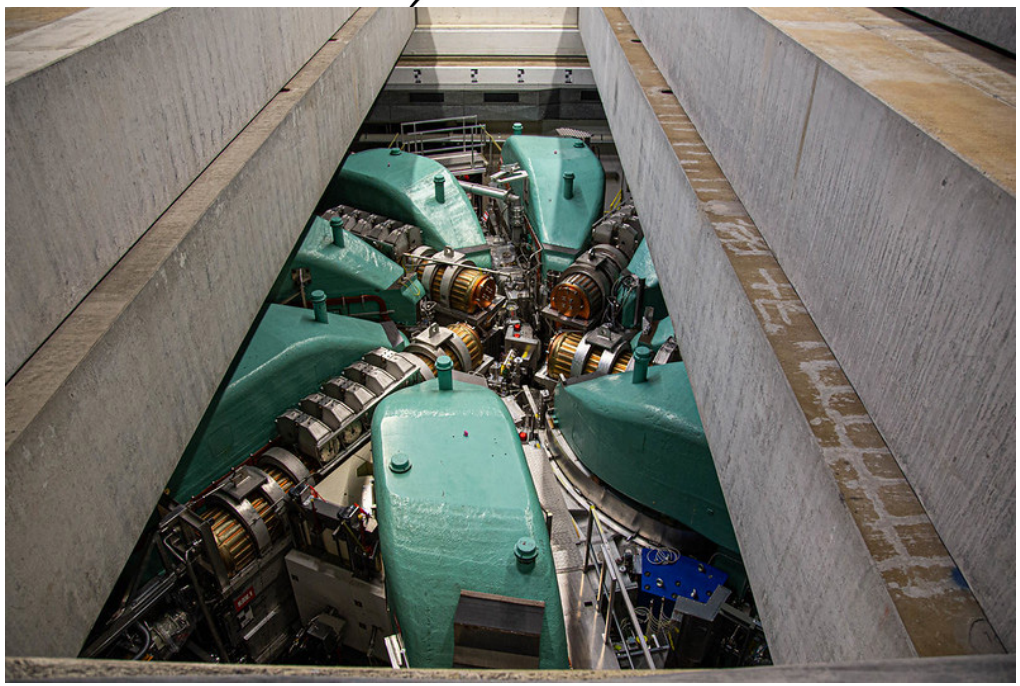


Searching for $\mu^+ \rightarrow e^+e^-e^+$

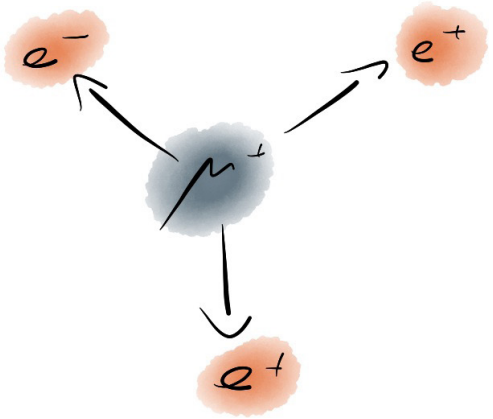
- Lepton flavour violating muon decays
- Extremely low branching fractions in the Standard Model
- Excellent probes for new physics
- BR($\mu^+ \rightarrow e^+e^-e^+$) < 10^{-12} (SINDRUM, 1988)

- Mu3e aims for a sensitivity of 1 in 10^{16}
- Very intense muon beam: Paul Scherrer Institute (PSI), Villigen, Switzerland
- $2 \cdot 10^{-15}$ 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





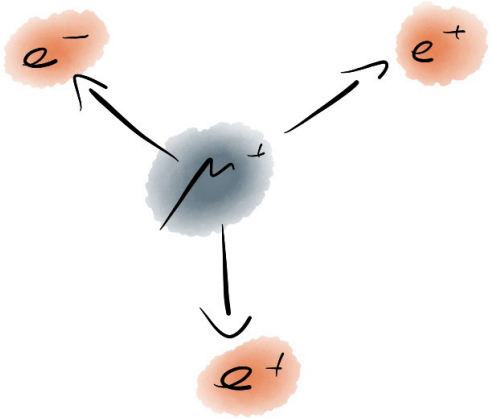
Signal and Background

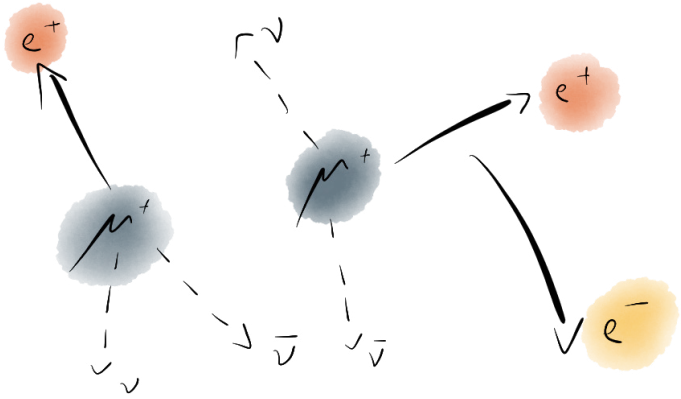


Signal

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

Signal and Background





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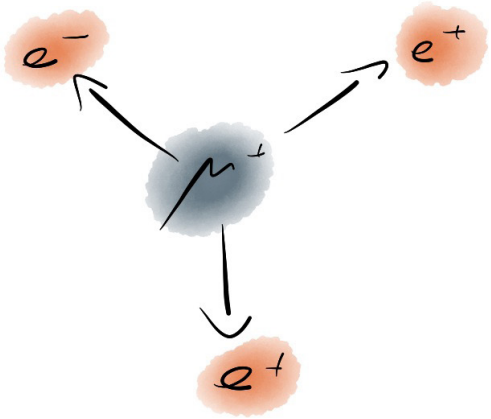
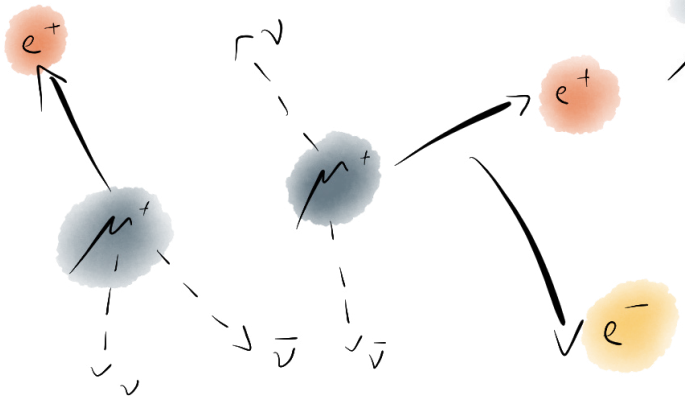
Accidental Background

- Several muon decays
- Plus an electron
- Need good vertexing
- Need good timing

Signal and Background





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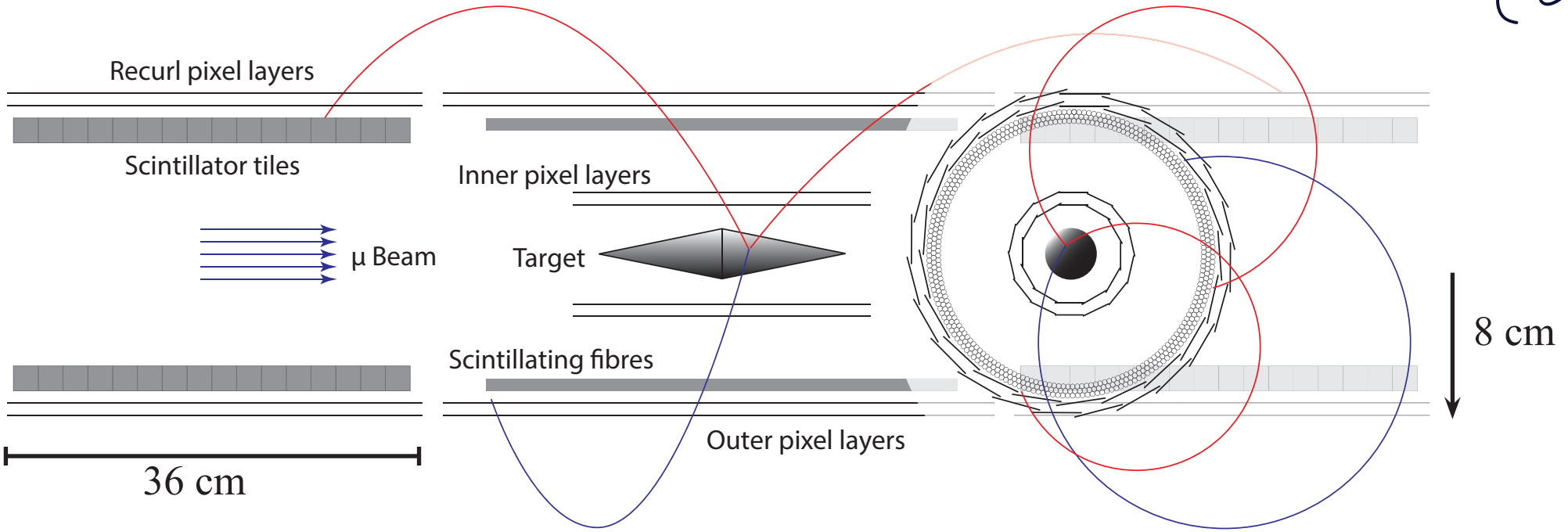
Internal conversion decay

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

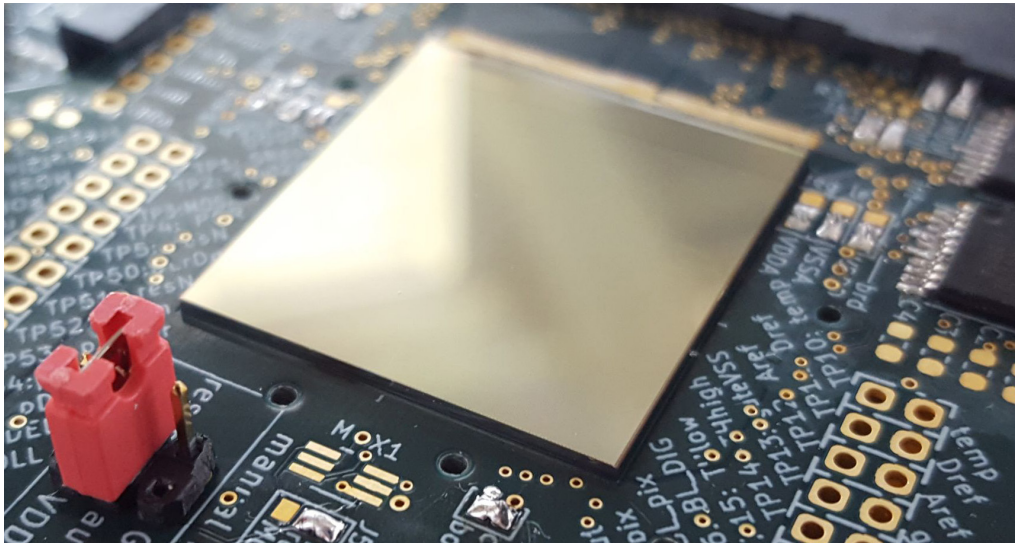
The Mu3e Detector

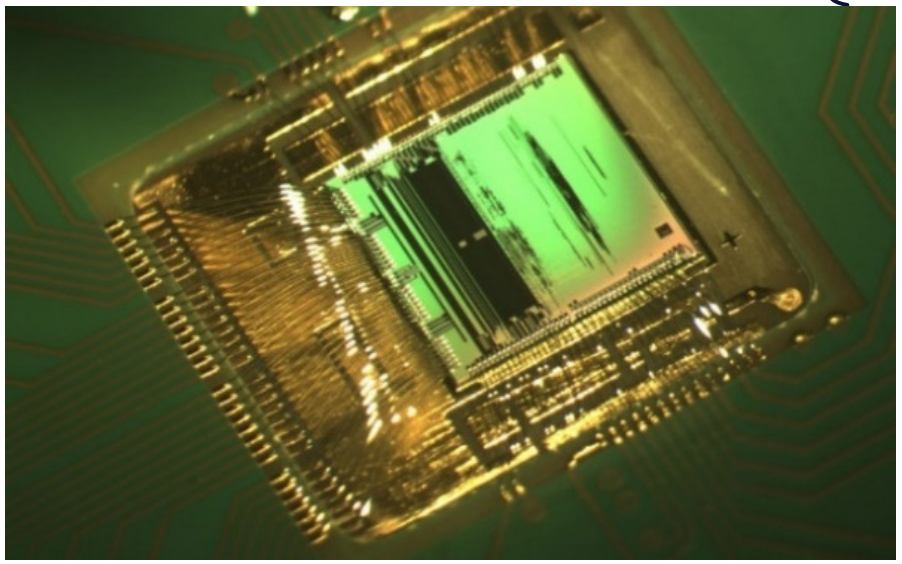


- 1 T solenoid field
- Helium atmosphere to reduce scattering and for cooling
- Minimize material to minimize scattering

- 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)

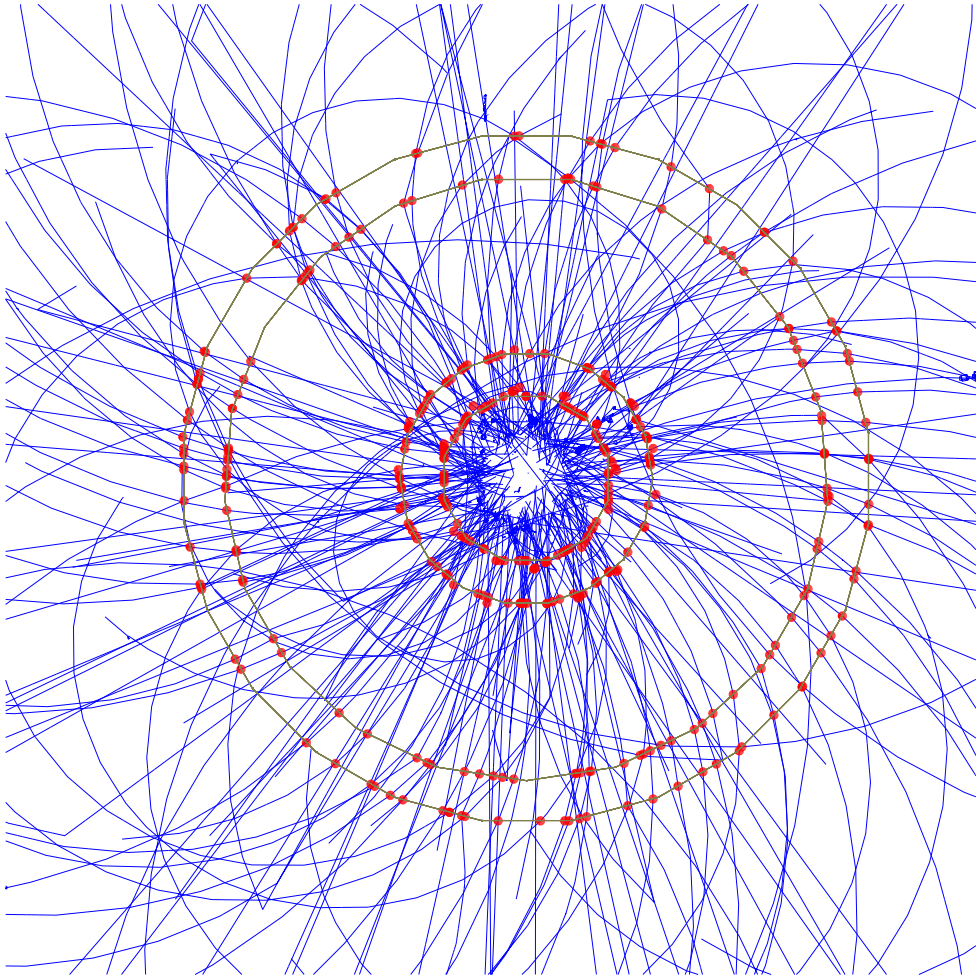
- 2 x 2 cm^2, 80 x 80 μm^2 pixels, 50 µm thin
- Discriminator, address generation and time-stamping for each pixel
- Readout state-machine, serializer
- 1.25 Gbit/s LVDS 8bit/10bit encoded output

MuTrig TDC for Silicon Photomultiplier readout (UMC 180 nm CMOS process)

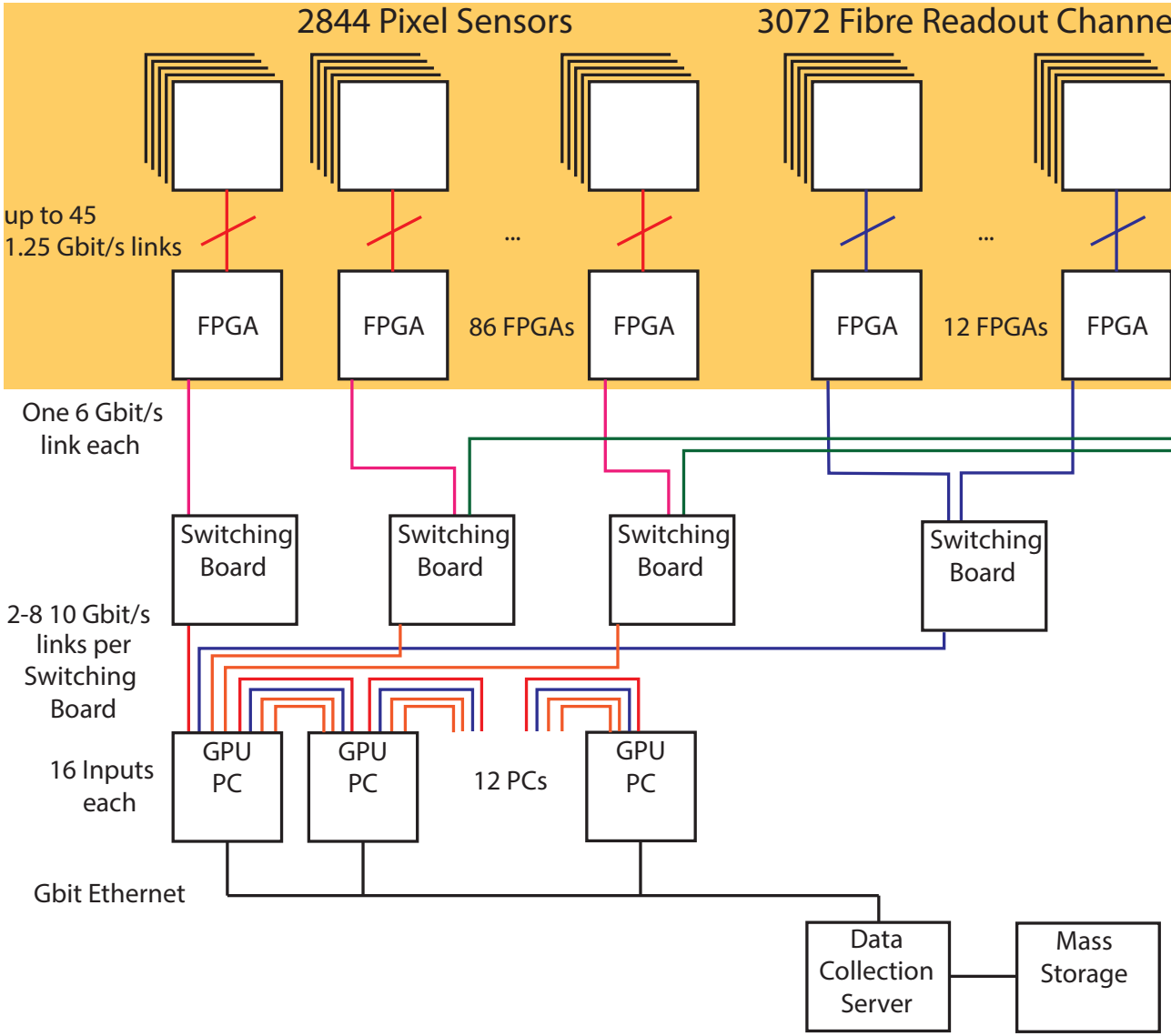
- 32 channels, 50 ps time bins
- Bias adjustment for the SiPMs
- Readout state-machine, serializer
- 1.25 Gbit/s LVDS 8bit/10bit encoded output

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



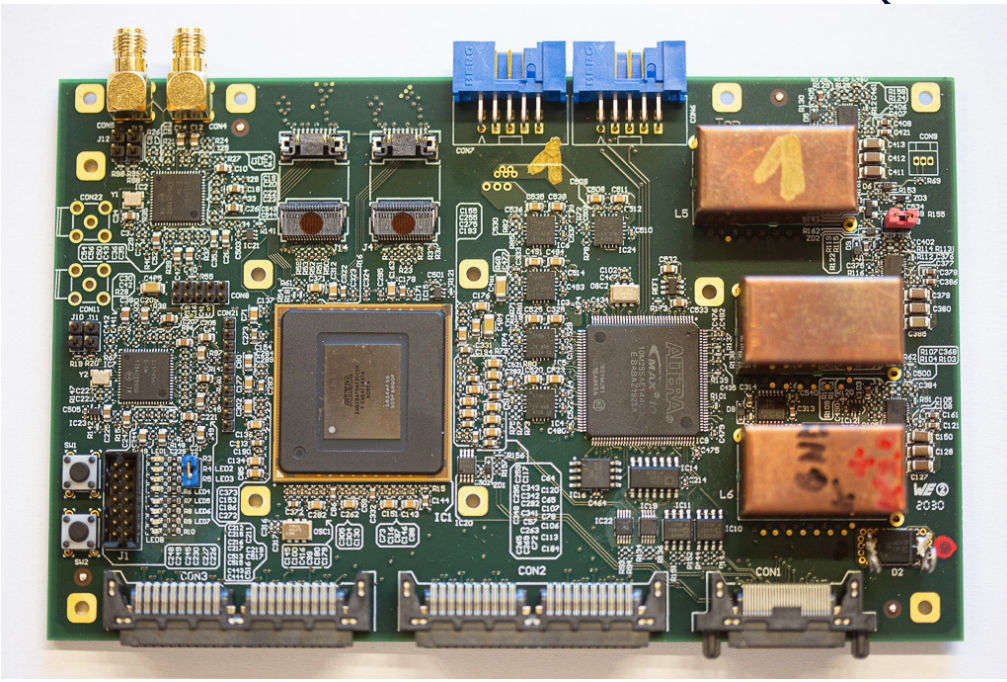
DAQ Design

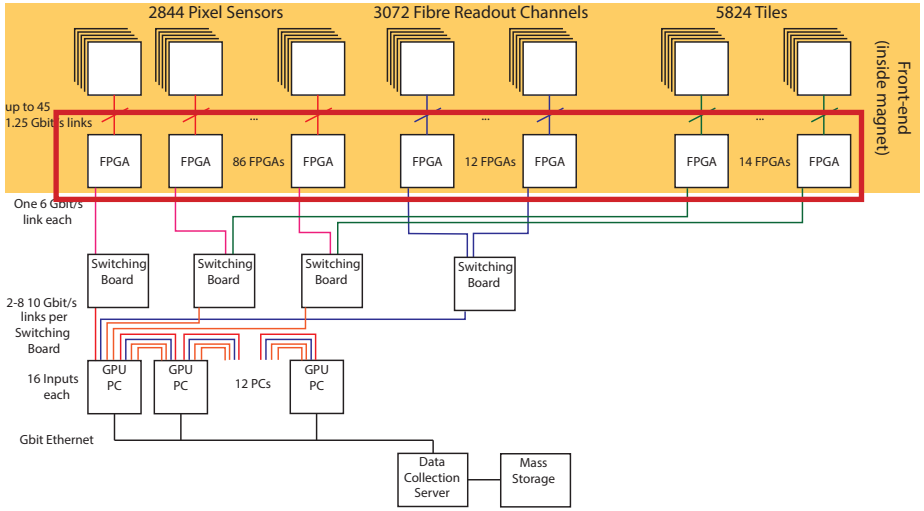


- Fully streaming DAQ
- Network of FPGAs and optical links
- Collect all data of a time slice on one PC
- Reconstruct tracks, then vertices on a GPU
- Write interesting events to disk

Front-end board

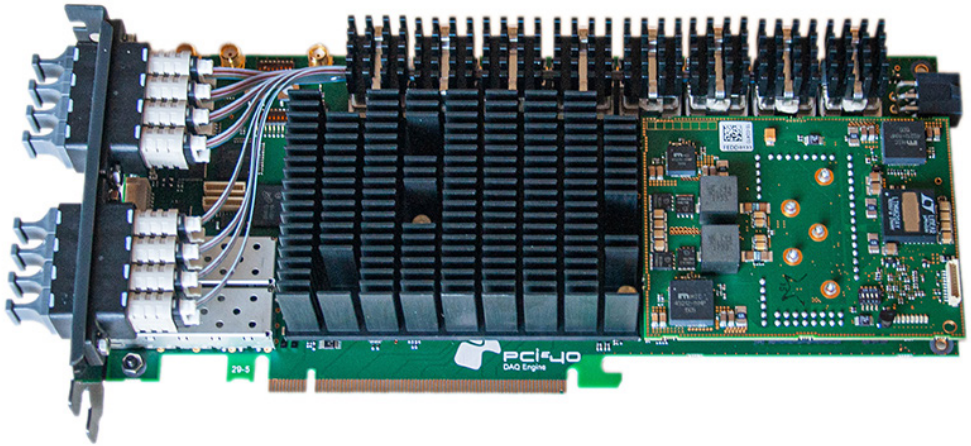
- Operates in magnet and helium atmosphere, space is tight
- Up to 45 1.25 GBit/s LVDS inputs from detector ASICs
- Intel Arria V A7 FPGA for time-sorting and clustering of hits
- Output to a 6 Gbit/s optical link on a Samtec Firefly Transceiver
- Two SiLabs 5345 jitter cleaners and clock multipliers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

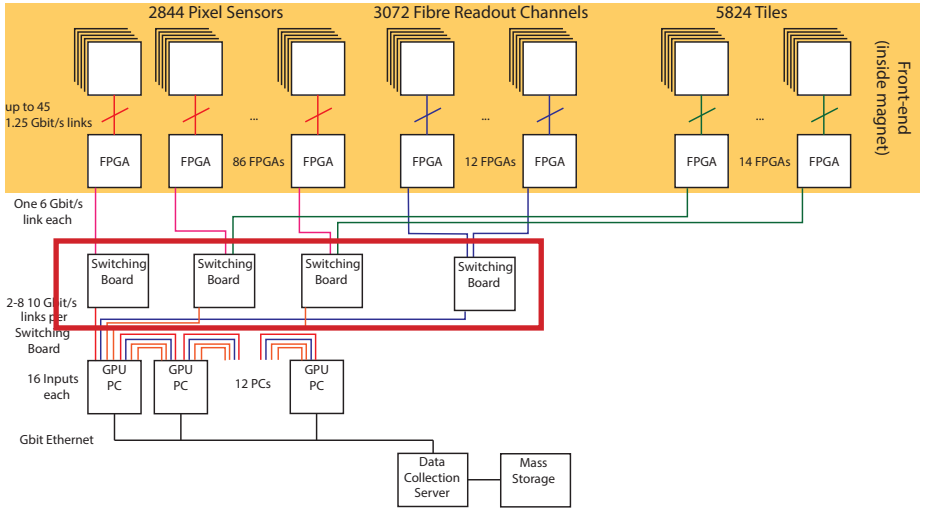




Switching board

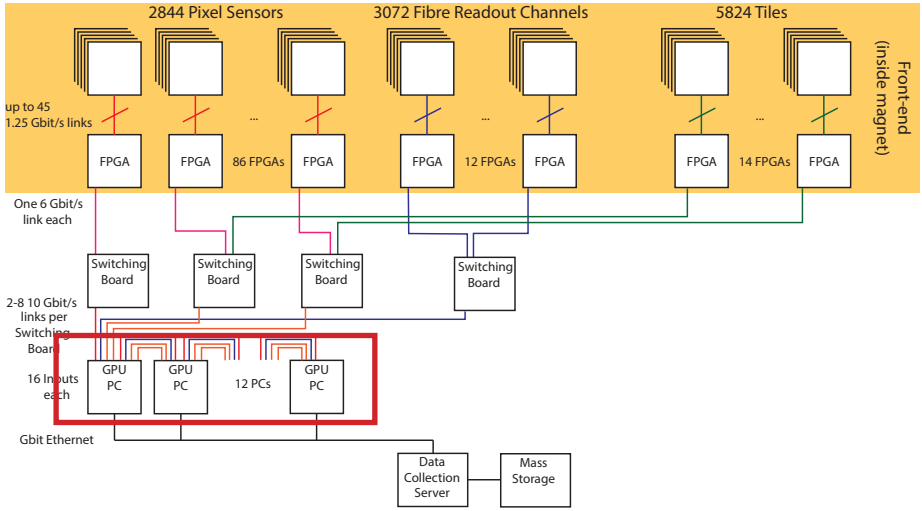
- Operates in a PC case
- Up to 37 front-end board inputs (and control lines)
- Up to eight 10 Gbit/s outputs to filter farm
- Use PCIe40 board developed in Marseilles for LHCb and ALICE upgrades
- Intel Arria 10 - 115 FPGA
- Avago MiniPod Transmitters and Receivers
- Two 8-lane PCIe 3.0 interfaces (used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



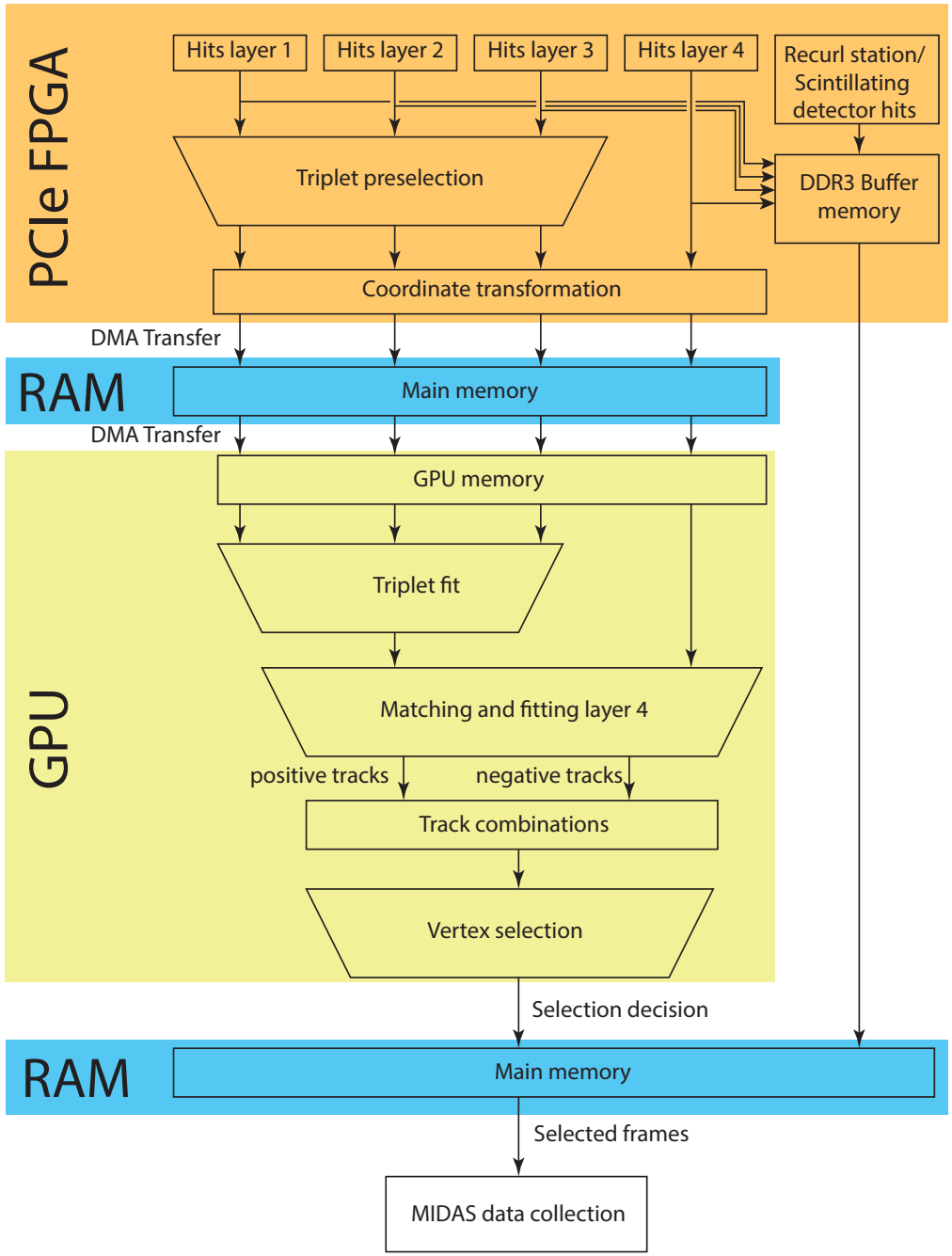


Receiving board

- 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



Farm data flow



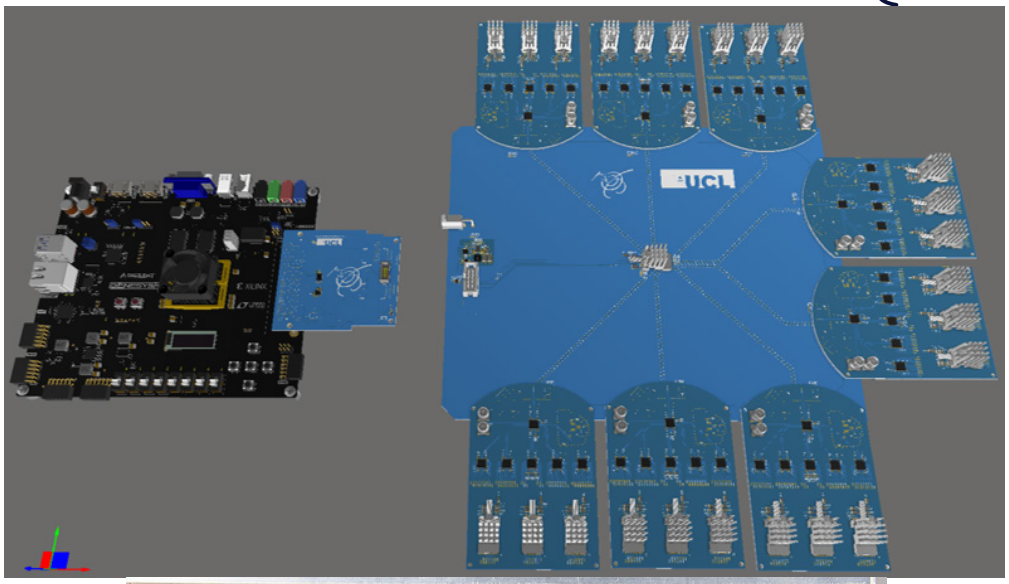
- Buffer all incoming data in DDR memory
- Use subset from central detector for track and vertex finding on a GPU
- If interesting: Get full data from buffer, send to PC
- Up to 38 Gbit/s PCIe DMA transfers using custom firmware and driver
- After full reconstruction: Send off to mass storage
- Use the MIDAS software for data collection, detector control and monitoring etc.
  (see talk by Stefan Ritt)

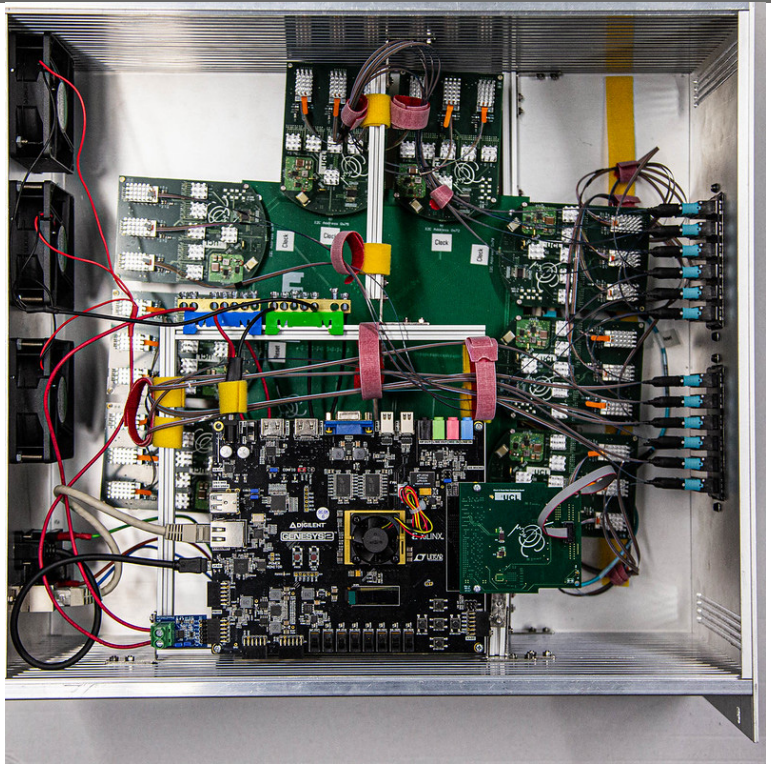
GPU reconstruction

- 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

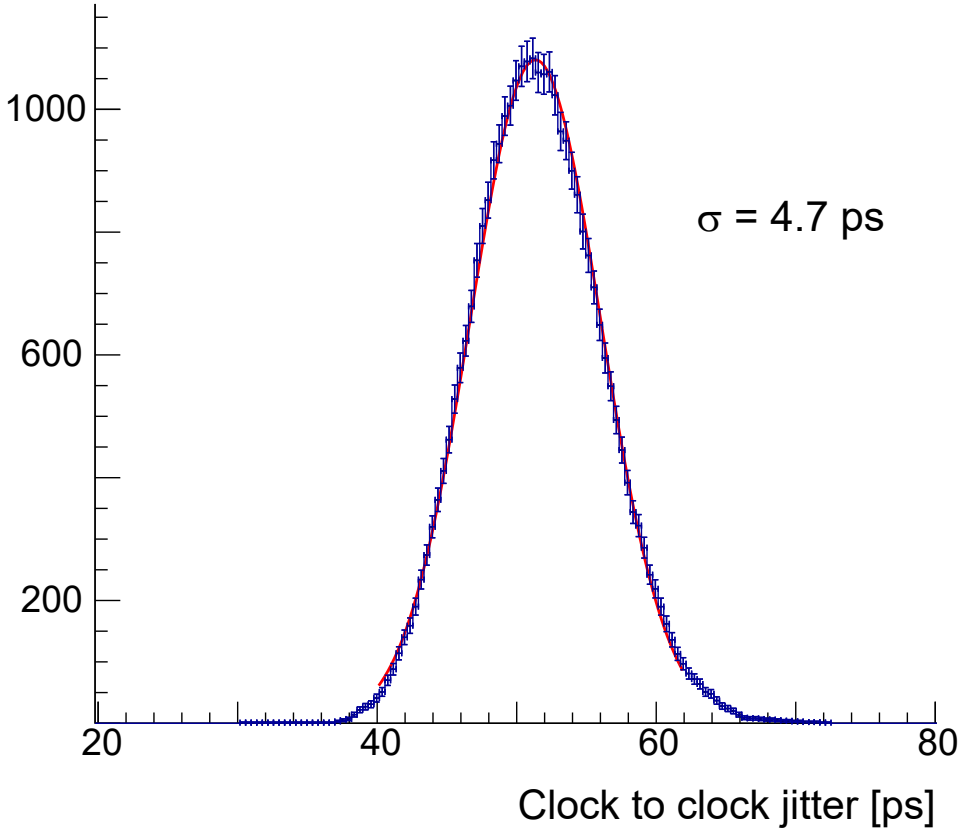
- Produce 144 copies of the 125 MHz system clock
- Produce 144 copies of the 1.25 Gbit/s, 8bit/10bit encoded reset and state transition signal
- Digilent Genesys FPGA board
- Samtec Firefly optical transmitters





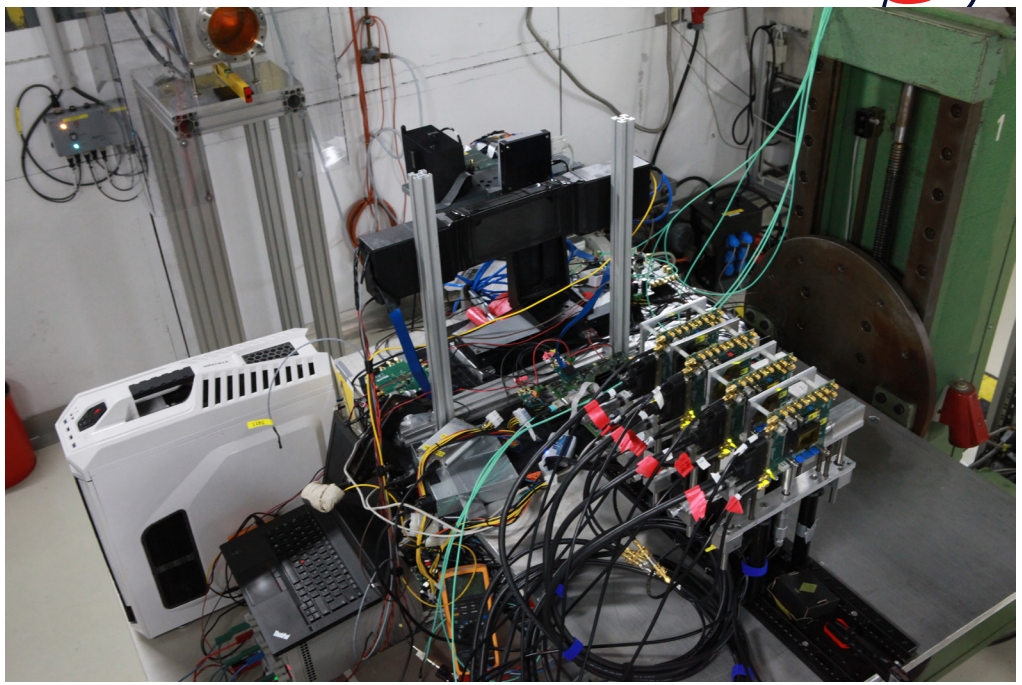
System synchronization

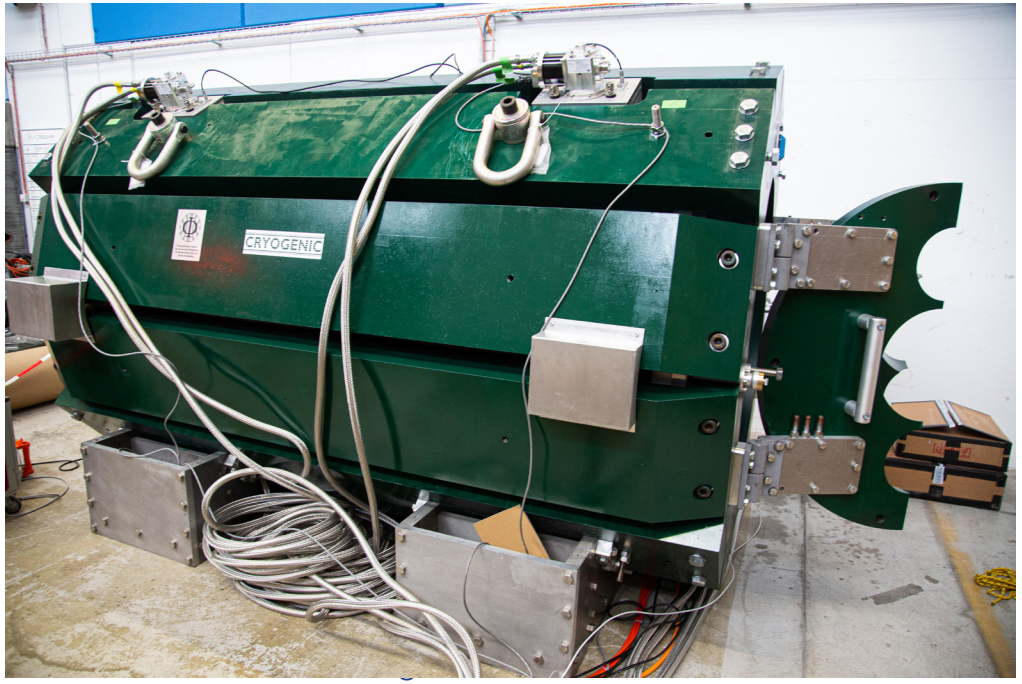
- Produce 144 copies of the 125 MHz system clock
- Produce 144 copies of the 1.25 Gbit/s, 8bit/10bit encoded reset and state transition signal
- Digilent Genesys FPGA board
- Samtec Firefly optical transmitters
- Less than 10 ps clock-to-clock jitter



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





Summary

- Mu3e is searching for charged lepton flavour violation:
  Aiming for a sensitivity for μ → eee of one decay in 10^{16}

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

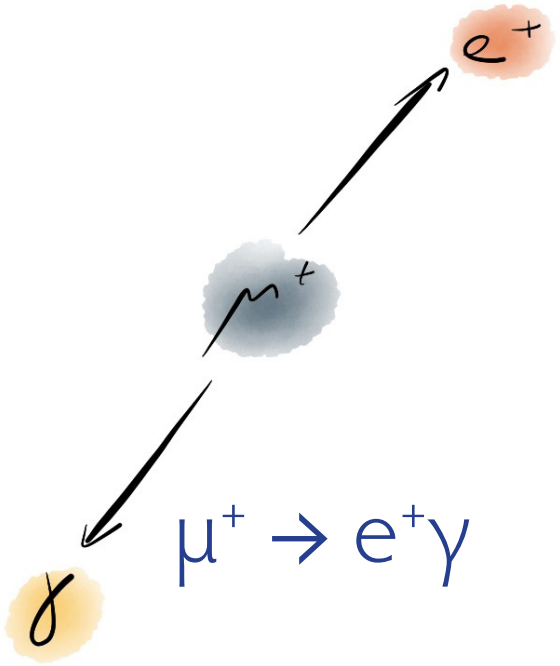
- Mu3e DAQ:
  Optical links and FPGAs for transporting and sorting data

- Mu3e filter farm:
  > 10^{9} tracks/s reconstructed on just a dozen GPUs

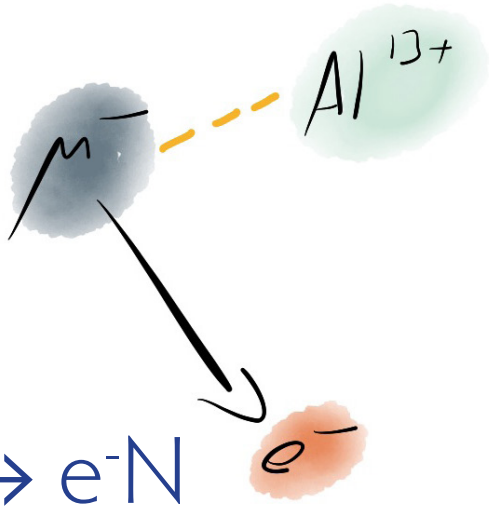
- For more:
  Just put out our TDR: arXiv:2009.11690

Backup

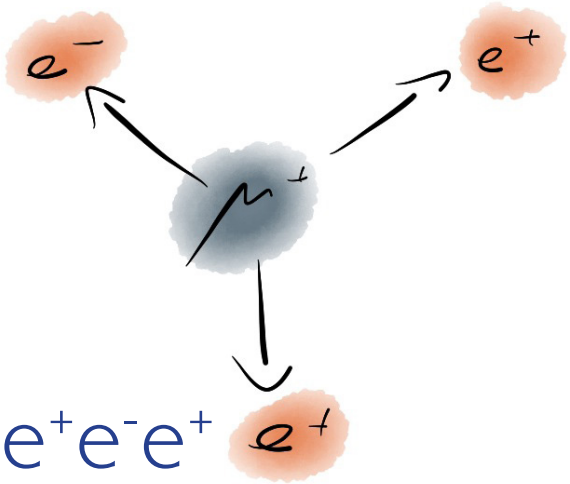
LFV Muon Decays



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

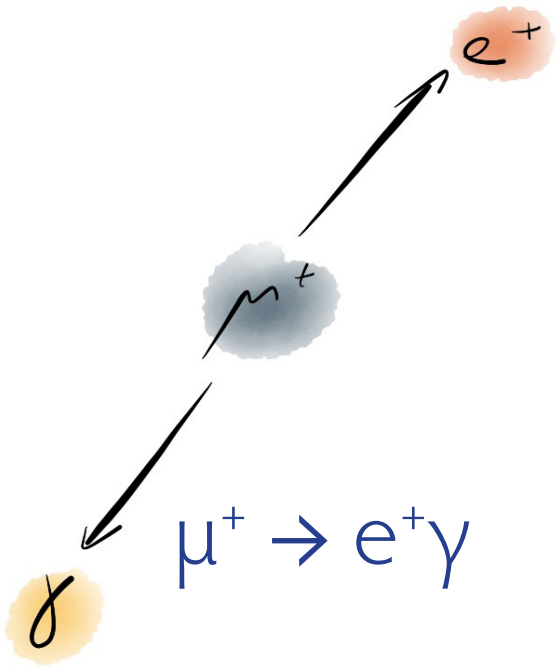


$\mu^-N \rightarrow e^-N$



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

LFV Muon Decays: Experimental Situation



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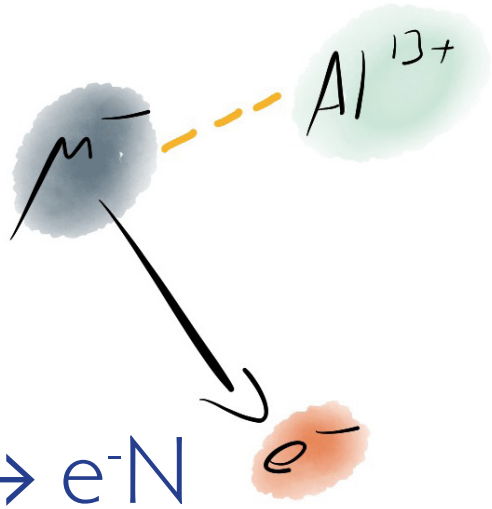

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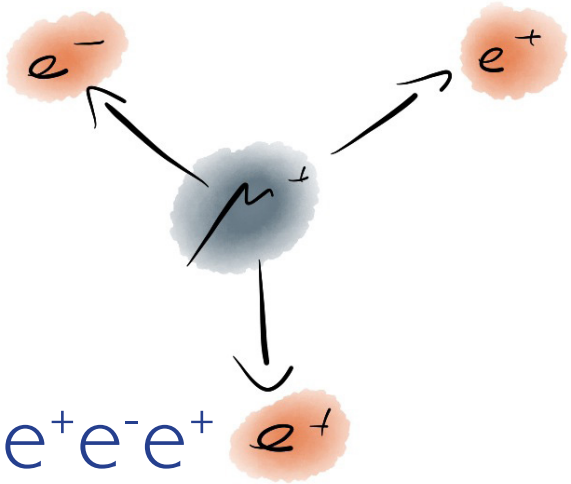


$\mu^+ \rightarrow e^+e^-e^+$

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)

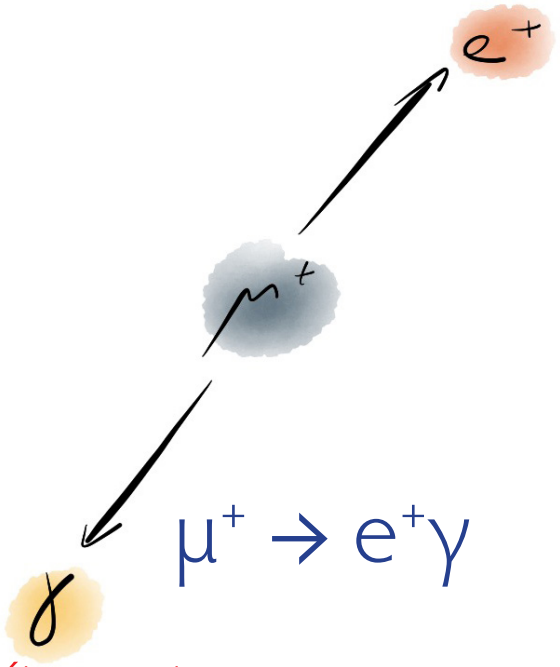
relative to nuclear capture

SINDRUM (PSI)

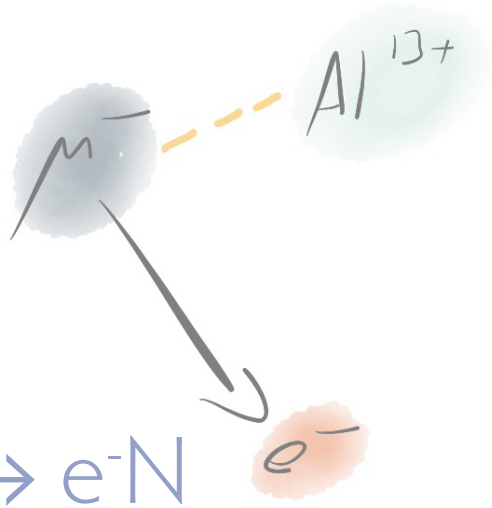
$B(\mu^+ \rightarrow e^+e^-e^+) < 1.0 \cdot 10^{-12}$

(1988)

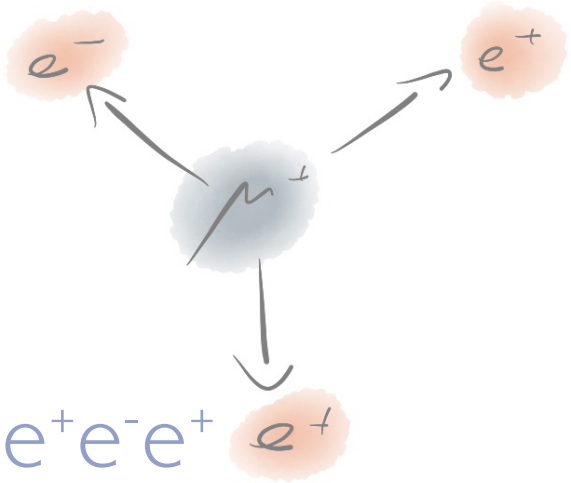
LFV Muon Decays: Experimental signatures



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



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

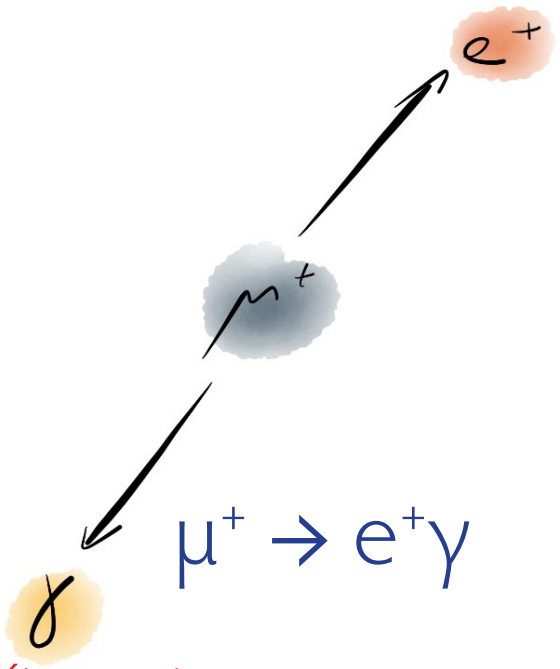


$\mu^+ \rightarrow e^+e^-e^+$

Kinematics

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

LFV Muon Decays: Experimental signatures



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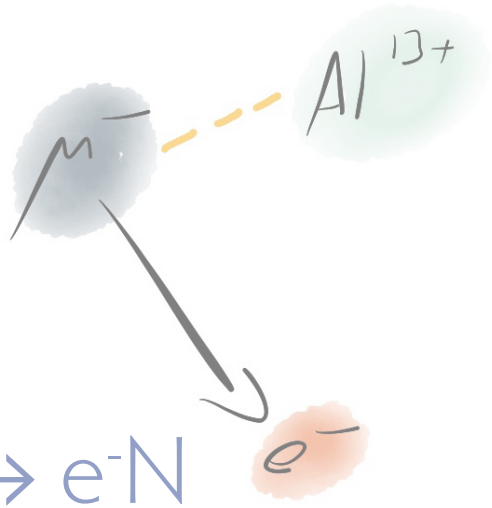

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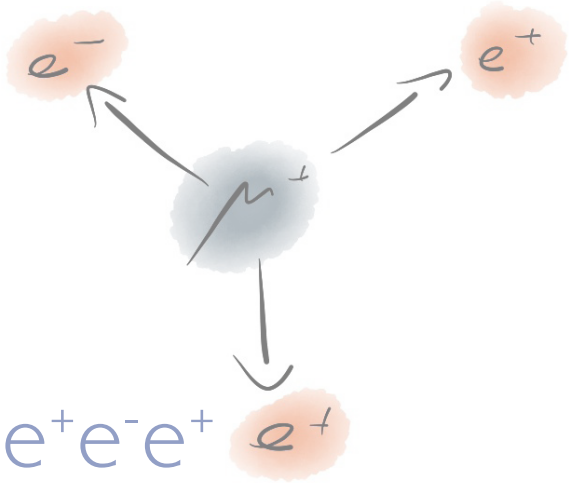


$\mu^+ \rightarrow e^+e^-e^+$

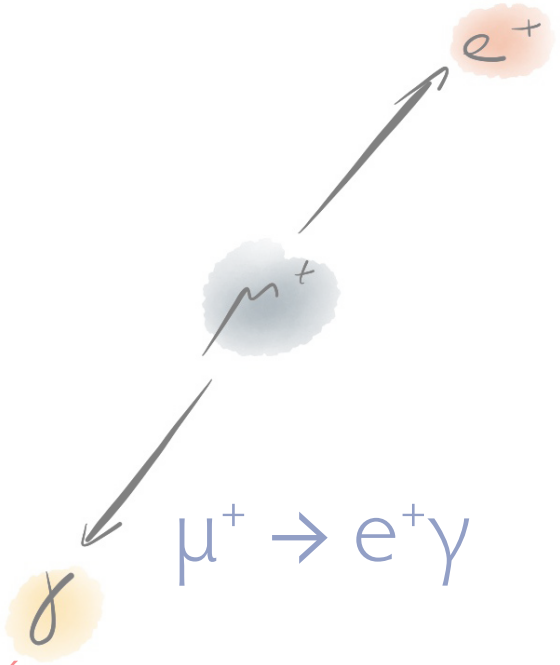
Kinematics

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

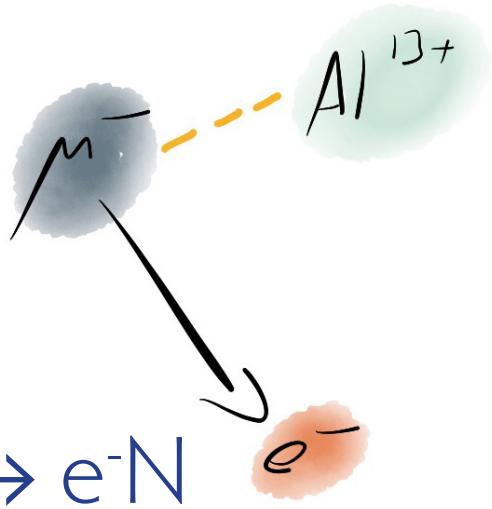
Background

- Accidental background
- Radiative decay

LFV Muon Decays: Experimental signatures



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



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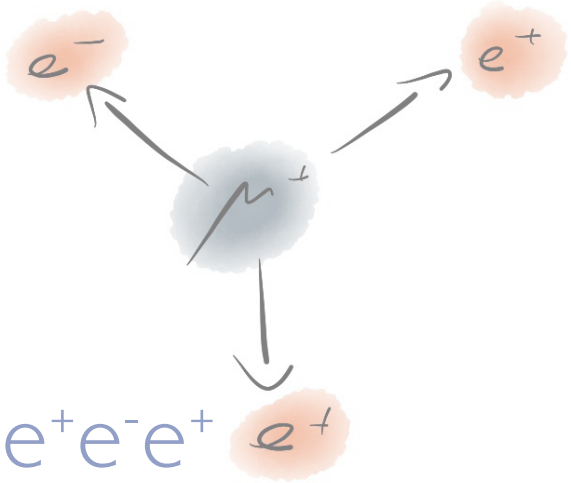


$\mu^+ \rightarrow e^+e^-e^+$

Kinematics

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

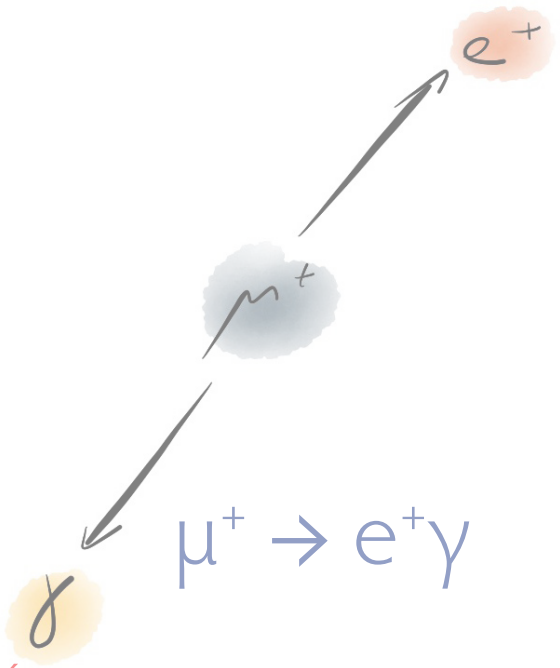
Background

- Accidental background
- Radiative decay

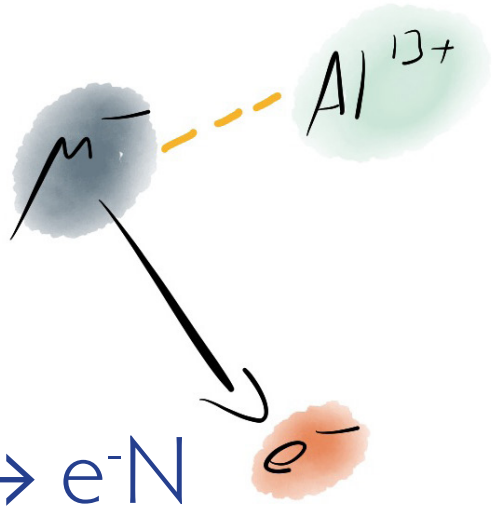
Kinematics

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

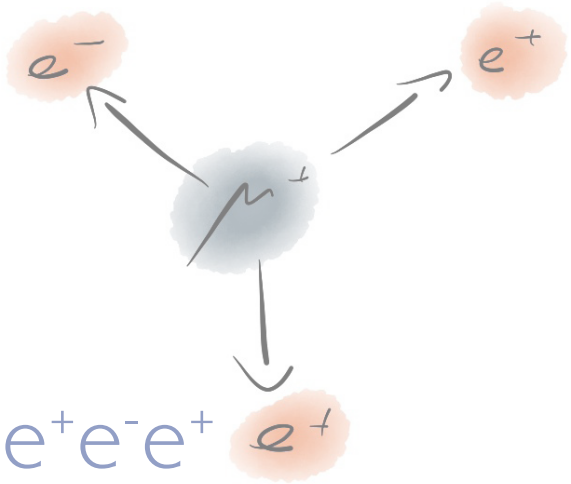
LFV Muon Decays: Experimental signatures



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



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



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

Kinematics

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

Background

- Accidental background
- Radiative decay

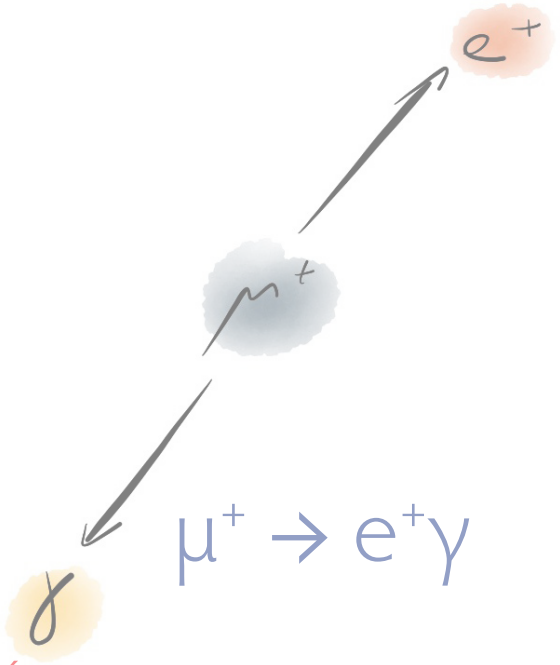
Kinematics

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

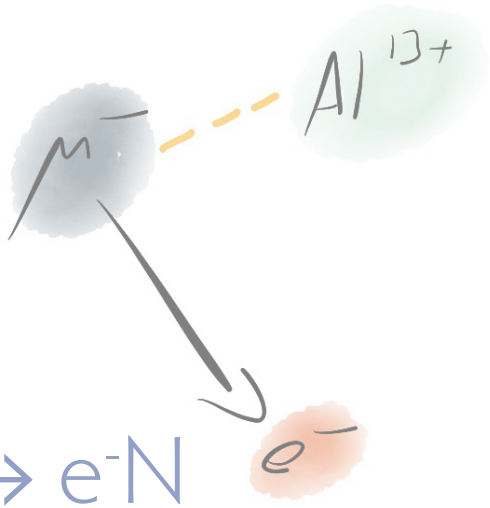
Background

- Decay in orbit
- Antiprotons, pions, cosmics

LFV Muon Decays: Experimental signatures



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



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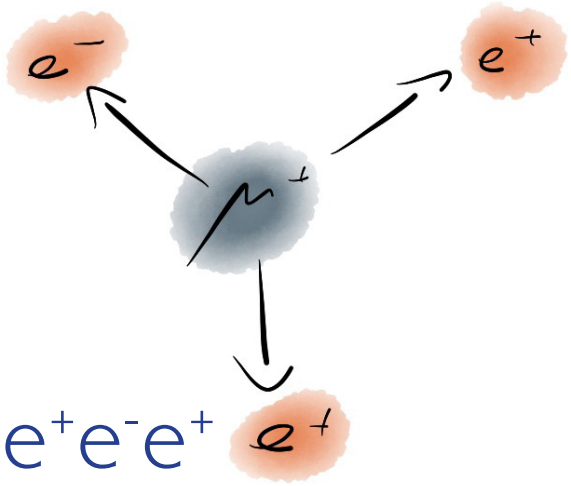


$\mu^+ \rightarrow e^+e^-e^+$

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

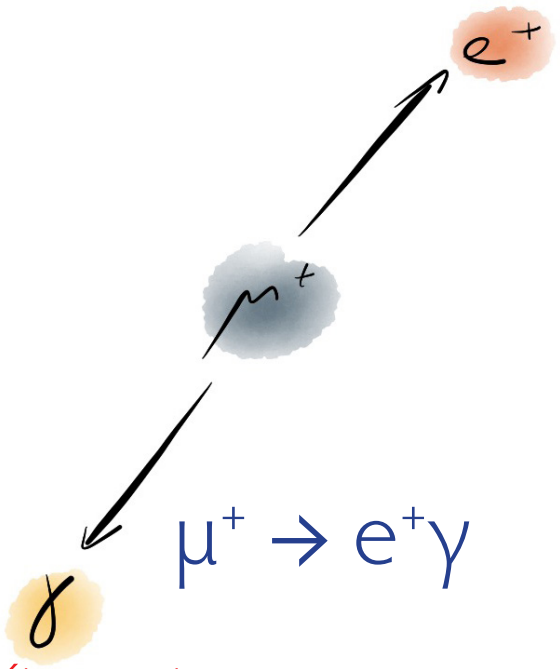
Kinematics

- 3-body decay
- Invariant mass constraint
- $\Sigma\, p_i = 0$

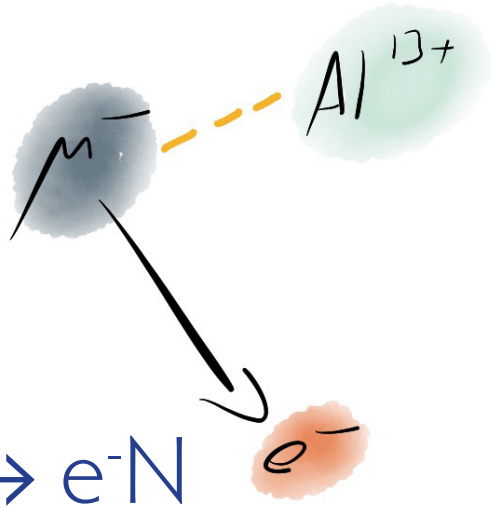
Background

- Internal conversion decay
- Accidental background

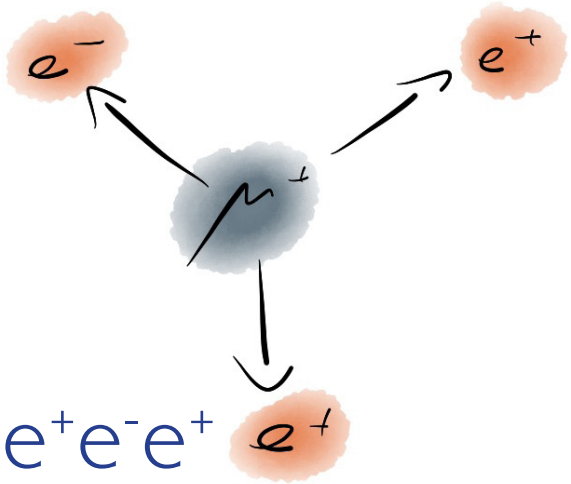
LFV Muon Decays: Experimental signatures



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



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



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

Kinematics

- 2-body decay
- Monoenergetic e^+, 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

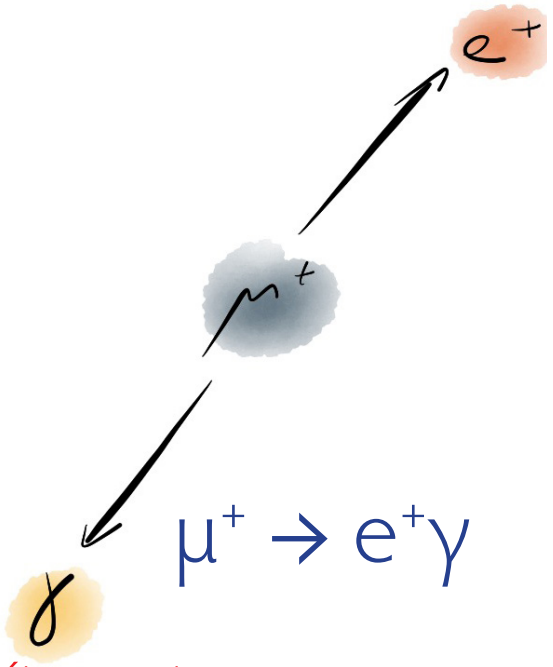
Kinematics

- 3-body decay
- Invariant mass constraint
- $\Sigma\, p_i = 0$

Background

- Internal conversion decay
- Accidental background

LFV Muon Decays: Experimental signatures



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

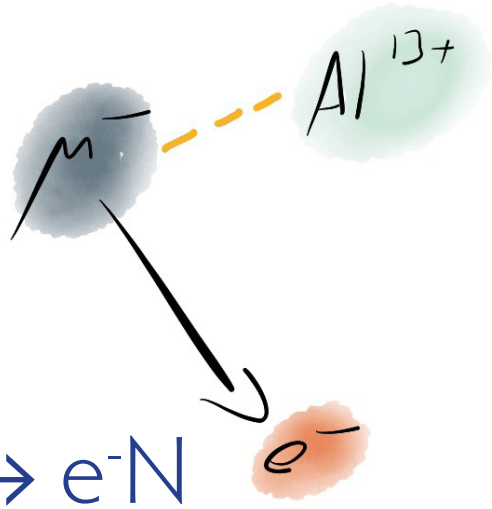
Kinematics

- 2-body decay
- Monoenerge
- Back-to-b

Backgro

- A al background

Continuous Beam



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

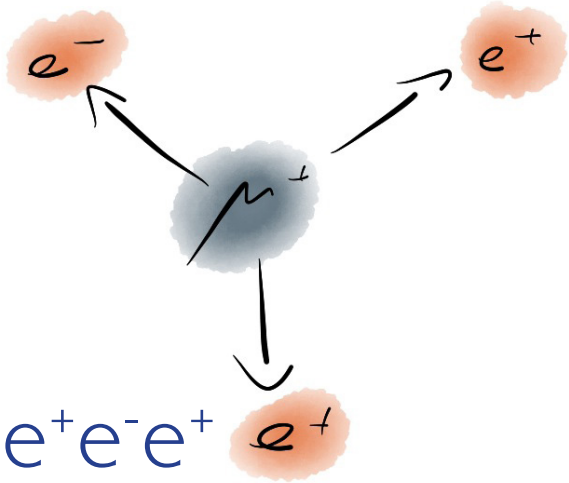
Kinematics

- Quasi 2-body d
- Monoenerge
- Single p etected

Backgro

- D orbit
- A protons, pions

Pulsed Beam



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

Kinematics

- 3-body decay
- Invariant mas aint
- $\Sigma p_i = 0$

Backgro

- R decay
- Ac ental background

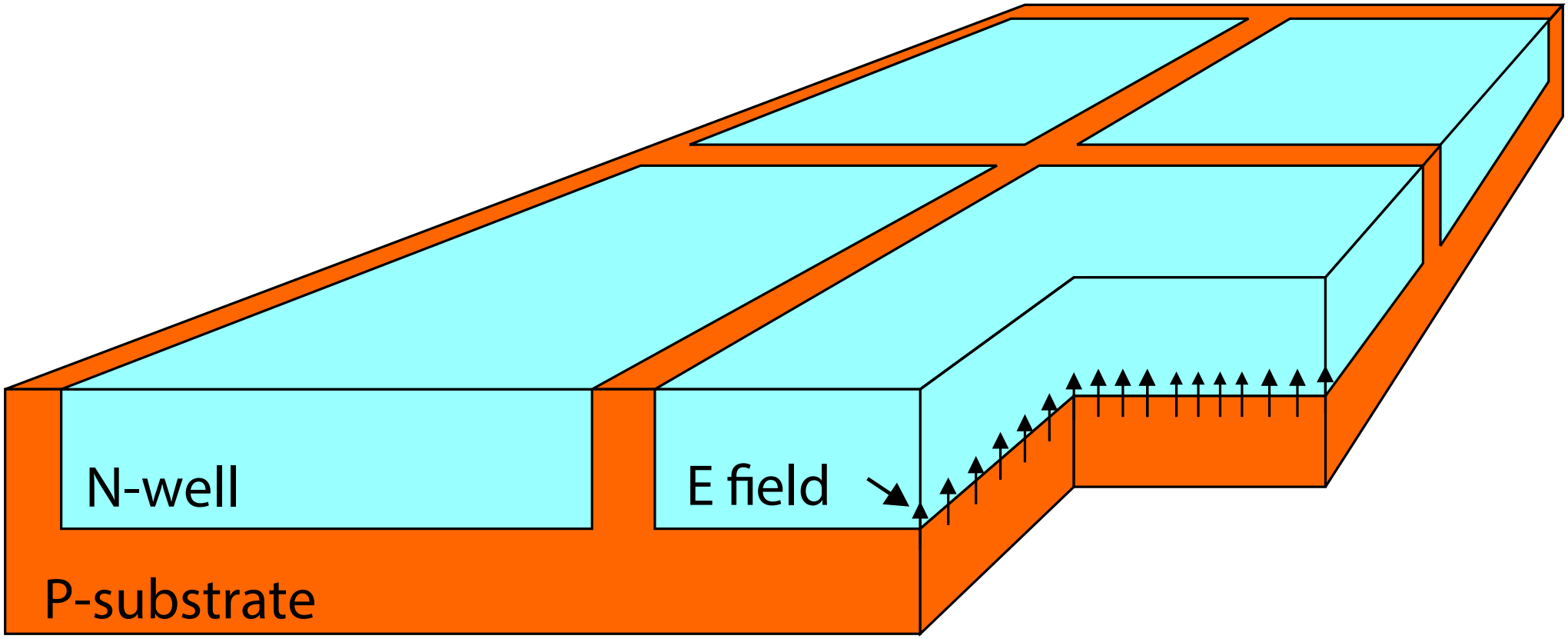
Continuous Beam

Very thin and fast silicon pixel sensors: HV-MAPS

Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

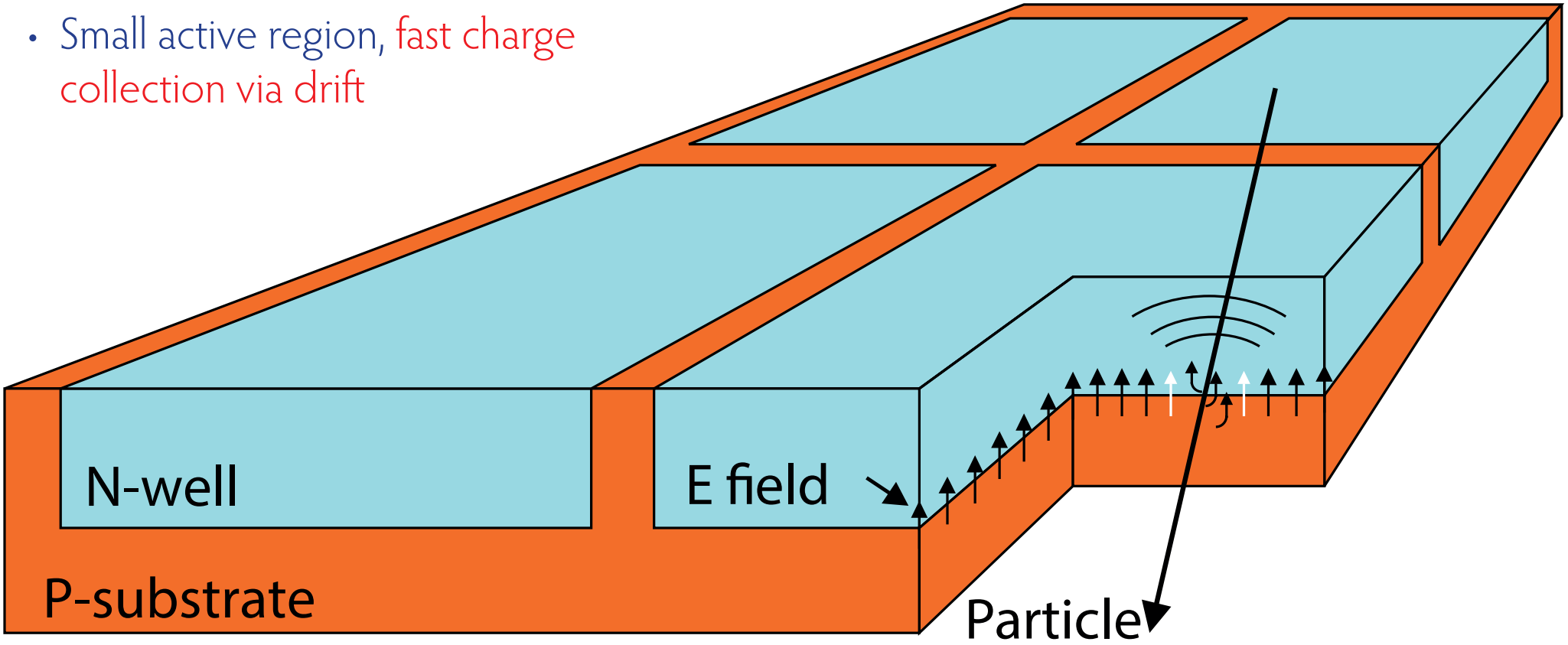
- Use a high voltage commercial process (automotive industry)



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



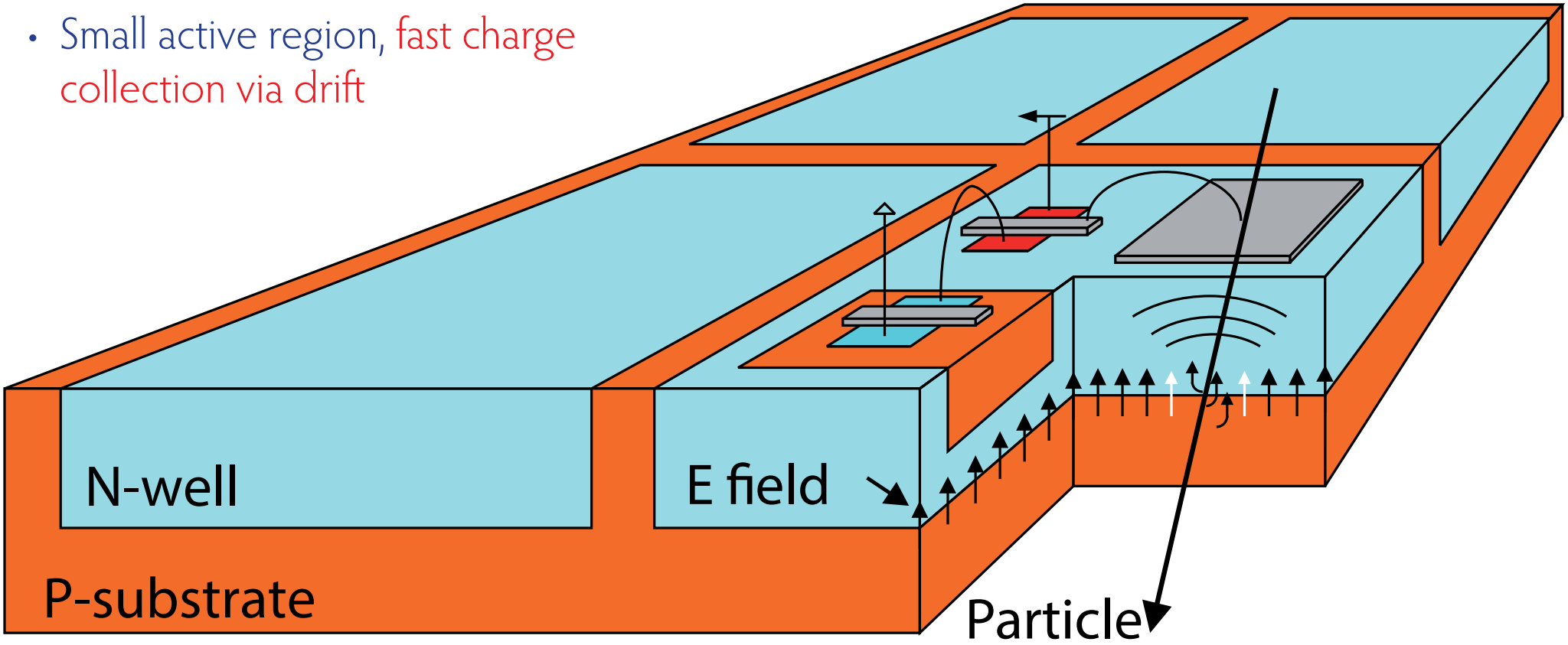
Fast and thin sensors: HV-MAPS

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

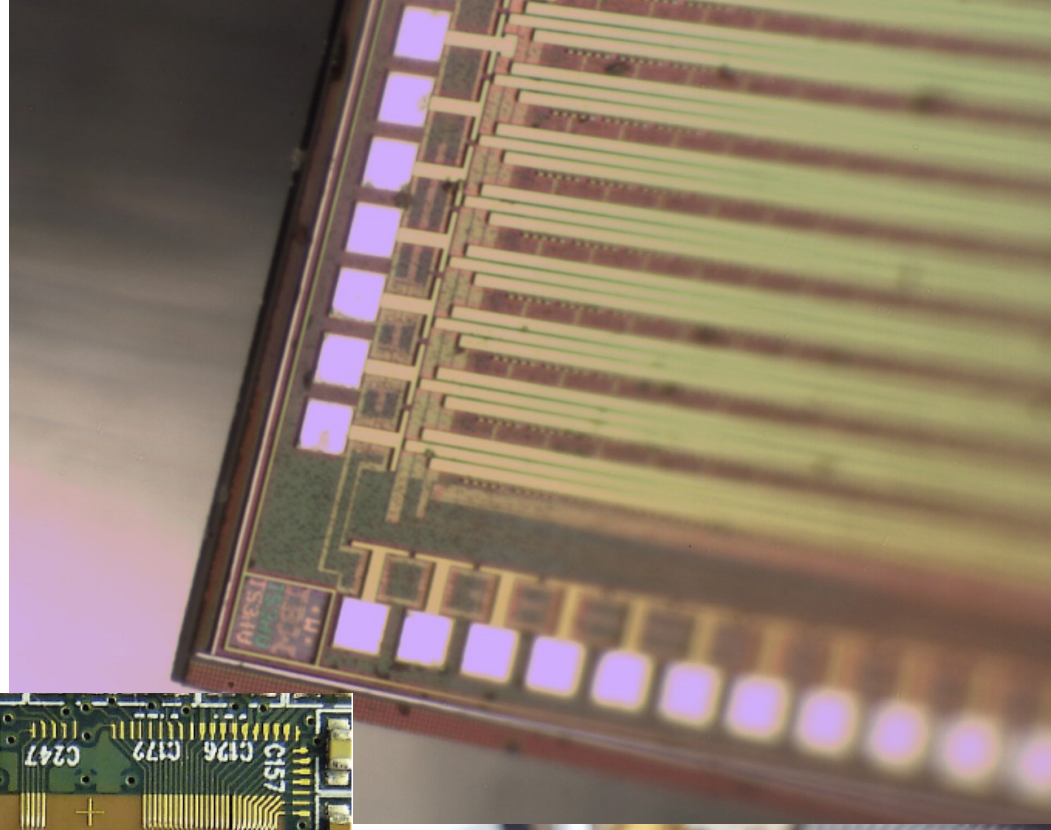
(I.Perić, NIM A 582 (2007) 876)

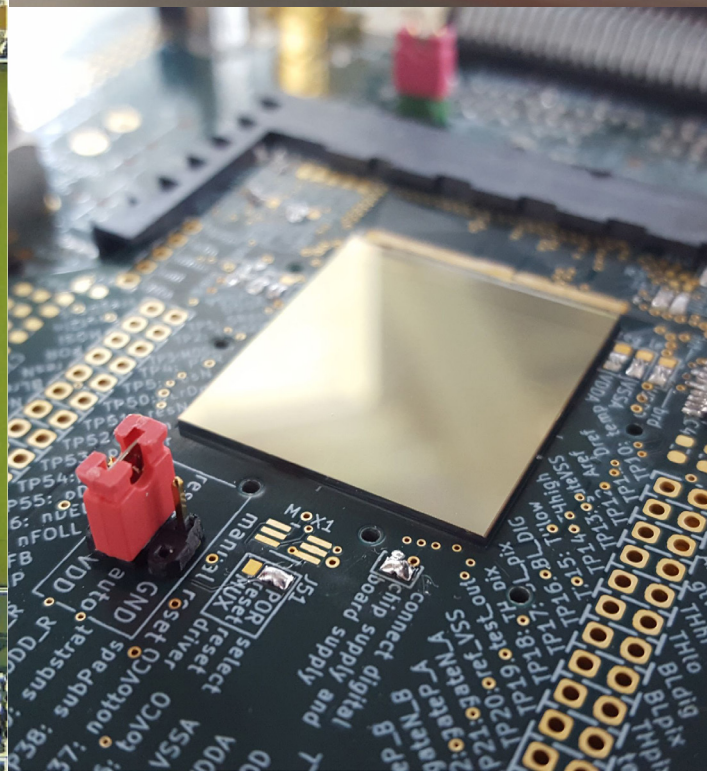


The MuPix Prototypes

Developed a series of HV-MAPS prototypes

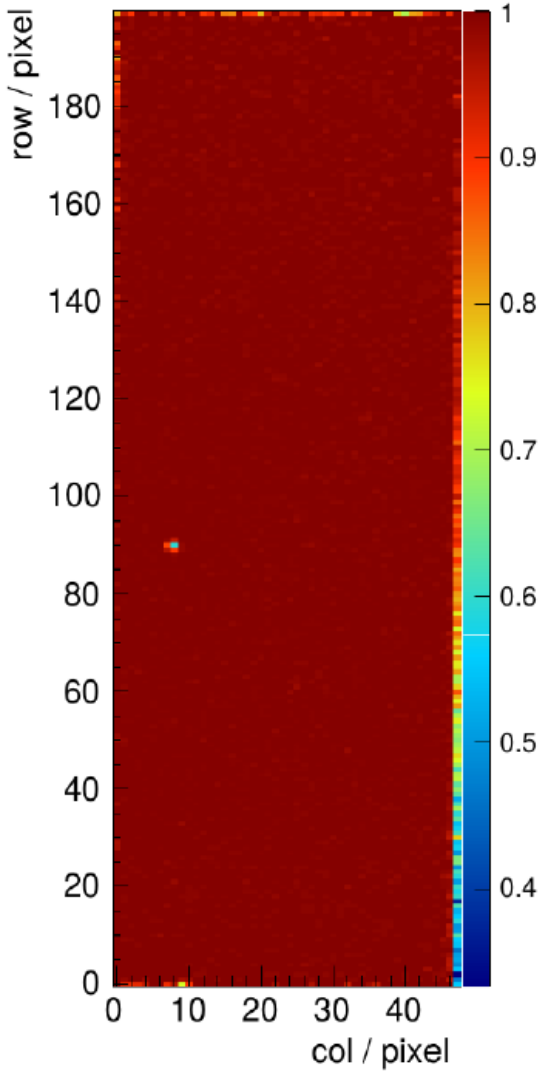
- Goal: Detection and signal processing with just 50 µm silicon
- 6th chip, MuPix7, was the first full system-on-a-chip
- Going "big" 2 x 1 cm^2 MuPix8 with 80 by 80 µm pixels also working nicely - some growing pains fixed
- Now: MuPix10, 2 x 2 cm^2, integration ready - under test



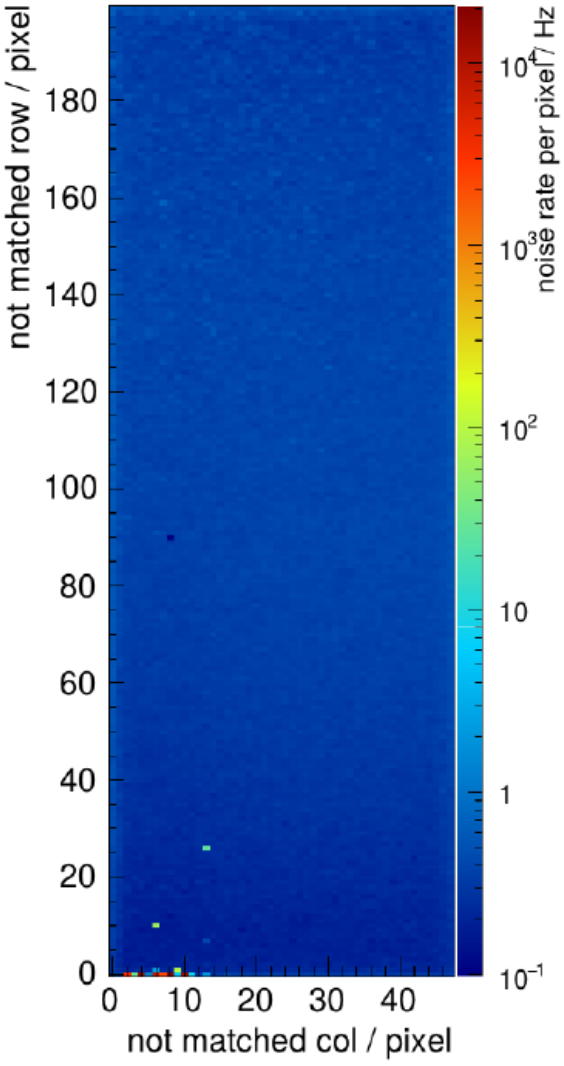


MuPix8: Results

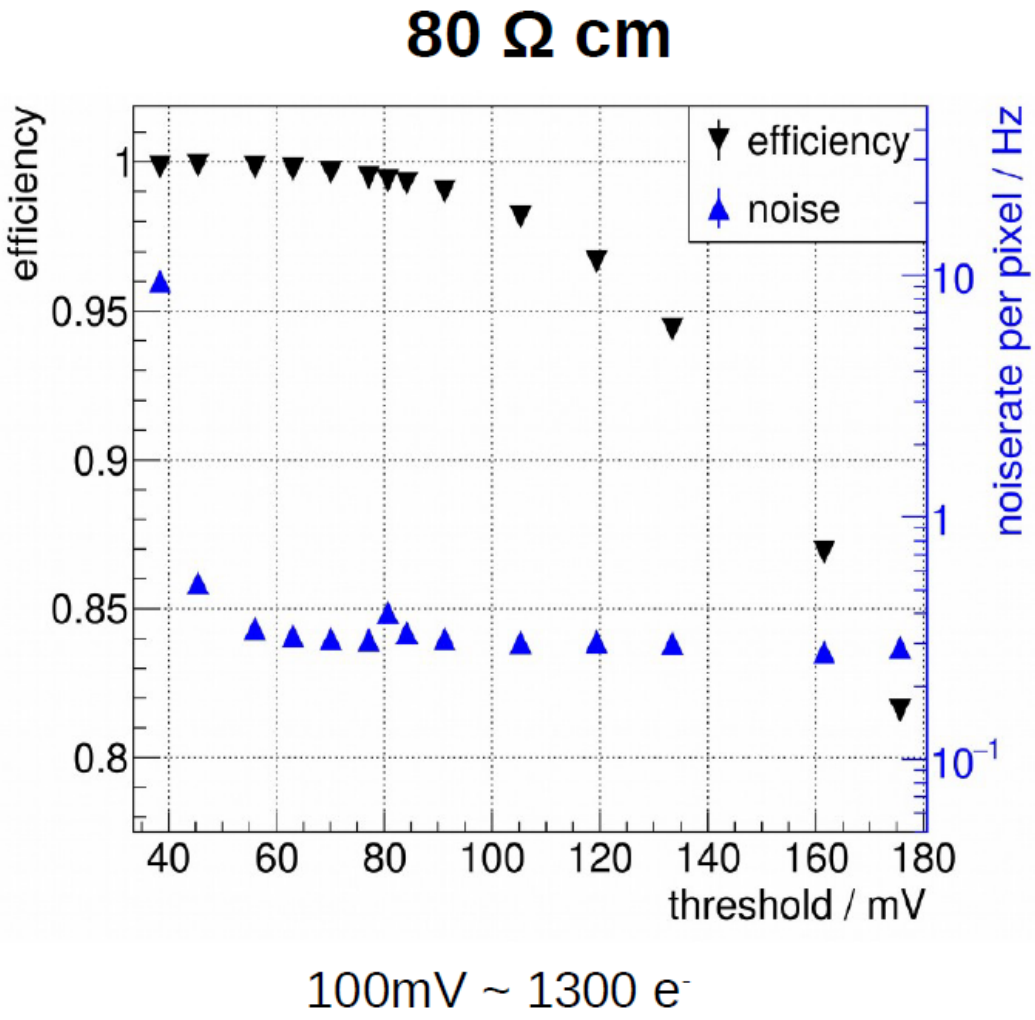
efficiency
~99.9%



noise
~1Hz/pixel

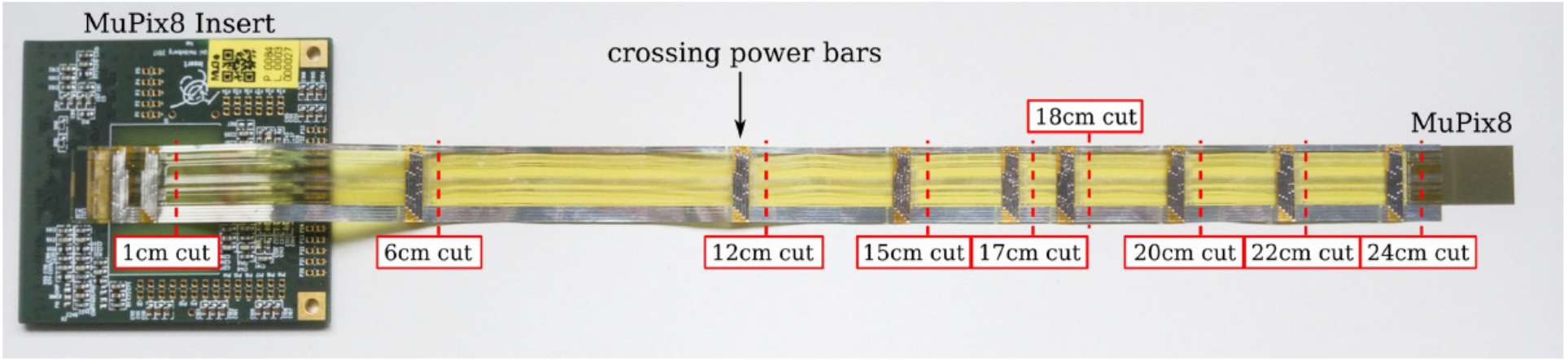


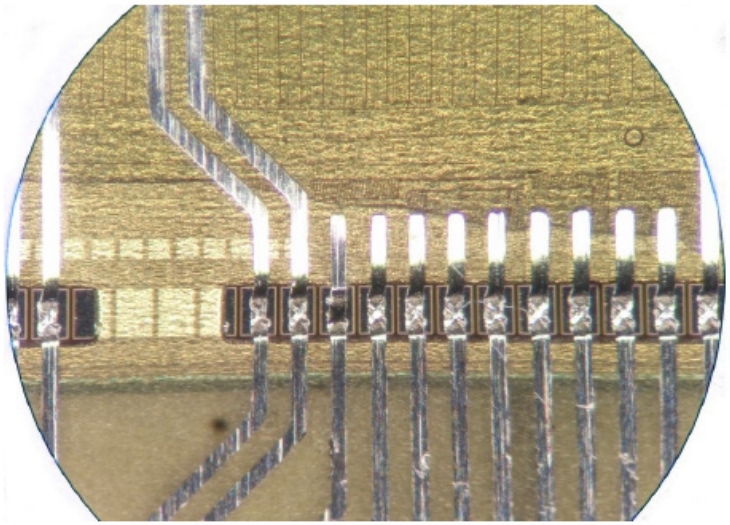
Time resolution of < 6 ns σ reached



100mV ~ 1300 e^-

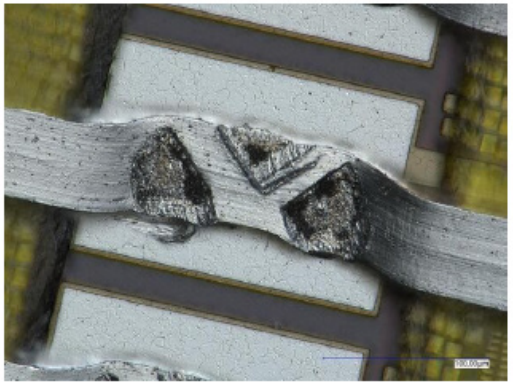
Integration with Flexprint





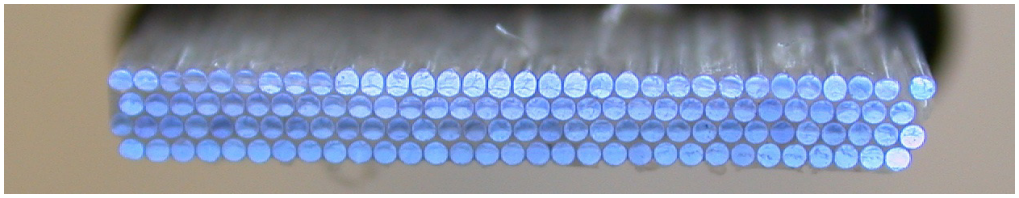
Operate MuPix on an aluminium-kapton flexprint without decoupling capacitors

- Low noise
- No transmission errors
- Longer than needed for Mu3e



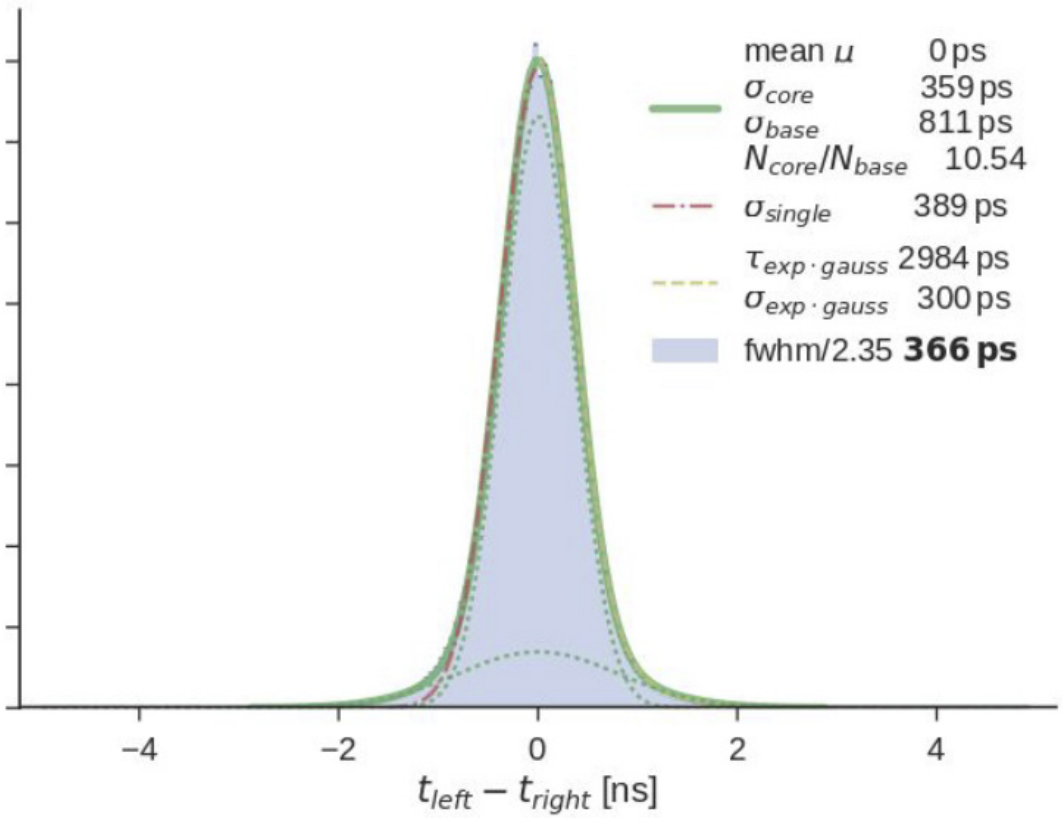
Better timing:
Scintillating fibres and tiles

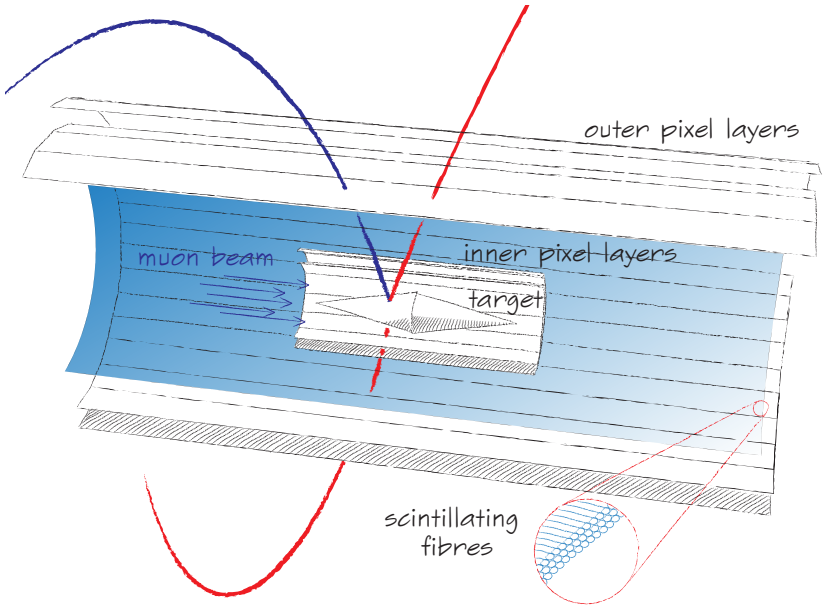
Timing Detector: Scintillating Fibres



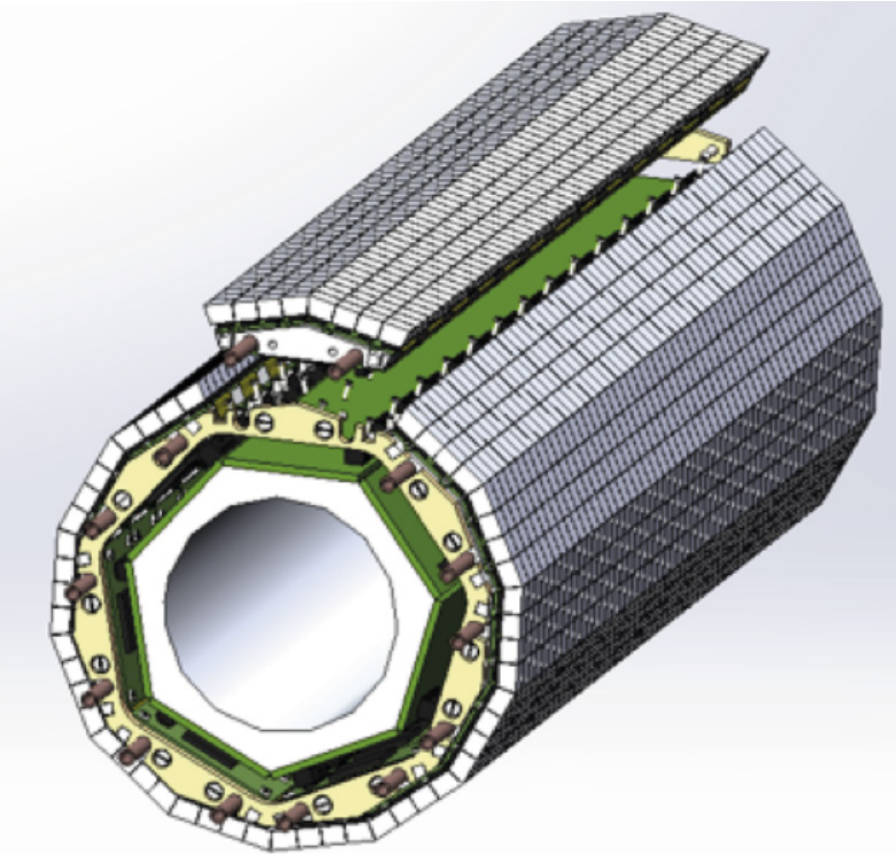
- 3 layers of 250 µm scintillating fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (MuTRiG)

Timing resolution < 400 ps including ASIC

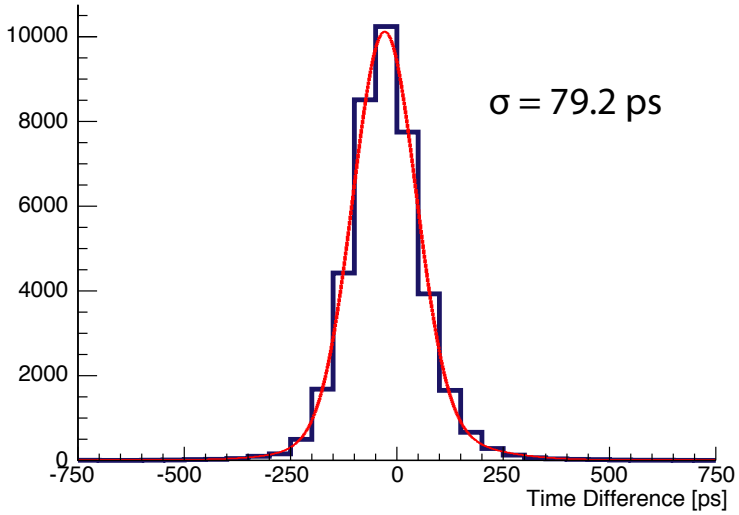


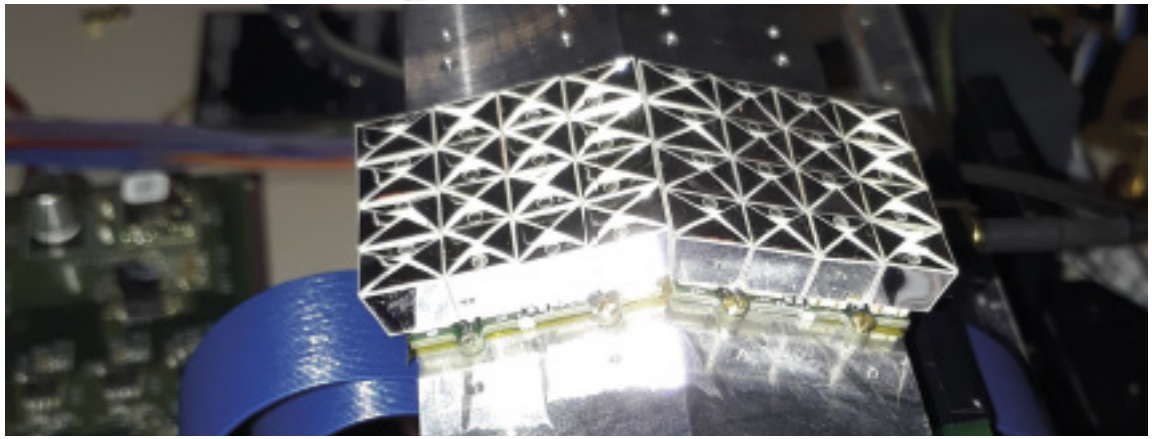


Timing Detector: Scintillating tiles



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





- 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