The Mu3e experiment

Frederik Wauters on behalf of the Mu3e Collaboration

Johannes Gutenberg University Mainz

CLFV & $\mu^+ \to e^+ e^+ e^-$

Search for Charged Lepton Flavour Violating ⊂ New Physics in the Lepton Sector ⊂ Beyond Standard Model Physics
@ precision / intensity frontier

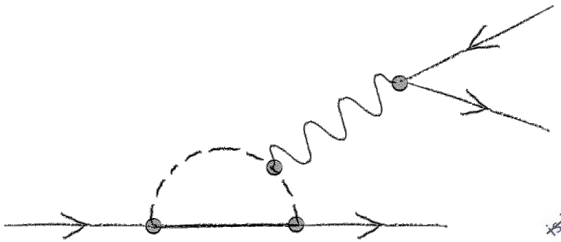
➔ Lepton Flavour is an *accidental* SM symmetry

➔ In the neutral/neutrino sector, Lepton Flavour Violation is experimentally observed → SM extended with PMNS

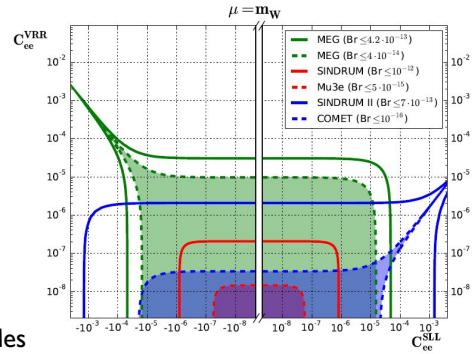
➔ Many new Physics Models (*Leptoquarks*, *SUSY*, *Z'*, *Composite Higgs*, …) predict CLFV, in an EFT framework sensitive many operators at a mass scale beyond LHC

For example, a systematic effective-field-theory approach presented in arXiv:1702.03020v3

New particle in the loop



Is it "boring BSM" or "interesting BSM"?

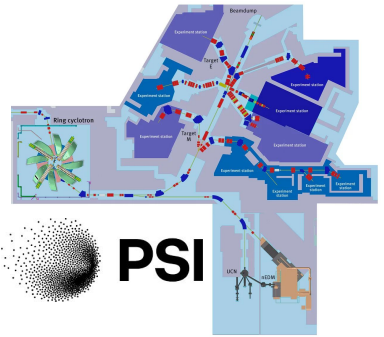


Sensitive to LHC direct production Λ > 1000 TeV energy scales

CLFV & $\mu^+ \to e^+e^+e^-$

Muons are great for CLFV:

- They are leptons with 100% leptonic decay modes very well described in the SM
- SM background free
- BSM contributions can be described by EFT arXiv:1702.03020 as $m_{mu} \ll \Lambda_{NP}$
- **We can make a lot of them at p-accelerator facilities**
- **They live long enough to production → experiment**



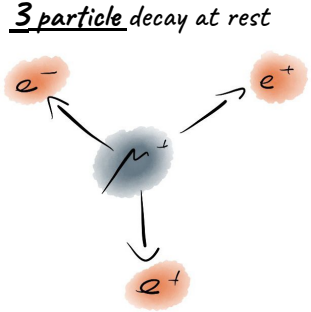
HIPA at PSI

Three golden channels

❑	$\mu^+ \to e^+\gamma$	MEG < $4 \cdot 10^{-13}$	⇨	MEGII < $5 \cdot 10^{-14}$
❑	$\mu^- N \to e^- N$	SUNDRUMII < $7 \cdot 10^{-13}$	⇨	DeeMee, Mu2e, COMET < 10^{-16}
❑	$\mu^+ \to e^+e^+e^-$	SINDRUM < $1 \cdot 10^{-12}$	⇨	Mu3e < $2 \cdot 10^{-15}$ ($1 \cdot 10^{-16}$ in a second phase)

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

How to look for $\mu^+ \rightarrow e^+e^+e^-$?



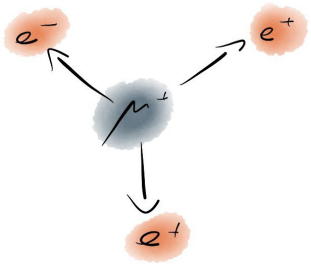
- ➔ Common vertex
- ➔ Time coincident
- ➔ $\sum E = m_\mu$
- ➔ $\sum \mathbf{p} = 0$

CLFV & $\mu^+ \to e^+e^+e^-$

How to look for $\mu^+ \to e^+e^+e^-$?

DC Beam @ **PSI**

3 particle decay at rest



- ➔ Common vertex
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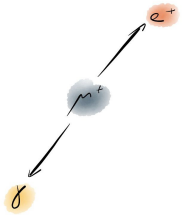
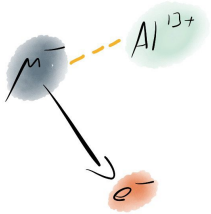
2 particle decay at rest, very clear signal



- ➔ Mono-energetic e^+ and γ
- ➔ back-back coincidence

Pulsed beam at FNAL, J-PARC

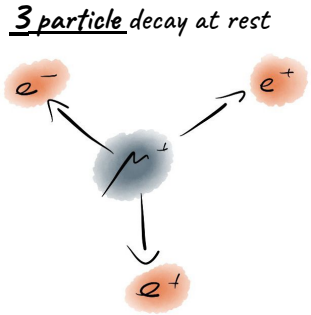
Only one particle in final state

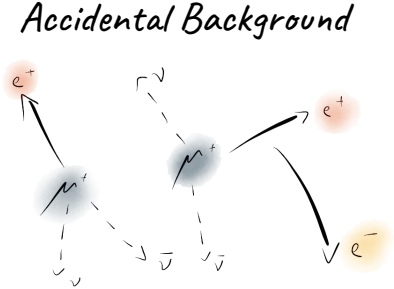


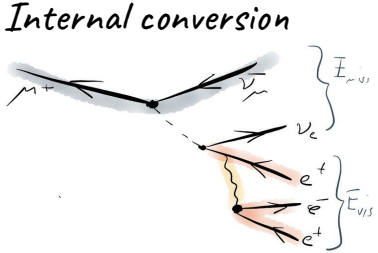
- ➔ Mono-energetic e^-
- ➔ No coincidence

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

How to look for $\mu^+ \rightarrow e^+e^+e^-$?







- ➔ Common vertex
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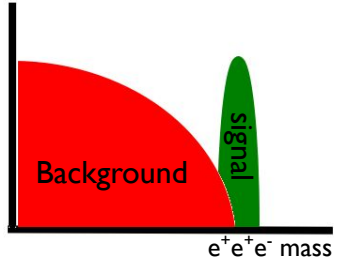
The Mu3e apparatus needs:

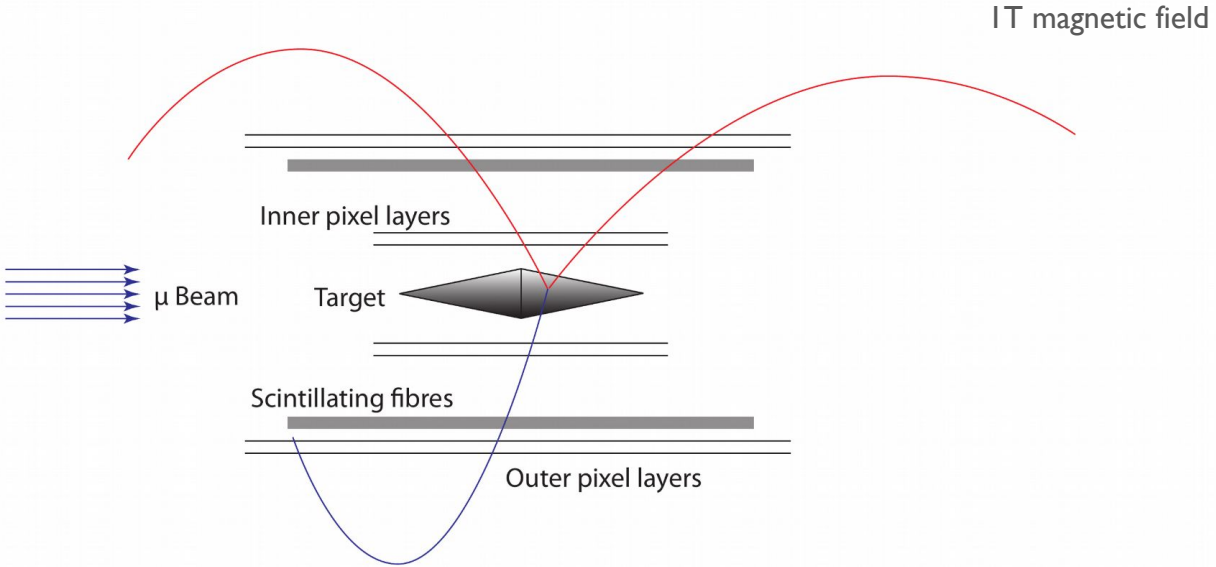
- ➢ Excellent momentum resolution
- ➢ Good time and vertex resolution
- ➢ High rate capability
- ➢ Large acceptance



Mu3e detector concept

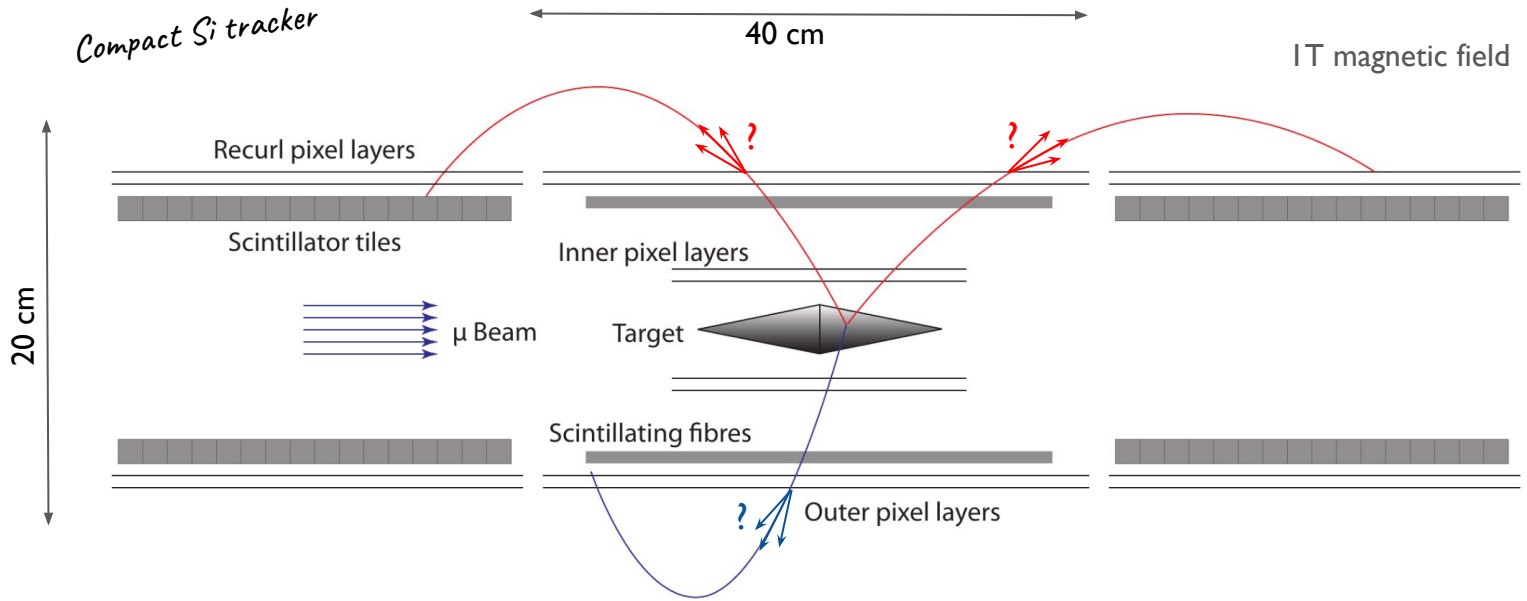
➢ Stop muons on hollow cone target

Mu3e detector concept



- Stop muons on hollow cone target
- Two layer Vertex Detector + 2 Outer Pixel layers
- Two more Si Pixel layers tracking (see our dedicated fast track fitter: https://arxiv.org/abs/1606.04990)
- Scintillating Fibre detectors to differentiate electrons and positrons

Mu3e detector concept



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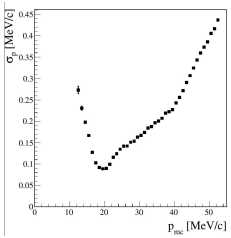
- Two layer Vertex Detector + 2 Outer Pixel layers
- Two more Si Pixel layers tracking (dedicated fast track fitter: https://arxiv.org/abs/1606.04990)
- Scintillating Fibre detectors to differentiate electrons and positrons
- Recurling tracks to get the optimal momentum resolution
- Scintillating Tiles to get the optimal time resolution

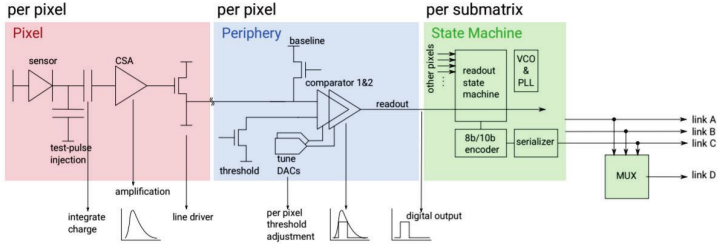


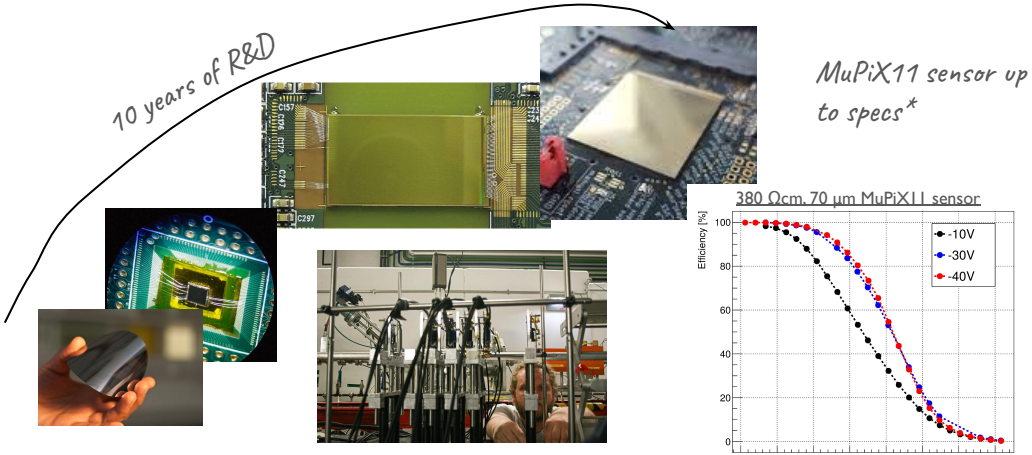
Momentum resolution dominated by multiple scattering
→ Ultra-thin Si pixel tracker, $\mathcal{O}(0.1\% X_0)$, with decent time resolution, $\mathcal{O}(10$ ns)

HV-MAPS pixel tracker

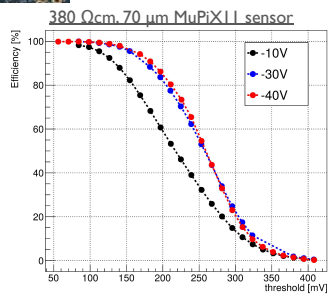
Lightweight pixel tracker build from MuPIX sensors*

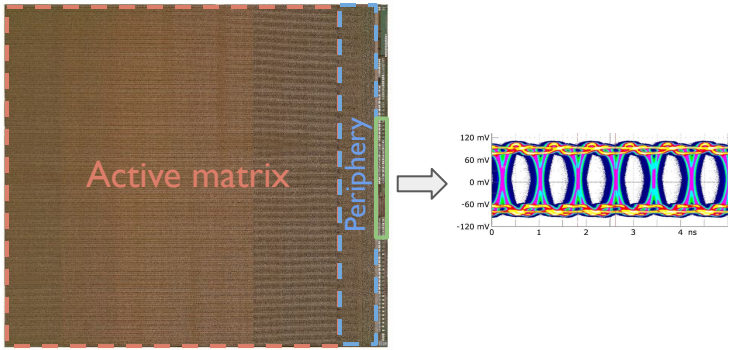
- Commercial HV-CMOS process
- Fast Charge collection
- Integrated analogue and digital RO, 1.25 Gb LVDS link
- Can be thinned to 50 µm
- 256x250 pixels, 2 x 2 cm matrix





*MuPiX11 sensor up to specs**





*https://doi.org/10.7566/JPSCP.42.011020

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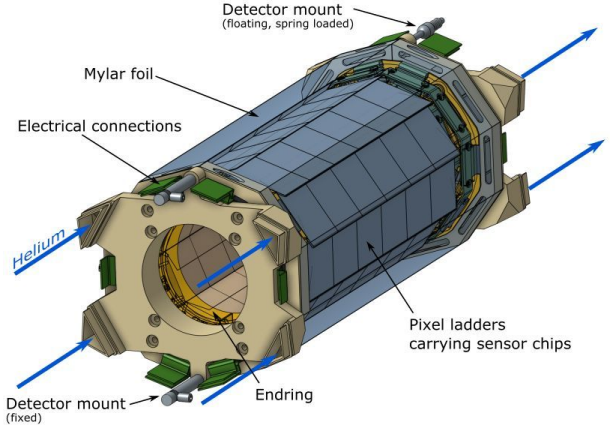
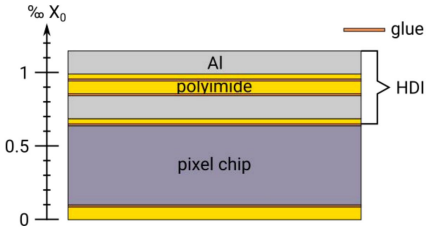
- Can be thinned to 50 µm
- 256x250 pixels, 2 x 2 cm matrix

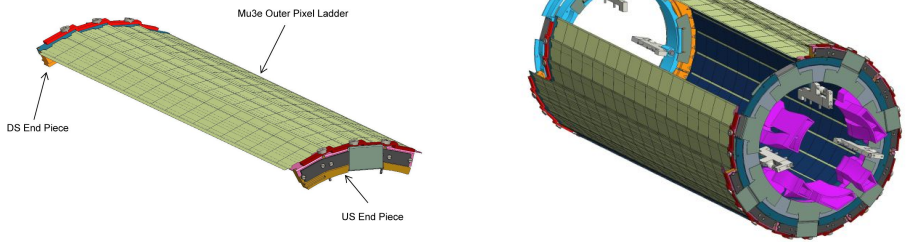
- 174 *ladders* with 2844 2x2 cm^2 MuPiX chips
- 2 Vertex layers
- 3 x 2 Outer Pixel layers
- 3060 1.25 Gb/s data links
- 50 g/s, 10m/s 5kW gaseous helium cooling

Vertex tracker





Outer Pixel Tracker



Scintillating fibres and tiles

The Mu3e Scintillating Fiber Detector
Gentian Shatri

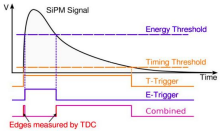
Scintillator fibres and tile detector readout by MuTRiG ASIC**

- Improve timing from 10-20 ns to 250 ps and 80 ps, respectively
- Resolve tracking ambiguities, deal with pile-up
- Differentiate between e+ & e-

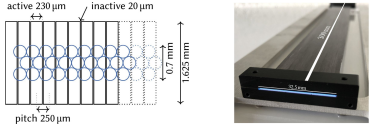
- Thin 3-layer SciFi ribbons at < p.e.Threshold
  - Low mass
  - Efficient
  - Decent time resolution

- Upstream and Downstream tile station
- *End of a track* → Scintillating cubes for optimal time resolution

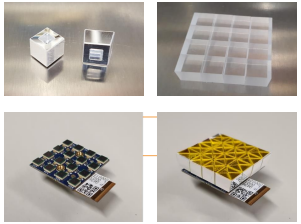
- Custom MuTRIG readout chip**
  - 50 ps TDC
  - High rate
  - 1.25 Gb/s readout link



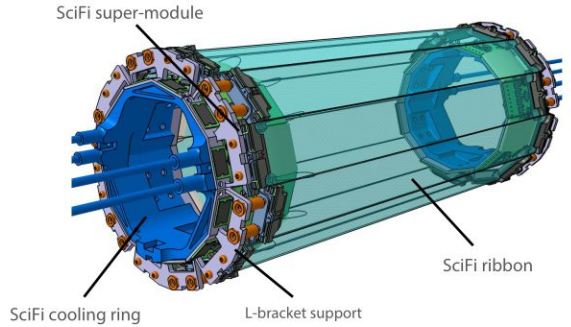
Fibre ribbon



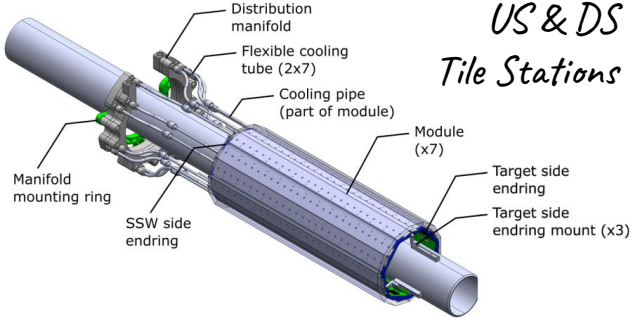
Tile Matrix



Central SciFi Tracker*

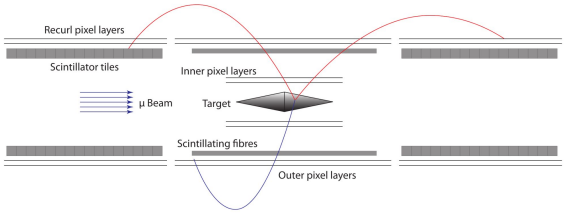


US & DS Tile Stations

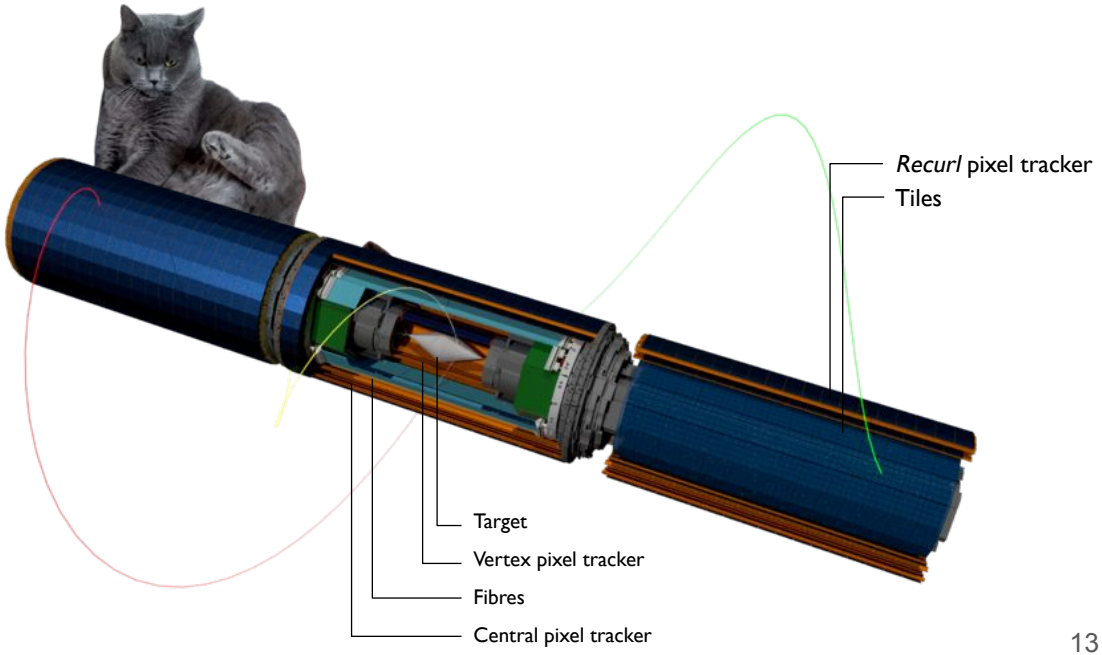


* https://doi.org/10.1016/j.nima.2023.168766 **https://iopscience.iop.org/article/10.1088/1748-0221/12/01/C01043

Mu3e detector design



Compact lightweight electron-positron tracker



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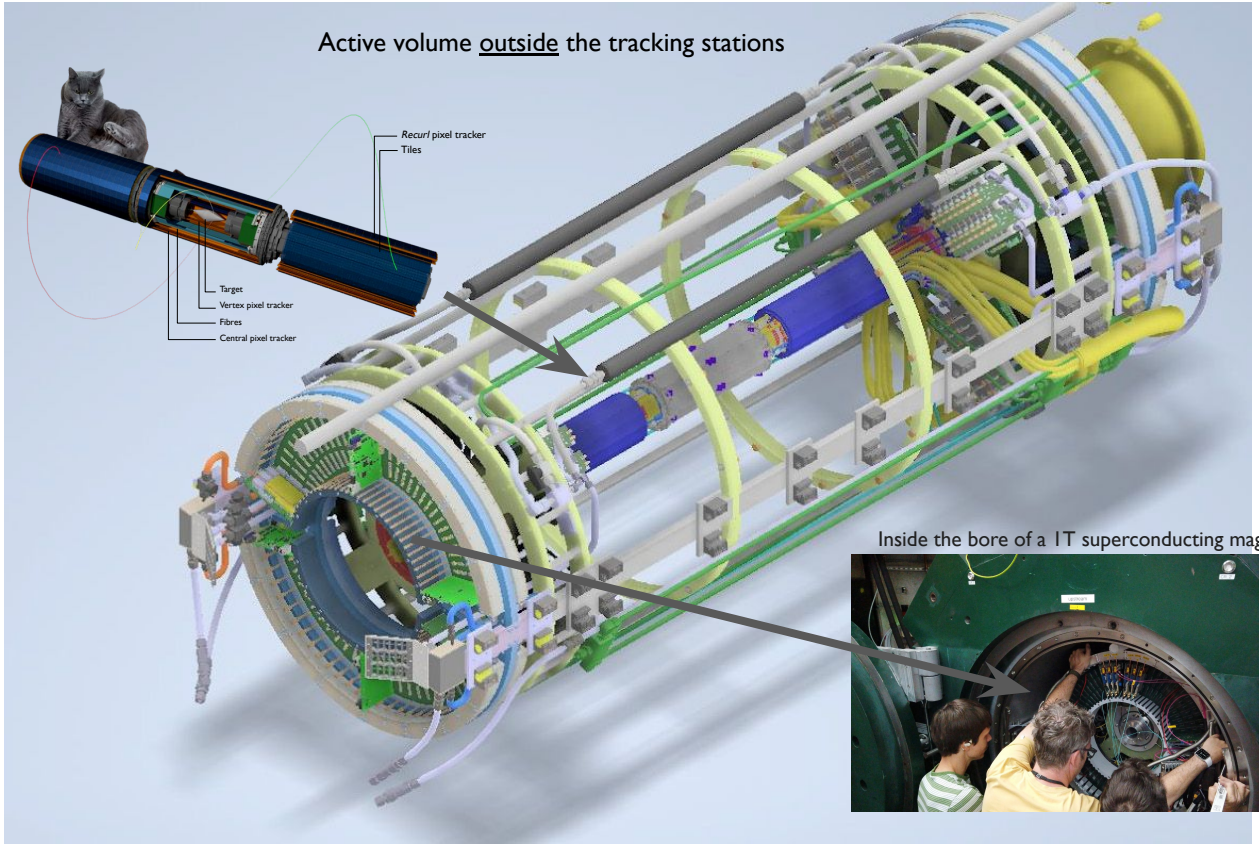
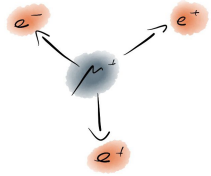


Compact lightweight electron-positron tracker **plus**

- ❏ Power, HV, and front-end readout services at the end-caps
- ❏ <10C liquid SiPM cooling
- ❏ Ca. 5kW gaseous helium for the pixel detector
- ❏ Streaming >100 Gb/s steaming DAQ + online GPU event selection



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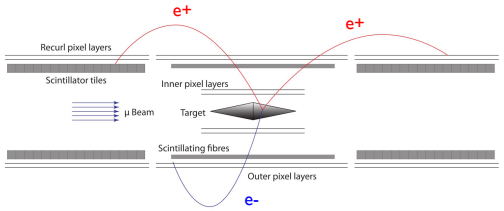
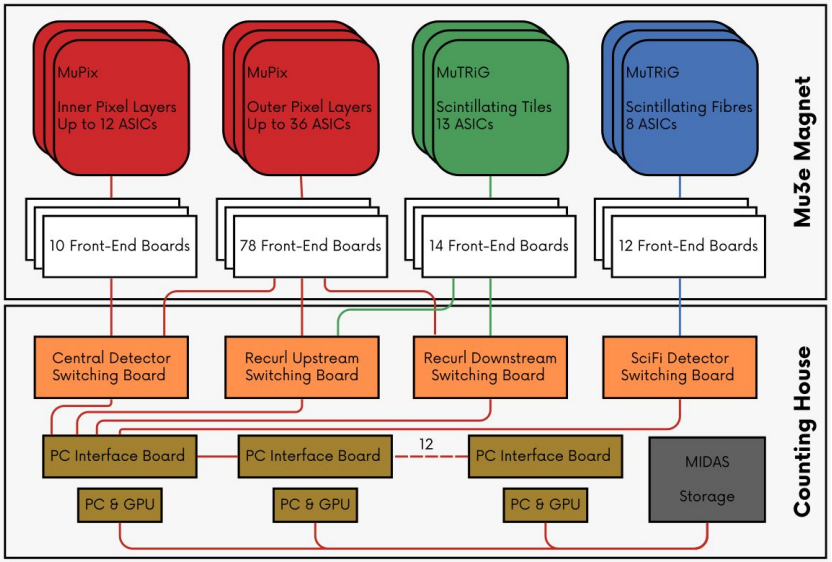
Mu3e DAQ



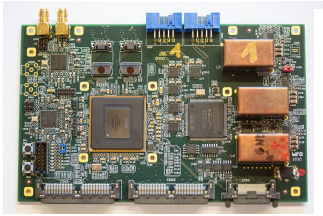
Reminder: the Mu3e event topology does not allow for a local readout trigger, every $e^{+/-}$ track could potentially be part of a $\mu^+ \rightarrow e^+e^+e^-$ event. Only the kinematics of the combined final state positrons/electron gives us an event selection criteria.

*Mu3e = lightweight and fast Michel electron tracker + high throughput online reconstruction & selection DAQ system**

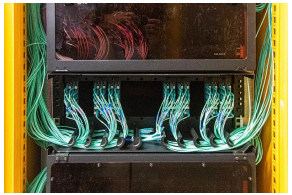


- ❏ Streaming DAQ
- ❏ Network of FPGA's and optical connections
- ❏ Collect time slices of the full detector on a single PC
- ❏ Online reconstruction and event selection on a GPUs
- ❏ Write selected events to disk at max 100 MB/s (up to 100x reduction)

Custom readout board electronics inside the magnet



On-the-shelf solutions in the counting house



* https://ieeexplore.ieee.org/document/9440905/

Mu3e DAQ

The Mu3e Data Acquisition System
Alexandr Kozlinskiy

Mu3e Online Event Selection on GPU
Chen Xie

Achieving determinism and real-time in Mu3e experiment
Yifeng Wang

½ of the Mu3e posters @ PSI2025

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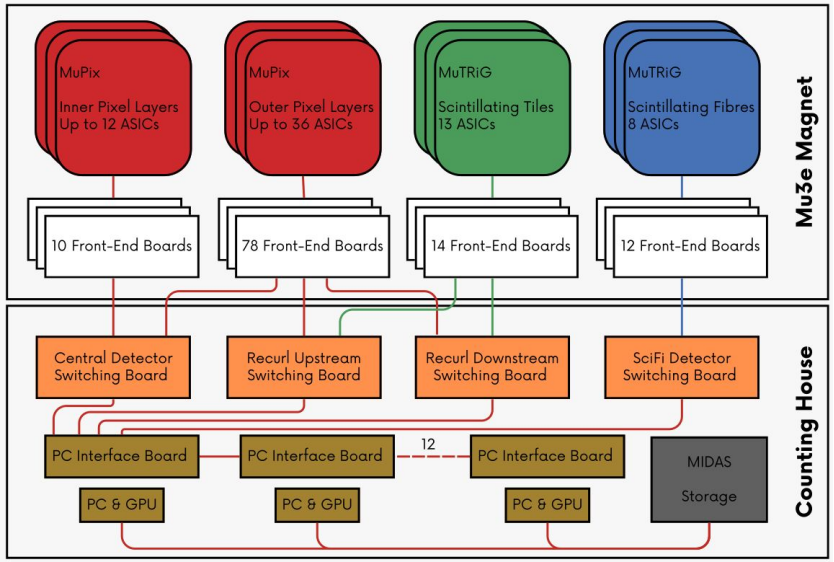

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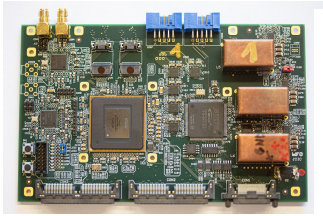

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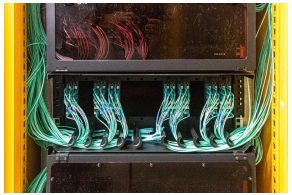

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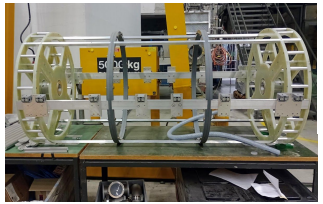
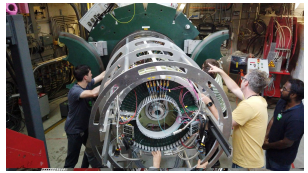
Mu3e = running experiment at PSI

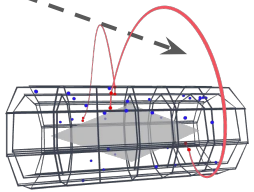
1.5 year ago:

- ❏ Detector modules in (pre)production
- ❏ Commissioned magnet + beamline
- ❏ Empty detector cage



[The Mu3e Commissioning Run at PSI in 2025](#)
Mikio Sakurai





June 2025: successful first Mu3e commissioning beamtime in πE5

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1.5 year ago:

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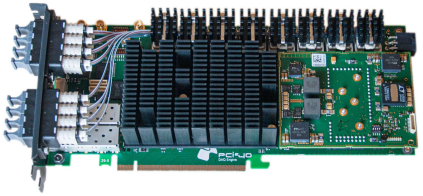
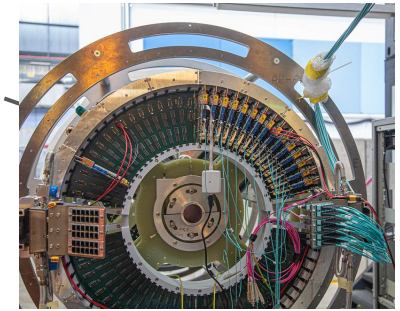
- ❏ Empty detector cage

Install DAQ hardware:

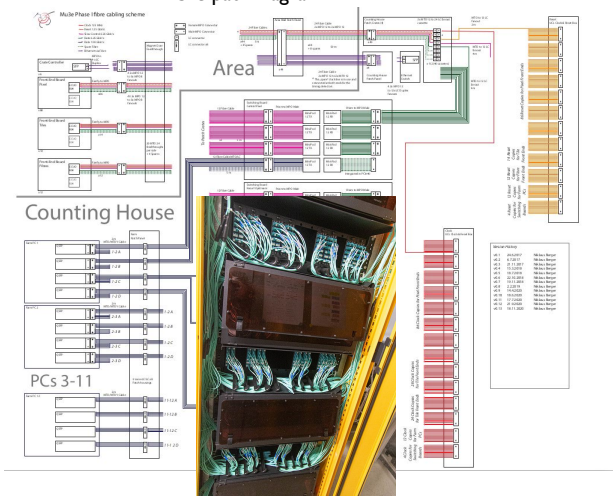
- Service support wheels with front-end FPGA boards
- Optical fibre network, including data merging
- Online GPU filter farm

Data merging and construct time slices of the full detector

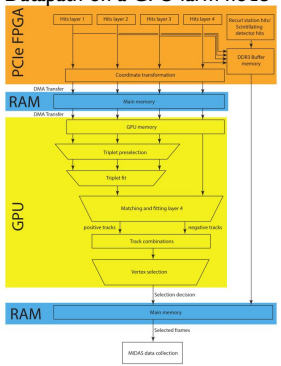




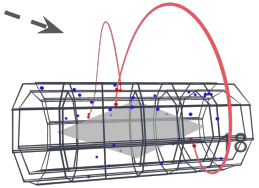
Fibre path diagram



Datapath on a GPU farm node



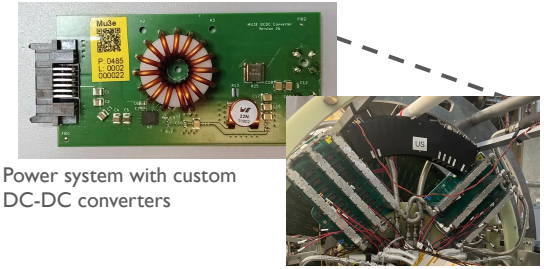
Plus combining a lot of **firmware** and **software** achieve a complete data path



Mu3e = running experiment at PSI

1.5 year ago:

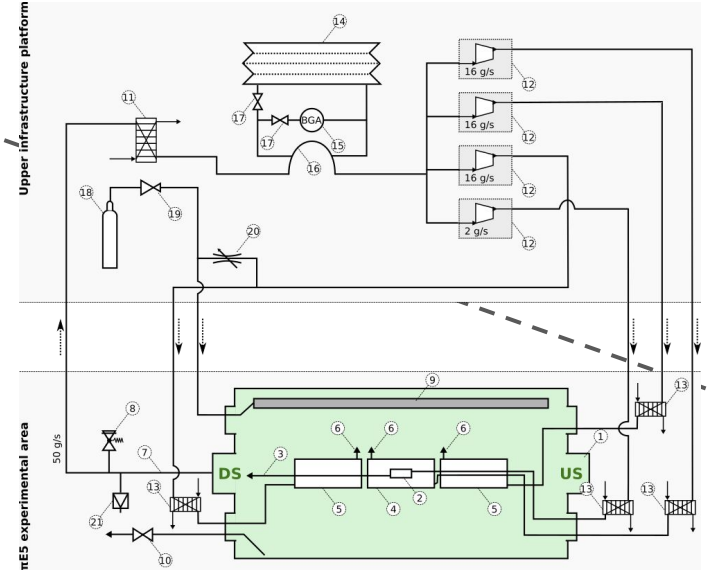
- ❏ Detector modules in (pre)production
- ❏ Commissioned magnet + beamline
- ❏ Empty detector cage

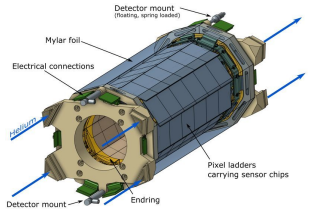


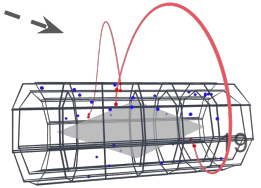
Power system with custom DC-DC converters

Install Power and cooling plants

- Power supplies, DC-DC converters, electrical wiring
- Electronic cooling plant
- <10C silicon oil based detector cooling (SiPM radiation damage)
- Novel gaseous helium plant







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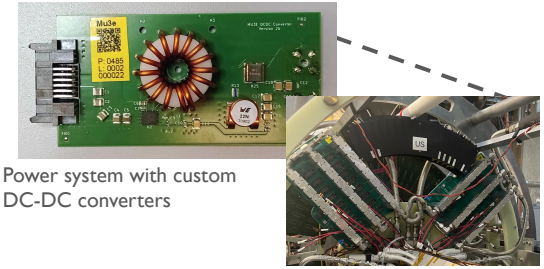
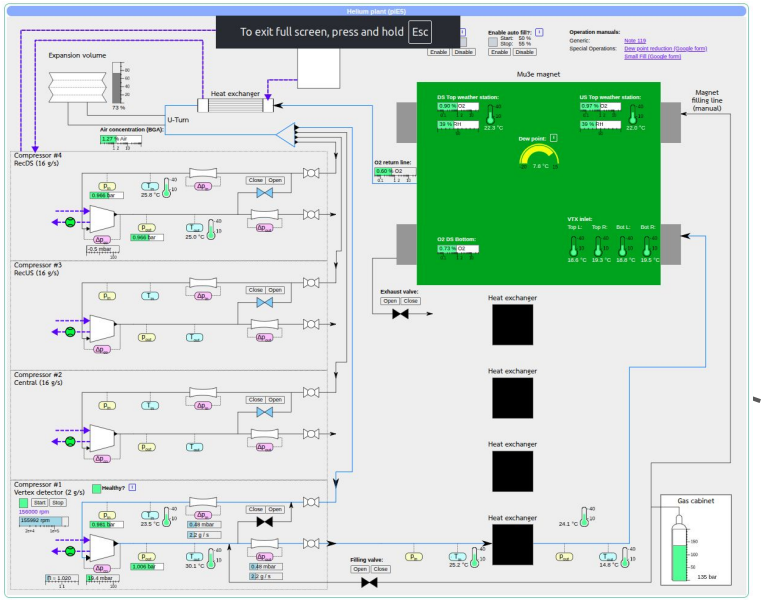
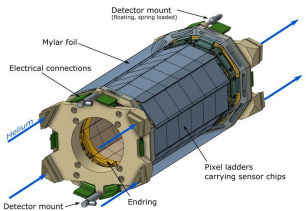


Power system with custom DC-DC converters

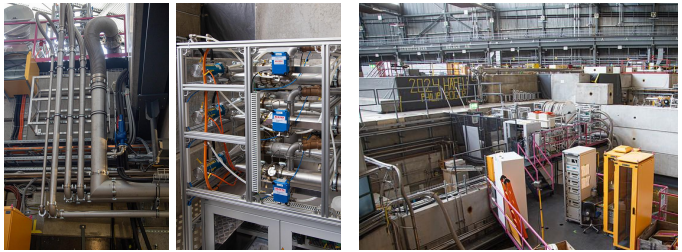
Install Power and cooling plants

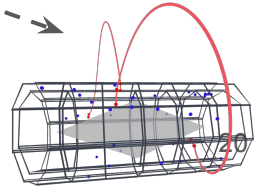
- Power supplies, DC-DC converters, electrical wiring
- Electronic cooling plant
- <10C silicon oil based detector cooling (SiPM radiation damage)
- Novel gaseous helium plant, > 10m^3/min





Significant infrastructure installation in PIE5





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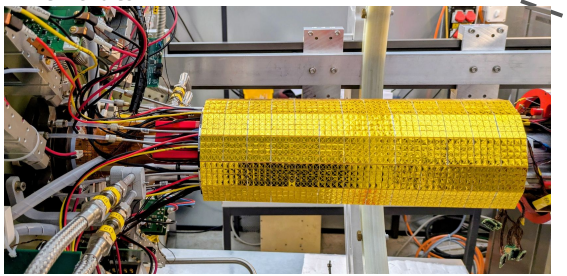
- ❑ Empty detector cage

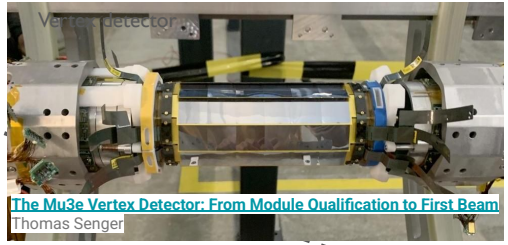
Install Detector modules

- Micro twisted-pair bundes to get data out to the periphery
- Full MuPIX11 based Vertex v1
- One SciFi and 3 Tile modules

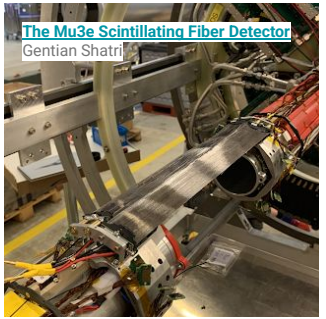
Tile modules

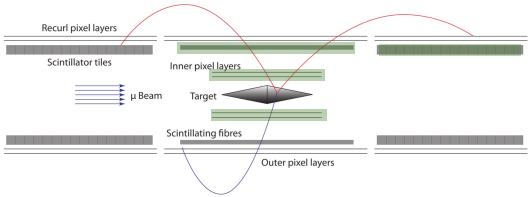


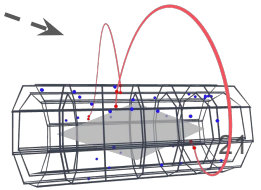
Vertex detector



SciFi Modules

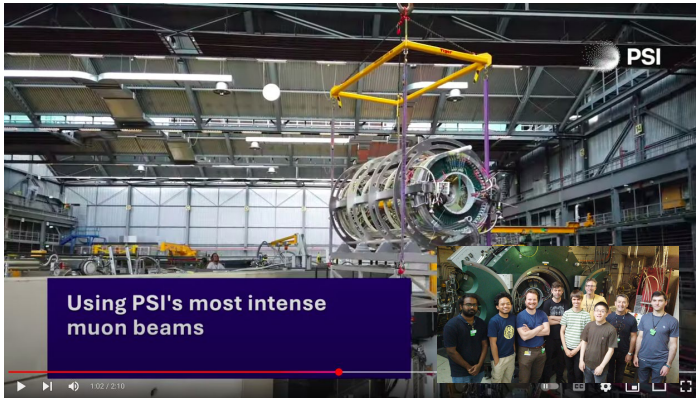


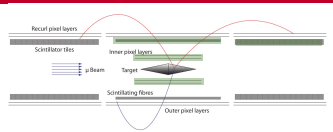




Mu3e = running experiment at PSI

The *flight* of Mu3e





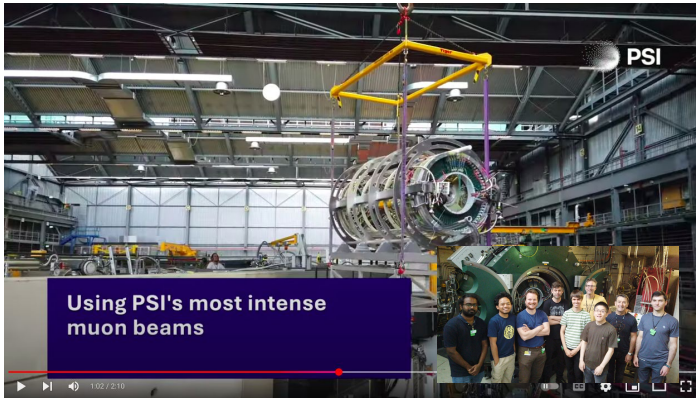
Three week long Mu3e commissioning beamtime

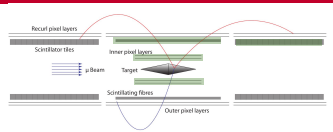
- ❑ Tune and operate pixel (vertex), scintillating fibre and tile detector with beam
- ❑ DAQ and DQM commissioning, full datapath readout system
- ❑ πE5 services commissioned
- ❑ Stress test system > 10^7 μ/s
- ❑ Running online GPU selection

The Mu3e Commissioning Run at PSI in 2025
Mikio Sakurai

Mu3e = running experiment at PSI

The *flight* of Mu3e





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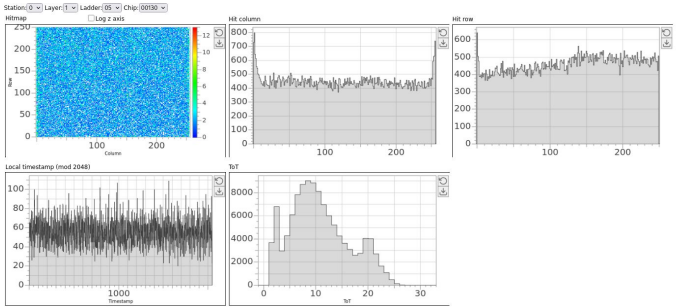
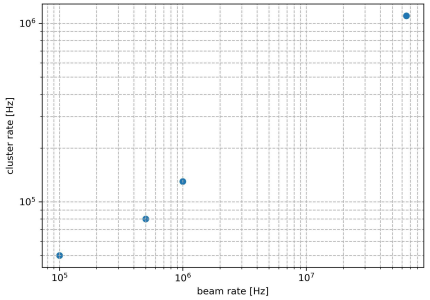
Mikio Sakurai

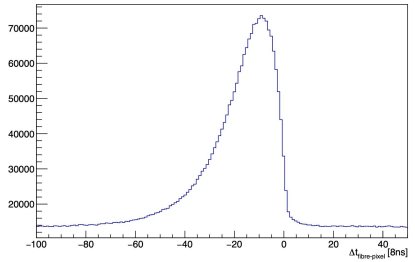
Online DQM of MuPIX sensor



Beam rate versus detector rate

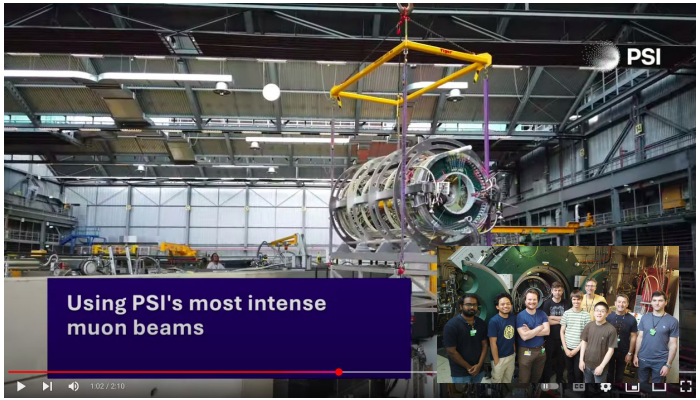


Vertex - Scintillator time coincidence

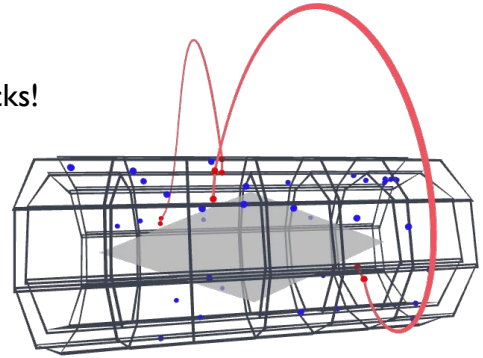


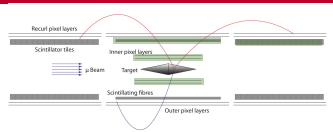
Further steps

The *flight* of Mu3e



Analysis ongoing.
But we see many tracks!





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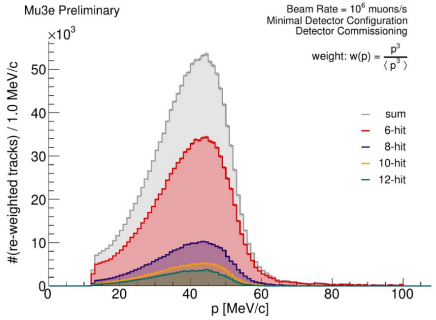
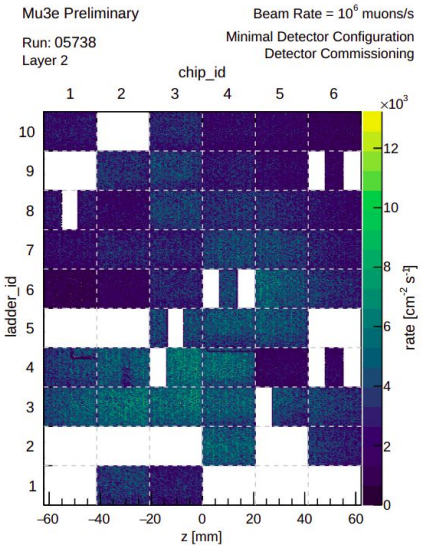
The Mu3e Commissioning Run at PSI in 2025
Mikio Sakurai

Momentum spectra



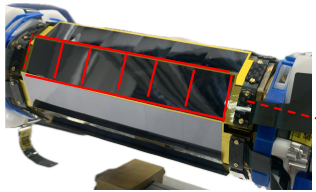
Full layer 2 hitmap

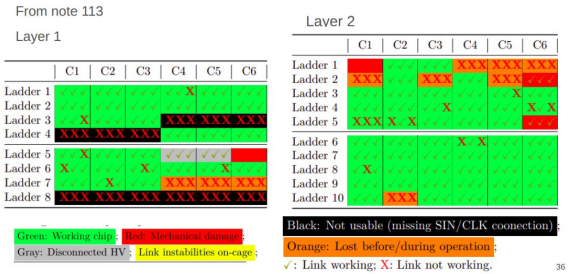


Towards physics

Mu3e Phase I aims for a $\mu^+ \rightarrow e^+e^+e^-$ S.E.S. of $2 \cdot 10^{-15}$. Next steps

- ➔ Investigate and fix all failure modes observed in 2025
- ➔ Construct Vertex v2 = 🚫
- ➔ Outer pixel production.
  - ❑ 6 → 18 chips per ladder
  - ❑ 18 → 156 ladders





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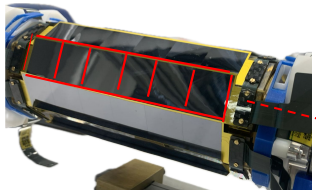
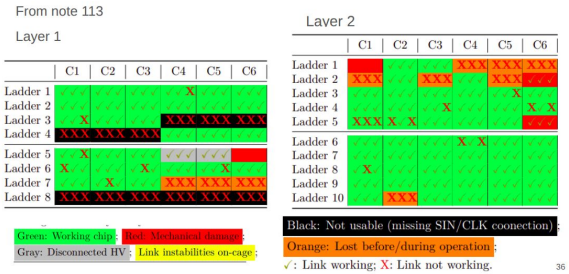
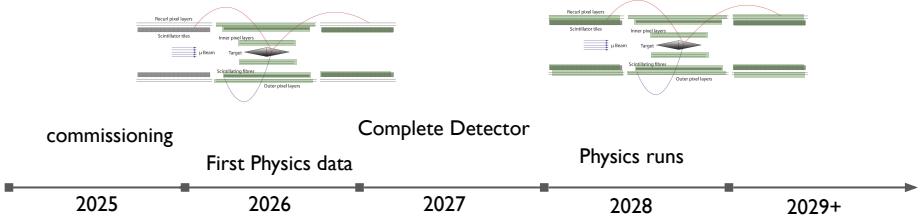




- ➔ Aim for central detector = first physics before the 2027 HIPA shutdown
- ➔ Mu3e Phase II at HIMB →
  - ❑ Need additional fast pixel layer (+ other stuff)
  - ❑ Aim for $\mu^+ \rightarrow e^+e^+e^-$ S.E.S. of $1 \cdot 10^{-16}$



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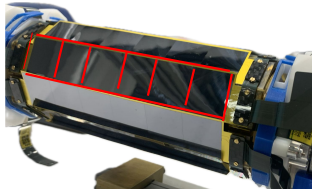

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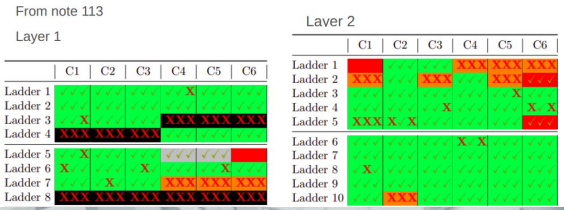
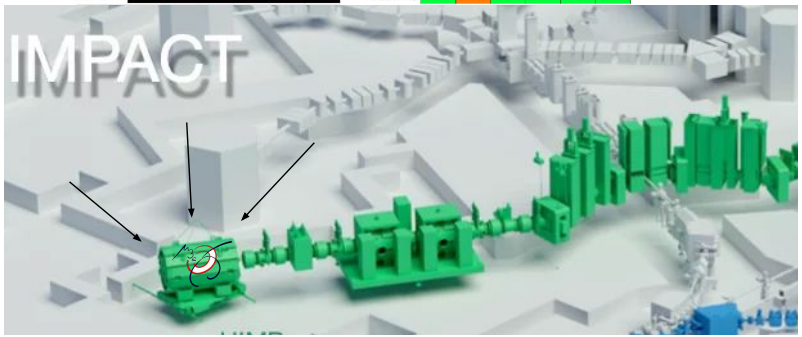
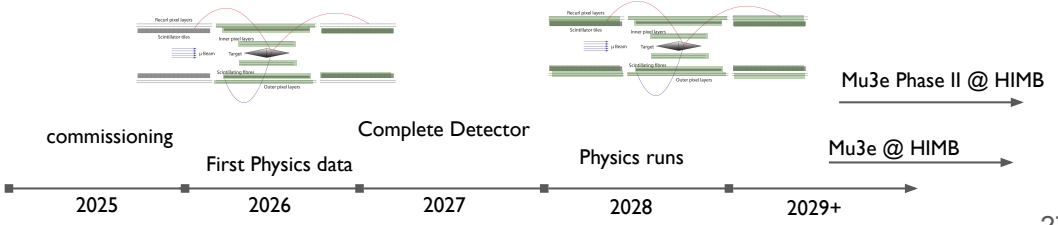
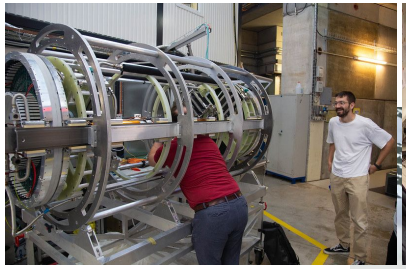
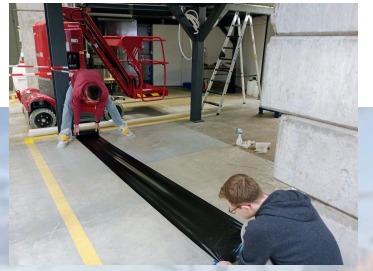
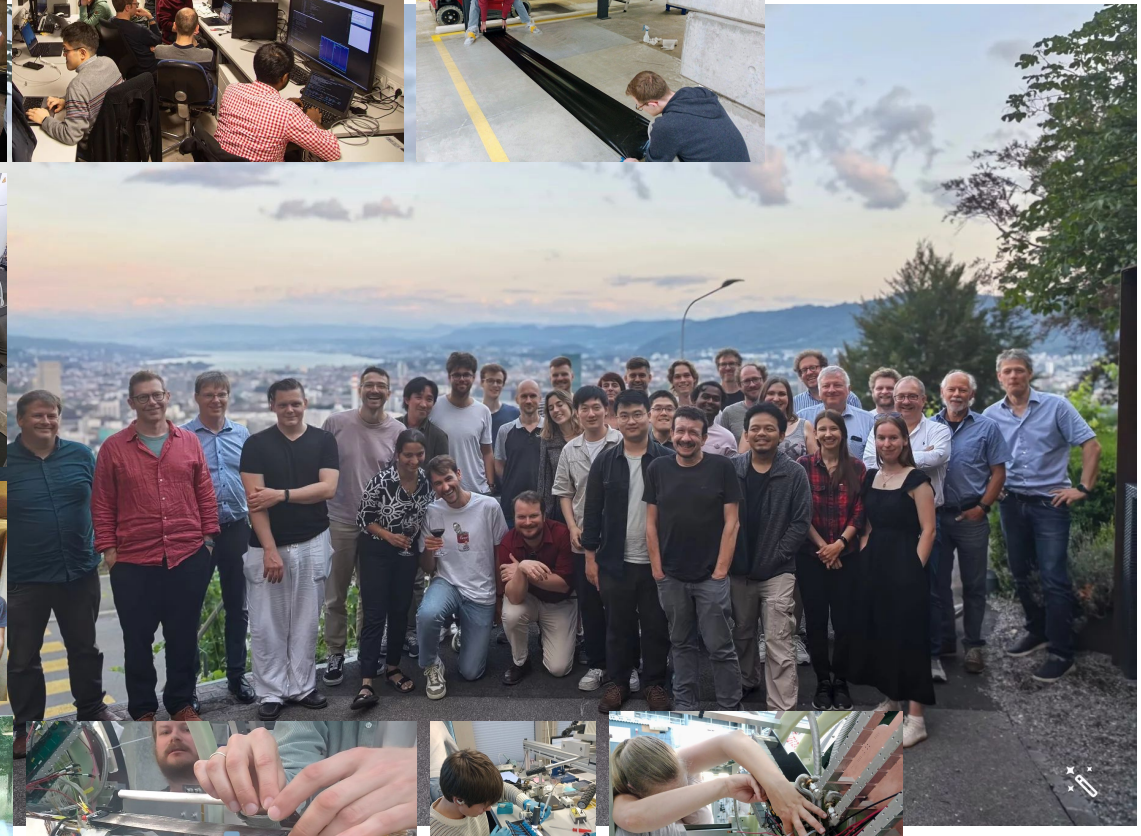


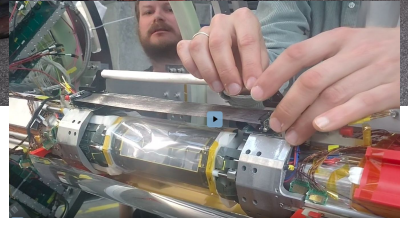


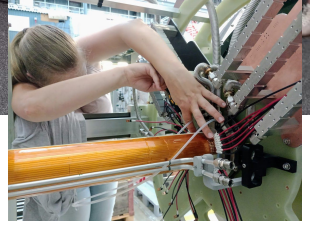












Mu3e collaboration:
www.psi.ch/en/mu3e

PSI

ETH zürich

Universität Zürich[UZH]

UNIVERSITÉ DE GENÈVE

UCL

UNIVERSITY OF OXFORD

University of BRISTOL

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

KIT Karlsruher Institut für Technologie

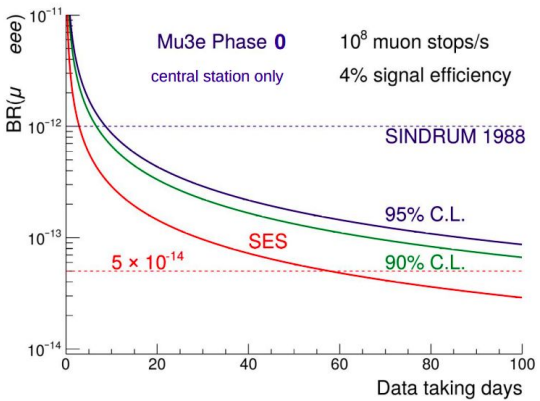
UNIVERSITY OF LIVERPOOL

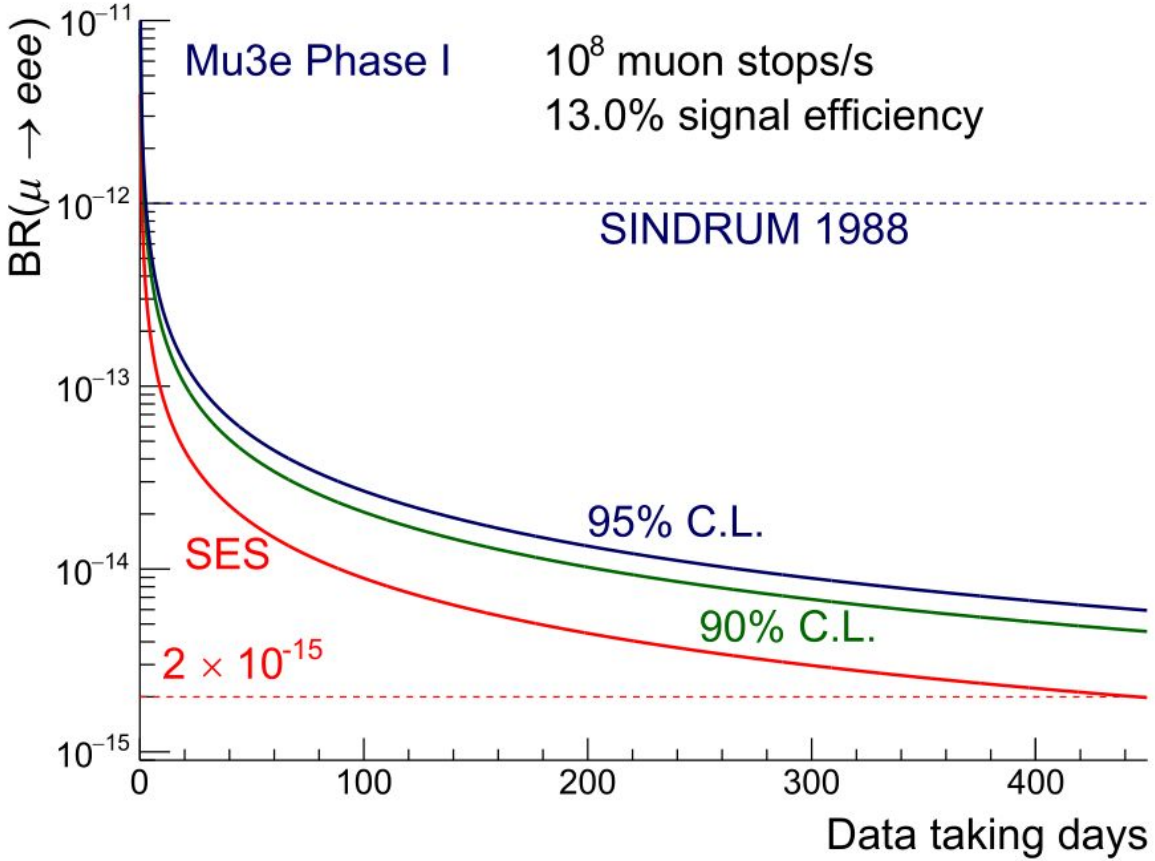
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Interested to join us as a PhD student?

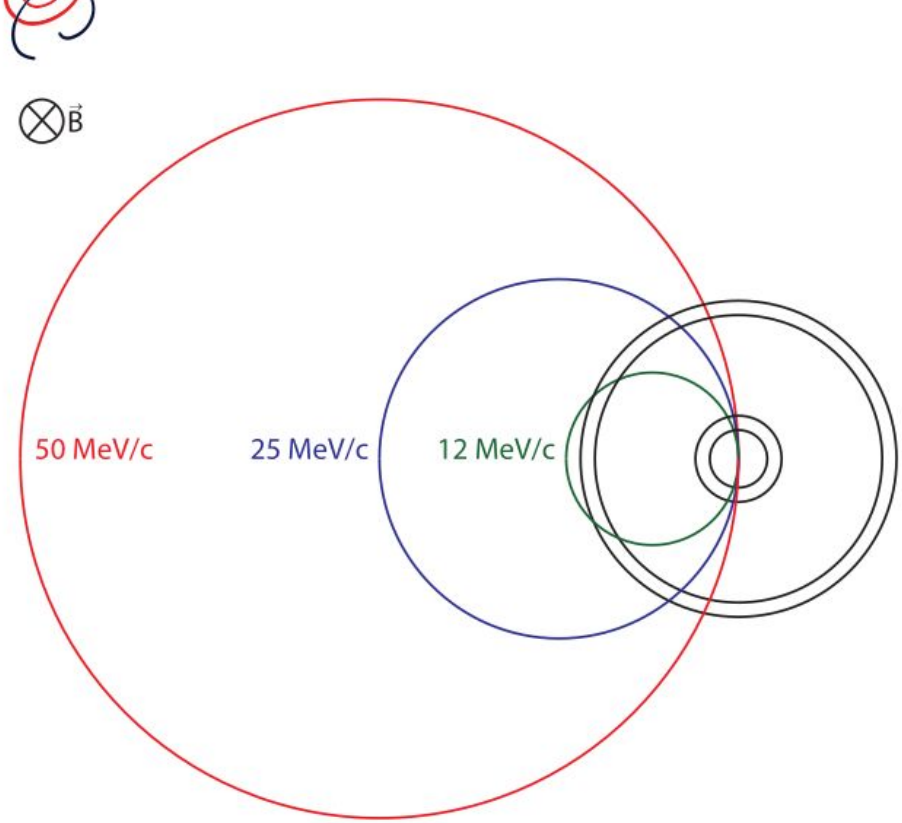
Contact us!

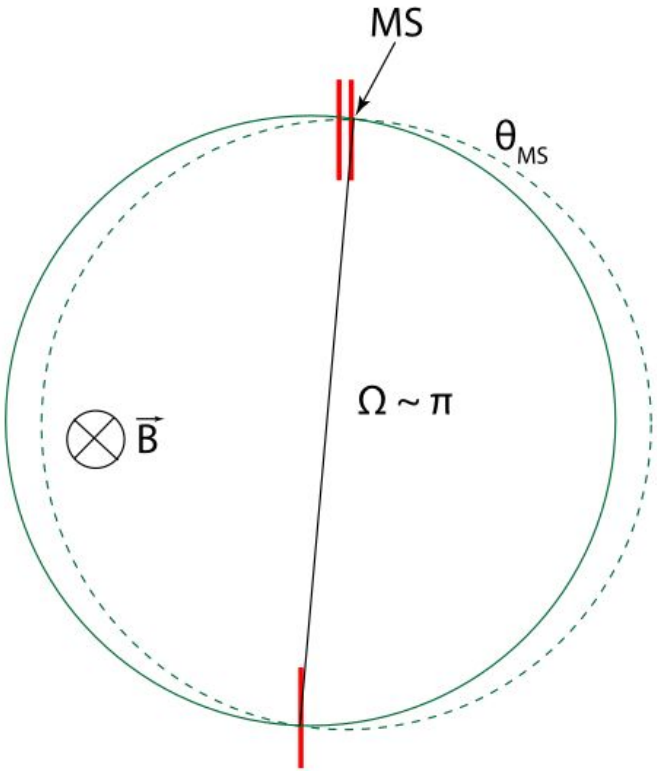
Extra

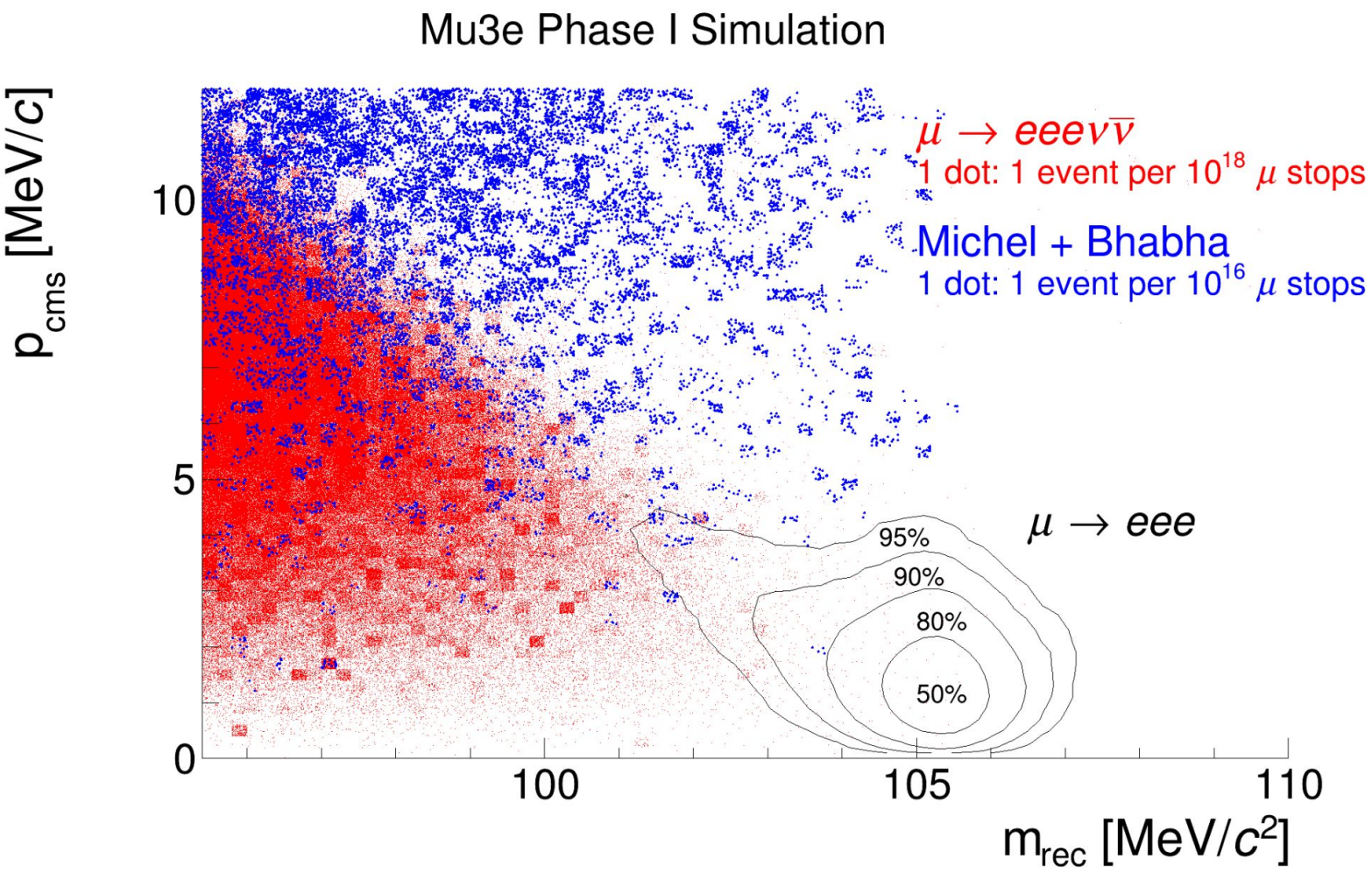

Mu3e Phase 0
central station only
10^8 muon stops/s
4% signal efficiency
SINDRUM 1988
95% C.L.
SES
90% C.L.
5×10^{-14}
BR(μ eee)
Data taking days

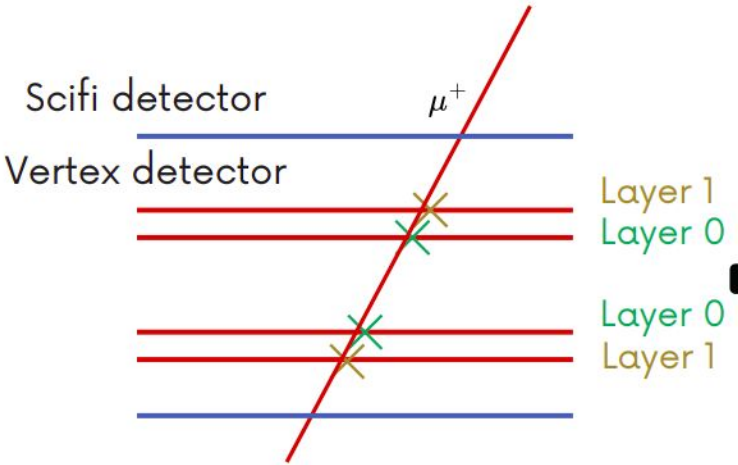

Mu3e Phase I
10^8 muon stops/s
13.0% signal efficiency
SINDRUM 1988
95% C.L.
SES
90% C.L.
2×10^{-15}
BR($\mu \rightarrow$ eee)
Data taking days

Precision vs. Acceptance





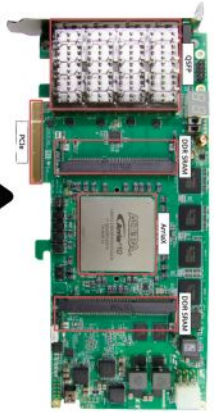

Mu3e Phase I Simulation
$\mu \rightarrow eee\nu\bar{\nu}$
1 dot: 1 event per 10^{18} μ stops
Michel + Bhabha
1 dot: 1 event per 10^{16} μ stops
$\mu \rightarrow eee$
95%
90%
80%
50%
p_{cms} [MeV/c]
m_{rec} [MeV/c^2]
0
5
10
100
105
110



Sort in Time

Time synchronization

Group detectors



Mupix11 Quad Module

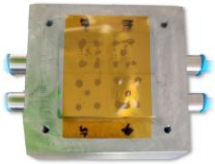
- Module with large active sensor area for beam monitoring and µSR detector prototype

Specifications:

- 2×2 grid of 50 µm **Mupix11** sensors
- 25 µm Kapton foil for structural support
- Active area: $40 \times 40\ \mathrm{mm}^2$
- Sensor spacing: 200 µm

Production:

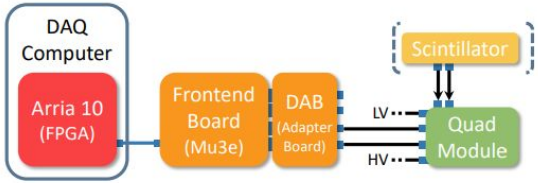
Sensor alignment

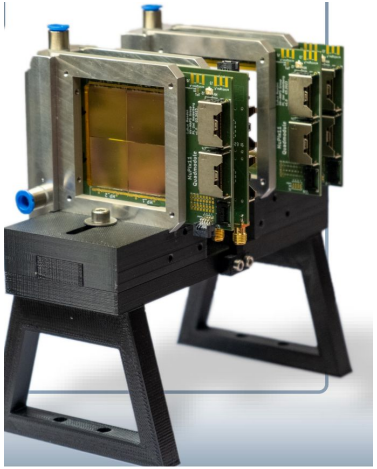


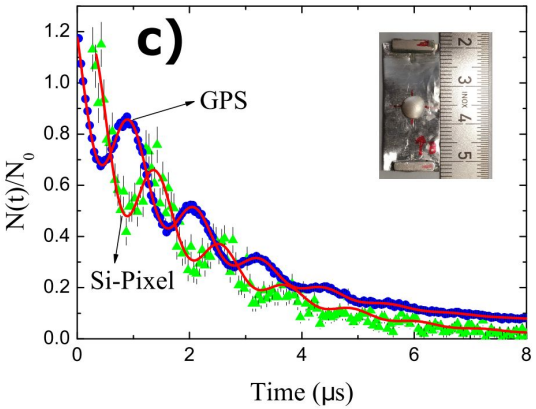
Sensor gluing

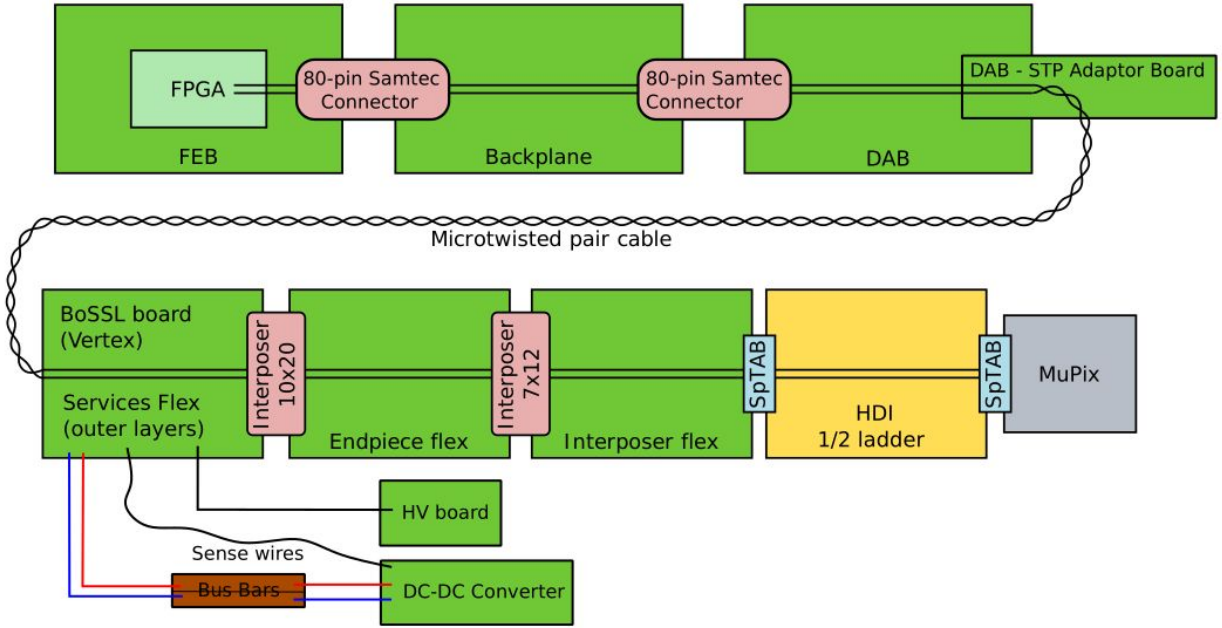
DAQ:

- Minimal, Mu3e compatible DAQ setup
- Optional scintillator input for improved timing

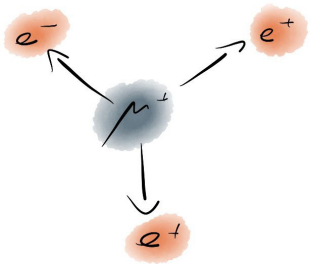







FPGA
80-pin Samtec Connector
80-pin Samtec Connector
DAB - STP Adaptor Board
FEB
Backplane
DAB
Microtwisted pair cable
BoSSL board (Vertex)
Services Flex (outer layers)
Interposer 10x20
Endpiece flex
Interposer 7x12
Interposer flex
SpTAB
HDI 1/2 ladder
SpTAB
MuPix
HV board
Sense wires
Bus Bars
DC-DC Converter

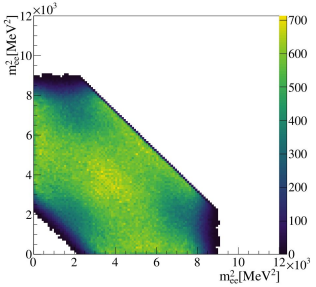
3 particle decay at rest



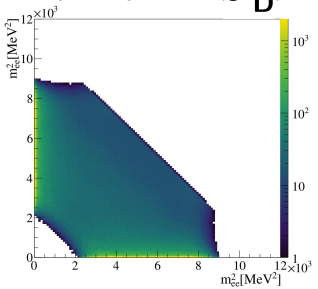
If we see a few events, we are sensitive to the type of NP interaction

- ➔ Common vertex
- ➔ Time coincident
- ➔ $\sum E = m_\mu$
- ➔ $\sum \mathbf{p} = 0$

Phase space ⊗ Acceptance



Dipole operator ($\mathcal{O}_D^{L*}$)



Figures from PhD Thesis A.-K. Perrevoort, operators from Rev.Mod.Phys.73:151-202,2001