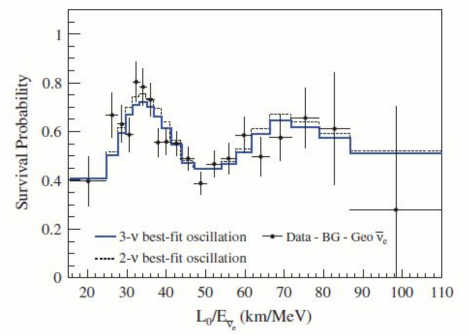
The Search for Charged Lepton-Flavour Violation with the Mu3e Experiment

Frederik Wauters on behalf of the Mu3e collaboration
Johannes Gutenberg University Mainz

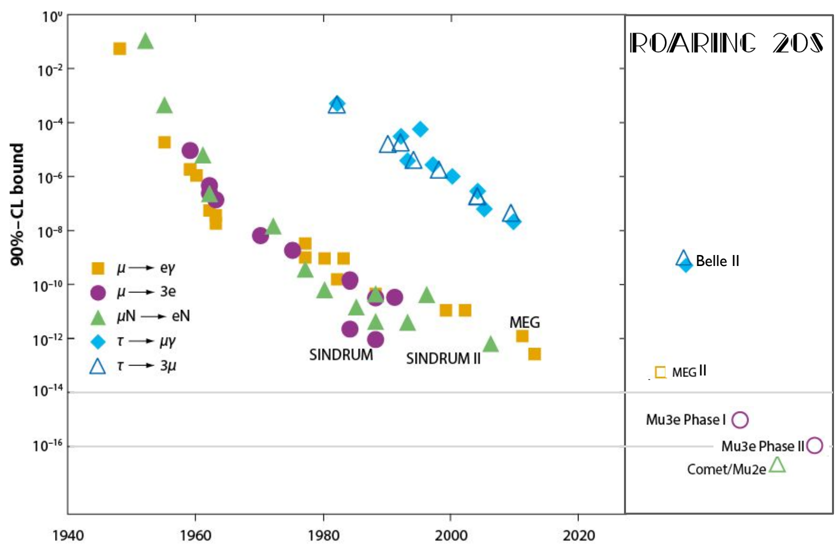
CLFV & $\mu^+ \to e^+e^+e^-$



<u>Charged Lepton Flavour Violation and the Standard Model</u>

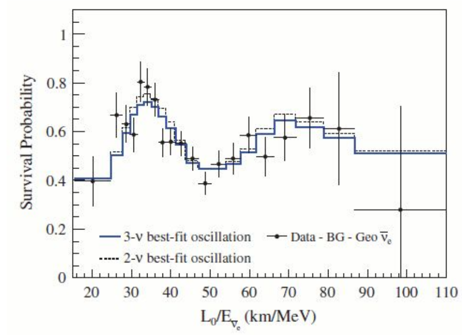
- ❑ Neutrino masses/oscillations have established LFV in the SM+
- ❑ **Charged** LFV has not yet been observed → search for beyond SM physics
- ❑ Lepton decays are a clean probe, i.e. free of SM background.
- ❑ Muons hit the sweet spot between sensitivity and availability.

  Note there are also $\tau \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to \mu\mu\mu$ searches at e.g. Belle II arXiv:2203.14919
- ❑ Three golden muon 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)



4 orders-of-magnitude for new physics searches!

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



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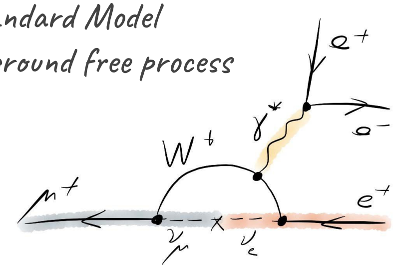
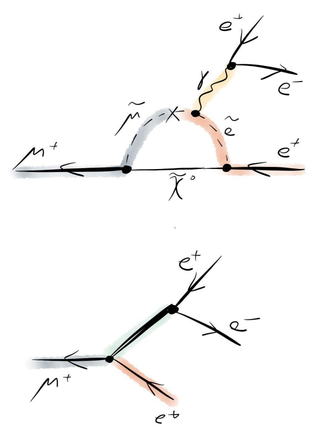
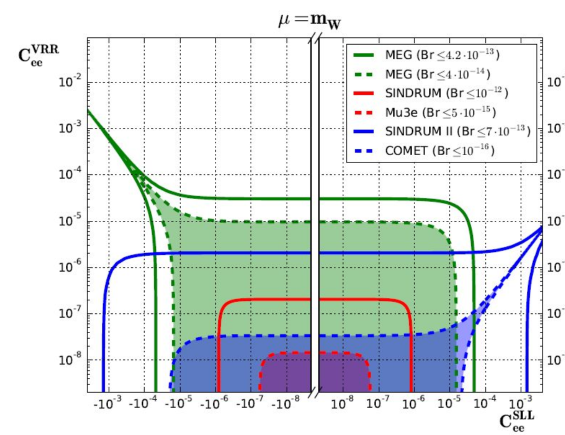
A Standard Model
Background free process



BR(SM) < 10^{-54}

Sensitive to loop and tree/contact level *new* interactions

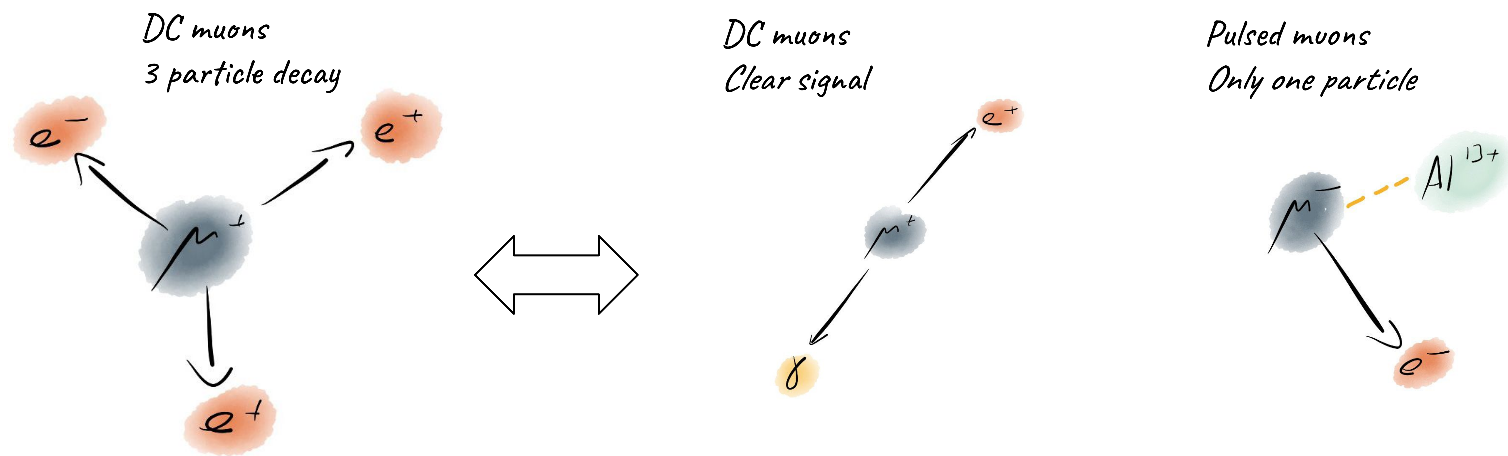




Renormalisation-group improved analysis of $\mu\rightarrow e$ processes in a systematic effective-field-theory approach. arXiv:1702.03020v3

$\mu^+ \rightarrow e^+e^+e^-$ & the Mu3e experiment

Detecting $\mu^+ \rightarrow e^+e^+e^-$ for muon decay at rest:



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

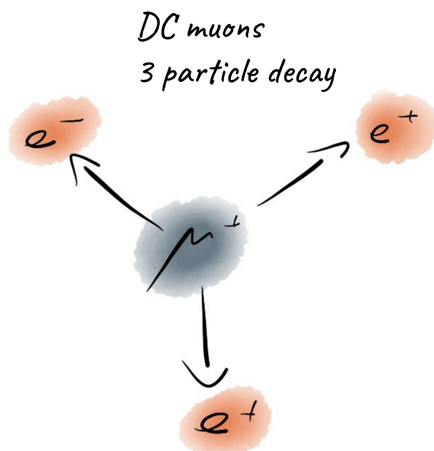
- ➔ Mono-energetic e^+ and γ
- ➔ back-back coincidence

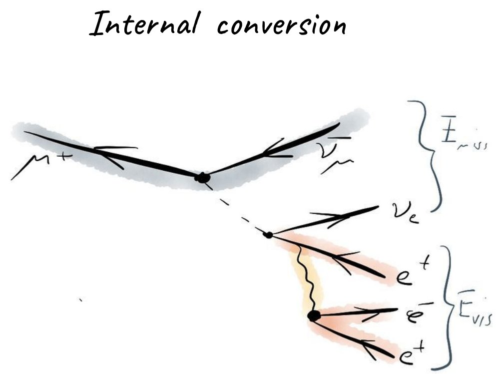
- ➔ Mono-energetic e^-
- ➔ No coincidence

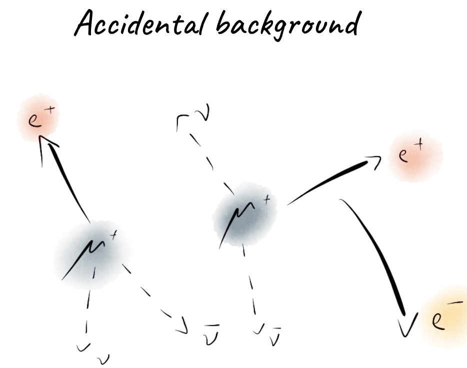
$\mu^+ \rightarrow e^+e^+e^-$ & the Mu3e experiment

~~Pulsed muons~~

Detecting $\mu^+ \rightarrow e^+e^+e^-$ for muon decay at rest → **Backgrounds**







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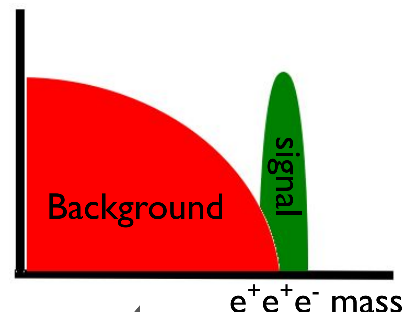


Michel decay positrons + electron from:

- ❏ Bhabha scattering
- ❏ Photon conversion
- ❏ Misreconstruction

Our detector needs:

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

Mu3e conceptual design

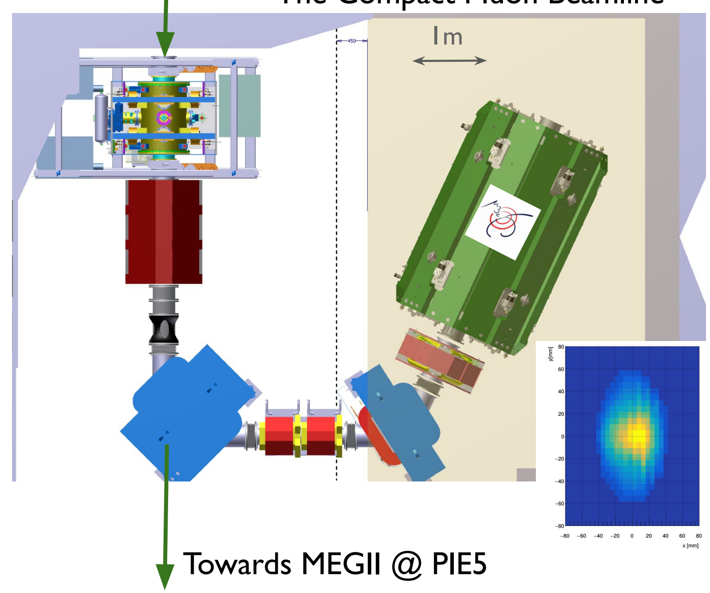
Target E

Beam Commissioning Comparison			
Rates	Collimator	QSM41	Mu3e
2021	2.11 10^8 μ^+/s	1.2 10^8 μ^+/s	4.76 10^7 μ^+/s
2022	2.47 10^8 μ^+/s	1.8 10^8 μ^+/s	7.46 10^7 μ^+/s

Table: All rates are normalised to 2.4 mA.

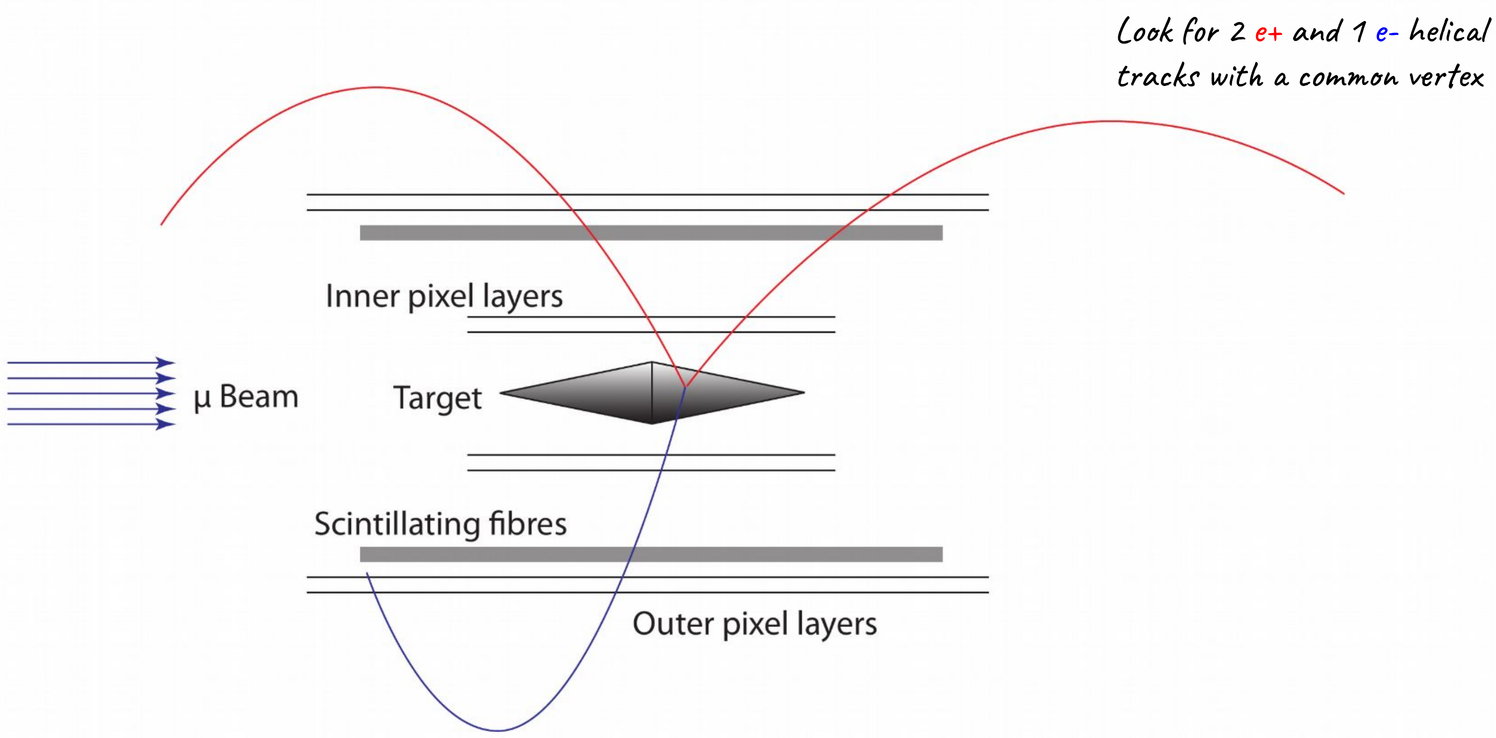
- ❑ 2.3 mA 600 MeV proton beam from HIPA at PSI
- ❑ 10^8 μ^+/s (DC) at the πE5 area
- ❑ Stopped on a thin Mylar target

The Compact Muon Beamline



Towards MEGII @ PIE5

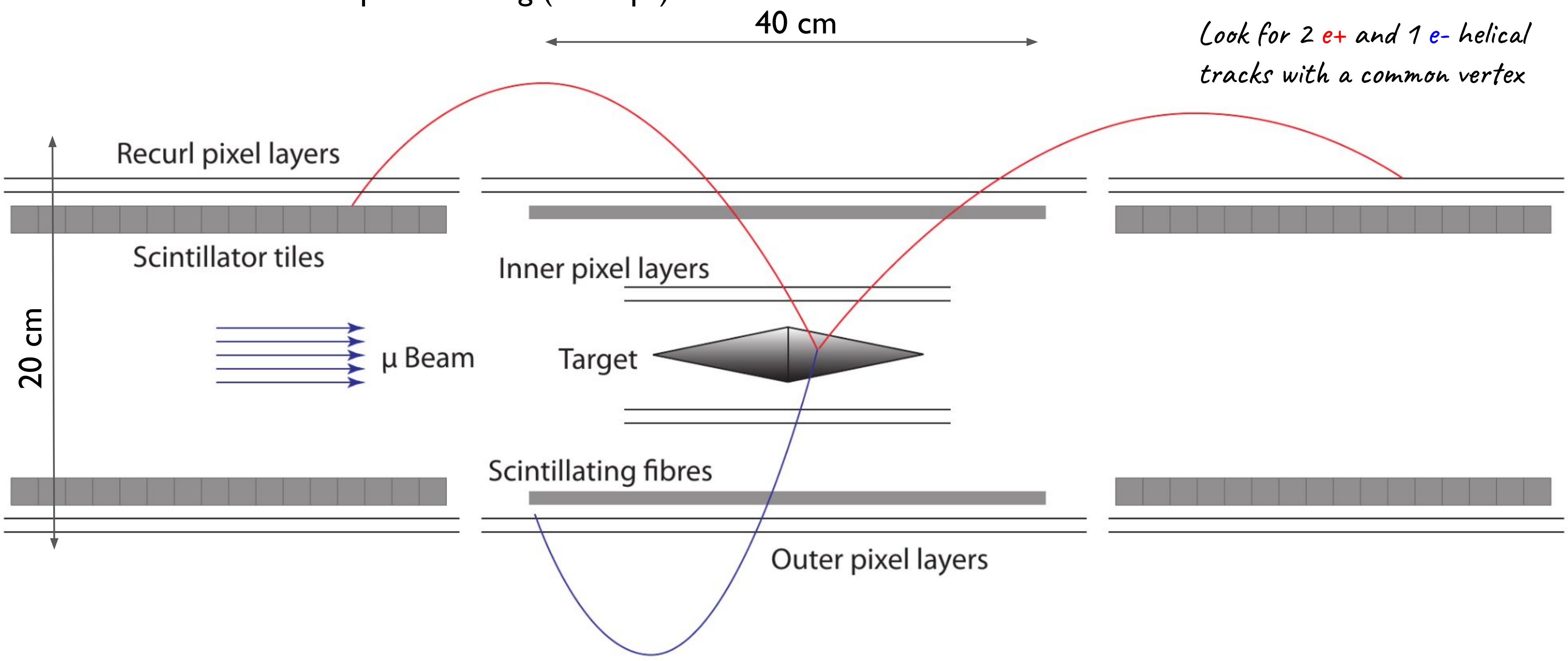
Mu3e conceptual design



- 1T uniform magnetic field
- 2 layer vertex detector
- 2 outer pixel layers → 3 hits to *start* a track   see our dedicated fast track fitter: https://arxiv.org/abs/1606.04990
- Fibre detector for the track direction, i.e. differentiate e+ from e-

Mu3e conceptual design

- ❑ Recurl trackingstation to accept more half turn tracks for optimal momentum resolution
- ❑ Tile detector for optimal timing (<100 ps)



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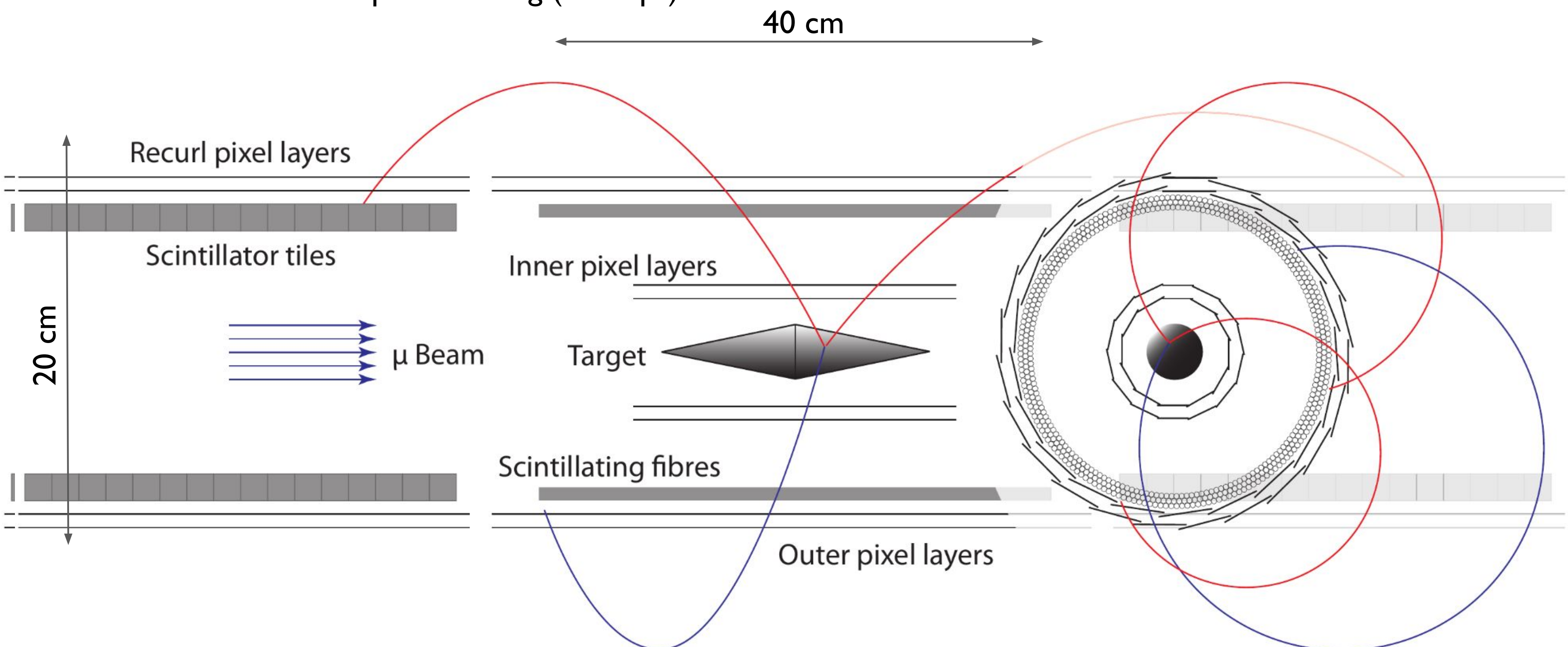
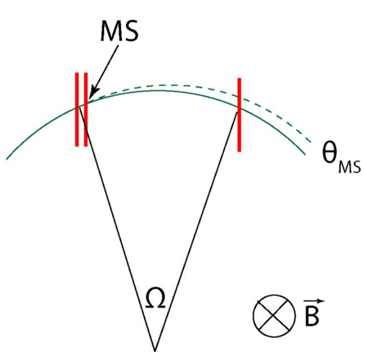
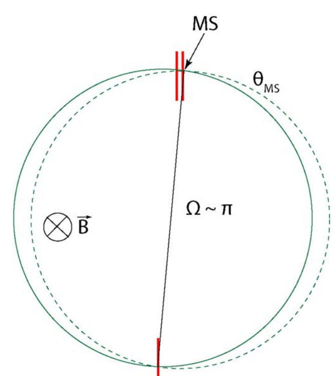
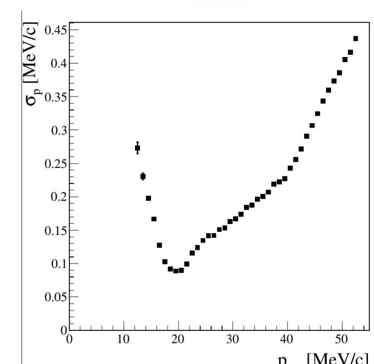




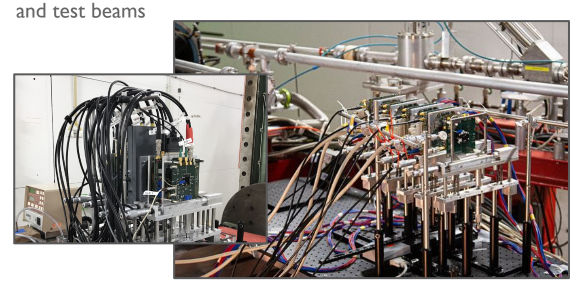
In the **MS dominated regime**, a half-turn spectrometer provides optimal momentum resolution





Mu3e Detectors

A decade of detector development
and test beams

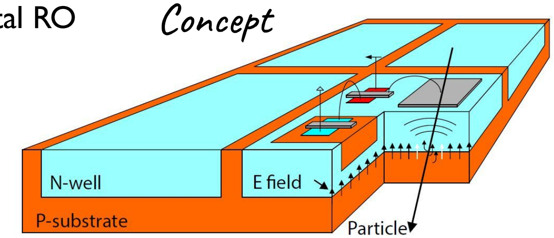


Lightweight pixel tracker build from
High-Voltage Monolithic Active Pixel Sensors (HV-MAPS) called MuPix

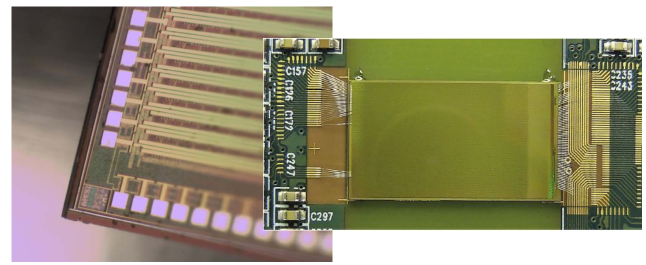
- Commercial HV-CMOS process
- Fast Charge collection
- Integrated analogue and digital RO
- Can be thinned to 50 µm
- 256x250 pixels

https://arxiv.org/abs/1603.08751
https://arxiv.org/abs/2002.07253

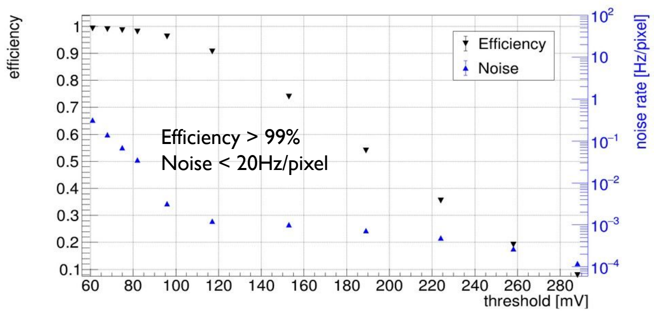
Concept

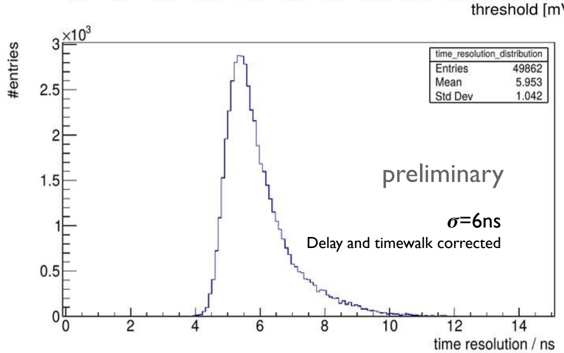


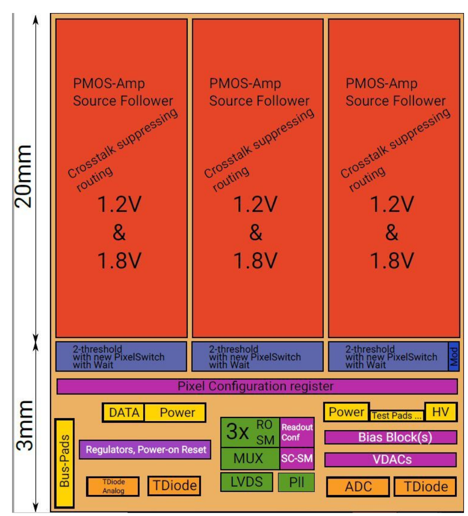
Prototyping MuPiX ... → 9



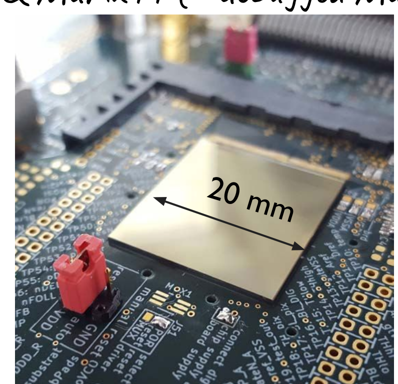
50 µm MuPiX10







Full Chip: MupiX10
& MuPix11 (= debugged MuPix10)

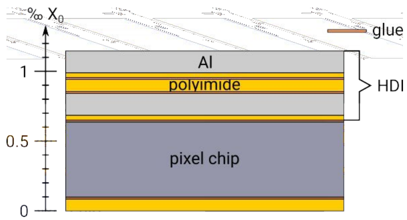


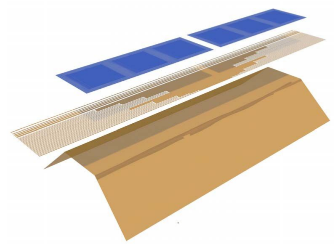
Mu3e Detectors

Thesis + Poster Thomas Rudzki

Lightweight pixel tracker build from
High Voltage Monolithic Active Pixel Sensors (HV-MAPS) called **MuPix**

Ladders from 50 μm of Si,
25 μm of Alu/Kapton flex, and
25 μm of kapton support.
→ ca. 0.1% of a radiation length!

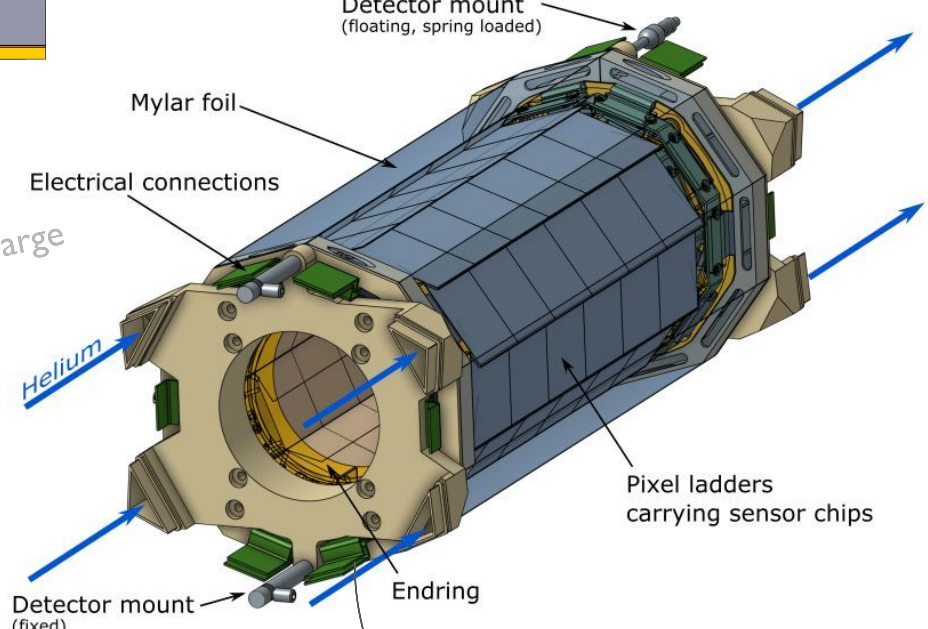




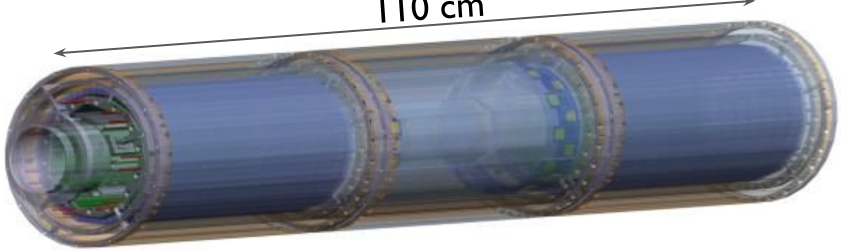
- ❏ 2 vertex layers
- ❏ 3 * 2 outer layers
- ❏ 174 ladders
- ❏ 2844 2x2 cm^2 MuPiX chips
- ❏ 3060 1.25 Gb/s data links
- ❏ 50 g/s, 10m/s 5kW gaseous helium cooling

The is a compact but large pixel tracker!

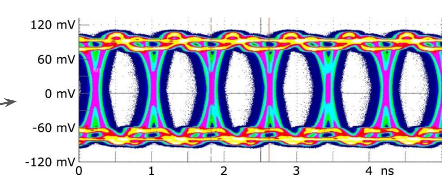
Vertex tracker



110 cm



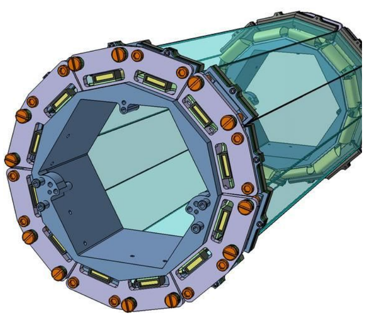
+ HV & power

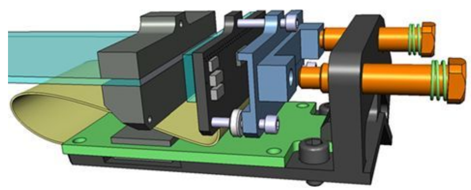


Mu3e Detectors

Timing detectors

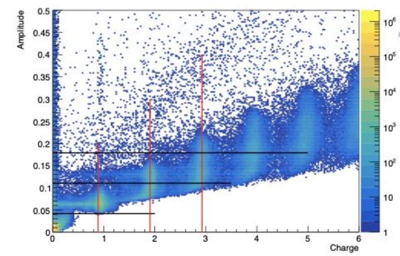
- ❏ 12 ribbon - 3 layer scintillating fibre detector surrounding the vertex detector
- ❏ Highly granular tile detector under the recurl stations



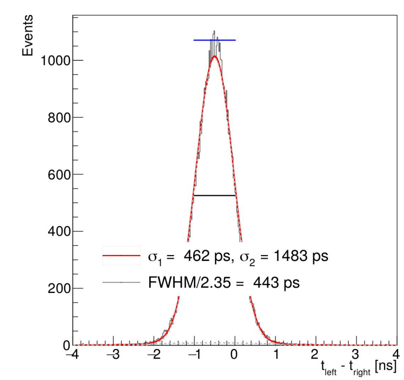


All fibre and pixel modules are spring loaded to compensate for thermal expansions.

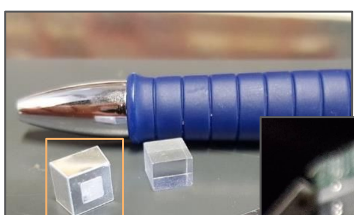
Operate fibre detector < p.e.

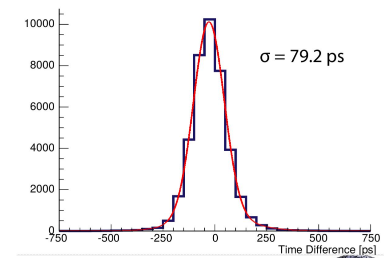


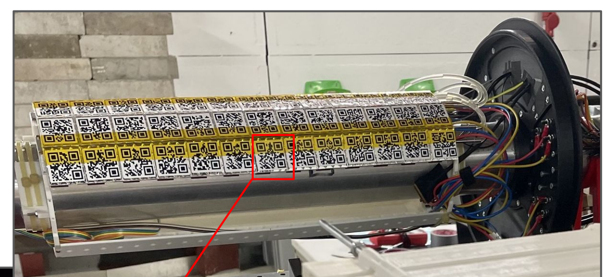
Ribbon MJ-3-Black

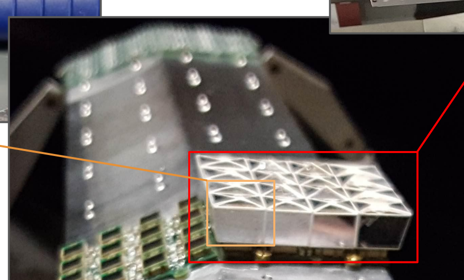


Both detectors use a custom readout chip called MuTrig

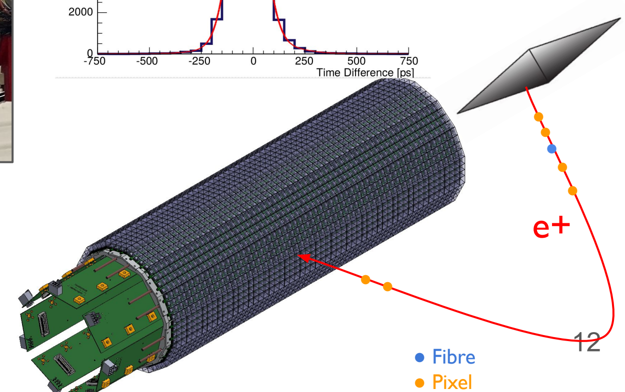




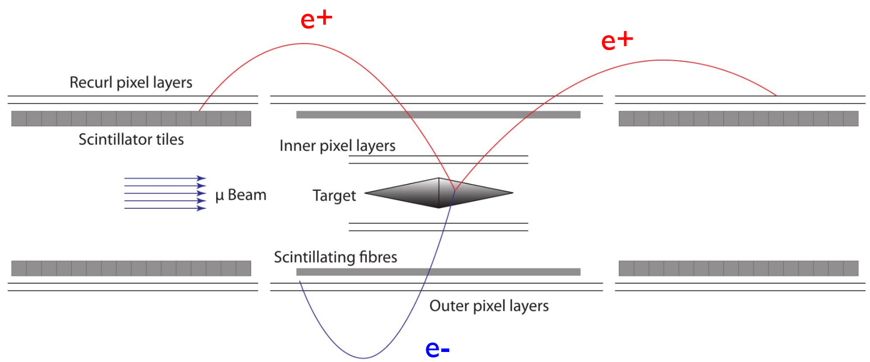




6272 tiles with plenty of light give us ca. 70 ps time resolution

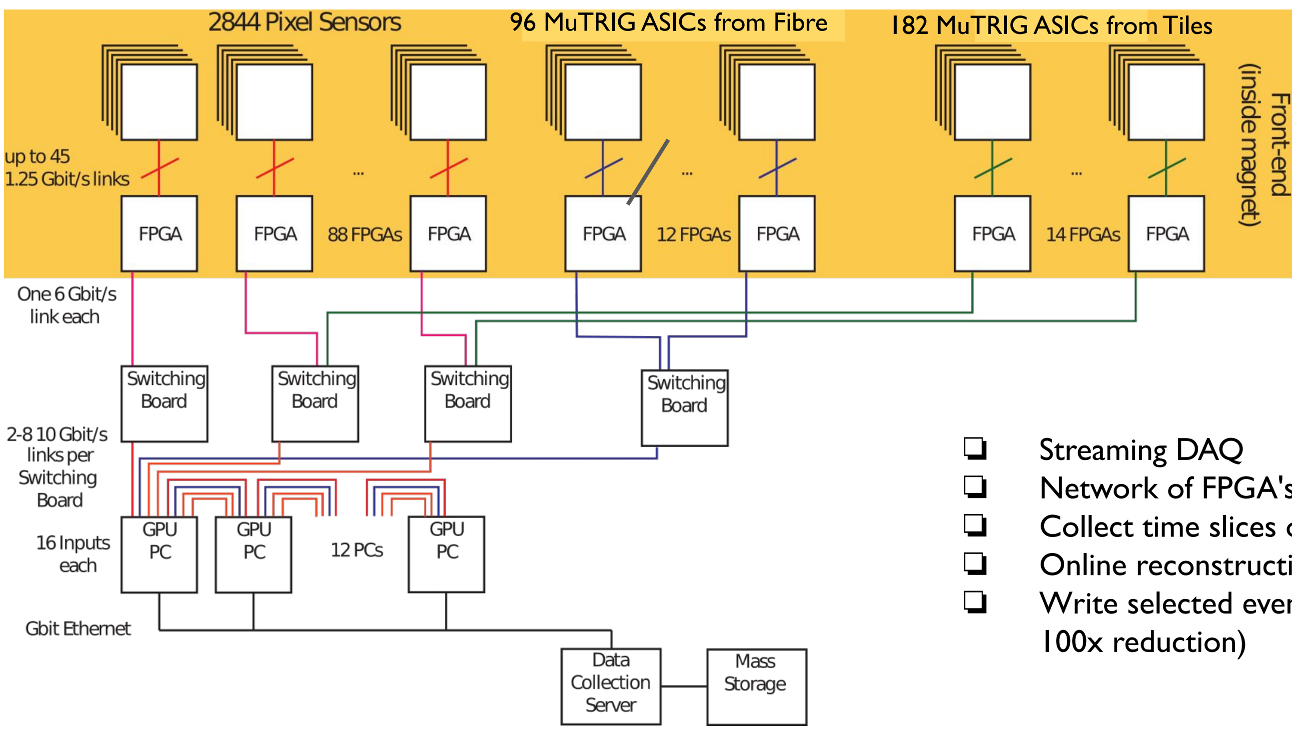


Mu3e DAQ



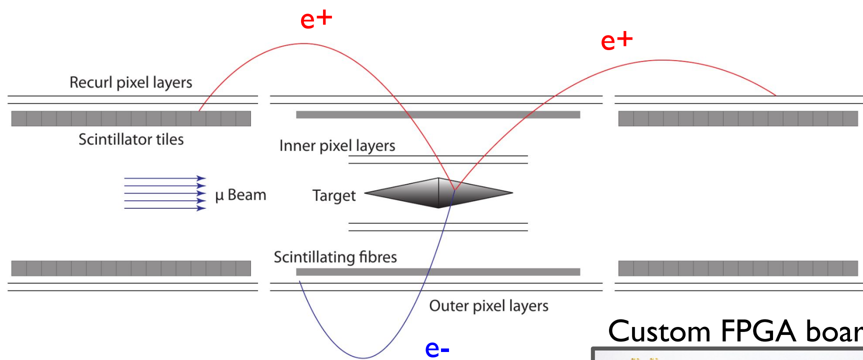
Reminder: the Mu3e event topology does not allow for a RO trigger, every $e^{+/-}$ track could potentially be part of a $\mu^+ \to e^+e^+e^-$ event. Only the kinematics of the combined final state positrons/electron gives us an event selection criteria.

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)

Mu3e DAQ



Reminder: the Mu3e event topology does not allow for a RO trigger, every Michel electron could also 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.

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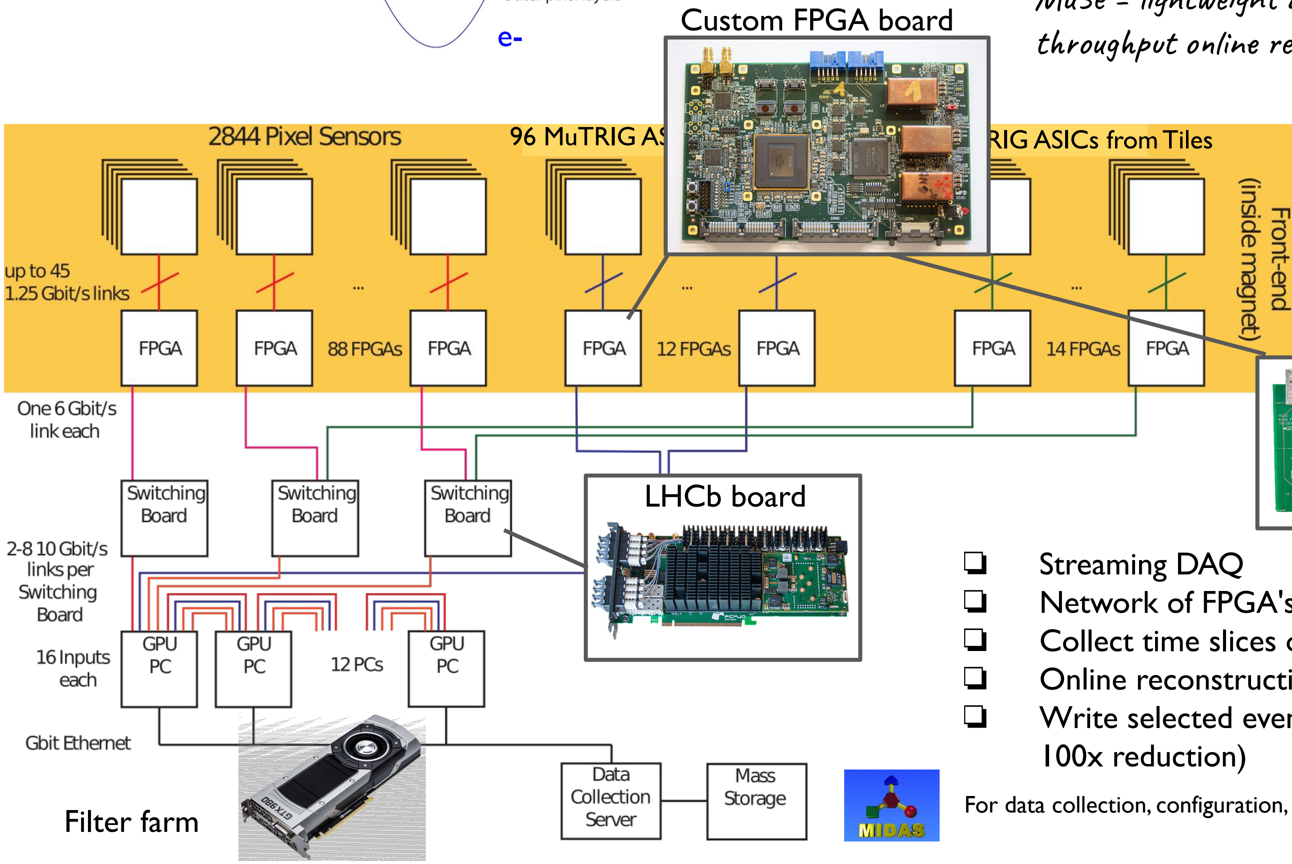
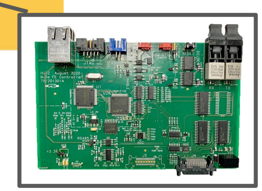


The Mu3e Data Acquisition:

arXiv:2010.15648v2

Mu3e DAQ integration:

Poster Marius Köppel



Crate controllers integrated in the MIDAS (Slow Control) System

- Streaming DAQ
- Network of FPGA's and optical connections
- Collect time slices of the full detector on a single PC
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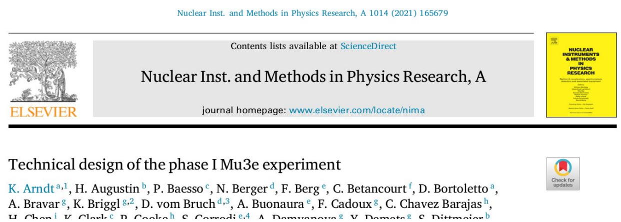
For data collection, configuration, monitoring, slow control, …

Mu3e sensitivity

Based on full Monte Carlo simulation of the experiment, an analytical track fitter, and a lot of detector R&D, we claim that:

The Mu3e Phase I detector can achieve a $2\cdot10^{-15}$ SES on $\mu^+\rightarrow e^+e^+e^-$


Nuclear Inst. and Methods in Physics Research, A 1014 (2021) 165679

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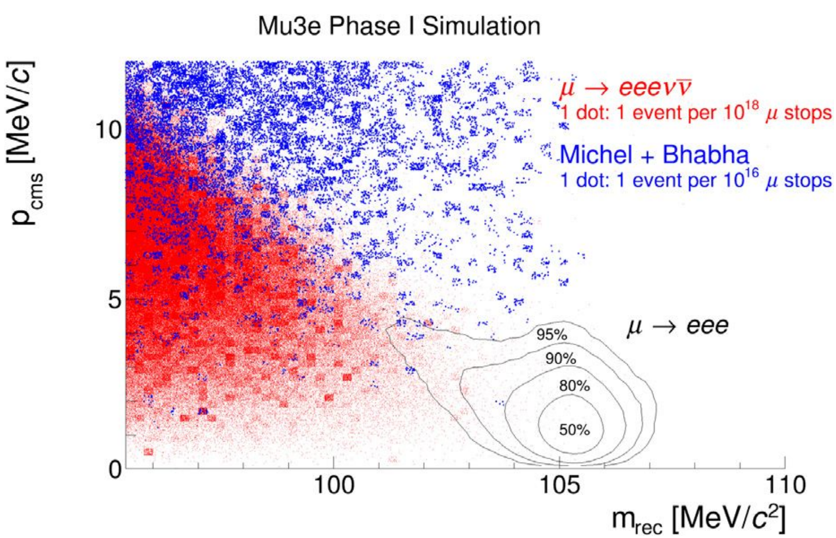
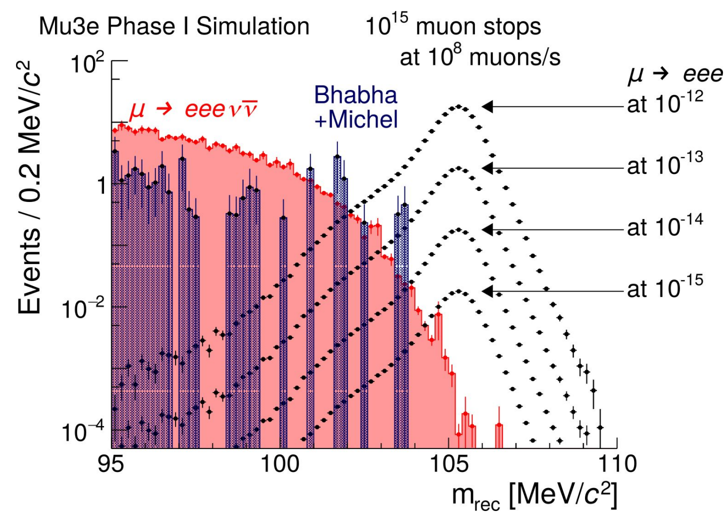
journal homepage: www.elsevier.com/locate/nima

ELSEVIER

Technical design of the phase I Mu3e experiment

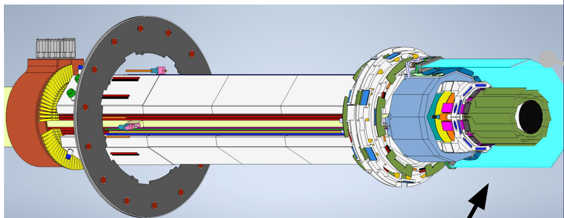
K. Arndt [a,1], H. Augustin [b], P. Baesso [c], N. Berger [d], F. Berg [e], C. Betancourt [f], D. Bortoletto [a], A. Bravar [g], K. Briggl [g,2], D. vom Bruch [d,3], A. Buonaura [e], F. Cadoux [g], C. Chavez Barajas [h],

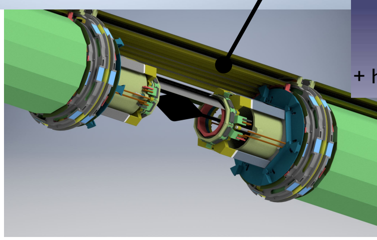


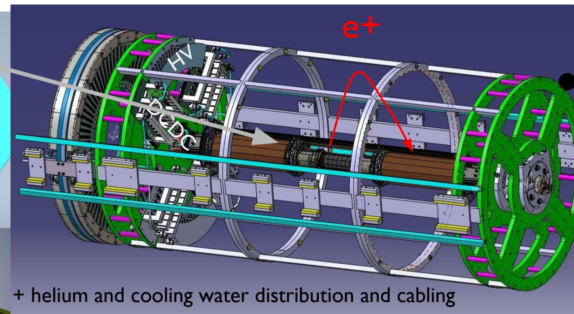


Mu3e detector construction & commissioning

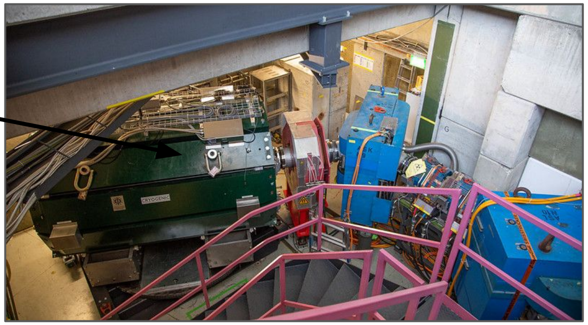
All sensors/components work to specs
→ We have to build a very compact/complex detector (+ services + DAQ)

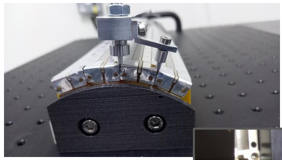


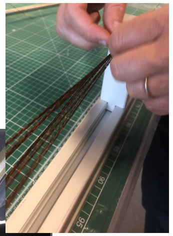


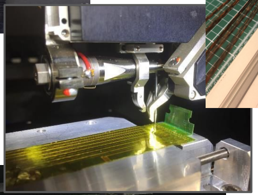


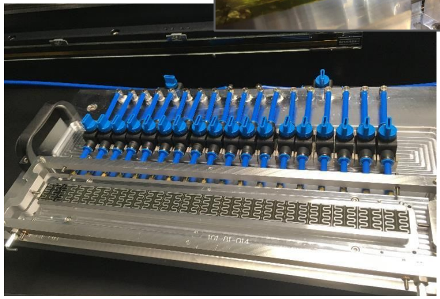
Detailed CAD



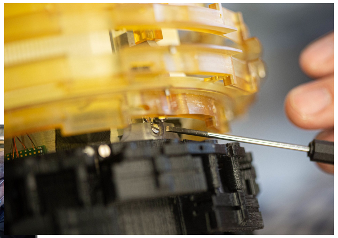




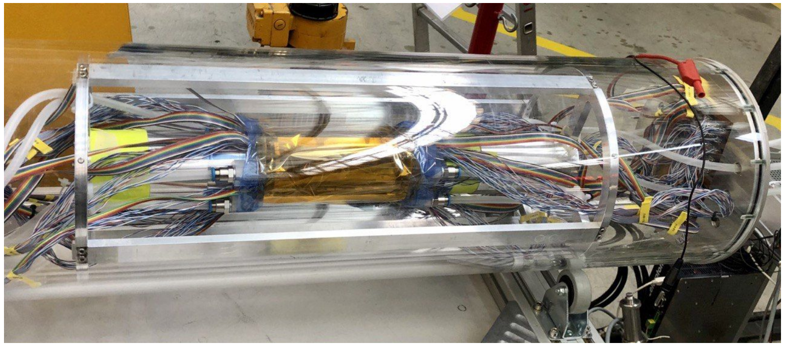




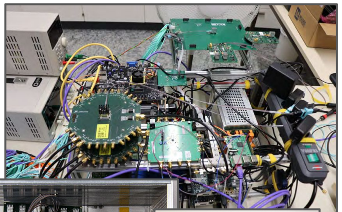
Tooling design

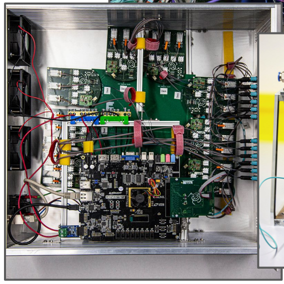


Mockup and assembly exercises



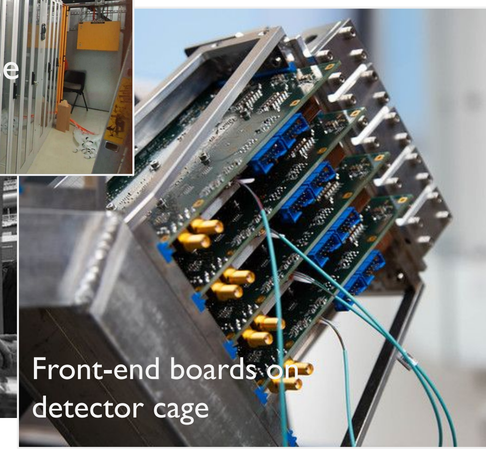
PCB design, firmware development, GPU programming, ...

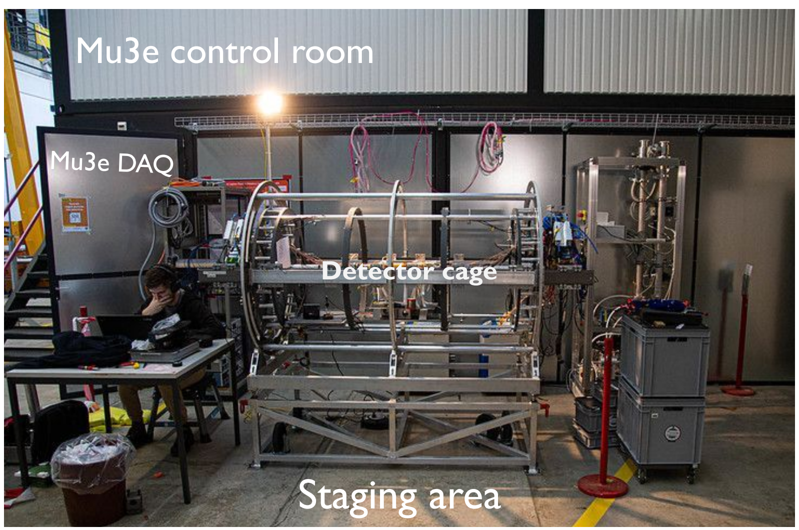


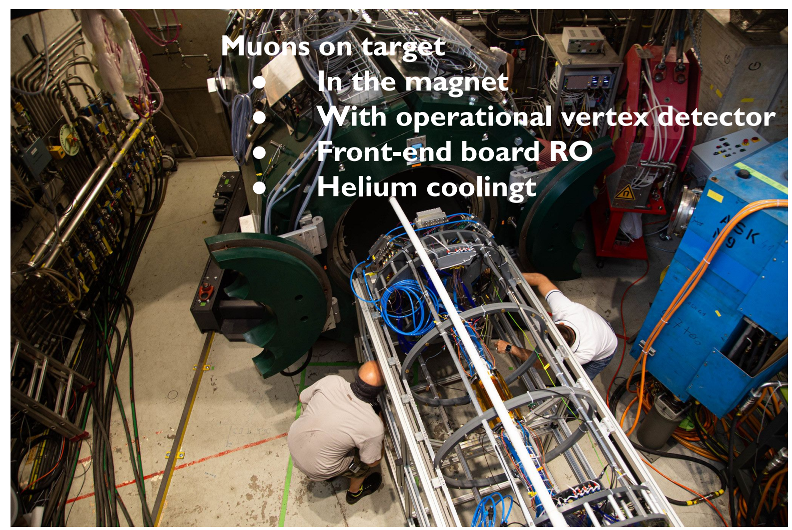


Mu3e detector construction & commissioning

Demonstrator vertex & SciFi detector: 2022 and 2021 commissioning runs @ PSI

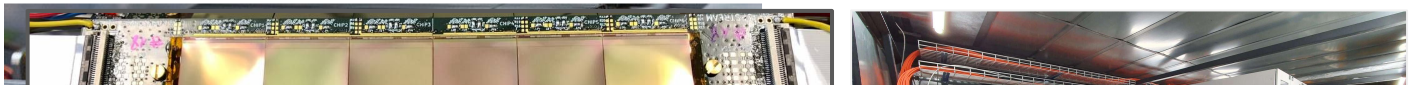


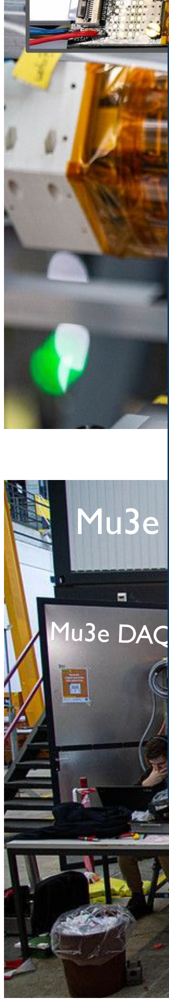




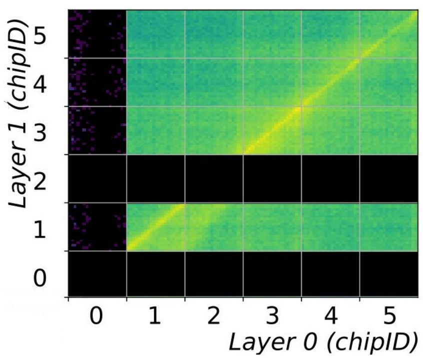
Mu3e detector construction & commissioning

Demonstrator vertex & SciFi detector: 2022 and 2021 commissioning runs @PSI

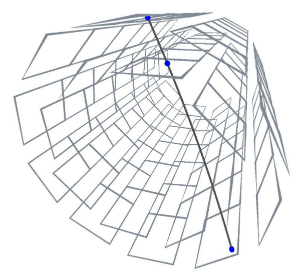




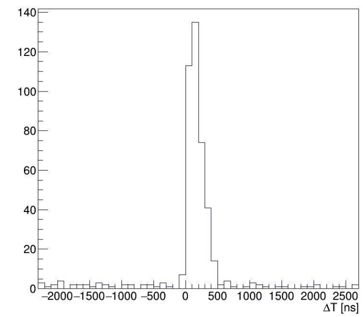
Spatial correlations of recurling e+

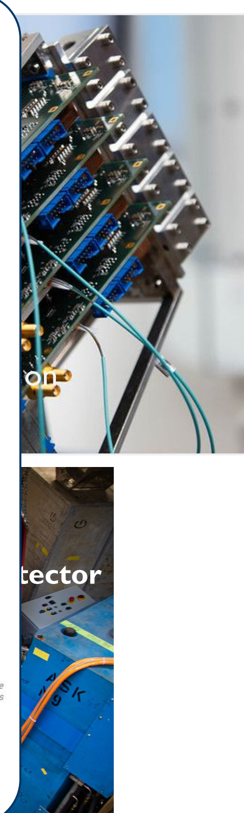


Cosmic tracks



Synchronize SciFi & Pixel detector





The DAQ of the Mu3e Integration Runs

The Mu3e experiment at the Paul Scherrer Institute (PSI) searches for the charged lepton flavour violating decay $\mu^+ \rightarrow e^+ e^+ e^-$. The experiment aims for an ultimate sensitivity of one in 10^{16} μ decays. The first ph

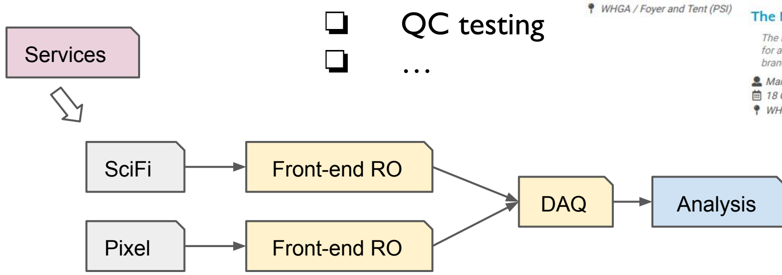
Marius Koeppel (JGU Mainz)
18 October 2022 16:26
WHGA / Foyer and Tent (PSI)

- UI for Mu3e
- QC testing
- …

The Mu3e Cosmic Run 2022

The Mu3e experiment will search for the lepton flavour violating decay $\mu^+ \rightarrow e^+ e^- e^+$ and is aiming for a sensitivity of one in 10^{16} muon decays. Since this decay is highly suppressed in the Standard Model to a branchi

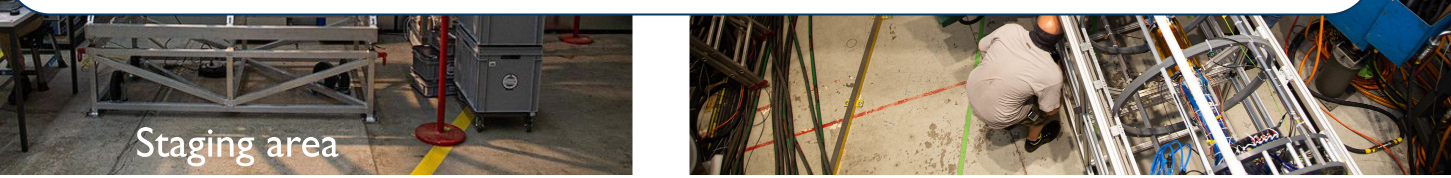
Martin Müller (JGU Mainz, Insititute for Nuclear Physics)
18 October 2022 16:41
WHGA / Foyer and Tent (PSI)



The Mu3e vertex detector - prototyping, cooling, and upcoming production

The Mu3e experiment searches for the lepton flavor violating decay $\mu^+\rightarrow e^+e^-e^+$ with an ultimate aimed sensitivity of 1 event in 10^{16} decays. For this goal a very high momentum resolution is required. This goal can on

Thomas Theodor Rudzki (Physikalisches Institut Heidelberg)
18 October 2022 17:12
WHGA / Foyer and Tent (PSI)



Mu3e services

Inside a 2.7mx1m magnet bore

Partition type (ASIC)	Total Power including DC–DC losses [W]
Pixel(MuPix)	
layer 1	102
layer 2	128
layer 3	2660
layer 4	3230
Fibre(MuTRiG)	153
Tile(MuTRiG)	291
Front-end board	2800
Total	**9370**

Power hungry
Detector ASICS,
e.g. 182M active pixels

120 FPGAs

Ca. 10 kW power in

→ 10 kW power out

Mu3e services

Inside a 2.7mx1m magnet bore

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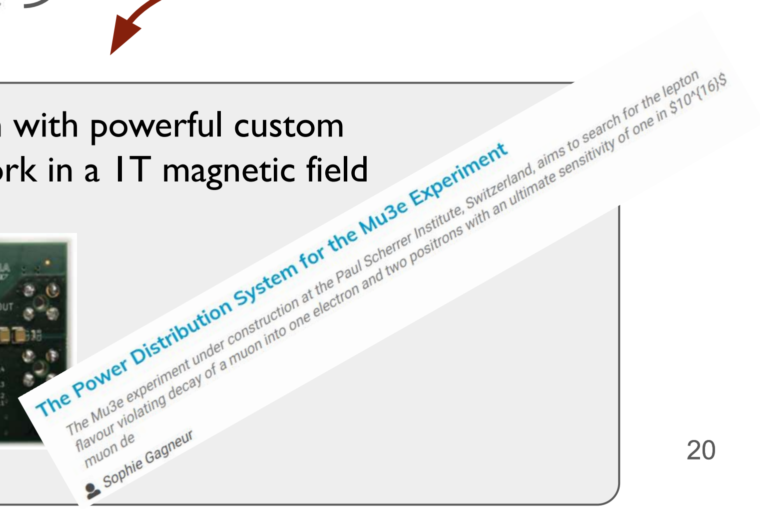
Power hungry
Detector ASICS,
e.g. 182M active pixels

120 FPGAs

Ca. 10 kW power in

→ 10 kW power out

Power distribution system with powerful custom DC-DC converters that work in a 1T magnetic field



Mu3e services

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Fibre(MuTRiG)	153
Tile(MuTRiG)	291
Front-end board	2800
Total	**9370**

Ca. 10 kW power in

⟶ 10 kW power out

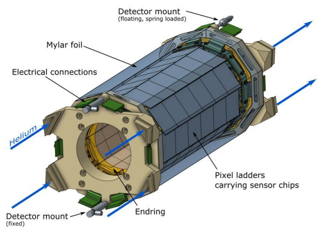
50% Liquid cooling

50% Gaseous helium cooling

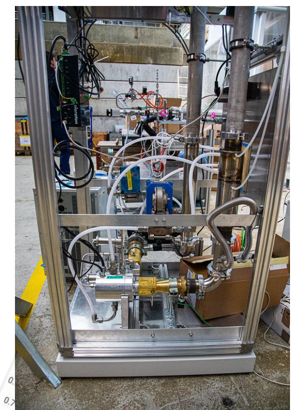
Mu3e services

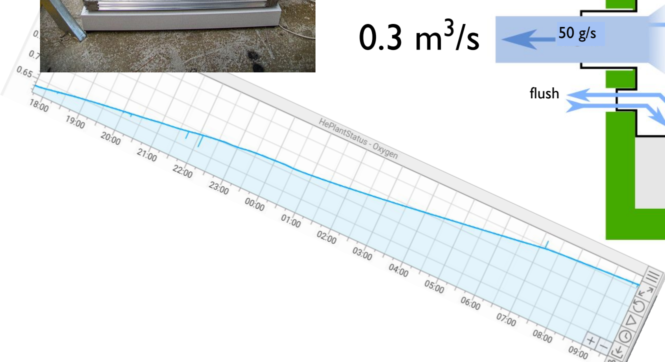
250 mW/cm^2 MuPix chips → <u>Novel 50 g/s, 5 kW helium cooling system</u>

Cooling channels run in the active area of the detector!

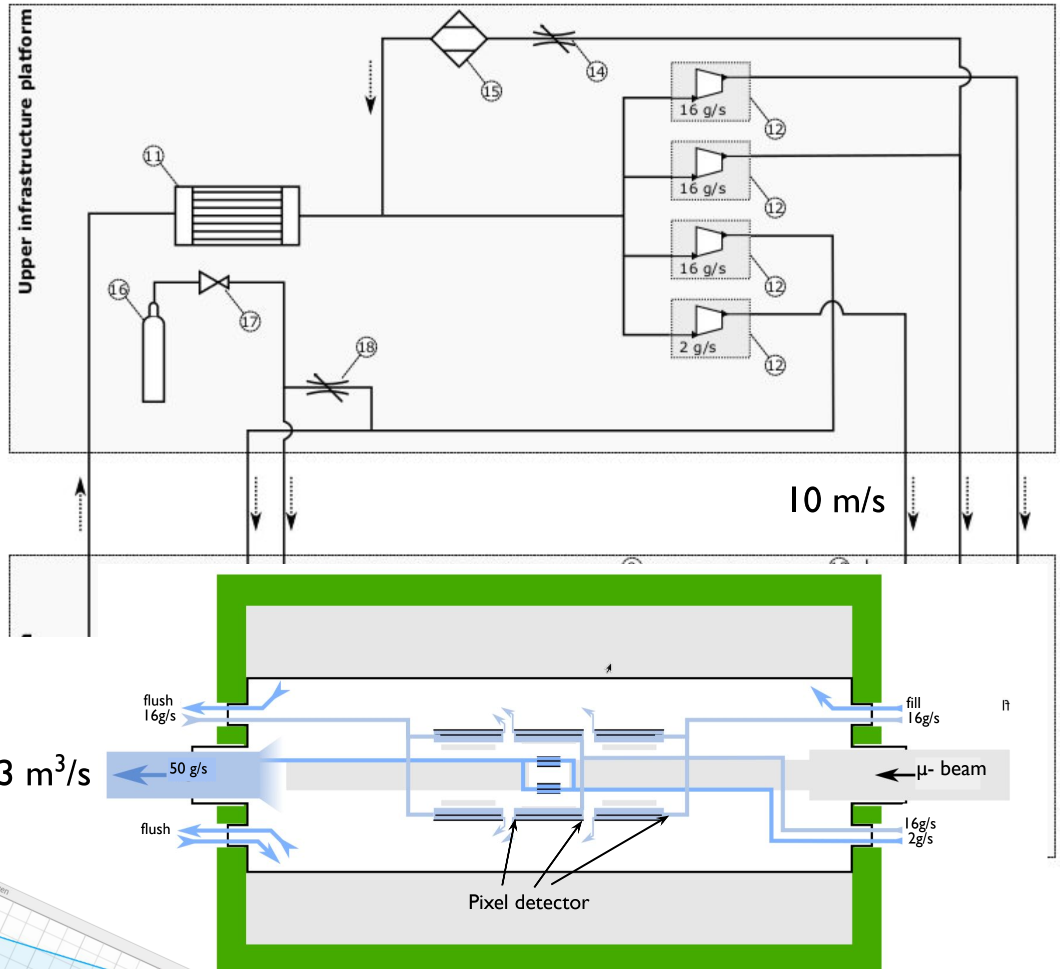


2 g/s operated of
3 months this spring



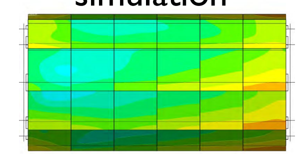


0.3 m^3/s

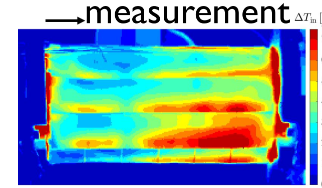


High speed turbo
compressors

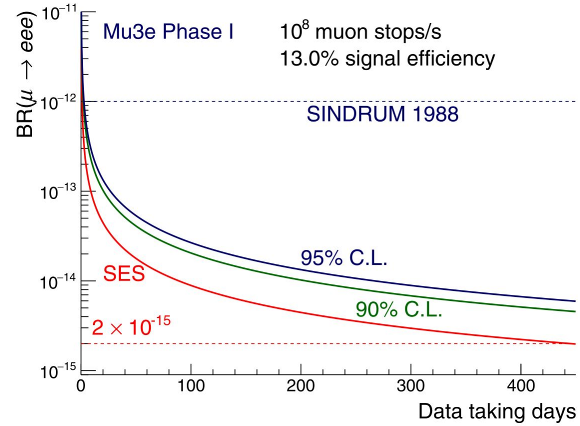
simulation



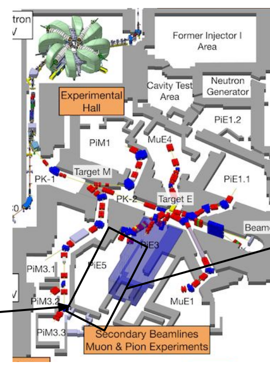
measurement

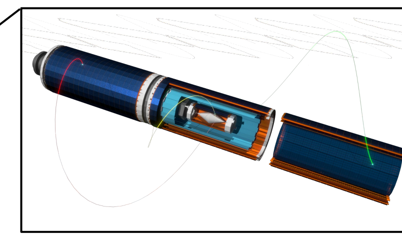


- Run at the πE5 CMBL
- Reach 2 x 10^{-15} S.E.S in 400 days
- First detector installation in 2023
- Infrastructure installation in next 1.5 years
- Commissioning in 2024-2025
- First physics data taking in 2025-2026



non-exhaustive list,
a lot is about to happen





Power and RO infrastructure

outer pixel modules

First pixel, fibre, and tile modules

scale helium system

2023	2024	2025	2026	2027	2028	2029

Cosmic data / detector integration

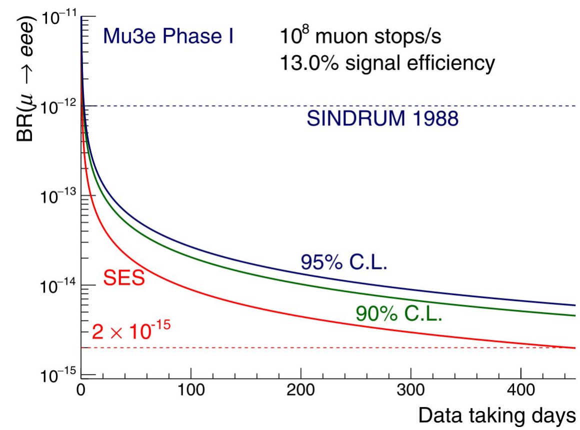
Beam / commissioning

A lot of beam, PHYSICS!

Long shutdown, HIMB construction

Mu3e phase I

- ❏ Run at the πE5 CMBL
- ❏ Reach 2 x 10^{-15} S.E.S in 400 days
- ❏ First detector installation in 2023
- ❏ Infrastructure installation in next 1.5 years
- ❏ Commissioning in 2024-2025
- ❏ First physics data taking in 2025-2026



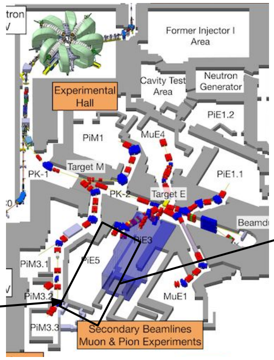
non-exhaustive list,
a lot is about to happen

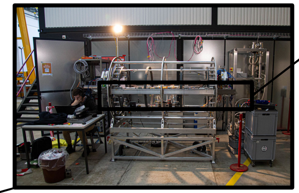
Power and RO
infrastructure

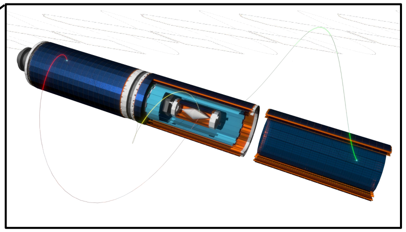
outer pixel modules

First pixel, fibre,
and tile modules

scale helium system







Mu3e Phase II

2023	2024	2025	2026	2027	2028	2029

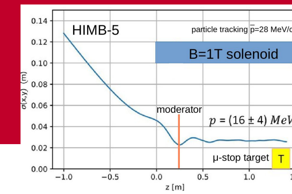
Cosmic data / detector integration

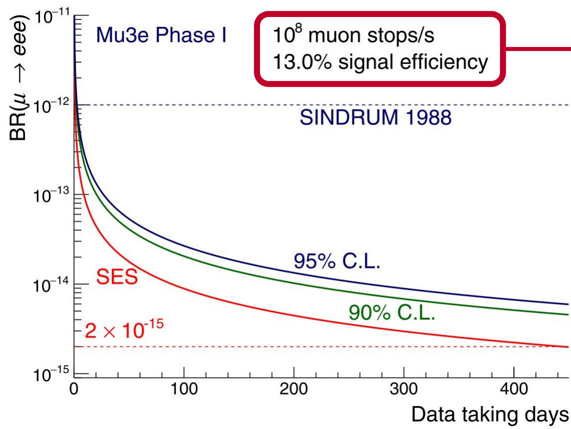
Beam / commissioning

A lot of beam, PHYSICS!

Long shutdown, HIMB construction

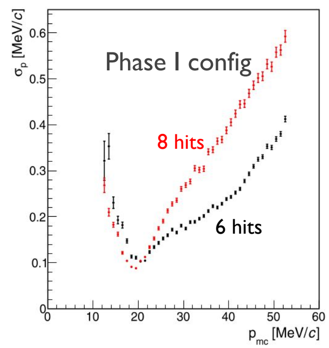
Mu3e phase II = S.E.S. of 10^{-16}

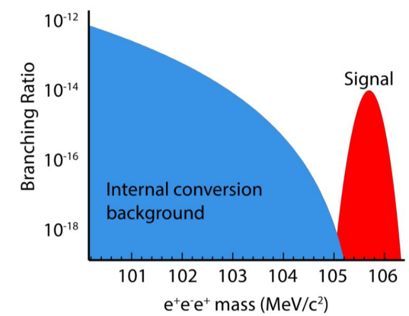


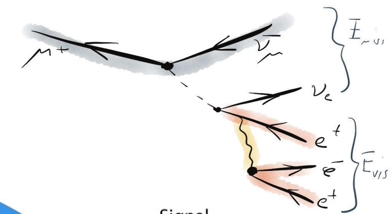


10^8 muon stops/s
13.0% signal efficiency

$>10^9$ μ-/s on target from HIMB

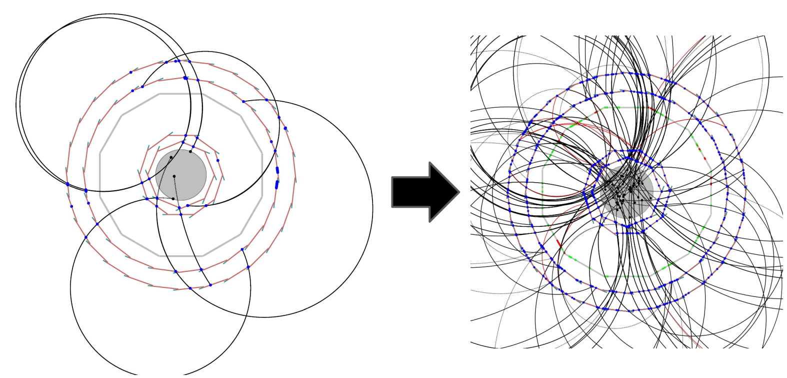






Accepting $>10^9$ muon per second on target comes with challenges

- ❏ Getting $>10^9$ muons per second on target
- ❏ Processing $>10^9$ muons per second
  → Many DAQ components have phase II capabilities
  - ❏ Raw bandwidth
  - ❏ 10^9 fits per second per GPU
- ❏ Needs fast & granular pixel detectors to reduce combinatorics with time and vertex cuts.
- ❏ Maintain or even improve Momentum resolution to deal with internal conversion background
- ❏ *Smarter* selection cuts to deal with combinatorics



there is another entire talk about ...

Mu3e beyond $\mu^+ \to e^+e^+e^-$

$\mu^+ \to e^+\gamma \to e^+e^+e^-$ with γ-conversion layer

$\mu^+ \to e^+$ + exotic particle

[Snowmass paper]

https://www.psi.ch/en/mu3e

PHYSIKALISCHES INSTITUT

KIRCHHOFF-INSTITUT FÜR PHYSIK

KIT
Karlsruher Institut für Technologie

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

UCL

UNIVERSITY OF OXFORD

University of BRISTOL

UNIVERSITY OF LIVERPOOL

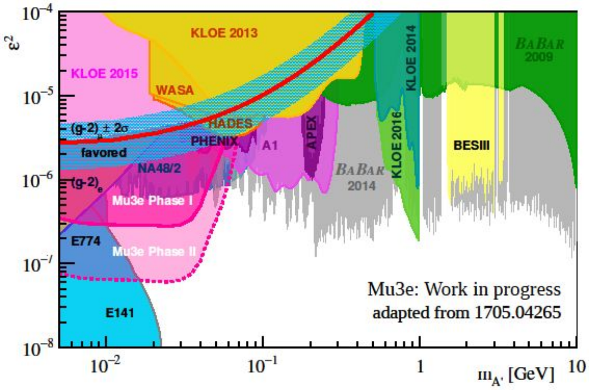
UNIVERSITÉ DE GENÈVE

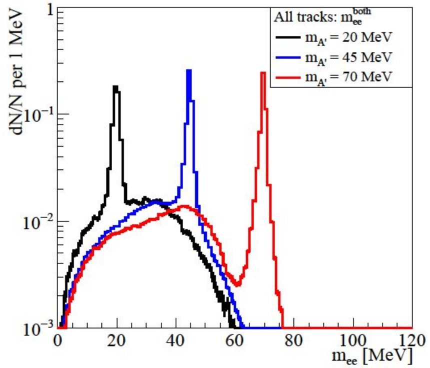
Universität Zürich UZH

PAUL SCHERRER INSTITUT
PSI

ETH zürich

Extra's



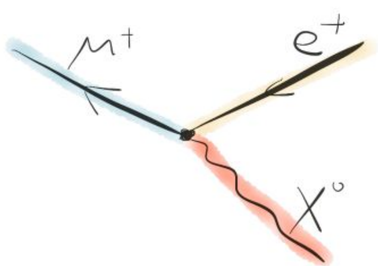


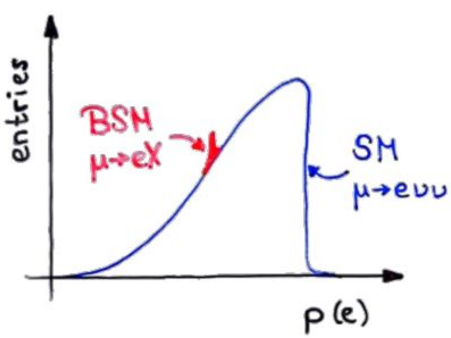
Other Exotic Physics with Mu3e

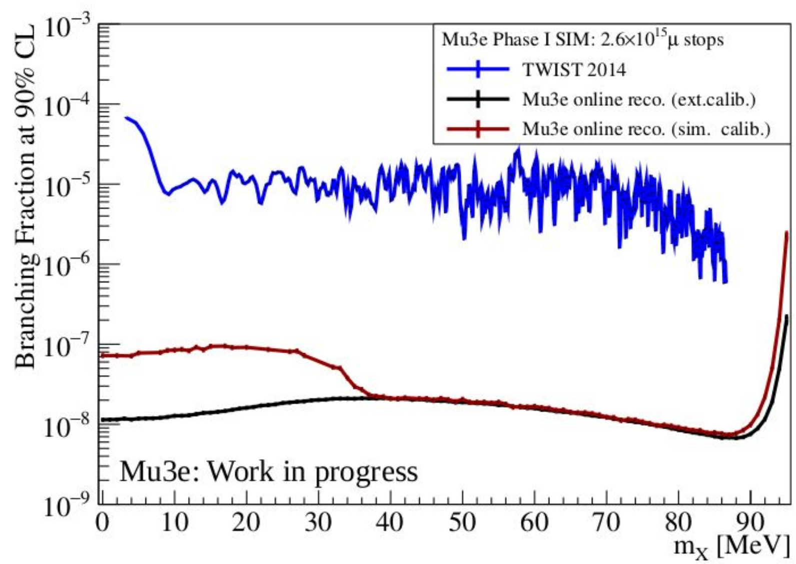
Familons

Slide A. PerreVoort

- Search for $\mu^+ \to e^+ X^0$ decays
- Ex: Familon
  (Goldstone boson from spontaneously broken flavour symmetry, Wilczek, PRL 49 (1982) 1549)







- Challenge: single-*e* events are not saved
- Histogramming on filter farm

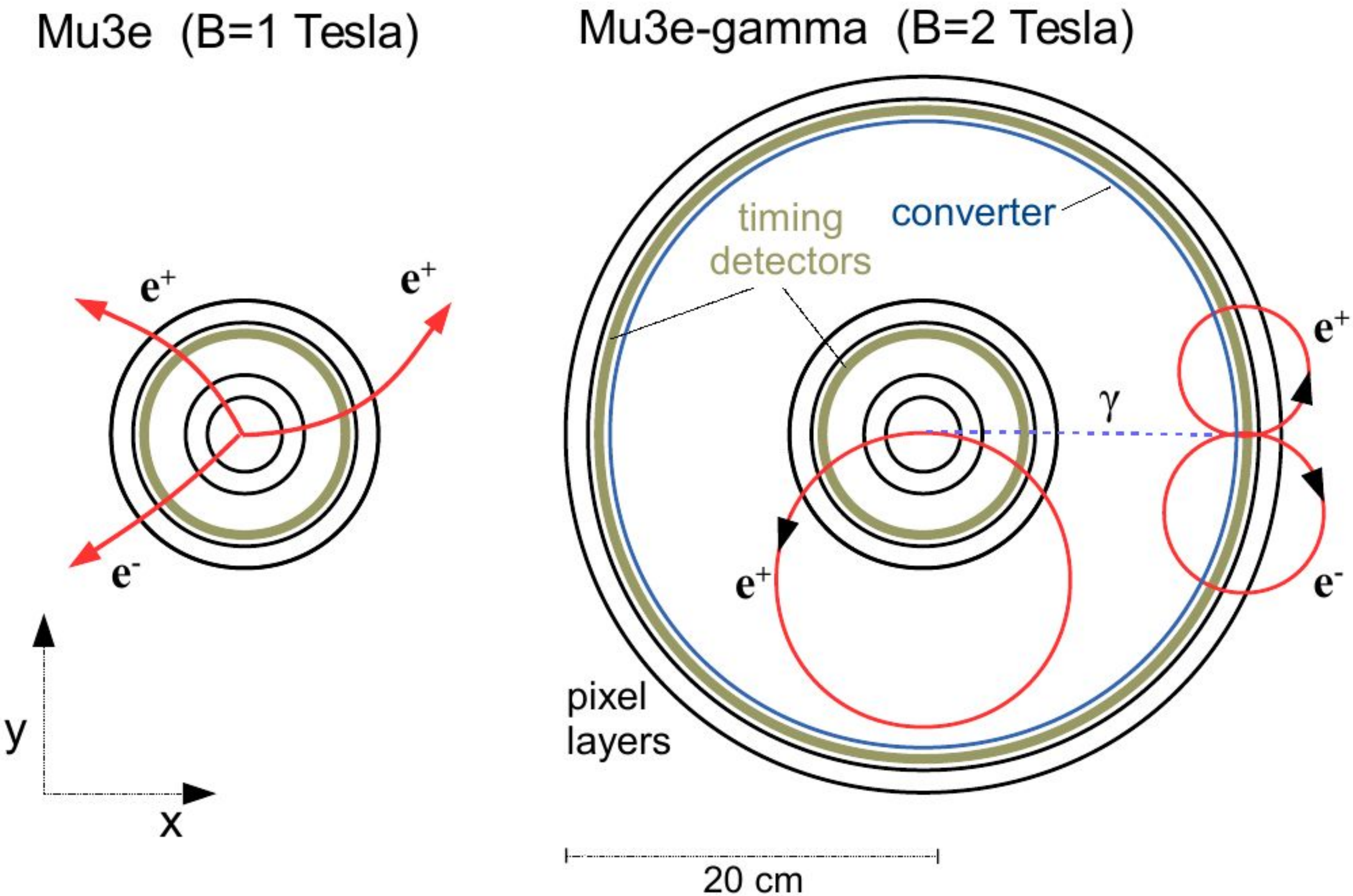
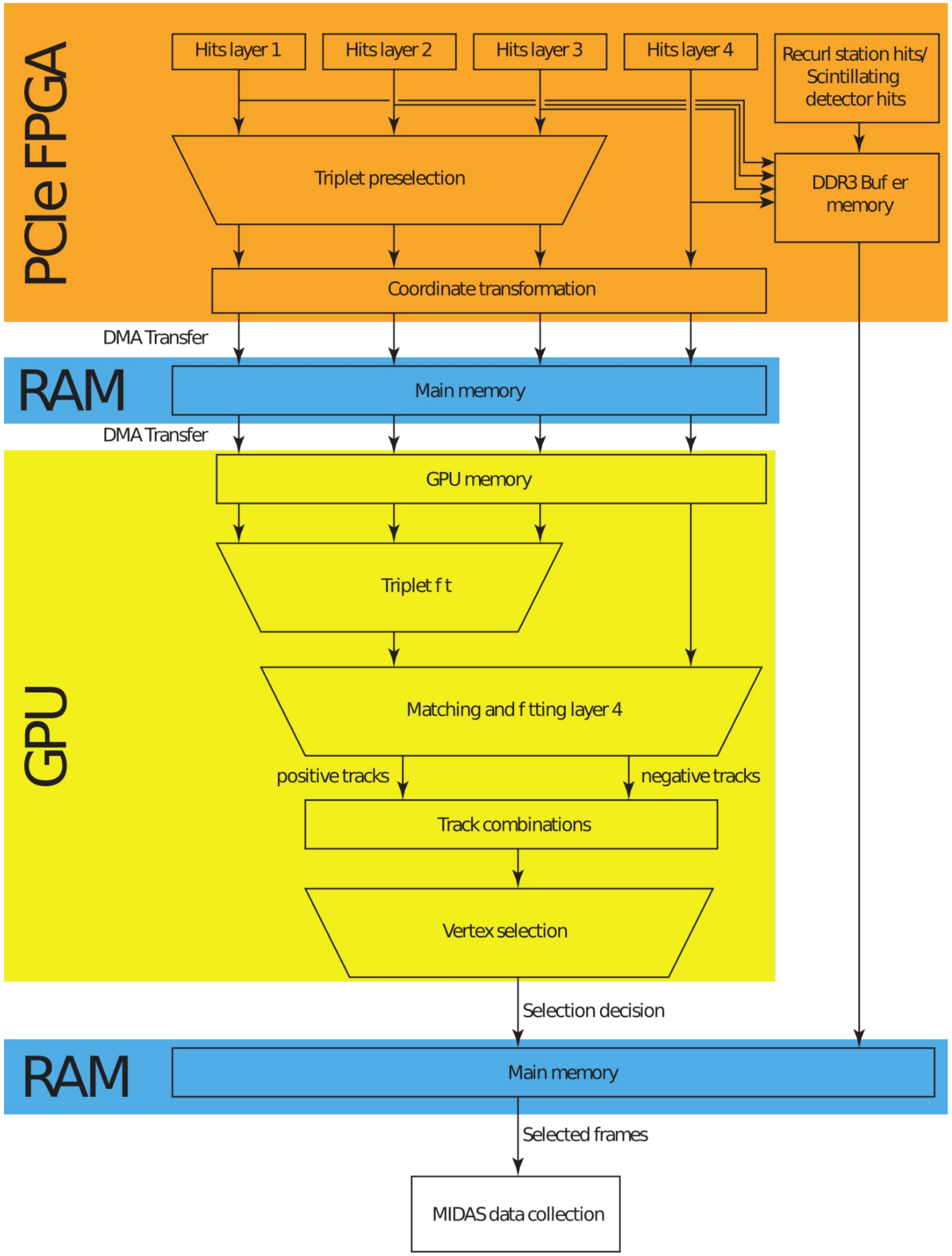

Mu3e (B=1 Tesla)
Mu3e-gamma (B=2 Tesla)
e+
e+
e-
y
x
timing
detectors
converter
γ
e+
e+
e-
pixel
layers
20 cm

Table 22.1
Efficiency of the various reconstruction and analysis steps.

Step	Step efficiency	Total efficiency
Muon stops	100%	100%
Geometrical acceptance, short tracks	38.1%	38.1%
Geometrical acceptance, long tracks	68.0%	25.9%
Short track reconstruction	89.5%	34.1%
Long track reconstruction[a]	67.2%	17.4%
Recurler rejection/Vertex fit convergence	99.4%	17.3%
Vertex fit $\chi^2 < 15$	91.3%	15.8%
CMS momentum $< 4\,\mathrm{MeV/c}$	95.6%	15.1%
$m_{ee,low} < 5\,\mathrm{MeV/c^2}$ or $> 10\,\mathrm{MeV/c^2}$	98.0%	14.9%
$103\,\mathrm{MeV/c^2} < m_{rec} < 110\,\mathrm{MeV/c^2}$	97.0%	14.4%
Timing	90.0%	13.0%

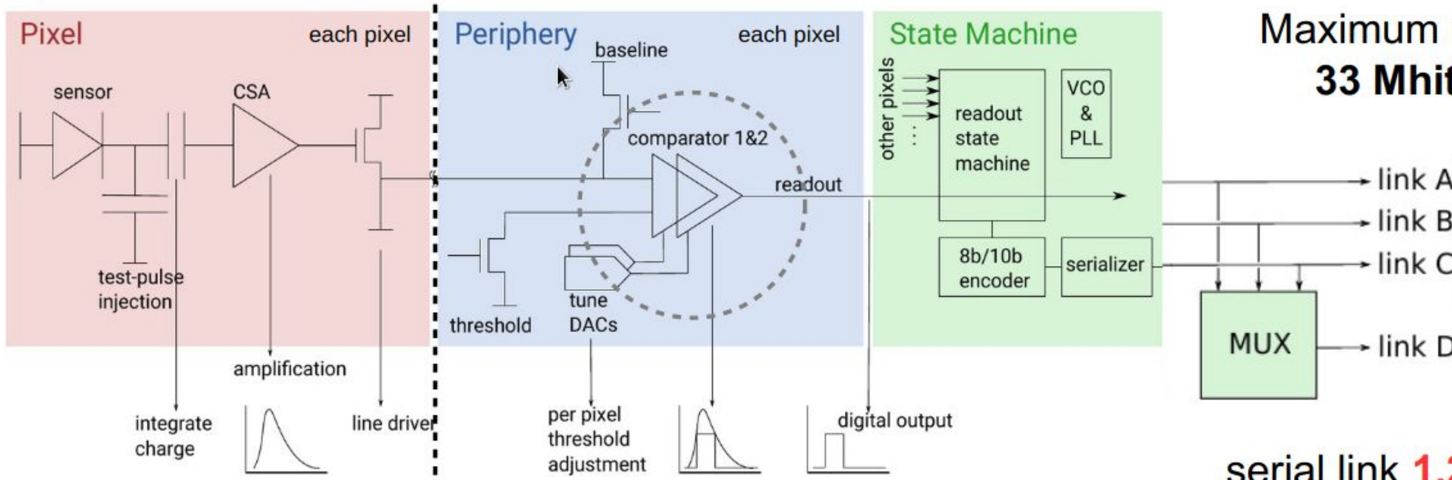
[a] Note that the efficiency of this step is quoted relative to the acceptance for long tracks.


PCIe FPGA
Hits layer 1
Hits layer 2
Hits layer 3
Hits layer 4
Recurl station hits/
Scintillating
detector hits
Triplet preselection
DDR3 Buf er
memory
Coordinate transformation
DMA Transfer
RAM
Main memory
DMA Transfer
GPU
GPU memory
Triplet f t
Matching and f tting layer 4
positive tracks
negative tracks
Track combinations
Vertex selection
Selection decision
RAM
Main memory
Selected frames
MIDAS data collection


GTX 980

High Rate & Continuous Readout

MuPix



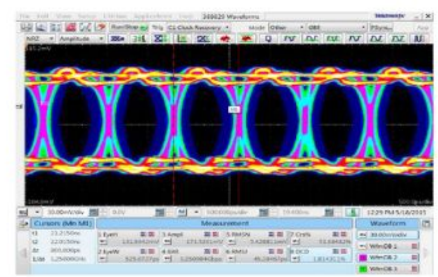
Maximum readout rate is **33 Mhits/s** per link

serial link **1.25 -1.6 Gbit/s**

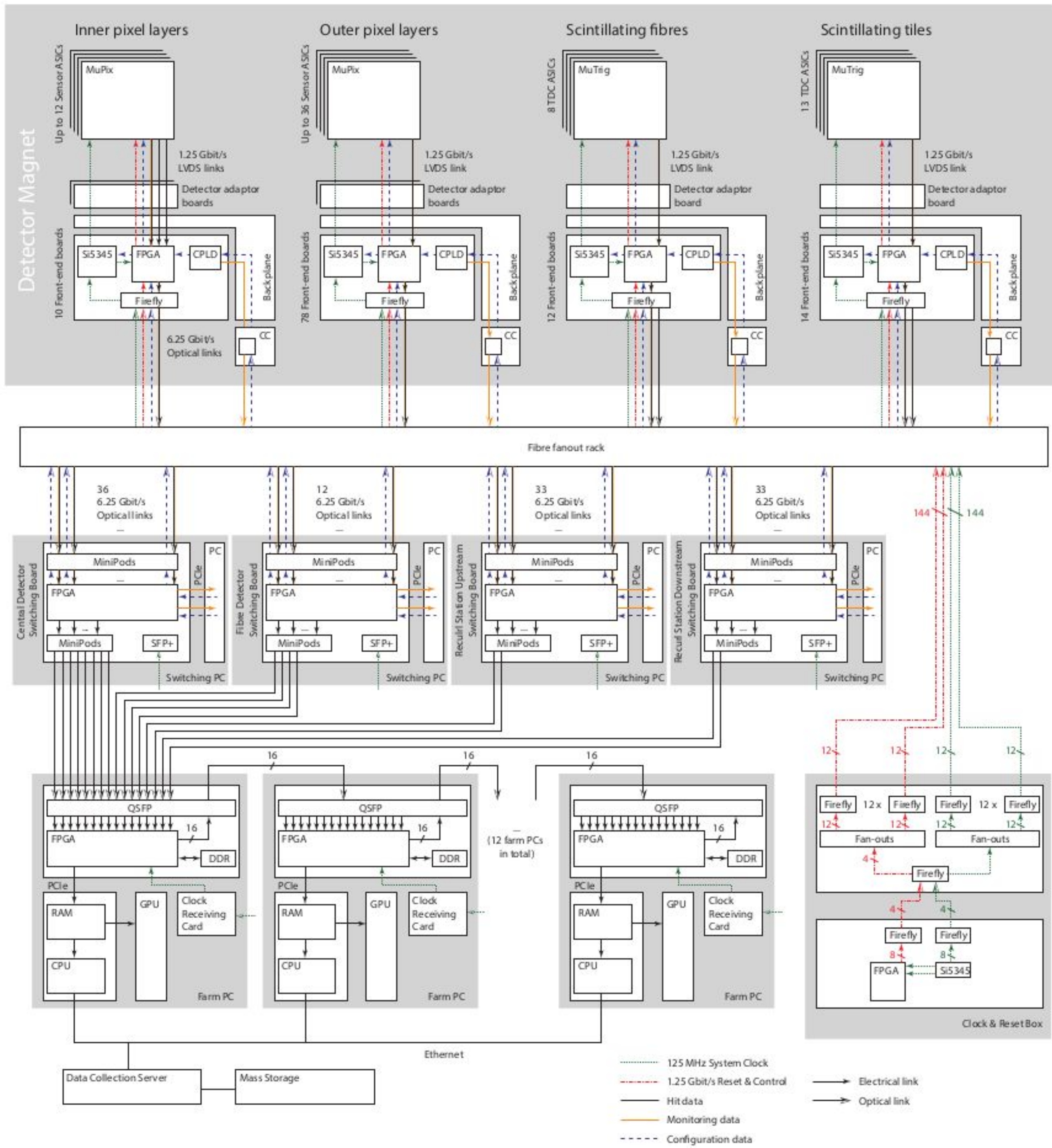
MuPix8 sensor

periphery & SM

eye diagram



MuPix series is the first monolithic pixel sensor with continuous sampling and readout!



Detector Magnet
Inner pixel layers
Outer pixel layers
Scintillating fibres
Scintillating tiles
Up to 12 Sensor ASICs
Up to 36 Sensor ASICs
8 TDC ASICs
13 TDC ASICs
MuPix
MuTrig
1.25 Gbit/s LVDS links
1.25 Gbit/s LVDS link
Detector adaptor boards
Detector adaptor board
10 Front-end boards
78 Front-end boards
12 Front-end boards
14 Front-end boards
Si5345
FPGA
CPLD
Firefly
Backplane
CC
6.25 Gbit/s Optical links
Fibre fanout rack
36 6.25 Gbit/s Optical links
12 6.25 Gbit/s Optical links
33 6.25 Gbit/s Optical links
144
MiniPods
PC
PCIe
SFP+
Switching PC
Central Detector Switching Board
Fibre Detector Switching Board
Recoil Station Upstream Switching Board
Recoil Station Downstream Switching Board
16
QSFP
DDR
RAM
GPU
CPU
Clock Receiving Card
Farm PC
(12 farm PCs in total)
12
12 x
Fan-outs
4
8
Clock & Reset Box
Ethernet
Data Collection Server
Mass Storage
125 MHz System Clock
1.25 Gbit/s Reset & Control
Hit data
Monitoring data
Configuration data
Electrical link
Optical link