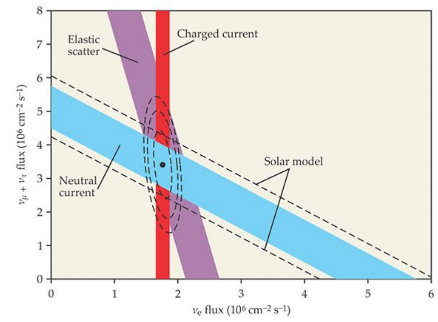
The mu3e experiment

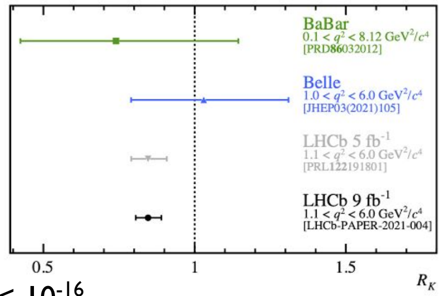
Frederik Wauters
Johannes Gutenberg University Mainz

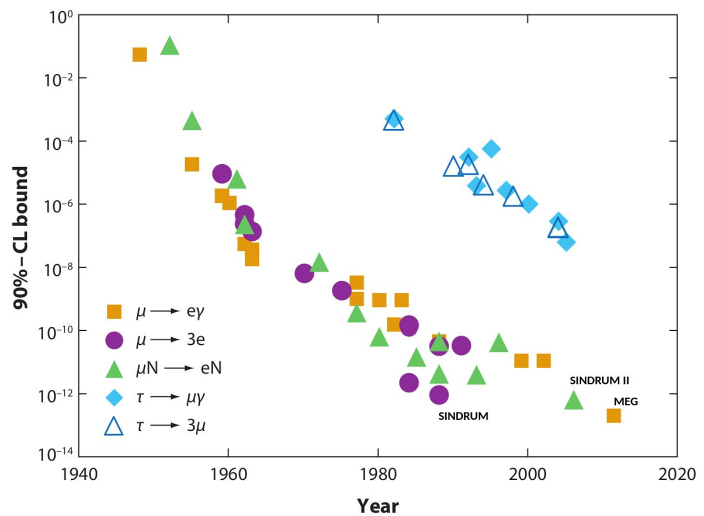
CLFV & $\mu^+ \to e^+e^+e^-$



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

- ❏ Neutrino masses/oscillations have established LFV in SM+
- ❏ **Charged** LFV has not yet been observed: beyond SM. But CLF is not a fundamental SM symmetry
- ❏ Leptons 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
- ❏ Three golden muon channels:
  - ❏ $\mu^+ \to e^+\gamma$ MEG $< 4 \cdot 10^{-13}$ ⇨ MEGII $< 5 \cdot 10^{-14}$
  - ❏ $\mu^+ \to e^+e^+e^-$ SINDRUM $< 1 \cdot 10^{-12}$ ⇨ Mu3e $< 2 \cdot 10^{-15}$
  - ❏ $\mu^- N \to e^- N$ SUNDRUMII $< 7 \cdot 10^{-13}$ ⇨ Mu2e, COMET, DeeMee $< 10^{-16}$

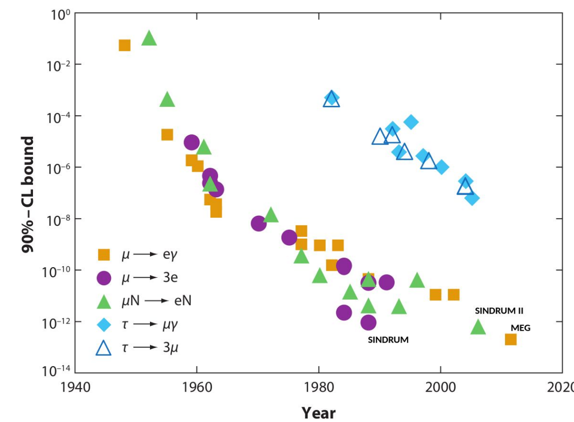


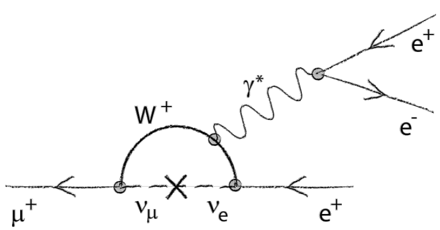


CLFV & $\mu^+ \rightarrow e^+e^+e^-$

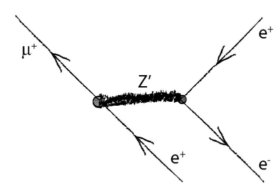
Charged Lepton Flavour Violation and the Standard Model

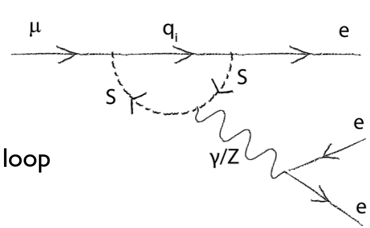
- ❑ Neutrino masses/oscillations have established LFV in SM+
- ❑ **Charged** LFV has not yet been observed: beyond SM. But CLF is not a fundamental SM symmetry
- ❑ Leptons are a clean probe, i.e. free of SM background
- ❑ Muons hit the sweet spot between sensitivity and availability. Note there are also $\tau \rightarrow e\gamma$, $\tau \rightarrow \mu\gamma$, $\tau \rightarrow \mu\mu\mu$ searches at e.g. Belle II
- ❑ Three golden muon channels:
  - ❑ $\mu^+ \rightarrow e^+\gamma$ MEG $< 4 \cdot 10^{-13}$ ⇨ MEGII $< 5 \cdot 10^{-14}$
  - ❑ $\mu^+ \rightarrow e^+e^+e^-$ SINDRUM $< 1 \cdot 10^{-12}$ ⇨ Mu3e $< 2 \cdot 10^{-15}$
  - ❑ $\mu^- N \rightarrow e^- N$ SUNDRUMII $< 7 \cdot 10^{-13}$ ⇨ Mu2e, COMET, DeeMee $< 10^{-16}$





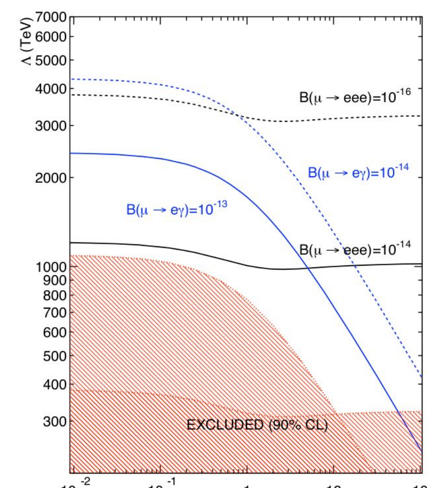
BR(SM) < 10^{-54}





Zoo of possible tree and loop level BSM contributions

Access to >1000 TeV

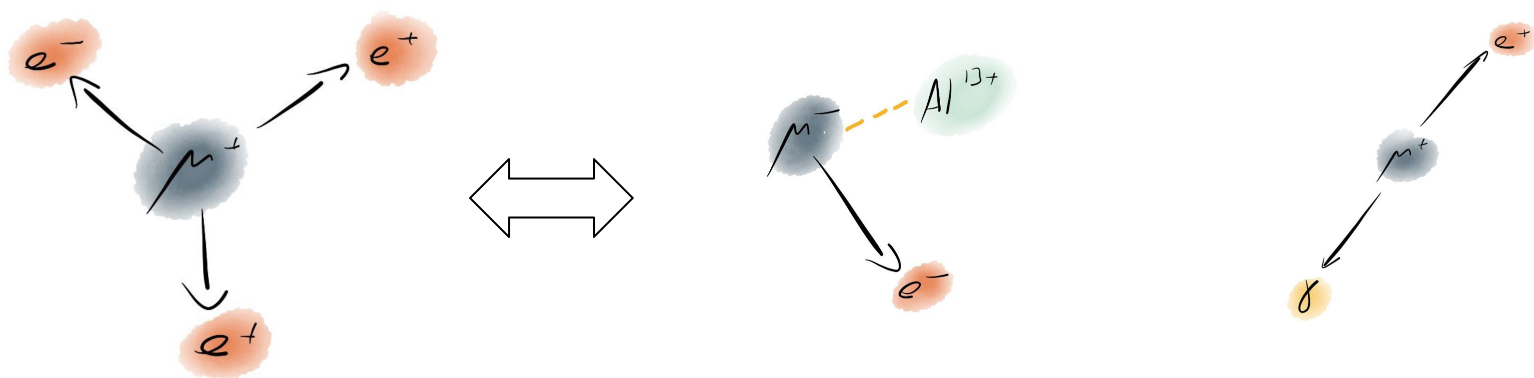


From Gouvea and Vogel arXiv:1303.4097

Kuno et al arXiv:hep-ph/990926
Crevellin et al. arXiv:1702.03020

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

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



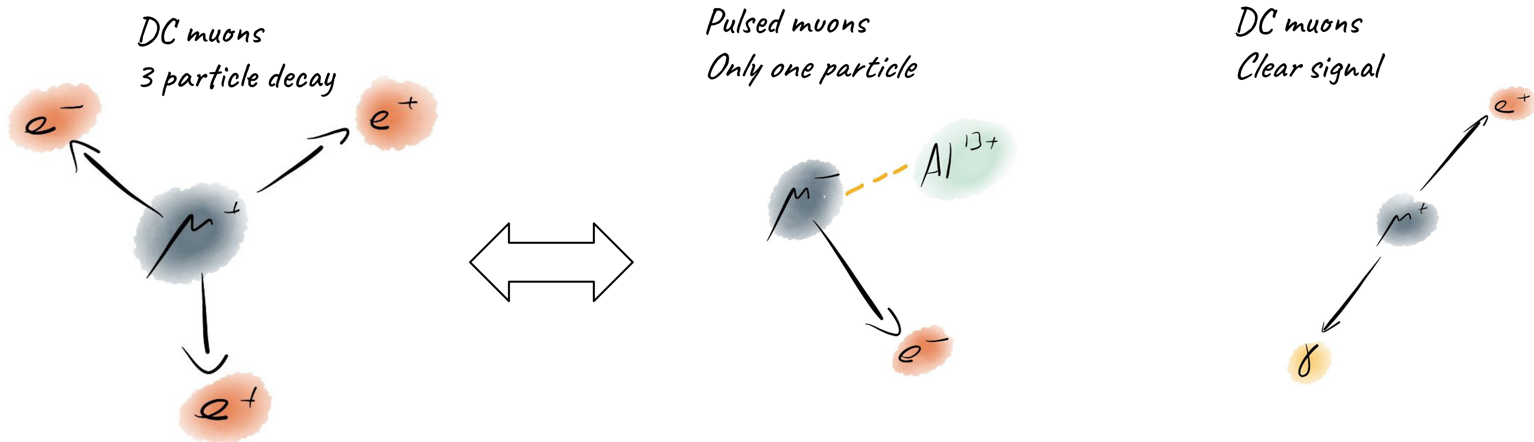
- ➔ Common vertex
- ➔ Time coincident
- ➔ $\sum E = m_\mu$
- ➔ $\sum \mathbf{p}=0$

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

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

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

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



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

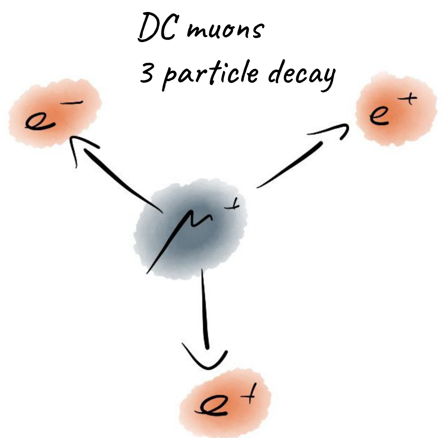
- ➔ Mono-energetic e^-
- ➔ No coincidence

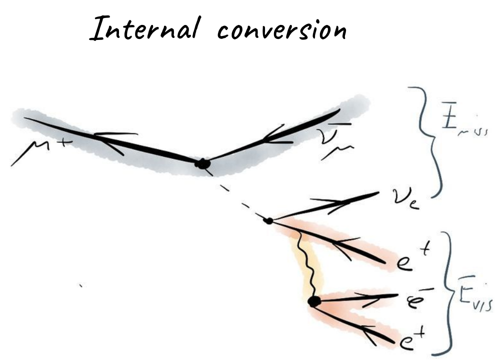
- ➔ Mono-energetic e^+ and γ
- ➔ back-back coincidence

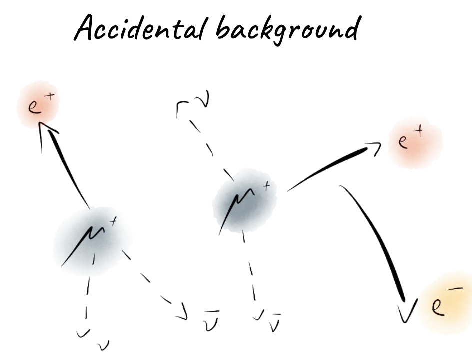
From Gouvea and Vogel arXiv:1303.4097

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

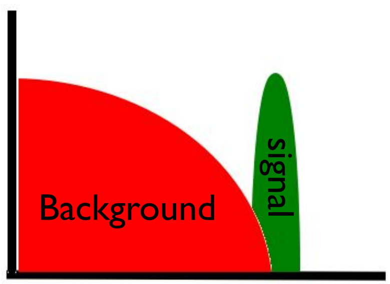
Detecting $\mu^+ \to e^+ e^+ e^-$ for muon decay at rest: Backgrounds







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



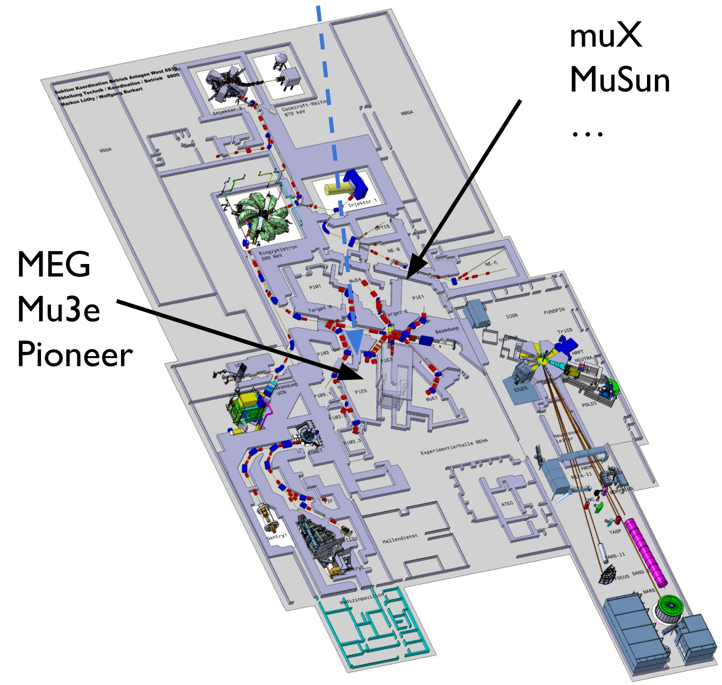
Michel decay positrons plus electron from:

- ❑ Bhabha scattering
- ❑ Photon conversion
- ❑ Mis reconstruction

Our detector needs:

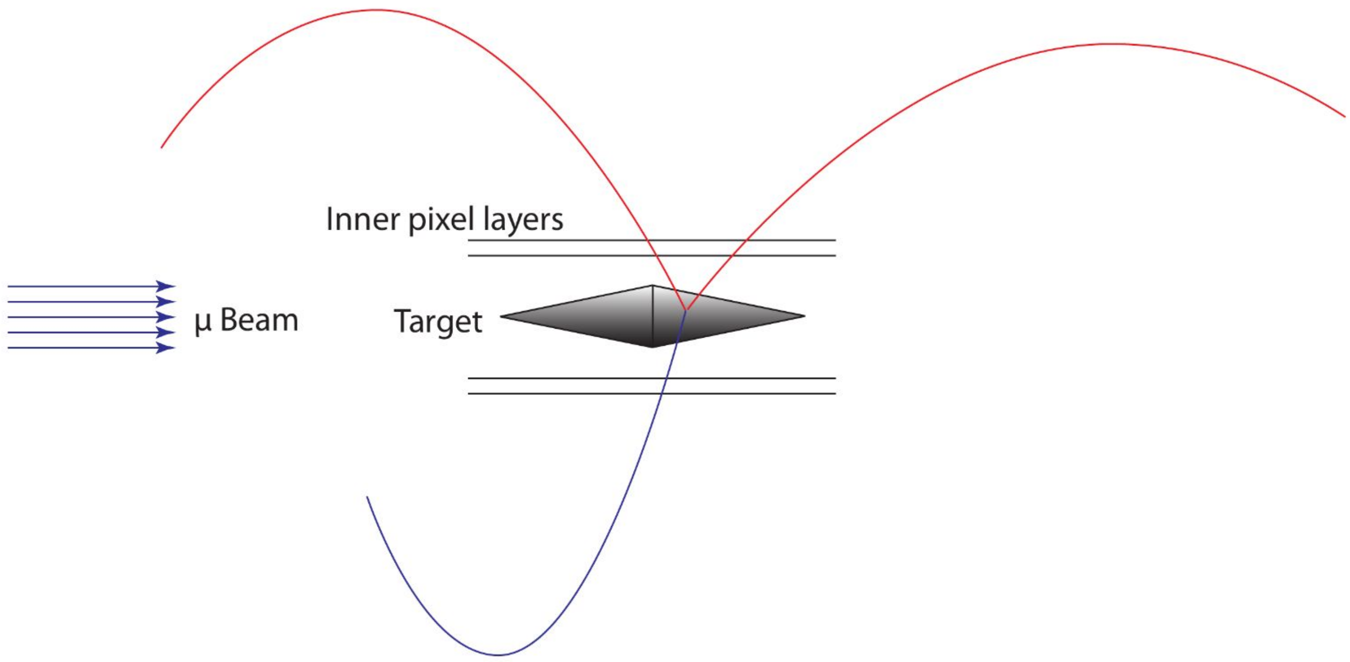
- ➢ Excellent momentum resolution
- ➢ Good time and vertex resolution
- ➢ High rate capability

Mu3e conceptual design



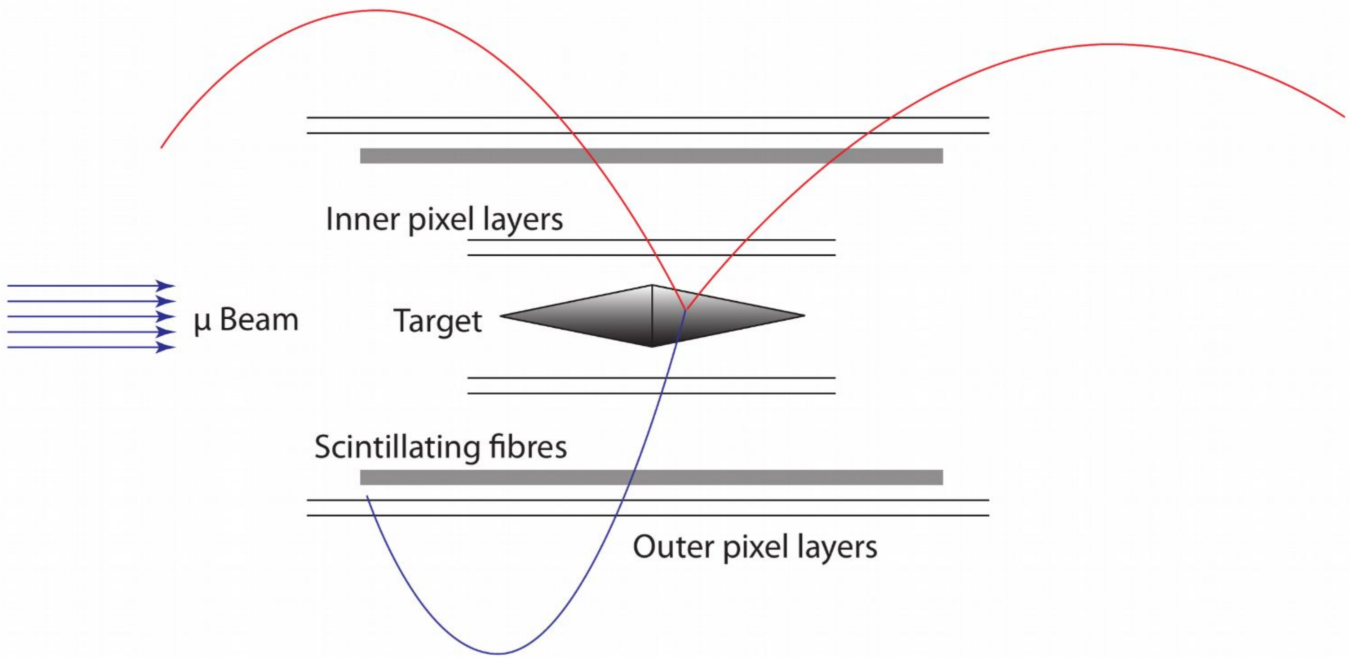
- 2.3 mA 600 MeV proton beam from HIPA at PSI
- 10^8 μ^+/s (DC) at the πE5 area
- Stopped on a thin Mylar target

Mu3e conceptual design



- 2 layer vertex detector
- 1T uniform magnetic field
- 2 e+ and e- helical tracks

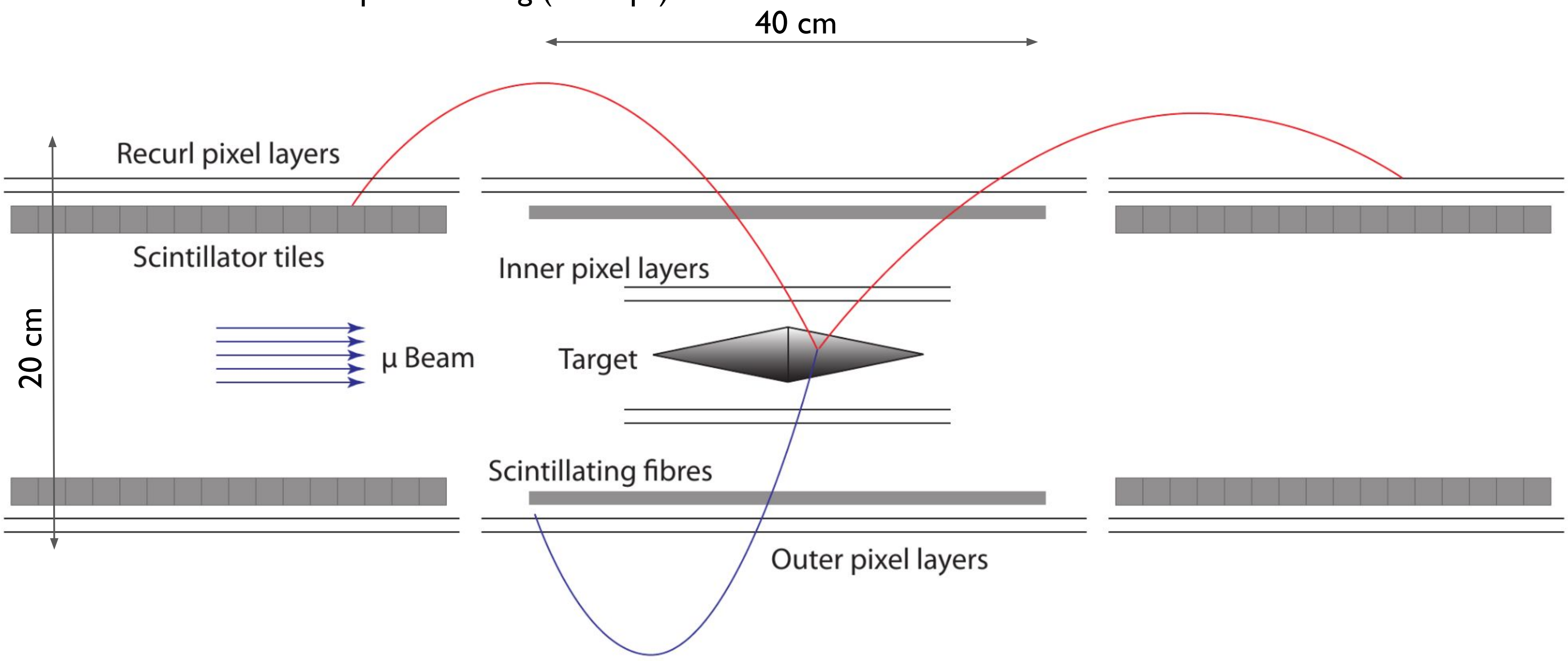
Mu3e conceptual design



- 2 outer pixel layers → 4 hits to *start* the track
- Fibre detector for the track direction, i.e. differentiate e+ from e-

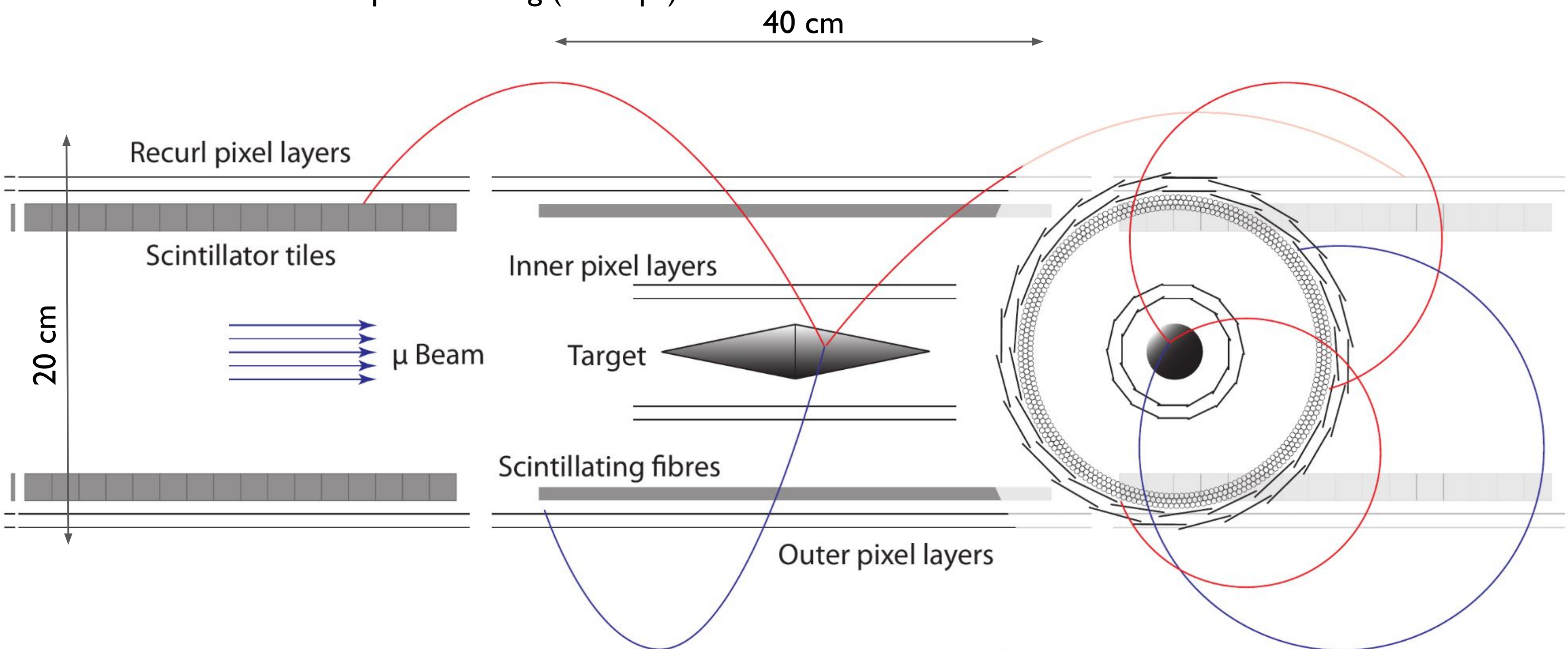
Mu3e conceptual design

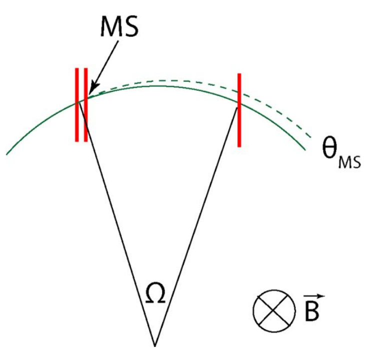
- Recurl trackingstation to accept half turn track for optimal momentum resolution
- Tile detector for optimal timing (<100 ps)



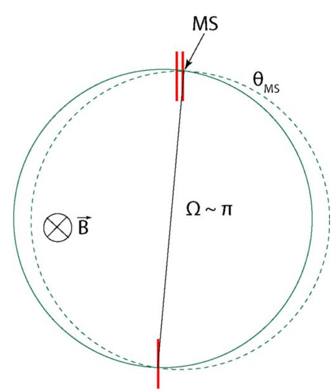
Mu3e conceptual design

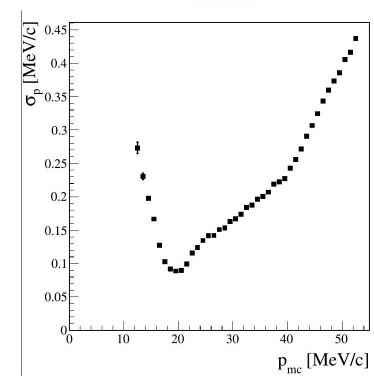
- ❑ Recurl trackingstation to accept half turn track for optimal momentum resolution
- ❑ Tile detector for optimal timing (<100 ps)





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





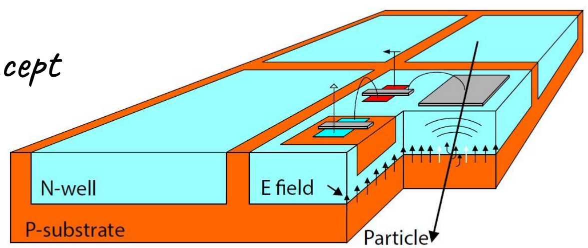
Mu3e Detectors

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

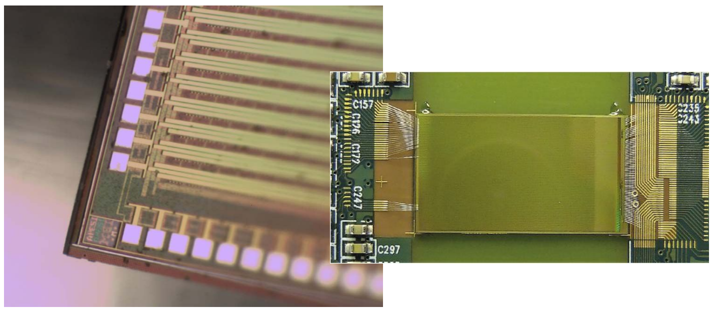
A decade of detector development and test beams

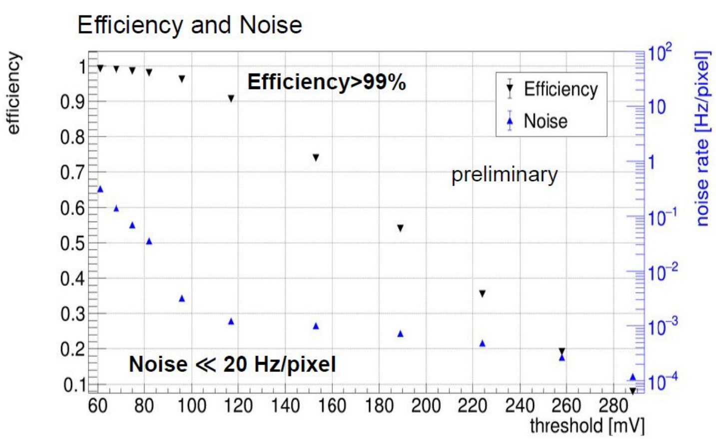
- Commercial CMOS process
- Fast Charge collection
- Integrated analogues and digital RO
- Can be thinned to 50 µm

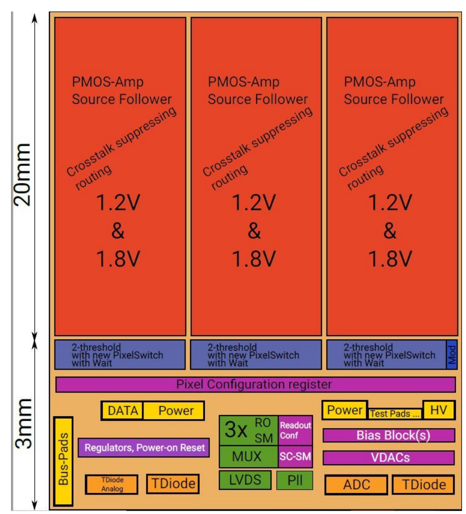
Concept



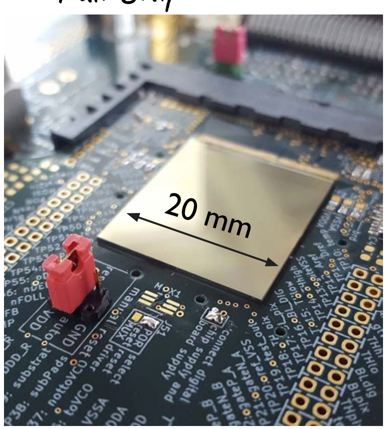
Prototyping MuPiX … → 9







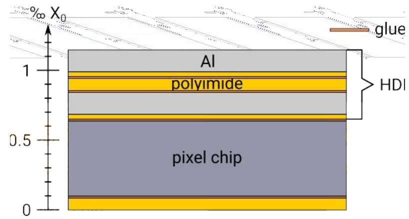
Full Chip

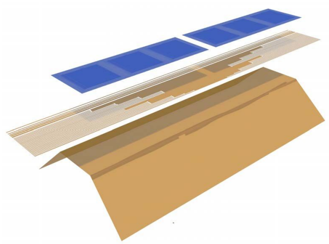


Mu3e Detectors

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!

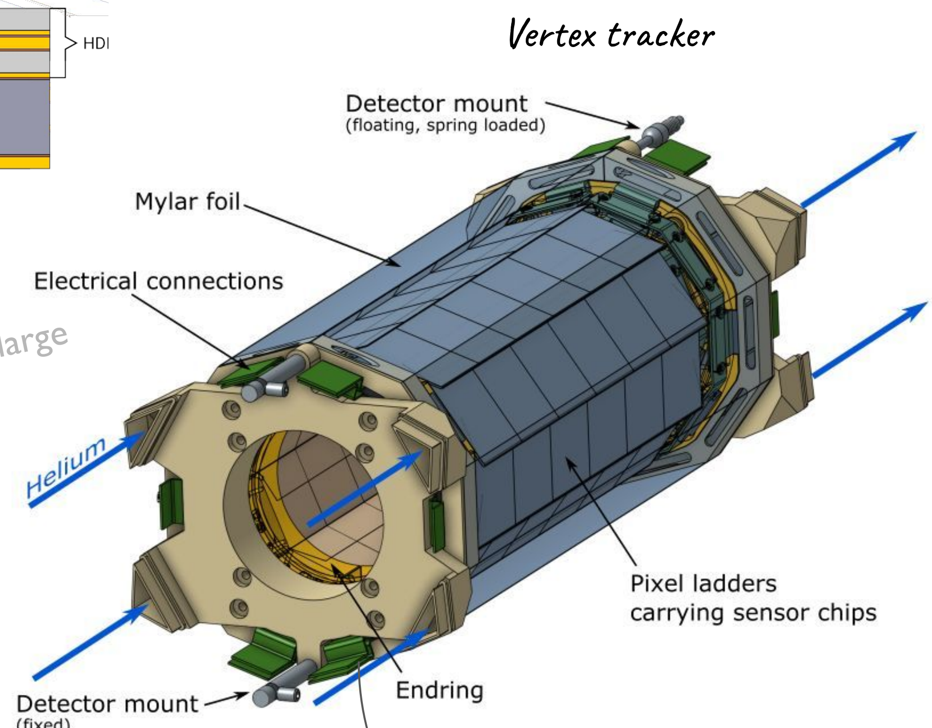


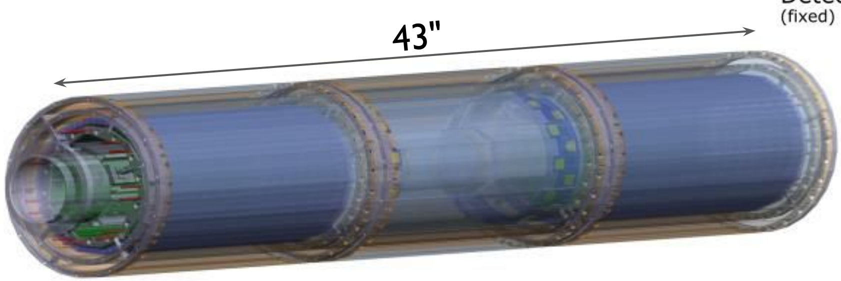


- 2 vertex layers
- 3 * 2 outer layers
- 174 ladders
- 2844 2x2 cm^2 MuPiX chips
- 3060 1.25 Gb/s data links
- 50 g/s, 10m/s 5kW gaseous helium cooling

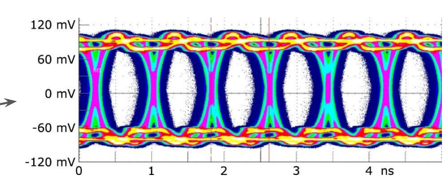
The is a compact but large pixel tracker!

Vertex tracker





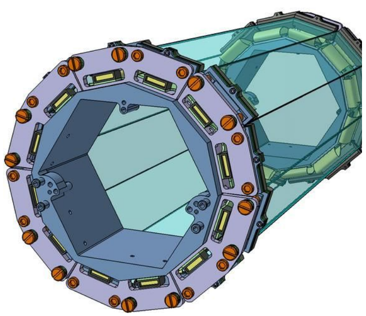
+ HV & power

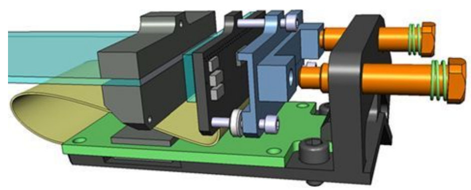


Mu3e Detectors

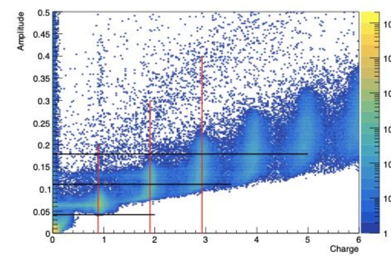
Timing detectors

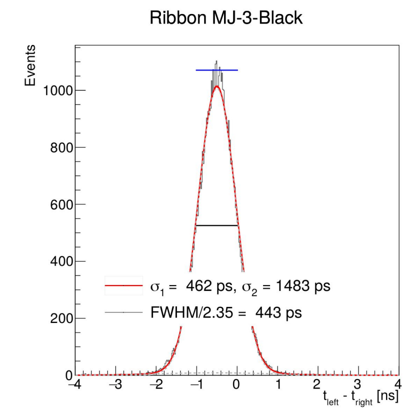
- ❑ 3 layer / 12 ribbons scintillating fibre detector surrounding the vertex detector
- ❑ Highly granular tile detector under the recurl stations



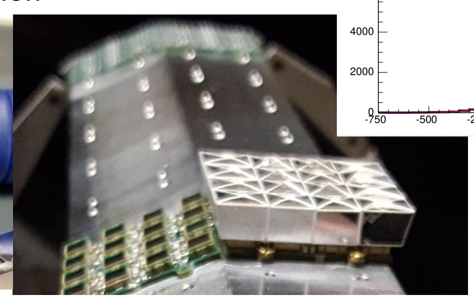


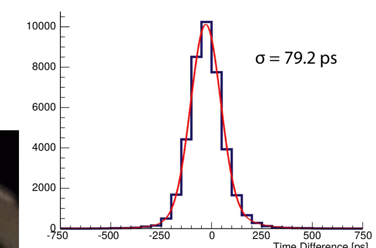
All fibre and pixel modules are spring loaded to compensate for thermal expansions.

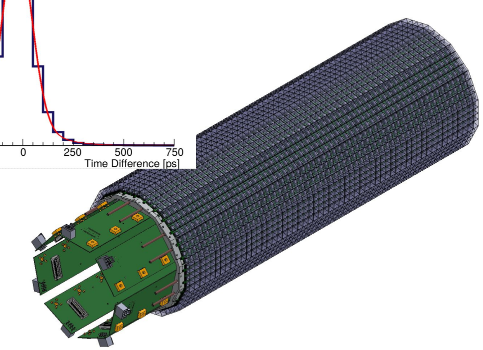




6272 tiles with plenty of light give us ca. 70 ps time resolution



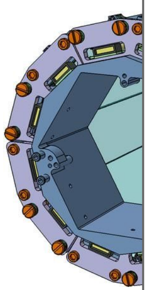


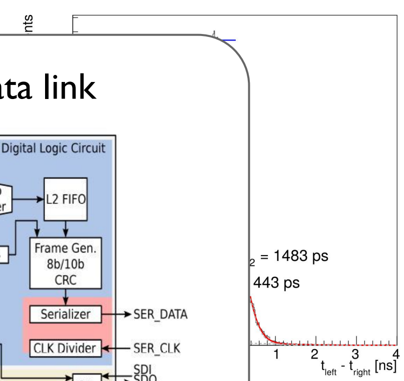


Mu3e Detectors

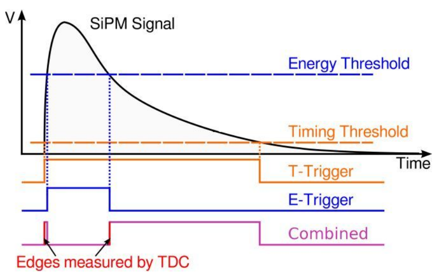
Timing detectors

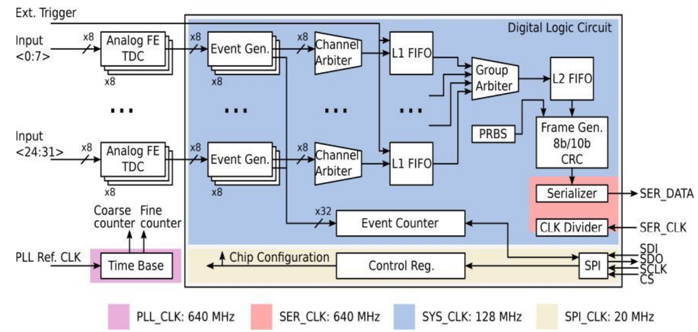
- 3 layer / 12 ribbons scintillating fibre detector surrounding the vertex detector
- Highly granular tile detector under the recurl stations

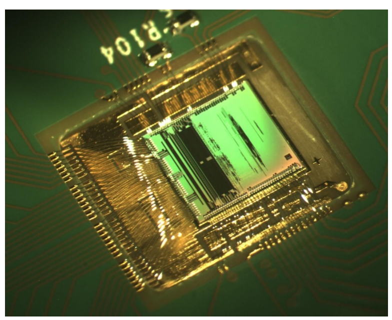


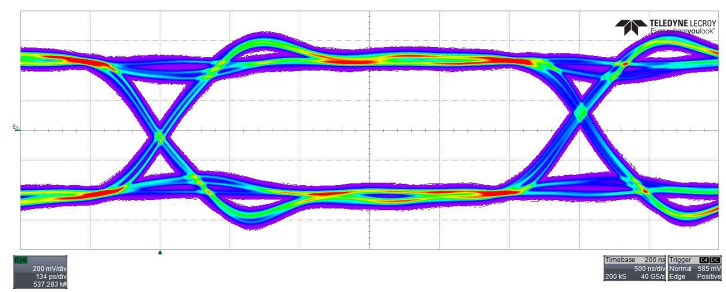


MuTrig: A custom 32 (SiPM) channel RO chip with a single 1.25 Gb/s data link

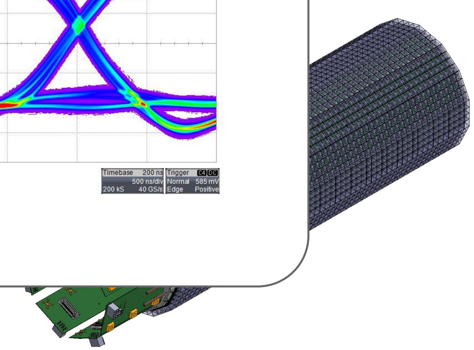




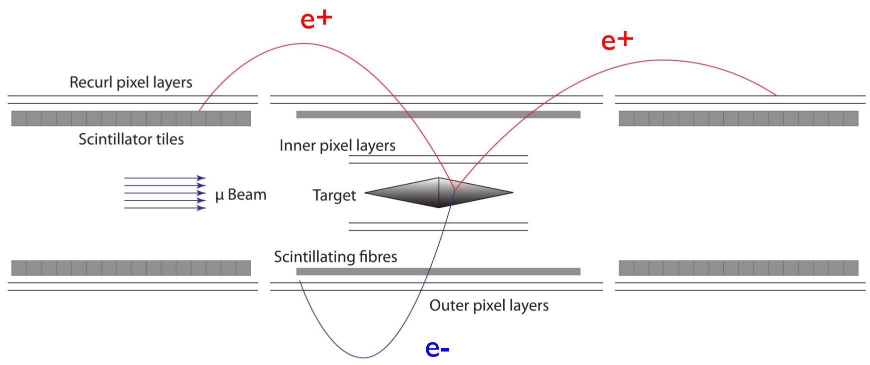




6272 tiles

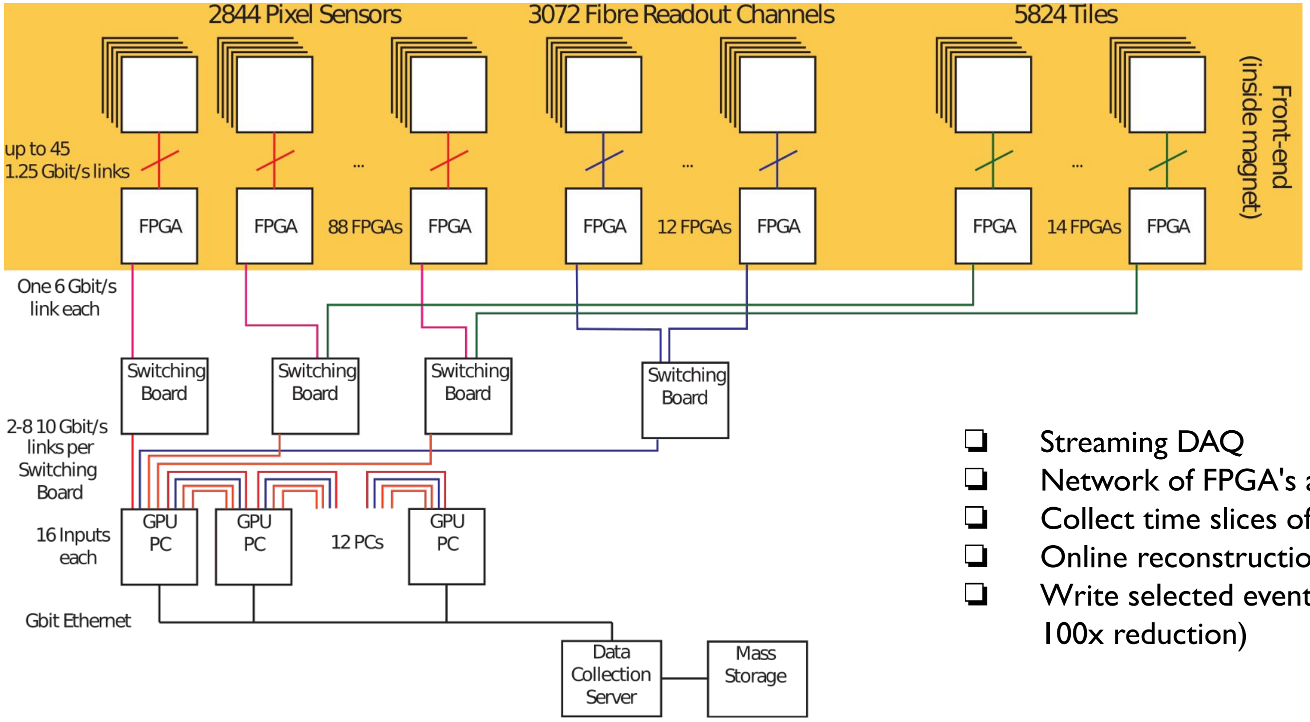


Mu3e DAQ



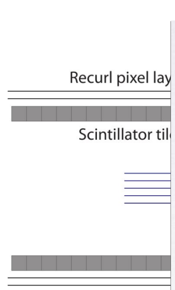
Reminder: the Mu3e event topology does not allow for a RO trigger, every Michel electron could also be part of a $\mu^+ \rightarrow e^+e^+e^-$ event. Only the kinematics of the combined final state positrons/electron gives us an event selection criteria.

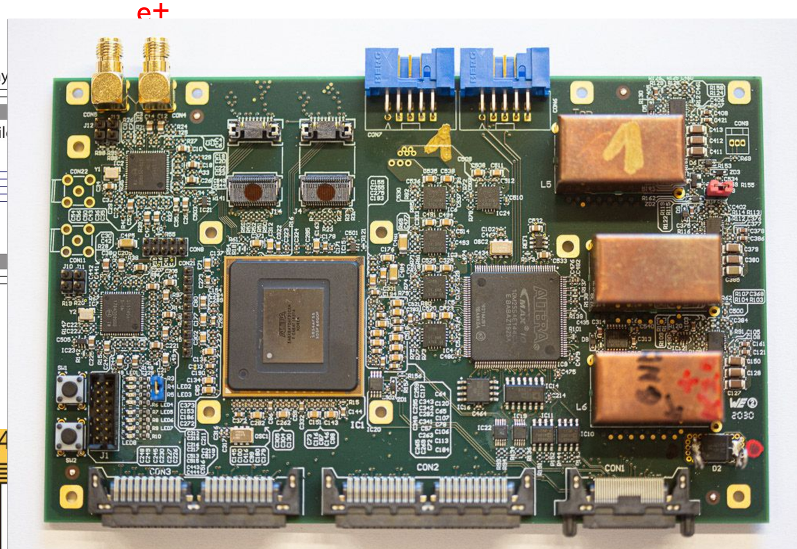
Mu3e = lightweight and fast Michel electron tracker + high throughput online reconstruction & selection DAQ system

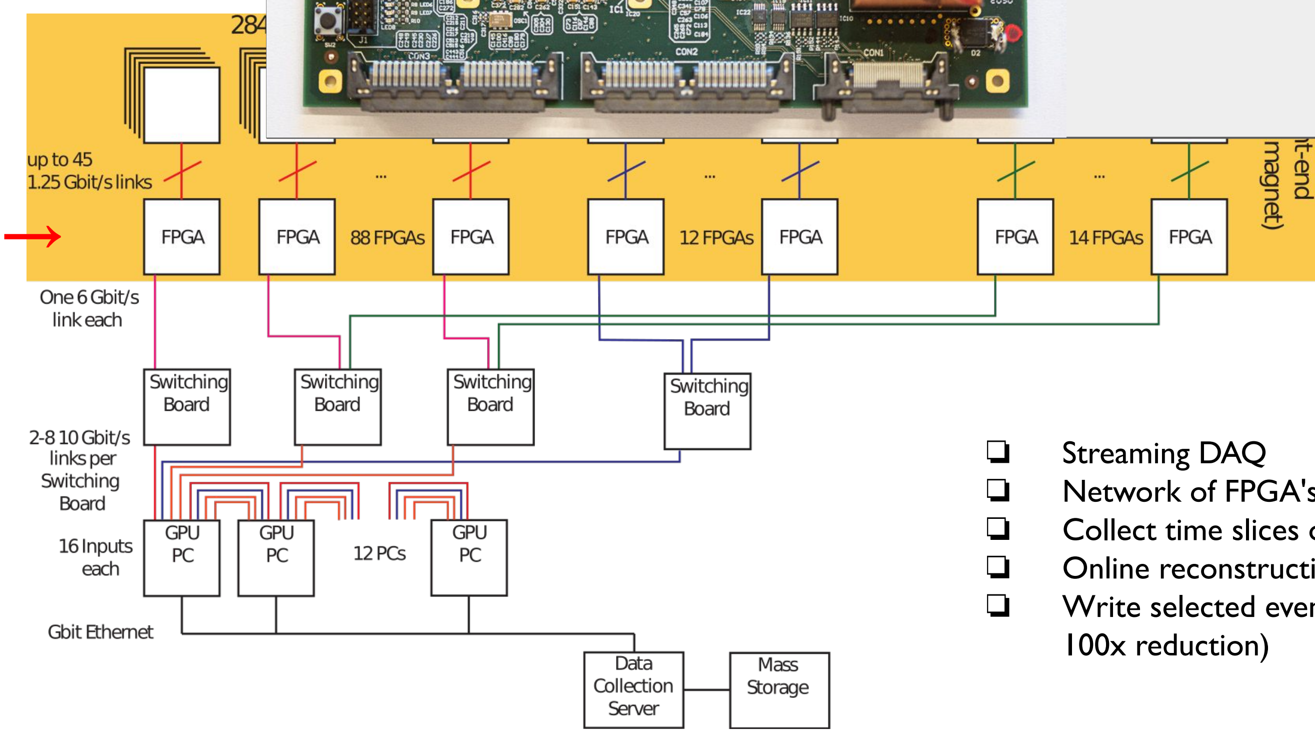


- Streaming DAQ
- Network of FPGA's and optical connections
- Collect time slices of the full detector on a single PC
- Online reconstruction and event selection on a GPUs
- Write selected events to disk at max 100 MB/s (up to 100x reduction)

Mu3e DAQ





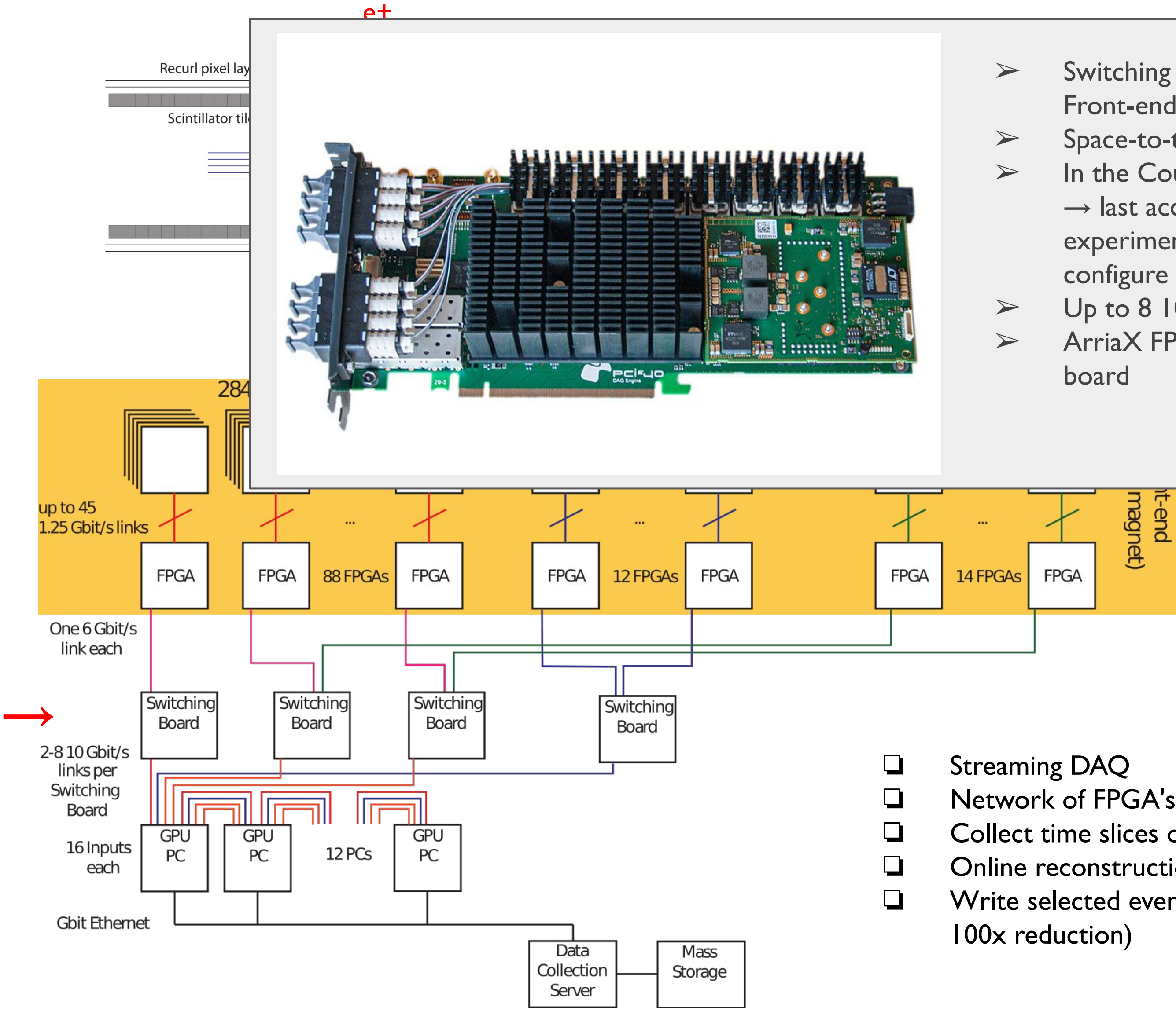


- Time sorting 45x1 MUX of the detector serial data
- Operates in magnetic field and helium atmosphere
- ArriaV FPGA
- 6 Gb/s link to the outside world

low for a RO
e part of a
ombined final
criteria.

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

Mu3e DAQ

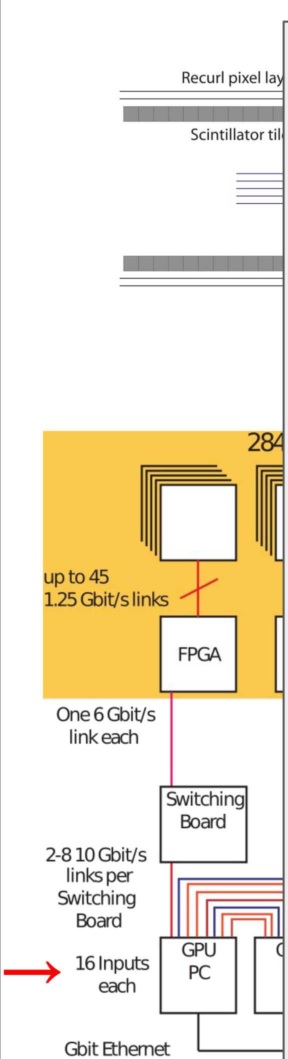


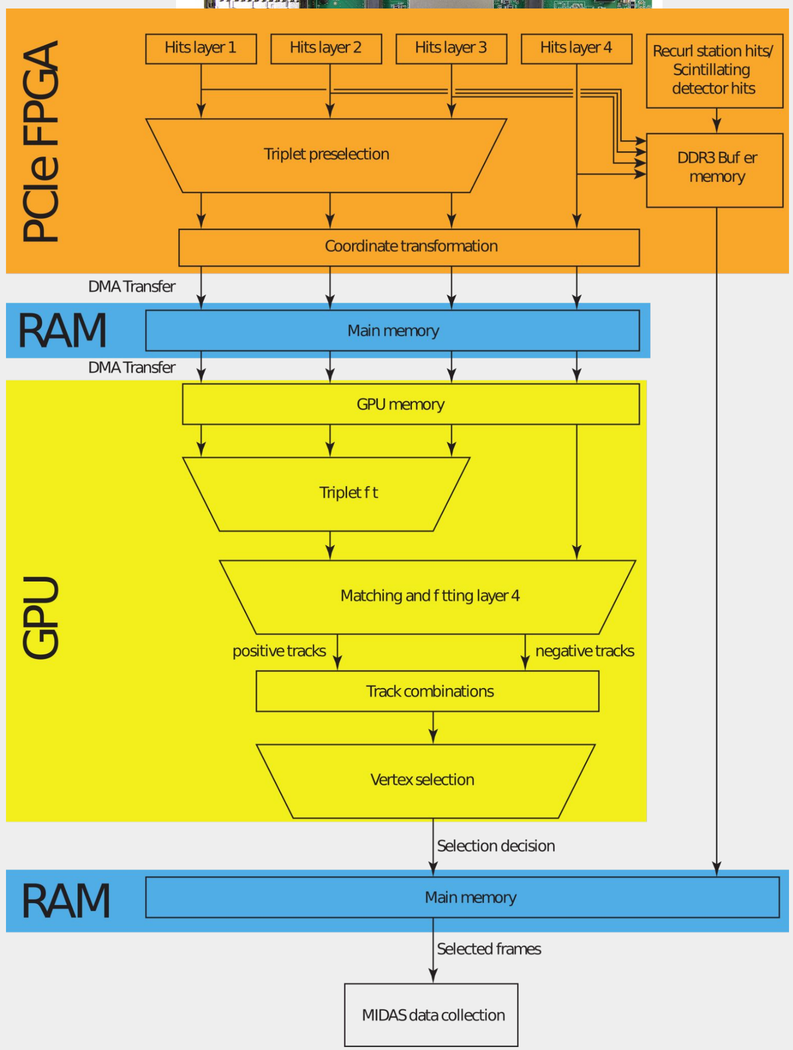
- ➢ Switching boards merging up to 37 Front-end board links
- ➢ Space-to-time slice transformation
- ➢ In the Counting house/inside a PC → last access point of the experiment through which e.g. we configure all the ASICs
- ➢ Up to 8 10Gb/s output links
- ➢ ArriaX FPGA on LHCb custom board

low for a RO
e part of a
ombined final
criteria.

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

Mu3e DAQ

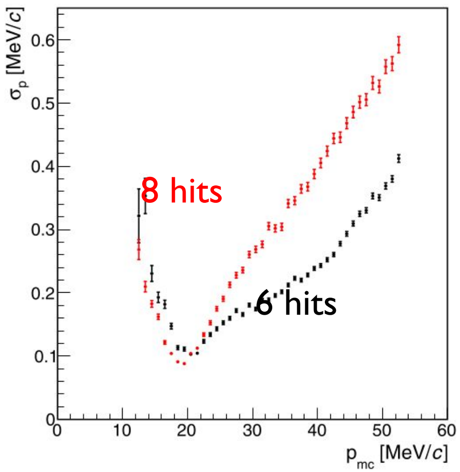




- ➢ Buffer all incoming data in DDR3 memory
- ➢ DMA of centra tracker data to selection PC
- ➢ Run online event selection on GPU
- ➢ Over 10^9 track fits/s achieved per GPU achieved, we can handle 10^8 μ/s
- ➢ Selected events to disk

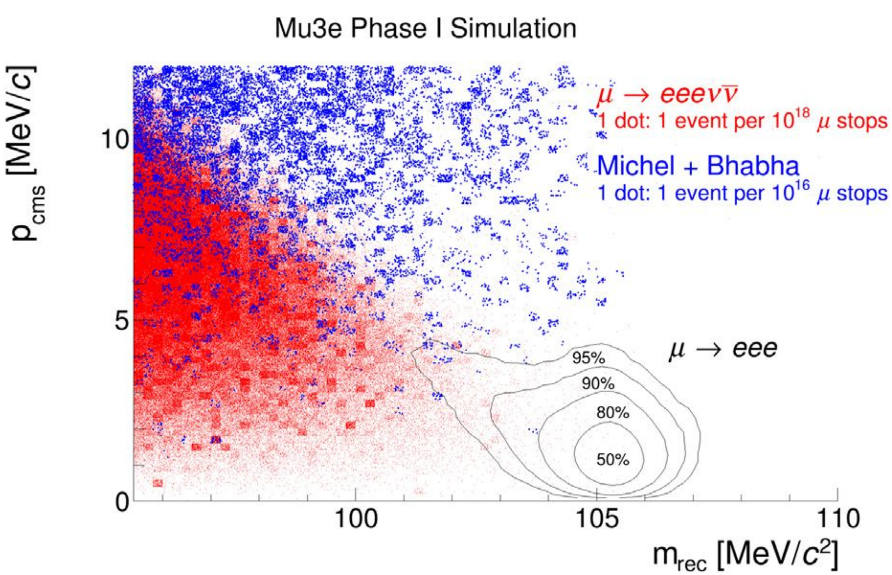
w for a RO
part of a
mbined final
riteria.
PC
up to

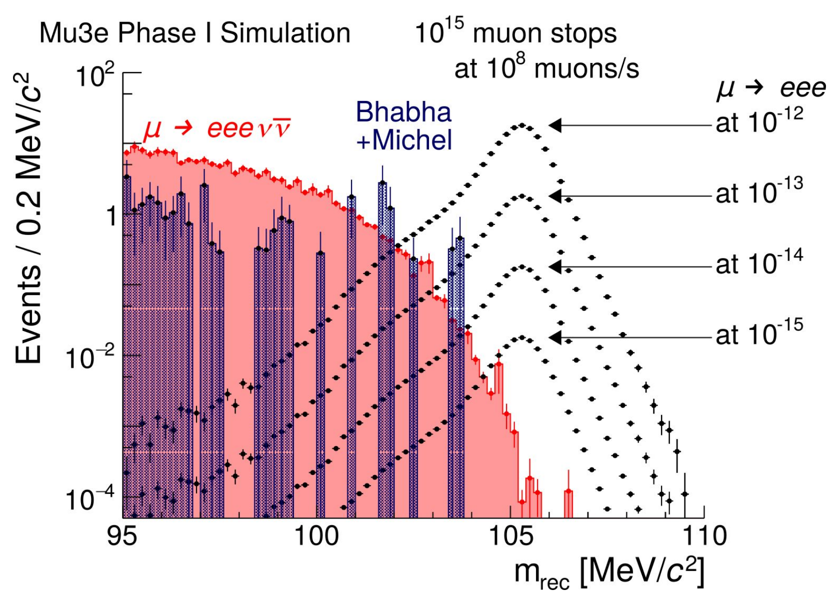
Mu3e sensitivity



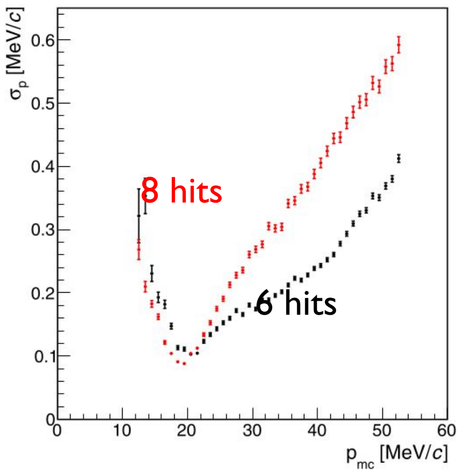
Based on full Monte Carlo simulation of the experiment, and an analytical track fitter https://arxiv.org/abs/1606.04990:

The Mu3e Phase I detector can achieve a $2 \cdot 10^{-15}$ SES on $\mu^+ \rightarrow e^+e^+e^-$





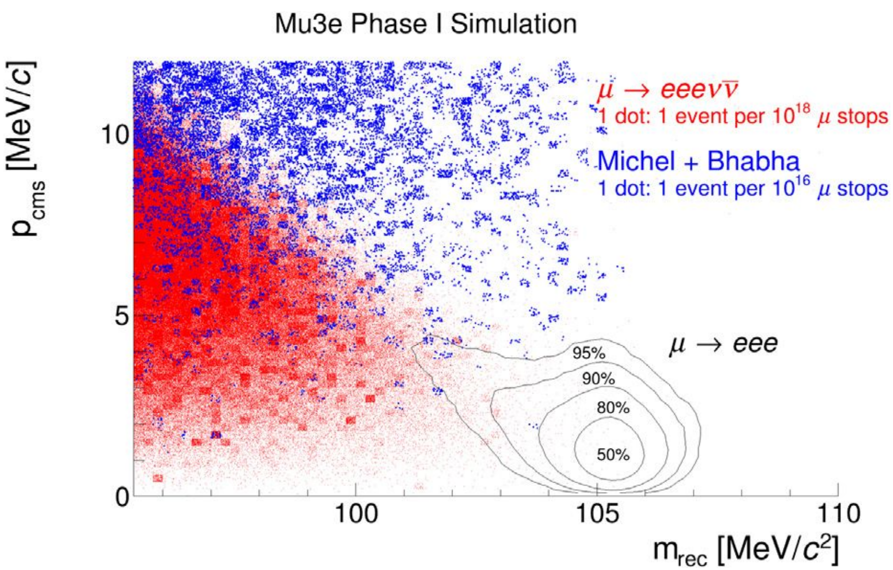
Mu3e sensitivity

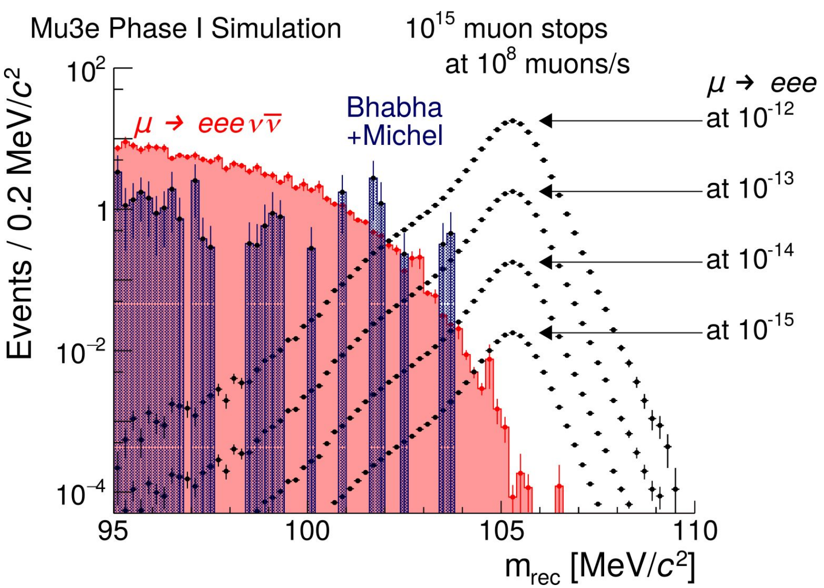


Based on full Monte Carlo simulation of the experiment, and an analytical track fitter https://arxiv.org/abs/1606.04990:

The Mu3e Phase I detector can achieve a $2 \cdot 10^{-15}$ SES on $\mu^+ \rightarrow e^+e^+e^-$

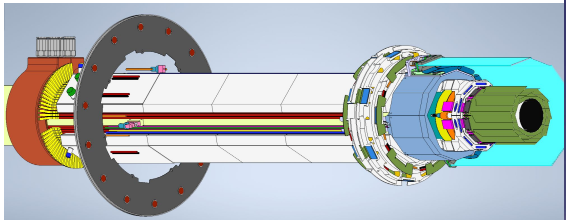
THE END?

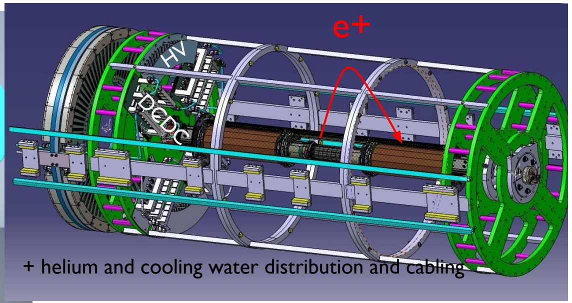




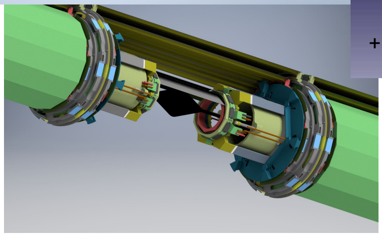
Mu3e detector construction & commissioning

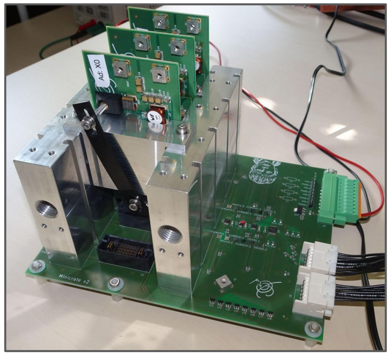
All sensors work to spects
→We have to build a very compact/complicated detector (+ services + DAQ)



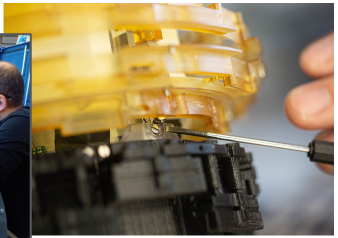


Detailed CAD



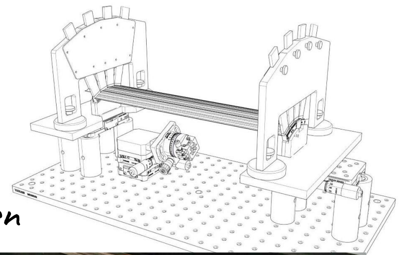


Custom DC-DC converters

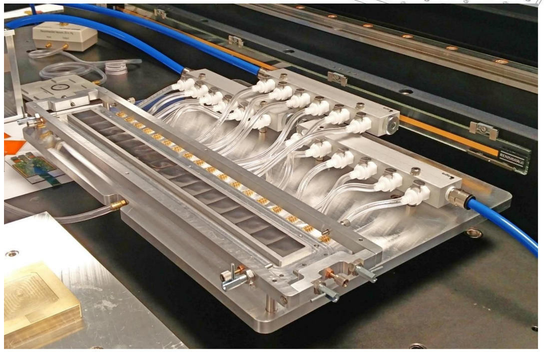


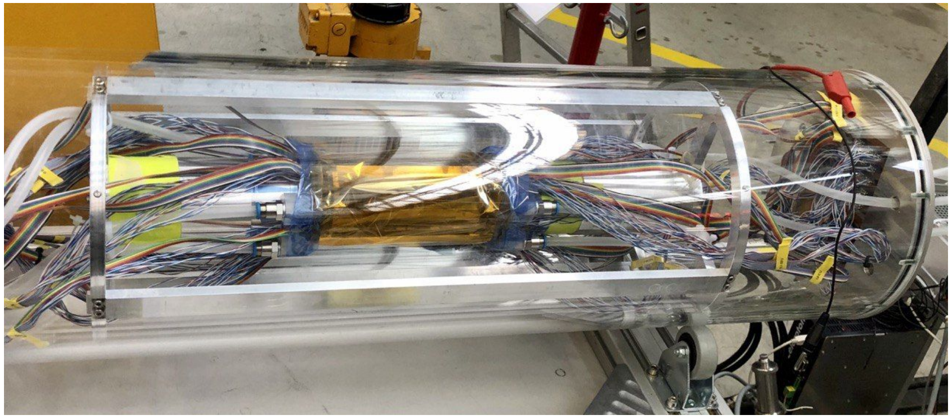
Mockup Mu3e in Heidelberg

……



Tooling design



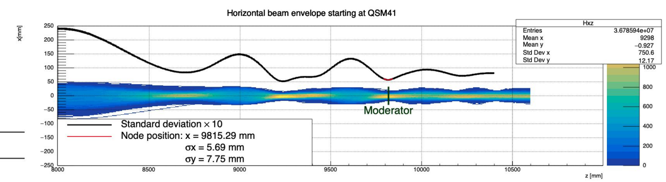


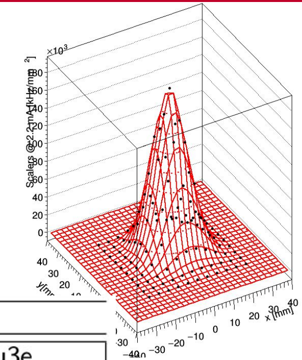
Thermo-mechanical mockup

Mu3e detector construction & commissioning

First we need a magnet and a beam line

Magnet parameter	Value
nominal field	1.0 T
warm bore diameter	1.0 m
warm bore length	2.7 m
field inhomogeneity $\Delta B/B$	$\leq 10^{-3}$
field stability $\Delta B/B$ (100 days)	$\leq 10^{-4}$
field measurement accuracy $\Delta B/B$	$\leq 2.0 \cdot 10^{-4}$
outer dimensions: length	≤ 3.2 m
width	≤ 2.0 m
height	≤ 3.5 m





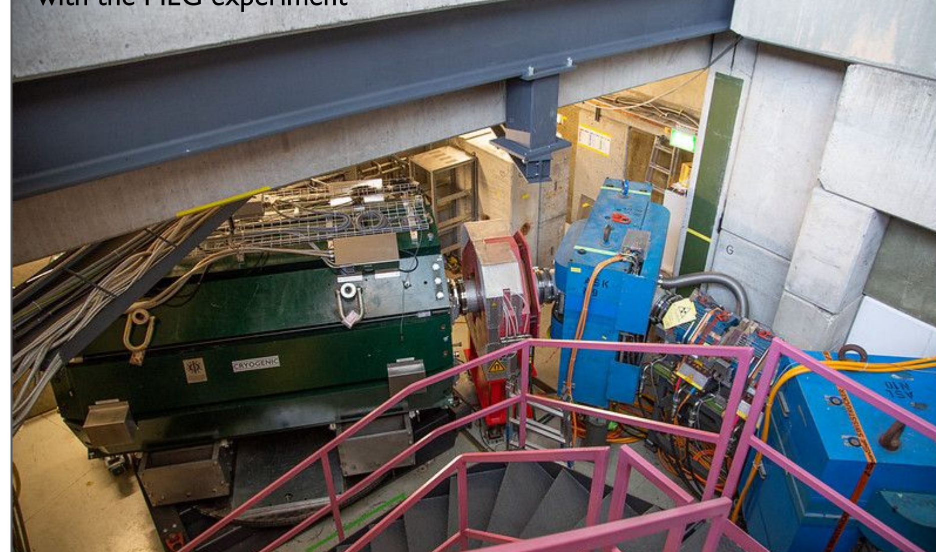
Beam Commissioning Comparison

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.

30T magnet arrives at PSI

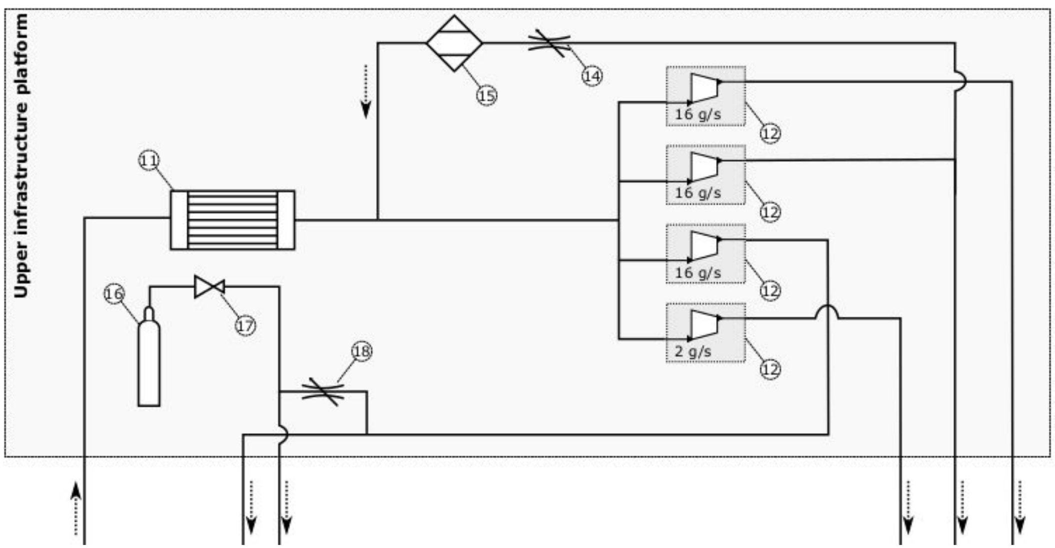
We are at the *Compact muon beamline* because we have to share πE5 with the MEG experiment

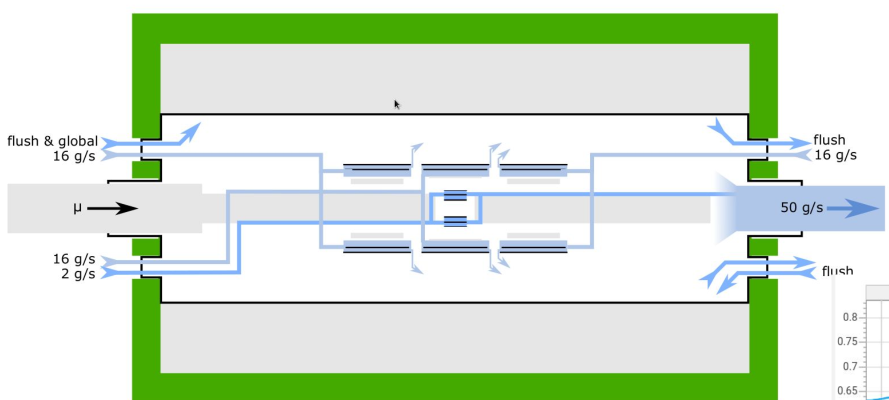


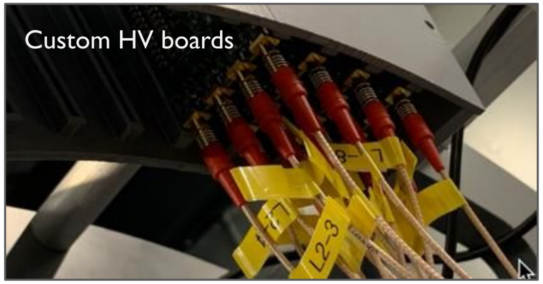
Mu3e detector construction & commissioning

We need services such as gaseous helium cooling, liquid cooling, power, high-voltage, …

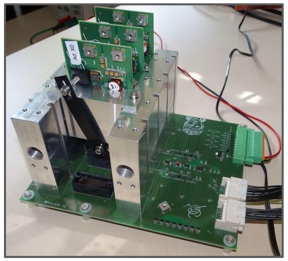
<u>Novel 50 g/s, 5 kW helium cooling system</u>





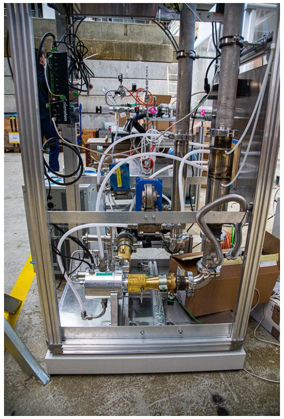


+ Liquid cooling under design. SipM < -10C

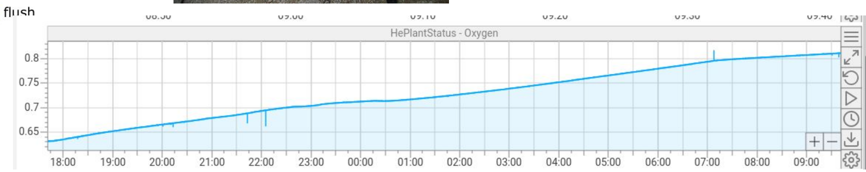


Custom DCDC boards

- 30A
- Magnetic field

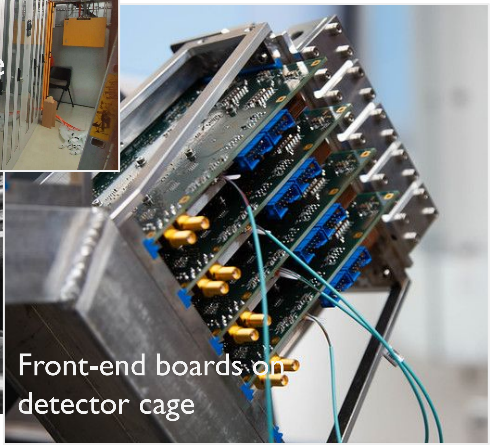


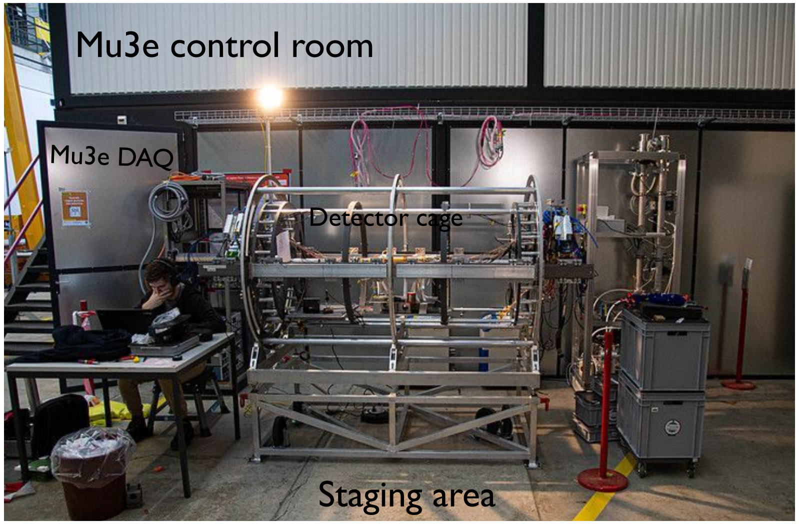
operated 2/9 system with vertex detector for 3 months

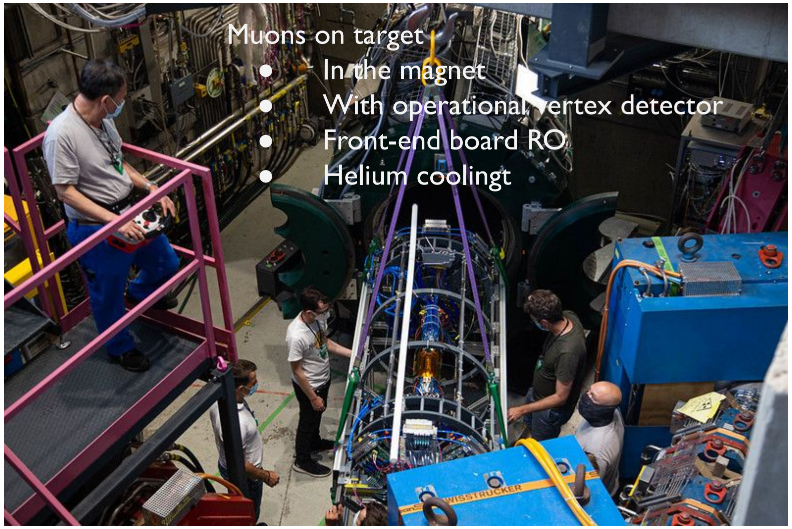


Mu3e detector construction & commissioning

Demonstrator vertex & SciFi detector: 2021 and 2020 commissioning runs

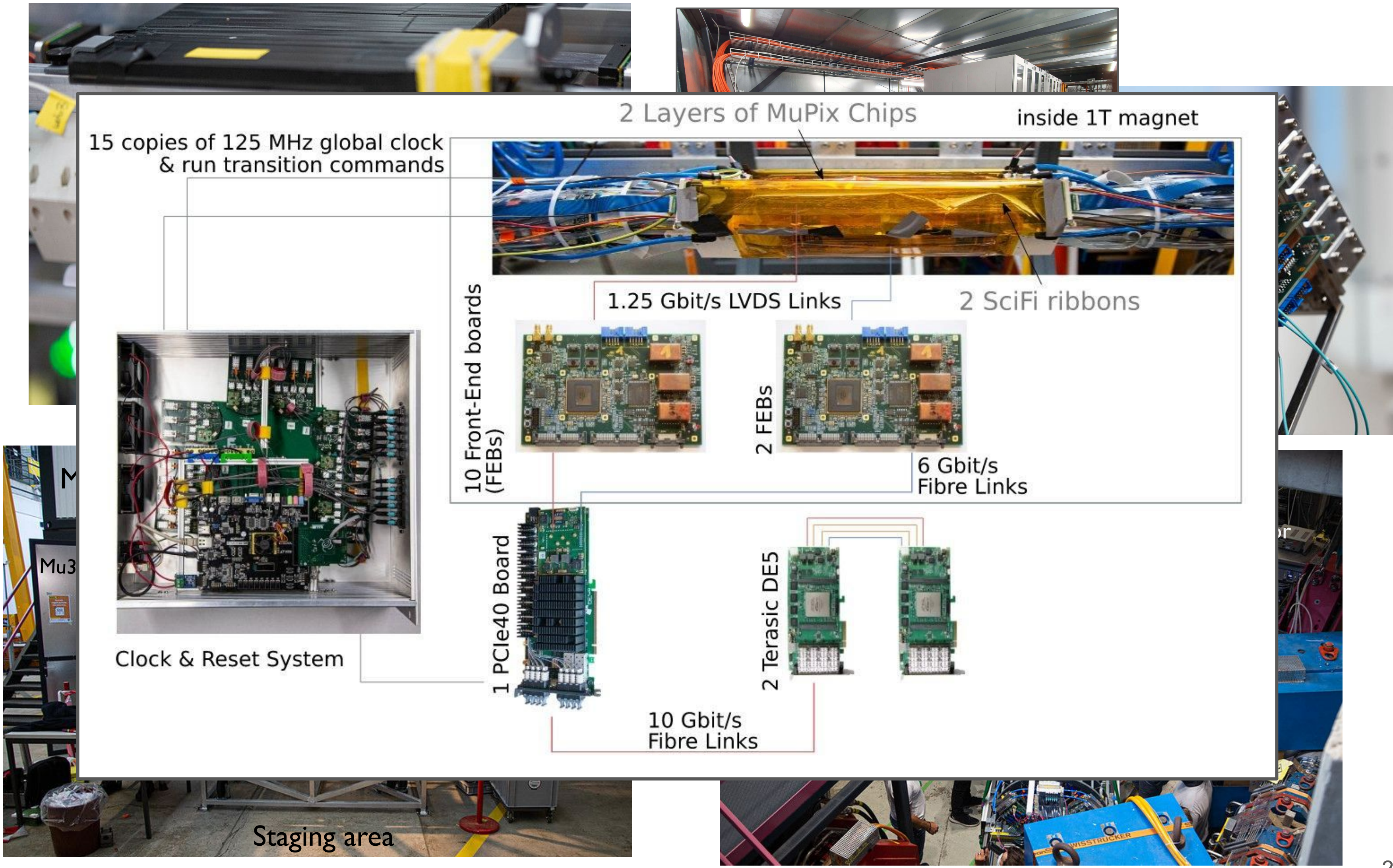






Mu3e detector construction & commissioning

Demonstrator vertex & SciFi detector: 2021 and 2020 commissioning runs



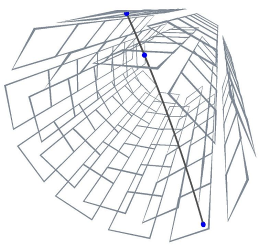
Mu3e detector construction & commissioning

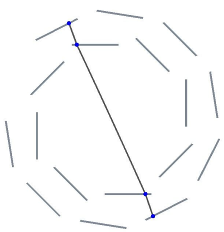
Demonstrator vertex & SciFi detector: 2021 and 2020 commissioning runs

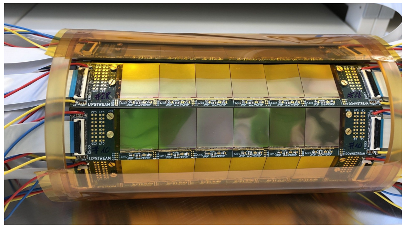
Synch SciFi and Pixel detector, QC test, Cosmic tracks detection, DAQ integration

First beam on target, first recurl positrons detected in magnet

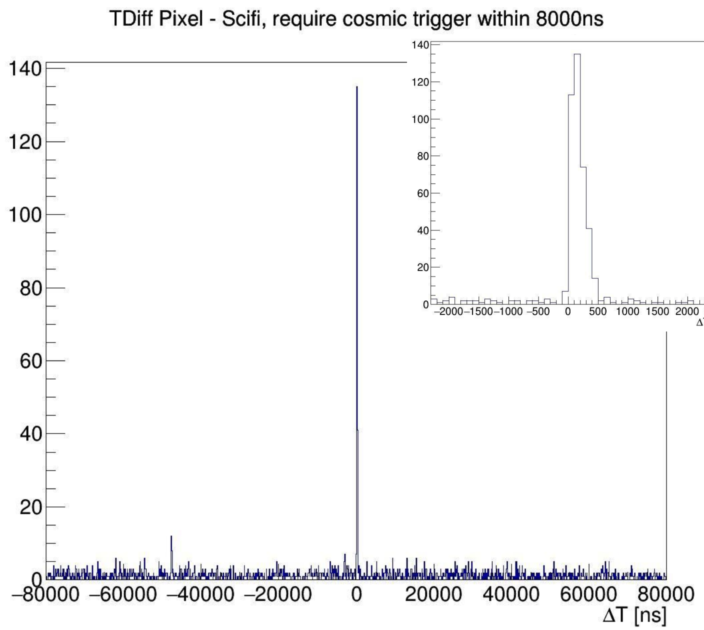
Cosmic track

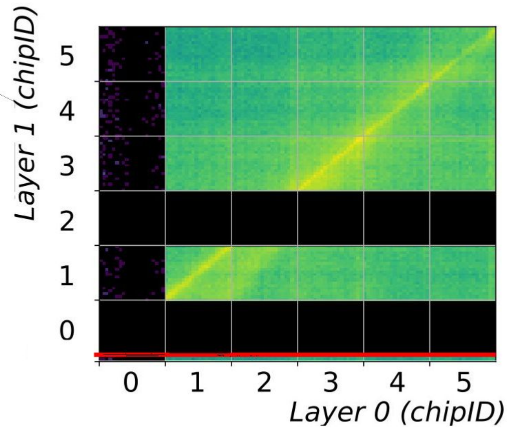




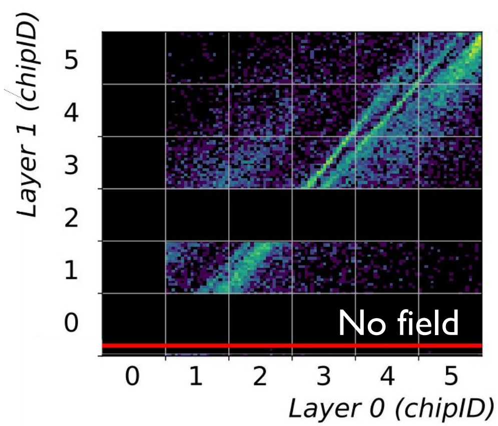


Pixel-SciFi coincidences





Strong correlation between layer 0 & 1
fuzziness because of recurlers

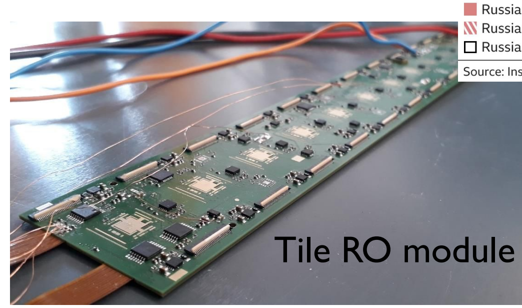


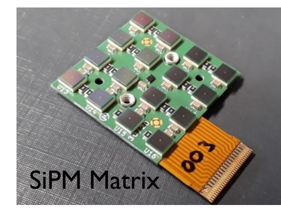
So what's next?

- ❑ *Final* pixel modules:
  - ❑ Alu-Kapton flex
  - ❑ MuPix 11 chip

Being wafer-tested, dices, and thinned

- ❑ Final timing detectors
  - ❑ MuTrig 3 chip end of summer
  - ❑ RO modules being produced





- ❑ Services installation
  - ❑ DC-DC modules under production
  - ❑ He system 2g/s ⟶ 50 g/s
  - ❑ Electronics cooling < 0C detector cooling

- ❑ Build the Phase I Mu3e detector in steps in our staging area (2022/2023)
- ❑ Full Commissioning in 2024
- ❑ Physics data taking in 2025-2026 of the Mu3e Phase I experiment, reaching SES of $2 \cdot 10^{-15}$ on $\mu^+ \rightarrow e^+ e^+ e^-$

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

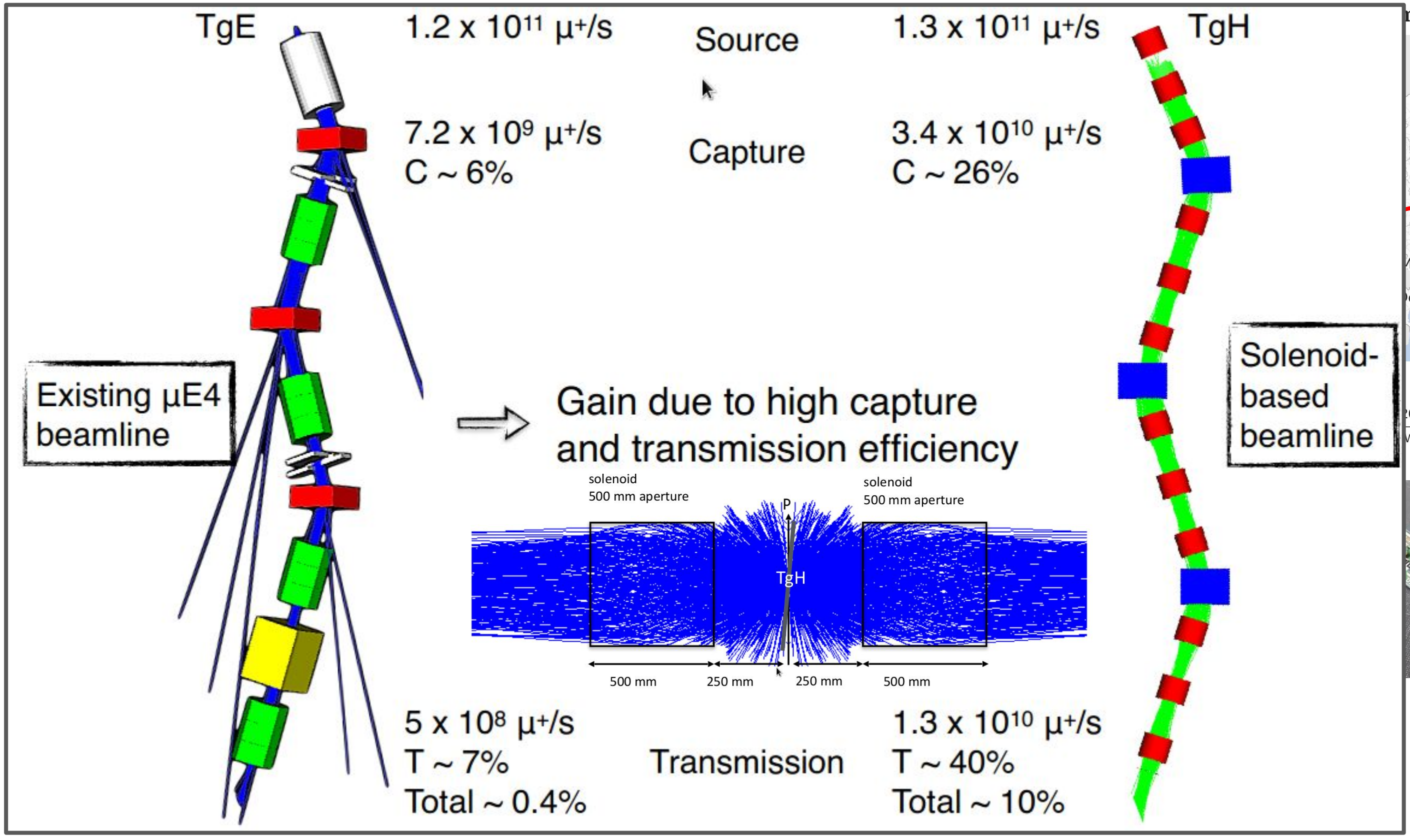
ELSEVIER

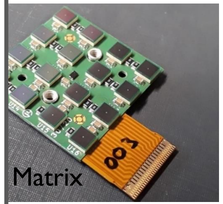
Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

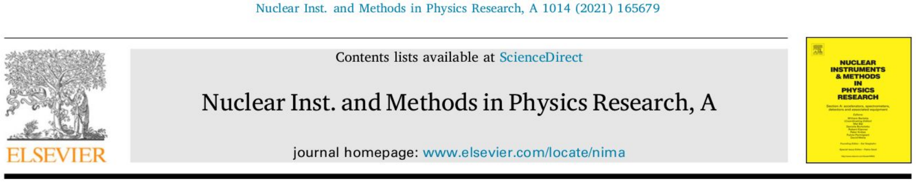
journal homepage: www.elsevier.com/locate/nima

So what's next?





- ❑ Full Commissioning in 2024
- ❑ Physics data taking in 2025-2026 of the Mu3e Phase I experiment, reaching SES of $2 \cdot 10^{-15}$ on $\mu^+ \rightarrow e^+e^+e^-$
- ❑ HiMB upgrade in 2027-2028, start preparing Mu3e Phase II aiming for $1 \cdot 10^{-16}$

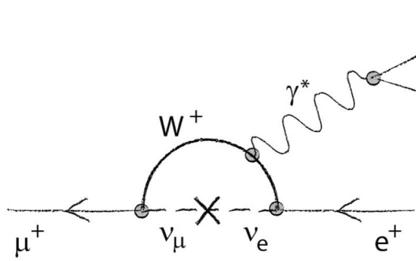

Nuclear Inst. and Methods in Physics Research, A 1014 (2021) 165679

Contents lists available at ScienceDirect

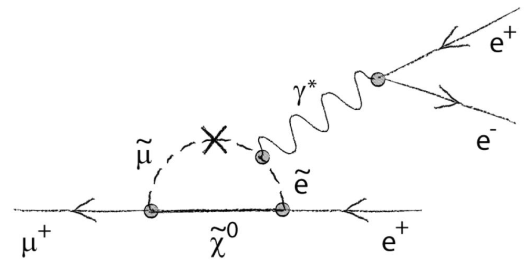
Nuclear Inst. and Methods in Physics Research, A

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

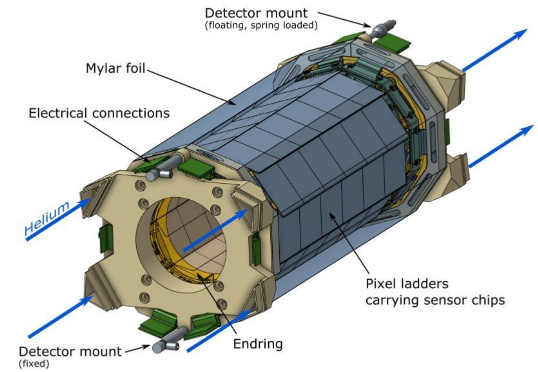
ELSEVIER

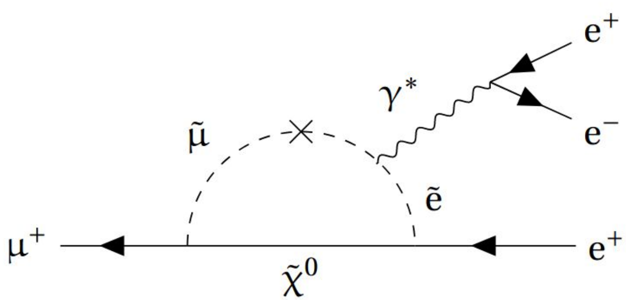

W+
γ*
e+
e-
μ+
νμ
νe
e+

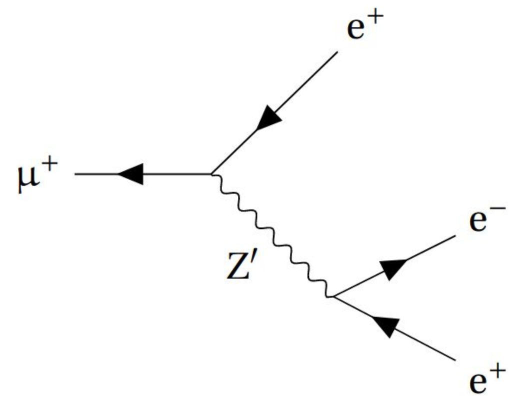
(a)

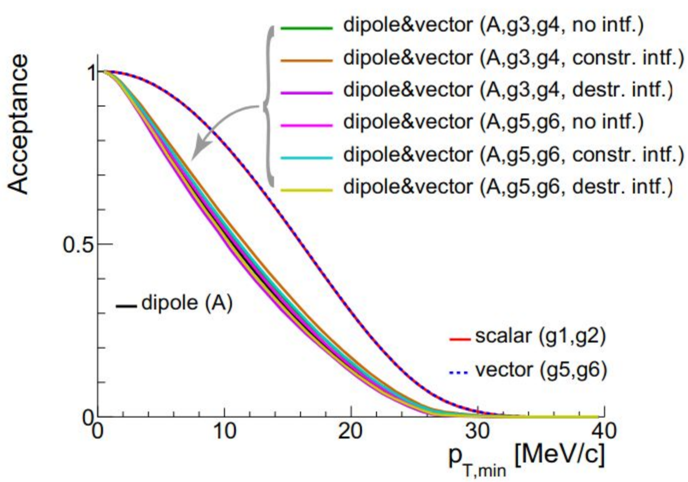

γ*
e+
e-
μ̃
ẽ
μ+
χ̃0
e+

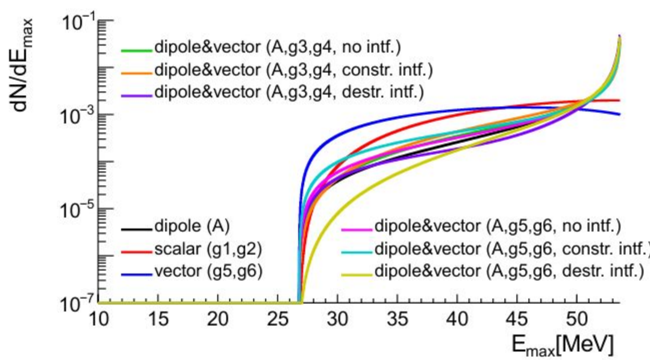
(b)


Detector mount
(floating, spring loaded)
Mylar foil
Electrical connections
Helium
Pixel ladders
carrying sensor chips
Endring
Detector mount
(fixed)


e+
γ*
e−
μ̃
ẽ
μ+
e+
χ̃0


e+
μ+
e−
Z′
e+


Acceptance
dipole&vector (A,g3,g4, no intf.)
dipole&vector (A,g3,g4, constr. intf.)
dipole&vector (A,g3,g4, destr. intf.)
dipole&vector (A,g5,g6, no intf.)
dipole&vector (A,g5,g6, constr. intf.)
dipole&vector (A,g5,g6, destr. intf.)
dipole (A)
scalar (g1,g2)
vector (g5,g6)
p_T,min [MeV/c]


dN/dE_max
dipole&vector (A,g3,g4, no intf.)
dipole&vector (A,g3,g4, constr. intf.)
dipole&vector (A,g3,g4, destr. intf.)
dipole (A)
scalar (g1,g2)
vector (g5,g6)
dipole&vector (A,g5,g6, no intf.)
dipole&vector (A,g5,g6, constr. intf.)
dipole&vector (A,g5,g6, destr. intf.)
E_max[MeV]

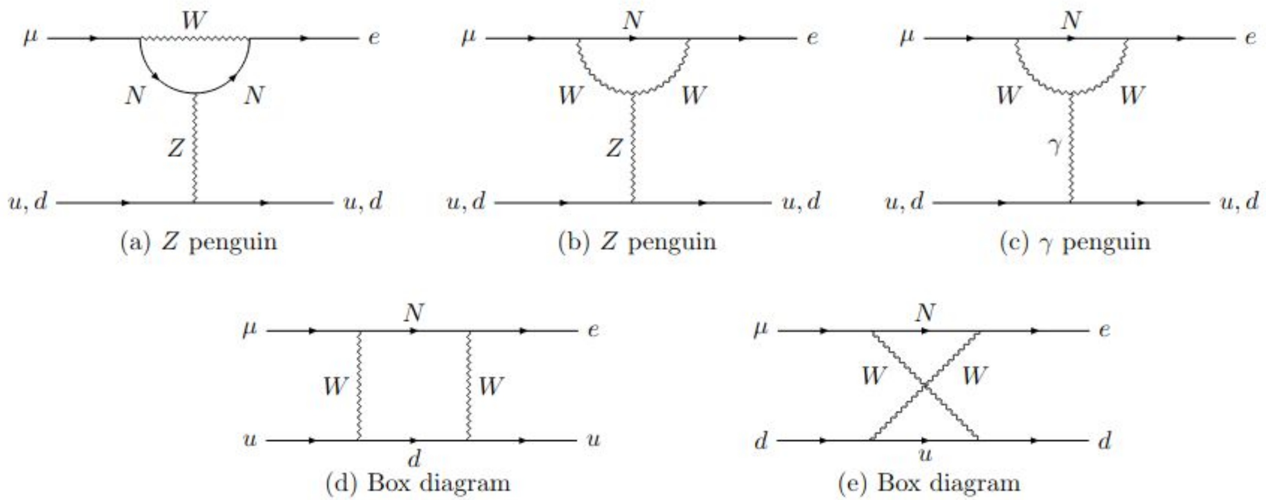


FIG. 1. One-loop diagrams contributing to the $\mu \to e$ conversion process, including 2 HNL "penguin" diagrams (a). Diagrams containing HNLs that dress external lines are not shown (see [24, 68–71] for the full list of such diagrams).

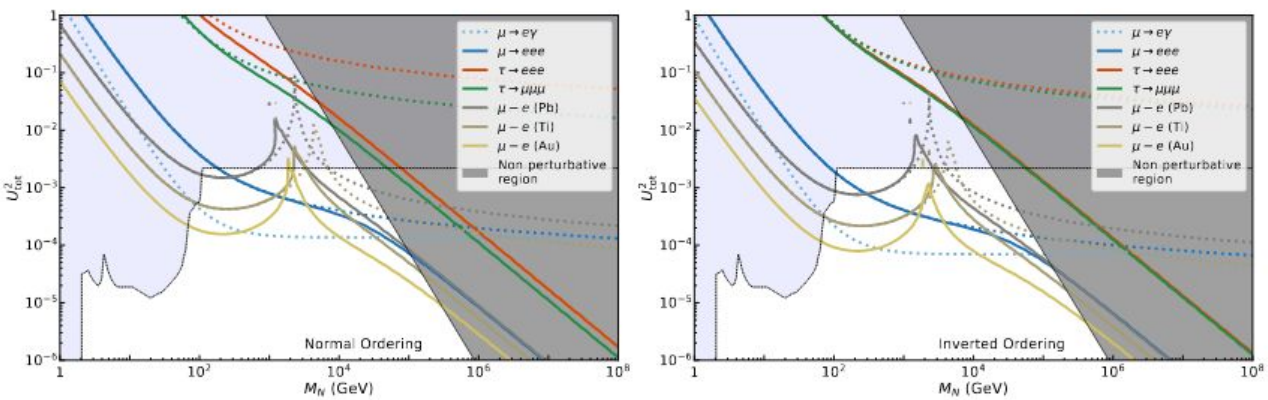
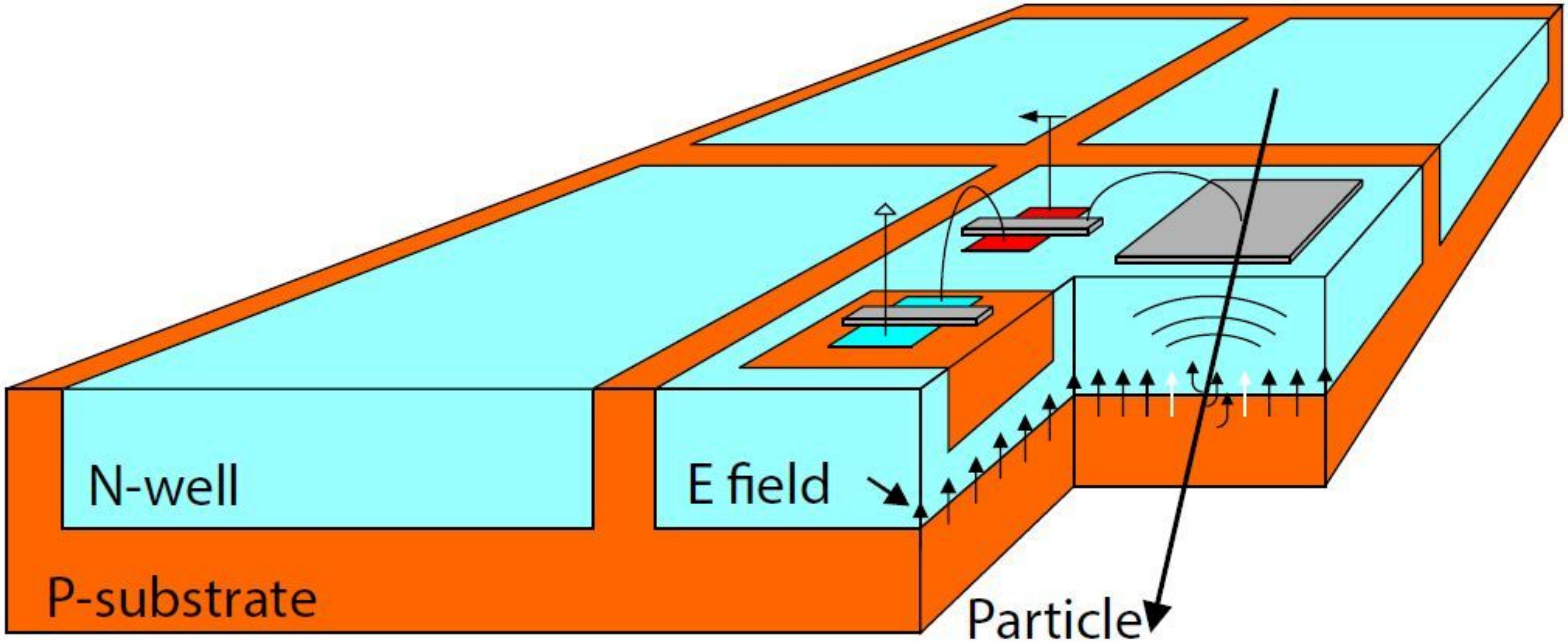
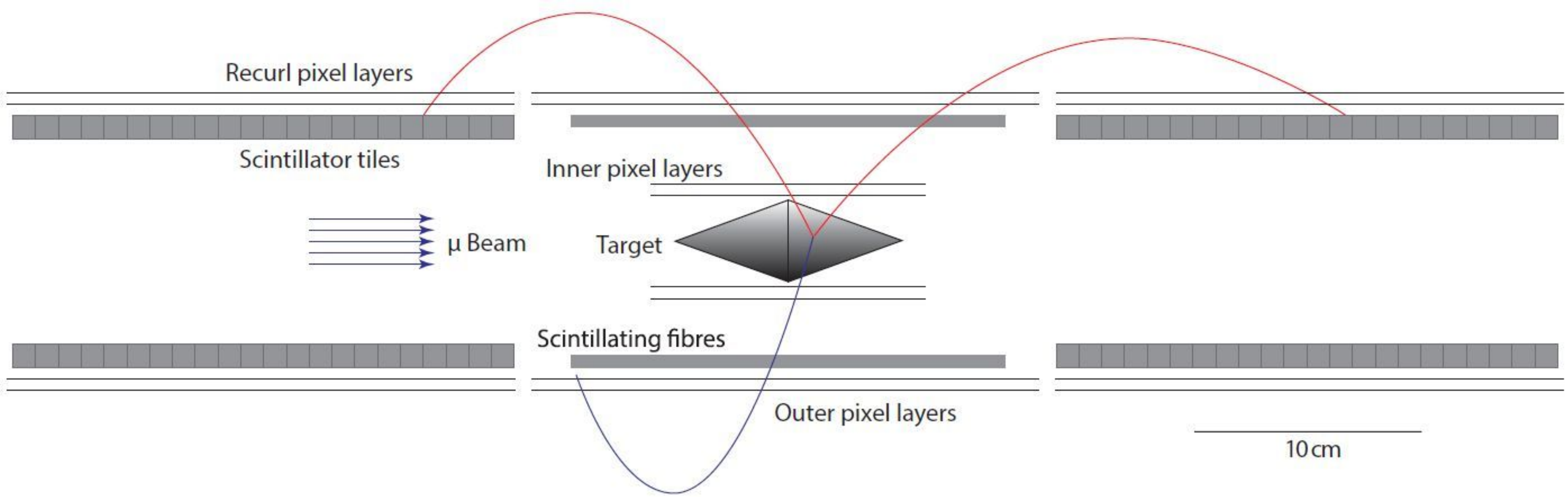
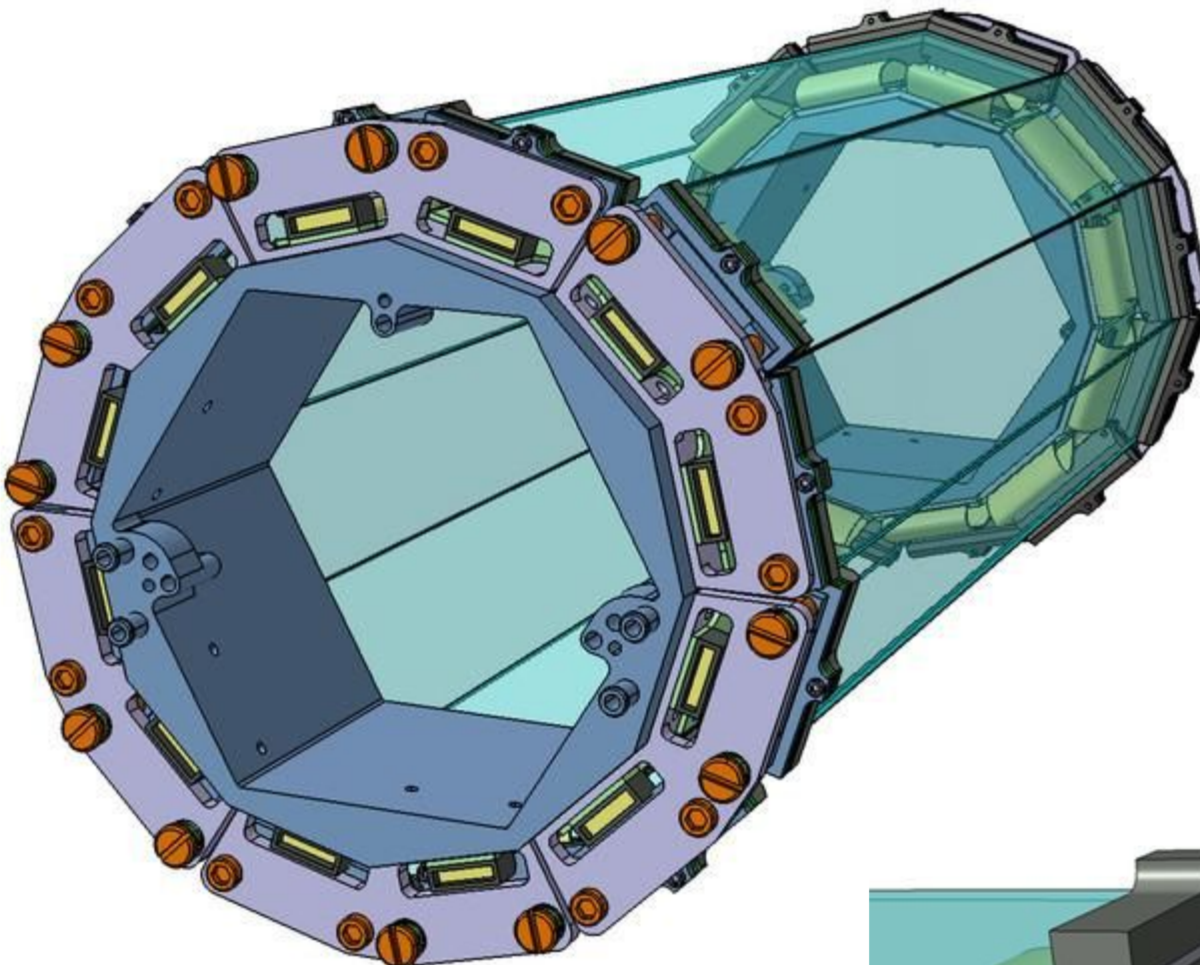


FIG. 2. Improved experimental limits on HNLs coupling from charged lepton flavor violation processes (solid lines). The strongest bound comes from the $\mu \to e$ conversion in gold [72]. Blue shaded region: previous constraints, not including cLFV. Gray shaded region: non-perturbative regime (see text for details). Dotted lines: previous cLFV constrains from the works [56, 59, 60, 67, 73]. Results are expressed in terms of $U^2_{\rm tot}$ for flavor ratios (4), see text for details.

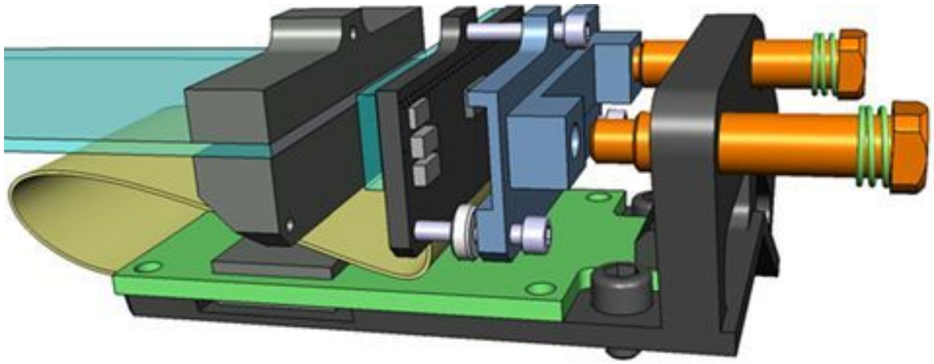
https://arxiv.org/abs/2206.04540

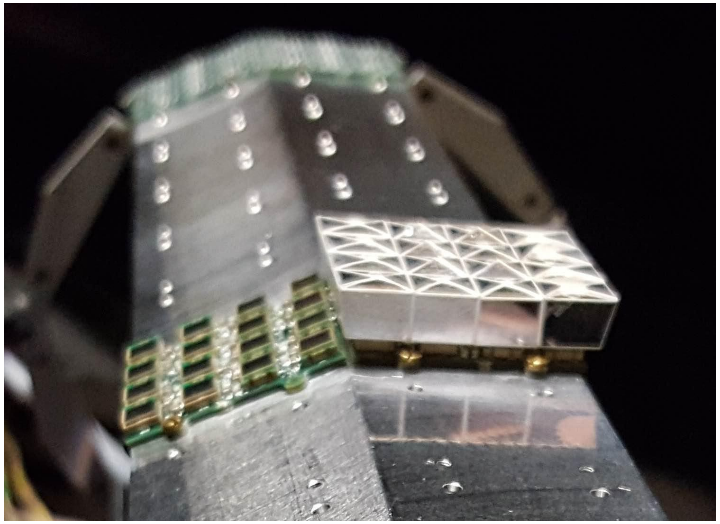

N-well
E field
P-substrate
Particle

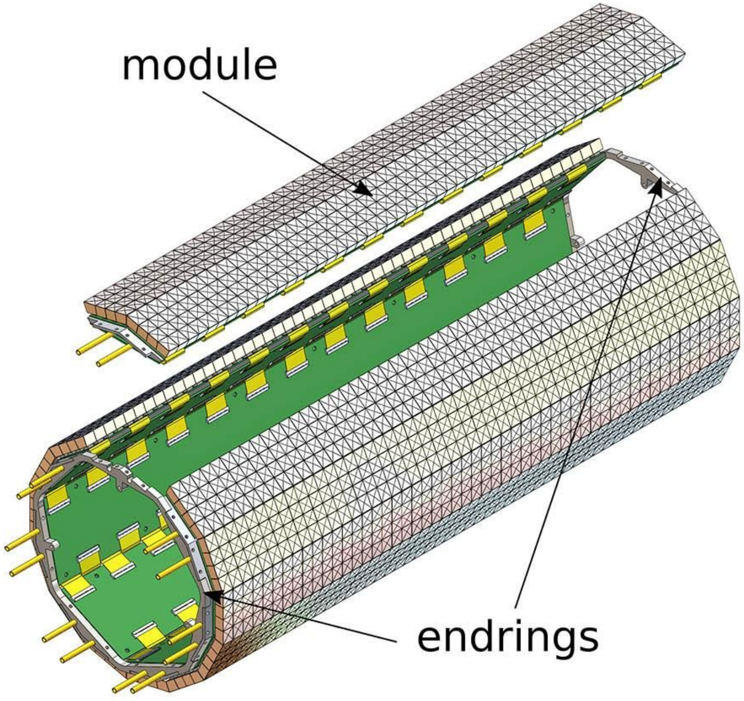

Recurl pixel layers
Scintillator tiles
Inner pixel layers
μ Beam
Target
Scintillating fibres
Outer pixel layers
10 cm




300 mm
32.5 mm



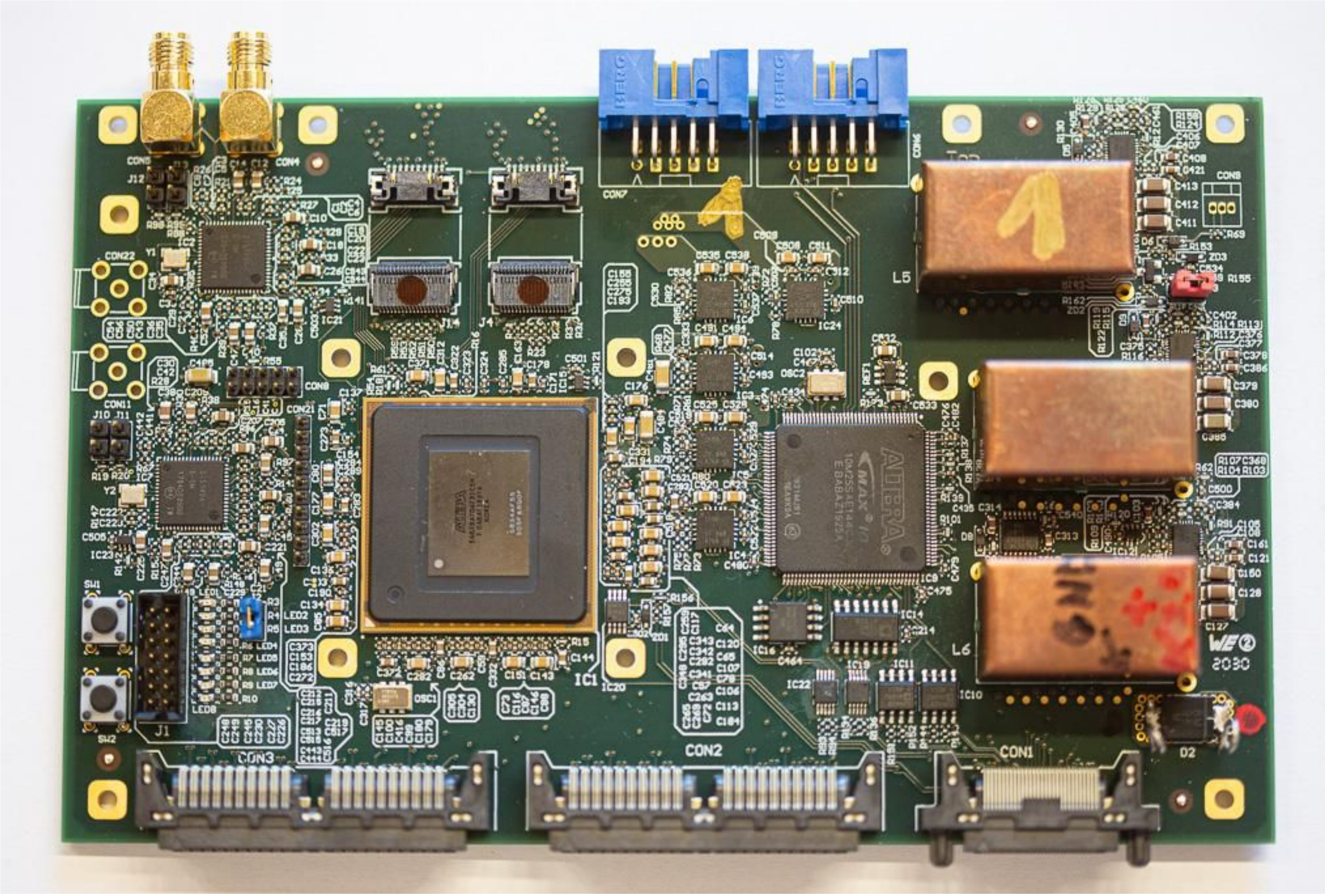


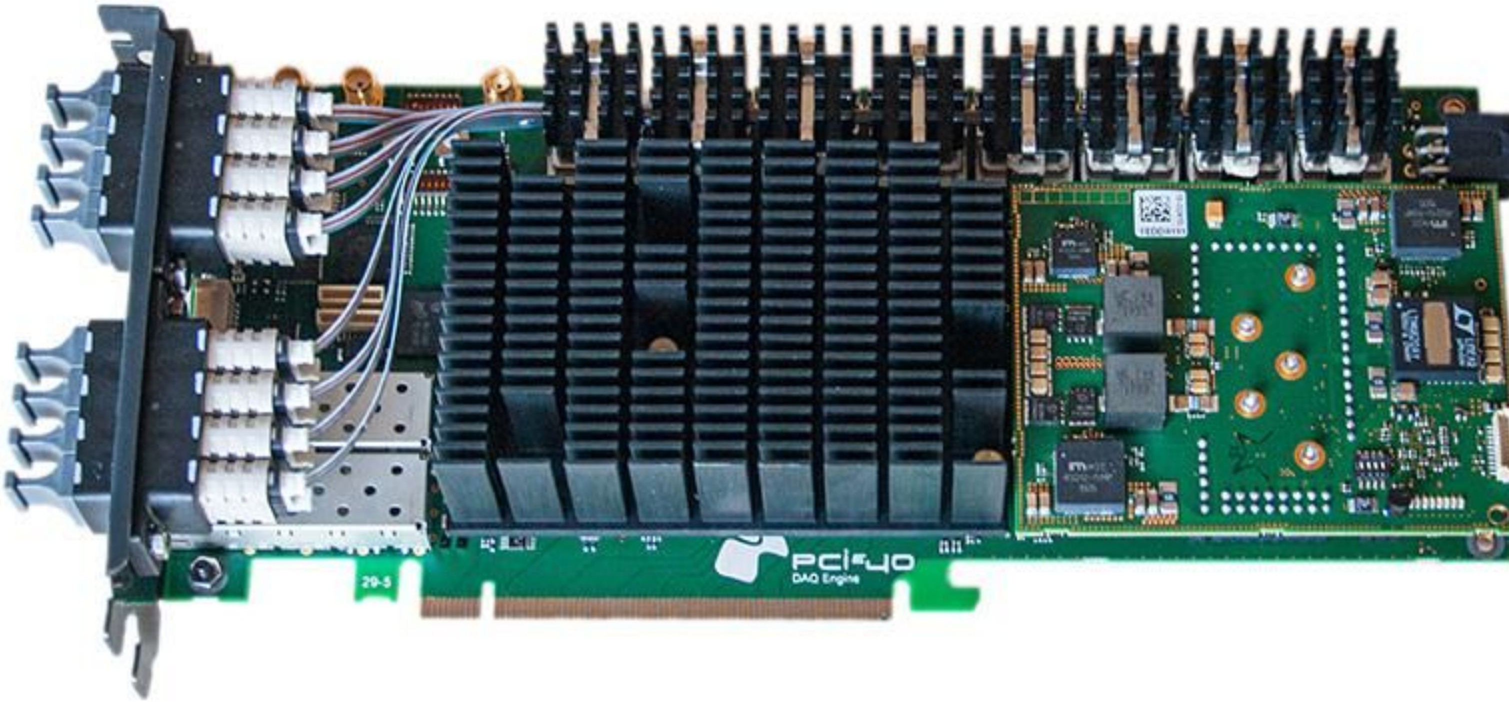

module
endrings

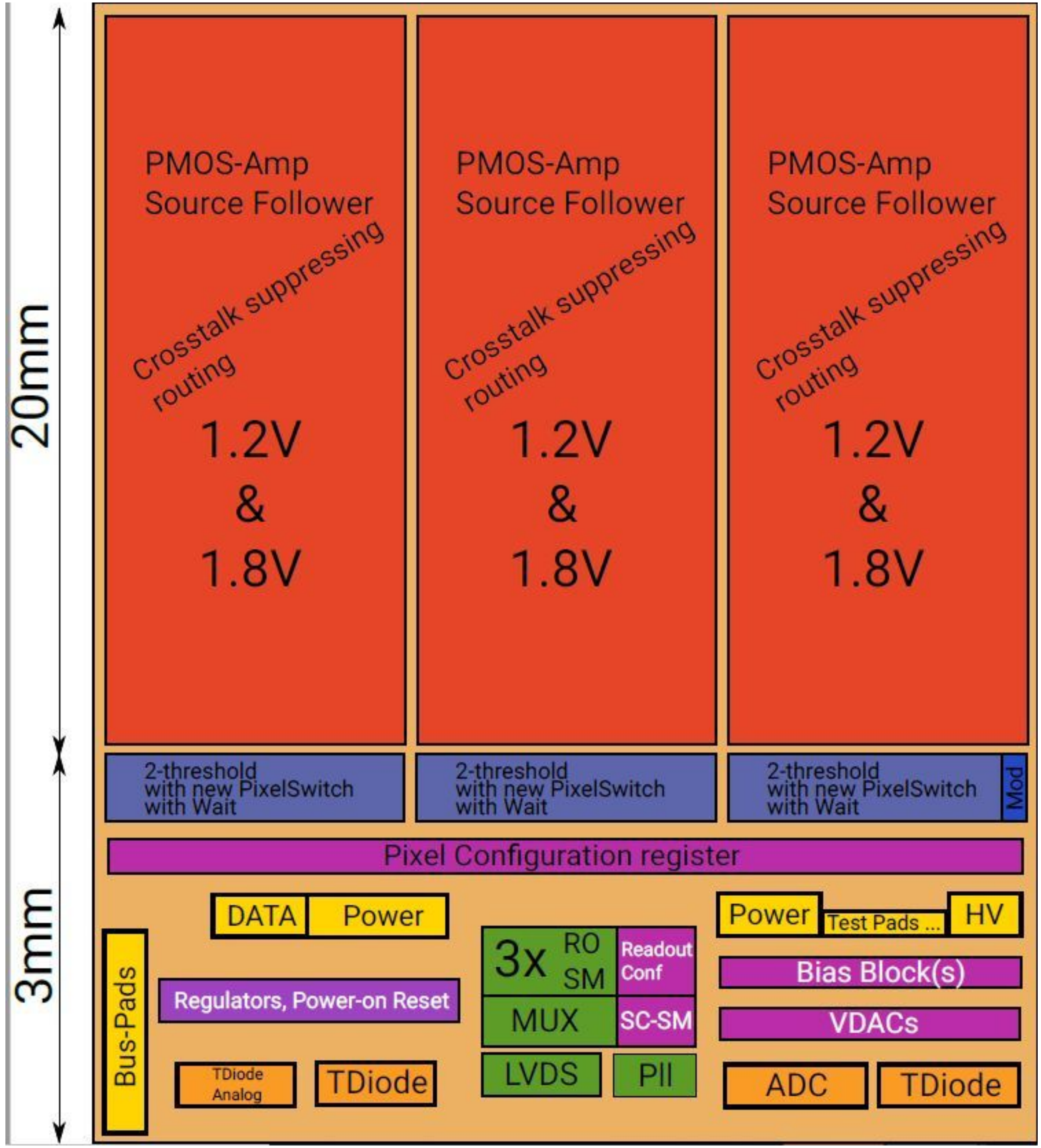
Gouvea and Vogel arXiv:1303.4097

Kuno Muon decay SM and BSM arXiv:hep-ph/9909265

https://www.youtube.com/watch?v=IIC8ioxToZg

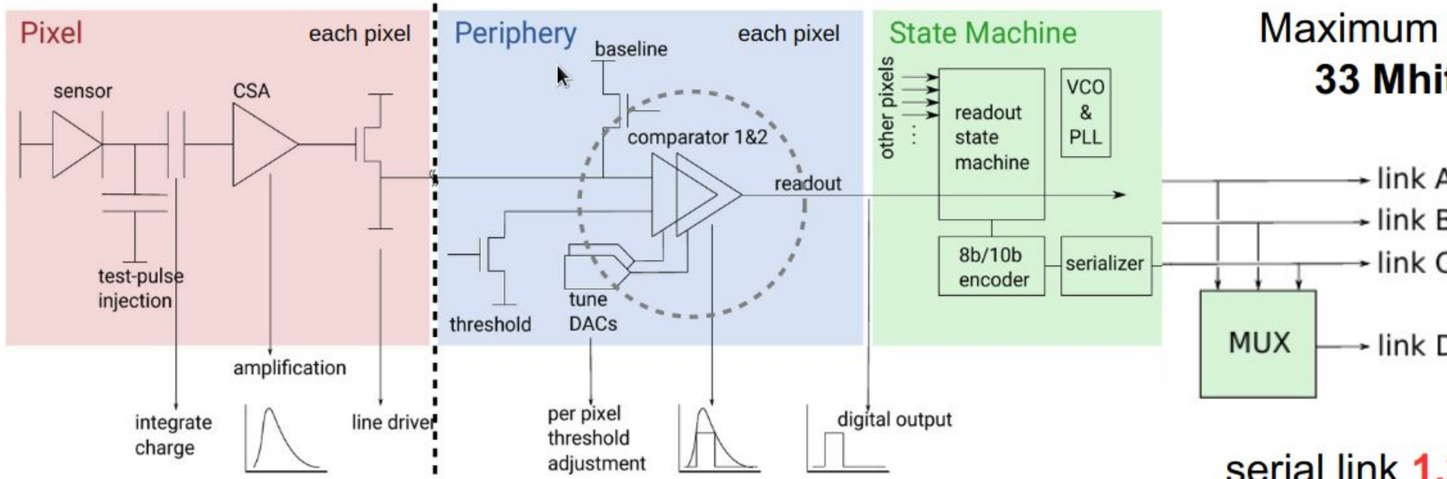

CON3
CON2
CON1
CON7
L5
L6
IC1
D2
J1
ALTERA
MAX 10
2030


pcie40
DAQ Engine
29-5


20mm
3mm
PMOS-Amp
Source Follower
Crosstalk suppressing
routing
1.2V
&
1.8V
PMOS-Amp
Source Follower
Crosstalk suppressing
routing
1.2V
&
1.8V
PMOS-Amp
Source Follower
Crosstalk suppressing
routing
1.2V
&
1.8V
2-threshold
with new PixelSwitch
with Wait
2-threshold
with new PixelSwitch
with Wait
2-threshold
with new PixelSwitch
with Wait
Mod
Pixel Configuration register
DATA
Power
Bus-Pads
Regulators, Power-on Reset
TDiode
Analog
TDiode
3x
RO
SM
Readout
Conf
MUX
SC-SM
LVDS
Pll
Power
Test Pads ...
HV
Bias Block(s)
VDACs
ADC
TDiode

High Rate & Continuous Readout

MuPix



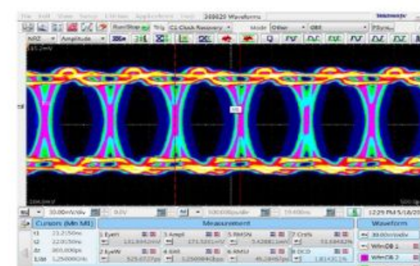
Maximum readout rate is
33 Mhits/s per link

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

MuPix8 sensor

periphery & SM

eye diagram

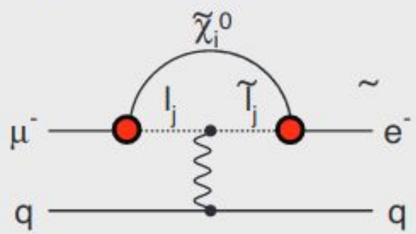


MuPix series is the first monolithic pixel sensor with continuous sampling and readout!

Possible Contributions to CLFV

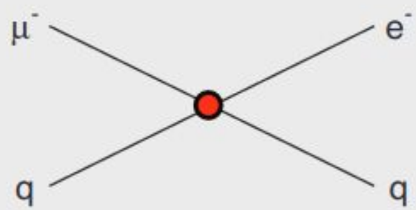
Supersymmetry

rate ~ 10^{-15}



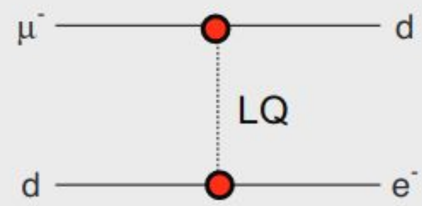
Compositeness

$\Lambda_c \sim 3000$ TeV



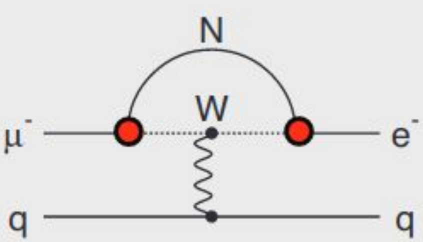
Leptoquark

$M_{LQ} = 3000\ (\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2



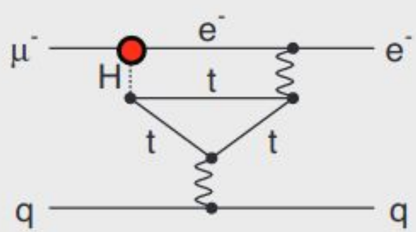
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2 \sim 8\times10^{-13}$



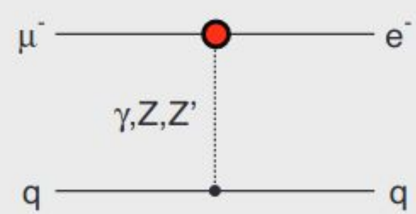
Second Higgs Doublet

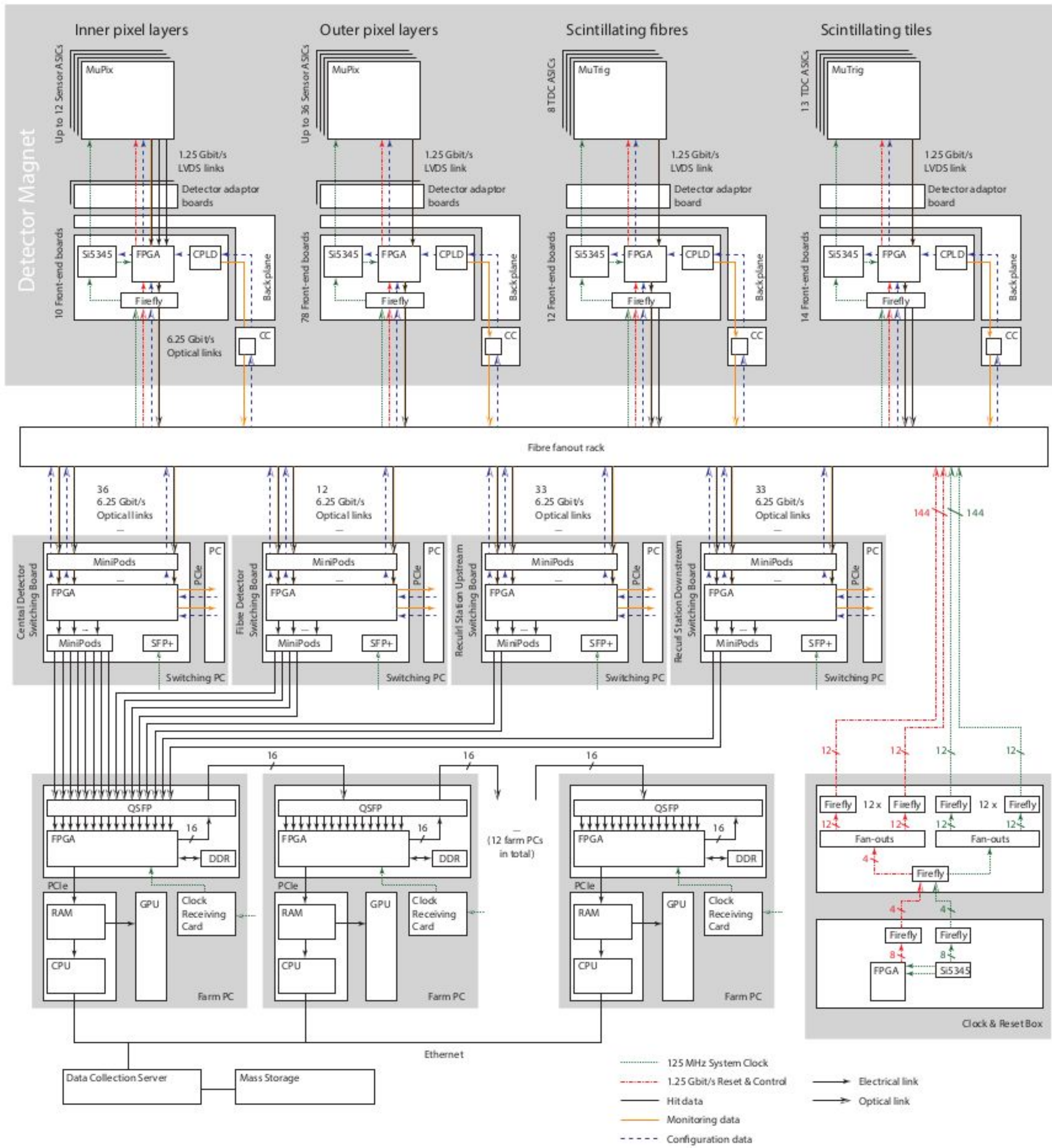
$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu\mu})$



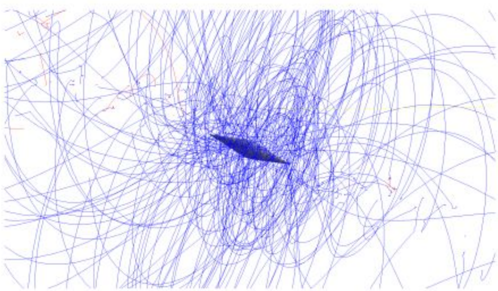
Heavy Z’ Anomal. Z Coupling

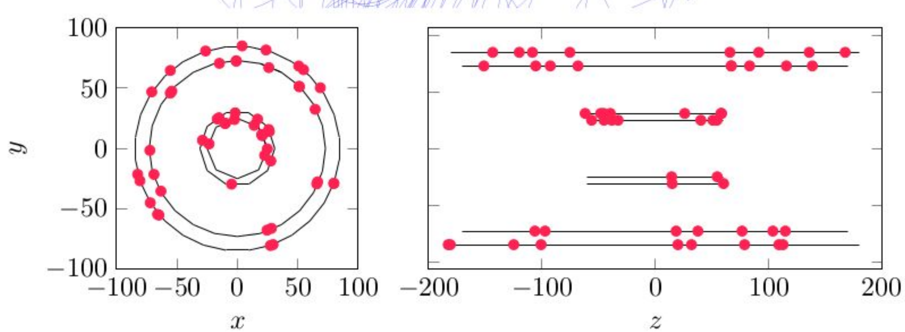
$M_{Z'} = 3000$ TeV/c^2

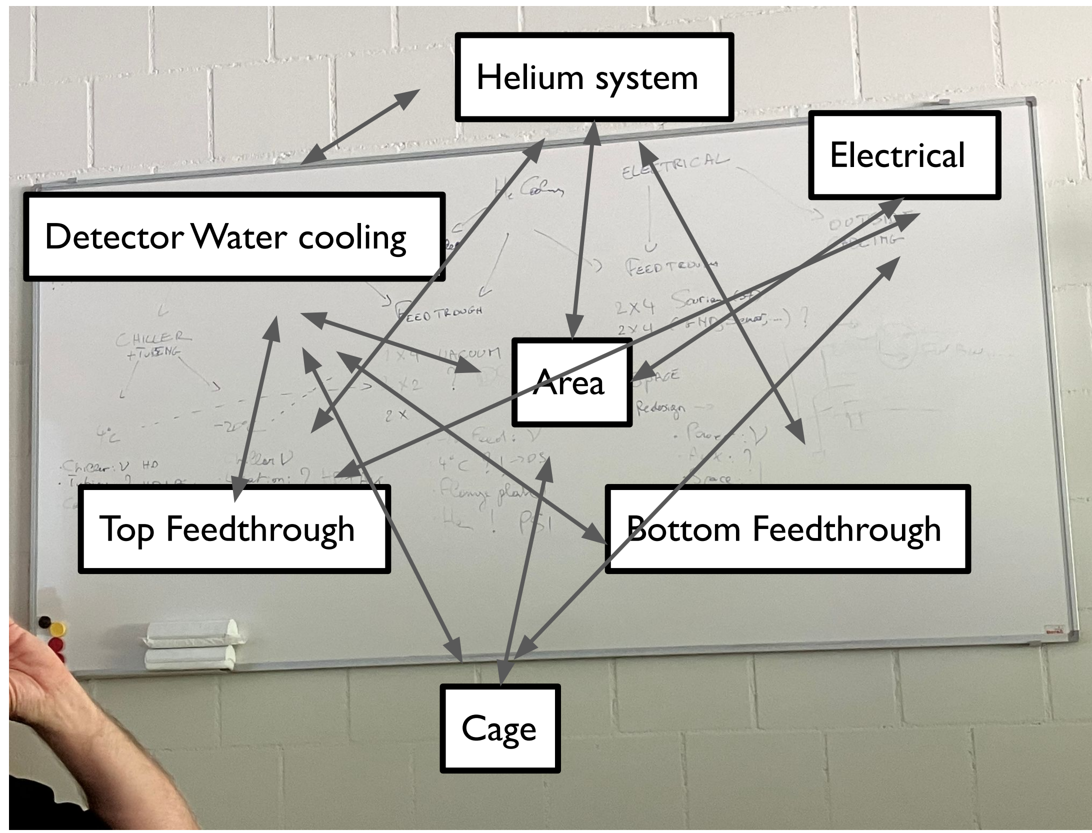


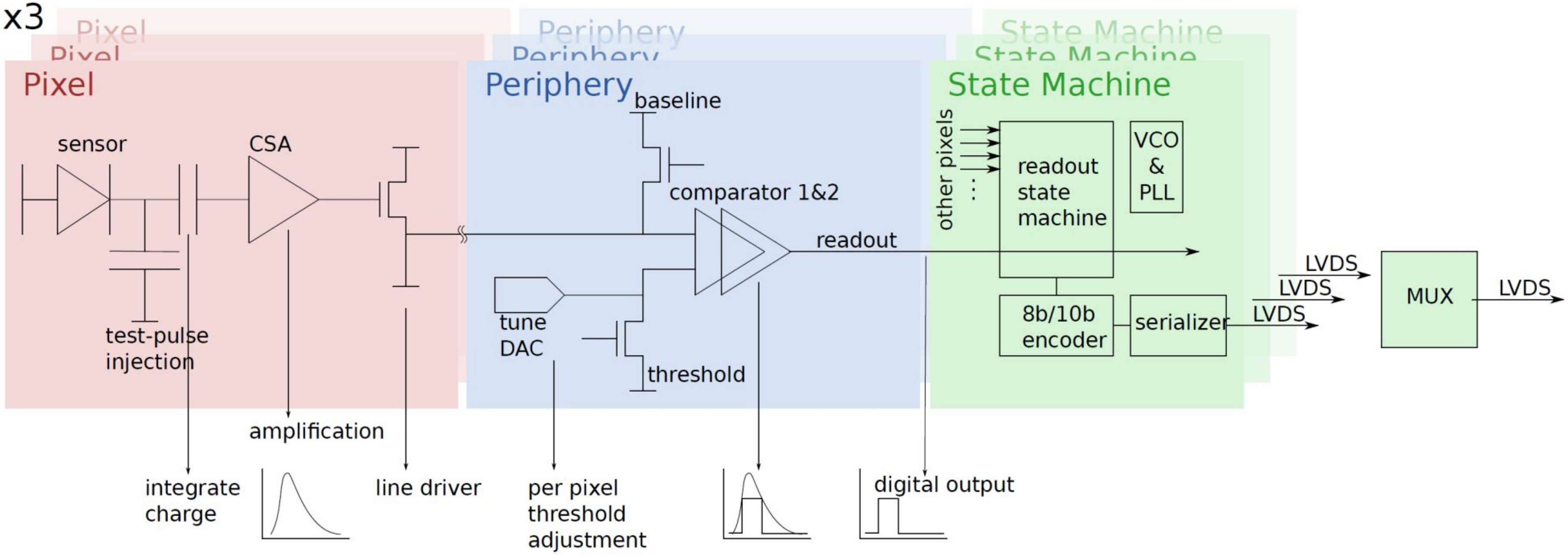


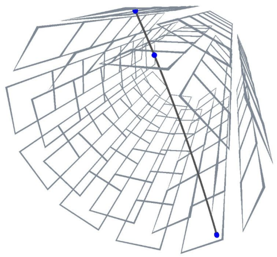
Detector Magnet
Inner pixel layers
Outer pixel layers
Scintillating fibres
Scintillating tiles
MuPix
MuTrig
Up to 12 Sensor ASICs
Up to 36 Sensor ASICs
8 TDC ASICs
13 TDC ASICs
1.25 Gbit/s LVDS links
1.25 Gbit/s LVDS link
Detector adaptor boards
Detector adaptor board
Si5345
FPGA
CPLD
Firefly
Backplane
CC
10 Front-end boards
78 Front-end boards
12 Front-end boards
14 Front-end boards
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
PCIe
PC
SFP+
Switching PC
Central Detector Switching Board
Fibre Detector Switching Board
Recurl Station Upstream Switching Board
Recurl Station Downstream Switching Board
16
QSFP
DDR
RAM
GPU
CPU
Clock Receiving Card
Farm PC
(12 farm PCs in total)
12 x
Fan-outs
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

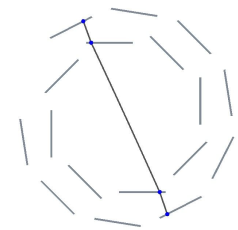


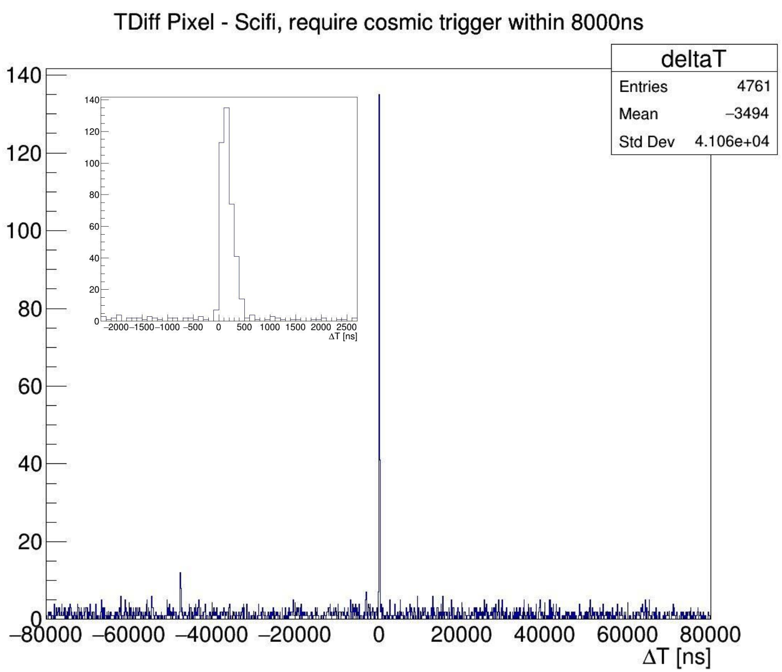

100
50
0
−50
−100
y
−100 −50 0 50 100
x
−200 −100 0 100 200
z

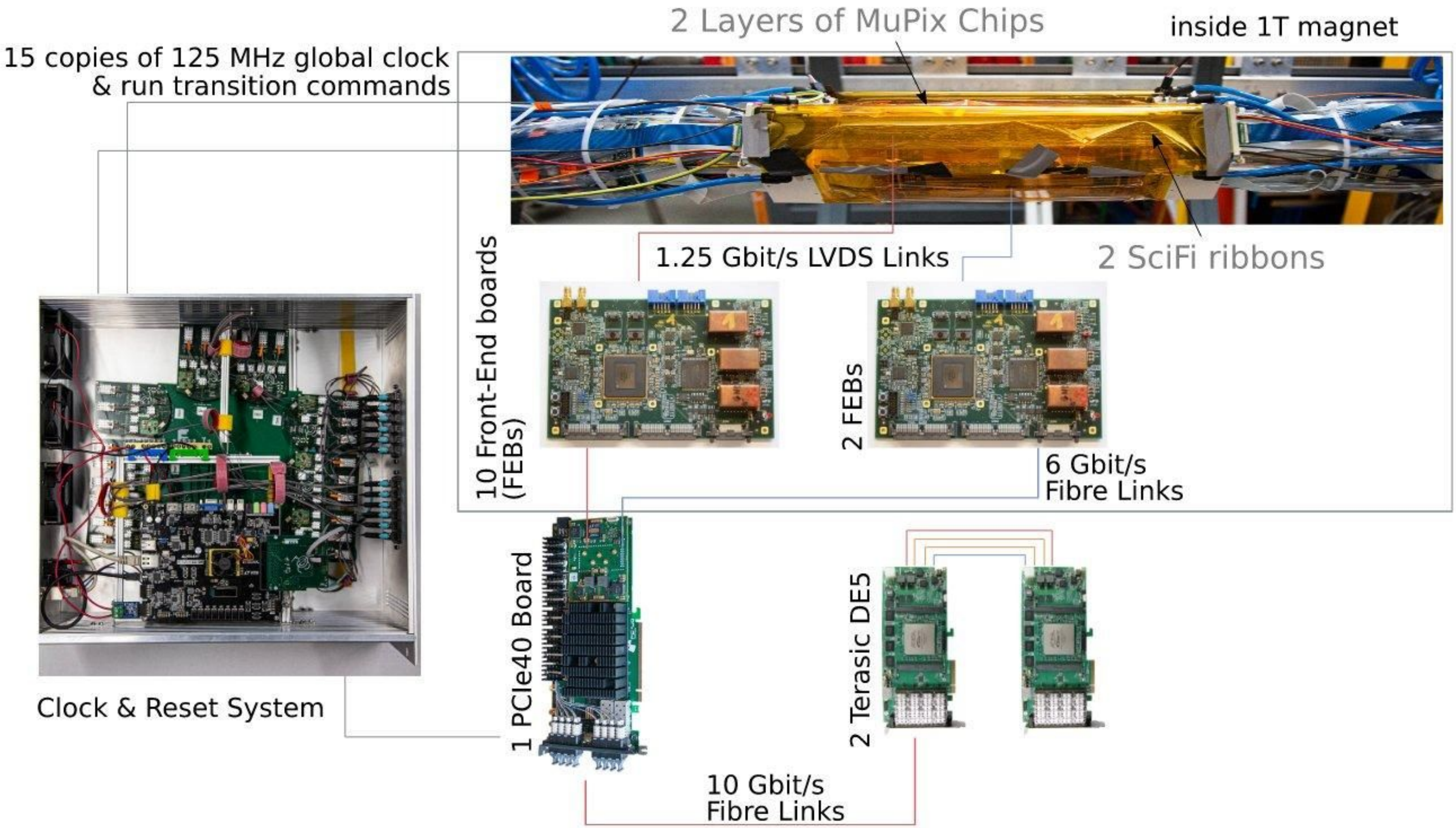

Helium system
Electrical
Detector Water cooling
Area
Top Feedthrough
Bottom Feedthrough
Cage


x3
Pixel
Periphery
State Machine
sensor
CSA
test-pulse injection
baseline
comparator 1&2
readout
tune DAC
threshold
other pixels
readout state machine
VCO & PLL
8b/10b encoder
serializer
LVDS
LVDS
LVDS
MUX
LVDS
amplification
integrate charge
line driver
per pixel threshold adjustment
digital output






TDiff Pixel - Scifi, require cosmic trigger within 8000ns
deltaT
Entries 4761
Mean −3494
Std Dev 4.106e+04
ΔT [ns]



2 Layers of MuPix Chips
inside 1T magnet
15 copies of 125 MHz global clock
& run transition commands
1.25 Gbit/s LVDS Links
2 SciFi ribbons
10 Front-End boards
(FEBs)
2 FEBs
6 Gbit/s
Fibre Links
Clock & Reset System
1 PCIe40 Board
2 Terasic DE5
10 Gbit/s
Fibre Links

Mu3e detector construction & commissioning

We have to build a very compact/complicated detector (+ services + DAQ)