The search for Lepton-Flavour Violation with

the Mu3e Experiment

on behalf of the Mu3e collaboration

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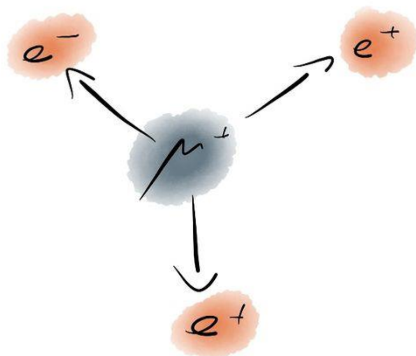
Johannes Gutenberg University Mainz

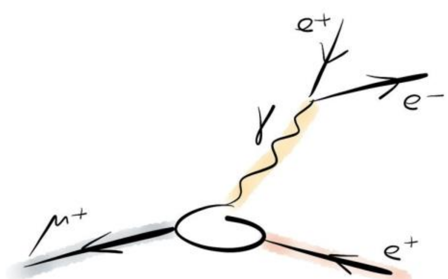
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Cluster of Excellence PRISMA Precision Physics, Fundamental Interactions and Structure of Matter

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

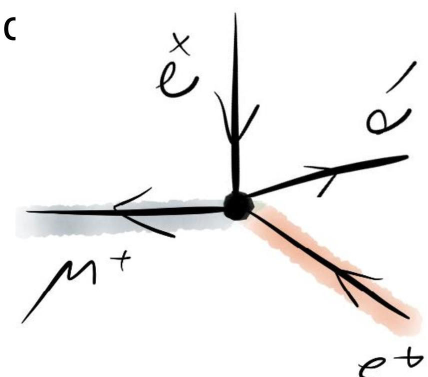


- Standard Model branching ratio $5 \cdot 10^{-55}$
- Mu3e aims for a single event sensitivity
  of $1 \cdot 10^{-16}$ (Phase II)
  of $2 \cdot 10^{-15}$ (Phase I = this talk)
  → Search for new physics
  → Previous limit $1 \cdot 10^{-12}$ (SINDRUM, 1988)
- Complementary to $\mu \rightarrow e\gamma$ and $\mu N \rightarrow e$ in technique and new physic



Loop

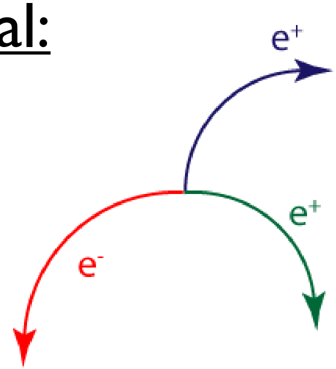
↔



Contact

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

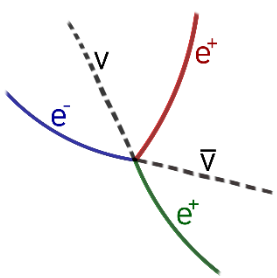
Signal:



- $\sum E = m_\mu$
- $\sum \overline{\boldsymbol{p}} = 0$

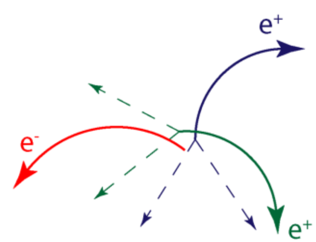
Background:

Internal conversion



- Allowed μ→eee
- ν's eat away E and **p**

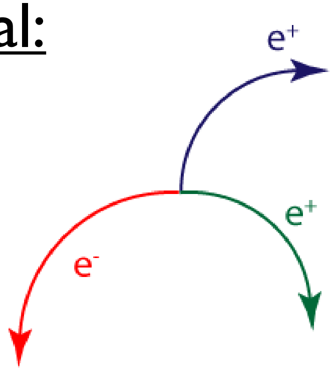
Combinatorial



- Michel decay + Bhabha scattering (beam or decay e$^+$)
- Michel decay + …
- Misreconstructed tracks
- …

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

Signal:



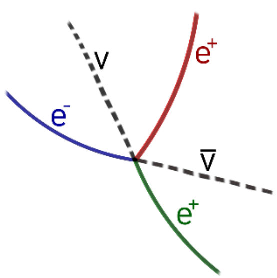
- $\sum E = m_\mu$
- $\sum \overline{\boldsymbol{p}} = 0$

Detector design

- DC beam
- Good timing resolution
- Low material budget detector
- Good vertex reconstruction
- Good momentum resolution

Background:

Internal conversion



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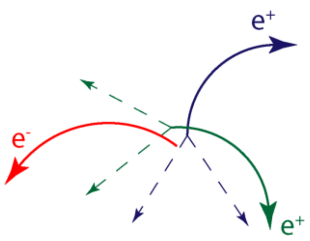

- Michel decay + Bhabha scattering (beam or decay e$^+$)
- Michel decay + …
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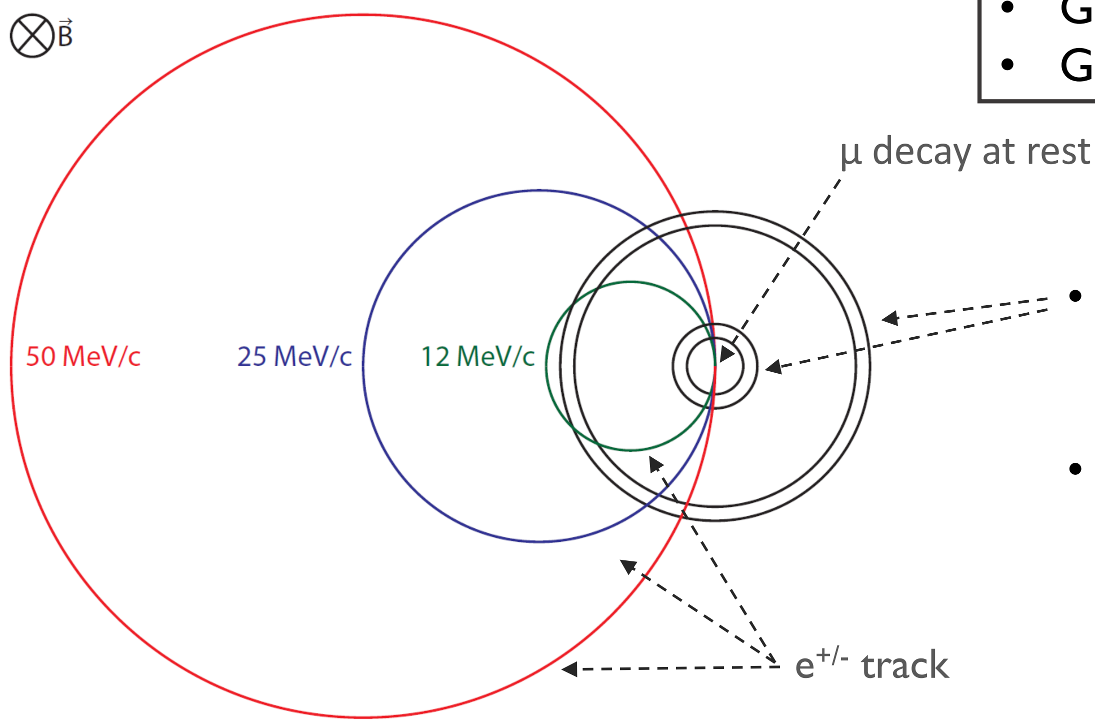
- …

The Mu3e detector concept

Recurl tracker with good vertex resolution and excellent momentum resolution over **a large energy range**



<u>Detector design</u>

- DC beam
- Good timing resolution
- Low material budget detector
- Good vertex reconstruction
- Good momentum resolution

- As thin as possible pixel detector
- Still Multiple Scattering dominated

The Mu3e detector concept

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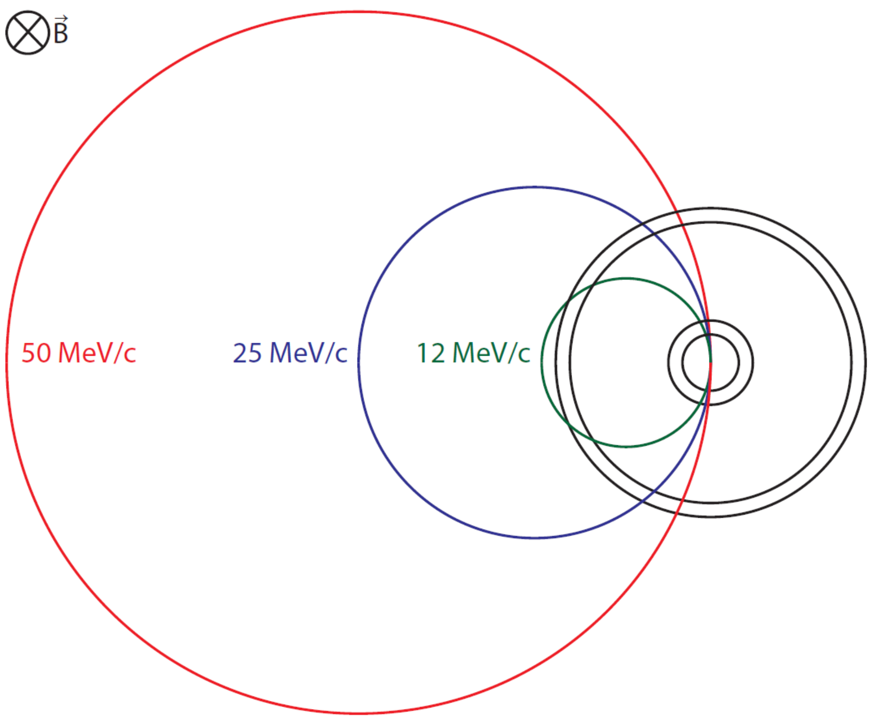

Detector design

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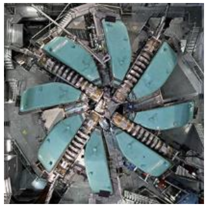
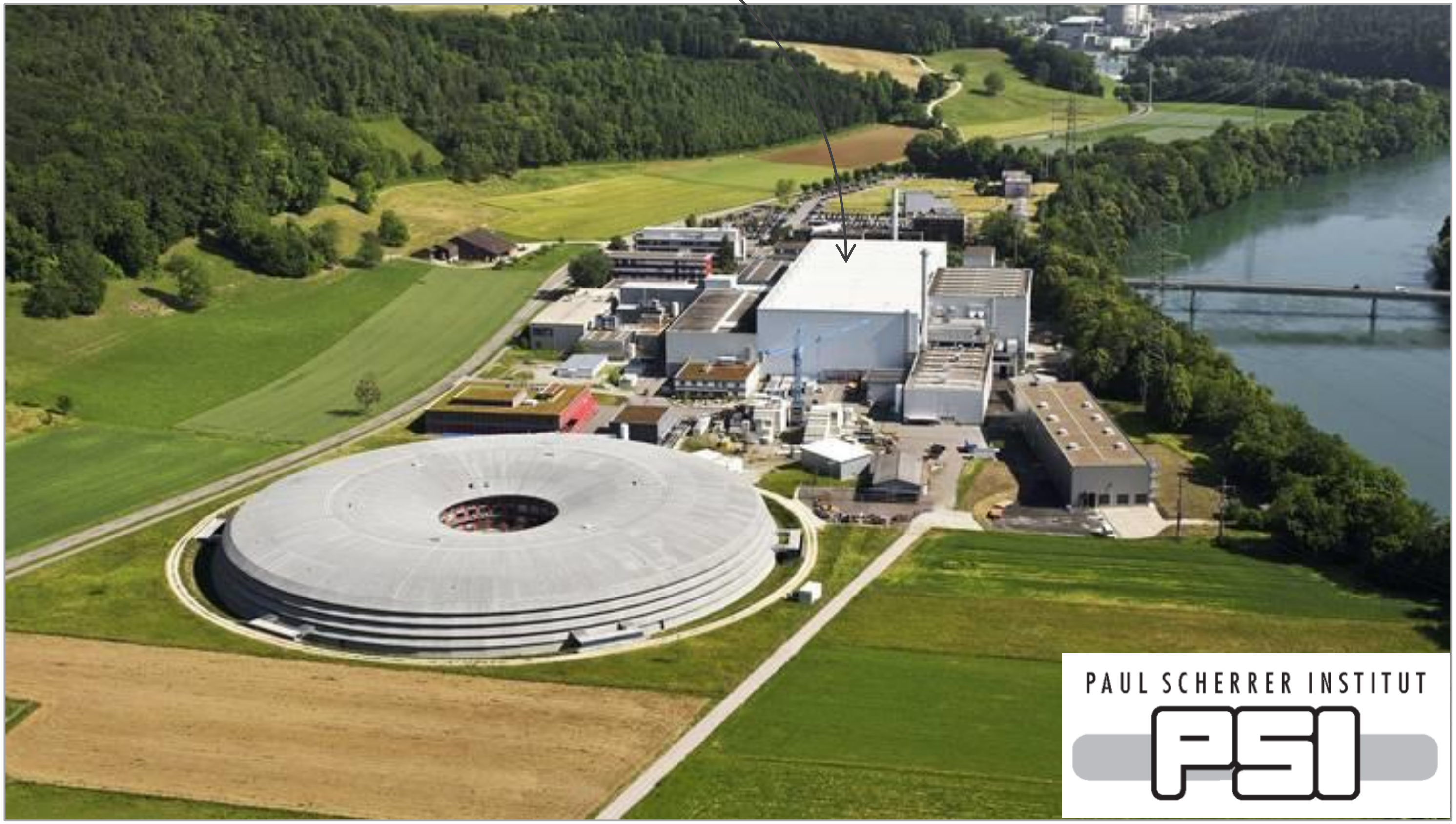
Getting our muons



HIPA and μ hall



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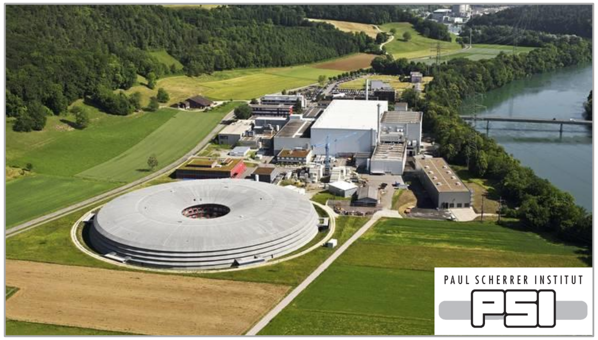
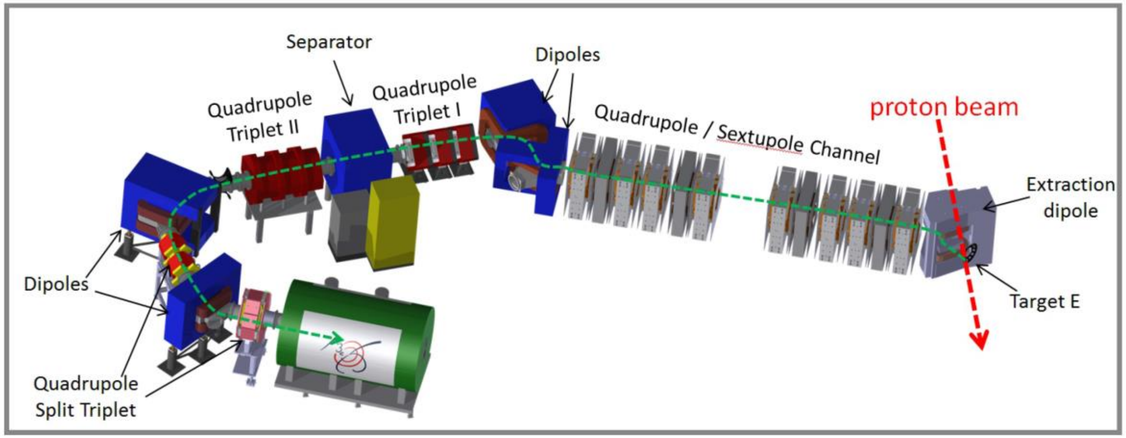
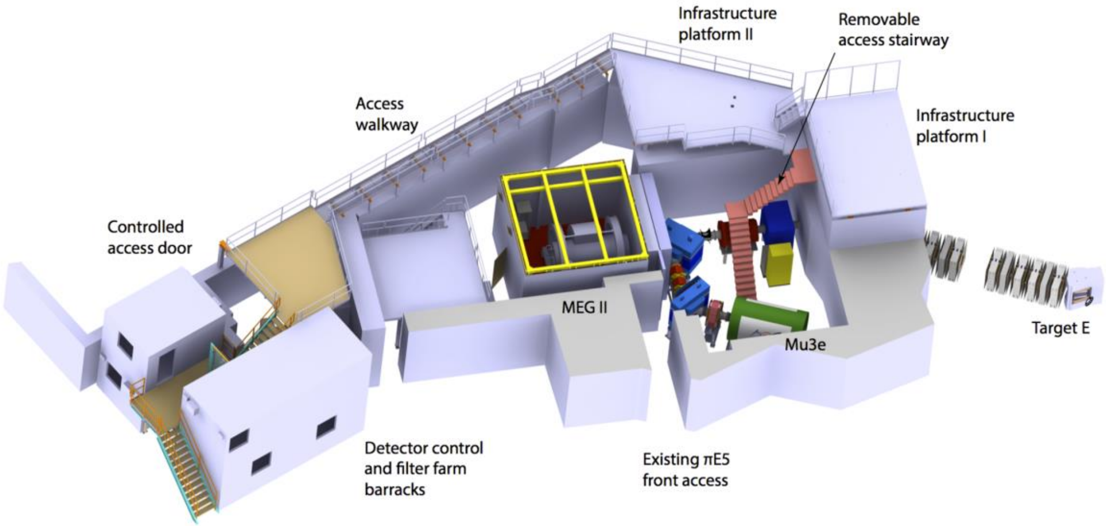


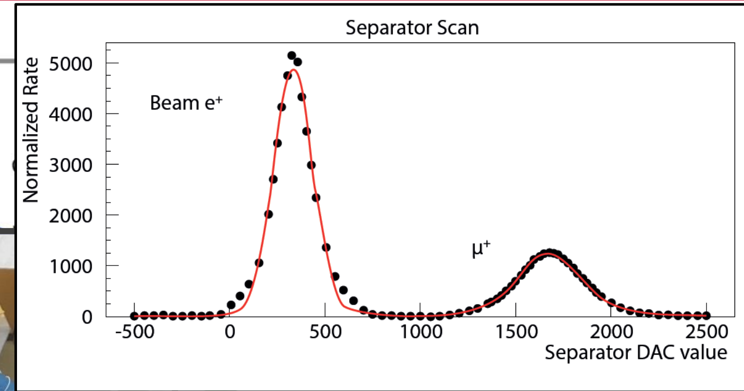




Front of πE5 area

- High μ^+ rate
- Limited space available

Getting our muons



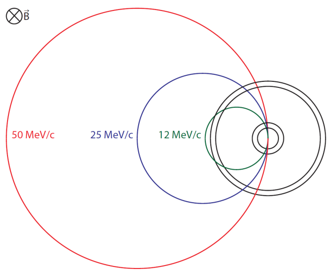
Front of πE5 area

- High μ^+ rate
- Limited space available
- $1 \cdot 10^8$ μ/s

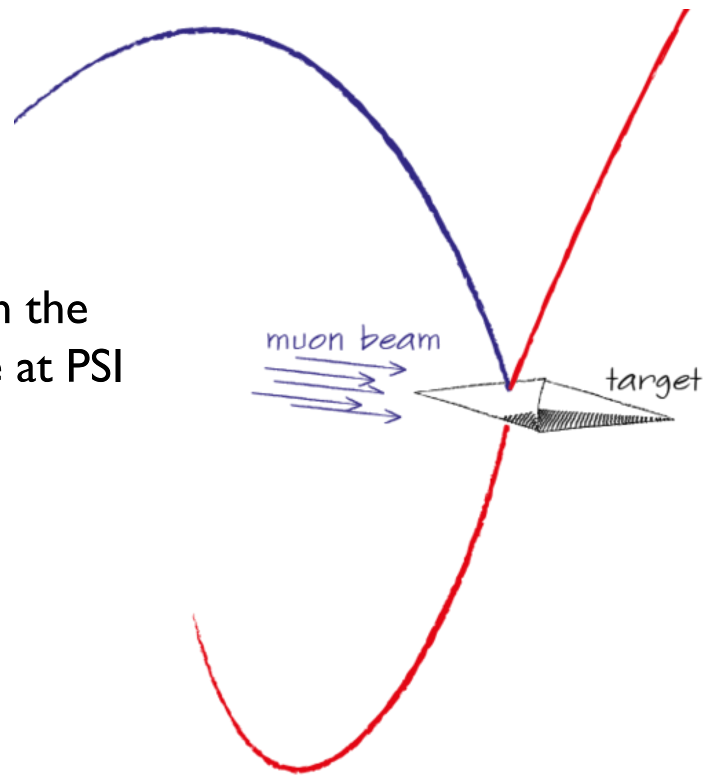
~~**Designing an experiment**~~

Building an experiment

The Mu3e detector

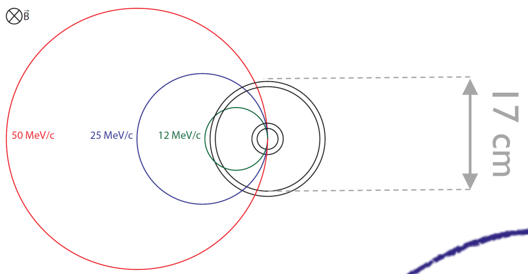


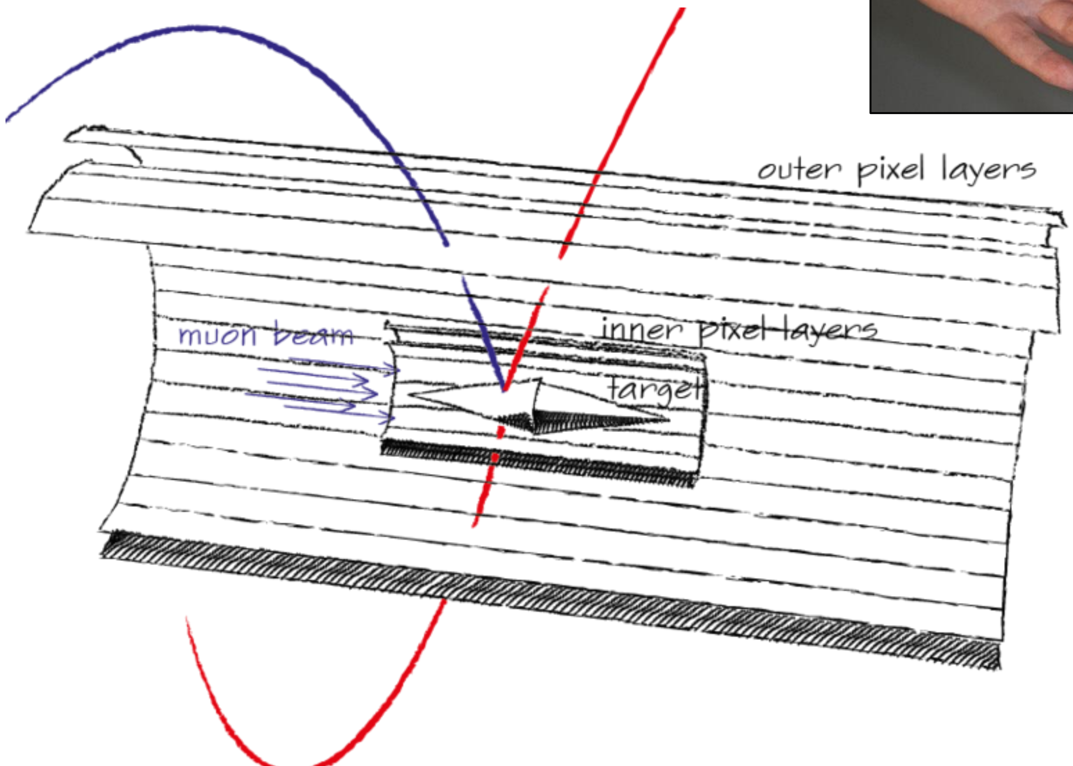
~10^8 μ/s from the πE5 beamline at PSI



Cone shaped thin target
→ well defined vertices, spread out in z

The Mu3e detector

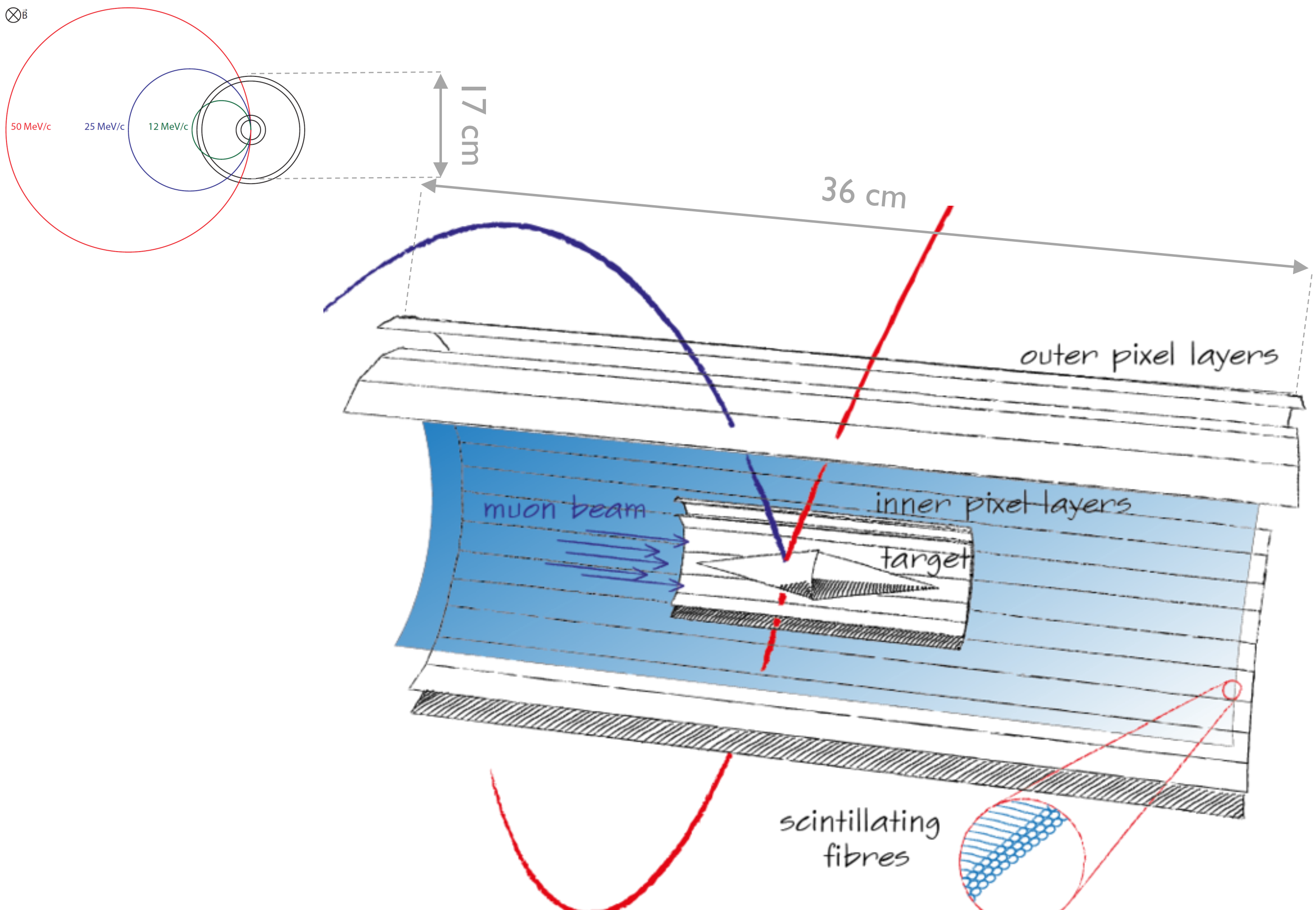




1 T magnetic field

2 x double layer of Si pixel detectors
Each layer is < 0.1 % of a radiation length

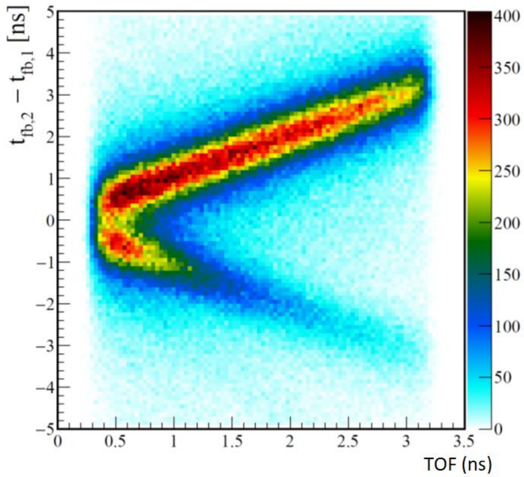
The Mu3e detector



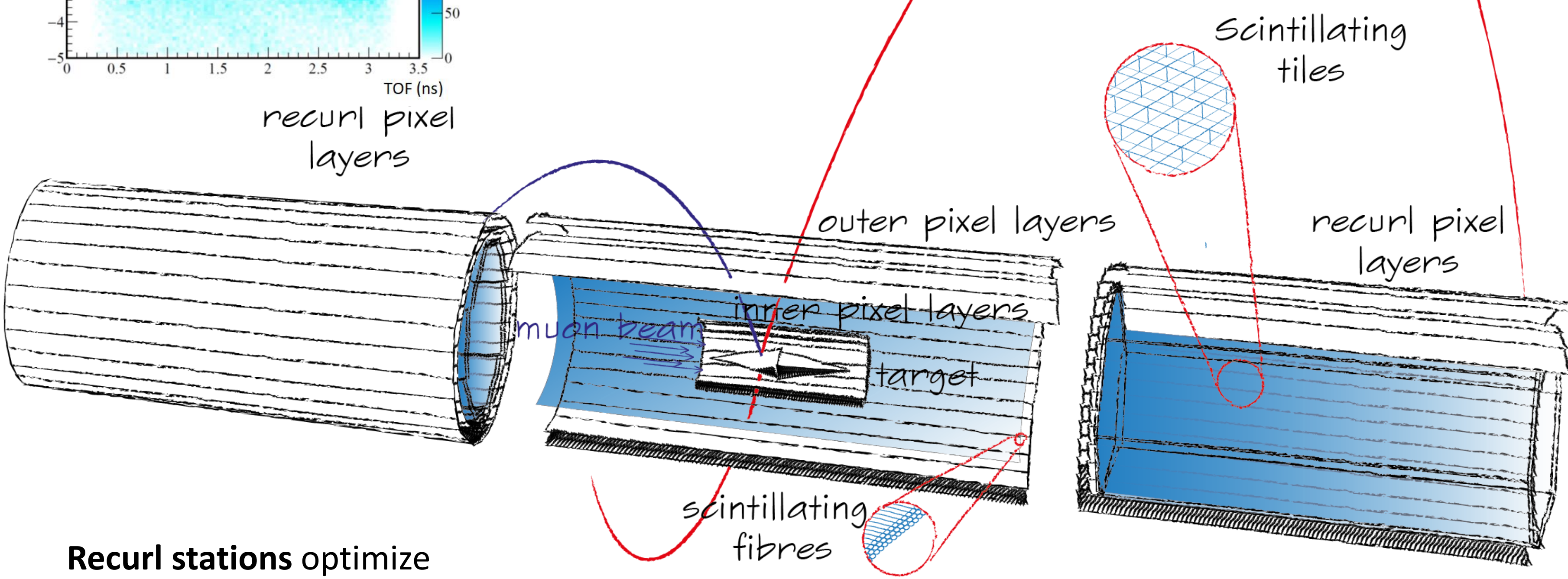
1 T magnetic field

Scintillating fibers as a thin, fast timing detector

The Mu3e detector



Timing detectors
reduce track multiplicity
and allow for charge ID

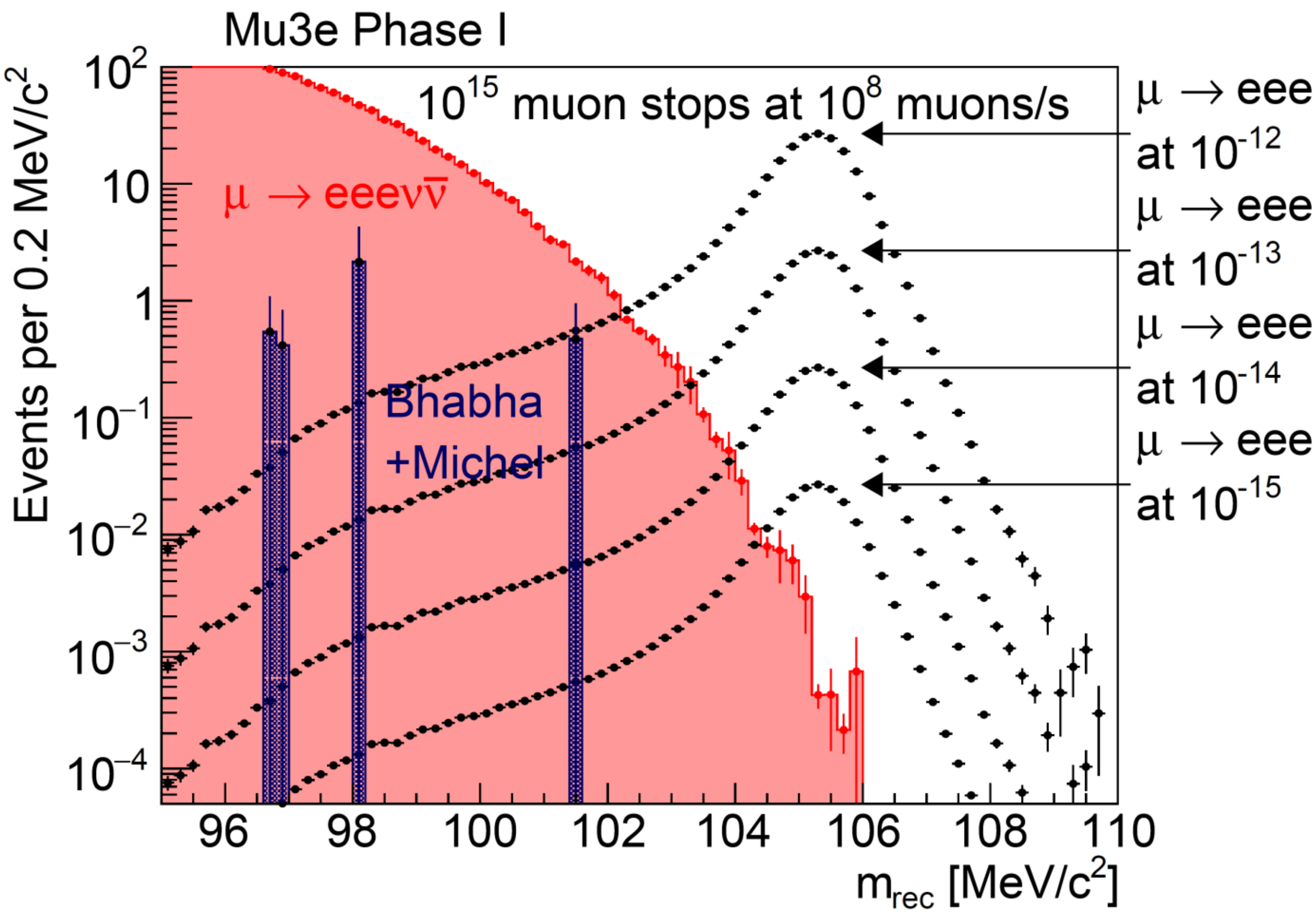


Recurl stations optimize
momentum resolution, minimizing
sensitivity to multiple scattering

Scintillating tiles yield optimal
timing resolution

The Mu3e detector

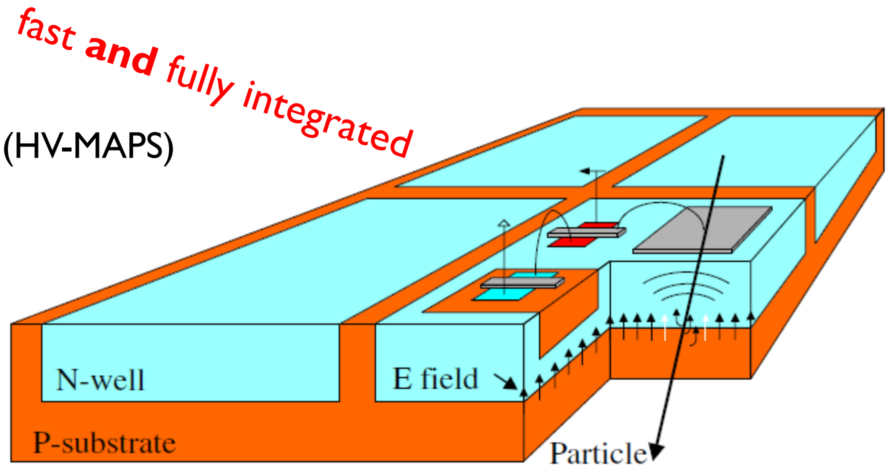
What Mu3e can do according to the Monte Carlo



Pixel detector

Mu3e Pixel detector:

- High Voltage Monolithic Active Pixel Sensors (HV-MAPS)
- Fast charge collection with HV ≈ -85V
- Readout and logic on chip
  - analogue part in pixel
  - digital part in periphery
- Thinned to 50 μm
- Pixel size: 80 x 80 μm
- 2 x 2 cm chip
- 1.25 Gb/s LVDS readout

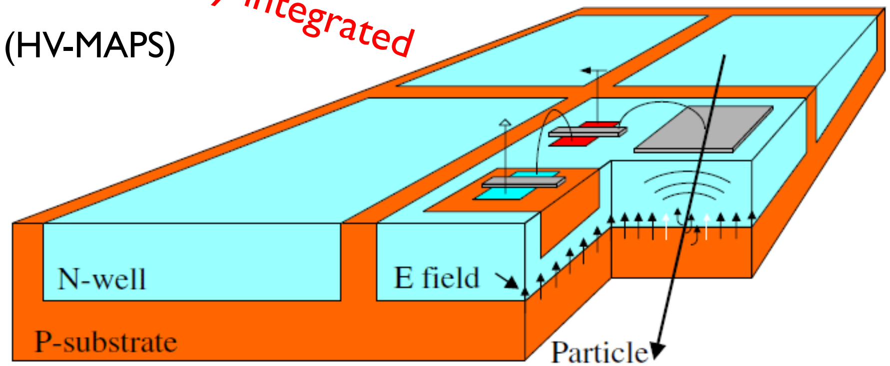


I. Peric et al., NIMA **731**, 131 (2008)

Pixel detector

Mu3e Pixel detector:

fast and fully integrated



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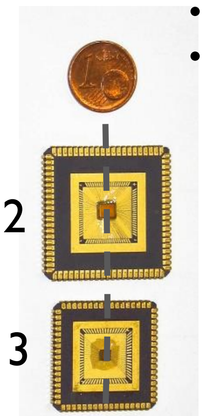
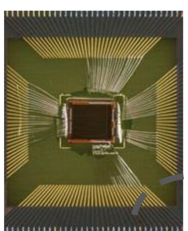
MuPix Sensors

2

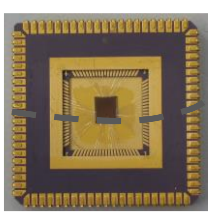
3

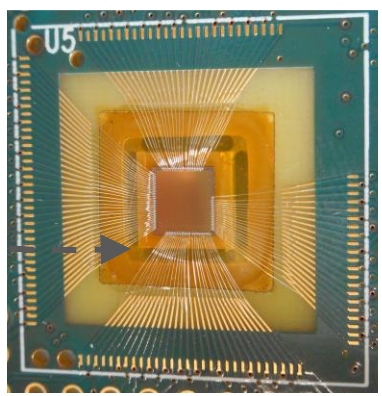


6



4

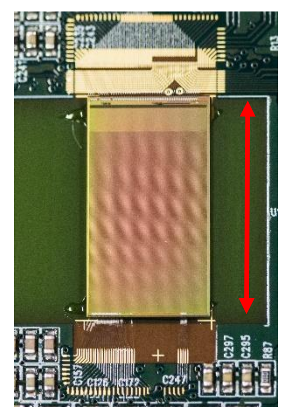




Mupix 7:

- 3x3 mm
- 50 µm
- > 99% eff
- all features of final sensor

arXiv:1803.01581



Full size

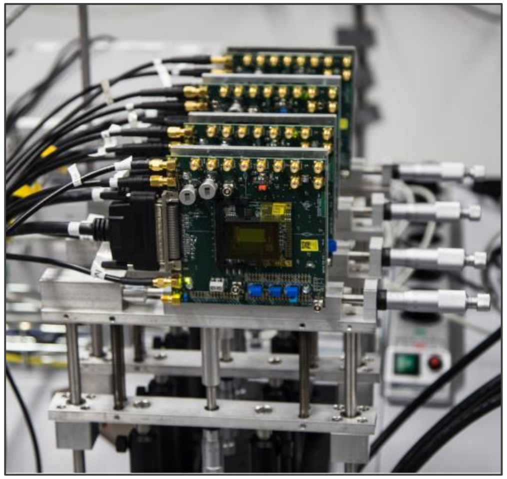
Mupix 8:

- 19x10 mm
- 20→80 Ωcm
- final design decisions

Pixel detector

Mu3e Pixel detector:

Telescope test-beam campaigns

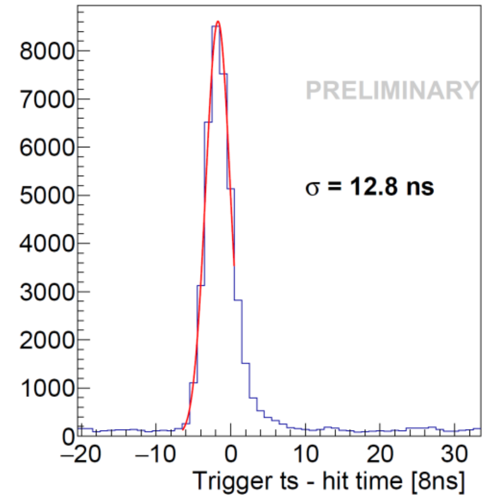


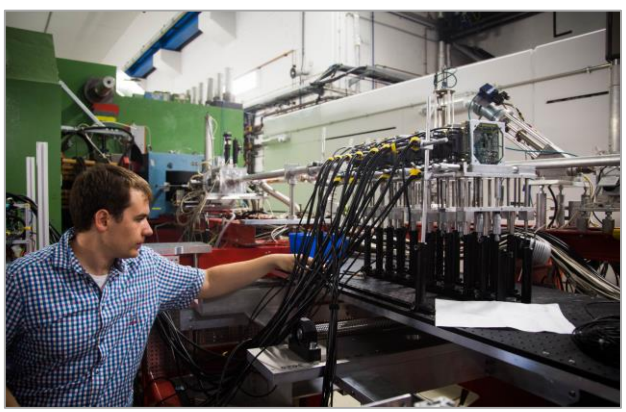
MAINZER MIKROTRON

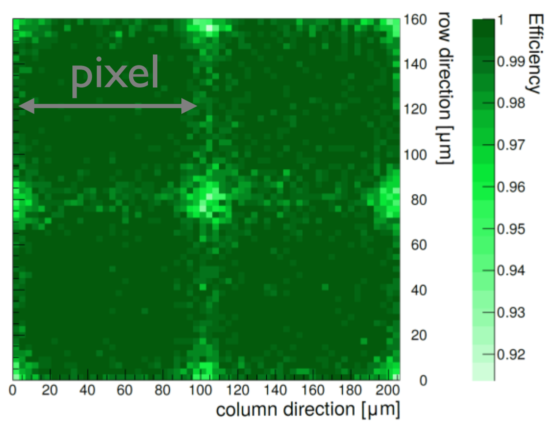
DESY

PAUL SCHERRER INSTITUT

PSI



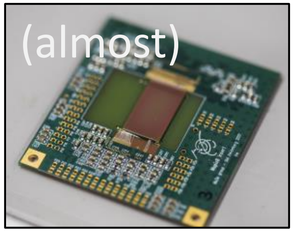




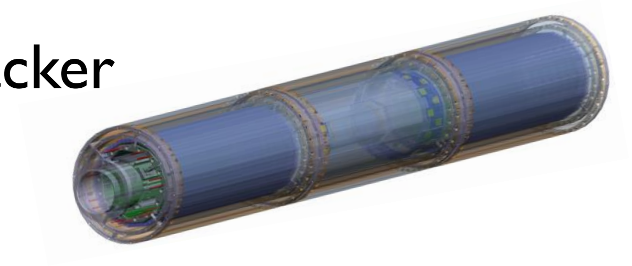
- (sub-pixel) efficiency
- optimizing settings
- timing measurements
- rate scans
- irradiation
- …

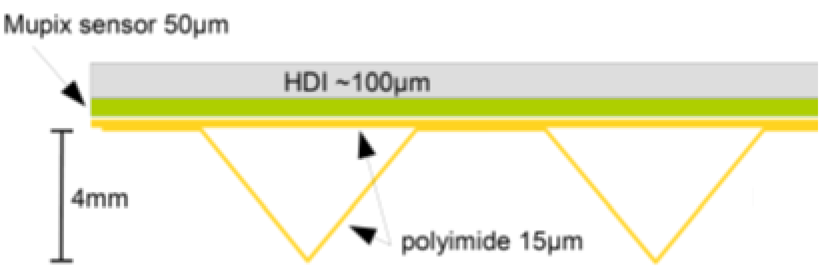
arXiv:1803.01581

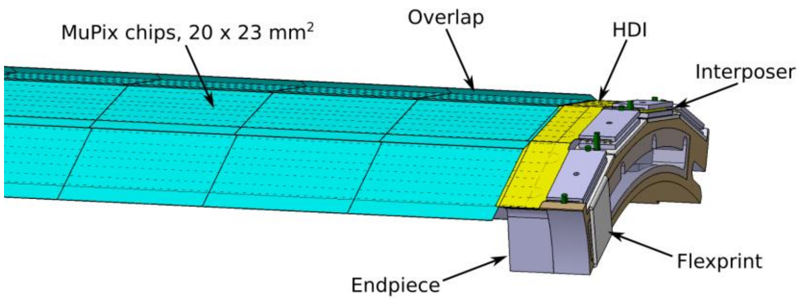
Pixel detector



2x2 cm
MuPix chip ⇨ Pixel tracker





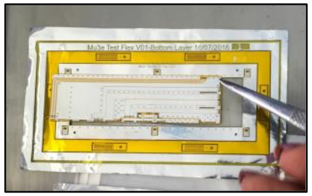


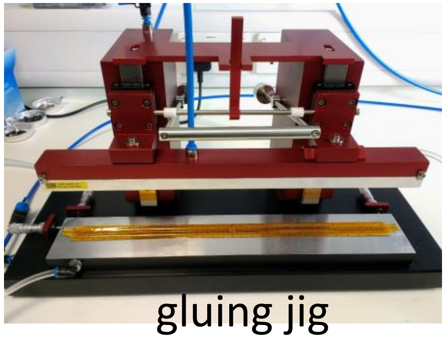
mechanical design → prototypes

~ 0.1 % radiation length total

- 50 µm sensor
- glue to Al/Kapton flat cable (HDI) for all electrical connections
- Kapton support structure with ducts for He cooling

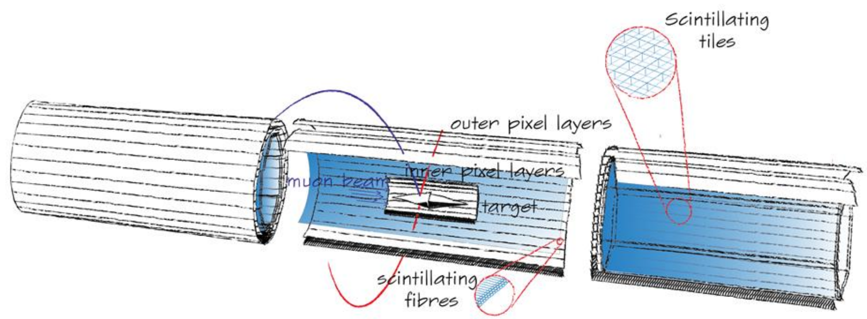
250-400 mW/cm^2
→ He gas cooling



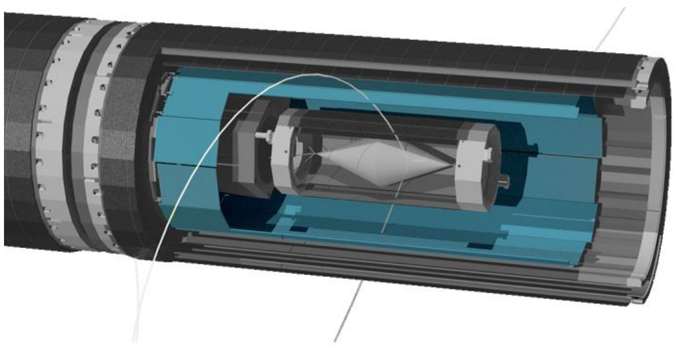


gluing jig

Timing detectors

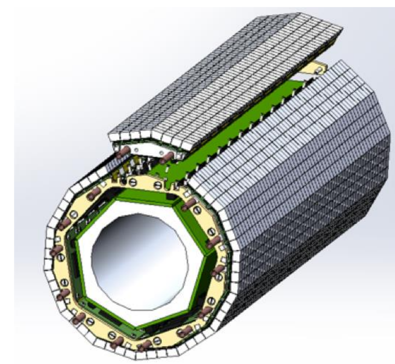


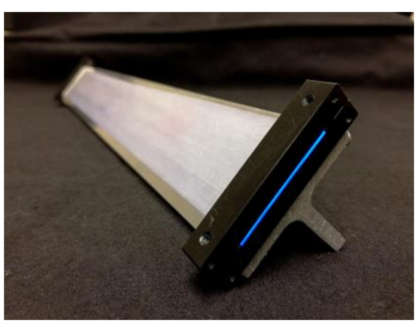
Fibres

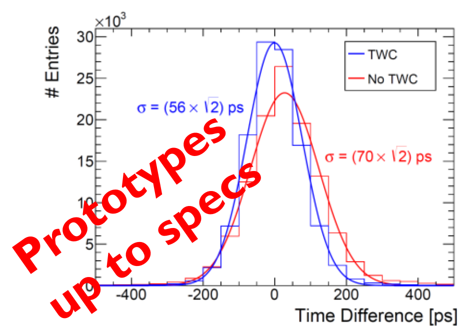


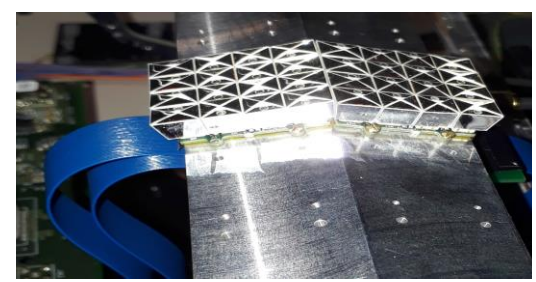
- Excellent timing
  - 350 ps < 500 ps (fibres)
  - 70 ps < 100 ps (tiles)
- Fibres: thin → light yield → single photon threshold
- SiPM + custom readout chip MuTrig (JINST 12 C01043 (2017))
- 1.25 Gb/s serial readout

Tiles

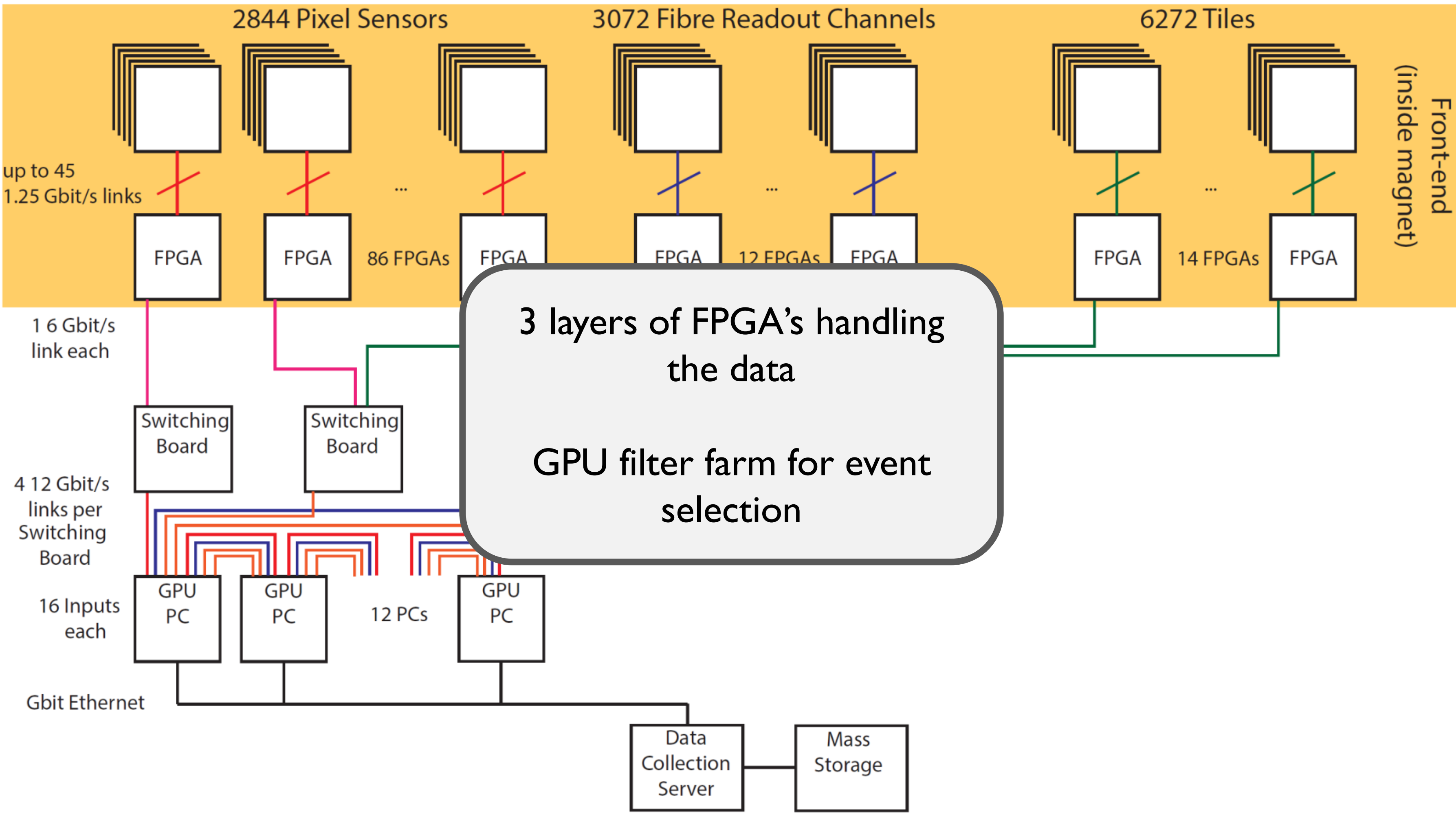








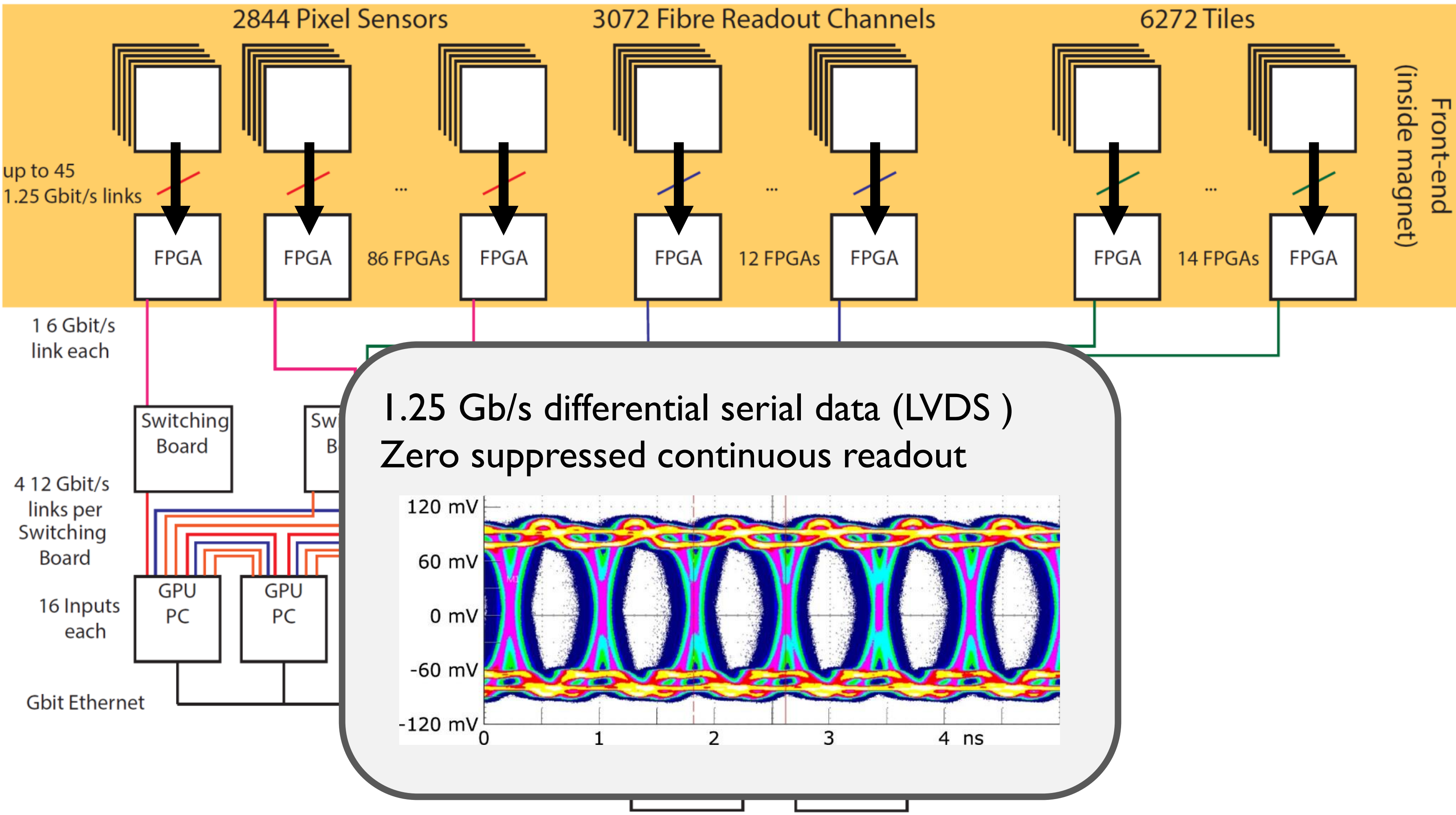
Readout



3 layers of FPGA's handling the data

GPU filter farm for event selection

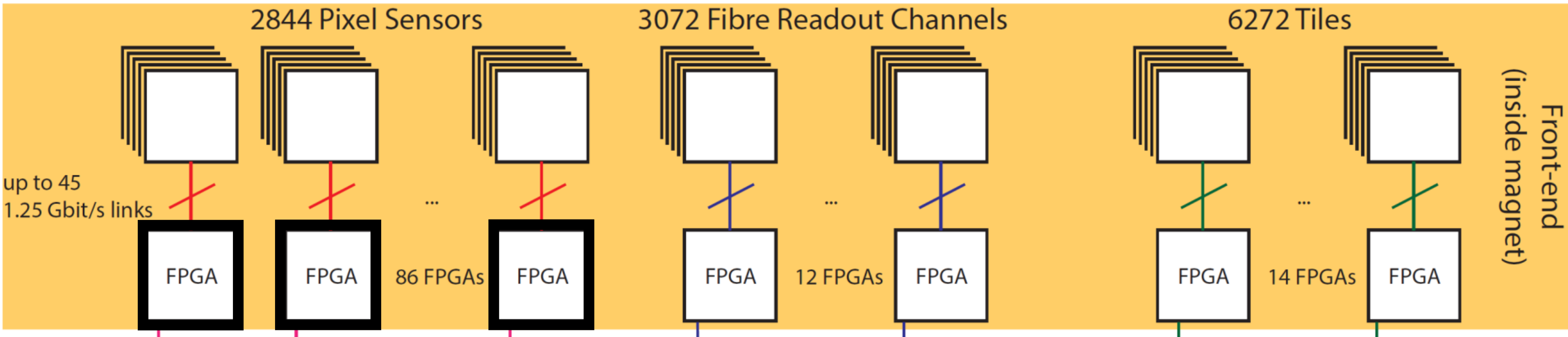
Readout



1.25 Gb/s differential serial data (LVDS)

Zero suppressed continuous readout

Readout



1 6 Gbit/s
link each

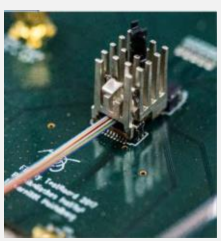
4 12 Gbit/s
links per
Switching
Board

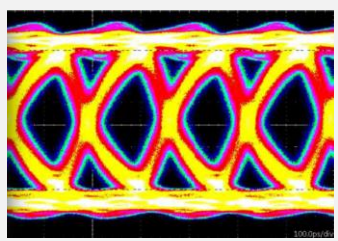
16 Input
each

Gbit Ether

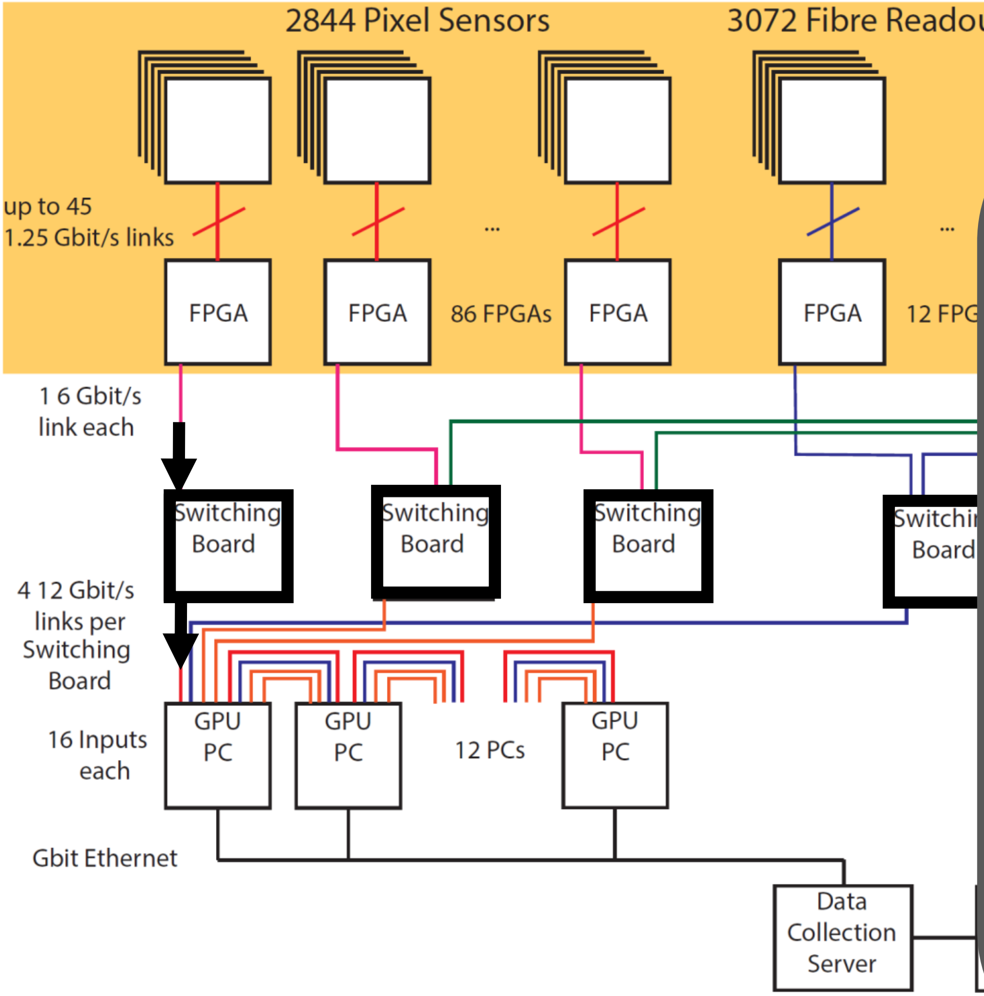
Frontend Board:

- ArriaV FPGA
- 6 to 36 LVDS inputs
- Sorting data
- 1 x 6.25 Gb/s optical link out (Firefly)





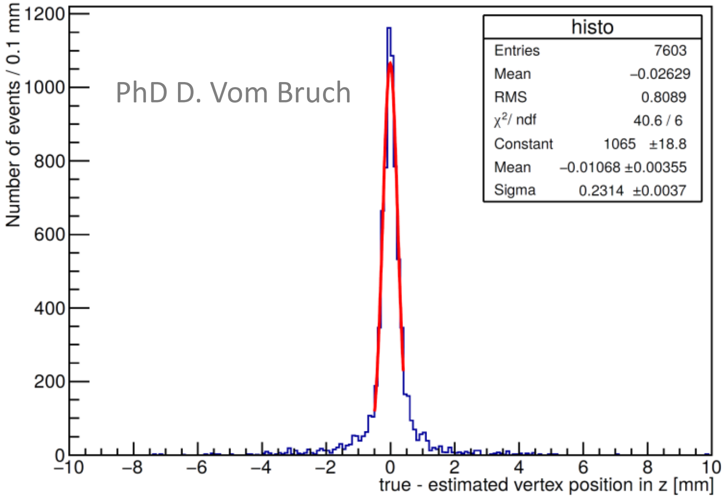
Readout

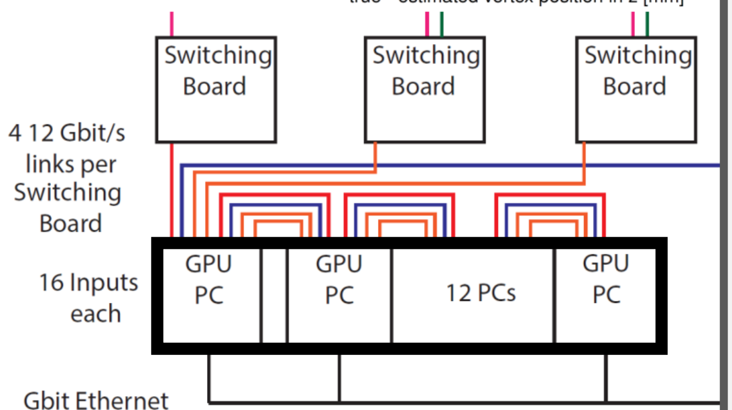


Switching Board:

- Aria10 FPGA
- PCIe board developed by LHCb JINST C04018 (2015)
- 48 full duplex optical links
- Transform subdetector slices (space) to time-slices of the full detector
- 4 x 10 Gb/s out to filter farm

Readout

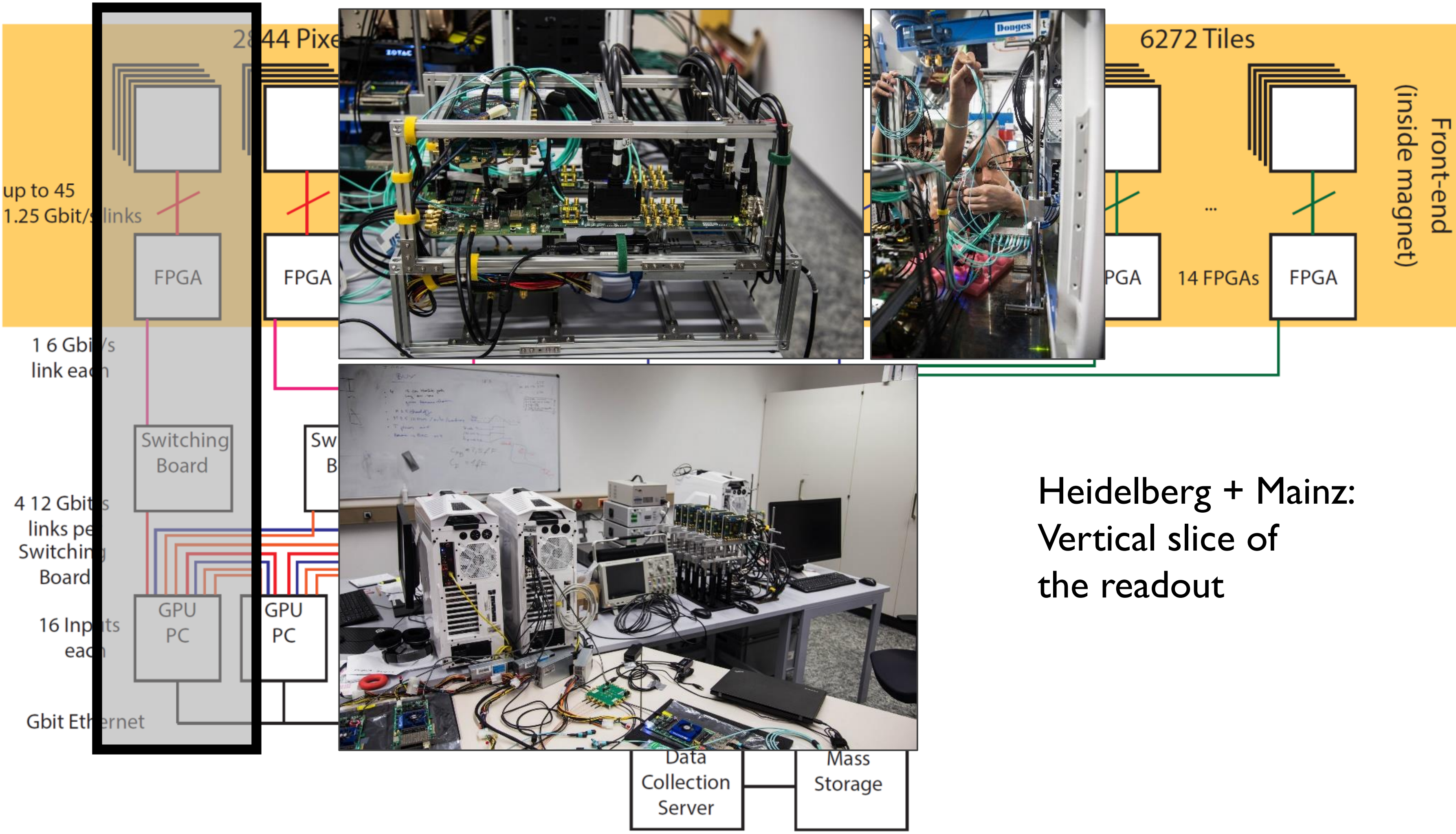




Filter farm:

- **100 Gb/s → < 100 MB/s**
- Arria10 FPGA on commercial PCIe board + ≥ GTX 1080 GPU
- Process 20 10^6 (50 ns) time slices per second
  1. Track fitting ("Triplet Fit" arXiv:1606.04990)
  2. Vertex fit
  3. Histogram data
  4. Send selected times slices off for permanent storage
- 2 10^6 slices per second nominal rate demonstrated → 12 PC's

Readout



Heidelberg + Mainz:
Vertical slice of
the readout

So what‘s next

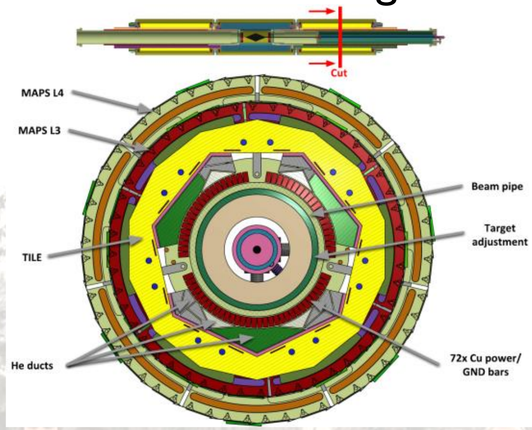
List of Mu3e Institutes

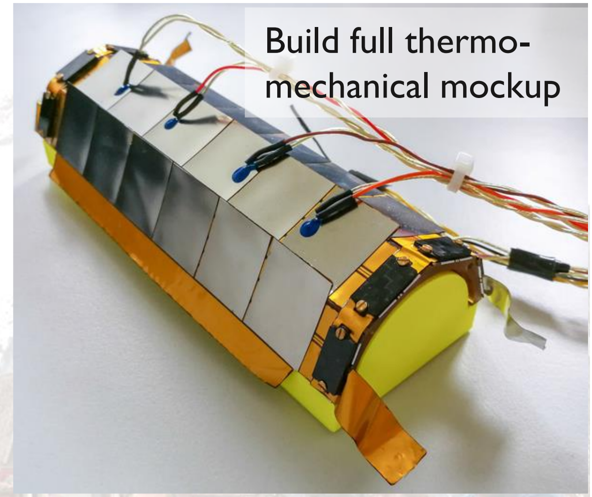
- Department of Physics at the University of Bristol (BRI)
- Department of Physics at the University Geneva (GVA)
- Kirchhoff Institute for Physics of the Ruprecht-Karls-Universität Heidelberg (HD-KIP)
- Physics Institute of the Ruprecht-Karls-Universität Heidelberg (HD-PI)
- Institute for Data Processing & Electronics of the Karlsruhe Institute of Technology (KIT)
- Department of Physics at the University of Liverpool (LIV)
- Department of Physics at the University College London (UCL)
- Institute for Nuclear Physics of the Johannes Gutenberg-Universität Mainz (JGU)
- Department of Physics at the University of Oxford (OXF)
- Particle Physics Laboratory at the Paul Scherrer Institut (PSI), Villigen
- Department of Physics at the ETH Zürich (ETHZ)
- Department of Physics at the University Zürich (UZH)

So what's next

Area and services at PSI are under construction

Full mechanical design





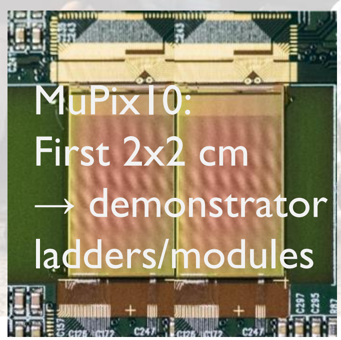
Build full thermo-mechanical mockup

Build a vertical slice of the detector

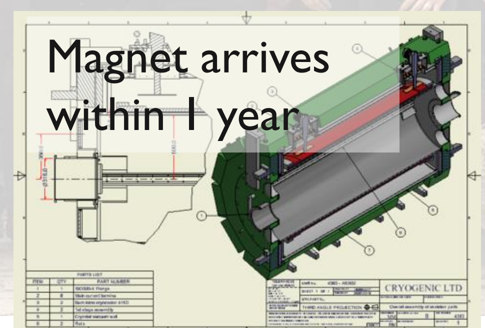
- fibres
- tiles
- pixels

and the entire readout

Detector production tools on the way

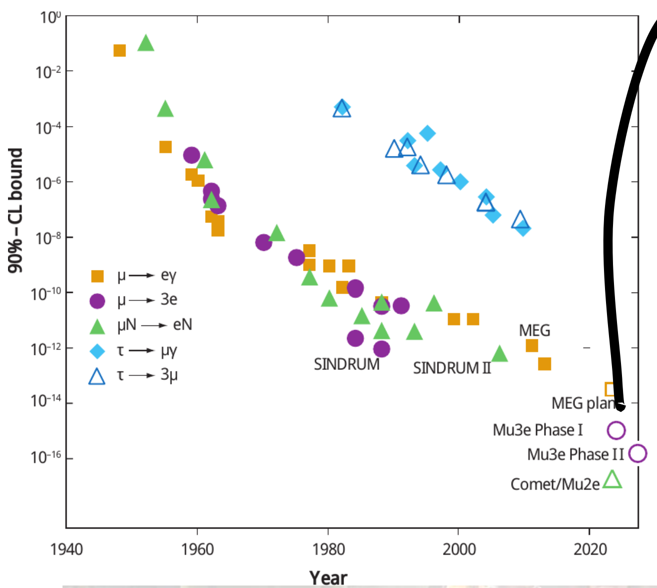


MuPix10:
First 2x2 cm
→ demonstrator ladders/modules



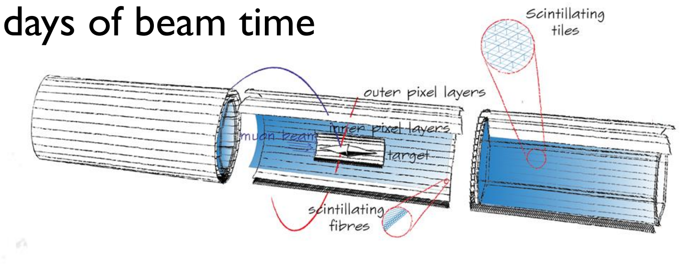
Magnet arrives within 1 year

Future



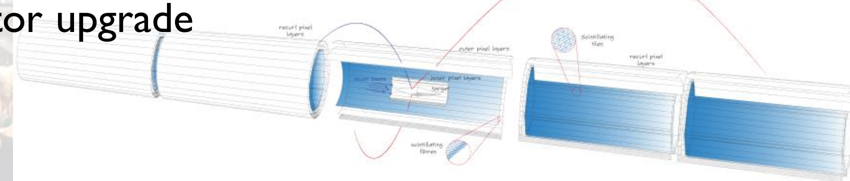
Do $\mu^+ \rightarrow e^+e^+e^-$ to B.R. 10^{-15}

- early 2020's
- 300 days of beam time

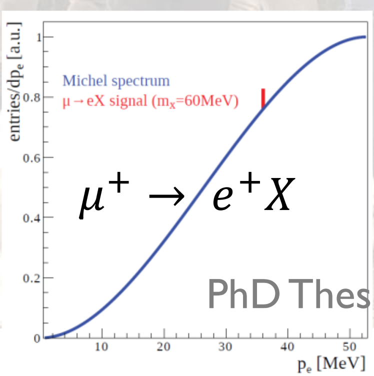


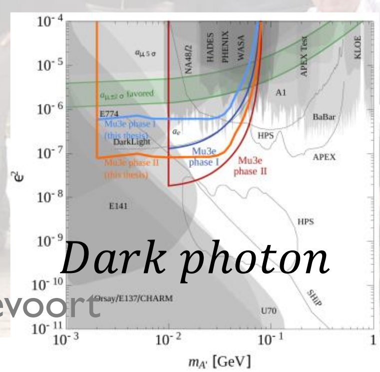
Phase 2: $\mu^+ \rightarrow e^+e^+e^-$ to B.R. 10^{-16}

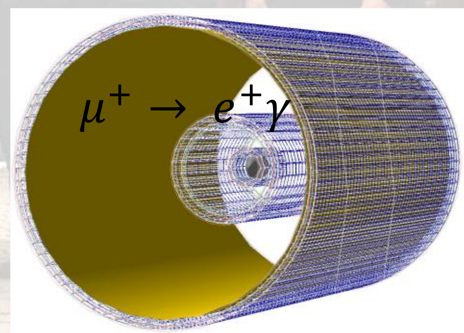
- Need 10^9 μ/s , needs HiMB! (→ A. Papa on Friday)
- Detector upgrade



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



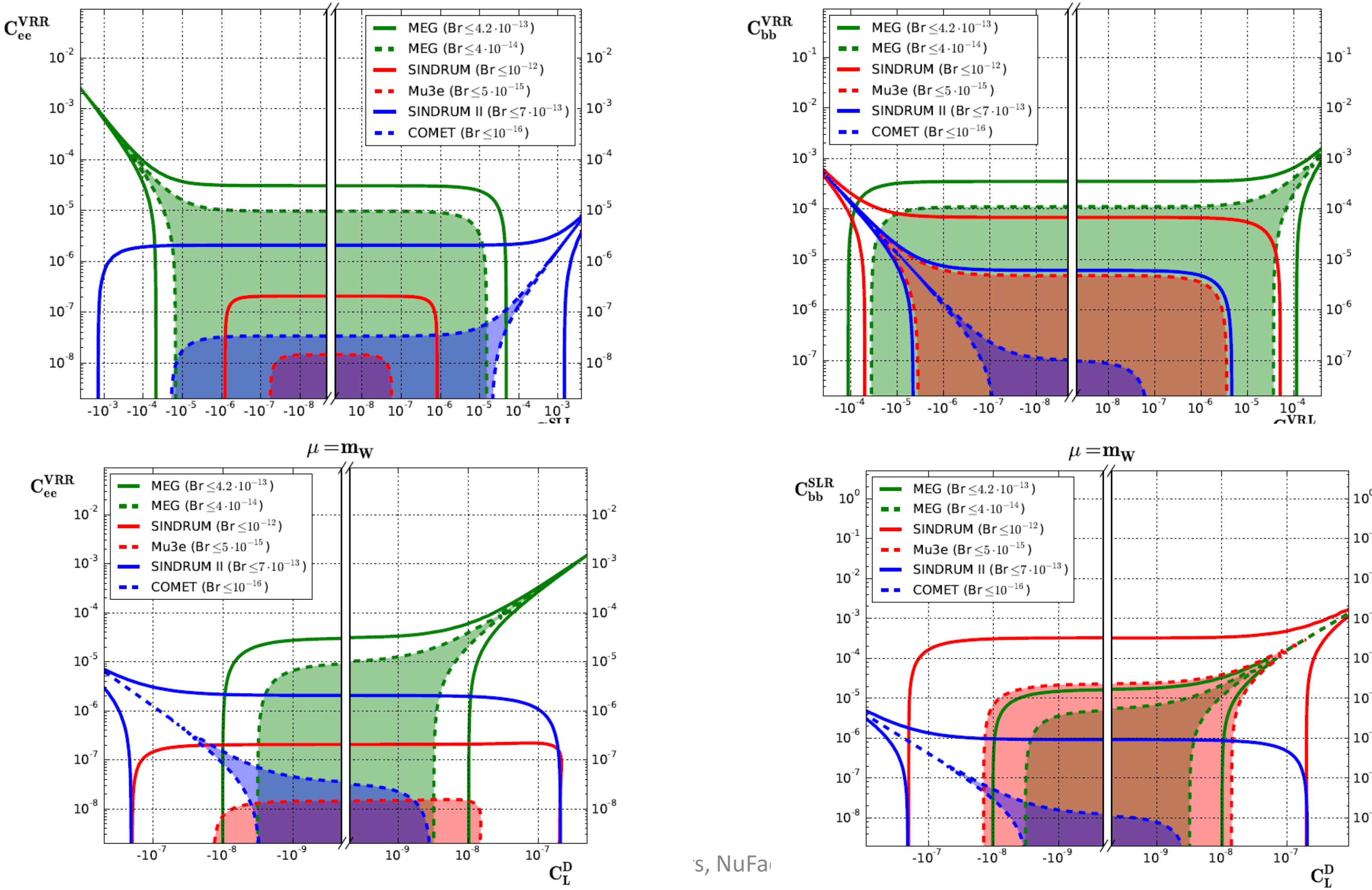


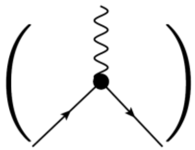
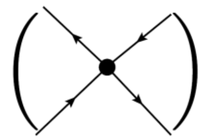


Extra slides

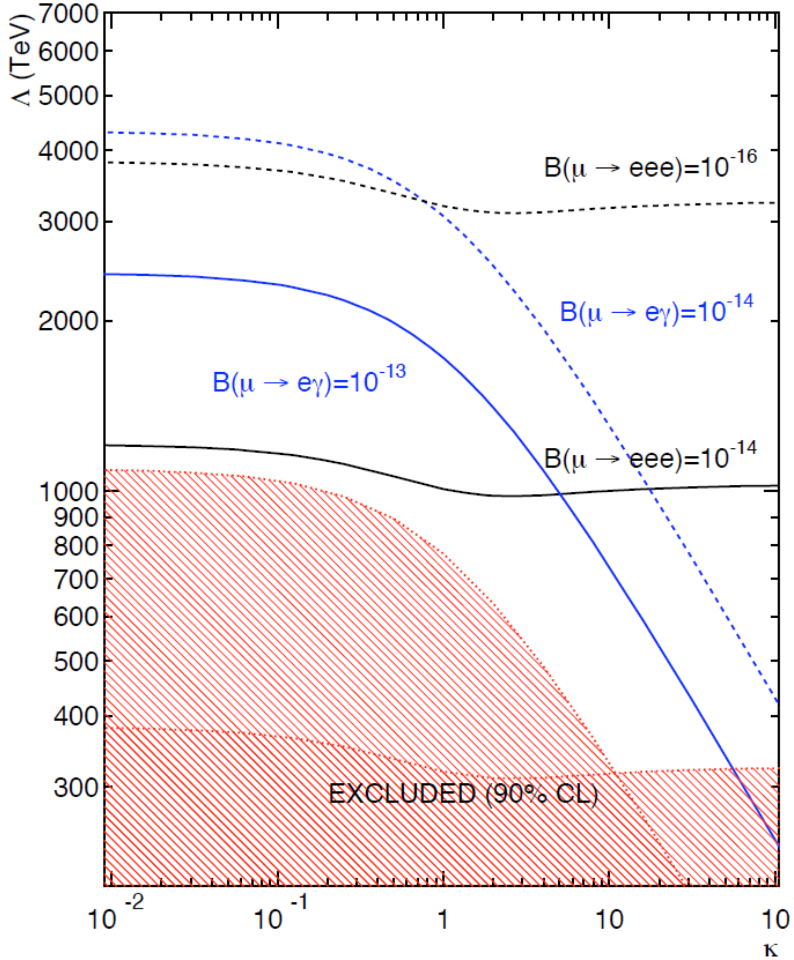
Renormalisation-group improved analysis of $\mu \to e$ processes in a systematic effective-field-theory approach

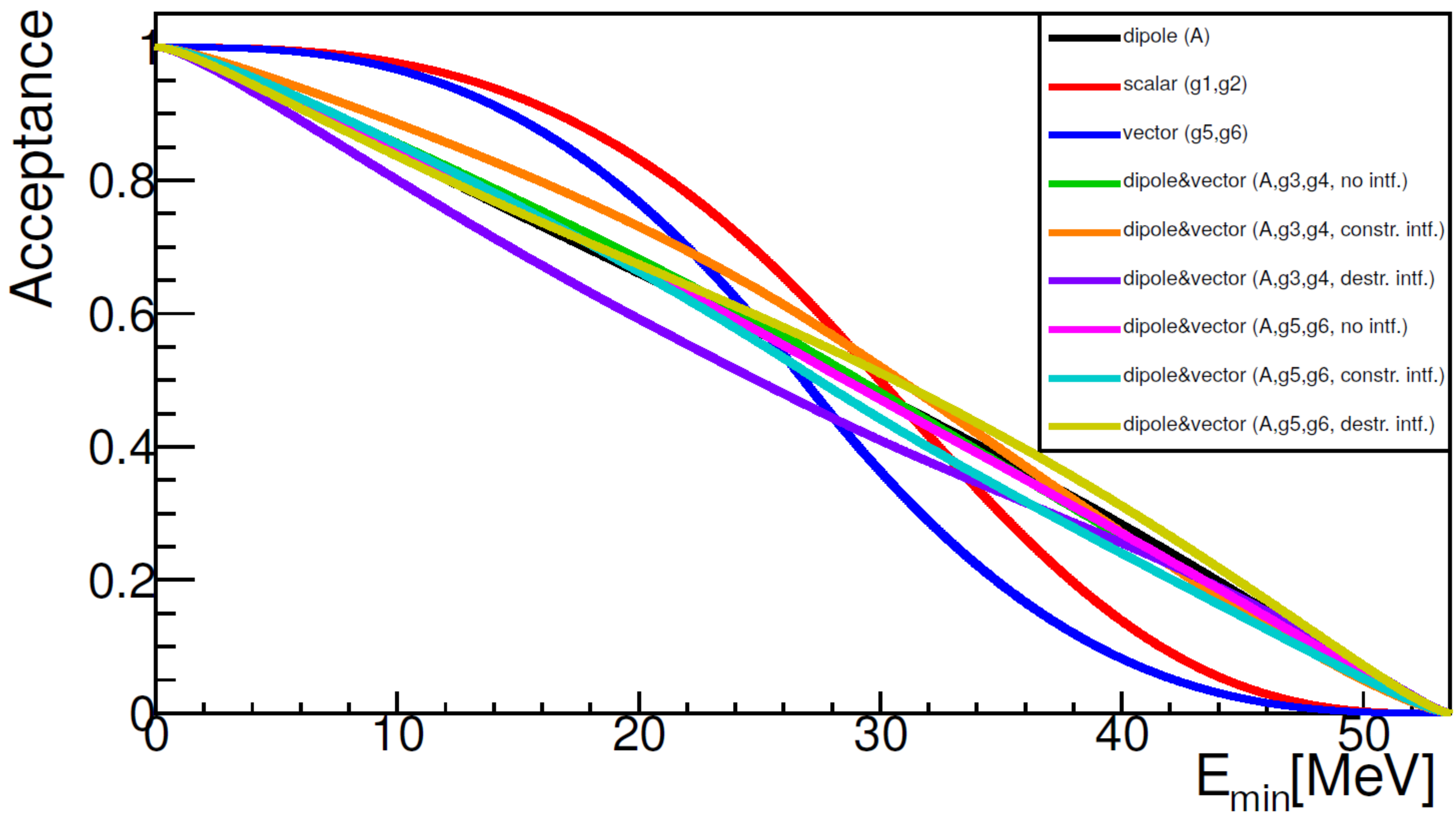
A. Crivellin[a,1], S. Davidson[b,2], G. M. Pruna[a,3] and A. Signer[a,c,4]

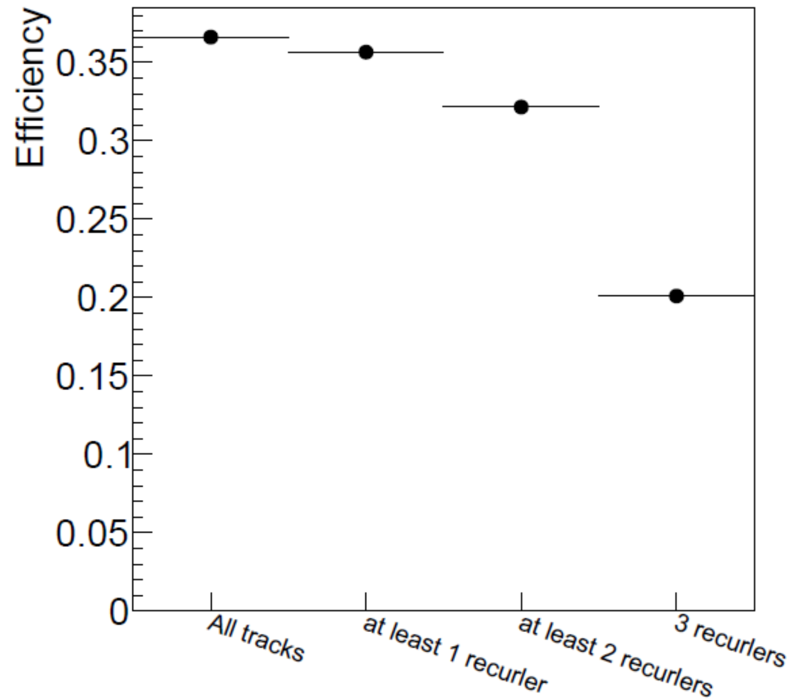


$$\frac{m_\mu}{(1+\kappa)\Lambda^2}$$  $$+\frac{\kappa}{(1+\kappa)\Lambda^2}$$ 

de Gouvea and Vogel, 2013

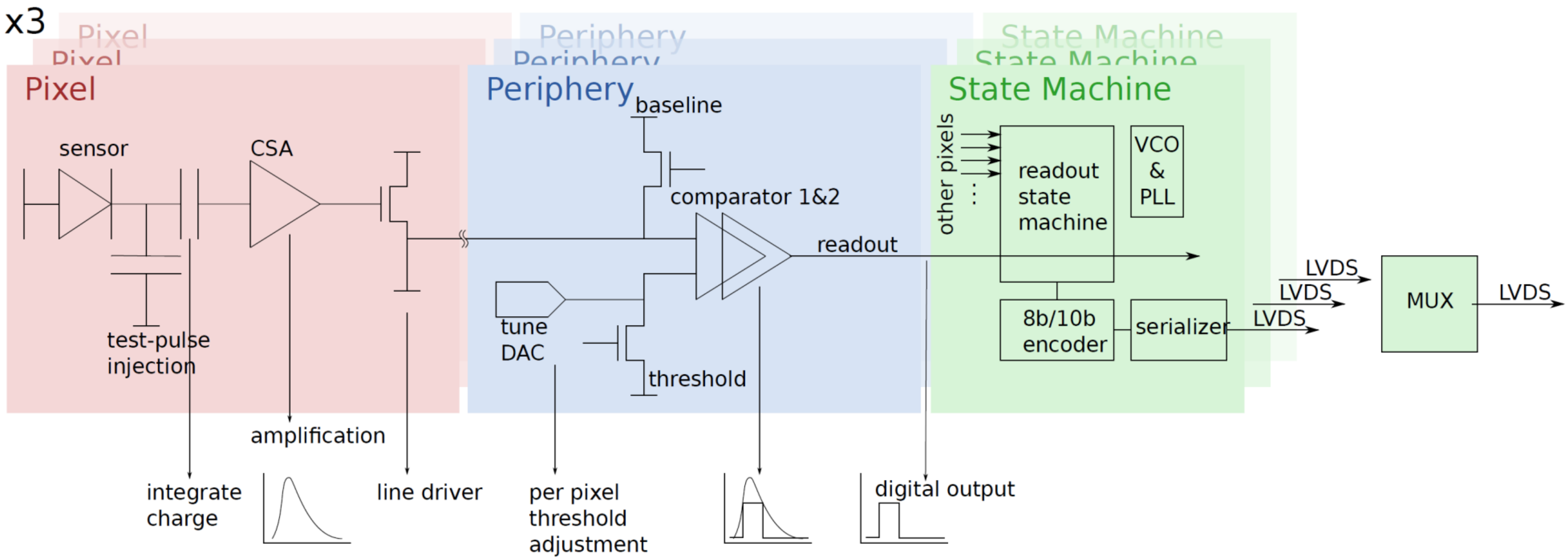



Acceptance
1
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
E_{min}[MeV]
dipole (A)
scalar (g1,g2)
vector (g5,g6)
dipole&vector (A,g3,g4, no intf.)
dipole&vector (A,g3,g4, constr. intf.)
dipole&vector (A,g3,g4, destr. intf.)
dipole&vector (A,g5,g6, no intf.)
dipole&vector (A,g5,g6, constr. intf.)
dipole&vector (A,g5,g6, destr. intf.)



Step	Step efficiency	Total efficiency
Muon stops	100%	100%
Geometrical acceptance, short tracks	43.2%	43.2%
Geometrical acceptance, long tracks	60.6%	26.2%
Short track reconstruction	89.9%	38.8%
Long track reconstruction	80.4%	21.0%
Vertex fit	98.6%	20.8%
Vertex fit $\chi^2 < 30$	98.1%	20.4%
CMS momentum $< 8\,\mathrm{MeV/c}$	98.7%	20.1%
Timing	98.0%	19.7%

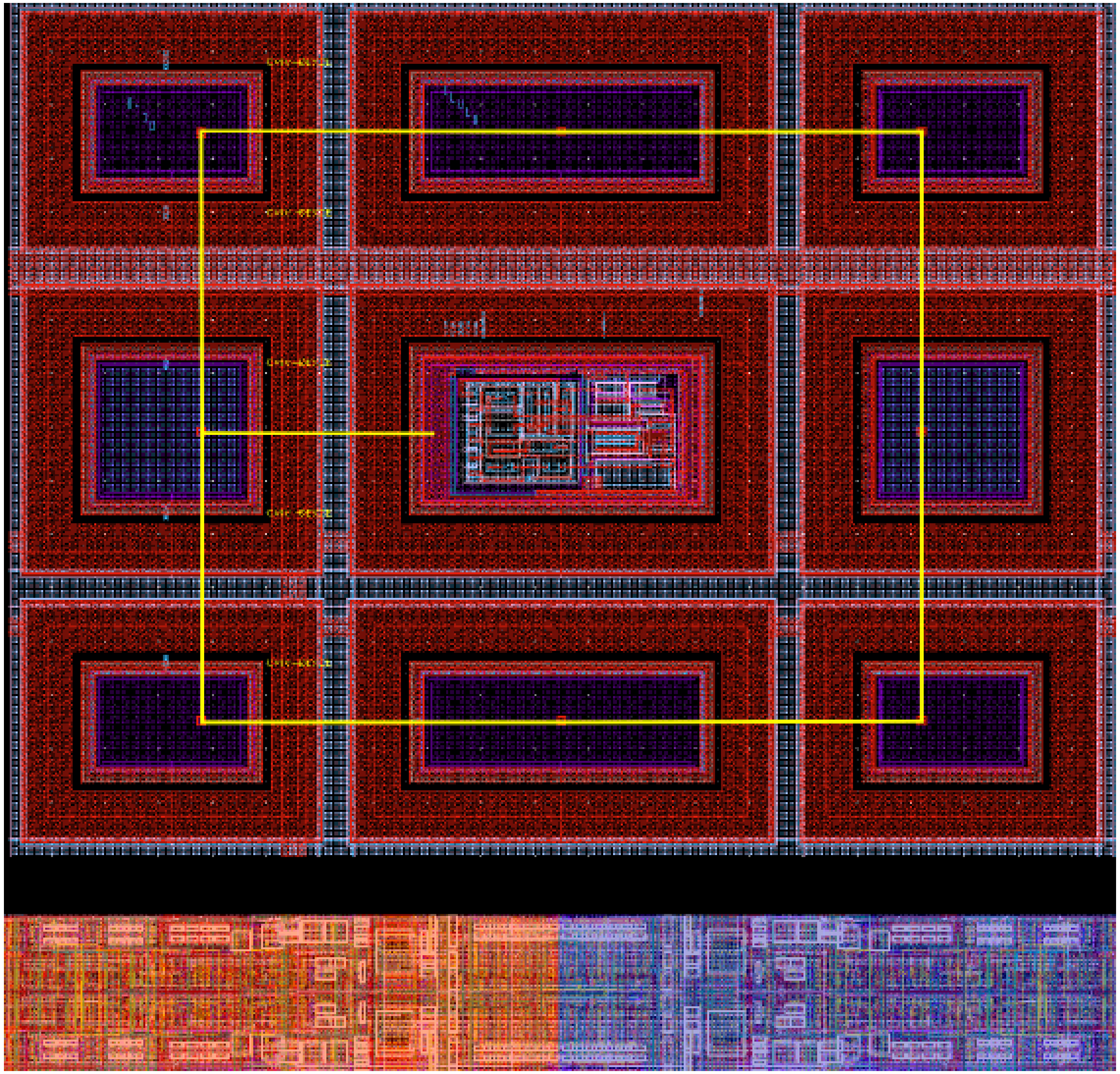
Table 21.1: Efficiency of the various reconstruction and analysis steps.

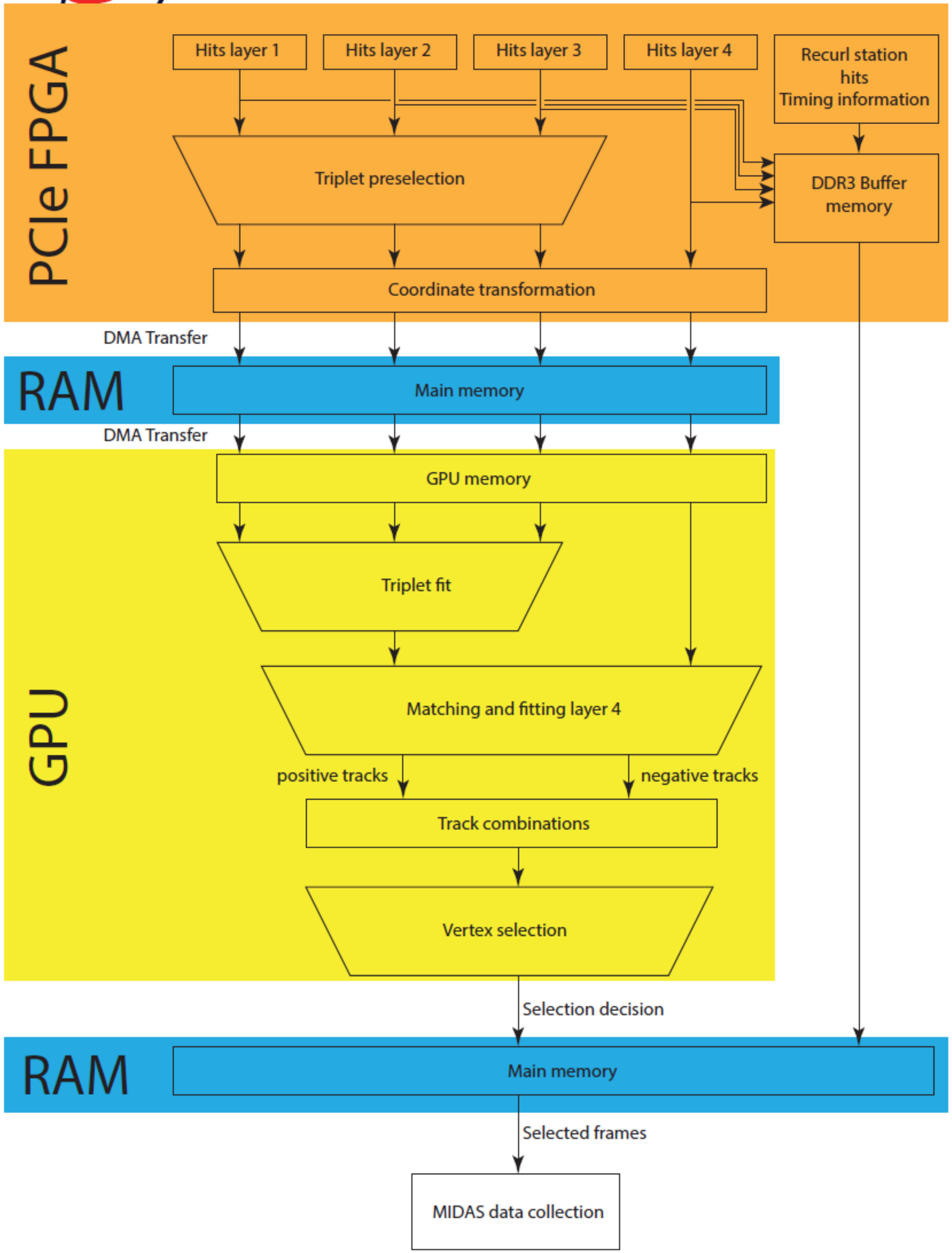


x3
Pixel
Periphery
State Machine
sensor
CSA
baseline
comparator 1&2
readout
other pixels
readout state machine
VCO & PLL
8b/10b encoder
serializer
LVDS
LVDS
LVDS
MUX
LVDS
tune DAC
threshold
test-pulse injection
amplification
integrate charge
line driver
per pixel threshold adjustment
digital output

Pixel:

Digital part:
periphery

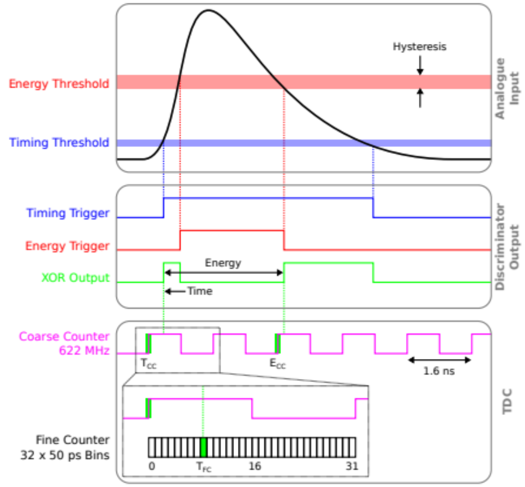



PCIe FPGA
Hits layer 1
Hits layer 2
Hits layer 3
Hits layer 4
Recurl station hits Timing information
Triplet preselection
DDR3 Buffer memory
Coordinate transformation
DMA Transfer
RAM
Main memory
DMA Transfer
GPU
GPU memory
Triplet fit
Matching and fitting layer 4
positive tracks
negative tracks
Track combinations
Vertex selection
Selection decision
RAM
Main memory
Selected frames
MIDAS data collection

SciFi Readout – custom ASIC: MuTRiG

mixed mode, $\approx$ 50 ps t-stamps

high impedance, opt. differential



Tiles: both Thresholds

Fibres: only Timing-Threshold

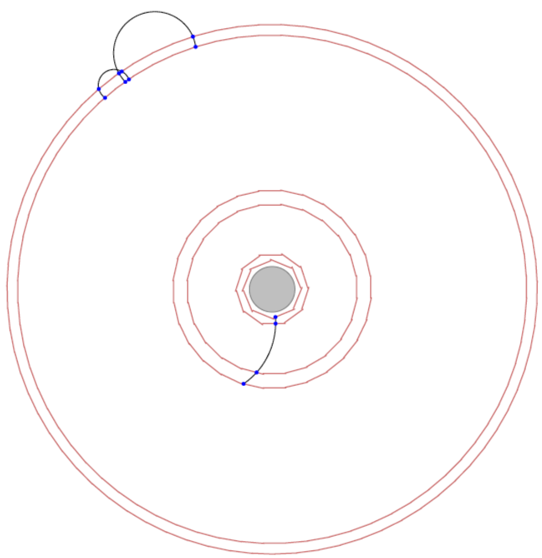
and Energy-Flag

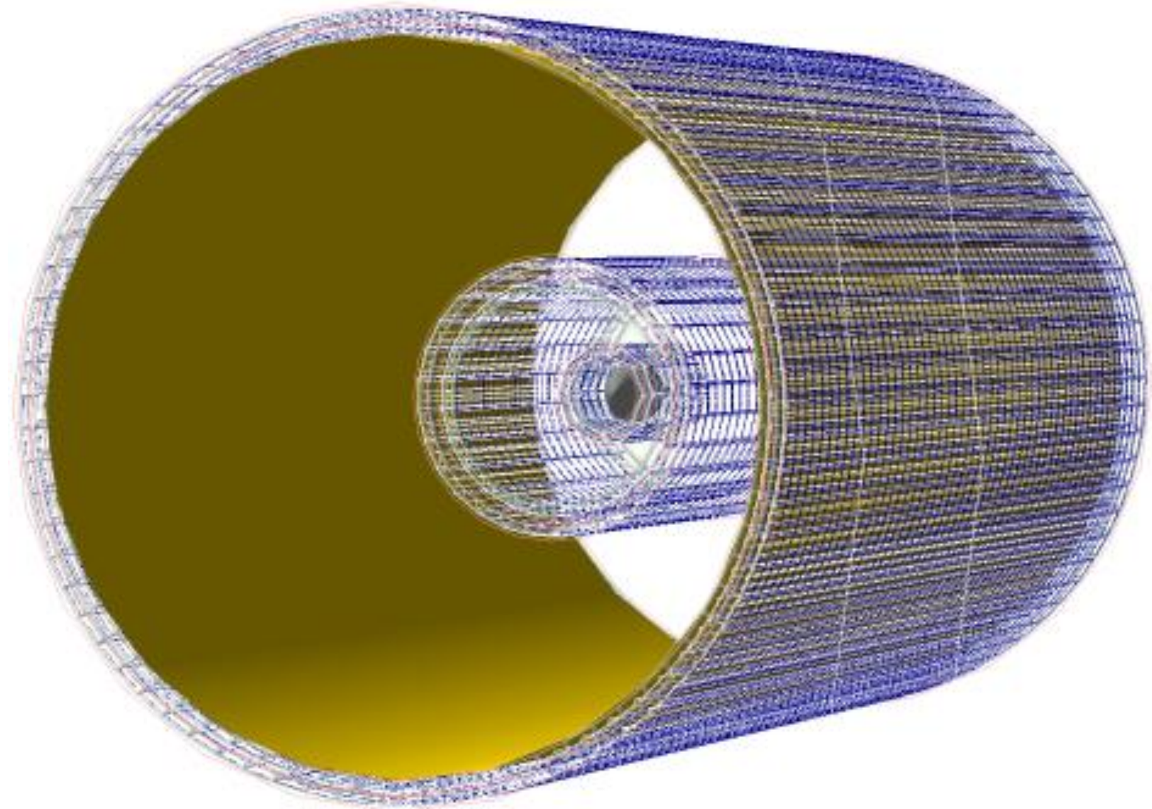
"time mode"

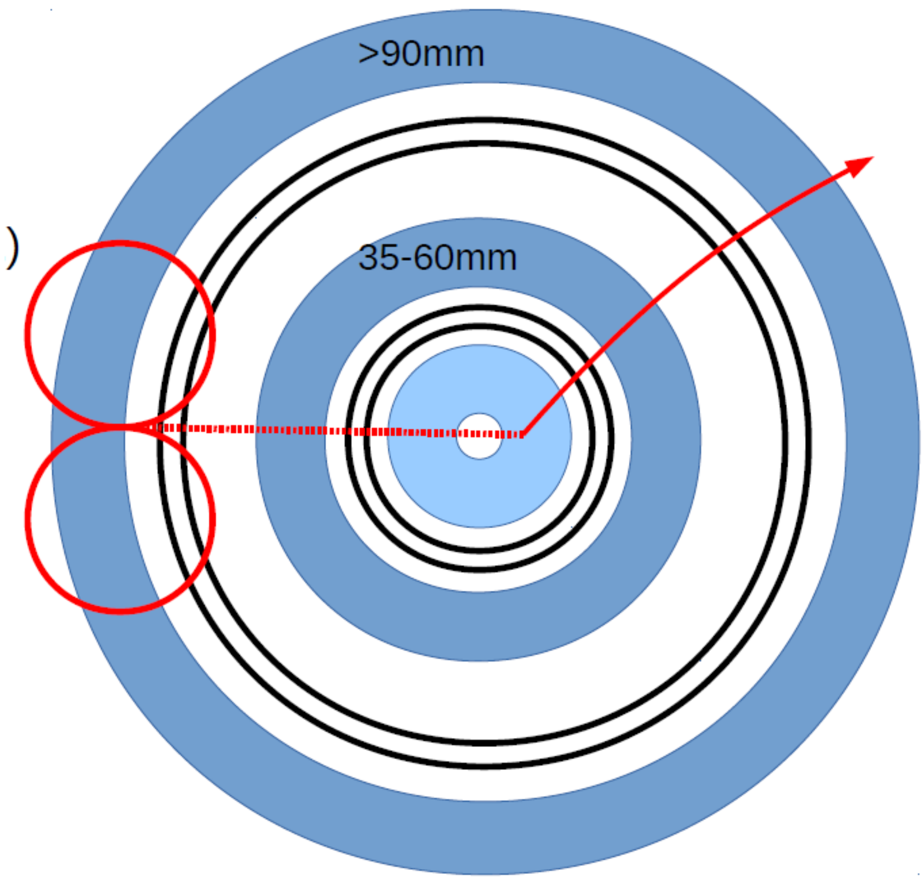
	STiC3.1	MuTRiG
	done	outlook
number of channels	64	32
LVDS speed [Mbit/s]	160	1250
event size [bit]	48	47
time mode	-	26
event rate / chip [MHz]	~2.6	~20
time mode	-	~38
event rate / ch [kHz]	~40	~650
time mode	-	**~1200**
power per channel [mW]	35	35
size [mm x mm]	5x5	5x5

PHYS

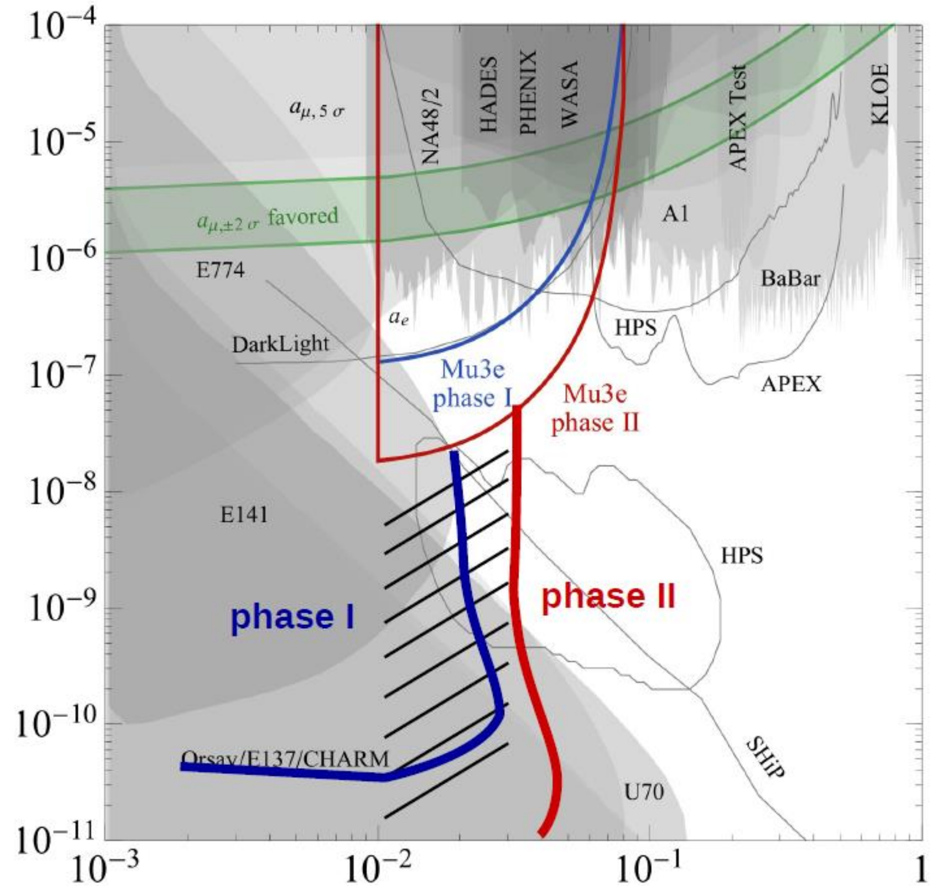
L. Gerritzen 2018-0

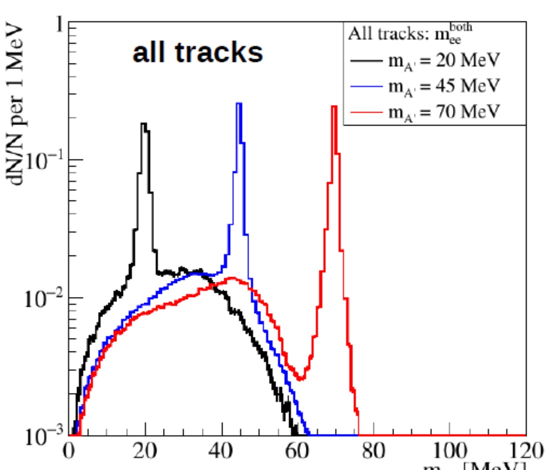


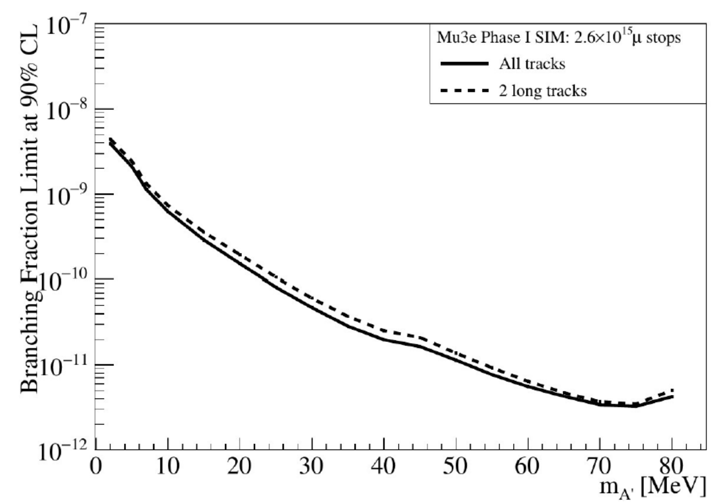




fiducial volume



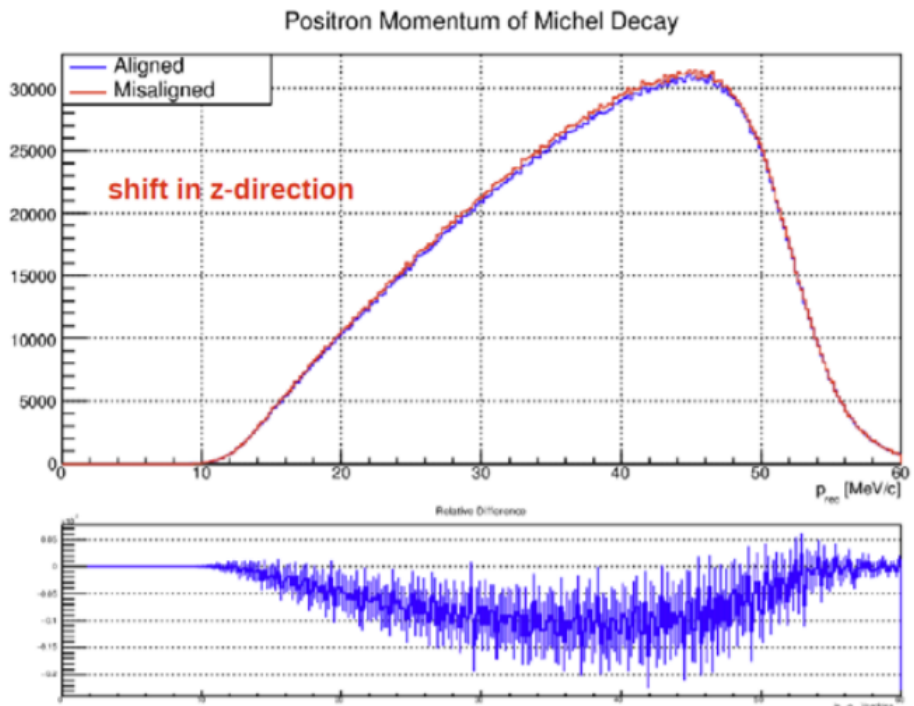


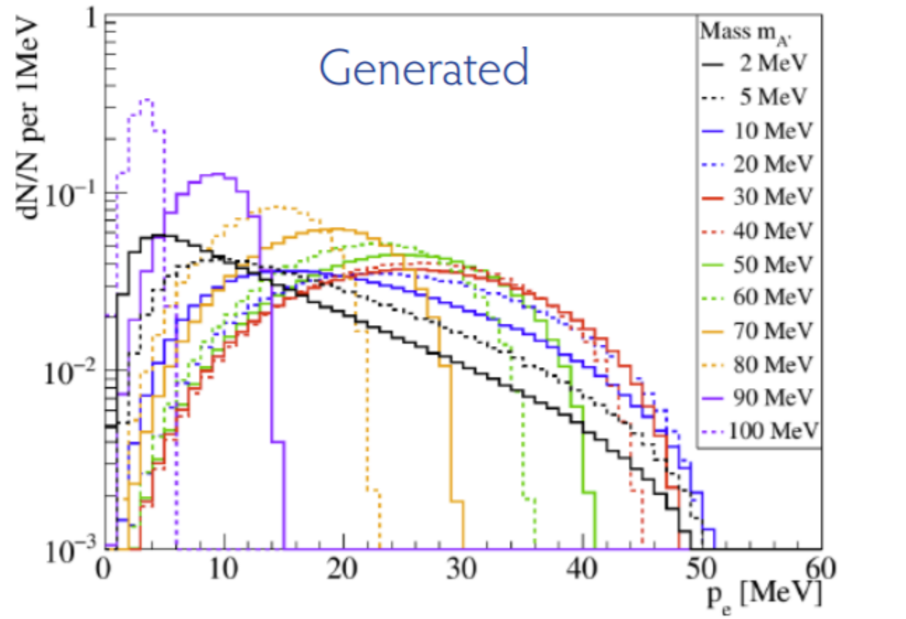


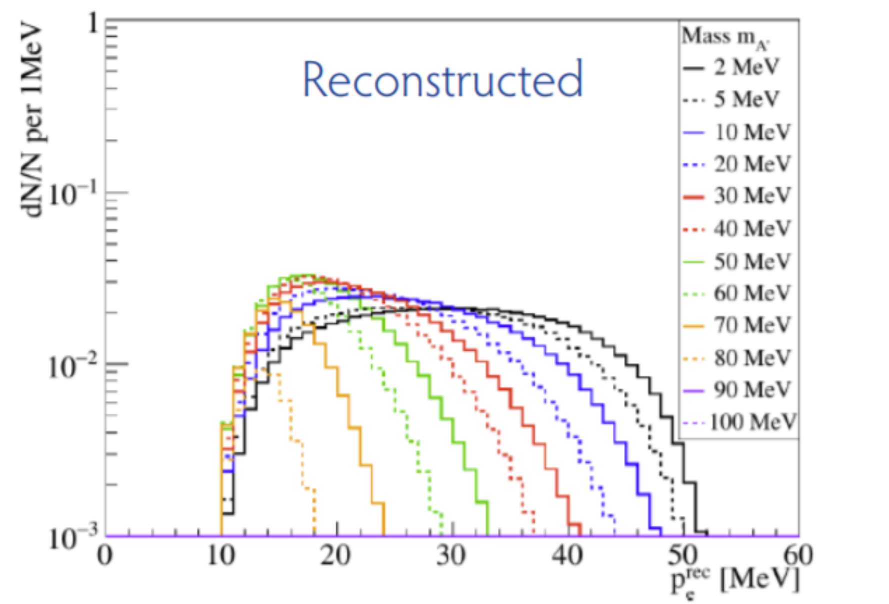
Invisible dark photons

$\mu \to e\nu\bar{\nu}A'$ is a four-body decay...

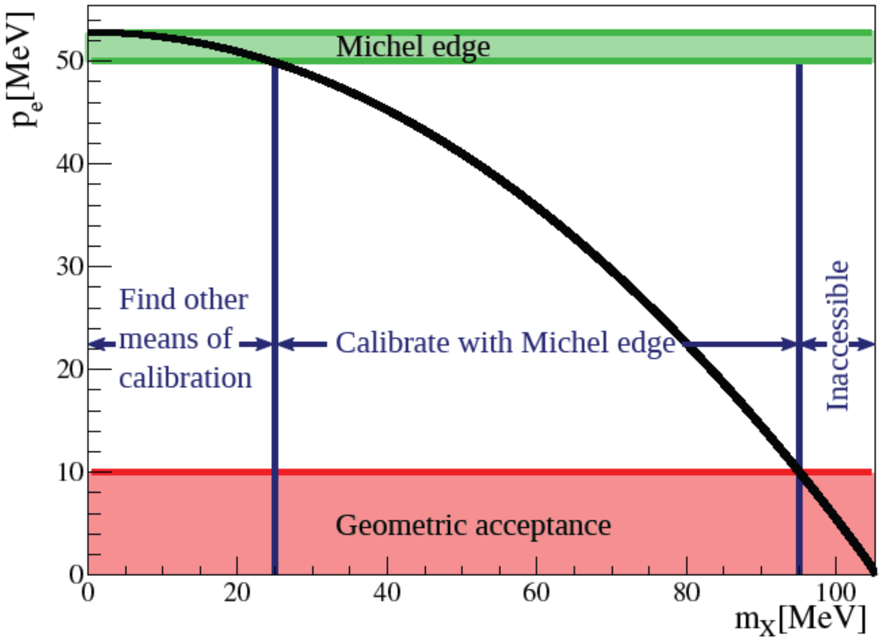
- Shift to Michel spectrum
- Can also come from detector misalignment
- Not really promising



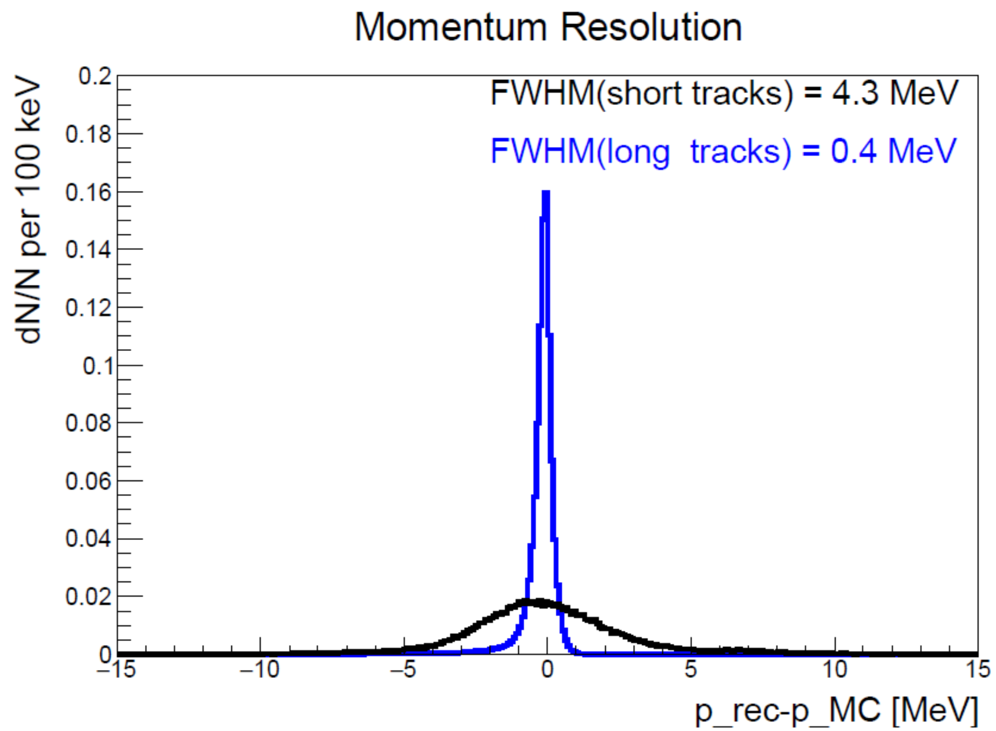


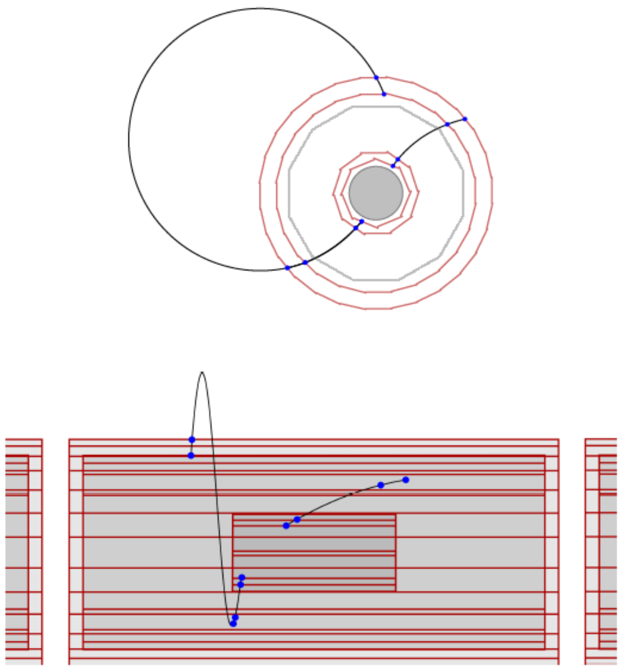


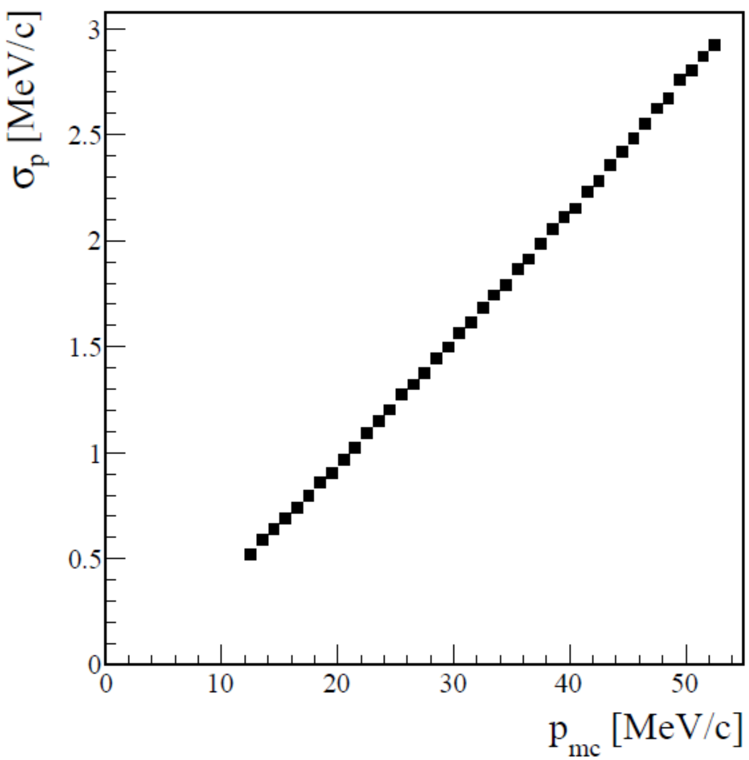
- $0 < m_X < m_\mu - m_e$
- Very large m_X: positron does not have enough momentum to be seen
- Very low m_X: "peak" sits on top of Michel edge, more a shift - have to be very careful not to calibrate it away
- m_X of 25 to 95 MeV "easy"



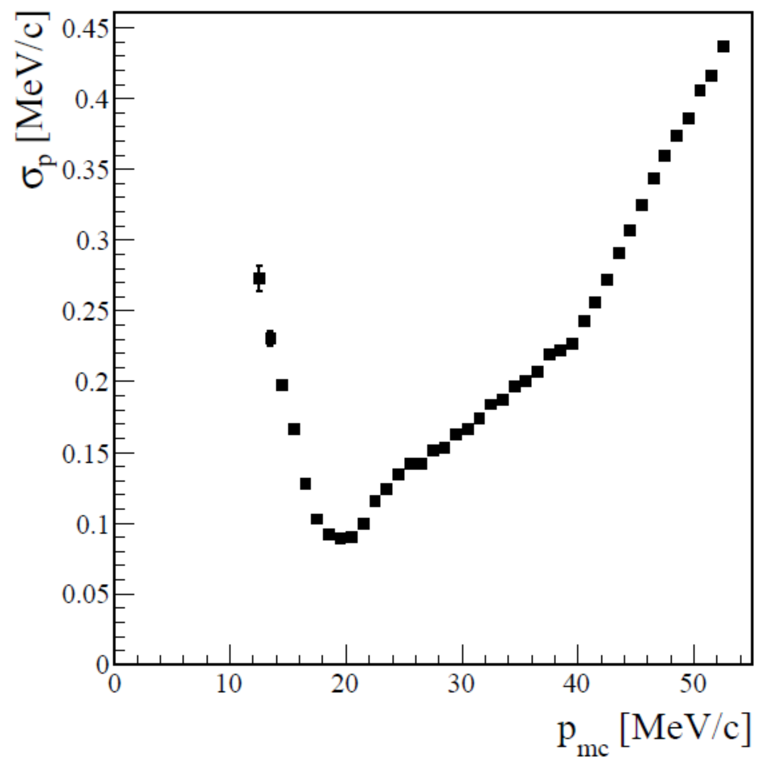
Momentum resolution for short and long tracks





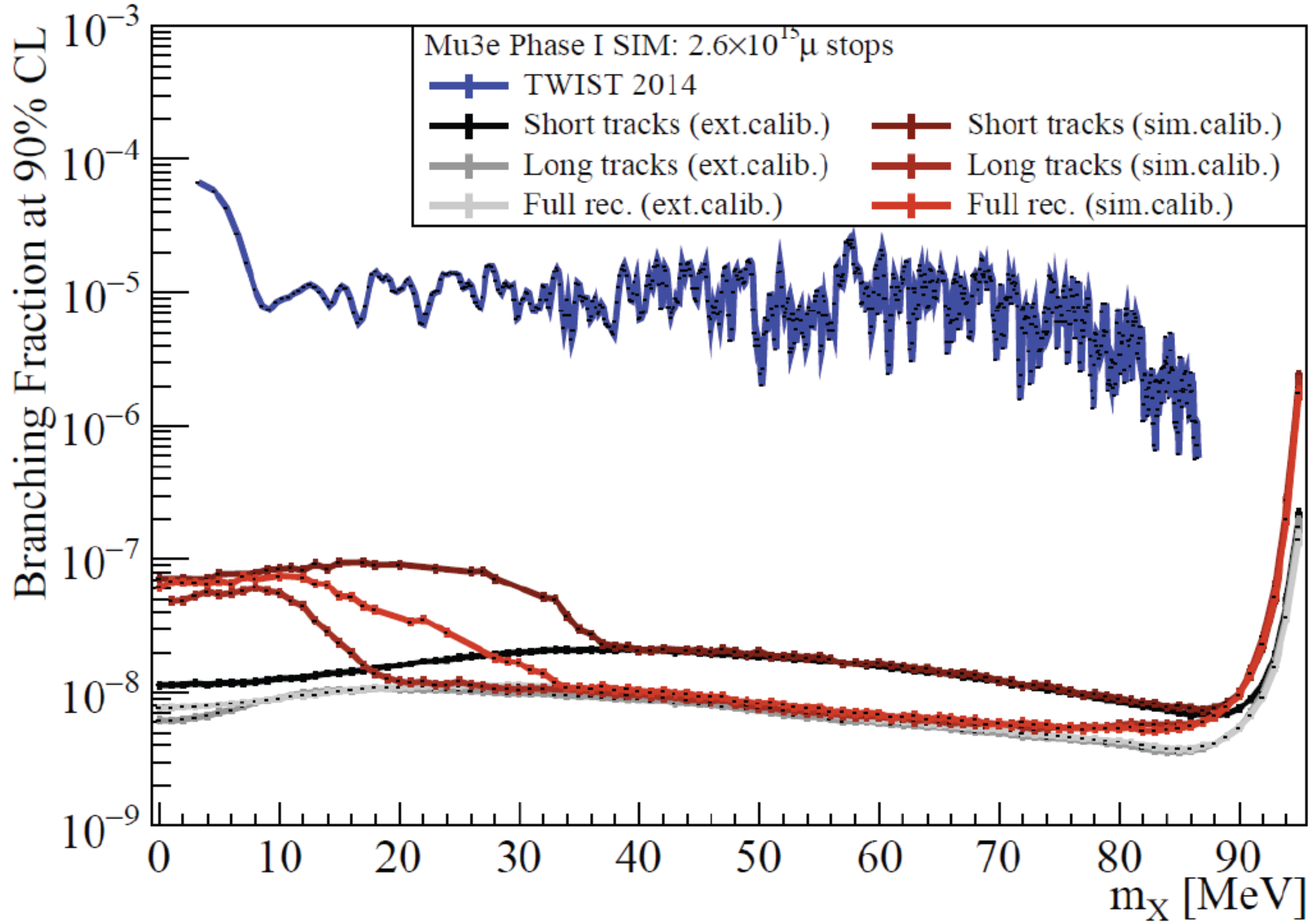


Momentum resolution short tracks.



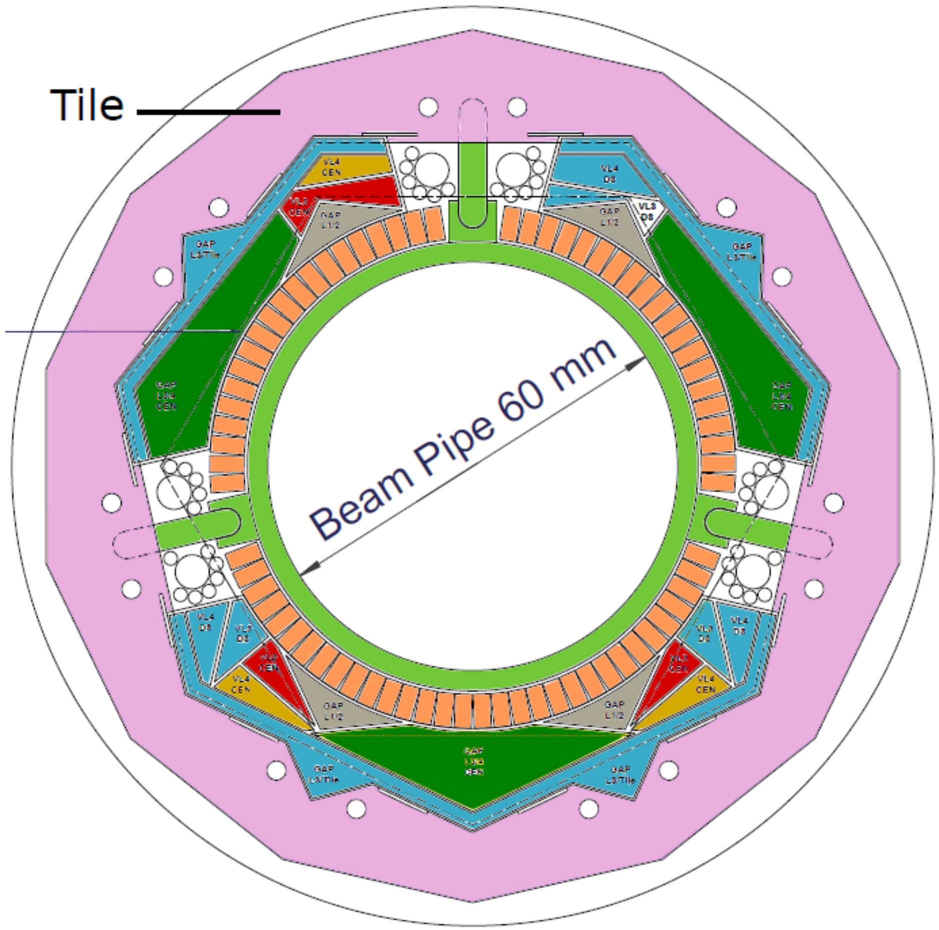
Momentum resolution long tracks.

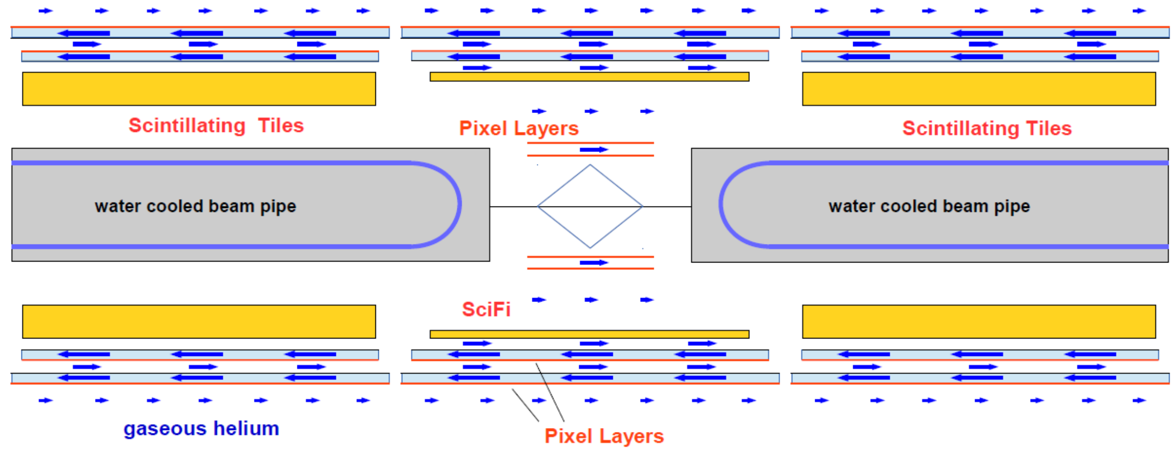
And in comparison



Tubing system

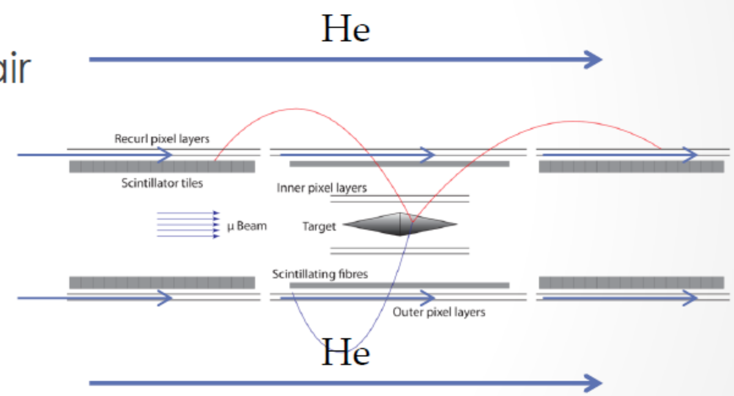
Flow channel	He flow speed $\mathrm{m\,s^{-1}}$	Cross-section $\mathrm{cm^2}$	Volumetric Flow $10^{-3}\,\mathrm{m^3\,s^{-1}}$
Gap L1/L2	10	12	12
Gap SciFi/L3	5	105	53
V-folds L3	20	$0.7 \times 24 \times 2$	20
Gap L3/L4	10	60	60
V-folds L3	20	$0.7 \times 28 \times 2$	23
Total		238	168





H

- Gaseous He cooling
  - Low multiple Coulomb scattering
  - He more effective than air
- Global flow inside Magnet volume
- Local flow for Tracker
  - V-shapes
  - Outer surface
    - In between layers
    - Between SciFi and layers



$$400 \text{mW/cm}^2 \times 11376 \text{cm}^2 = 4.5504 \text{ KW}$$

Material