Mu3e Experiment Update

Dr. Carlos A. Chavez Barajas

Liverpool HEP Annual Meeting

(29/04/2021)

Construction status update, overall and in the UK, schedule, issues and physics preparation

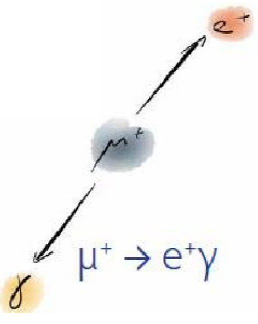
Joost Vossebeld, Nikolaos Rompotis, Helen Heyward, Jason Hempstead, Eva Vilella, Carlos Chavez, Andrew Groves, Afaf Wasili, Sean Hughes, Peter Cooke, Tim Jones, Peter Sutcliffe, Dave Sim

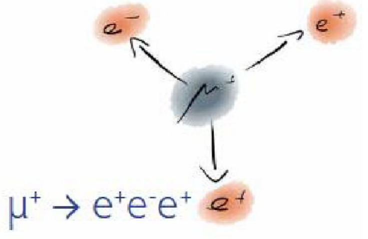
Motivation : Charged Lepton Flavour Violation (**CLFV**)

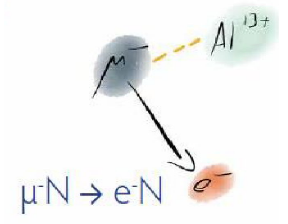
- **We observe flavour violation for quarks and neutrinos but not for charged lepton**
  - This appears to be “accidental”.
- **SM (with m_v) allows for only a very small amount of CLFV (10^{-54})**
  - Any observation would be evidence of new physics
- **Recent results on Lepton Universality (LHCb) and muon g-2 (Brookhaven & Fermilab)**
  - There may be new physics affecting muons
  - New muon CLFV experiments have the sensitivity to tell us more about any such new physics

If charged lepton flavour is not conserved we expect neutrinoless muon decays:

	Best limits	Projected sensitivities (90%CL)
$\mu \rightarrow e\gamma$	< 4.3×10^{-13} MEG (PSI)	4×10^{-14} MEG II (PSI)
$\mu \rightarrow eee$	< 1.0×10^{-12} SINDRUM (PSI)	4×10^{-15} Mu3e I (PSI) 1×10^{-16} Mu3e II (PSI)
$\mu N \rightarrow eN$	< 7.0×10^{-13} SINDRUM II (PSI) μ Au $\rightarrow$ e Au	6×10^{-17} Mu2e (FNAL) 7×10^{-15} COMET I (J-PARC) 6×10^{-17} COMET II (J-PARC)





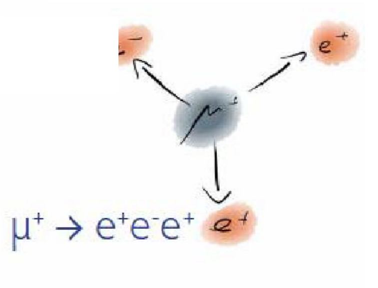


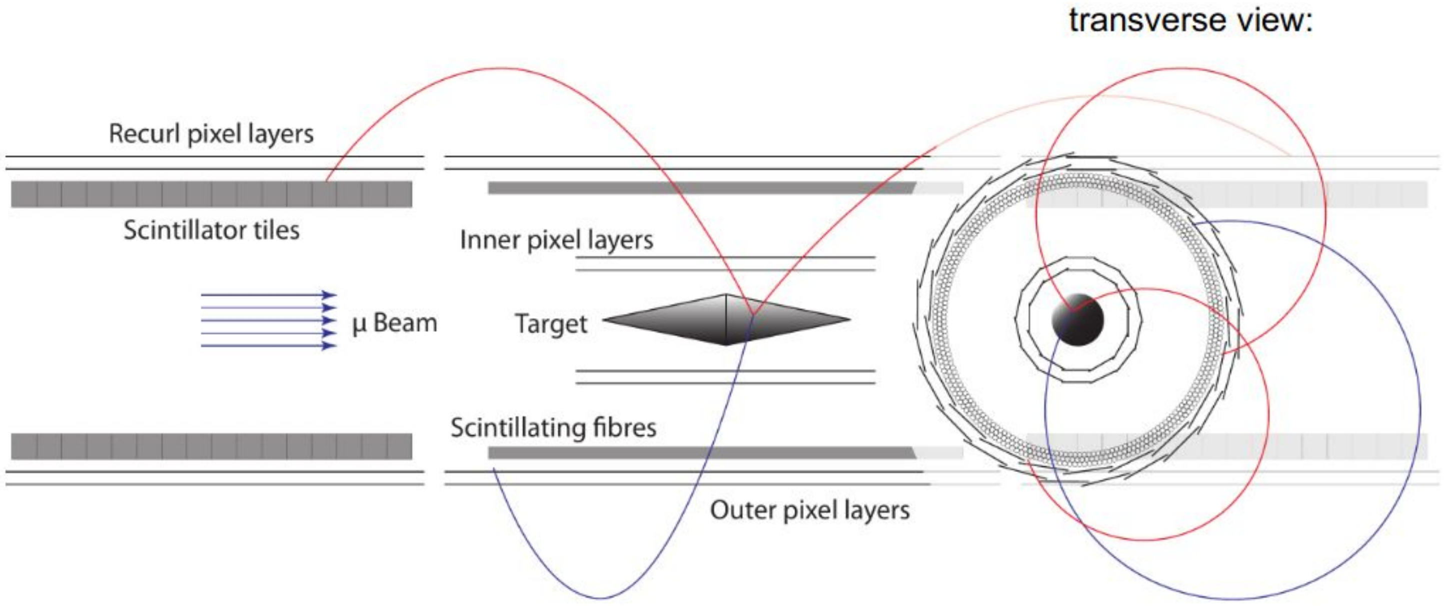
Generically, the planned CLFV experiments probe NP at 1-10 PeV scale.

The Mu3e experiment

- **Located at PSI**
- **Signal : looking for** $\mu^+ \to e^+e^+e^-$
  - From the same vertex and energy 1 MeV < E_e < $m_\mu/2$
  - Aiming for a branching fraction of > 10^{-16} (@90% CL) in Phase I

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





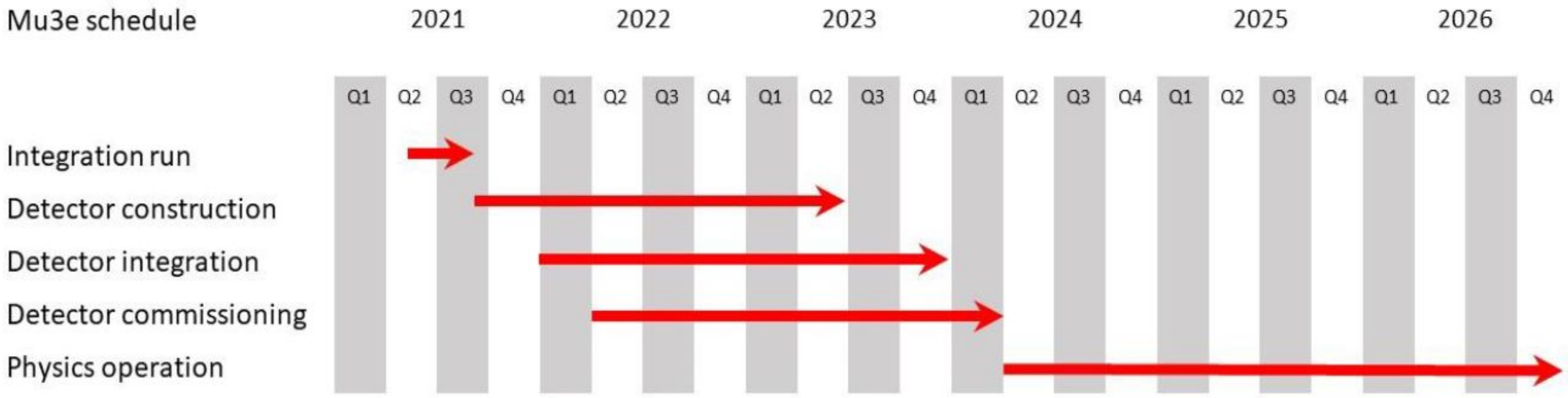
+ strong magnetic field (B=1T)
+ helium gas cooling

in helium atmosphere

UK deliverables:
- Clock and reset system (distributed via optical fibres). (completed!)
- MuPix outer tracker layers (1.1 m^2 HVMAPS tracker)

Mu3e schedule and physics readiness

Strong physics case, there are no immediate competitors



- Mupix and covid delays means that detector construction will be finished in early 2023
- Detector commissioning finished by early 2024 & start of physics operation

Status of the experiment

Experimental area ready

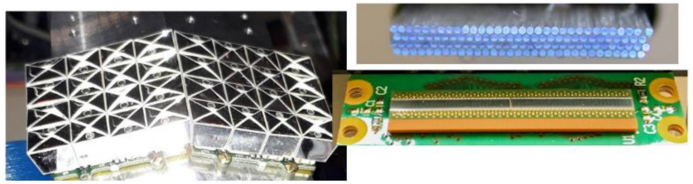
Magnet commissioning complete

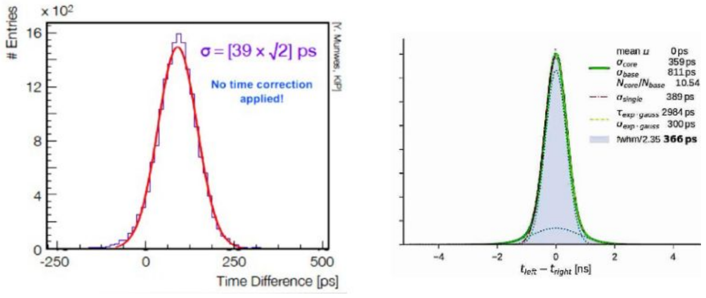
2T super conducting

- TDR published 2009.11690.pdf (arxiv.org)
- Successful annual review at PSI
- Phase I muon beam line commissioned : 10^8 μ/s delivered to experiment
- Integration run with muon beams scheduled for May-July 2021
- First demonstration 6 chip inner pixel ladder
- So far (low statistics) satisfactory yield on MuPix10 chips and inner ladder production
- Off detector readout system successfully demonstrated on final slice test
- Demonstration Helium cooling system and simplification through removal v-channel cooling.

  (Some UK development work needed to change assembly procedure)
- Recent funding news:
  - DFG funding next batch awarded last week (next 4 years of contribution German groups experiment)
  - FLARE infrastructure funding for Helium cooling system (including tech support) awarded.

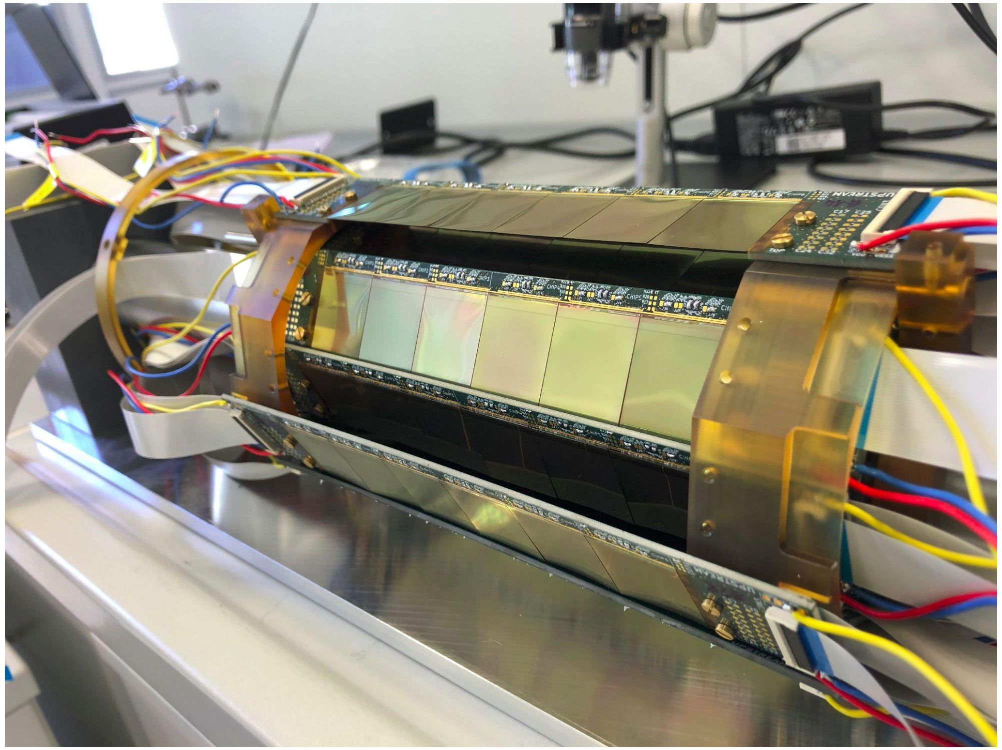
Scintillating fibre and tile detectors ready for production





Progress on MuPix project

- **MuPix chip**: The first full size and final prototype pixel tracker chip, Mupix10, has been delivered and its characterisation has shown excellent performance. An issue to configure the chip through a minimal number of electrical connections is to be resolved for the final detector chip Mupix11 (to be submitted in Autumn), but a work-around has been identified, meaning that crucially, the chip is suitable for the production and evaluation of the full size demonstrator MuPix modules needed to achieve production readiness. Small design modifications on HDI.
  - Inner pixel ladders (6 chips)) shown to configure and send data.
  - Production full inner pixel layers for integration run on schedule

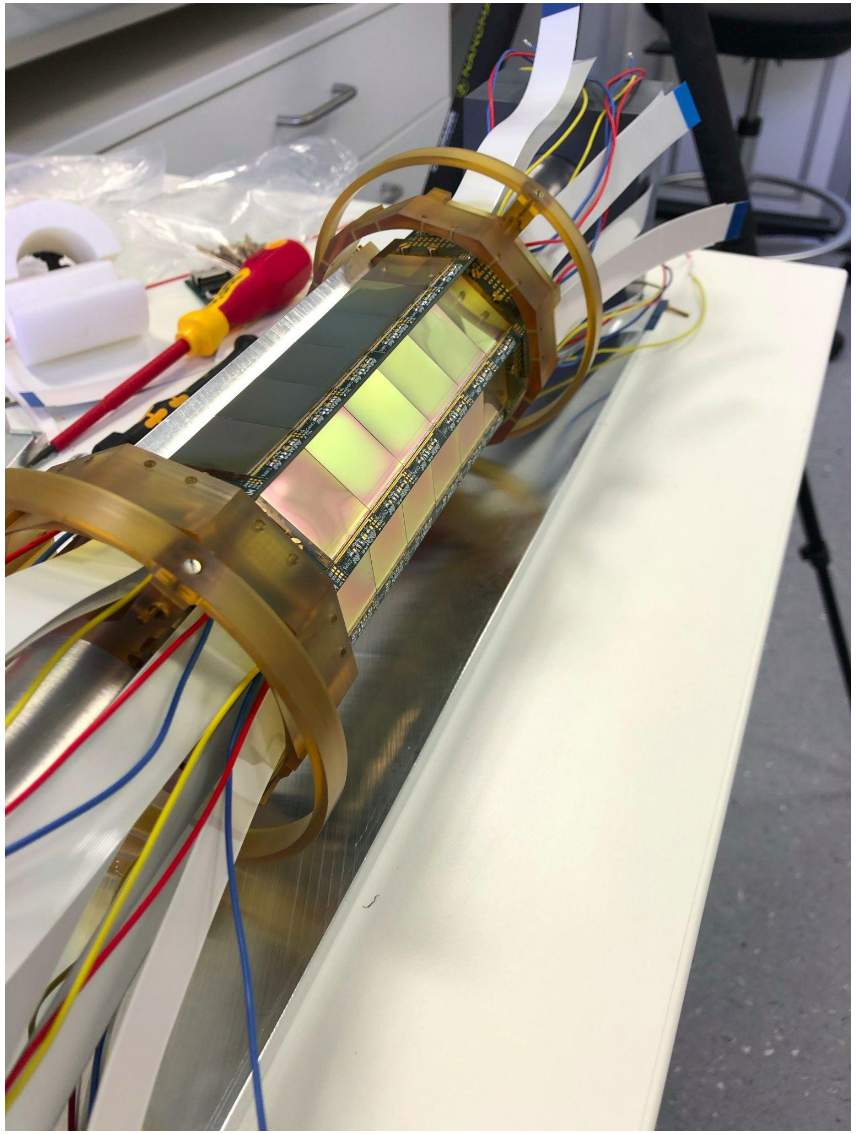


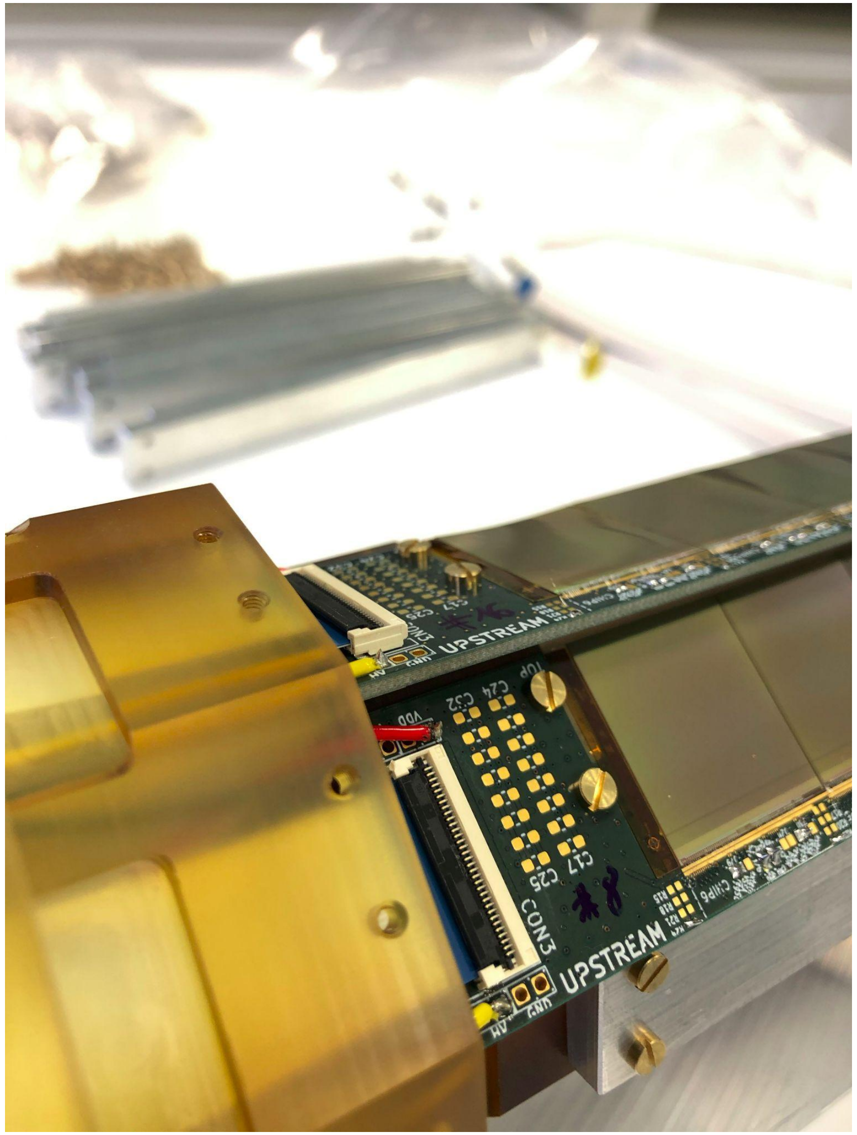
- **Flex circuits**: Submission of HDI interconnect circuits for the readout of MuPix10
  - HDI from inner layers back from manufacturer any day for further test.
  - Outer HDI nearly ready for submission

- **Assembly test**: Successful test assembly of seven layer-4

thermo-mechanical mock-up modules to the detector mounting rings.
  - First prototype load transfer tooling under test

Integration Run preparation

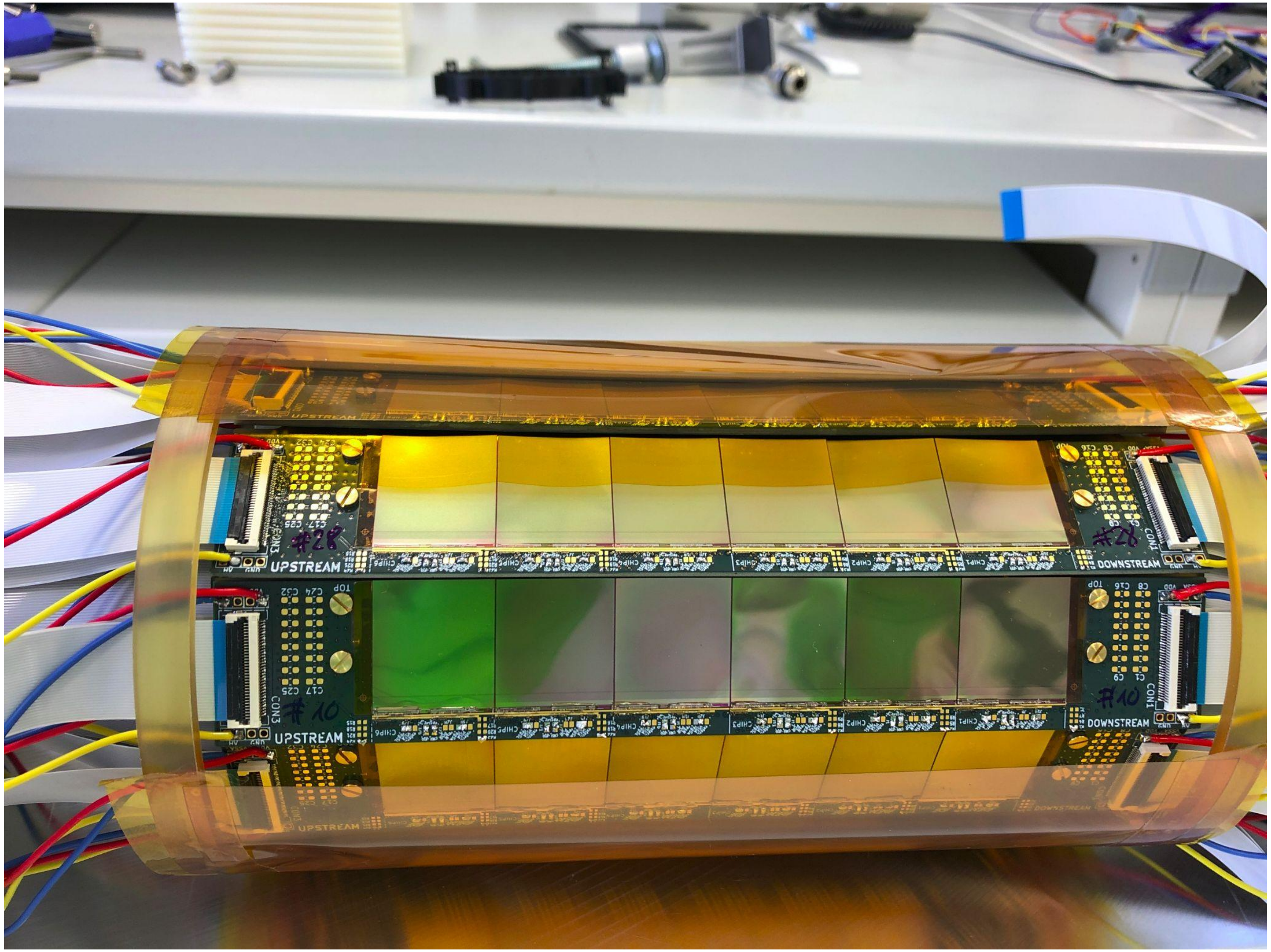




Production Finished

Inner Layers with
MuPix10 chips

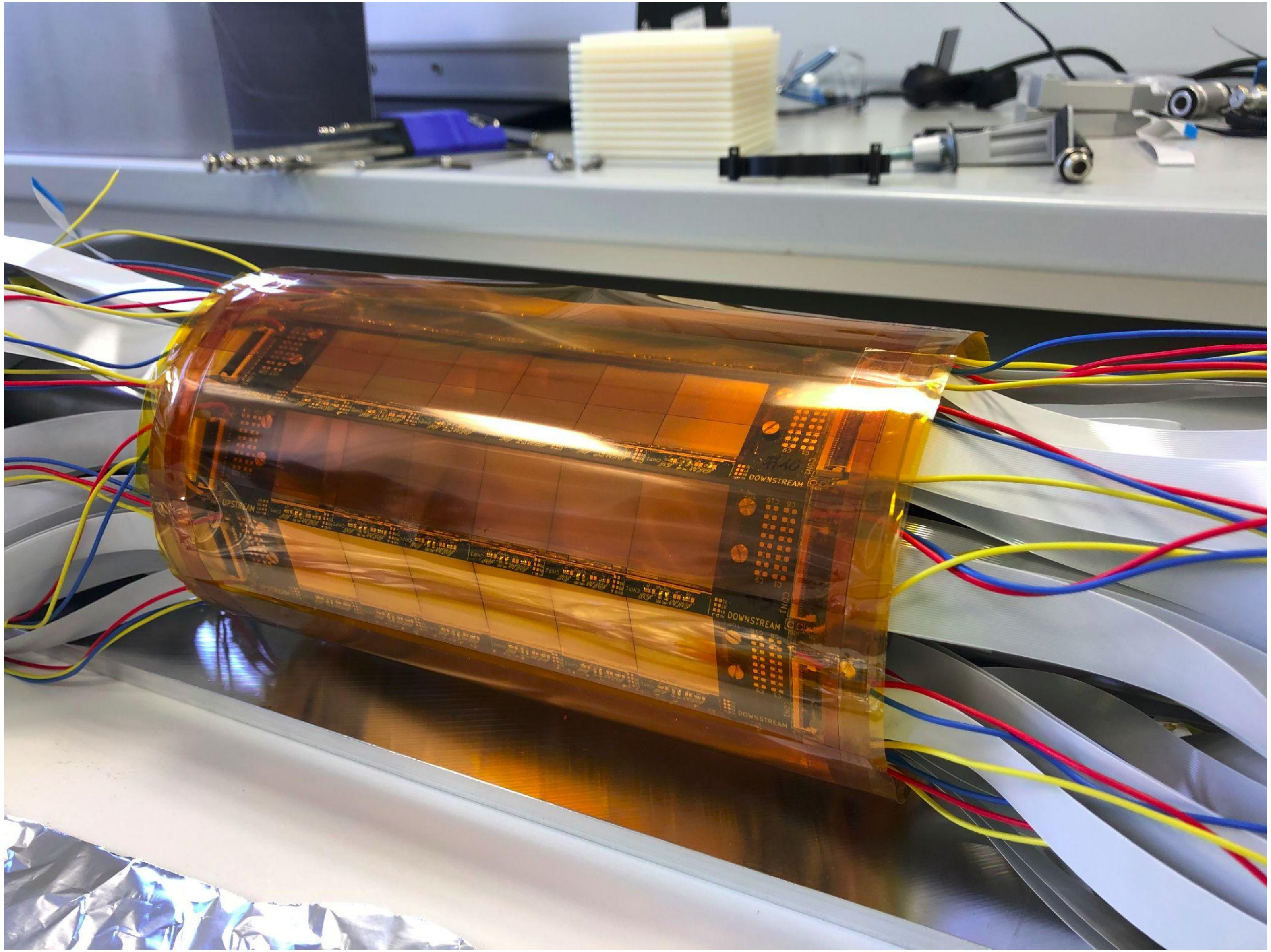
Integration Run preparation



Production Finished

Inner Layers with MuPix10 chips

Integration Run preparation



Production Finished

Arrived at PSI today

UK deliverables

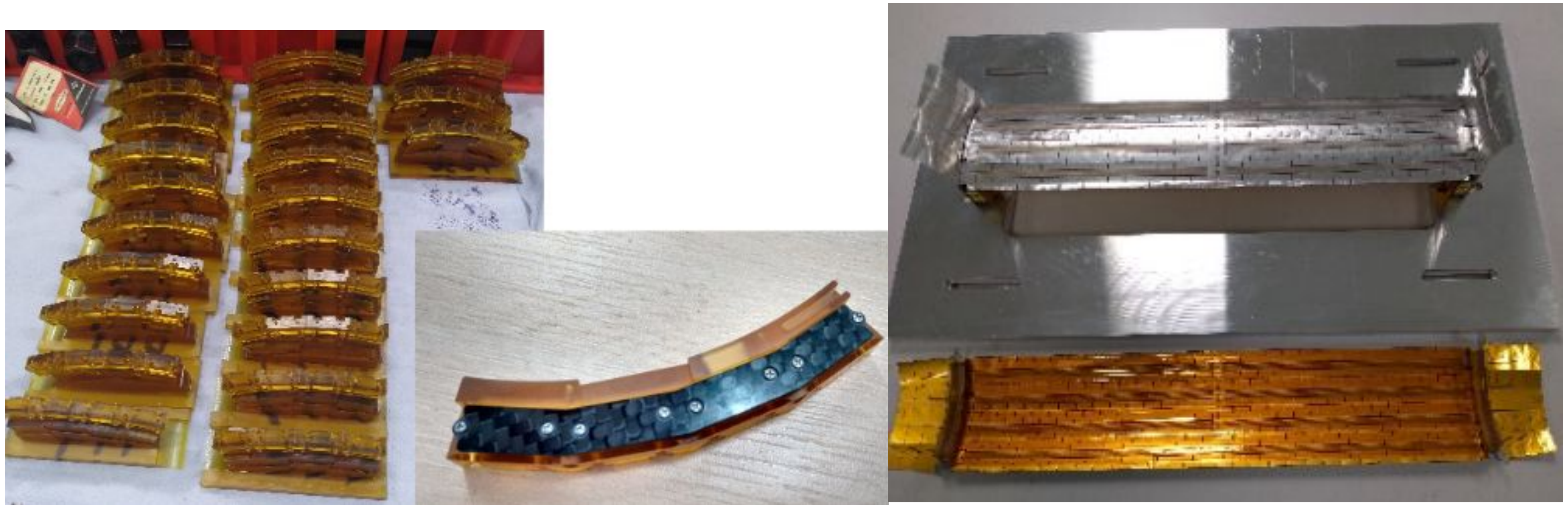
<u>MuPix tracker Outer and Recurl layers (Bristol, Oxford, Liverpool)</u>

World's first use of HV-MAPS technology in an experiment.

UK provides 18 layer-3 and 21 layer-4 modules, consisting of 4 pixel ladders each, and hosting in total 68 or 72 MuPix ASICs each, respectively.

UK contributions MuPix tracker

- MuPix probing
- HDI and interposer flex design
- Endpiece manufacture
- Ladder assembly
- Module assembly
- Ladder and module QA
- Macro assembly



Mockup ladders
Module construction process

<u>Clock and Reset system (UCL) – complete</u>

Accurate clock distribution key for future 4D tracking application.

- The system has been developed and built!
- Provides clock/reset distributions: 1 $\rightarrow$ 144 with time jitter of ~5ps.
- Successfully demonstration in vertical slice test.
- To be integrated with Mu3e readout as the detector is completed.

Physics analysis and performance studies

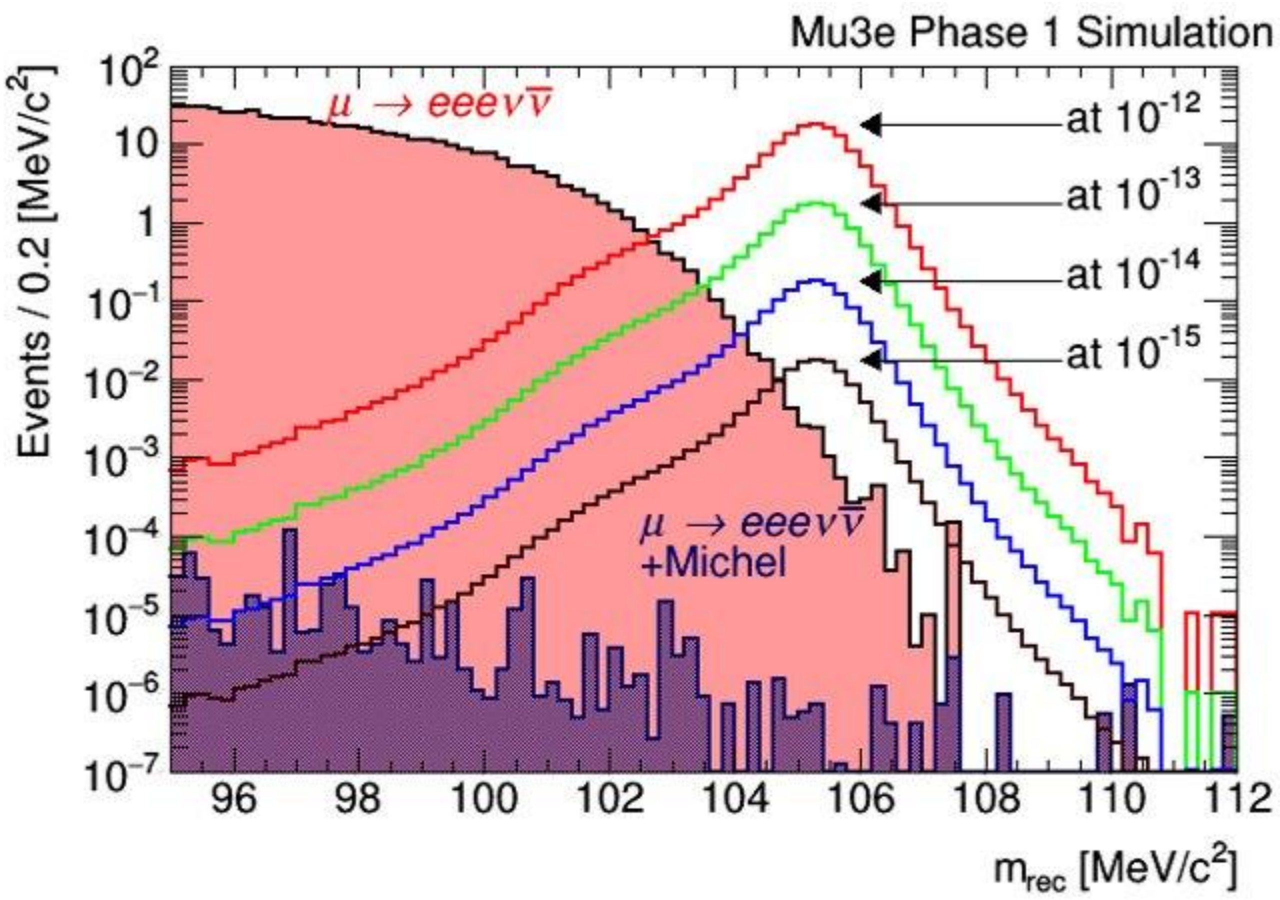
PhD students :

Afaf Wasili

Andrew Groves

Sean Hughes

Combinatoric background estimate (Andrew G.)



First estimate of a potential source of background, included in the recently published TDR

Internal Conversion estimate of background events
103-110 : 0.53 ± 0.02
104-110: 0.052 ± 0.003

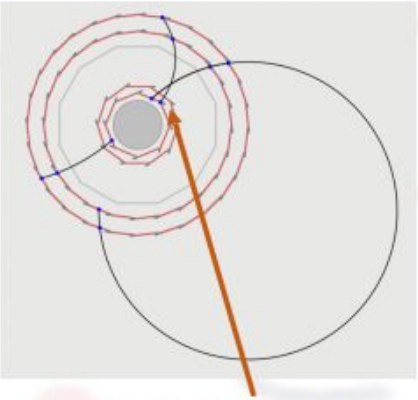
Internal Conversion and Michel estimate of background events
103-110 : $(1.64 \pm 0.71) \times 10^{-5}$
104-110: $(9.5 \pm 5.8) \times 10^{-6}$

Studies of Mu3e tracking performance for different categories of particle tracks in three scenarios (Afaf Wasili)

1. Missing hits due to by dead layers dead chip or individual dead pixels

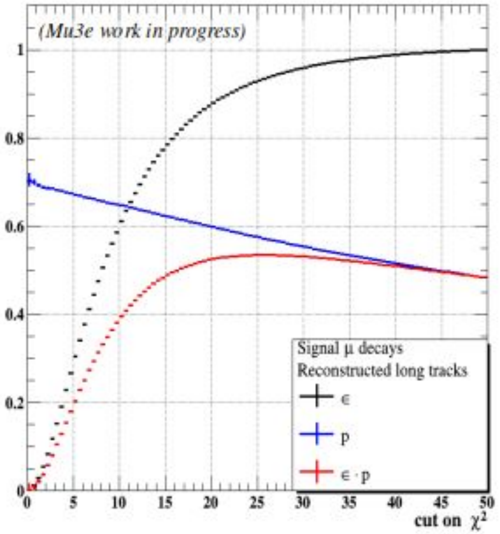
- Artificially introduce different inefficiencies level into pixel layers in the central station and investigate recovering track efficiency by allowing holes on the track
- Goal was to allow tracking algorithm to access dead sensor in a missing layer
- More fake/mis-reconstructed tracks and less track/vertex efficiency of signal muon decays

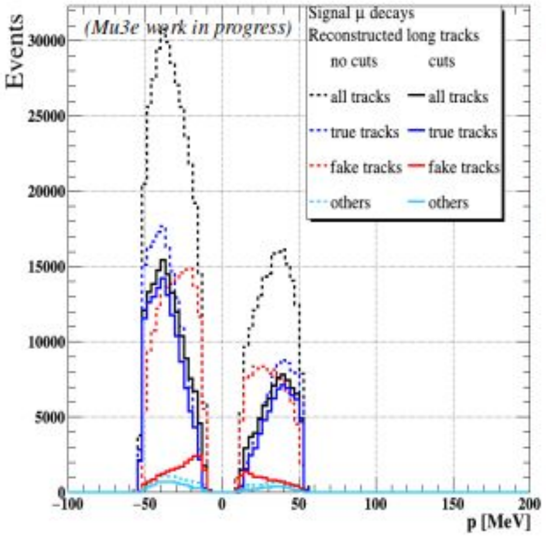
]



Imperfect track with missing pixel hit in 1-silicon layer

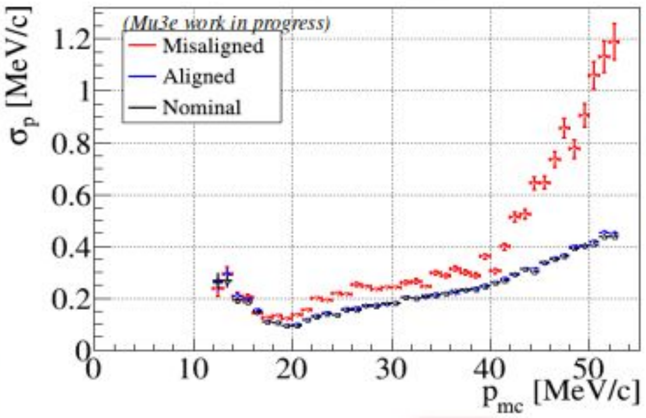
Imperfect reconstructed tracks with 5-pixel hits In the CS and RS of the detector (100% inefficiency in 2-pixel layer)





2. Misaligned detector

- Many misalignment modes can be applied successfully for all individual sensors or composite parts level
- Using Millipede-II alignment algorithm to align detector
- Study the performance of nominal tracks with misaligned and aligned and compare it with nominal detector

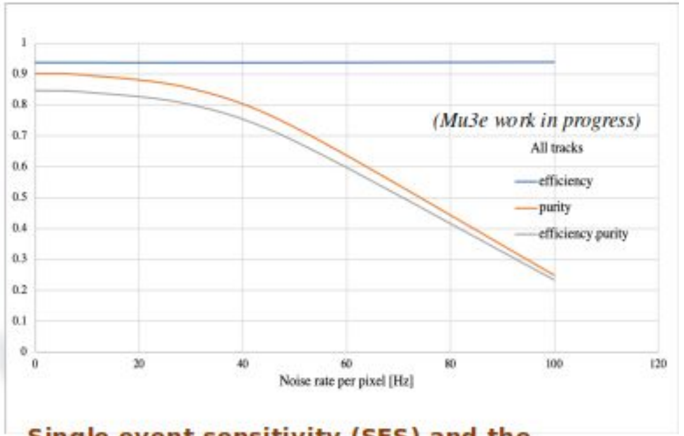


Results of the vertex reconstruction of signal events with three recurlers required; for a nominal, a misaligned and an aligned detector

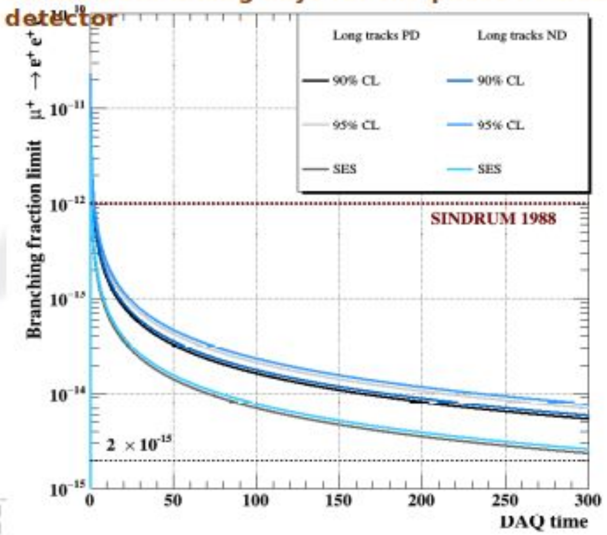
parameter [mm]	nominal	misaligned	aligned
$x_{rec} - x_{true}$	$\mu = -0.004 \pm 0.002$ $\sigma = 0.212 \pm 0.002$	$\mu = 3.00 \pm 0.00$ $\sigma = 6.72 \pm 0.009$	$\mu = -0.003 \pm 0.002$ $\sigma = 0.212 \pm 0.002$
$y_{rec} - y_{true}$	$\mu = 0.004 \pm 0.002$ $\sigma = 0.214 \pm 0.002$	$\mu = -0.261 \pm 0.08$ $\sigma = 0.570 \pm 0.03$	$\mu = 0.005 \pm 0.002$ $\sigma = 0.217 \pm 0.002$
$z_{rec} - z_{true}$	$\mu = -0.0 \pm 0.001$ $\sigma = 0.115 \pm 0.001$	$\mu = 0.001 \pm 0.00$ $\sigma = 0.760 \pm 0.00$	$\mu = -0.00 \pm 0.001$ $\sigma = 0.115 \pm 0.001$

3. Noise in the pixel sensors

- *Purity is relatively stable until a noise rate of approximately 40Hz, which is much larger that the highest noise rate seen for the MuPix8 prototypes of 20 Hz*



Single event sensitivity (SES) and the corresponding 90% and 95% C.L. upper limits versus data taking days for the phase I Mu3e detector



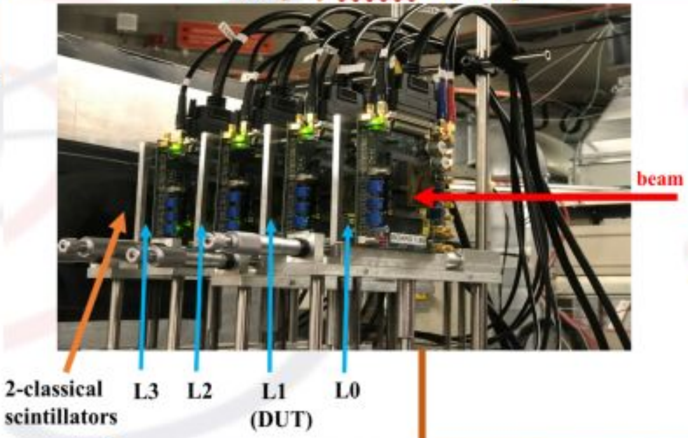
Analysis of test beam data and characterization of Mupix chip

Afaf Wasili & Andrew G.

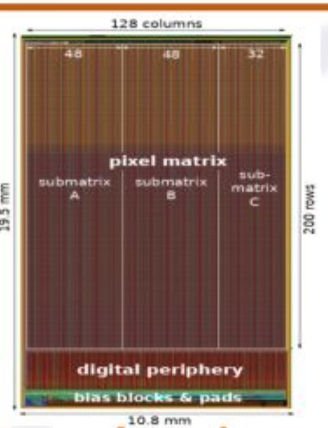
Test-beam @ PSI

The beam with momentum 270 MeV (pion, electrons, and muons), and electrical current is 1860.10μA at πM1 beam area in PSI

Setup of MuPix Telescope



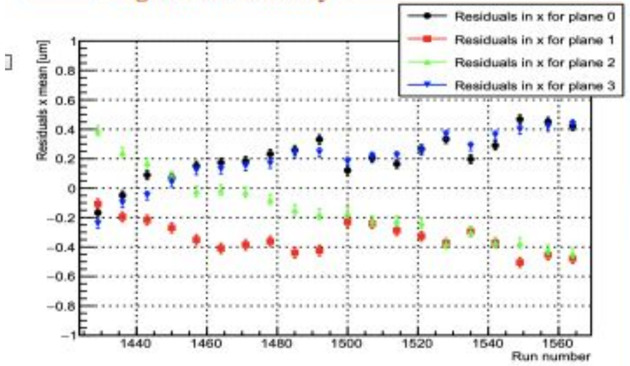
- 3-layers of MuPix8 sensors with DUT layer
- Layer 1 is DUT layer
- 2-classical trigger scintillators
- All PCBs were connected to a HV power supply, and set to - 60 V for all MuPix8 measurements

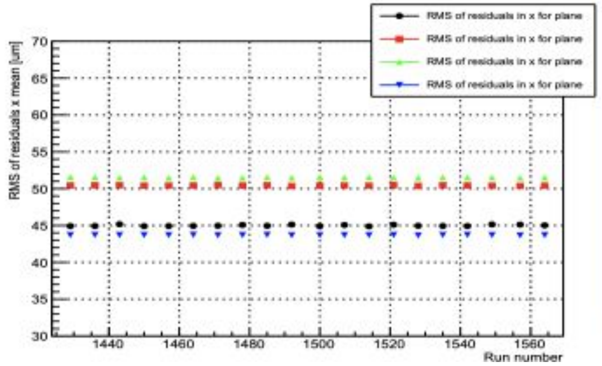


MuPix8 sensor?

- First large prototype in MuPix group
- Pixels have a size of $81 \times 80 \mu m^2$
- Pixels are arrayed in 128×200pixel matrix
- Fast charge collection (O(1ns))
- Integrated readout electronics
- Thickness: 100 μm

Alignment Stability



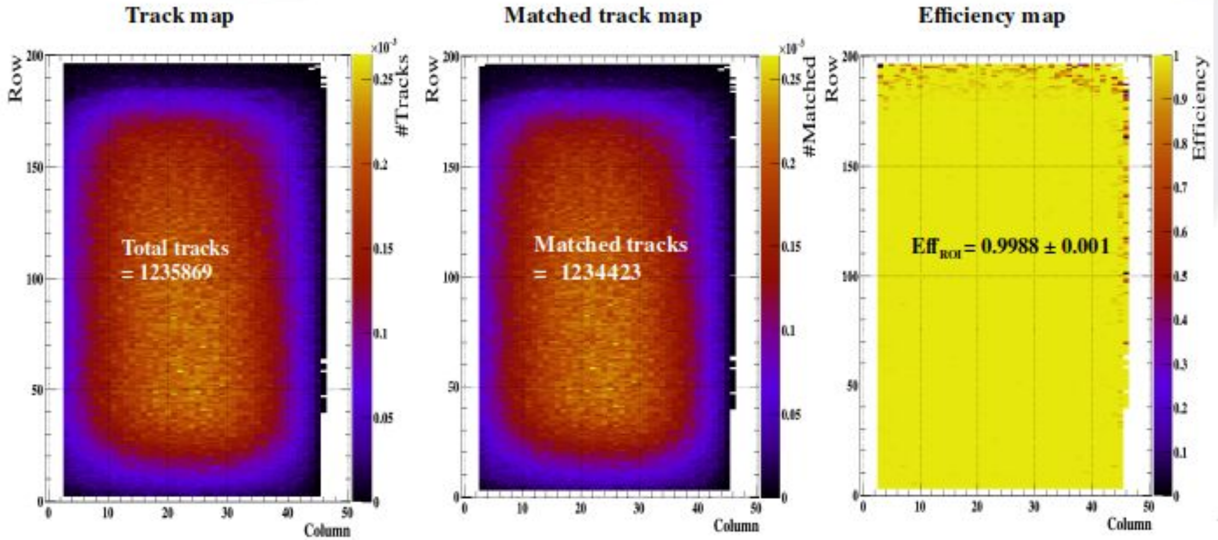


Efficiency Analysis

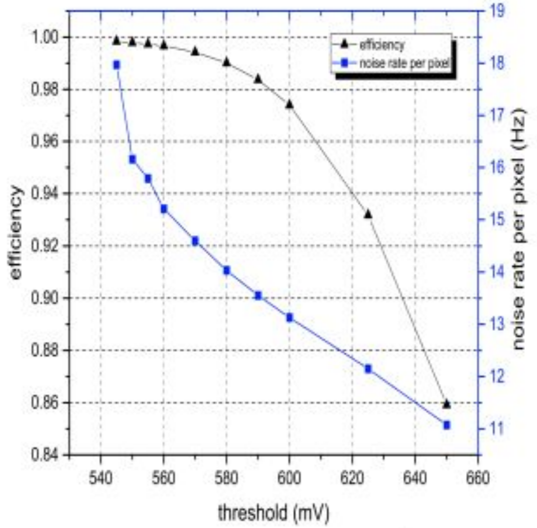
- Efficiency of run 1429 with threshold 545 mV

$$Eff_{ROI} = \frac{\#matched\ tracks}{\#total\ tracks}$$

$$\text{Noise rate per pixel} = \frac{\#hits - \#matched\ tracks}{runtime\ .\ \#pixels}$$



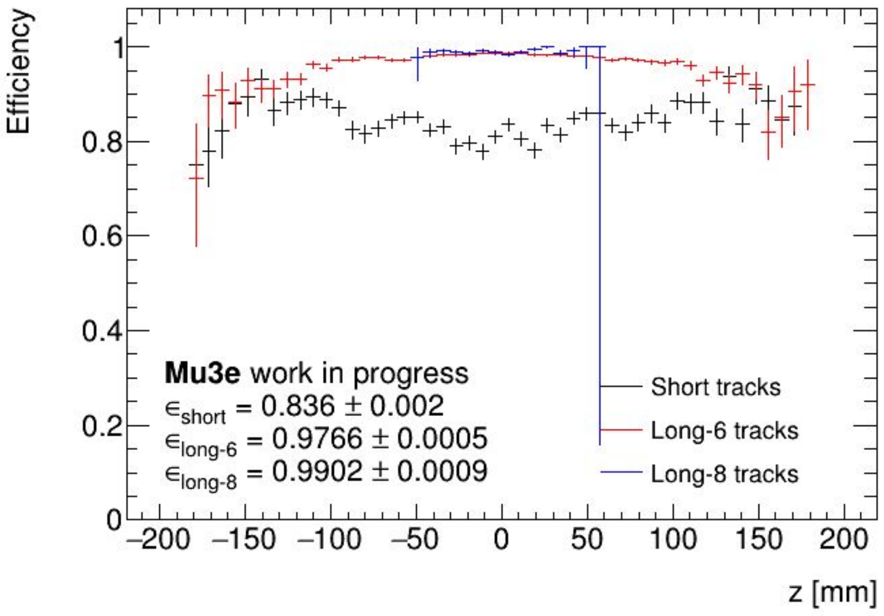
Efficiency and Noise Rate per Pixel for Different DAQ Runs

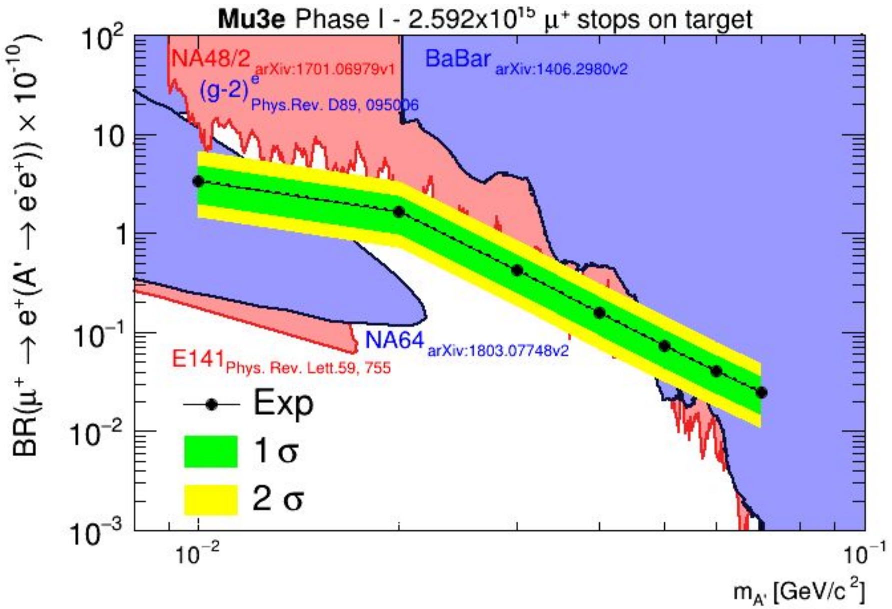


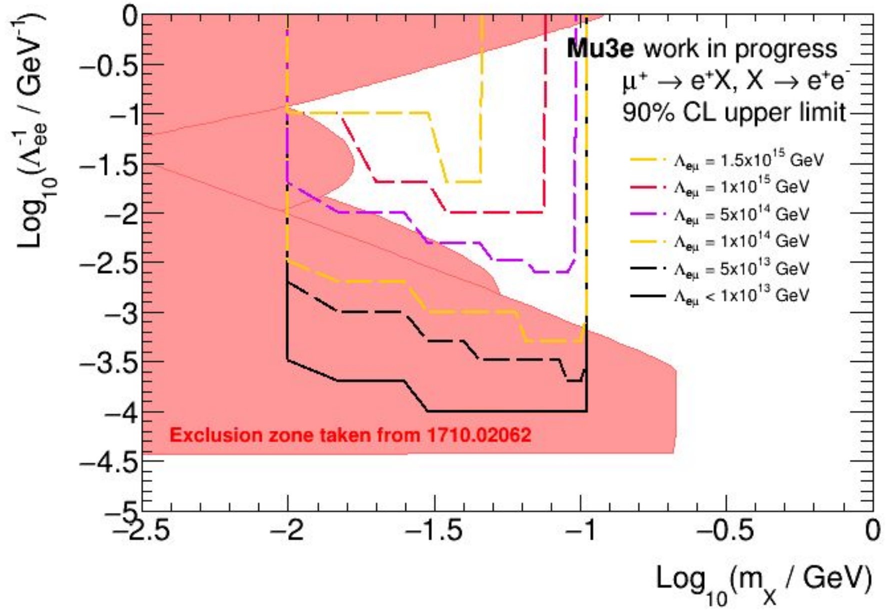
Sensitivity and performance studies (Sean Hughes)

- Undertaken studies on the performance of the simulated Mu3e detector + improved Mu3e detector geometry
- Sensitivity studies using Mu3e detector to detect:
  - Dark Photons
  - Axion-like particles

Tracking efficiency studies







Computing activities

- Mu3e is now on the GRID
  - Thanks to lots of work from Andrew Groves
- Virtual Organization is mu3e.org
  - Both VO adminds are liverpool staff (N. Rompotis. and C. Chavez)
- We run our jobs in opportunistic mode in UK sites (most of them)
- Recently ran a big MC production for a TDR study
- Official MC production and Data management role within the collaboration (C. Chavez)

Mu3e Phase II @ HiMB

- HiMB = High intensity Muon Beamline (at PSI)
- HiMB physics case workshop (6-9 April 2021)

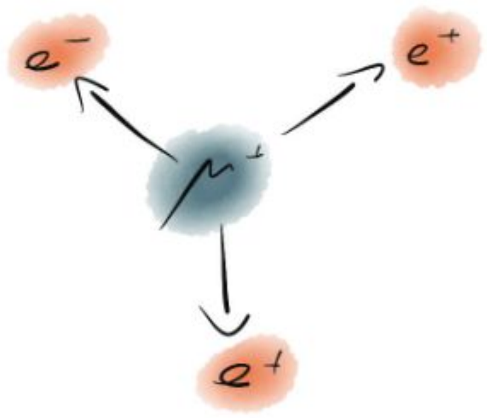
Aim sensitivity for (SES) : **Requires :**

$BR(\mu \rightarrow eee) = 2\cdot10^{-15}$	(phase I)	$\rightarrow$	**10^8 muons/s (PiE5)**	**~next 5 years**
$BR(\mu \rightarrow eee) < 10^{-16}$	(phase II)	$\rightarrow$	**>10^9 muons/s (HiMB)**	**R&D**

- Ongoing work towards higher muon rates : **20 x higher rate**
  - Final focus of beam, beam size, redesign of stopping target
- Detector design change required :
  - Faster detectors, larger detector modules (acceptance), larger readout bandwidth

THANKS

The signal



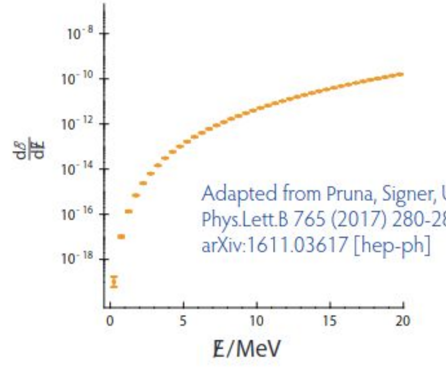
- $\mu^+ \to e^+e^-e^+$
  three particles need large acceptance
- Two positrons, one electron
  need clear charge ID
- From same vertex
  needs precise vertexing
- Same time
  needs good timing measurement
- $\Sigma p_e = m_\mu$
  needs good momentum measurement
- Maximum momentum: $\frac{1}{2} m_\mu = 53$ MeV/c
  Everything is multiple scattering dominated; get rid of as much material as possible

Internal conversion background

- Allowed radiative decay with internal conversion:

  $\mu^+ \to e^+e^-e^+\nu\bar{\nu}$

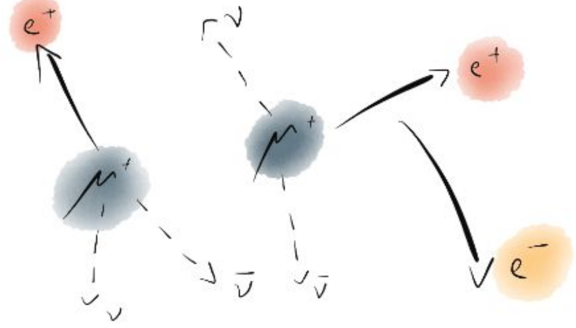
- Only distinguishing feature:
  Missing momentum carried by neutrinos



Adapted from Pruna, Signer, Ulrich, Phys.Lett.B 765 (2017) 280-284 arXiv:1611.03617 [hep-ph]

- Need excellent momentum resolution
- Close to the endpoint: BF drops as 6th power of the 3-particle invariant mass

Accidental Background



- Electron plus Michel positron
- 2+1:
  Bhabha scattering + Michel
  Photon conversion + Michel
  Internal conversion + Michel
- 1+1+1:
  Electron from above + 2 Michel
  Compton electron + 2 Michel
- Need very good timing, vertex and momentum resolution
- Scales unpleasantly with rate

Phase I Sensitivity

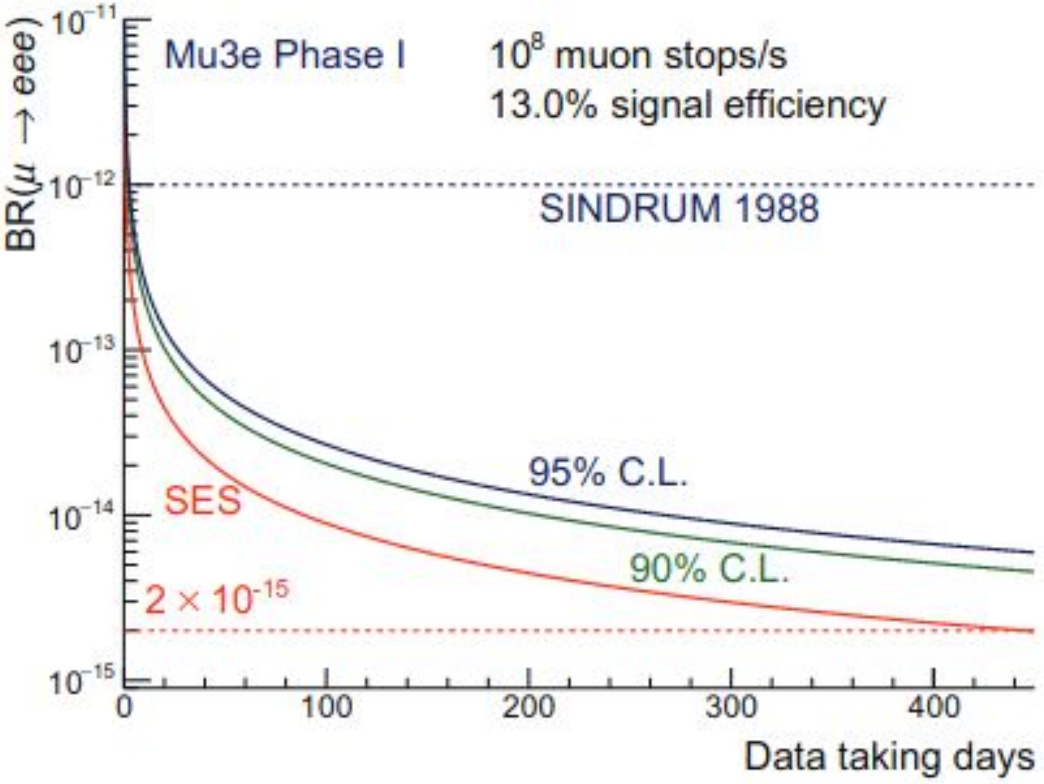
Then the single event sensitivity is just

$$SES = \frac{1}{\epsilon R t}$$

with ε the efficiency, R the rate and t the run time

10^8 μ-stops/s optimistic for πE5

Signal efficiency is essentially *(acceptance · track reconstruction eff.)*^{3}



Phase II Sensitivity

- Mu3e@HiMB: $2 \cdot 10^9$ μ-stops/s
- Assume same efficiency: better acceptance, tighter cuts
- Phase I sensitivity in a month SES of 10^{-16} in ~450 days

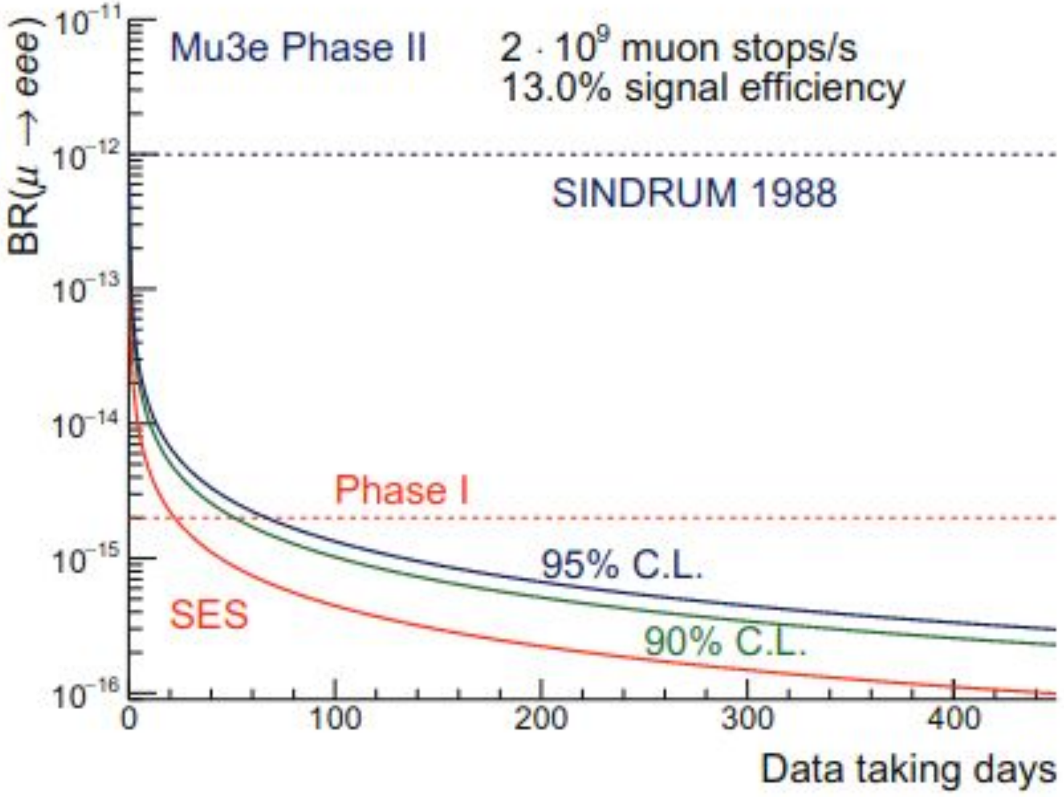
Then the single event sensitivity is just

$$SES = \frac{1}{\epsilon R t}$$

with ε the efficiency, R the rate and t the run time

10^8 μ-stops/s optimistic for πE5

Signal efficiency is essentially *(acceptance · track reconstruction eff.)*^{3}

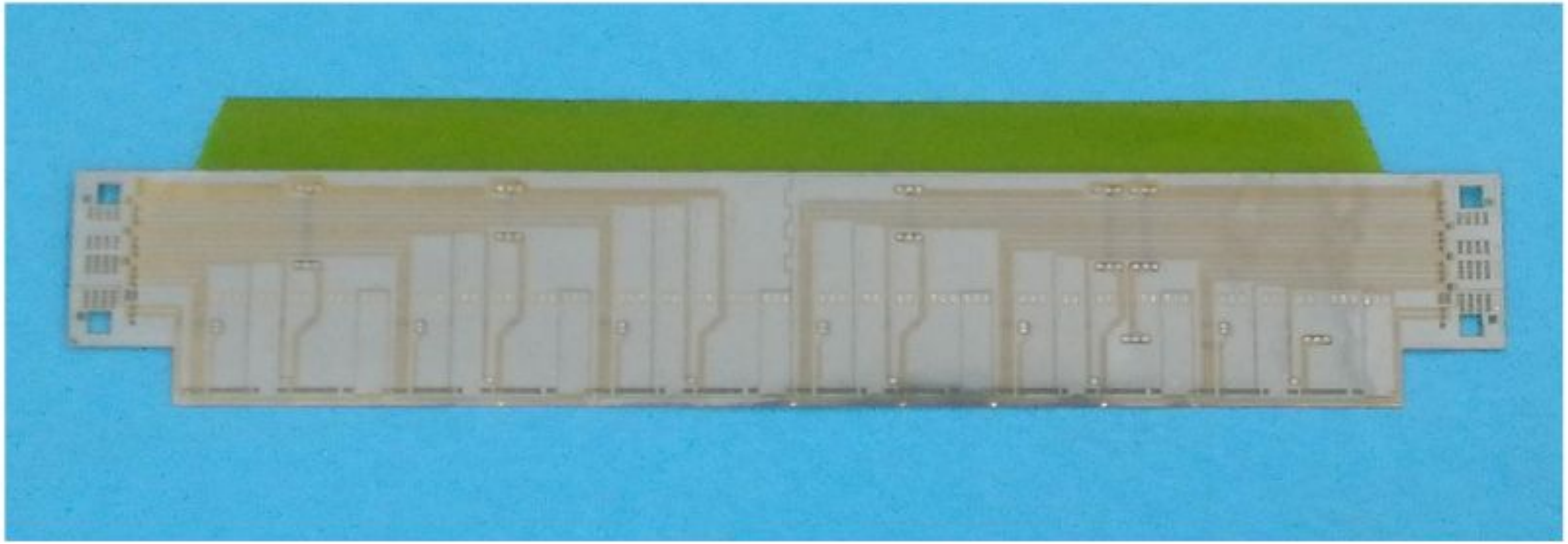


Ladder update

6-chip Mupix10 HDIs shipped from LTU

Currently at custom (DHL delays). Expected soon.

18-chip Mupix10 HDIs design under development.



(Images from LTU,
Used by permission)