Searching for cLFV with the Mu3e experiment

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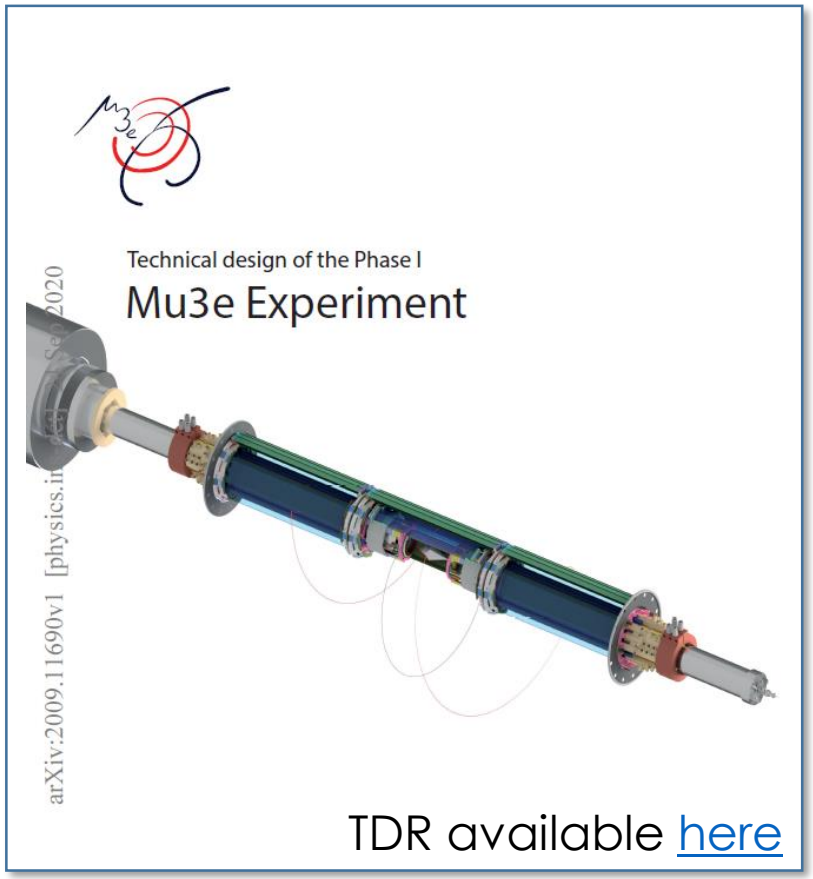
The Goal of the Mu3e Experiment

Current best limit on $\mu^+ \rightarrow e^+e^-e^+$

$\mathbf{BR_{meas} < 10^{-12}}$ (SINDRUM 1988)

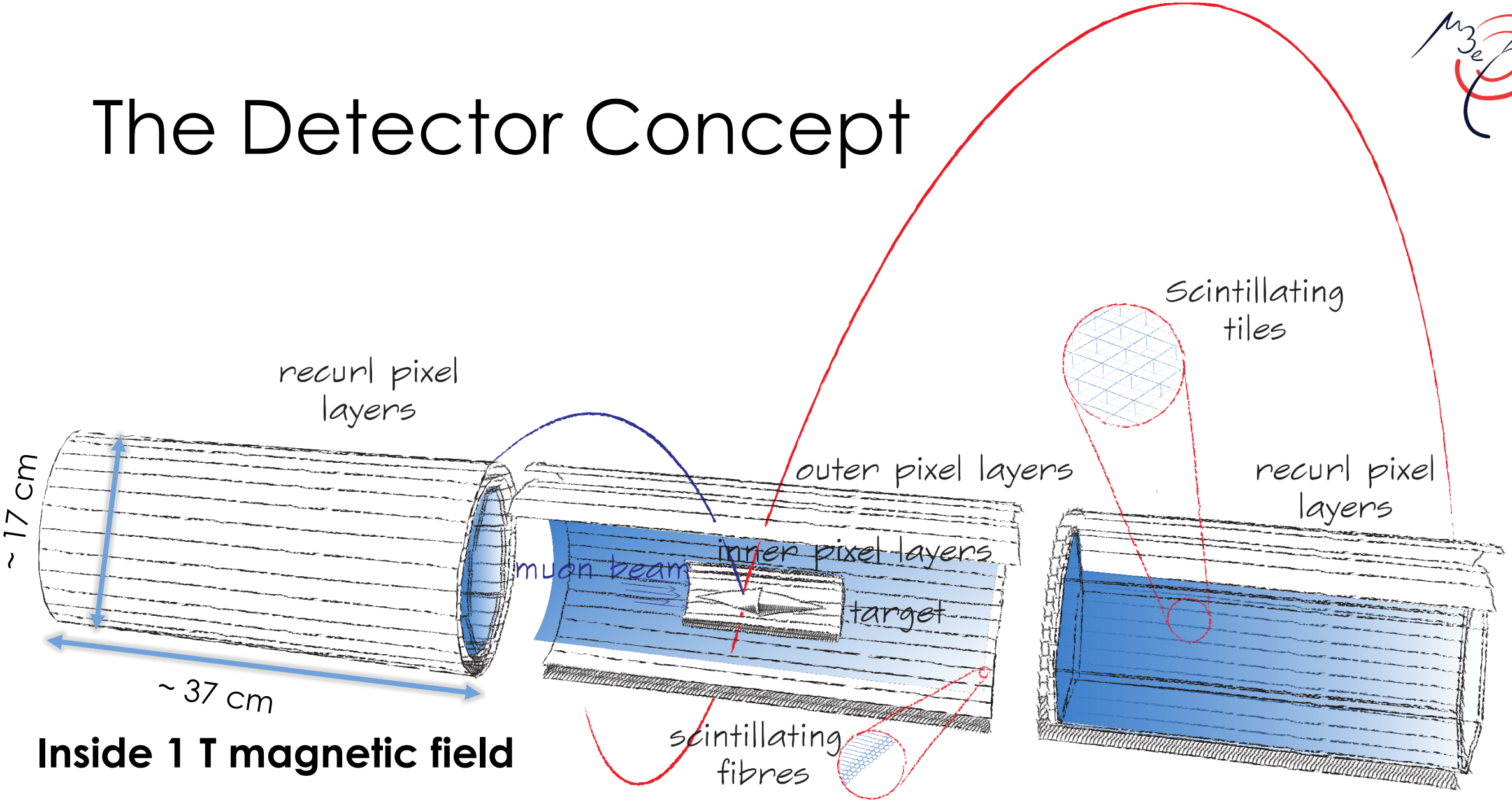
*The **Mu3e** experiment aims to **find or exclude** the lepton flavor violating decay $\boldsymbol{\mu^+ \rightarrow e^+e^-e^+}$ at branching fractions above $\mathbf{10^{-16}}$*



TDR available here

The Experimental Concept

The Detector Concept

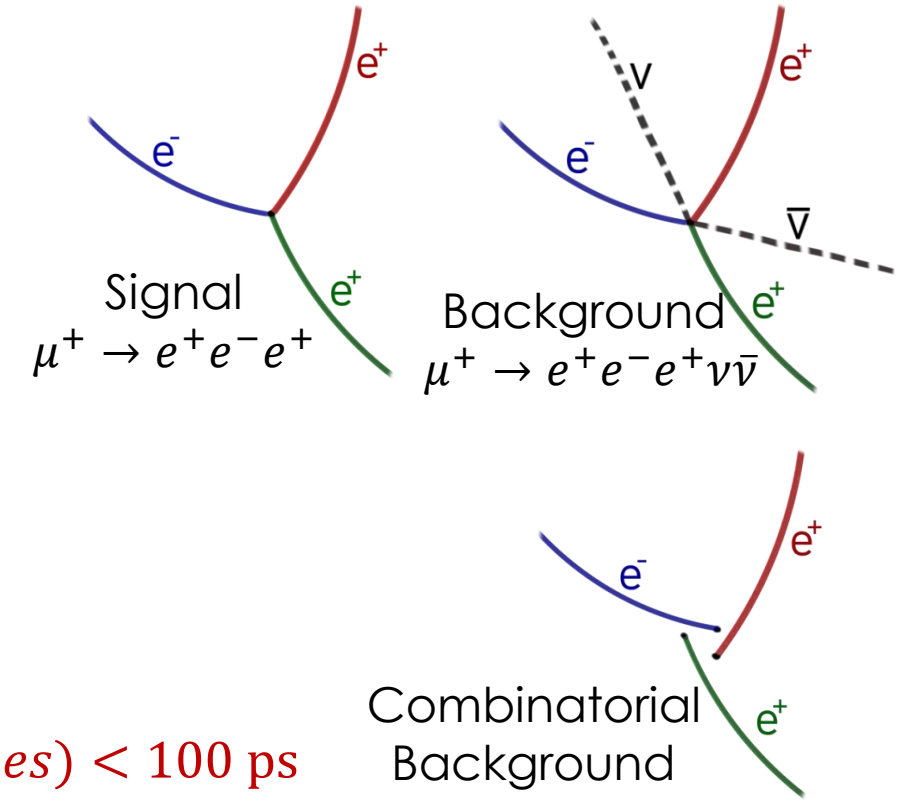


Inside 1 T magnetic field

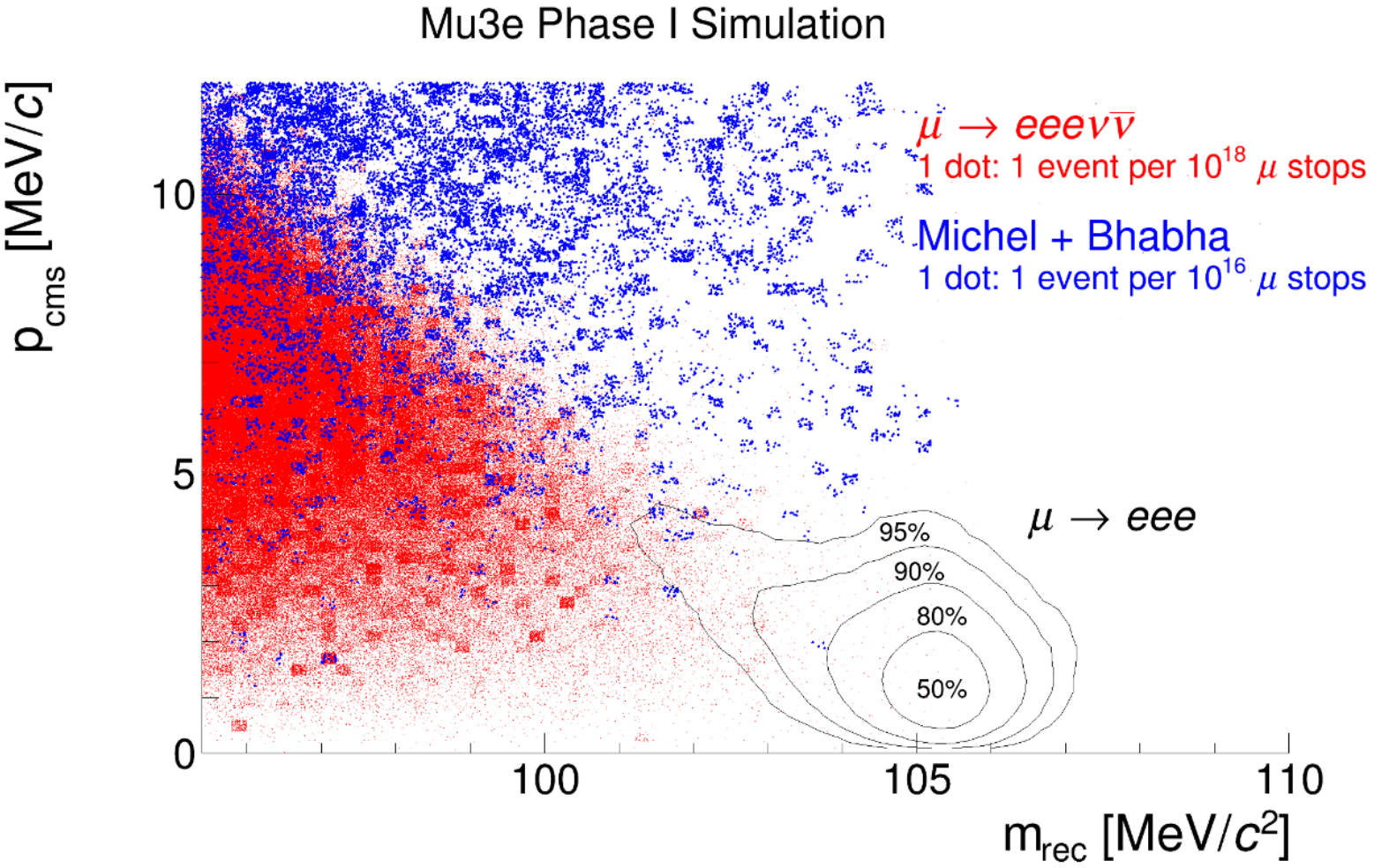
The Detector Requirements

- Precise **invariant mass** measurement
  - Momentum resolution $\sigma_p < 1.0\ \mathrm{MeV/c}$
- Stopped muons → **Low energy electrons**
  - Ultra thin pixel detector $\leq \mathbf{1‰}\ X_0$ per layer
- **High muon rates**
  - High rate capabilities and good timing

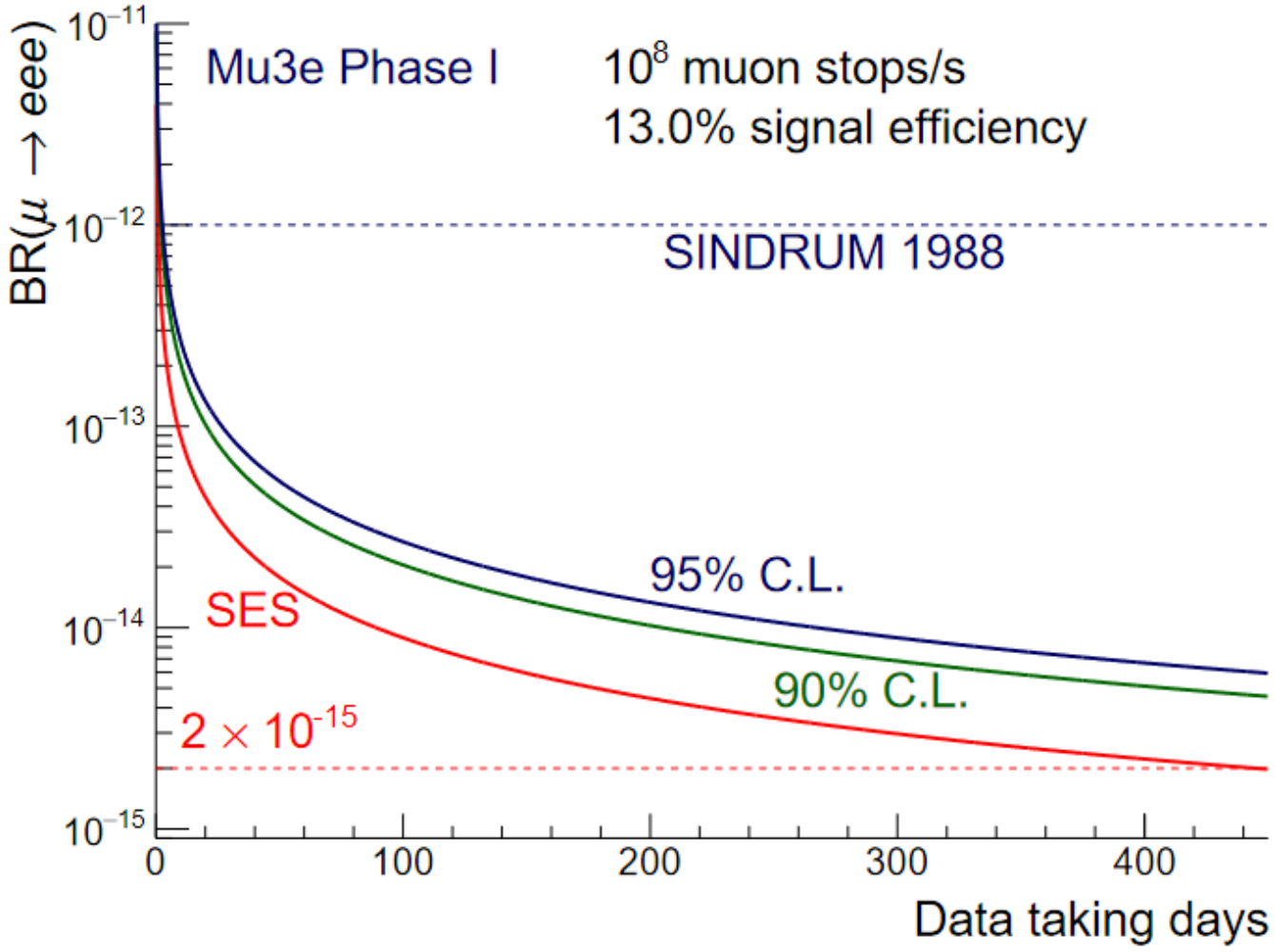
$\sigma_t(pixels) < 20\ \mathrm{ns}$ $\sigma_t(fibre) < 1.0\ \mathrm{ns}$ $\sigma_t(tiles) < 100\ \mathrm{ps}$



Performance Study



Expected Sensitivity Mu3e Phase I

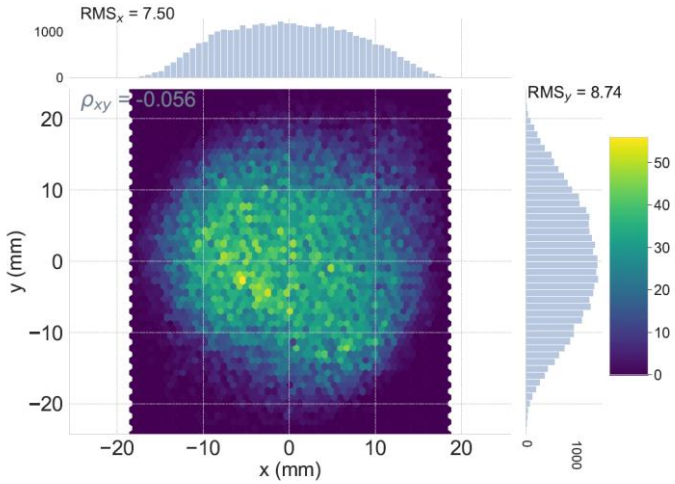


Experimental Infrastructure

Muon Beam @ PSI

- **Most intense DC muon beam** available at Paul-Scherrer-Institut
- Phase I: $\mathcal{O}(10^8\ s^{-1})$
  - **Compact Muon Beamline**
  - Single event sensitivity goal: $\mathcal{O}(10^{-15})$
- Phase II: $\mathcal{O}(10^9\ s^{-1})$
  - **High Intensity Muon Beamline** (2028)
  - Sensitivity goal: $\mathcal{O}(10^{-16})$

Commissioned CMBL in place @ PSI



Expected beam spot profile at the Mu3e target position

The Mu3e Solenoid

- Produced by Cryogenic Ltd. and delivered to PSI in July 2020
- Nominal magnetic field for experiment 1.0 Tesla (range 0.5 – 2.7 Tesla)
- Very homogeneous magnetic field

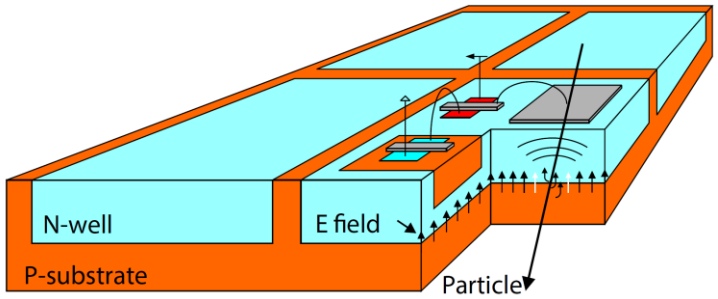
$$\frac{\Delta B}{B} < 10^{-3}$$

The Pixel Tracking Detector

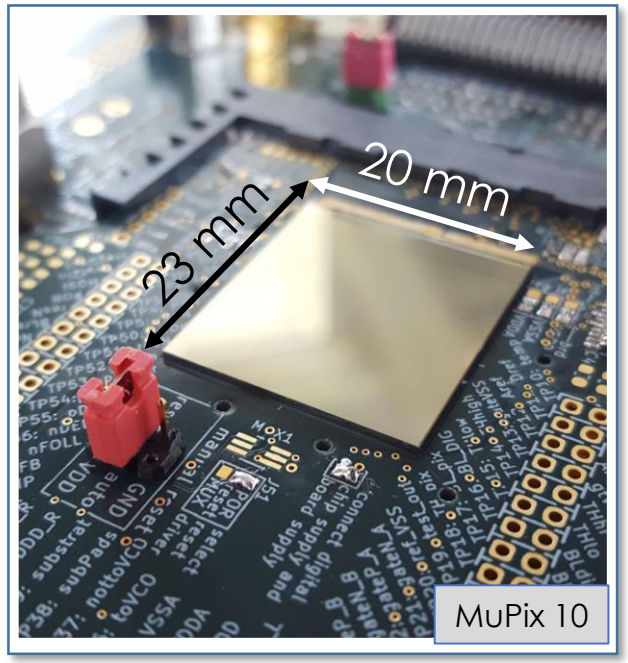
The Mu3e Pixel Sensors – **MuPix**

- High-Voltage Monolithic Active Pixel Sensors
- Produced in 180 nm **HV-CMOS** technology
- **Fast** charge collection via drift
- **Fully integrated** digital readout
- Can be **thinned** to 50 μm ~ 0.5 ‰ X_0

Mu3e requirements	
Efficiency	≥ 99 %
Noise rate	≤ 20 Hz / pixel
Time resolution	≤ 20 ns
Power consumption	≤ 350 mW / cm^2

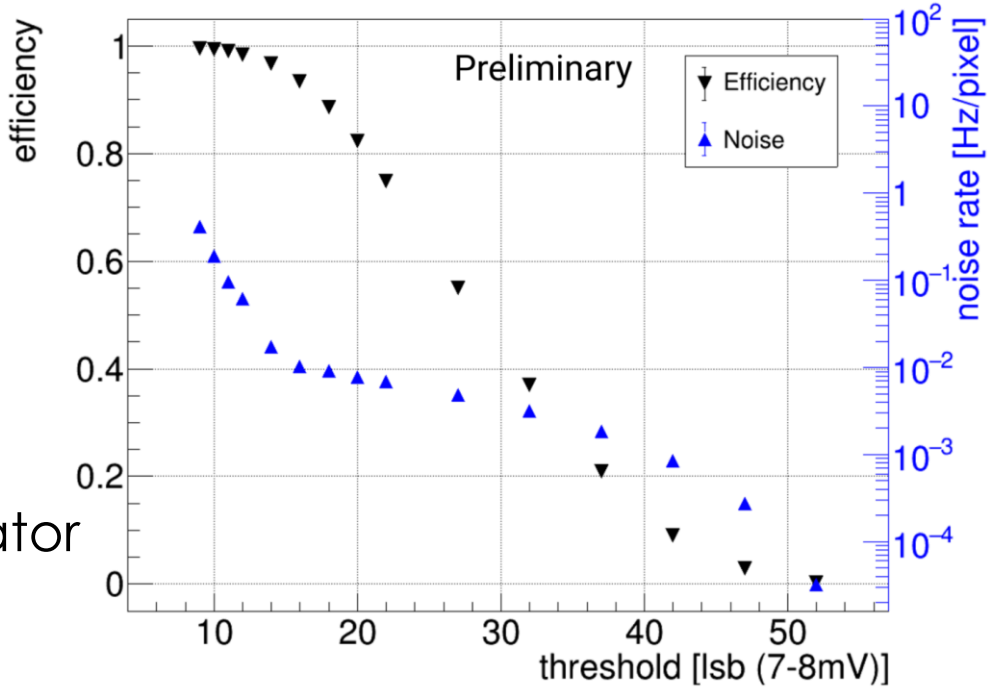


I.Perić, NIM A 582 (2007) 876

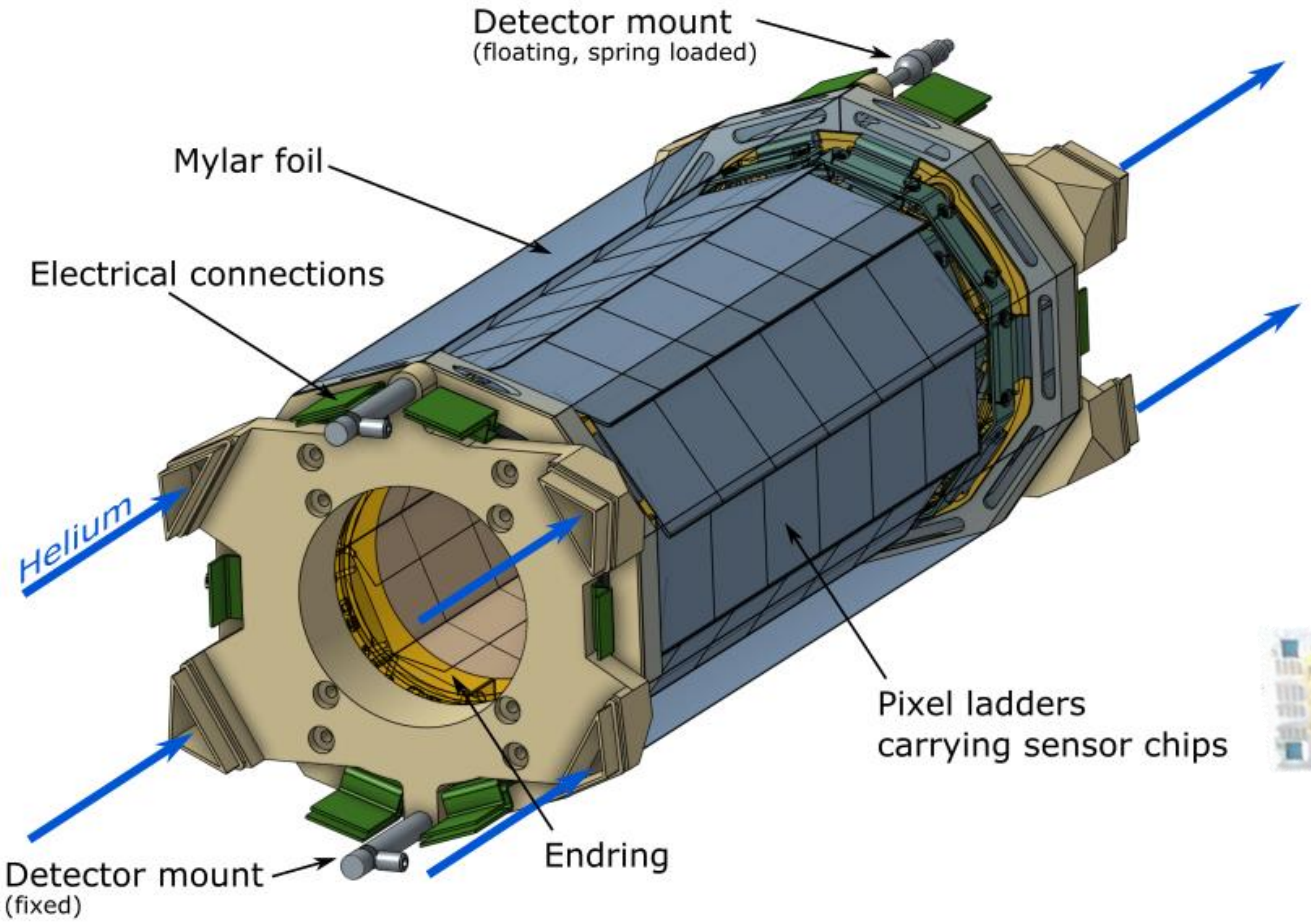


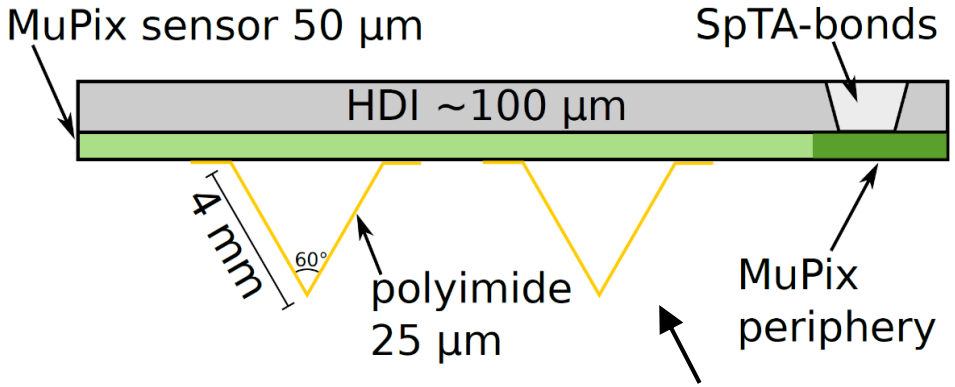
The Mu3e Pixel Sensors – **MuPix**

- **MuPix10** thinned to 50 μm **fulfills specifications**
- Efficiency and time resolution (~10 ns) measured at test beam at DESY
- **MuPix11** will be the final chip for Phase I
  - Improved powering scheme
  - Readout and slow control fix
  - New pixel routing scheme
  - Increased coupling capacitance to comparator
  - Expected to arrive this summer



The Vertex Detector



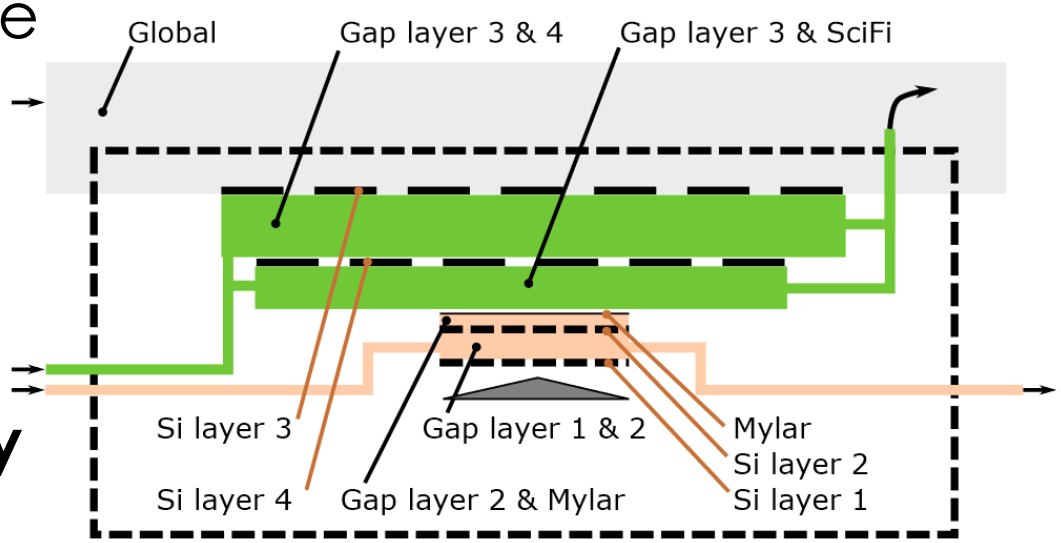


V-channels for
mechanical support
(outer layers only)

Aluminium-Kapton
High Density Interconnect
~ 0.5 ‰ X_0

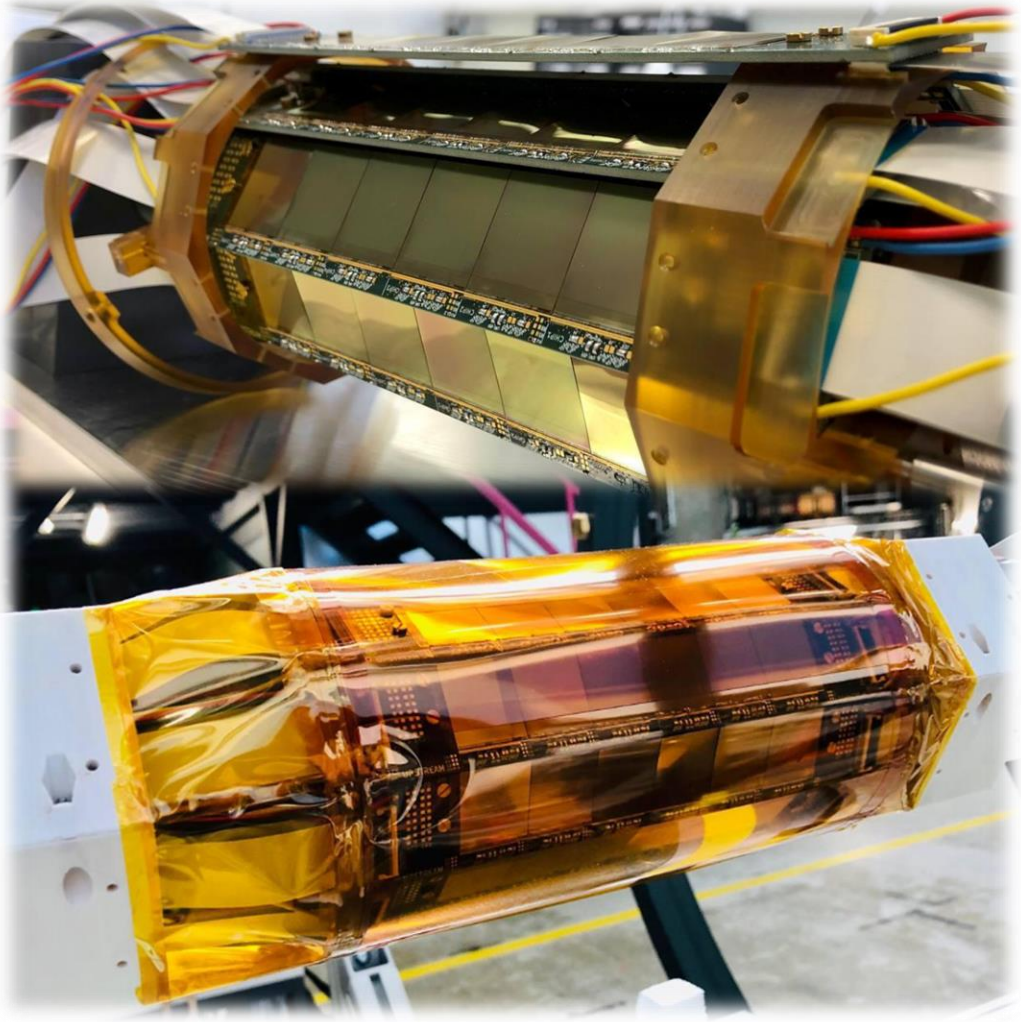
Pixel Detector Cooling with Helium

- **Cooling** of sensors **required** (max surface power density $400\ \mathrm{mW/cm^2}$)
- As little material as possible
- Gaseous **Helium**: low density, reasonable cooling capabilities
- Miniature turbo compressors **specifically designed** to be operated with helium
- Helium circuit optimized for **minimized pressure drops**



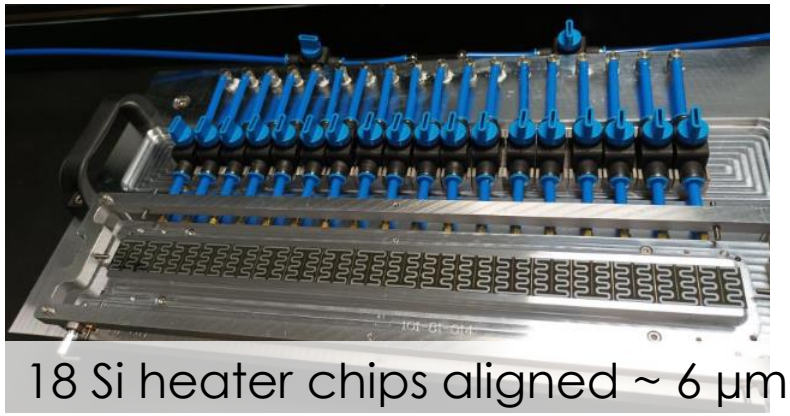
Prototype Vertex Detector

- Simplified PCB-based **demonstrator**
  - **Full-scale MuPix10** chips wire bonded
  - PCB ladders instead of HDI
  - Manual placement of chips with precision of 5 µm
- Simplified **helium distribution**
- **Full detector operated successfully**
  - ~ 100 W heat load cooled with 2 g/s helium gas cooling

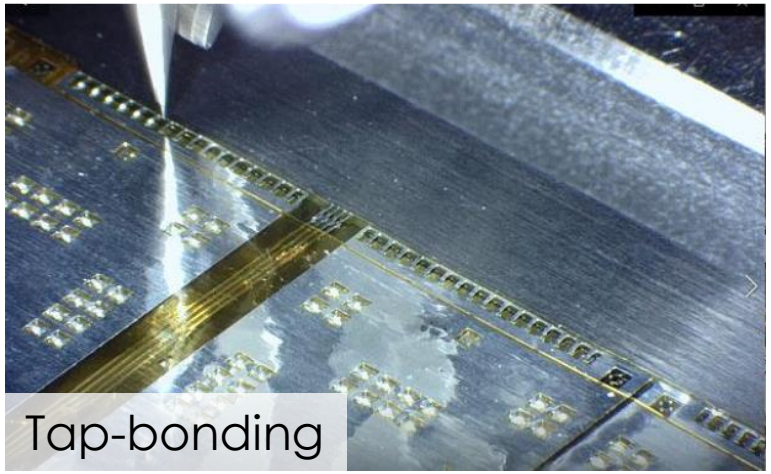


Outer Pixel Layers

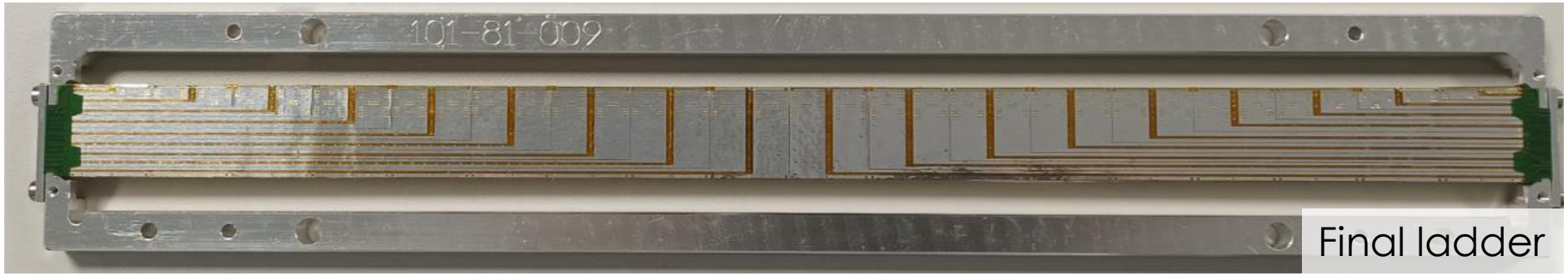
- **Production procedure** with robotic gantry and robotic glue dispensor has been **developed**
- **Mock-up ladders** with **18 chips** and HDIs have been **produced**



18 Si heater chips aligned ~ 6 µm



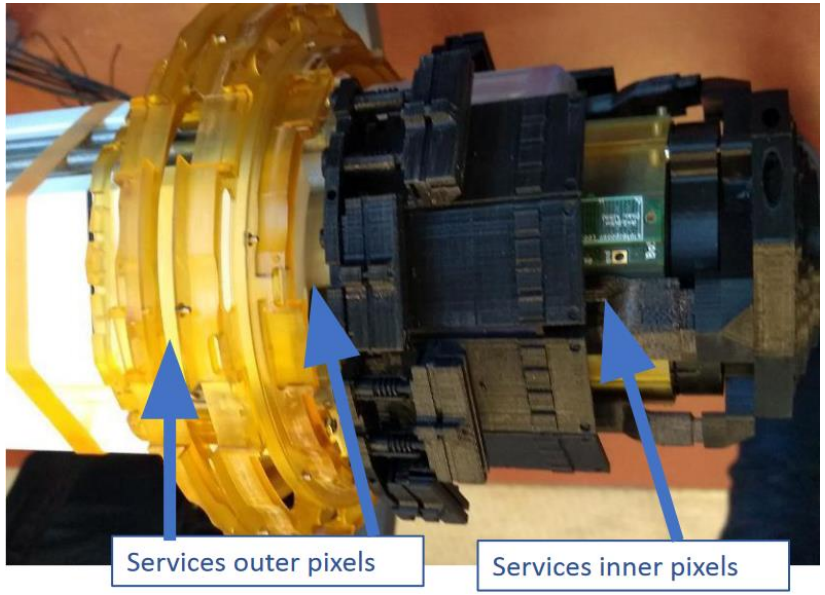
Tap-bonding



Final ladder

Pixel Detector Status for Phase I

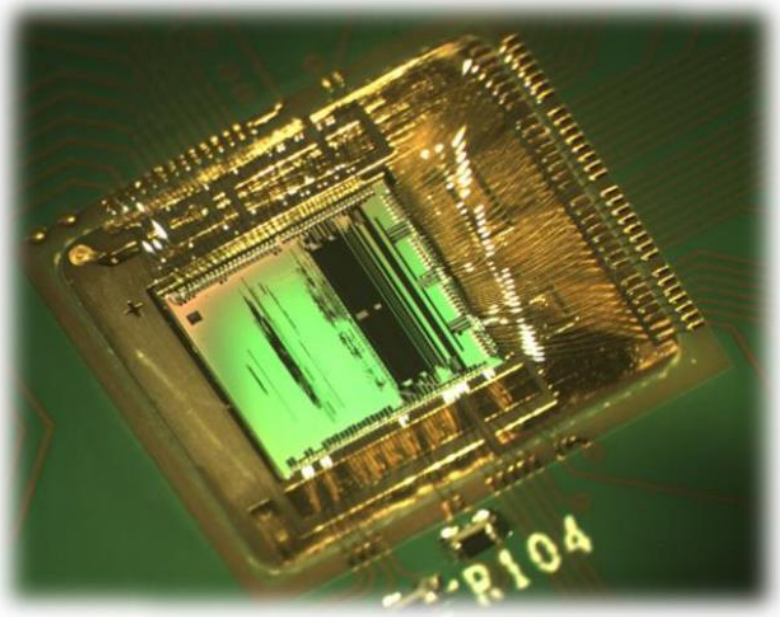
- **Production chains** developed for inner and outer pixel layers
- **MuPix11 Q/A** single chip needle socket test stand developed
- MuPix11 module pre-production starts autumn 2022
- **Full production** starts beginning of **2023**
- On detector services are being finalized



The Timing Detectors

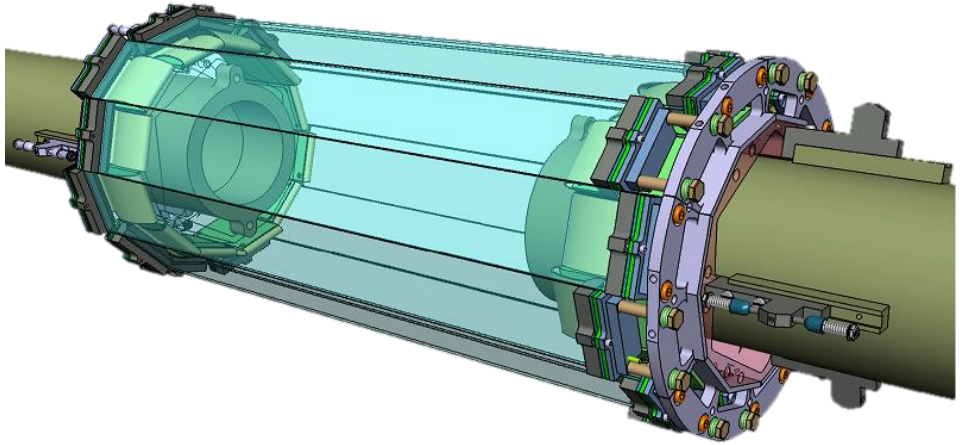
Common Readout ASIC – **MuTRiG**

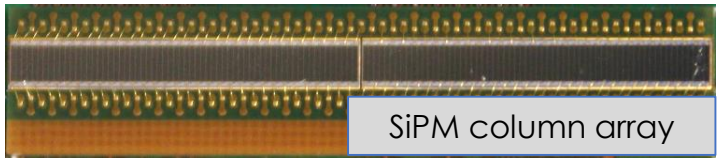
- Both timing detectors use **silicon photomultipliers**
- Custom designed SiPM readout ASIC: **MuTRiG**
- 32-channels
- **50 ps Time-to-digital converter**
- Version 3 has been submitted in May 2022
  - Higher thresholds
  - Reduction of IOs
  - Triple redundant config register

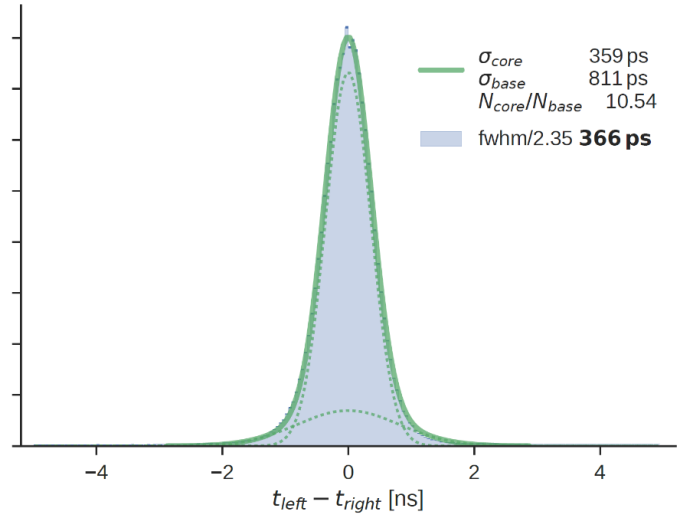


Fibre Detector

- 12 fibre ribbons
  - 30 cm long
  - 3 staggered layers of $250\ \mu m$ thin fibres
  - Material budget < 2‰ X_0
- 128 channel Hamamatsu S13552-HRQ **SiPM column arrays**
- Measured **time resolution ~ 250 ps**





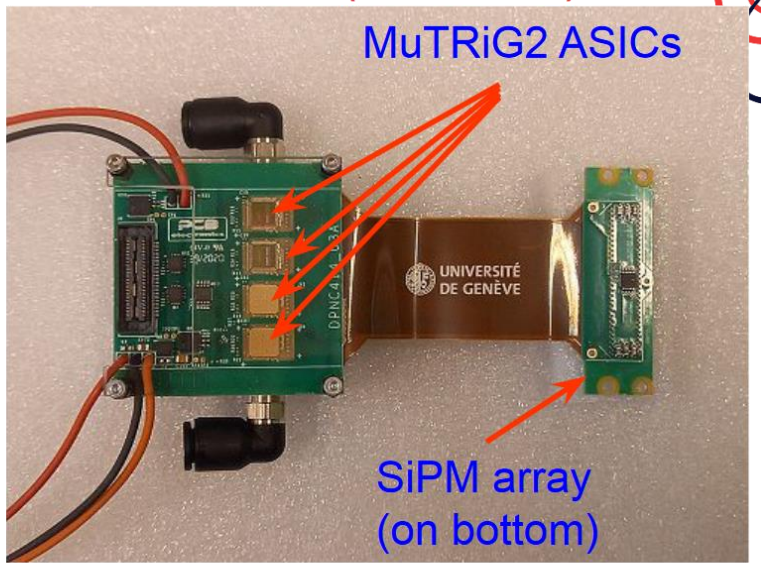


Example time resolution measured with 4-layer prototype ~ 200 ps

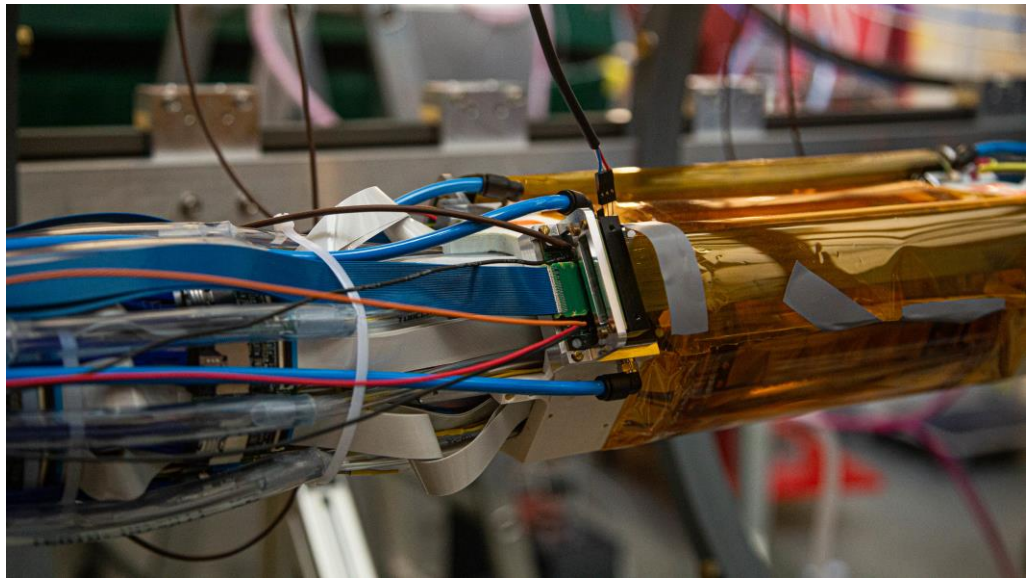
Fibre Detector Status

- Finalizing mechanical design including liquid cooling system (~ -20°C)
- **Readout tested succesfully** with MuTRiG v2
- On-detector SciFi readout boards for Phase I are being finalized
- Prototype ribbons have been operated @ PSI
- **DAQ integration ongoing**

SciFi board (version 2)

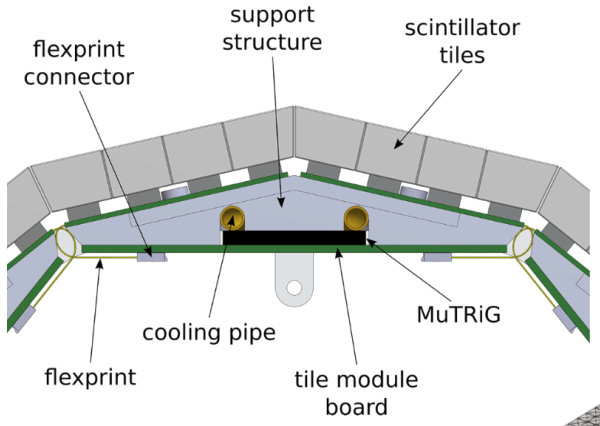


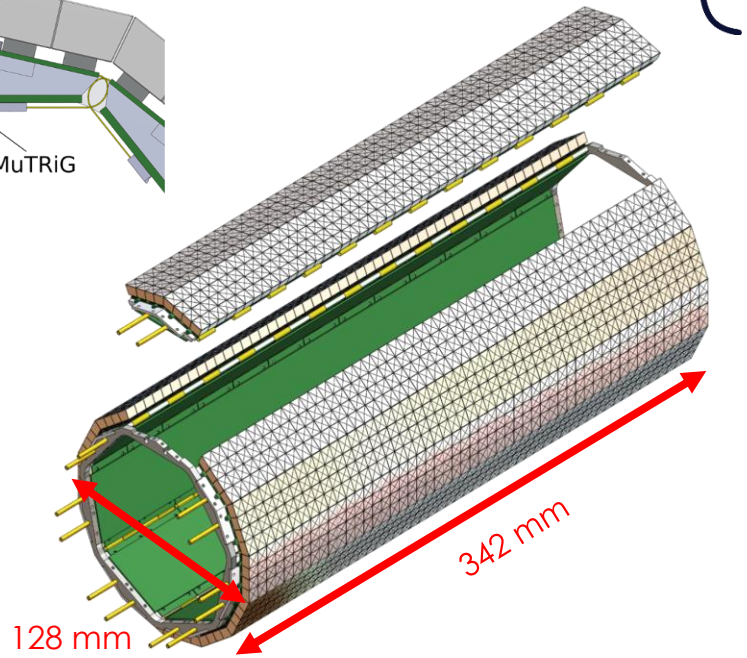
Readout based on the MuTRiG ASIC

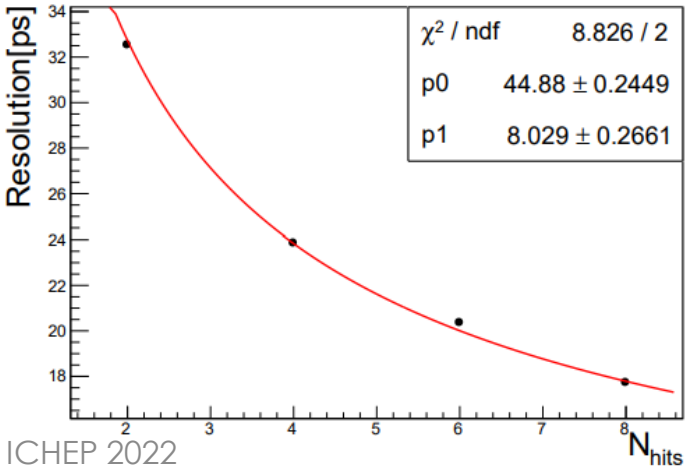


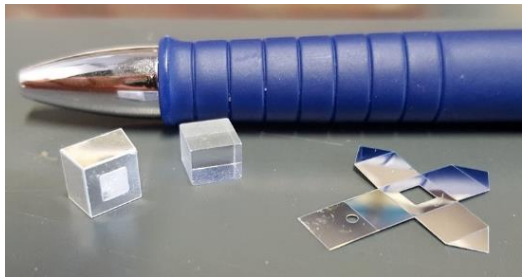
Tile Detector

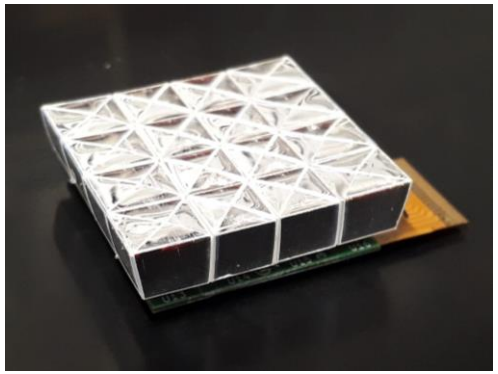
- Scintillating tiles ~ 5 × 5 × 5 mm^3
- Hamamatsu MPPC S13360-3050VE
- ~ 6000 channels
- Up to **60 kHz/channel**
- Measured **time resolution < 50 ps** (single channel)







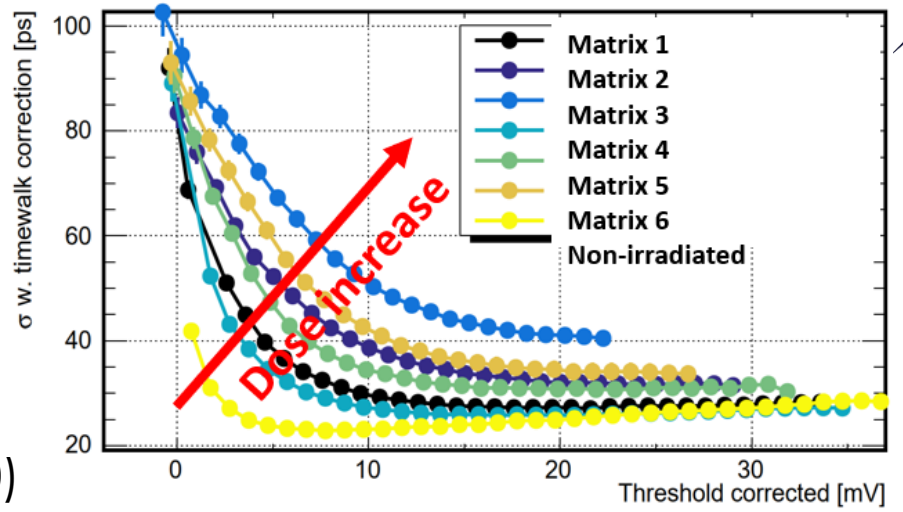




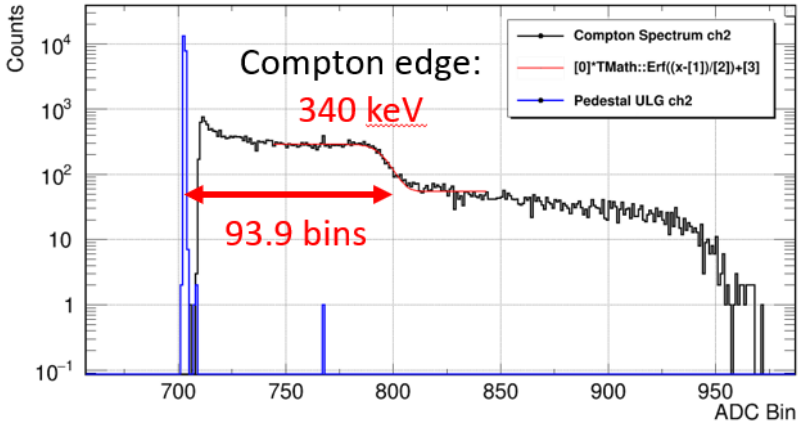
Tile Detector Status

- **2021: study impact of irradiation damage**
  - For tiles closest to target @ ~ expected dose of Phase I: increase of dark count rate (DCR) by O(1000)
  - Intrinsic time resolution measured after irradiation
- **Production of final demonstrator modules**
  - Matrices for 2 demonstrator modules assembled and characterized
  - Q/A test stands for SiPM parameters/Light yield in place
- **Readout electronics**
  - Second version of module board is fully functional
  - Integration in Mu3e DAQ system ongoing
- **Assembly of final detector components about to be started**

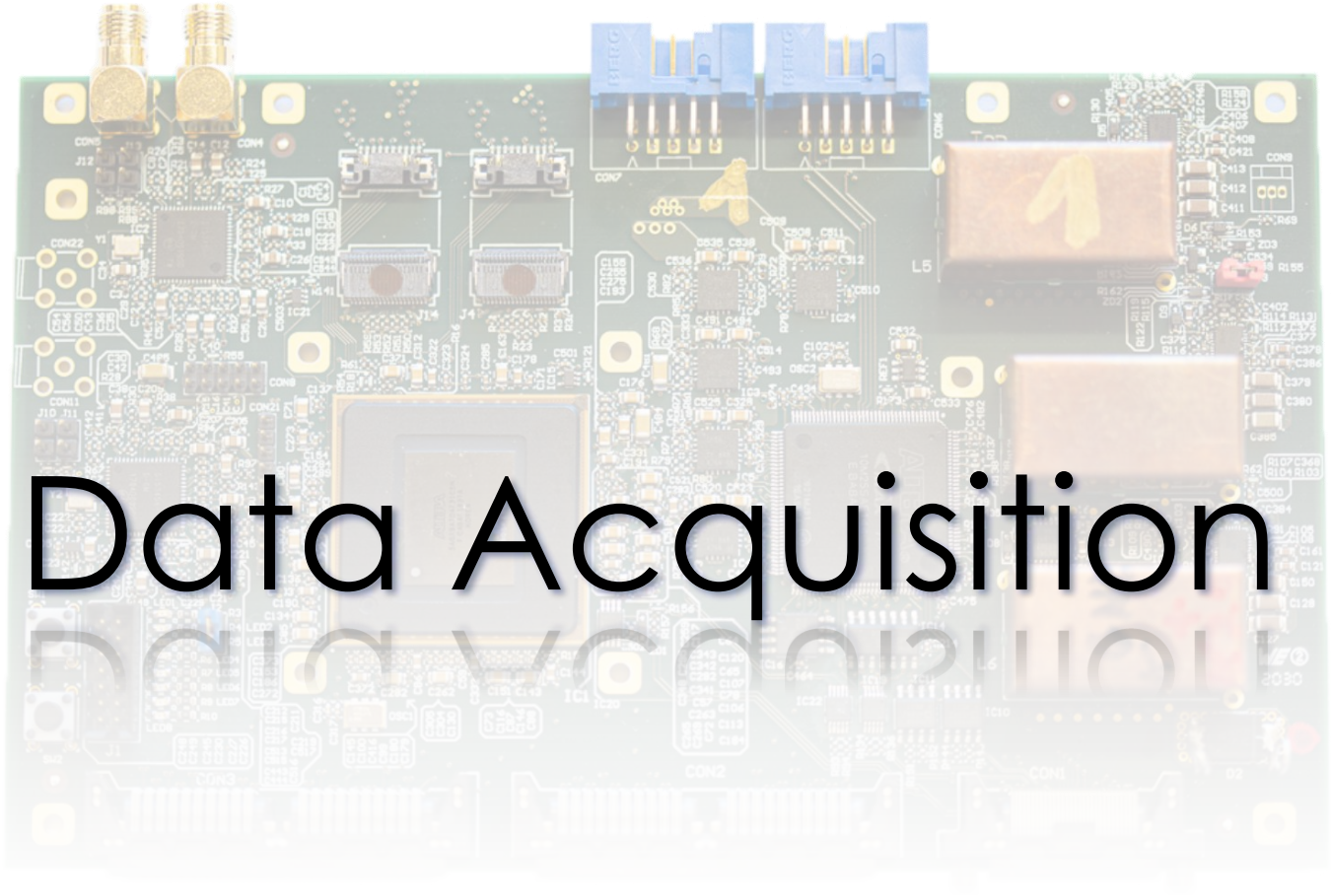
Time resolution after irradiation



Characterization of sensor matrices



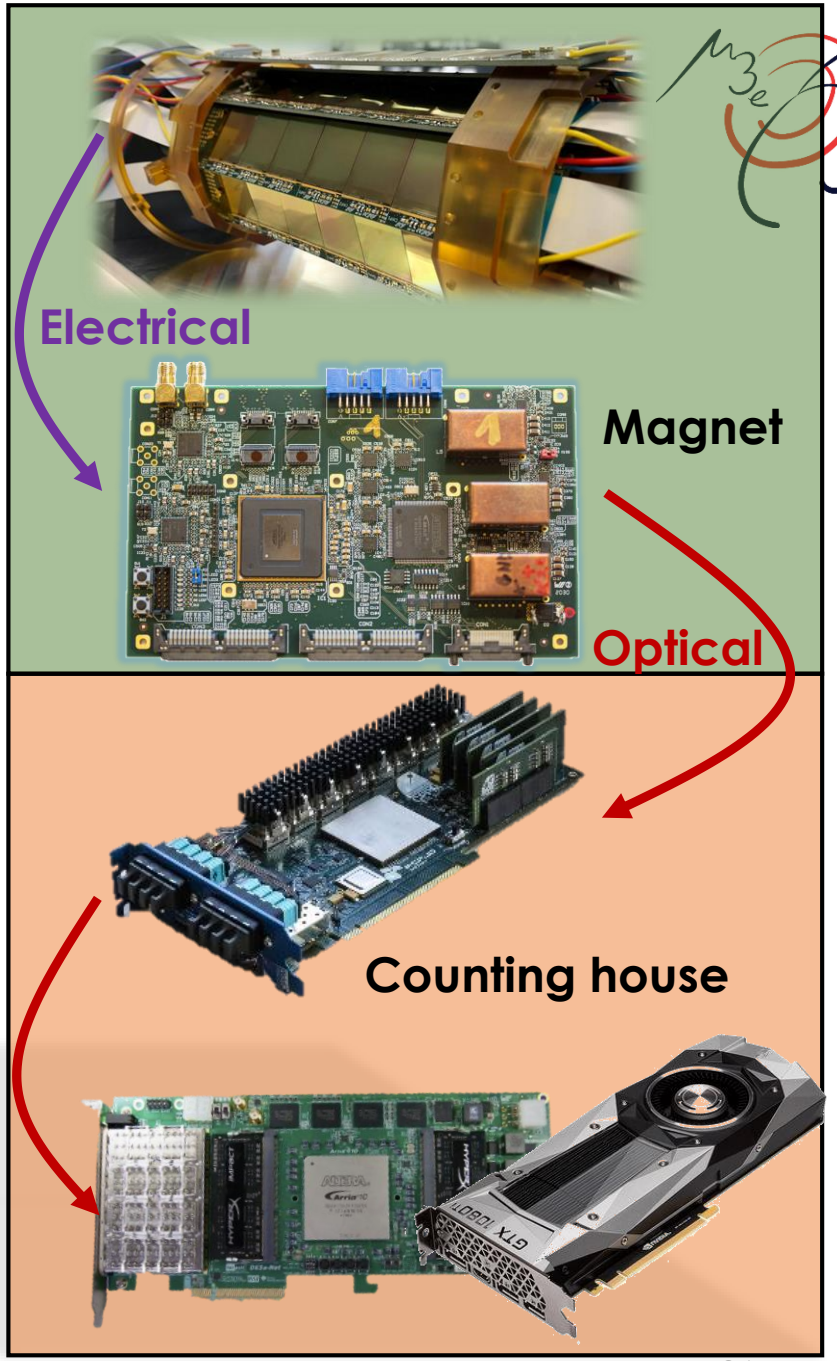
Preproduction readout boards



Data Acquisition

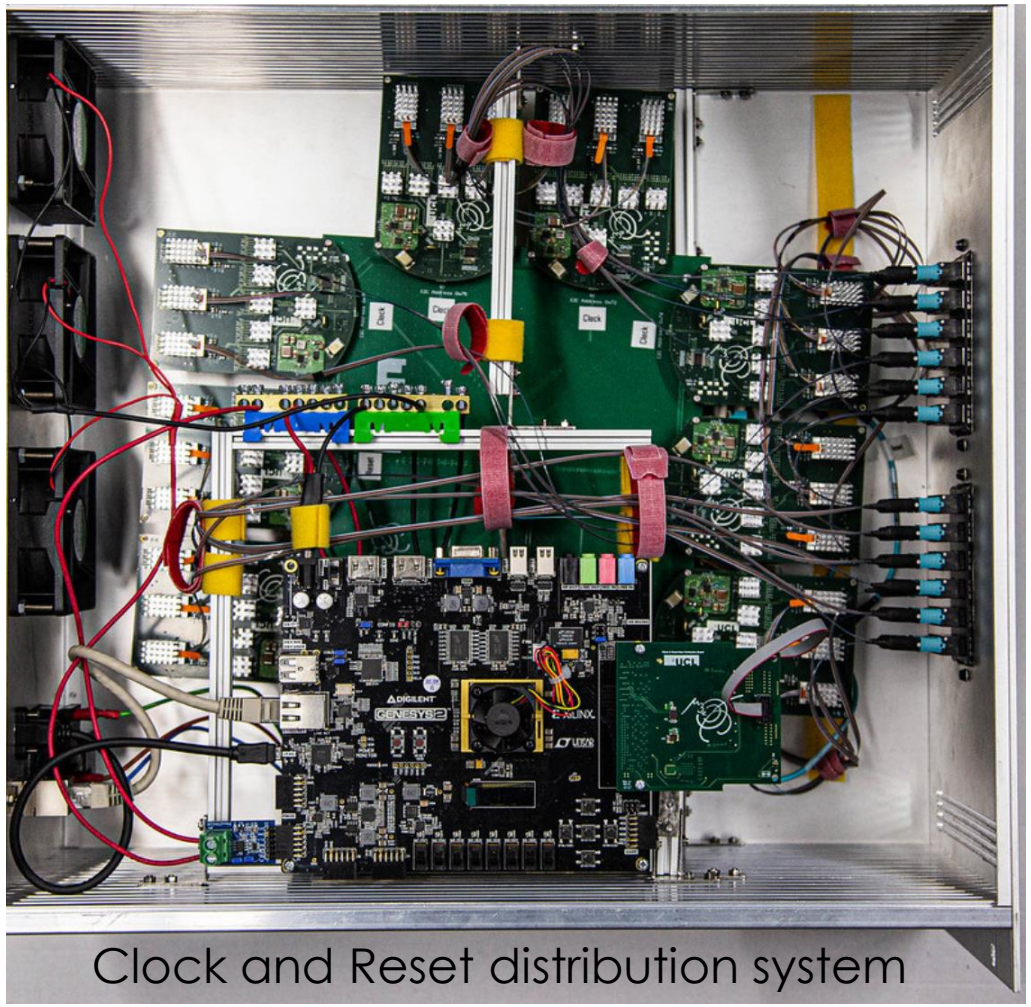
The Readout Concept

- Fully **synchronized** detector operation
- **Streaming readout** of zero-suppressed data (MuPix & MuTRiG)
- Custom **FPGA** front-end boards inside the magnet
- **Optical** data transfer out of magnet
- Data aggregation on **PCIe40** boards
- **Online event selection** based on track and vertex reconstruction on **GPUs**



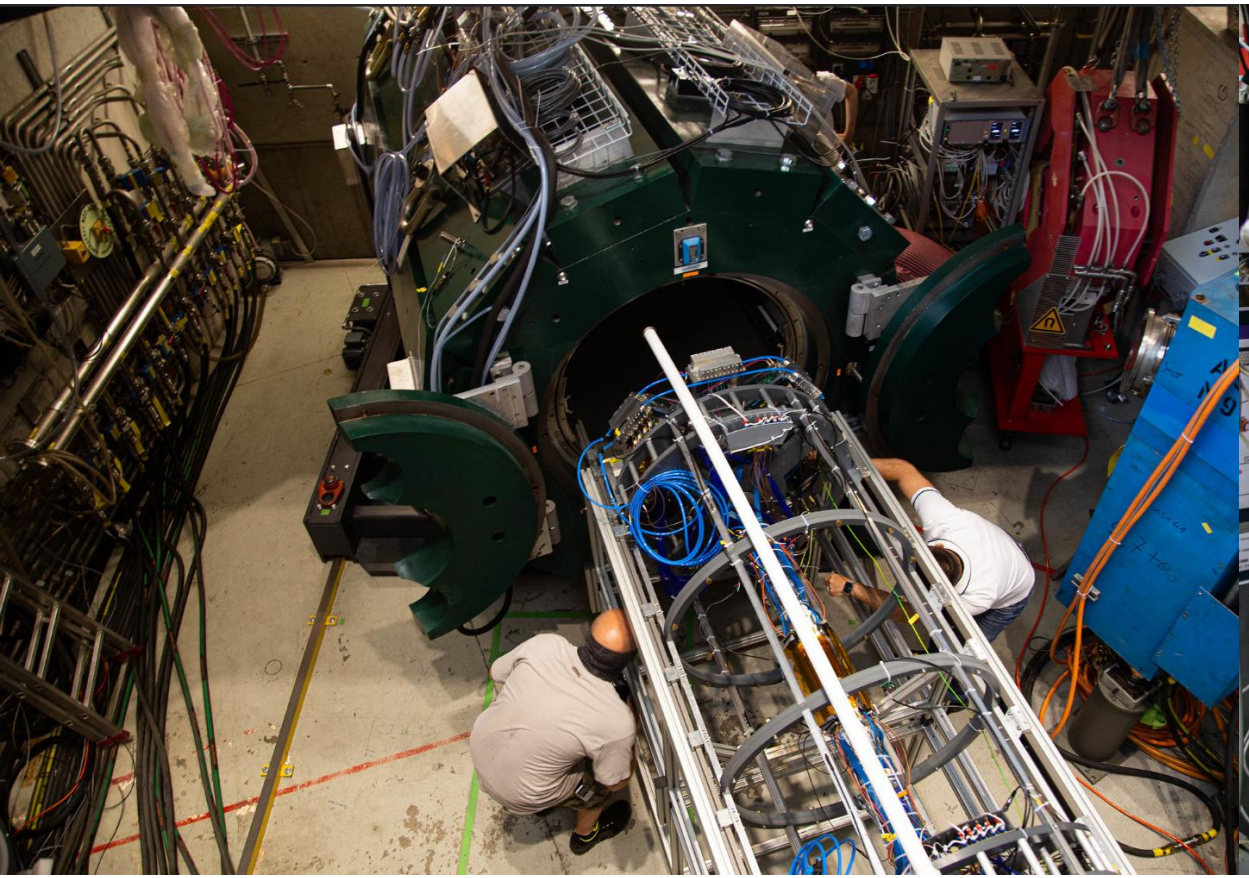
DAQ Status

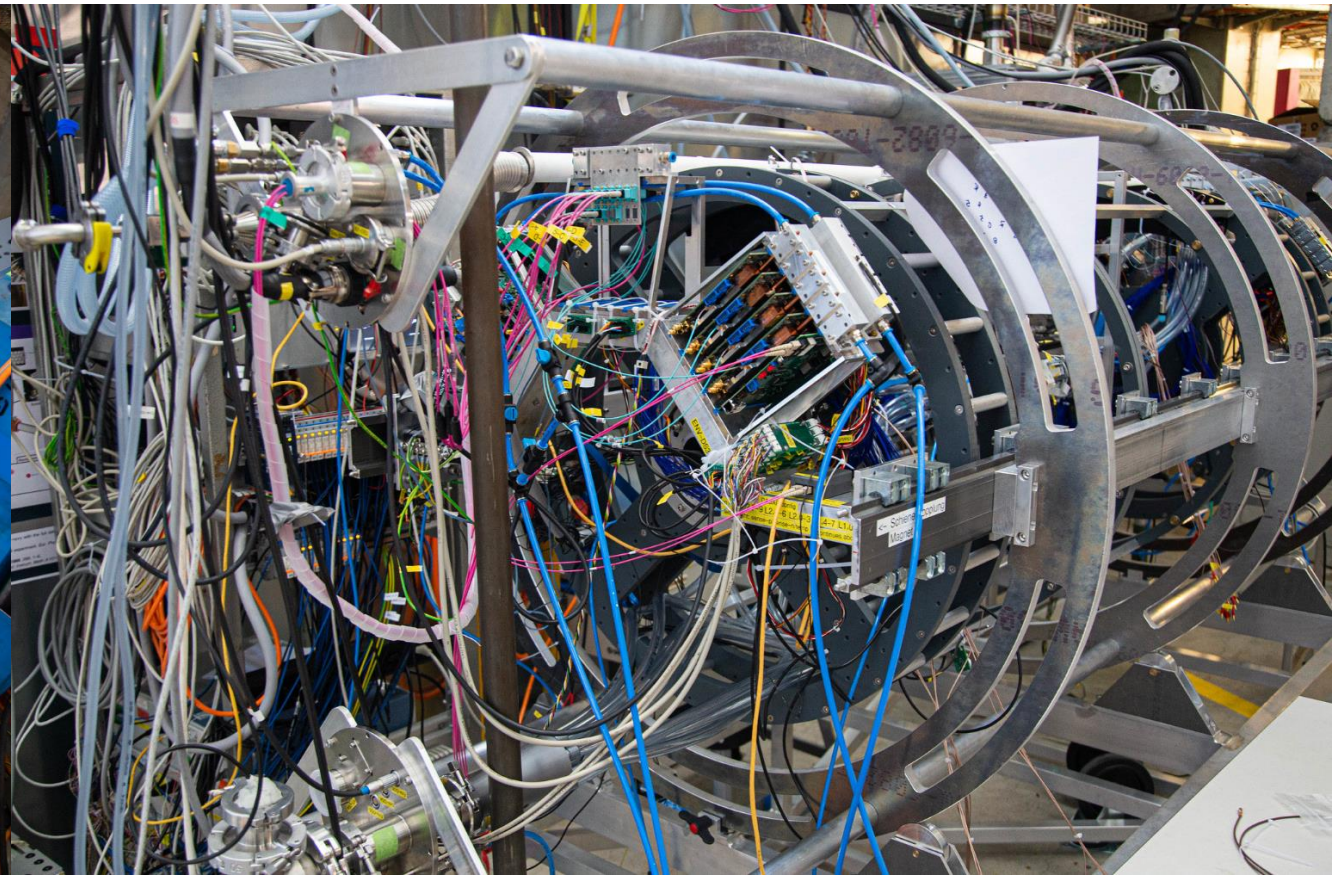
- Working first batch of **front-end boards**
- Working **Clock & Reset** distribution
- Rest are COTS or already available
- Major FPGA firmware blocks available and tested in hardware
- **Integration** and **scaling-up** in progress
- Concentrated efforts during "**Integration Run 2021**" and "**Cosmics Run 2022**"



Clock and Reset distribution system

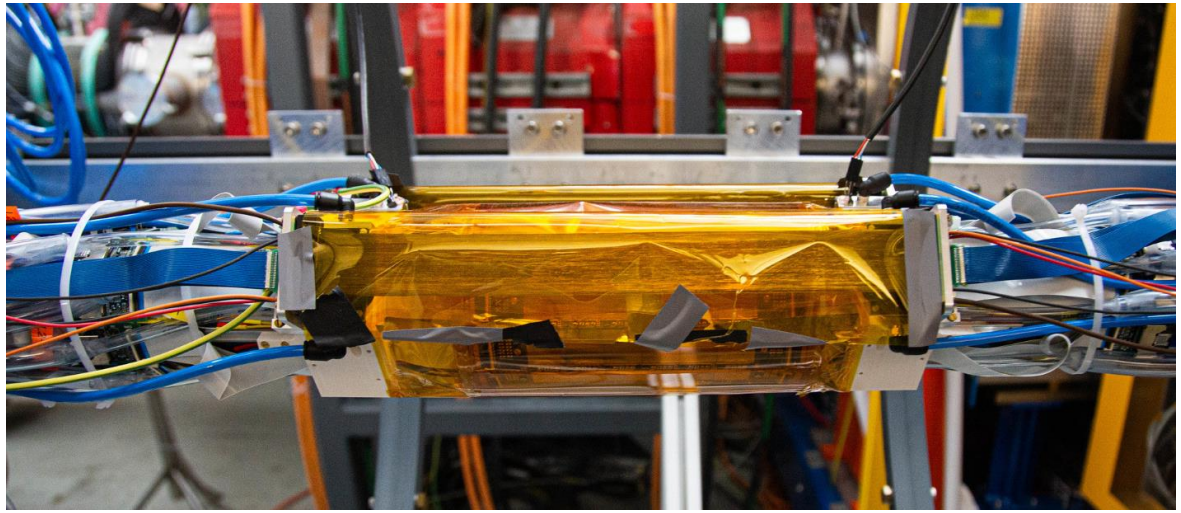
Integration Run 2021: Services

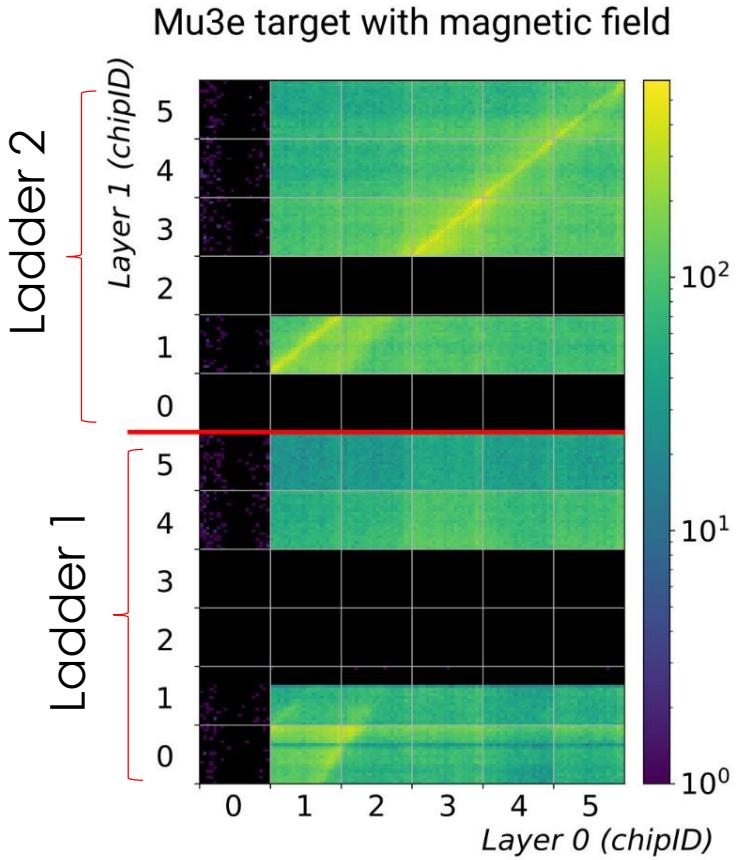




Integration Run 2021: Results

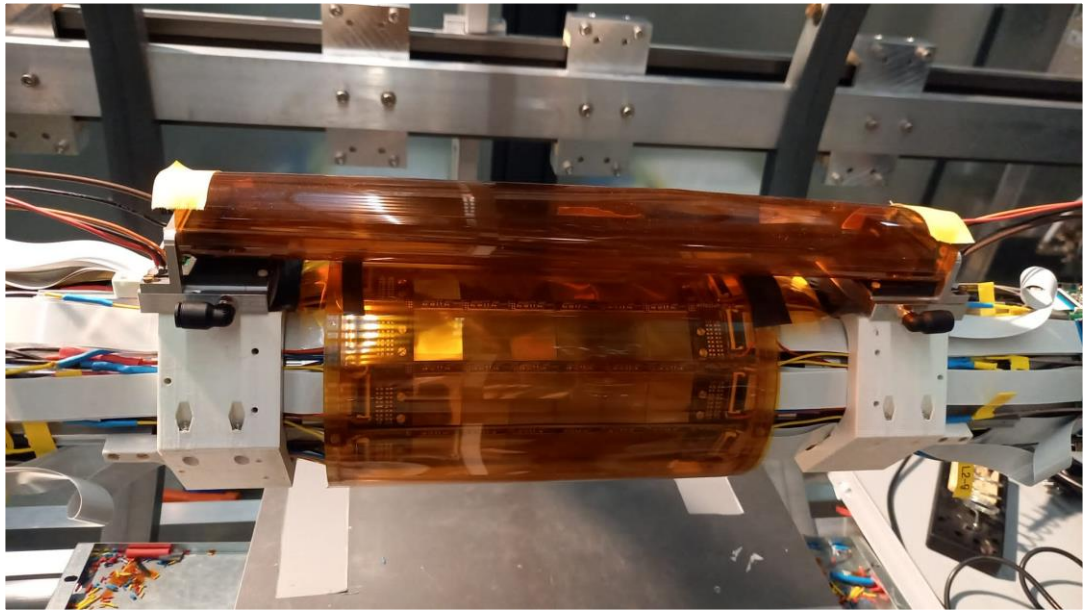
- Prototype pixel detector + 2 SciFi Ribbons **successfully operated** in magnet with helium cooling and beam
- We saw correlations between pixel sensors!

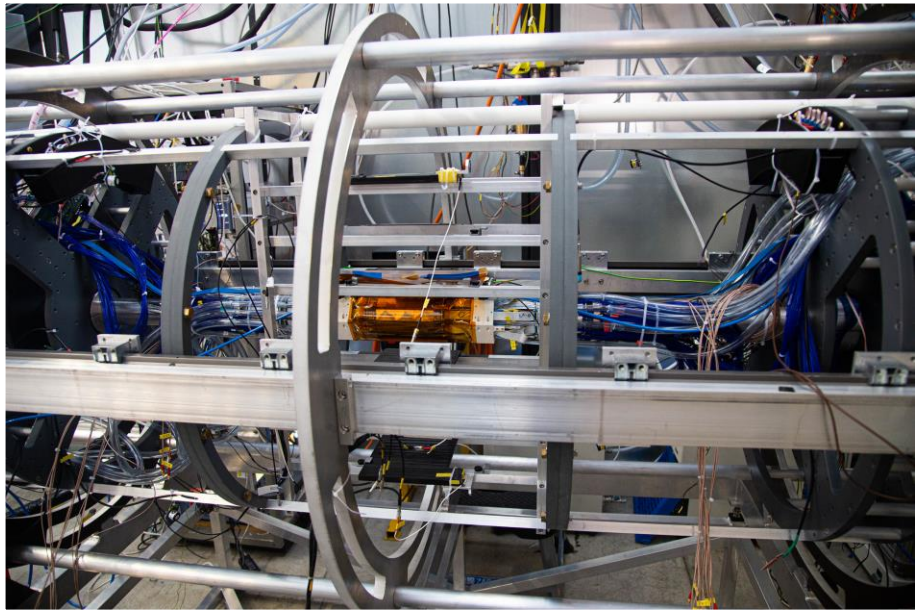




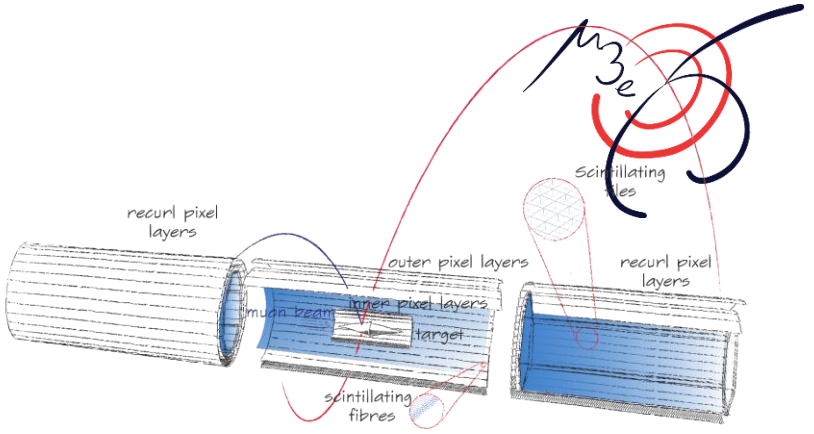
Cosmics Run 2022

- Currently on-going at PSI
- Goal: **Synchronization** of Pixel and SciFi
- Results will follow soon!

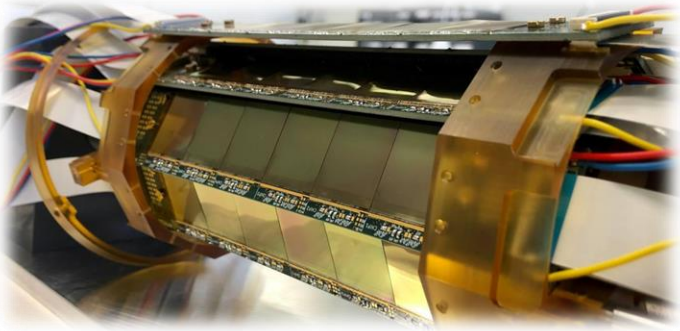


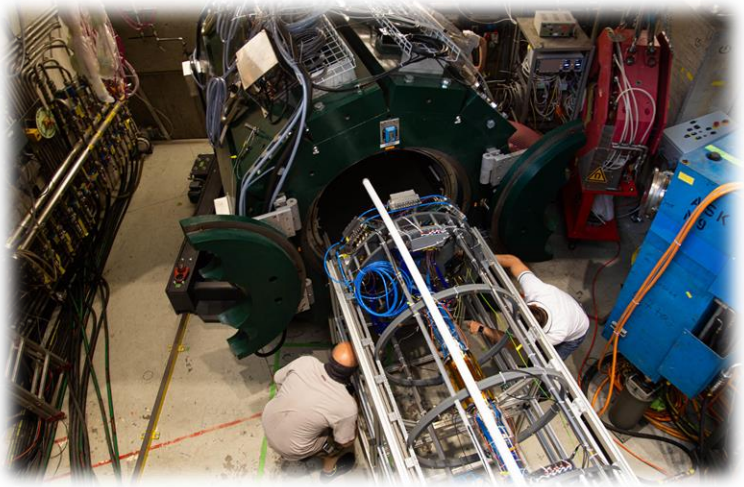


Summary and Outlook



- The Mu3e experiment will search for the cLFV decay $\mu^+ \rightarrow e^+e^-e^+$
- **Prototype detectors have successfully been operated in magnet, in helium, with beam**
- All detectors are preparing for mass production
- **Inner system comissioning** planned for **2023**
- Final integration, comissioning, and **physics data taking** will start in **2024**





Backup

Charged Lepton Flavour Violation

Lepton flavor *is* ***not*** *an* ***exact symmetry*** *and*

not conserved *in the Standard Model*

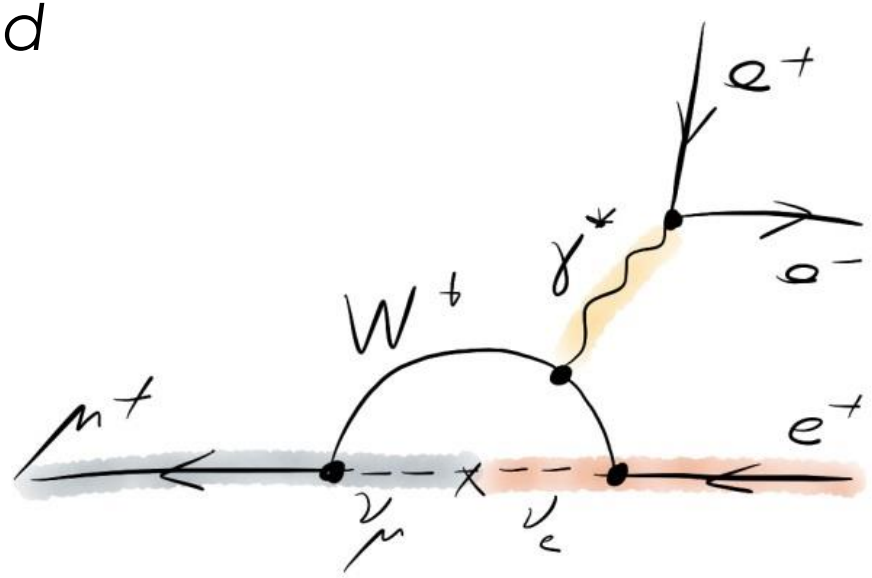
cLFV in general possible

BUT

Highly suppressed branching ratio

e.g. $\mu^+ \rightarrow e^+e^-e^+$ $\mathbf{BR} = \mathcal{O}(\mathbf{10^{-55}})$

Increased by many New Physics models!



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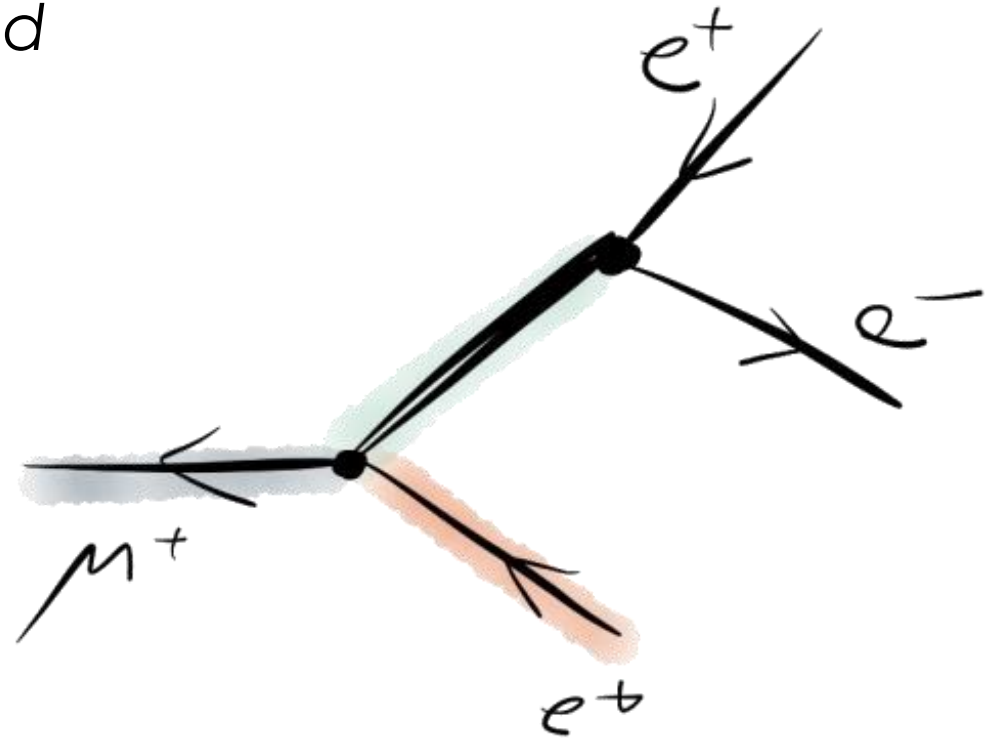

Charged Lepton Flavour Violation

Lepton flavor *is* ***not*** *an* ***exact symmetry*** *and*

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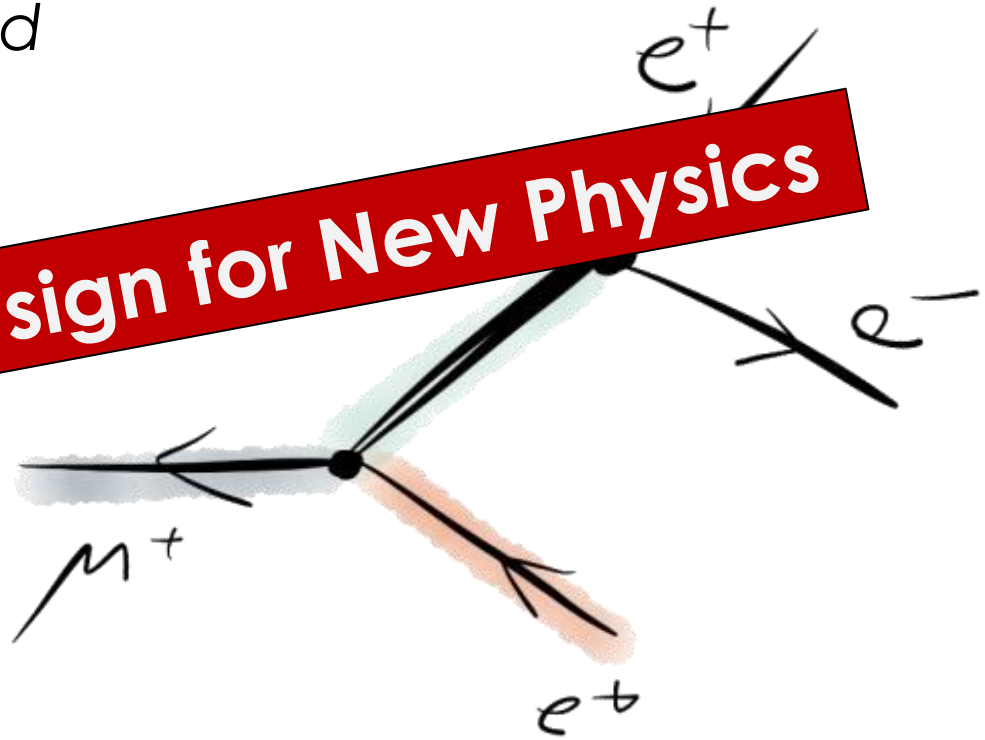
cLFV in general possible

So if we observe cLFV → clear sign for New Physics

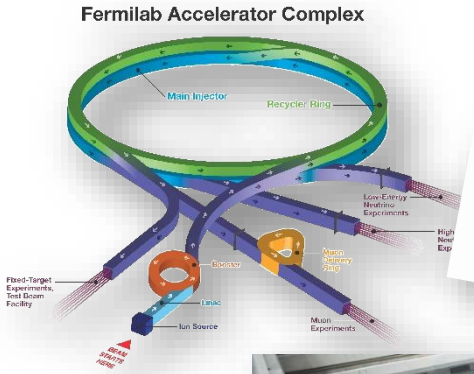


…ly suppressed branching ratio

e.g. $\mu^+ \to e^+e^-e^+$ $\mathbf{BR} = \mathcal{O}(\mathbf{10^{-55}})$

Increased by many New Physics models!

Tests of cLFV




ACCELERATORS | NEWS

Muons accelerated in Japan

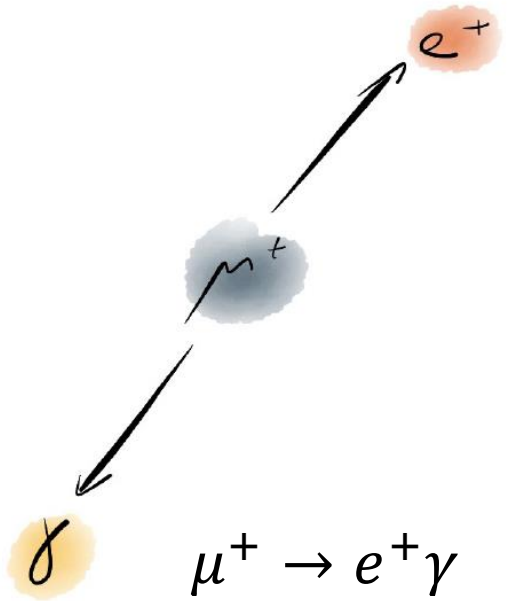
9 July 2018

- **Muons** are a versatile probe for cLFV
- **High intensity** muon beams available around the world (PSI, J-PARC, Fermilab)
- Search for
  - **Deviations from SM expectations**
  - **Forbidden or extremely suppressed phenomena**

Also at colliders (LHC, Belle II)

- LFV decays of Higgs
- Leptoquark searches
- LFV decays of B-mesons
  $B^0 \to e^{\pm}\mu^{\mp}, B_s^0 \to e^{\pm}\mu^{\mp}$
- LFV decays of τ
  $\tau \to 3l, \tau \to \mu\gamma$

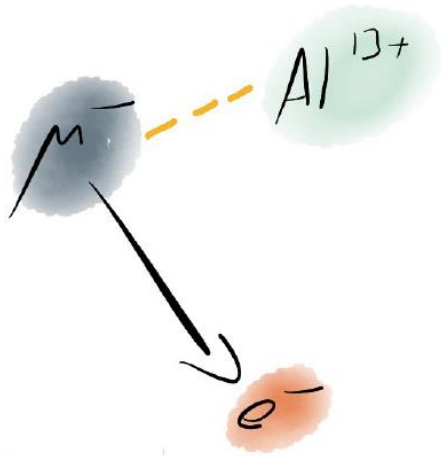
Golden Muon Decay Channels



$\mu^+ \to e^+\gamma$

MEG (PSI)

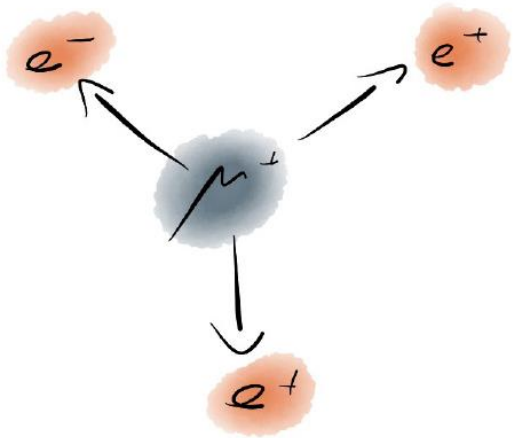
$\mathrm{BR} < 4.2 \times 10^{-13}$



$\mu^- N \to e^- N$

SINDRUM II (PSI)

$\mathrm{BR} < 7 \times 10^{-13}(\mathrm{Au})$

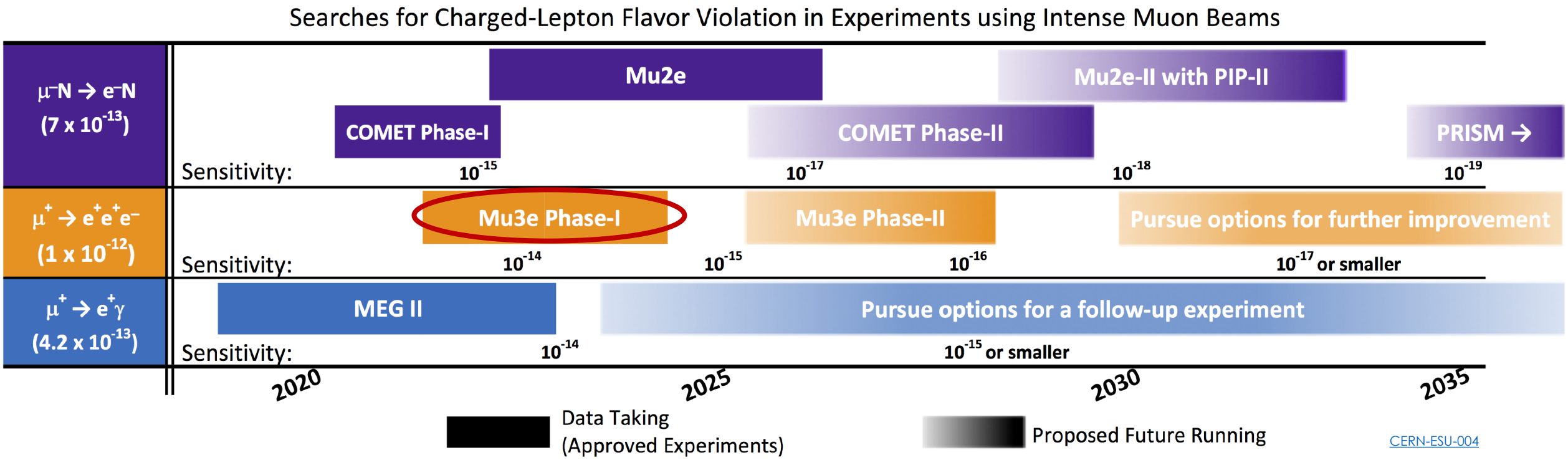


$\mu^+ \to e^+e^-e^+$

SINDRUM (PSI)

$\mathrm{BR} < 1 \times 10^{-12}$

Timeline of Muon cLFV Searches

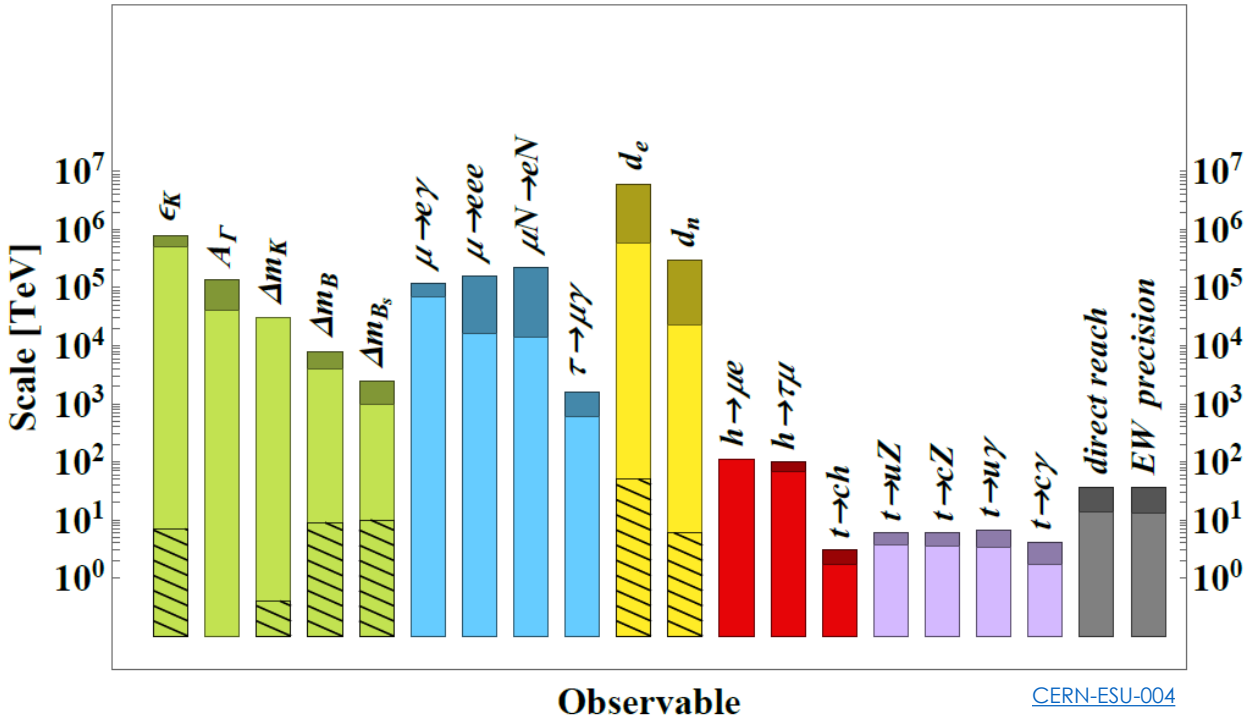


Senstivity of Muon cLFV Searches

- Extremely high mass scales
- Model-independent effective Lagrangian

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{C_5}{\Lambda_M}\mathscr{O}^{(5)} + \sum_a \frac{C_6^a}{\Lambda^2}\mathscr{O}_a^{(6)} + \cdots$$

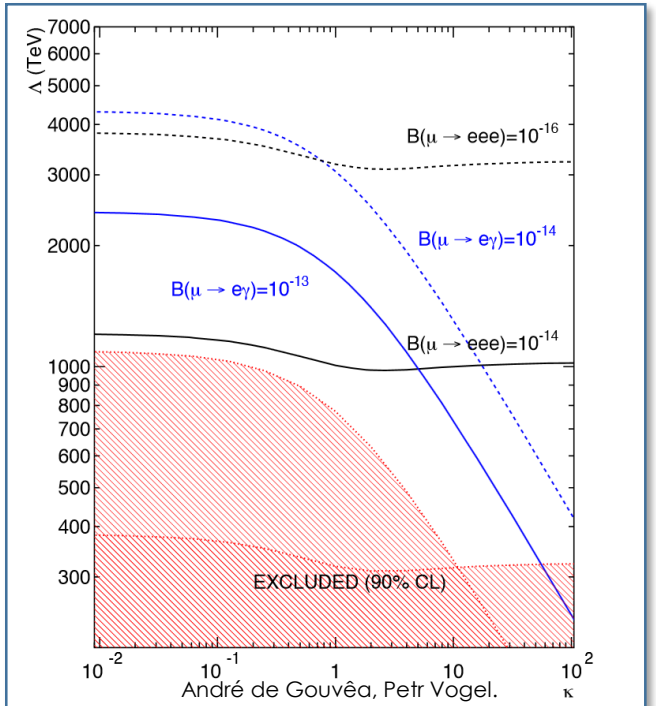
$\mathcal{O}_a^6$ encodes new particles with generic mass scale Λ



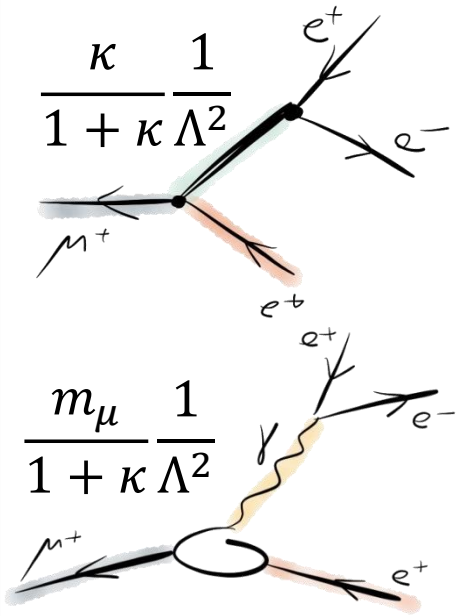
CERN-ESU-004

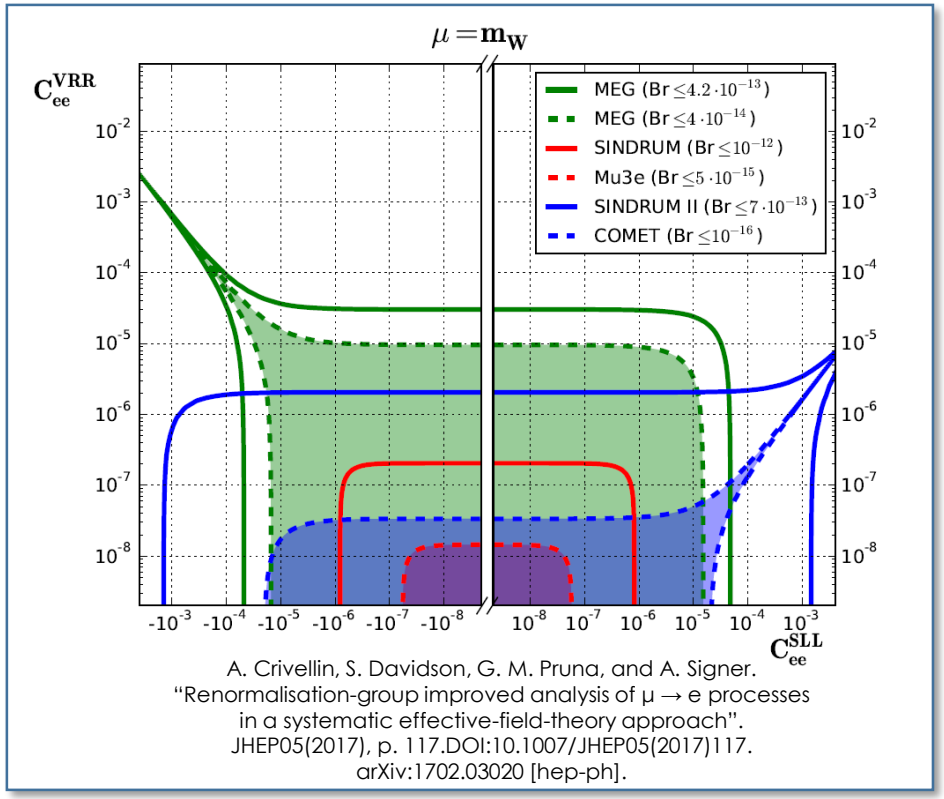
Complementarity

- The 3 processes have different sensitivities to scalar, vector, tensor, ... interactions
- New Physics may enter at tree or loop level



André de Gouvêa, Petr Vogel.
"Lepton flavor and number conservation, and physics beyond the standard model".
Progress in Particle and Nuclear Physics, 71 (2013) 75-9.





A. Crivellin, S. Davidson, G. M. Pruna, and A. Signer.
"Renormalisation-group improved analysis of μ → e processes in a systematic effective-field-theory approach".
JHEP05(2017), p. 117.DOI:10.1007/JHEP05(2017)117.
arXiv:1702.03020 [hep-ph].

Model	$\mu \to eee$	$\mu N \to eN$	$\frac{BR(\mu\to eee)}{BR(\mu\to e\gamma)}$	$\frac{CR(\mu N\to eN)}{BR(\mu\to e\gamma)}$
MSSM	Loop	Loop	$\approx 6\times10^{-3}$	$10^{-3}-10^{-2}$
Type-I seesaw	Loop	Loop	$3\times10^{-3}-0.3$	$0.1-10$
Type-II seesaw	Tree	Loop	$(0.1-3)\times10^{3}$	$\mathcal{O}(10^{-2})$
Type-III seesaw	Tree	Tree	$\approx 10^{3}$	$\mathcal{O}(10^{3})$
LFV Higgs	Loop	Loop	$\approx 10^{-2}$	$\mathcal{O}(0.1)$
Composite Higgs	Loop	Loop	$0.05-0.5$	$2-20$

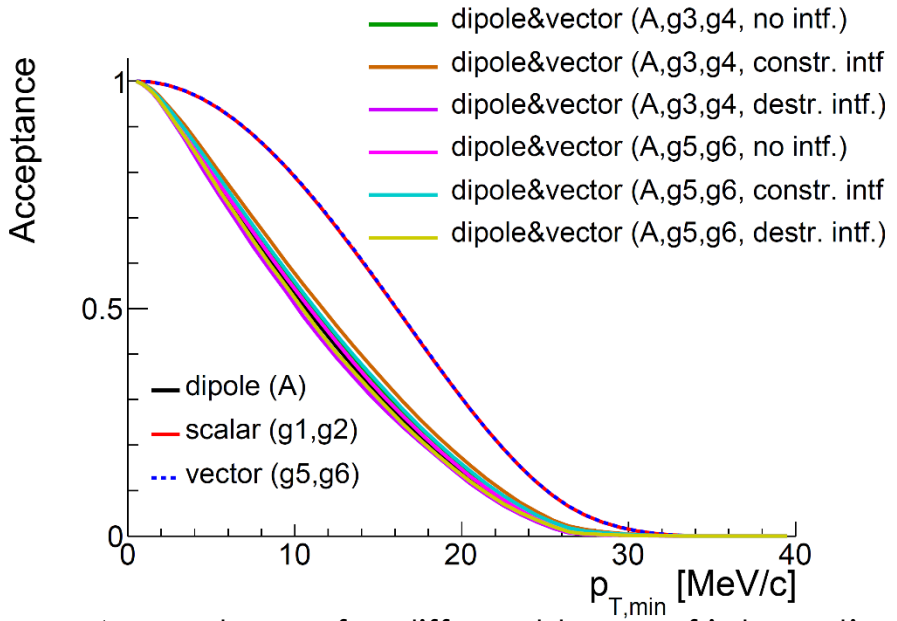
L. Calibbi, G. Signorelli, arXiv:1709.00294
Ana M. Teixeira, PoS(NuFact2019)016

Signal Modelling

- Important input for the design of the Mu3e experiment
- Need high acceptance in all regions of phase space
- Minimum energy of **few MeV**, with **large solid angle** coverage!

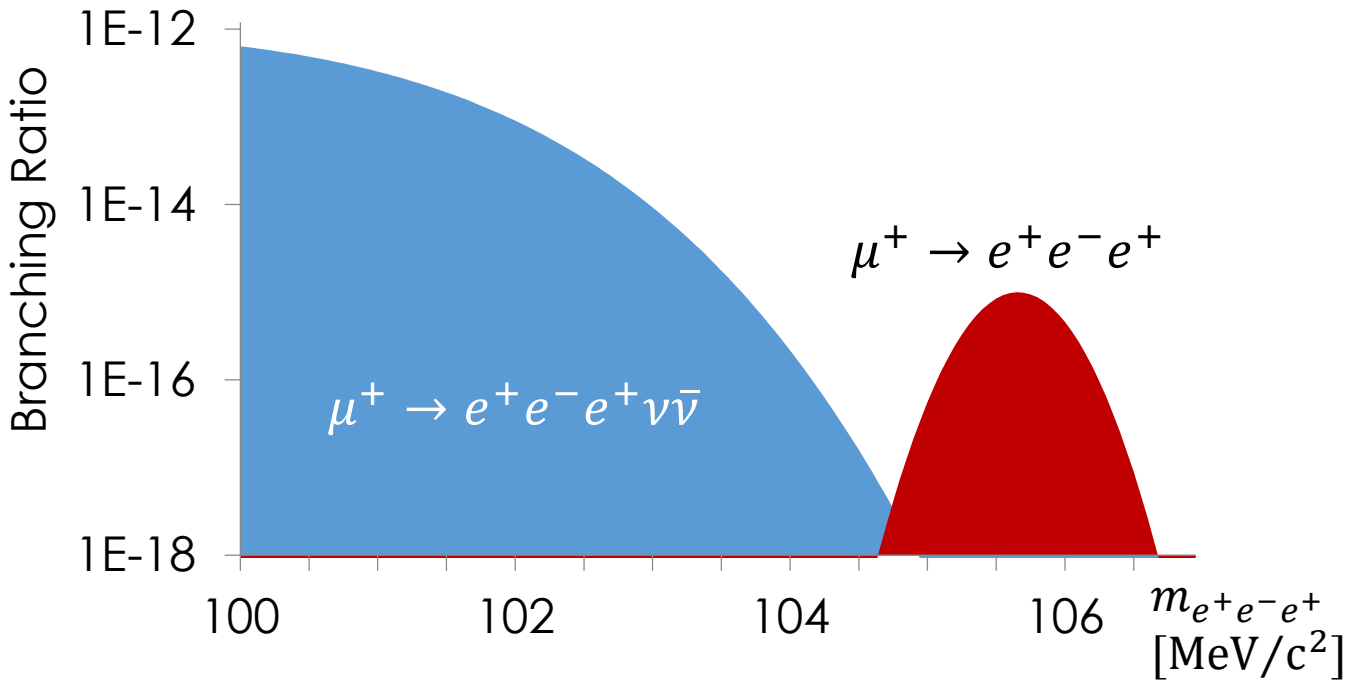
$$
\begin{aligned}
L_{\mu\to eee} = & -\frac{4G_F}{\sqrt{2}}\,[m_\mu A_R\,\overline{\mu_R}\sigma^{\mu\nu}e_L F_{\mu\nu} \\
& + m_\mu A_L\,\overline{\mu_L}\sigma^{\mu\nu}e_R F_{\mu\nu} \\
& + g_1\,(\overline{\mu_R}e_L)\,(\overline{e_R}e_L) \\
& + g_2\,(\overline{\mu_L}e_R)\,(\overline{e_L}e_R) \\
& + g_3\,(\overline{\mu_R}\gamma^\mu e_R)\,(\overline{e_R}\gamma_\mu e_R) \\
& + g_4\,(\overline{\mu_L}\gamma^\mu e_L)\,(\overline{e_L}\gamma_\mu e_L) \\
& + g_5\,(\overline{\mu_R}\gamma^\mu e_R)\,(\overline{e_L}\gamma_\mu e_L) \\
& + g_6\,(\overline{\mu_L}\gamma^\mu e_L)\,(\overline{e_R}\gamma_\mu e_R) + H.c.\,]
\end{aligned}
$$

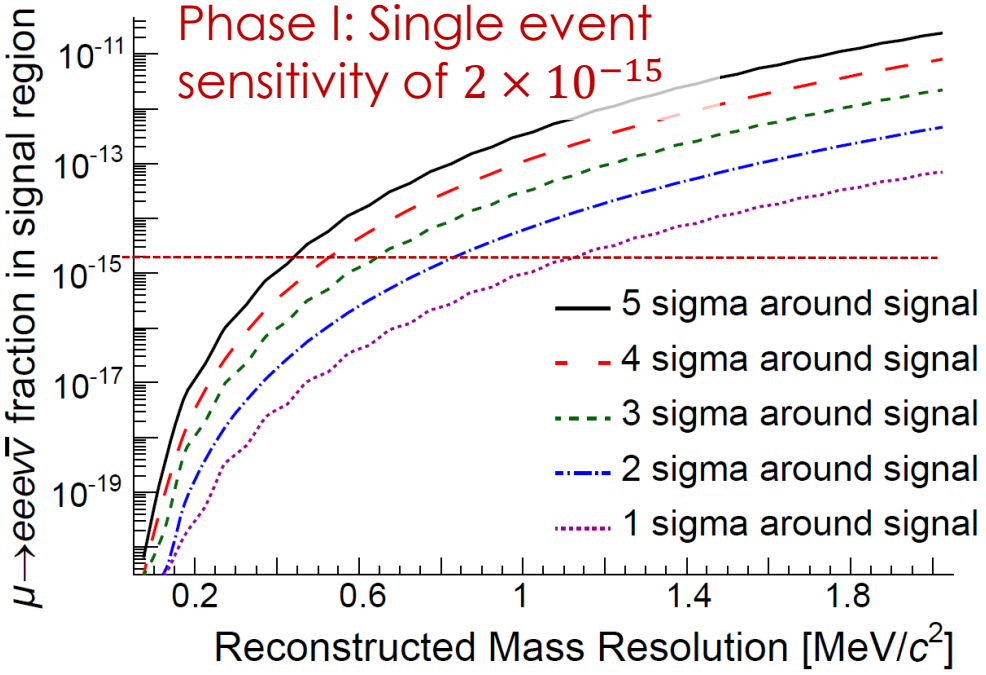
Parametrised Lagrangian by Kuno and Okada



Acceptance for different types of interaction depending on the transverse momentum threshold

Momentum Resolution Requirement





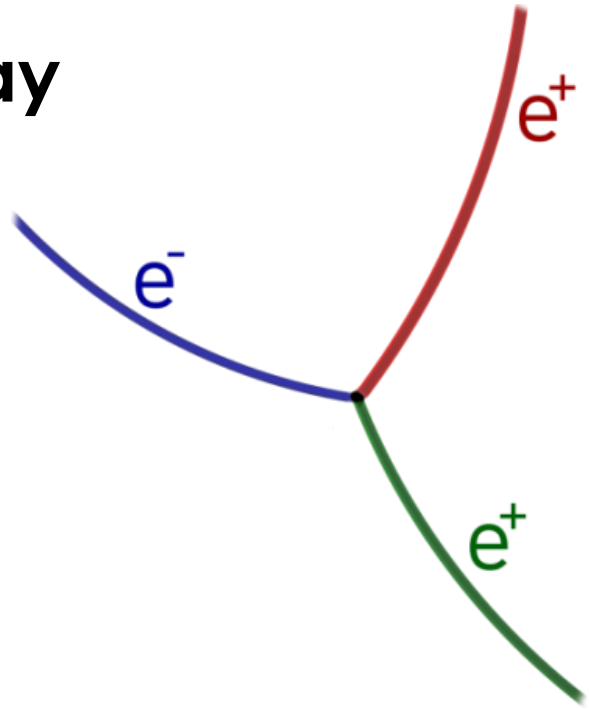
- Distinguish signal and background: missing momentum
- Requires excellent average momentum resolution $\sigma_p < 1.0$ MeV/c

The Signal Decay

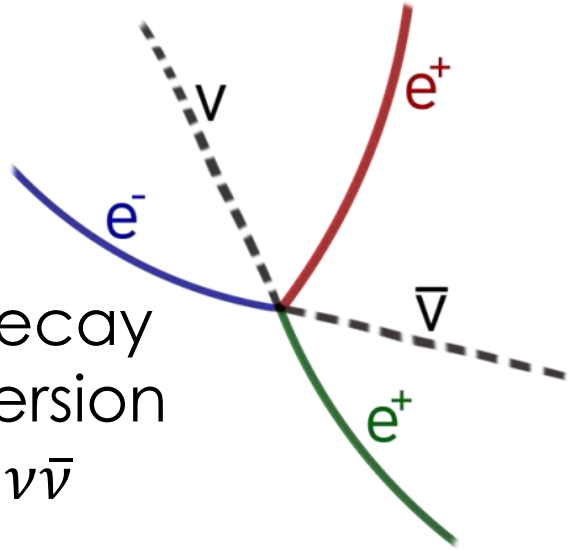
Muons are stopped before decay

Experimental Signature

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

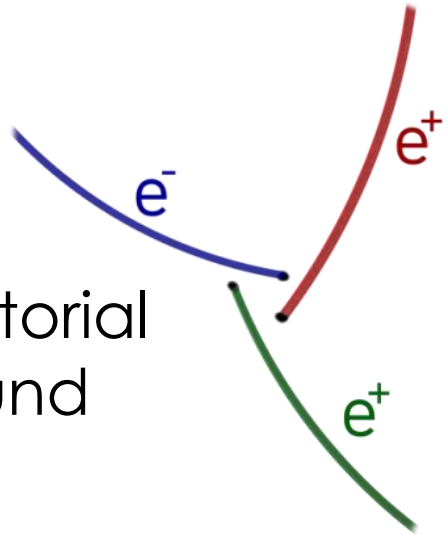


Main Sources of Background



Radiative SM decay
+ photon conversion
$\mu^+ \rightarrow e^+e^-e^+\nu\bar{\nu}$

Experimental Signature
- Common vertex
- Time coincident
- $\sum \vec{p} \neq 0$
- $\sum E \neq m_\mu$

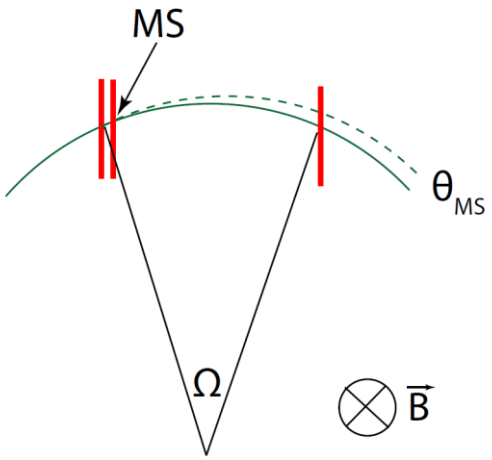


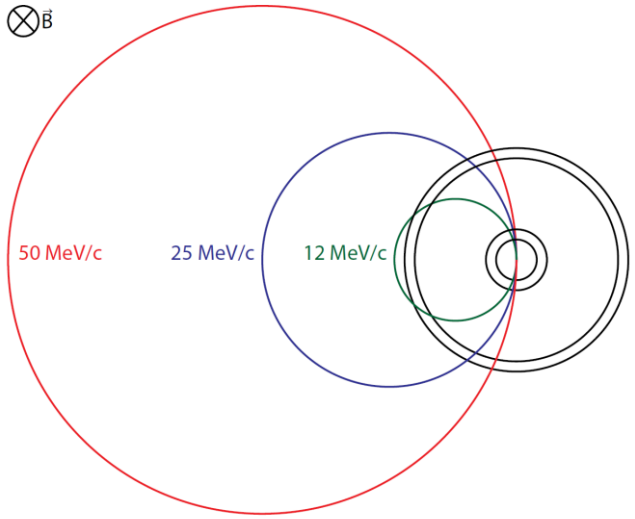
Combinatorial
background

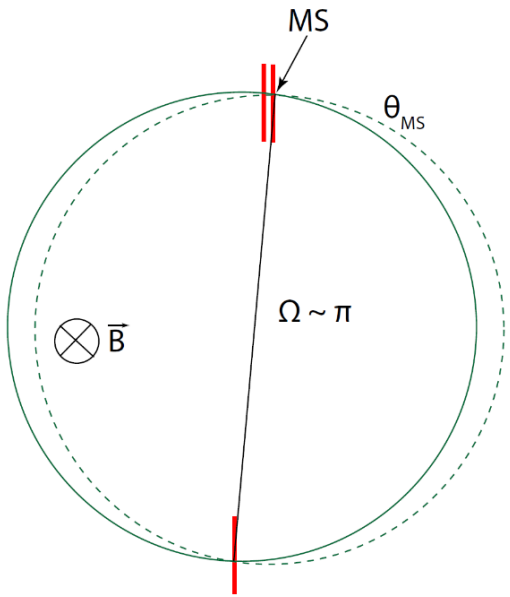
Experimental Signature
- No common vertex
- Not time coincident
- $\sum \vec{p} \neq 0$
- $\sum E \neq m_\mu$

Momentum Measurement

- Stopped muons → **low momentum e^-e^+**
- Momentum resolution limited by **multiple scattering** $\sigma_p/p \propto \theta_{MS}/\Omega$
- Large lever arm Ω & Reducing multiple scattering θ_{MS}
  - Material budget ≤ $\mathbf{1‰\ X_0}$ per layer
  - Particles recurl into the detector

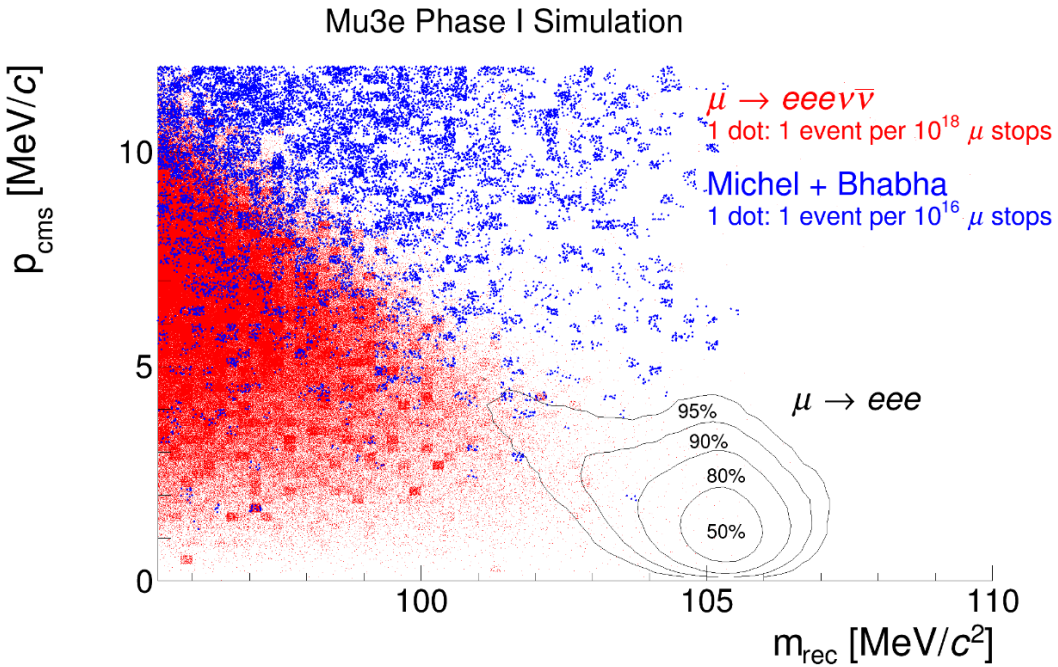


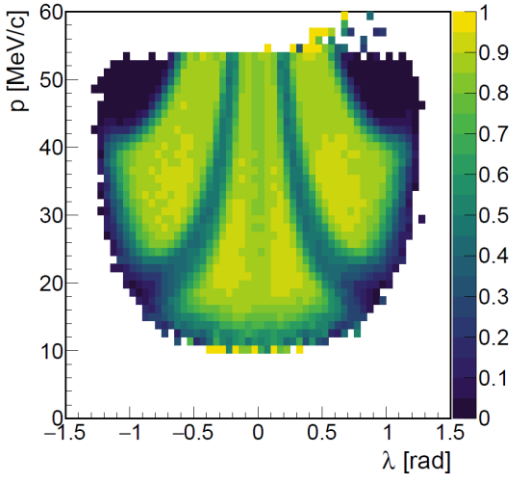




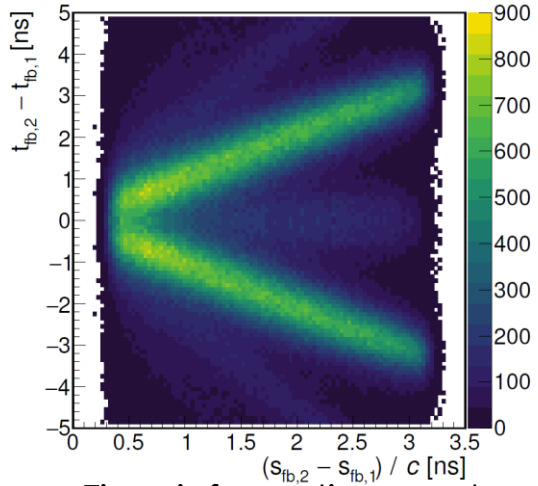
Performance Study (Simulation)

- Geant4 based detector simulation
- Track reconstruction relying on MS-fit (triplet fit arXiv:1606.04990)

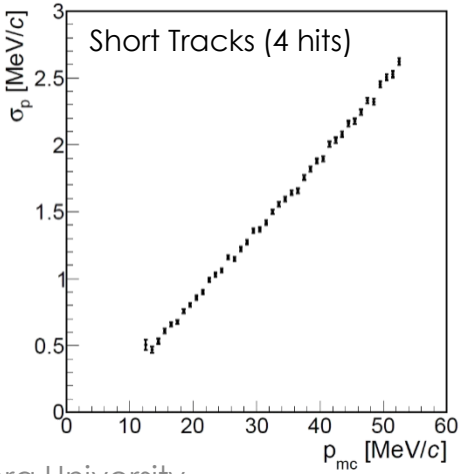


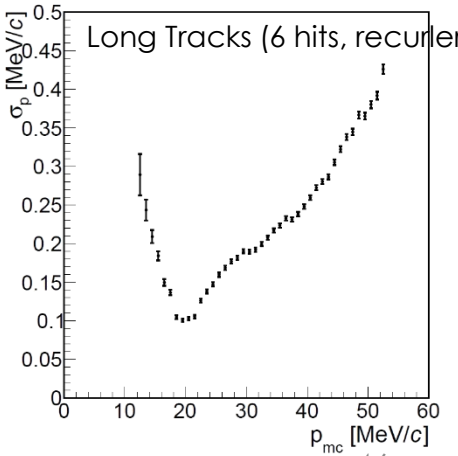


Ratio of reconstructed long vs short tracks

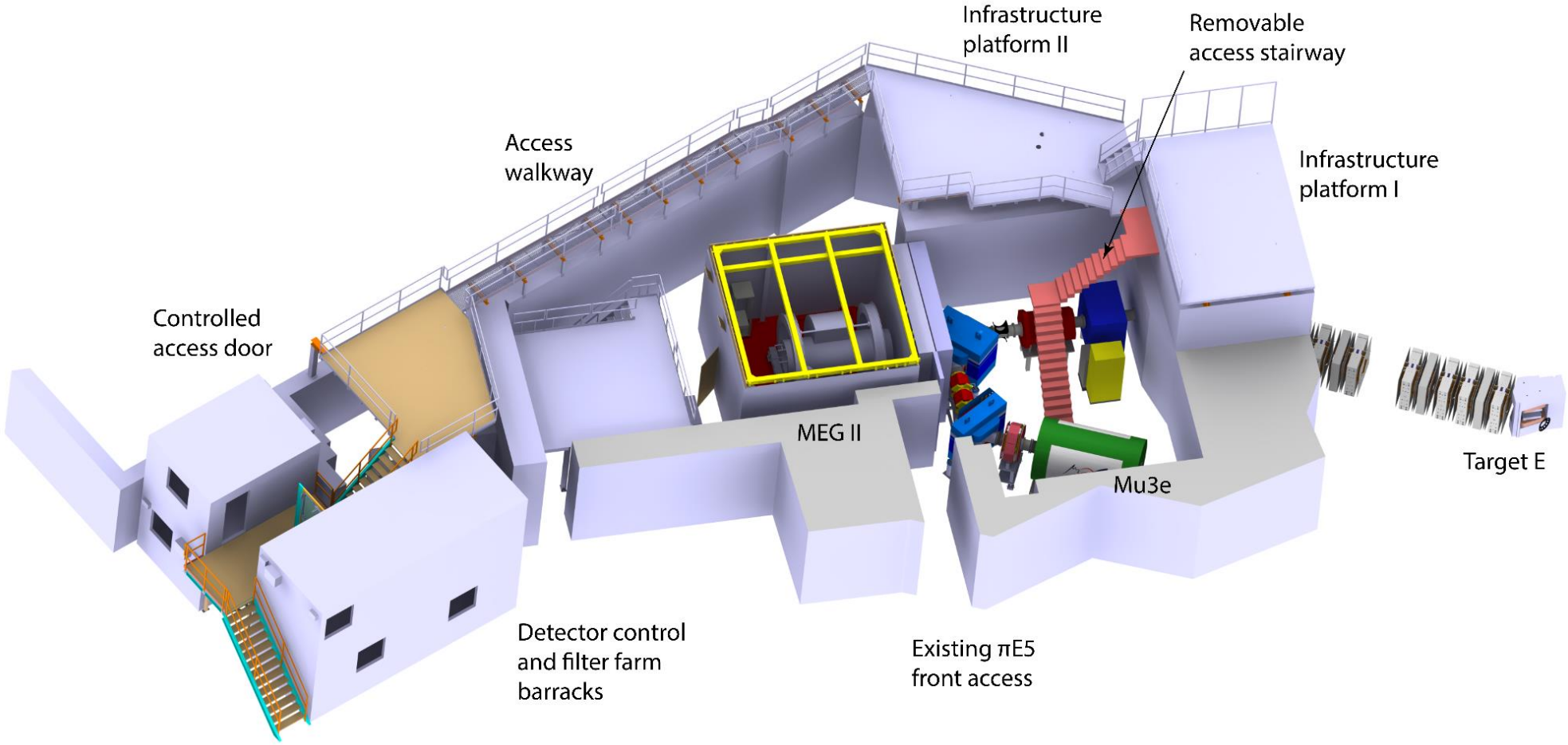


Time information used for charge assignment





Experimental Area @ PSI



Material Budget of Selected Pixel Detectors

Experiment	Material budget per layer
ATLAS IBL ‡	$1.9\ \%\ X_0$
CMS (current)†	$\sim 2.0\ \%\ X_0$
CMS (upgrade)†	$\sim 1.1\ \%\ X_0$
ALICE (current)*	$1.1\ \%\ X_0$
ALICE (upgrade)*	$0.3\ \%\ X_0$
STAR ◇	$0.4\ \%\ X_0$
BELLE II △	$0.2\ \%\ X_0$
Mu3e	$\mathbf{0.1\ \%\ X_0}$

‡ ATL-INDET-PROC-2015-001

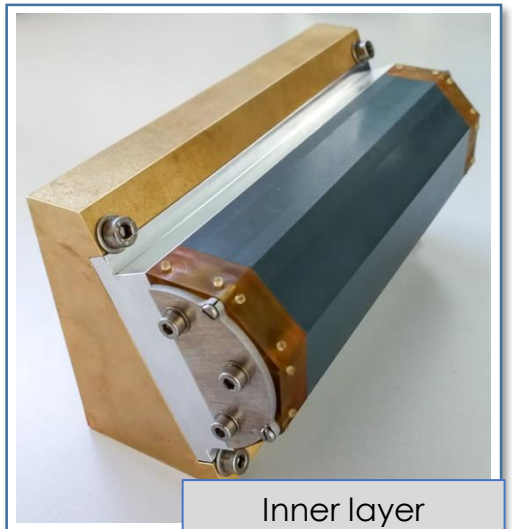
† CERN-LHCC-2012-016 ; CMS-TDR-11

* arXiv:1211.4494v1

◇ talk by G. Contin at PIXEL 2016

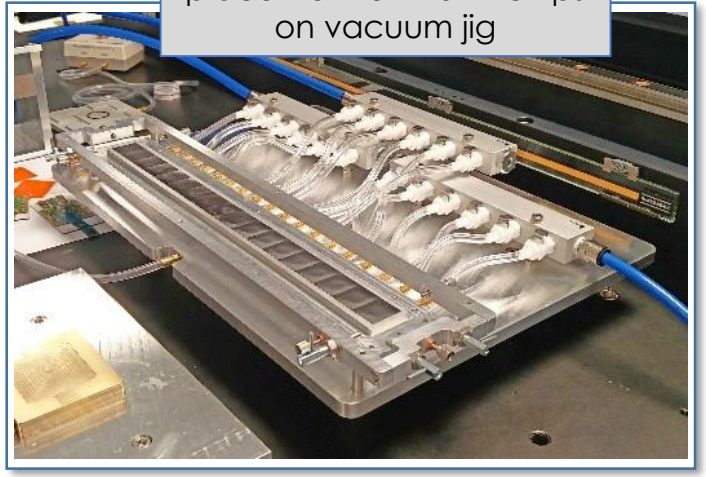
△ talk by C. Koffmane at PIXEL 2016

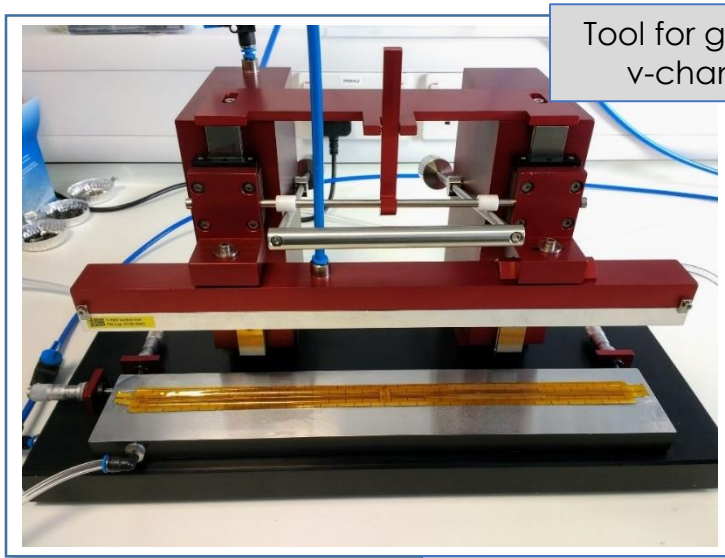
Development of Tooling



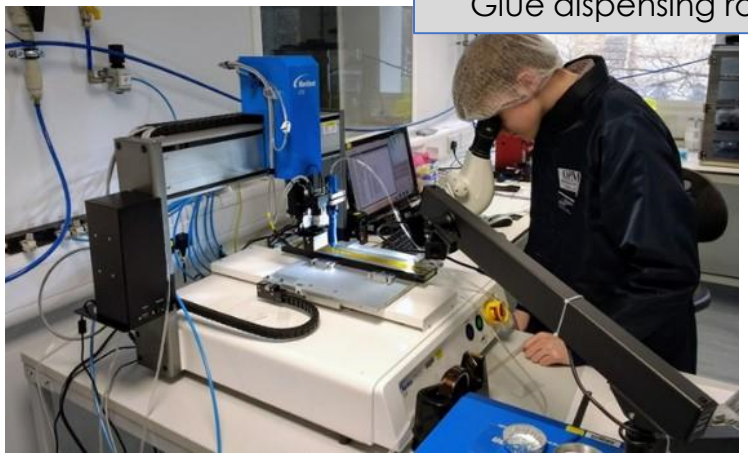
Inner layer assembly tool

Robotic gantry for placement of MuPix chips on vacuum jig





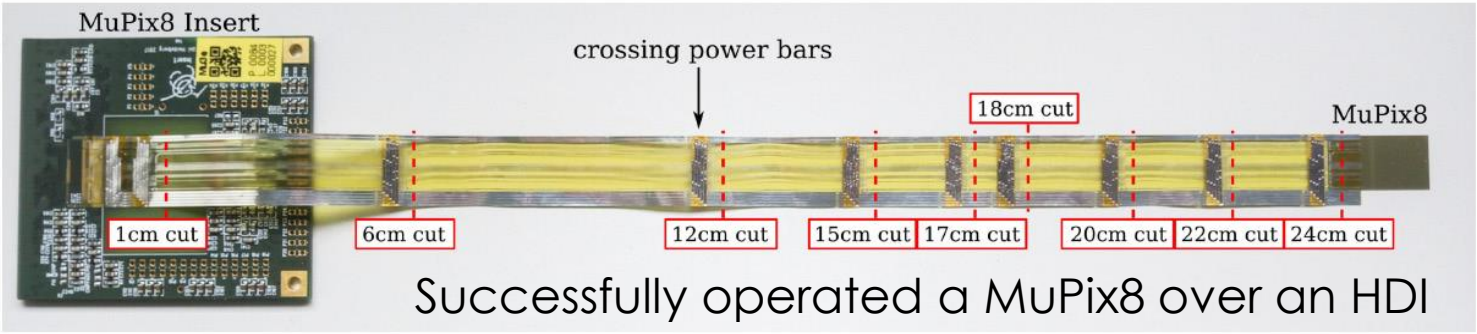
Tool for gluing of v-channels



Glue dispensing robot

High Density Interconnect

- Produced by LTU Ltd.
- **Thin foils**: 14 µm **Aluminium** per layer
- Dielectric spacing: polyimide foils
- **SpTAB** technology: Single point Tape Automated Bonding



Successfully operated a MuPix8 over an HDI

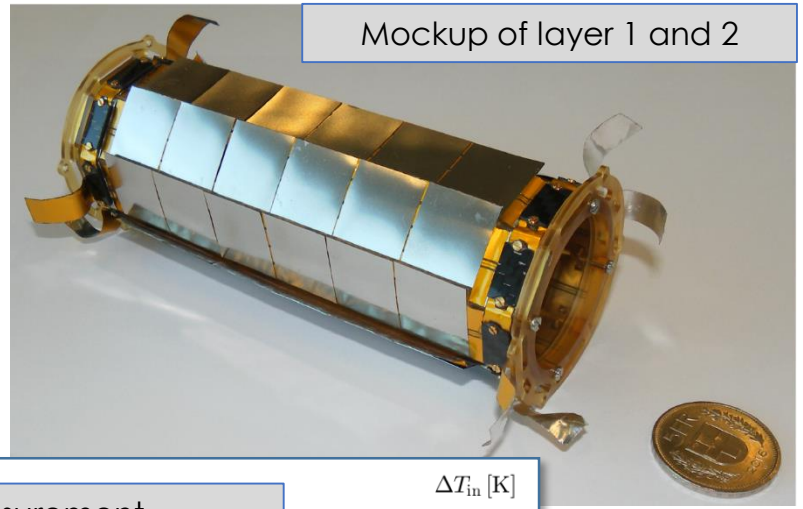
Material budget

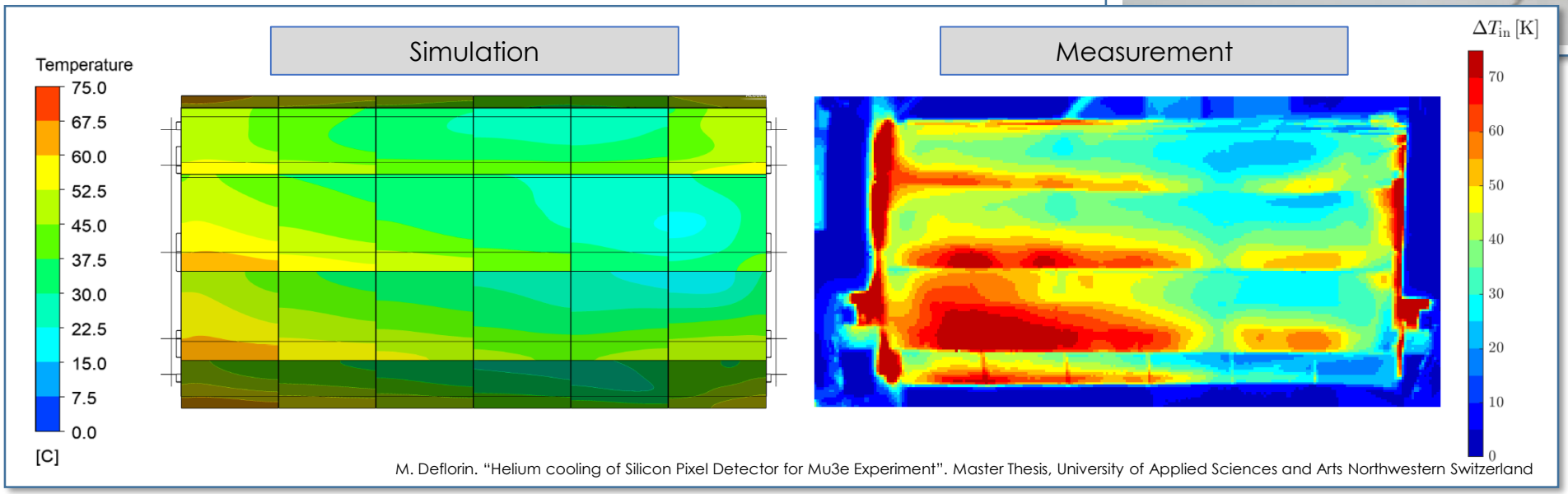
45 µm Polyimide
+ 28 µm Aluminium
+ 10 µm Glue

~ 0.5‰ X_0

Thermo-Mechanical Mockup

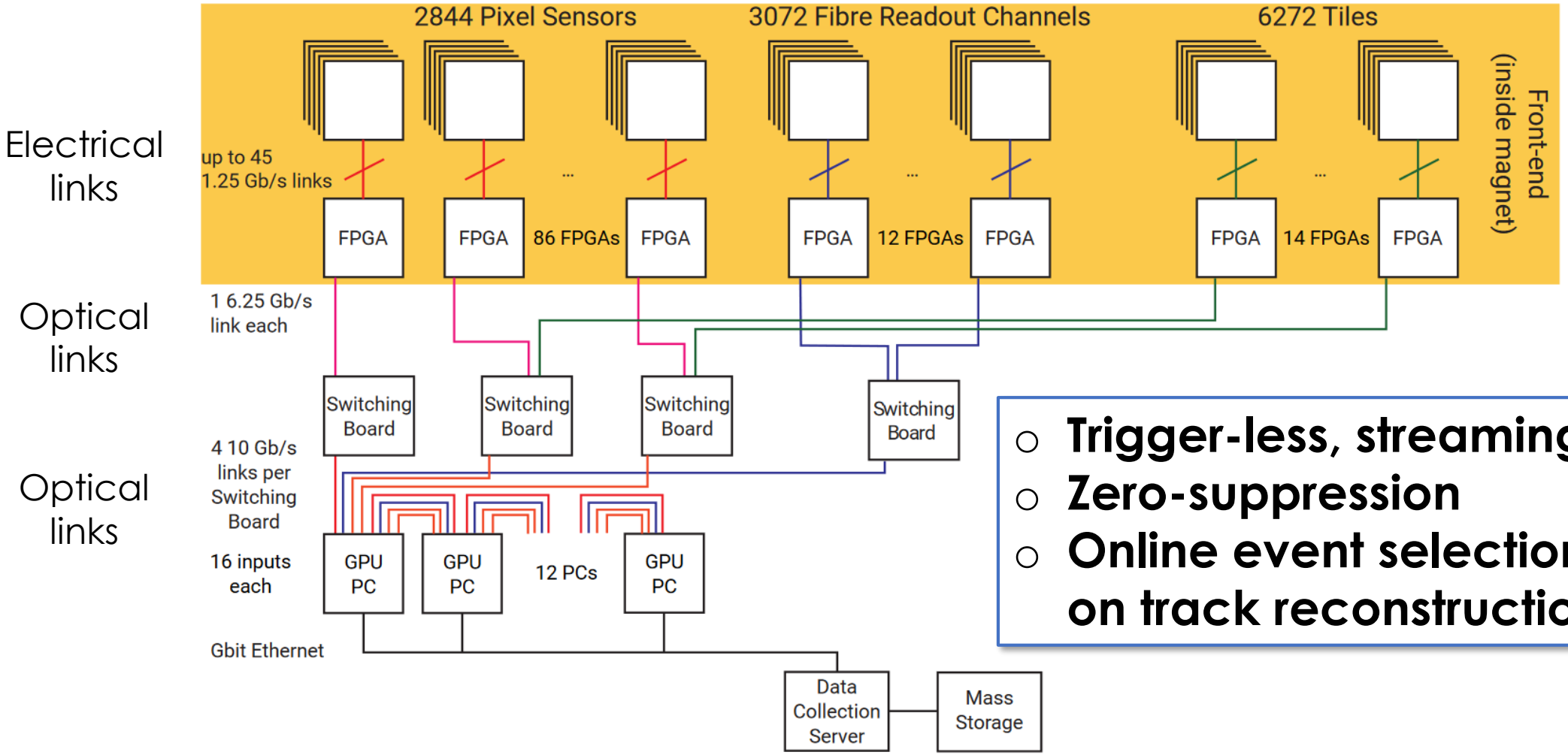
- Validate mechanical and electrical concept
- Test and optimize the cooling system
- Compare CFD simulations with measurements





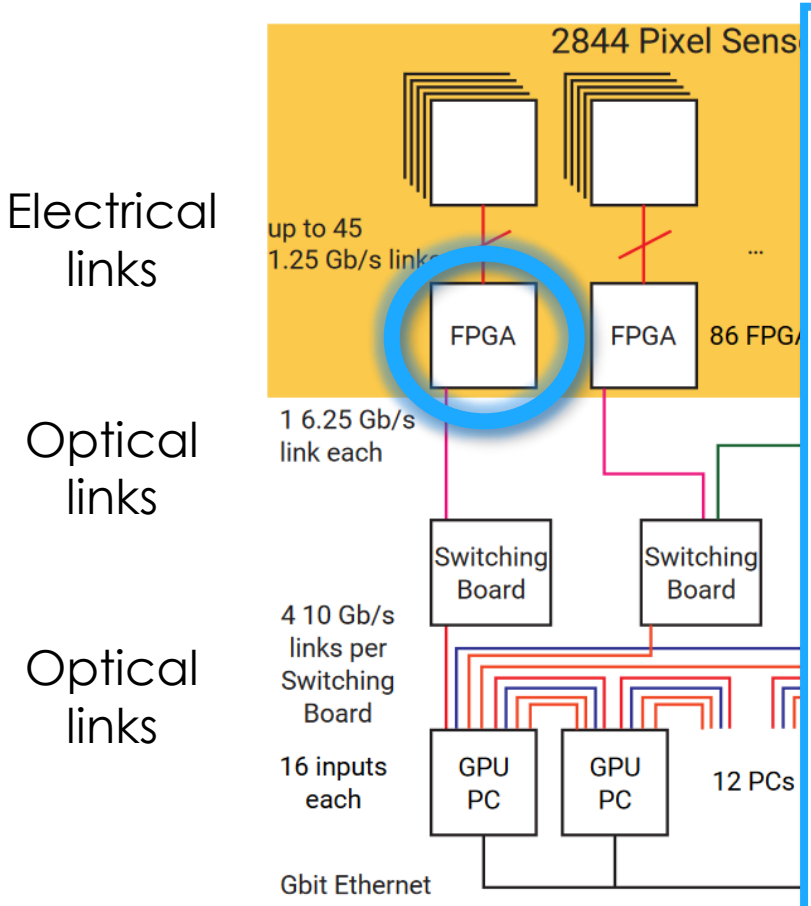
M. Deflorin. "Helium cooling of Silicon Pixel Detector for Mu3e Experiment". Master Thesis, University of Applied Sciences and Arts Northwestern Switzerland

The Mu3e Readout Concept



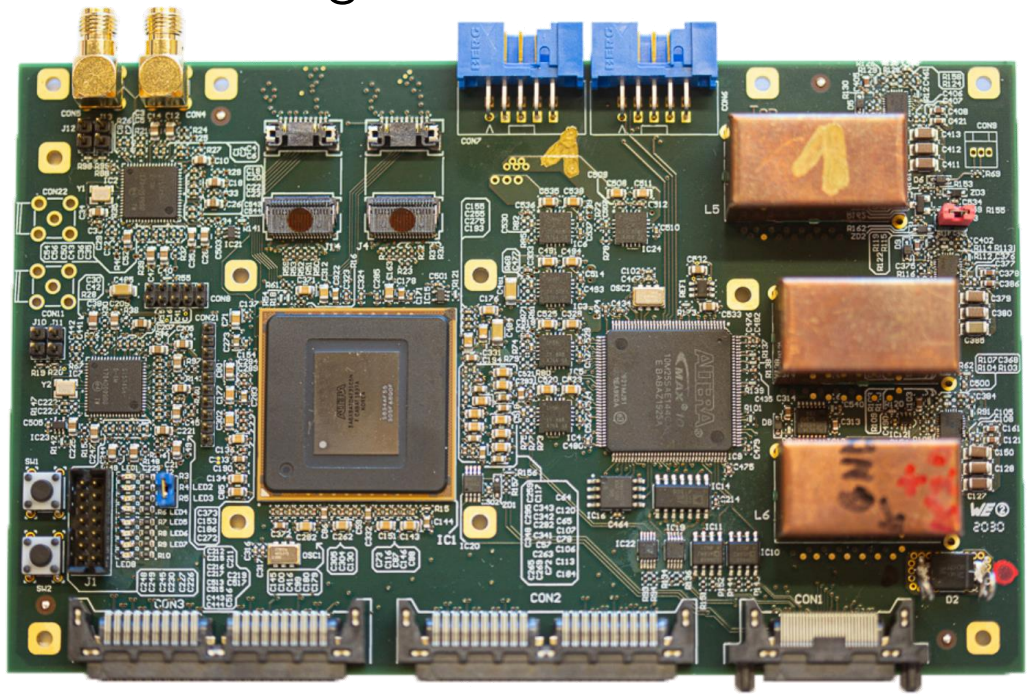
- **Trigger-less, streaming readout**
- **Zero-suppression**
- **Online event selection based on track reconstruction**

The Mu3e Readout Concept

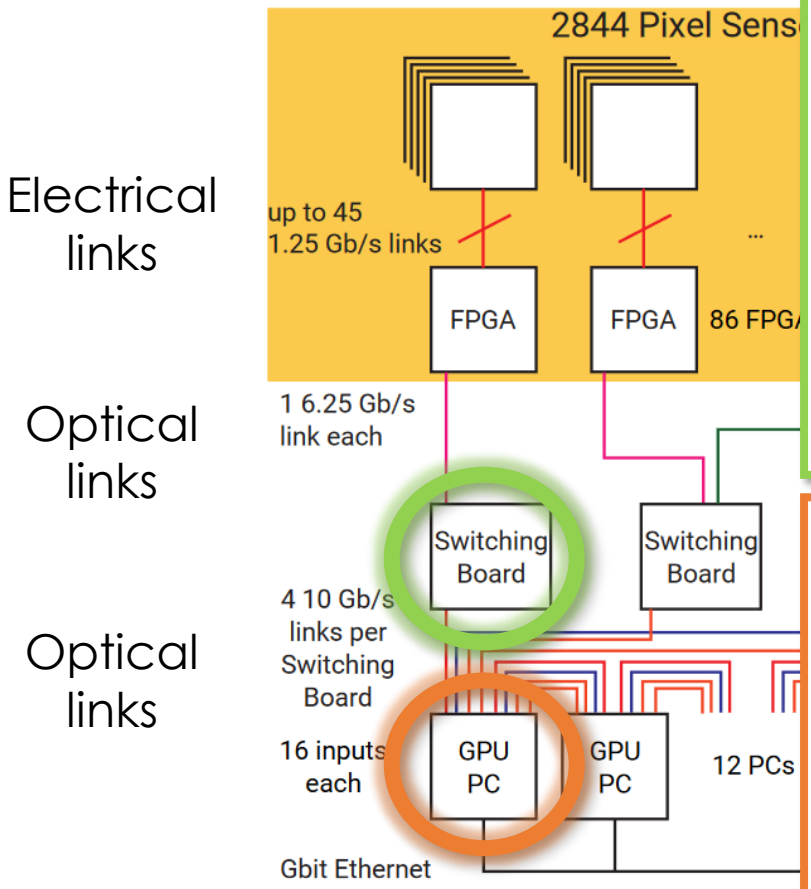


The Front-end Board

- **Sorts** hits by timestamps
- Distributes clock and reset to ASICs
- Custom designed board



The Mu3e Readout Concept



The Switching Board

- **Collects** data of several front-end boards
- **Merges** into single data stream
- PCIe40 board (LHCb)

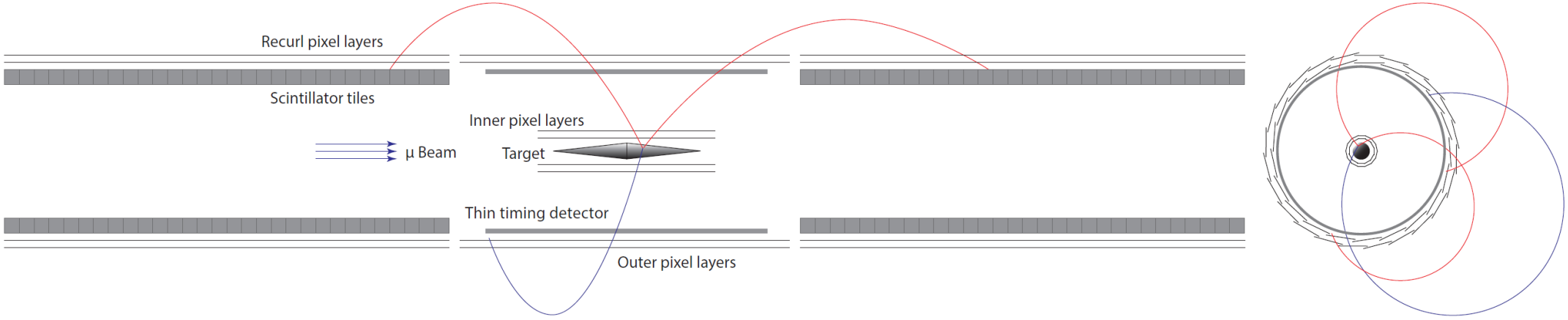
The GPU Filter Farm

- **Online track reconstruction** and **event selection**
- Large Arria10 FPGA card
- High-end commercial GPU
  - Triplet fit (arXiv:1606.04990)
  - Vertex fit

And what's beyond Phase I?

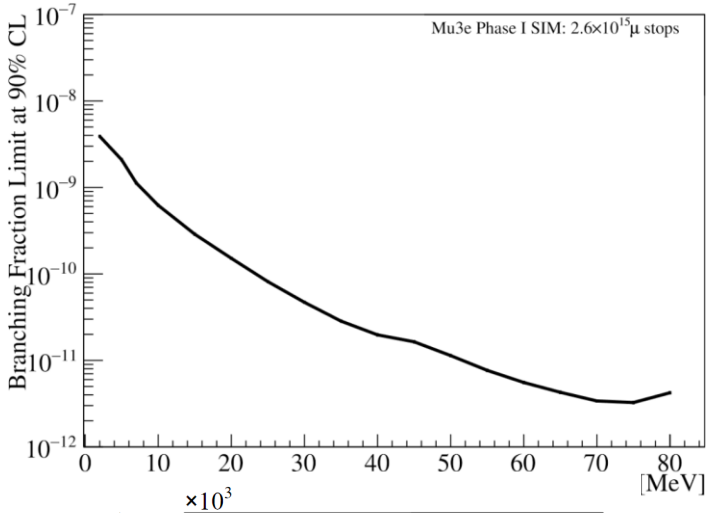
Mu3e Phase II

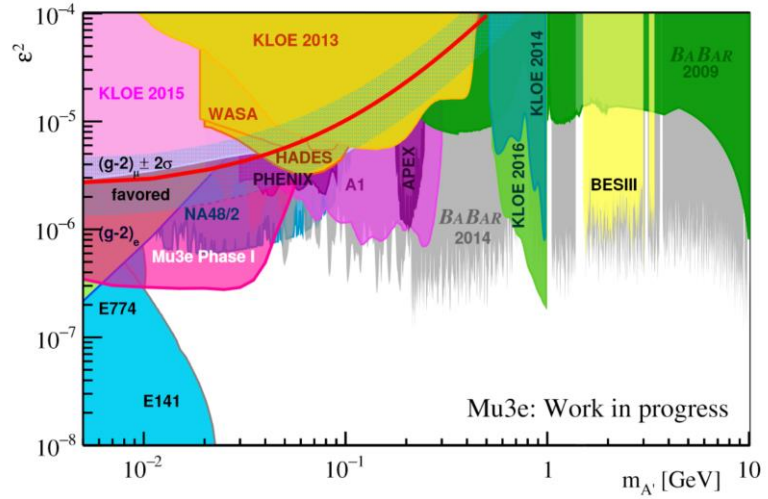
- For the ultimate sensitivity goal for $\mathrm{BR} \leq 1 \times 10^{-16}$ a muon rate of $2 \times 10^{9}\ s^{-1}$ is required (HIMB for Phase II >2025)
- Adapt detector geometry
- Fully exploit HV-MAPS time resolution $\mathcal{O}$(1 ns)
- Investigate reduction of material by applying wafer-scale technologies

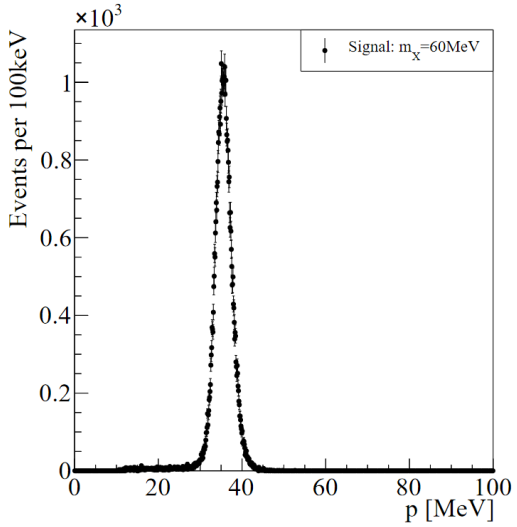


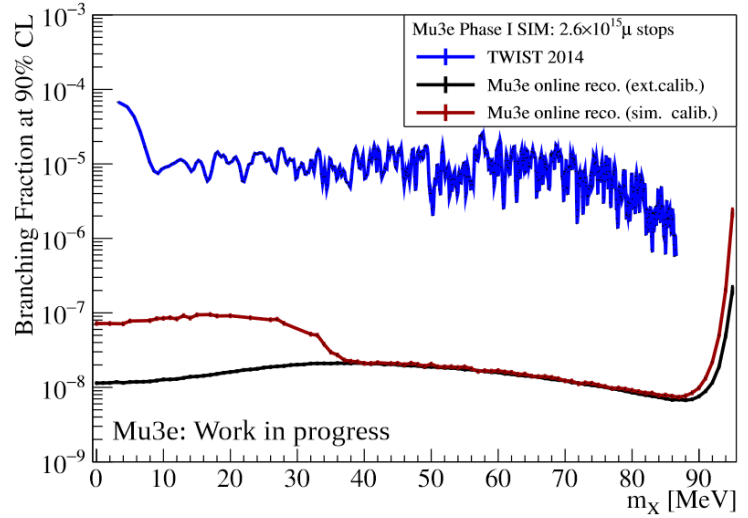
Potential other Physics Searches arXiv:1812.00741

- Resonance searches in $\mu^+ \to e^+ A'(e^- e^+)\nu\bar{\nu}$
  - Light dark photons
  - Kinetic mixing
  - Not background free
- LFV two-body decays
  - $\mu^+ \to e^+ X$
  - Monoenergetic e^+

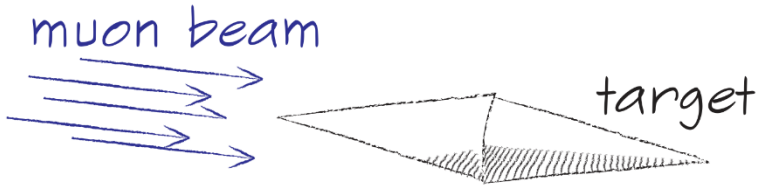








Inside 1 T magnetic field

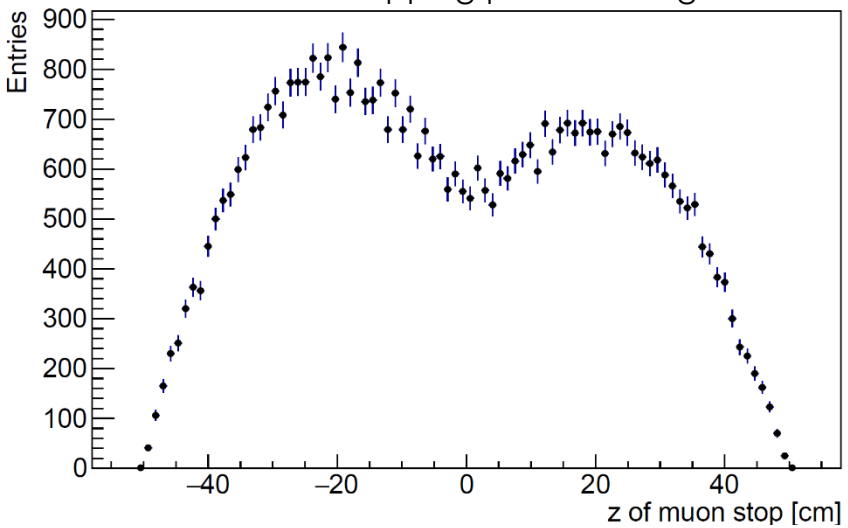


Mylar target

Front	70 μm
Back	80 μm
Length	100 mm
Radius	19 mm

Stopping target prototype

Simulation of stopping power of target



Simulation: reconstructed muon mass

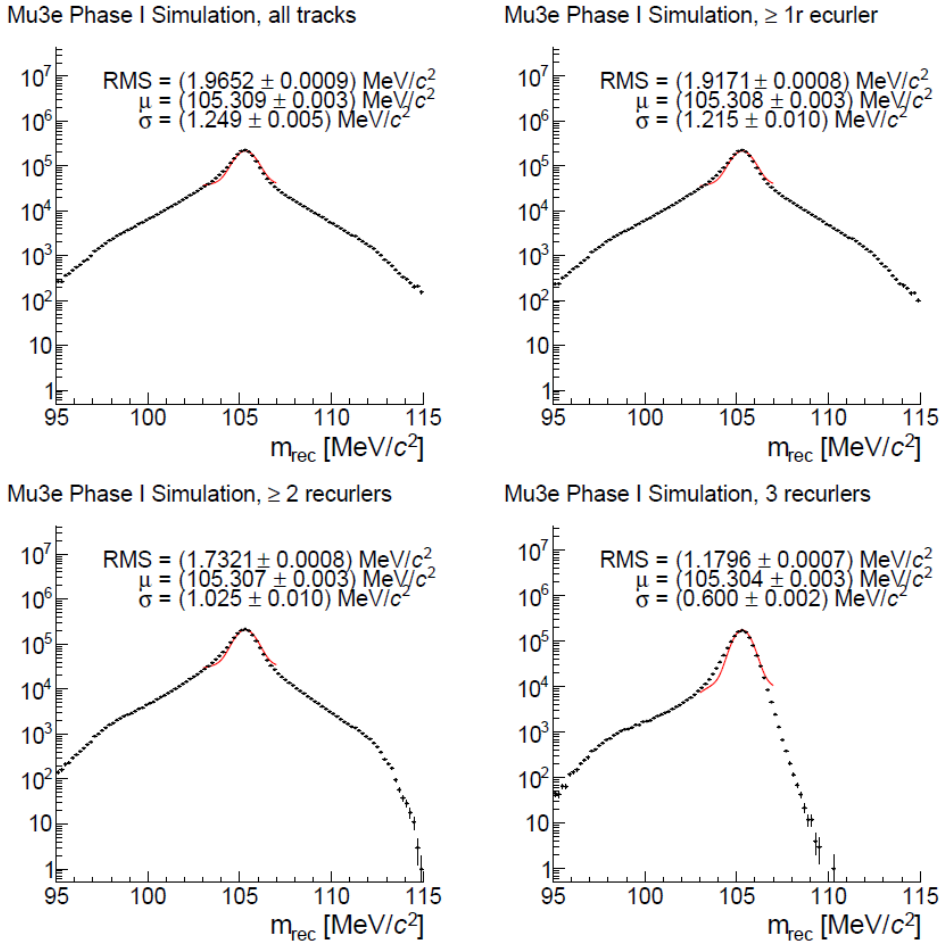


Figure 22.5: Reconstructed muon mass for all tracks (top left), at least one recurler (top right), at least two recurlers (bottom left) and three recurlers (bottom right). The fits are the sum of two Gaussian distributions and the quoted σ is the area-weighted mean; the main purpose of the fit is to guide the eye and highlight the non-symmetric resolution distribution.

Simulation: Efficiencies

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[1]	67.2%	17.4%
Vertex fit	99.4%	17.3%
Vertex fit $\chi^2 < 30$	97.6%	16.9%
CMS momentum $< 8\,\mathrm{MeV/c}$	97.6%	16.5%
Timing	90.0%	14.9%

Table 22.1: Efficiency of the various reconstruction and analysis steps.
[1]: Note that the efficiency of this step is quoted relative to the acceptance for long tracks.

Clock and Reset Distribution

- Phase stability requirement < 100 ps
  - Precise timing measurements
  - Synchronize all detectors
- Custom designed optical clock distribution system ready
  - Master clock generation
  - Electrical fanout to 288 optical copies
  - Connects to front-end boards