The Mu3e experiment

from concepts to construction

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Physikalisches Institut – Heidelberg University

SLAC FPD Seminar – December 1, 2020

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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)

Nuclear Physics B299 (1988) 1–6
North-Holland, Amsterdam

SEARCH FOR THE DECAY $\mu^+ \rightarrow e^+ e^+ e^-$

SINDRUM Collaboration

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Received 1 October 1987

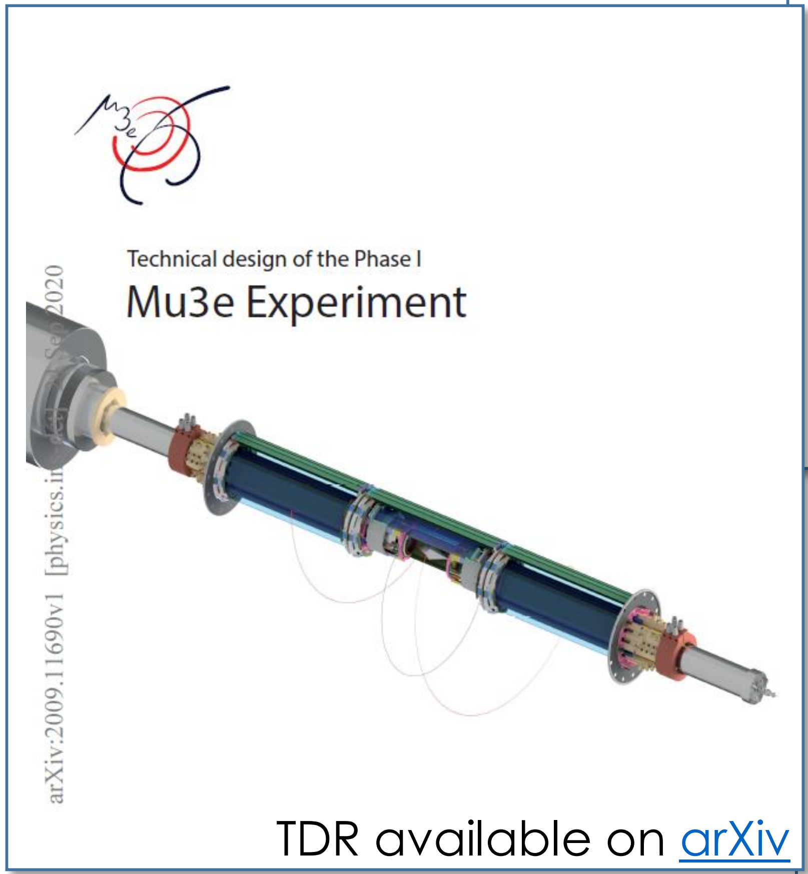
The search for the decay $\mu^+ \rightarrow e^+ e^+ e^-$ with the SINDRUM spectrometer has been continued. The result is a new upper limit for the branching ratio $B_{\mu \rightarrow 3e} = \Gamma(\mu \rightarrow 3e)/\Gamma(\mu \rightarrow e2\nu) < 1.0 \times 10^{-12}$ (90% CL).

The Goal of the Mu3e Experiment

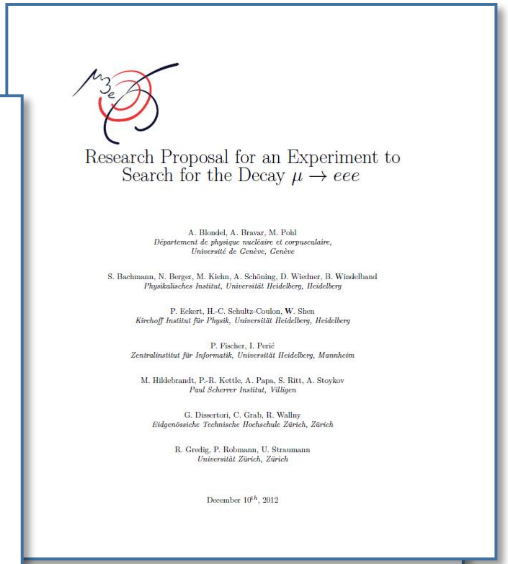
Current best limit on $\mu^+ \rightarrow e^+e^-e^+$

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

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



TDR available on arXiv



Research Proposal for an Experiment to Search for the Decay $\mu \rightarrow eee$

A. Blondel, A. Bravar, M. Pohl
Département de physique nucléaire et corpusculaire, Université de Genève, Genève

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Paul Scherrer Institut, Villigen

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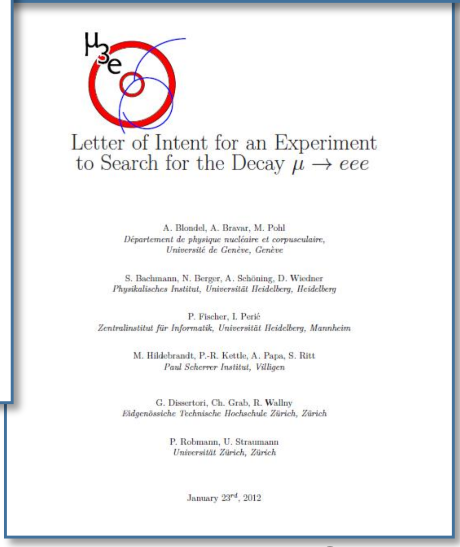
R. Gredig, P. Robmann, U. Straumann
Universität Zürich, Zürich

December 10^{th}, 2012



Letter of Intent for an Experiment to Search for the Decay $\mu \rightarrow eee$

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Eidgenössiche Technische Hochschule Zürich, Zürich

P. Robmann, U. Straumann
Universität Zürich, Zürich

January 23^{rd}, 2012

Why to search for $\mu^+ \to e^+e^-e^+$

Tensions in Lepton Physics

Muon anomalous magnetic moment

$$a_\mu = \frac{g_\mu - 2}{2}$$

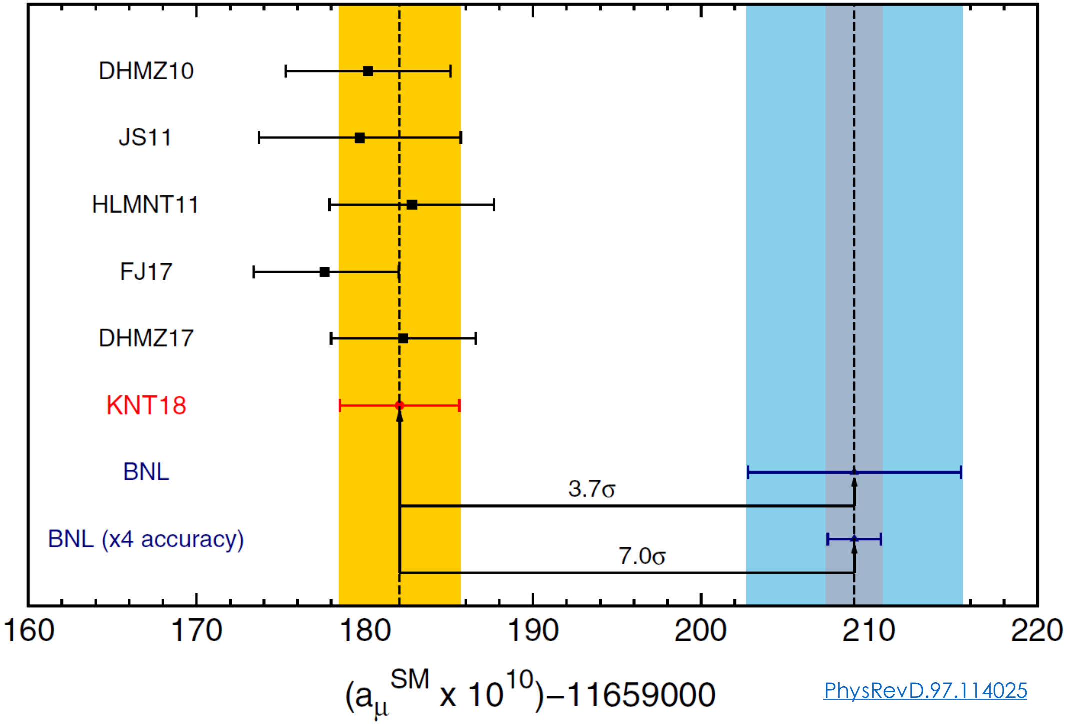
Calculated to fantastic precision

$$a_\mu^{SM} = (11659182.04 \pm 3.56) \times 10^{-10}$$

Tension $\updownarrow$ $> \mathbf{3\sigma}$

$$a_\mu^{exp} = (11659209.1 \pm 5.4 \pm 3.3) \times 10^{-10}$$

And measured to fantastic precision!

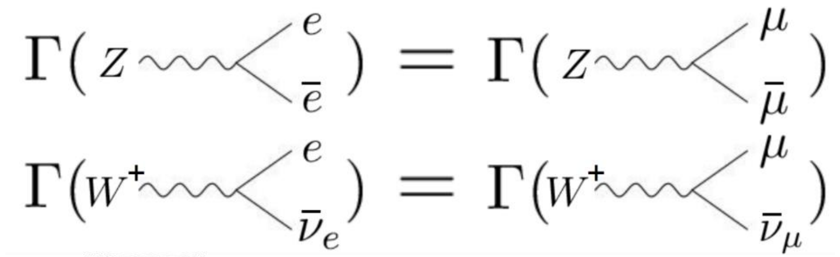


PhysRevD.97.114025

New Physics could be involved...

Tensions in Lepton Physics

Lepton Flavour Universality Violation?



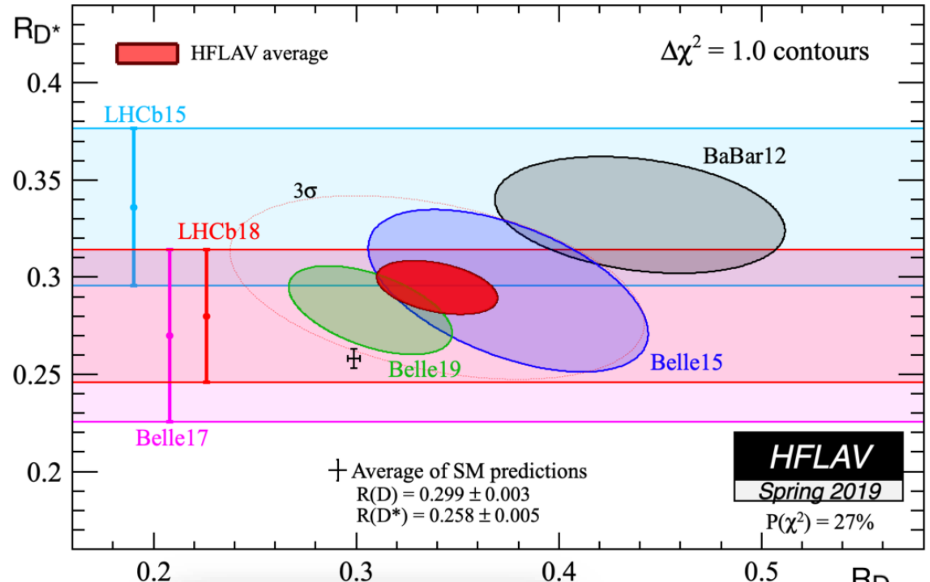
B-meson decays that only differ in final lepton content

$$R_{X^{(*)}} = \frac{BR(B \to X^{(*)} ll/l\nu)}{BR(B \to X^{(*)} l'l'/l'\nu')}$$

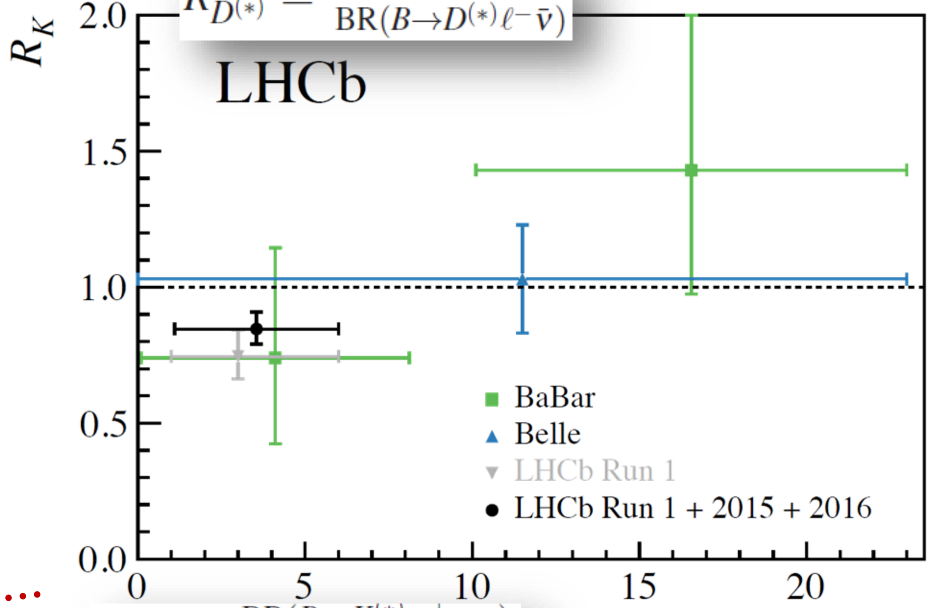
$\mathbf{2.5 - 3\sigma}$ **tension** between measurements and SM predictions

New Physics could be involved...

https://hflav-eos.web.cern.ch/hflav-eos/semi/spring19/html/RDsDsstar/RDRDs.html



$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau^-\bar{\nu})}{BR(B \to D^{(*)}\ell^-\bar{\nu})}$$



$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu^+\mu^-)}{BR(B \to K^{(*)}e^+e^-)}$$

CERN-ESU-004

https://cds.cern.ch/record/2668514/files/LHCb-PAPER-2019-009.pdf

Lepton Flavour Symmetry in the SM

No right-handed neutrinos

↕

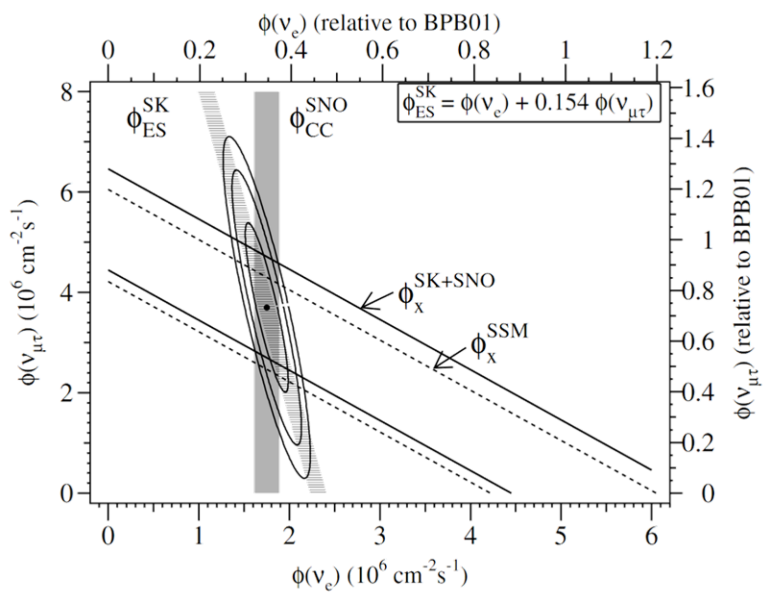
Neutrinos are massless

Lepton flavor *is an* ***exact symmetry*** *and*
conserved *in the Standard Model*

… at least that's what we thought in the early days of the SM

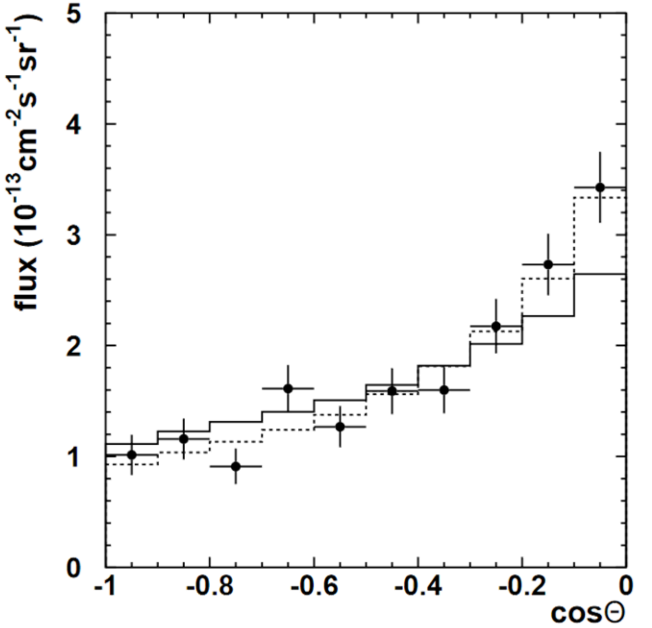
But wait – Neutrinos mix!

Solar neutrinos
Dissapearance of electron neutrinos



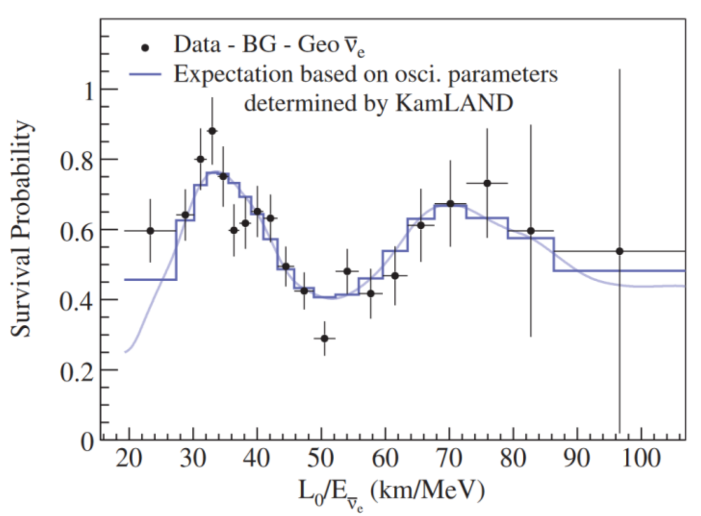
Q. R. Ahmad *et al.* (SNO Collaboration)
Phys. Rev. Lett. 87, 071301

Zenith angle dependence in atmospheric neutrinos



Y. Fukuda *et al.* (Super-Kamiokande Collaboration)
Phys. Rev. Lett. 82, 2644

Oscillations in reactor anti-neutrinos



S. Abe et al. (The KamLAND Collaboration).
Phys. Rev. Lett. 100, 221803.

And since then: many more precise measurements!

There has to be some sort of New Physics involved!

Lepton Flavour Symmetry in the SM

No right-handed neutrinos**?**

↕

Neutrinos are **not** massless

Lepton flavor *is* ***not*** *an* ***exact symmetry*** *and*
not conserved *in the Standard Model*

Charged Lepton Flavour Violation

Include neutrino mixing in the SM*

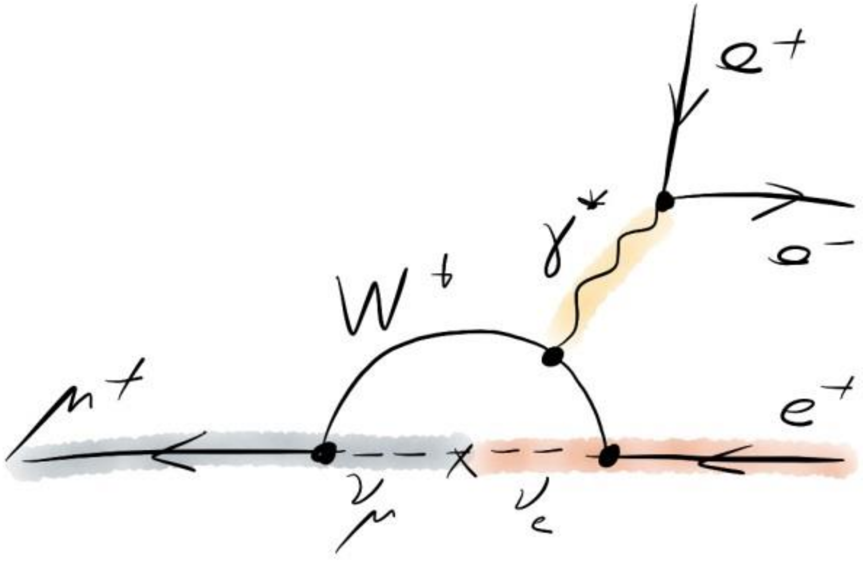
cLFV in general possible

BUT

Highly suppressed branching ratio

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

Increased by many New Physics models!



* without specifying origin of neutrino mass

Charged Lepton Flavour Violation

Include neutrino mixing in the SM*

cLFV in general possible

BUT

Highly su... ratio

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

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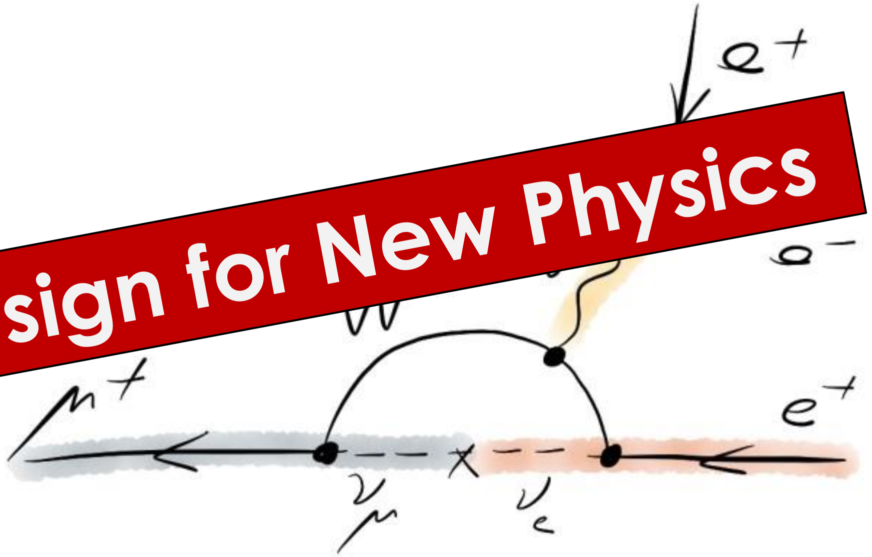
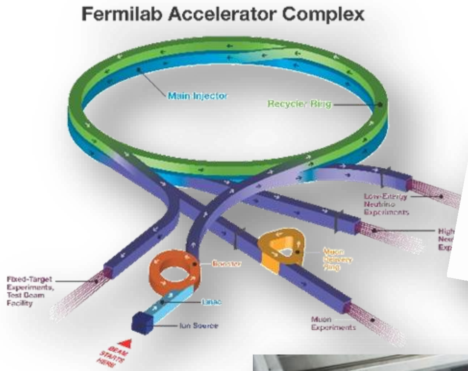


So if we observe cLFV → clear sign for New Physics

* without specifying origin of neutrino mass

Tests of cLFV

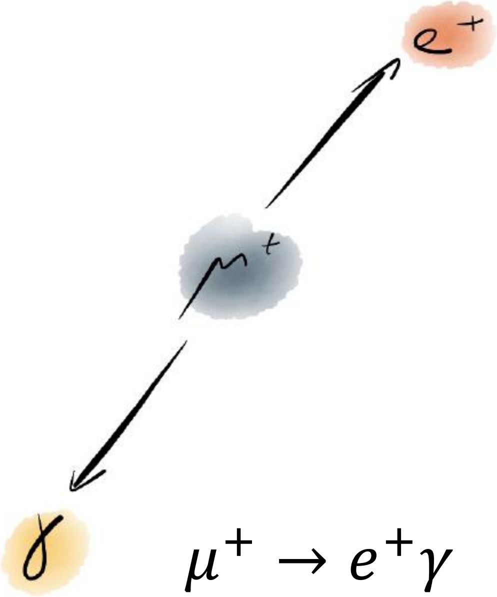



ACCELERATORS | NEWS
Muons accelerated in Japan
9 July 2018

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

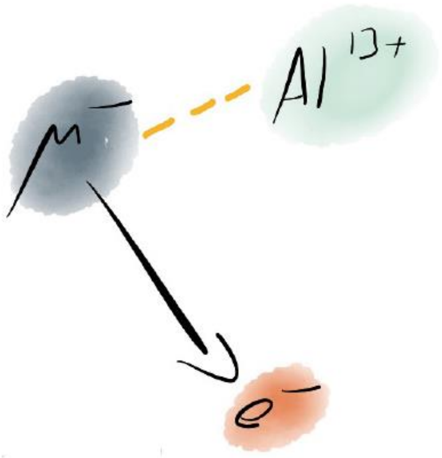
Golden Muon Decay Channels



$\mu^+ \rightarrow e^+\gamma$

MEG (PSI)

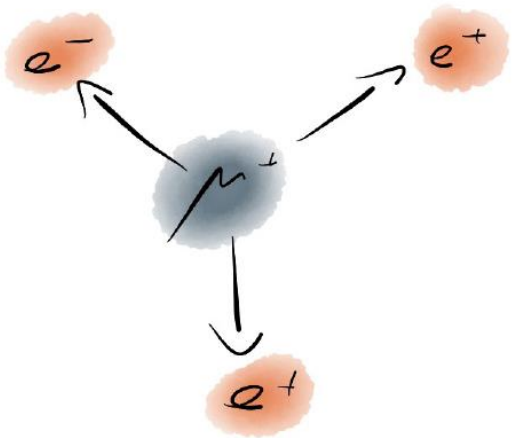
$\mathrm{BR} < 4.2 \times 10^{-13}$



$\mu^- N \rightarrow e^- N$

SINDRUM II (PSI)

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

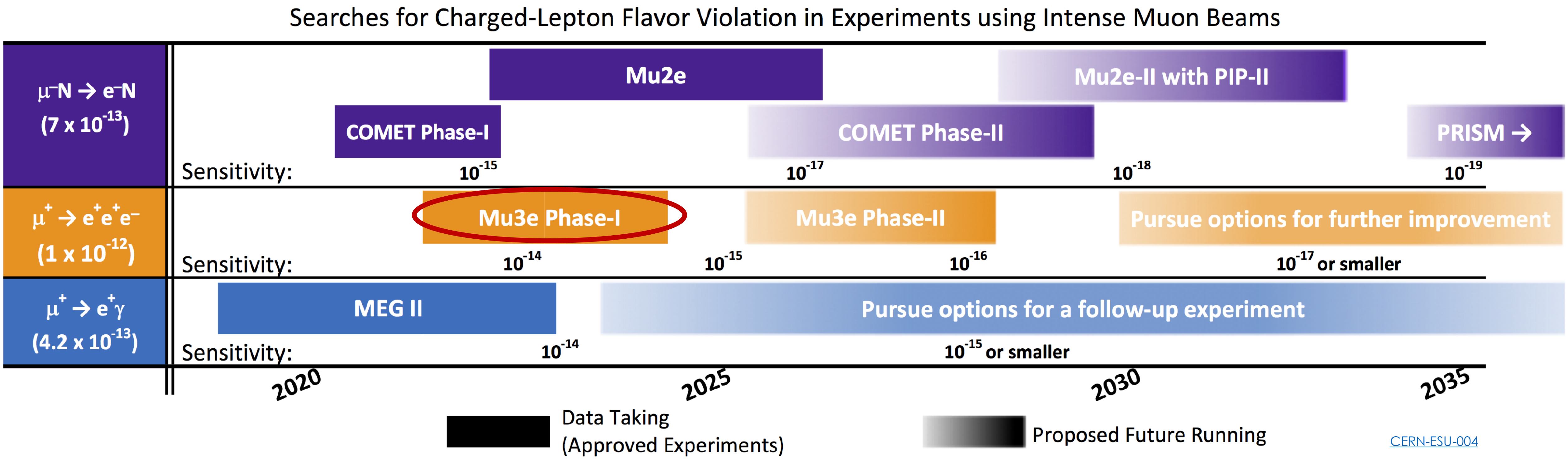


$\mu^+ \rightarrow e^+e^-e^+$

SINDRUM (PSI)

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

Timeline of Muon cLFV Searches

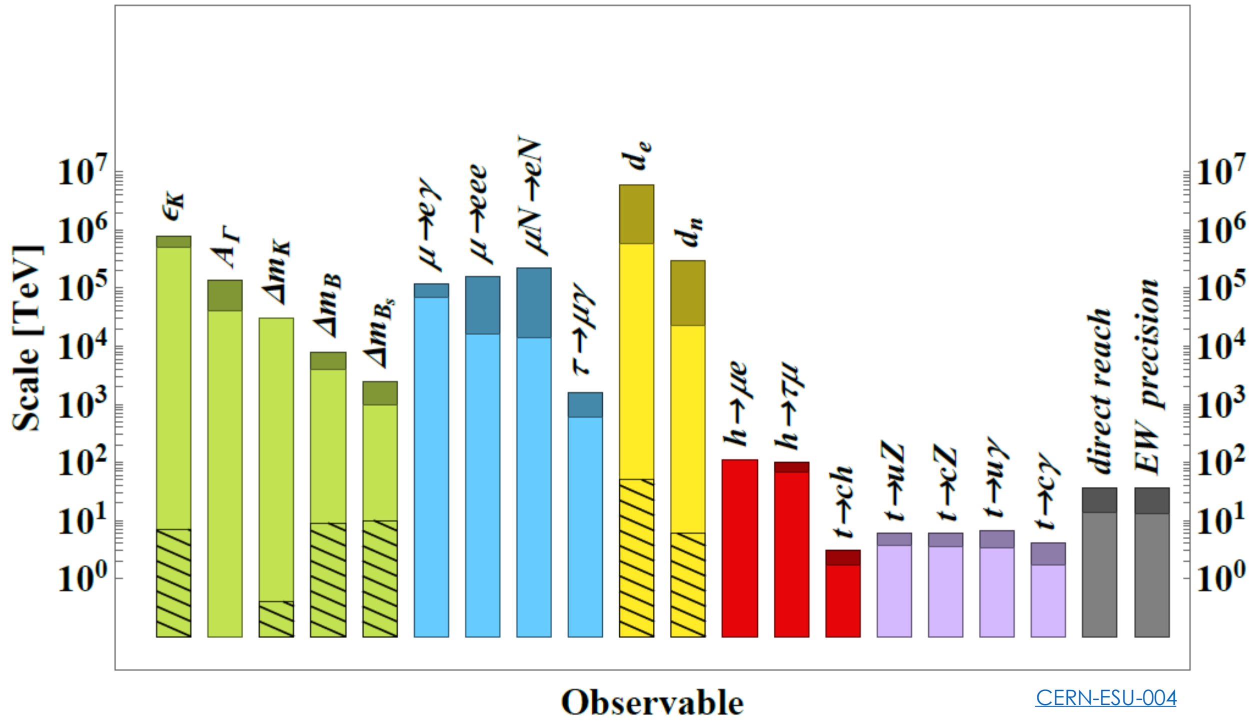


Senstivity of Muon cLFV Searches

- Extremely high mass scales
- Model-independent effective Lagrangian

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

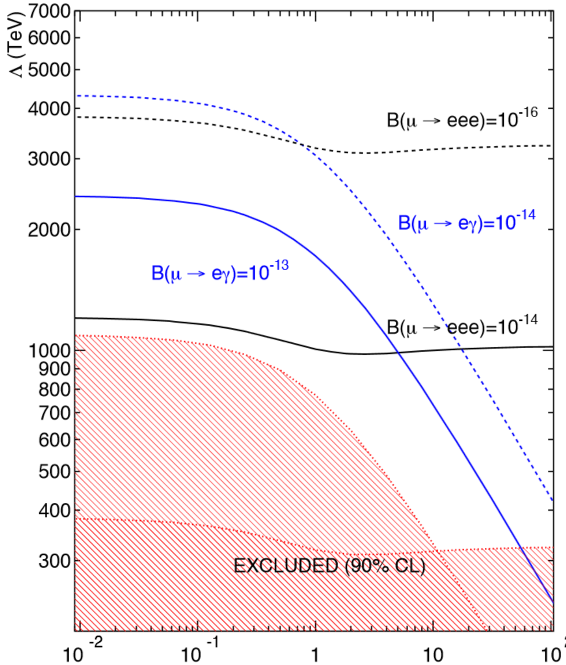
$\mathcal{O}_a^6$ encodes new particles with generic mass scale Λ



CERN-ESU-004

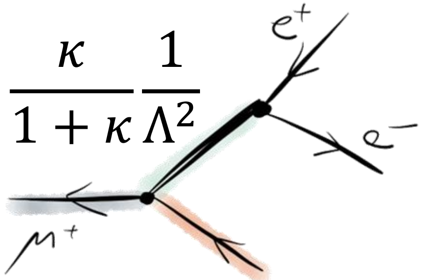
Complementarity

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

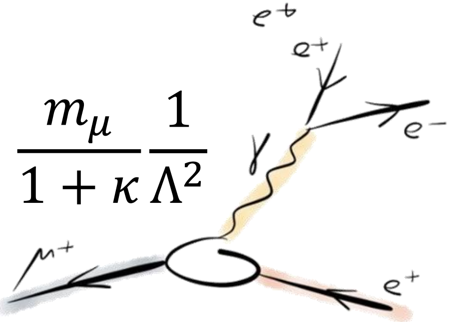


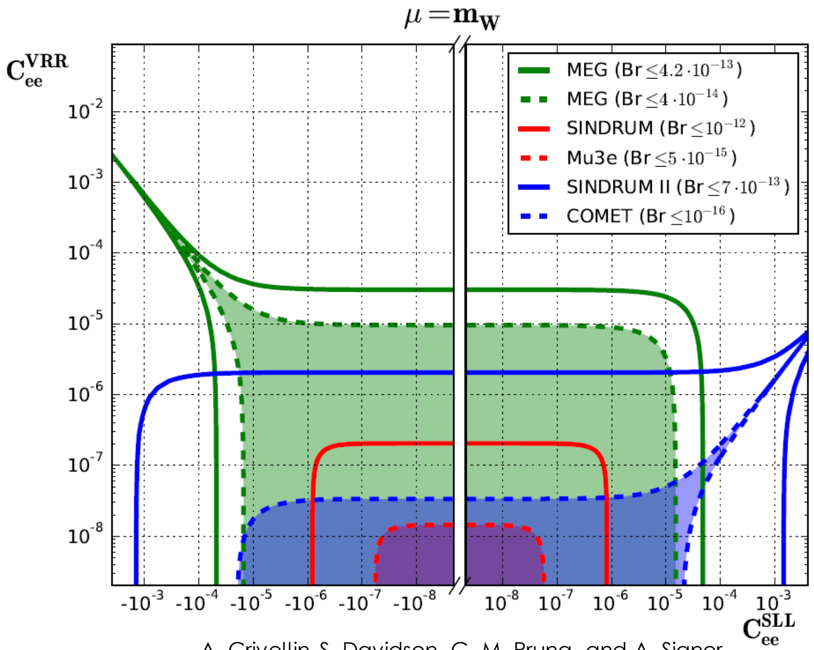
André de Gouvêa, Petr Vogel. "Lepton flavor and number conservation, and physics beyond the standard model". Progress in Particle and Nuclear Physics, 71 (2013) 75-9.

$$\frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}$$



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





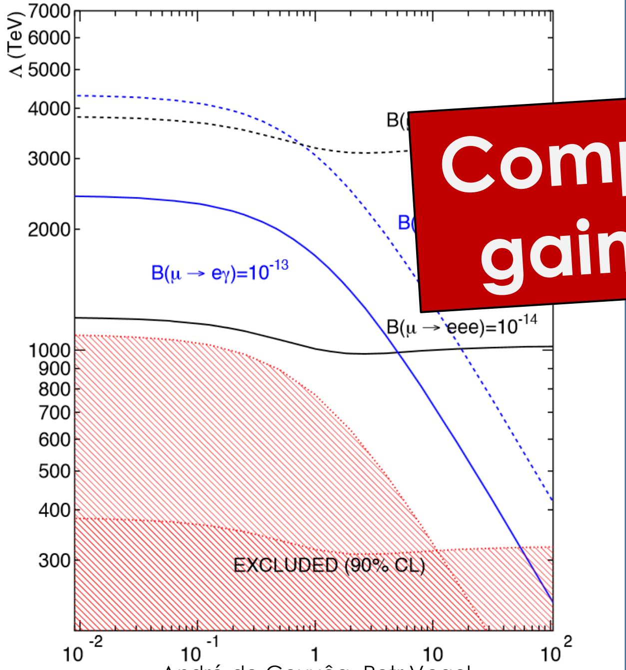
A. Crivellin, S. Davidson, G. M. Pruna, and A. Signer. "Renormalisation-group improved analysis of μ → e processes in a systematic effective-field-theory approach". JHEP05(2017), p. 117.DOI:10.1007/JHEP05(2017)117. arXiv:1702.03020 [hep-ph].

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	$\approx 6 \times 10^{-3}$	$10^{-3} - 10^{-2}$
Type-I seesaw	Loop	Loop	$3 \times 10^{-3} - 0.3$	$0.1 - 10$
Type-II seesaw	Tree	Loop	$(0.1 - 3) \times 10^{3}$	$\mathcal{O}(10^{-2})$
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	$0.05 - 0.5$	$2 - 20$

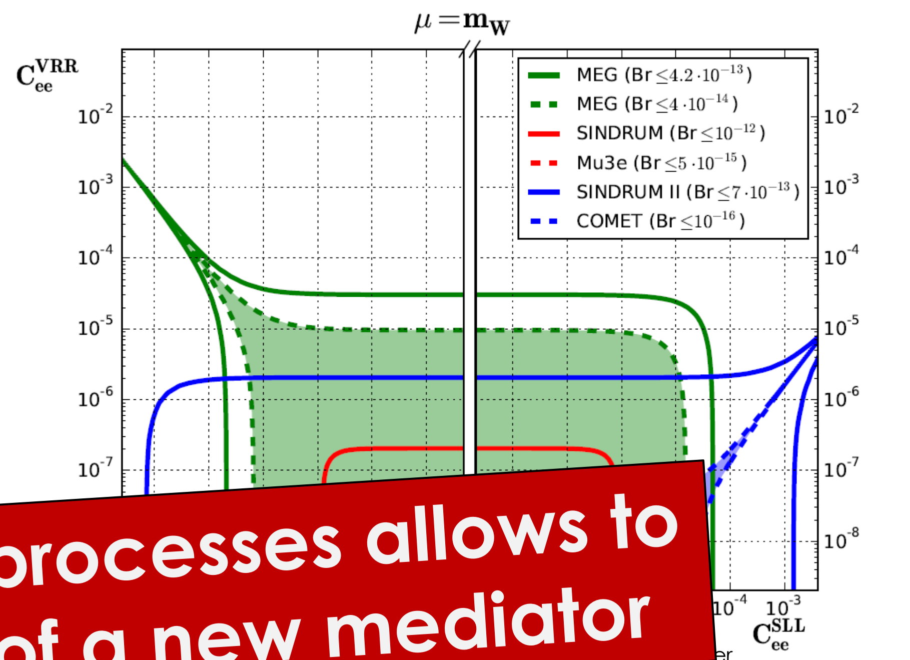
L. Calibbi, G. Signorelli, arXiv:1709.00294
Ana M. Teixeira, PoS(NuFact2019)016

Complementarity

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

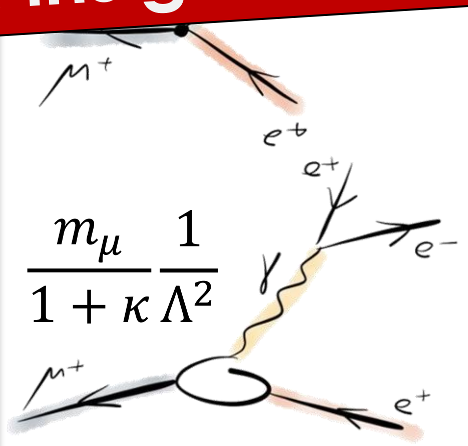


André de Gouvêa, Petr Vogel. "Lepton flavor and number conservation, and physics beyond the standard model". Progress in Particle and Nuclear Physics, 71 (2013) 75-9.



...er. ...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].

Comparison of different processes allows to gain insight into nature of a new mediator



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

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	$3\times10^{-3}-0.3$	$0.1-10$
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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

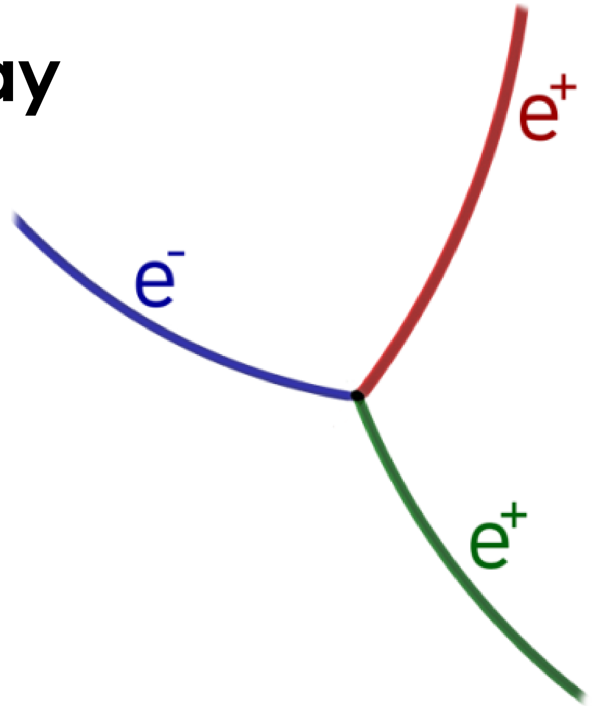
The Experimental Concept

The Signal Decay

Muons are stopped before decay

Experimental Signature

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

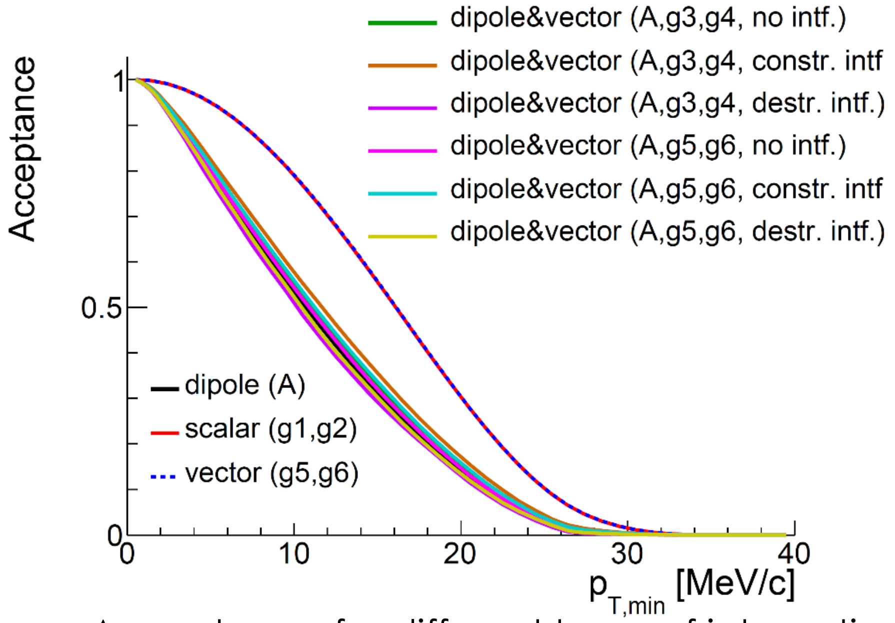


Signal Modelling

- 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!

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

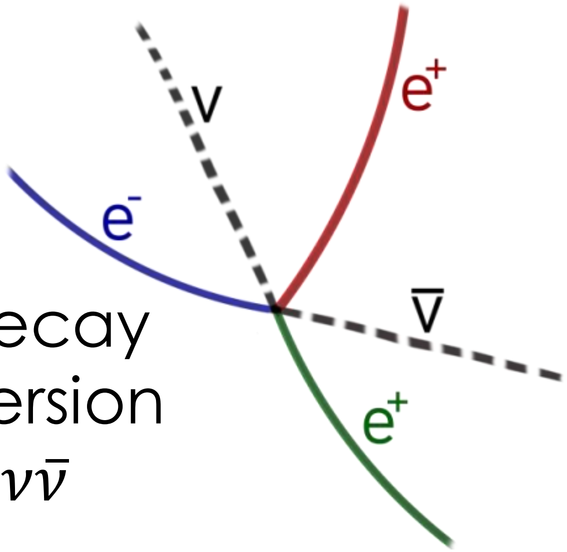
Parametrised Lagrangian by Kuno and Okada



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

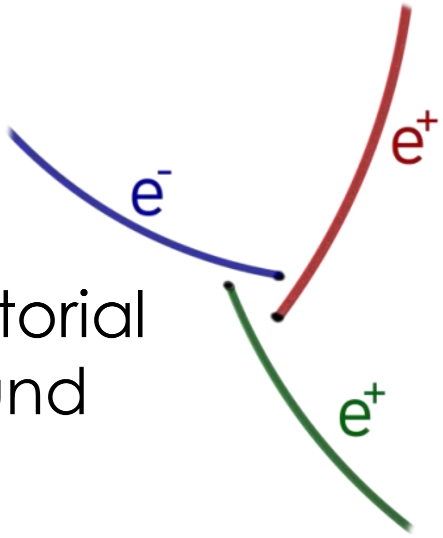
Main Sources of Background

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



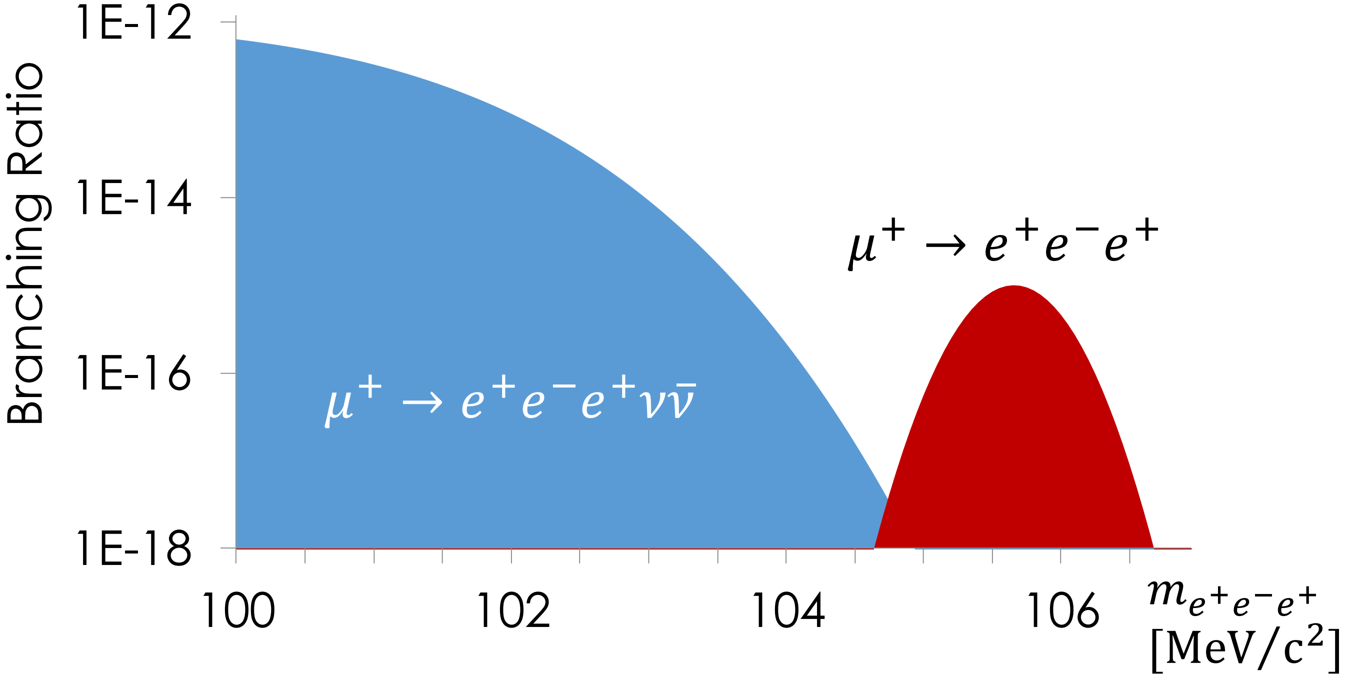
Experimental Signature
- Common vertex
- Time coincident
- $\sum \vec{p} \neq 0$
- $\sum E \neq m_\mu$

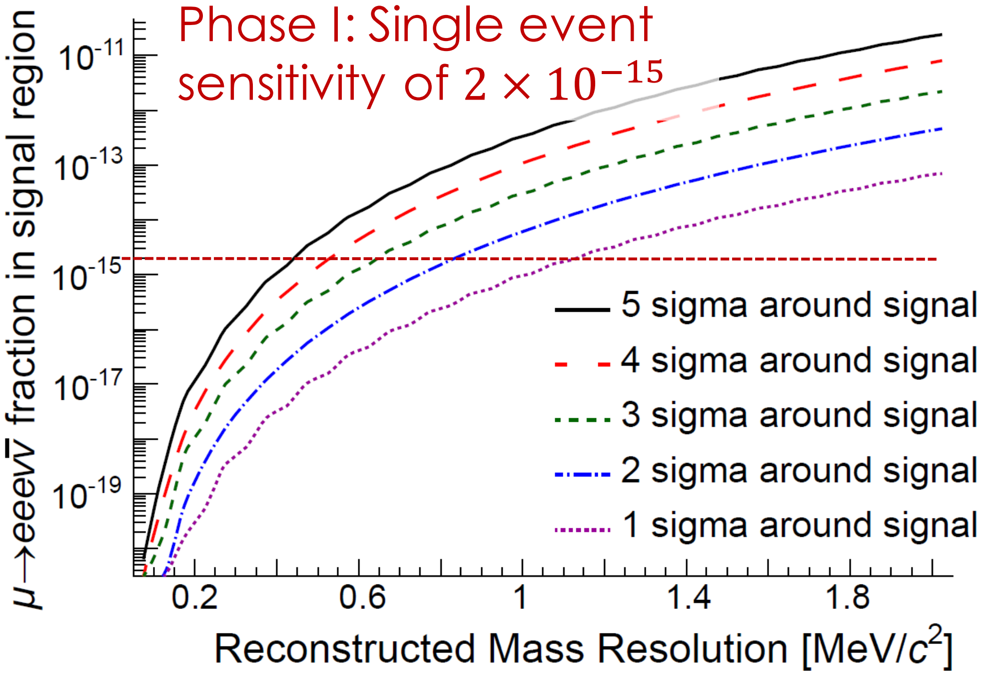
Combinatorial
background



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

Momentum Resolution Requirement

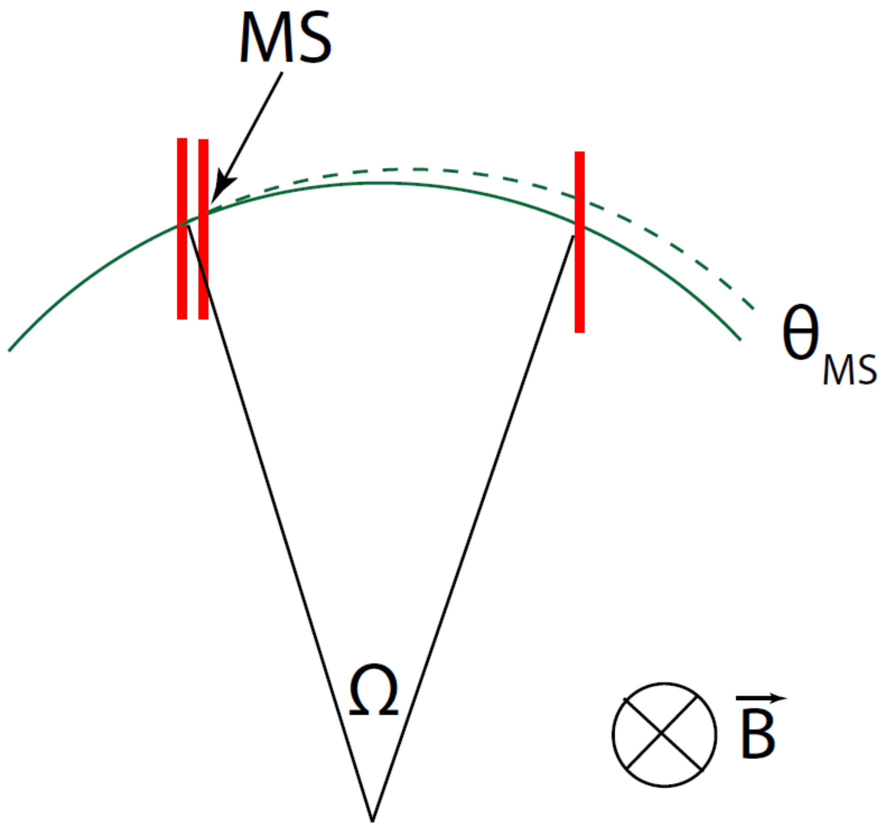




- Distinguish signal and background: missing momentum
- Requires excellent average momentum resolution $\sigma_p < 1.0\ \mathrm{MeV/c}$

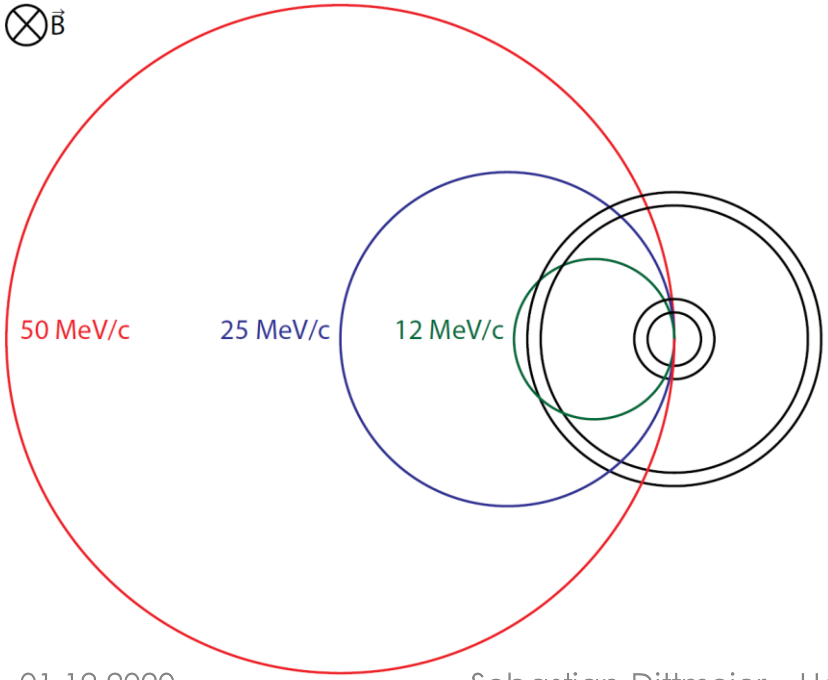
Momentum Measurement

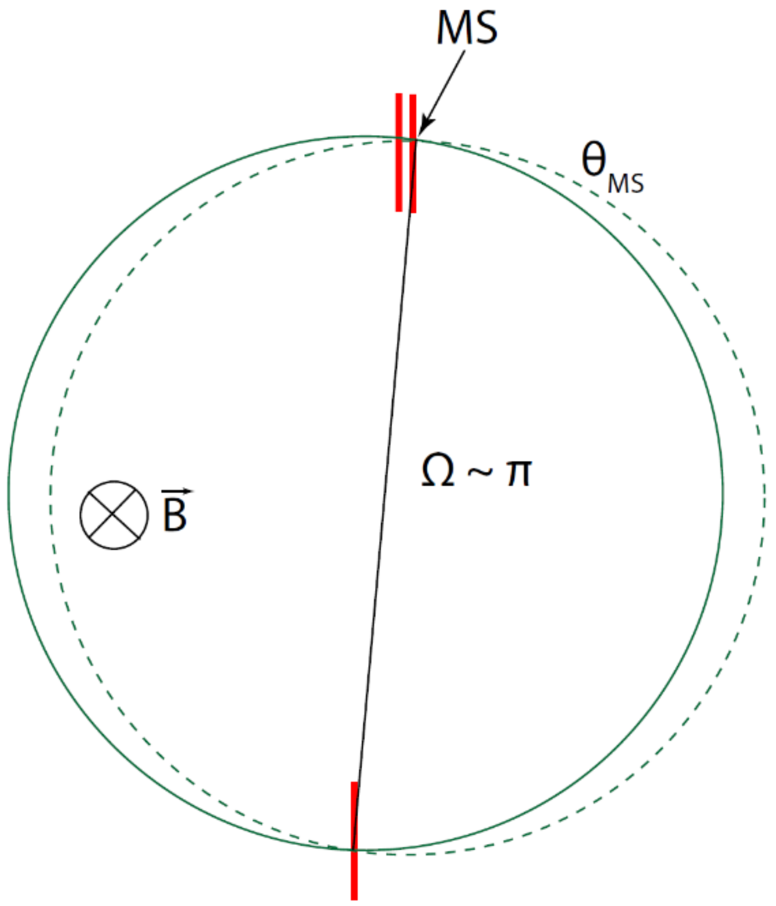
- Stopped muons
  → **low momentum e^-e^+**
- Momentum resolution limited by **multiple scattering** $\sigma_p/p \propto \theta_{MS}/\Omega$
- Advantageous
  - Large lever arm Ω
  - Low multiple scattering θ_{MS}
  - ➢ Material budget $\leq$ **1‰** X_0 per layer



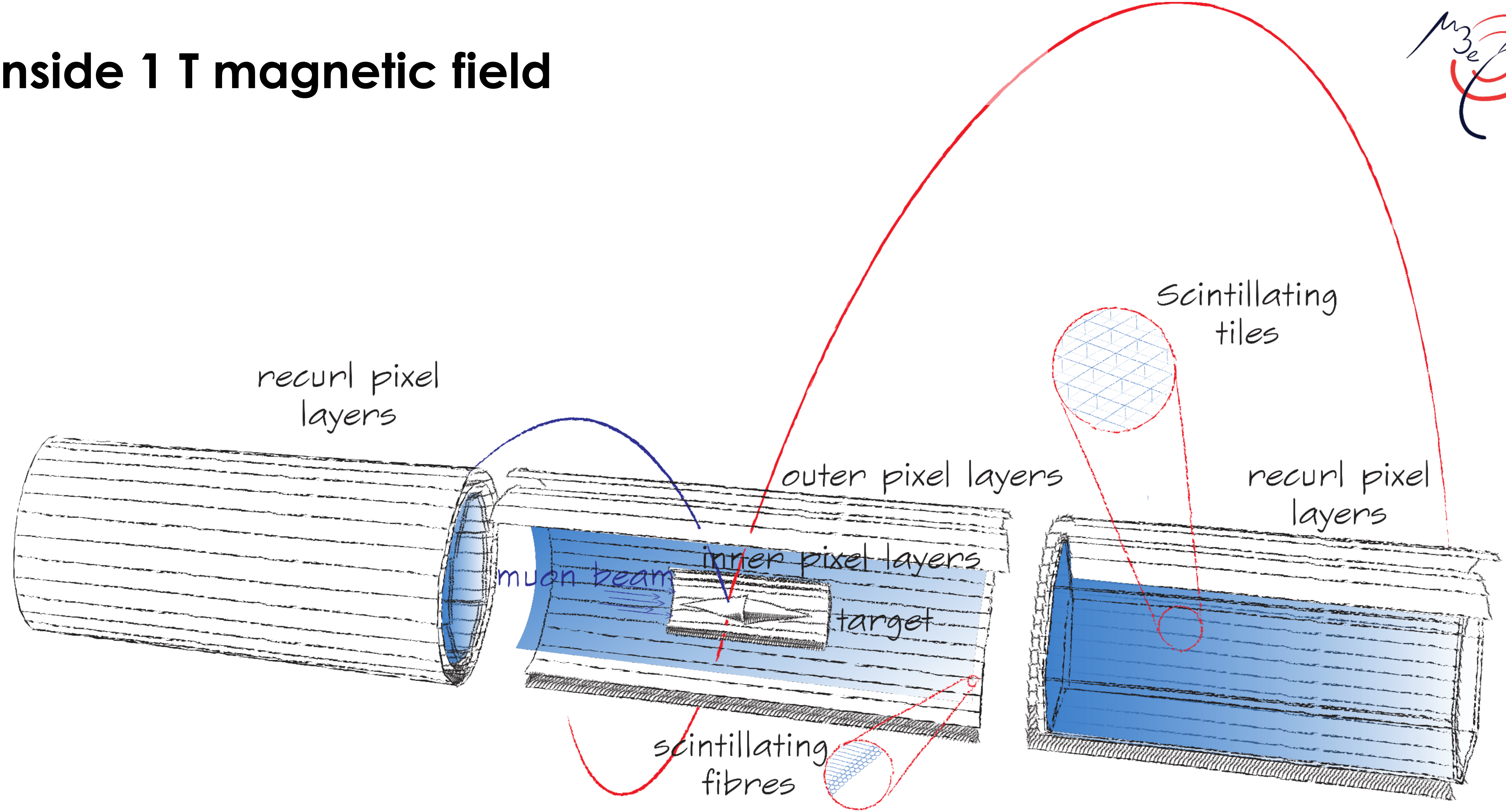
Enhancing Momentum Measurement

- Allow particles to **recurl** into the detector
- Multiple scattering **uncertainty cancels** to first order for a half-turn



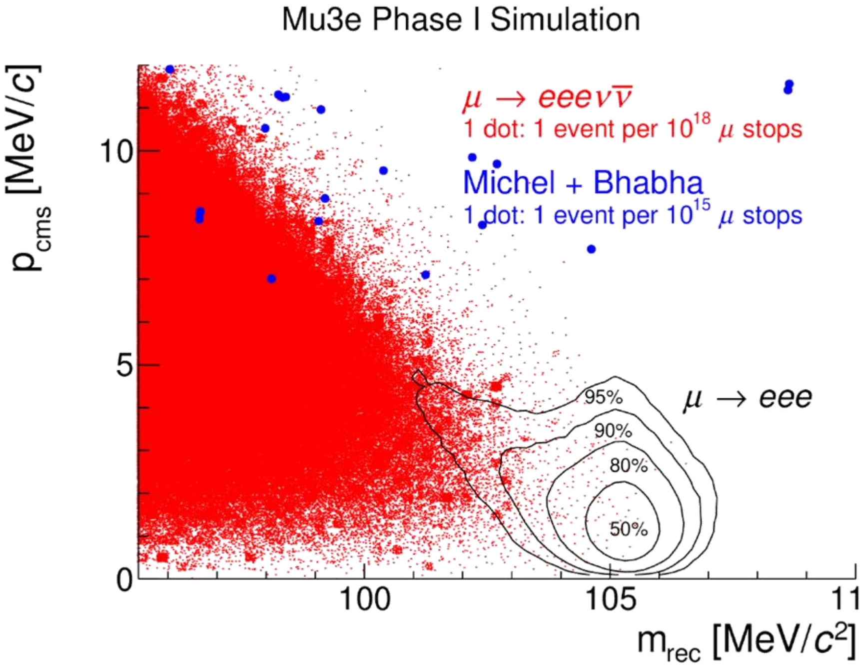


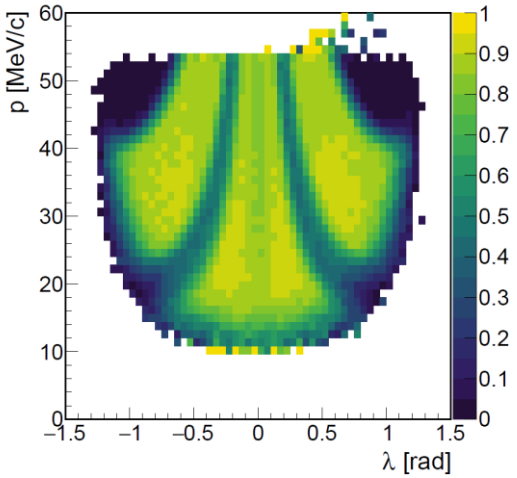
Inside 1 T magnetic field



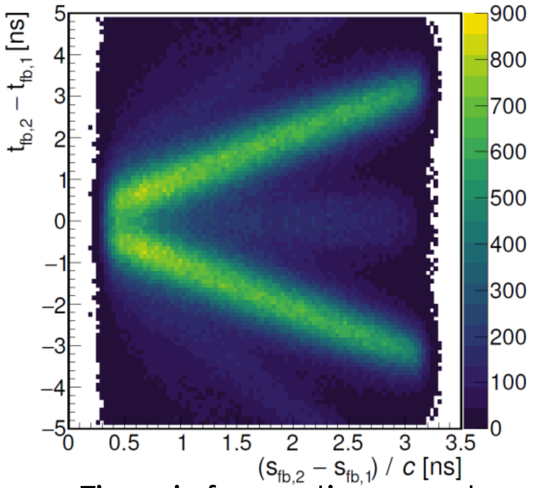
Detector Simulation and Performance

- Geant4 based detector simulation
- Track reconstruction relying on MS-fit (triplet fit [arXiv:1606.04990](https://arxiv.org/abs/1606.04990))

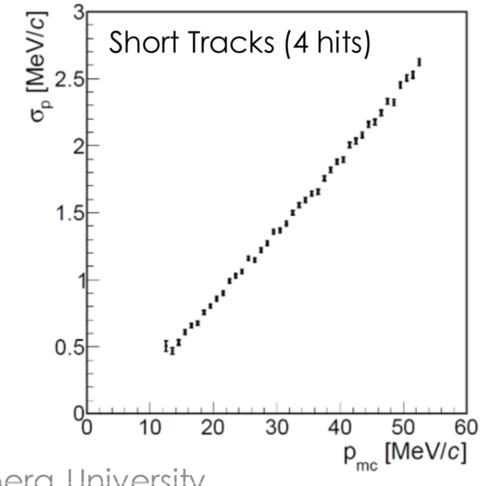


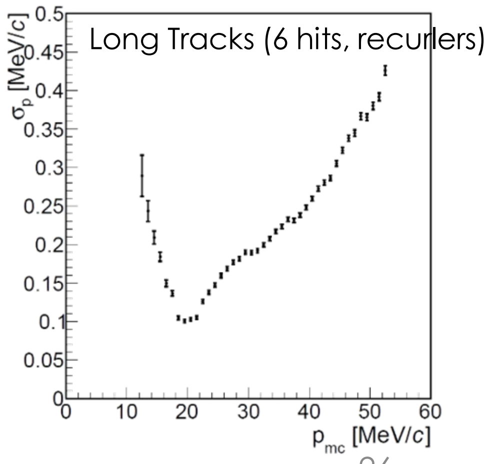


Ratio of reconstructed long vs short tracks

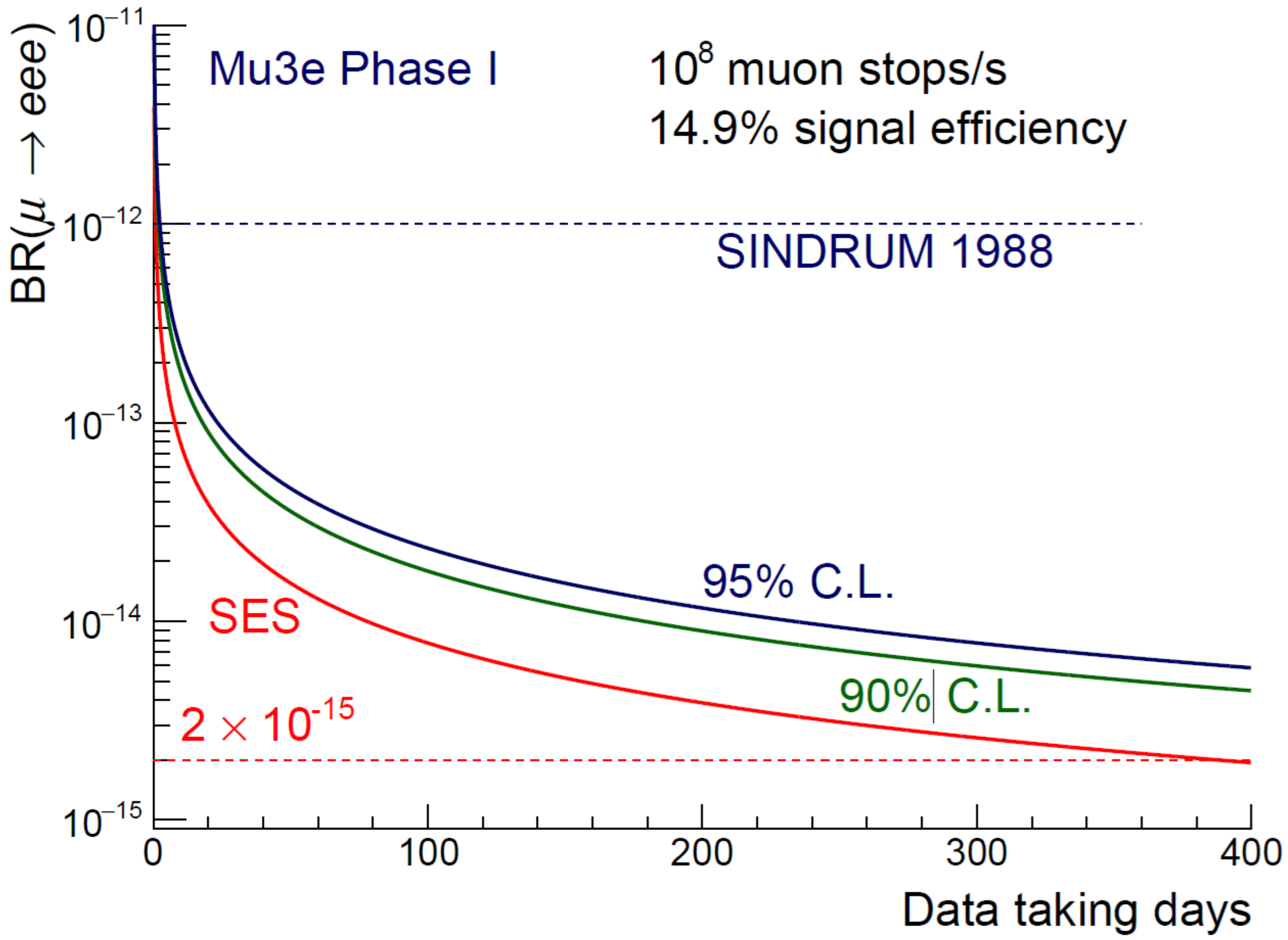


Time information used for charge assignment



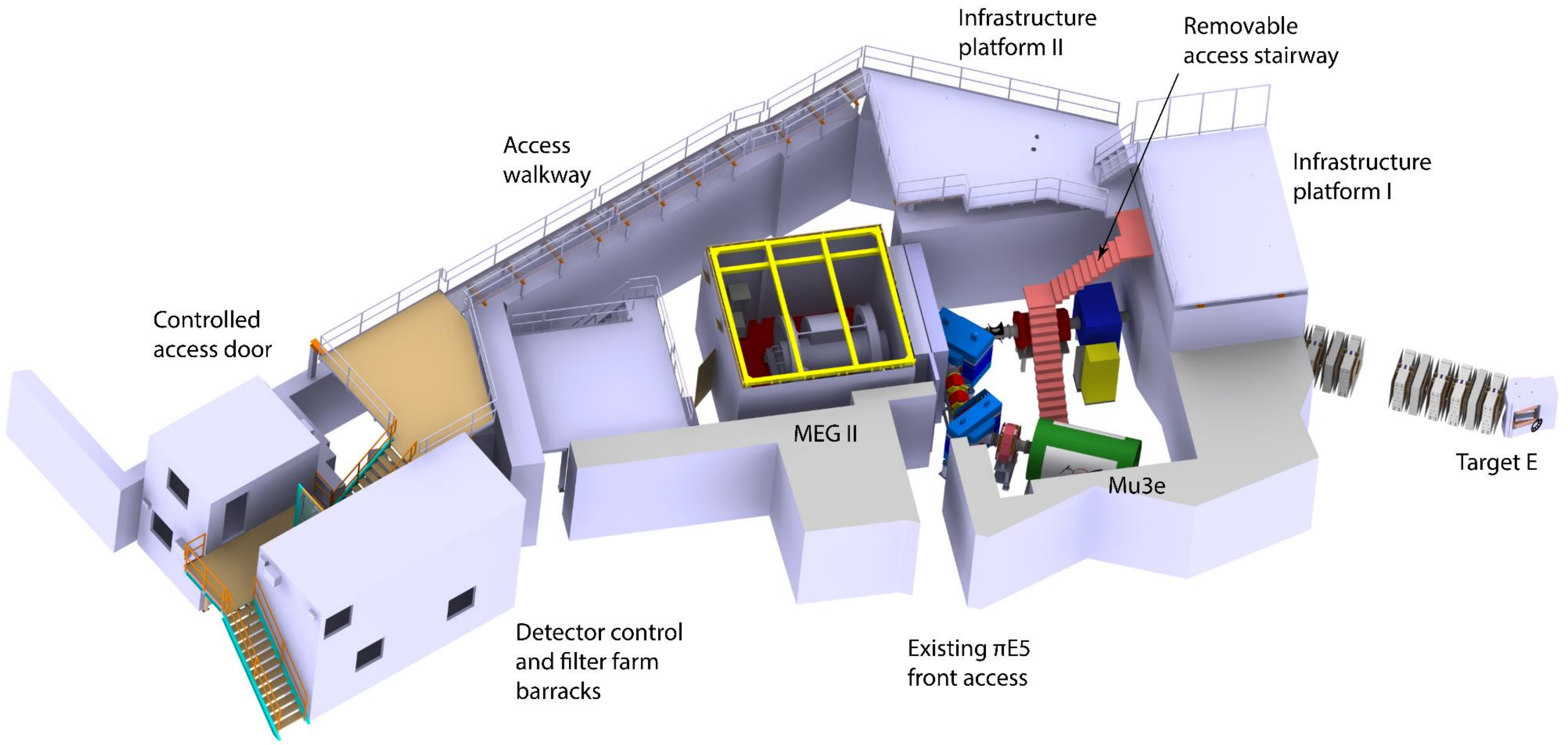


Expected Sensitivity Mu3e Phase I



Experimental Infrastructure

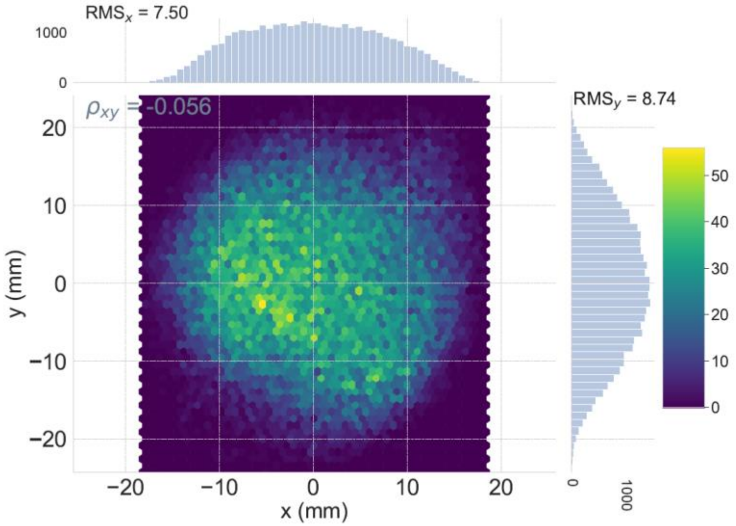
Experimental Area @ PSI



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: 2×10^{-15}
- Phase II: $\mathcal{O}(10^9\ s^{-1})$
  - High Intensity Muon Beamline
  - Under investigation
  - Sensitivity goal: $\mathcal{O}(10^{-16})$

Commissioned CMBL in place @ PSI



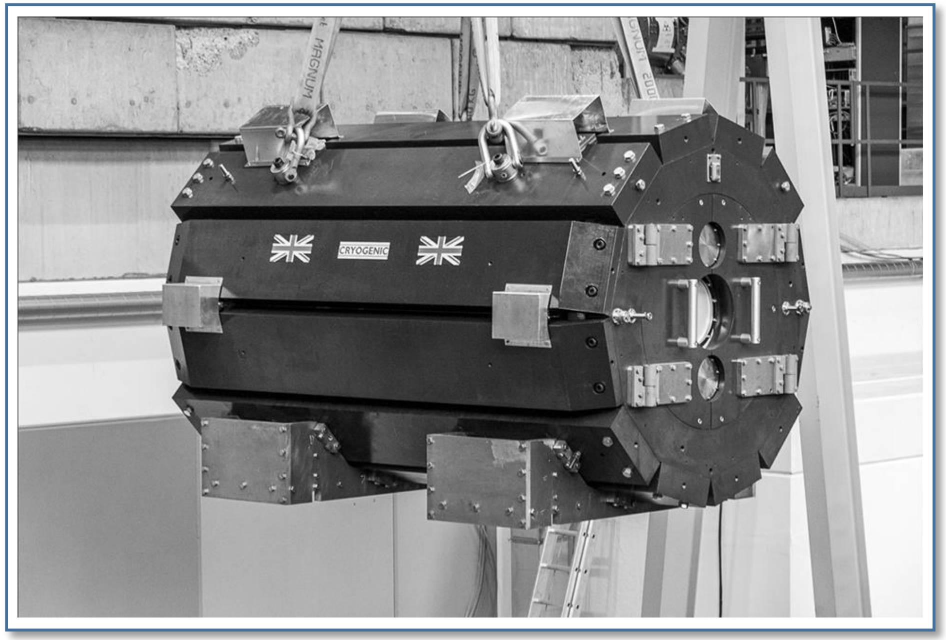
Expected beam spot profile at the Mu3e target position

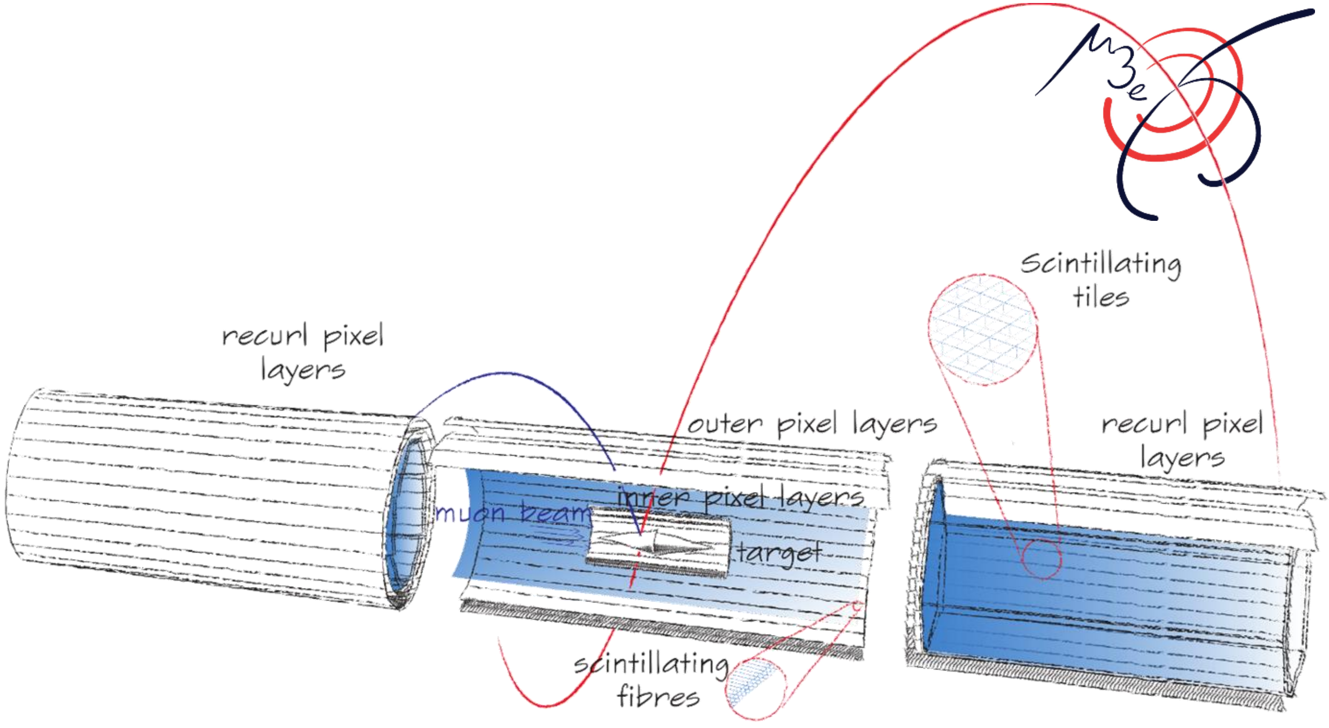
The Mu3e Solenoid

- Produced by Cryogenic Ltd. and delivered to PSI in July 2020
- Nominal magnetic field for experiment 1.0 Tesla (range 0.5 – 2.0 Tesla)
- Very homogeneous magnetic field

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

- November 2020:
  successfully ramped up at PSI to 1 Tesla



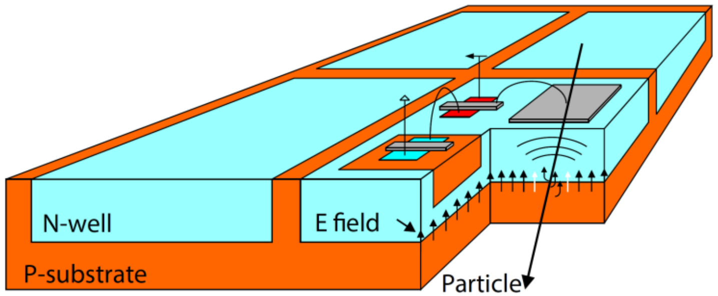


The Pixel Tracking Detector

The Mu3e Pixel Sensors – **MuPix**

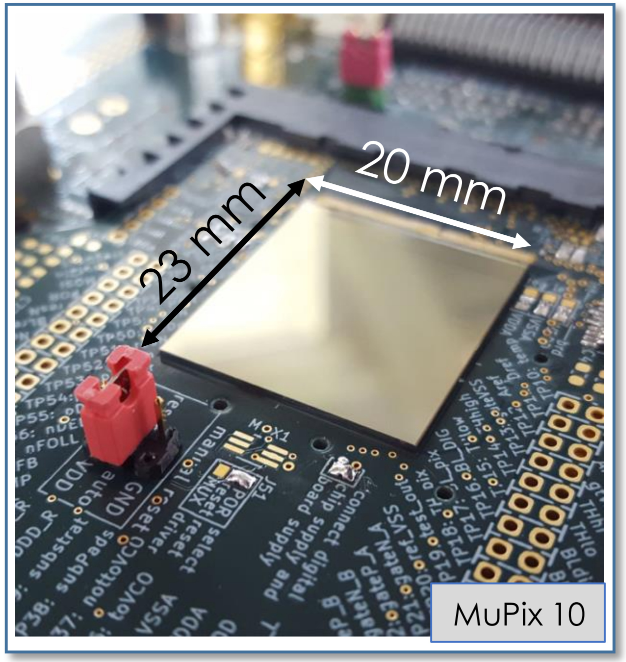
- High-Voltage Monolithic Active Pixel Sensors
- Produced in 180 nm **HV-CMOS** technology
- **Fast** charge collection via drift
- **Fully integrated** digital readout
- Can be **thinned** to 50 $\mu m \sim 0.5$ ‰ X_0

Mu3e requirements	
Efficiency	≥ 99 %
Time resolution	≤ 20 ns



I.Perić, NIM A 582 (2007) 876

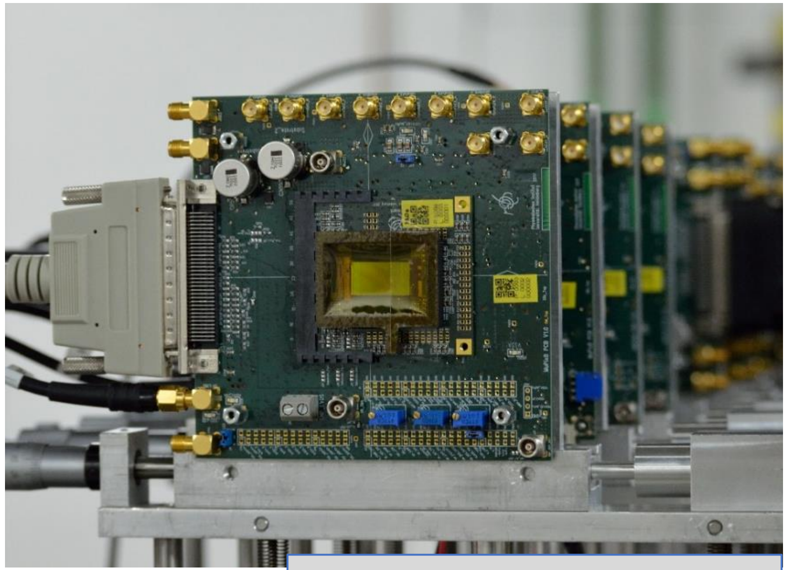

MuPix 8



MuPix 10

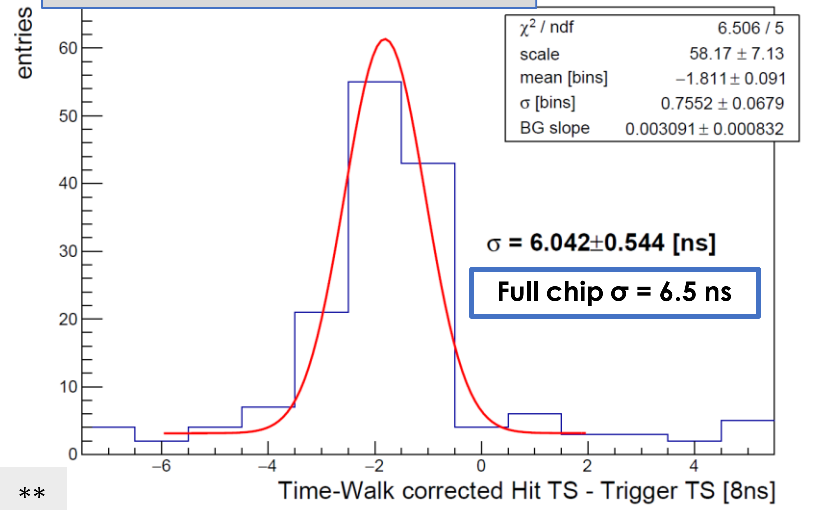
Selected **MuPix8** Results

- Extensive lab + test beam characterization: Efficiency, timing, rate capability, irradiation, ...
- Fullfils Mu3e requirements



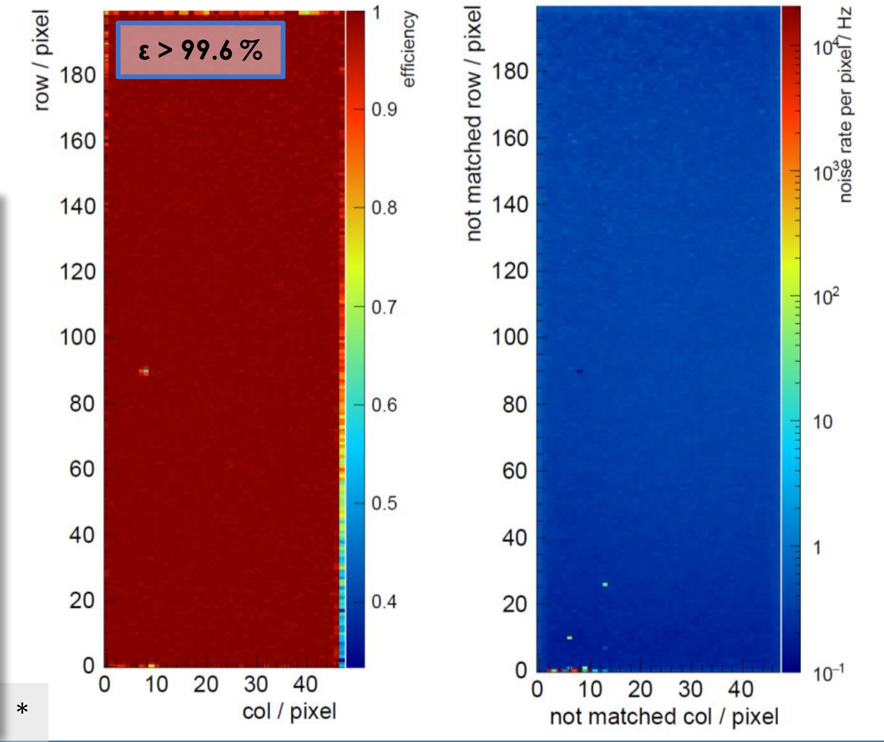
MuPix 8 beam telescope

Single pixel time resolution obtained with Sr-90 source



**

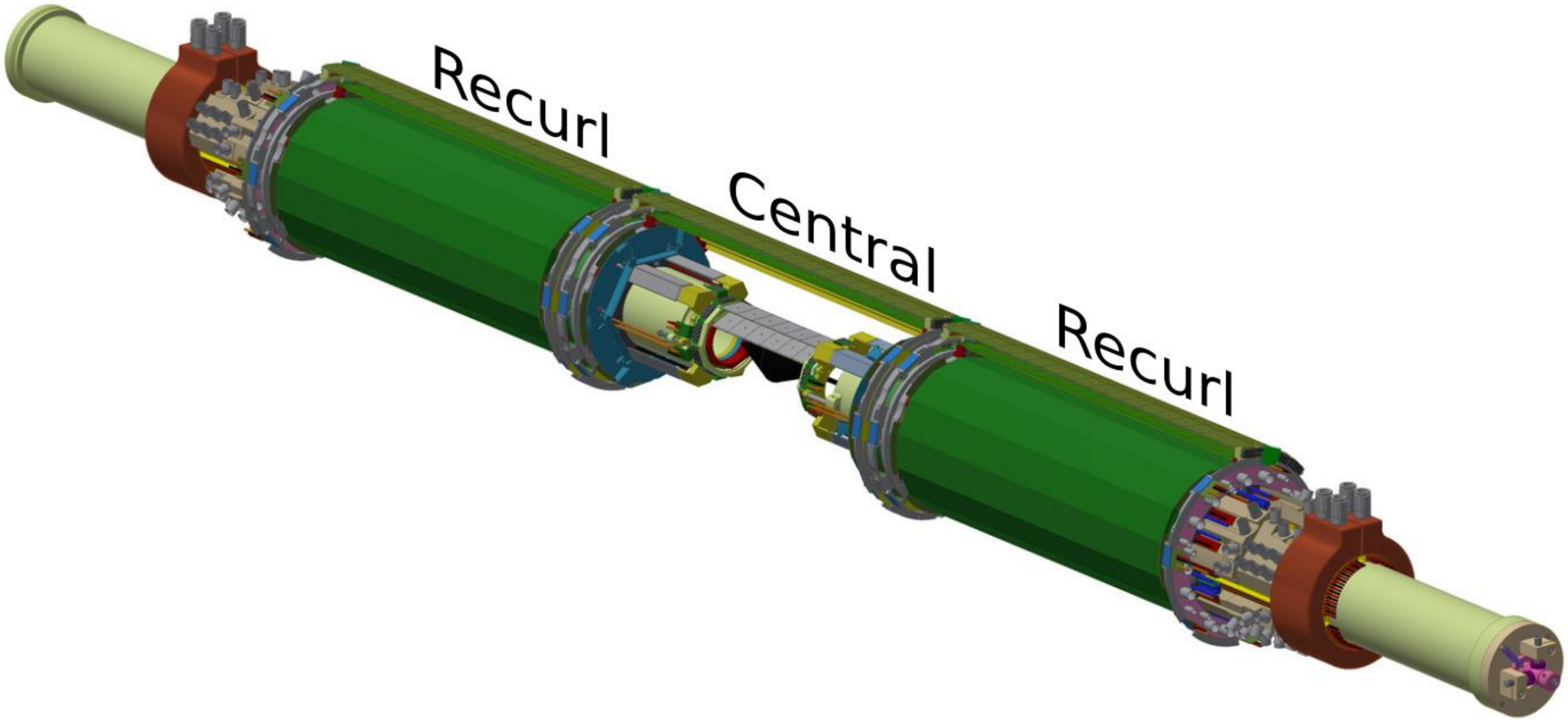
Efficiency/Noise map



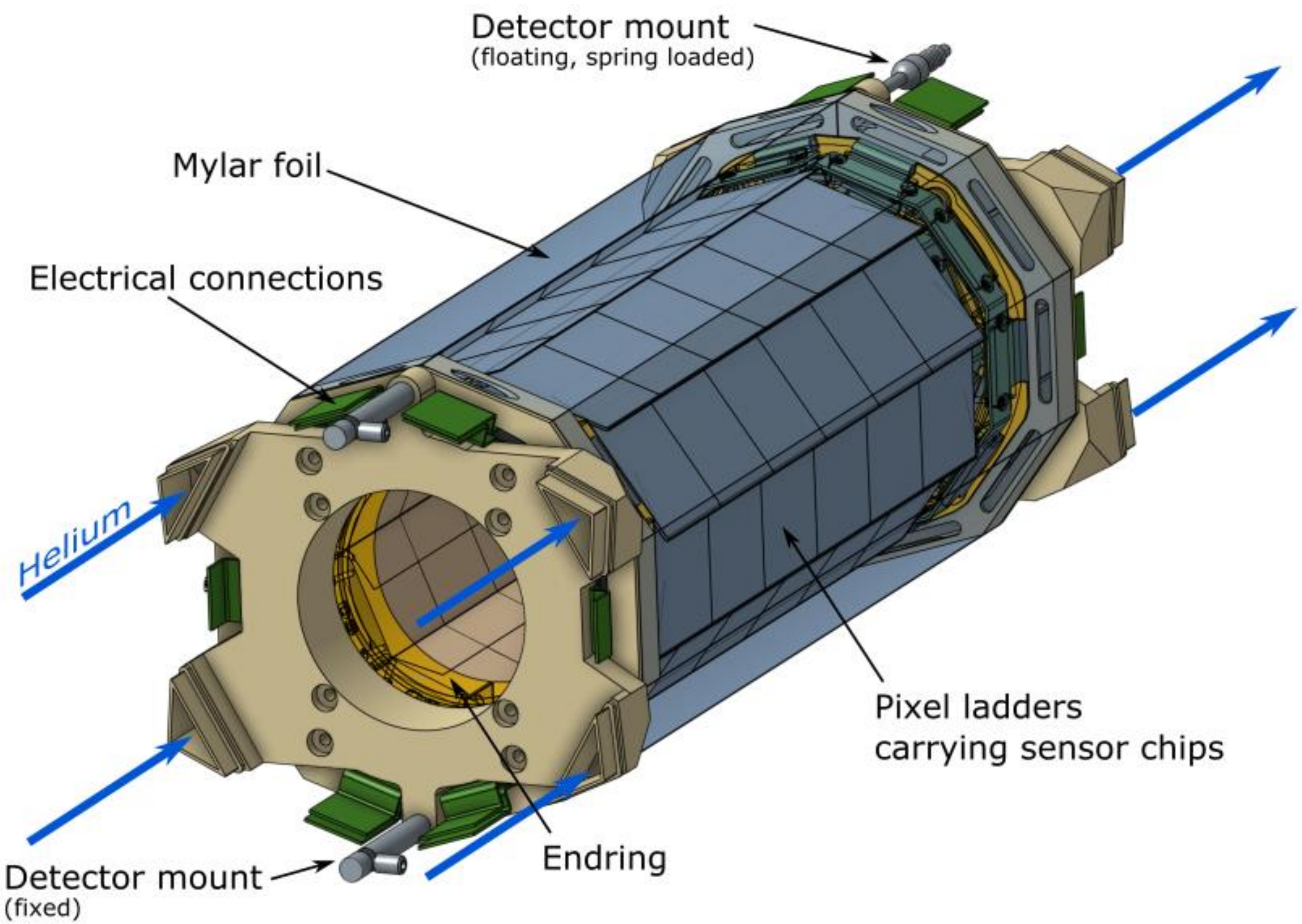
*

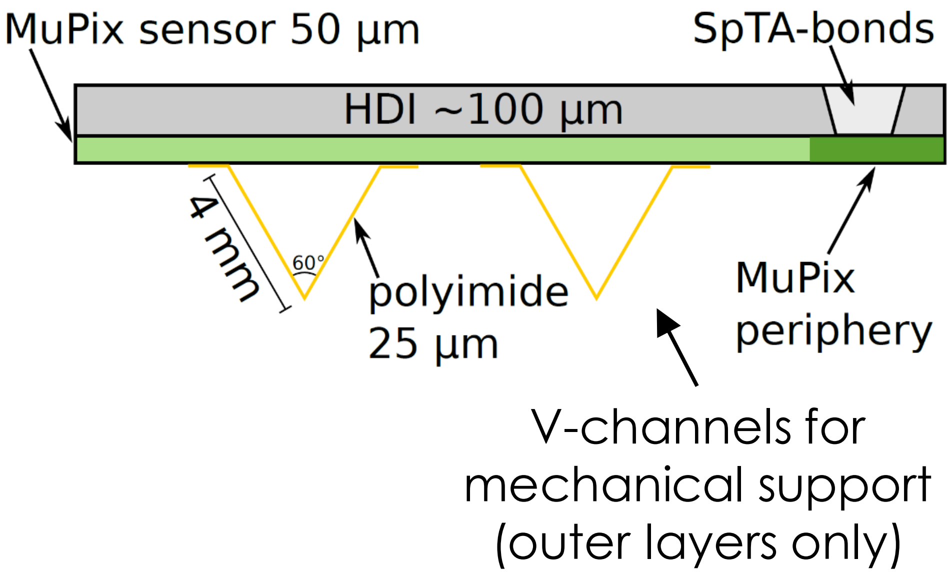
* L.Huth. "A High Rate Testbeam Data Acquisition System and Characterization of High Voltage monolithic Active Pixel Sensors". PhD Thesis, Heidelberg University
** J. Hammerich. "Analog Characterization and Time Resolution of a large scale HV-MAPS Prototype". Master Thesis, Heidelberg University

Building the Pixel Tracking Detector



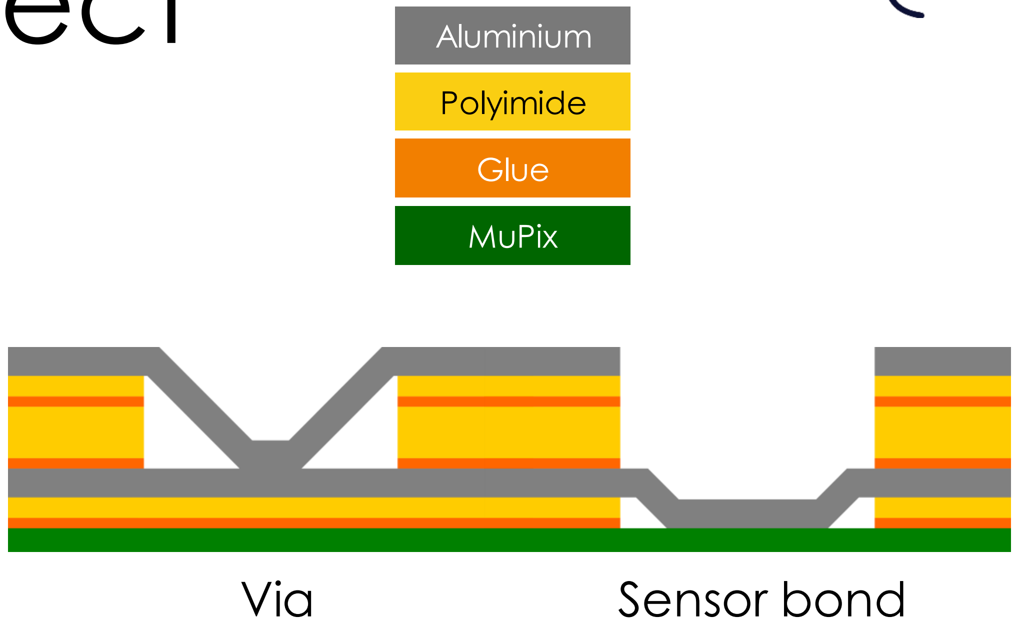
The Vertex Detector

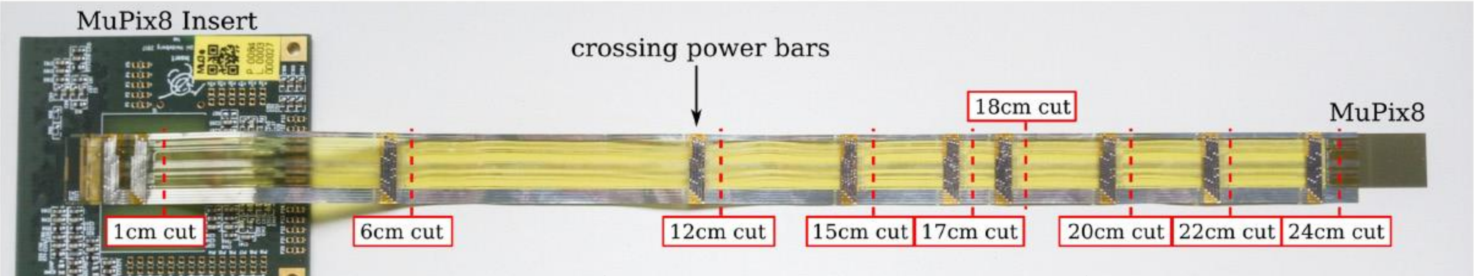




High Density Interconnect

- 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

$\sim 0.5‰\, X_0$

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

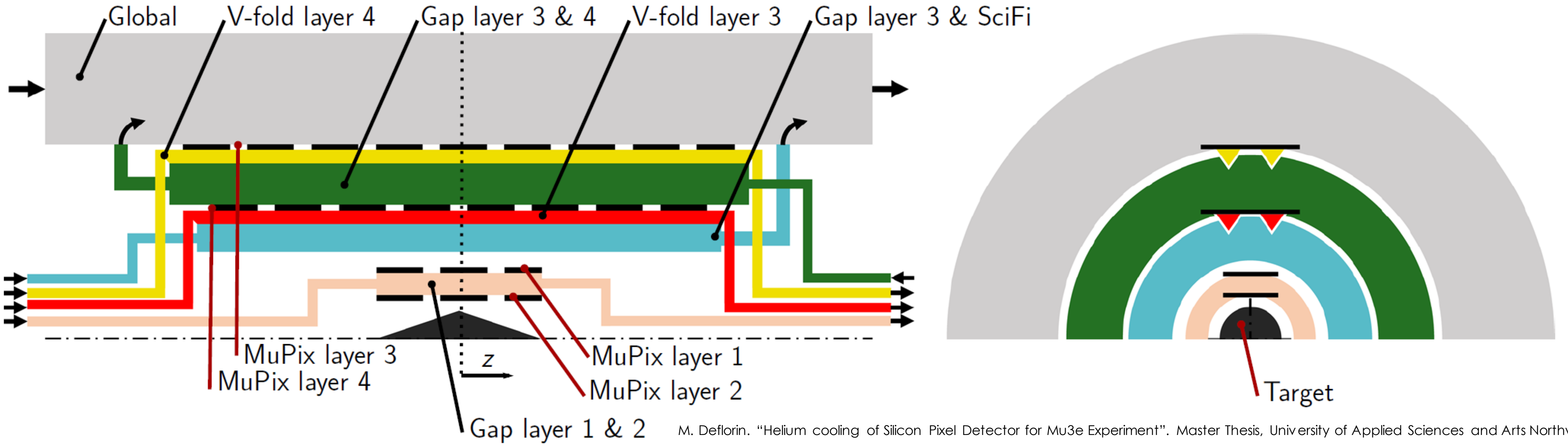
* arXiv:1211.4494v1

◊ talk by G. Contin at PIXEL 2016

△ talk by C. Koffmane at PIXEL 2016

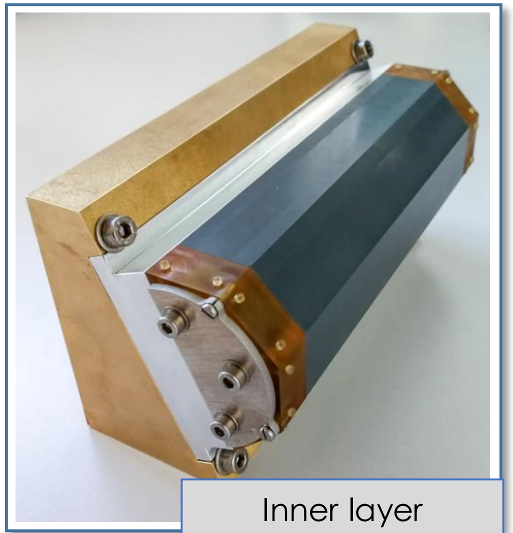
Pixel Tracker Cooling with Helium

- 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

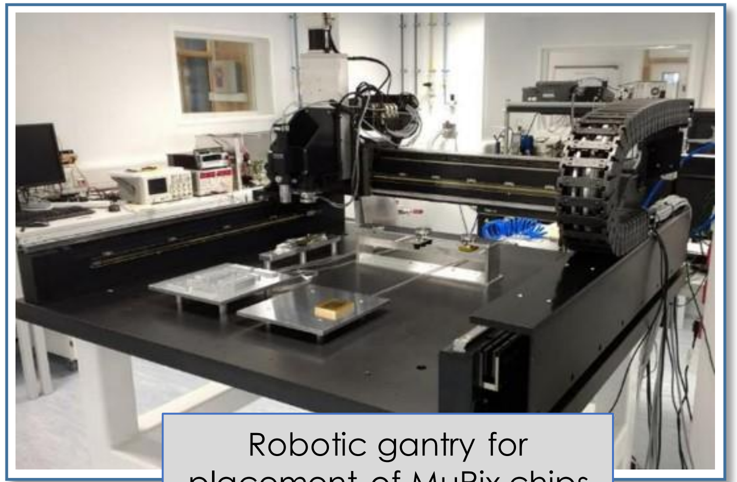


M. Deflorin. “Helium cooling of Silicon Pixel Detector for Mu3e Experiment”. Master Thesis, University of Applied Sciences and Arts Northwestern Switzerland

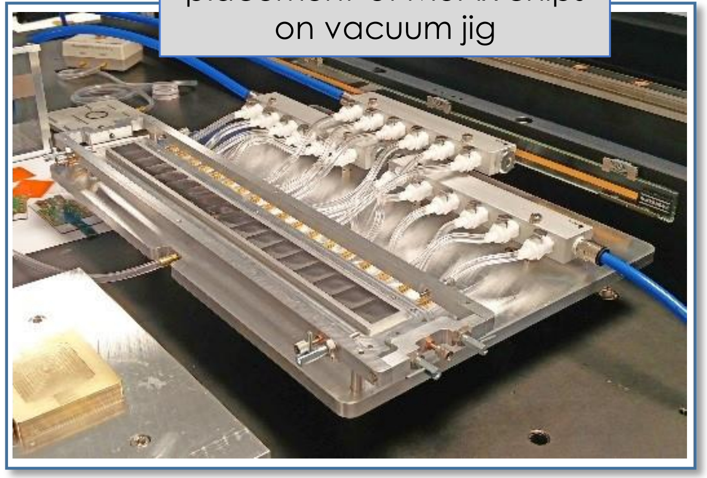
Development of Tooling

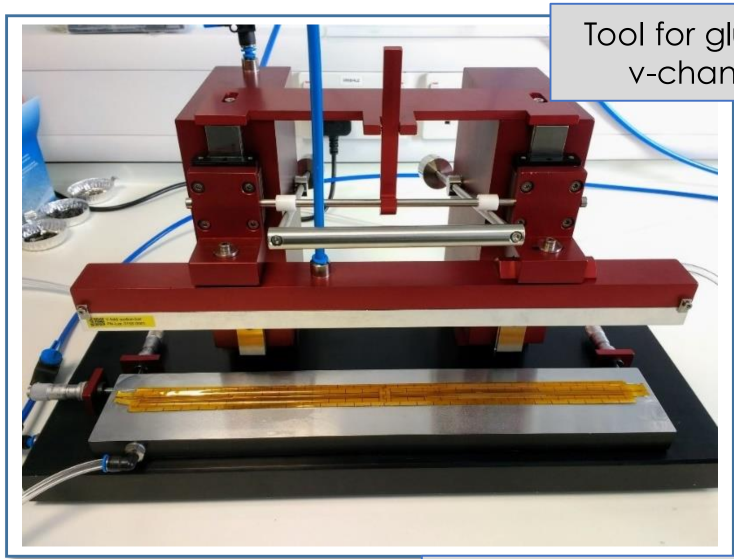


Inner layer assembly tool



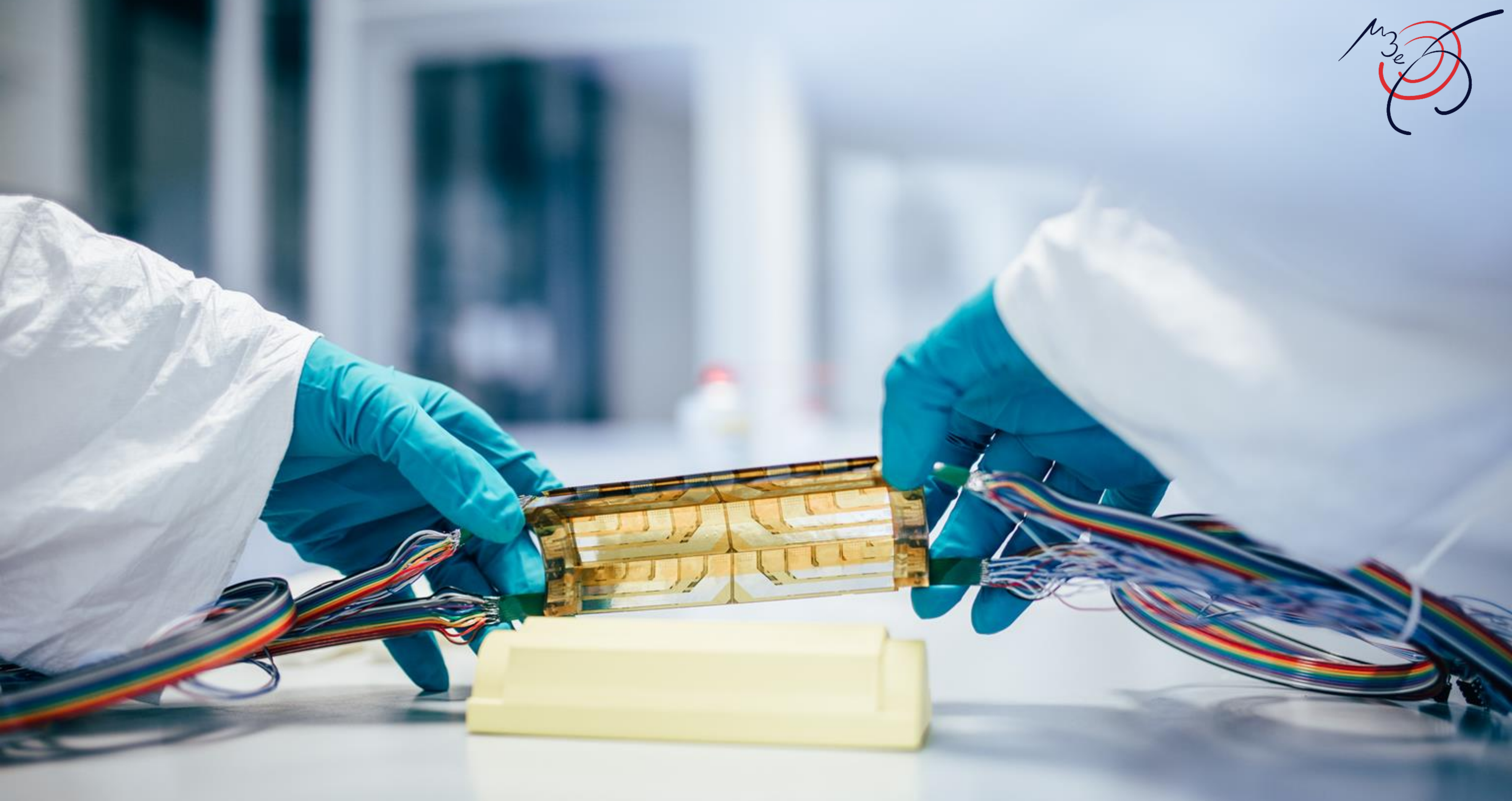
Robotic gantry for placement of MuPix chips on vacuum jig





Tool for gluing of v-channels

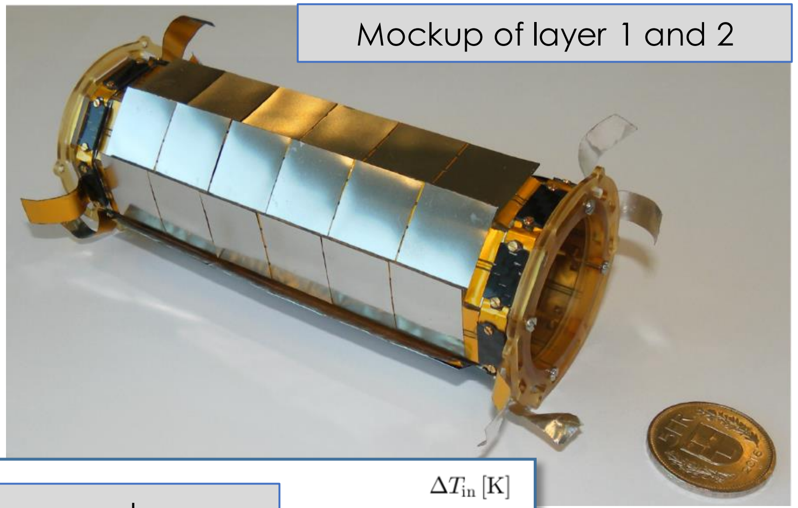
Glue dispensing robot

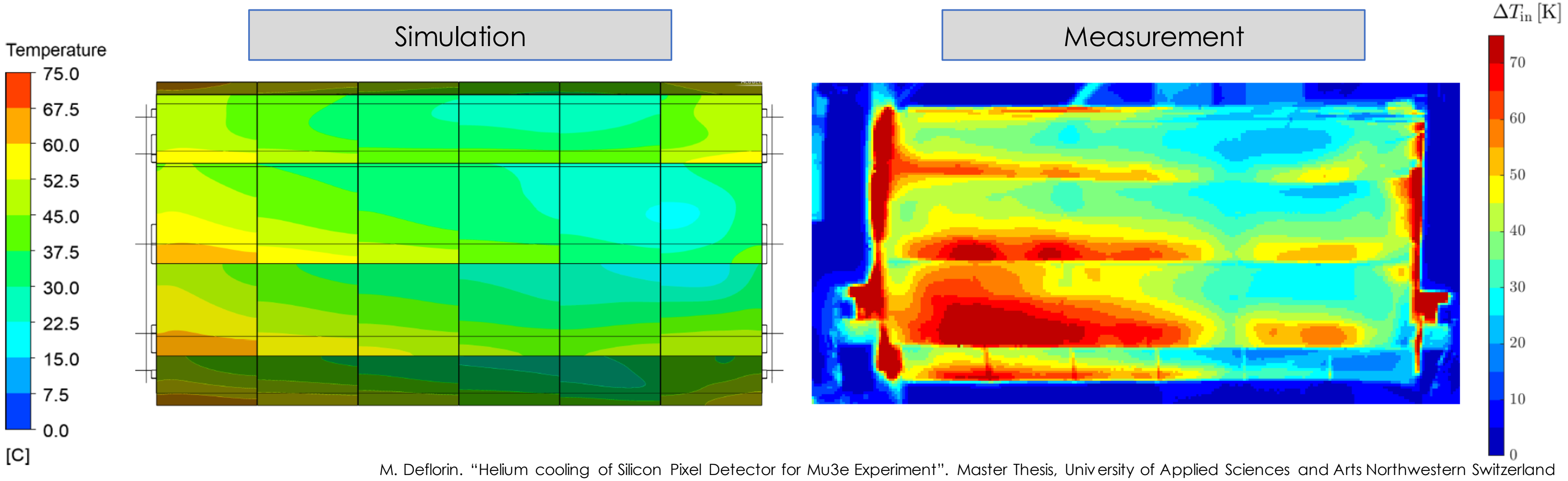


Thermo-Mechanical Mockup

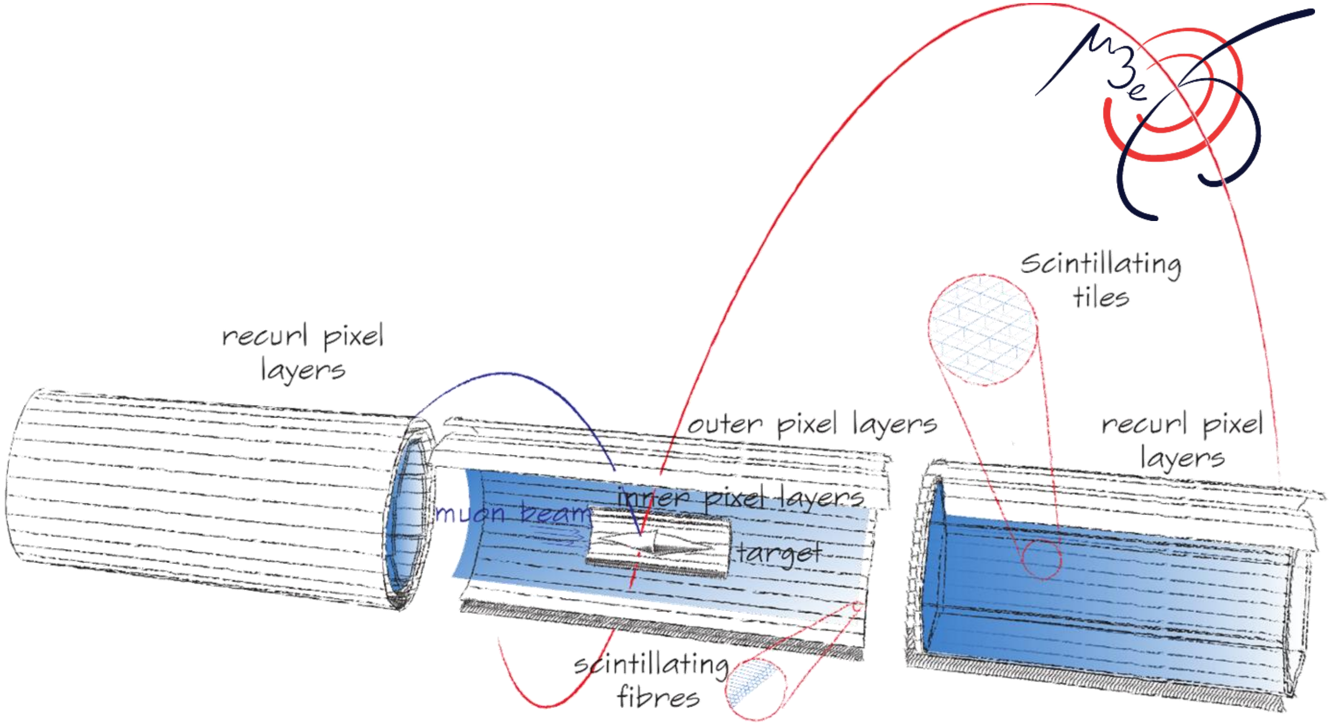
- Validate mechanical and electrical concept
- Test and optimize the cooling system
- Compare CFD simulations with measurements

Mockup of layer 1 and 2





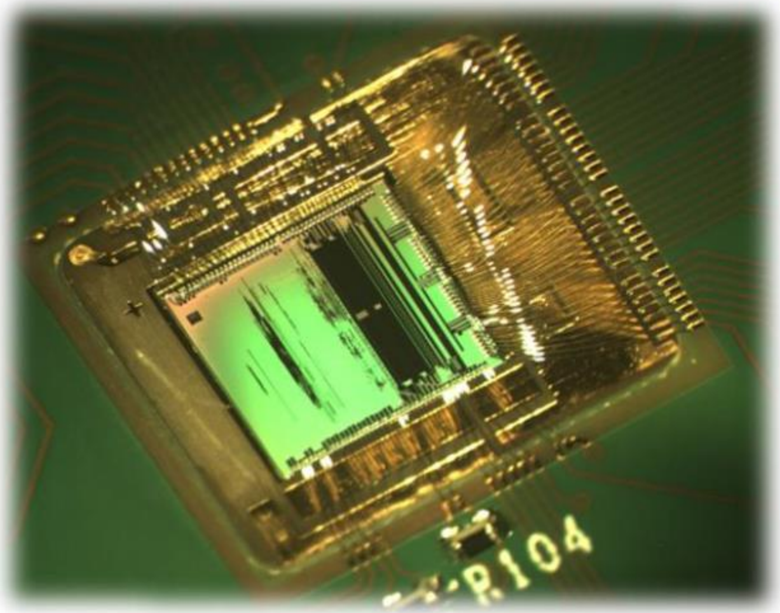
M. Deflorin. "Helium cooling of Silicon Pixel Detector for Mu3e Experiment". Master Thesis, University of Applied Sciences and Arts Northwestern Switzerland



The Timing Detectors

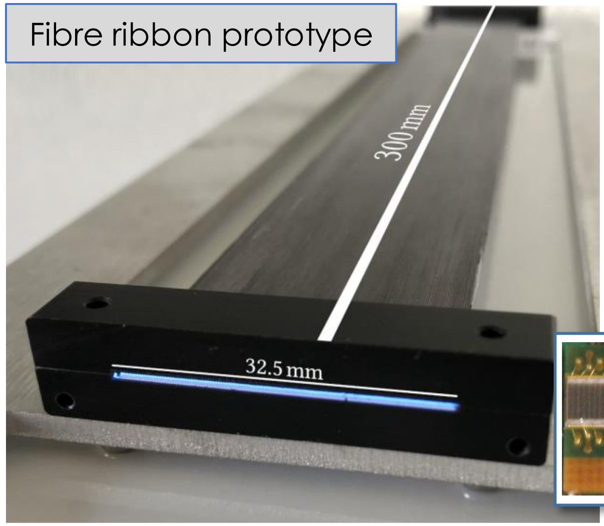
Common Readout ASIC – **MuTRiG**

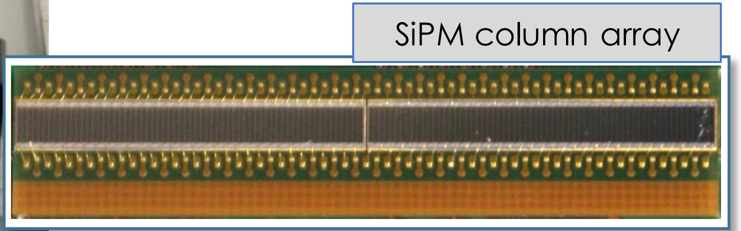
- Both timing detectors use silicon photomultipliers
- Custom designed SiPM readout ASIC: **MuTRiG**
- 32-channels
- **50 ps Time-to-digital converter**

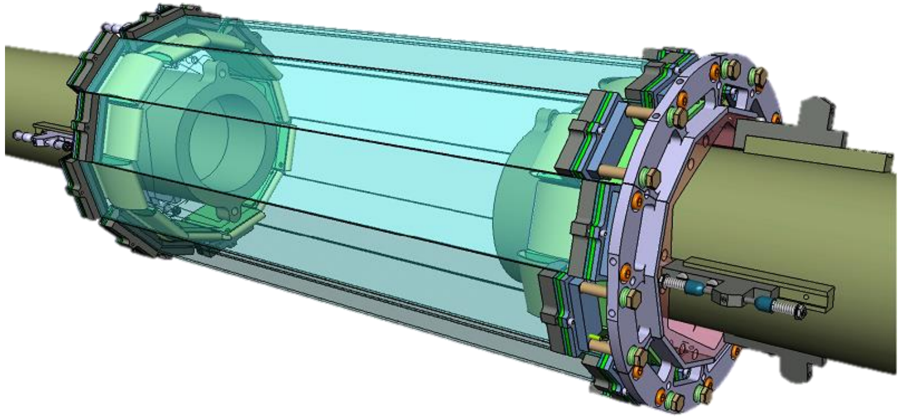


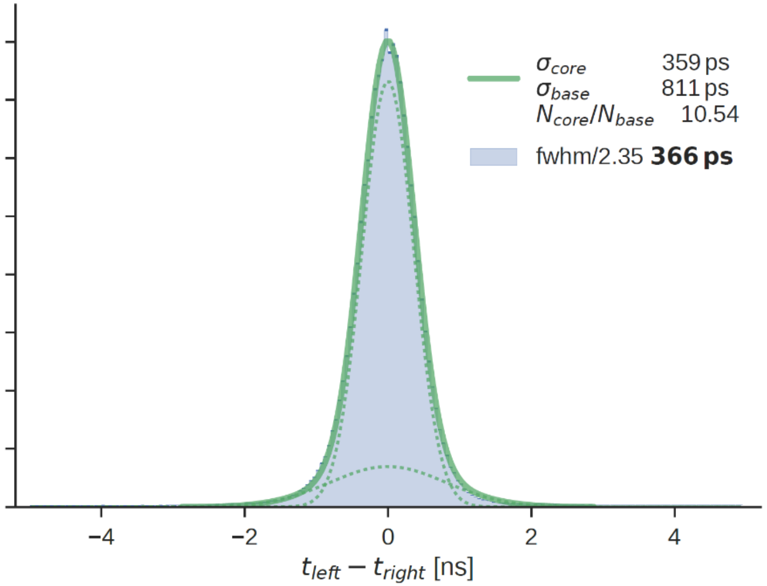
Fibre Detector

- Precise timing suppresses combinatorial background
- 12 fibre ribbons
  - 30 cm long
  - **3 staggered layers** of $250\ \mu m$ thin fibres
  - Material budget $< 2‰\ X_0$
- 128 channel **SiPM column arrays**



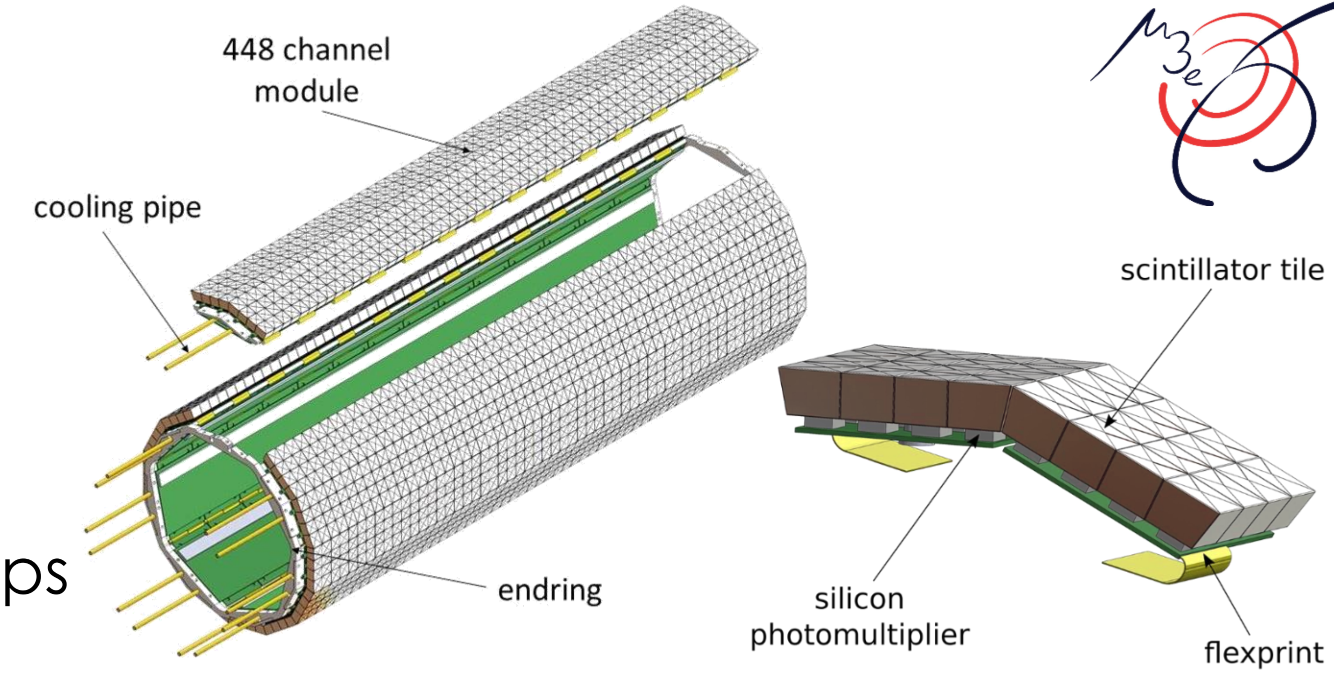


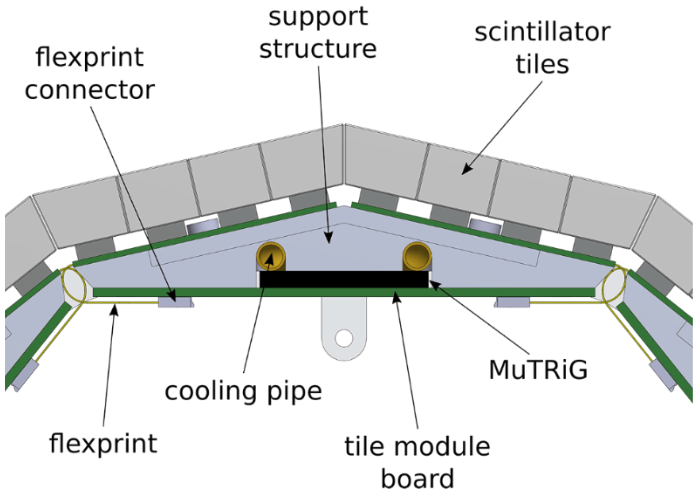




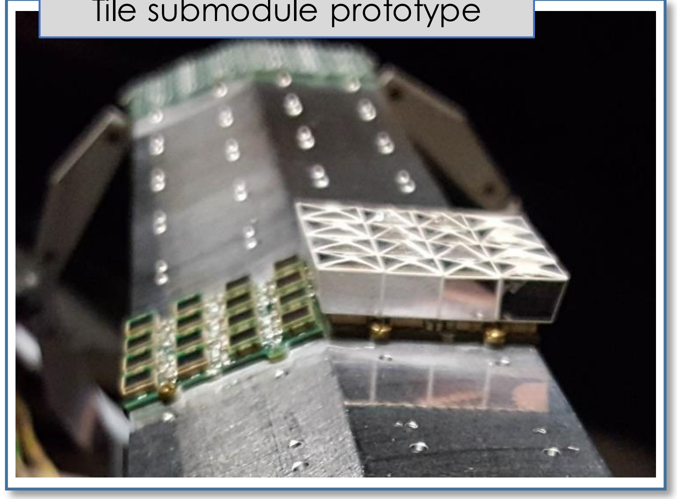
Tile Detector

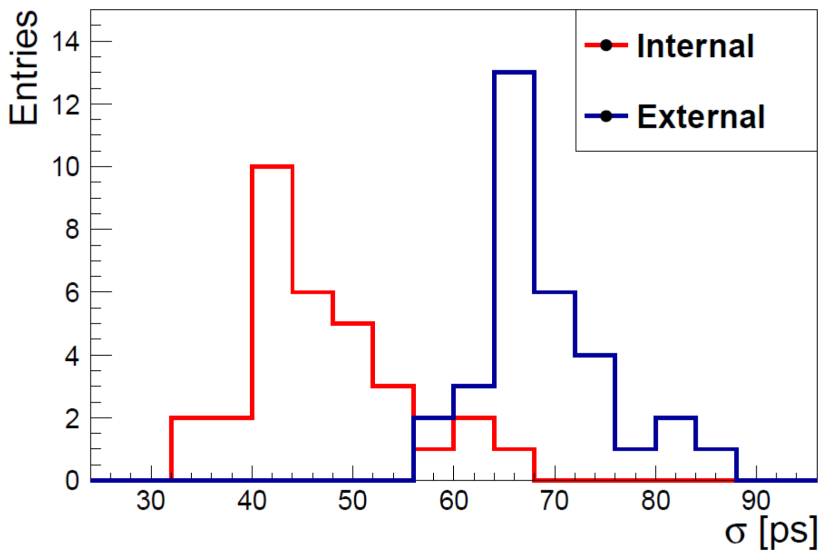
- Scintillating tiles $6 \times 6 \times 5\ \mathrm{mm}^3$
- Prototype modules produced
- Required time resolution < 100 ps
- Measured single channel
  $$\sigma_t = 45 \pm 4\ ps$$





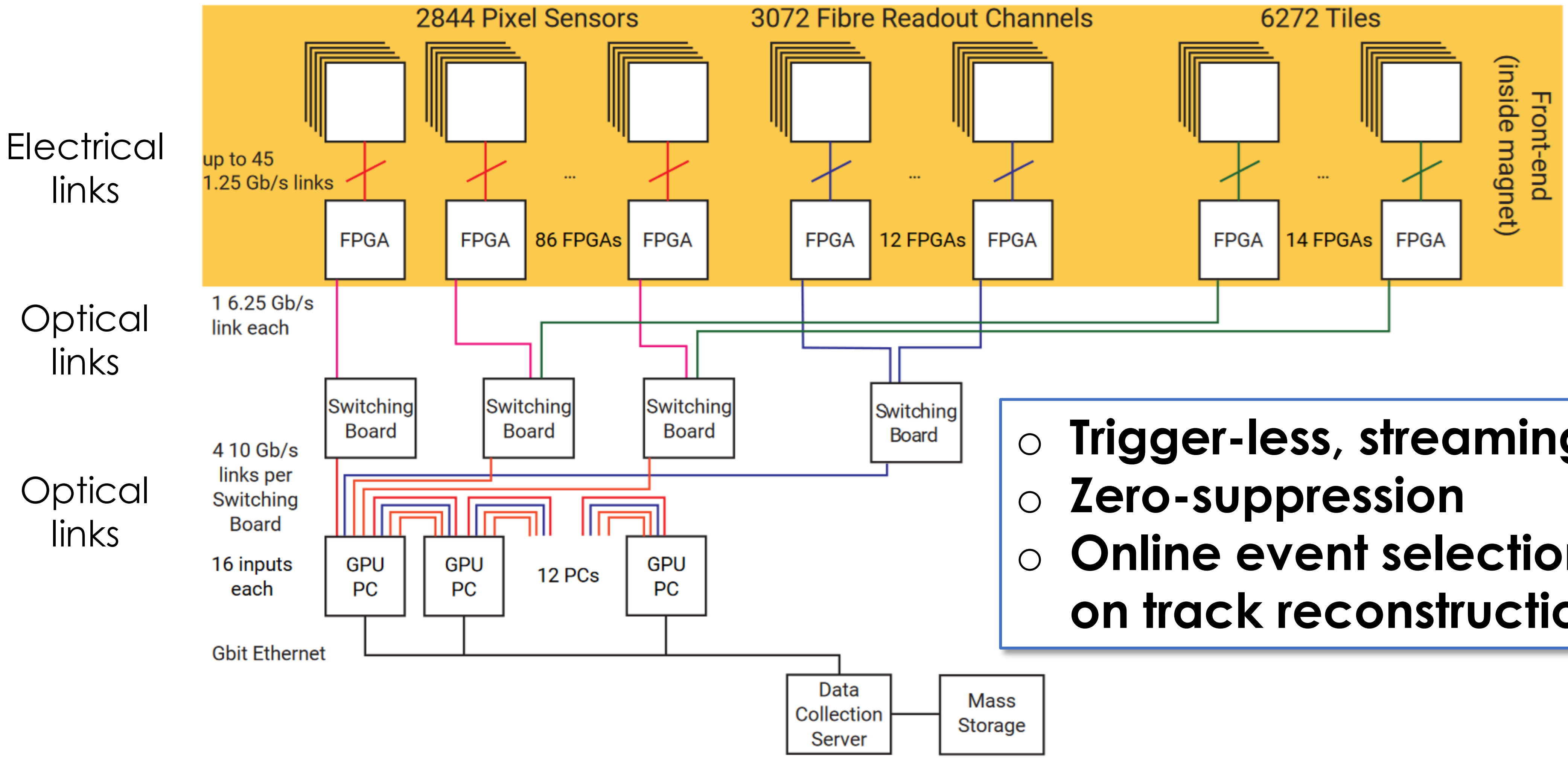
Tile submodule prototype





The Readout System

The Mu3e Readout Concept



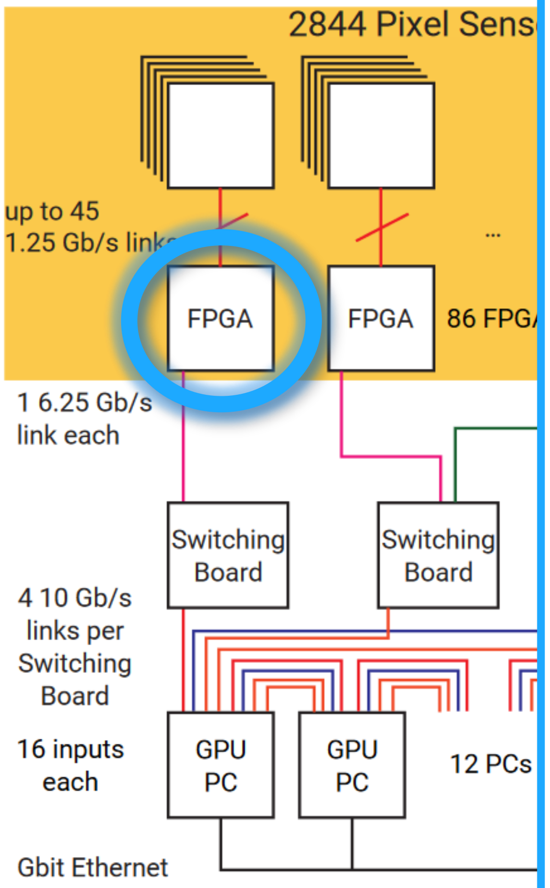
- Trigger-less, streaming readout
- Zero-suppression
- Online event selection based on track reconstruction

The Mu3e Readout Concept

Electrical links

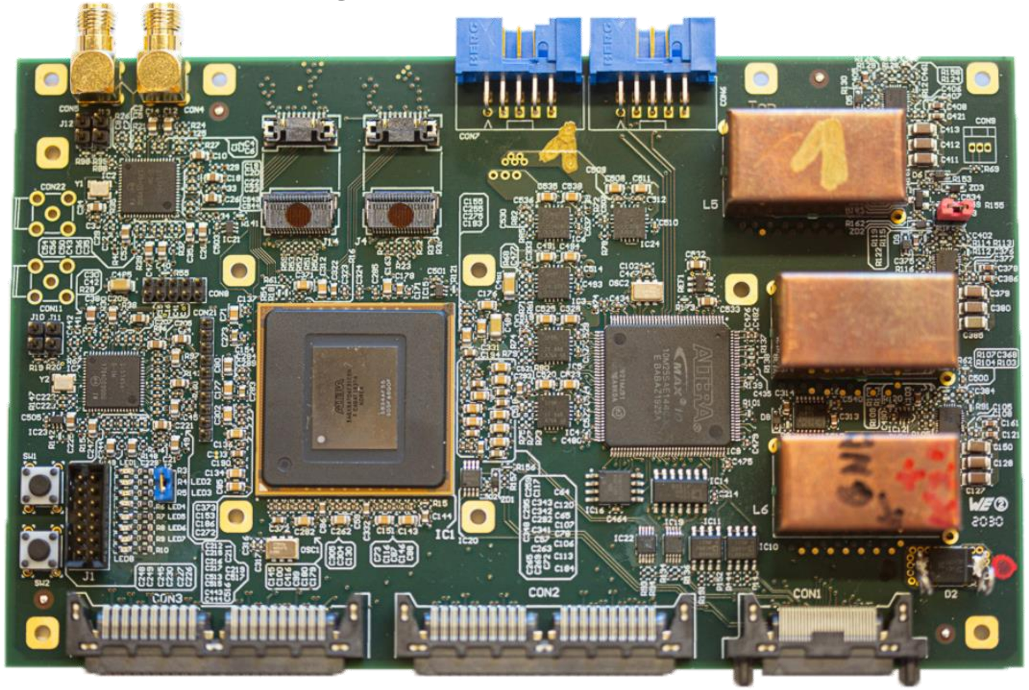
Optical links

Optical links

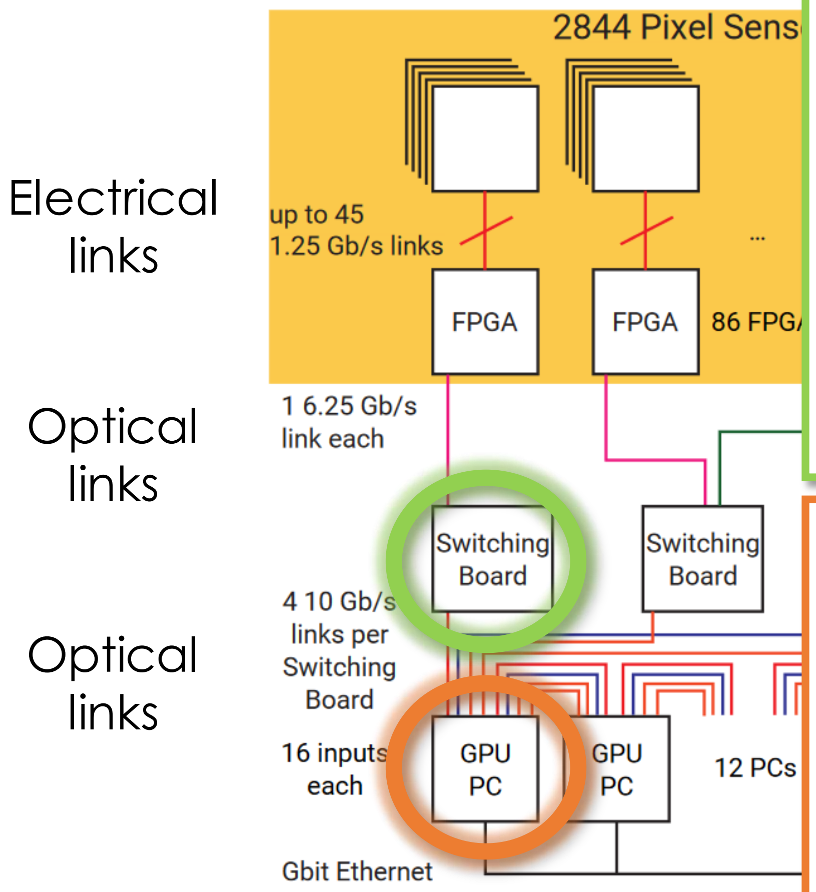


The Front-end Board

- **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)

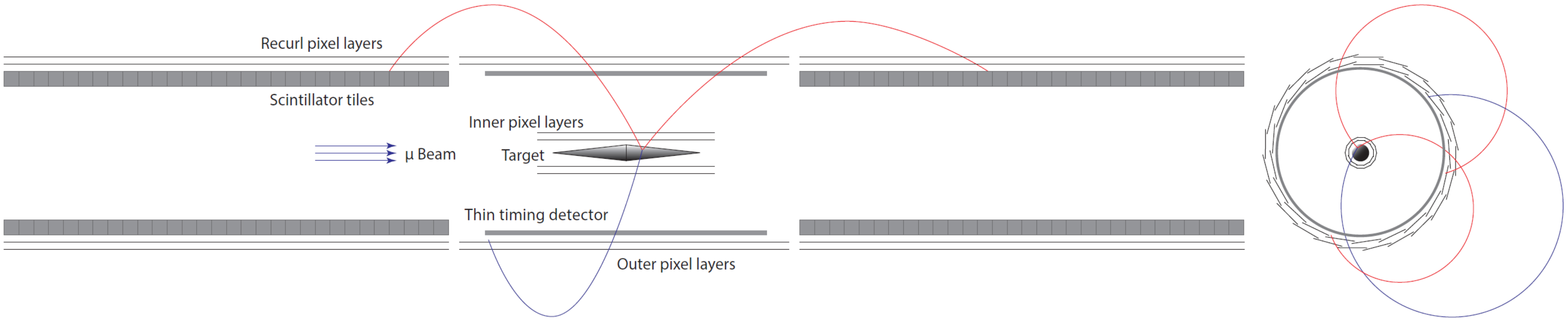
The GPU Filter Farm

- **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

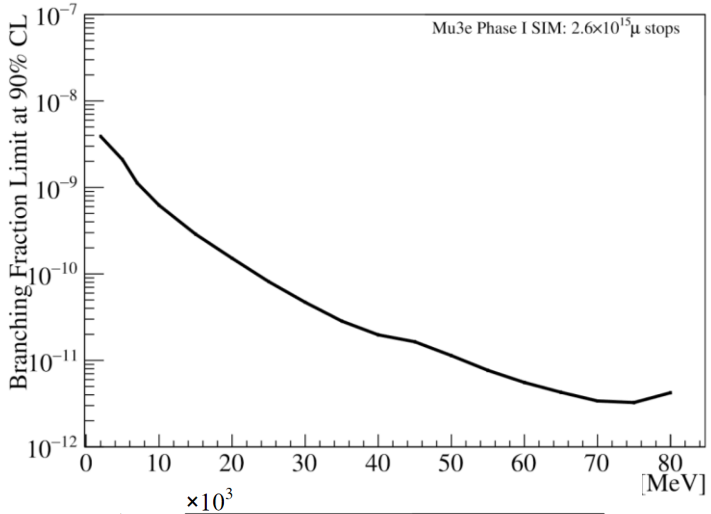
- For the ultimate sensitivity goal for $\mathrm{BR} \leq 1 \times 10^{-16}$ a muon rate of $2 \times 10^{9}\ s^{-1}$ is required (HIMB for Phase II >2025)
- Adapt detector geometry
- Fully exploit HV-MAPS time resolution $\mathcal{O}(1\ \mathrm{ns})$
- Investigate reduction of material by applying wafer-scale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

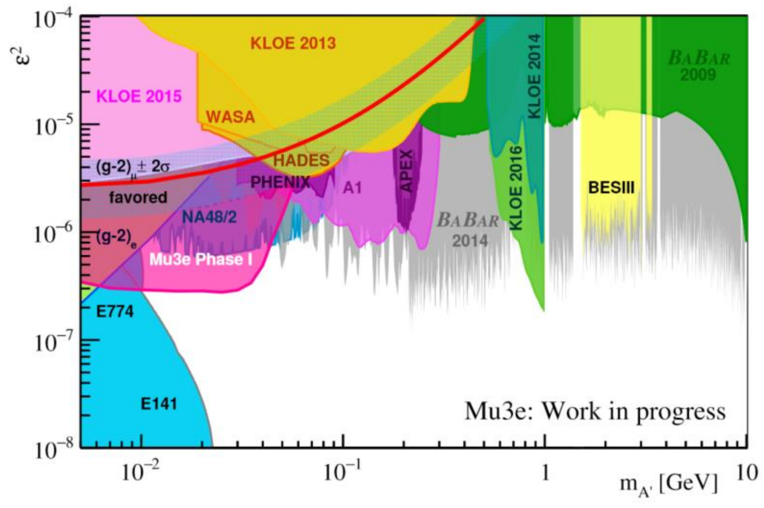


Potential other Physics Searches

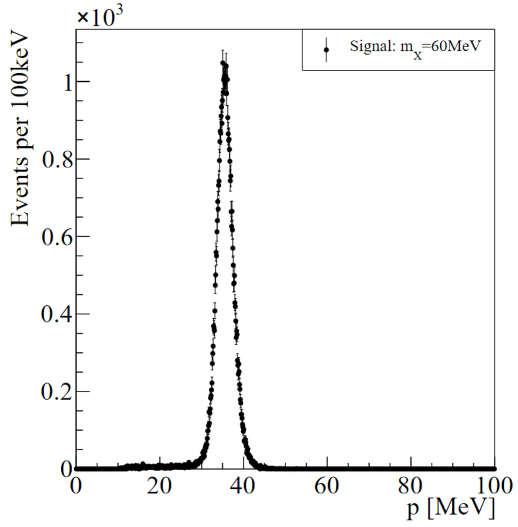
arXiv:1812.00741

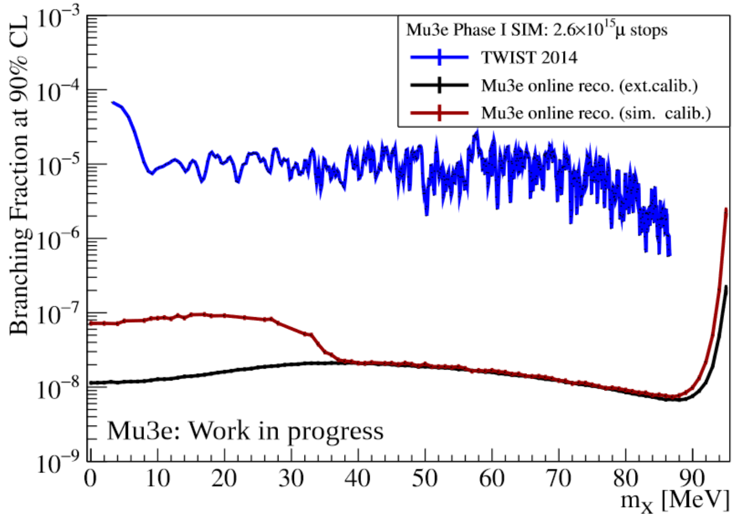
- Resonance searches in $\mu^+ \rightarrow e^+ A'(e^- e^+)\nu\bar{\nu}$
  - Light dark photons
  - Kinetic mixing
  - Not background free



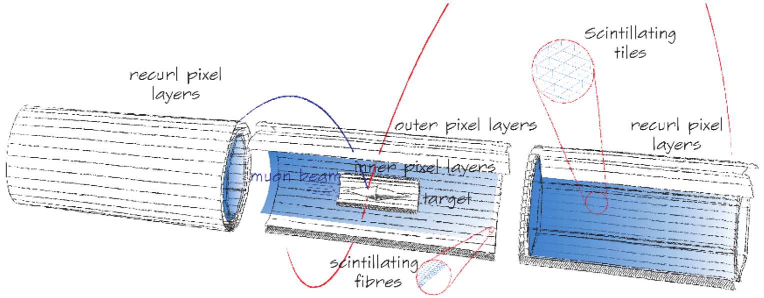


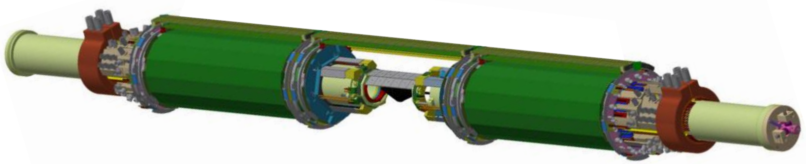
- LFV two-body decays
  - $\mu^+ \rightarrow e^+ X$
  - Monoenergetic e^+

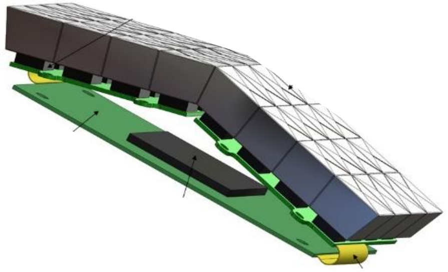




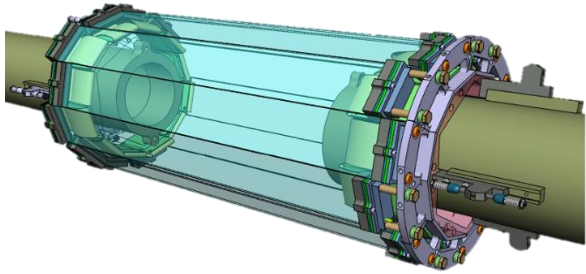
Summary and Outlook

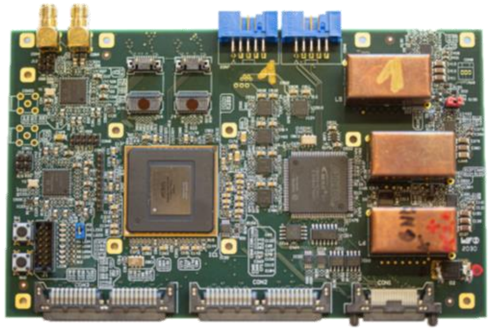






- Observation of cLFV would be a clear sign for New Physics!
- The Mu3e experiment will push the limits in the channel $\mu^+ \rightarrow e^+e^-e^+$
- Mechanical design including services available
- TDR submitted, available on [arXiv]
- Magnet delievered to PSI and first ramp up successful
- In preparation of a detector integration run in first half of 2021





Mu3e Collaboration

About 60 members from 12 institutes

University of Geneva
Paul Scherrer Institute
ETH Zürich
University Zürich

Bristol
Liverpool
Oxford
UC London

University Heidelberg (PI + KIP)
Karlsruhe Institute of Technology
University Mainz

Backup

Tensions in Lepton Physics

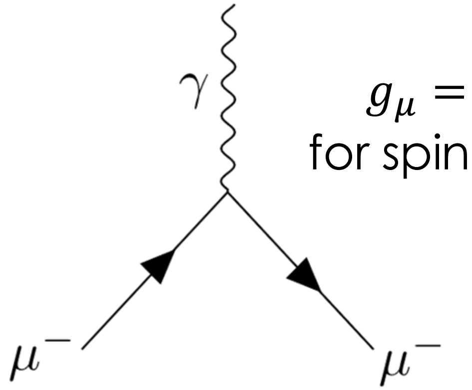
Muon anomalous magnetic moment
=
difference from spin-1/2 expectation due to higher order corrections

Calculated to fantastic precision

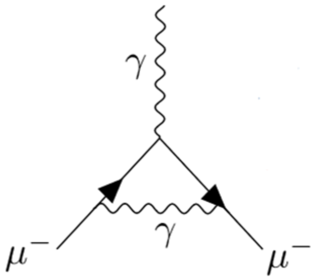
$a_\mu^{SM} = (11659182.04 \pm 3.56) \times 10^{-10}$ PhysRevD.97.114025

$$\vec{\mu} = g \frac{e}{2m} \vec{s}$$

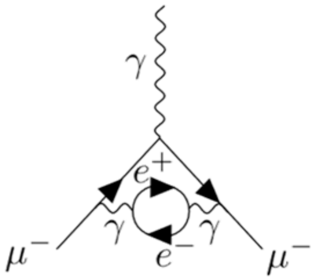
$$a_\mu = \frac{g_\mu - 2}{2}$$



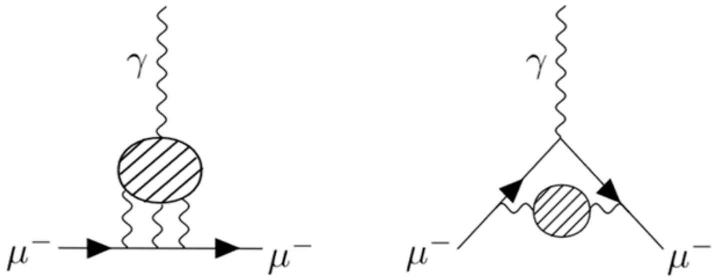
$g_\mu = 2$
for spin-1/2



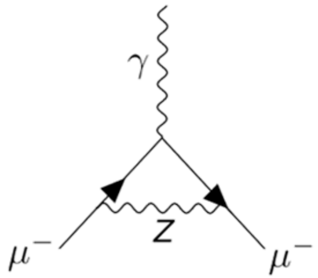
first order QED (Schwinger)



Vacuum polarization higher order QED

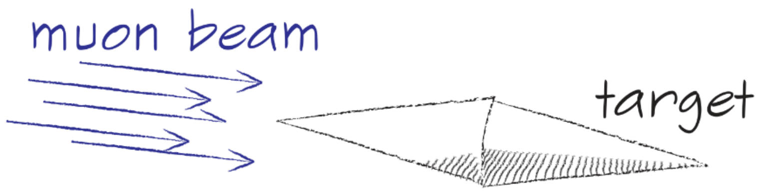


Hadronic
light-by-light scattering and vacuum polarization



Electroweak

Inside 1 T magnetic field

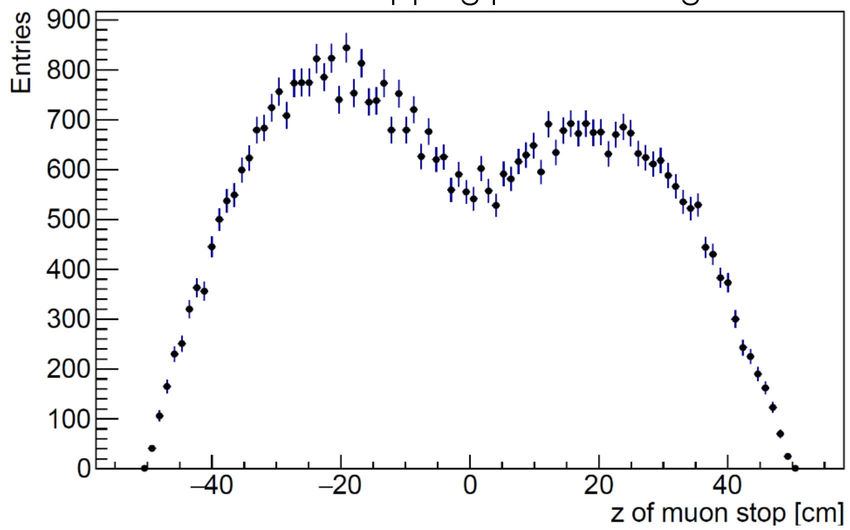


Mylar target

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

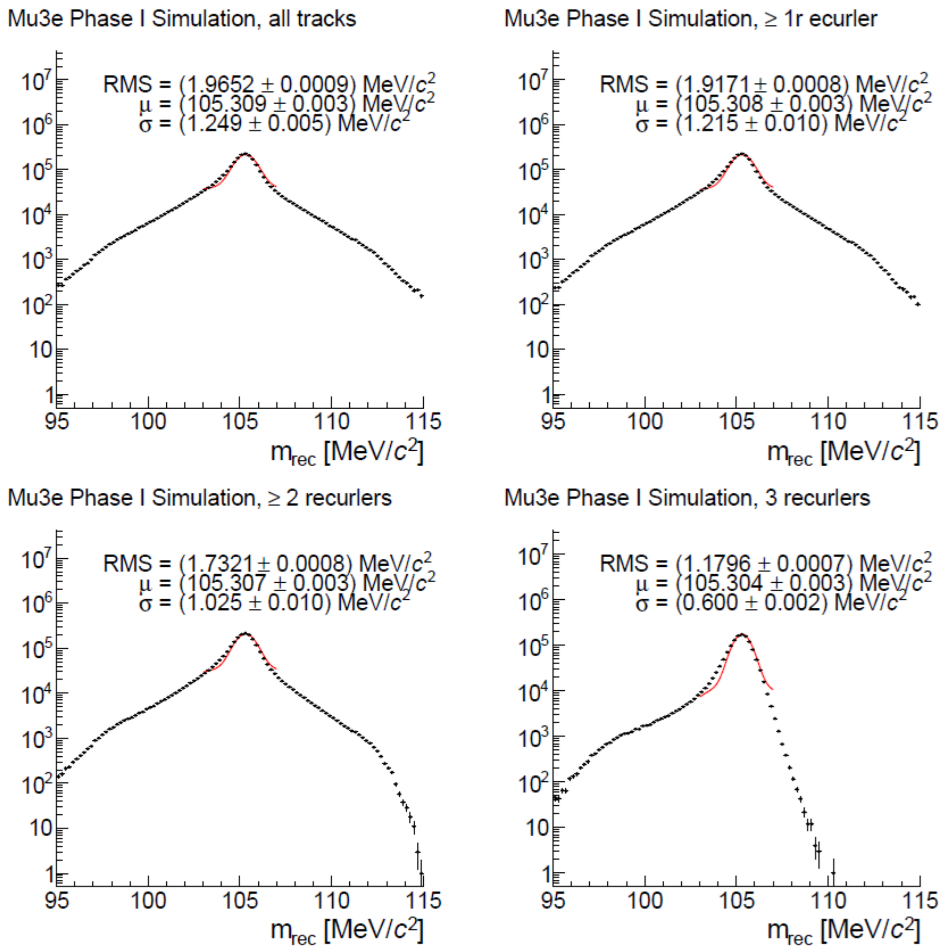


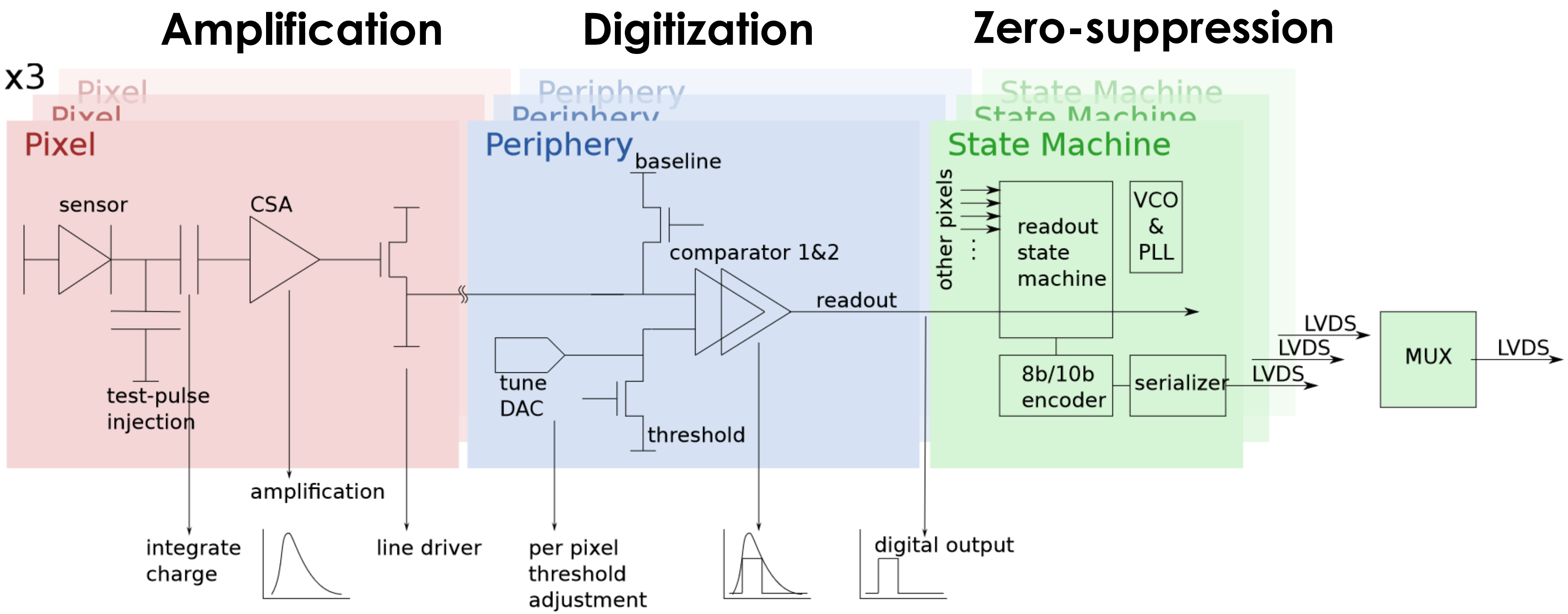
Figure 22.5: Reconstructed muon mass for all tracks (top left), at least one recurler (top right), at least two recurlers (bottom left) and three recurlers (bottom right). The fits are the sum of two Gaussian distributions and the quoted σ is the area-weighted mean; the main purpose of the fit is to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

MuPix8 Readout Architecture I



MuPix8 Readout Architecture II

- Hits are tagged with an on-chip **timestamp**
- **Position priority based** readout:

  Hit chronology not strictly conserved
- **Trigger-less, continuous** readout
- **Serial** data outputs @ 1.25 Gb/s

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