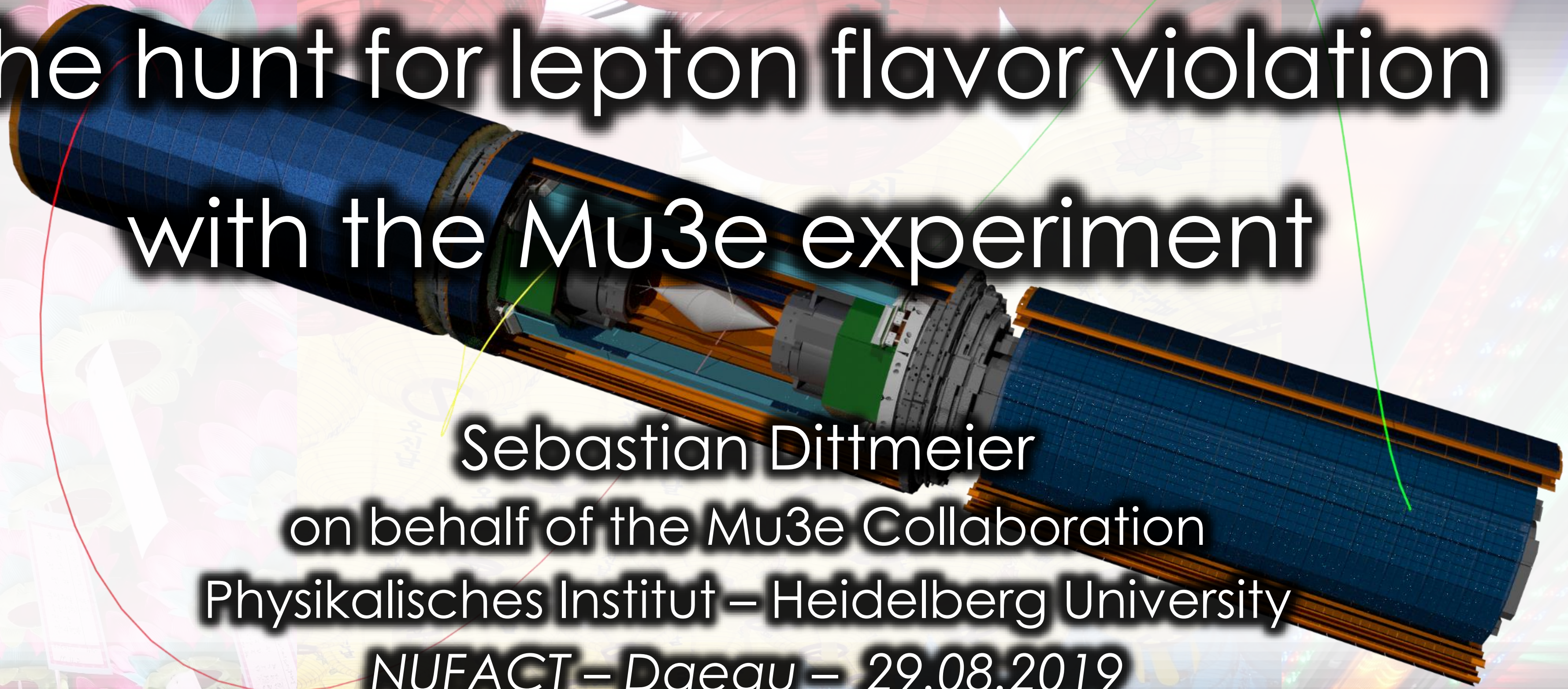
The hunt for lepton flavor violation with the Mu3e experiment



Sebastian Dittmeier
on behalf of the Mu3e Collaboration
Physikalisches Institut – Heidelberg University

NUFACT – Daegu – 29.08.2019

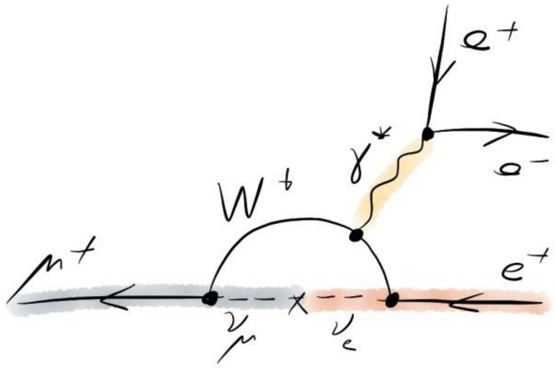
The Mu3e Experiment in a Nutshell

Search for the **charged lepton flavor violating** decay $\mu^+ \rightarrow e^+e^-e^+$

Standard Model

Highly suppressed branching ratio

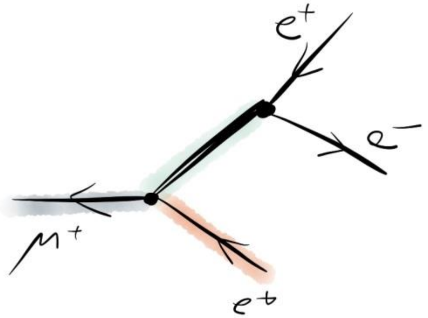
$\mathbf{BR < 10^{-50}}$

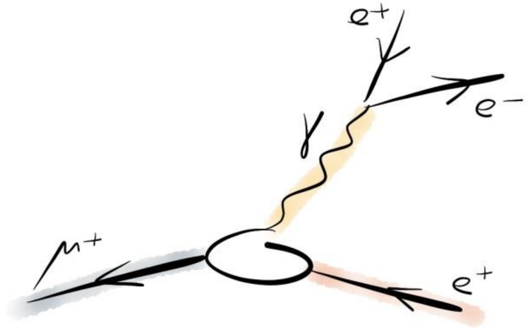


Ideal probe for physics beyond SM

Any observation is a clear sign

for **new physics!**





The Mu3e Experiment in a Nutshell

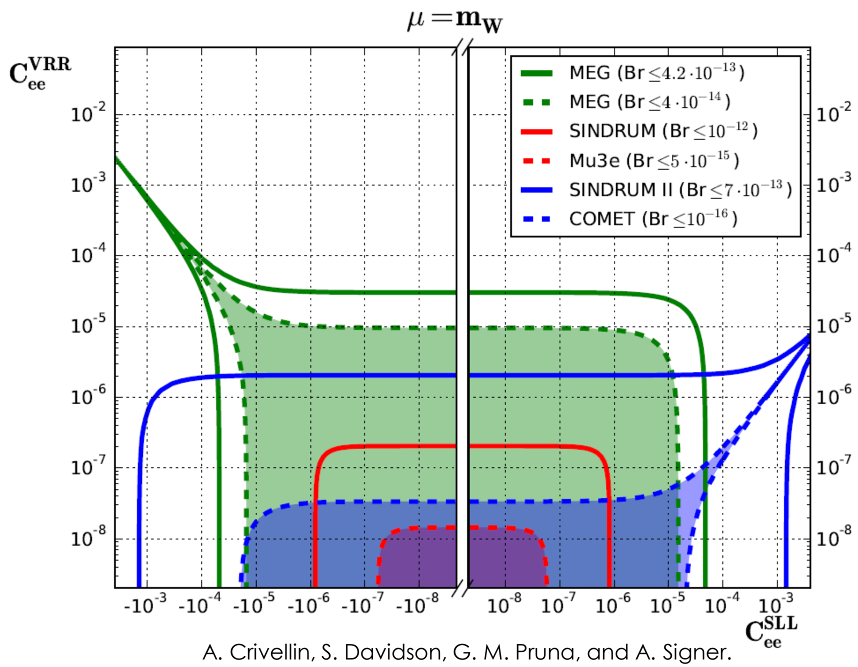
Current limit on $\mu^+ \rightarrow e^+e^-e^+$ $\mathbf{BR}_{meas} < \mathbf{10^{-12}}$ (SINDRUM 1988)

<u>Goal of Mu3e</u>

Enhance sensitivity to branching ratios $\mathcal{O}(10^{-16})$

Why search for $\boldsymbol{\mu^+ \rightarrow e^+e^-e^+}$?

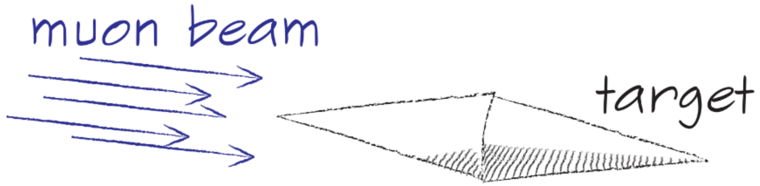
- Physics may be closely related to **neutrino mixing/masses**
- Sensitive to **very high mass scales**
- **Complementary** to other muon cLFV searches



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].

The Experimental Concept

Inside 1 T magnetic field

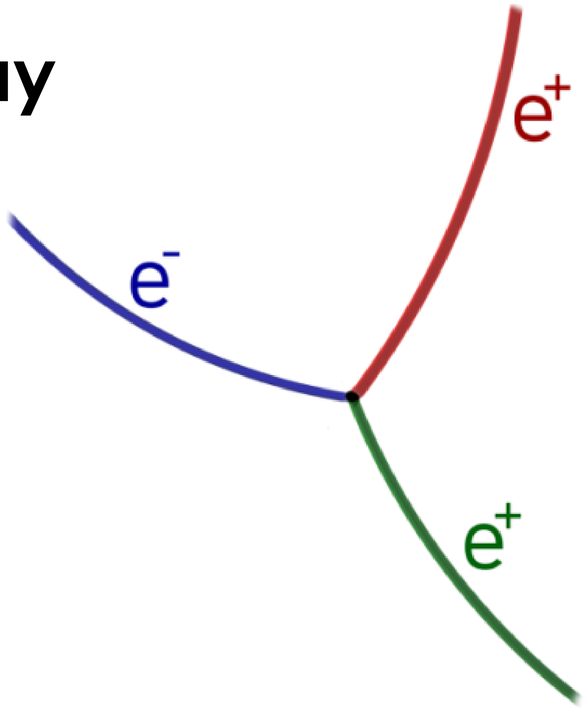


The Signal Decay

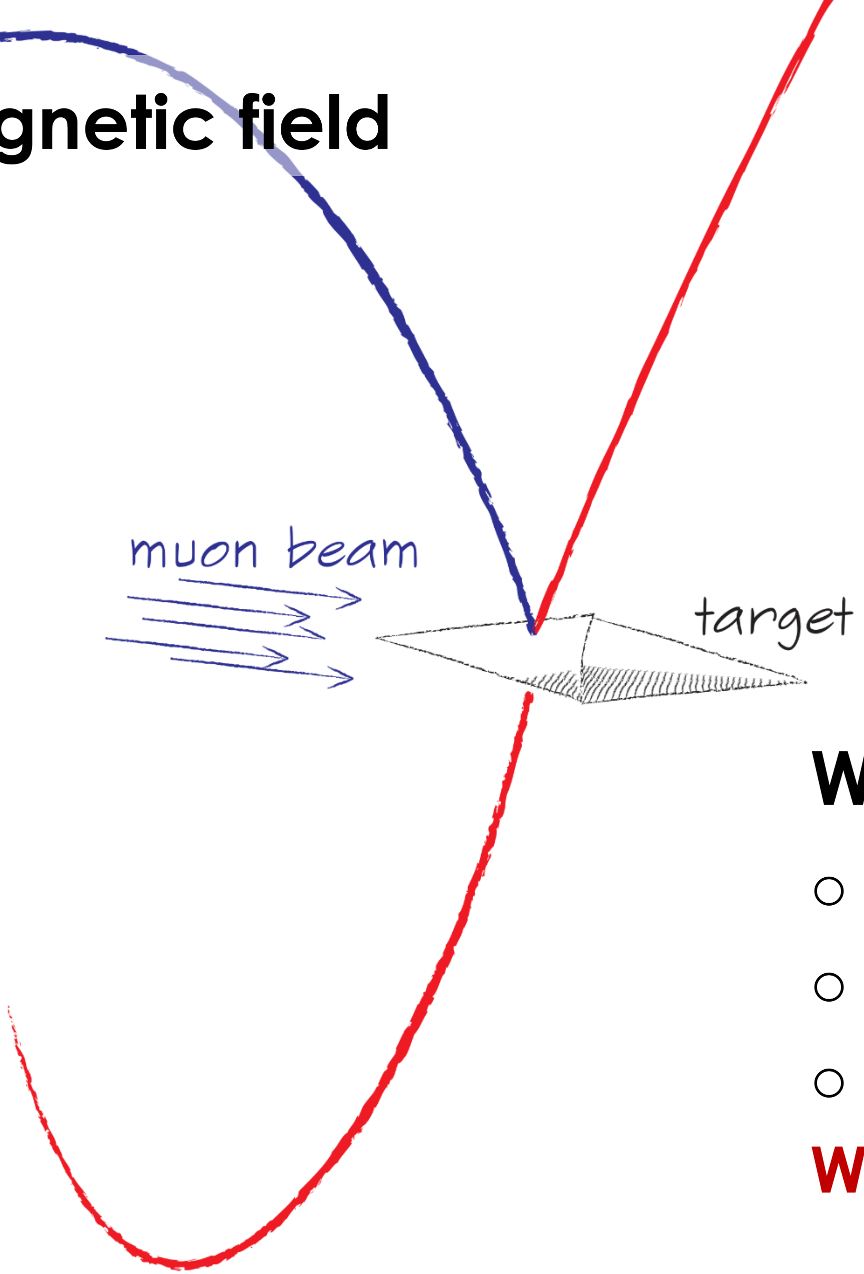
Muons are stopped before decay

Experimental Signature

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



Inside 1 T magnetic field

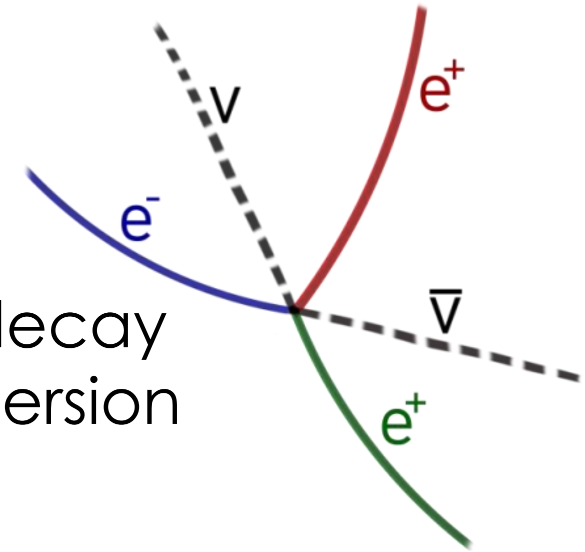


We need to measure precisely

- Decay vertex
- Momentum of decay particles
- Time of the tracks

Why? Because of backgrounds!

Main Sources of Background

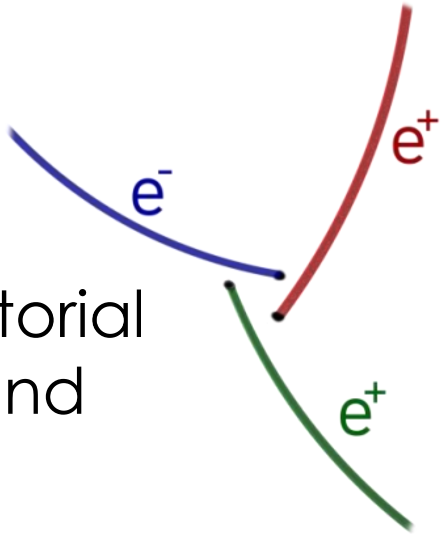


Radiative SM decay
+ photon conversion

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

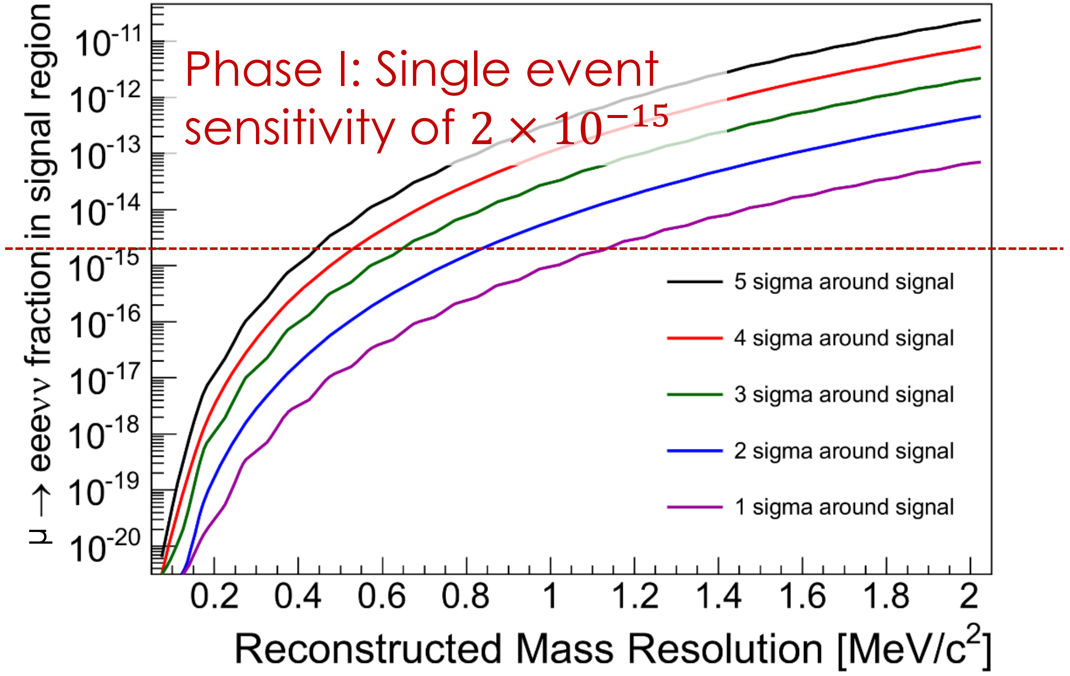
Experimental Signature
- Common vertex
- Coincident
- $\sum \vec{p} \neq 0$
- $\sum E \neq m_\mu$

Combinatorial background



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

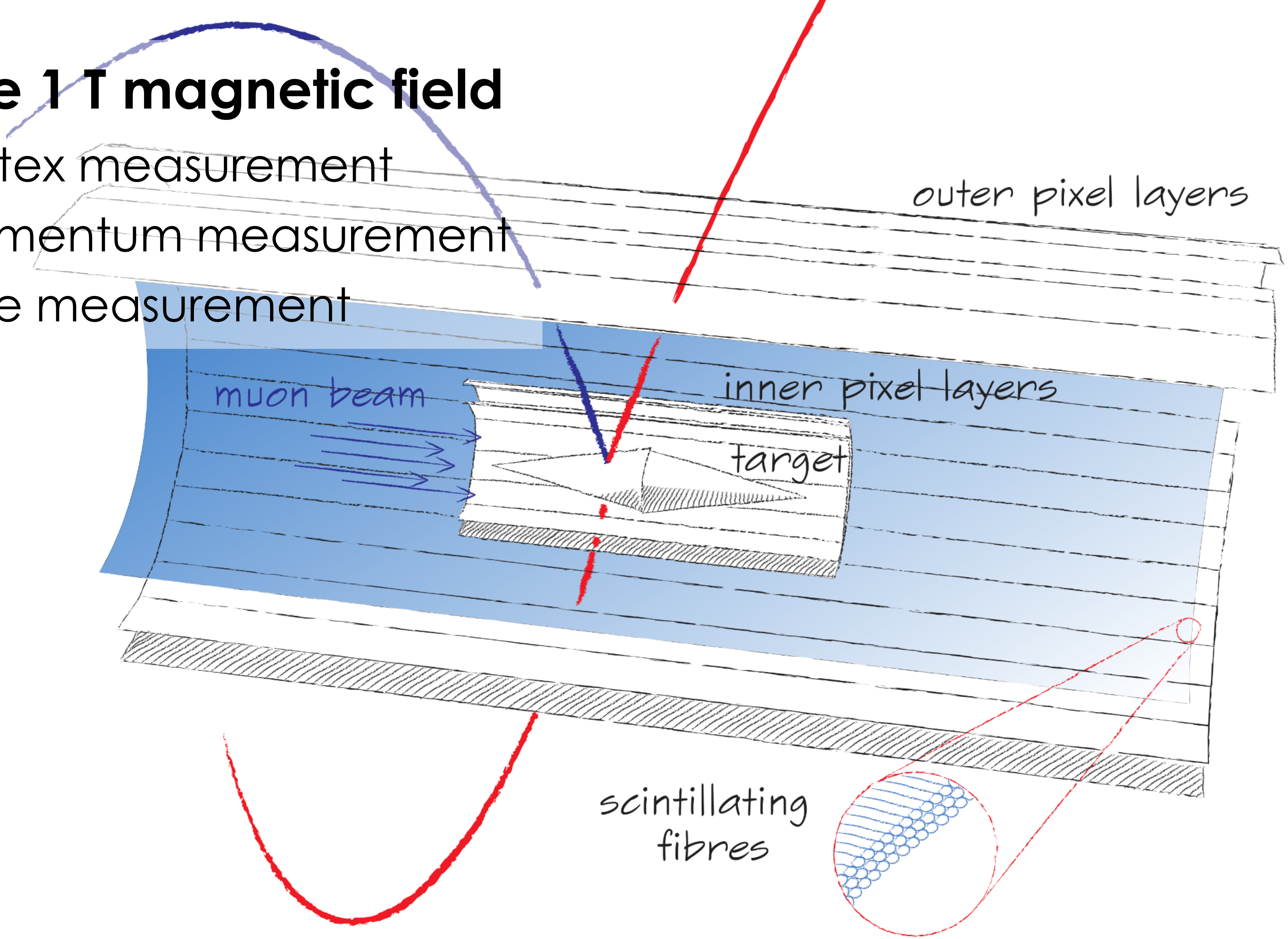
Detector Requirements



- Required average momentum resolution $\sigma_p < 1.0\ \mathrm{MeV/c}$
  - Momentum resolution limited by **multiple scattering**
  - ➢ Material budget $\leq \mathbf{1‰}\ \boldsymbol{X_0}$ per layer
- High muon decay rates (Phase II) require $\sigma_t < 500\ \mathrm{ps}$ per track

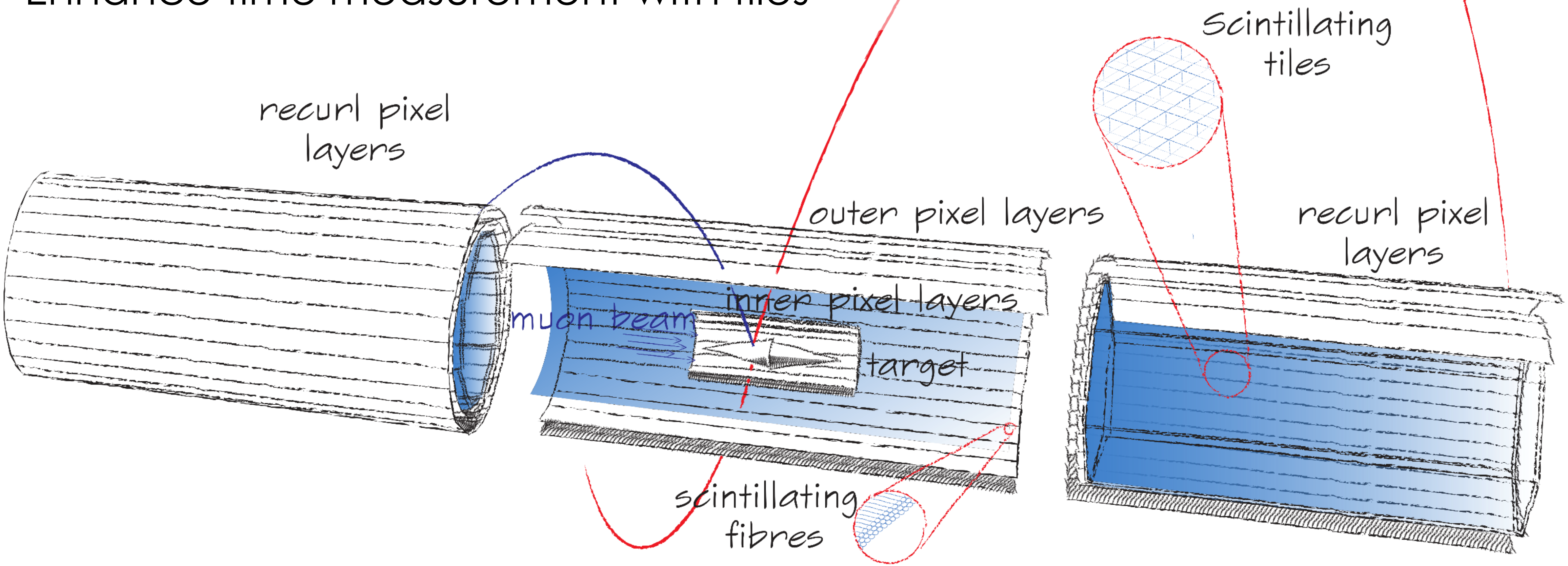
Inside 1 T magnetic field

- Vertex measurement
- Momentum measurement
- Time measurement

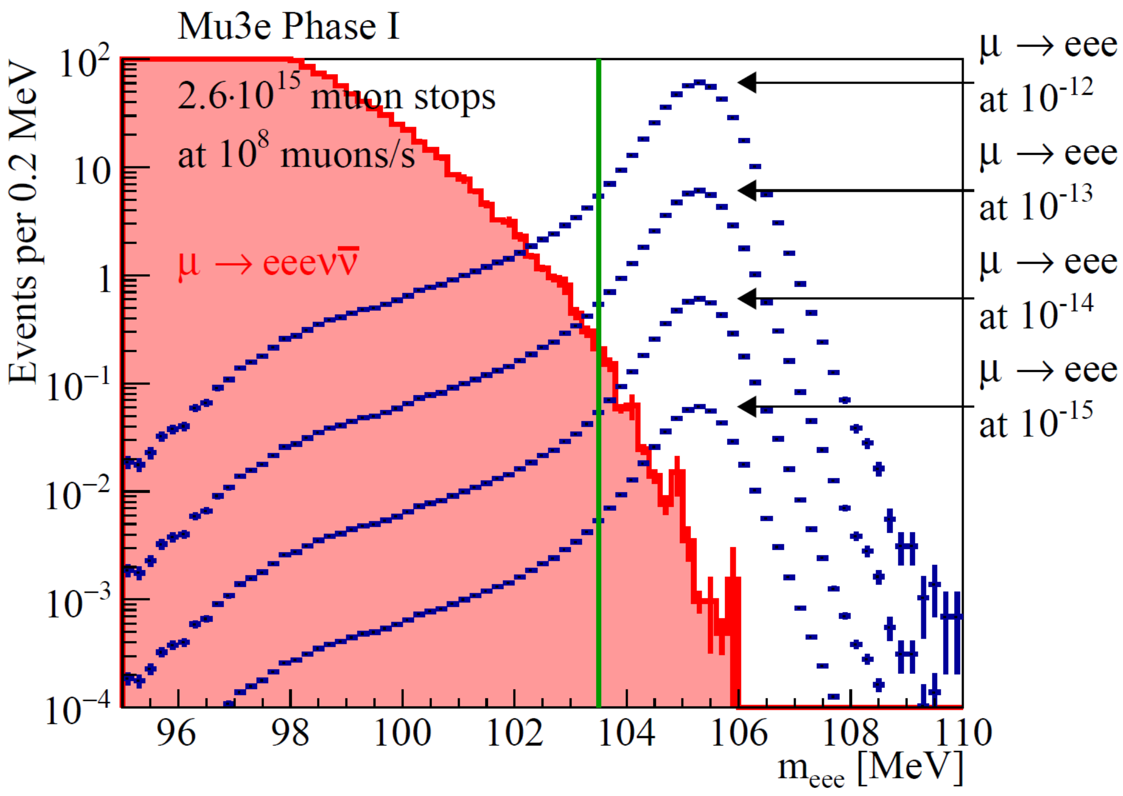


Inside 1 T magnetic field

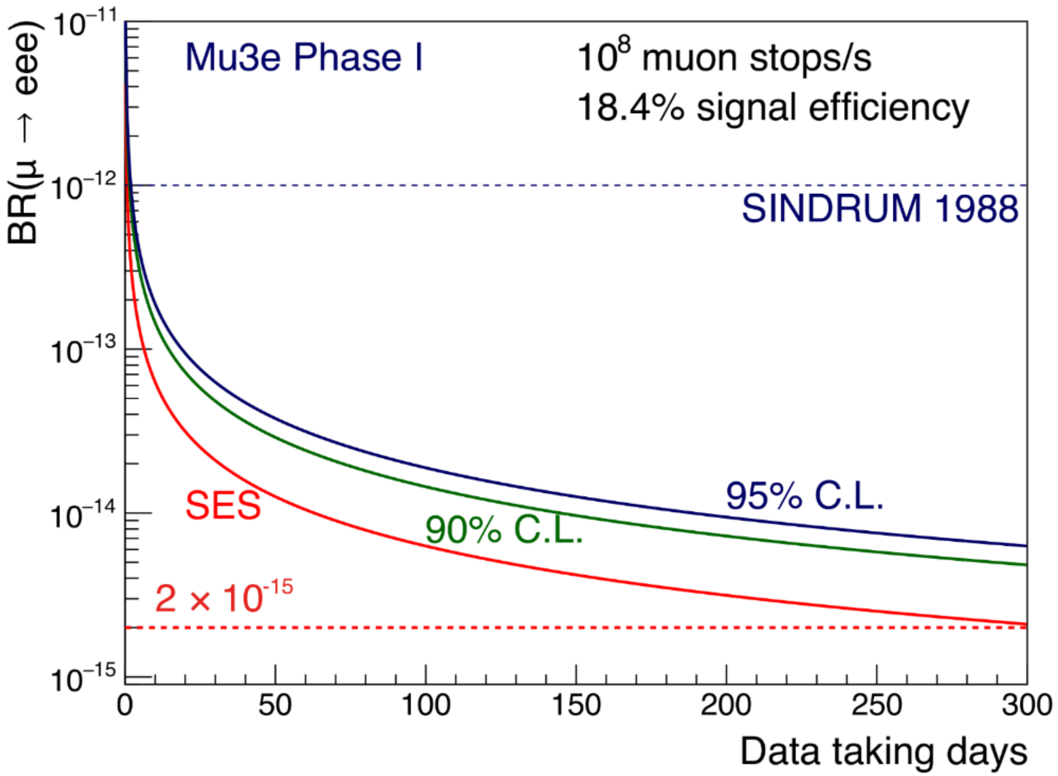
- Vertex measurement
- Enhance momentum measurement with recurlers
- Enhance time measurement with tiles



Simulated Performance

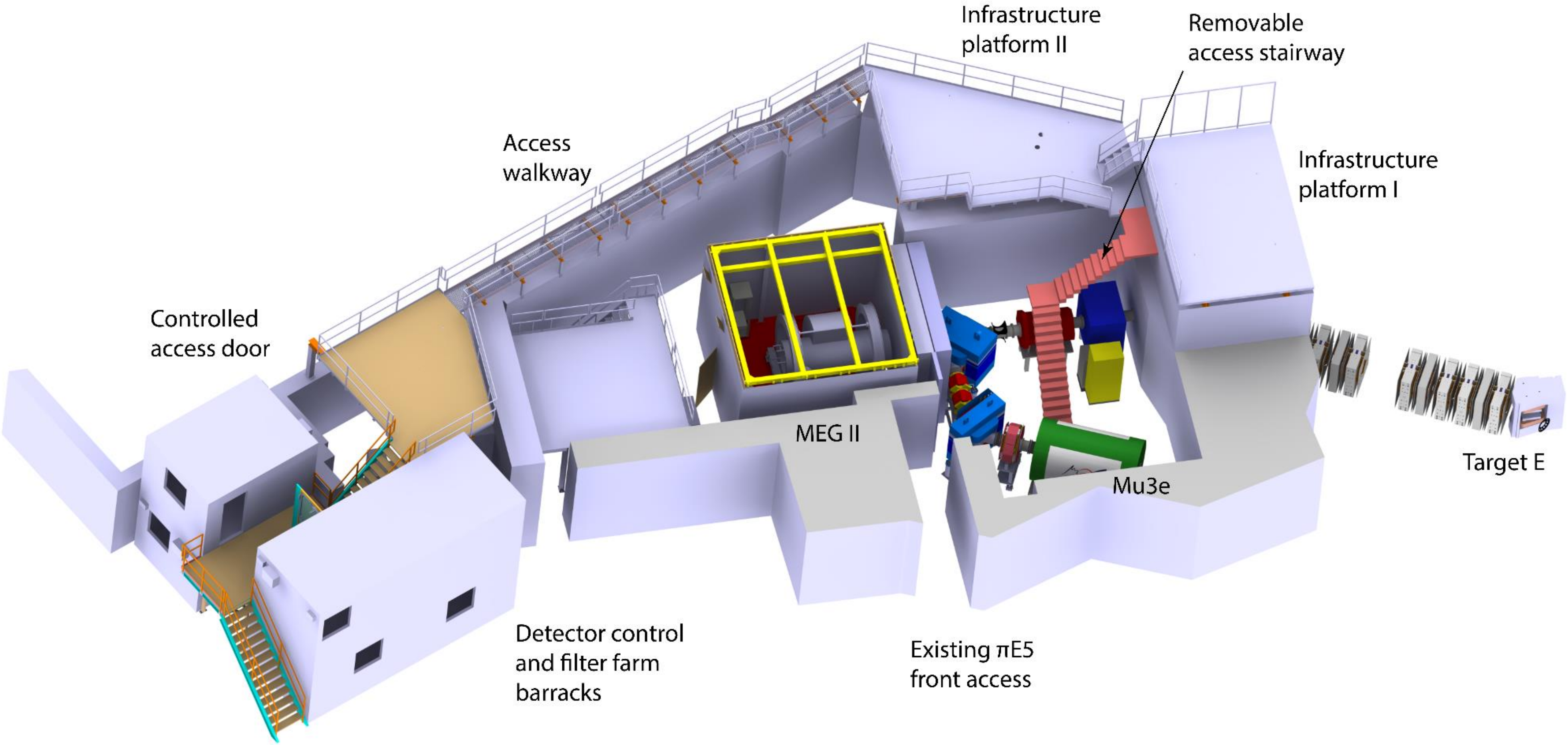


A.-K. Perrevoort. "Sensitivity Studies on New Physics in the Mu3e Experiment and Development of Firmware for the Front-end of the Mu3e Pixel Detector". PhD Thesis, Heidelberg University



Experimental Infrastructure

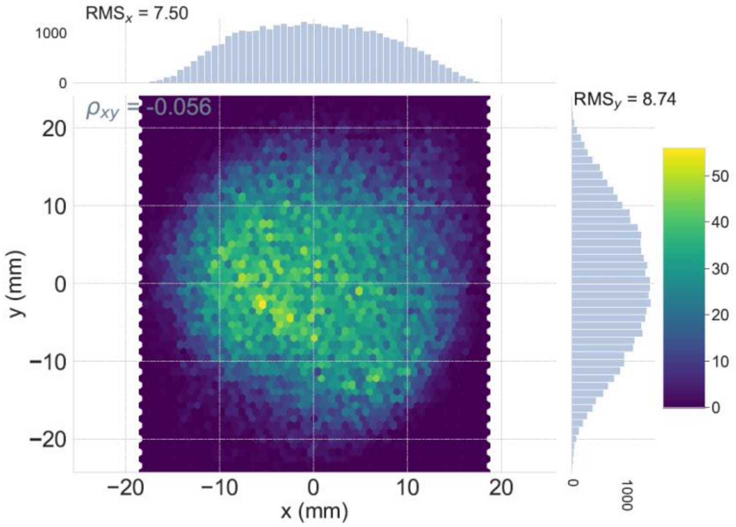
Experimental Area @ PSI



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

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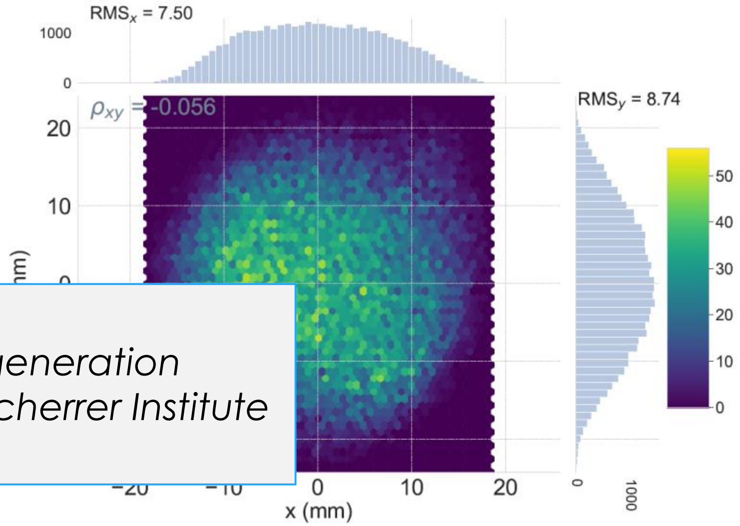


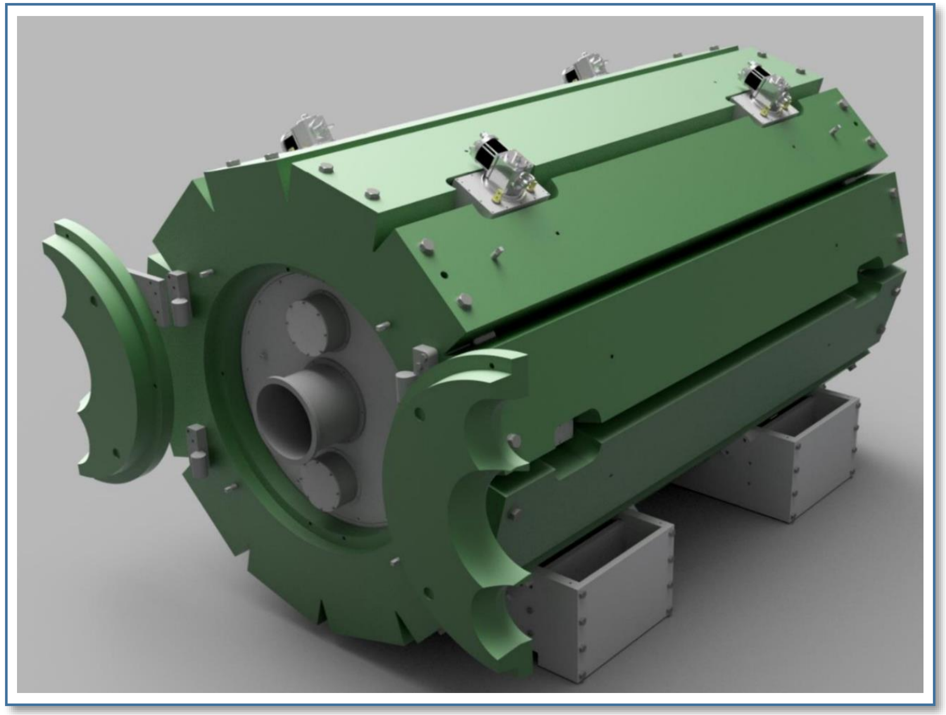
Talk this afternoon:
Development of next generation muon beams at Paul Scherrer Institute
by Ryoto Iwai

Expected beam spot profile at the Mu3e target position

The Mu3e Solenoid

- Being produced by Cryogenic Ltd.
- Magnetic field range 0.5 – 2.0 Tesla
- Very homogeneous magnetic field in a large volume > 2 m³

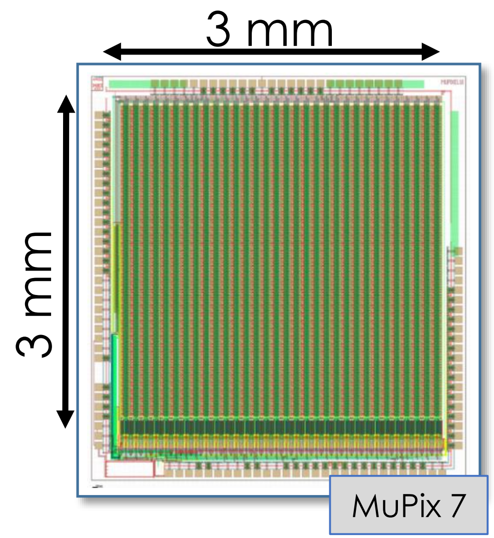
$$\frac{\Delta B}{B} < 2 \cdot 10^{-4}$$

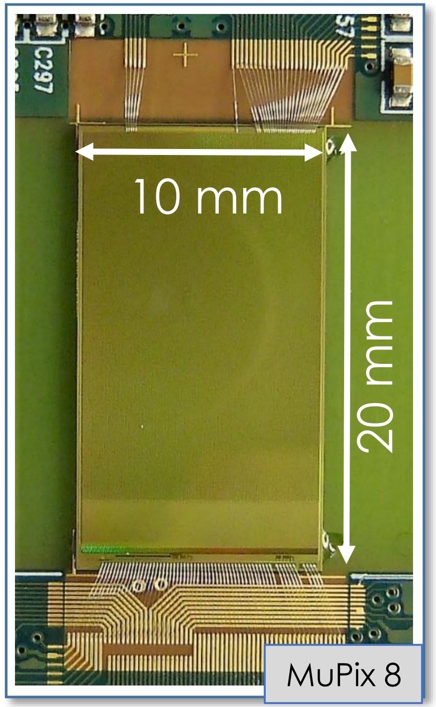


The Pixel Tracking Detector

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



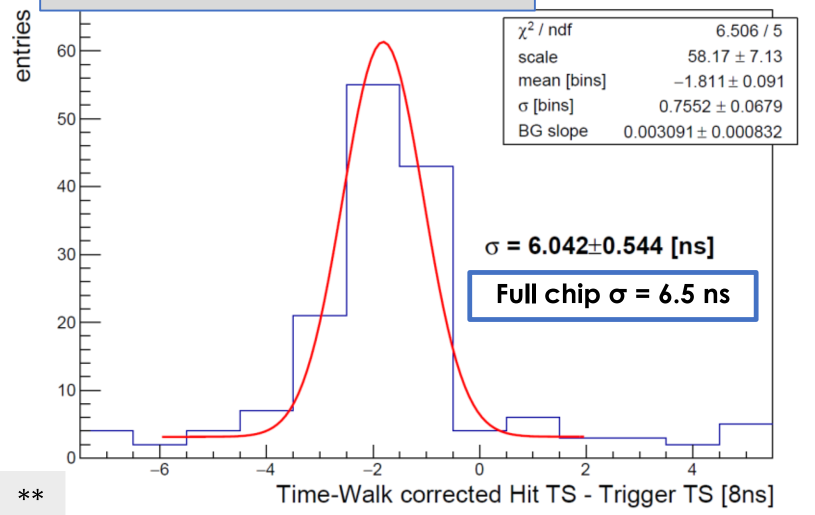


Mu3e requirements	
Efficiency	≥ 99 %
Time resolution	≤ 20 ns

Selected **MuPix8** Results

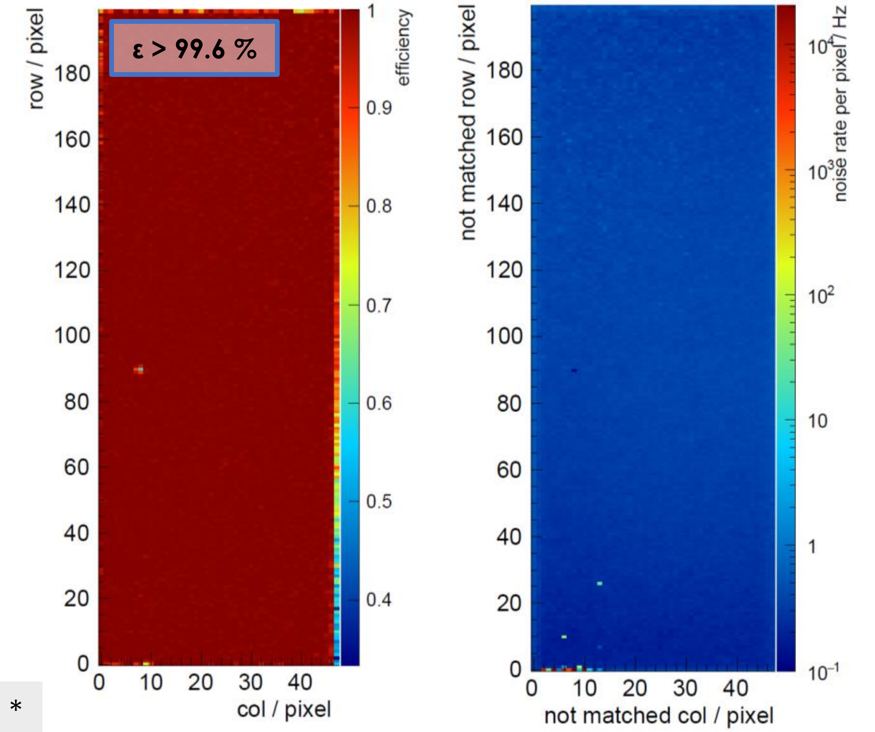
- Extensive lab + test beam characterization: Efficiency, timing, rate capability, irradiation, ...
- Fullfils Mu3e requirements

Single pixel time resolution obtained with Sr-90 source



**

Efficiency/Noise map



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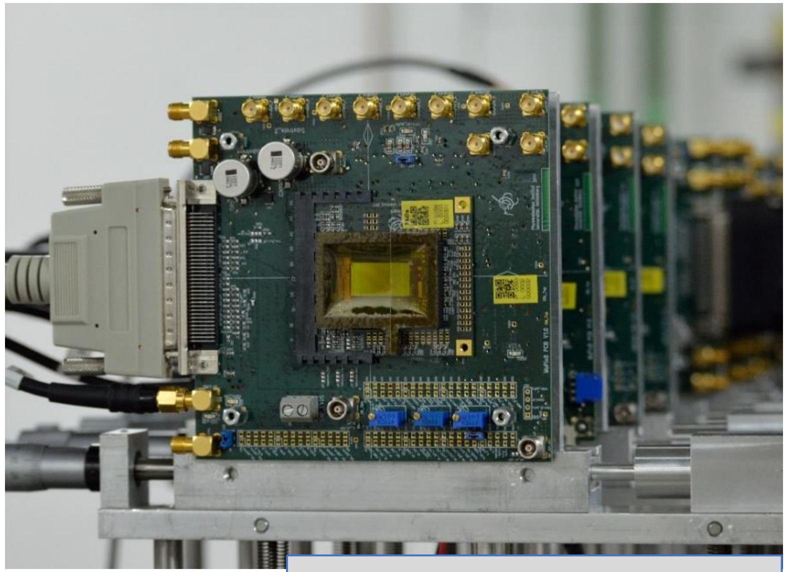
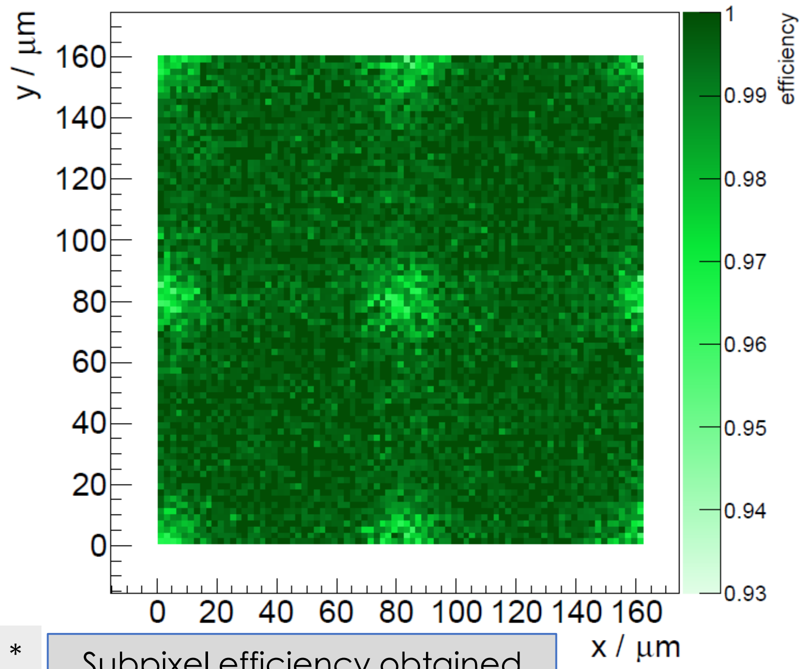


MuPix 8 beam telescope



*

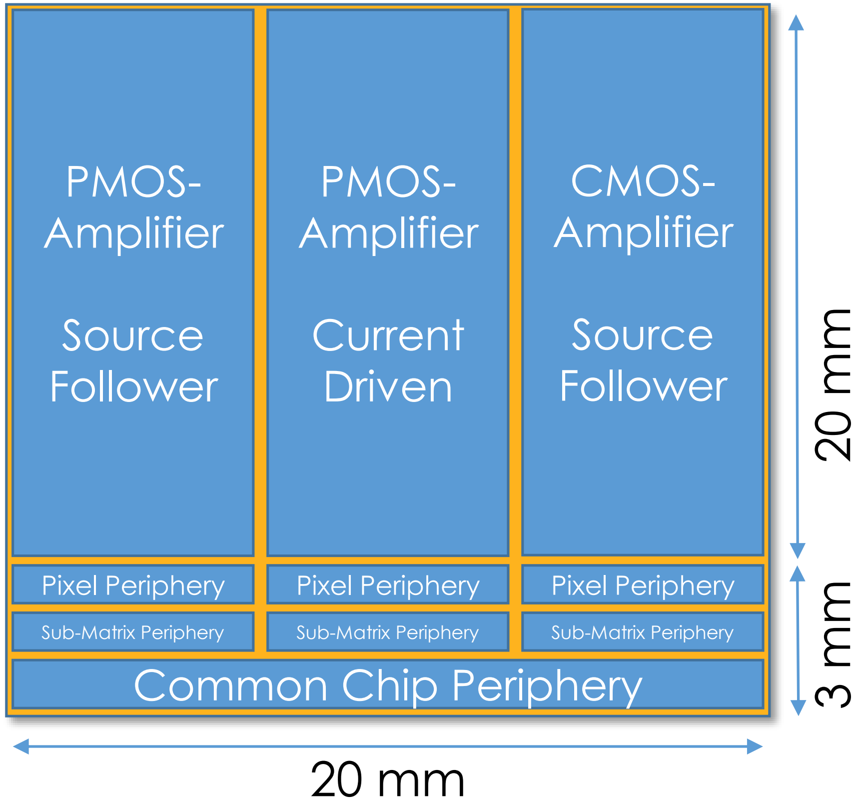
Subpixel efficiency obtained with EUDET Telescope @ DESY
Reduced HV setting

* 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

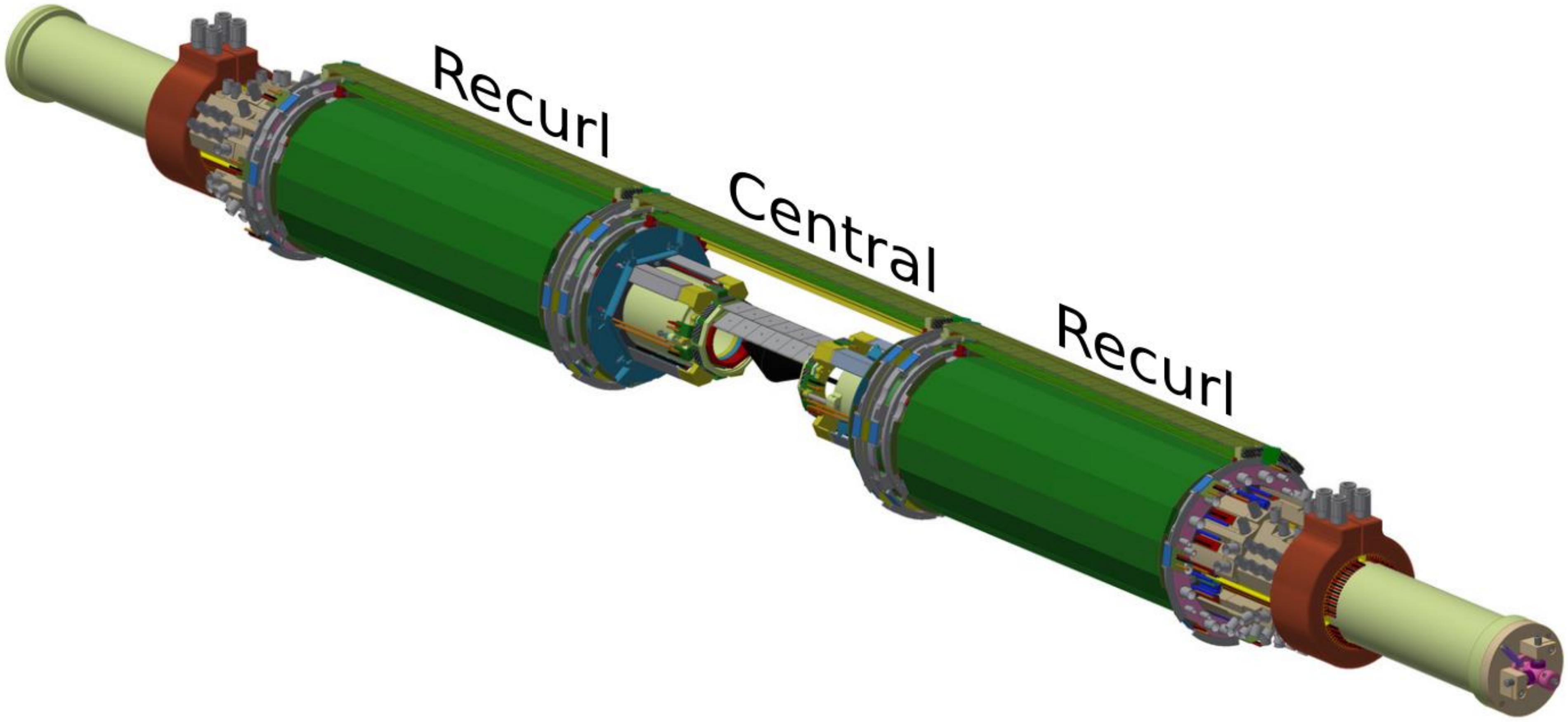
Upcoming Prototype **MuPix10**

Main requirement:
module production readiness

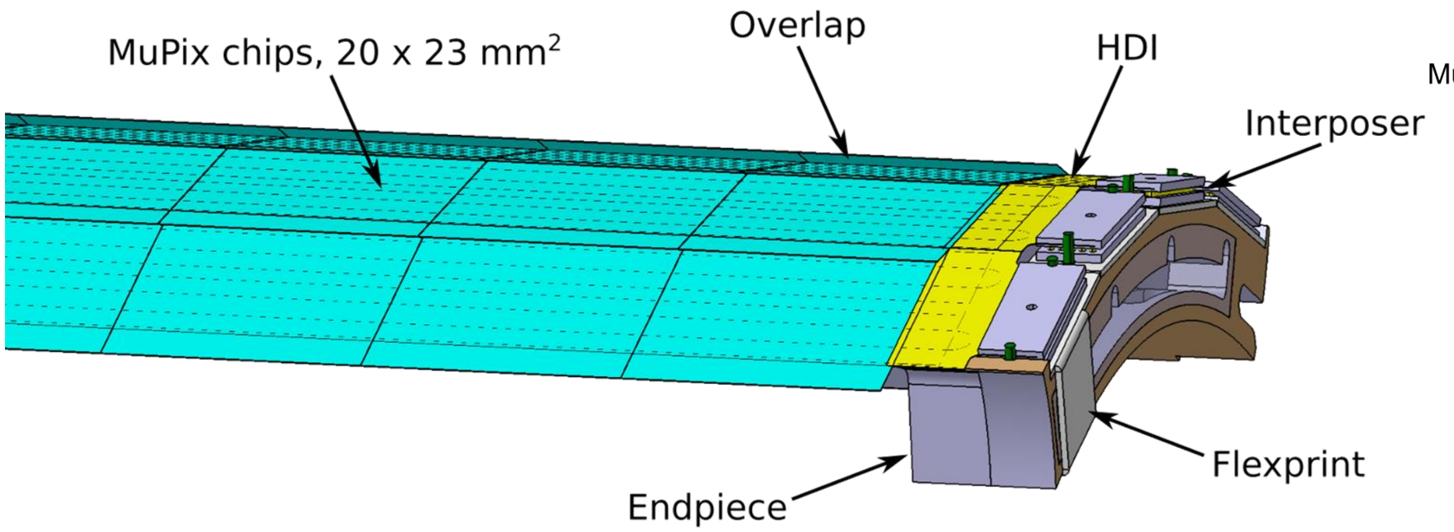
- Full scale $2 \times 2\ \mathrm{cm}^2$ active pixel matrix
- Single non-sensitive edge
- Minimal amount of pad connections
- Last prototype for final design decision

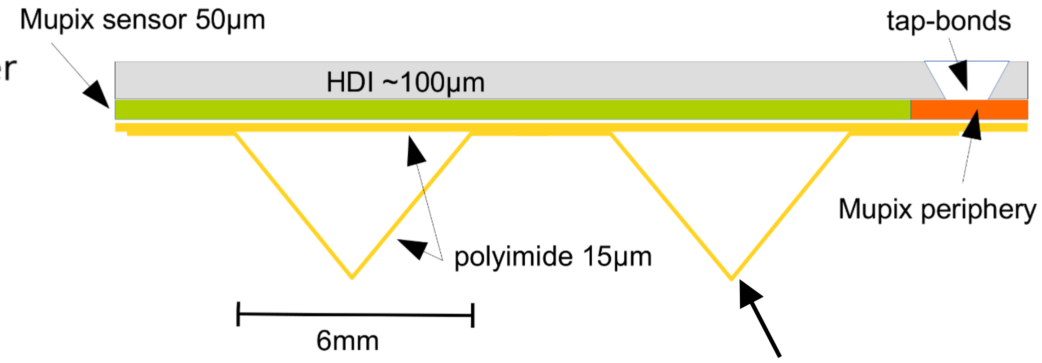


Building the Pixel Tracking Detector



A Tracking Detector Module

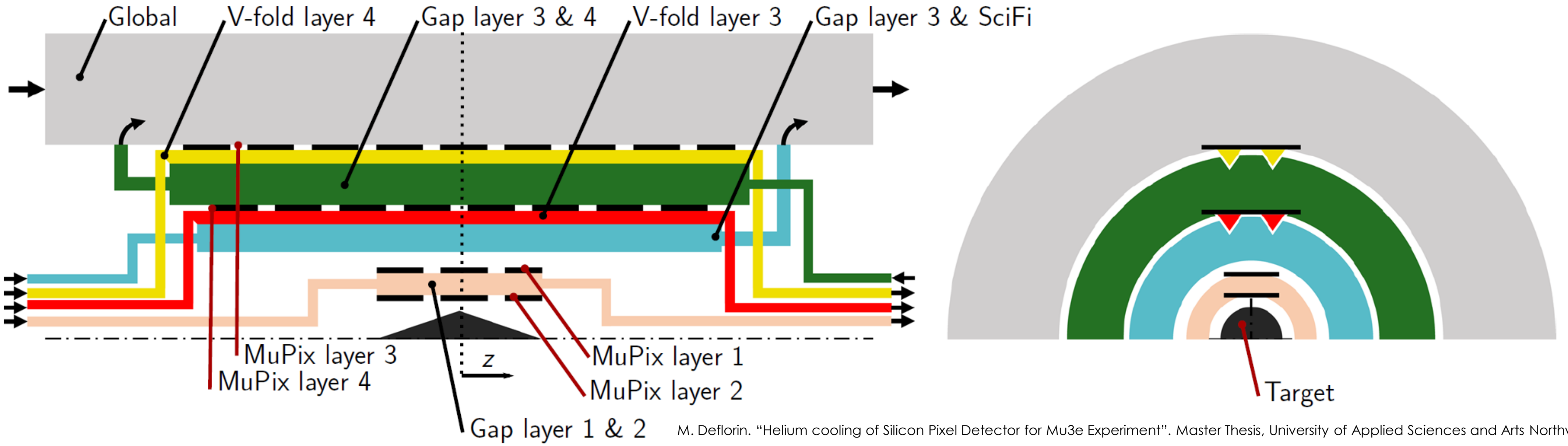




V-channels for support and cooling

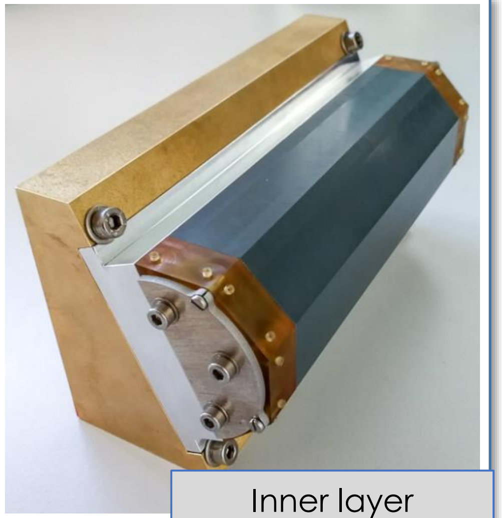
Pixel Tracker Cooling with Helium

- Cooling of sensors required (surface power density up to $400\ \mathrm{mW/cm^2}$)
- As little material as possible
- Gaseous **Helium**: low density, reasonable cooling capabilities



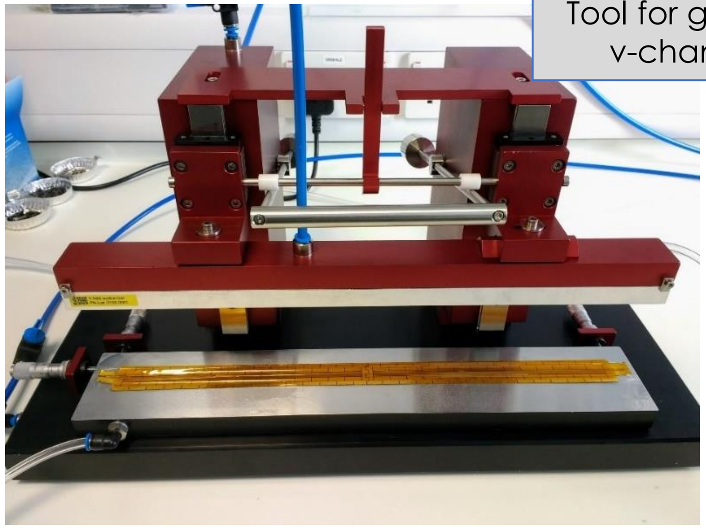
M. Deflorin. "Helium cooling of Silicon Pixel Detector for Mu3e Experiment". Master Thesis, University of Applied Sciences and Arts Northwestern Switzerland

Development of Tooling

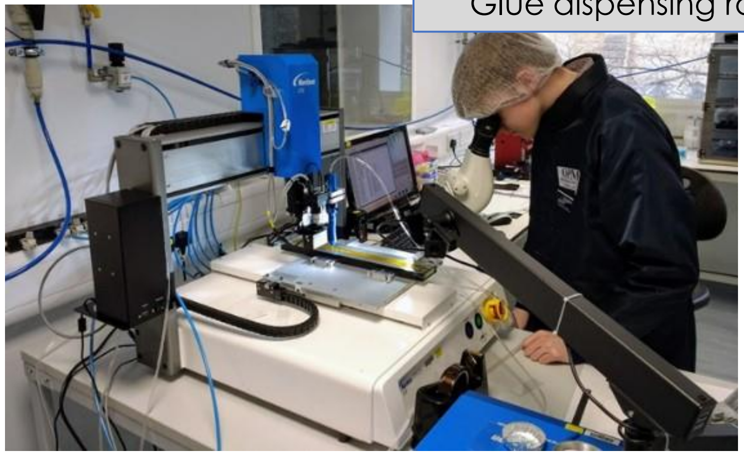


Inner layer assembly tool

Robotic gantry for placement of MuPix chips on vacuum jig



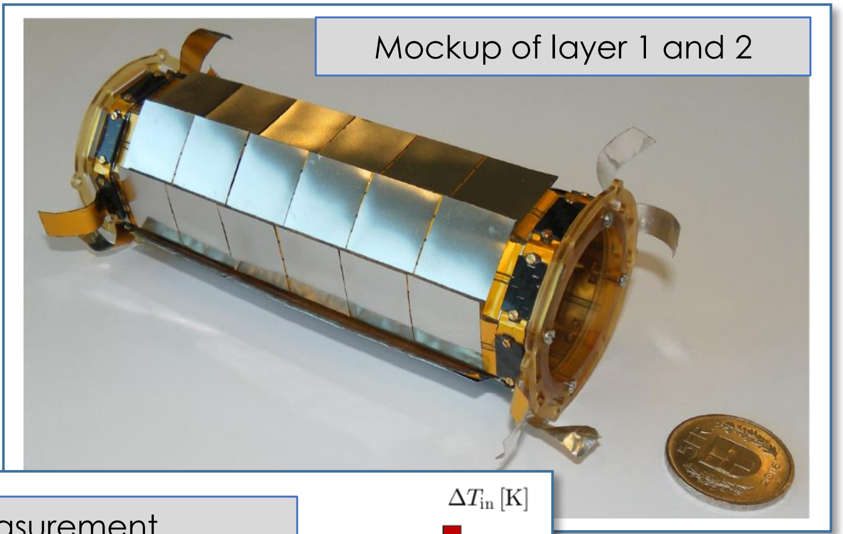
Tool for gluing of v-channels

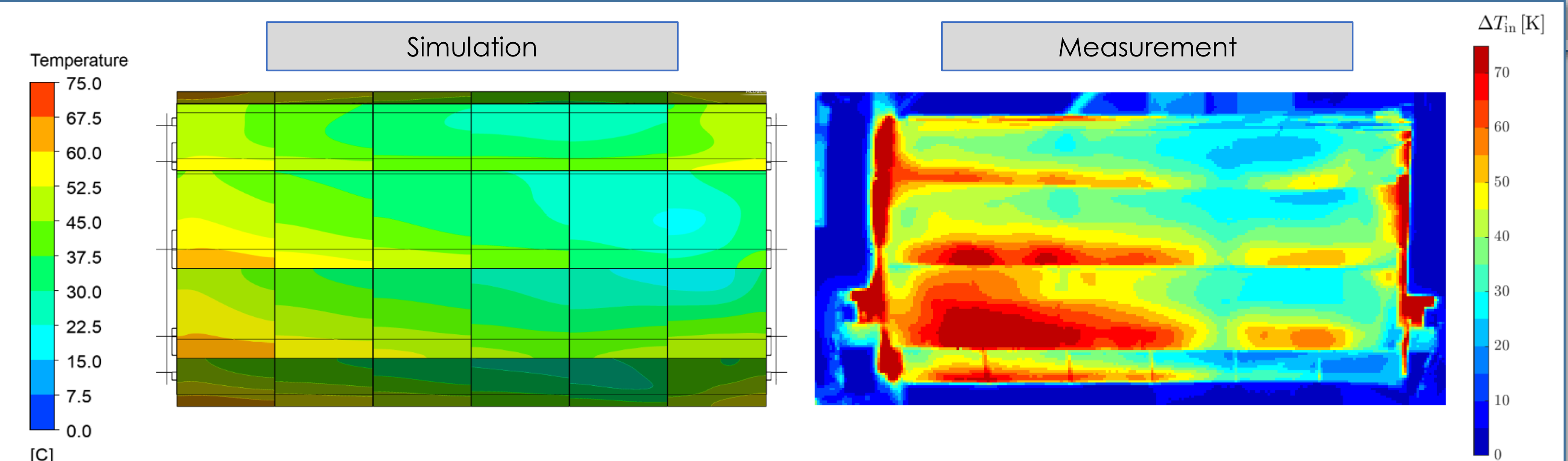


Glue dispensing robot

Thermo-Mechanical Mockup

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





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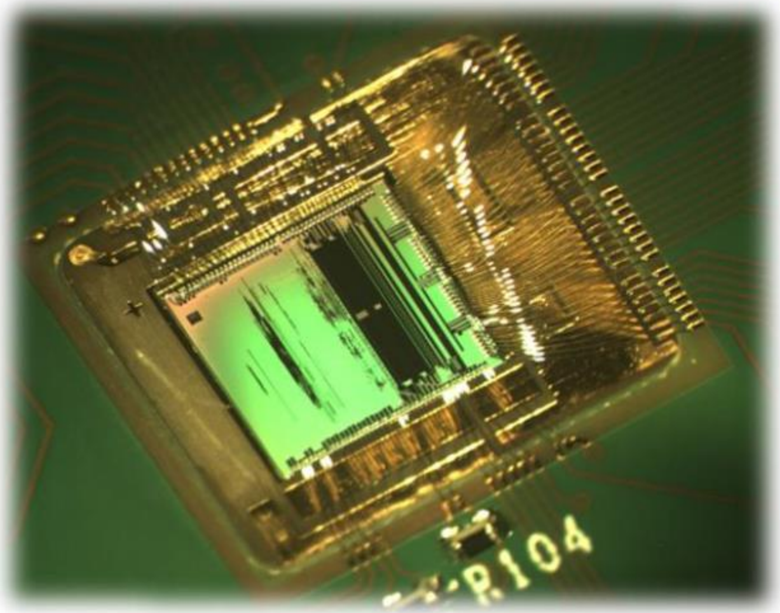
The Timing Detectors

Common Readout ASIC – **MuTRiG**

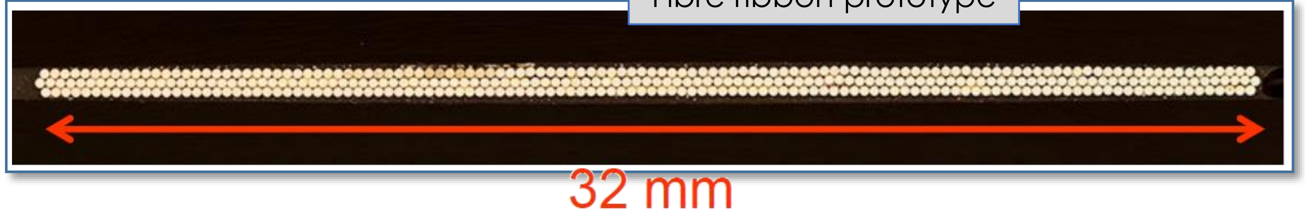
- Both timing detectors use silicon photomultipliers
- Custom designed SiPM readout ASIC: **MuTRiG**
- 32-channels
- **50 ps Time-to-digital converter**



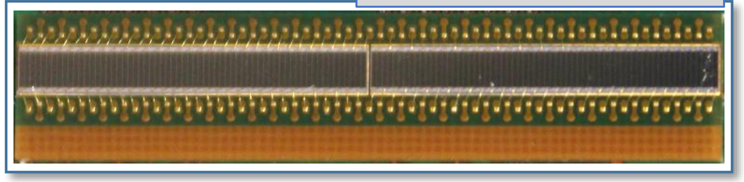
Fibre Detector

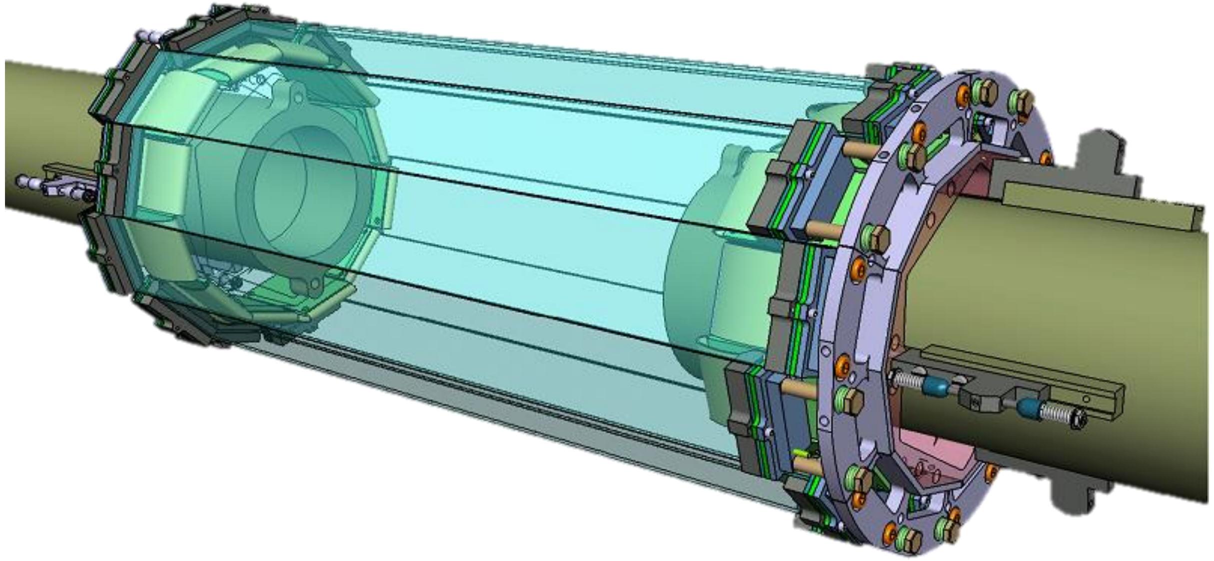
- Precise timing suppresses combinatorial background
- 12 fibre ribbons
  - 30 cm long
  - **3 staggered layers** of $250\ \mu\text{m}$ thin fibres
  - Material budget $< 2‰\ X_0$ fulfills requirement $\leq 3‰\ X_0$
- 128 channel **SiPM column arrays**
- Complete mechanical CAD-model

Fibre ribbon prototype



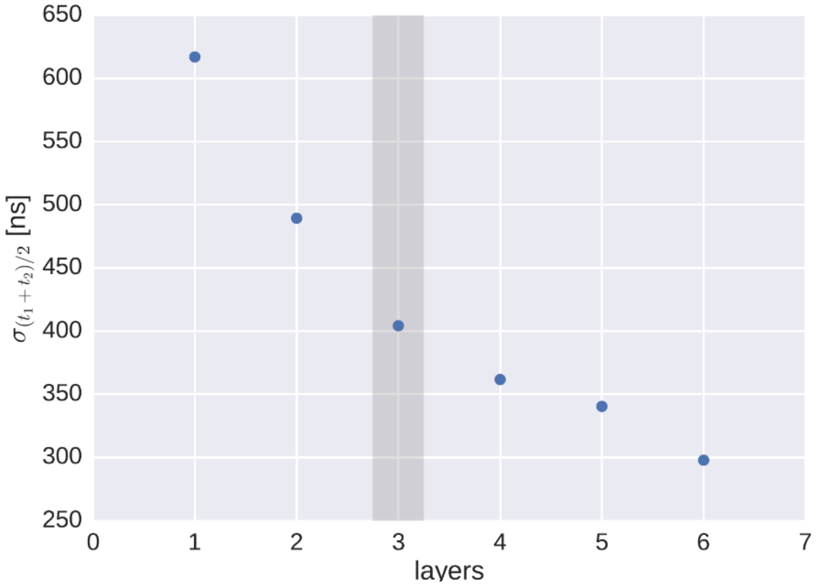
SiPM column array

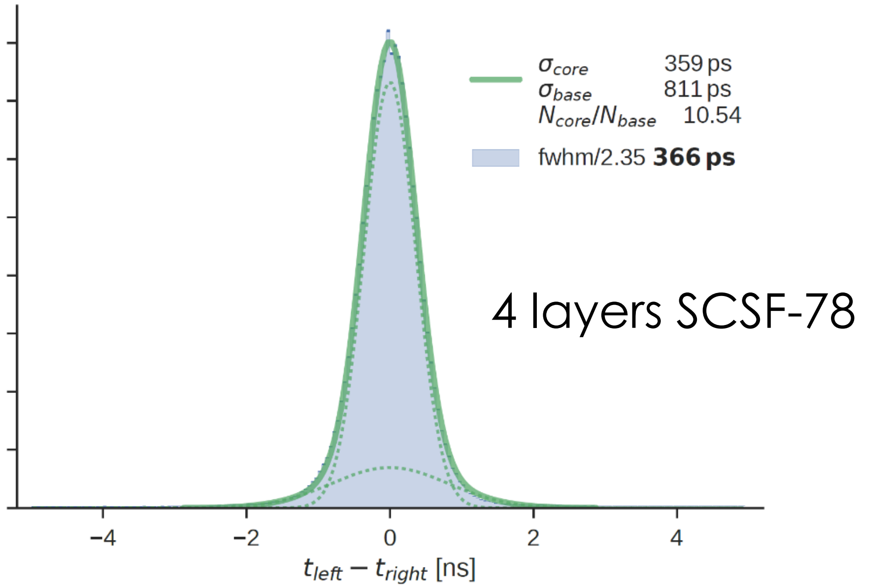




Fibre Detector Studies

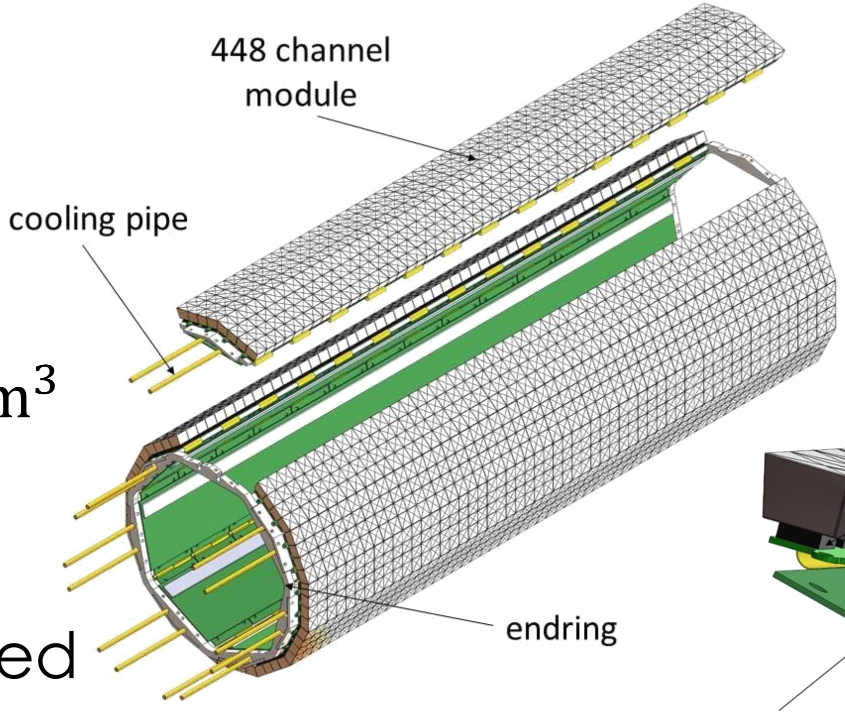
- Studied different **fibre types**
- **Number of fibre layers**:
  Trade-off
  timing, efficiency ↔ material budget
- Required time resolution < 500 ps
  - **Fulfilled by prototypes including readout ASIC**
  - Efficiency > 95 %

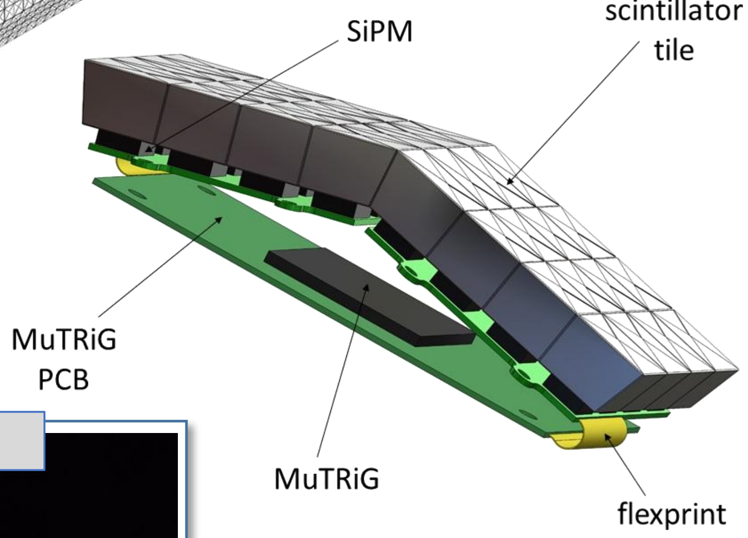


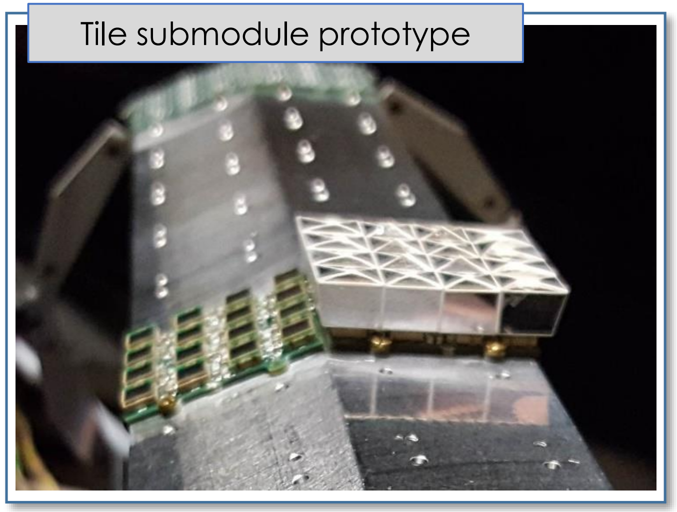


Tile Detector

- Scintillating tiles $6 \times 6 \times 5\ \mathrm{mm}^3$
- Complete mechanical CAD-model
- Prototype modules produced
- Required time resolution < 100 ps
- Test beam: **single channel time resolution** of **45 ps**

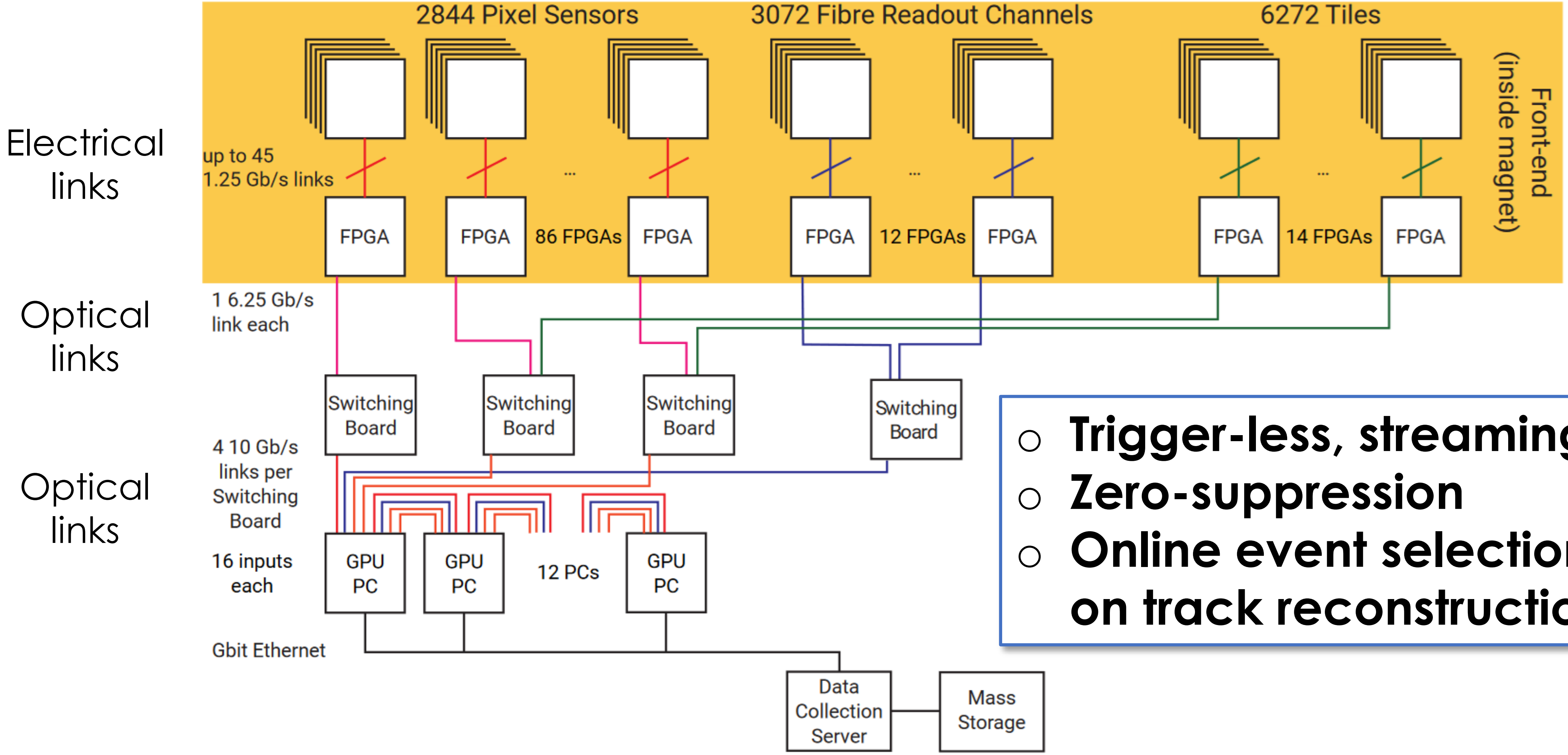






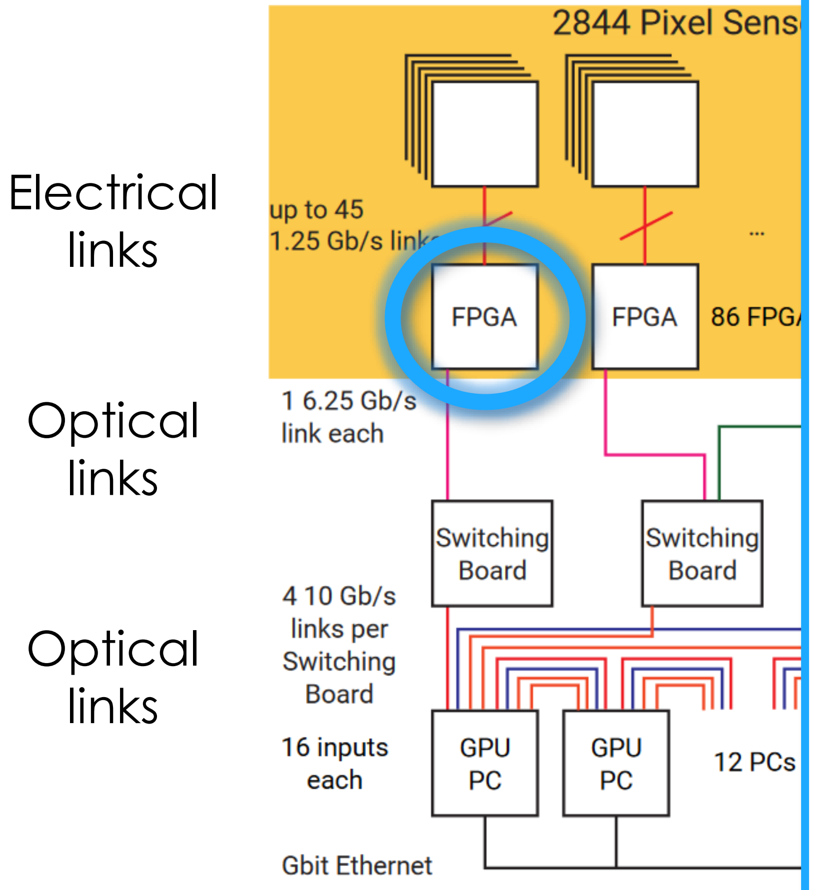
The Readout System

The Mu3e Readout Concept



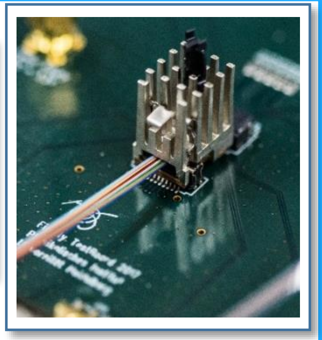
- **Trigger-less, streaming readout**
- **Zero-suppression**
- **Online event selection based on track reconstruction**

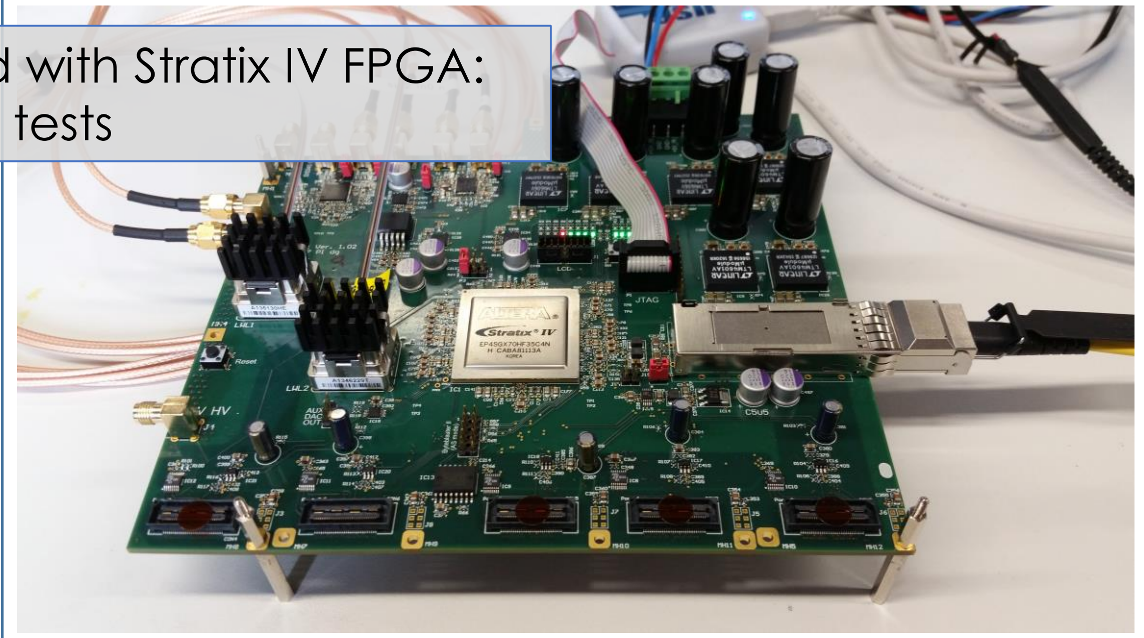
The Mu3e Readout Concept



The Front-end Board

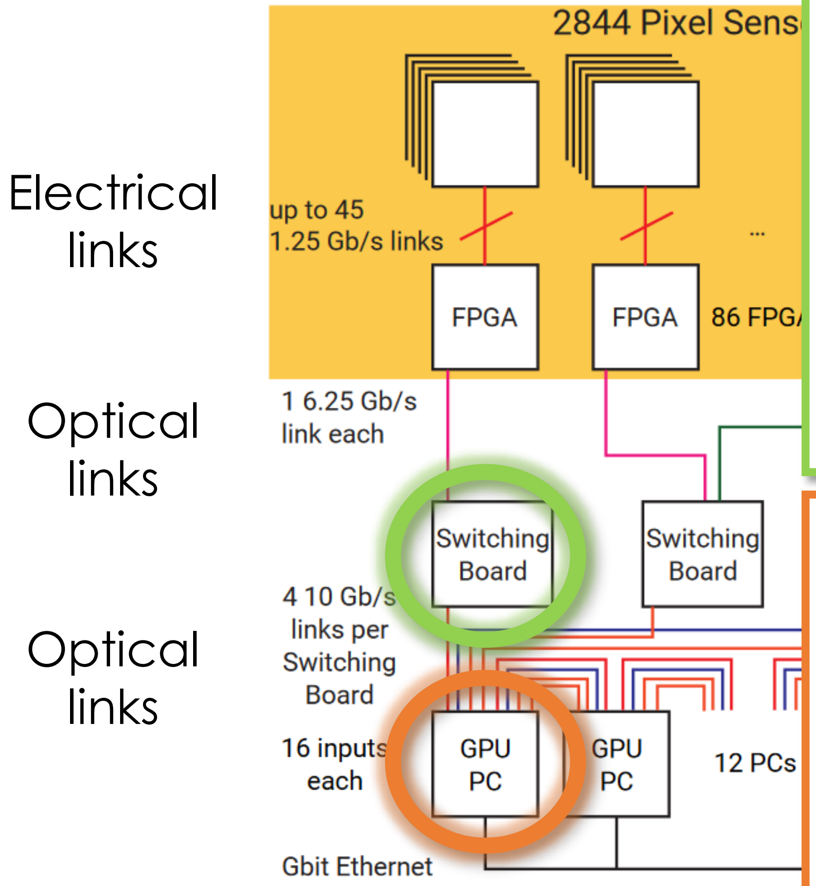
- **Sorts** hits by timestamps
- Distributes clock and reset to ASICs
- Custom designed board





Prototype board with Stratix IV FPGA: first vertical slice tests

The Mu3e Readout Concept



The Switching Board

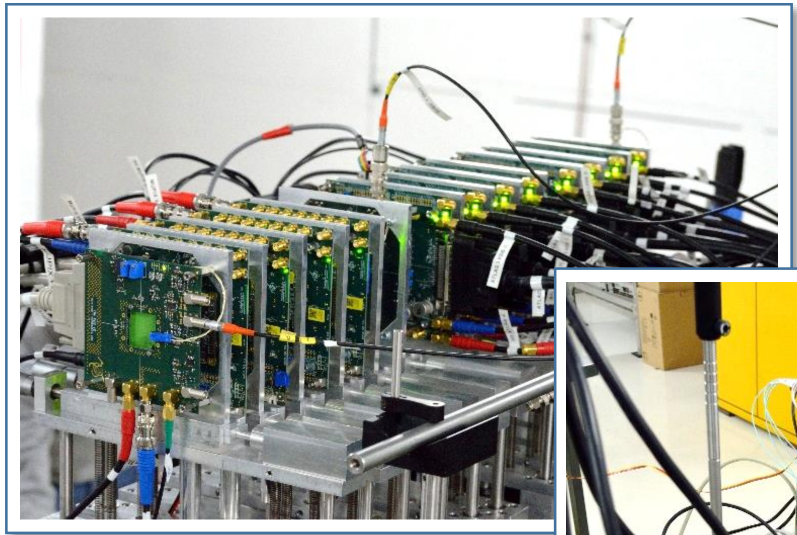
- **Collects** data of several front-end boards
- **Merges** into single data stream
- PCIe40 board (LHCb)

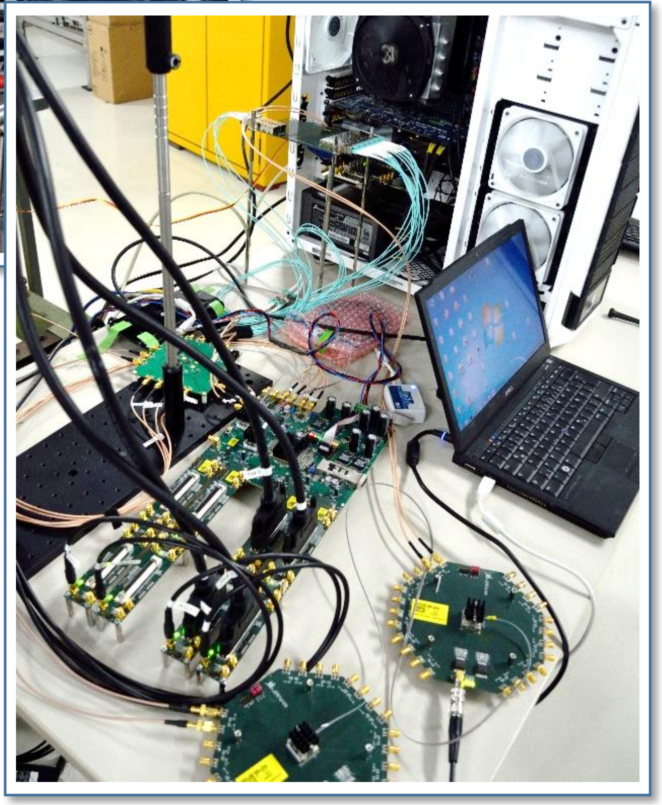
The GPU Filter Farm

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

Pixel Readout Integration

- 8 × **MuPix8** as a beam telescope
- Parallel operation using one **front-end board prototype**
- Performed rate scans up to ~ 10 MHz per sensor
- Checked performance of
  - Sensor data links
  - Firmware implementation
- **First vertical slice tests successful**
- Timing detectors currently working on vertical slice tests





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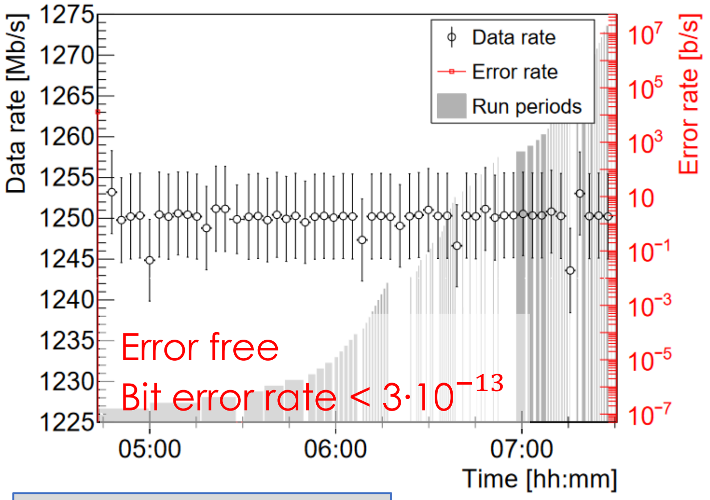
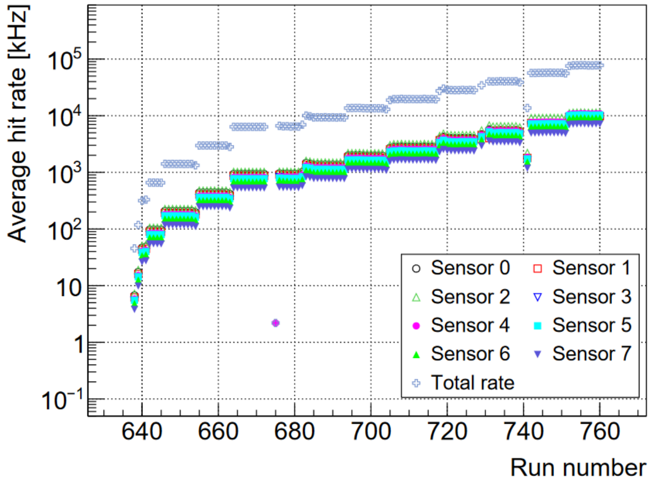
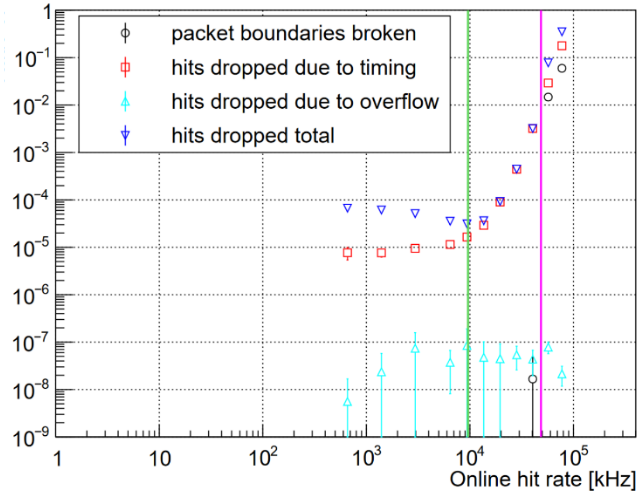
Bit error rate monitoring of sensor serial data link



Rate scan

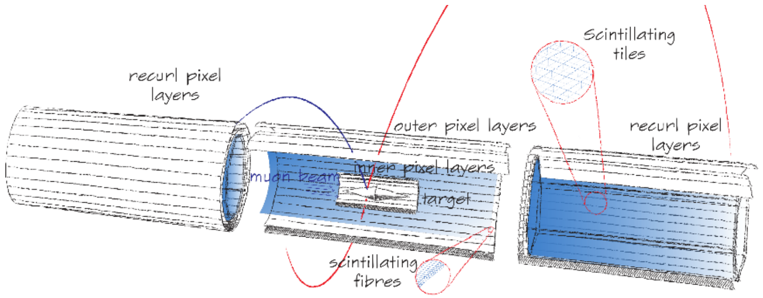


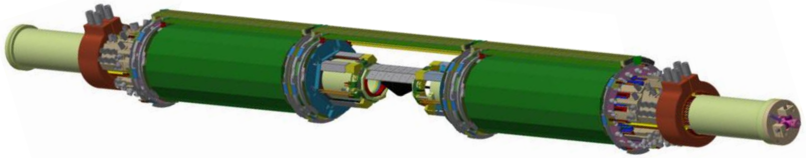
Performance test of sorting algorithm

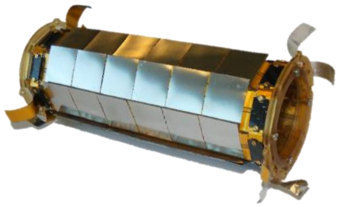


S, Dittmeier. "Fast data acquisition for silicon tracking detectors at high rates". PhD Thesis, Heidelberg University

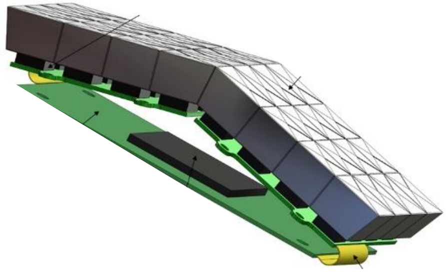
Summary and Outlook

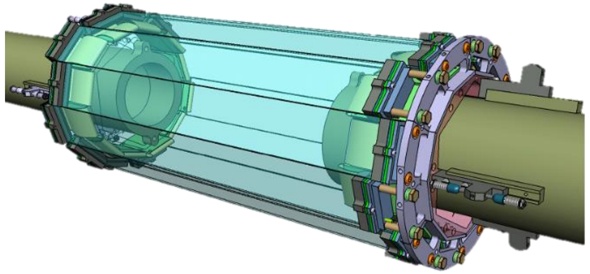






- Mechanical design including services available
- Thermo-mechanical mockup
  - Verify and optimize cooling/mechanical concepts
  - Continuation with outer layers and silicon heater chips
- Production readiness of all detectors expected within 2020
- Pixel detector
  - MuPix10 upcoming prototype (submission soon)
  - Modules: study operation of a MuPix sensor on an HDI
- Vertical slice tests of pixel and timing detectors





The Mu3e Collaboration

About 60 members from 12 institutes

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

University of Geneva
Paul Scherrer Institute
ETH Zurich
University Zurich

Bristol
Liverpool
Oxford
UC London

Acknowledgements

Many important test beam campaigns have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).

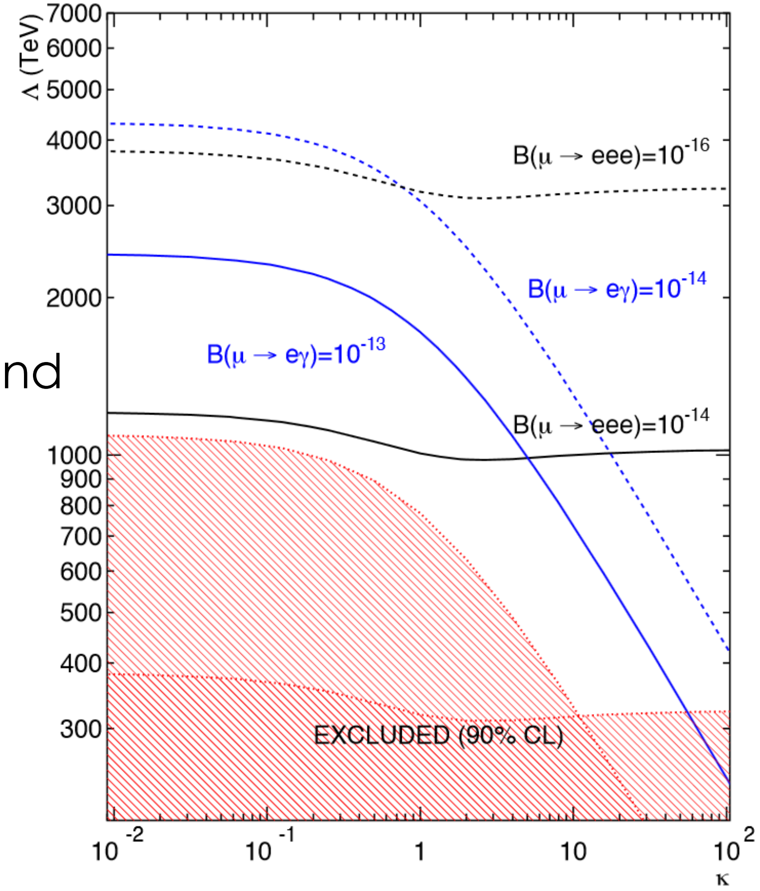
We would like to thank the PSI for providing high rate test beams under excellent conditions.

We thank the Institut für Kernphysik at the JGU Mainz for giving us the opportunity to take data at MAMI.

Backup

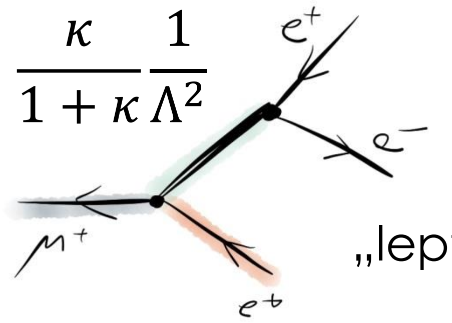
Searching for New Physics with Mu3e

Considers effective Lagrangian with dipole and four fermion interaction



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

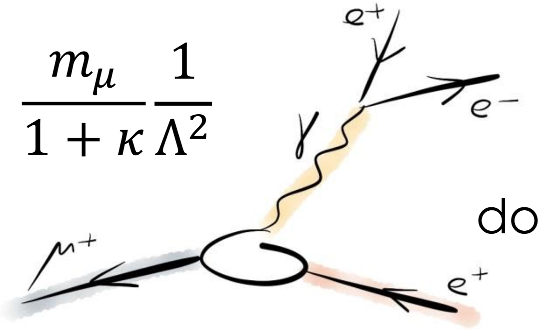
$$\frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}$$



Four fermion
dominates for large κ
At tree level for
„leptons only“-Lagrangian

+

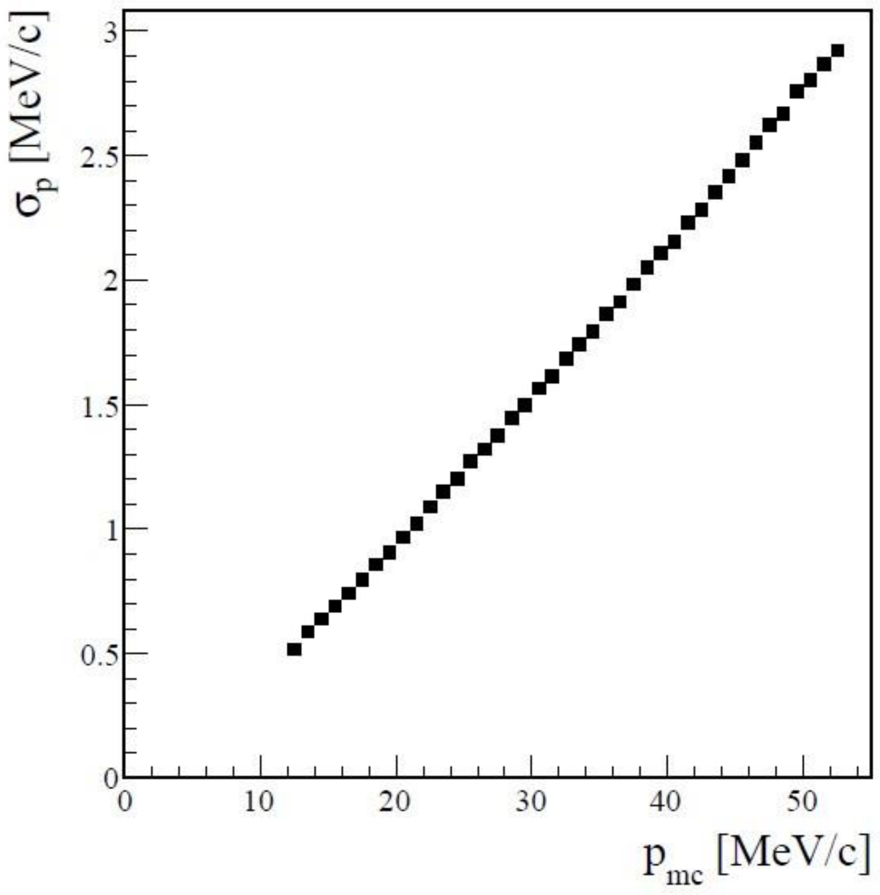
$$\frac{m_\mu}{1+\kappa}\frac{1}{\Lambda^2}$$



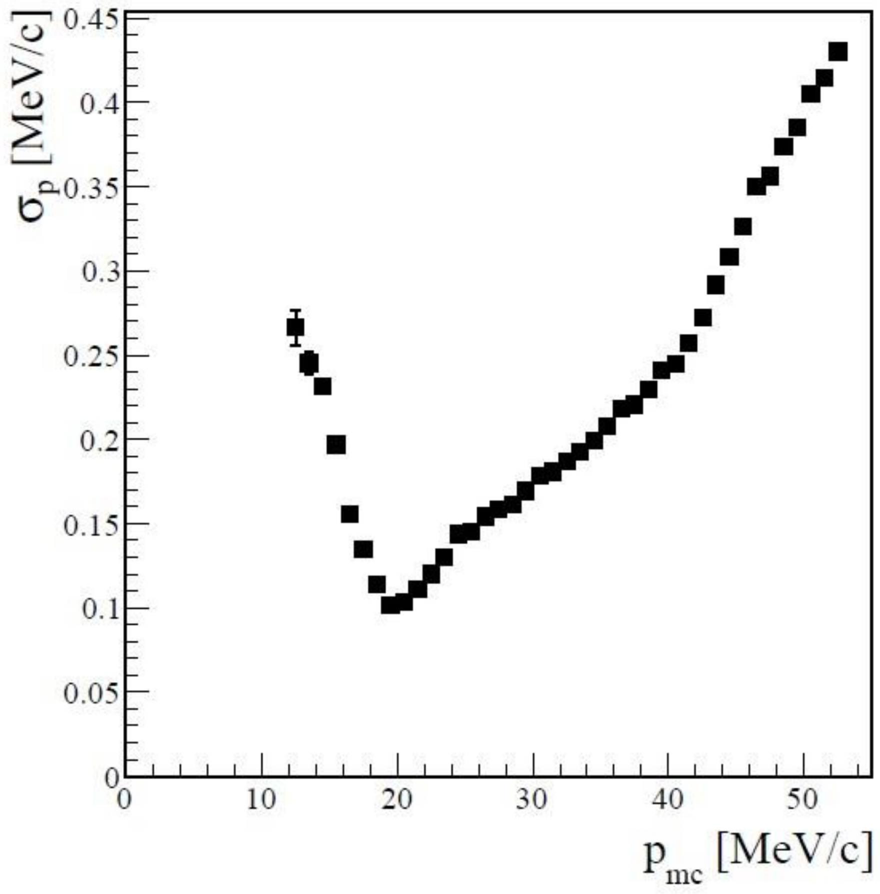
Dipole type
dominates for small κ

Simulation: Momentum Resolution

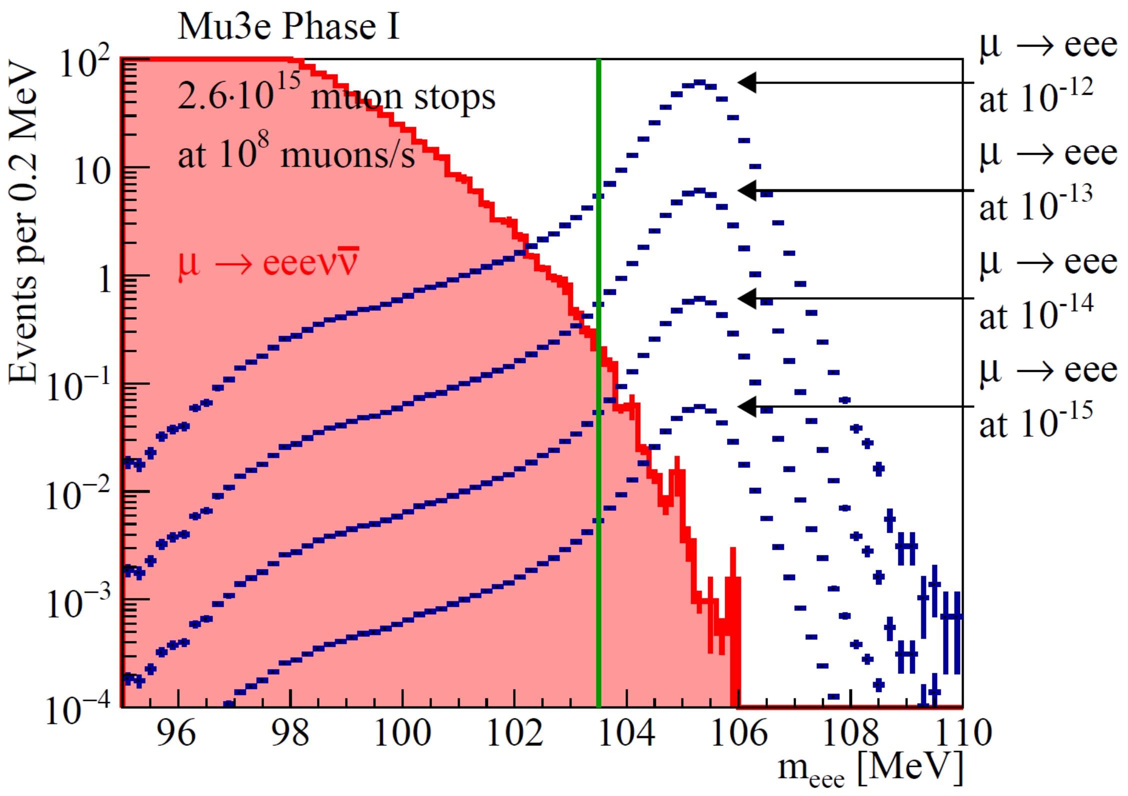
Short Tracks (4 hits)

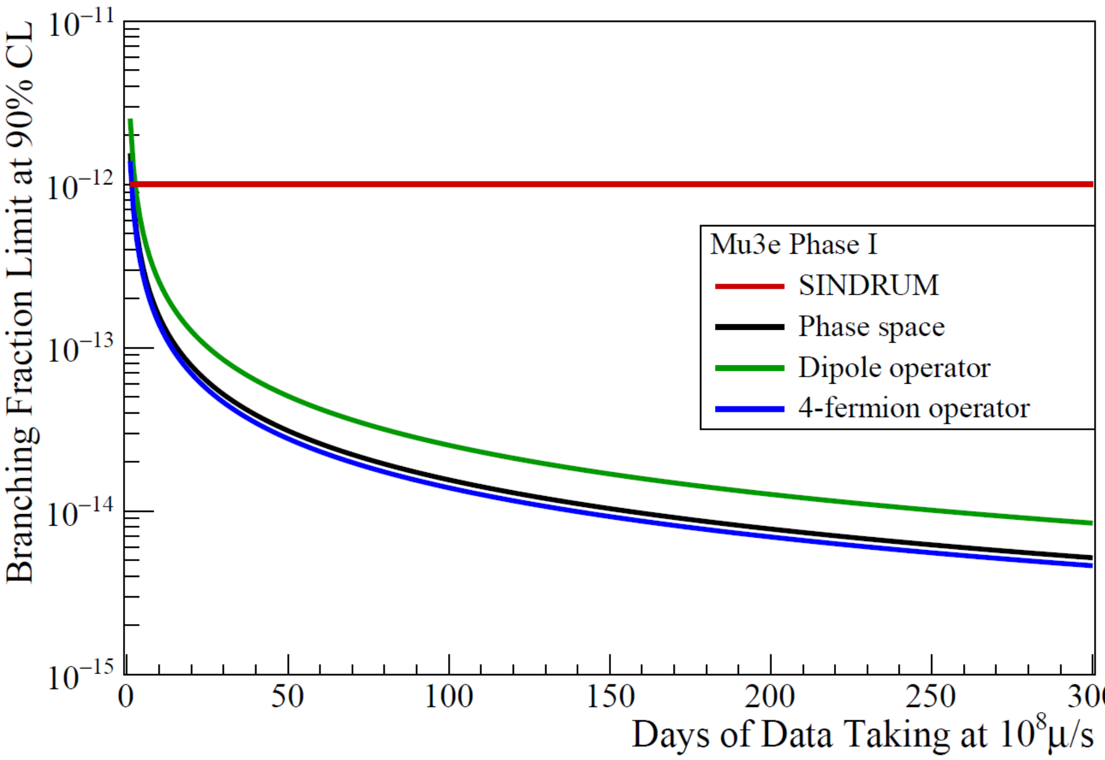


Long Tracks (6 hits, recurlers)



Simulated Performance

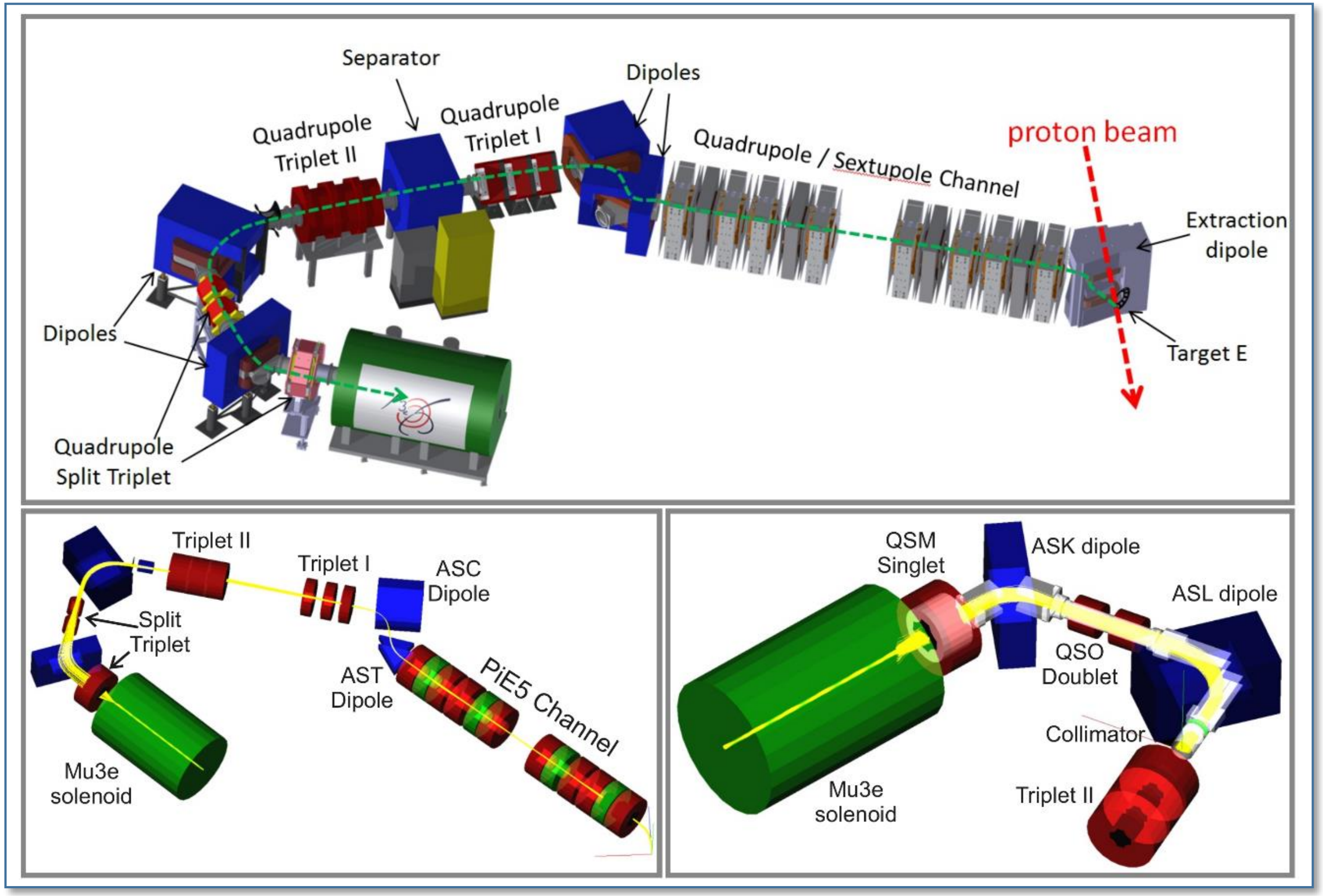




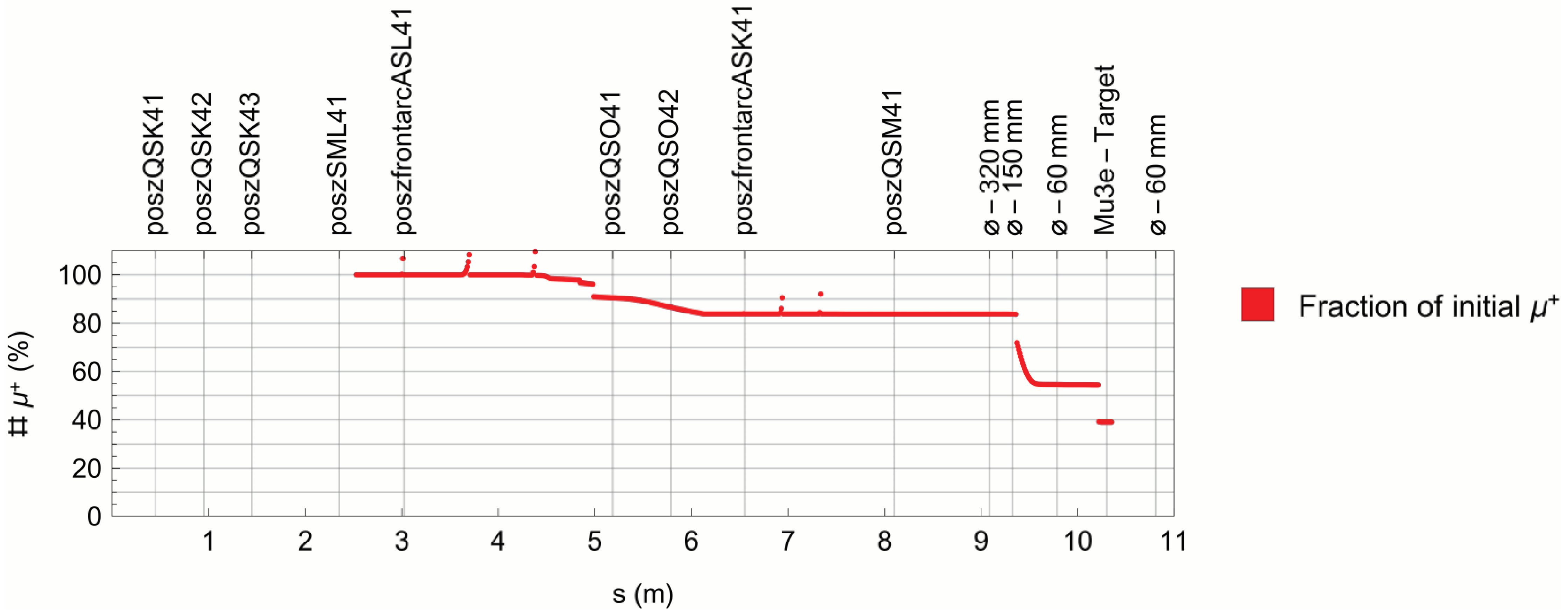
A.-K. Perrevoort. "Sensitivity Studies on New Physics in the Mu3e Experiment and Development of Firmware for the Front-end of the Mu3e Pixel Detector". PhD Thesis, Heidelberg University

Experimental Area

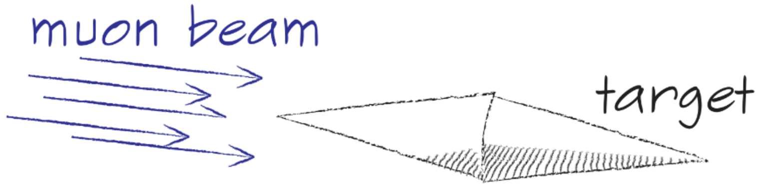
Muon Beam


Separator
Dipoles
Quadrupole Triplet II
Quadrupole Triplet I
Quadrupole / Sextupole Channel
proton beam
Extraction dipole
Target E
Dipoles
Quadrupole Split Triplet
Triplet II
Triplet I
ASC Dipole
Split Triplet
AST Dipole
PiE5 Channel
Mu3e solenoid
QSM Singlet
ASK dipole
ASL dipole
QSO Doublet
Collimator
Triplet II
Mu3e solenoid

Beam losses along the beam line

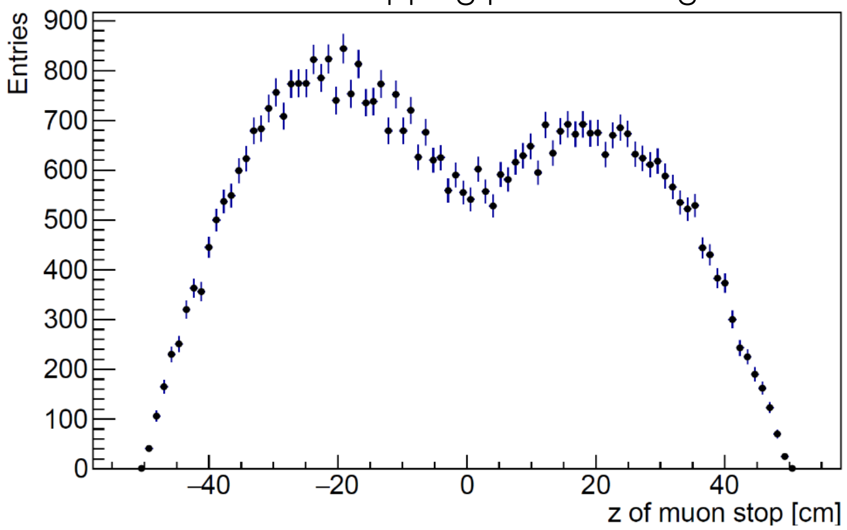


Inside 1 T magnetic field



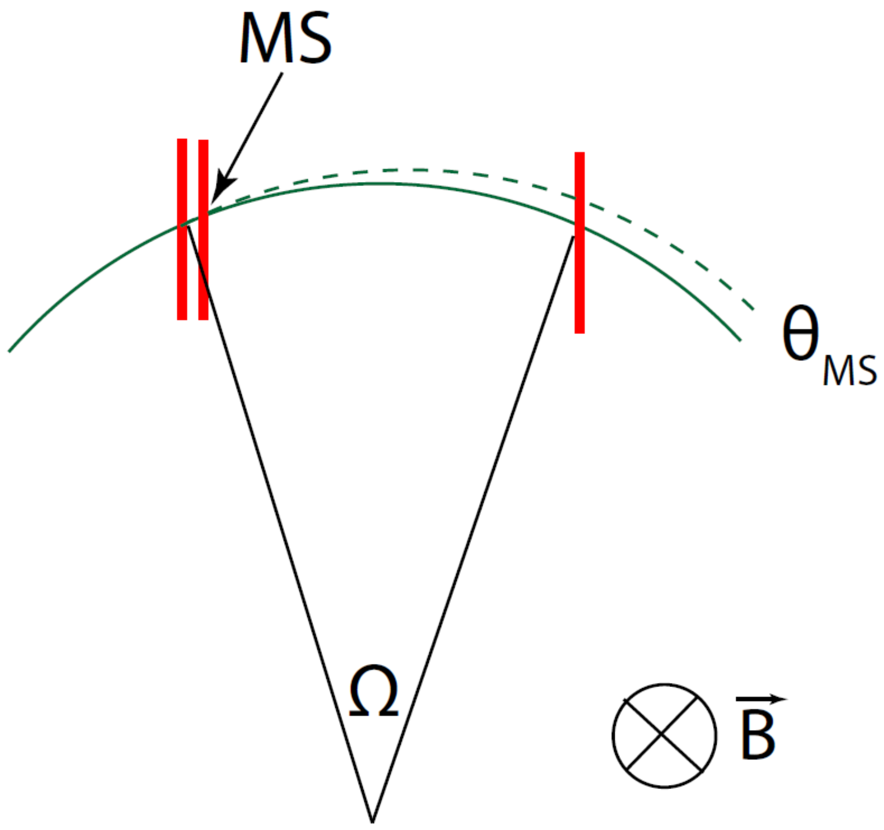
Stopping target prototype

Simulation of stopping power of target



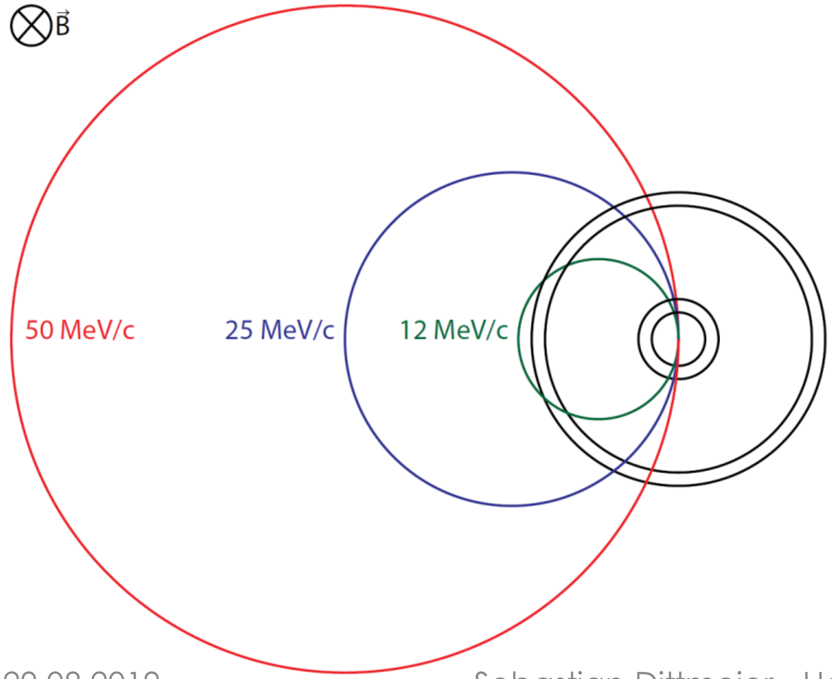
Momentum Measurement

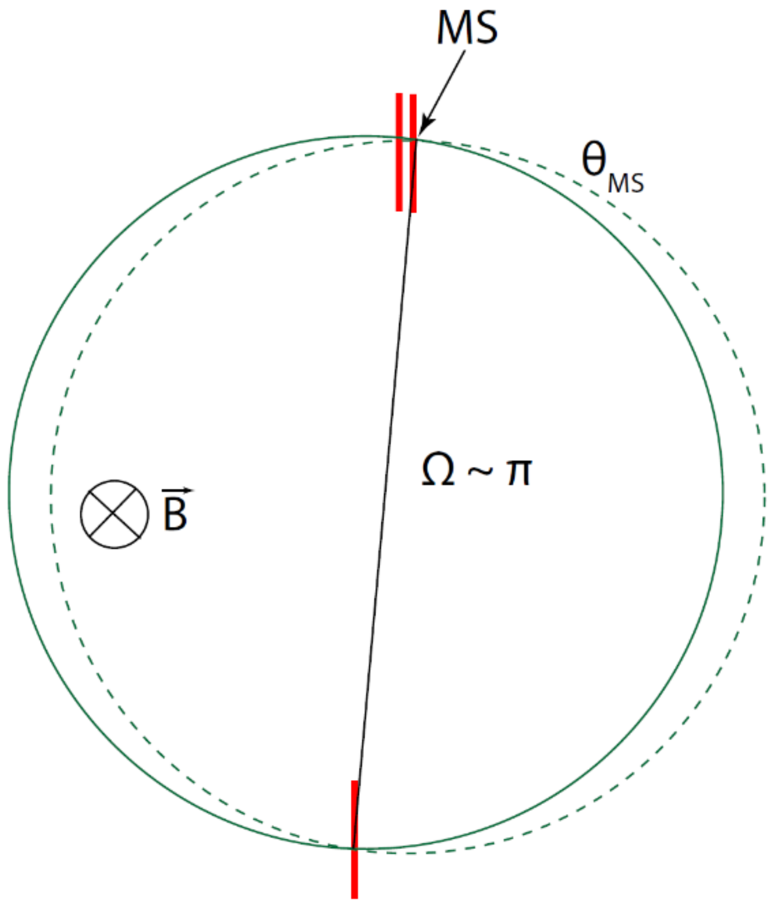
- Stopped muons
  $\rightarrow$ **low momentum e^-e^+**
- Momentum resolution limited by **multiple scattering**
- Advantageous:
  - Large lever arm Ω
  - Low multiple scattering θ_{MS}
    $\rightarrow$ Material budget $\leq$ **1‰ X_0** per layer



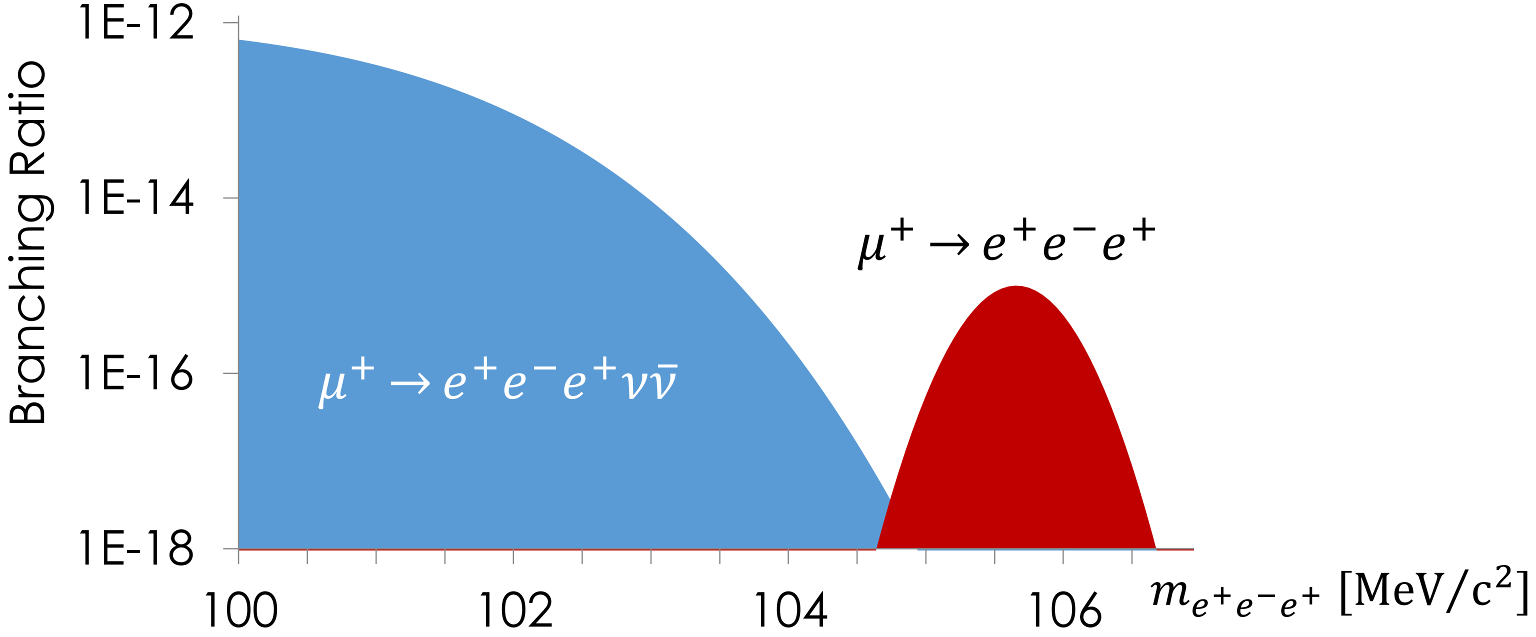
Enhancing Momentum Measurement

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





Invariant Mass Resolution

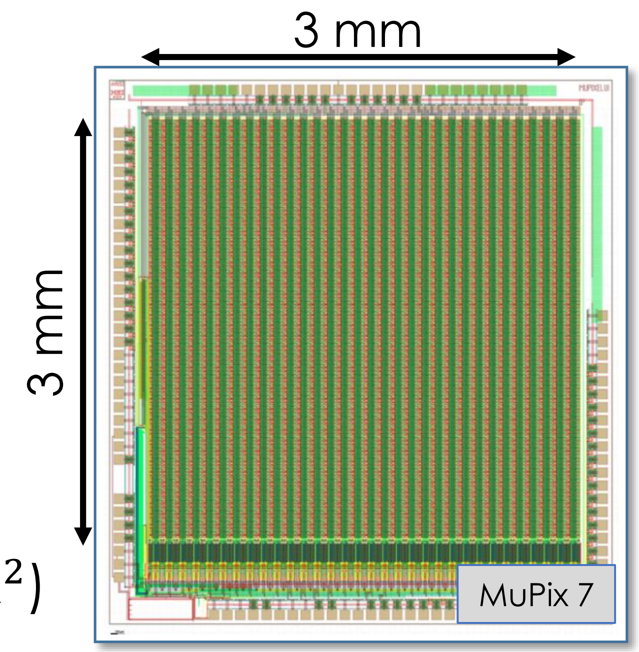


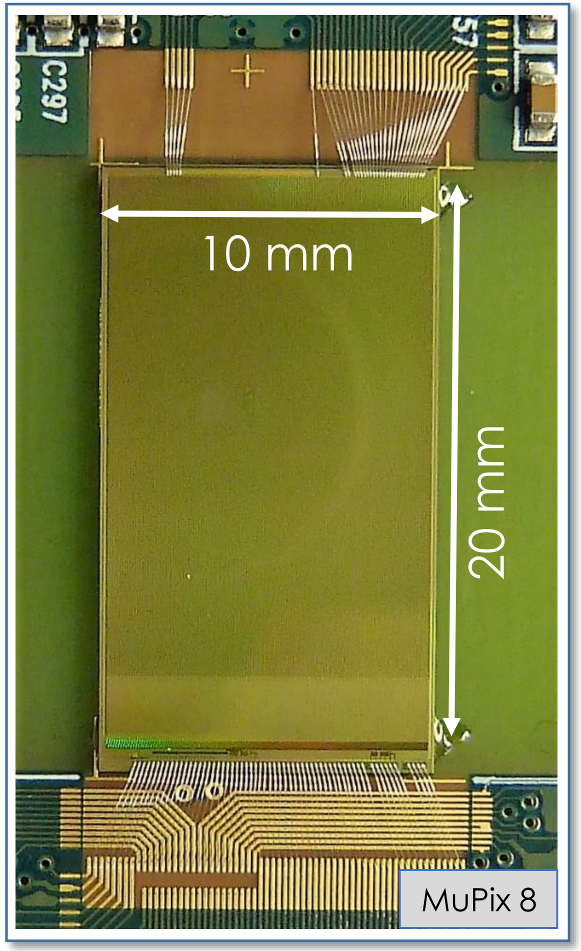
- Requires momentum resolution $\sigma_p < 0.5\ \mathrm{MeV/c}$
- Multiple scattering dominates momentum resolution $\sigma_p/p \propto \sqrt{x/X_0}$

Material budget $\boldsymbol{x \leq 1‰\, X_0}$ per layer

The Latest **MuPix** Prototypes

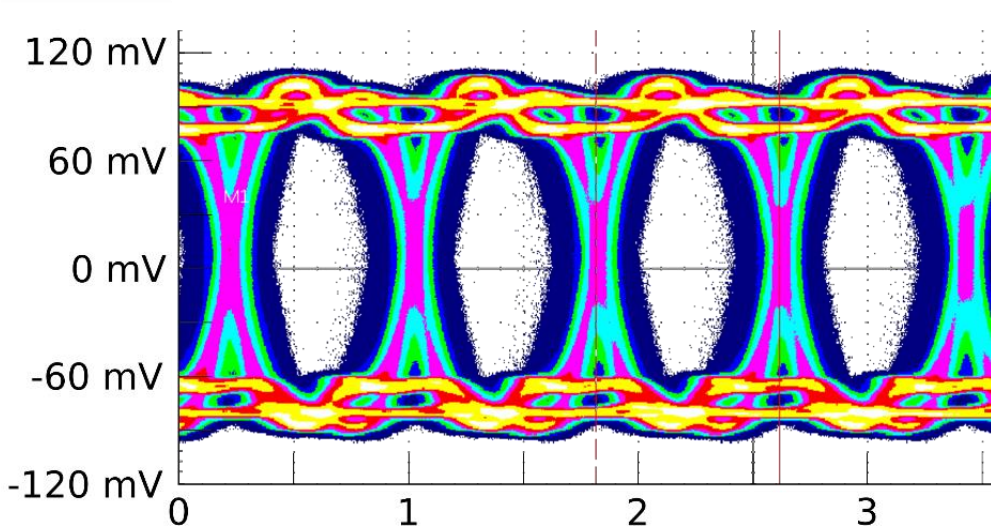
- **MuPix7**
  - AMS H18
  - First fully integrated HV-MAPS
  - Resubmitted in TSI H18
- **MuPix8**
  - AMS AH18
  - First large scale HV-MAPS ($2 \times 1\ \mathrm{cm}^2$)
- **MuPix9**
  - AMS AH18
  - Command decoder
  - Power regulators

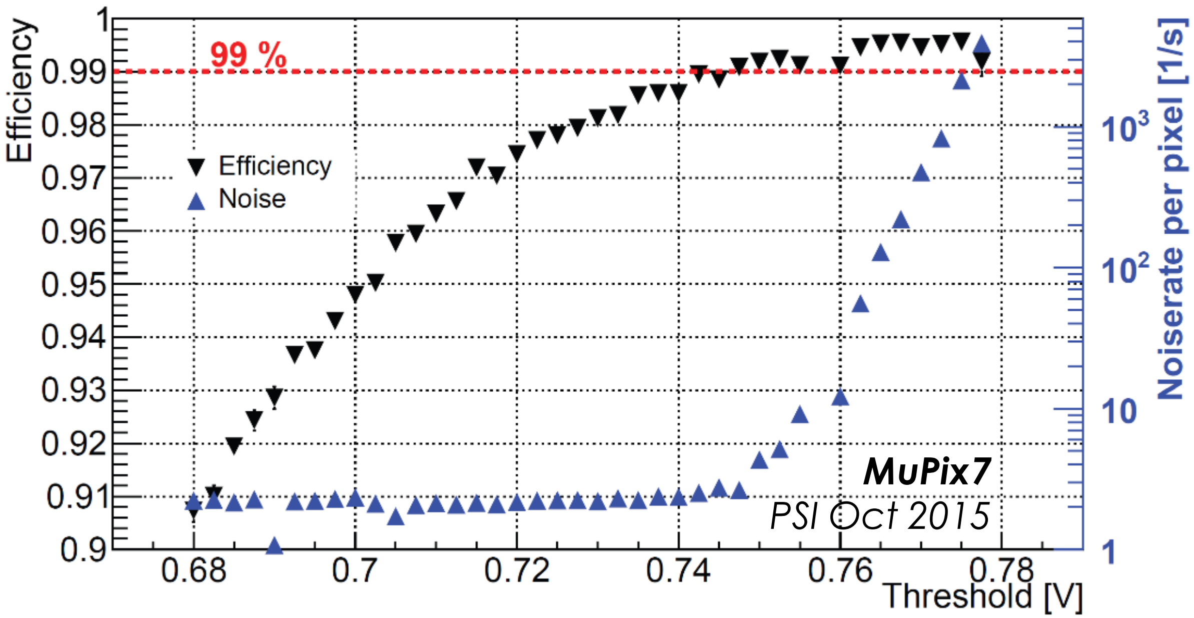




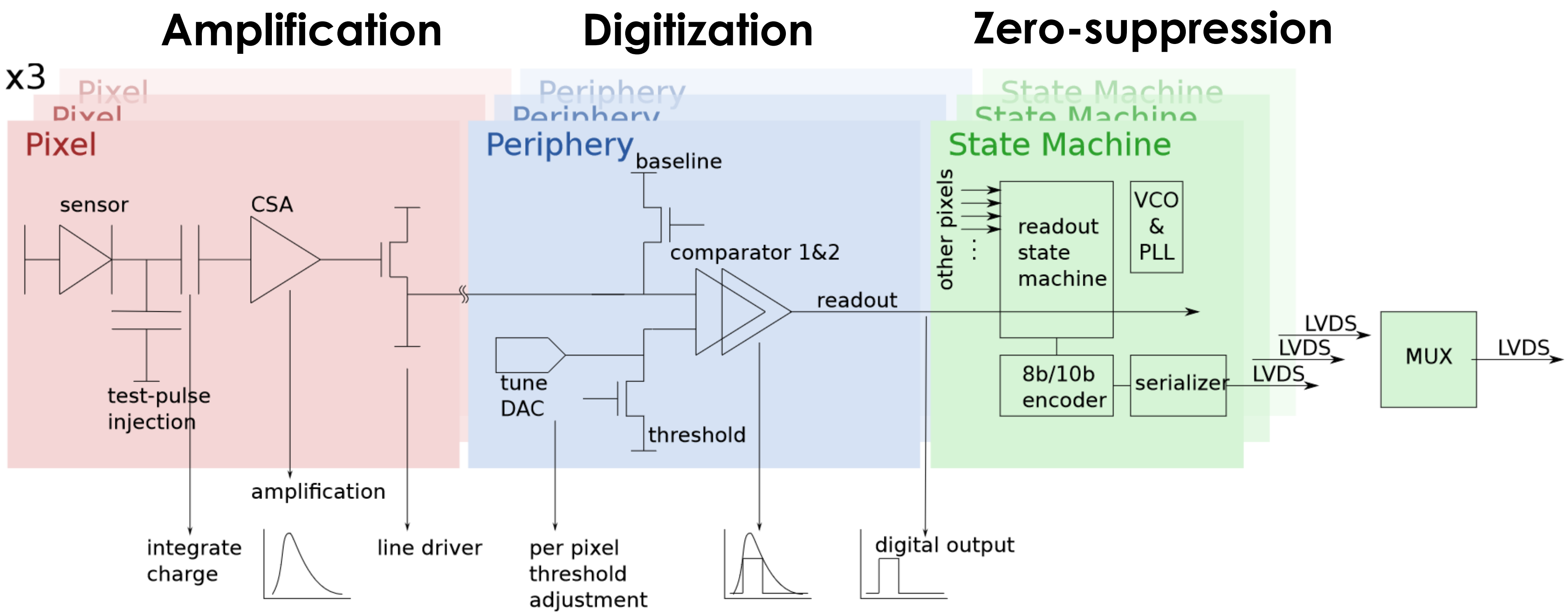
MuPix7

- Active area 3 x 3 mm^2
- Pixel size 80 x 103 μm^2
- Integrated readout state machine
- Untriggered readout
- Serial data output @ 1.25 Gb/s





MuPix8 Readout Architecture I



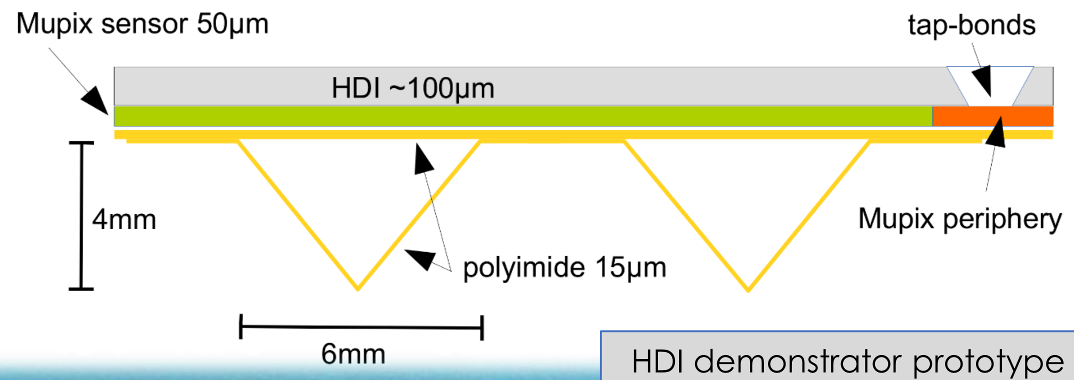
MuPix8 Readout Architecture II

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

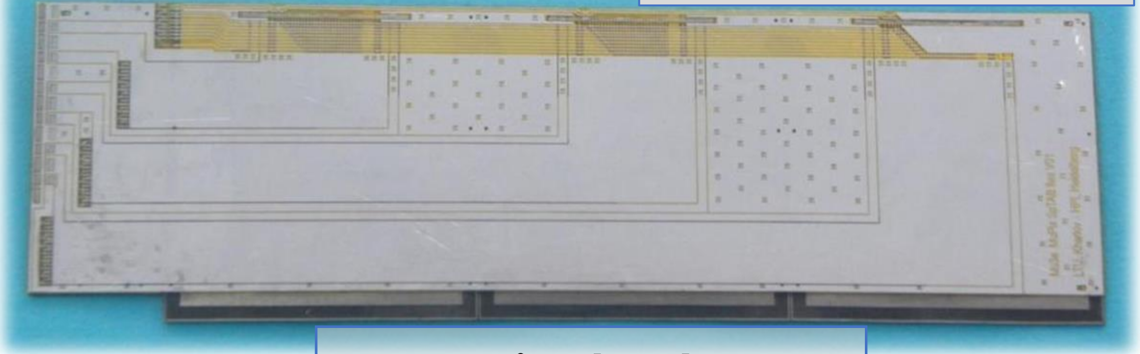
  Hit chronology not strictly conserved
- **Trigger-less, continuous** readout
- **Serial** data outputs @ 1.25 Gb/s

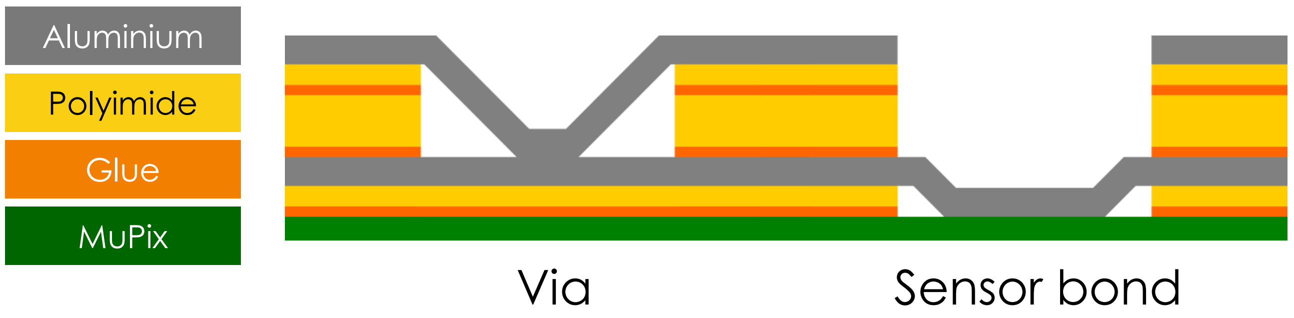
High Density Interconnect

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



HDI demonstrator prototype





Material budget

$$
\begin{aligned}
&\ 45\ \mu\text{m Polyimide}\\
&+ 28\ \mu\text{m Aluminium}\\
&+ 10\ \mu\text{m Glue}\\
\hline
&\sim 0.5‰\ X_0
\end{aligned}
$$

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

Readout Bandwidth Requirements

- Hit rates derived from full detector simulation
- Pixel detector only: 2844 sensors = 178 MPixel
- Hit rates increase by a factor of **20** for Phase II

Muon stopping rate (Phase I)	$100\ \mathrm{MHz}$
Maximum hit rate of the busiest pixel sensor	$1.5\ \mathrm{MHz/cm^2}$
Average total pixel hit rate	$1.06\ \mathrm{GHz}$
Data rate due to pixel hits (32 bits per hit)	$34\ \mathrm{Gb/s}$
Data rate due to pixel noise	$5.7\ \mathrm{Gb/s} \cdot R_{noise,pix}/\mathrm{Hz}$
Total readout bandwidth	$3.8\ \mathrm{Tb/s}$

$R_{noise,pix}$: Noise rate per pixel ≪ 10 Hz

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