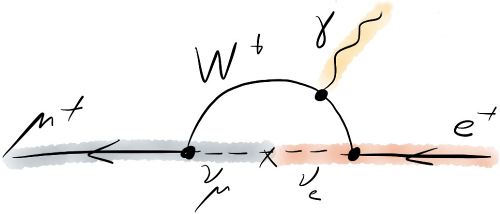
The Mu3e Experiment

Simon Corrodi

4^{th} October, 2018, MD Journal Club

Part 1:
Charged Lepton Flavour Violation

Charged Lepton (Muons) Flavour Violation



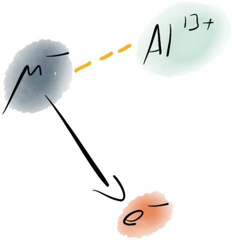
Standard Model branching fractions

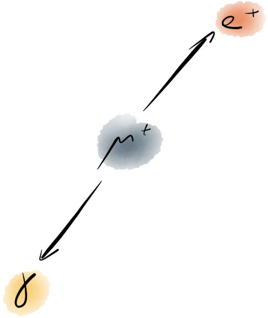
$< 10^{-54}$

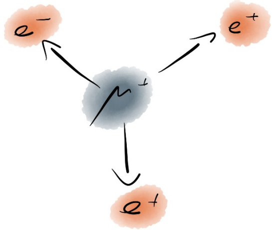
any observation is **new physics**

$\sim \left(\frac{\Delta m_\nu^2}{m_W^2} \right)^2$

Charged Lepton (Muons) Flavour Violating **Decays**







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

SINDRUM II (PSI, 2006)
$Br < 7 \cdot 10^{-13}$ $(N = Au)$

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

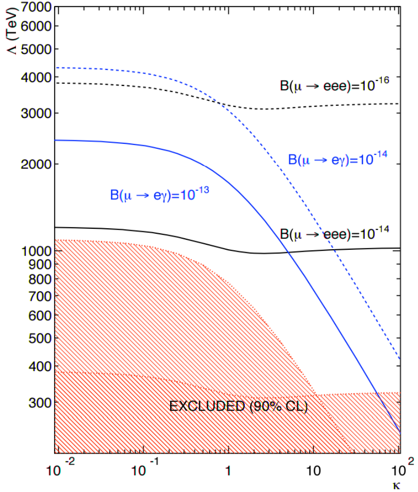
MEG (PSI, 2016)
$Br < 4.2 \cdot 10^{-13}$

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

SINDRUM (PSI, 1988)
$Br < 1.0 \cdot 10^{-12}$

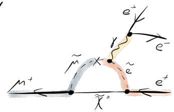
complementary processes

Comparison of Processes



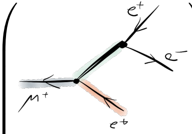
A. Gouvea1 and P. Vogle, Lepton Flavor and Number Conservation, and Physics Beyond the Standard Model, arXiv:1303.4097 (2013)

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

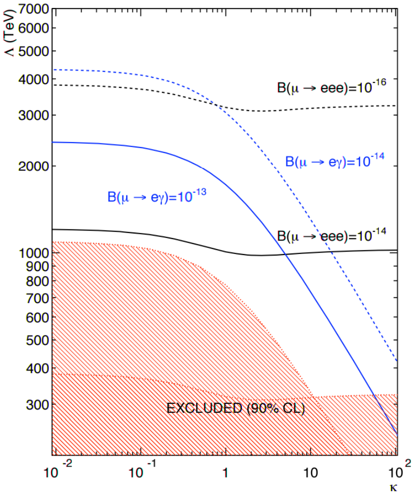


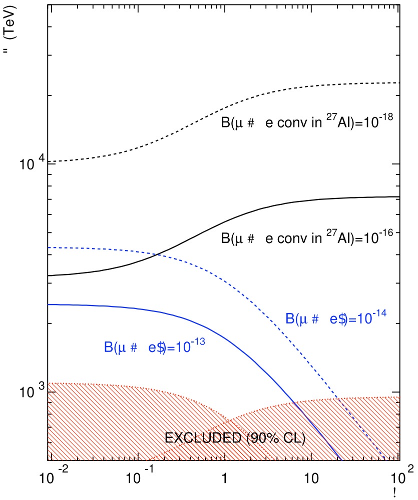
$$+$$

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



Comparison of Processes

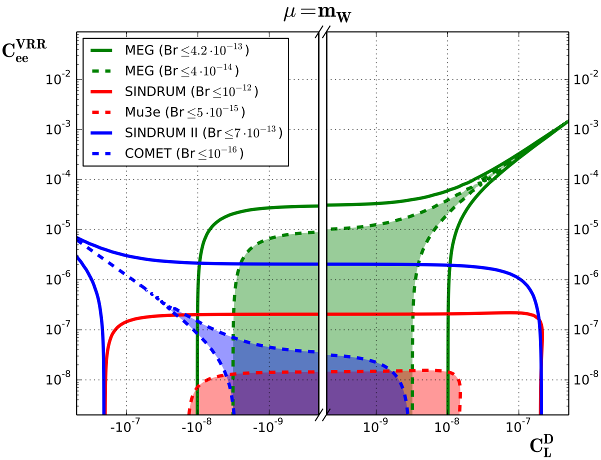




A. Gouvea1 and P. Vogle, Lepton Flavor and Number Conservation, and Physics Beyond the Standard Model, arXiv:1303.4097 (2013)

Comparison of Processes: Effective Field Theory (EFT)

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \sum C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2} \sum C_k^{(6)} Q_k^{(6)} + \dots$$



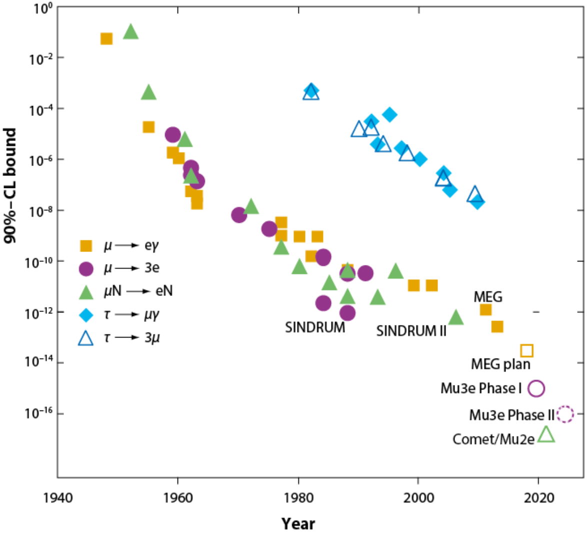
A. Crivellin, S. Davidson, G. M. Pruna, and A. Signer, "Renormalisation-grou improved analysis of $\mu \to e$ processes in a systematic effective-field-theory approach", JHEP, vol. 05, p. 117, 2017.

cLFV Decay **Experiments** History

SINDRUM (PSI, 1988)
$B(\mu^+ \to e^+ e^- e^+) < 1.0 \cdot 10^{-12}$

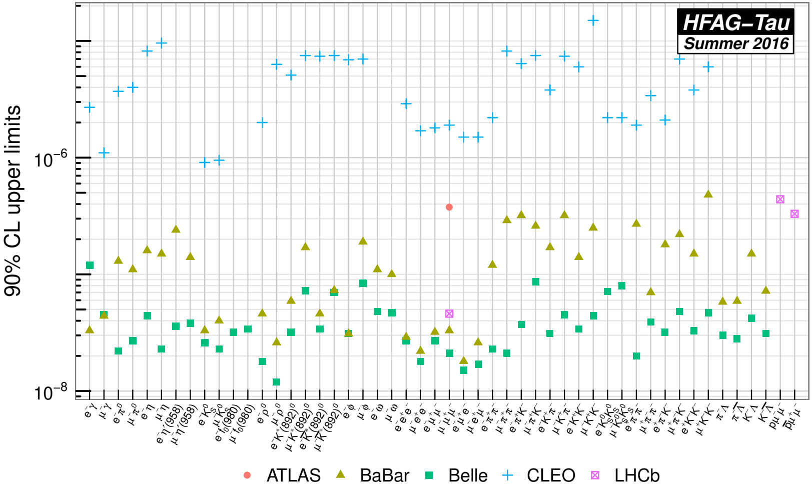
SINDRUM II (PSI, 2006)
$B(\mu^- Au \to e^- Au) < 7 \cdot 10^{-13}$

MEG (PSI, 2016)
$B(\mu^+ \to e^+ \gamma) < 4.2 \cdot 10^{-13}$



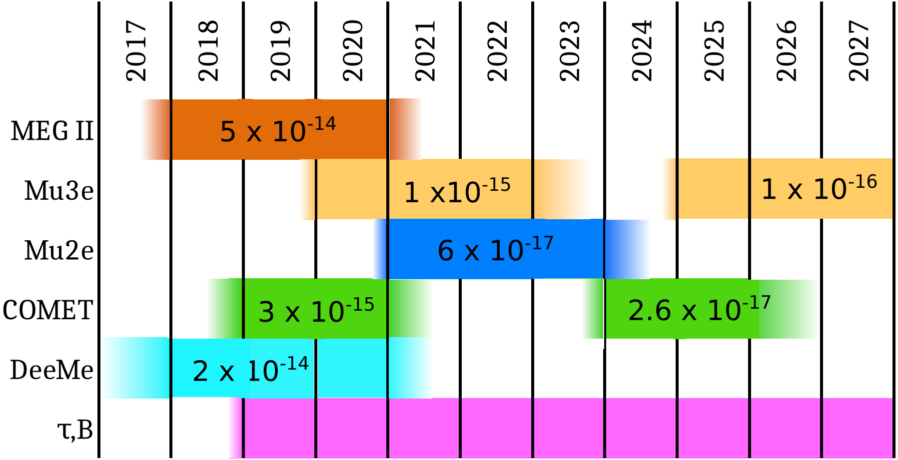
Updated from W.J. Marciano et al., Ann.Rev.Nucl.Part.Sci. 58, 315 (2008).

Charged Lepton (Tau) Flavour Violating **Decays**



from the HFAG working group from L. Calibbi and G. Signorelli, "Charged Lepton Flavour Violation: An Experimental and Theoretical Introduction" arXiv:1709.00294v2, 2017.

cLFV Decay **Experiments** Future



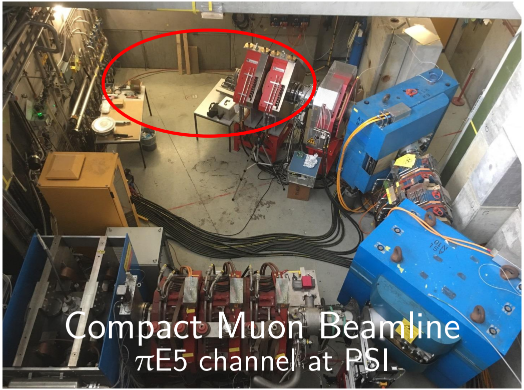
Modified from L. Calibbi and G. Signorelli, Charged Lepton Flavour Violation: An Experimental and Theoretical Introduction. arXiv:1709.00294v2, 2017.

The Mu3e Experiment

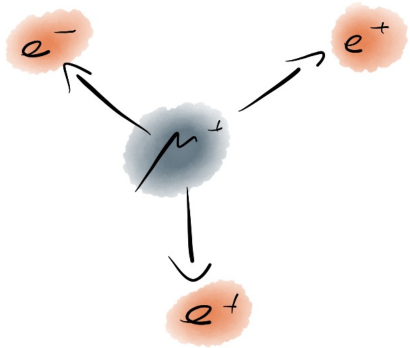
Mu3e is a **dedicated** experiment for the search of the charged **lepton flavour violating** decay

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

that aims at a sensitivity better than $\mathbf{10^{-16}}$.

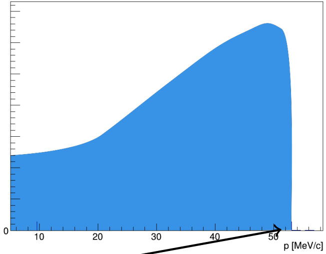


Signal Signature



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

- 3-body decay at rest
- same vertex, coincident in time
- $\sum \vec{p}_e = 0, \quad \sum E_e = m_\mu$



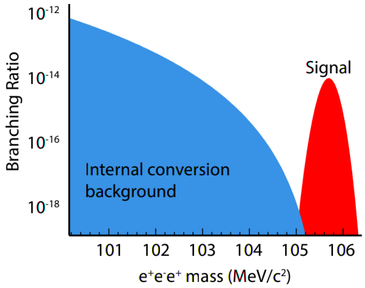
$$E_{max,e} = \frac{m_\mu}{2} \approx 53\,\mathrm{MeV/c}$$

Internal Conversion Background

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

$$B = (3.4 \pm 0.4) \cdot 10^{-5}$$

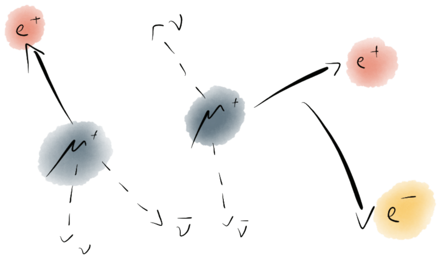
- radiative decay with internal conversion
- distinction: **Missing E** carried by neutrinos



Requirements

Excellent momentum resolution ($\Delta m_\mu < 0.5\,\mathrm{MeV/c^2}$)

Combinatorial Background (Accidentals, "Pileup")

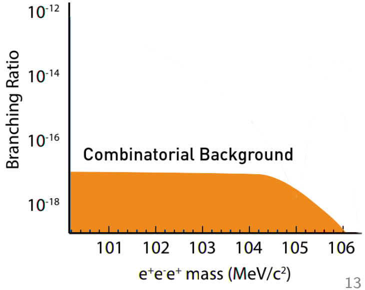


$$2 \times (\mu^+ \to e^+ \nu \bar{\nu})$$

$$? \to e^- \; ?$$

Ordinary μ^+ decay superposed with e^- from:

- Bhabha scattering
- photon conversion
- mis-reconstruction

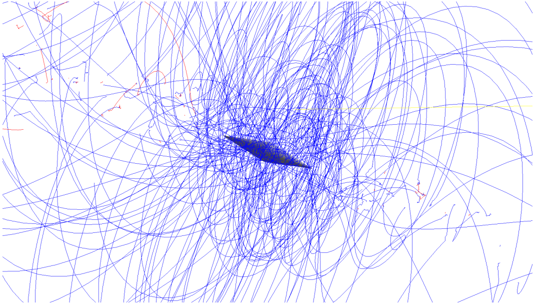


Requirements

Excellent momentum resolution
Excellent vertexing and timing

Further Challenges

High Rates



Tracks within ∼10 µs.

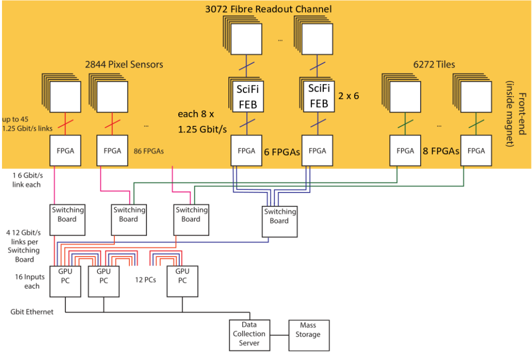
reasonable time → high rates required → MuE5 at PSI

continuous surface muon beam

Online Reconstruction

due to topology

reconstruction farm: each **GPU** receives data from **the full detector** of a **time slice**

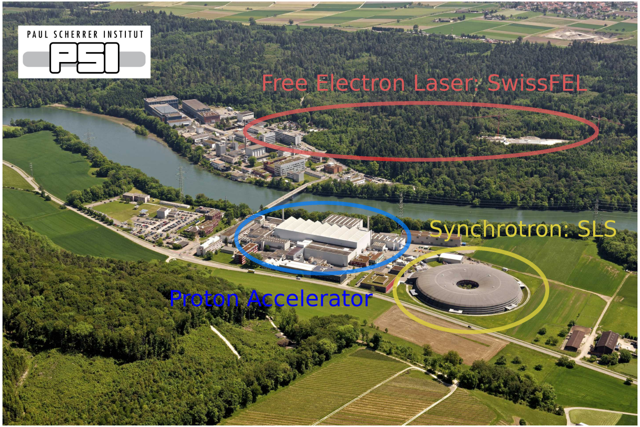


Part 2: The Facility PSI

Paul Scherrer Institute (PSI)

- multi-purpose lab:
  - Matter and Material;
  - Energy and the Environment;
  - Human Health
- Proton Accelerator: - 80% Swiss Spallation Neutron Source (SINQ)
  - two carbon production targets

Paul Scherrer Institute (PSI)



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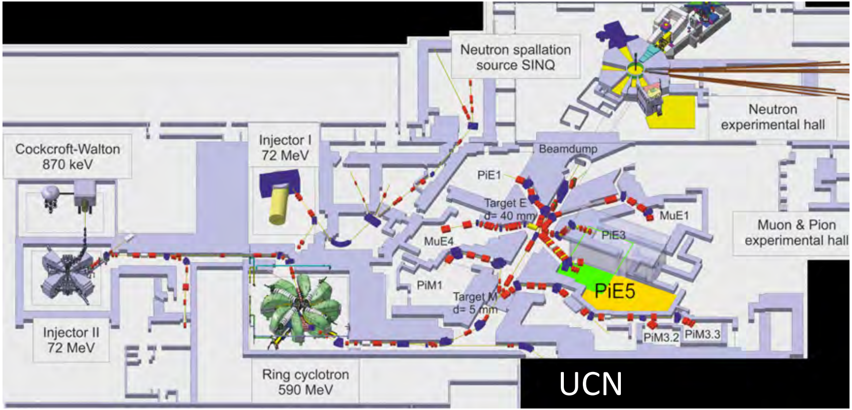
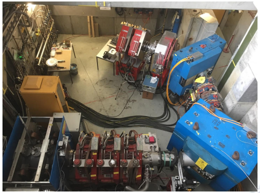
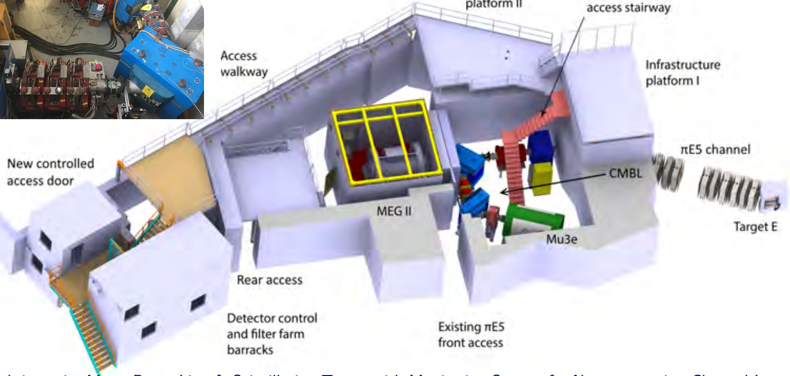


40 MHz bunched, 590 MeV protons up to 2200 mA,
rotating carbon production targets M (5 mm) and E (40 mm)
world's most intense continuous beam muon source

Paul Scherrer Institute (PSI)



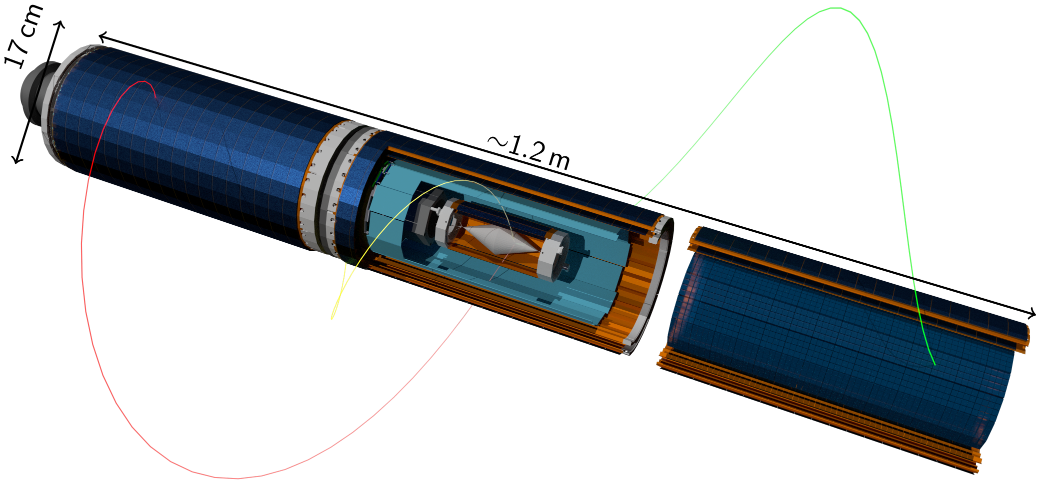


Felix Berg, "CMBL - A High-intensity Muon Beam Line & Scintillation Target with Monitoring System for Next-generation Charged Lepton Flavour Violation Experiments", ETH Zurich, 2017.

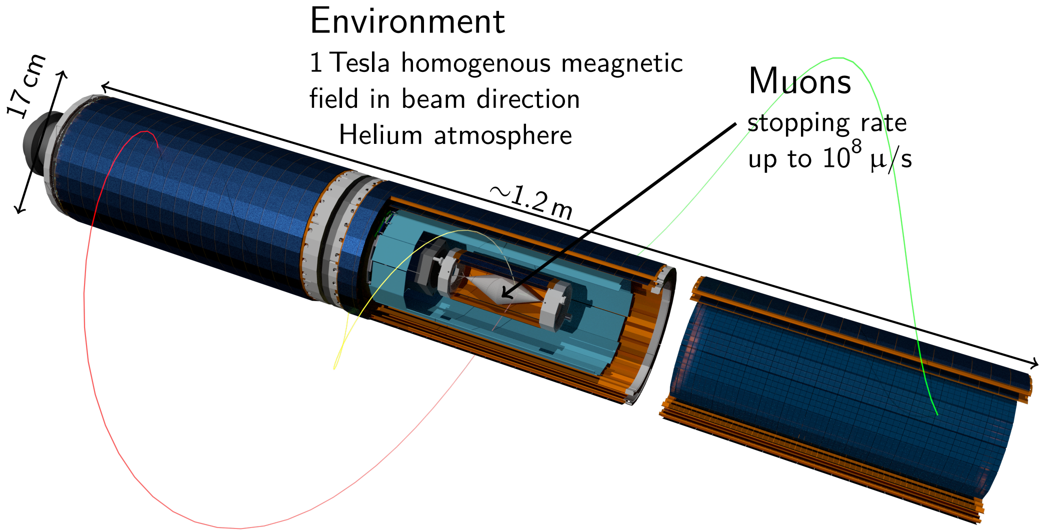
πE5 is shared between Mu3e and MEG II
Compact Muon Beamline (CMBL) delivers 27 MeV/c surface μ to Mu3e,
rates up to 10^8 muons/s have been demonstrated

Part 3: The Detector

The Mu3e Detector



The Mu3e Detector



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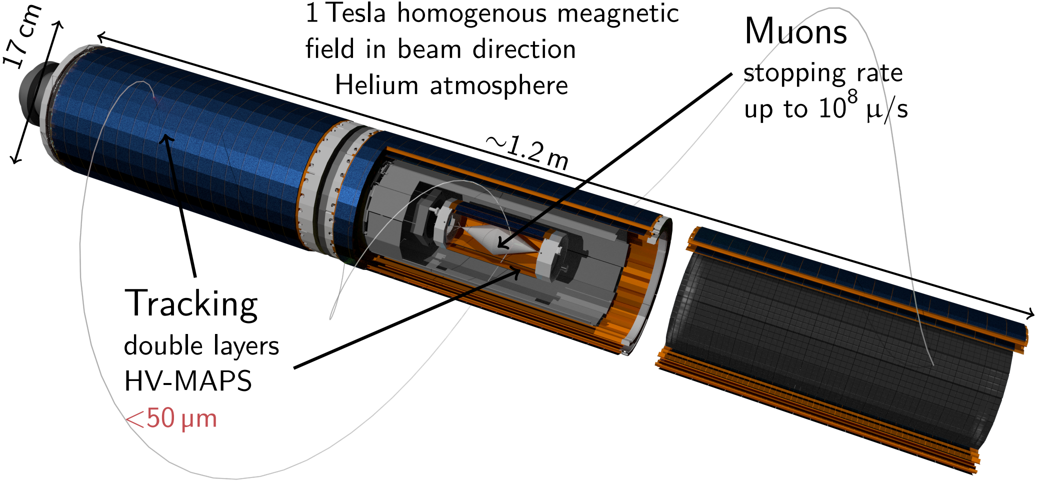

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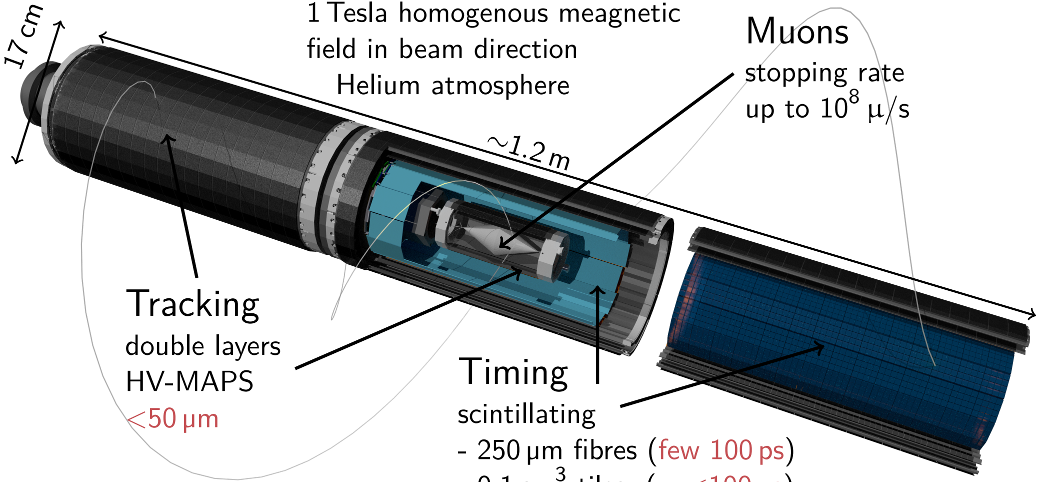


Environment

1 Tesla homogenous meagnetic field in beam direction

Helium atmosphere

Muons

stopping rate up to 10^8 μ/s

Tracking

double layers

HV-MAPS

<50 μm

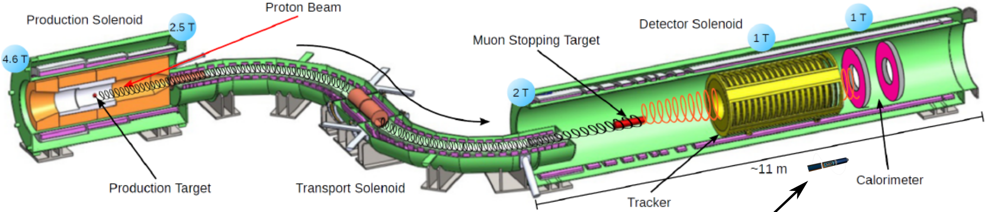
Timing

scintillating

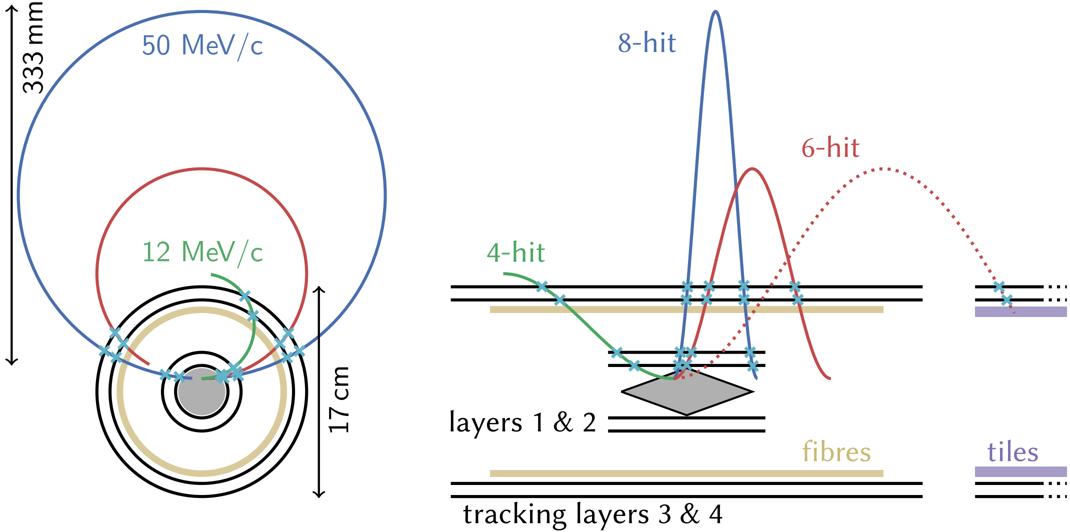
- 250 μm fibres (few 100 ps)
- 0.1 cm^3 tiles (<100 ps)

Silicon Photomultipliers

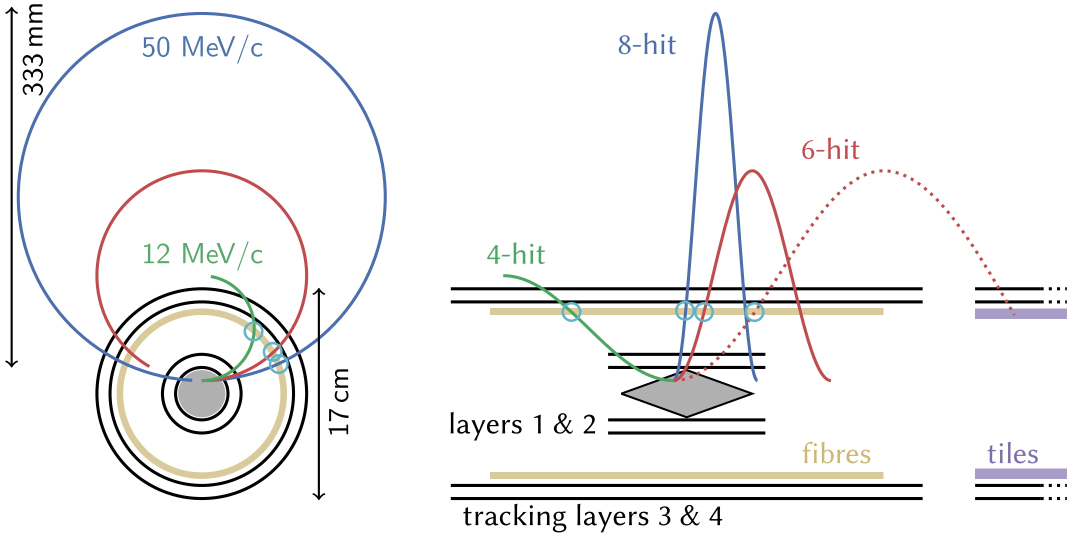
The Mu3e Detector



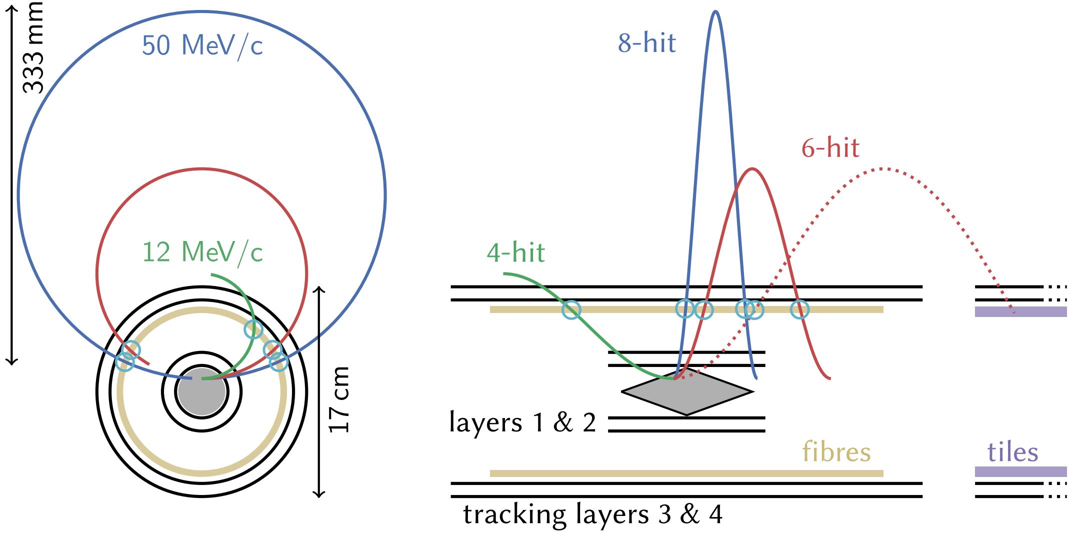
The Mu3e Detector Concept



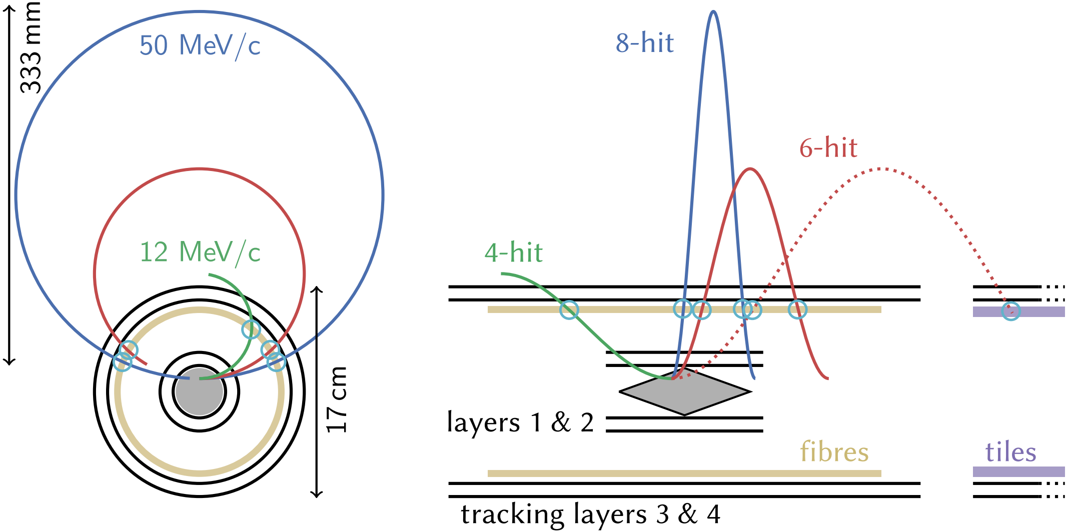
The Mu3e Detector Concept



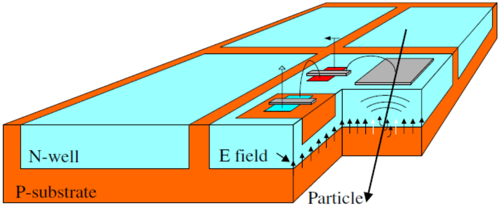
The Mu3e Detector Concept



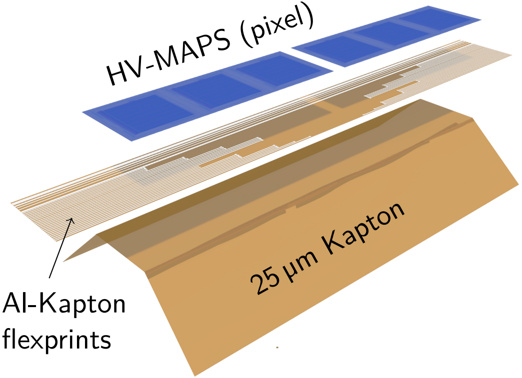
The Mu3e Detector Concept



Pixel Sub-Detector: **HV-MAPS**



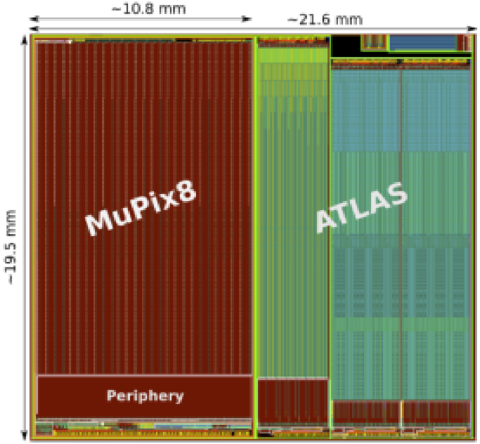
I.Perić, P. Fischer et al., NIM A 582 (2007) 876



HV-MAPS: High Voltage Monolithic Active Pixel Sensors
fast: small active region, charge collection ($\mathcal{O}(1\,\text{ns})$), $\sigma_T \approx 13\,\text{ns}$
thin: $< 50\ \mu m$
zero-suppressed data: addresses and timestamps
$<$ **1** ‰ radiation length per layer
final version: $2\,\text{cm} \times 2\,\text{cm}$

Pixel Sub-Detector: Status

MuPix8

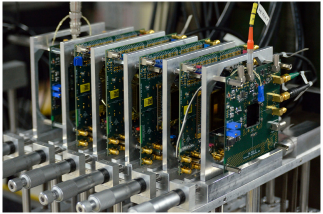


H. Augustin, S. Dittmeier, C. Grzesik, J. Hammerich, A. Herkert, L. Huth,

I. Sorokin, D. Immig, J. Kroeger, M. Zimmermann 2017

- 128×200 pixel
- $80 \times 81\,\mu m^2$
- 4 LVDS links each at 1.25 GBit/s
- **time resolution** $\boldsymbol{\sigma} \approx 13$ ns
- efficiency above 0.98 at noise rate < 1 Hz/pixel
- NEWS: two fabs: AMS and TSI

MuPix8 Telescope Configuration



Track Reconstruction: A Triplet Based Fitting

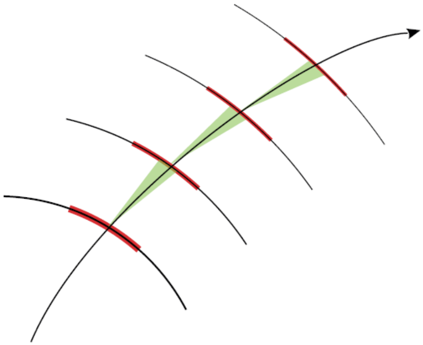


Figure 3.1: Tracking in the spatial resolution dominated regime

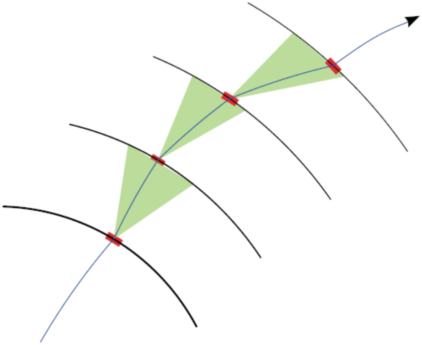
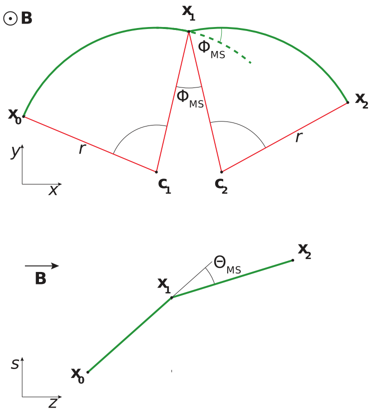


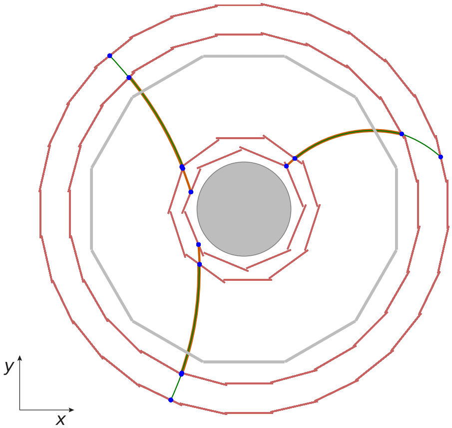
Figure 3.2: Tracking in the scattering dominated regime

Track Reconstruction: A Triplet Based Fitting

$$\chi^2(R_{3D}) = \frac{\Phi MS(R_{3D})^2}{\sigma_\phi^2} + \frac{\Theta_{MS}(R_{3D})^2}{\sigma_\vartheta^2}$$



Triplets



N. Berger et al. "A New Three-Dimensional Track Fit with Multiple Scattering", arXiv:1606.04990v2.

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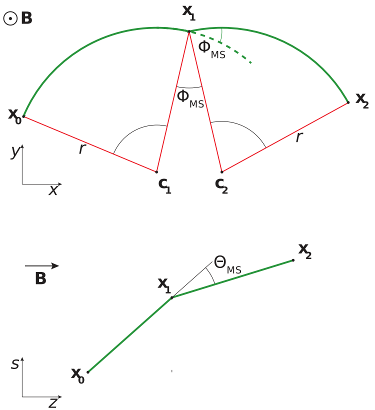
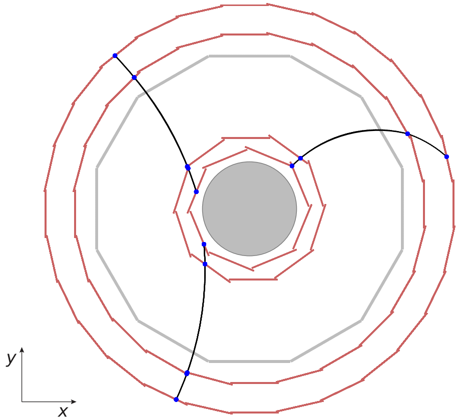


Triplets, Short Tracks



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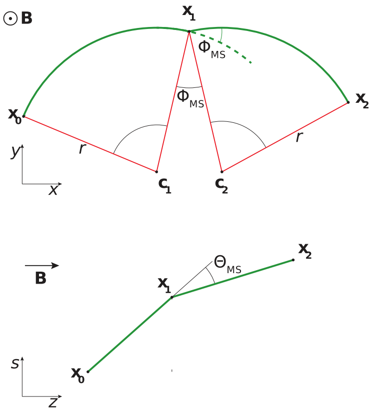
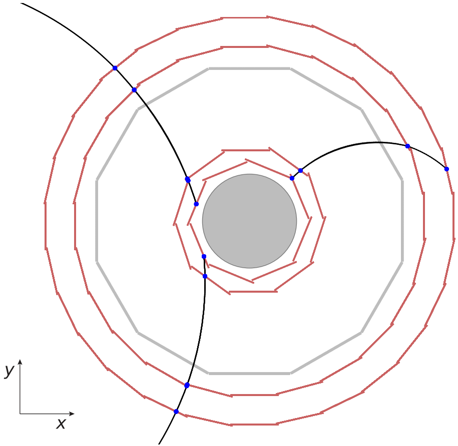
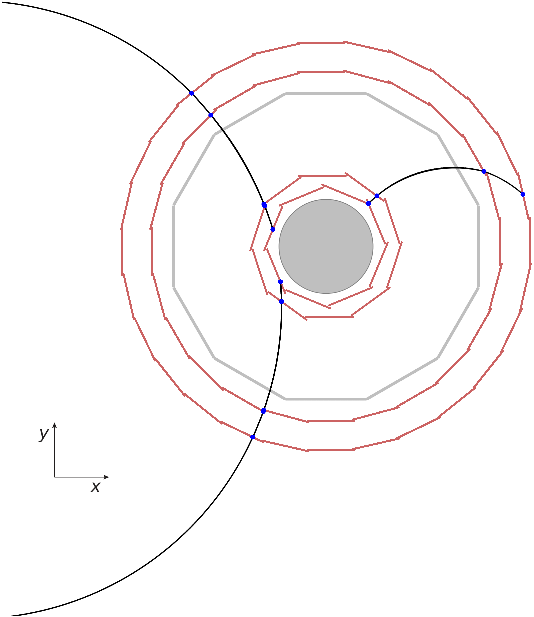


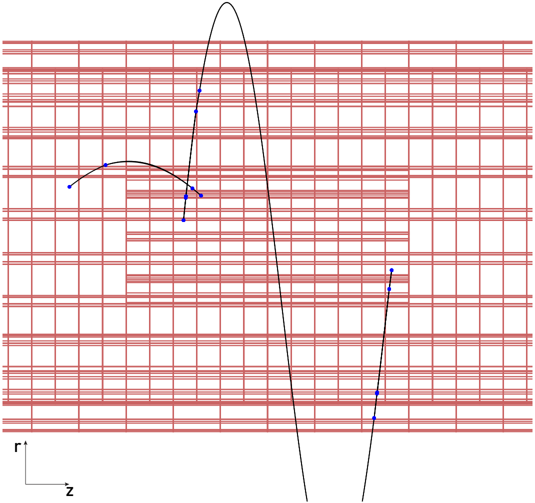
N. Berger et al. "A New Three-Dimensional Track Fit with Multiple Scattering", arXiv:1606.04990v2.

Triplets, Short Tracks, Long Tracks

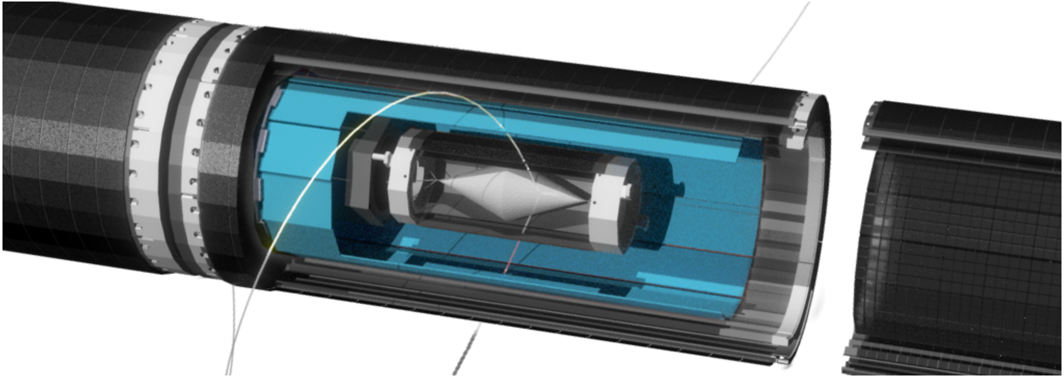


Track Reconstruction





The Scintillating Fibre Detector: Overview



Components

- cylindrical at r $\sim$ 6 cm; 28.8 cm long
- 4 layers of 250 μm fibres in 12 ribbons
- SiPM column arrays
- mixed mode ASIC: MuTRiG

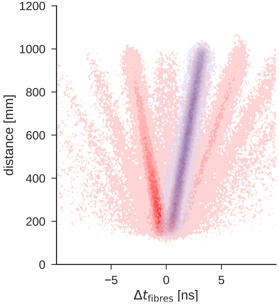
Requirements

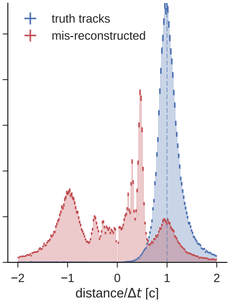
- as thin as possible; $\leq 0.5\,\%X_0$ (1 mm)
- as efficient as possible; close to 100 %
- time resolution better than 500 ps
- up to 250 kHz/fb; 500 kHz/channel

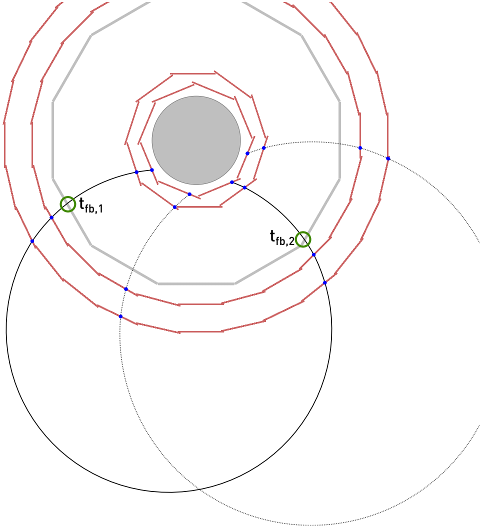
The Fibre Detector: Impacts

Rejection of Mis-Reconstructed Track Candidates

Time resolution $\lesssim 0.35\,\mathrm{ns}$ allows reliable charge identification for recurling tracks.



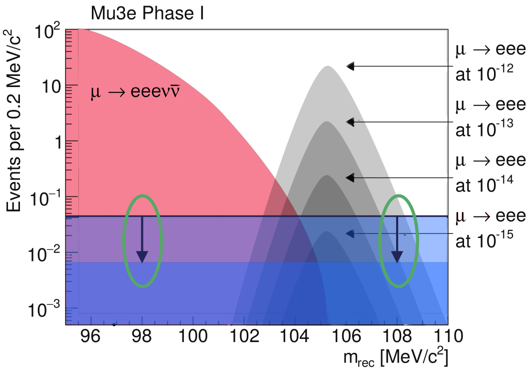




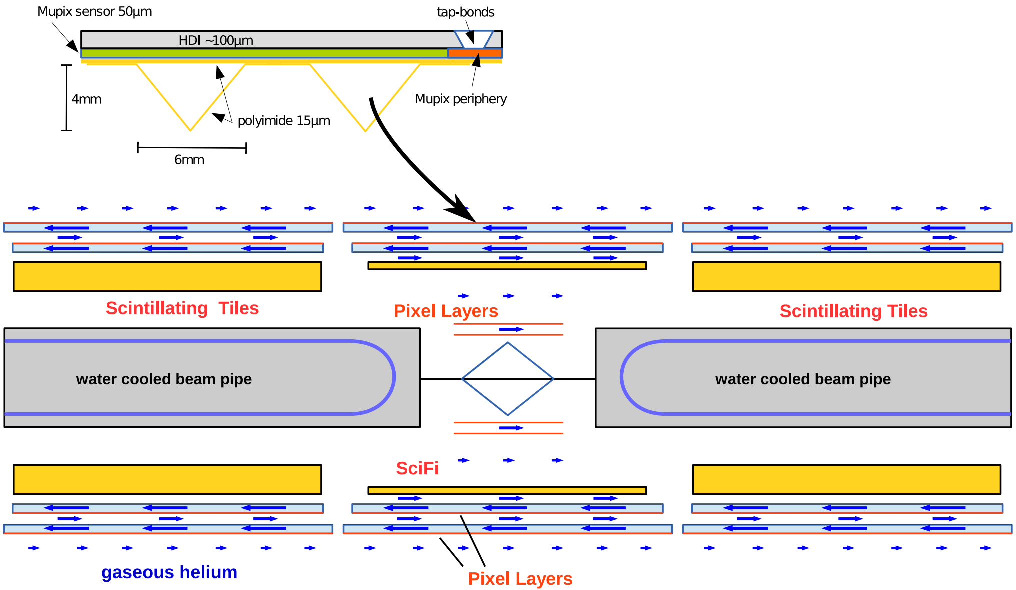
The Fibre Detector: Impacts

Impact II: Background Suppression

Combinatorial: Bhabha pair + Michel

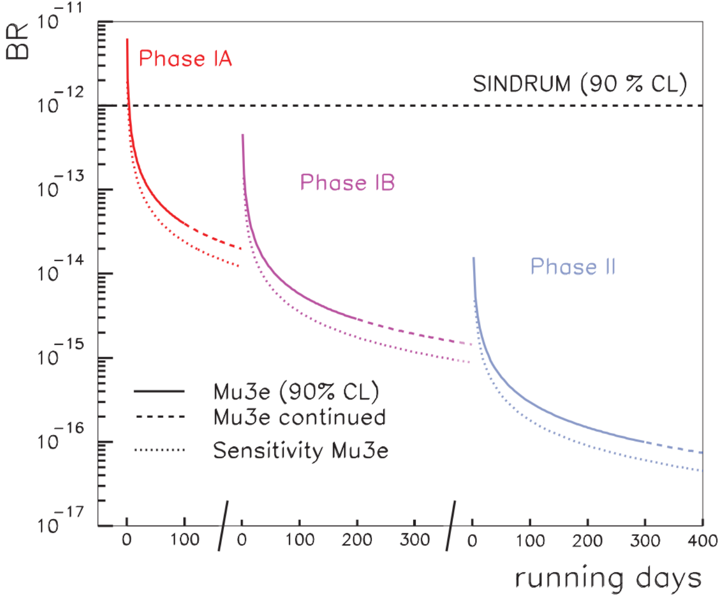


Cooling Concept

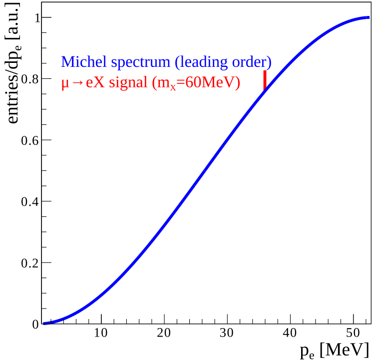


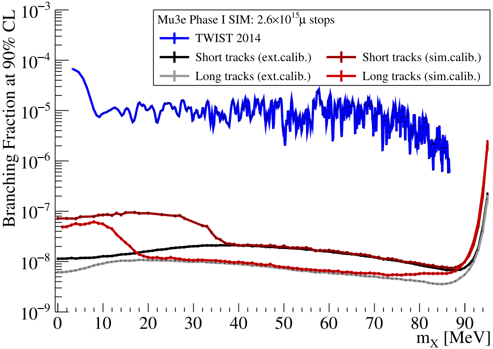
Part 4: Status & Outlook

Expected Sensitivity



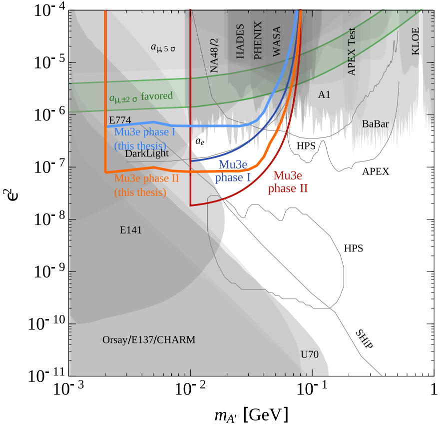
New Physics: $\mu^+ \to e^+X$





Ann-Kathrin Perrevoort, “Sensitivity Studies on New Physics in the Mu3e Experiment and Development of Firmware for the Front-End of the Mu3e Pixel Detector“, University of Heidelberg, 2017.

New Physics: $A' \to ee$

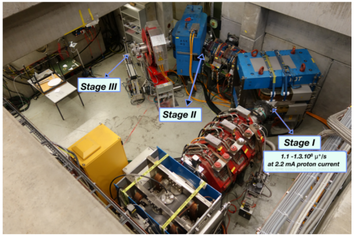


95 % CL on the kinetic mixing parameter ε^2 in $\mu \to e\nu\nu(A' \to ee)$

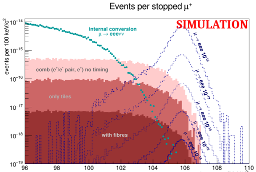
Ann-Kathrin Perrevoort, "Sensitivity Studies on New Physics in the Mu3e Experiment and Development of Firmware for the Front-End of the Mu3e Pixel Detector", University of Heidelberg, 2017.

Status

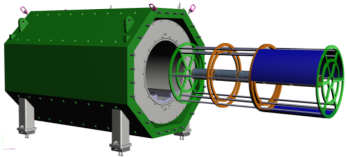
Beamline
achieved $10^8 \mu/s$ ✓



Simulation/Reconstruction
running framework ✓



Mechanics
Technical Design Report (phase I) ready, not published yet

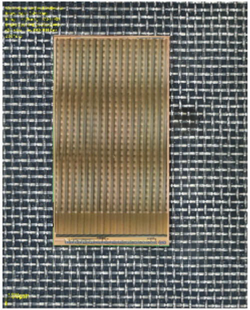


Detector support inside magnet.

Magnet ordered, delivery is scheduled for early 2019.

Readout
sub-systems come together

Pixel
up-scaling (MuPix8) ✓
switch from R&D to production runs
MuPixX ≥ 10

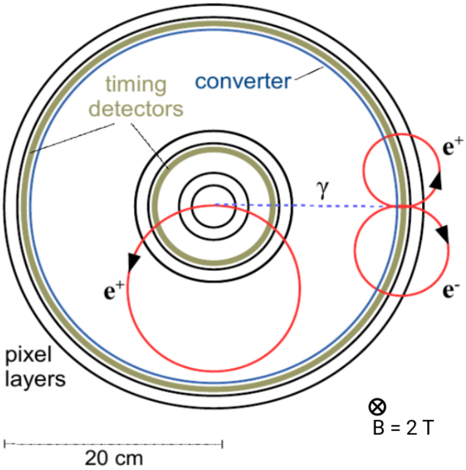


Mupix8: first "large" version

Outlook

end 2018	sub-detector prototypes
2019	magnet delivery
	detector final construction
2019+	engineering run
$\geq$2020	phase I (SES 10^{-15})
2023+	phase II (BR 10^{-16})
	new beamline for $10^9 \mu/$s under study (HiMB)

Potential Upgrades: Mu3e-Gamma

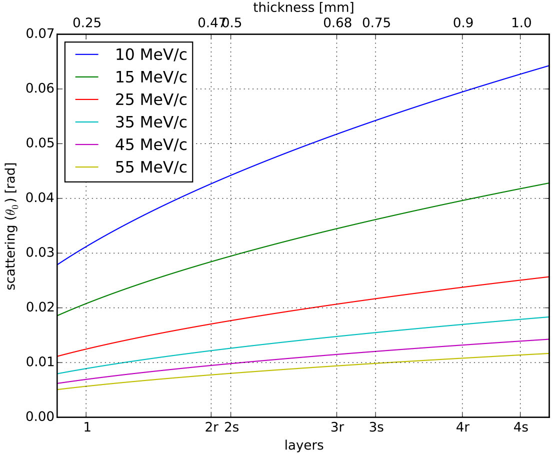


The Collaboration

Appendix

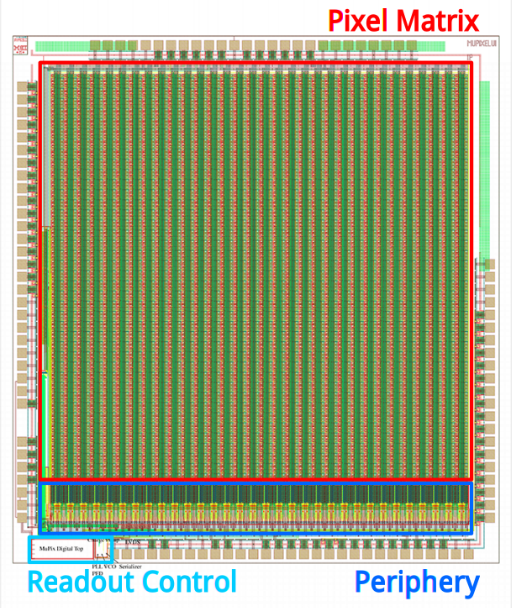
Multiple Coulomb Scattering

$$\theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta c p} z \sqrt{x/X_0}\left[1 + 0.038 \ln x/X_0\right]$$

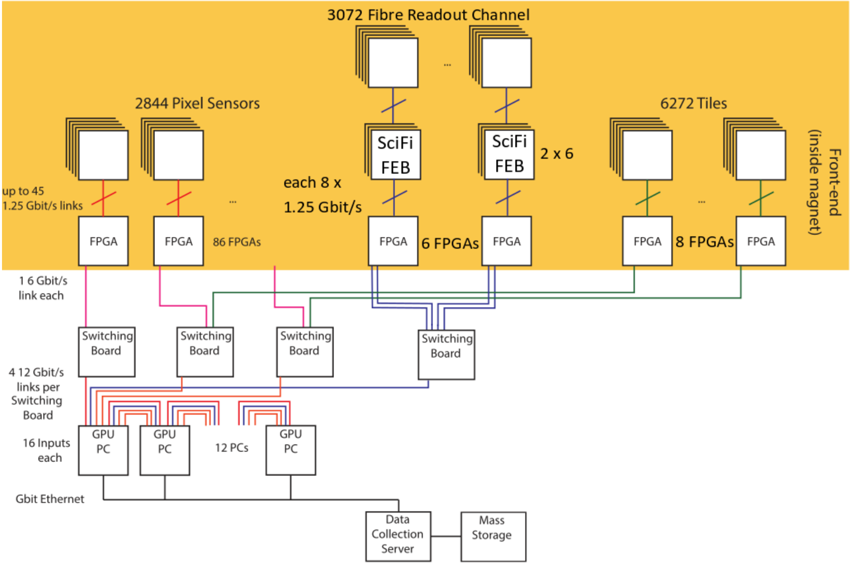


Caution: θ_0 with of Gaussian for central 98 %. The larger tails are not described with this.

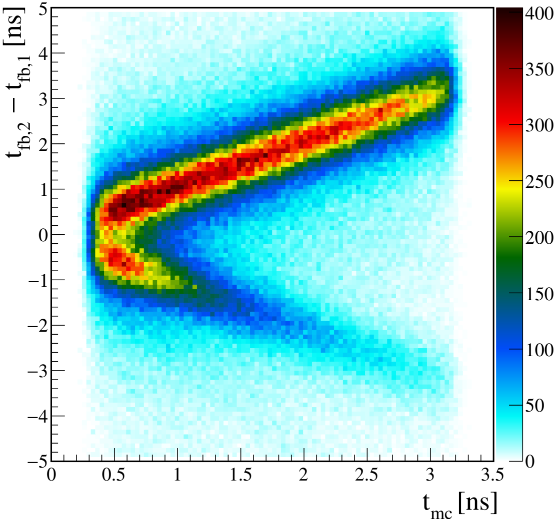
MuPix7



Readout Concept

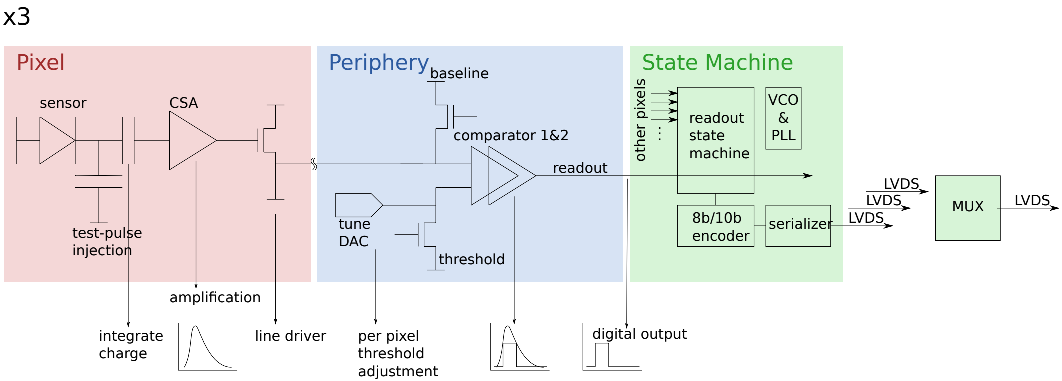


Charge Identification



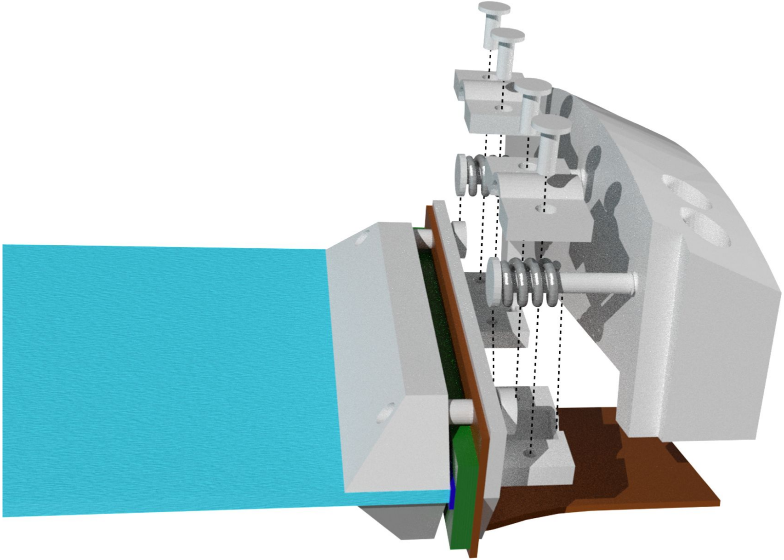
Time difference between fibre clusters assigned to **recurling** (long 8-hits track) as function of distance along trajectory. The upper branch corresponds to the correct charge assignment and direction of rotation and the lower branch to the wrong charge assignment.

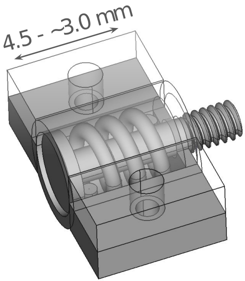
Mupix Schematic



Lennart Huth (PI HD) July 2017.

Spring Loading

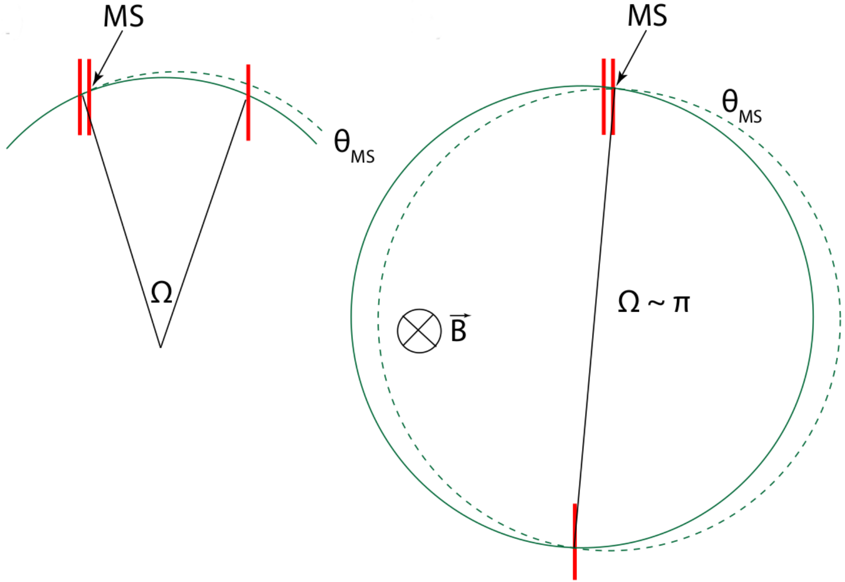




The Collaboration

	involvement	Senior (incl. Prof)	PostDoc	PhDs
Paul Scherrer Institut PSI	infrastructure, scifi, target, pixel	8	1	1
Ruprecht-Karls-Universität Heidelberg PI	pixel, integration	2	1	4
Ruprecht-Karls-Universität Heidelberg KIP	tile detector, readout ASIC	2	1	3
JG|U Johannes Gutenberg Universität Mainz	simulation, reconstruction, readout	1	2	1
KIT Karlsruher Institut für Technologie	sensor design	1	0	1
Université de Genève	scifi	1	0	2
ETH zürich	scifi	3	0	2
Universität Zürich UZH	simulation, scifi	2	2	0
University of Liverpool	pixel	6	1	0
University of Oxford	pixel	6	0	0
University of Bristol	pixel	3	1	0
UCL	clocking	2	0	0
total	**60**	**37**	**9**	**14**

Multiple Scattering



Momentum Resolution