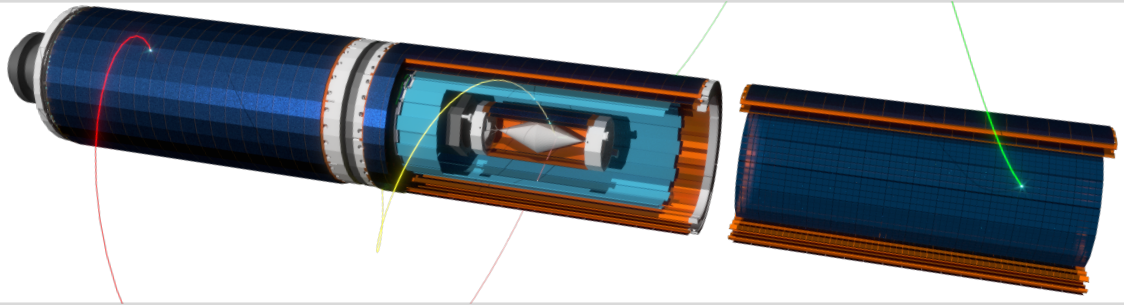


Searching for Charged Lepton Flavour Violation with Mu3e

Ann-Kathrin Perrevoort | August 2nd, 2022 | NuFact 2022



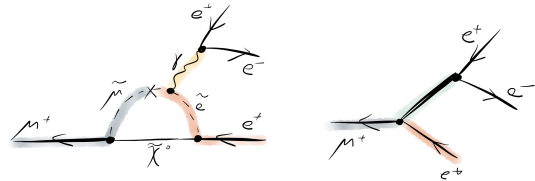
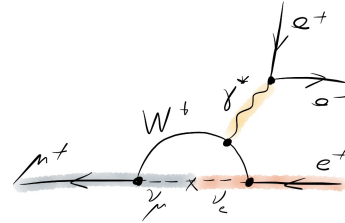
Mu3e Experiment

Searching for the LFV Decay $\mu \rightarrow eee$

- Lepton flavour is an **accidental symmetry** of the Standard Model (SM)
... and often violated in beyond SM (BSM) models
- charged LFV (cLFV) is heavily suppressed if only ν mixing is considered:

$$\mathcal{B}_{\mu \rightarrow eee} \propto \left(\frac{\Delta m_{\nu}^2}{m_W^2} \right)^2 \rightarrow \mathcal{B}_{\mu \rightarrow eee} < 10^{-54}$$

⇒ Observation would be an **unambiguous sign of physics beyond the SM**



Mu3e Experiment

Goals and Challenges

- Current strongest limit: $\mathcal{B}(\mu \rightarrow eee) < 1.0 \times 10^{-12}$ at 90% CL (SINDRUM, 1988)
- Mu3e will perform a **background-free** search for $\mu \rightarrow eee$ and aims to find or exclude the decay with a sensitivity in \mathcal{B} of

a few 10^{-15} in phase I

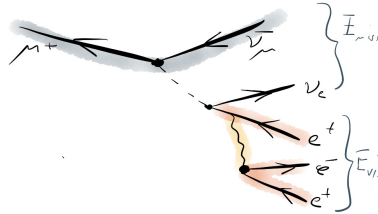
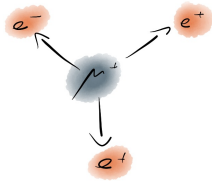
10^{-16} in phase II

- Challenges

- Background suppression
- High muon decay rates



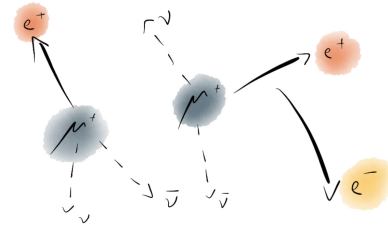
Signal and Background



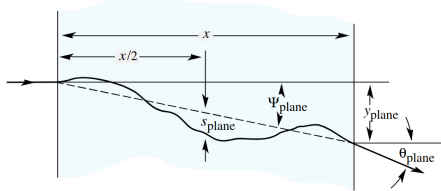
- Signal $\mu^+ \rightarrow e^+ e^- e^+$
- Same vertex, coincident
- Decay at rest
 - $\sum P_e = (m_\mu, 0, 0, 0)$
 - $\theta(\vec{p}_e) = 10 \text{ MeV}$

- Accidental combinations of e^+ from $\mu \rightarrow e\nu\nu$ with e^- or e^+e^- from Bhabha scattering, photon conversion, mis-reconstruction
- Need good timing and vertexing, low material

- Background from rare decay: $\mathcal{B}(\mu \rightarrow eee\nu\nu) = 3.4 \times 10^{-6}$
- Missing momentum due to neutrinos
- Need excellent momentum resolution



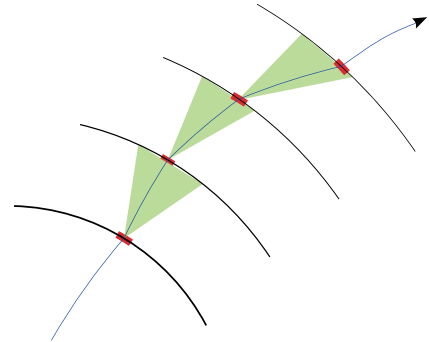
Track Reconstruction



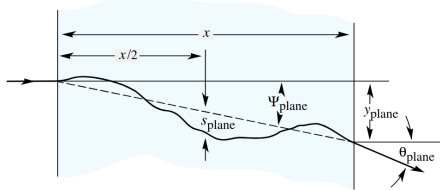
- Low energy e^+ / e^- affected by **multiple Coulomb scattering**
 - Energy loss and deflection
- Momentum resolution is dominated by scattering not pixel size

$$\frac{\sigma_p}{p} \propto \frac{\theta_{MS}}{\Omega}$$

- 'Recover' momentum resolution
 - Consider scattering in track reconstruction
 - **Low material**
 - Optimized geometry, i.e. **large lever arm Ω**



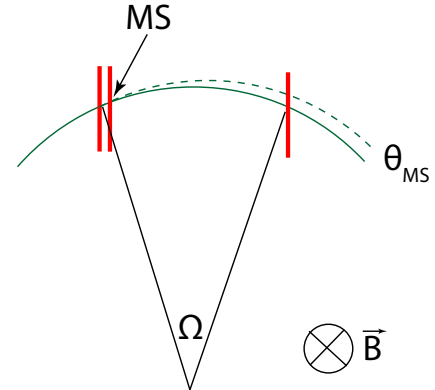
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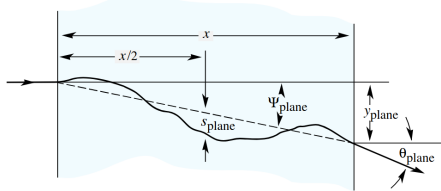
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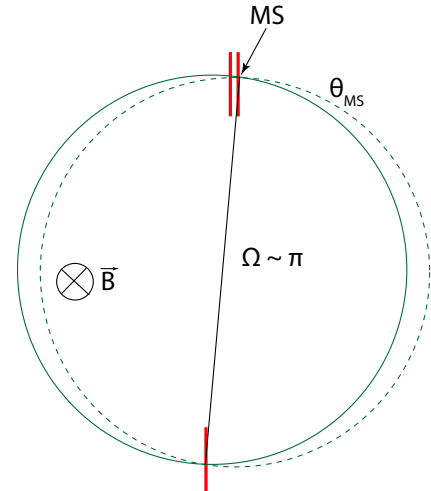
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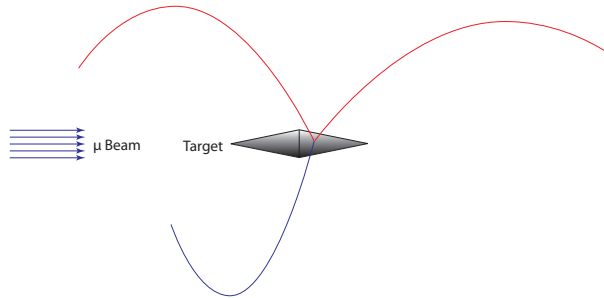


Experimental Concept



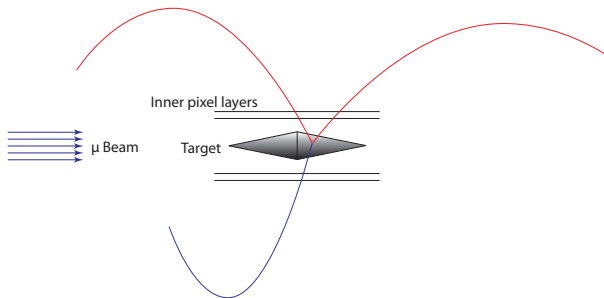
- Muons stopped on target
→ decay at rest

Experimental Concept



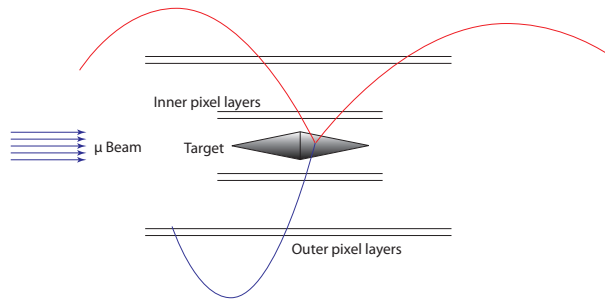
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- Track e^+ / e^- trajectories in
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Experimental Concept



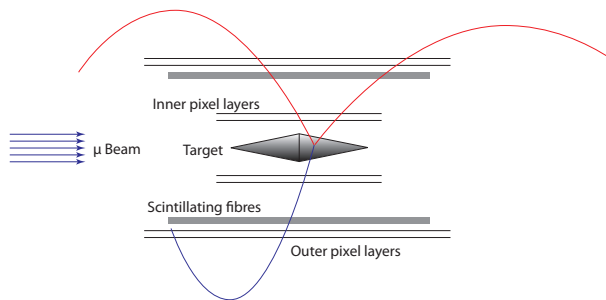
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- 4 layers of ultra-thin silicon
pixel sensors

Experimental Concept



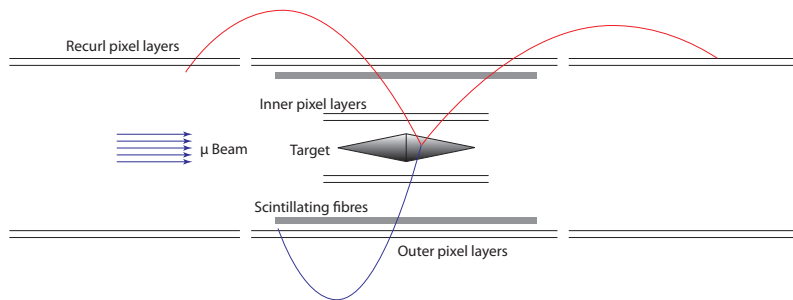
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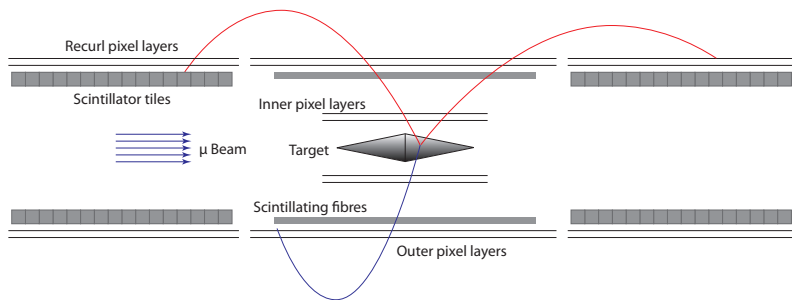
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- Timing with scintillating fibres

Experimental Concept



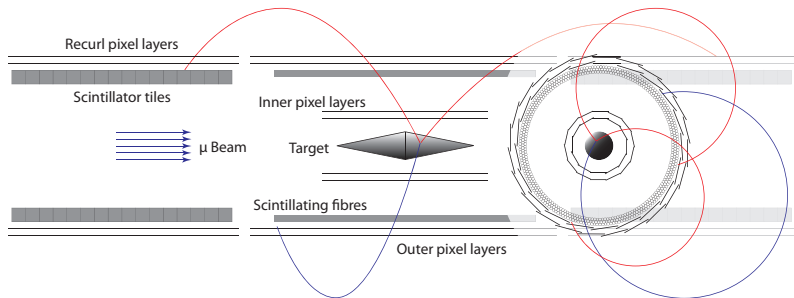
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- 4 layers of ultra-thin silicon
pixel sensors
- Timing with scintillating fibres
- Recurl-stations with pixel
sensors

Experimental Concept



- Muons stopped on target
→ decay at rest
- Track e^+ / e^- trajectories in
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- 4 layers of ultra-thin silicon
pixel sensors
- Timing with scintillating fibres
- Recurl-stations with pixel
sensors and scintillating tiles

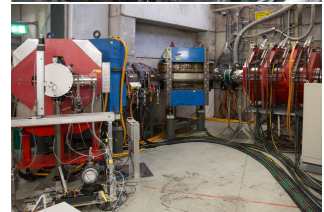
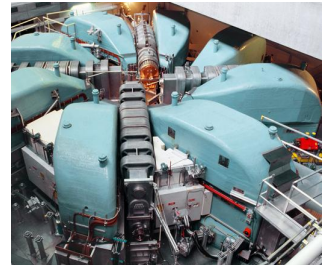
Experimental Concept



- Muons stopped on target
→ decay at rest
- Track e^+ / e^- trajectories in 1 T solenoidal field
- 4 layers of ultra-thin silicon pixel sensors
- Timing with scintillating fibres
- Recurl-stations with pixel sensors and scintillating tiles
- Cooling with gaseous Helium
- 120 cm long, 18 cm diameter

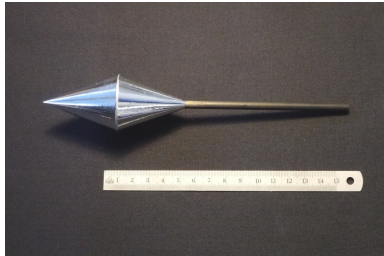
Muon Beam

- Mu3e will be hosted at the Paul Scherrer Institute (PSI)
- PSI is home of world's most **intense continuous muon beam**
- Cyclotron produces 2.2 mA proton beam with 590 MeV
- Production of pions and muons on Carbon target
- Continuous, sub-surface μ^+ with 28 MeV
 - $10^8 \mu/s$ at Compact Muon Beamline (CMB)
 - $10^{10} \mu/s$ with the future High Intensity Muon Beams (HIMB) project (2029+)



Stopping Target

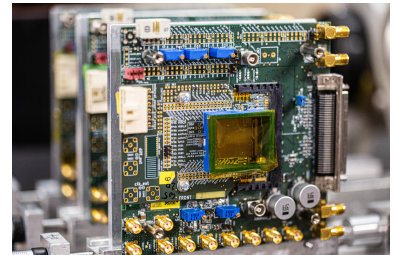
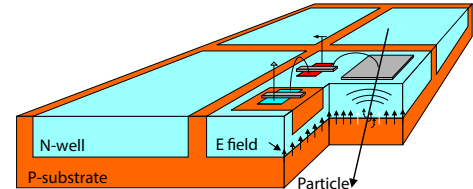
- Distribute muon stops over large surface
- Reduce material traversed by decay products
- Hollow, double-cone target made from Mylar
- 100 mm long, 38 mm diameter, 70 μm /80 μm thick
- Stopping rate of 95.5 %



- Solenoid magnet with 1.0 T nominal field (range 0.5 T to 2.7 T)
- Warm bore: $L = 2.7 \text{ m}$, $\varnothing = 1.0 \text{ m}$
- Homogeneous magnetic field: $\frac{\Delta B}{B} < 10^{-3}$

Pixel Detector

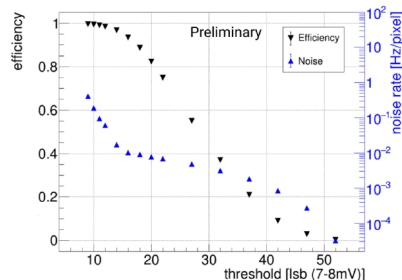
- High Voltage Monolithic Active Pixel Sensor (HV-MAPS)
- Fast charge collection in small active region
- Fully integrated digital readout
- Thinned to 50 μm
 - only 1.15% of radiation length
 - incl. flexprint and support structure
- Active sensor size 2 cm \times 2 cm
 - Pixel size 80 μm \times 80 μm



Pixel Detector

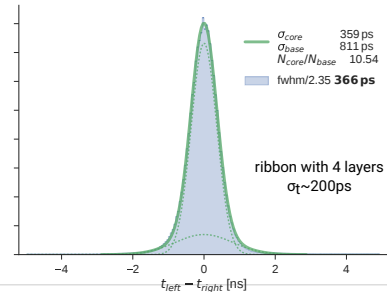
Status

- Latest prototype MuPix10 fulfills all specifications
 - Thinned to 50 μm
 - Test beam campaign at DESY: efficiency, noise and time resolution (~ 10 ns)
- MuPix11
 - Final sensor for phase I
 - Small improvements on powering and routing
 - Submitted in early 2022, expected to arrive soon
- Status
 - MuPix10 vertex demonstrator: successfully operated incl. Helium cooling
 - Production chains for inner and outer layer developed
 - MuPix11 module pre-production starting in fall 2022
 - Full production starting beginning of 2023



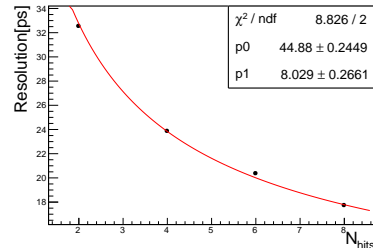
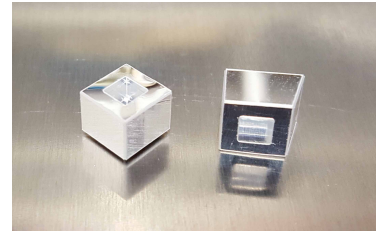
Scintillating Fibre Detector

- 12 fibre ribbons in central detector
- 30 cm long
- 3 layers of 250 μm fibres
- 128ch SiPM column array
(Hamamatsu S13552-HRQ)
- Readout with custom **MuTRiG** ASIC
(32ch, 50 ps time-to-digital convertor)
- Time resolution of ~ 250 ps



Scintillating Tile Detector

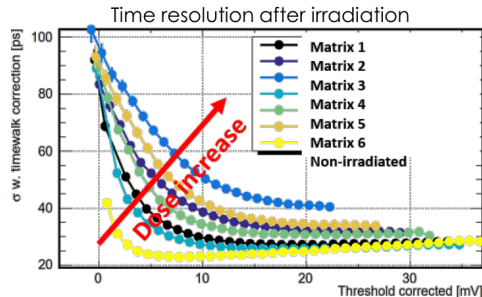
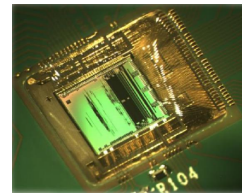
- Scintillating tiles of size 6 mm × 6 mm × 5 mm in recurl stations
- Wrapped in ESR reflective foil
- Readout with SiPMs (Hamamatsu MPPC S13360-3050VE) and MuTRiG
- Single channel time resolution < 50 ps



Timing Detectors

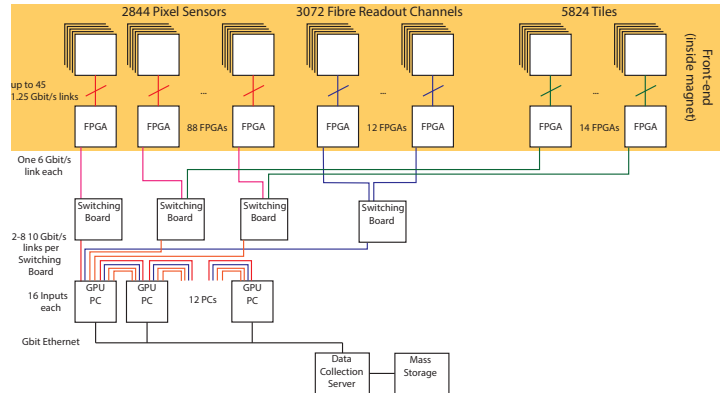
Status

- Final version of MuTRiG submitted in spring 2022
- SciFi readout already successfully established with previous MuTRiG
- Finalization of SciFi mechanical design and readout boards
- Studied irradiation impact on SciTiles close to target
- SciTile demonstrator modules assembled and characterized
- SciTile module board fully functional
- Assembly of final SciTile components to be started soon
- Integration of both systems into the Mu3e data acquisition ongoing



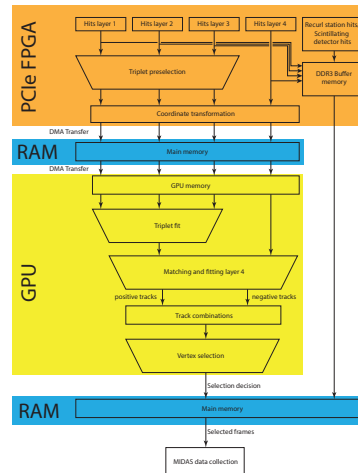
Data Acquisition

- **Triggerless**, continuous readout of all sub-detectors
- **Filter farm** sees whole detector information for a time slice
 - Track reconstruction in central detector and vertex finding on GPUs
 - Events with $\mu \rightarrow eee$ candidates are send off to mass storage
 - **Data reduction** by a factor of 80



Data Acquisition

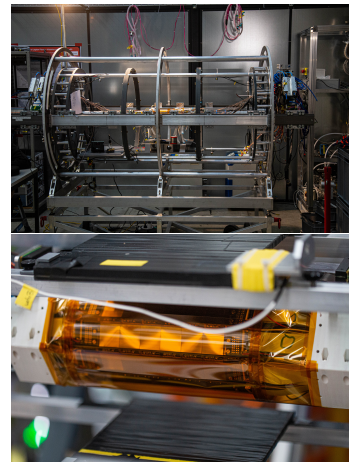
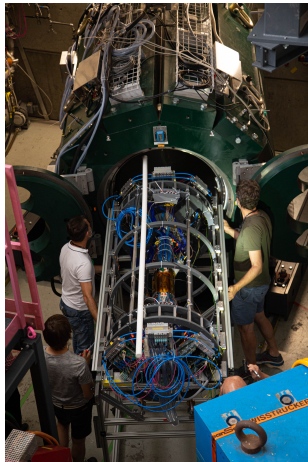
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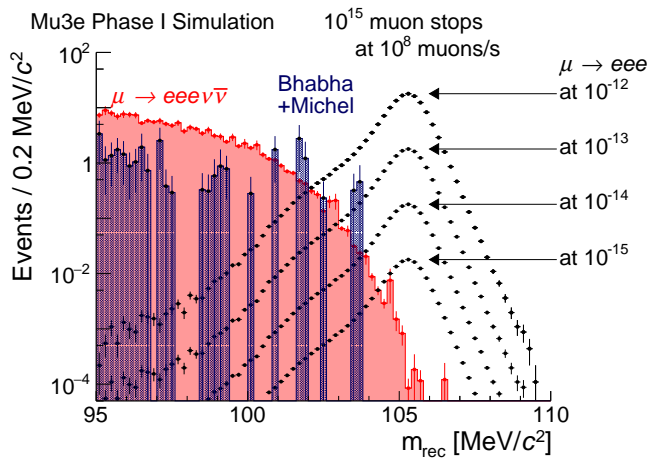
Status

- Custom front-end boards and clock & reset distribution working
- Integration and up-scaling in progress
- Integration run in 2021
 - Vertex prototype + 2 SciFi ribbons in magnet
 - Helium cooling
 - Operated in beam
- Cosmics run in 2022
 - Additional scintillators for triggering cosmics
 - Goal: synchronize Pixel and SciFi
 - Just finished



Sensitivity Studies

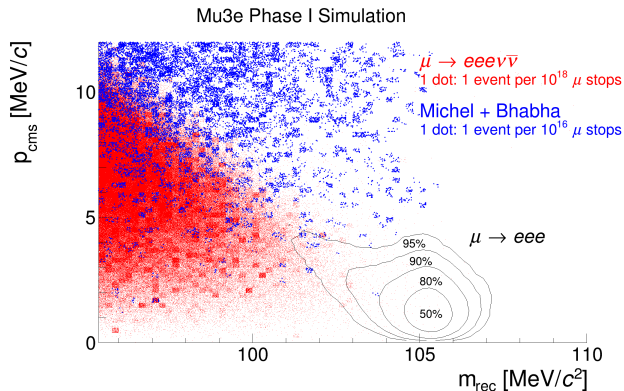
- Track reconstruction and vertex fitting
- Simulated full phase I data taking
- Sensitivities to \mathcal{B} in the range of 10^{-14} to a few 10^{-15} at 90% CL in reach



Sensitivity Studies

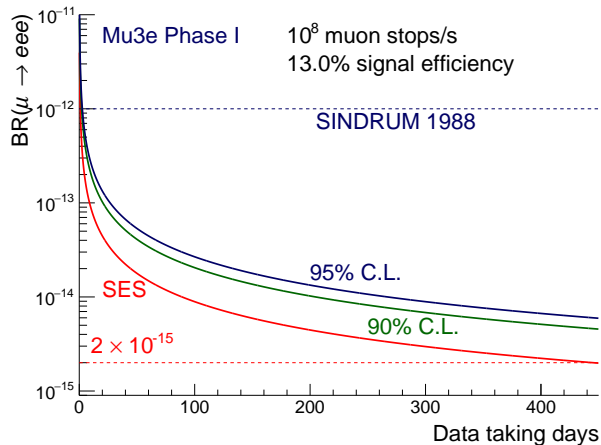
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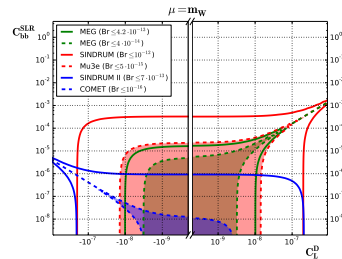
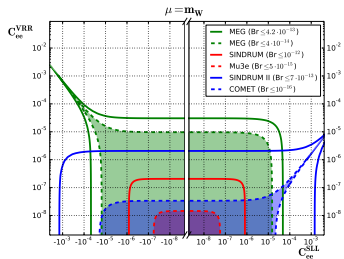
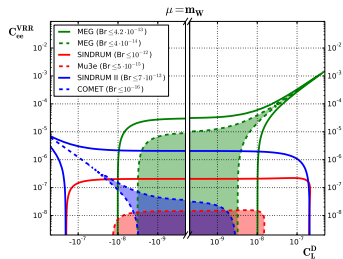
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Lepton Flavour Violation In Effective Theories

- Classical muon LFV searches:
 $\mu \rightarrow e\gamma, \mu \rightarrow eee, \mu N \rightarrow eN$
- Each channel has specific strengths and weaknesses

- Comparison by means of **effective field theories**:
 $\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \sum \mathcal{O}_{5\text{-dim}} + \frac{1}{\Lambda^2} \sum \mathcal{O}_{6\text{-dim}} + \dots$
- Pin down **type of BSM interaction** by **combination** of the searches
- Dalitz plots of $\mu \rightarrow eee$ in case of discovery

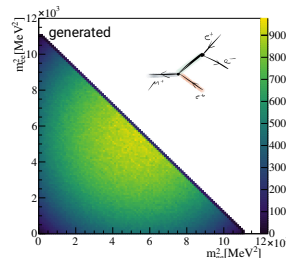
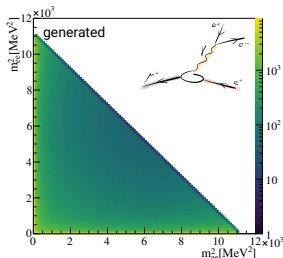
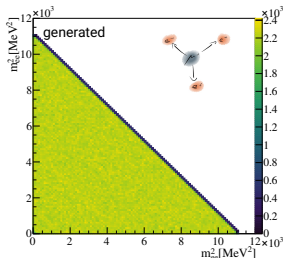


Crivellin, Davidson, Pruna, Signer, JHEP 05 117 (2017)

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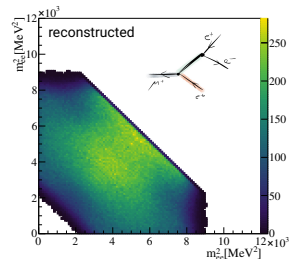
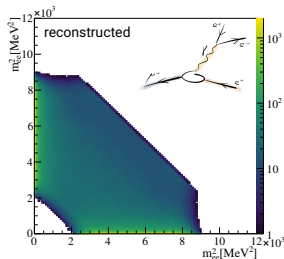
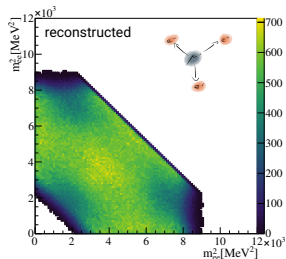
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Lagrangian from Kuno, Okada, Rev.Mod.Phys. 73 (2001) 151-202

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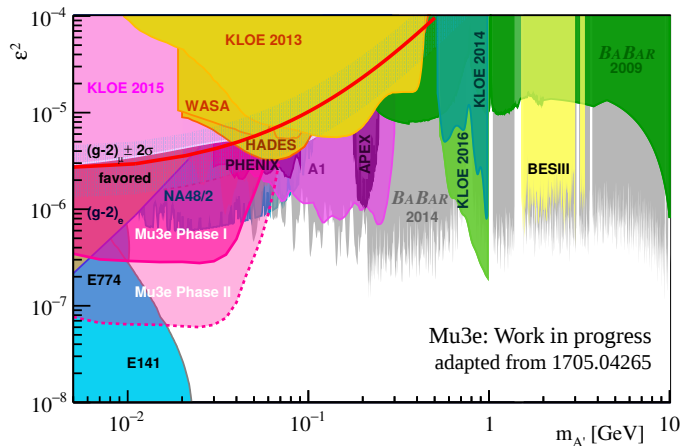
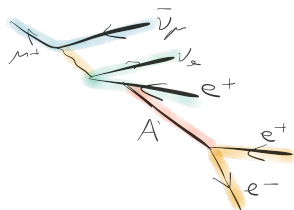


Lagrangian from Kuno, Okada, Rev.Mod.Phys. 73 (2001) 151-202

Other Exotic Physics with Mu3e

Dark Photons

- Large dataset of muon decays can be exploited in other searches
- Ex: Dark photon emitted in muon decays with prompt decay
→ Resonance in e^+e^-



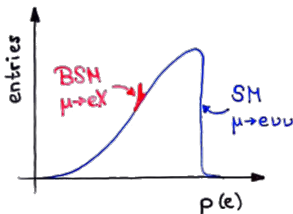
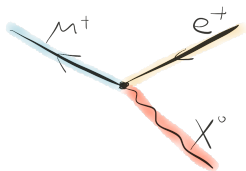
Mu3e: Work in progress
adapted from 1705.04265

Lagrangian from Echenard, Essig, Zhong, JHEP 01 (2015) 113

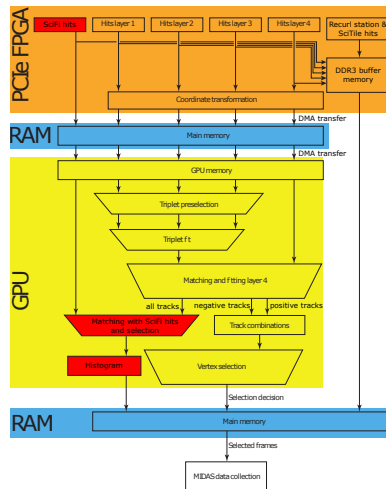
Other Exotic Physics with Mu3e

Familons

- Search for $\mu^+ \rightarrow e^+ X^0$ decays
- Ex: Familon
(Goldstone boson from spontaneously broken flavour symmetry, Wilczek, PRL 49 (1982) 1549)



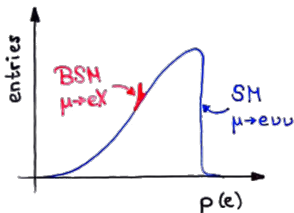
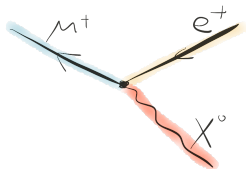
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- Histogramming on filter farm



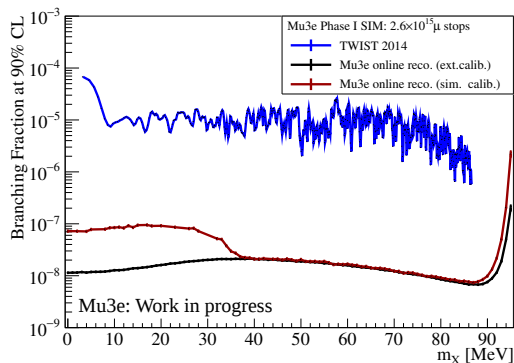
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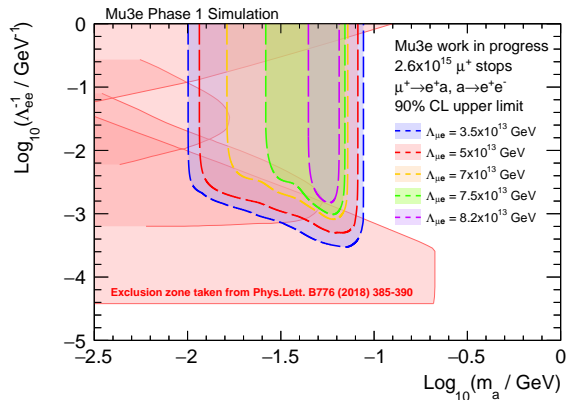
Long-lived Particles

- Axion-like particle with lifetime:

$$\mu^+ \rightarrow e^+ a \text{ with } a \rightarrow e^+ e^-$$

[Heeck, Rodejohann, Phys.Lett.B 776 (2018) 385-390]

- Same final state as $\mu \rightarrow eee$
- Back-to-back e^+ and $e^+ e^-$ pair
- Sufficient efficiency with default $\mu \rightarrow eee$ vertex reconstruction for lifetimes $\mathcal{O}(1 \text{ ns})$

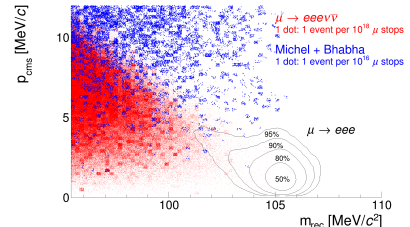


Summary

- Mu3e phase I aims to find or exclude the LFV decay $\mu \rightarrow eee$ with \mathcal{B} as low as a few 10^{-15}
- Low-mass tracking detector operated at $10^8 \mu/s$
- Online event reconstruction and filtering
- Opportunities for searches beyond $\mu \rightarrow eee$
- All detector system are preparing for mass production
- Planning for final commissioning and first data in 2024



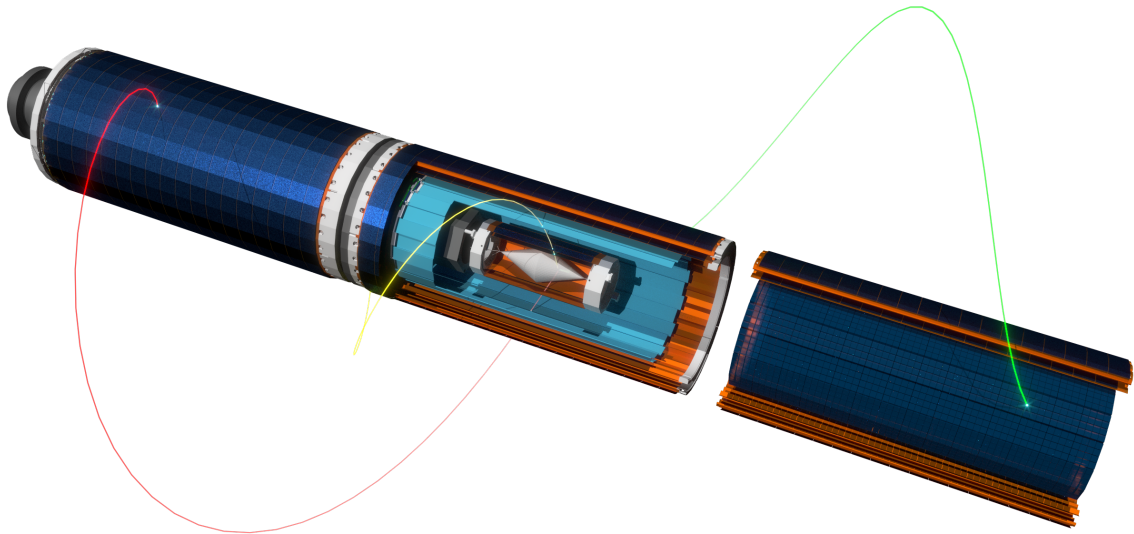
Mu3e Phase I Simulation



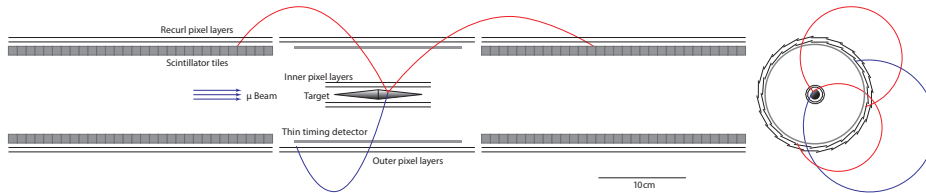
TDR: NIM A 1014 (2021) 165679



www.psi.ch/en/mu3e



Phase II and HIMB



- Reach final sensitivity of 10^{-16} with upgraded phase II detector
 - Elongated recurl station
 - Target with smaller radius
 - To be operated at $2 \times 10^9 \mu/s$
- High-Intensity Muon Beams (HIMB) project at PSI
 - New target and new capturing solenoids
 - Muon rates of $10^{10} \mu/s$
 - Planned to be operational in 2029

