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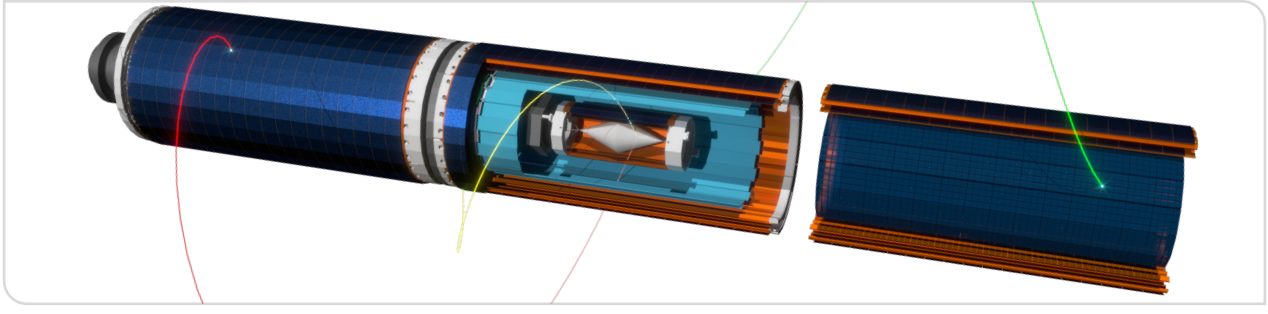
On the Quest for BSM with the Mu3e Experiment

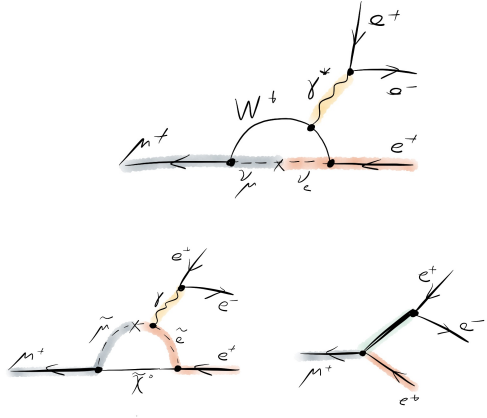
Ann-Kathrin Perrevoort (Mu3e) | Muons in Minneapolis 2023 | Dec 7, 2023



Lepton Flavour Violation
as a sign for Physics Beyond the SM

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

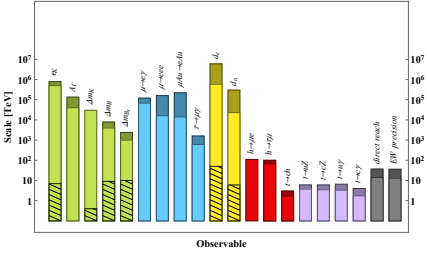
$\Rightarrow$ Observation would be an unambiguous sign of BSM physics



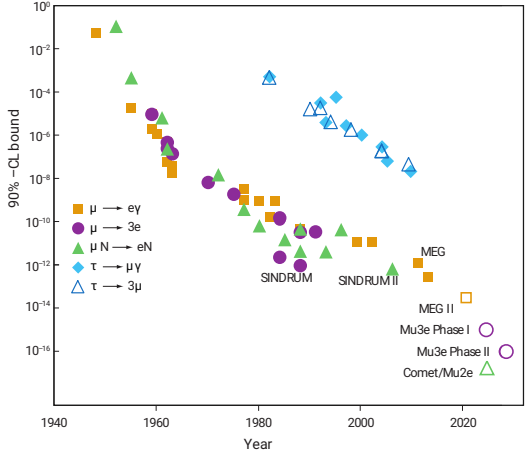
Lepton Flavour Violation

with Muons

- High-intensity muon sources paired with dedicated high-precision experiments
- Current limits at $\mathscr{B} < 10^{-12}$ to 10^{-13}
- Prospected sensitivities in the range of 10^{-15} to 10^{-17} at near-future experiments
- Interpreted in effective field theories (EFT), μLFV searches test $\mathscr{O}(\Lambda) = 10^5$ TeV



[European Strategy 2020, arXiv:1910.11775]



Adapted from [Ann.Rev.Nucl.Part.Sci 58 (2008) 315–341]

Mu3e Experiment
Goals and Challenges

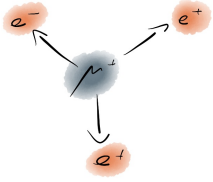
- Current strongest limit: $\mathscr{B}(\mu \to eee) < 1.0 \times 10^{-12}$ at 90% CL (SINDRUM, 1988)
- Mu3e will perform a background-free search for $\mu \to eee$ and aims to find or exclude the decay with a sensitivity in $\mathscr{B}$ of

  a few 10^{-15} in phase I

  10^{-16} in phase II

- Challenges
  - Background suppression
  - High muon decay rates

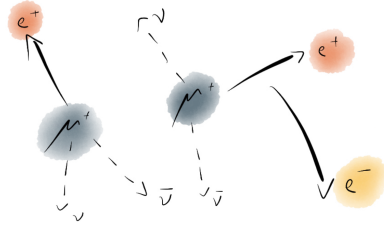
Signal and Background



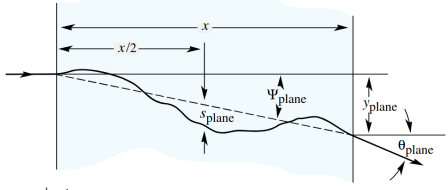
- Signal $\mu^+ \to e^+ e^- e^+$
- Same vertex, coincident
- Decay at rest
  - $\sum P_e = (m_\mu, 0, 0, 0)$
  - $\mathcal{O}(\vec{p}_e) = 10\,\mathrm{MeV}$

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

- Background from rare decay: $\mathcal{B}(\mu \to eee\nu\nu) = 3.4 \times 10^{-5}$
- Missing momentum due to neutrinos
- Need excellent momentum resolution



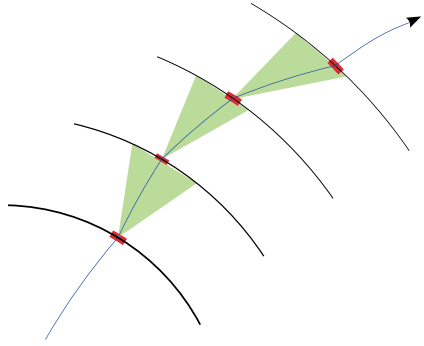
Track Reconstruction



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

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

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



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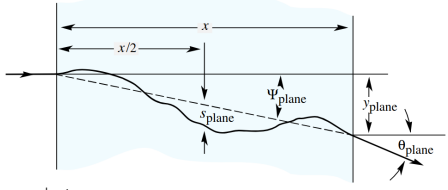

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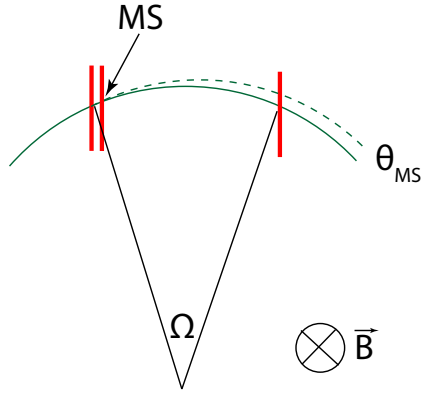

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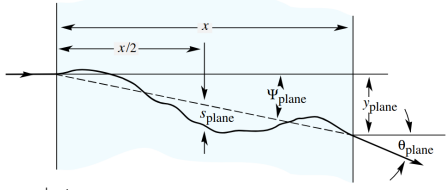

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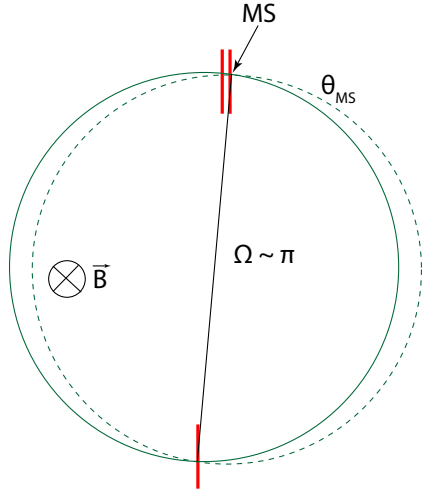

Experimental Concept

- Muons stopped on target
  → decay at rest

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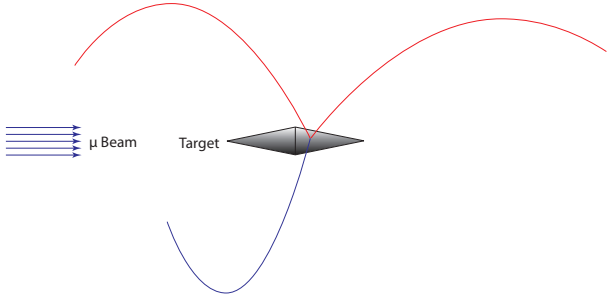

- Muons stopped on target
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- Track e^+/e^- trajectories in
  1 T solenoidal field

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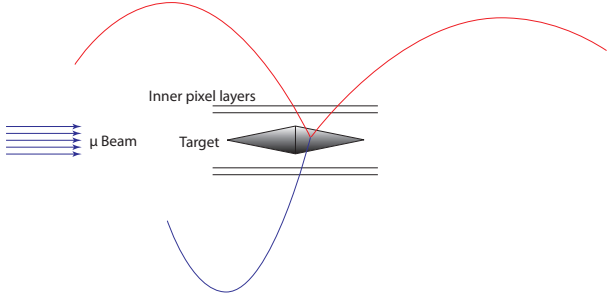

- Muons stopped on target → decay at rest
- Track e^+/e^- trajectories in 1 T solenoidal field
- 4 layers of ultra-thin silicon pixel sensors

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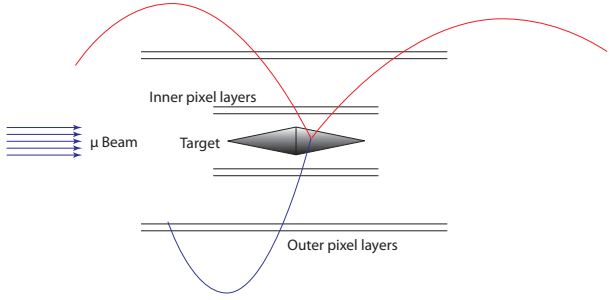

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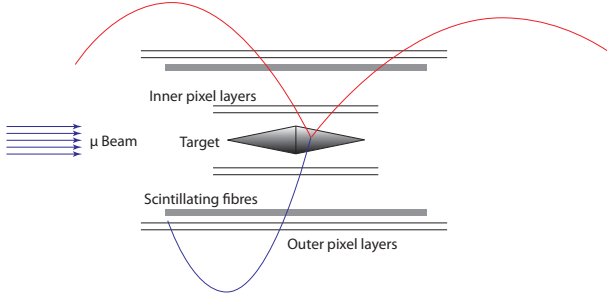
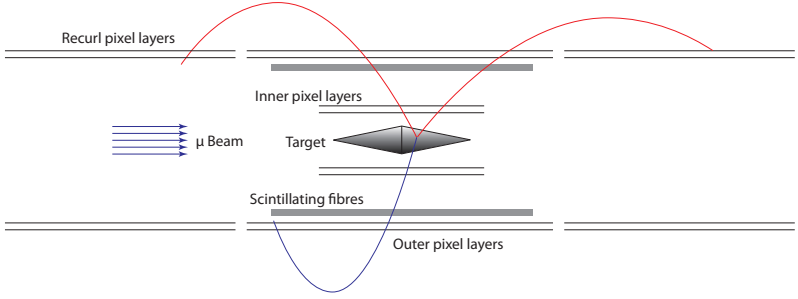


- Muons stopped on target → decay at rest
- Track e^+/e^- trajectories in 1 T solenoidal field
- 4 layers of ultra-thin silicon pixel sensors
- Timing with scintillating fibres

Experimental Concept



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- Timing with scintillating fibres
- Recurl-stations with pixel sensors

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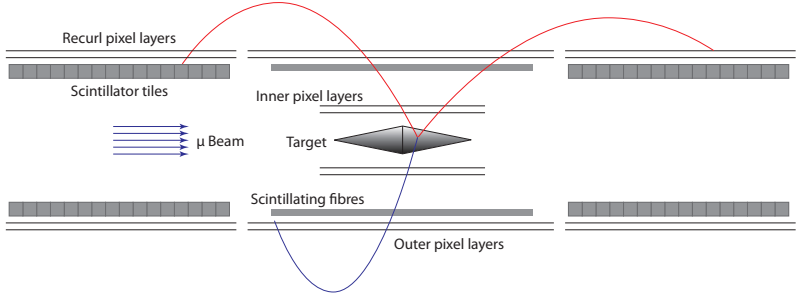
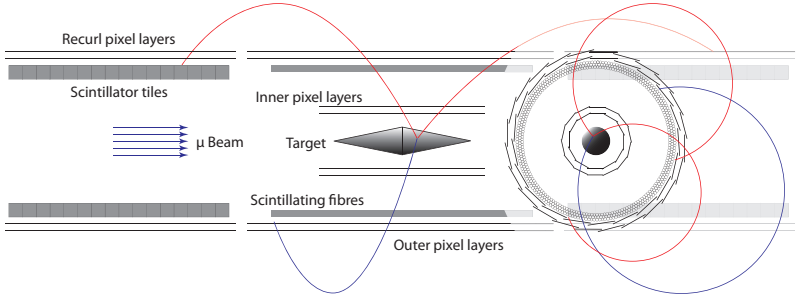


- Muons stopped on target → decay at rest
- Track e^+/e^- trajectories in 1 T solenoidal field
- 4 layers of ultra-thin silicon pixel sensors
- Timing with scintillating fibres
- Recurl-stations with pixel sensors and scintillating tiles

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

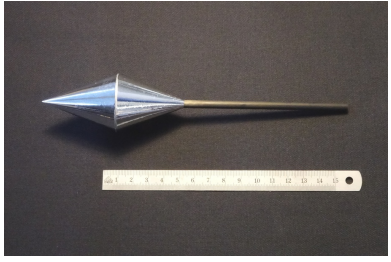
- Recurl-stations with pixel sensors and scintillating tiles
- Cooling with gaseous Helium
- 120 cm long, 18 cm diameter

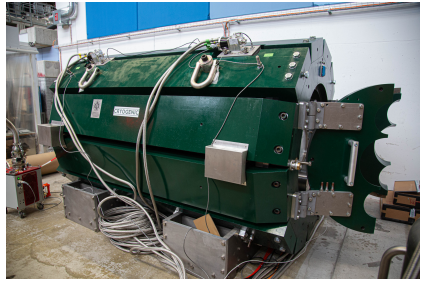
Muon Beam

- 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 μ/s at Compact Muon Beamline (CMB)
  - 10^{10} μ/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, $\varnothing = 38$ mm, 70 µm/80 µm thick
- Stopping rate of 95.5 %



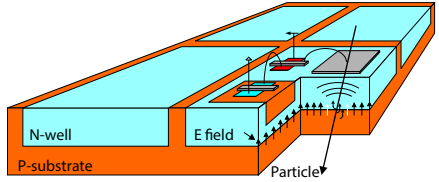


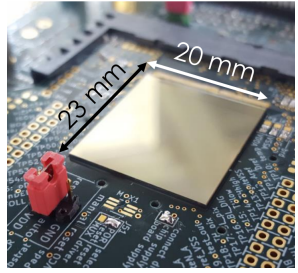
- Solenoid magnet with 1.0 T nominal field (range 0.5 T to 2.7 T)
- Warm bore: $L = 2.7$ m, $\varnothing = 1.0$ m
- Homogeneous magnetic field: $\frac{\Delta B}{B} < 10^{-3}$

Pixel Detector

- Custom designed MuPix sensor
- 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 × 2 cm
  Pixel size 80 µm × 80 µm

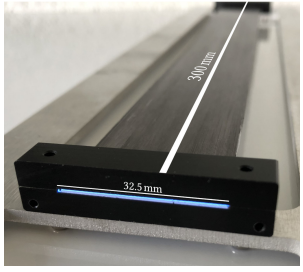
- Full production of final MuPix11 almost finished
- Pre-production of modules

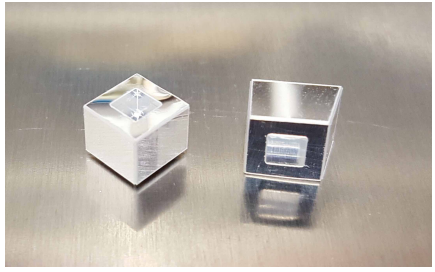




Timing Detectors

- Scintillating fibres with SiPMs in central station
  - 30 cm long ribbons with 3 layers of 250 µm fibres
  - 128ch SiPM column arrays
- Readout with custom MuTRiG ASIC

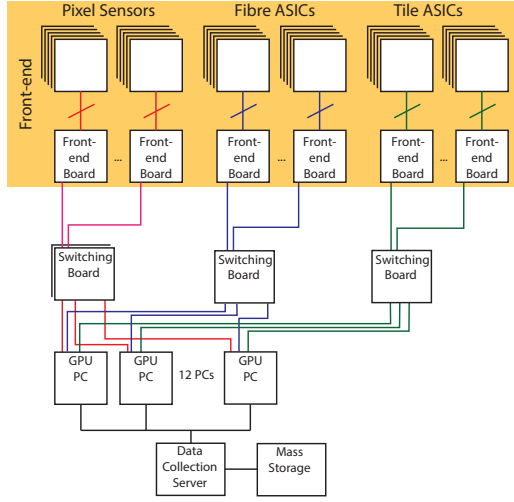




- Scintillating tiles with SiPMs in recurl stations
  - 6 mm × 6 mm × 5 mm cubes wrapped in ESR reflective foil
  - Photon detection with SiPMs
- Readout with MuTRiG

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 sent off to mass storage
  - Data reduction by a factor of 80
- Tested in integration and cosmics runs
- Full integration of timing data and upscaling ongoing



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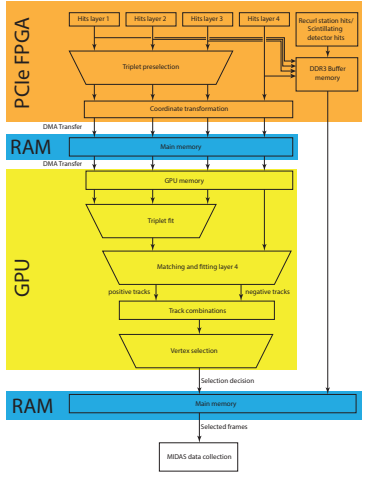
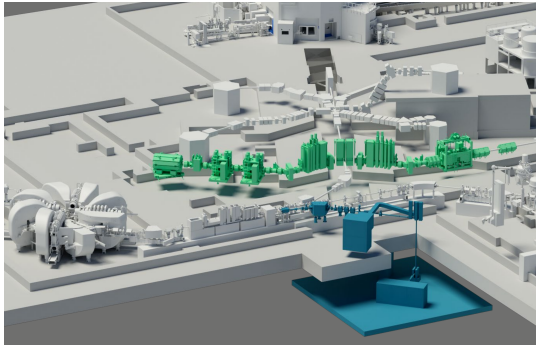
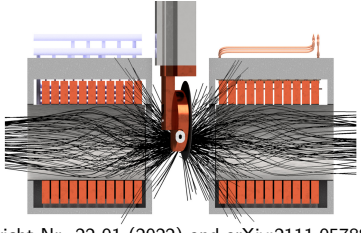


Phase II
HIMB



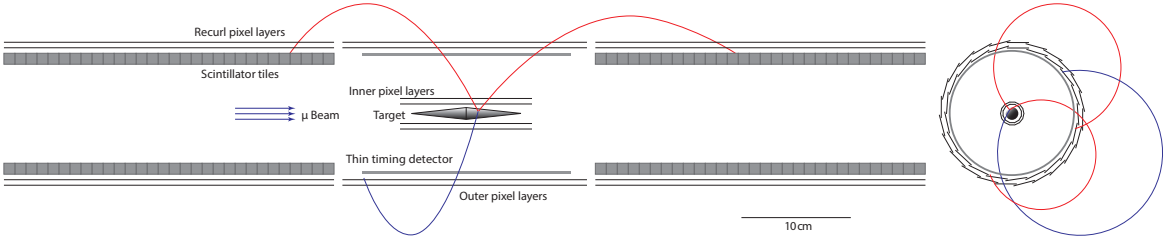
High-Intensity Muon Beams (HIMB) project at PSI

- New target and new capturing solenoids
- Muon rates of $10^{10}\,\mu/\mathrm{s}$
- Shutdown for installation in 2027-2028
- Planned to be operational in 2029



see PSI Bericht Nr. 22-01 (2022) and arXiv:2111.05788

Phase II
Detector

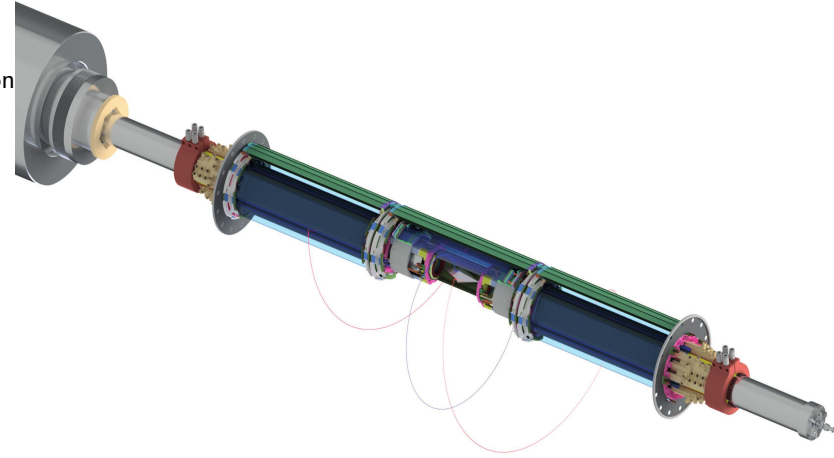


Goal: Reach final sensitivity of 10^{-16} with upgraded phase II detector

- To be operated at $2 \times 10^9\,\mu/\mathrm{s}$ at HIMB
- Accidental background becomes a challenge
- Longer target
- Elongated recurl station
- SciFi replaced by ultrafast pixel layer (SiGe)
- Improved online reconstruction and filtering

Sensitivity Studies

- Full Geant4 based detector simulation
- Track reconstruction and vertex fitting in place



Sensitivity Studies

- Full Geant4 based detector simulation
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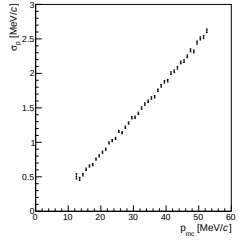
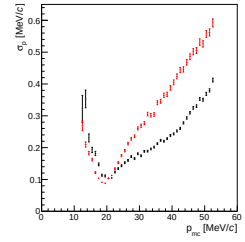
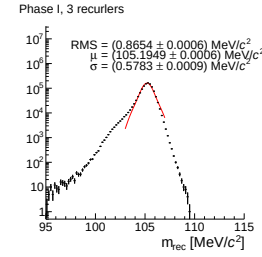
- Reconstruction of recurling tracks pays off
- Improvement in $\frac{\sigma_p}{p}$ by up to a factor 10
- Require 3 recurling tracks for reconstructed m_{eee}



outgoing tracks only (4 hits)

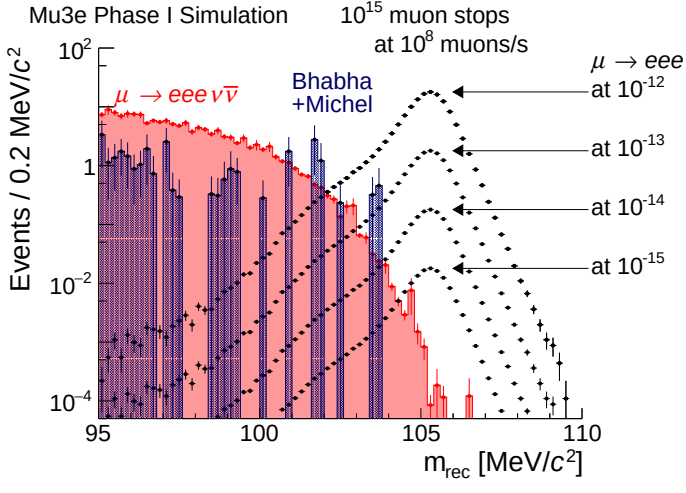


recurling tracks (6 and 8 hits)



Sensitivity Studies

- Simulated full phase I data taking
- Sensitivities to $\mathscr{B}$ in the range of 10^{-14} to a few 10^{-15} at 90 % CL in reach



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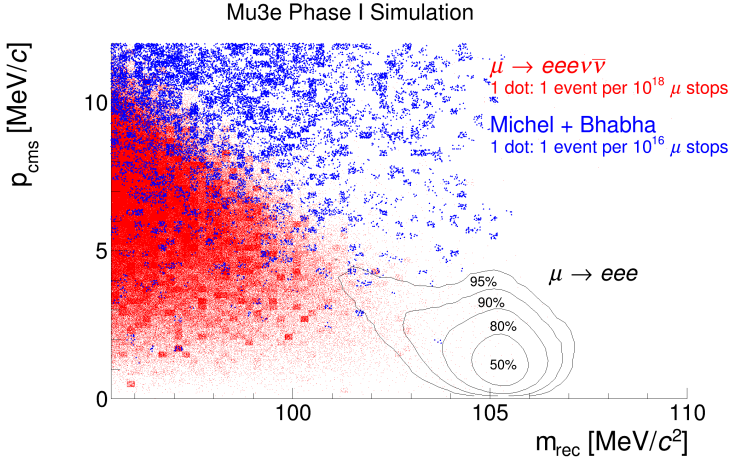

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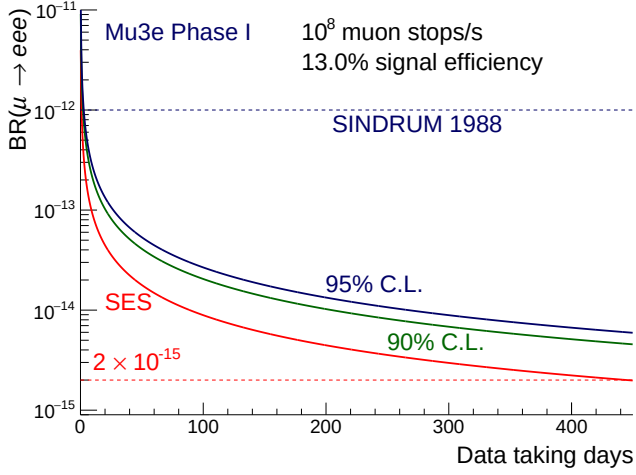
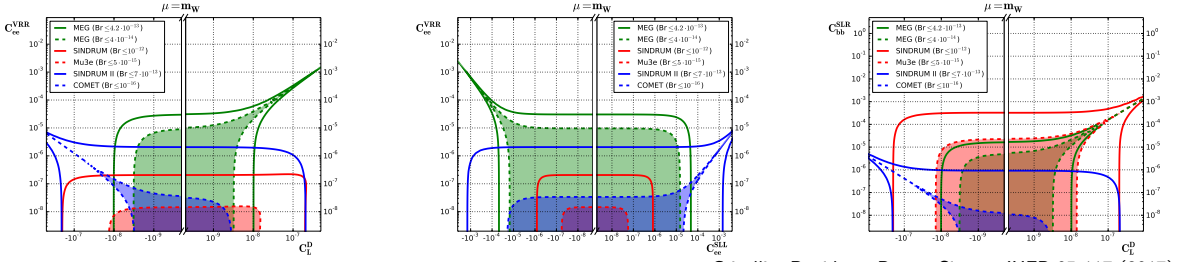


LFV in Effective Theories

- Three golden muon LFV channel:
  $\mu \to e\gamma$, $\mu \to eee$, $\mu N \to eN$
- Each channel has specific strengths and weaknesses
- Comparison by means of effective field theories:
  $\mathscr{L} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda}\sum \mathscr{O}_{\text{5-dim}} + \frac{1}{\Lambda^2}\sum \mathscr{O}_{\text{6-dim}} + \dots$



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

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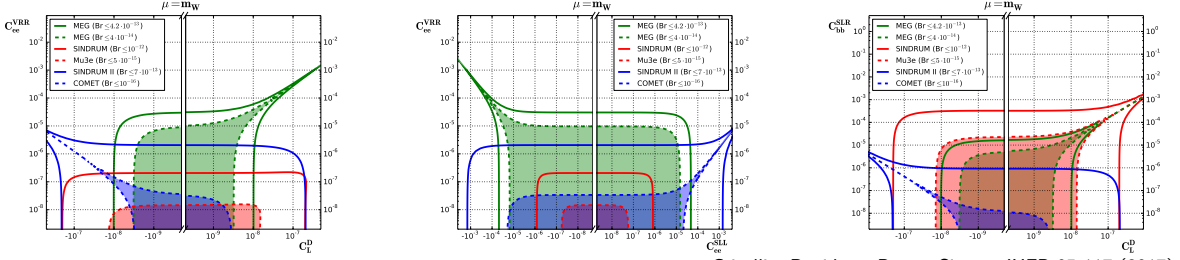
- Pin down type of BSM interaction by combination of the searches
- In case of discovery
  - Exchange target in $\mu N \to eN$
  - Dalitz plots, asymmetry ratios and resonance searches in $\mu \to eee$



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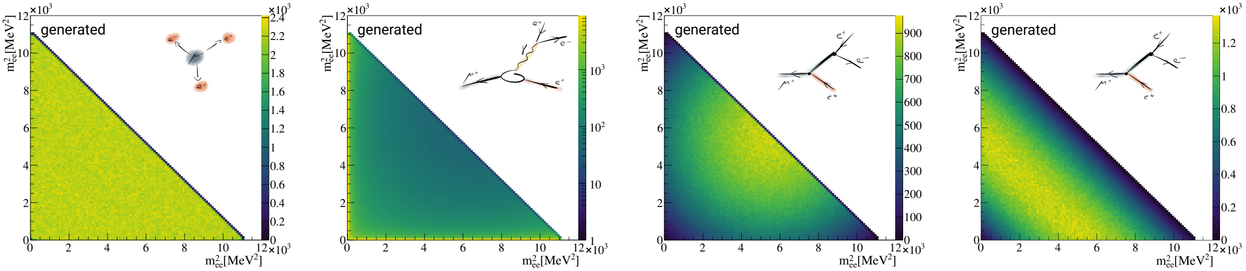

Lagrangian from Kuno, Okada, Rev.Mod.Phys. 73 (2001) 151-202

LFV in Effective Theories

- Three golden muon LFV channel:
  $\mu \to e\gamma$, $\mu \to eee$, $\mu N \to eN$
- Each channel has specific strengths and weaknesses
- Comparison by means of effective field theories:
  $\mathscr{L} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda}\sum \mathscr{O}_{\text{5-dim}} + \frac{1}{\Lambda^2}\sum \mathscr{O}_{\text{6-dim}} + \dots$

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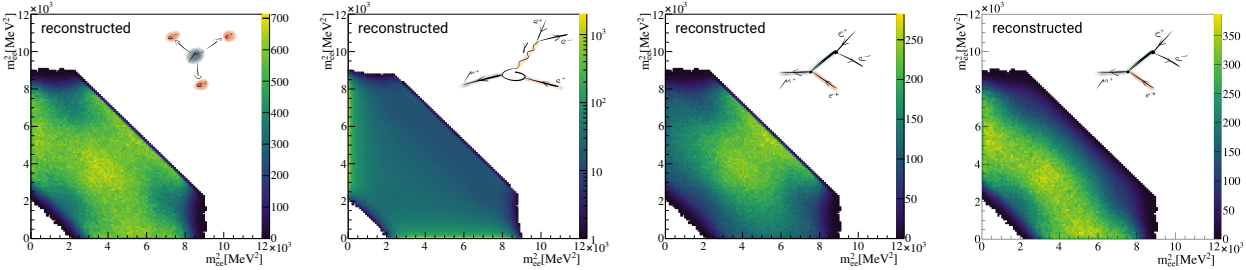

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More Physics with Mu3e

Mu3e is a versatile muon physics experiment

- Capable to measure $e^{+/-}$ with excellent resolution at high rates
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  - Agnostic wrt to additional (in)visible particles
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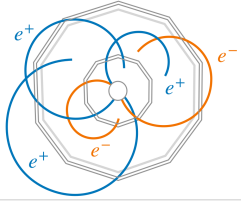

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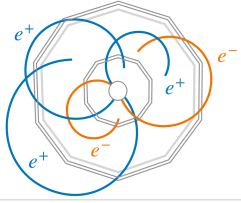

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  - Histograms of track fit results (p, ϕ, θ, q, ...)
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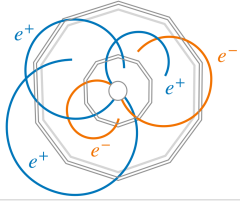

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- Possible modifications (in conflict with $\mu \to eee$ search)
  - Change B field (0.5 T to 2.7 T)
  - Add photon conversion layer, extra pixel layers
  - Change beam to pions
  - ...

More Physics with Mu3e

ALPs with Lifetime

- Axion-like particle with lifetime:
  $\mu^+ \to e^+ a$ with $a \to e^+ e^-$
  [Heeck, Rodejohann, Phys.Lett.B 776 (2018) 385-390]
- Same final state as $\mu \to eee$
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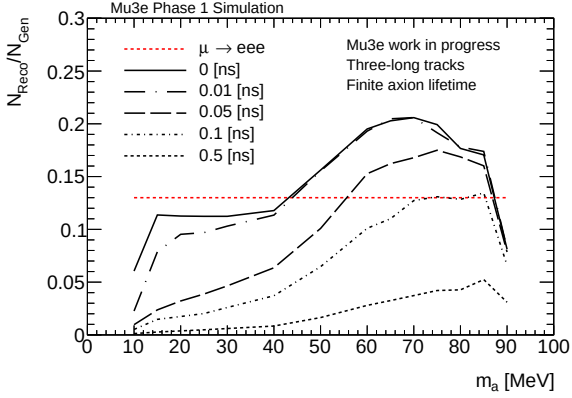

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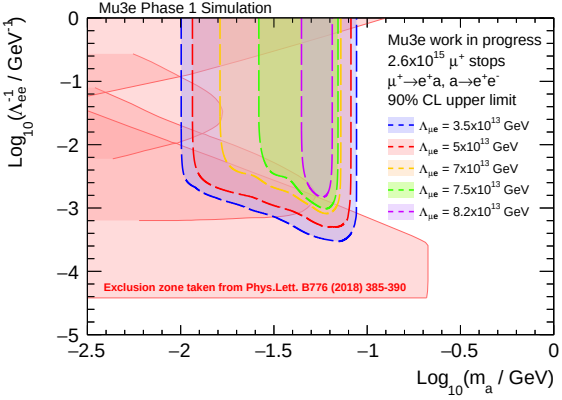

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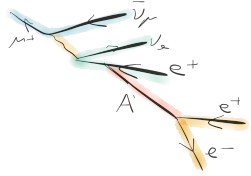
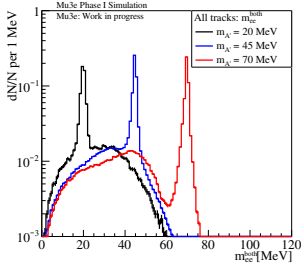
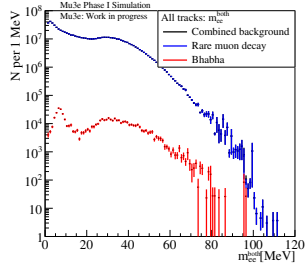
- Search for e^+e^- resonance in $\mu \to eee\nu\nu$
- Example: Dark photon emitted in muon decays with prompt decay $\mu \to eA'\nu\nu$ with $A' \to ee$



- Background from $\mu \to eee\nu\nu$ and Bhabha scattering events





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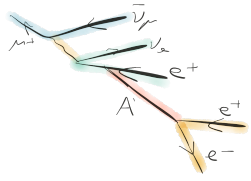

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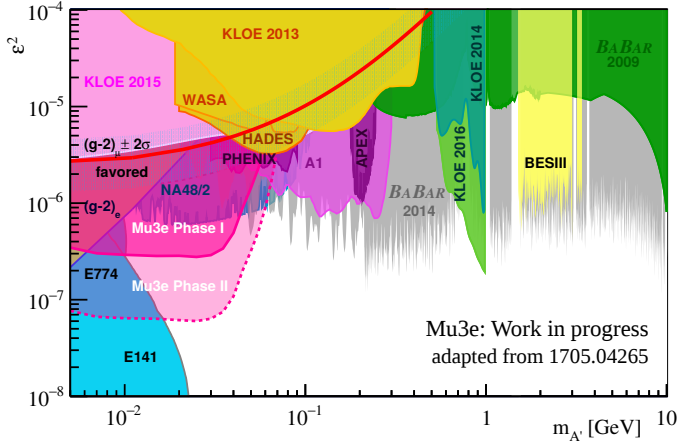

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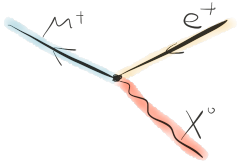
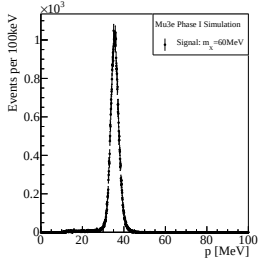
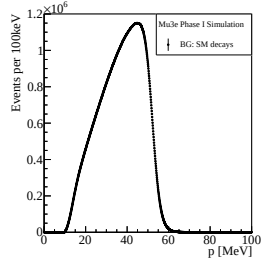
- Search for $\mu^+ \to e^+ X^0$ decays
- Ex: Familon [Wilczek, PRL 49 (1982) 1549]







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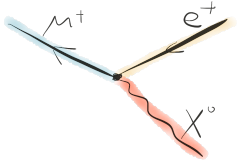

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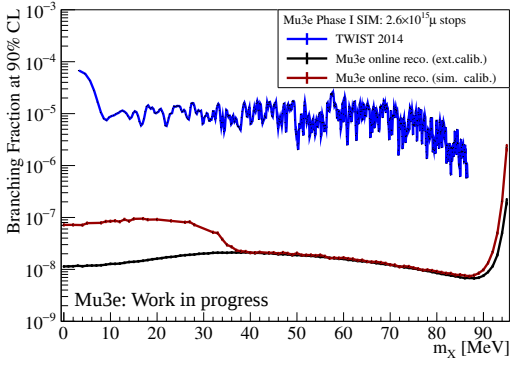

Summary

- Mu3e phase I aims to find or exclude the LFV decay $\mu \to eee$ with $\mathscr{B}$ as low as a few 10^{-15}
- Low-mass tracking detector operated at $10^8\,\mu/\mathrm{s}$
- Online event reconstruction and filtering
- Planning to take data in 2025 & 2026
- Phase II after HIMB installation (2029+) aiming at sensitivity of 10^{-16}

We can investigate more than $\mu \to eee$!
Any ideas? Get in touch!

Checkout https://www.psi.ch/en/mu3e for more details