Karlsruhe Institute of Technology

Institute of Experimental Particle Physics

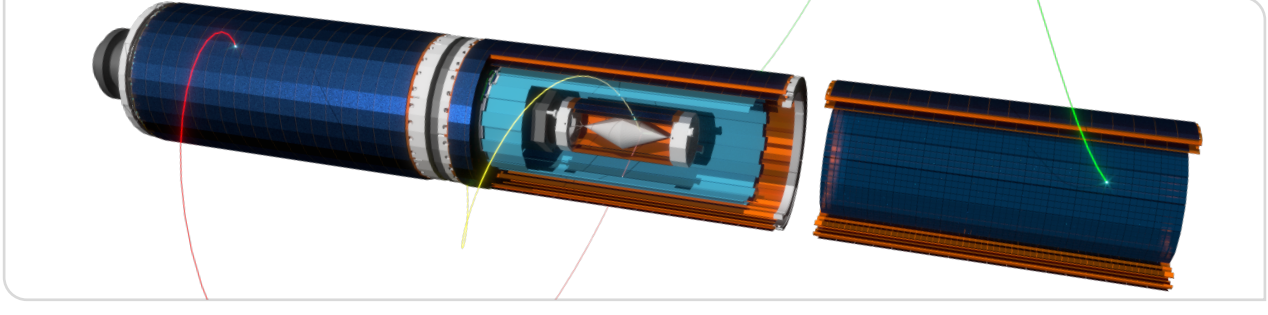
Bundesministerium für Bildung und Forschung

Baden-Württemberg
MINISTERIUM FÜR WISSENSCHAFT, FORSCHUNG UND KUNST

The Flavour of Muons

Searching for Lepton Flavour Violation with the Mu3e Experiment

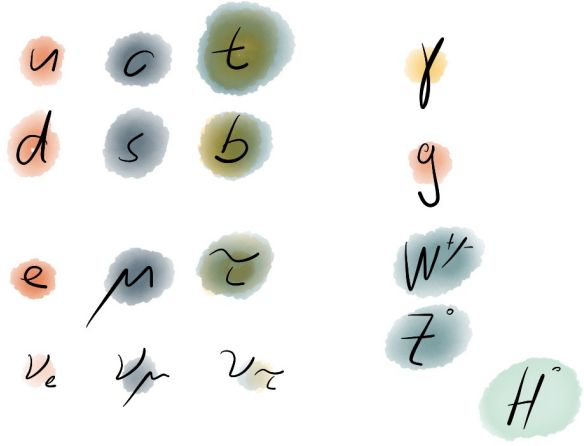
Ann-Kathrin Perrevoort | May 19, 2022



Overview

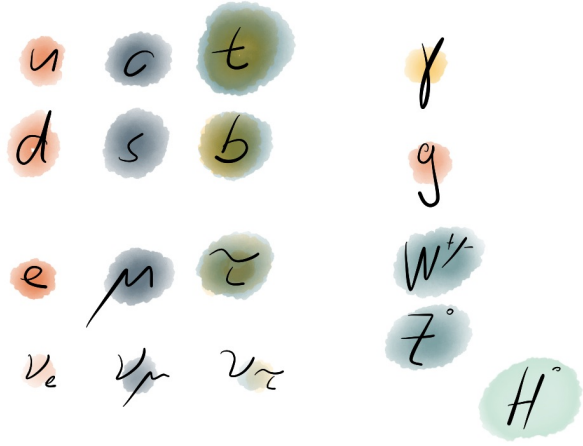
1. Lepton Flavour Violation (in muon decays)
2. Mu3e Experiment
3. Other searches for exotic physics with Mu3e

Lepton Flavour Violation
as a sign for Physics Beyond the SM



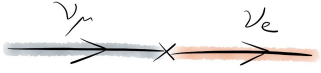
Lepton Flavour Violation
as a sign for Physics Beyond the SM

- Lepton flavour is an accidental symmetry of the Standard Model (SM)
- ... often violated in extensions of the SM



Lepton Flavour Violation
as a sign for Physics Beyond the SM

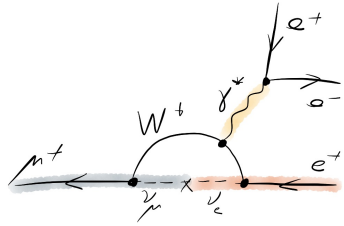
- Lepton flavour is an accidental symmetry of the Standard Model (SM)
- ... often violated in extensions of the SM
- ... as well as in nature: neutrino oscillations



Lepton Flavour Violation
as a sign for Physics Beyond the SM

- Lepton flavour violation (LFV) in the charged lepton sector not (yet?) observed
- cLFV is heavily suppressed in the νSM:

$$\mathcal{B}_{\mu\to eee} \propto \left(\frac{\Delta m^2_\nu}{m^2_W}\right)^2 \quad \to \quad \mathcal{B}_{\mu\to eee} < 10^{-54}$$



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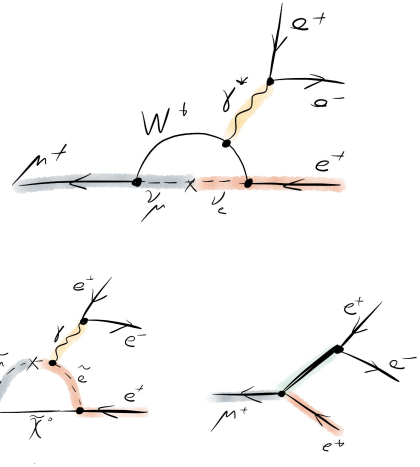
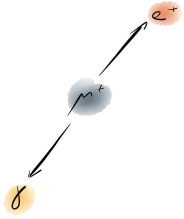
- Observation would be an unambiguous sign of physics beyond the SM



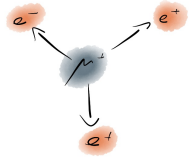
Lepton Flavour Violation

with Muons



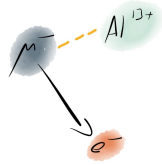
$\mu^+ \to e^+\gamma$

- Monoenergetic e^+ and γ, back-to-back
- Continuous beam
- Background from accidental combinations



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

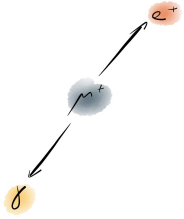
- Invariant mass of $e^+e^-e^+ = m_\mu$
- $\sum \vec{p}_e = \vec{0}$
- Continuous beam
- Background from $\mu \to eee\nu\nu$ and accidental combinations



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

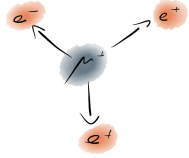
- Monoenergetic e^-
- Pulsed beam
- Background from decay in orbit, antiprotons, pions, cosmics

Lepton Flavour Violation
with Muons



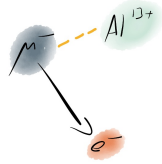
$\mu^+ \to e^+\gamma$

- Current limit:
  MEG (PSI, 2016):
  $\mathscr{B}(\mu \to e\gamma) < 4.2 \times 10^{-13}$
- Future: upgrade MEG II



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

- Current limit:
  SINDRUM (PSI, 1988):
  $\mathscr{B}(\mu \to eee) < 1.0 \times 10^{-12}$
- Future: Mu3e (PSI)



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

- Current limit:
  SINDRUM II (PSI, 2006):
  $\mathscr{B}(\mu\text{Au} \to e\text{Au}) < 7 \times 10^{-13}$
- Future: Mu2e (Fermilab) and
  Comet (J-PARC)

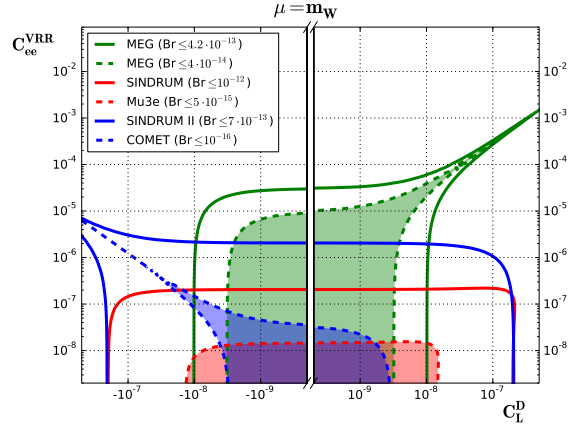
Lepton Flavour Violation
with Muons

- Each experiment has specific strengths and weaknesses
- Comparison by means of effective field theories

- Exemplary operators:

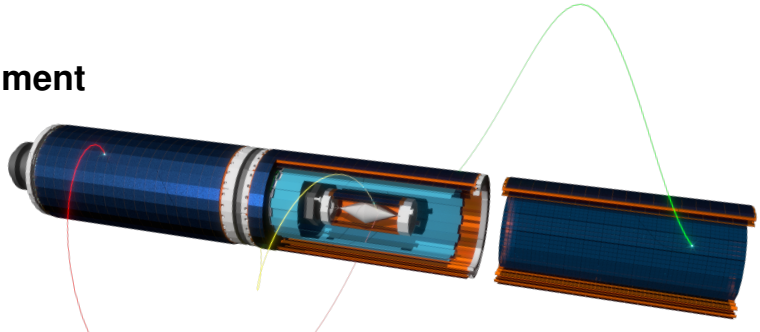
Dipole: $\mathcal{O}_{\mathrm{L}}^{\mathrm{D}} = e m_\mu (\bar{e}\,\sigma^{\mu\nu} P_{\mathrm{L}}\,\mu) F_{\mu\nu}$

4-fermion (vector): $\mathcal{O}_{ee}^{\mathrm{VRR}} = (\bar{e}\,\gamma^\mu P_{\mathrm{R}}\,\mu)(\bar{f}\,\gamma_\mu P_{\mathrm{R}}\,f)$



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

Mu3e Experiment



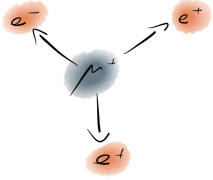
- Mu3e is a future experiment to perform a background-free search for the cLFV decay $\mu^+ \to e^+ e^- e^+$
- Under construction at Paul Scherrer Institute (PSI) in Switzerland
- Aiming for a sensitivity in $\mathscr{B}$ of

a few 10^{-15} in phase I

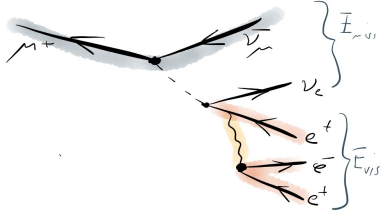
10^{-16} in phase II

Mu3e Experiment

Signal and Background

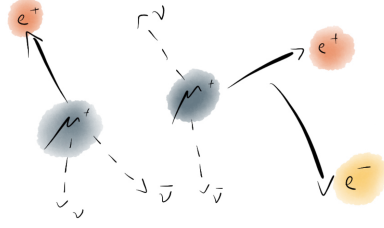


- Signal $\mu^+ \to e^+e^-e^+$
- Same vertex, coincident
- Decay at rest
  - $\sum P_e = (m_\mu, 0, 0, 0)$
  - $\mathcal{O}(\vec{p}_e) = 10\,\mathrm{MeV}$



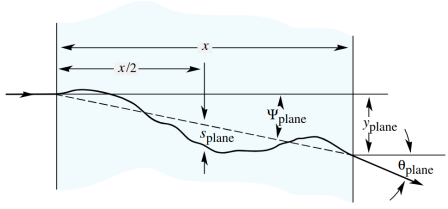
- Accidental combinations of e^+ from $\mu \to e\nu\nu$ with e^- or e^+e^- from Bhabha scattering, photon conversion, mis-reconstruction
- Need good timing and vertexing, low material

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



Mu3e Experiment

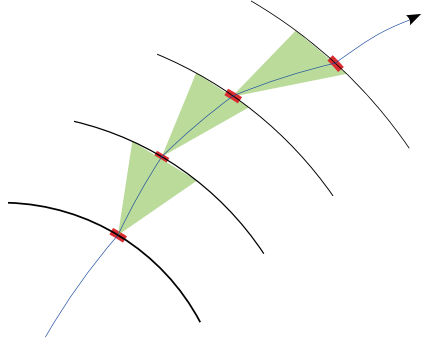
Track Reconstruction



- Low energy e^+/e^- undergo multiple Coulomb scattering
  - Energy loss and deflection
- Momentum resolution

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

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



Mu3e Experiment

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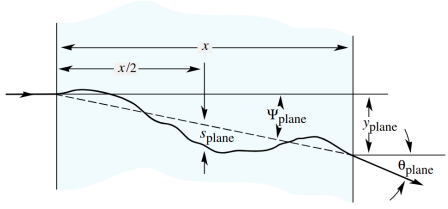

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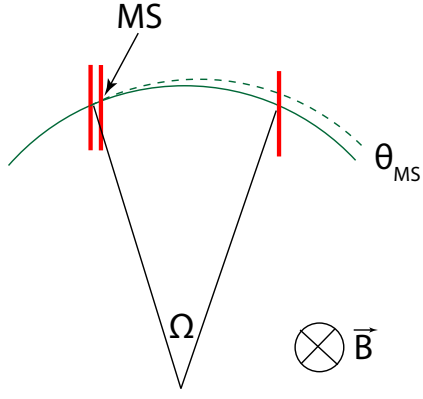

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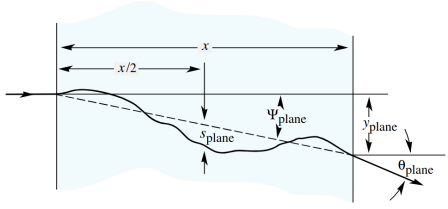

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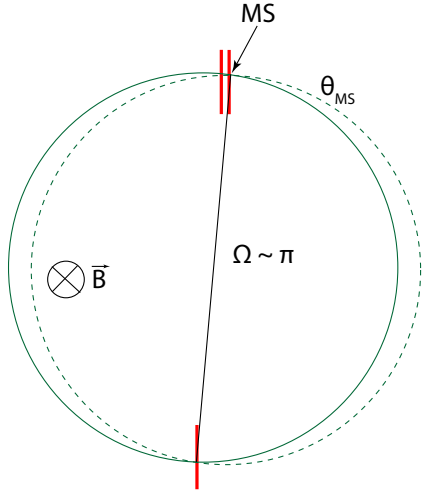

Mu3e Experiment
Experimental Concept

- Muons stopped on target
  $\rightarrow$ decay at rest

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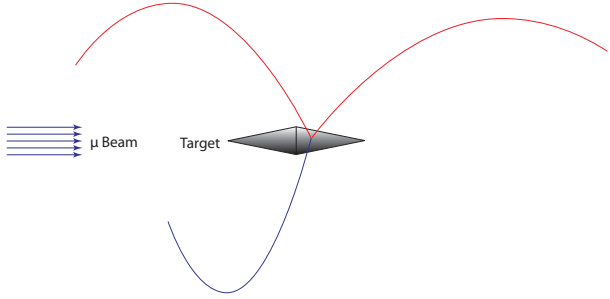

- Muons stopped on target
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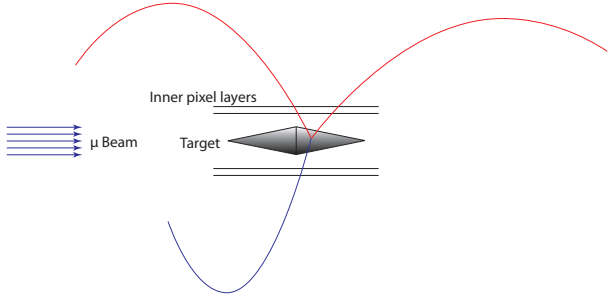
- Track e^+/e^- trajectories in 1 T solenoidal field

Mu3e Experiment

Experimental Concept



- Muons stopped on target
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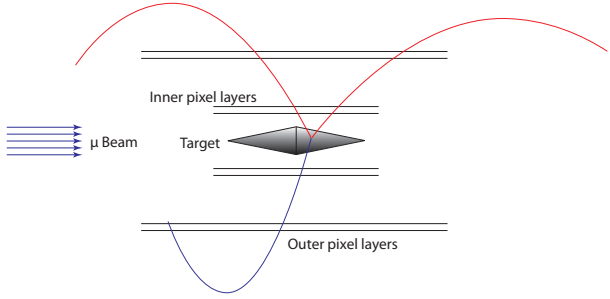
- 4 layers of ultra-thin silicon pixel sensors

Mu3e Experiment
Experimental Concept



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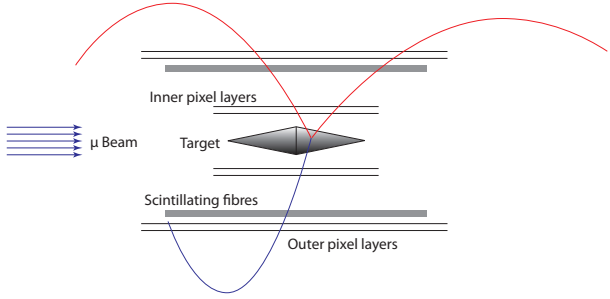

- Muons stopped on target
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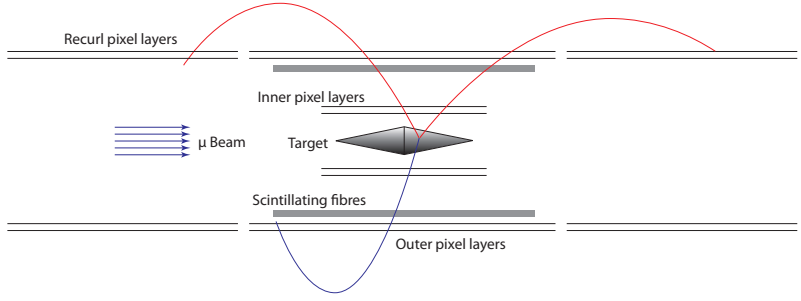
- Track e^+/e^- trajectories in 1 T solenoidal field
- 4 layers of ultra-thin silicon pixel sensors
- Timing with scintillating fibres

Mu3e Experiment

Experimental Concept



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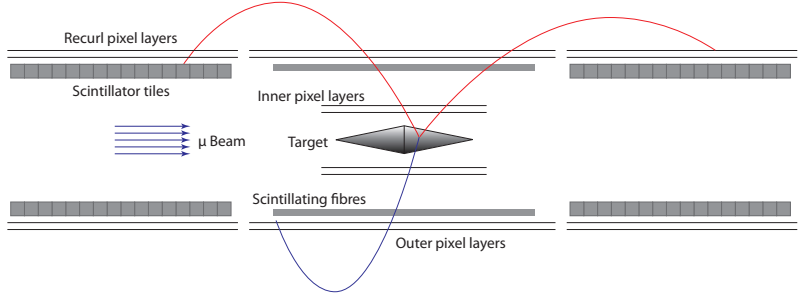
- Recurl-stations with pixel sensors

Mu3e Experiment

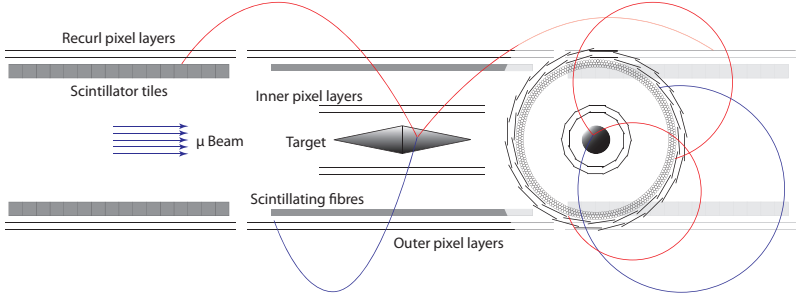
Experimental Concept



- Muons stopped on target $\rightarrow$ 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

Mu3e Experiment

Experimental Concept



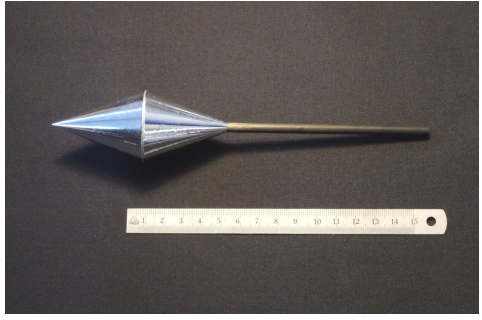
- Muons stopped on target $\rightarrow$ decay at rest
- Track e^+/e^- trajectories in 1 T solenoidal field
- 4 layers of ultra-thin silicon pixel sensors
- Timing with scintillating fibres
- Recurl-stations with pixel sensors and scintillating tiles
- Cooling with gaseous Helium
- 120 cm long, 18 cm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

Mu3e Experiment
Muon Beam

- 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
- Sub-surface μ^+ with 28 MeV
  - 10^8 $\mu/$s at existing beamline
  - 10^{10} $\mu/$s with the future High Intensity Muon Beams (HIMB) project (2029+)

Mu3e Experiment
Stopping Target

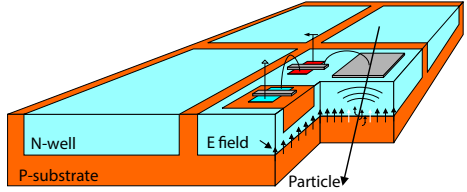
- Distribute muon stops over large surface
- Reduce material traversed by decay products
- Hollow, double-cone target made from Mylar
- 100 mm long, 38 mm diameter, 70 µm/80 µm thick
- Stopping rate of 95.5 %

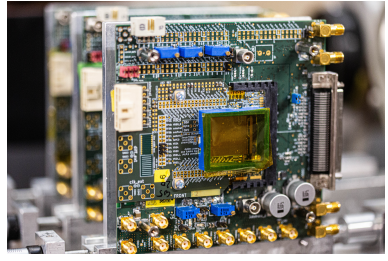


Mu3e Experiment

Pixel Detector

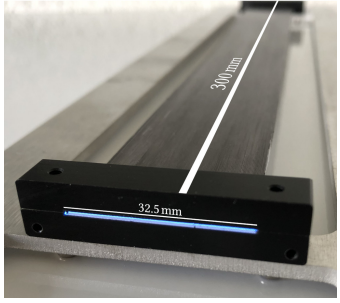
- High Voltage Monolithic Active Pixel Sensor (HV-MAPS) developed at IPE (KIT)
- Fast charge collection in small active region
- Thinned to 50 µm
  only 1.15 ‰ of radiation length incl. flexprint and support structure
- Logic implemented in N-well
- Sensor size 2 cm × 2 cm
  Pixel size 80 µm × 80 µm
- Final version submitted

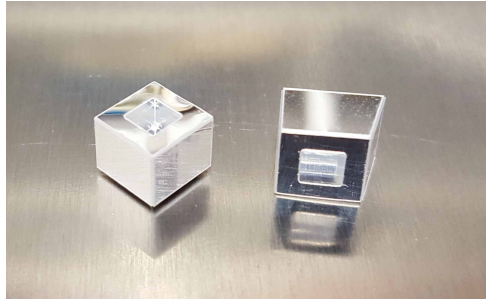




Mu3e Experiment
Scintillating Timing Detectors

- 3 layer ribbons of 250 µm scintillating fibres in central detector
- Scintillating tiles of size 6 mm $\times$ 6 mm $\times$ 5 mm in recurl stations
- Readout with SiPMs and custom MuTRiG ASIC

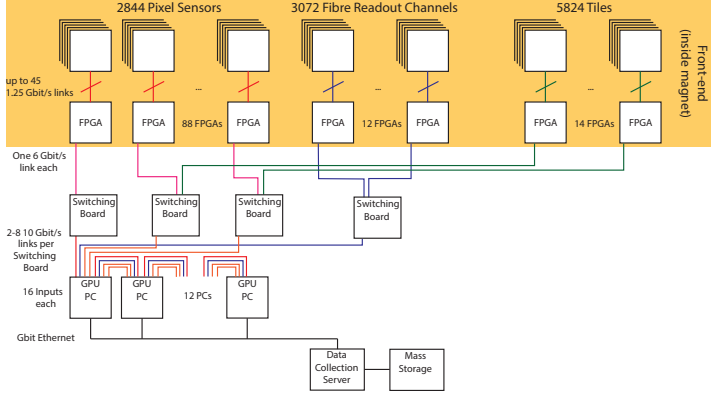




Mu3e Experiment

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
  - Interesting events are send off to mass storage
  - Data reduction by a factor of 80



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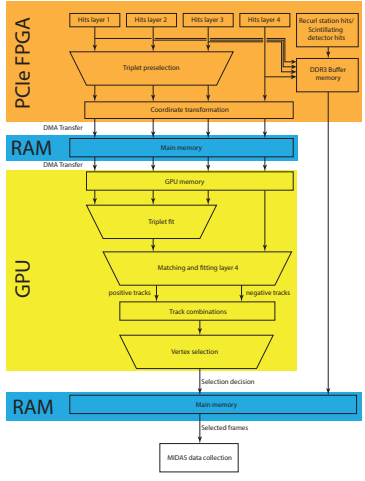
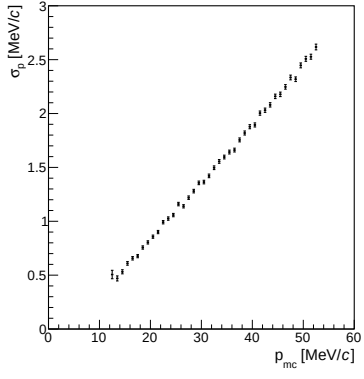


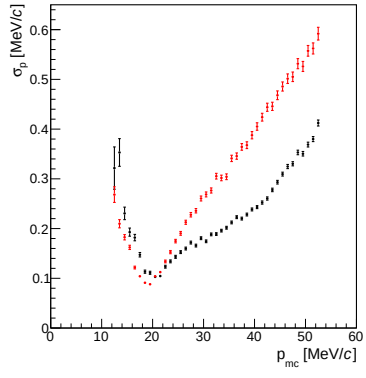
Mu3e Experiment

Sensitivity Studies

- Geant4 based detector simulation
- Reconstruction of recurling tracks pays off
- Improvement in $\frac{\sigma_p}{p}$ by up to factor 10



outgoing tracks only (4 hits)

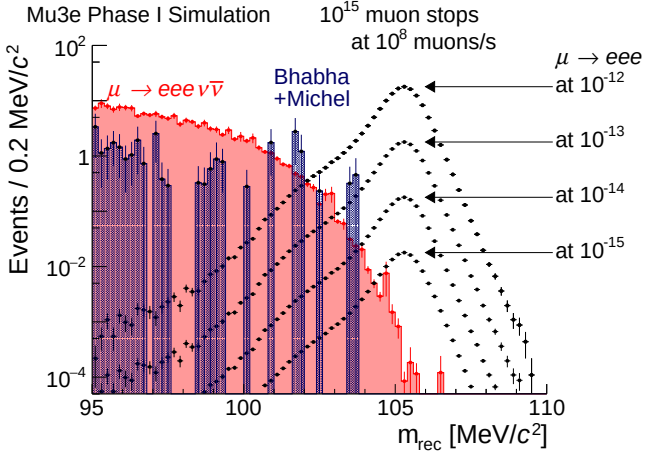


recurling tracks (6 and 8 hits)

Mu3e Experiment

Sensitivity Studies

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



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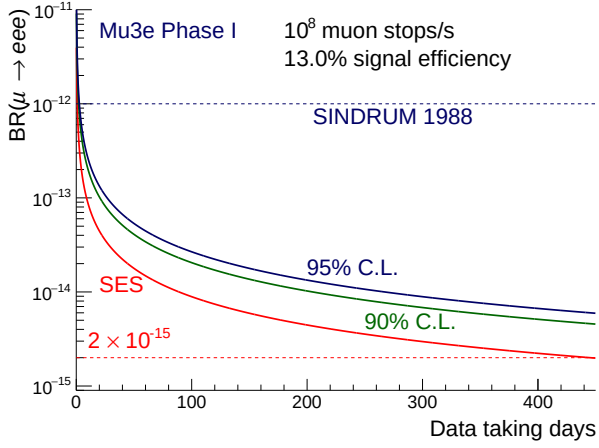
- Simulated full phase I data taking
- Sensitivities to $\mathscr{B}$ in the rage of 10^{-14} to a few 10^{-15} at 90 % CL in reach



Mu3e Experiment
Status

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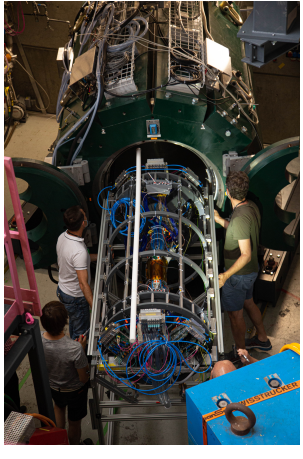
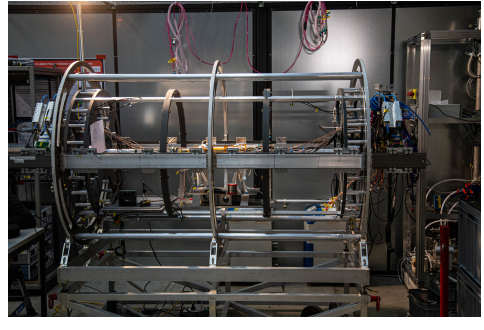
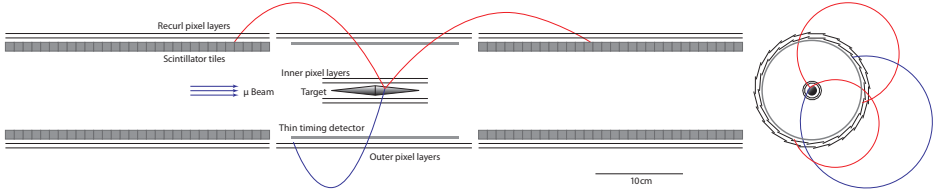


- Final versions of MuPix and MuTRiG submitted
- Integration run in 2021
- Cosmics run now
- Moving into production phase
- First data expected in 2024

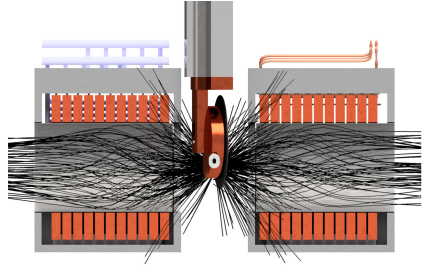


Mu3e Experiment

Phase II and HIMB



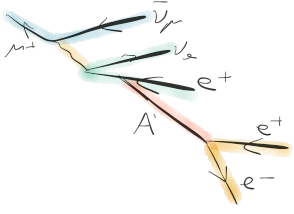
- Reach final sensitivity of 10^{-16} with upgraded phase II detector
  - Elongated recurl station
  - Target with smaller radius
  - To be operated at $2 \times 10^9\ \mu/\mathrm{s}$
- High-Intensity Muon Beams (HIMB) project at PSI
  - New target and new capturing solenoids
  - Muon rates of $10^{10}\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

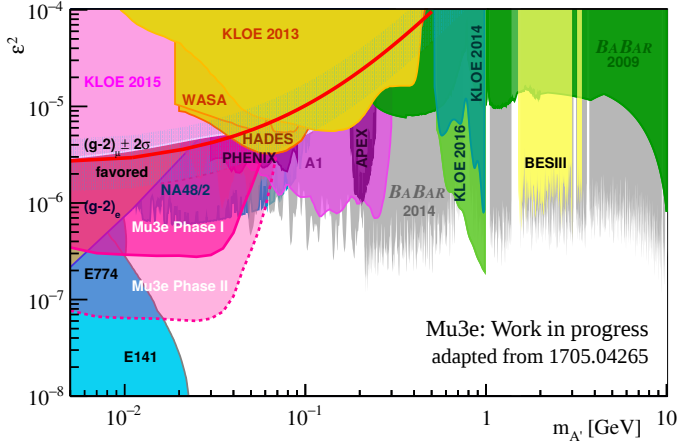


Other Exotic Physics with Mu3e

Dark Photons

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



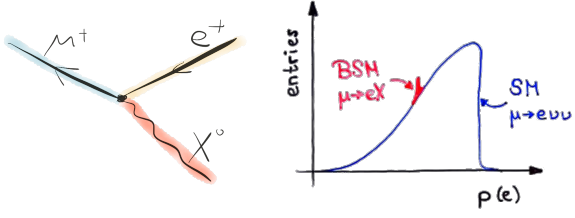


Lagrangian from Echenard, Essig, Zhong, JHEP 01 (2015) 113

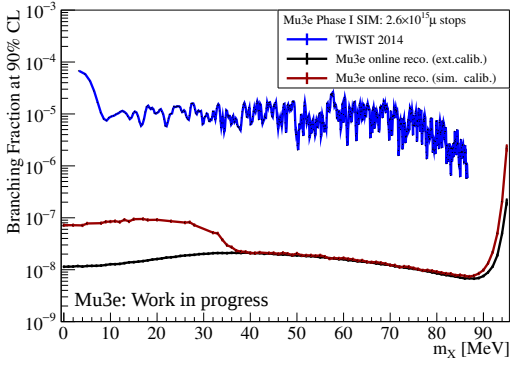
Other Exotic Physics with Mu3e

Familons

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



- Challenge: single-e events are not saved
- Histogramming on filter farm



Summary

- Mu3e aims to search for the LFV decay $\mu \to eee$ with an ultimate sensitivity of 10^{-16}
- Low-mass tracking detector
- Online event reconstruction and filtering
- Opportunities for searches beyond $\mu \to eee$

Technical Design Report

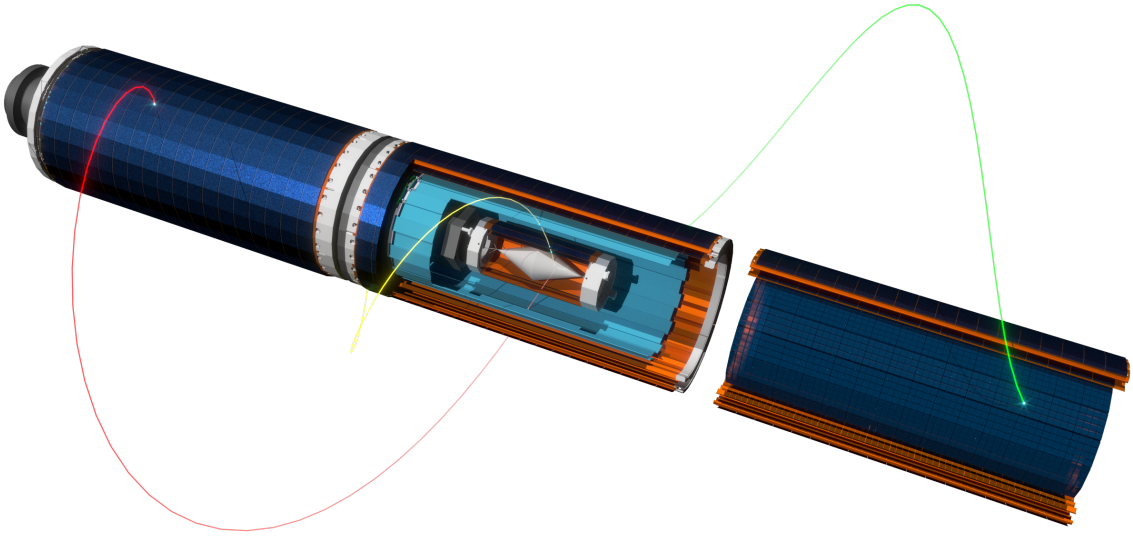
NIM A 1014 (2021) 165679

Mu3e at PSI

www.psi.ch/en/mu3e

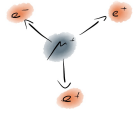
Mu3e at ETP

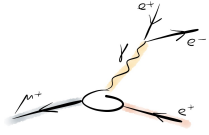
etpwww.etp.kit.edu/~aperrevoort

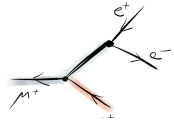


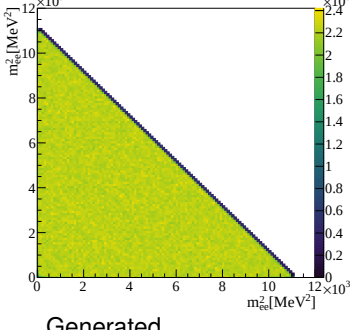
Mu3e Experiment

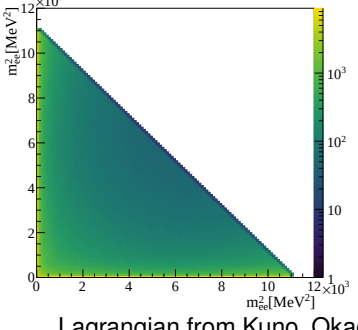
Signal Decay with EFTs

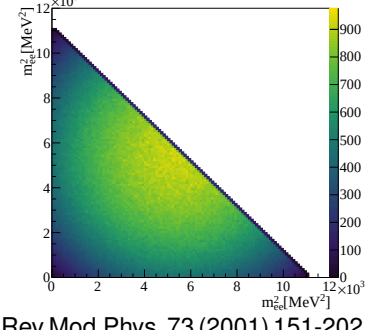










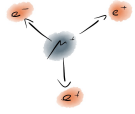


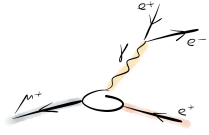
Generated

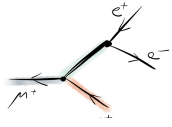
Lagrangian from Kuno, Okada, Rev.Mod.Phys. 73 (2001) 151-202

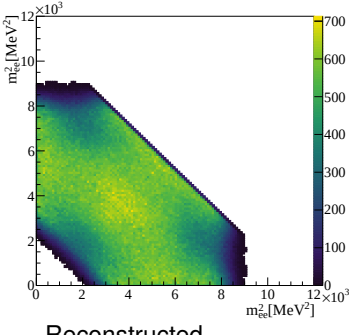
Mu3e Experiment

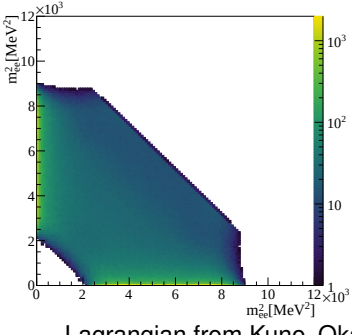
Signal Decay with EFTs

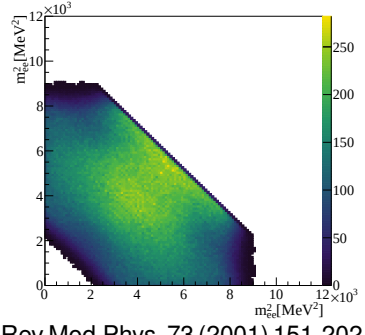












Reconstructed

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