Probing Physics beyond the Standard Model with the Mu3e Experiment

Ann-Kathrin Perrevoort for the Mu3e Collaboration

NIKHEF, Amsterdam (formerly Physics Institute, Heidelberg)

Flavour and Dark Matter Karlsruhe

September 26, 2018
Mu3e in a Nutshell

- Search for cLFV in $\mu \rightarrow eee$
- Observe $O(10^{15})$ to $O(10^{16})$ muons
- Precise tracking of $e^+/e^-$
- High geometric and momentum acceptance ($p_T > 10$ MeV)
- Online reconstruction of all tracks
- Filtering of $\mu \rightarrow eee$ candidates

Current limit:
BR $< 1.0 \cdot 10^{-12}$ at 90% CL (SINDRUM 1988)

What can Mu3e achieve?

What else can we look for with so many muon decays?
Outline

- \( \mu \to eee \) in effective theories

- Dark photons in \( \mu \) decays

- Lepton flavour violating two body decays \( \mu \to eX \)
Signal and Background

**Signal**

\[ \mu^+ \rightarrow e^+ e^- e^+ \]

- Common vertex
- Coincident
- \( \sum E_e = m_\mu \)
- \( \sum \vec{p}_e = 0 \)

**Background**

**Combinatorial background**

- No common vertex
- Not coincident
- \( \sum E_e \neq m_\mu \)
- \( \sum \vec{p}_e \neq 0 \)

**Internal conversion**

\[ \mu^+ \rightarrow e^+ e^- e^+ \bar{\nu}_\mu \nu_e \]

- Common vertex
- Coincident
- \( \sum E_e < m_\mu \)
- \( \sum \vec{p}_e \neq 0 \)
Sensitivity to $\mu \rightarrow eee$ in Phase I

- Full Geant4-based detector simulation
- Generators of physics processes (SM and BSM)
- Track reconstruction and vertex fit
Sensitivity to $\mu \rightarrow eee$ in Phase I

Reconstructed $\mu \rightarrow eee$ events (signal and background)

- Long tracks only
- Cuts on $\Delta t_{e_i e_j}$, $\chi^2_{\text{vertex}}$, $d_{\text{vertex-target}}$, $|\sum p_e|$, $m_{eee}$
- Background-free with $2.6 \cdot 10^{15}$ stopped $\mu$
- Signal efficiency $17\%$

$\Rightarrow$ $\text{BR} \geq 5.2 \cdot 10^{-15}$ at $90\%$ CL
\( \mu \rightarrow eee \) in Effective Theories

Use an EFT approach to model possible New Physics

\[
\mathcal{L}_{\text{EFT}} = \sum_i \frac{c_i}{\Lambda^2} O_i
\]

- Kinematics differ for each operator
  - \( \rightarrow \) different sensitivities
  - \( \rightarrow \) characteristic decay distributions

- Complementarity of \( \mu \rightarrow eee \), \( \mu \rightarrow e\gamma \), \( \mu \rightarrow e \) conversion
Sensitivity to $\mu \rightarrow eee$ using Effective Theories

Phase space

Efficiency is $17\% \Rightarrow BR \geq 5.2 \cdot 10^{-15}$ at $90\%$ CL

Generated distribution

After reconstruction and vertex fit
\( \mu \rightarrow \text{eee} \) in Effective Theories

Dipole operator \( e m_\mu \overline{\mu} R \sigma^{\mu \nu} e_L F_{\mu \nu} \)

Efficiency is 11\% \( \Rightarrow \) \( \text{BR} \geq 8.5 \cdot 10^{-15} \) at 90\% CL

Generated distribution

After reconstruction and vertex fit
μ → eee in Effective Theories

Vector 4-fermion operator \((\overline{\mu_R} \gamma^\mu e_R)(\overline{e_L} \gamma^\mu e_L)\)

Efficiency is 19% \(\Rightarrow\) \(\text{BR} \geq 4.6 \cdot 10^{-15}\) at 90% CL

Generated distribution

After reconstruction and vertex fit
\( \mu \to eee \) in Effective Theories

![Graph showing branching fraction limits at 90\% CL vs. days of data taking at 10\(^8\)\(\mu/s\). The graph includes lines for Mu3e Phase I, SINDRUM, Phase space, Dipole operator, and 4-fermion operator.](image-url)
Dark Photon Searches with Mu3e

Dark Photon $A'$

- Vector portal:
  $A'$ as messenger to a dark sector
- Interaction with SM particles via kinetic mixing with the photon
  \[ \mathcal{L}_{A'} = -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{A'} A'_\mu A'^\mu \]
- $A'$ with $m_{A'} < m_\mu$ can be emitted in muon decays
Dark photons in muon decays

• $\mu \rightarrow e\nu\nu A'$
  ‘stable’ $A'$ or decay to dark particles

• $\mu \rightarrow e\nu\nu (A' \rightarrow ee)$
  prompt decay of $A'$ to $e^+e^-$

• $\mu \rightarrow e\nu\nu A'$ followed by $A' \rightarrow ee$
  long-lived $A'$
Invisible Dark Photons: $\mu \rightarrow e\nu\nu A'$

- Only $e^+$ can be detected
- Deviation in the $p_e$ spectrum of SM $\mu$ decays
- Can be easily interpreted as detector misalignment
- Single-$e^+$ events rejected in filter farm

![Graph](image)
Invisible Dark Photons: $\mu \rightarrow e\nu\nu A'$

- Only $e^+$ can be detected

$\Rightarrow$ Deviation in the $p_e$ spectrum of SM $\mu$ decays

- Can be easily interpreted as detector misalignment

- Single-$e^+$ events rejected in filter farm

Misalignment vertex layers shifted in $z$

Misalignment study by U. Hartenstein
Promptly Decaying Dark Photons: $\mu \rightarrow e\nu\nu(A' \rightarrow ee)$

- Observe three electrons from a common vertex
  - Same dataset as in $\mu \rightarrow eee$ searches
- Search for resonance in $m_{ee}$
- Main background from $\mu \rightarrow eee\nu\nu$ and combinations of Bhabha scattering events with Michel decays
Promptly Decaying Dark Photons: $\mu \rightarrow e\nu\nu(A' \rightarrow ee)$

**Signal**

sharp peak in $m_{ee}$

**Background**

combinatorial BG contributes a factor $\sim 800$ less

---

**Distributions**

- **Signal**
  - $m_{ee}$ distribution for different $m_{A'}$ values:
    - $m_{A'} = 20$ MeV
    - $m_{A'} = 45$ MeV
    - $m_{A'} = 70$ MeV

- **Background**
  - Combined background
  - Internal conversion
  - Bhabha
Promptly Decaying Dark Photons: $\mu \rightarrow e\nu\nu(A' \rightarrow ee)$

Two possible $e^+e^-$ combinations

Both $e^+e^-$ pairs

Lower $m_{ee}$ pair for $m_{ee} < 45$ MeV

Higher $m_{ee}$ pair for $m_{ee} \geq 45$ MeV
Promptly Decaying Dark Photons: $\mu \rightarrow e\nu\nu (A' \rightarrow ee)$

Sensitivity in phase I assuming $2.6 \cdot 10^{15}$ muon decays
Promptly Decaying Dark Photons: $\mu \rightarrow e\nu\nu (A' \rightarrow ee)$

Investigate currently uncovered parameter space  

$$(BR(A' \rightarrow ee) = 1)$$

Phase II: $5.5 \cdot 10^{16}$ $\mu$ decays at $2 \cdot 10^9$ $\mu$/s, improvements to the detector not considered
Longlived $A'$: $\mu \rightarrow e\nu\nu A'$ with subsequent $A' \rightarrow ee$

- Search for $e^+e^-$ pairs from displaced vertices + resonance
- Background from Bhabha scattering and photon conversion
- Decay lengths of several cm can be studied
  \[
  cT = 0.8 \text{ mm} \frac{10^{-8} \text{ 10 MeV}}{\epsilon^2 m_{A'}}
  \]
  [Echenard et al., JHEP 01 (2015), 113]
- Extend reach to smaller $\epsilon^2$
- Needs modifications of reconstruction and event filtering
- Currently under study
**LFV Two Body Decays: $\mu \rightarrow e X$**

- **Motivation:** Familon  
  (Wilczek, PRL 49 (1982) 1549)  
  Spontaneous breaking of flavour symmetry  
  $\rightarrow$ (Pseudo-)Goldstone boson  
  emitted in flavour-changing decays

- $\mu^+ \rightarrow e^+ X^0$  
  Neutral, light boson $X$ not observed  
  Monoenergetic positron

- **Background:**  
  $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$, $\mu^+ \rightarrow e^+ \gamma \bar{\nu}_\mu \nu_e$,  
  $\mu^+ \rightarrow e^+ e^- e^+ \bar{\nu}_\mu \nu_e$, Bhabha scattering, photon conversion, ...

---

**Graph:**  
- **Michel spectrum (leading order)**  
- **$\mu \rightarrow e X$ signal ($m_X=60$MeV)**

---

A. Perrevoort (NIKHEF)  
BSM Physics with Mu3e

Flavour and DM 2018  23 / 33
Previous Experiments Searching for $\mu \rightarrow eX$

Jodidio et al. at TRIUMF (Phys.Rev. D34, 1986)

- $1.8 \cdot 10^7$ highly polarized muons
- Search for massless familon expected to be isotropic
- Look for excess in end-point of Michel spectrum at $\cos \theta = -1$
- $\text{BR} < 2.6 \cdot 10^{-6}$ at 90\% CL

Michel spectrum, $\theta = \angle (\vec{P}_\mu, \vec{p}_e)$
Previous Experiments Searching for $\mu \to eX$

**TWIST at TRIUMF**
(Bayes et al. Phys.Rev. D91, 2014)

- $5.8 \cdot 10^8$ $\mu$ decays analyzed from highly polarized $\mu$ beam
- Search for anisotropic $\mu \to eX$ decays
  $$\frac{\partial \Gamma}{\partial \cos \theta} \propto 1 - A P_{\mu} \cos \theta$$

- Massive $X$ (on average):
  \[
  \begin{align*}
  BR_{A=0} &< 9 \cdot 10^{-6} \text{ at } 90\% \text{CL} \\
  BR_{A=+1} &< 10 \cdot 10^{-6} \text{ at } 90\% \text{CL} \\
  BR_{A=-1} &< 6 \cdot 10^{-6} \text{ at } 90\% \text{CL}
  \end{align*}
  \]
Searching for $\mu \rightarrow eX$ with Mu3e

- High muon rate
  ⇒ Cannot store all single-track events
- But: online reconstruction of all tracks as ‘short’ tracks
  (i.e. no reconstruction of recycler)
→ Keep histogram of momenta for $\mu \rightarrow eX$ searches

- No acceptance for $p_T < 10$ MeV
- Calibration with Michel edge, use of Mott and Bhabha scattering under investigation
→ $25$ MeV $\leq m_X \leq 95$ MeV can be investigated
Data selection

- $\chi^2$ of track fit
- $z$ of track propagated to target region
- Inclination angle $\lambda_{01}$
Searching for $\mu \rightarrow e X$ with Mu3e

Background

Signal $m_X = 60$ MeV

Events per 100keV

$10^6$

$10^3$

$p$ [MeV]

$0$ $20$ $40$ $60$ $100$

$p$ [MeV]

$0$ $20$ $40$ $60$ $80$ $100$
Searching for $\mu \rightarrow eX$ with Mu3e

Branching Fraction at 90% CL

Mu3e Phase I SIM: $2.6 \times 10^{15} \mu$ stops

TWIST 2014
Mu3e online reco. (ext.calib.)
Mu3e online reco. (sim. calib.)

TWIST results by courtesy of R. Bayes

Mu3e: Work in progress
Searching for $\mu \to eX$ with Mu3e

Anisotropic $\mu \to eX$ decays:

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + hP \cos\theta$$

- $h=0, m_X = 60$ MeV
- $h=+1, m_X = 60$ MeV
- $h=-1, m_X = 60$ MeV
Searching for $\mu \rightarrow e X$ with Mu3e

TWIST results by courtesy of R. Bayes
Further channels involving familons

- $\mu \rightarrow eX, \ X \rightarrow ee$:  
  it’s a $\mu \rightarrow eee$ search

- $\mu \rightarrow eeeee$:  
  suffers from low acceptance at low $p_T$  
  can run at lower B field
Summary

- $\mu \to eee$ in effective theories
  - Operators show characteristic decay distributions
  - Sensitivity of some $10^{-15}$ in phase I

- Dark photons in $\mu$ decays
  - Search for $m_{ee}$ resonances
  - Investigate currently uncovered parameter space

- Lepton flavour violating two body decays $\mu \to eX$
  - Bump search on $e^+$ momentum spectrum from online reconstruction
  - More than 2 orders of magnitude more sensitive than previous searches
\textbf{μ → eee in Effective Theories}

Vector 4-fermion operator \((\bar{\mu}_R \gamma^\mu e_R)(\bar{e}_R \gamma^\mu e_R)\)

Scalar 4-fermion operator \((\bar{\mu}_R e_L)(\bar{e}_R e_L)\)

Efficiency is \(19\%\) \(\Rightarrow\) \(\text{BR} \geq 4.6 \cdot 10^{-15}\) at \(90\%\) CL
Promptly Decaying Dark Photons: $\mu \rightarrow e\nu\nu(A' \rightarrow ee)$

Two possible $e^+e^-$ combinations (background)

Both $e^+e^-$ pairs

Lower $m_{ee}$ pair
for $m_{ee} < 45$ MeV

Higher $m_{ee}$ pair
for $m_{ee} \geq 45$ MeV

---

A. Perrevoort (NIKHEF)
Promptly Decaying Dark Photons: $\mu \rightarrow e\nu\nu (A' \rightarrow ee)$

Acceptance low for low $p_T$ electrons, i.e. at low and high $m_{ee}$

![Graph showing the ratio of reconstructed to generated events vs. $m_{A'}$ (MeV)]
Appendix

Promptly Decaying Dark Photons: $\mu \rightarrow e\nu\nu(A' \rightarrow ee)$

Comparison with external study

Echenard et al., JHEP 01 (2015), 113

Phase I: $1 \cdot 10^{15}$ muons

Mu3e simulation

E. Perrevoort (NIKHEF)
Appendix

Promptly Decaying Dark Photons: $\mu \rightarrow e\nu\nu (A' \rightarrow ee)$

Comparison with external study

Phase II: $5.5 \cdot 10^{16}$ muons

Echenard et al., JHEP 01 (2015), 113

Mu3e simulation
Promptly Decaying Dark Photons: $\mu \rightarrow e\nu\nu(A' \rightarrow ee)$

Comparison with external study

Echenard et al., JHEP 01 (2015), 113

Mu3e simulation
Promptly Decaying Dark Photons: $\mu \to e\nu\nu (A' \to ee)$

Comparison with external study

adapted from Echenard et al., JHEP 01 (2015), 113
Short Tracks: 4 Hits
Short Tracks

Efficiency.

Momentum resolution.
Appendix

Long Tracks: 6 Hits

A. Perrevoort (NIKHEF)
Long Tracks: 8 Hits
Long Tracks

Efficiency.

Momentum resolution.
Searching for $\mu \rightarrow e X$ with Mu3e

Background

Signal $m_X = 60$ MeV
Searching for $\mu \to eX$ with Mu3e

TWIST results by courtesy of R. Bayes

BSM Physics with Mu3e
Flavour and DM 2018
Upgrades to Mu3e

Potential Mu3eGamma upgrade

- Search for $\mu \rightarrow e\gamma$
- Additional photon converter and tracking detectors
- Increase B field: from 1 T to 2 T
- Can also investigate $\mu \rightarrow eX\gamma$ and dark photons from displaced vertices