A Review of $\mu \to eee$, $\mu \to e\gamma$ and $\mu N \to eN$ Conversion

Ann-Kathrin Perrevoort (Mu3e) | FPCP 2023, Lyon | May 30, 2023

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GEFÖRDERT VOM

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MINISTERIUM FÜR WISSENSCHAFT, FORSCHUNG UND KUNST

Lepton Flavour Violation
as a sign for Physics Beyond the SM

Karlsruhe Institute of Technology

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  ... but not necessarily in BSM (ex.: SUSY, heavy neutrinos, extended gauge sectors)

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Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

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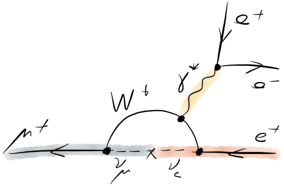
  … but not necessarily in BSM (ex.: SUSY, heavy neutrinos, extended gauge sectors)
- Neutrino oscillations $\Rightarrow$ Lepton flavour violation (LFV) occurs in nature
- LFV with charged leptons is heavily suppressed in the SM+neutrino mixing:

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

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences



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

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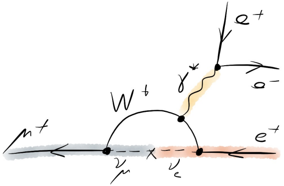

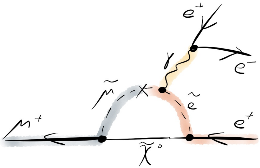

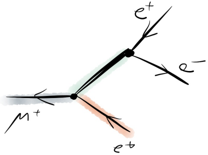

Lepton Flavour Violation
with Muons

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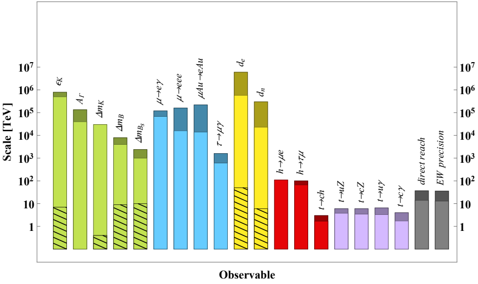
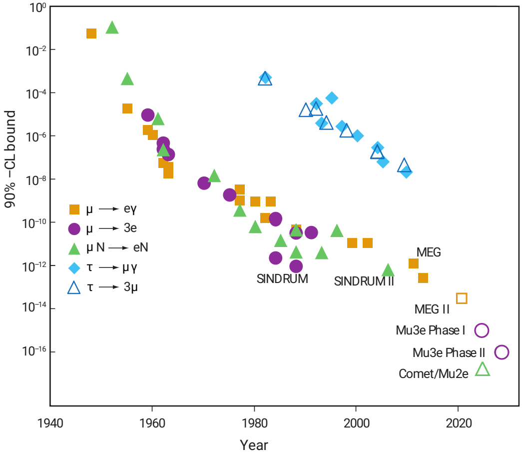
- High-intensity muon sources paired with dedicated high-precision experiments
- Interpreted in effective field theories (EFT), μLFV searches test $\mathscr{O}(\Lambda) = 10^5$ TeV



[European Strategy 2020, arXiv:1910.11775]



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

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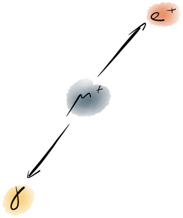
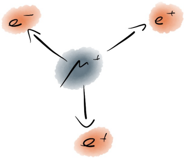


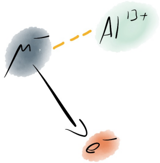
$\mu^+ \rightarrow e^+\gamma$

- MEG and MEG II at PSI



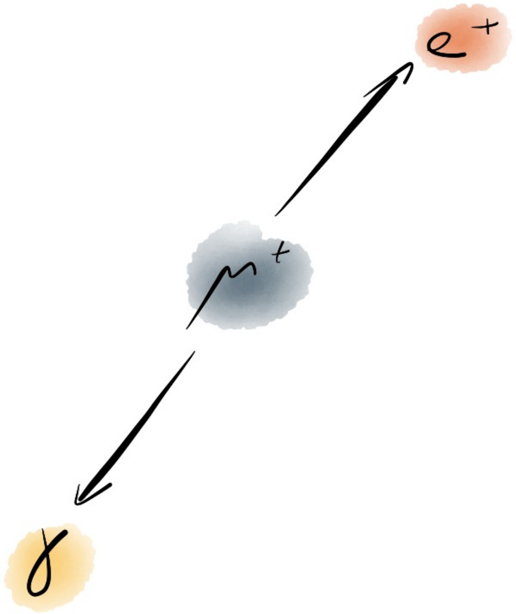
$\mu^+ \rightarrow e^+ e^- e^+$

- Mu3e (PSI) succeeding SINDRUM



$\mu^- N \rightarrow e^- N$

- Mu2e (FNAL), DeeMe and COMET (J-Parc) succeeding SINDRUM II

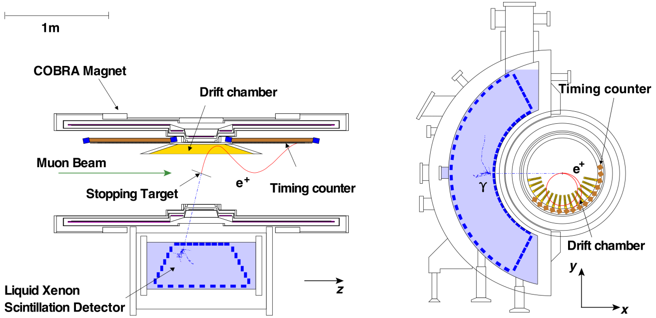


e^+
μ^+
γ

Searching for $\mu \to e\gamma$

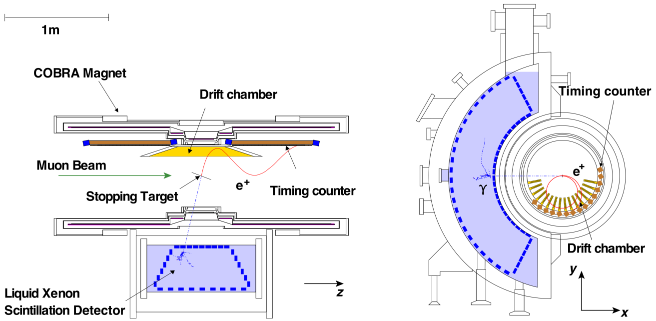
MEG and MEG II at PSI

- MEG and MEG II search for $\mu^+ \to e^+\gamma$
- Muon decay at rest:
  Mono-energetic e^+ and γ,
  back-to-back and coincident
- Background from radiative muon decay
  $\mu^+ \to e^+\gamma\nu\nu$
- Excellent E/p measurement
- And background from accidental combinations
- Continuous μ^+ beam at PSI and precise timing



Searching for $\mu \to e\gamma$
MEG at PSI

- Slanted muon stopping target
- γ measured in liquid Xenon (LXe) photon detector
- e detection with drift chamber (DCH) and timing counter (TC, scintillating bars with PMTs)
- COnstant Bending RAdius magnet sweeps out e



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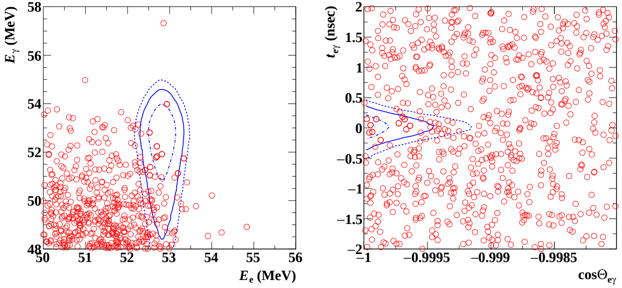
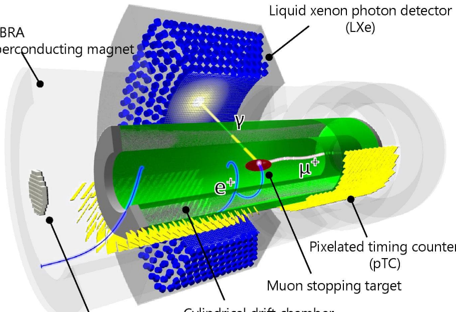


- MEG operated from 2009 - 2013
- Current limit
  $\mathscr{B}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$ at 90 % CL
  [Eur.Phys.J.C 76 (2016) 8, 434]

Searching for $\mu \to e\gamma$
MEG II at PSI

- Increased stopping rate from $3 \times 10^7\ \mu/\mathrm{s}$ to $1 \times 10^8\ \mu/\mathrm{s}$
- Cylindrical drift chamber (CDCH) with high wire density
- Pixelated timing counter (pTC) build from scintillating tiles+SiPMs
- LXe: PMTs on entrance surface replaced by SiPMs
- Radiative decay counter (RDC) to veto background-e
  LYSO crystals and plastic scintillators



- MEG II running since 2021 with exp. sensitivity to $\mathscr{B}(\mu^+ \to e^+\gamma)$ down to 6×10^{-14} at 90 % CL

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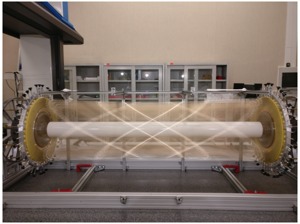

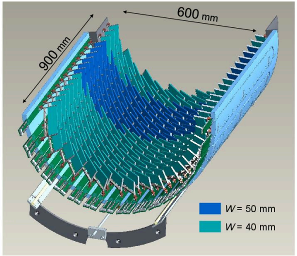

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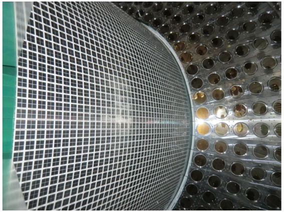

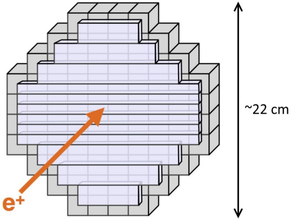

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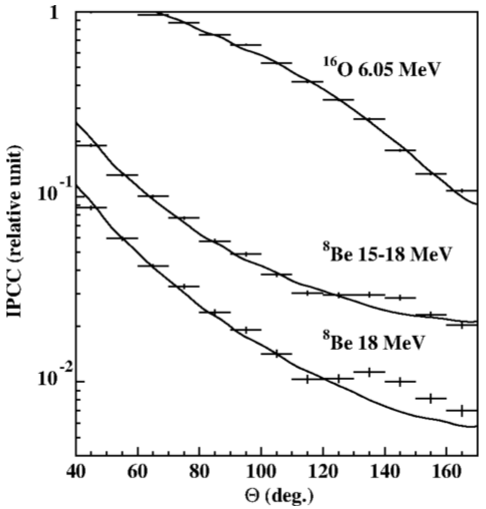
Beyond Searching for $\mu \to e\gamma$

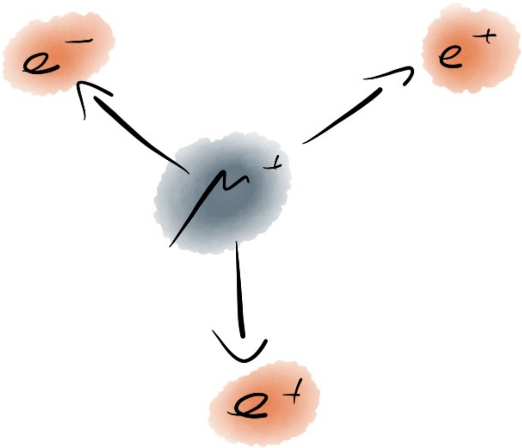
X(17) Search with MEG II

- Atomki experiment reports excess in angular distributions of internal pair creation in $^{7}\mathrm{Li}(p, e^{+}e^{-})^{8}\mathrm{Be}$ [PRL 116, 042501 (2016)]
- Also in $^{3}\mathrm{H}(p, e^{+}e^{-})^{4}\mathrm{He}$ [JPhys.Conf.Ser. 1643 012001 (2020)]
- New mediator X(17)? Or experimental artifact?

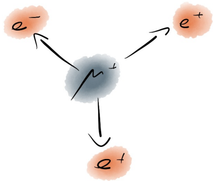
- MEG II will repeat the measurement
- p beam from Cockcroft-Walton accelerator and $Li_2B_4O_7$ target (normally used for calibration)

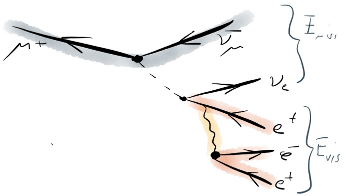
- Searches for $e^{+}e^{-}$ resonances in Mu3e ($\mu \to ee e\nu\nu$) also sensitive to X(17)




e^-
e^+
μ^+
e^+

Searching for $\mu \to eee$

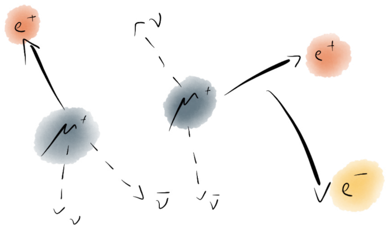




- Background from rare decay: $\mathscr{B}(\mu \to ee e\nu\nu) = 3.4 \times 10^{-6}$
- Missing momentum due to neutrinos
- Need excellent momentum resolution

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

- 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, continuous μ beam

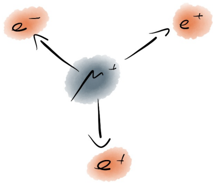


Searching for $\mu \to eee$

Current limit by SINDRUM (PSI)
$\mathscr{B}(\mu^+ \to e^+ e^- e^+) < 1.0 \times 10^{-12}$ at 90 % CL

[Nucl.Phys.B 299 (1988) 1–6]

Mu3e aims to improve this by up to 4 orders of magnitude



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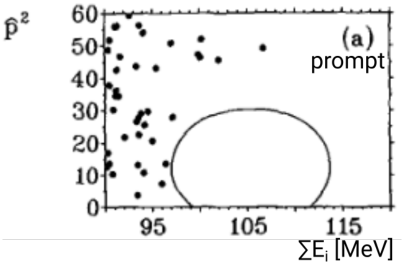
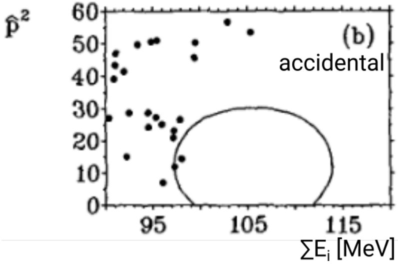
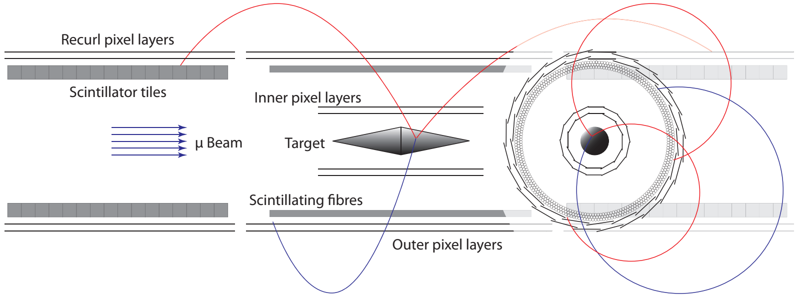




Searching for $\mu \to eee$

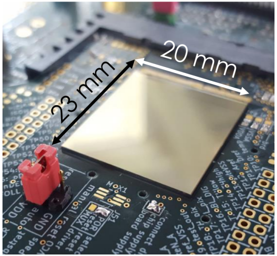
Mu3e at PSI



- 10^8 μ/s stopped on target $\to$ decay at rest
- Track e^+/e^- trajectories in 1 T solenoidal field
- 4 layers of ultra-thin silicon pixel sensors
- Timing with scintillating fibres
- Cooling with gaseous Helium
- Recurl-stations with pixel sensors and scintillating tiles
- Online event reconstruction and filtering

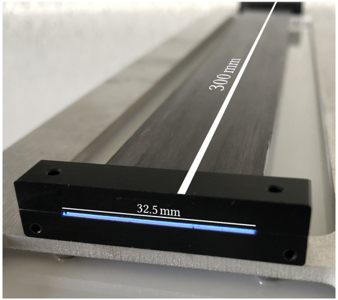
Searching for $\mu \to eee$

Mu3e at PSI

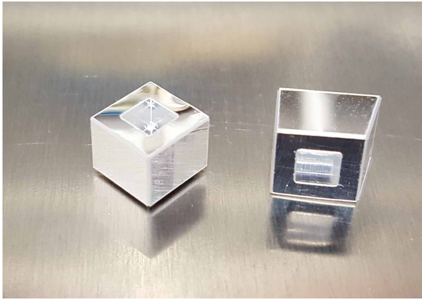


- Custom designed MuPix (High Voltage Monolithic Active Pixel Sensor)
- Can be thinned to 50 µm ($\sim 1\,‰ X_0$ per layer)
- Final version operational

- Scintillating fibres with SiPMs in central station
- Readout with custom MuTRiG ASIC



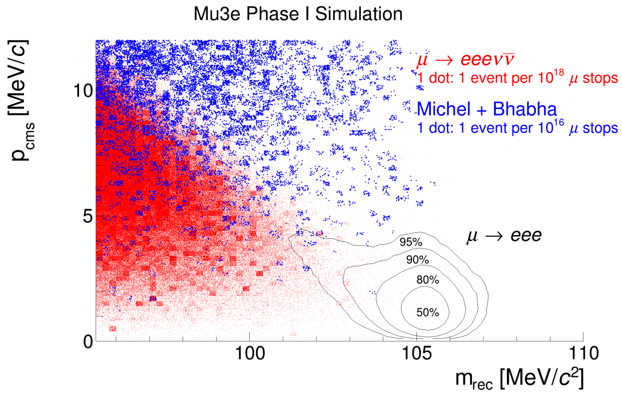
- 6 mm × 6 mm × 5 mm scintillating tiles with SiPMs in recurl stations
- Readout with MuTRiG



Searching for $\mu \rightarrow eee$
Mu3e at PSI

- Mu3e is in construction and integration phase
- First data runs expected in 2025
- Reach sensitivities of $\mathcal{B}(\mu \rightarrow eee) \sim 10^{-15}$ in phase I

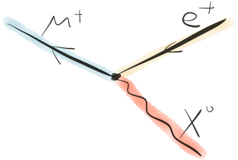
- High Intensity Muon Beam (HIMB) construction in 2027/8
- Phase II operating at 2×10^9 μ/s
- Substantially upgraded detector
- Sensitivity to $\mathcal{B}(\mu \rightarrow eee) \sim 10^{-16}$



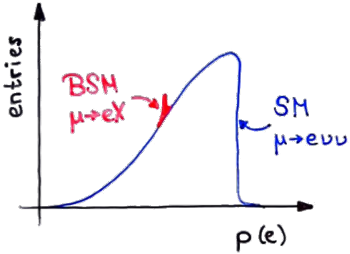
Beyond Searching for $\mu \to eee$

Familons in $\mu \to eX$

- Mu3e search for $\mu^+ \to e^+ X \Rightarrow$ mono-energetic e^+
- Goldstone boson X from broken symmetry (familon, majoron, ALPs, ...)
- Single-e events are not recorded by default
- Online histogramming



- $\mathcal{B}(\mu^+ \to e^+ X) < 2.6 \times 10^{-6}$ at 90 % CL ($m_X = 0$ MeV)
  Jodidio et al.[Phys.Rev.D 34 (1986) 1967]
- $\mathcal{B}(\mu^+ \to e^+ X) < 9 \times 10^{-6}$ at 90 % CL on average for 13 MeV $< m_X <$ 80 MeV
  TWIST [Phys.Rev.D 91 (2015) 052020]
- Mu3e phase I sensitivity at around 10^{-8}



- Ideas for $\mu \to eX$ searches also at MEG II, muon conversion experiments and Muχe

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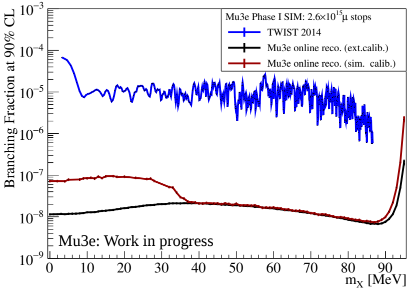

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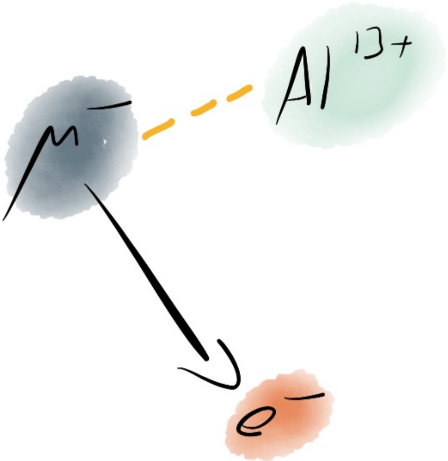
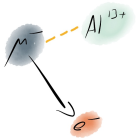


μ⁻
Al 13+
e⁻

Searching for $\mu N \to eN$

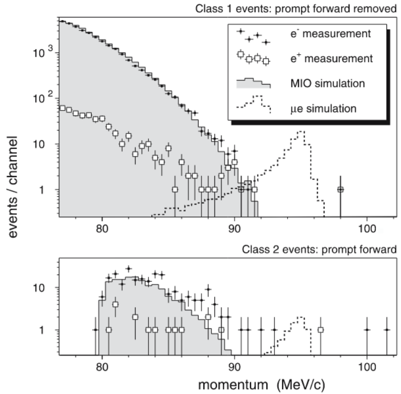
- Conversion of $\mu \to e$ in muonic atom: $\mu^- N \to e^- N$
- Signal is mono-energetic e^- at $\sim 105\,\mathrm{MeV}$



- Background from muon decay in orbit $\mu N \to e\nu\bar{\nu}N$
- Need excellent momentum/energy resolution
- Beam-related backgrounds from e^-, μ^- decays in flight, $\bar{p}$, π
- Pulsed beam and μN with long lifetime ($T(\mu\mathrm{Al} = 864\,\mathrm{ns})$)
- Additional cosmics veto

SINDRUM II (PSI, 2006):
$\mathcal{R}(\mu^- \mathrm{Au} \to e^- \mathrm{Au}) < 7.0 \times 10^{-13}$ at 90 % CL

[Eur.Phys.J.C 47 (2006) 337–346]



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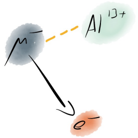

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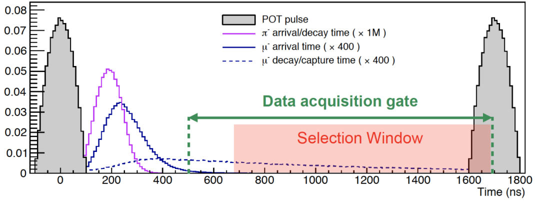
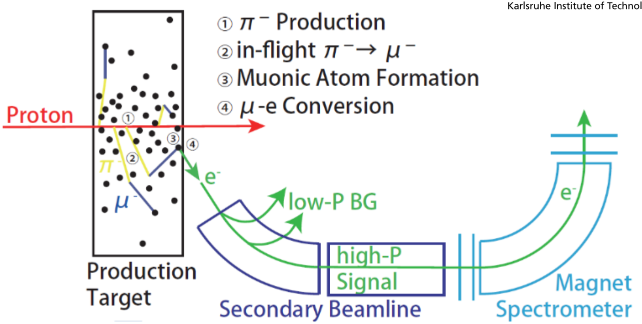


Searching for $\mu N \to eN$

- Muon production:
  intense proton beam on *production target*: $\pi \to \mu$
- Formation of muonic atoms:
  stopping muons on *stopping target*
- Wait for the decay
- Measure decay-electrons in detector

- DeeMe and COMET at J-Parc and Mu2e at Fermilab



- DeeMe has a combined production and stopping target
- Background e^- filtered out in secondary beamline
- Remaining e^- measured with spectrometer and MWPCs
- Expected single-event sensitivity (SES):
  $\mathscr{R}_{\mu e}(\mu^- \mathrm{C} \to e^- \mathrm{C})$ of 1×10^{-13}

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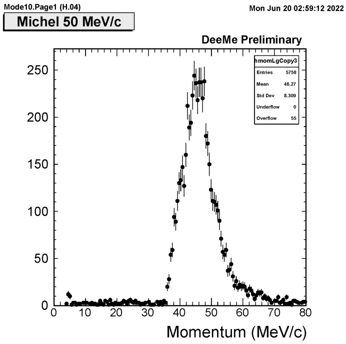
- Measure decay-electrons in detector

- DeeMe and COMET at J-Parc and Mu2e at Fermilab



- DeeMe has a combined production and stopping target
- Background e^- filtered out in secondary beamline
- Remaining e^- measured with spectrometer and MWPCs
- Expected single-event sensitivity (SES):
  $\mathscr{R}_{\mu e}(\mu^- \mathrm{C} \rightarrow e^- \mathrm{C})$ of 1×10^{-13}

Searching for $\mu N \to eN$

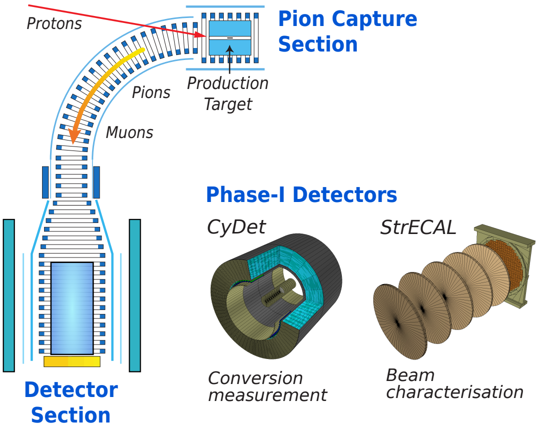
COMET-I at J-Parc

- COherent Muon to Electron Transition: Search for $\mu^- \text{Al} \to e^- \text{Al}$ in two phases

Phase I

- π/μ produced with 8 GeV p beam on graphite target
- Production target separated from stopping target by a 90° transport solenoid
- SES to $\mathscr{R}_{\mu e} \approx 3.0 \times 10^{-15}$ with 1.5×10^{16} stopped muons

- 1st beam delivered to COMET exp. area
- Planning for first data taking in 2024/5



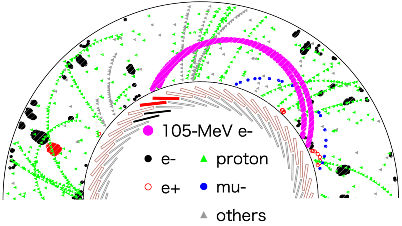
Searching for $\mu N \rightarrow eN$

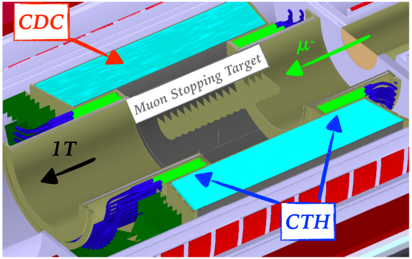
COMET-I at J-Parc

- Cylindrical Detector CyDet (CyDet) surrounding the stopping target
- Cylindrical drift chamber (CDC)
- CyDet trigger hodoscope (CTH) made from 2 layers of plastic scintillators

- StrECAL for direct beam measurements
- Straw tube tracker
- ECAL: LYSO crystals with APD readout for fast timing and full energy absorption
- Prototypes for COMET phase II

- Cosmic ray veto





Searching for $\mu N \to eN$

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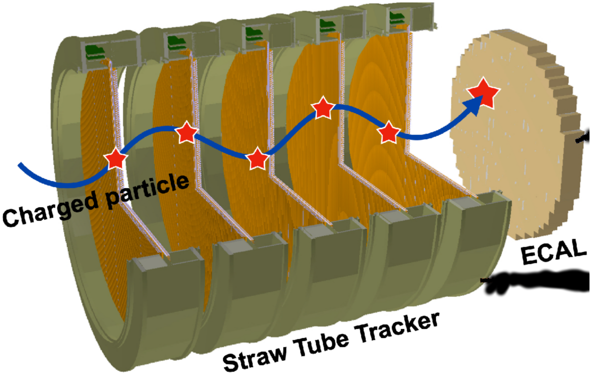
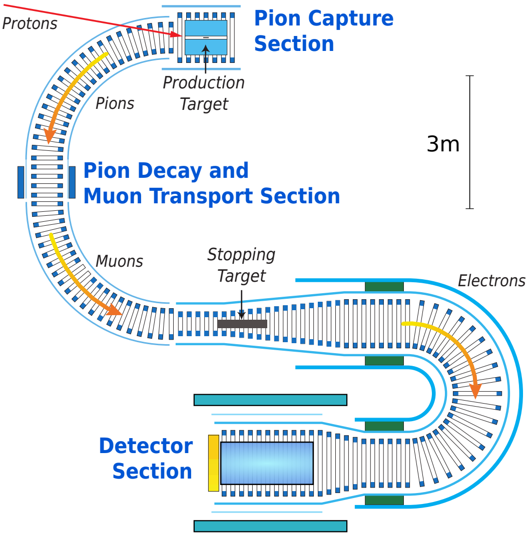


Searching for $\mu N \rightarrow eN$
COMET-II at J-Parc

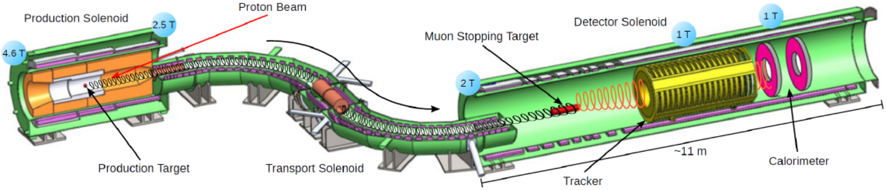


Phase II

- Increased μ production by factor of $\sim$20 (p beam, target, capture solenoid)
- Muon transport section extended from 90° to 180° turn
- Increased muon stopping efficiency
- Stopping target and detector section separated by electron spectrometer
- SES to $\mathscr{R}_{\mu e} \approx 1.4 \times 10^{-17}$ with 3.3×10^{18} stopped muons

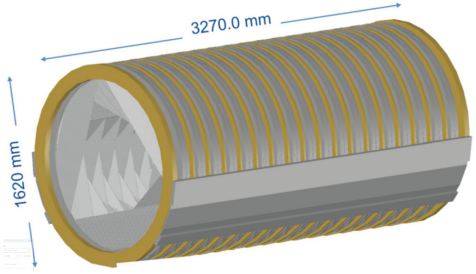
Searching for $\mu N \to eN$

Mu2e at FNAL



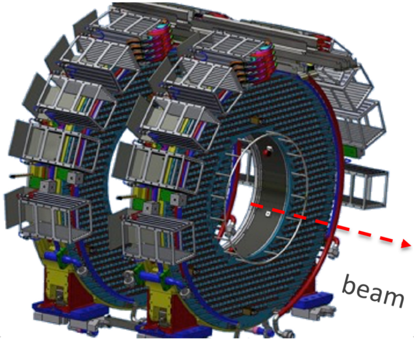
- 2-stage search for $\mu^- \text{Al} \to e^- \text{Al}$
- Transport solenoid separates production and stopping target
- Stopping target in front of tracker and calorimeter in detector solenoid
- $\mathscr{R}_{\mu e} < 6.2 \times 10^{-16}$ at 90 % CL
- Phase I to be constructed by end of 2025
- Commissioning and first data in 2026
- 2 years long shutdown at FNAL for LBNF/PIP-II construction
- Phase II to be operated at 10× increased p beam intensity
- Upgrades to all systems
- $\mathscr{R}_{\mu e} < 6 \times 10^{-17}$ at 90 % CL in phase II

Searching for $\mu N \rightarrow eN$
Mu2e at FNAL



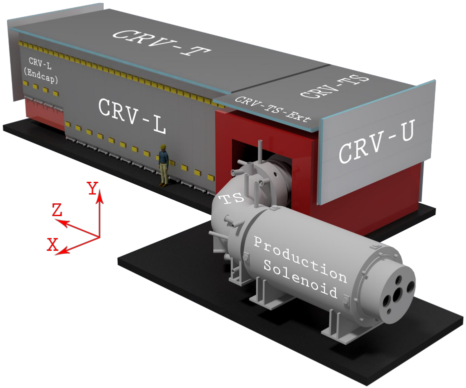
- Straw tube tracker: 18 stations à 2 planes
- Around 2/3 of planes produced
- Integration tests with cosmics

- Calorimeter for PID and triggering
- 2 disks of 674 crystals with SiPM readout
- 1st disk fully assembled



Searching for $\mu N \to eN$

Mu2e at FNAL

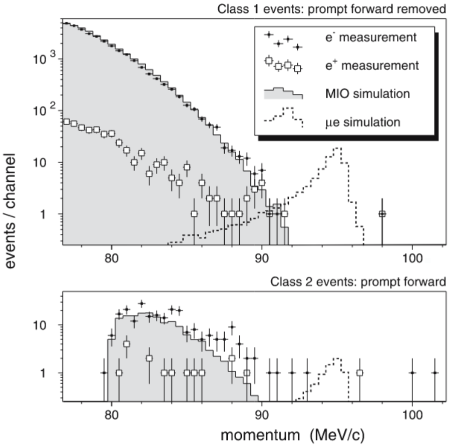


- Cosmic ray muons generate background events via decay, scattering, or material interactions at rate of $\sim 1/\text{day}$
- Cosmic ray veto system consisting of 4 layers of scintillators of each side covering 335 m^2
- Scintillator counter with embedded wavelength shifting fibre and SiPM readout
- Production almost completed and ready to be tested with cosmics

Beyond searching for $\mu N \to eN$
Violation of LF and LN

- Majorana process $\mu^- N \to e^+ N'$ is LFV and LNV
- Background from radiative muon capture (RMC) $\mu^- N \to \nu_\mu N' \gamma (\to e^+ e^-)$
- Published limit on Ti by SINDRUM II (1998): $\mathscr{R}(\mu^- \text{Ti} \to e^+ \text{Ca}) < 1.7 \times 10^{-12}$ a 90 % CL

- Needs better theoretical understanding of the RMC endpoint

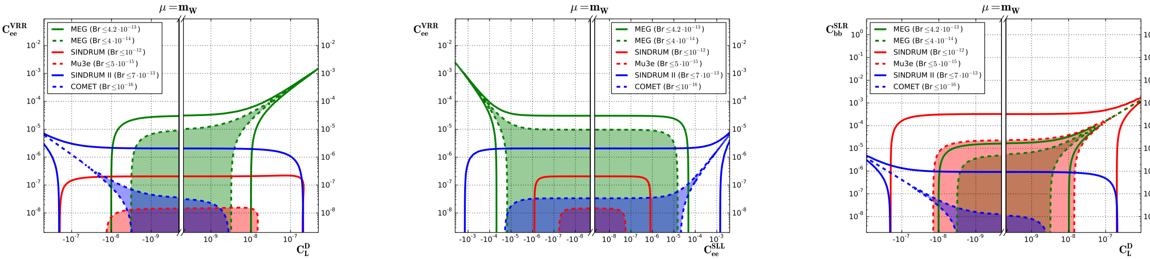


Searching for Lepton Flavour Violation with Muons

What to learn if we see something?

Karlsruhe Institute of Technology

- Comparison by means of effective field theories: $\mathscr{L} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda}\sum \mathscr{O}_{\text{5-dim}} + \frac{1}{\Lambda^2}\sum \mathscr{O}_{\text{6-dim}} + \dots$
- $\mu \to e\gamma$, $\mu \to eee$ and $\mu N \to eN$ have specific strengths and weaknesses
- Pin down type of BSM interaction by combination of the searches



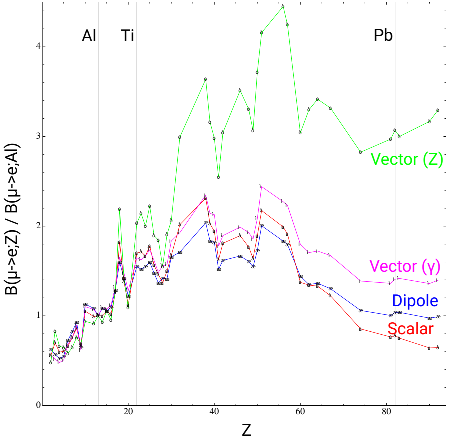
Crivellin, Davidson, Pruna, Signer, JHEP 05 117 (2017)

Searching for Lepton Flavour Violation with Muons

What to learn if we see something?

- $\mu N \rightarrow eN$ conversion rate has dependence on N
- Exchange of stopping target material

- Requires to repeat the measurement campaign
- Limited choice of suited target materials (Mu2e II mentions Ti, V, Li)



adapted from Cirigliano, Kitano, Okada, Tuzon, arXiv:0904.0957 [hep-ph]

Searching for Lepton Flavour Violation with Muons

What to learn if we see something?

- Exploit the three-body kinematics of $\mu \to eee$
- Is it a e^+e^-/e^+e^+ resonance?

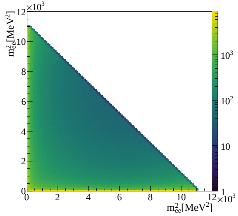
Searching for Lepton Flavour Violation with Muons

What to learn if we see something?

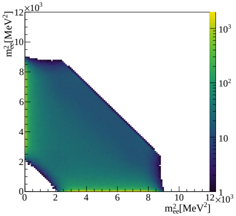
- Exploit the three-body kinematics of $\mu \to eee$
- Is it a e^+e^-/e^+e^+ resonance?
- Asymmetry ratios
- Dalitz plots

- Exclusion limits differ with operator

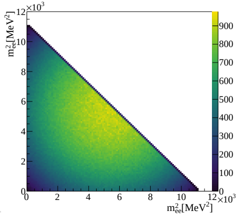
Dipole, generated



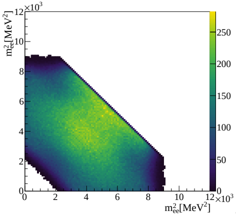
Dipole, reconstr.



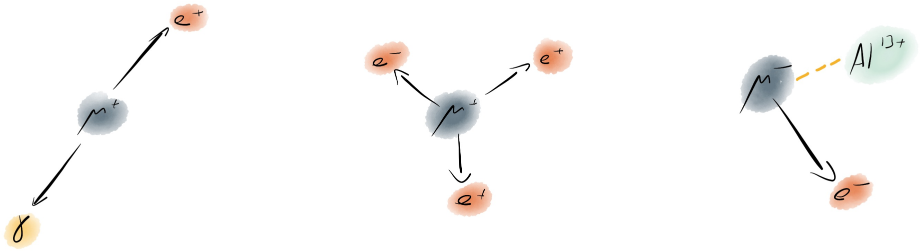
4-fermion, generated



4-fermion, reconstr.



Lepton Flavour Violation with Muons



- In the coming years, limits on cLFV muon decays will be improved by orders of magnitude
- Complementary BSM tests with the golden channels
- Experiments are further expanding their physics program