MuM̄u oscillations?

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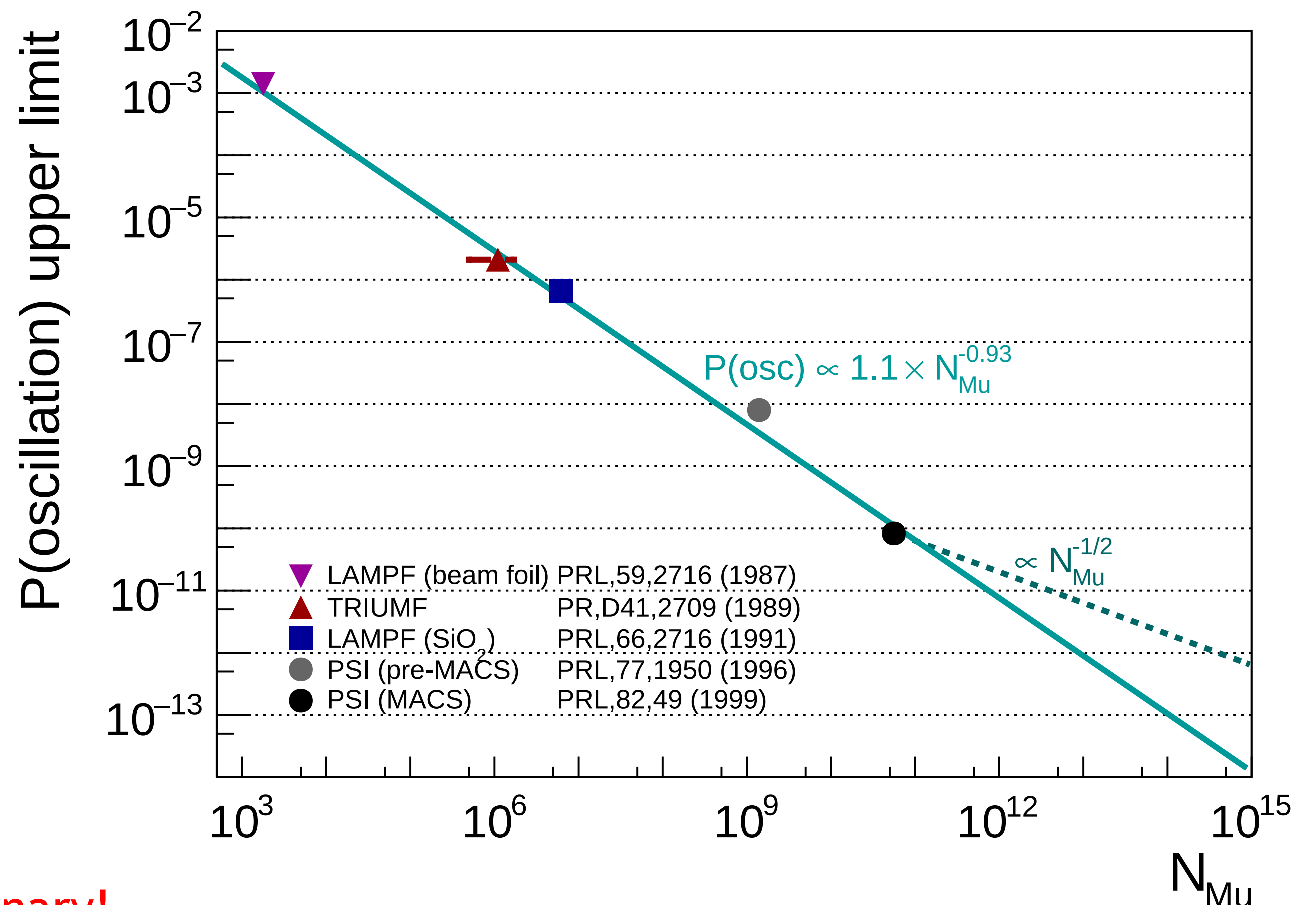
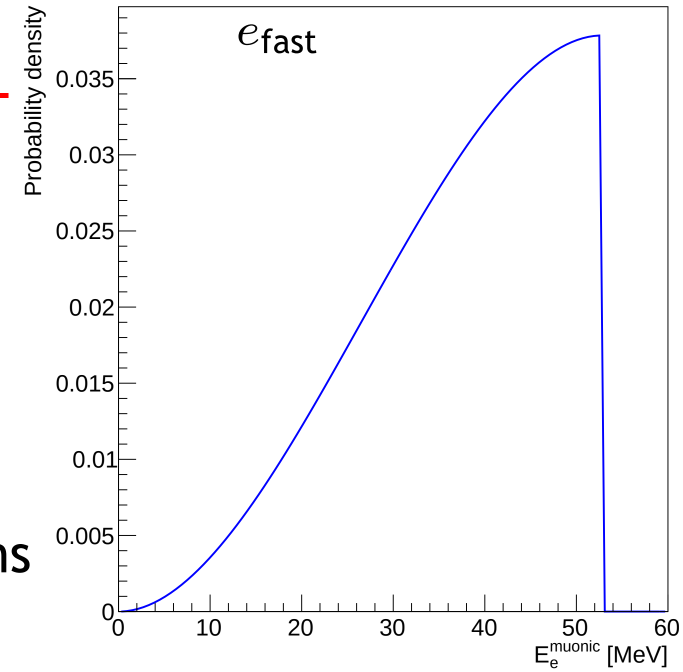


all very preliminary!

Introduction

Conlin/Petrov, PR, D102, 095001 (2020)



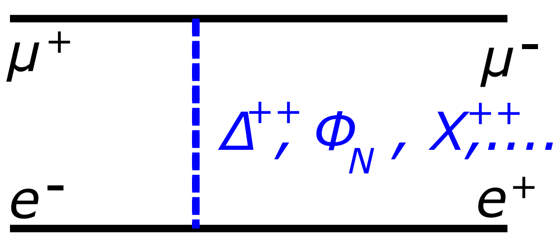
- Muonium Mu: QED bound state of μ and e:

$$\text{Mu} \equiv \mu^+ e^- \rightarrow e^+_{\text{fast}}\, e^-_{\text{atomic}}\, (+\bar{\nu}_\mu \nu_e)$$

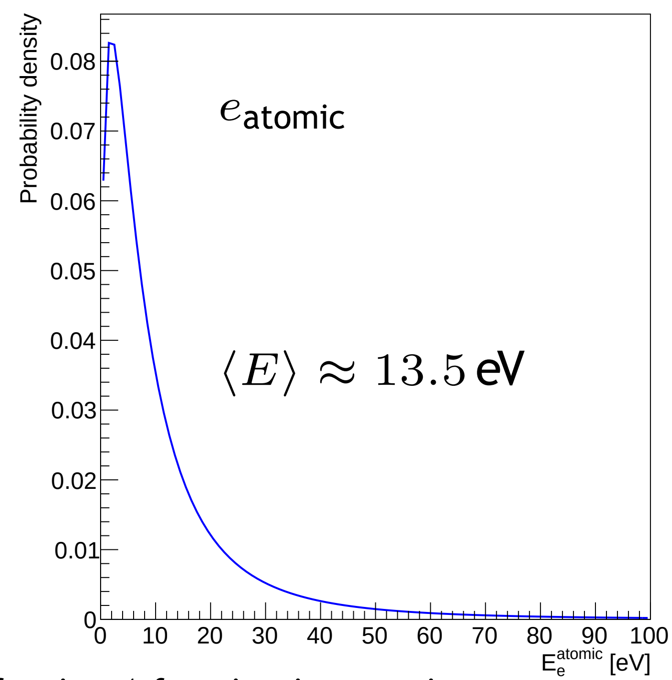
$$\overline{\text{Mu}} \equiv \mu^- e^+ \rightarrow e^-_{\text{fast}}\, e^+_{\text{atomic}}\, (+\nu_\mu \bar{\nu}_e)$$

  - ▷ Lifetime $\tau_{\text{Mu}} = 2.2\,\mu$s
  - ▷ LFV interactions could induce Mu$\overline{\text{Mu}}$ oscillations (extremely tiny and unmeasurable in SM)

- Mu$\overline{\text{Mu}}$ oscillations?
  - ▷ 1957: in analogy to K^0 mixing (Pontocorvo)
  - ▷ 1960: additive vs. multiplicative lepton number conservation (Feynman/Weinberg)
  - ▷ 'now': effective four-fermion interactions 'anything' goes



$$(\bar{\mu}\Gamma e)(\bar{\mu}\Gamma e)$$



  - ▷ Experimental limits on $\mathcal{P}(\text{Mu}\overline{\text{Mu}})$ or coupling constant $G_{\text{Mu}\overline{\text{Mu}}}$ for effective 4-fermion interaction

Conlin/Petrov, PR, D102, 095001 (2020)

$\text{Mu}\overline{\text{Mu}}$ oscillations

- Given (B)SM interactions coupling Mu and $\overline{\text{Mu}}$

$$i\frac{d}{dt}\begin{pmatrix} |\text{Mu}(t)\rangle \\ |\overline{\text{Mu}}(t)\rangle \end{pmatrix} = \left(m - \frac{\Gamma}{2}\right)\begin{pmatrix} |\text{Mu}(t)\rangle \\ |\overline{\text{Mu}}(t)\rangle \end{pmatrix}$$

  - ▷ diagonalization leads to new mass eigenstates $|\text{Mu}_{1,2}\rangle$

$$|\text{Mu}_{1,2}(t)\rangle = \frac{1}{\sqrt{2}}\left(|\text{Mu}(t)\rangle \mp |\overline{\text{Mu}}(t)\rangle\right)$$

    with m and τ differences

$$\begin{aligned} \Delta &\equiv m_1 - m_2 \\ \Delta\Gamma &\equiv \Gamma_2 - \Gamma_1 \end{aligned} \quad \rightarrow \quad \begin{aligned} x &\equiv \frac{\Delta m}{\Gamma} \\ y &\equiv \frac{\Delta\Gamma}{2\Gamma} \end{aligned}$$

- Study oscillations with decays $\text{Mu} \to f$ and $\text{Mu} \to \overline{\text{Mu}} \to \bar{f}$

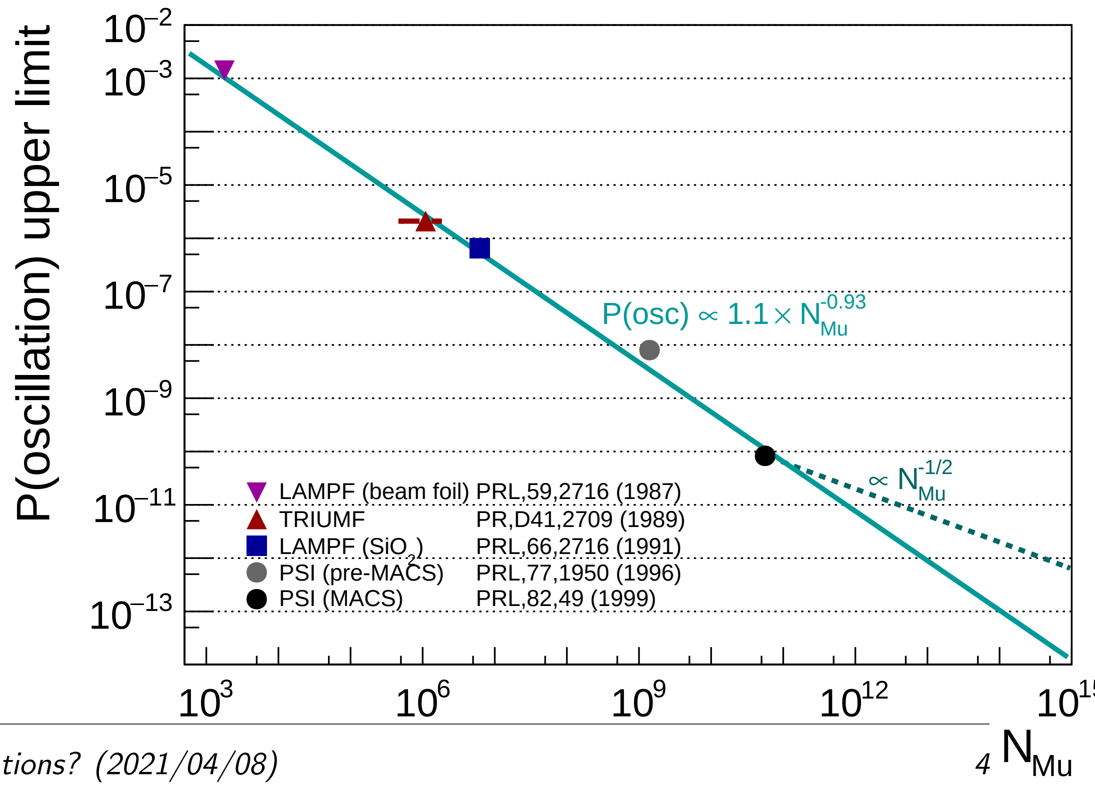
$$\mathcal{P}(\text{Mu} \to \overline{\text{Mu}}) = \frac{\Gamma(\text{Mu} \to \bar{f})}{\Gamma(\text{Mu} \to f)} = \frac{1}{2}(x^2 + y^2)$$

$\Rightarrow$ Experimentally: produce Mu and measure ‘wrong-sign’ final state

Previous experimental results

Location Characteristic Reference Year	LAMPF beam foil PRL,59,2716 1987	LAMPF SiO_2 PRL,66,2716 1991	PSI SiO_2 PRL,82,49 1998
beam rate f_{beam} beam momentum experiment duration T	3×10^5/s 10 MeV 150 h	10^6/s 20 MeV 270 h	8×10^6/s 26 MeV 1730 h
Mu formation probability N_{Mu} in vacuo	$\approx 3 \times 10^{-4}$ (??) 2×10^3	5% 6×10^6	2% 5.6×10^{10}
$\overline{\text{Mu}}$ cands/background	95/80	8/8	1/1.7

- Notes
  - all background limited
  - 'high' muon momenta
  - 'crude' detectors

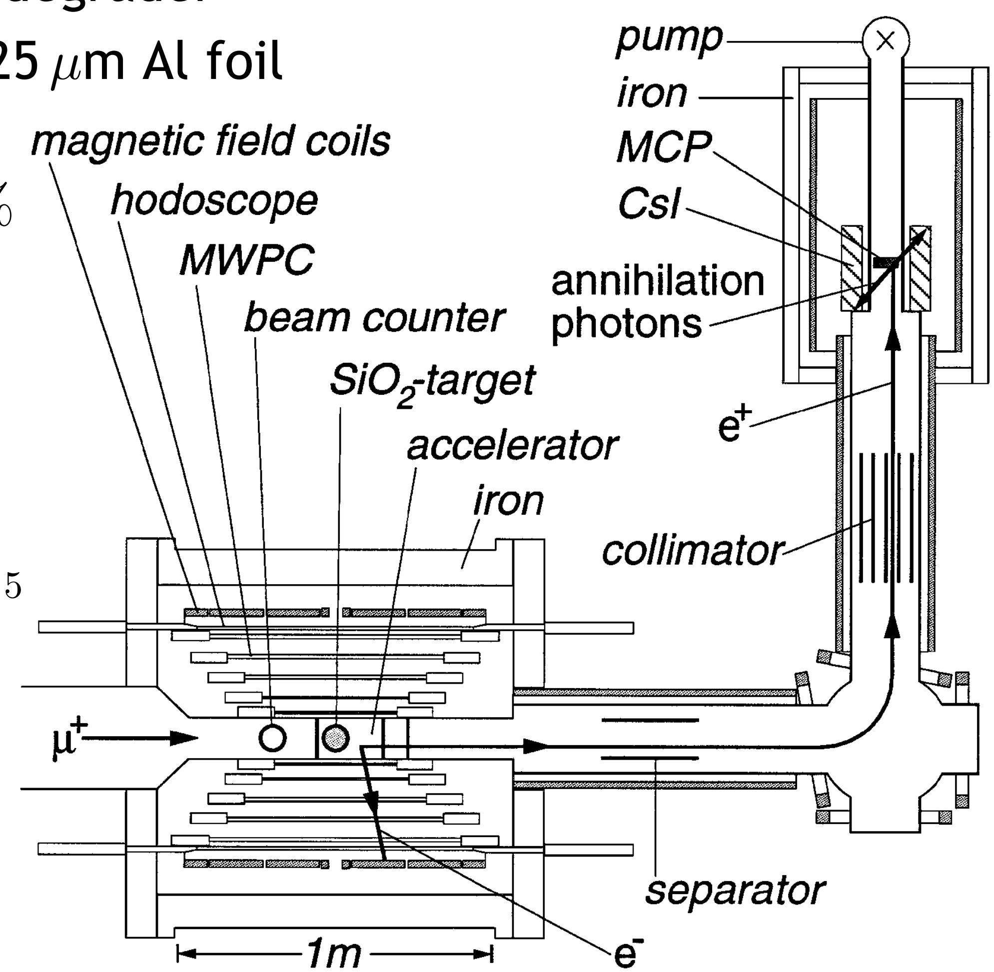


PRL, 82, 49 (1998)

MACS at PSI

- Muonium-Antimuonium Conversion Spectrometer
  - ▷ πE5 with $8 \times 10^6 \mu^+/\,\mathrm{s}$ at $p = 26\,\mathrm{MeV}$
  - ▷ 280 μm scintillator, 270 μm Mylar degrader
  - ▷ SiO_2 powder target $8\,\mathrm{mg/\,cm^2}$ on 25 μm Al foil
    replaced twice/week
  - ▷ $\varepsilon^{\text{Mu prod.}} = 0.61_{\text{prod}} \times 0.033_{\text{trsf}} = 2\%$
  - ▷ $N_{\text{Mu}} = 5.6 \times 10^{10}$ in vacuo
- Background limitations
  - ▷ coincidental e^- from
    Bhabha e^+-scattering
  - ▷ $\mathcal{B}(\mu^+ \to e^+e^+e^-\nu_e\bar{\nu}_\mu) = 3.4 \times 10^{-5}$
  - ▷ at 50 MeV: $\Delta(p_\perp)/p_\perp = 54\%$
- Results (1730 h data taking)
  - ▷ $\overline{\text{Mu}}$ like events:
    1 observed, 1.7 bg expected

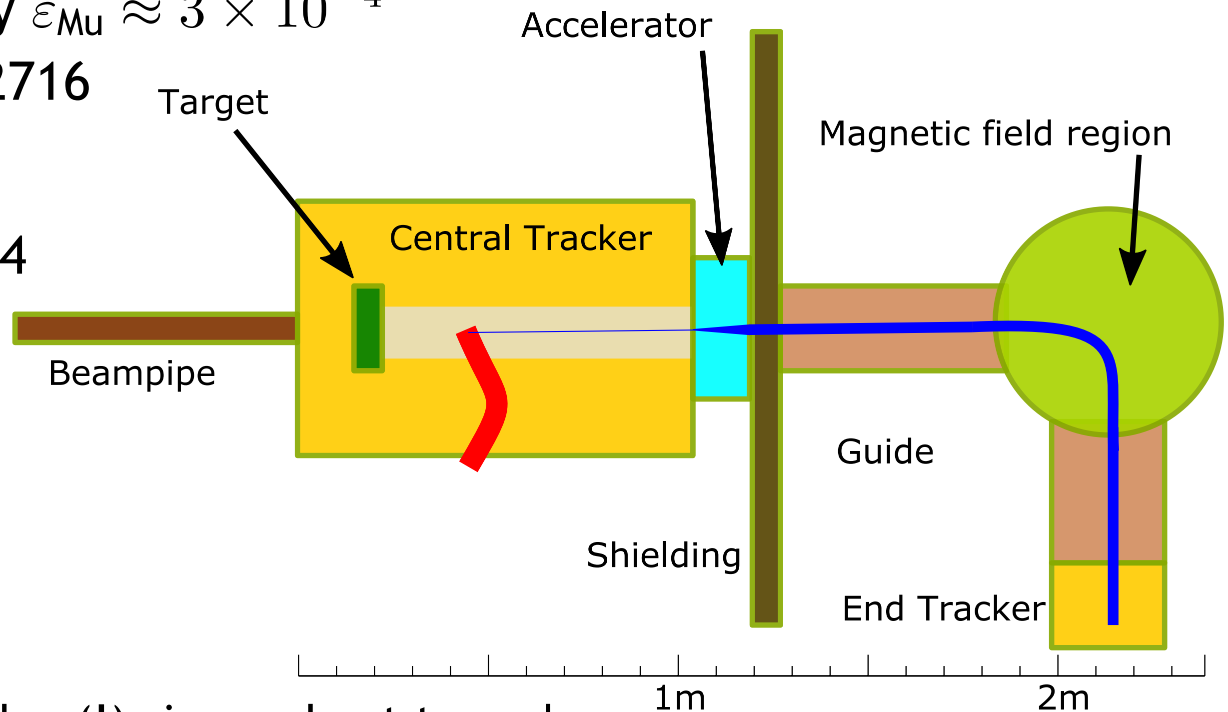
$\rightarrow$ $\mathcal{P}_{\text{Mu}\overline{\text{Mu}}}(0.1\,\mathrm{T}) < 8.3 \times 10^{-11}$ **(90% CL)**



(normalization by reversal of fields)

Straw-man sketch

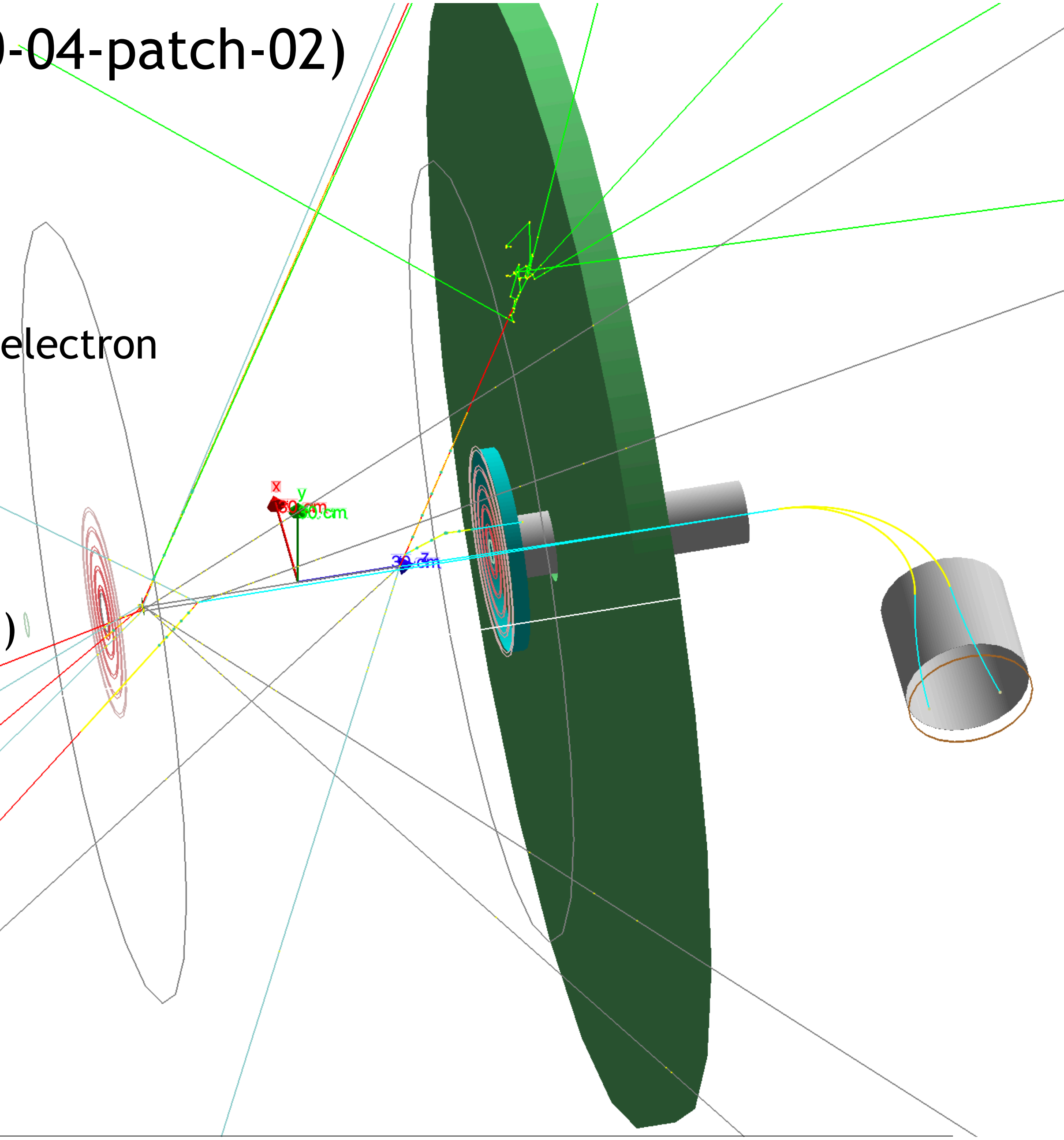
- Look at Mu production with high-rate μ^+ beams
  - ▷ foil (degradation of SiO_2 already at low intensities)
  - ▷ background situation
- Goal? Improve MACS by an order of magnitude in one week?
  - ▷ need 10^{12} Mu in vacuo
  - ▷ with $10^{10}\mu^+/\,\mathsf{s} \times 3600\,\mathsf{s}/\,\mathsf{h} \times 100\,\mathsf{h} = 3.6 \times 10^{15}\mu^+$
  - → Mu production efficiency $\varepsilon_{\mathsf{Mu}} \approx 3 \times 10^{-4}$
  - → not so far from PRL,59,2716
- Try
  - ▷ Mu production in GEANT4
  - ▷ with high-rate μ^+ beam (many μ^+ per frame)
  - → production?
  - → acceptance?
  - → background?



Note: random(!) size and not to scale

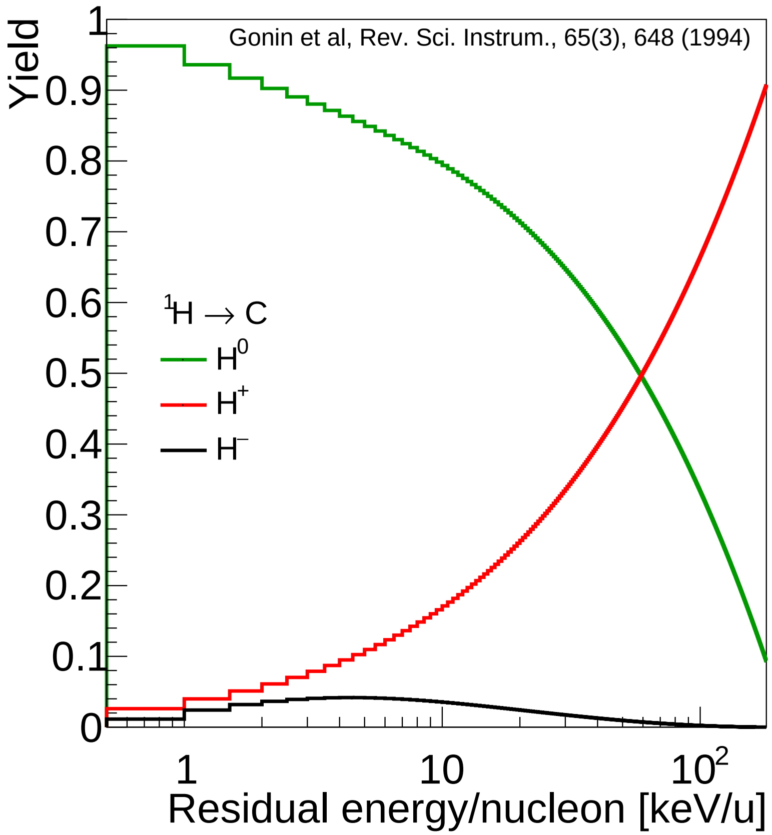
Geant4 strawman setup

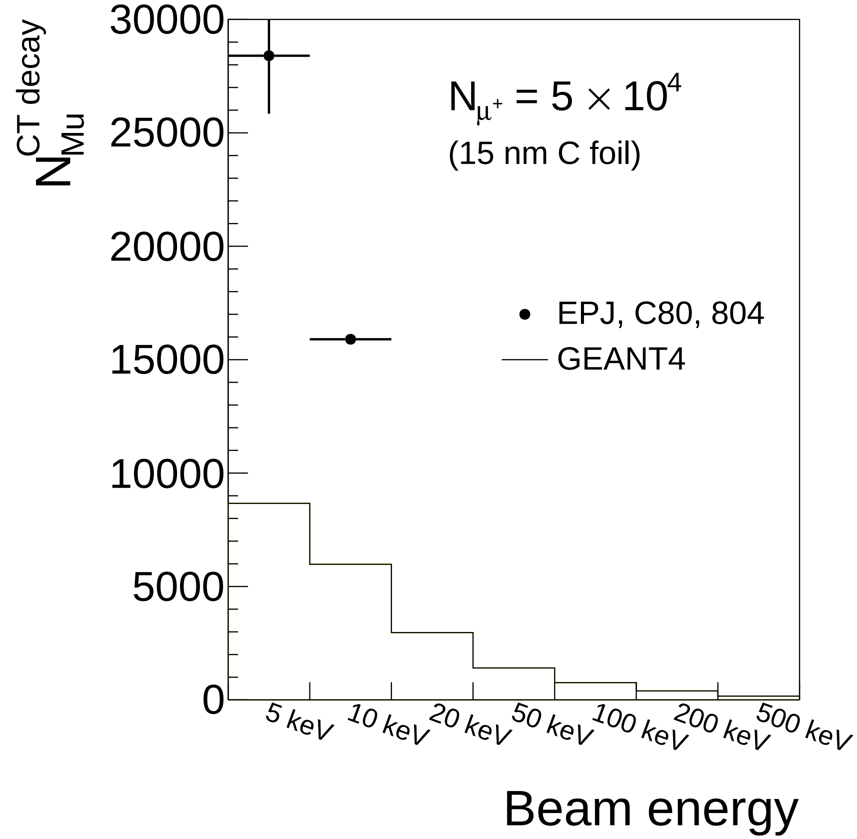
- GEANT4 setup (geant4-10-04-patch-02)
  - ▷ started from
    - musrsim
    - mu3e decay models
  - ▷ changes
    - Mu decay including atomic electron
    - Mu propagation in
      target
      vacuum
    - Mu 'energy loss'
      (ad hoc Landau distribution)
  - ▷ muon beam
    - arb. number of muons
  - ▷ muon decay modes
    - $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$
      (only this one for Mu)
    - $\mu^+ \to e^+ \gamma \nu_e \bar{\nu}_\mu$
    - $\mu^+ \to e^+ e^- e^+ \nu_e \bar{\nu}_\mu$



Mu production in (C) foils

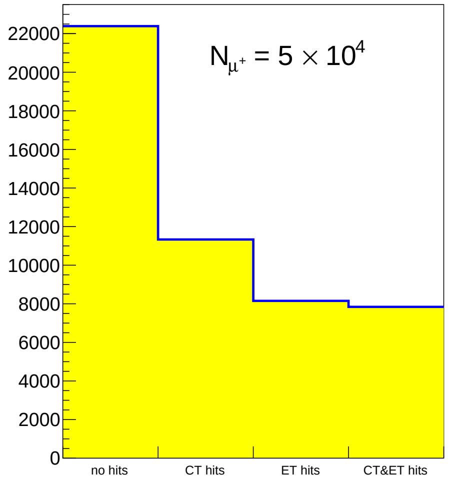
- musrSim relies on (rescaled) measurements by Gonin *et al.*
- for comparison, f_{Mu/μ^+} measurements by Janka *et al.*
  - therefore, here C foil with 15 nm thickness
  - no tuning of any parameters, i.e. 'snapshot'



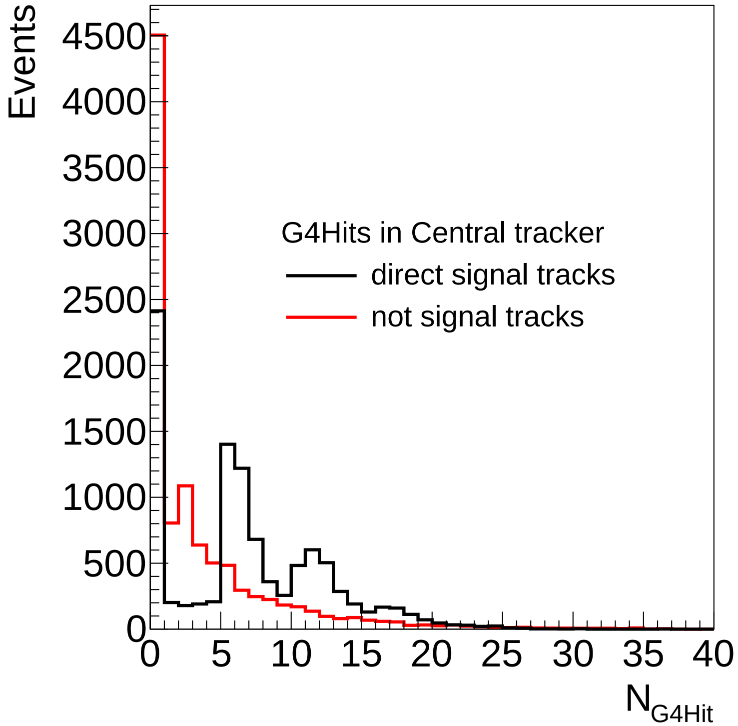


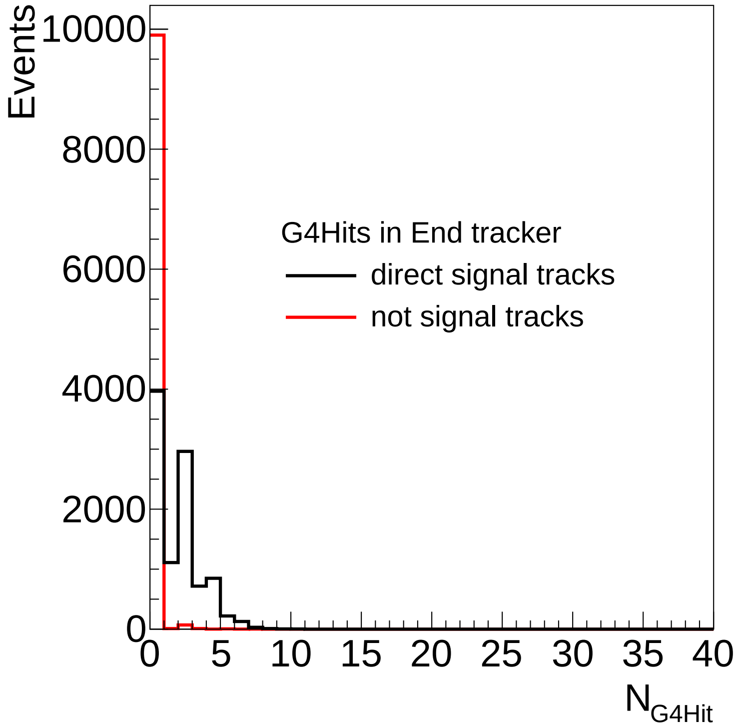
Signal and background

- Hits split into signal and background hits (G4Hits)
  - ▷ signal: directly from e_{fast} or e_{atomic}
  - ▷ background: other sources (incl. secondaries of signal tracks)
  - $\rightarrow$ End tracker with very low background level



- 'Acceptance' driven by End tracker
  - ▷ no optimization/tuning at all





Summary

- $\mathrm{Mu}\overline{\mathrm{Mu}}$ oscillations with large potential at HiMB + beam-foil
- Geant4 strawman setup
  - ▷ production, drift, and decay of Mu with background
- Future studies
  - ▷ beam momentum/rate and foil thickness
  - ▷ detector changes
    - simultaneous Mu and $\overline{\mathrm{Mu}}$ measurements (accelerator perpendicular to beam?)
    - resolutions required
    - (ultra)low-field configuration in decay volume
    - optimizations
  - ▷ high-rate background simulations
- To reach $\frac{1}{10} \times$MACS in 1 week:

Scenario	minimum $A \times \varepsilon$
HIMB-3	3×10^{-4}
HIMB-cool	3×10^{-1}