Feasibility of Low-Energy **True Muonium** via Near-Threshold Photoproduction

ETH zürich IPA

Ivo Schulthess & Paolo Crivelli, ETH Zurich

18th of May 2026, Austrian Academy of Sciences, Vienna

International Conference on Precision Physics of Simple Atomic Systems

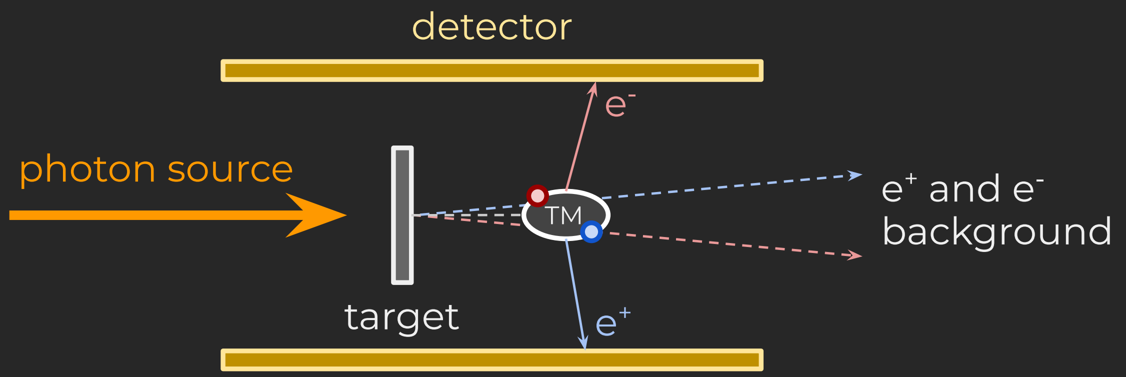
True Muonium
Introduction

- exotic atom ➔ bound-state QED
- Bohr radius of only ~512 fm
- point-like leptonic constituents
- allows stringent tests of bound-state QED and new physics in the muon sector

- not yet observed!

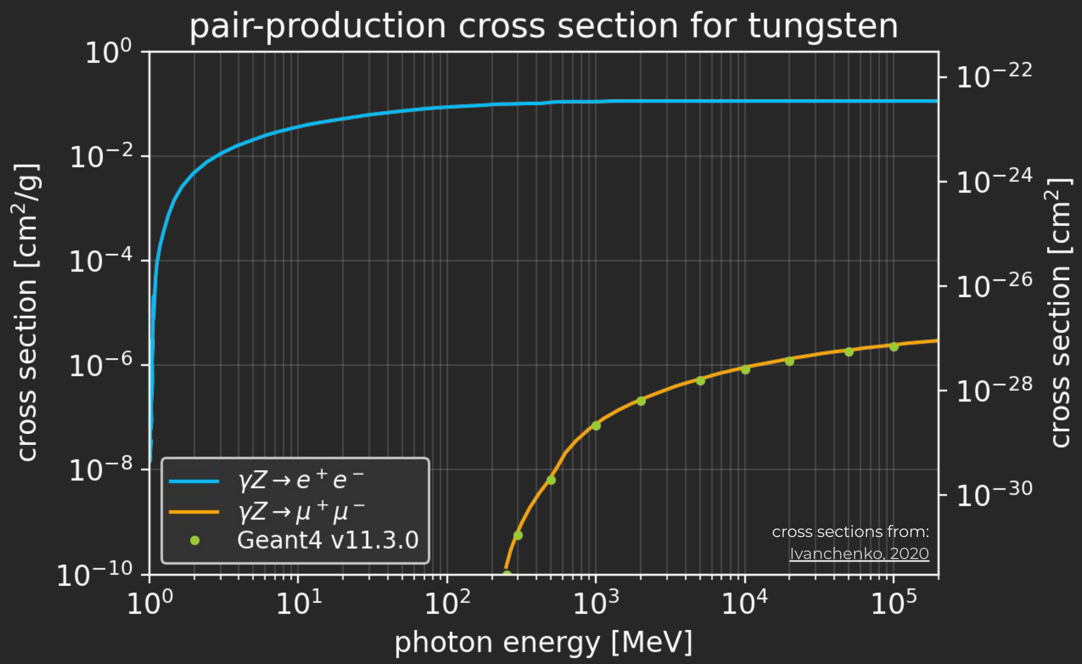
True Muonium

Photoproduction



True Muonium

Photoproduction Cross Section



- high energy limit $E_\gamma \gg m_\mu$:

$$\sigma_{\gamma Z} = 0.139\,\mathrm{GeV}\,\frac{\pi\alpha^8}{m_\mu^4} \times \frac{Z^4}{A^{2/3}}$$

$$\sigma_{\gamma Z=74} = 10^{-35}\,\mathrm{cm}^2$$

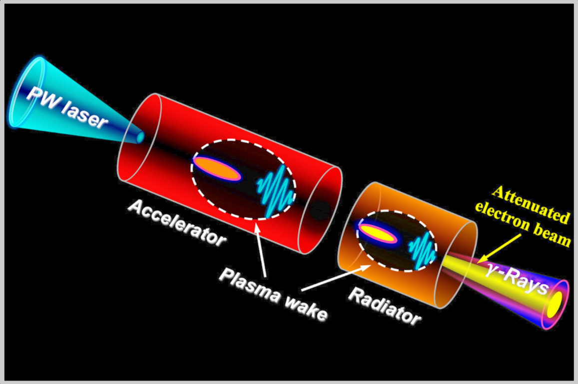
- assumption:
  $\sigma_{\gamma Z \to TM} / \sigma_{\gamma Z \to \mu+\mu-}$ = const.

input from the theoretical community needed!
➔ sivo@ethz.ch

Photon Source

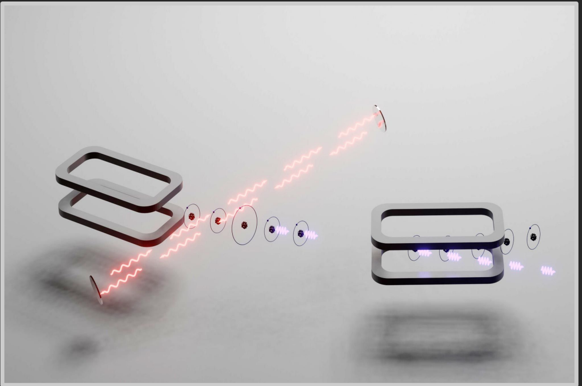
Possibilities

plasma sources



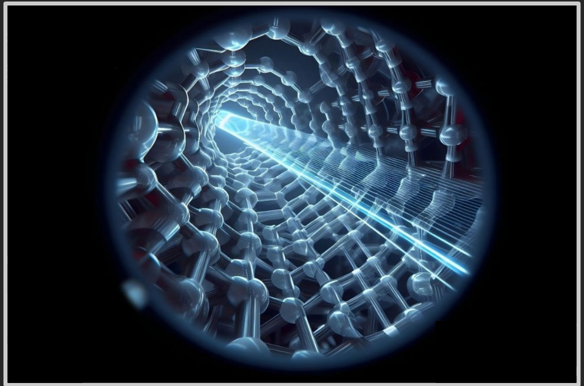
X. Zhu (2020)

Gamma Factory



A. Petrenko (2020)

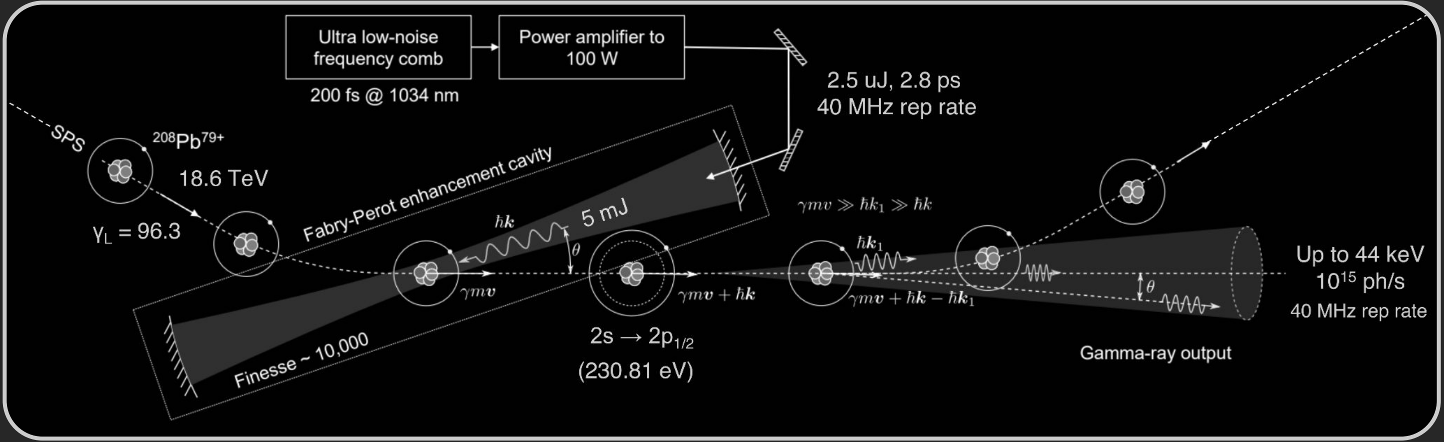
crystal radiators



L. Bandiera (2024)

Photon Source

Gamma Factory Concept



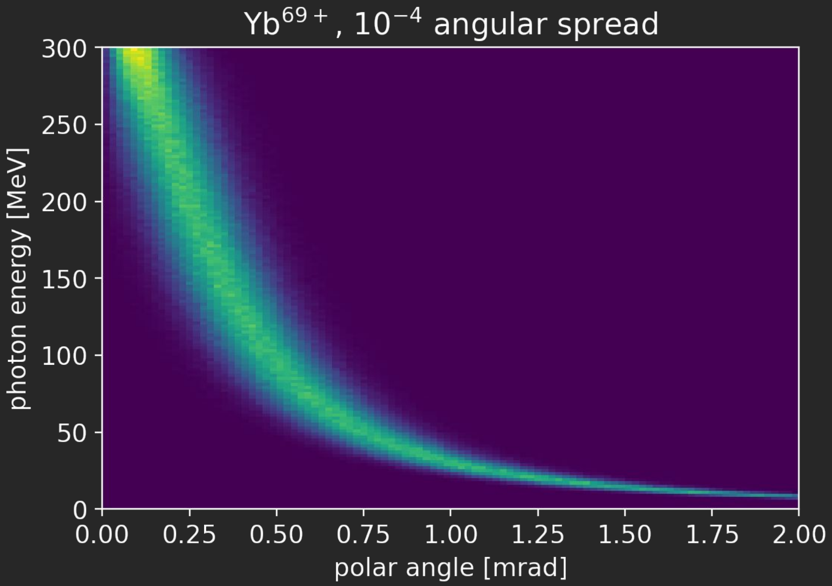
E. Granados (2024)

$$E_\gamma = 2\,\gamma\,E_a = 2\,\gamma\,(2\,\gamma\,E_l) = 4\,\gamma^2\,E_l$$

E_a: atomic transition energy
E_l: laser photon energy

Photon Source

Gamma Factory at 300 MeV



- use highest possible $\gamma \approx 3000$:
  - $E_a = 50$ keV
  - $\Delta E_{1s\text{-}2p} = 10.2\ \text{eV} \times Z^2$
    ➔ $Z \approx 70$
    ➔ Yb^{69+}
  - $E_l = 8.33$ eV ($\lambda_l = 149$ nm)

Photon Source

Gamma Factory Rates

- R_{GF} = 10 MHz
- τ_l = 500 ps
- E_l = 5 mJ

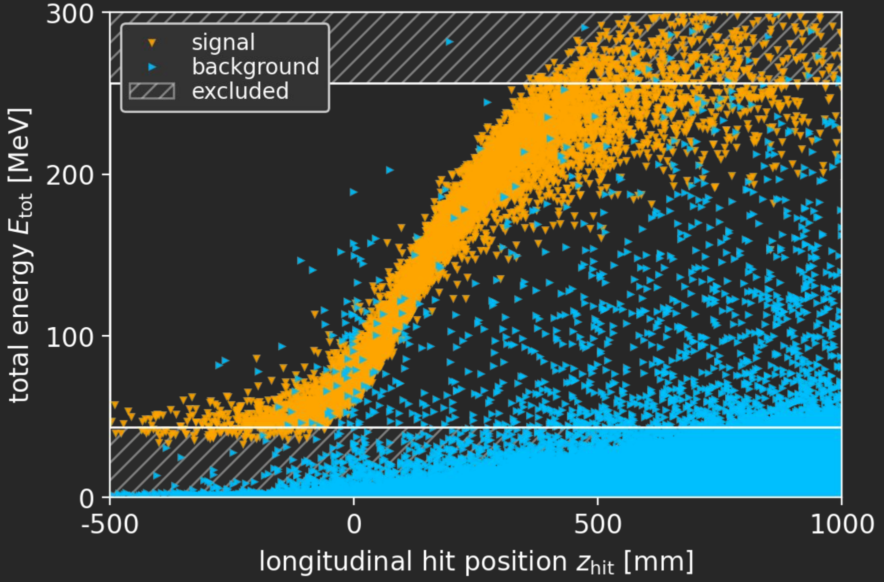
➔ $\dot{N}_\gamma$ scales linearly in R_{GF}, τ_l, and E_l

J. Bieroń et al. (2022)

$L_{GF \to TM}$	δE / E	$\dot{N}_\gamma$	$\dot{N}_{TM}$
0 m	57.8 %	380 x 10^{13} s^{-1}	23.2 d^{-1}
100 m (1 cm^2)	10.3%	6.47 x 10^{13} s^{-1}	0.4 d^{-1}
200 m (1 cm^2)	9.6%	1.63 x 10^{13} s^{-1}	0.1 d^{-1}

Background Rejection

Background Numbers



preselection:

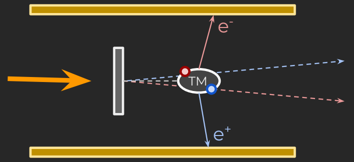
- E in [43.5, 256.5] MeV
- z in [-500, 1000] mm

signal:

- 7.0×10^{-20} TM/γ
- 1.4×10^{19} γ/TM

background:

- 4.6×10^{-8} e^-/γ
- 4.1×10^{-8} e^+/γ



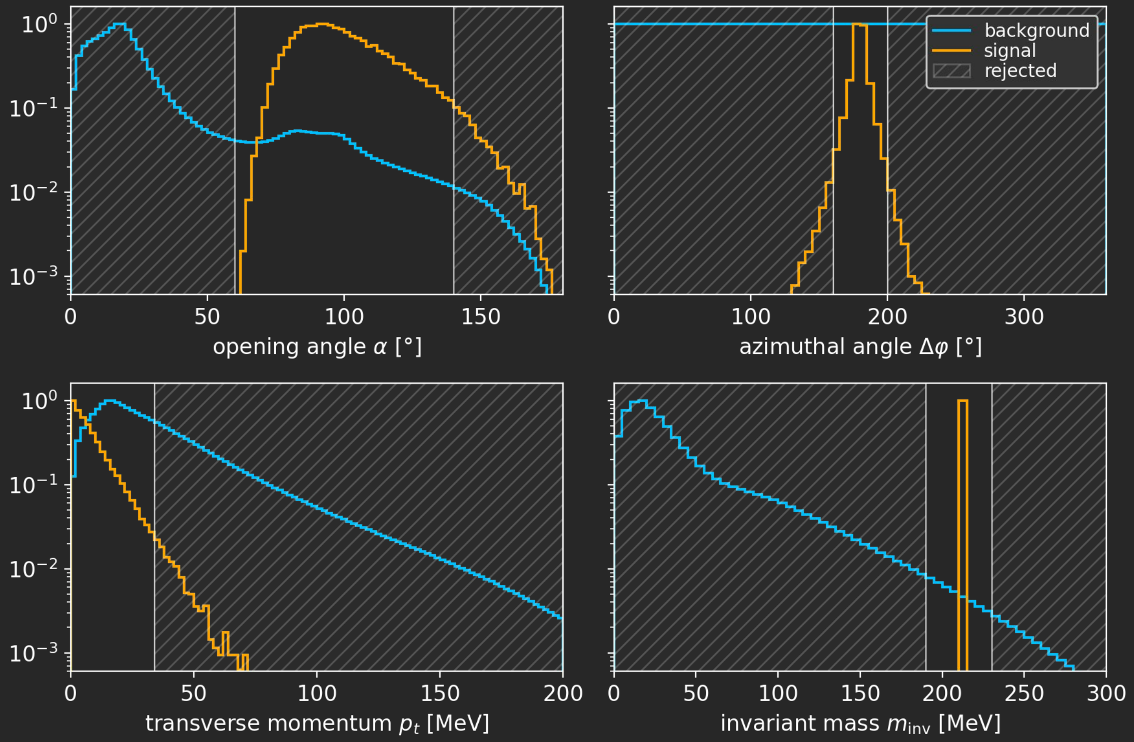
Gamma factory (10^8 γ/BX):

- 4.6 e^-/BX
- 4.1 e^+/BX
- 19 BG/BX

➔ **2.7×10^{12} BG/TM**

Background Rejection

Signal / Background Distributions



simulation:

- 4×10^{13} primaries
- 3×10^{12} BG

apply cuts:

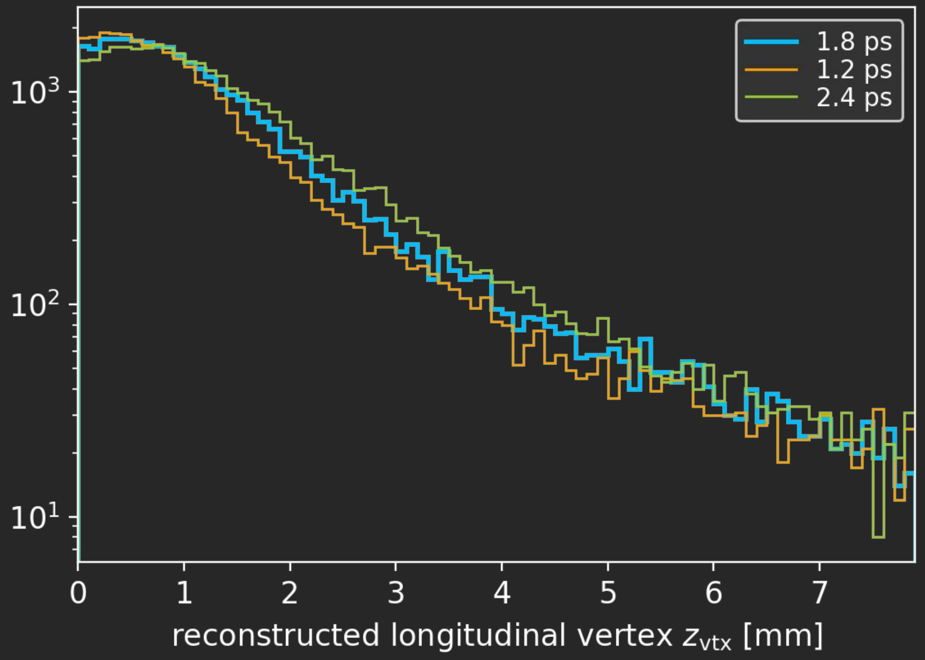
- $60° < \alpha < 140°$
- $160° < \Delta\varphi < 200°$
- $|p_t| < 34$ MeV
- 190 MeV $< m_{inv} <$ 230 MeV

results:

- signal efficiency
  ➔ 94.4%
- background efficiency
  ➔ $< 9.8 \times 10^{-13}$ (95% C.L.)

Precision Measurements

Lifetime

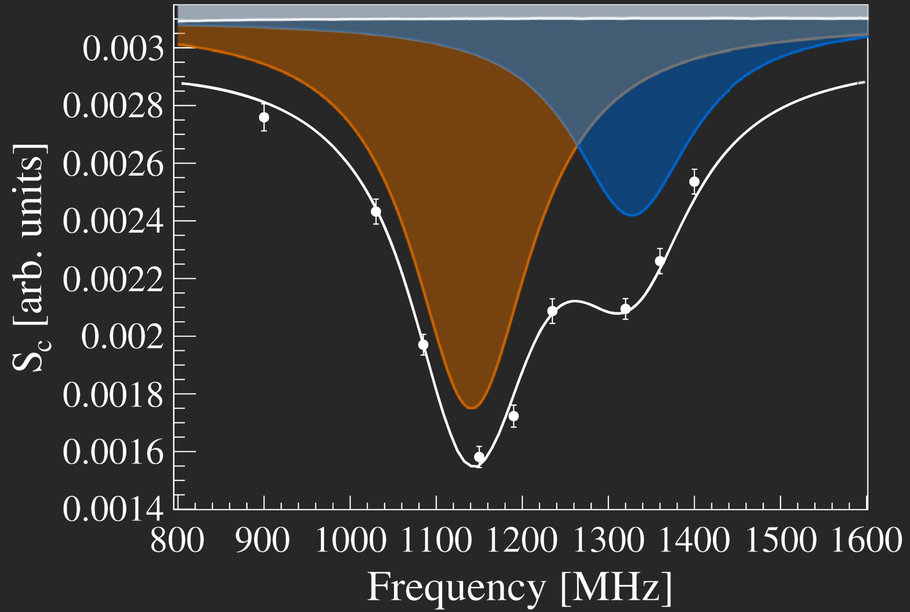


- lifetime from decay length reconstruction
- ultra-low material budget tracking detector required
- distribution comparison to Monte-Carlo templates

Precision Measurements

Hyperfine Splitting

Mu-MASS Collaboration (2022)



- 1^1S_0 - 1^3S_1 transition between the parallel and antiparallel spin state
- 42 THz accessible with 7 μm quantum cascade lasers
- measurement principle analog to muonium Lamb shift measurement
- when transition is excited the signal disappears

True Muonium

Summary

- true muonium is an interesting object
  - to test bound-state QED
  - to search for new physics
- sources are challenging but possible
  - Gamma Factory
  - crystal radiators
- background can be suppressed
  - $< 9.8 \times 10^{-13}$ (95% C.L.)
- near-threshold photoproduction enables precision measurements

preprint available today, check it out on **arXiv**

Swiss National Science Foundation
grant no. 230596