Muon generation from laser wakefield accelerators

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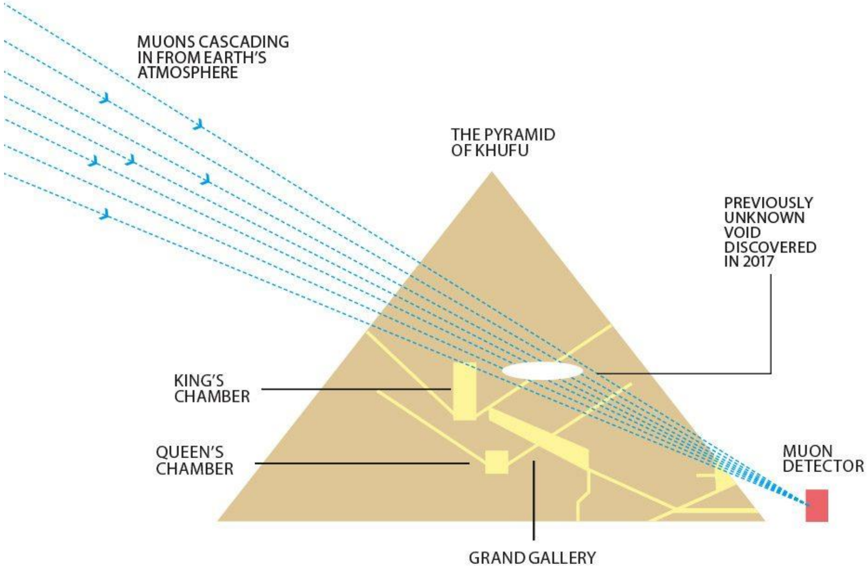
Muons: motivation

Muon radiography is an established technique for the detection of high-Z materials in otherwise inaccessible conditions (e.g., through thick-wall containers).

Typically, existing detection methods rely on either sources of cosmic nature or proton-based conventional accelerators.

However, the **low rate of cosmic muons** (~1 muon/cm^2/minute) implies acquisition times of several weeks, while the size and cost of conventional accelerators make them unviable for practical applications.



Cartoon of discovery of a hidden chamber in the pyramid of khufu using cosmic muons (2017).

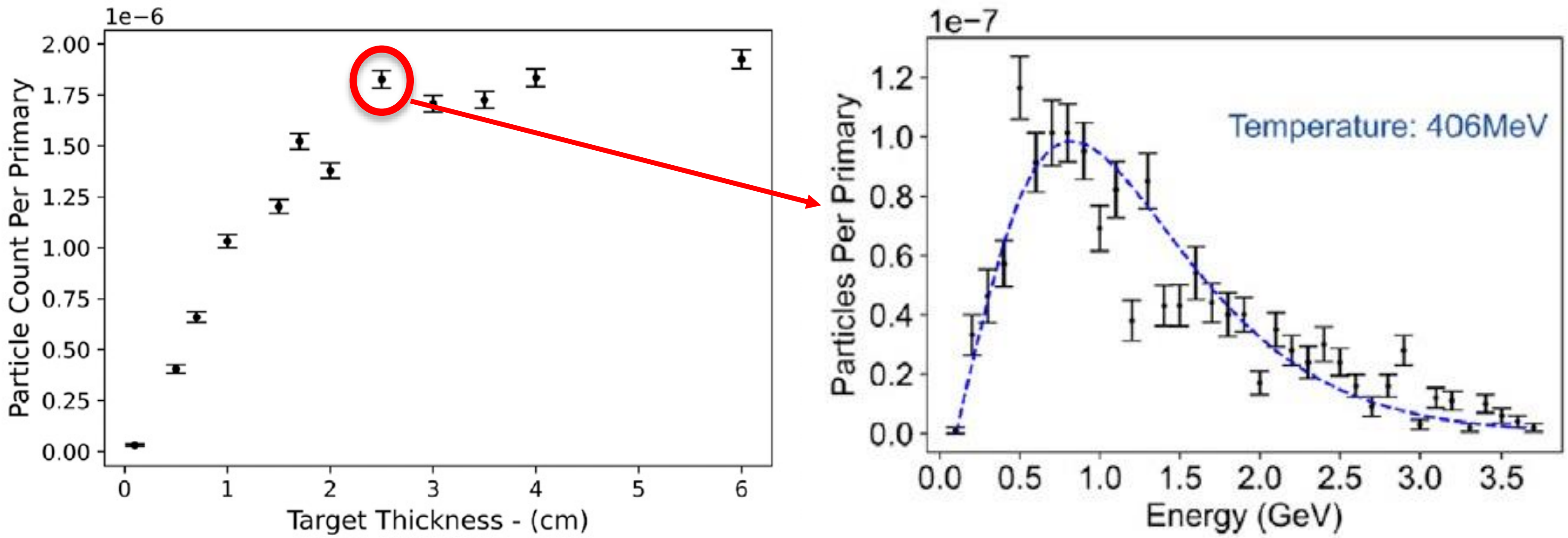
K. Morishima et al., Nature (2017)

Laser-driven particle accelerators offer the possibility of generating high average flux populations of energetic muons with high quality in a relatively inexpensive and compact setup, opening the way for widespread radiographic use of muons

Examples of expected yield

PW-scale lasers such as EPAC can now generate high charge (>nC) electron beams with maximum energies well exceeding 1 GeV at 1-10 Hz repetition rates.

Sizeable muon populations can be generated during the propagation of such electron beams through cm-scale high-Z solid targets.



Simulated number of muons per electron for a 5 GeV primary electron beam as a function of converter thickness. For a 1 nC electron beam, this corresponds to >10⁴ muons per laser shot

Muon spectrum at source for a 2 cm lead target

L. Calvin et al., Frontiers in Physics 11:1177486 (2023)

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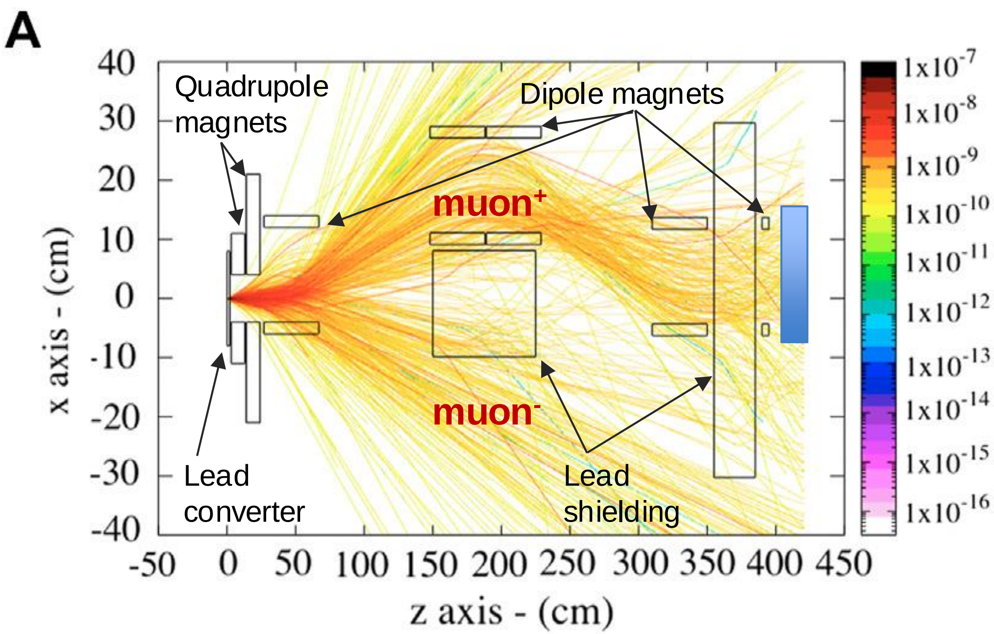
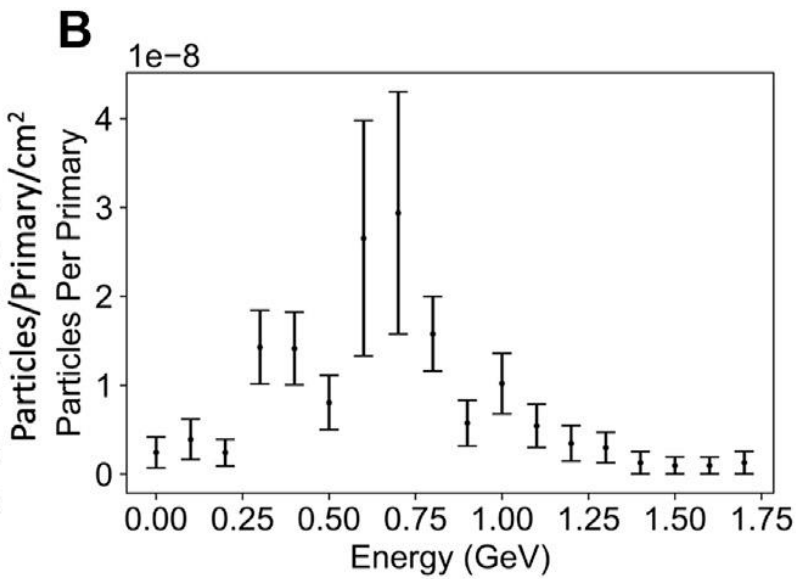
Proposed muon beamline

[dstl] The Science Inside

The muons must be collected and guided onto the radiographic end-station, while minimizing the noise associated with secondary particles and gamma-ray radiation



Sideview of muon trajectories through a beamline designed to provide wide-area radiographic capabilities (region for radiography highlighted in blue).



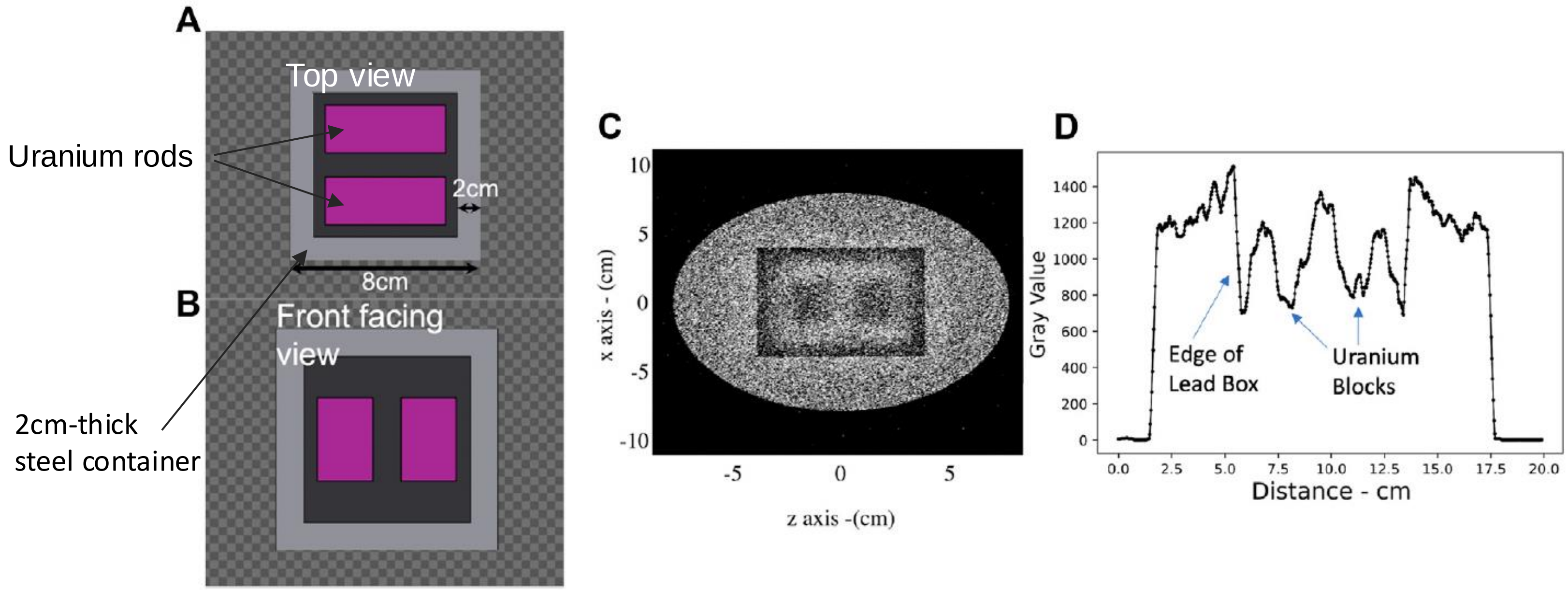
Spectrum of muons at the radiographic end-station (blue rectangle in frame A)

A 4m-long beamline using conventional magnetic elements can deliver, in a laser facility such as EPAC, more than **100 muons per shot over a 10cm irradiation area**

L. Calvin et al., Frontiers in Physics 11:1177486 (2023)

Synthetic radiographs

The muon populations guided through the proposed beamline allow for high-resolution detection of rods of sensitive material even through few-cm thick containers.



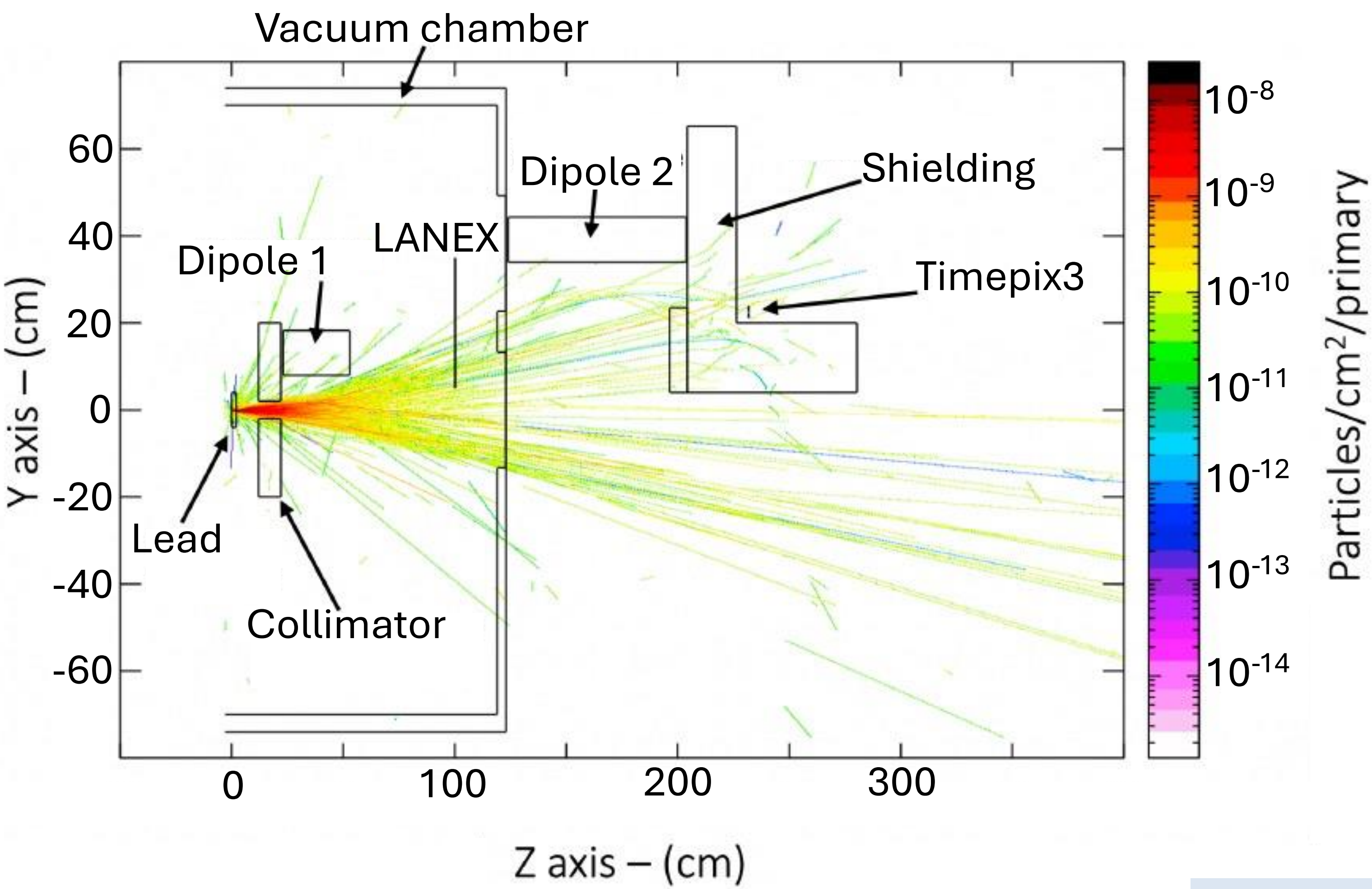
FLUKA simulated muon radiography of two uranium blocks concealed within a lead box of 2 cm wall thickness. **(A)** and **(B)** in-scale top view and front view of the box (grey) and uranium (purple) inside. **(C)** Face-on muon distribution at the detector plane after the lead container. Darker regions represent lower muon signal, in linear scale. **(D)** Lineout of the muon distribution along the z-axis, clearly showing the lead box walls and the position of the uranium blocks. From this simulation, the spatial resolution of the radiography is of the order of 6 mm.

With operations at 10 Hz, a radiograph of this kind can be obtained in less than a minute

L. Calvin et al., Frontiers in Physics 11:1177486 (2023)

Experimental evidence

Recent campaign at ELI-NP using the 1PW arm (~20 J, 28fs, f/26 focusing)



L. Calvin et al., *submitted* (2025)

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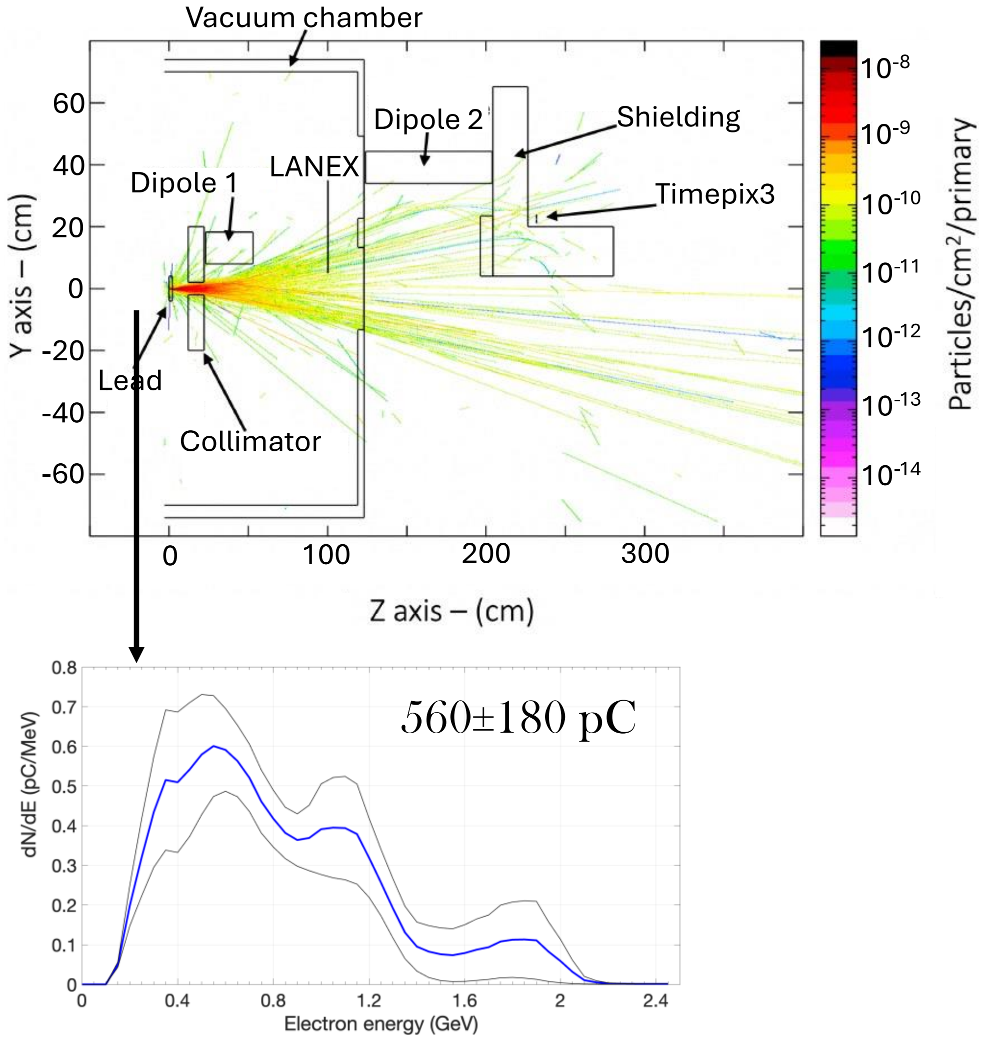

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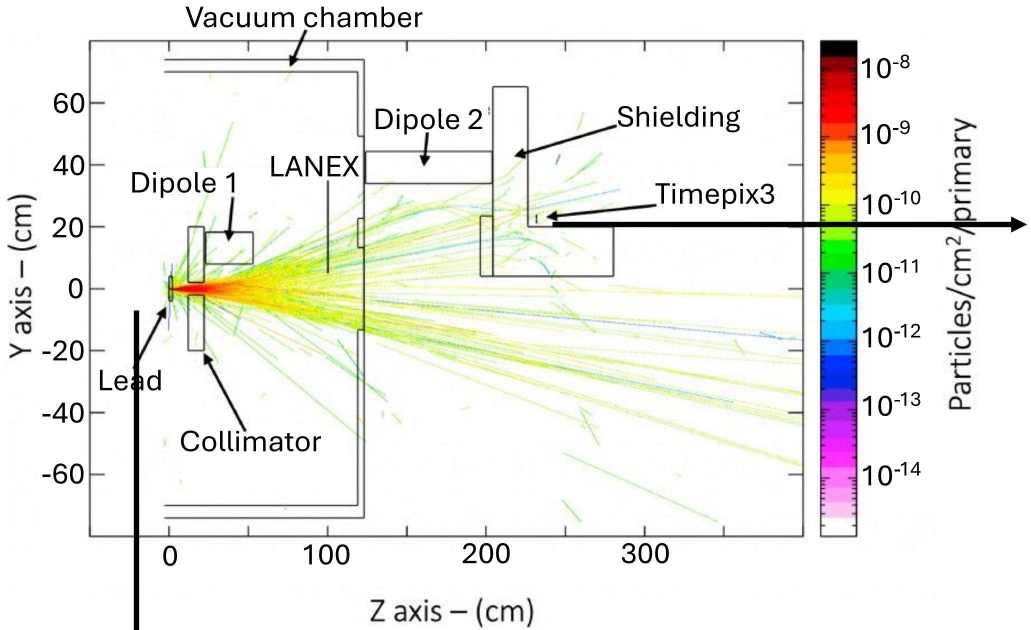

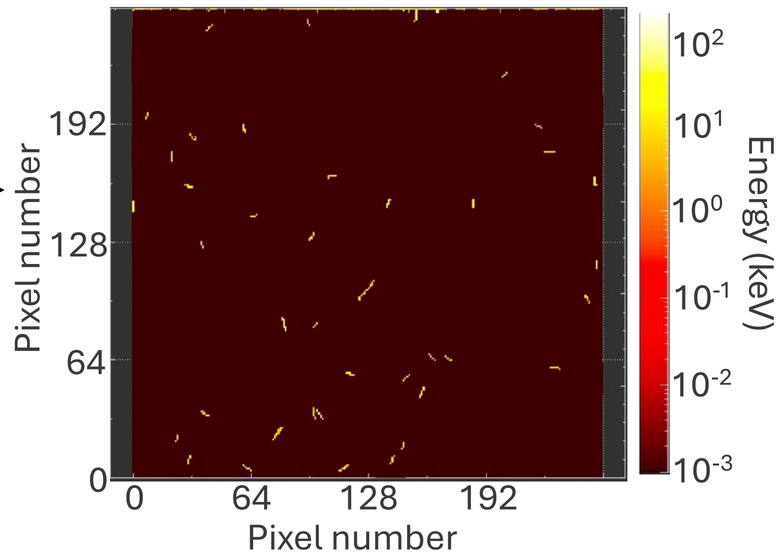

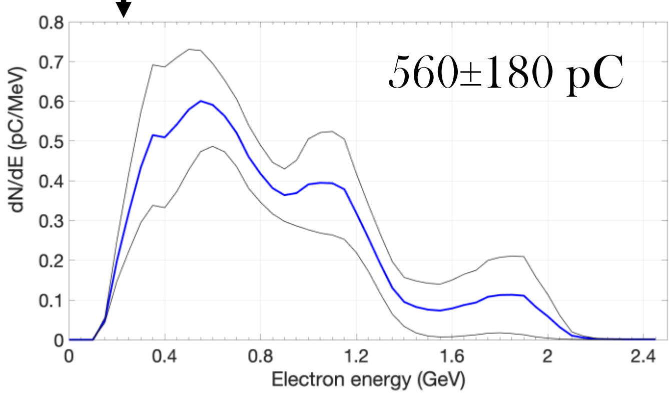

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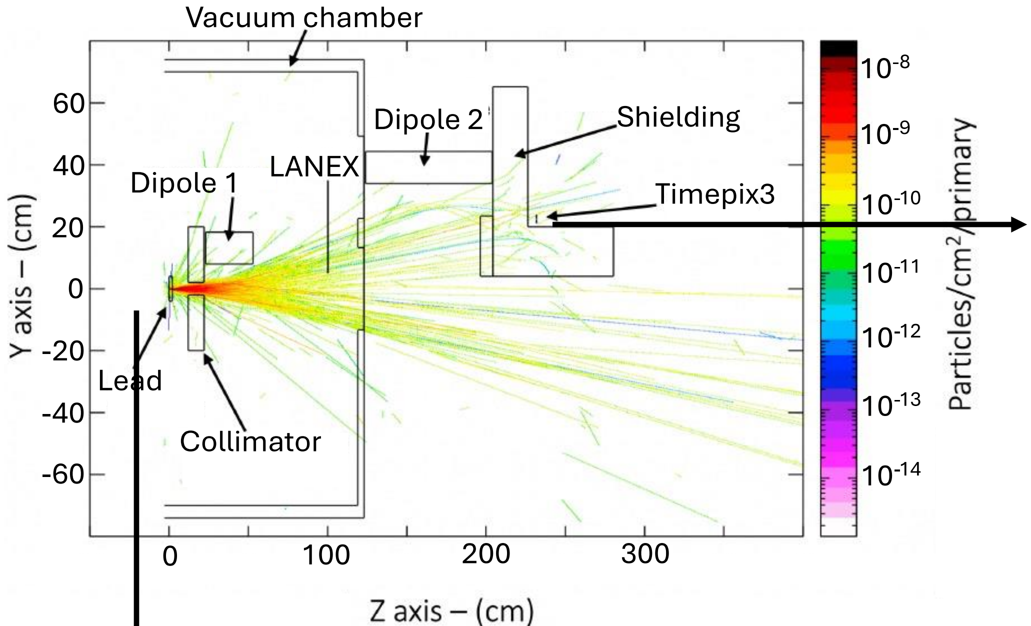

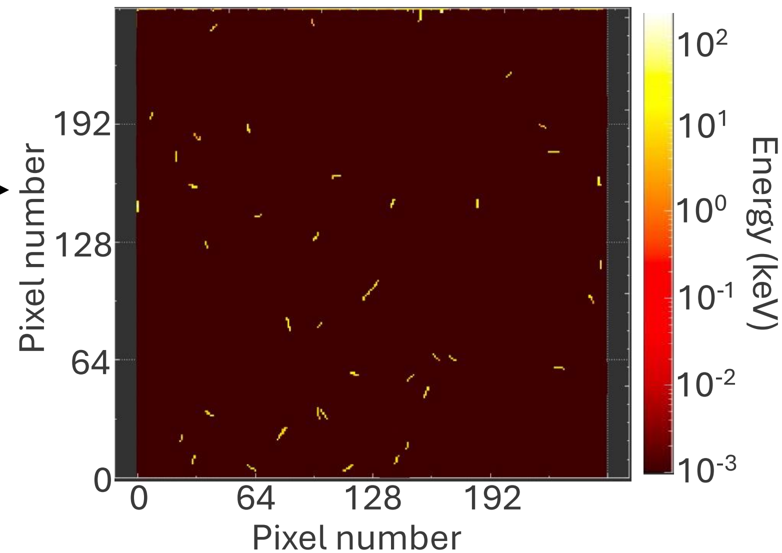

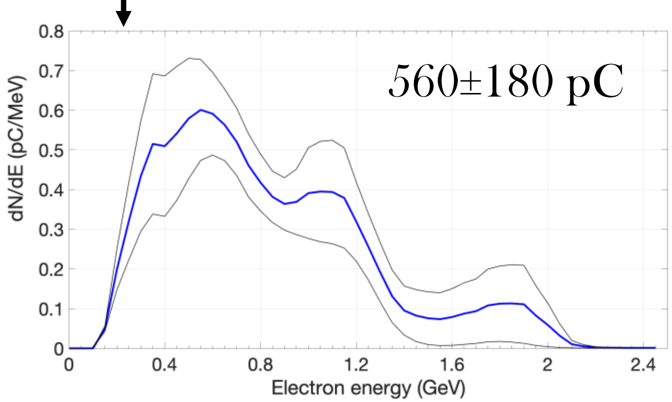

~3 muons over 10 shots, to be compared with 100s of noise electrons and positrons.

They can be distinguished though, based on track characteristics

L. Calvin et al., *submitted* (2025)

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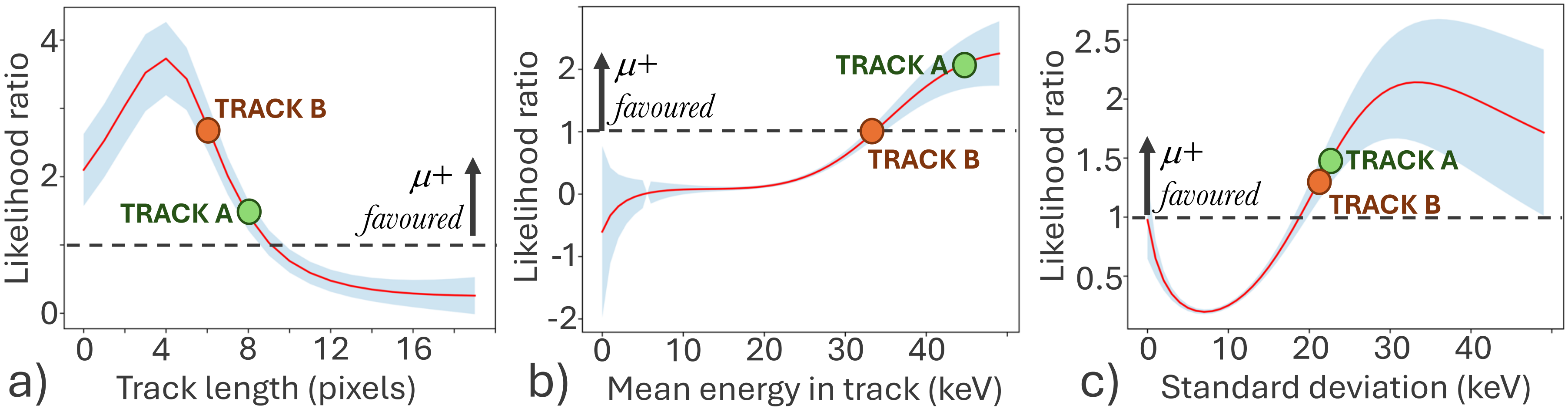

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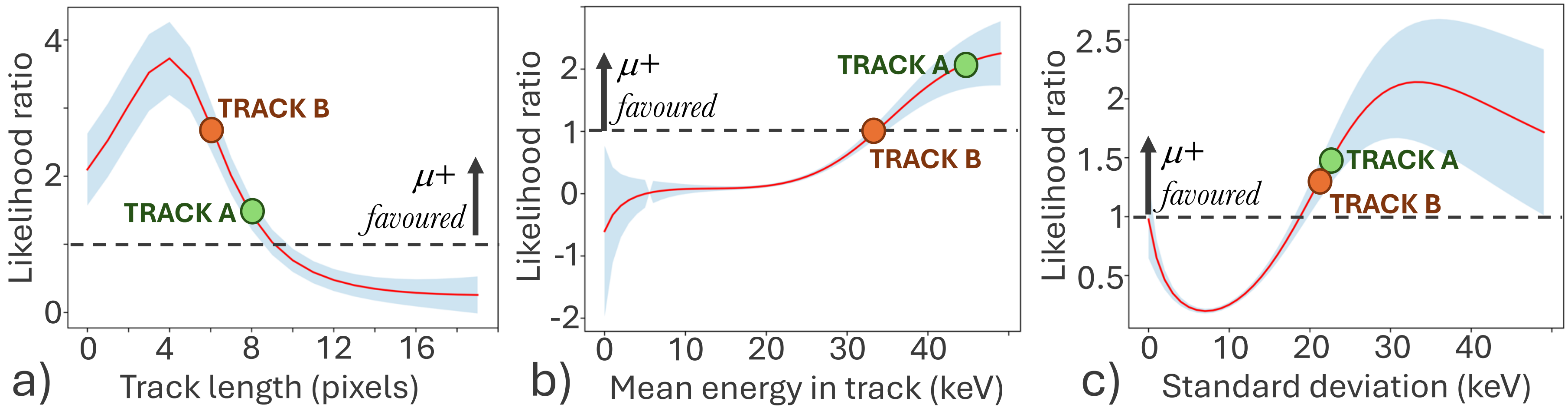

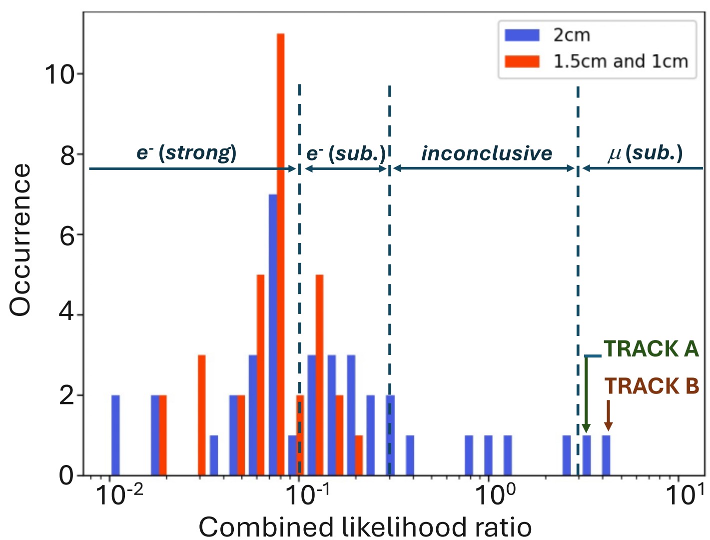

- 98.8±1.2 % confidence of muon detection over noise
- Same analysis yields zero candidates for thinner converter targets

Extrapolation of the data to a 1-10PW system with a suitable beamline, shows ~10^{3-4} μ/shot in cm^2-scale areas. **Suitable for Vulcan2020, EPAC, and EuPRAXIA**

Thanks for your attention!

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