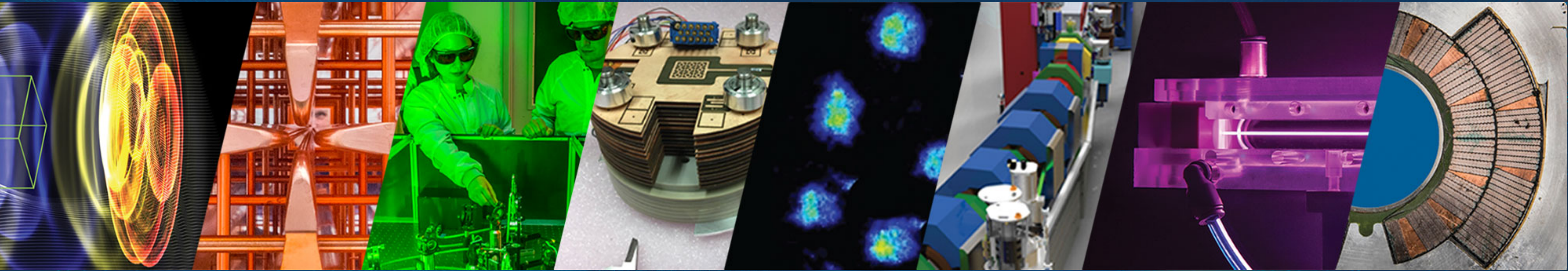
Measurement of directional muon beams generated at the Berkeley Lab Laser Accelerator

Sarah Schröder, Davide Terzani And Colleagues

Lawrence Berkeley National Laboratory (LBNL)

European Advanced Accelerator Conference, Elba, Italy — September 22-26 2025



BERKELEY LAB

ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

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Contributors

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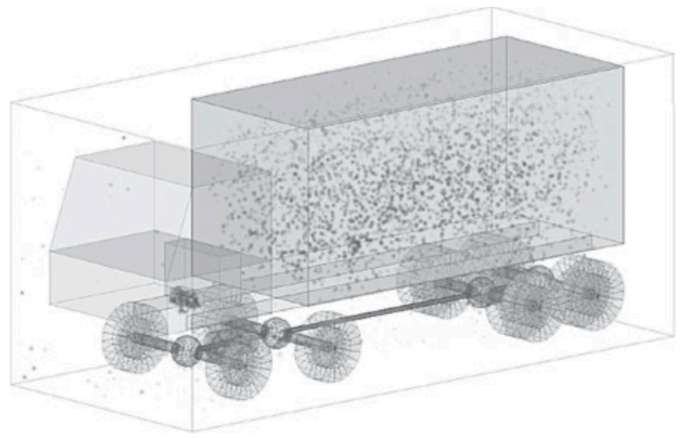
Muon Applications — An Increasing Interest

Muon		
Mass [MeV]	Charge [e]	Lifetime [μs]
105.7	1	2.2

- 105.7 → Reduced Bremsstrahlung
- 1 → Interacts with detectors
- 2.2 → Limited spatial reach due to decay

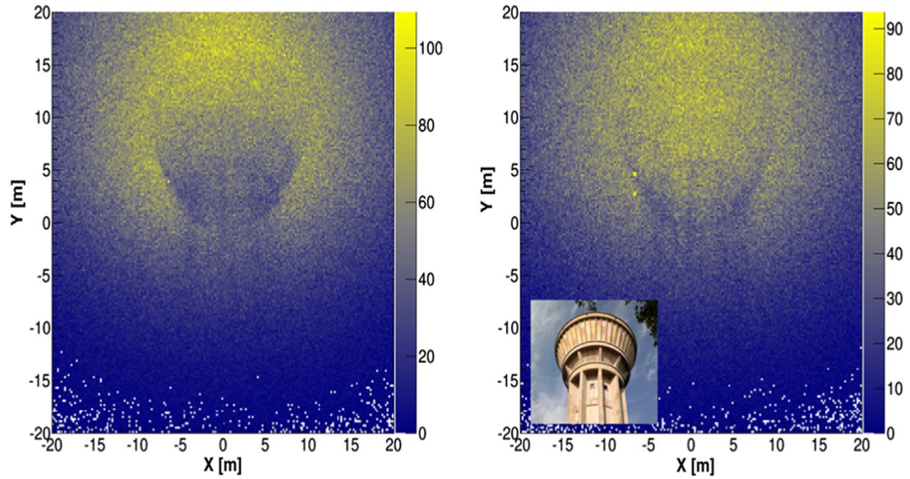
Muons' unique properties enable applications requiring deep penetration of dense materials.

Penetration of high-Z materials



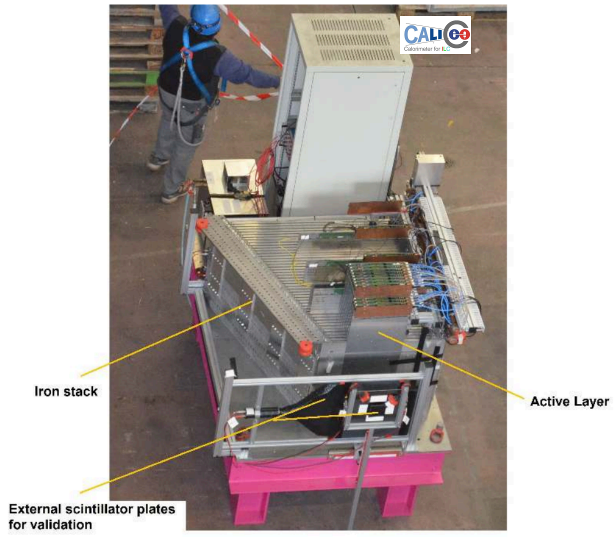
S. Vanini et al., Philosophical Transactions of the Royal Society A377, 20180051 (2018)

Imaging of large objects



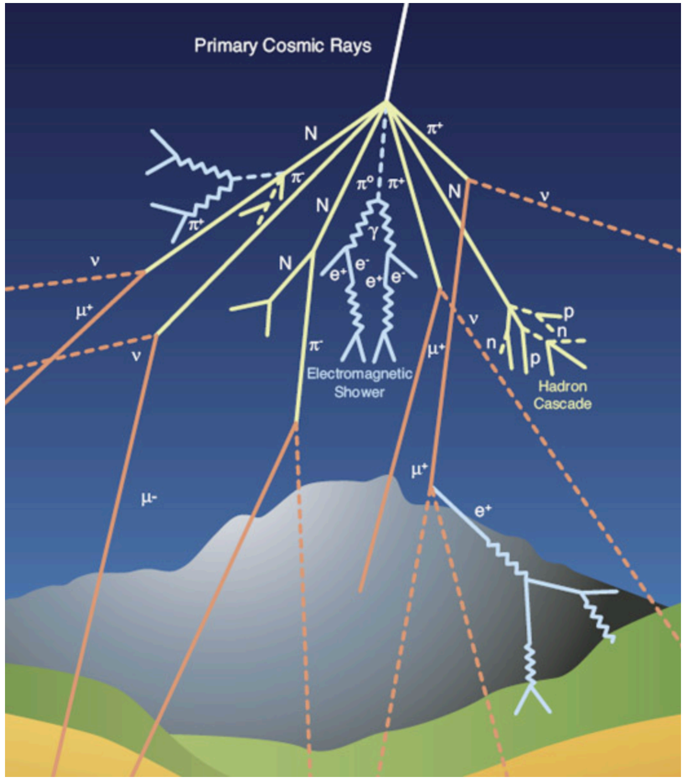
S. Bouteille et al., Nucl. Instrum. Methods A 834 (2016)

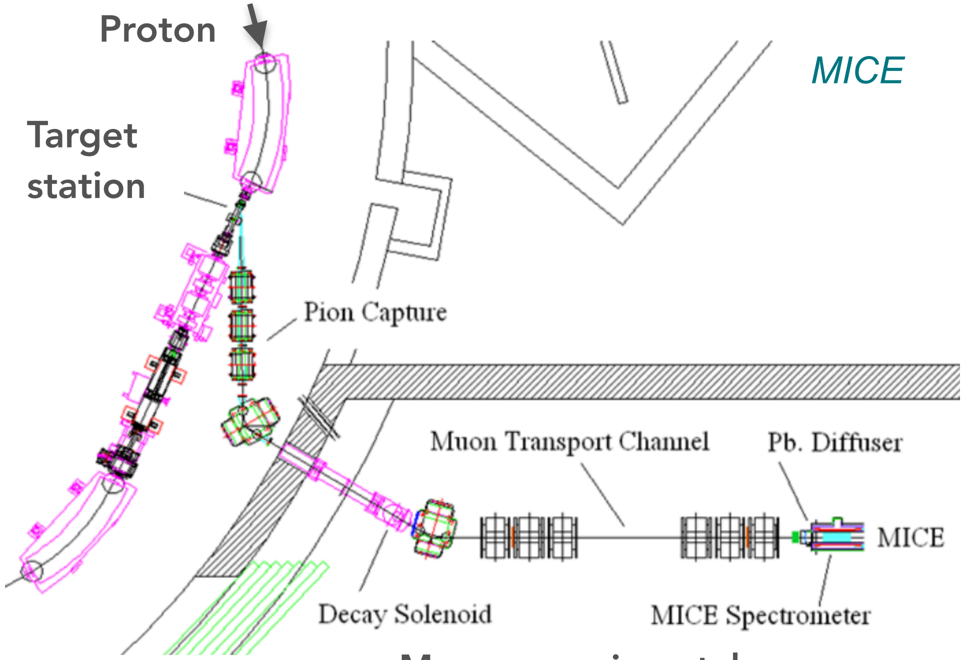
Detector response calibration



State Of The Art Of Muon Sources

cms.cern





MICE

Muon experimental area

Similar concept for the majority of muon sources (Fermilab, J-PARC, CERN, etc.)

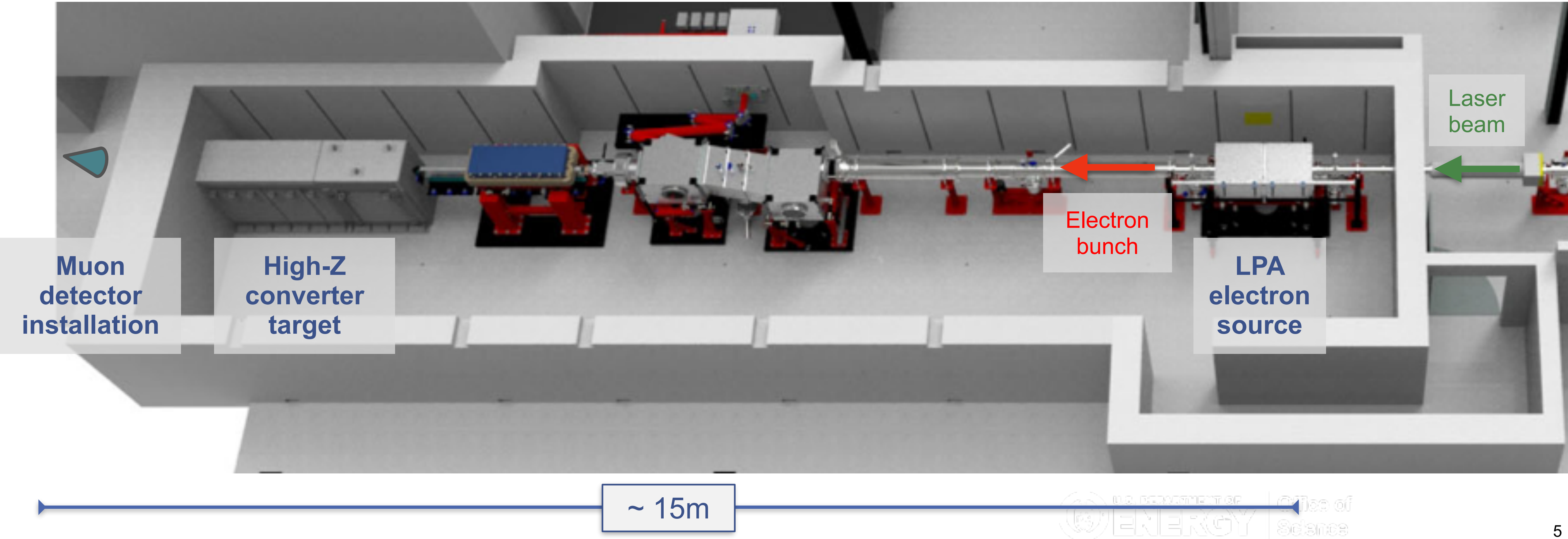
Compact LPA designs for multi-GeV electron beams unlocking new opportunites for muon applications

A. I. Titov et al., PRSTAB 12, 111301 (2009)
B. S. Rao et al., PPCF 60 (2018)
L. Calvin *et al.*, Frontier in Physics 11 (2023)
P-F. Geng *et al.*, *Phys. Plasmas* 31, 023109 (2024)

Muon Generation At BELLA — The Experimental Concept

> Petawatt laser system generating multi-GeV electron bunches

> Muon production in high-Z converter target



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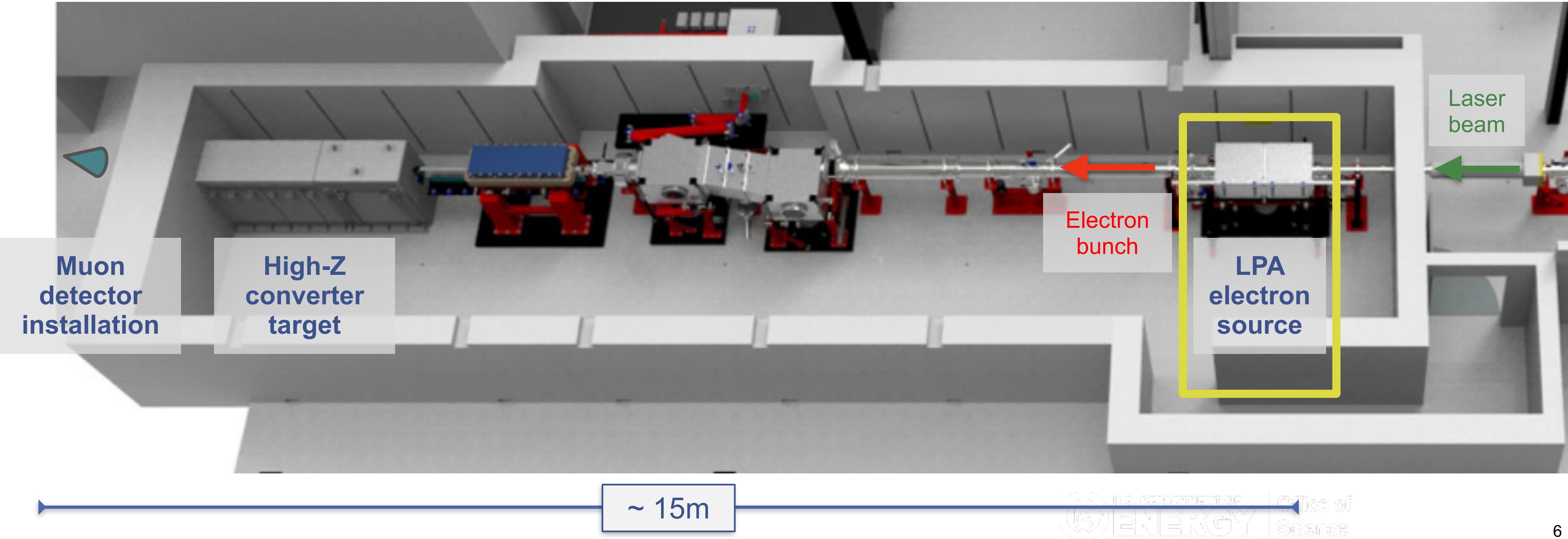
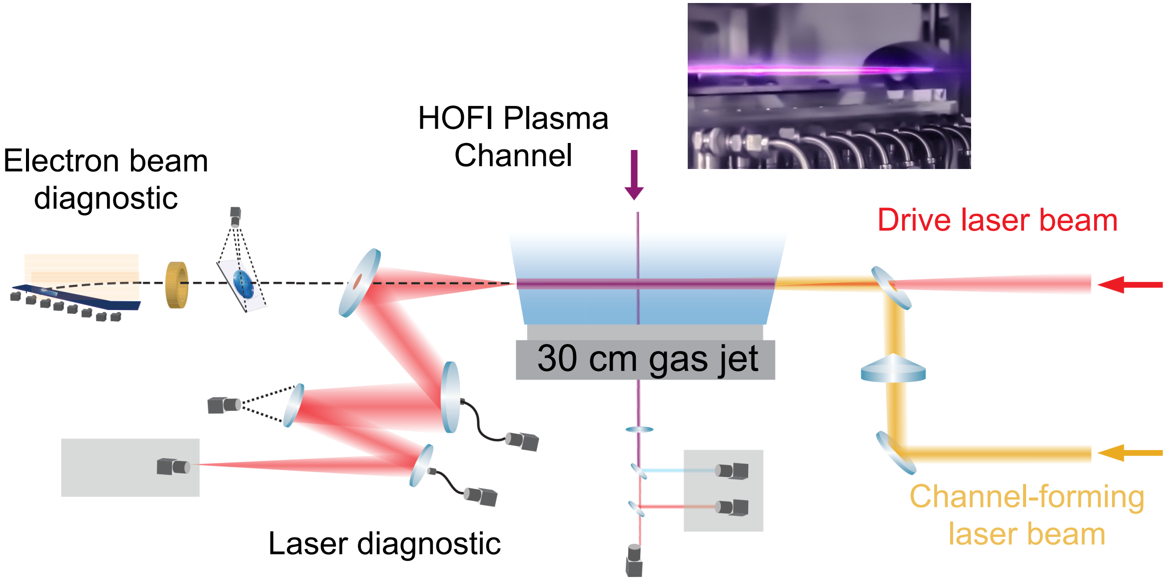
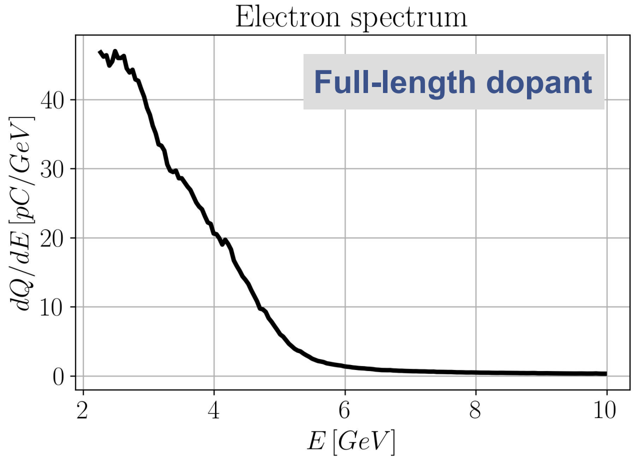


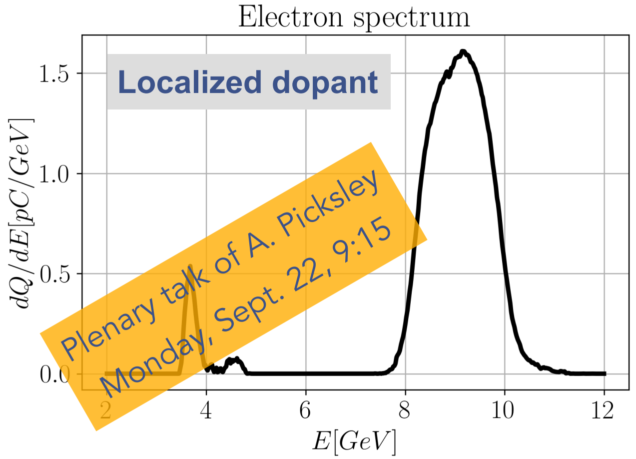
The Electron Source: Bella-PW Laser System

- Laser
  - Laser power: 500 TW
  - Laser energy on target: ~21J
  - a0: ~2.2
- Plasma source
  - 30 cm gas jet
  - All-optical HOFI channel for laser guiding
- Resulting electron bunches
  - Broad-band spectrum with energies up to 8 GeV
  - ~80 pC charge above 2 GeV
  - Femtosecond bunch duration



A. Picksley et al., Phys. Rev. Lett. ***133*** *(2024)*





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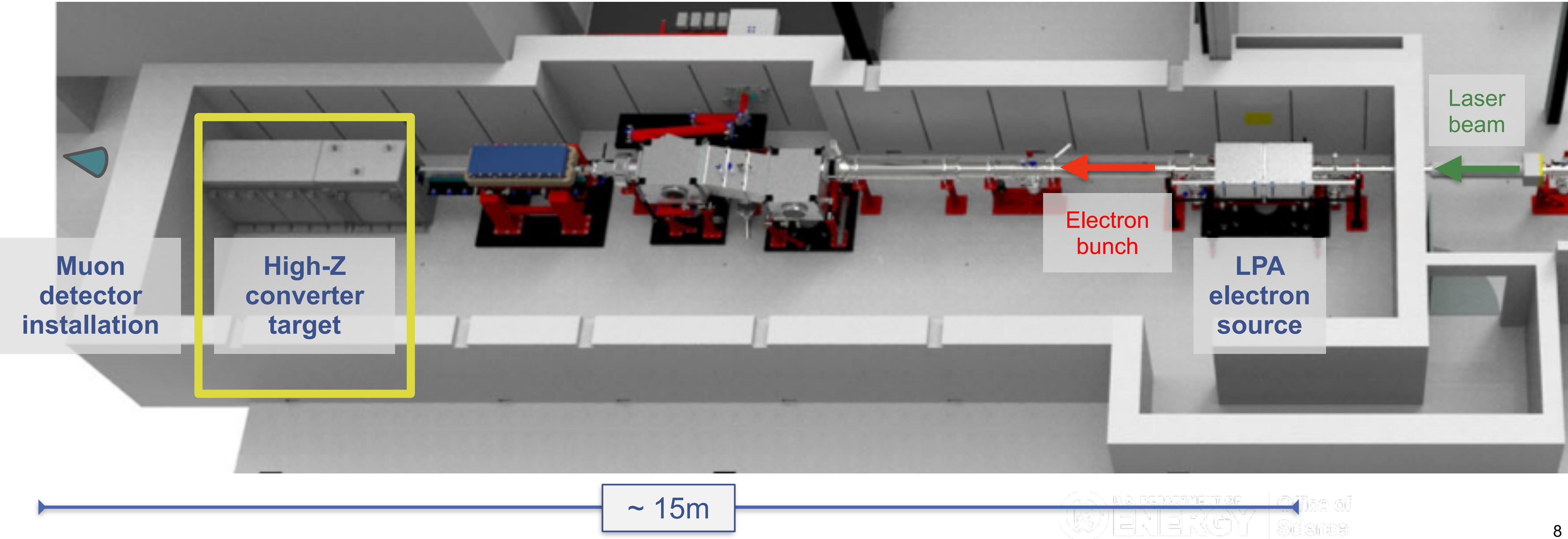
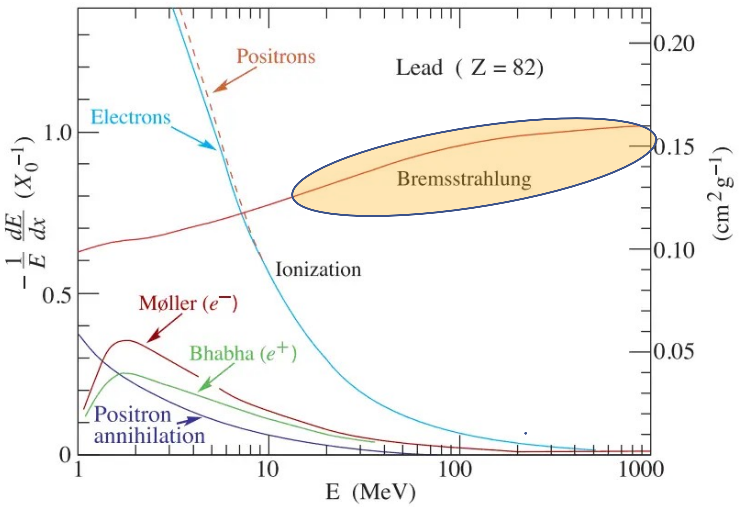


Primary Processes Of Electron-Matter Interaction In A Converter Target

1. GeV-level electrons primarily interact with matter via **Bremsstrahlung**



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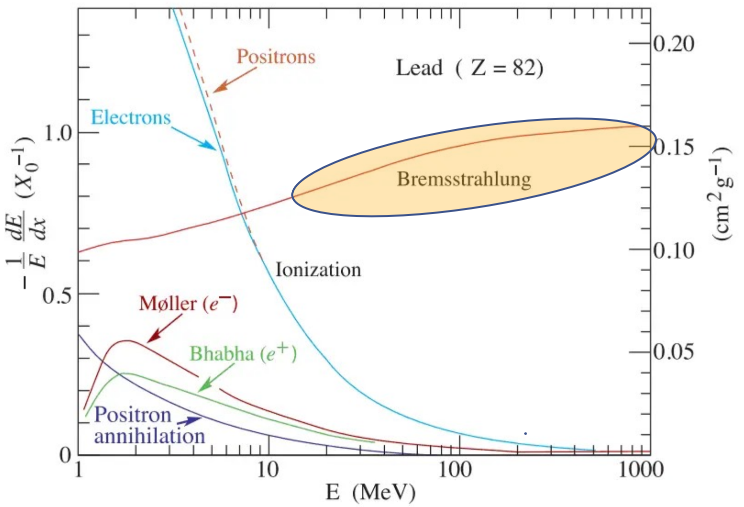
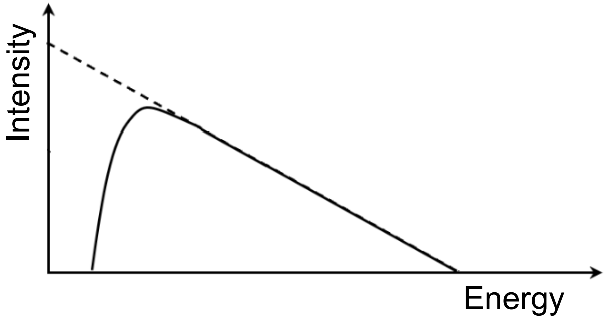


Characteristic Bremsstrahlung spectrum



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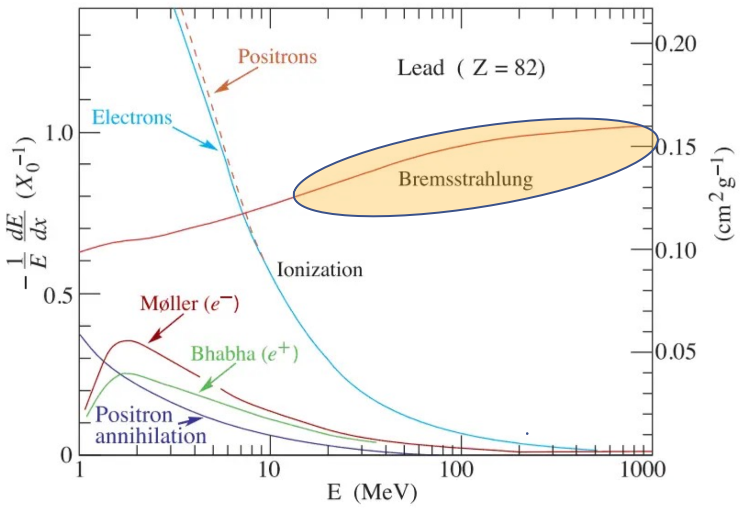

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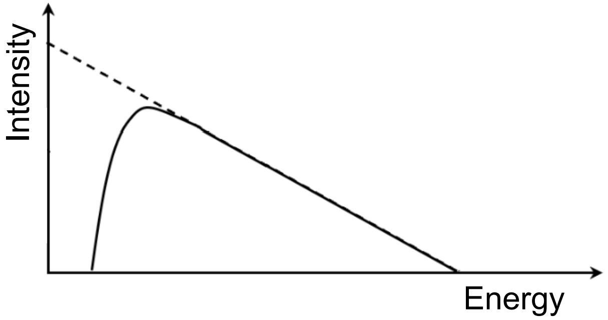
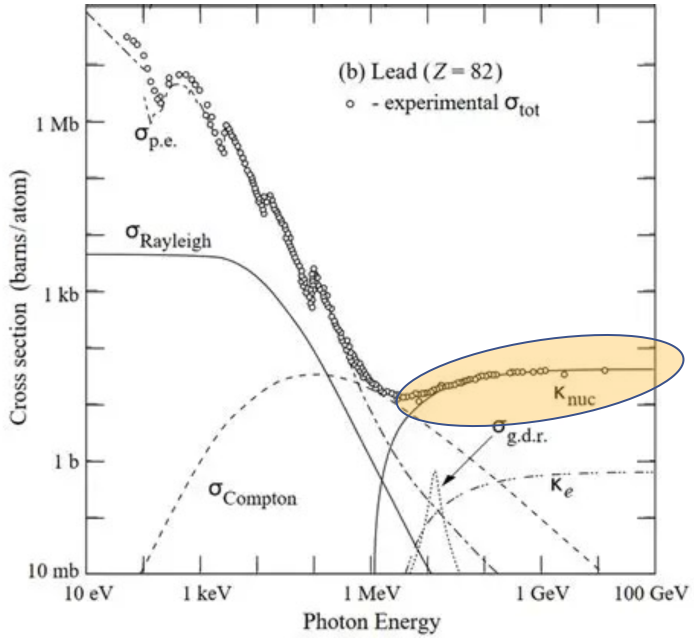
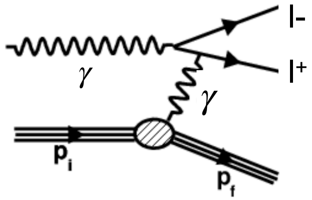


2. High-energy gammas primarily interact with material through **pair production**



Bethe-Heitler process:



Pairs are produced over a 1/γ (<< 0.1 rad) cone

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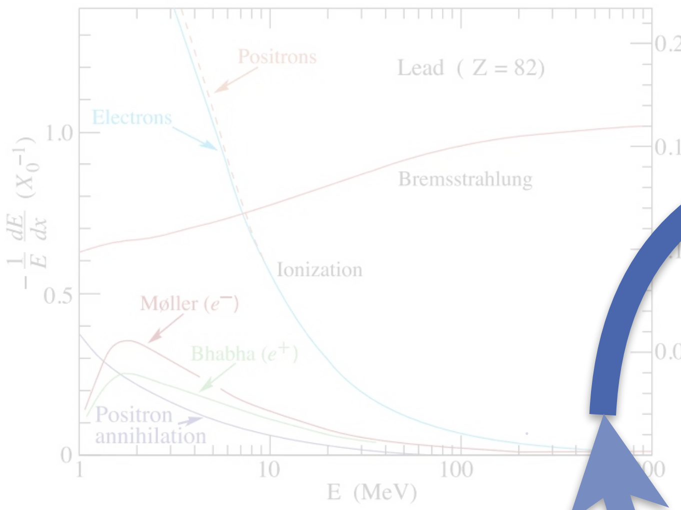

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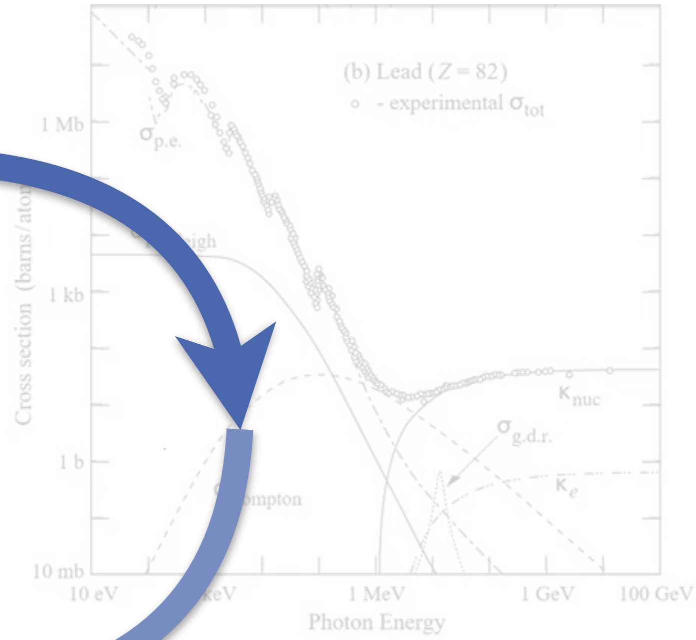

Bethe-Heitler process

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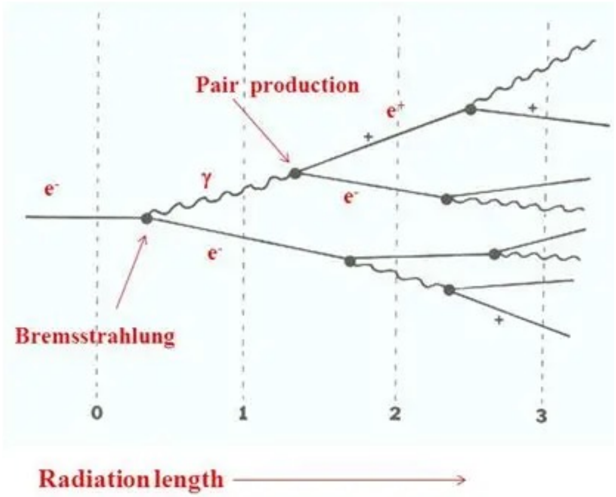
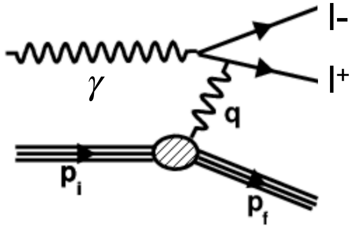
Electro-magnetic shower



Primary dynamics in target

Muon Production Channels In A Converter Target

Bethe-Heitler process



e^-/e^+

μ^-/μ^+

$E_\gamma \geq 2m_0c^2$

$\sigma_{BH} \propto 1/m_0^2$

Pair-production channel

> Muon production suppressed compared to electron-positron production by $R = m_e^2/m_\mu^2 = 2.34 \times 10^{-5}$

> Muon lifetime: $\tau_\mu = 2.2\,\mu s$

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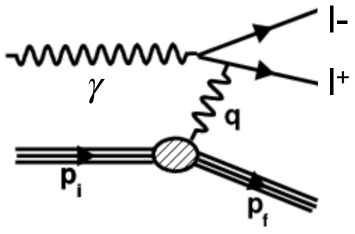

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Photoproduction of pions and their decay

$\gamma + p \rightarrow \pi^+ + n$

$\gamma + n \rightarrow \pi^- + p$

$\gamma + N \rightarrow \pi^+ + \pi^- + N$

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

Decay channel

> Pion lifetime: $\tau_\mu = 30\,ns$

> Isotropic muon production over 2π

F. Zang et al. Nature Physics 21, 1050–1056 (2025)

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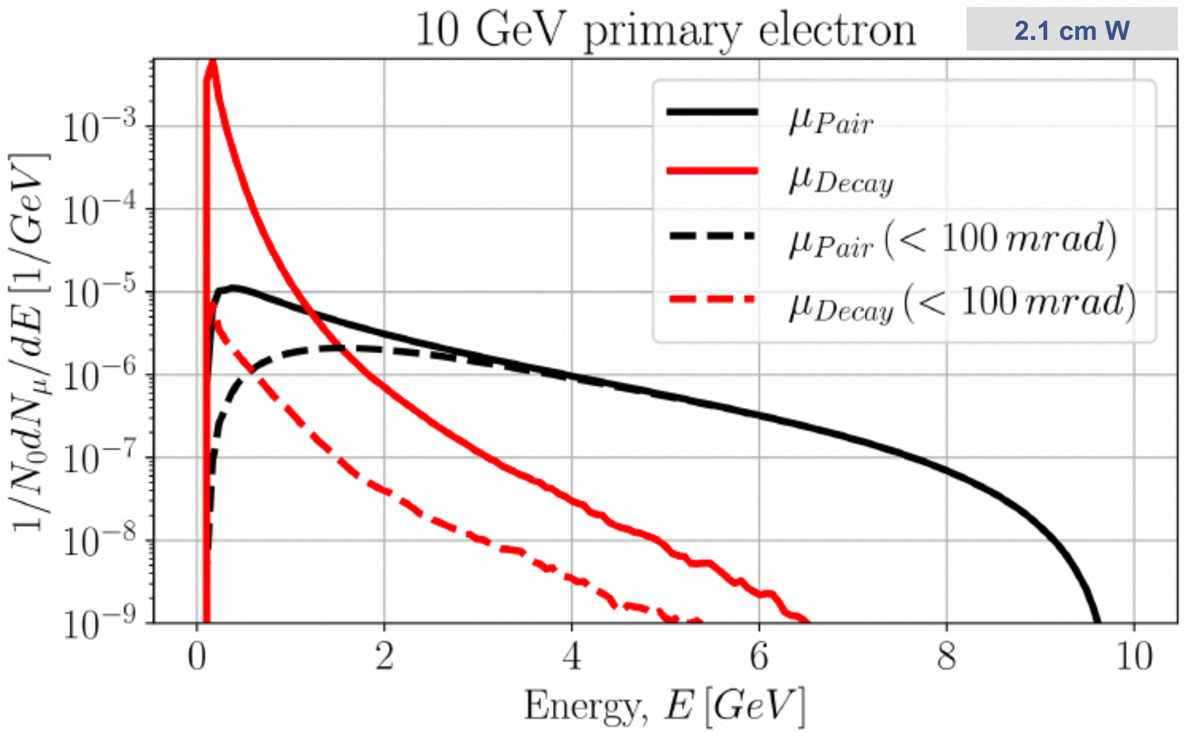
Muon Beam Energy Spectrum

Bethe-Heitler process

Pair-production channel



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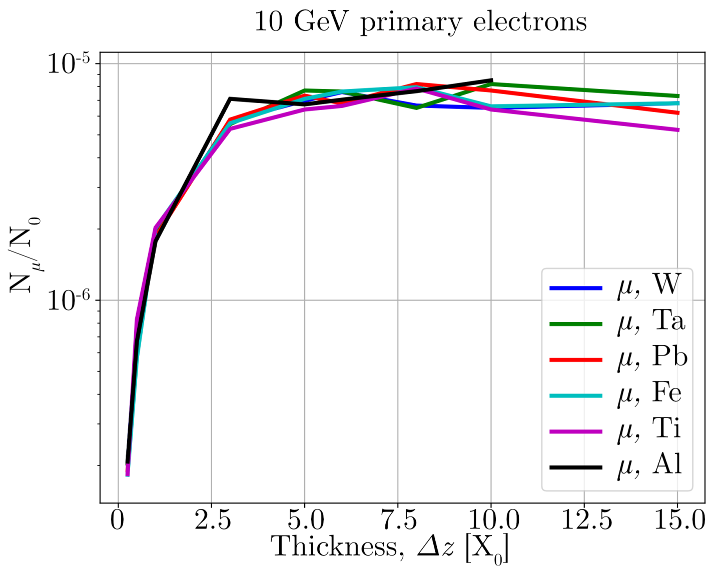
Muon Production With Target Length

Terzani et al., accepted in PRAB (arXiv:2411.02321v3)

Theoretical optimisation



- Optimal target thickness (10 GeV electrons): ~6-10 X_0
- Experimental configuration: 142 X_0

X0 (radiation length): Mean distance over which an electron loses all but 1/e of its energy by Bremsstrahlung

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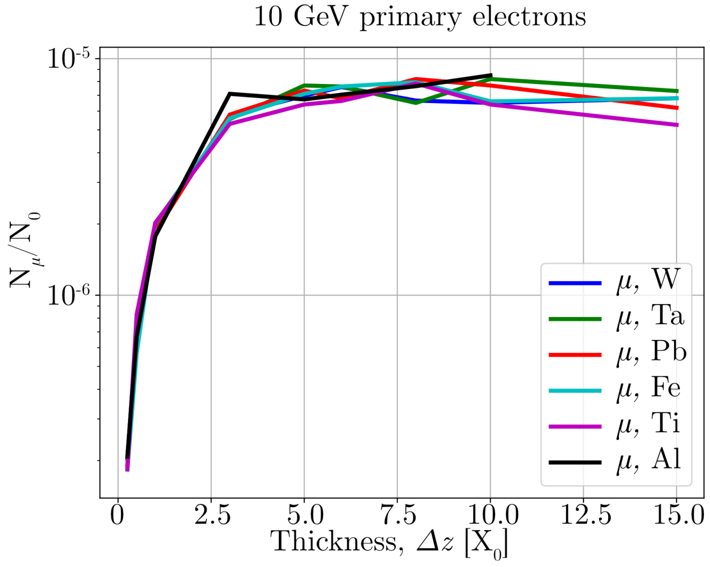
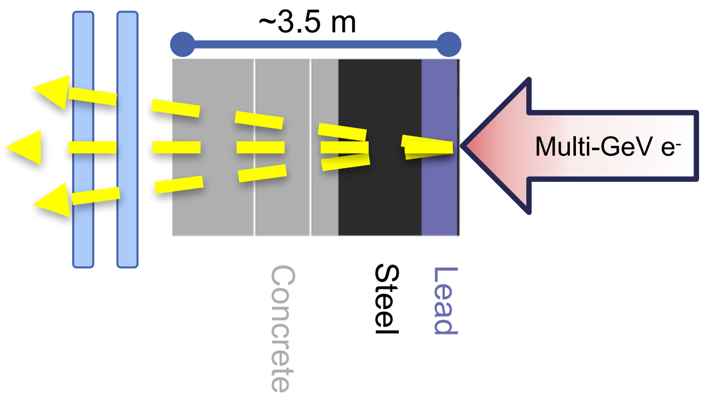


Experimental reality



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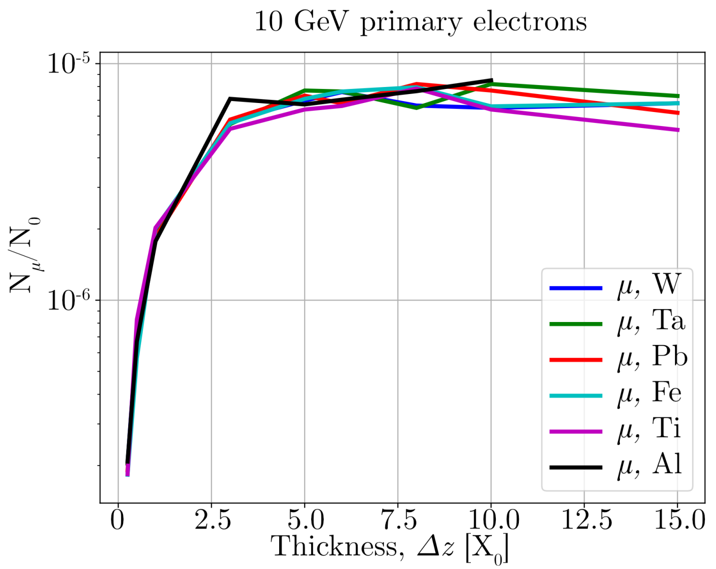

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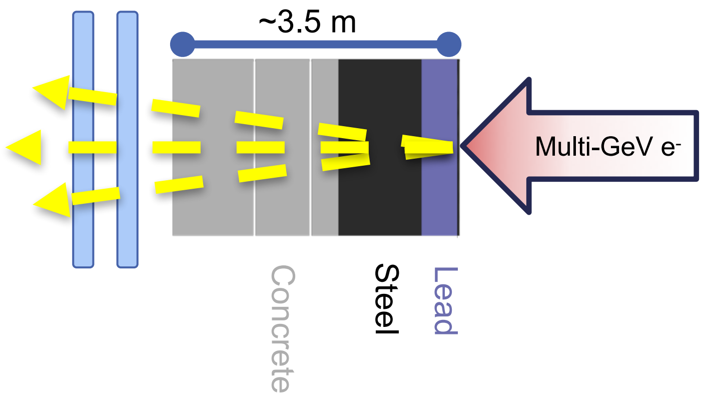
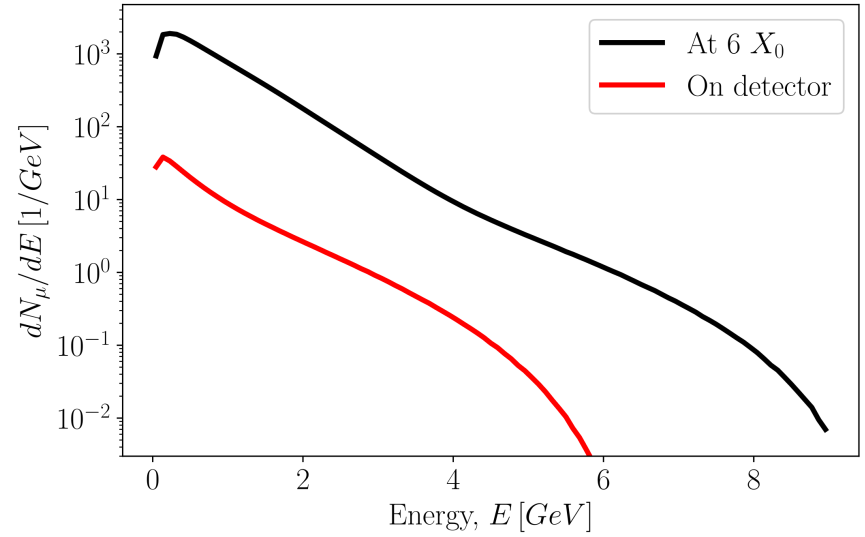


Expected muon production



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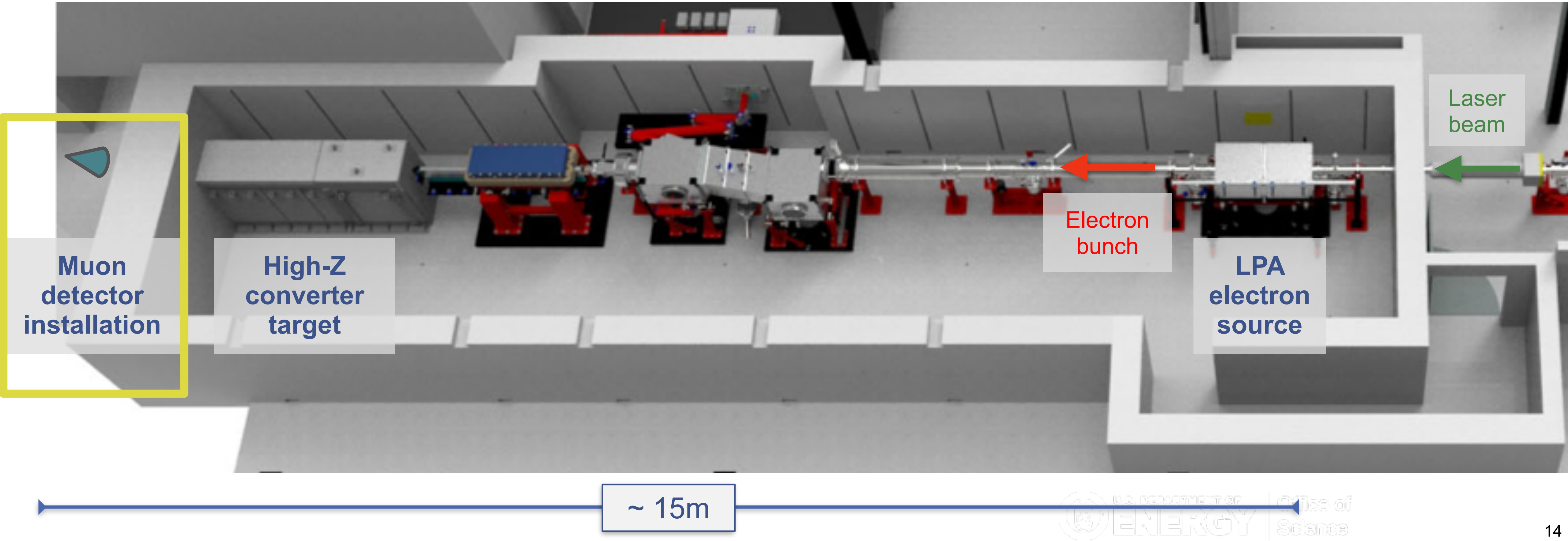
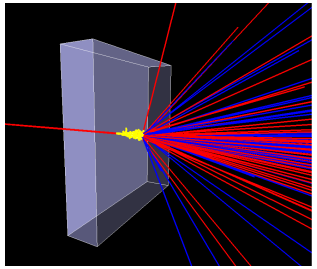


Muon Identification Principle

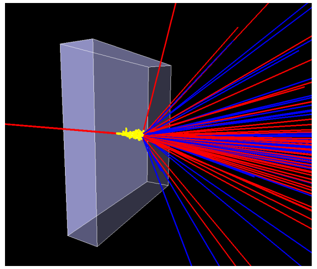


Event

Does the beam contains muons?

Is *this* particle a muon?

Muon Identification Principle



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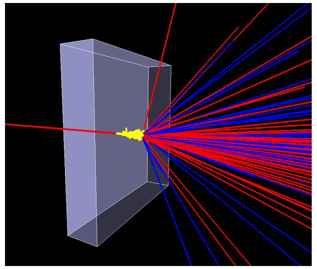

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Scintillator	Semiconductor	Gas chambers	Cherenkov

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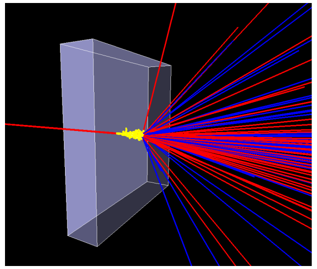

Event

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Work in progress

Particle features for identification:

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~2.2 μs

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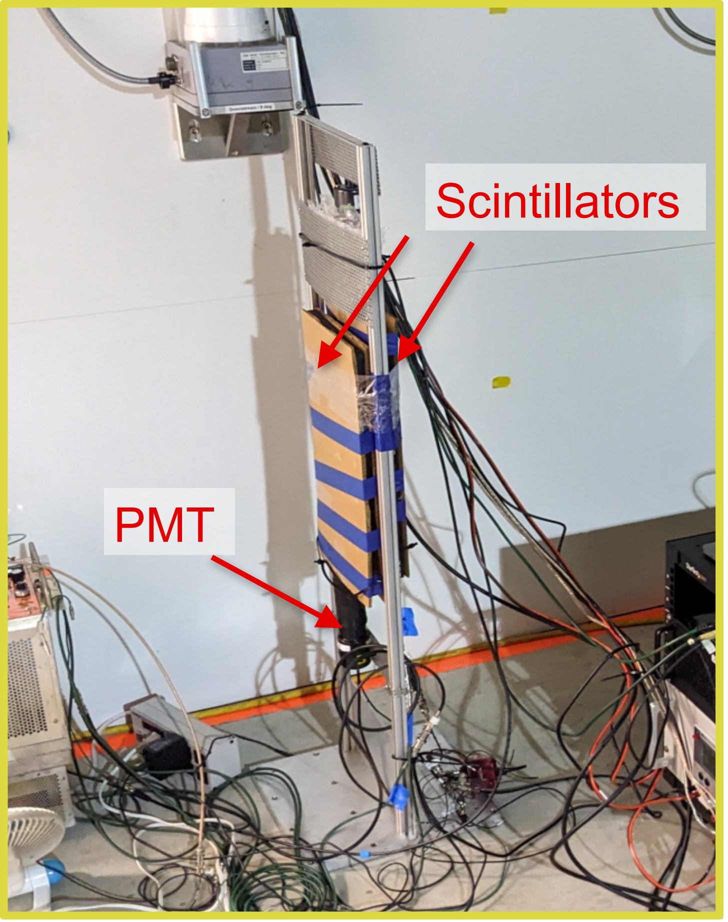
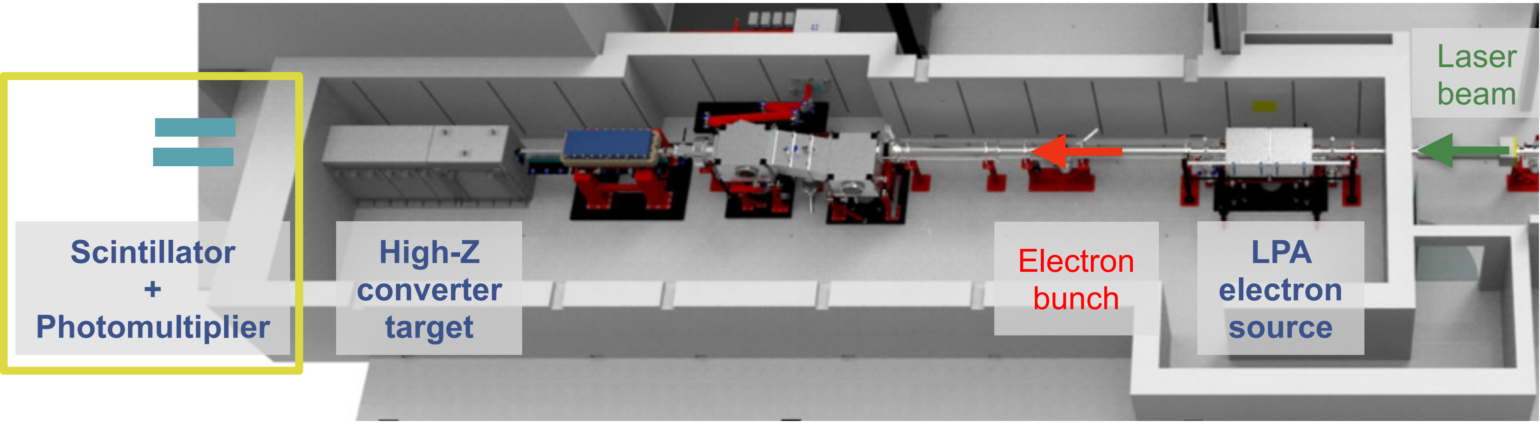
Muon Detection Scheme





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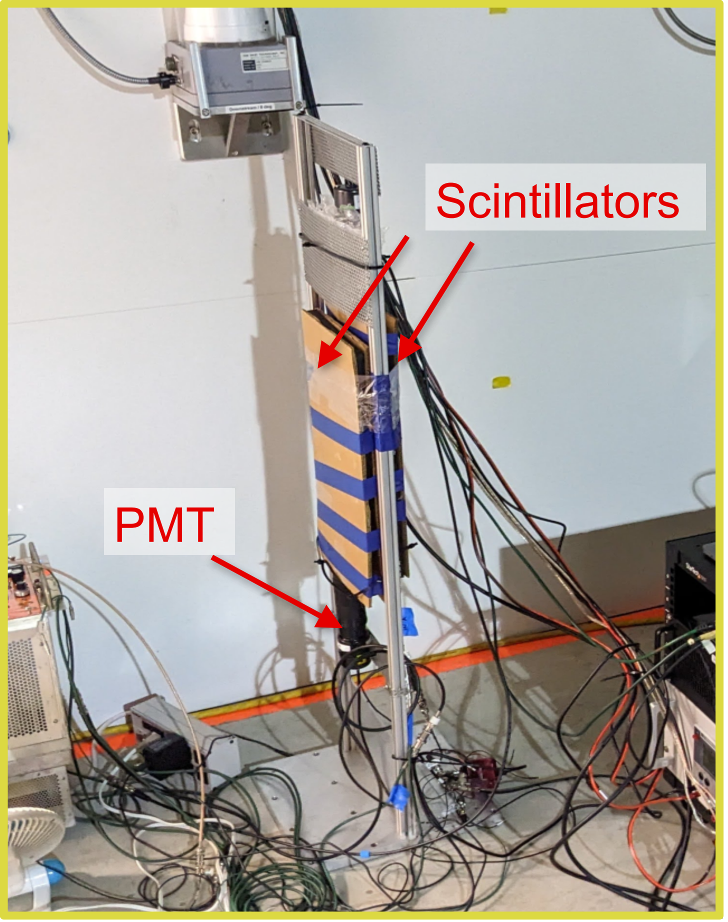
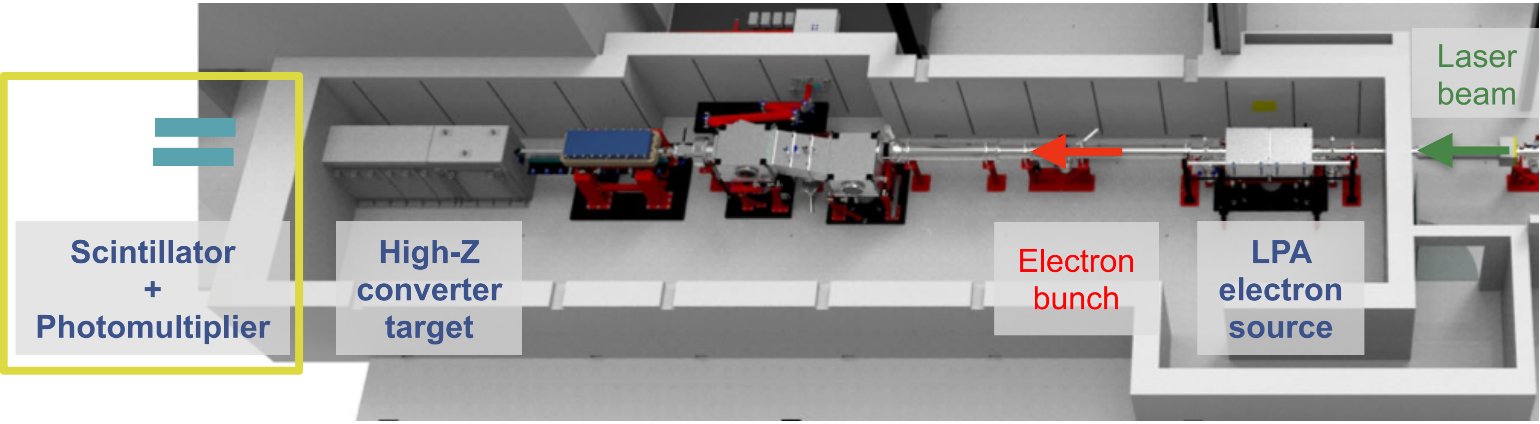




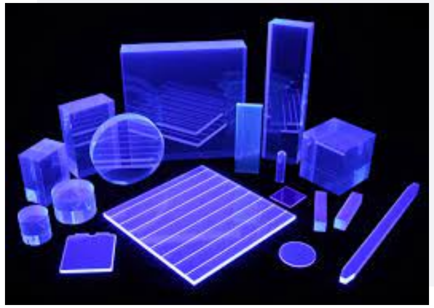
Scintillator

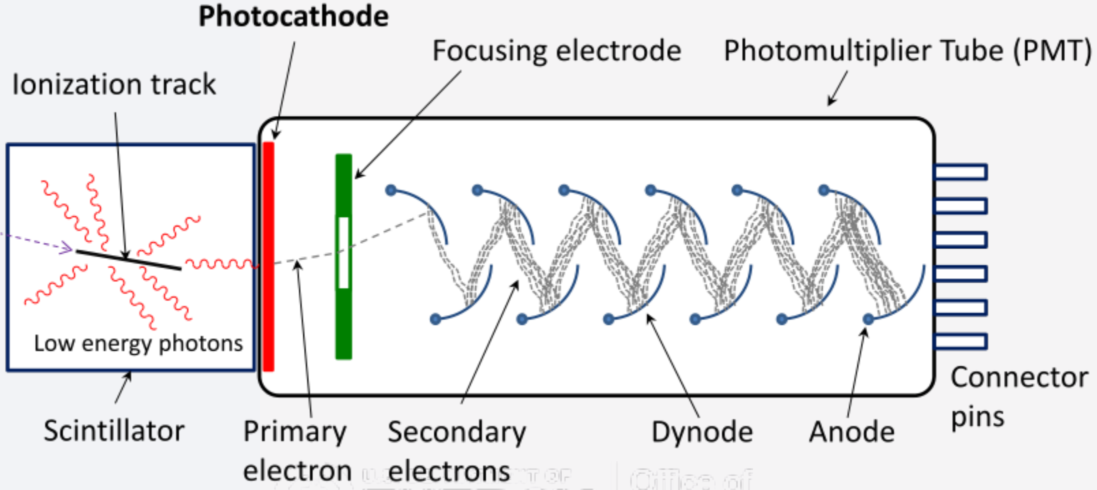
luminescence via

ionisation radiation

Photomultiplier

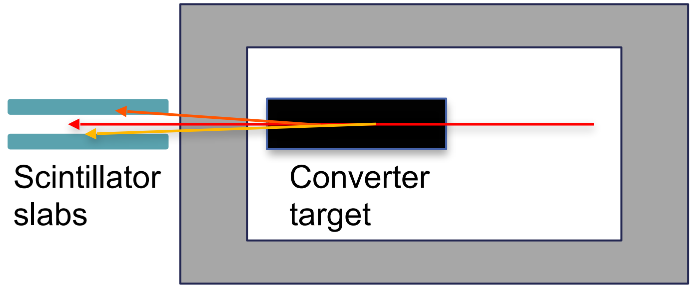
Photons are converted to an electronic signal





Detection Of Muon Production Using A Scintillators

1. Particles generated in the converter target, a fs-duration particle (γ, e+, μ-, μ+ etc.) cloud, hits the scintillators



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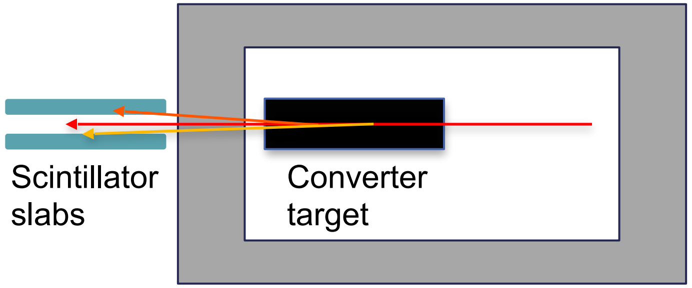
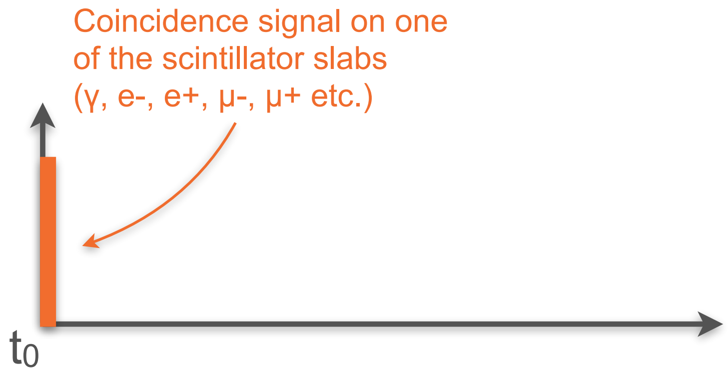
2. Coinciding signals on both scintillator slabs self-trigger the detection, determining t_0 and opening the gate for later signals
    a. Scintillator decay time: ~100 ns
    b. Gating time: 50 μs





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    a. Scintillator decay time: ~100 ns
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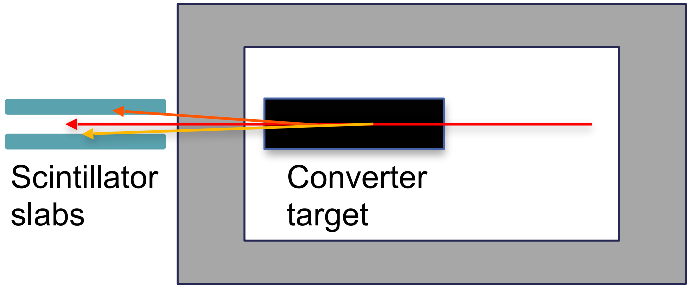
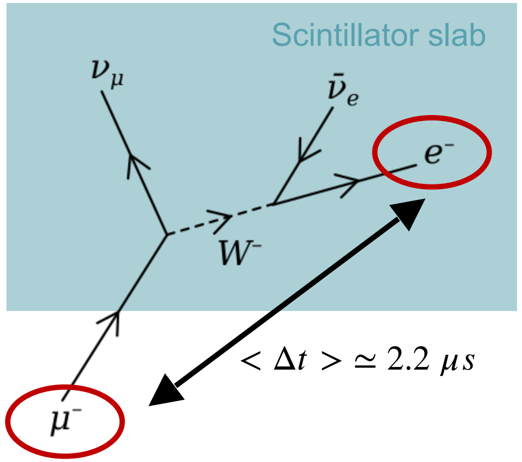
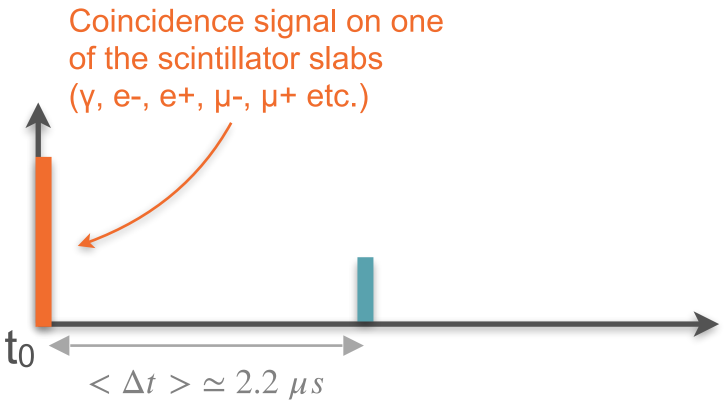
3. A **low-energy muon** that hits and **decays within the scintillator** produces a signal via the generated electron with a delay equal to the muon lifetime.







Note: only the low-energy part of the energy spectrum of produced muons is actually detected.

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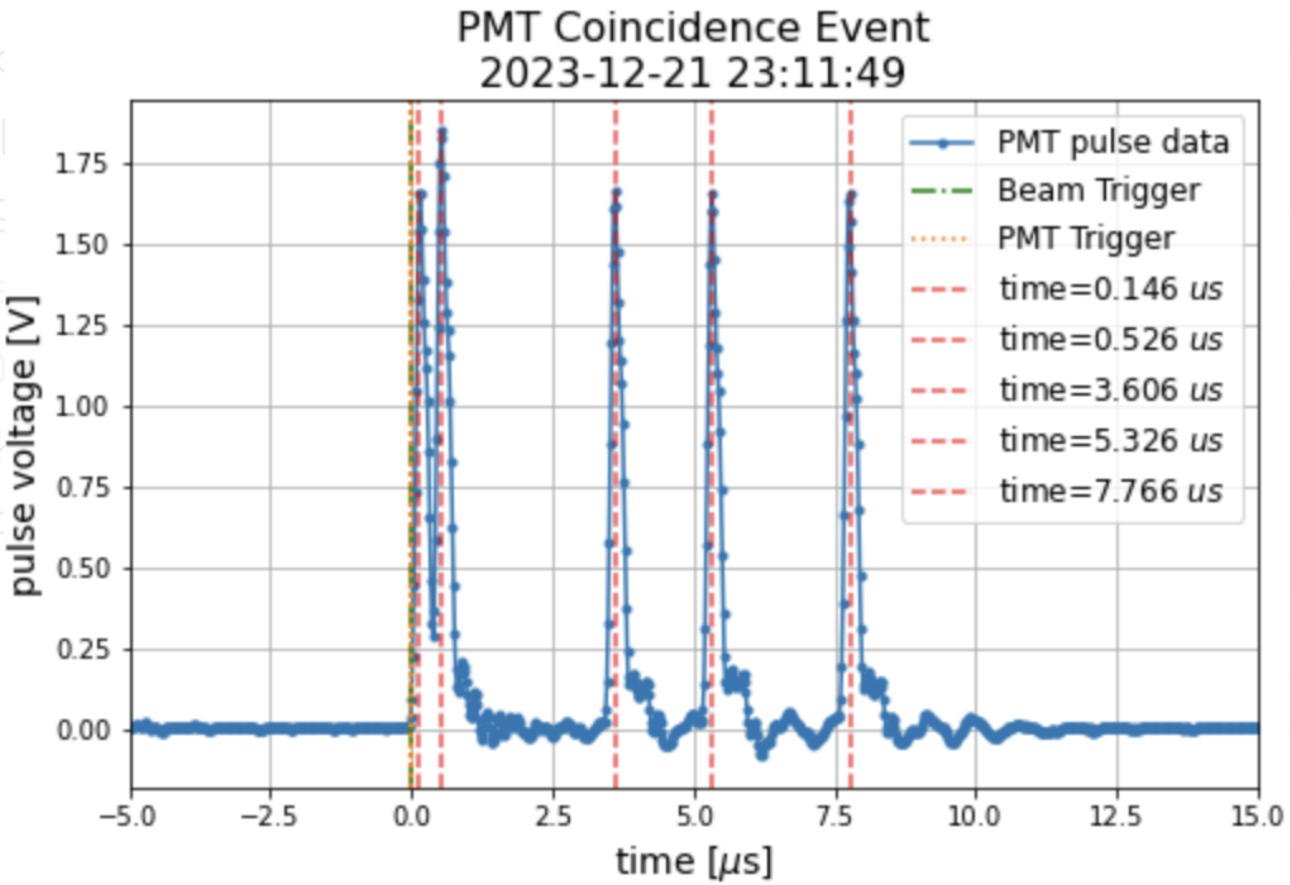
   produces a signal via t
   the muon lifetime.



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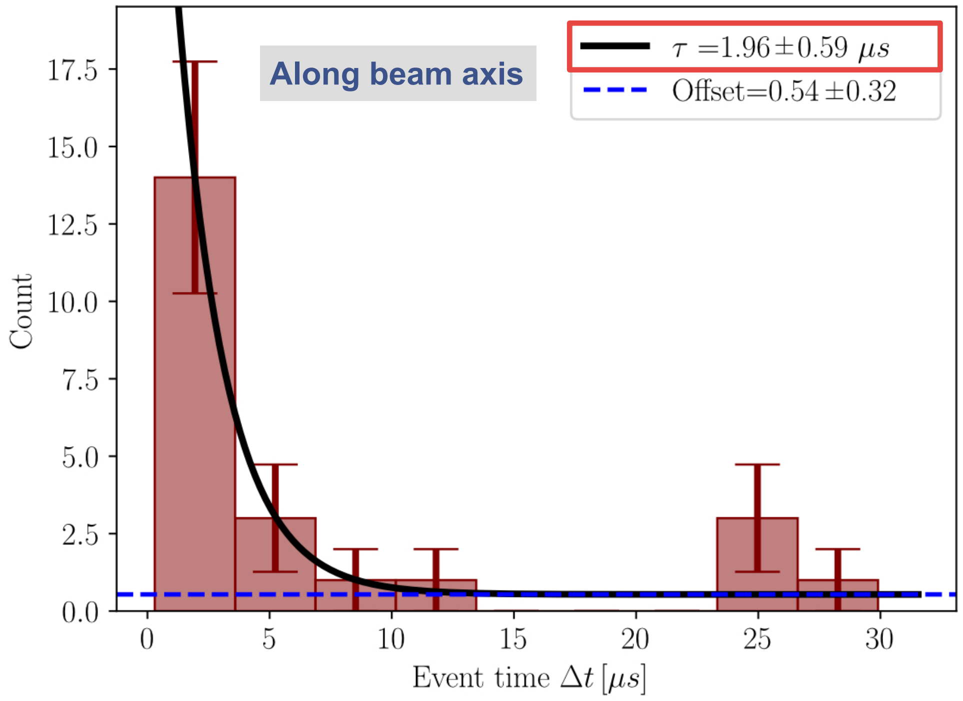
Signal Counts

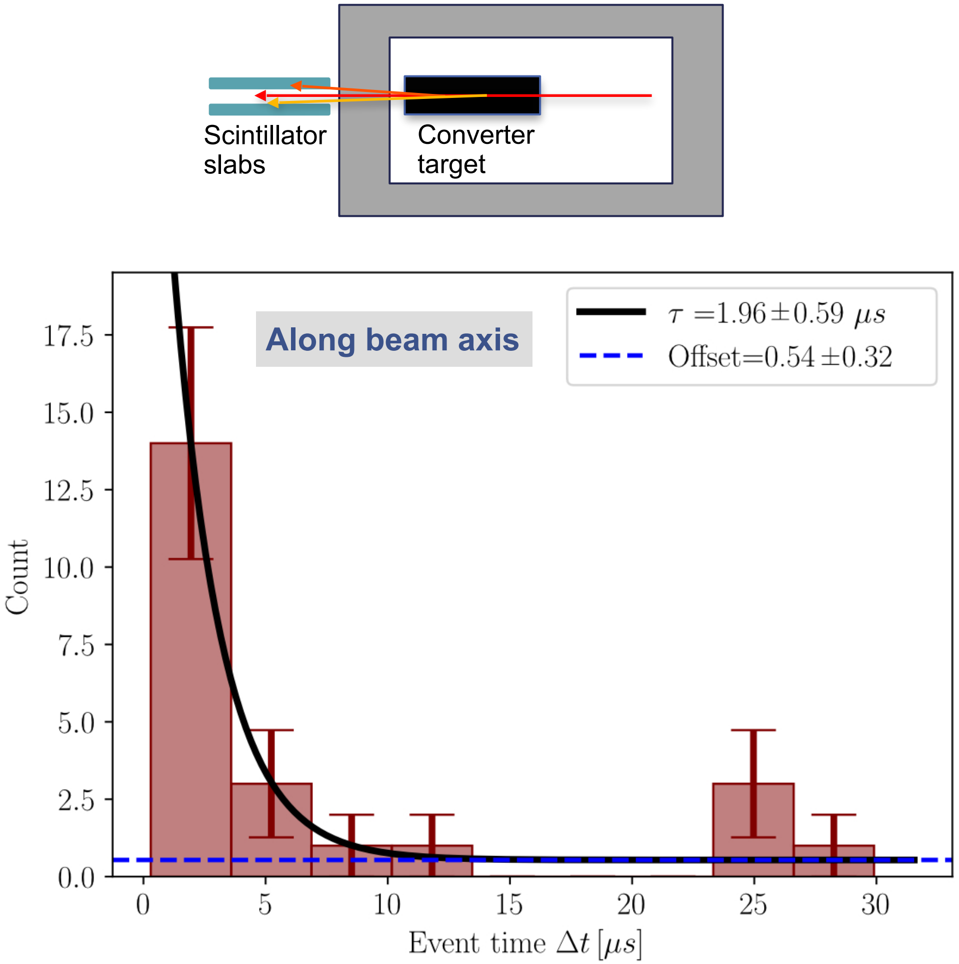
Terzani et al., accepted in PRAB (arXiv:2411.02321v3)

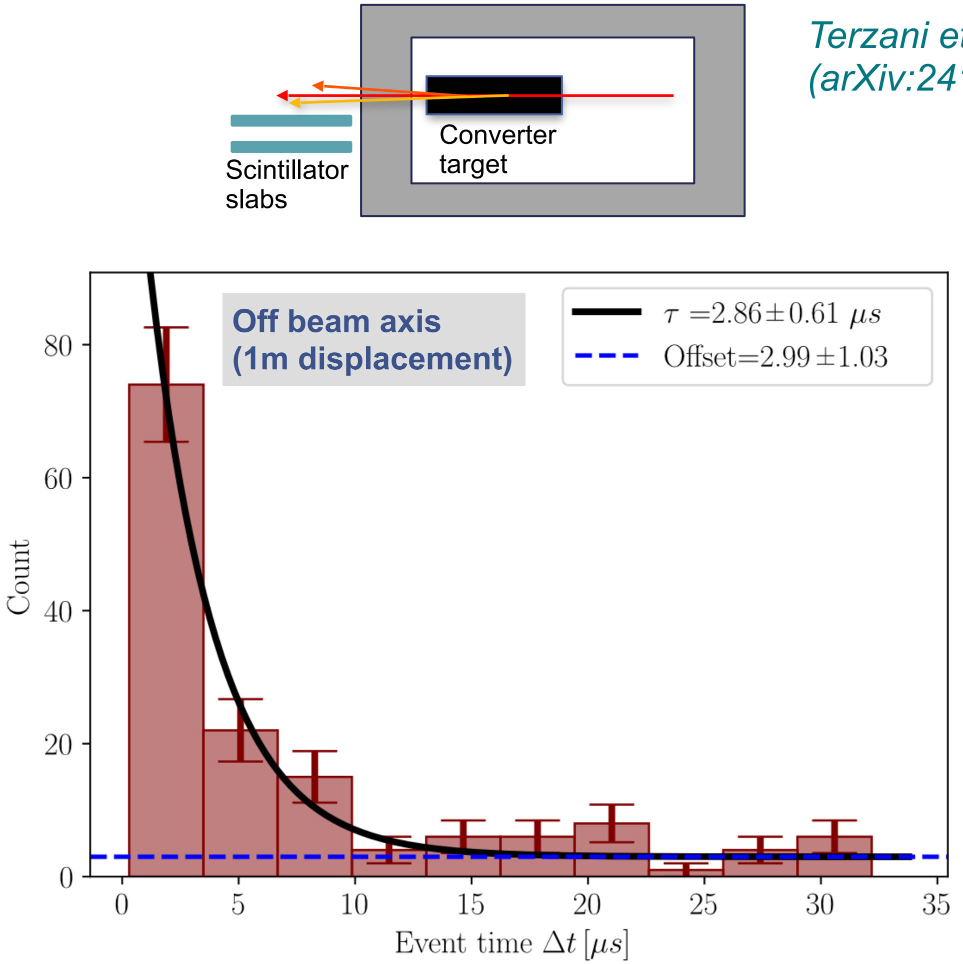


Muon lifetime: 2.2 μs

Displaced Scintillators Also Provide Evidence For Muon Production

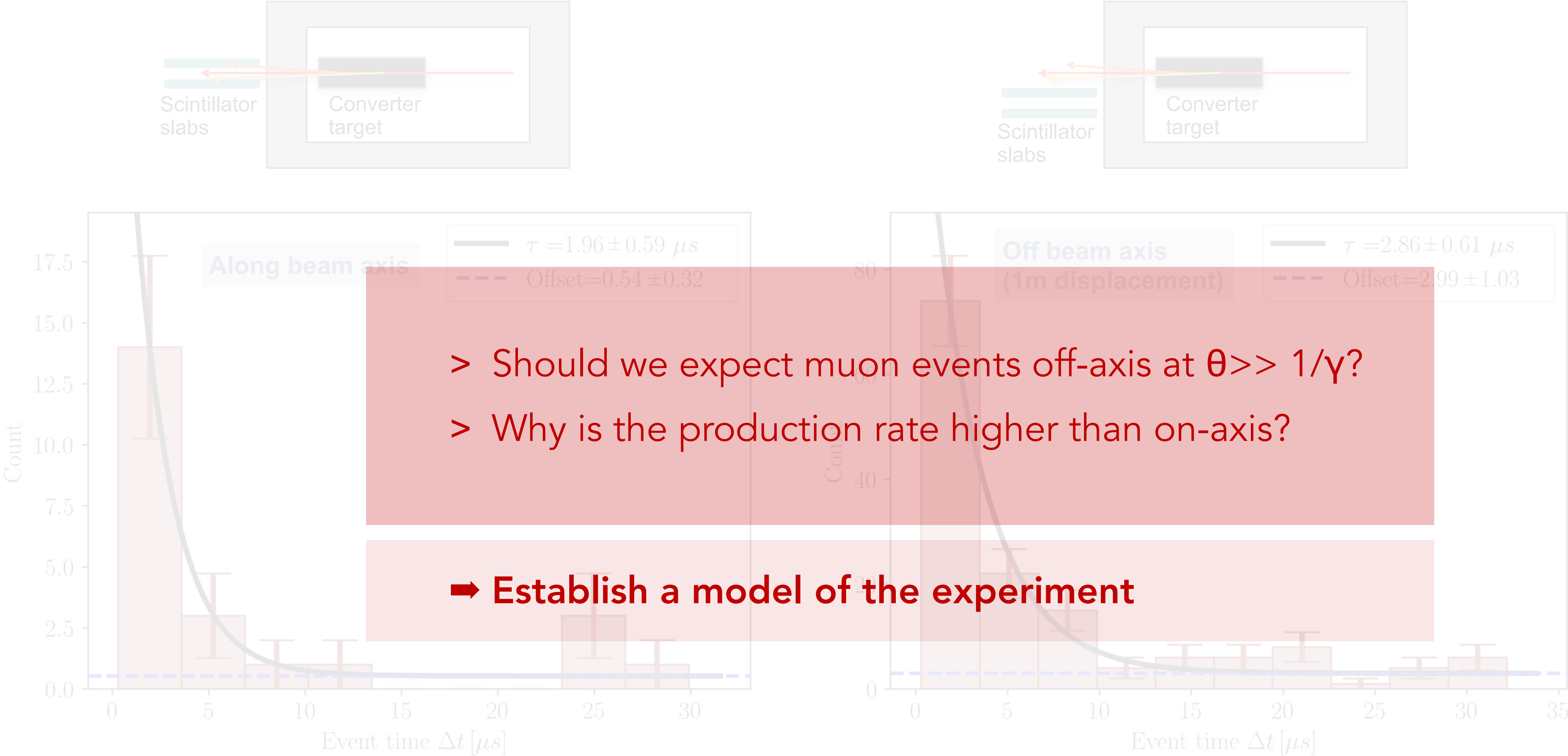
Terzani et al., accepted in PRAB (arXiv:2411.02321v3)





Both Off-axis and On-axis scintillator slab pairs measure muons, but the Off-axis assembly records more events.

Displaced Scintillators Also Provide Evidence For Muon Production



> Should we expect muon events off-axis at $\theta >> 1/\gamma$?

> Why is the production rate higher than on-axis?

➡ **Establish a model of the experiment**

Both Off-axis and On-axis scintillator slab pairs measure muons, but the Off-axis assembly records more events

Simulation Setup

Terzani et al., accepted in PRAB (arXiv:2411.02321v3)

Beam

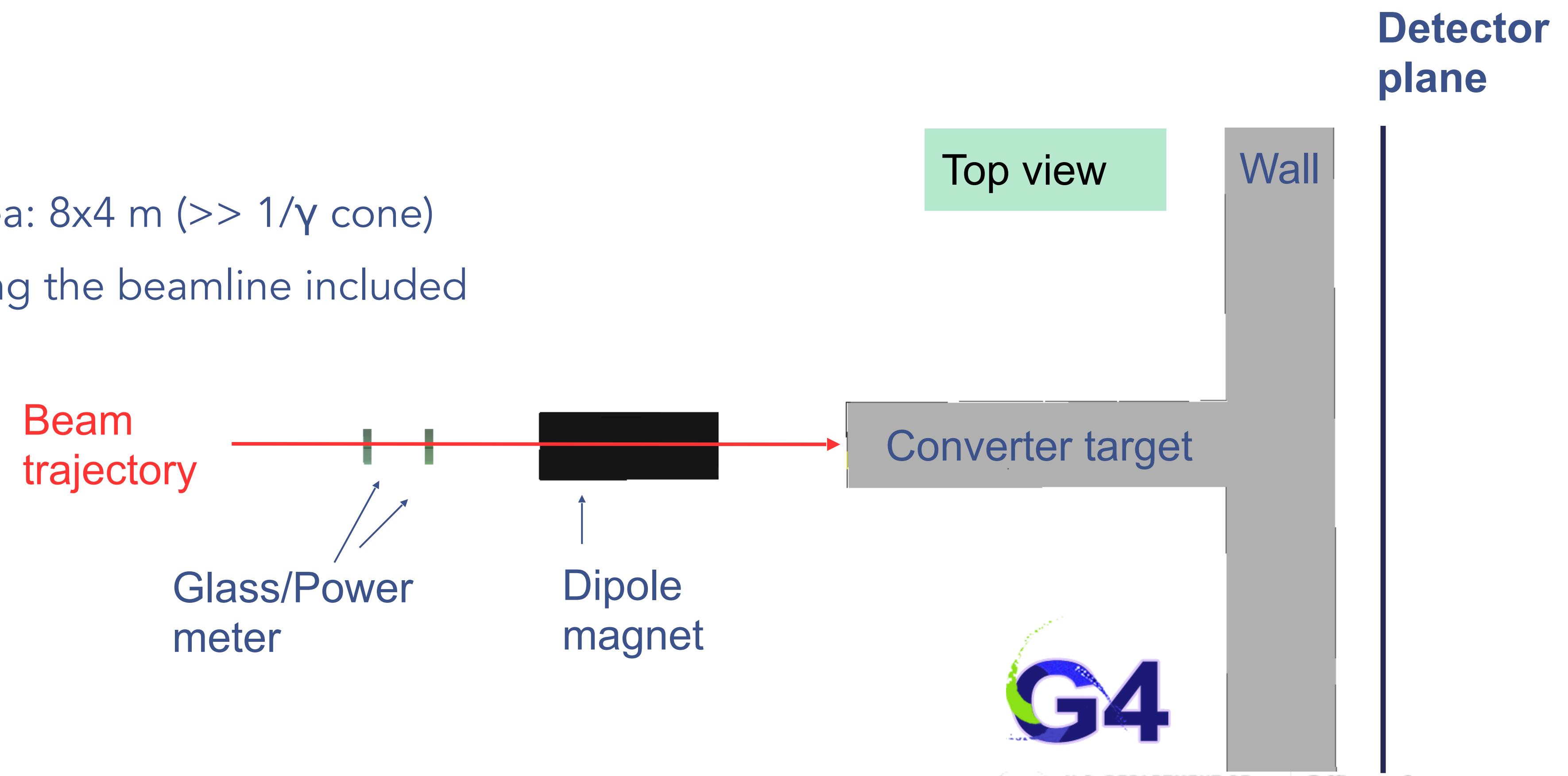
> Experimentally determined energy spectrum

> Divergence: 0.1mrad

Detection

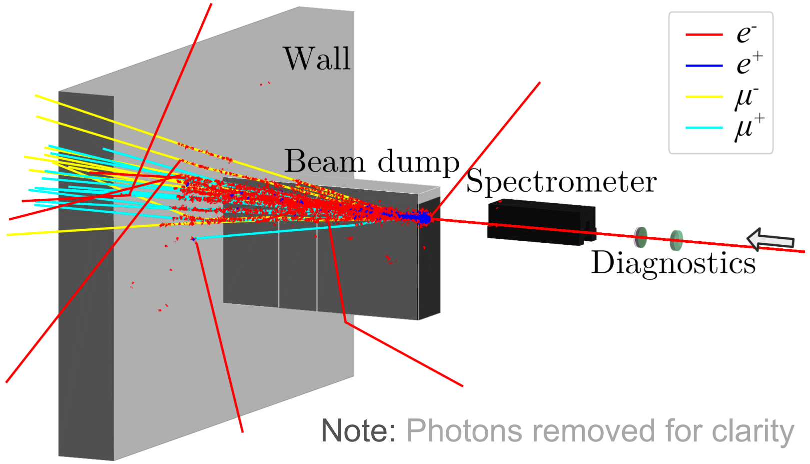
> Particle detection area: 8x4 m (>> 1/γ cone)

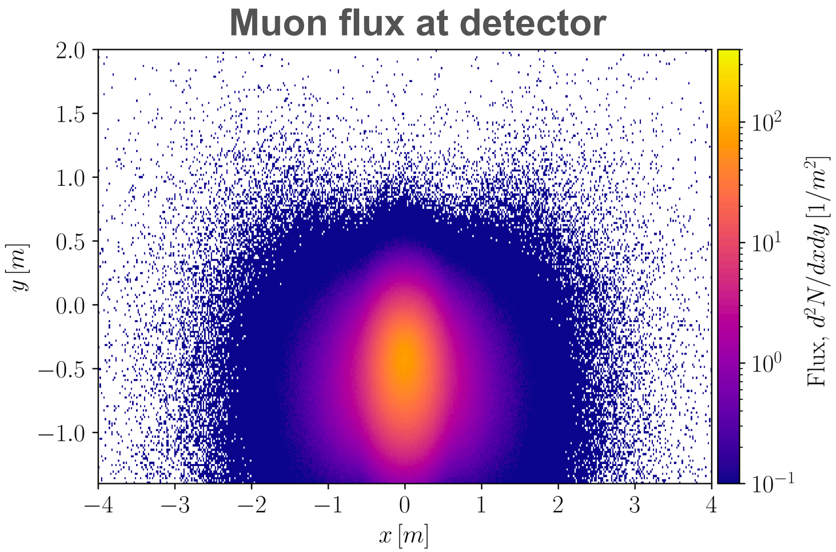
> High-Z elements along the beamline included



Muon Production At BELLA — A Numeric Insight

Terzani et al., accepted in PRAB (arXiv:2411.02321v3)





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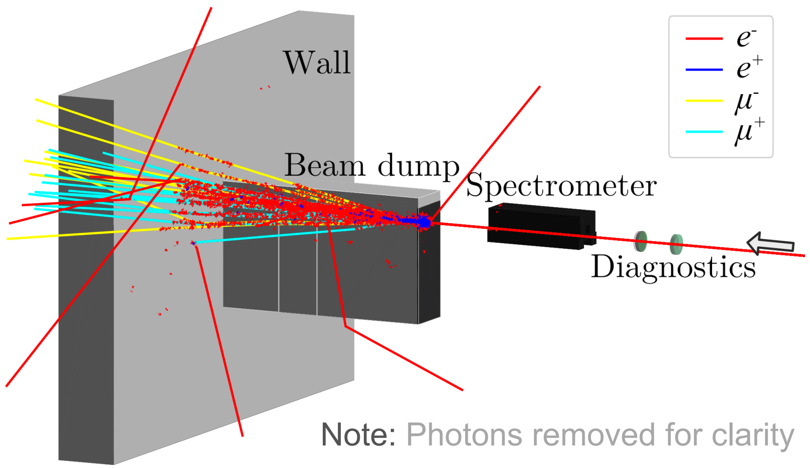
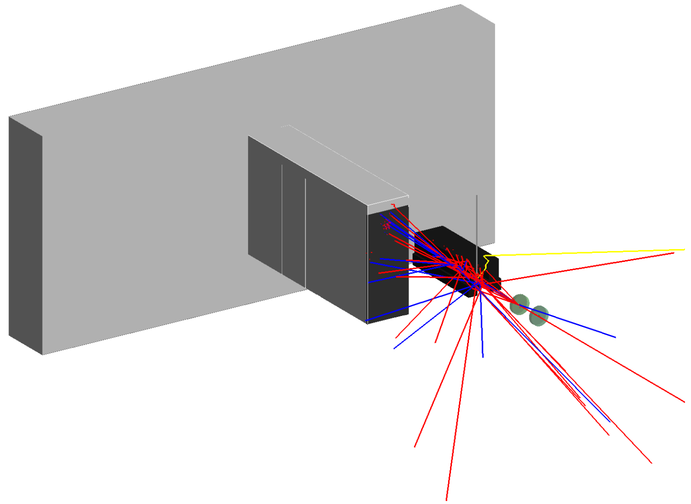
Terzani et al., accepted in PRAB (arXiv:2411.02321v3)

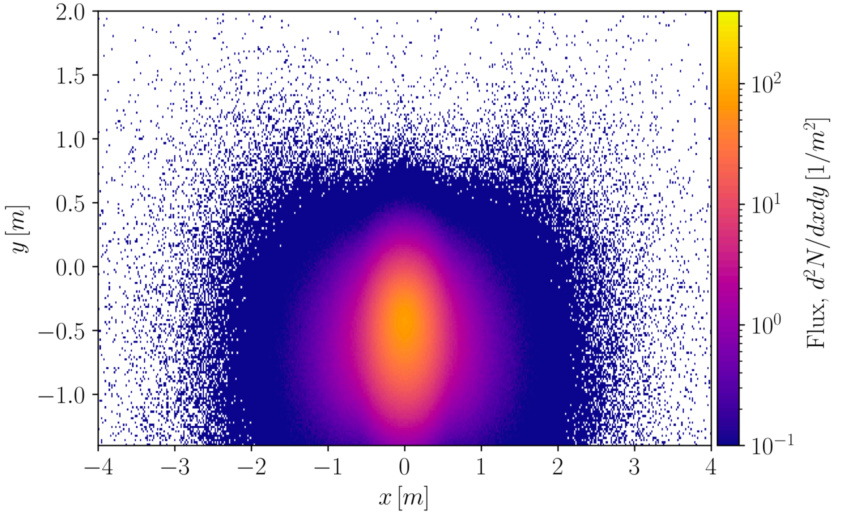
Perfect beam alignment



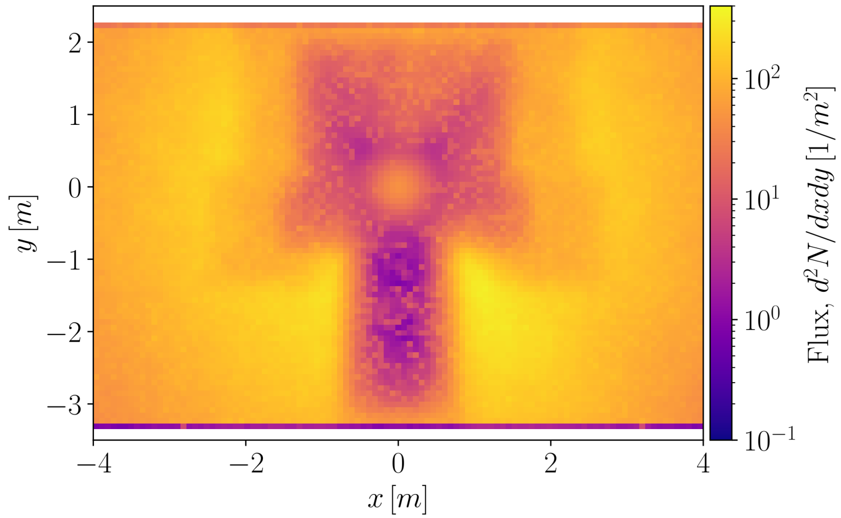
Beam pointing: 1.5 mrad



Muon flux at detector



Muon flux at detector



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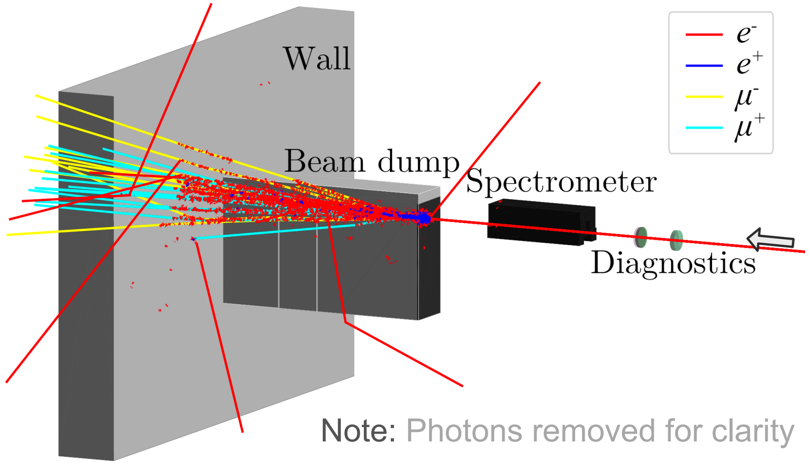
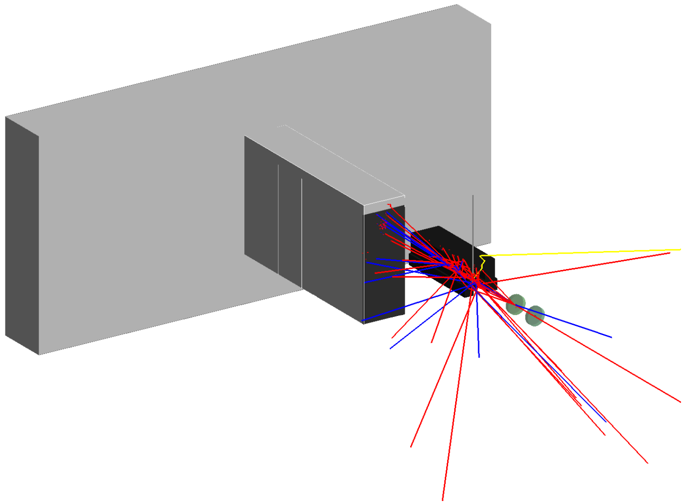
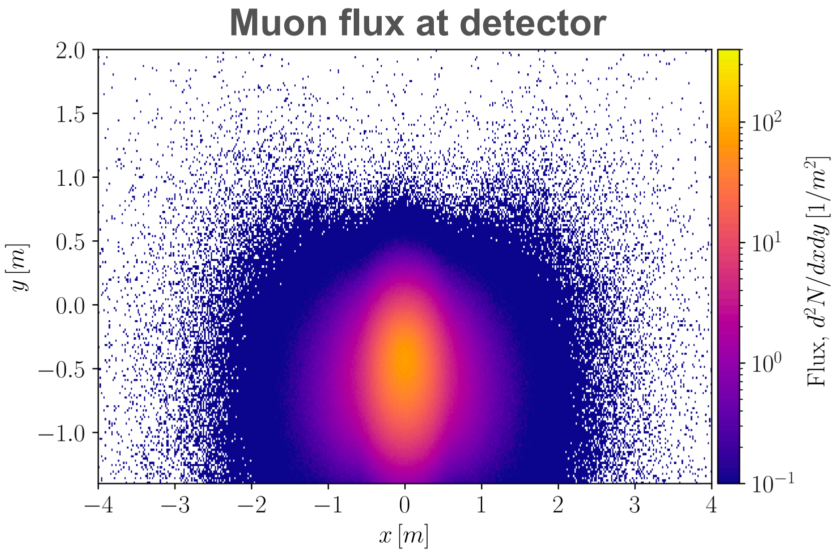
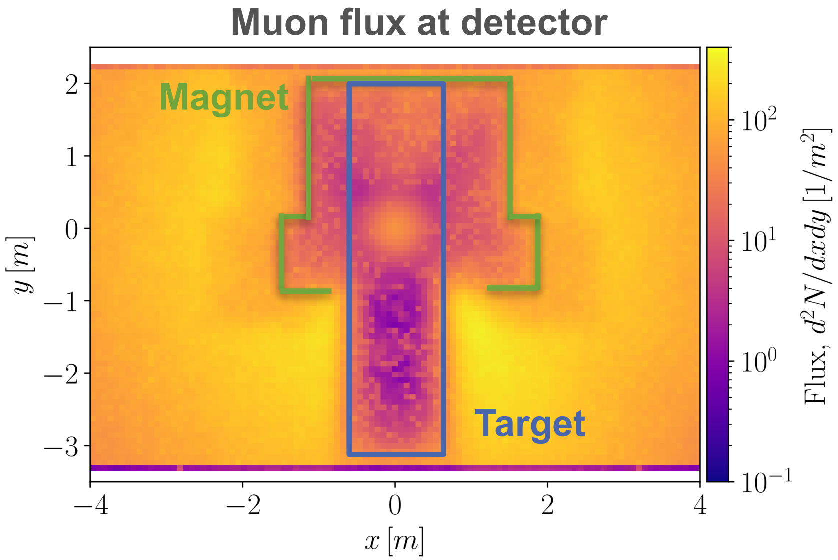


Beam pointing: 1.5 mrad

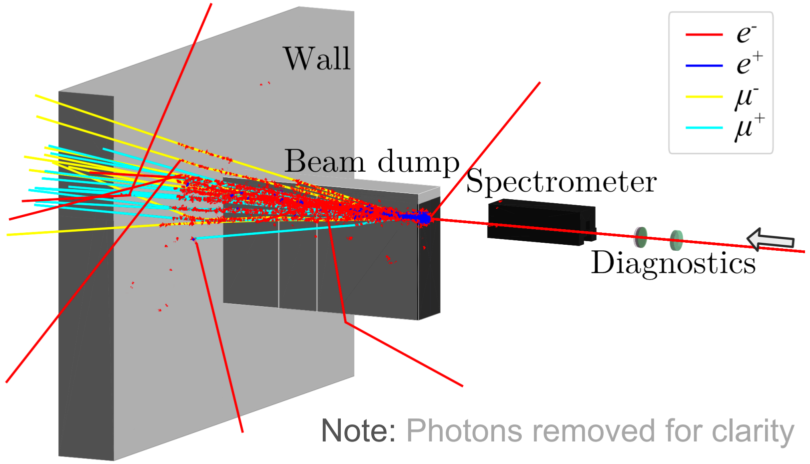




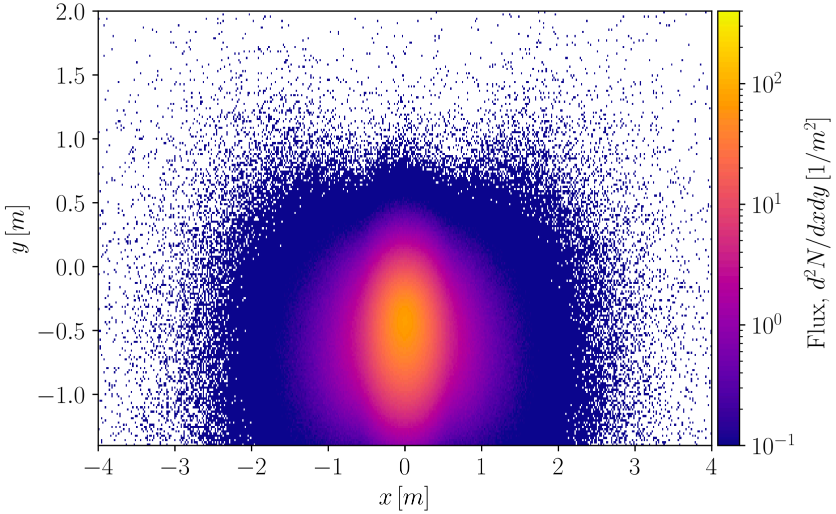


Muon Production At BELLA — A Numeric Insight

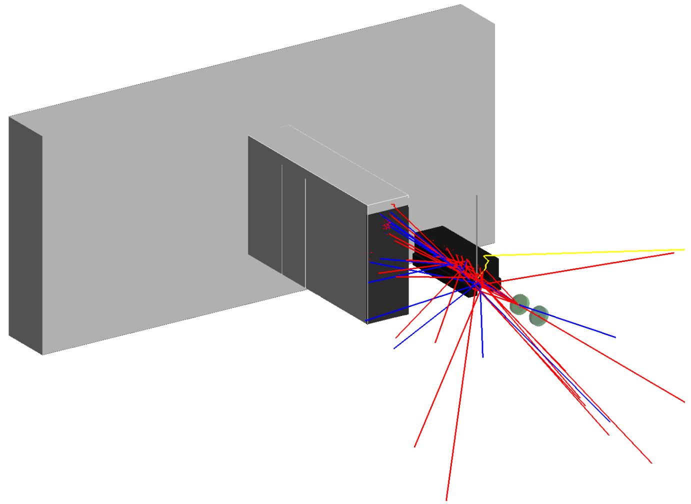
Perfect beam alignment



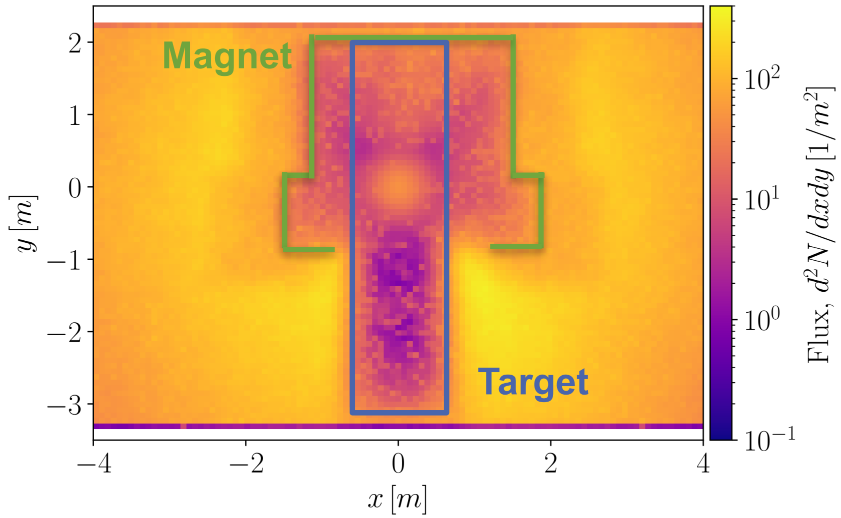
Muon flux at detector



Beam pointing: 1.5 mrad



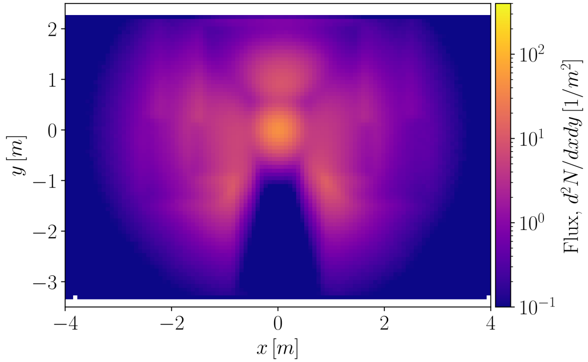
Muon flux at detector



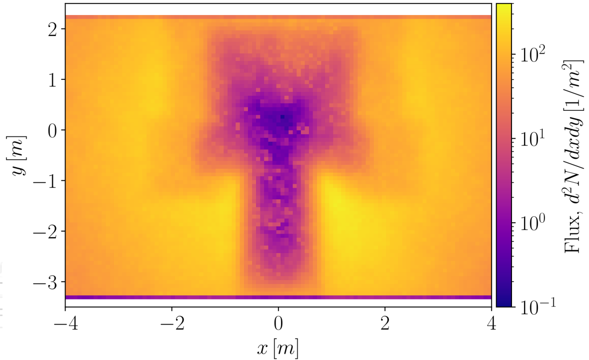
Terzani et al., accepted in PRAB (arXiv:2411.02321v3)

- Off-axis muons are predominantly produced through pion decay after the electron beam hitting upstream beamline components
- The long converter target naturally filters isotropic low-quality muons.

Pair production



Pion decay

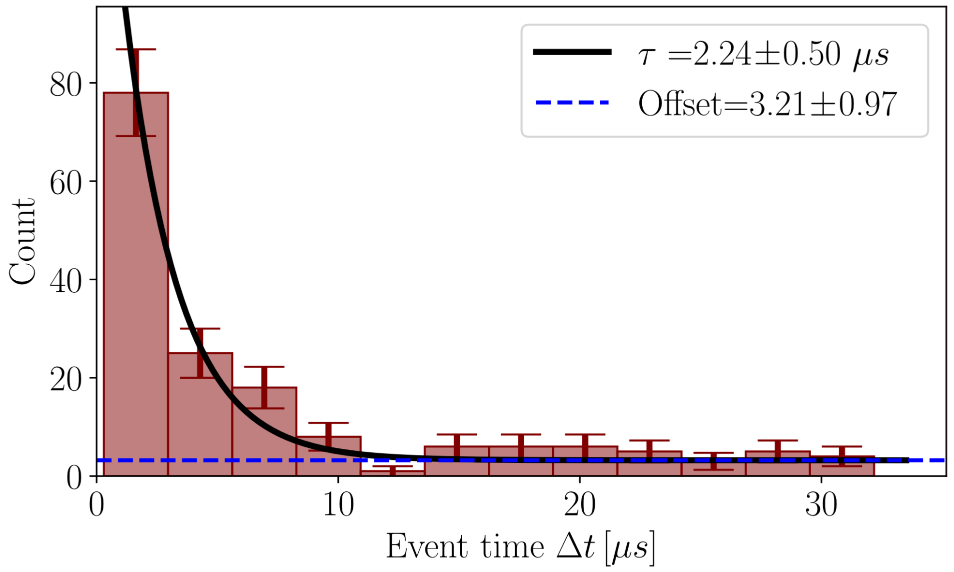


Summary And Outlook

Terzani et al., accepted in PRAB (arXiv:2411.02321v3)

Summary

- Multi-GeV-class directional muon beams produced in a high-Z material converter target
- Pairs of scintillators unambiguously detect muons in correspondence to the beam passage
- Numerical analysis confirms the experimental results
- Two muon production mechanisms distinguished by emission angles and typical energies



261 ± 12 decayed muon candidates detected:

- Over 2h of operation @ 0.1Hz (~700 shots)
- Detector area: 0.05 m^2
- 13-foot filtering converter

Outlook

- Muon trajectory reconstruction
- Single-muon energy measurements
- Advanced design of detector shielding