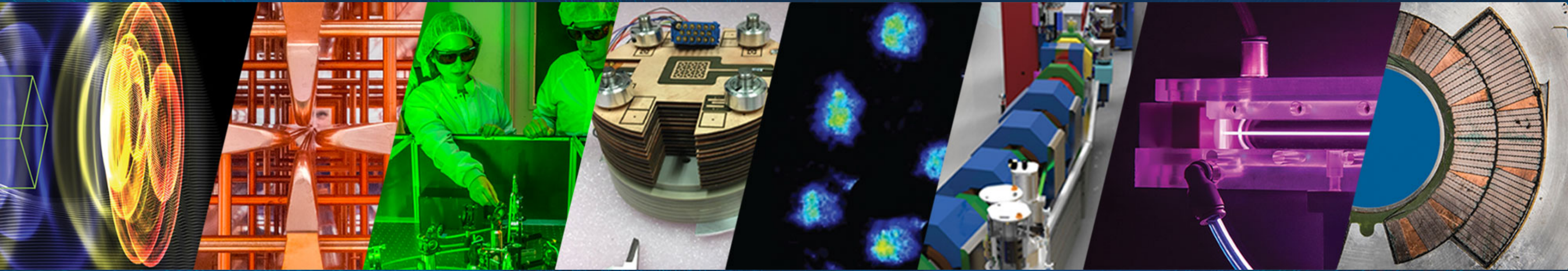
Generation and characterization of directional muon beams using Laser-Plasma Acceleration at the BELLA Center

Davide Terzani



Workshop on Laser-driven GeV Muon Sources at ELI

March 19, 2025

BERKELEY LAB

ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

U.S. DEPARTMENT OF ENERGY | Office of Science

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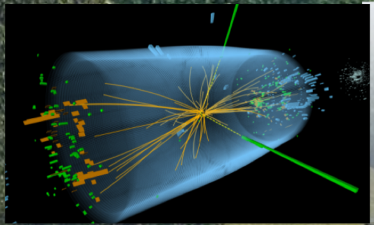
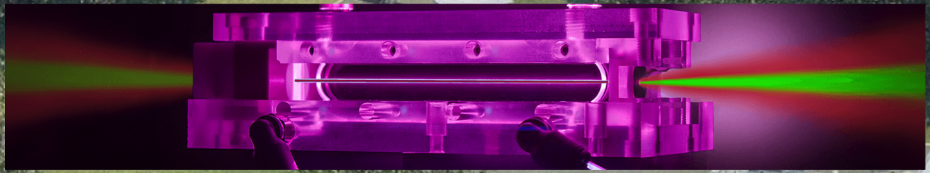
Outline

- Motivations
- Overview of the experimental setup
- Muon identification from the scintillator’s signal
- Numerical analysis of the muon production
- Summary and next steps

BELLA (BErkeley Lab Laser Accelerator) Center houses multiple laser systems enabling a wide range of LPAs and their applications

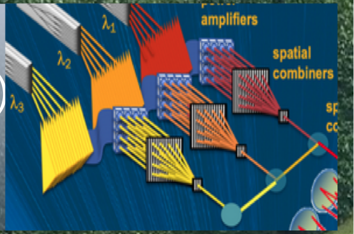


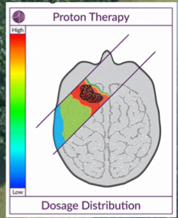
BELLA-PW (iP1)
40 Joule in 40fs (1 PW)
GeV acceleration, Staging
Proton & ion acceleration



BELLA-HTT
3 Joule in 30fs (100 TW)
Mono-chromatic gamma rays

BELLA FIBER
100s mJ in <100fs (>1kHz)
- Laser R&D
- Light sources at >1kHz

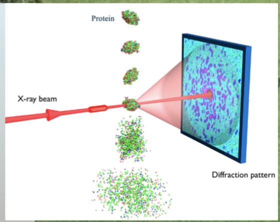




BELLA-iP2 at BELLA-PW
40 Joule in 40fs (1 PW)
Proton & ion acceleration

BELLA-KHz
A few mJ in 5fs (TW)
MeV Acceleration

BELLA-HTU
3 Joule in 30fs (100 TW)
X-ray laser



[1] K. Nakamura et al., Journal of the Particle Accelerator Society of Japan 19, 205 (2023)

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Imaging applications benefit from a compact muon source

Muon →

Mass [MeV]	Charge [e]	Spin	Lifetime [μs]
105.7	± 1	$\hbar/2$	2.2

Reduced Bremsstrahlung

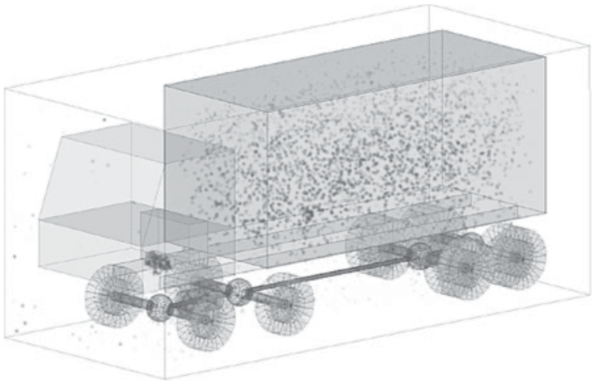
Interacts with detectors

Limited spatial reach due to decay

At the present time, only few facilities (e.g., MICE, Fermilab) produce muons, other applications rely on cosmic rays → ~1 particle/(min cm^2)

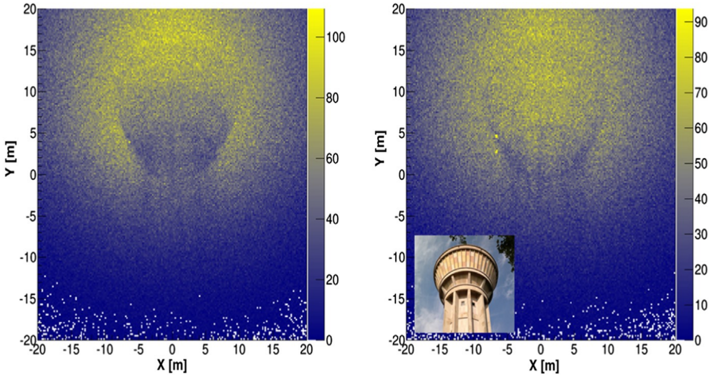
Muography

Penetration of high-Z materials



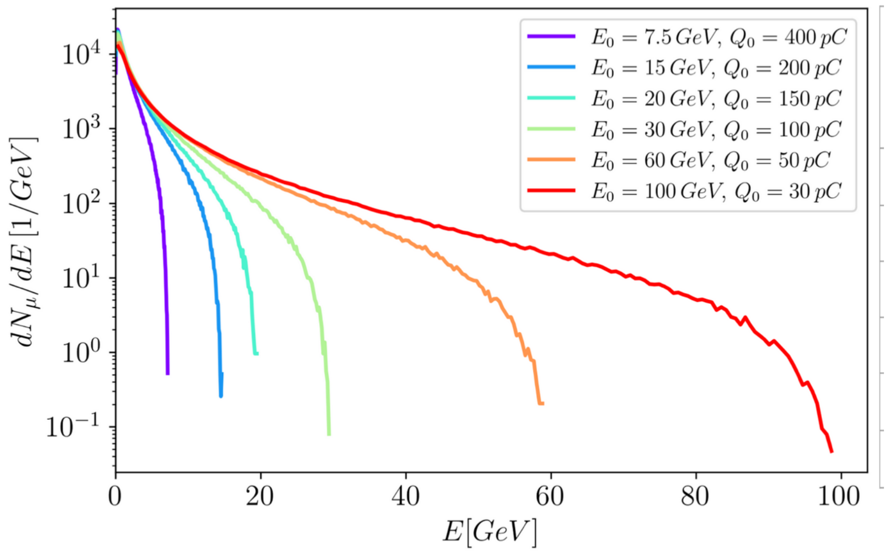
[S. Vanini, et al., Philosophical Transactions of the Royal Society A377, 20180051 (2018)]

Imaging of large objects

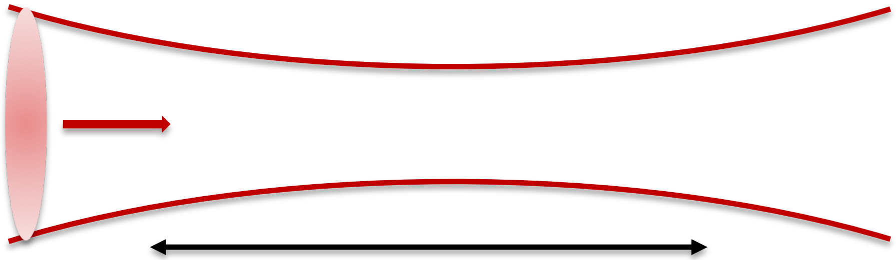


[S. Bouteille, et al., Nucl. Instrum. Methods A 834 (2016) 223]

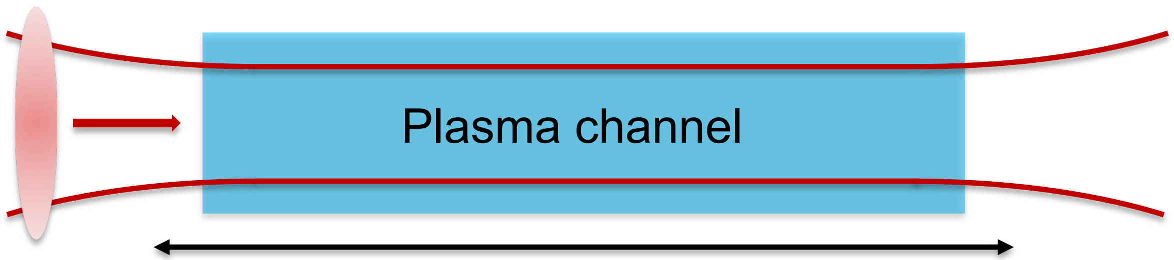
Muon spectra from e- beams



Laser pulse guiding prevents diffraction and enables electron beam acceleration up to and above the 10 GeV scale

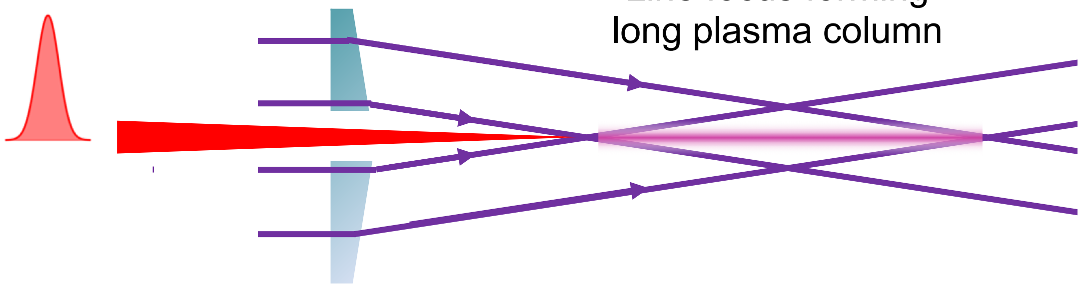


Diffraction length ~ 1 cm

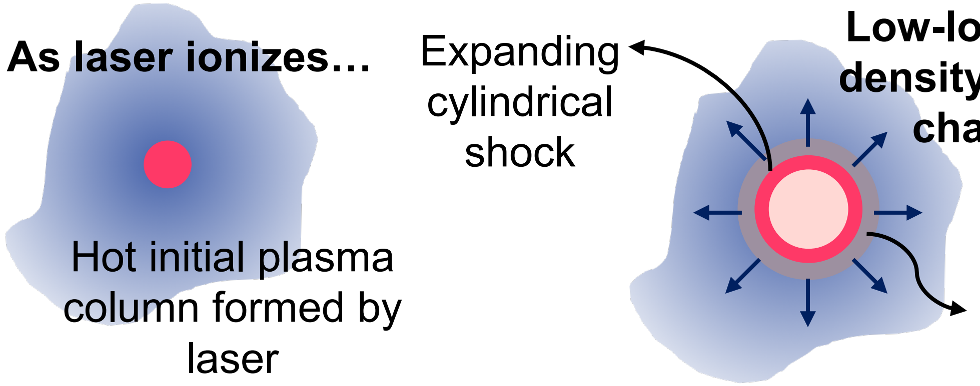


Meter-scale accelerating stage

HOFI-channel enables pulse guiding for densities ~ 10^{17}cm^{-3}



A few ns later…

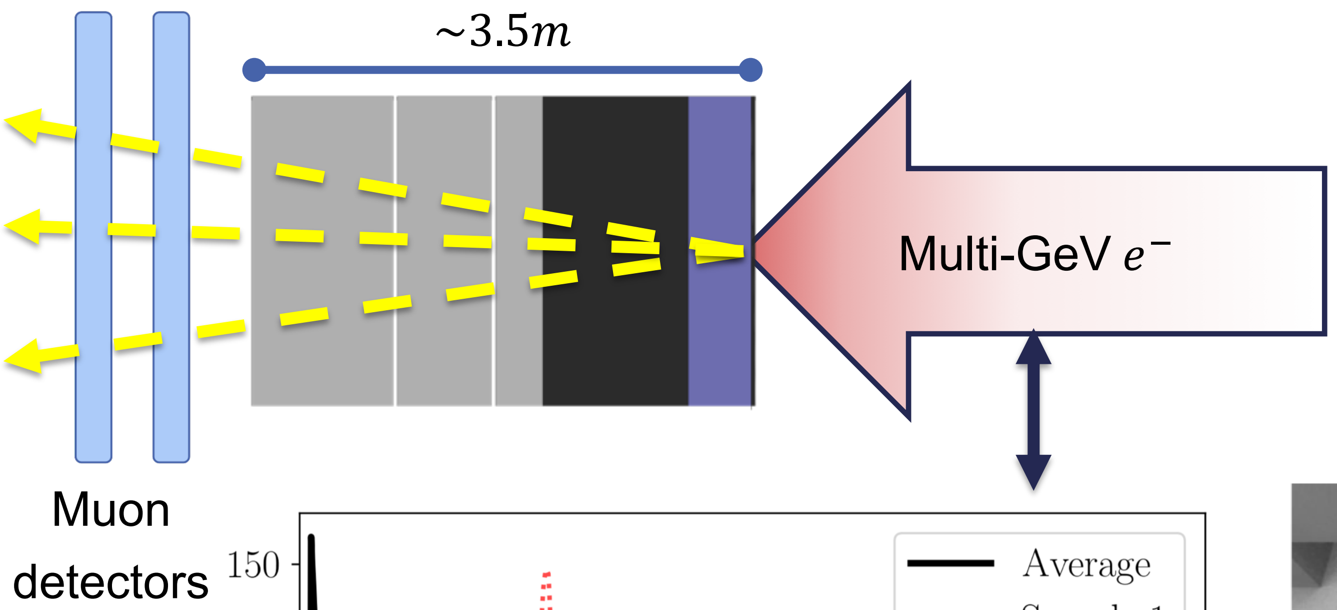


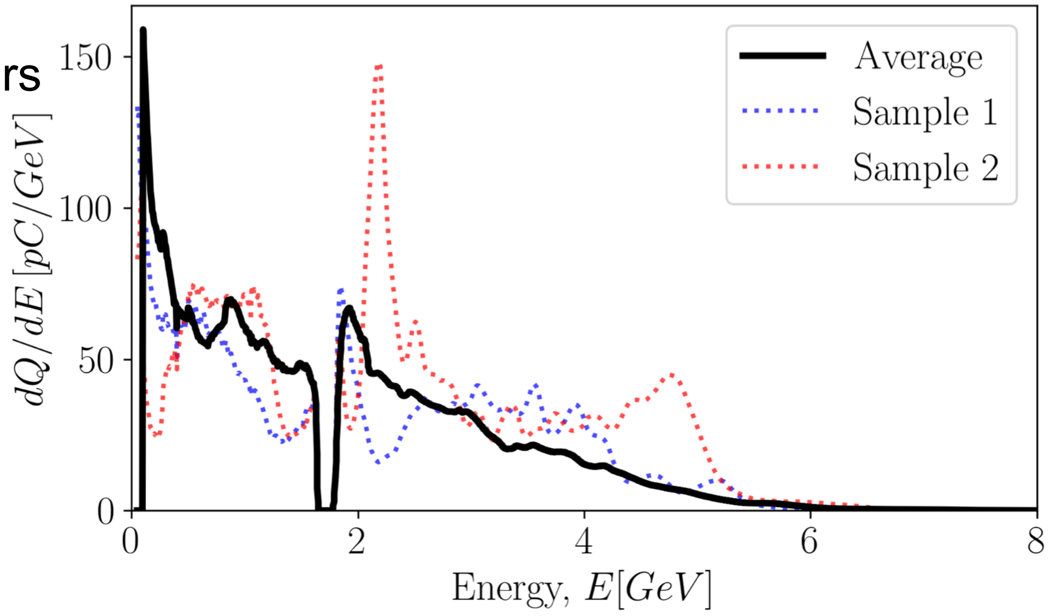
HOFI channels lower the energy requirements for the laser pulse

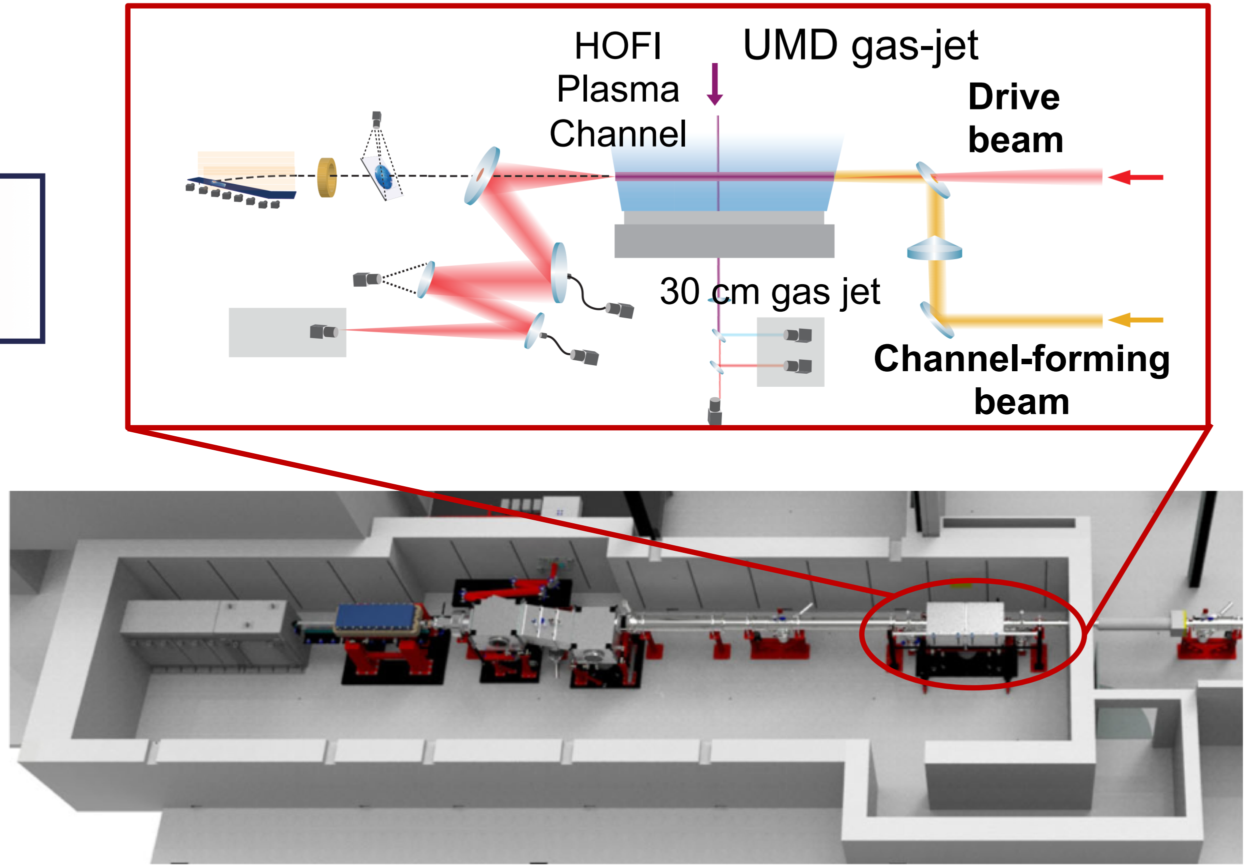
[*Durfee C., et al.*, PRL, 1993]
[*Shalloo R. J., et al.*, PRE, 2018]
[*Morozov A., et al.*, PoP, 2018]
[*Lemos N., et al.*, Sci. Rep, 2018]
[*Shalloo R. J., et al.*, PRAB, 2019]
[*Picksley A., et al.*, PRAB, 2020]
[*Picksley A., et al.*, PRE, 2020]
[*Feder L., et al.*, PRR, 2020]
[*Miao B., et al.*, PRL, 2020]
[*Picksley A., et al.*, PRL, 2024]
[*Shrock J., et al.*, PRL, 2024]

Courtesy of A. Picksley

We used the electron beam dump as a muon converter target







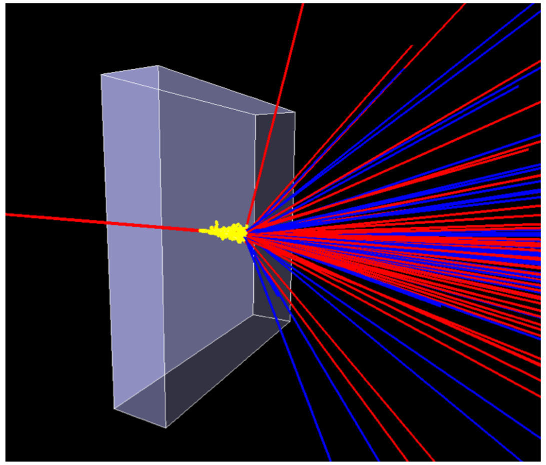
Two modes of operation:

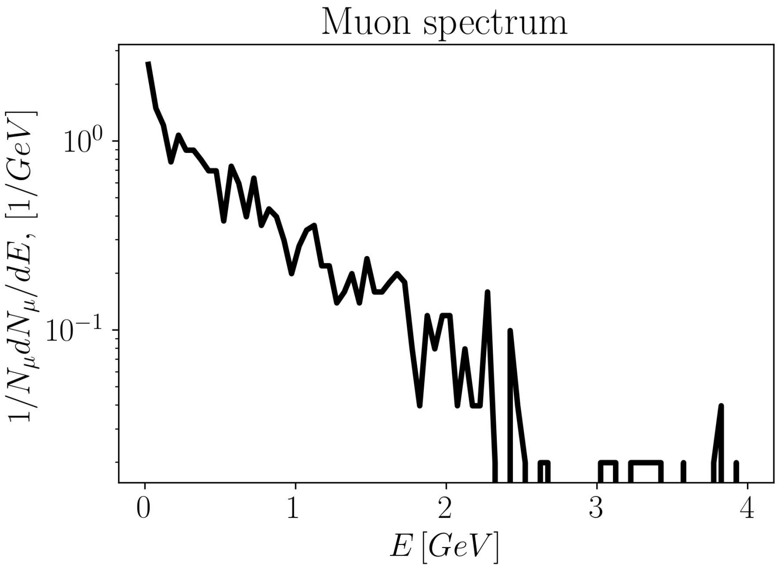
1. High-charge, broad spectrum (used for muon measurements)
2. e^- beams with mono-energetic energies up to 10 GeV

[*Picksley et al.*, PRL, 2024], in collaboration with UMD

High-energy electron beams produce muons in high-Z materials

X_0 Radiation length: the mean distance over which an electron loses all but $1/e$ of its energy by Bremsstrahlung





The dominating process is the production of gammas via Bremsstrahlung

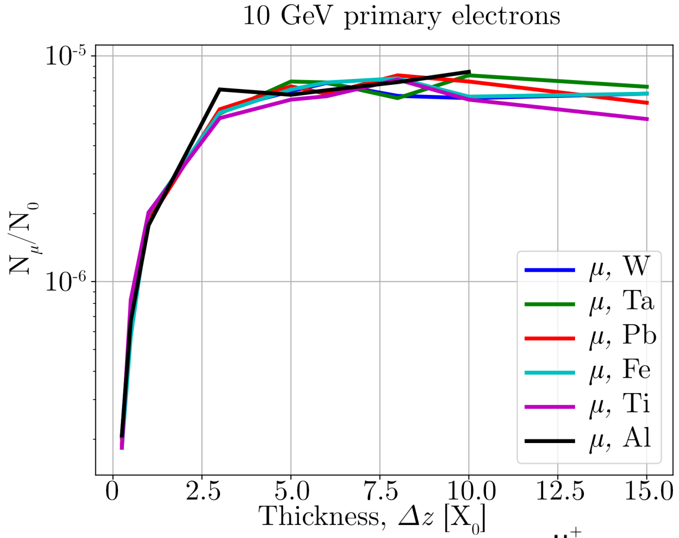
Possible decay channels for γ

- e^+e^- pairs
- $\mu^+\mu^-$ pairs
- photoproduction of pions

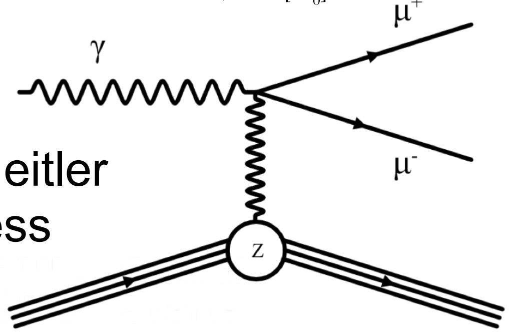
Sources of muons via different channels (but pion propagation is quickly suppressed for large thickness)

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

Muon yield produced in different materials as a function of the thickness

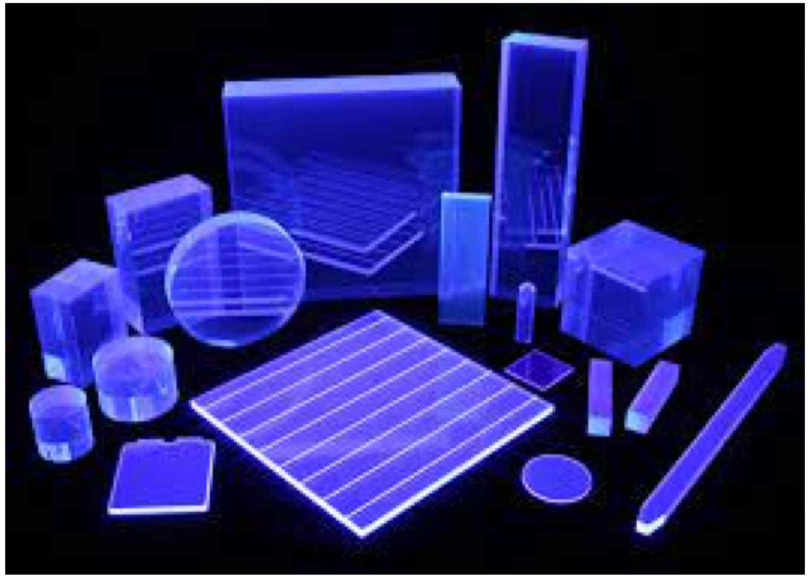


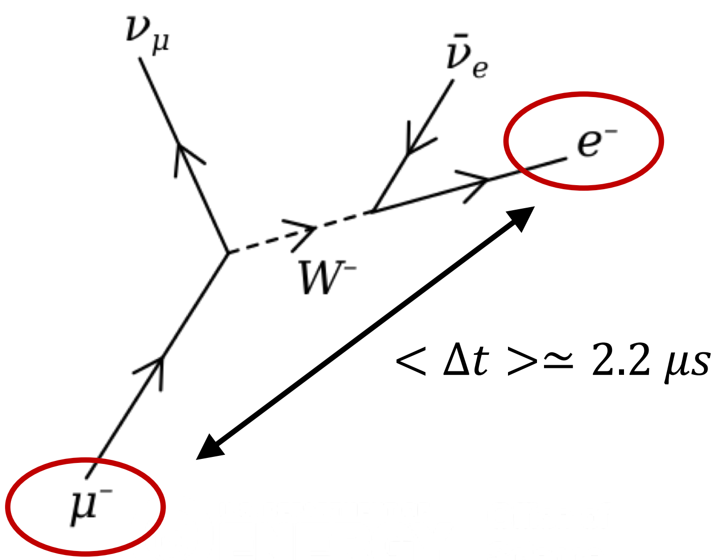
Bethe-Heitler process



Plastic scintillators enable particle identification through signal timing

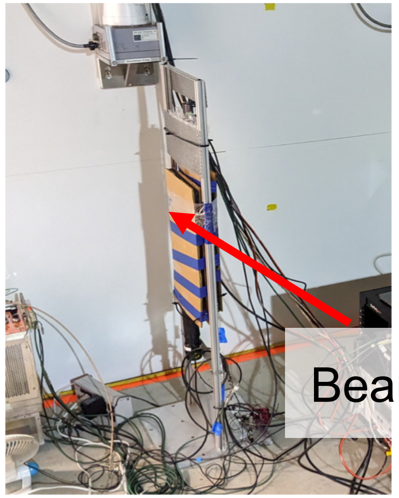
- Two ways to approach particle-ID questions:
  - **Does the beam contain muons?**
  - Is *this* particle a muon?
- Key identifying features:
  - Ionization density / range
  - **Lifetime ~2.2 μs**
  - Mass 105.7 MeV/c^2
  - Cherenkov thresholds, scattering angles, etc…
- Ionization detection technique?
  - **Scintillator + light detector**
  - Semiconductor tracking
  - …

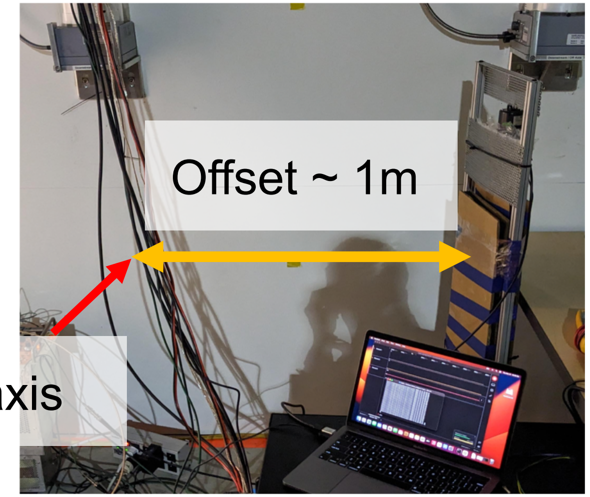


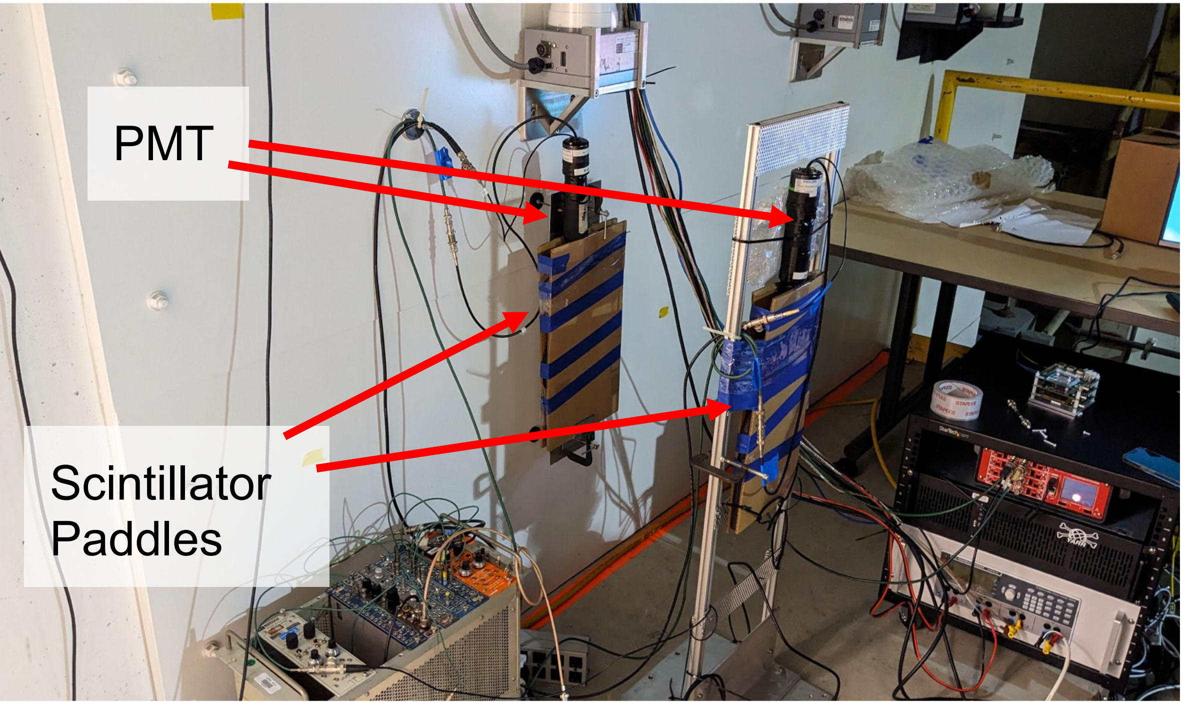


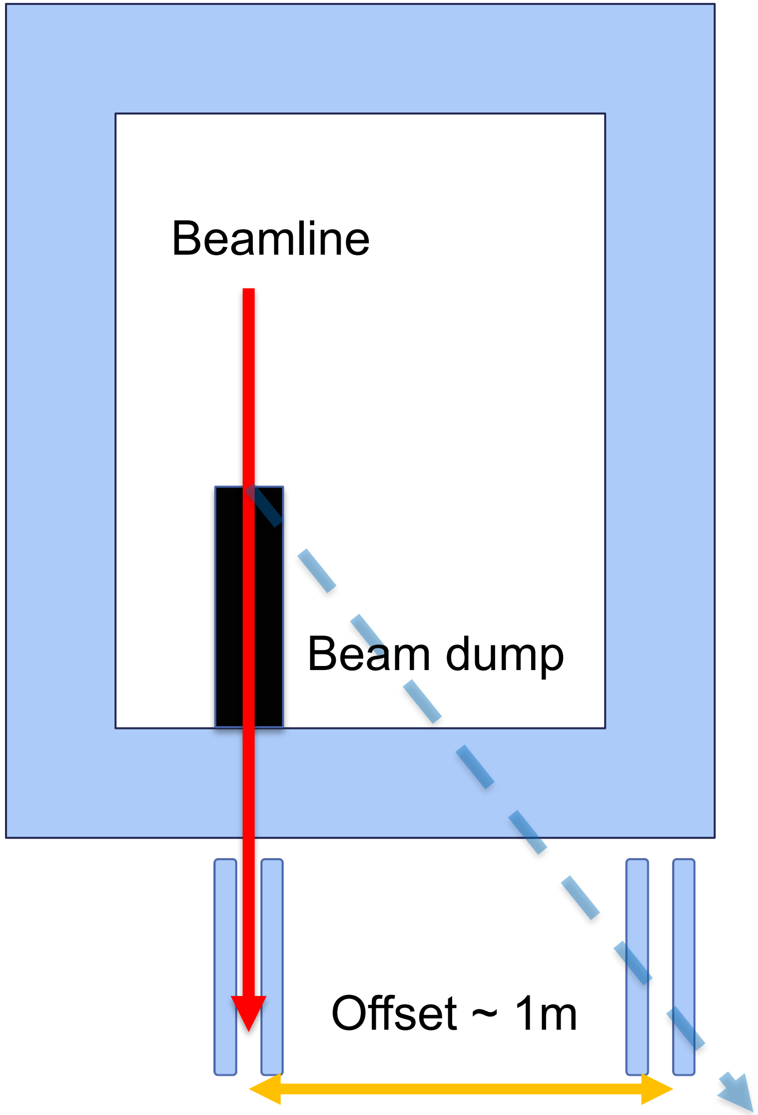
Scintillators identify muon candidates by checking the time difference between two hits

We positioned the scintillators in the hallway behind the wall of the experimental cave





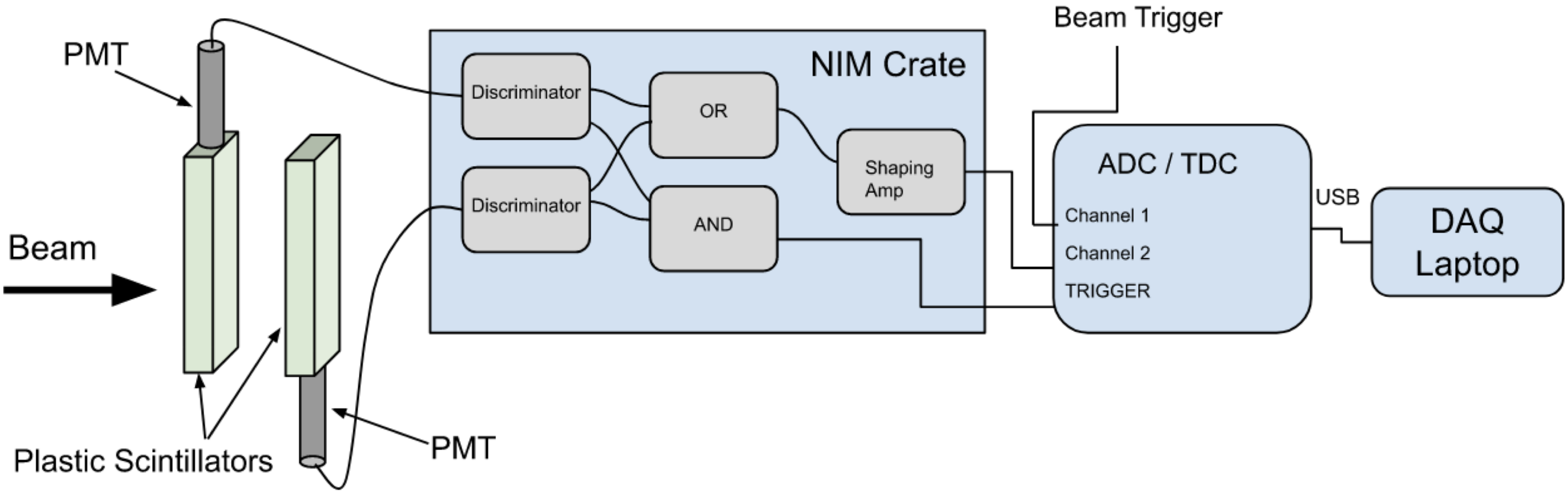




[*Terzani et al.*, arXiv:2411.02321v1]

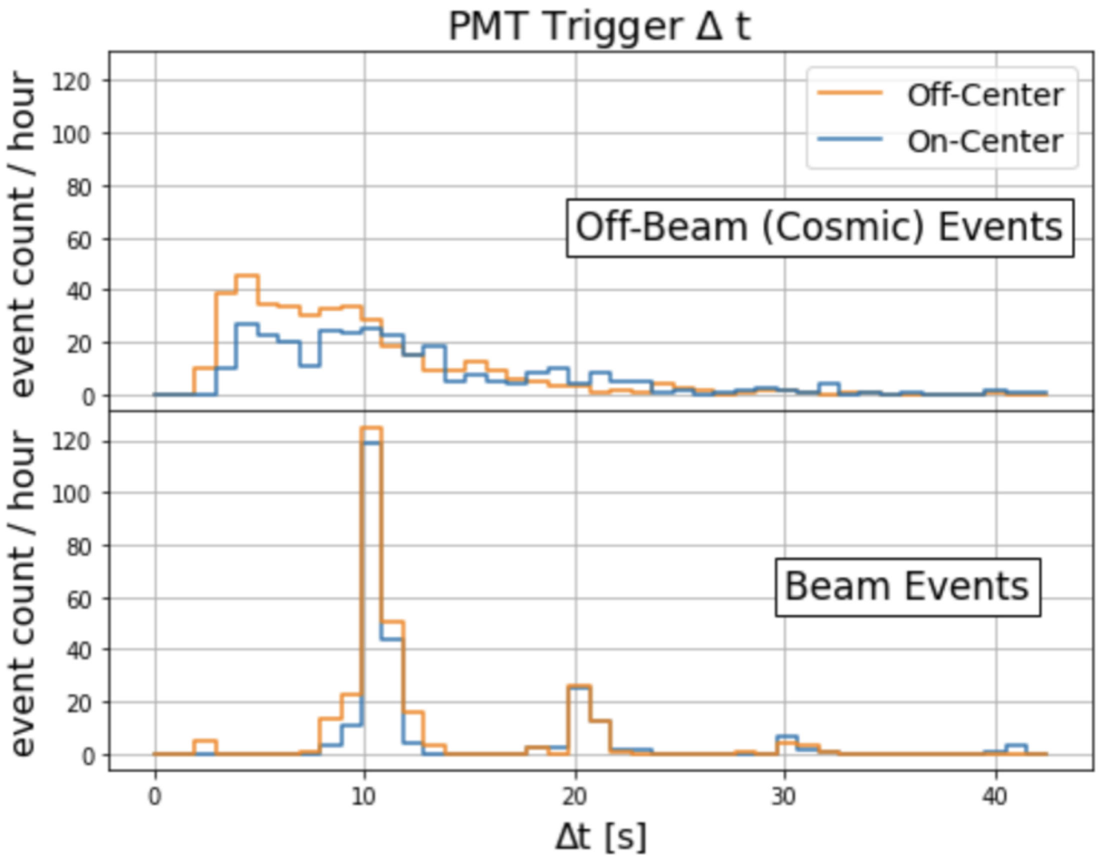
A pair of scintillators was used to trigger measurements on simultaneous detection

- Two ~80 in.^{2} scintillating plastic "paddles" with photomultiplier tubes (PMTs)
- Readout by ADC triggered by "hit" coincidence on both paddles
- Beam trigger stored, can be matched to beam logbook offline



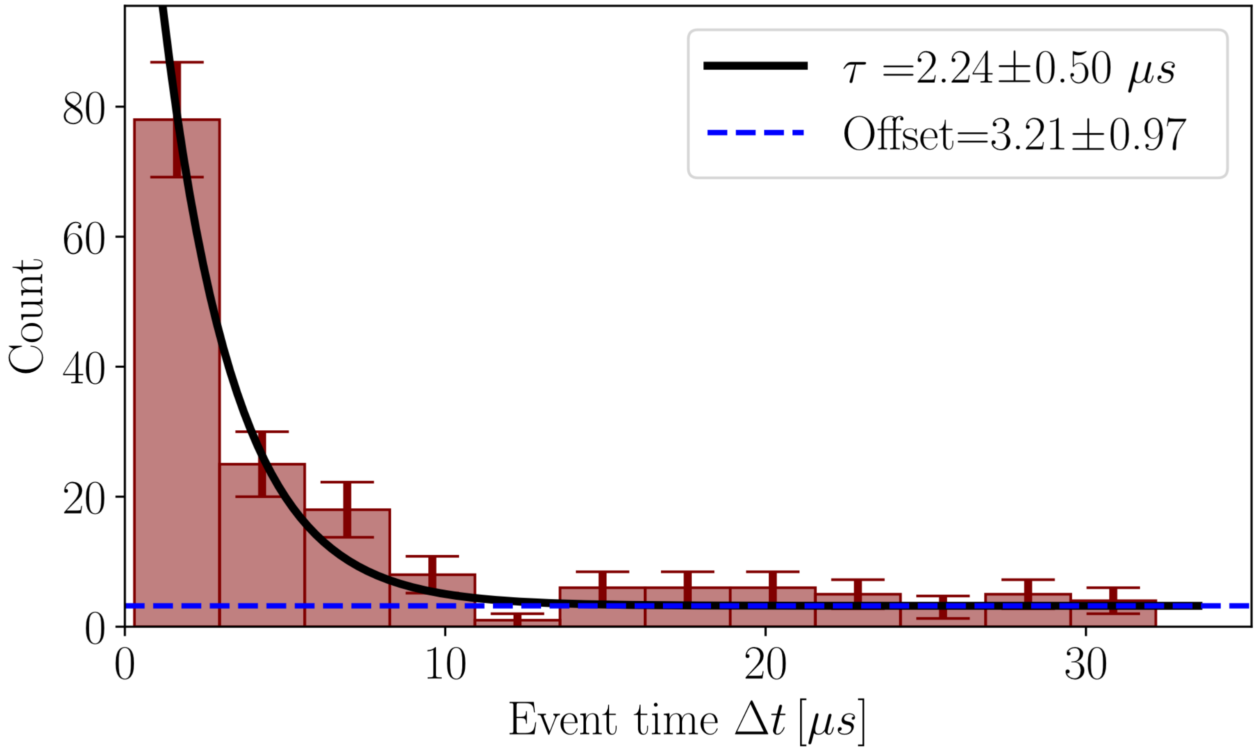
Measurements show unambiguous muon detection following the passage of the BELLA electron beam

Detector calibration with cosmic events shows that the number of hits with the beam on is much higher than background



[*Terzani et al.*, arXiv:2411.02321v1]

Fitting all the data collected by the scintillators with an exponential distribution + a constant background



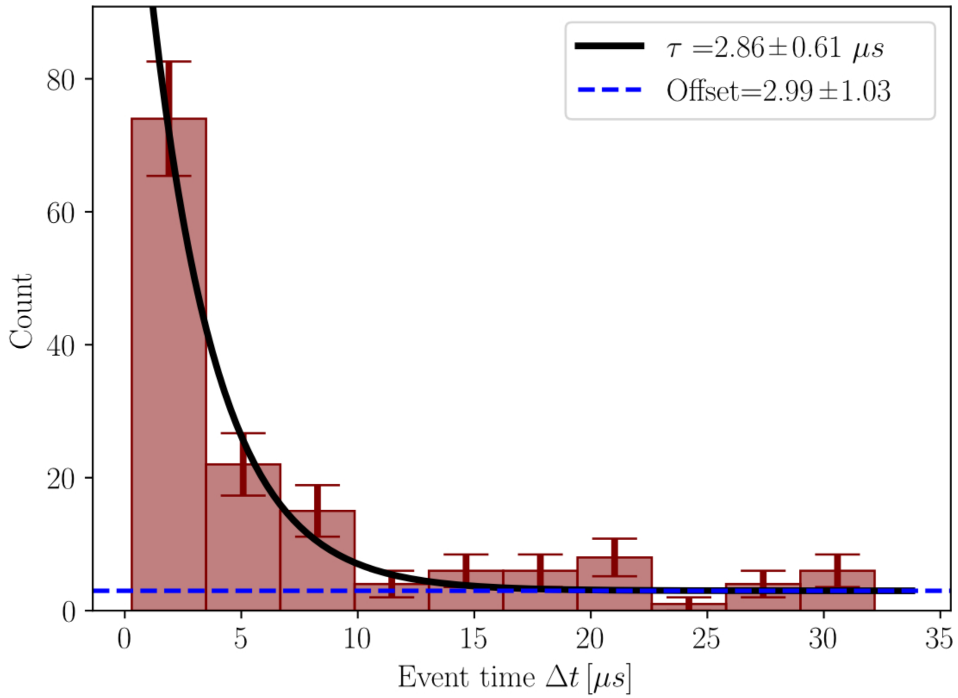
Data show muon decay ($\tau \simeq 2.2\ \mu s$)

μ Candidates	Background
126 ± 12	39 ± 12

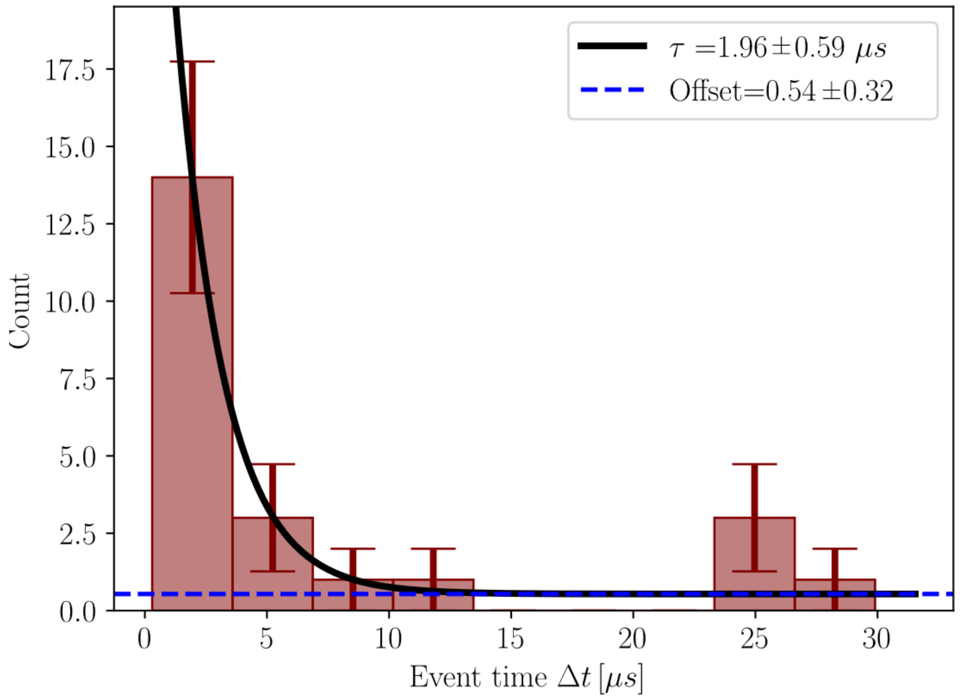
Displacing the scintillator off-axis provides us with insights into the process and the background

Both Off-axis and On-axis scintillators measure muons, but Off-axis records more events

Off-beam axis



On-beam axis



Should we expect muon events off-axis?

The angle is >> 1/γ

Investigate two aspects of the measurements:

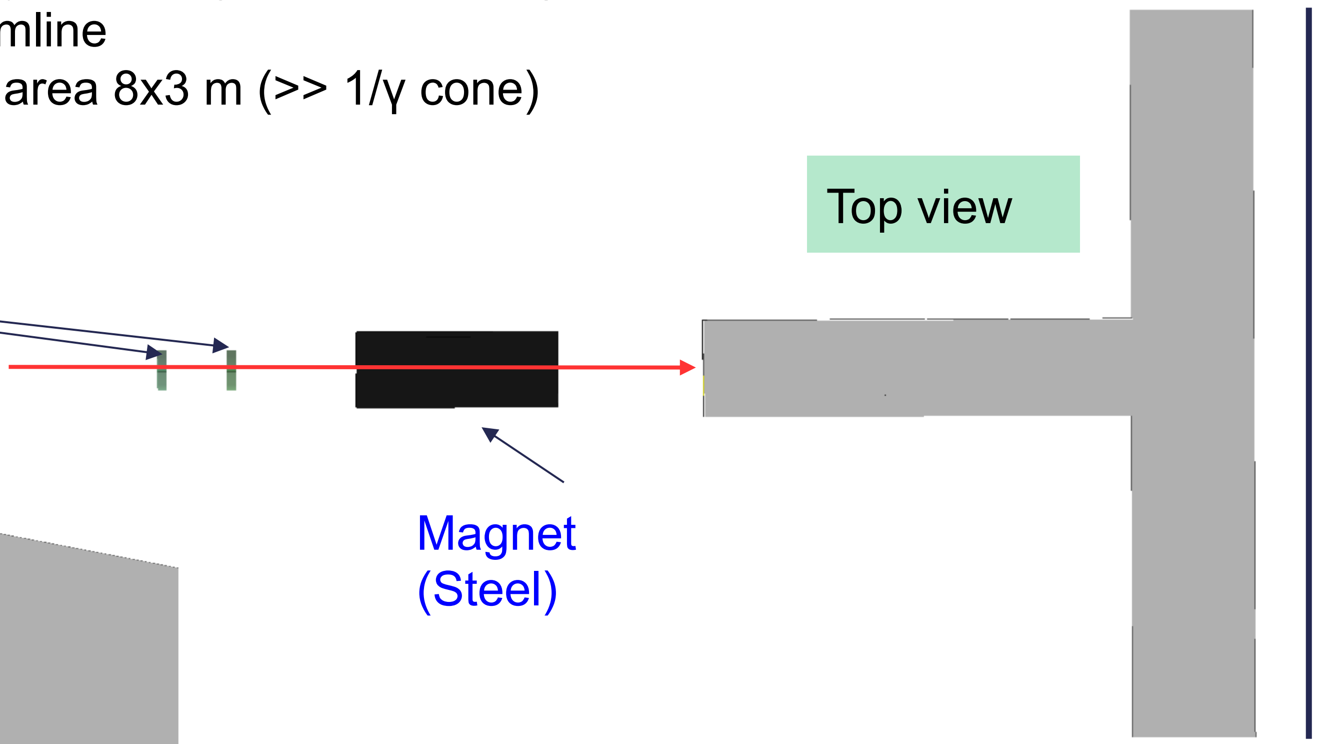
1) Off-axis the detector records muon decay more often
2) Signal is characterized by a constant background

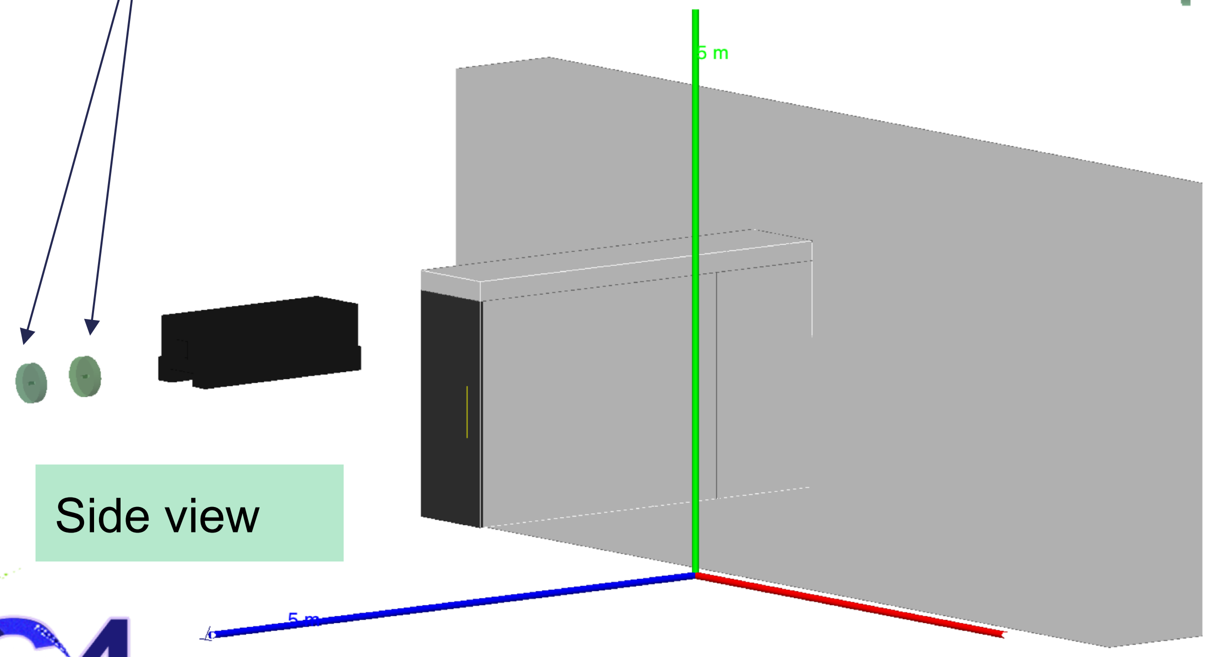
[*Terzani et al.*, arXiv:2411.02321v1]

Simulations included critical elements along the beamline to identify noise and muon sources

Beyond the zeroth-order approximation (i.e., only modeling a beam dump):

- We included high-Z elements along the beamline
- We extended particle detection to a surface area 8x3 m (>> 1/γ cone)



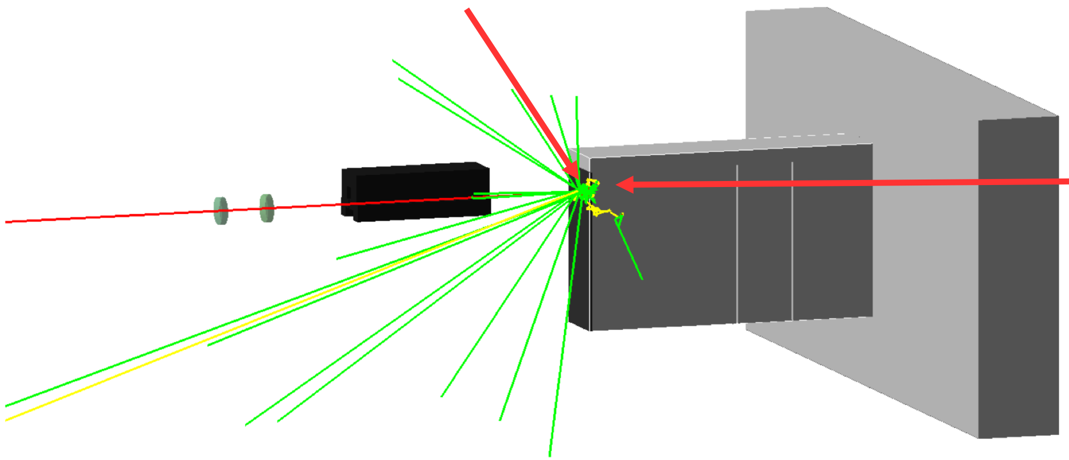


We performed simulations including all the cave walls and they didn't show significant differences. Following slides show that elements along the beamline suffice to reproduce experiments.

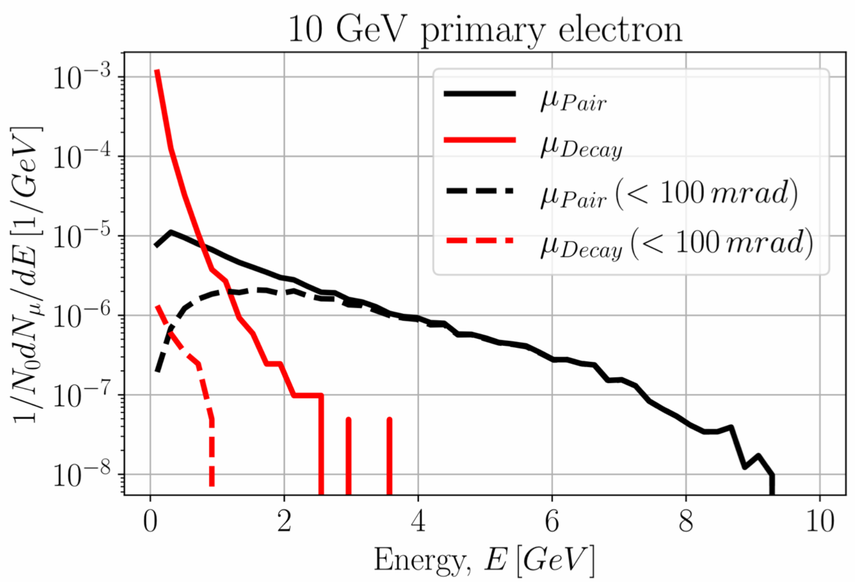
[*Terzani et al.*, arXiv:2411.02321v1]

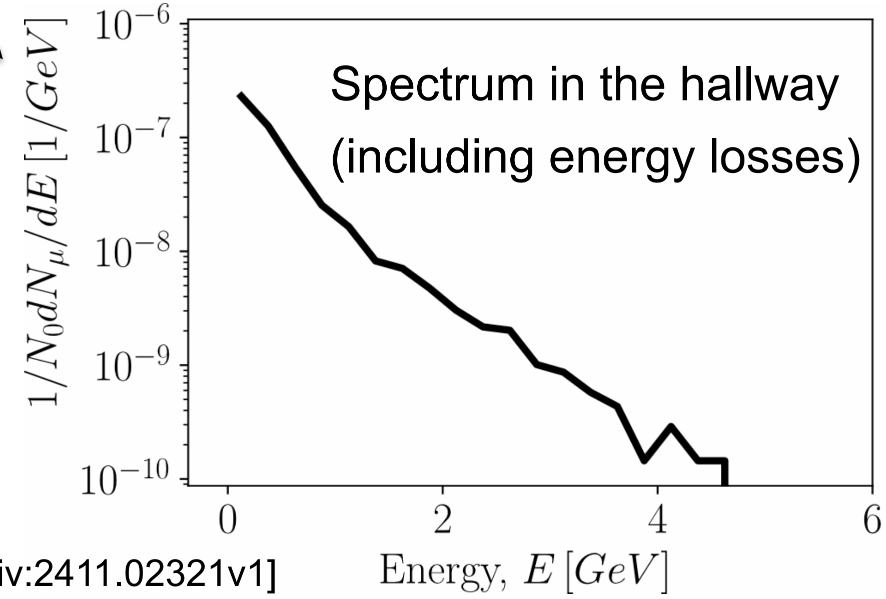
For a well aligned electron beam, a directional (on-axis) muon beam produced with highest energy ~E_{e-}

Main interaction point



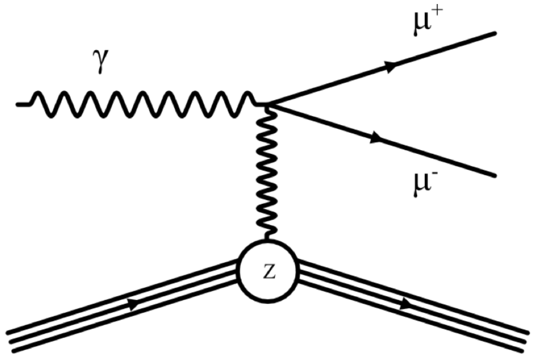
Spectrum at IP
(example at 10 GeV)





Muon production channels

Bethe-Heitler



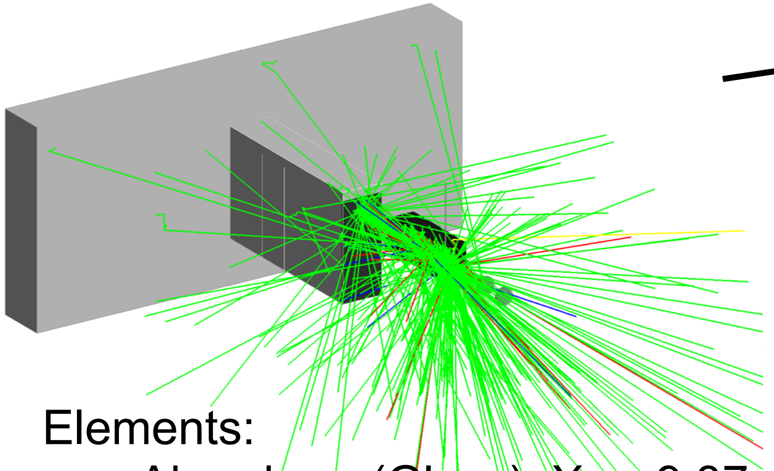
Pion decay

1. Pion production (mostly isotropic and low energy)
2. Pions decay into muons

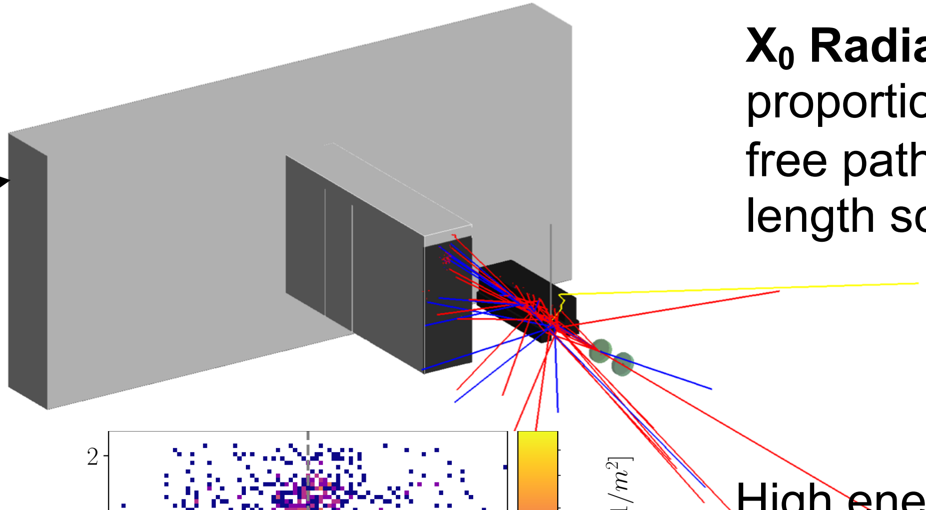
[*Terzani et al.*, arXiv:2411.02321v1]

Beam interaction with high-Z elements leaves muon beam unaffected and produces additional low-energy muons around the beam dump

The electron beam hits the elements along the beamline when θ=1.5mrad

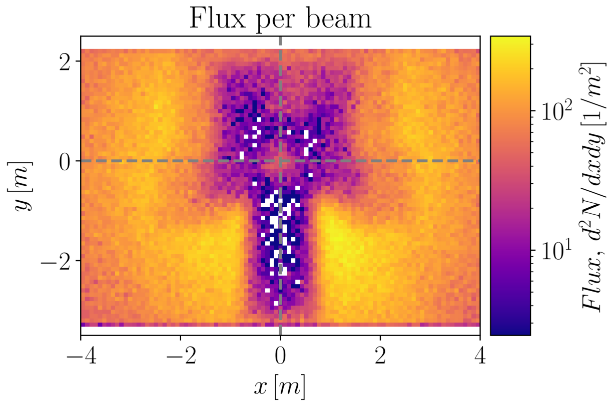


Photons removed for clarity

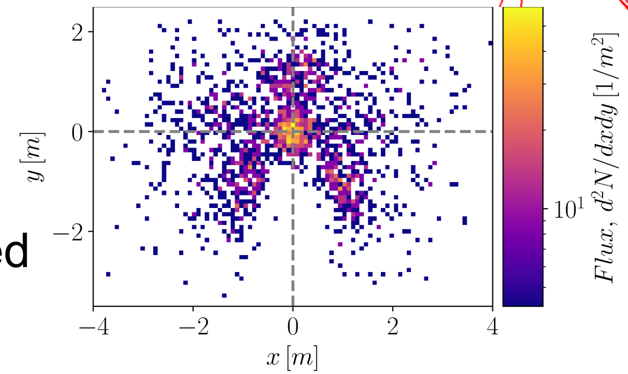


X_0 Radiation length: proportional to photon mean free path - pair production length scale

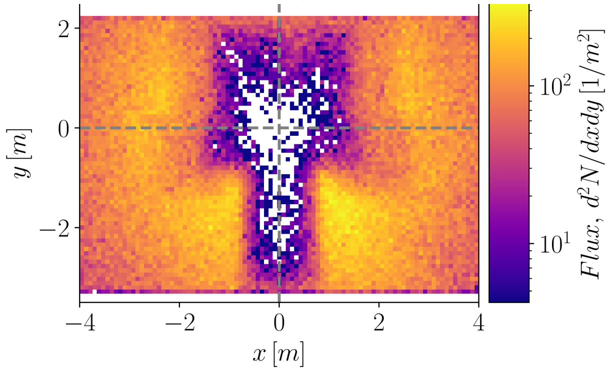
Elements:
- Absorbers (Glass): X_0 = 9.37cm
- Magnet (Steel): X_0 = 1.54 cm



Pair-produced



From decay



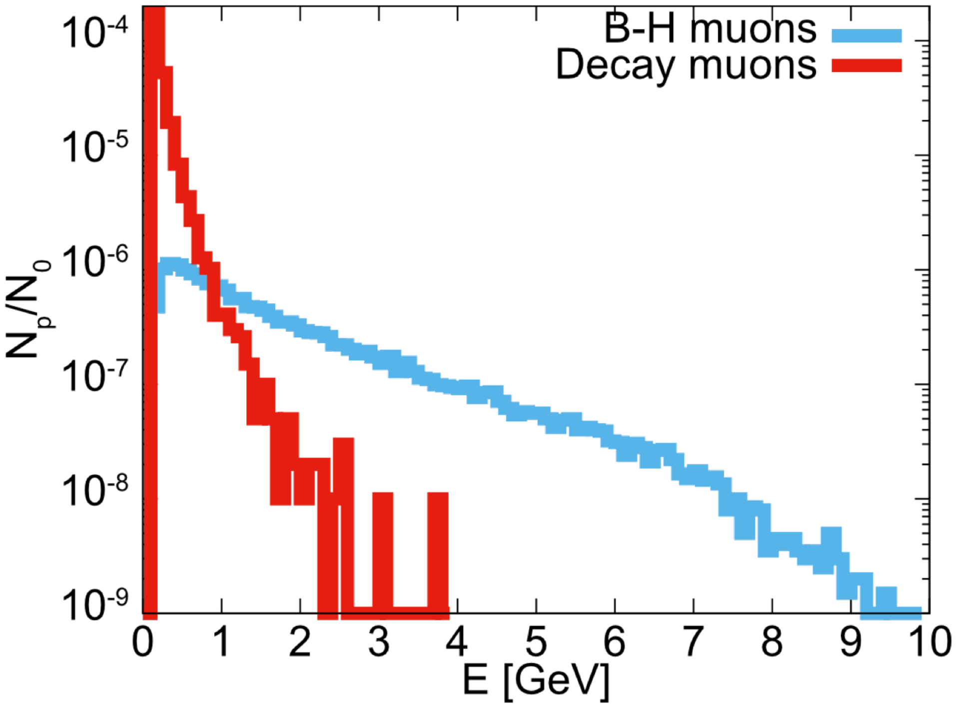
High energy muon beam from pairs not affected: material independent and collimated

Additional low energy muons visible due to off-axis production from pions (not absorbed)

[*Terzani et al.*, arXiv:2411.02321v1]

Experimentally observed higher muon count off-axis can be explained by the lower energy muons from pion decay

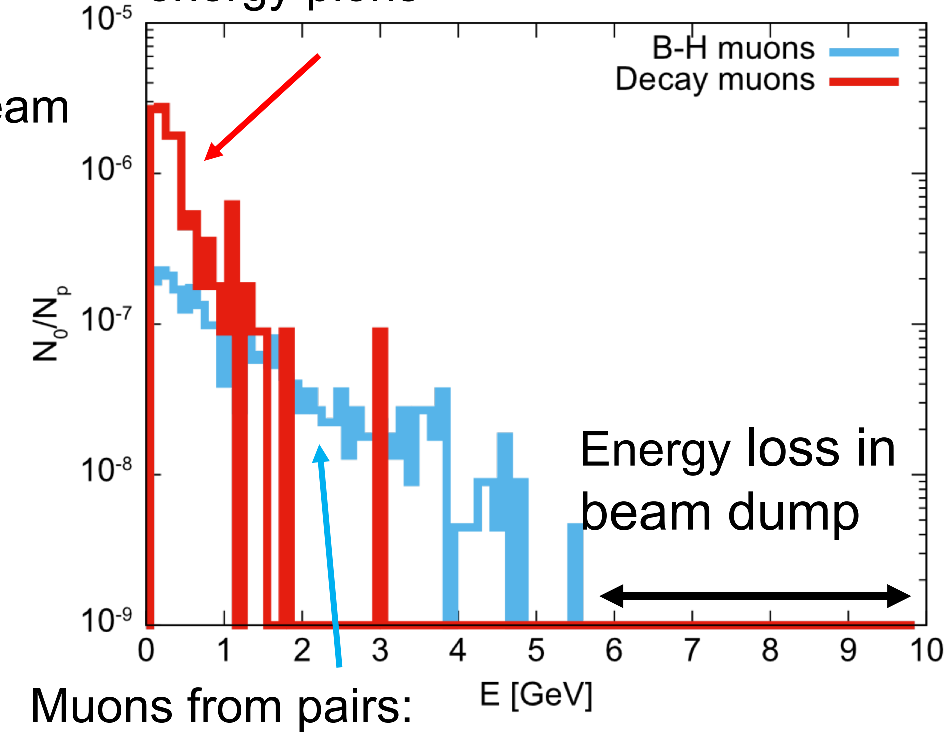
Muons at IP (up to 10 GeV)



Passage through beam dump and wall

Muons from decay:

- Almost isotropic
- Peaked at low energy because emitted by low energy pions



Muons from pairs:

- Mainly forward directed
- Exponential-like energy distribution (Bremsstrahlung)

The two muon species are spatially separated therefore the measurement is selective depending if the detector is on/off axis.

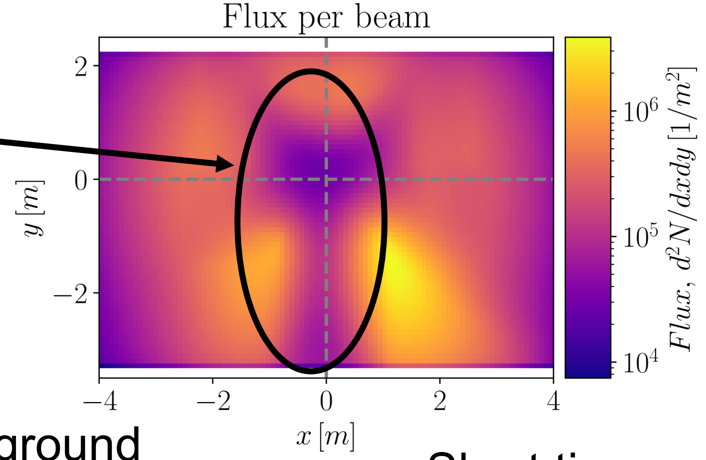
[*Terzani et al.*, arXiv:2411.02321v1]

Understanding photon background is essential to design additional shielding for the tracking detectors

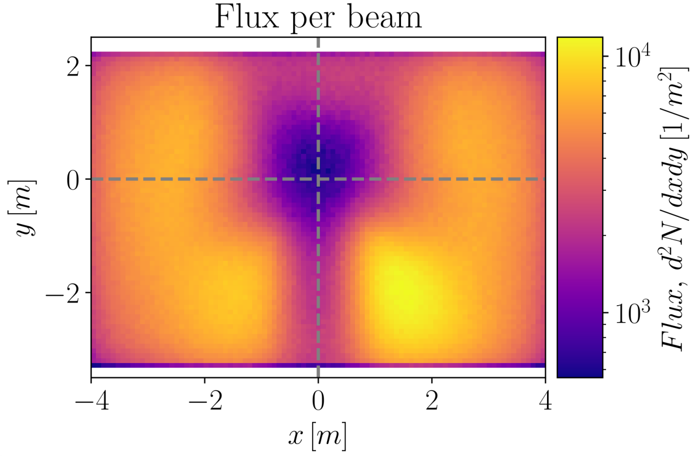
[*Terzani et al.*, arXiv:2411.02321v1]

Lower background behind the beam dump

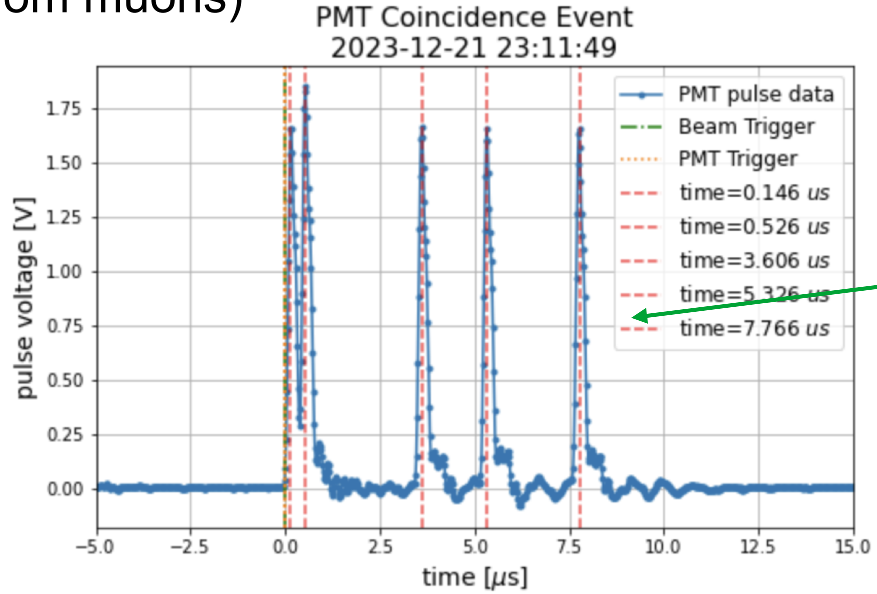
Photon flux on the virtual detector



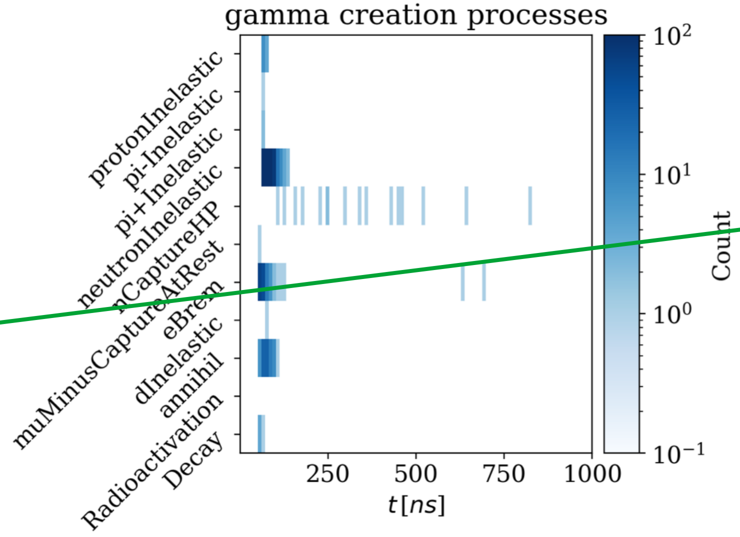
Neutron flux on the virtual detector



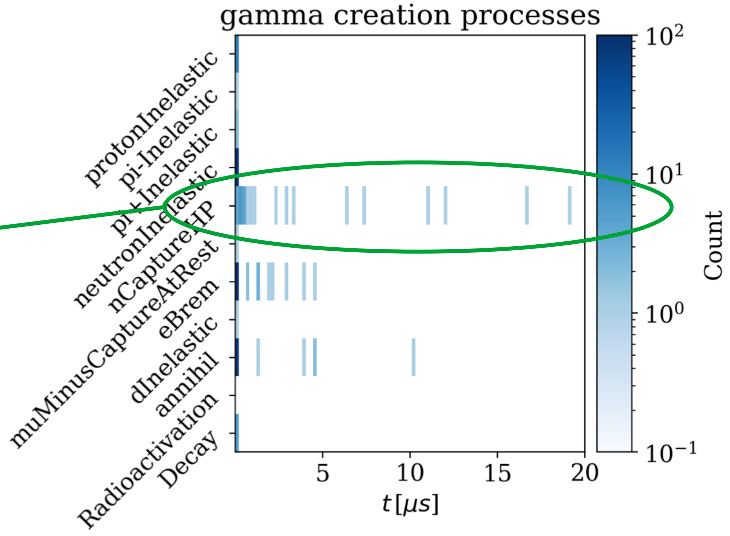
Scintillator revealed gamma background around the beam dump (distinguished from muons)



Short time scale (ns)



Medium time scale (μs)

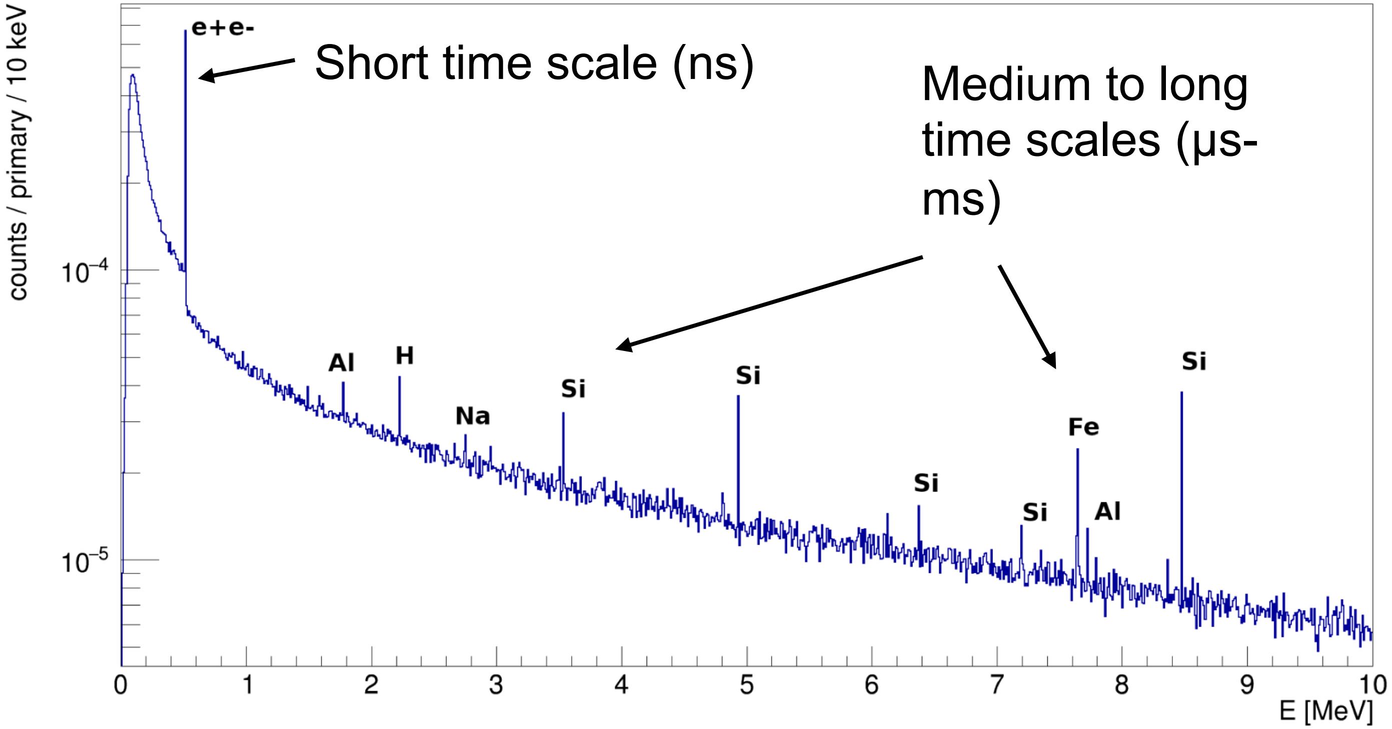


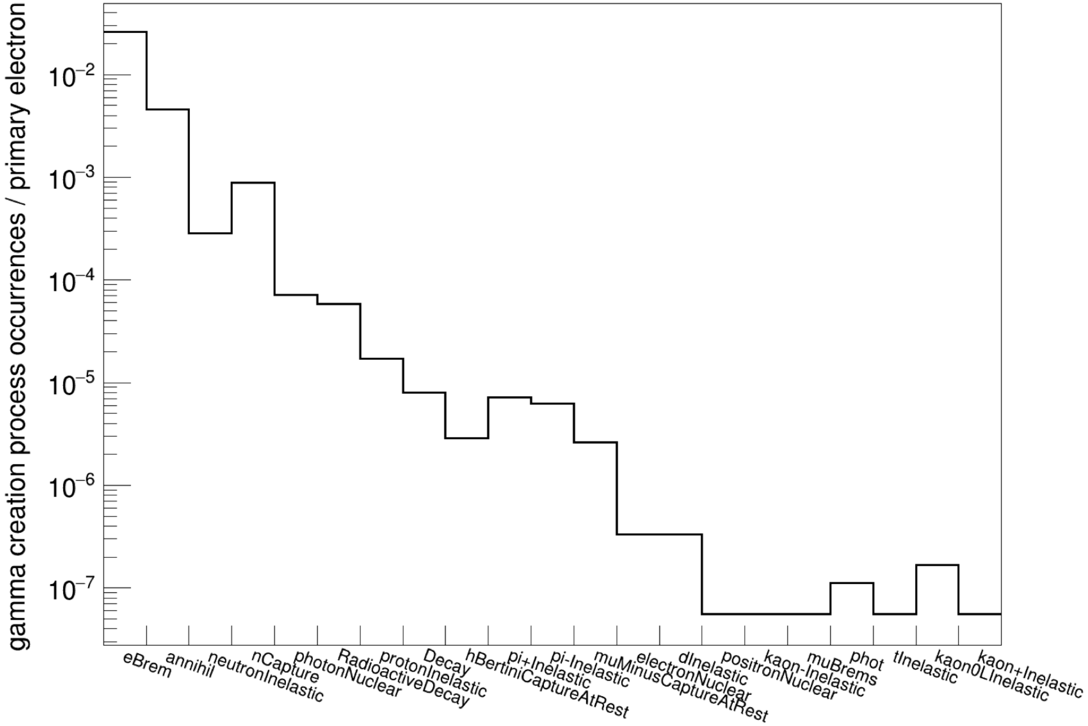
Pursuing extra shielding to reduce background

The γ-ray spectrum shows signatures of neutron absorption and e^+e^- annihilation

Energy distribution of gamma rays at the PW area hallway:

- multiple occurrences of neutron capture and inelastic scattering (only measured in scintillators and distinguished from muons)
- e^+e^- annihilation gammas at short time scales could hit trackers, but possible to shield since E<1MeV





[*Terzani et al.*, arXiv:2411.02321v1]

Summary and next steps

- We produced e^- beams up to 8 GeV
- We used our electron beam dump (several layers of high-Z materials) as a converter target
- Pairs of scintillators measured unambiguously muons in correspondence to the beam passage
- Numerical analysis confirmed the measurements and provided us with insights into the signals we recorded
- We recognize two separated sources of muons distinguished by the angle and the typical energy
- We identified the main sources of background noise (i.e., neutron capturing)

Next steps

- We are now working with silicon-based detectors in addition to scintillators
- We developing single-muon energy measurements
- We are designing appropriate shielding for the detectors