The ICMuS2 Project: Production of a Multi-GeV Muon Beam using Laser Wakefield Acceleration

Anna Cimmino[1] on behalf of ICMuS2 Collaboration[1-6]

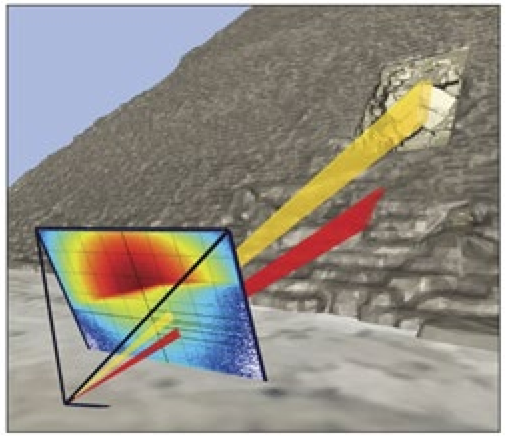
1- The Extreme Light Infrastructure ERIC, ELI Beamlines Facility, Dolni Brezany, 25241, Czech Republic
2 - Lawrence Livermore National Laboratory, Livermore CA 94550, USA
3 - Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, Maryland 20742, USA
4 - Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, CO, 80523, USA
5 - Lawrence Berkeley National Laboratory, Berkeley, CA, USA
6 - Lockheed Martin Corporation
7 - XUV Lasers Inc, Fort Collins, CO 80527, USA

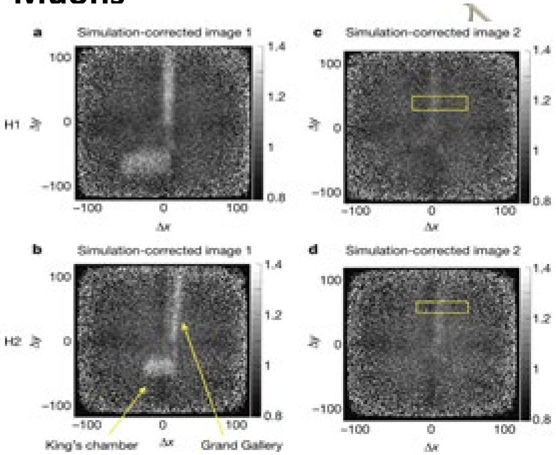
Work supported by DARPA under the Muons for Science and Security (MuS2) Program

Prepared by LLNL under Contract DE-AC52-07NA27344

Muons as Unique Imaging Technique

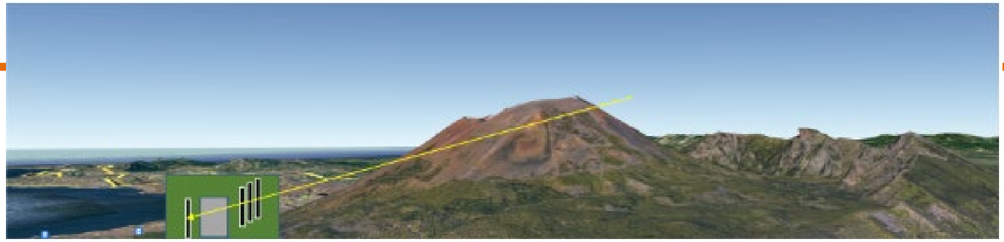
Discovery of a hidden chamber in the Great Pyramid of Giza using Cosmic-ray Muons

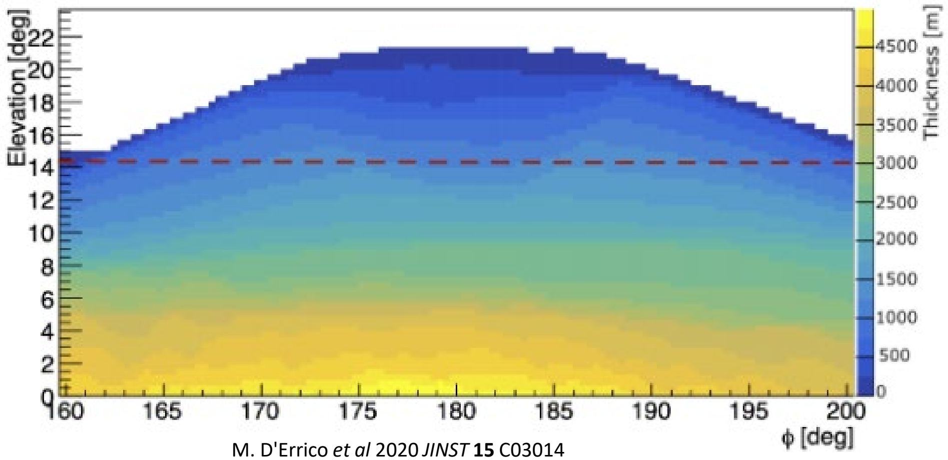




Morishima, K., Kuno, M., Nishio, A. *et al.*, "Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons," *Nature*, 552, 386–390 (2017). [Link](#).

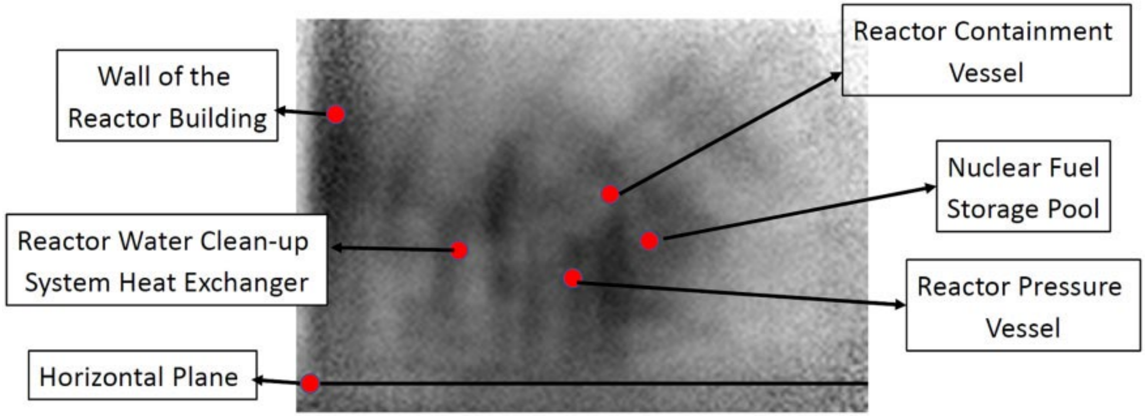
Study of the Vesuvius Great Cone



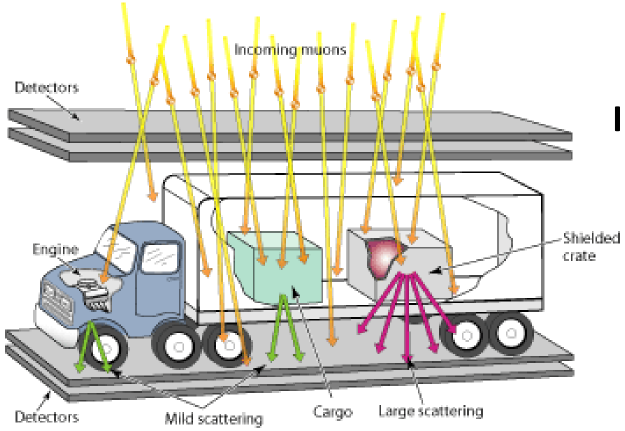


M. D'Errico *et al* 2020 *JINST* **15** C03014
10.1088/1748-0221/15/03/C03014

Inspection of the inside of the Fukushima Daiichi reactor



Fujii, H., Hara, K., Hashimoto, S., *et al.*, "Performance of a remotely located muon radiography system to identify the inner structure of a nuclear plant," *Prog. Theor. Exp. Phys.*, 2013, 7, 073C01 (2013). [Link](#).



Inspection of cargo containers using cosmic-ray muon tomography

https://science.osti.gov/np/Benefits-of-NP/Applications-of-Nuclear-Science/Archives/Muon-Radiography-at-LANL

Muon Beams with Laser-Driven Sources

- Average cosmic-muon flux at sea-level is only about 1 muon/cm^2/min. They have an inherent vertical directionality. Mean energy at sea level is 4 GeV. → limits application utility

- Conventional GeV-TeV particle accelerators are good sources of artificial muons but they are kilometer-scale size structure → limits application utility
  - 5 muon user facilities for multidisciplinary research: SμS at PSI, CMMS at TRIUMF, ISIS at STFC/RAL, MUSE at J-PARC, and MuSIC at RCNP

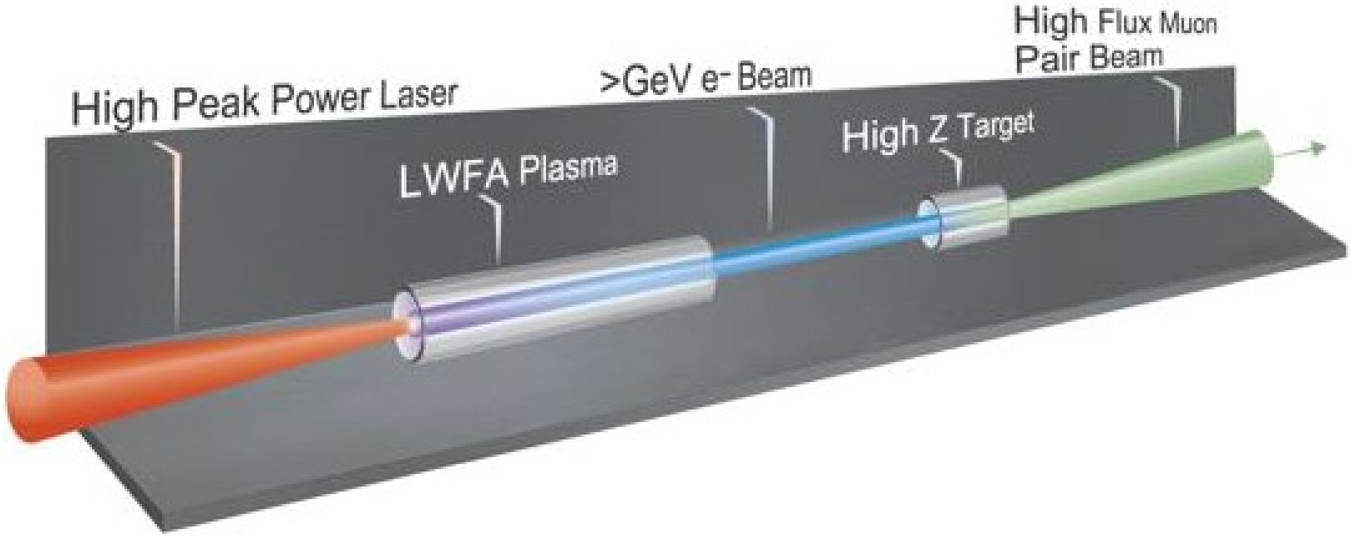
- Laser Wake Field Acceleration (LWFA) with next generation laser driver technology provides a promising path to realizing a high energy, high flux, mobile muon source.
  - ELI Beamlines (ELI ERIC - CZ) future LWFA-based muon user facility.

Laser Wake Field Acceleration and Muon Beams

- Laser Wake Field Acceleration (LWFA)
  - high intensity (PW-class) ultra-short (fs) lasers propagate inside a gas ionizing it and expelling the plasma electrons
  - a wake is created behind the laser in which acceleration gradients of up to **hundreds of GV/m** can be achieved.

- LWFA can be used to produce high-energy muon beams (>GeV) in the space of tens of centimeters compared to hundreds of meters needed for state-of-the art linear accelerators.

- Muons via pion decay and Bethe-Heitler pair production. The resulting muons have a large Lorentz boost in the incident electron direction and this results in a relatively narrow beam divergence.



The ICMuS2 Project

- Intense and Compact Muon Sources for Science and Security (ICMuS2)
  - Led by Lawrence Livermore National Laboratory (LLNL)

- Funded by the Defense Advanced Research Projects Agency (DARPA) Muons for Science and Security Program.

https://www.darpa.mil//news-events/2022-07-22

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- Develop a compact and transportable muon sources, directional and with energy ranging from 10s to 100s of GeVs employing LWFA.

- ***Phase 1: Sub-10GeV Muon Generation Demonstration***
  - experiments are being conducted at the Colorado State University's L-ALEPH

- ***Phase 2: Laser driven high energy muon generation and muon imaging demonstration***
  - high energy acceleration and muon generation experiments will be conducted at ELI Beamlines using the L4-Aton 10 PW laser system

Parameter	Phase 1	Phase 2 (notional)
Electron Energy Range (GeV)	>10	>100
Muon Energy (GeV)	10	100
Muon Production	Yes	10^6 - 10^8 /experiment

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Muon Generation/Detection Experiment

- Demonstration of generation and detection of high energy muons
- March 2024 @ at the Laboratory for Advanced Lasers and Extreme Photonics (L-ALEPH) at CSU.
  - 0.85 PW, λ= 800nm, up to 3.3 Hz
  - all-optical LWFA schemes developed at UMD

B. Miao, et al., Multi-GeV Electron Bunches from an All-Optical Laser Wakefield Accelerator, Phys. Rev. X 12, 31038 (2022).J.E.
Shrock et al., Guided mode evolution and ionization injection in meter-scale multi-GeV laser wakefield accelerators. Accepted in Phys Rev Lett (2024)

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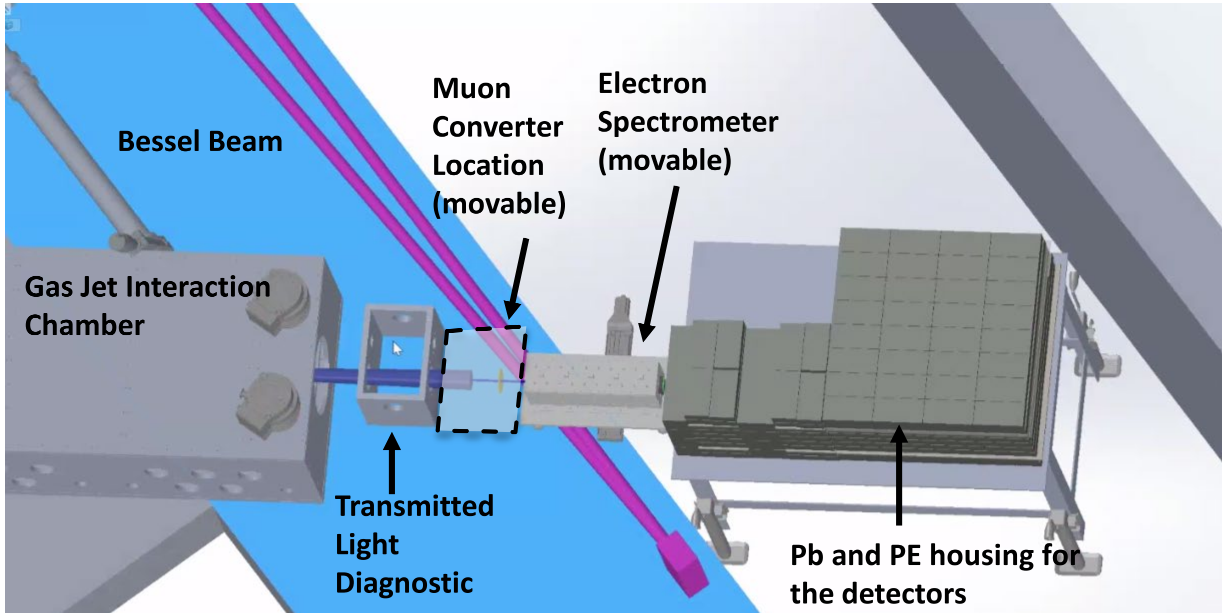
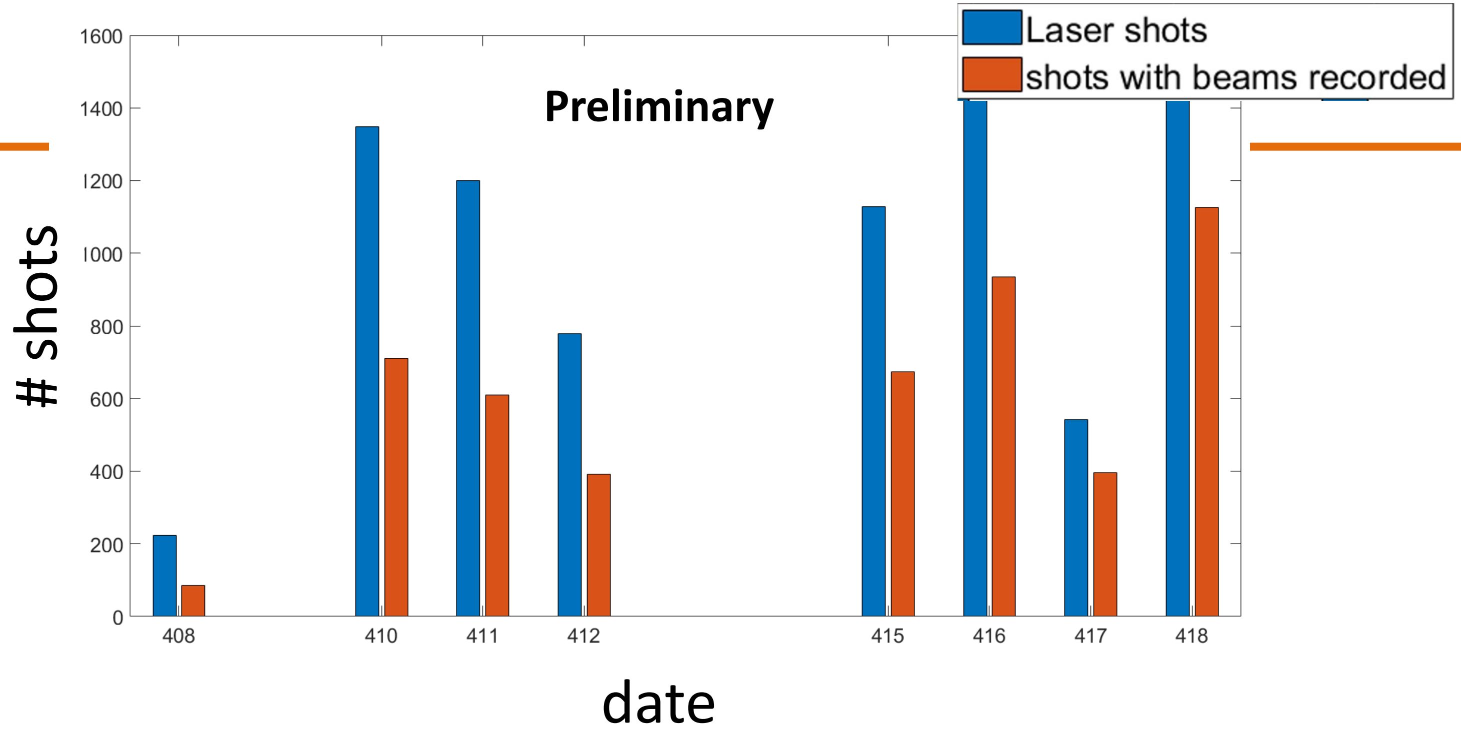
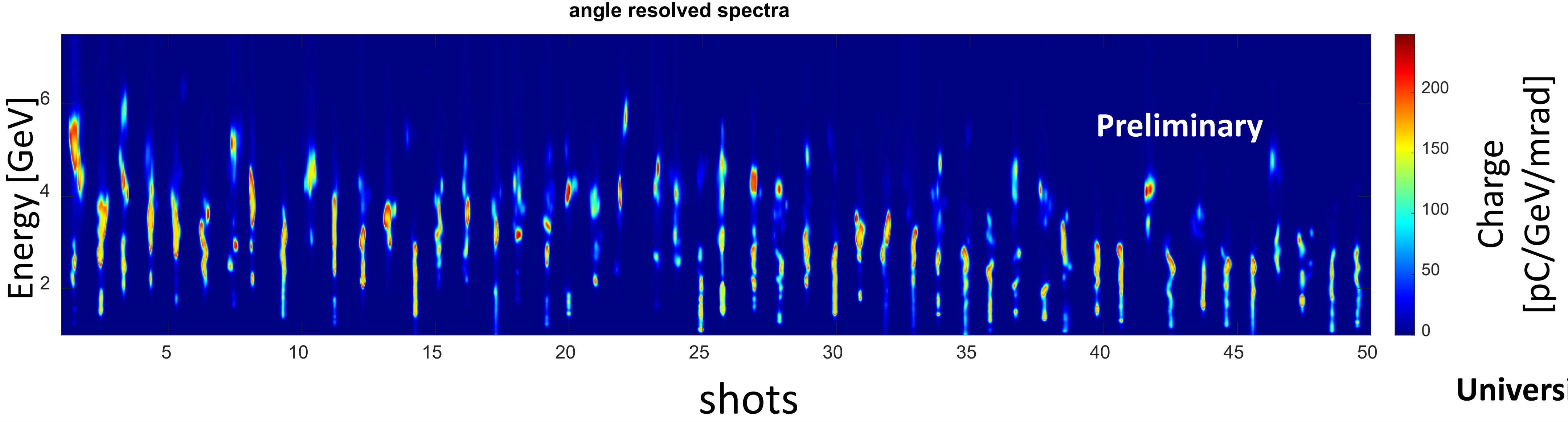


The Electron Beam

- High quality e⁻beams



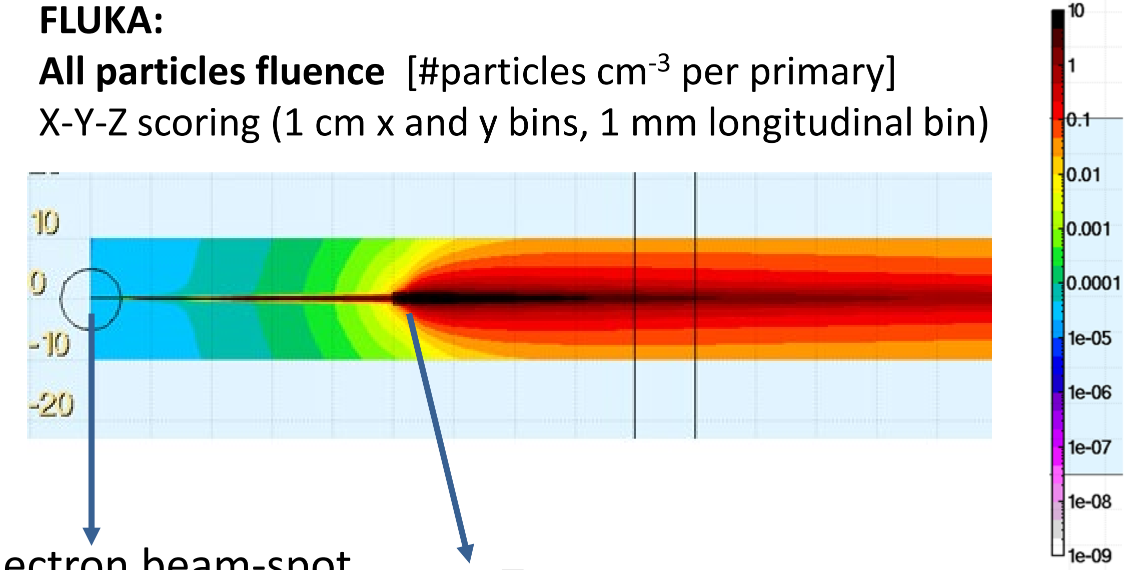


University of Maryland

Muon Generation/Detection Experiment

FLUKA Monte Carlo Simulation Parameter
Primary Particle: electrons
Gaussian beam radial profile: $FWHM_{x,y}$=0.0015 cm
Energy spectrum: monochromatic 5 GeV

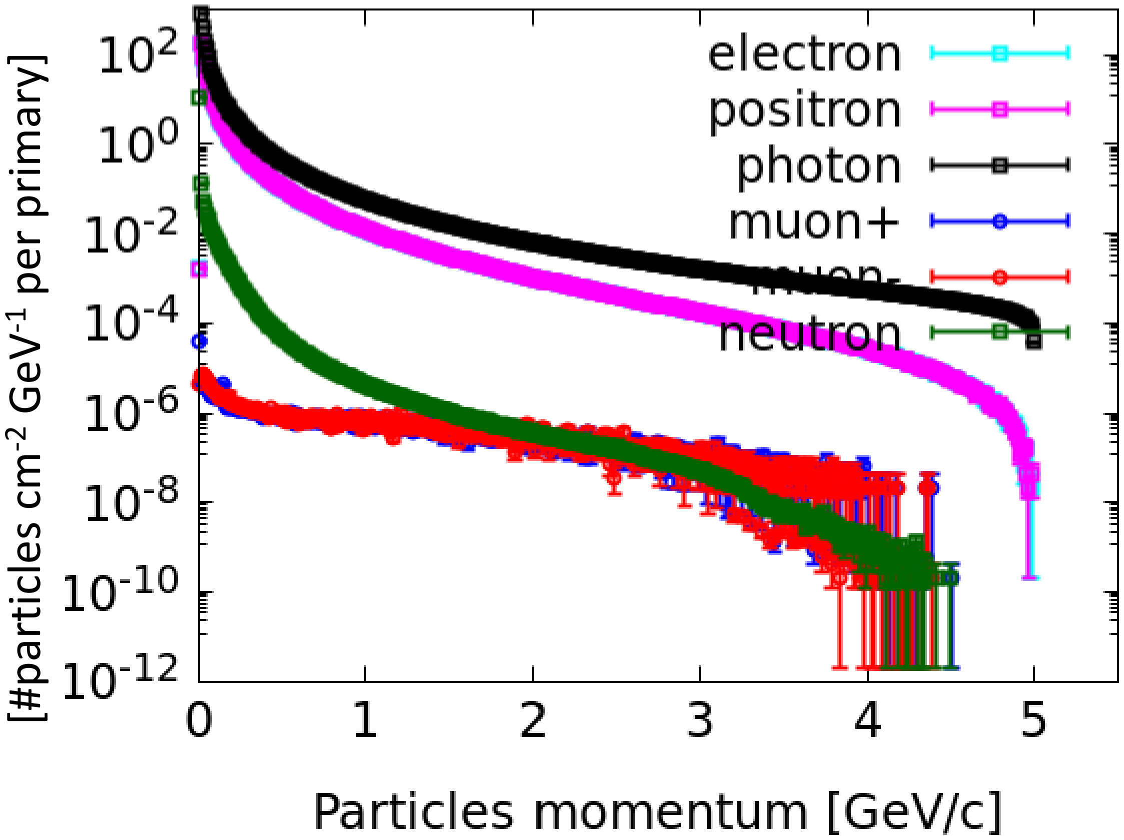
FLUKA:
All particles fluence [#particles cm^{-3} per primary]
X-Y-Z scoring (1 cm x and y bins, 1 mm longitudinal bin)



Electron beam-spot

Tungsten converter

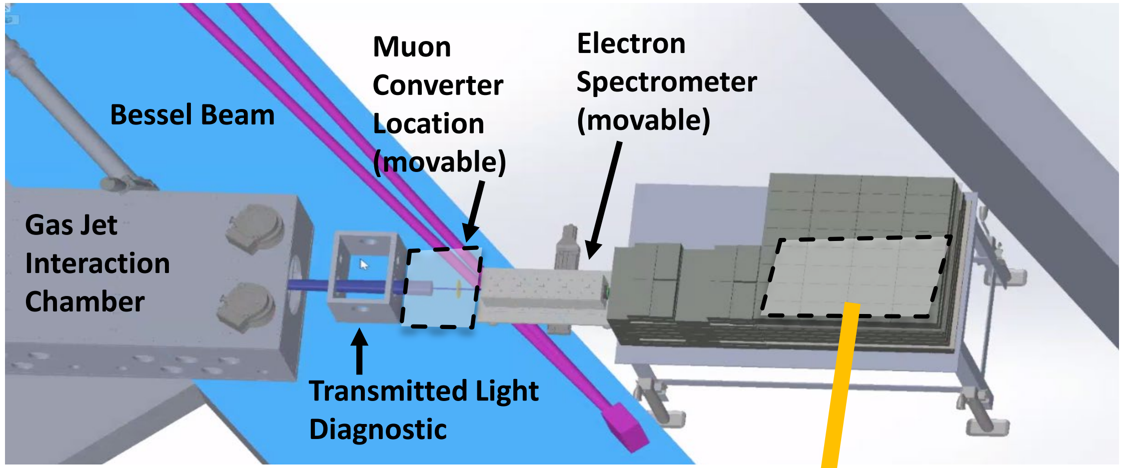
FLUKA Simulation Results – 5 GeV electrons

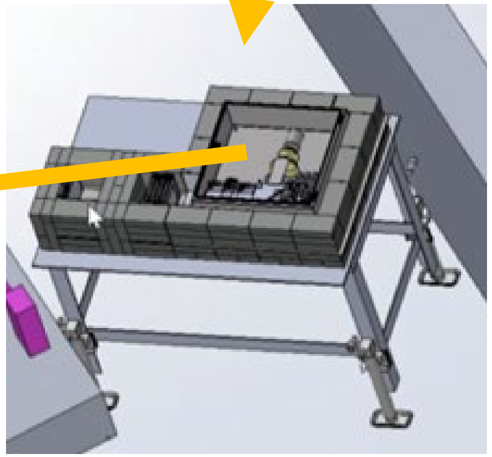


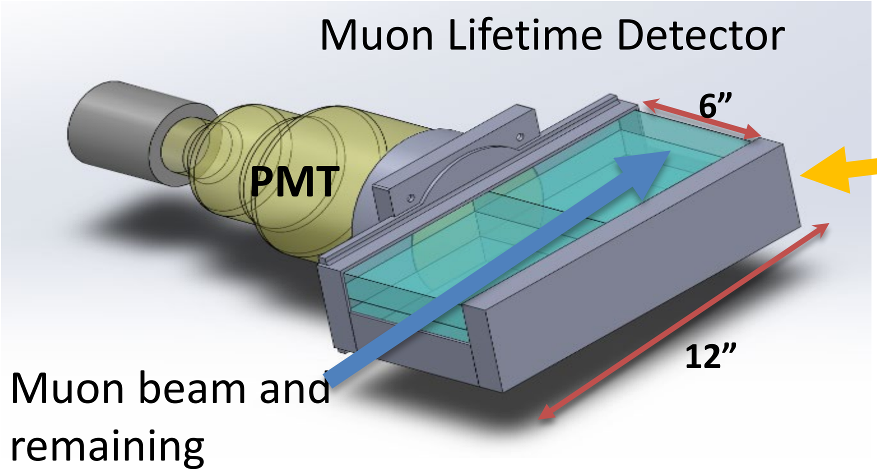
ELI Beamlines

Muon Generation/Detection Experiment

- <u>Large scintillator-PMT muon decay detector</u>
  - Preliminary results from lifetime detector will be presented today.





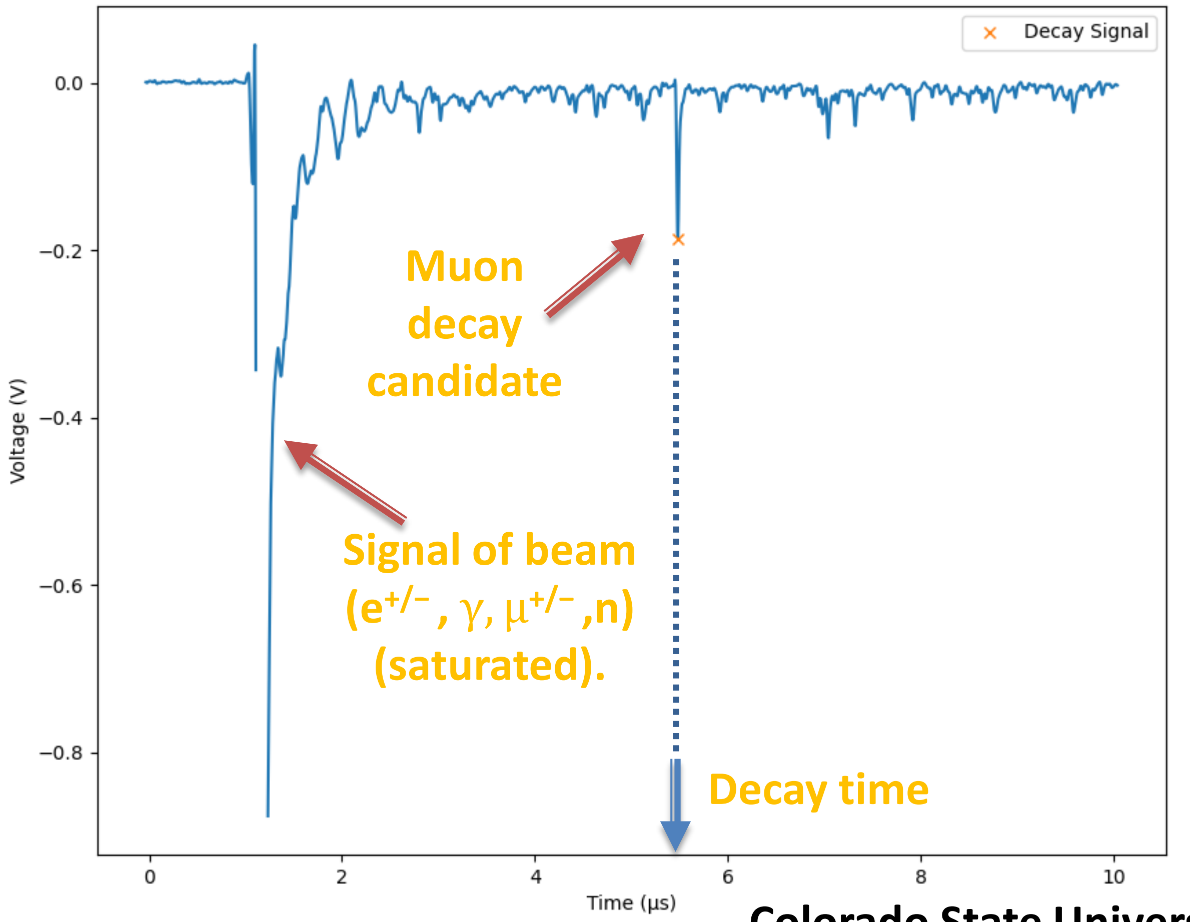


Colorado State University

Representative "raw" detector PMT signal showing muon decay candidate

- Most of the beam goes through the plastic producing the large initial signal in the detector in the figure. This determines the time of arrival of the muons.
- A fraction of the muons stop in the plastic and decay. This signal is also recorded by the PMT. The plot shows the time of one muon candidate muon decay.
- Many traces show multiple peaks corresponding to multiple muons as well as other peaks at later timeframes, potentially neutrons.
- Background has been studied (no-laser setup)

Preliminary
Raw PMT signal from a single shot

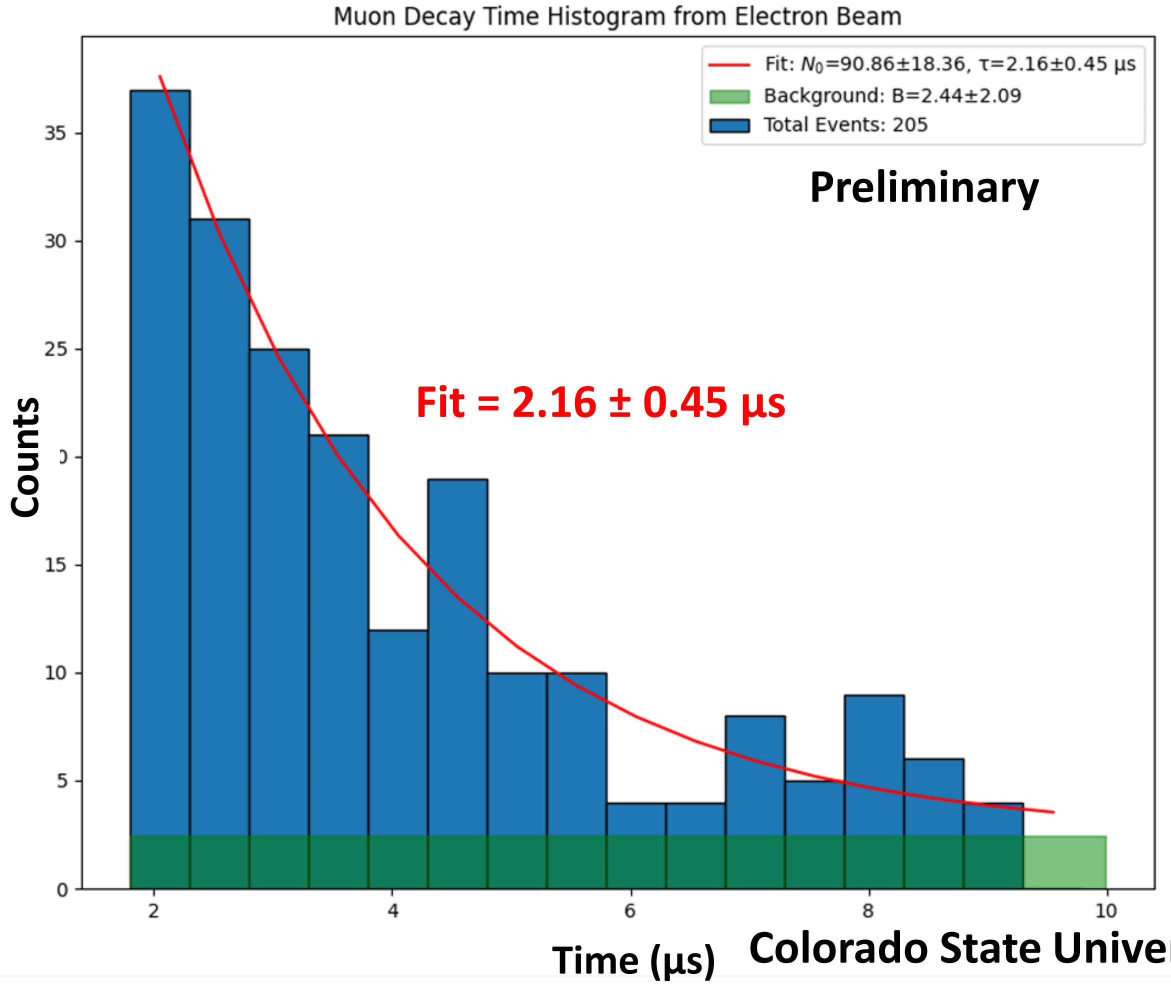


Colorado State University

Preliminary analysis of a portion of the data shows definitive muon detection!

- Preliminary analysis of a subset of the data (171) is here presented
- The histogram shows a count of muon candidates as a function of their time of decay.
- The measured muon counts closely match the theoretical exponential decay curve with the well-known 2.1969811± 0.0000022 µs (PDG value) muon lifetime.
- Paper in preparation.

<1 day of CSU muon candidate signals (200 MHz bandwidth oscilloscope)



Colorado State University

Monte Carlo FLUKA simulations support conclusion that candidate signal originates from muons and not other particles

Primary Electron Beam

Gaussian momentum:

p_z=6.5 GeV, $FWHM_z$=0.5 GeV

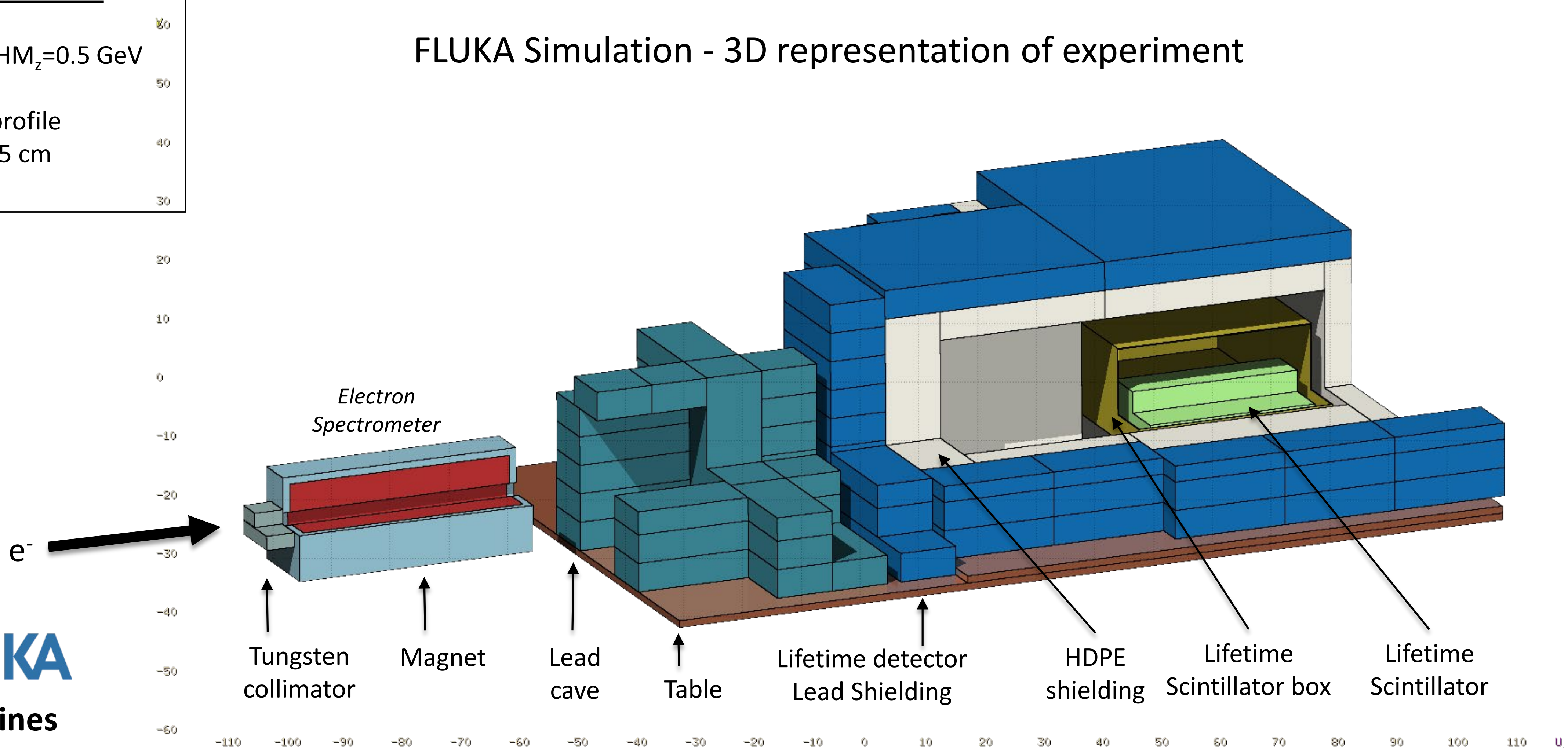
p_θ=10 mrad

Gaussian beam radial profile

$FWHM_{x,y}$=0.0015 cm

#Primaries = 1.2e11

FLUKA Simulation - 3D representation of experiment



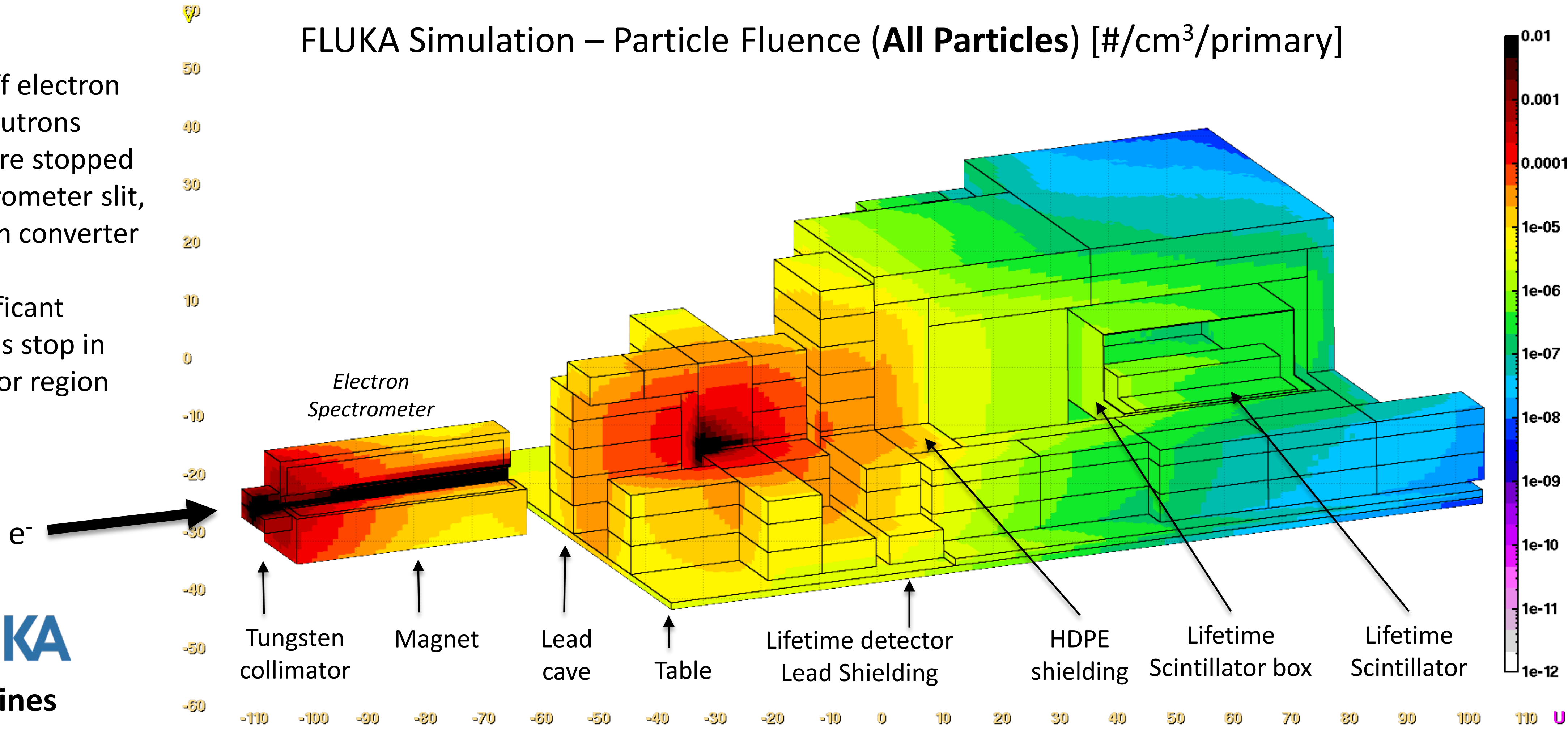
FLUKA

ELI Beamlines

Monte Carlo FLUKA simulations support conclusion that candidate signal originates from muons and not other particles

Observations:

- Most particles off electron beam axis are neutrons
- Most electrons are stopped at e-beam spectrometer slit, remainder stop in converter 'cave'
- Statistically significant number of muons stop in lifetime scintillator region



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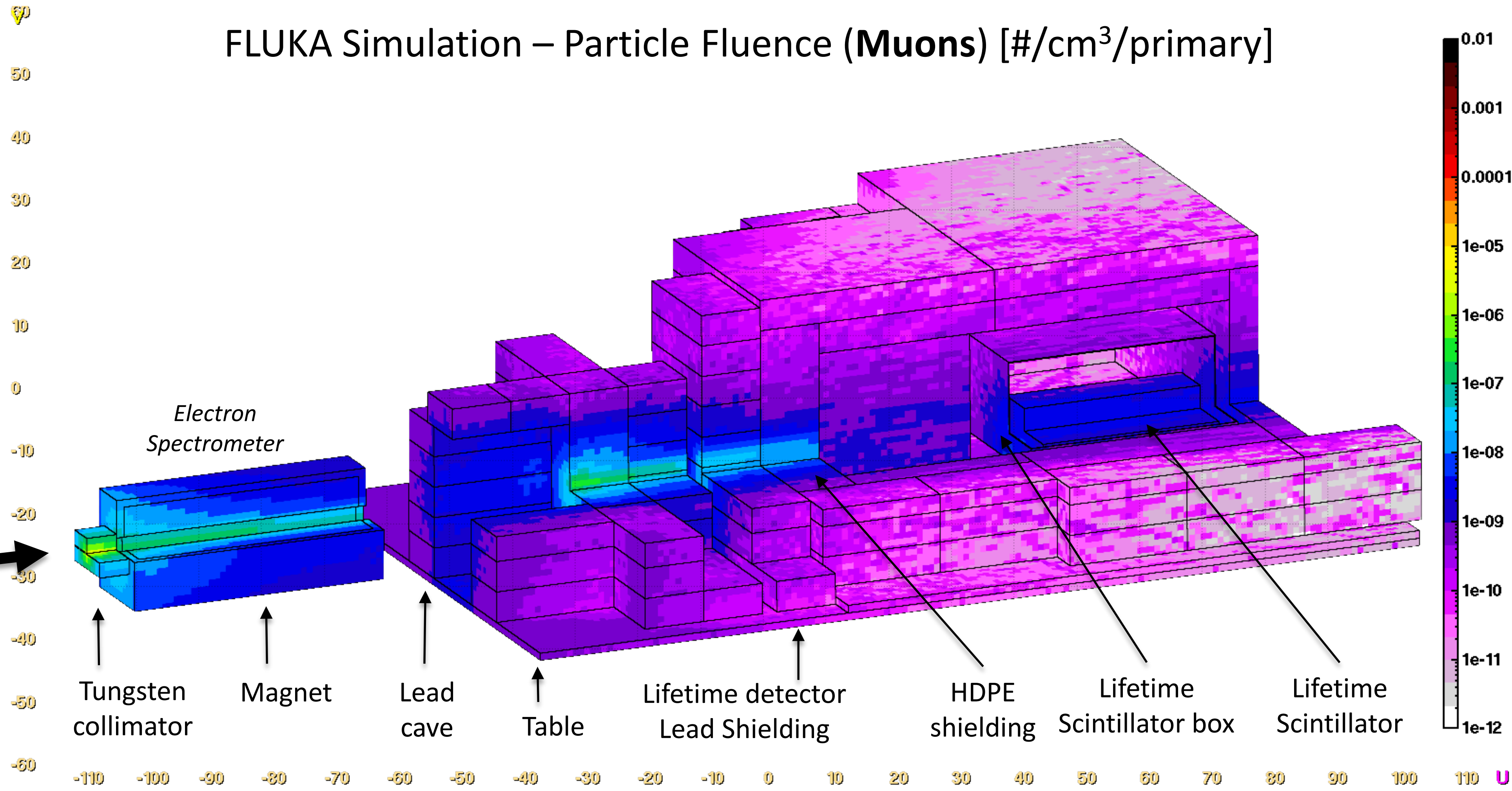


FLUKA

ELI Beamlines

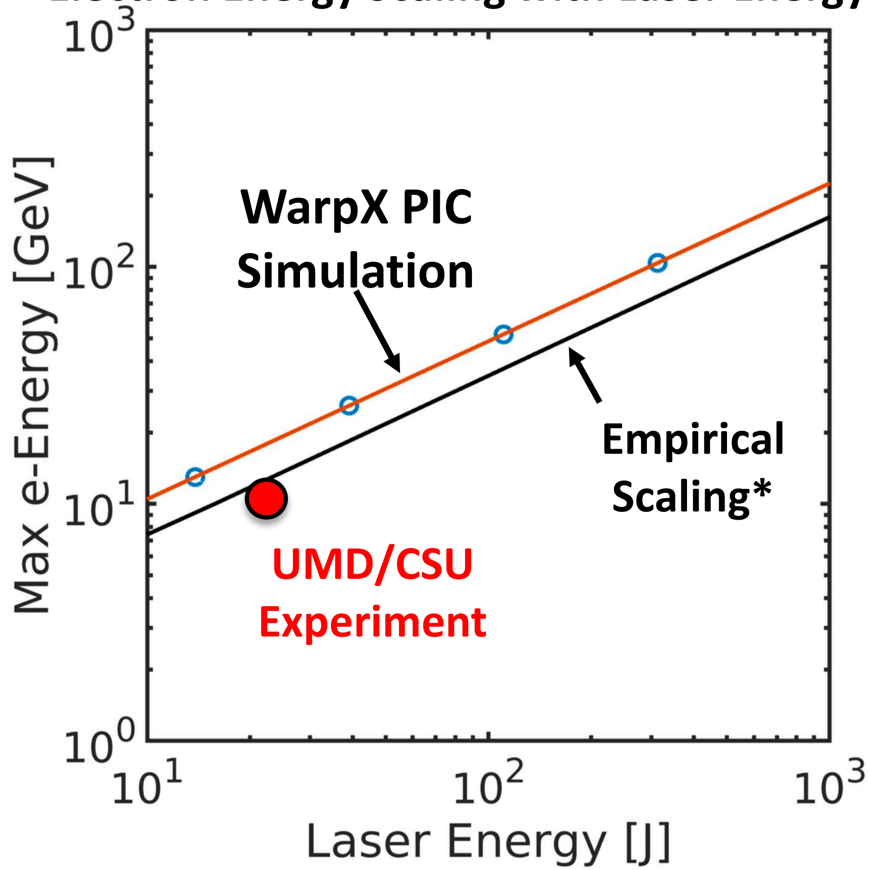
Future Plans - Phase 2

- Awaiting approval of Phase 2 (autumn 2024)
- Theoretical studies and simulation to extend <10 GeV experiments at CSU to 100 GeV at ELI Beamlines (10 PW, 1.5 kJ in 150 fs, 1 pulse/min)

In Support of experiments

Warp-X PIC RZ simulation of future LWFA experiment

Electron Energy Scaling with Laser Energy

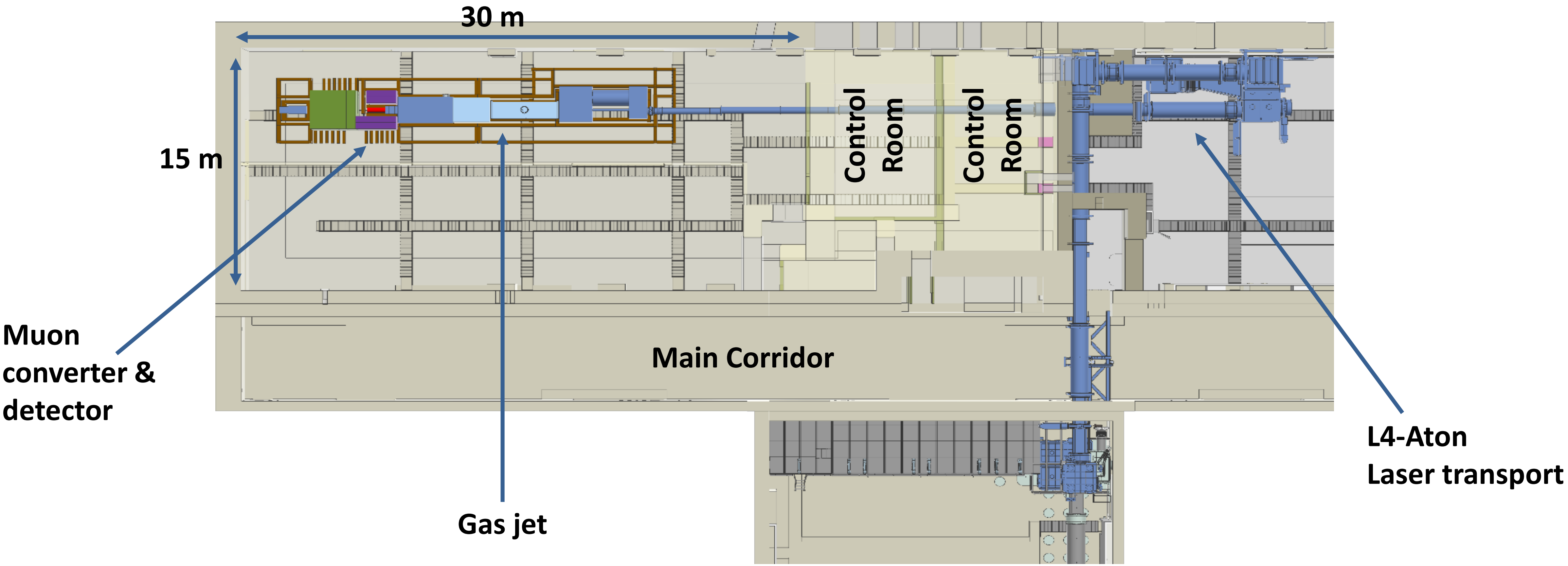


J. Ludwig, et al., *Laser-Based 100 GeV Electron Acceleration Scheme for Muon Production*, Submitted to PRX 2024

*W. Lu, et al", IEEE Particle Accelerator Conference (PAC) (2007)

Future Plans – Phase 2

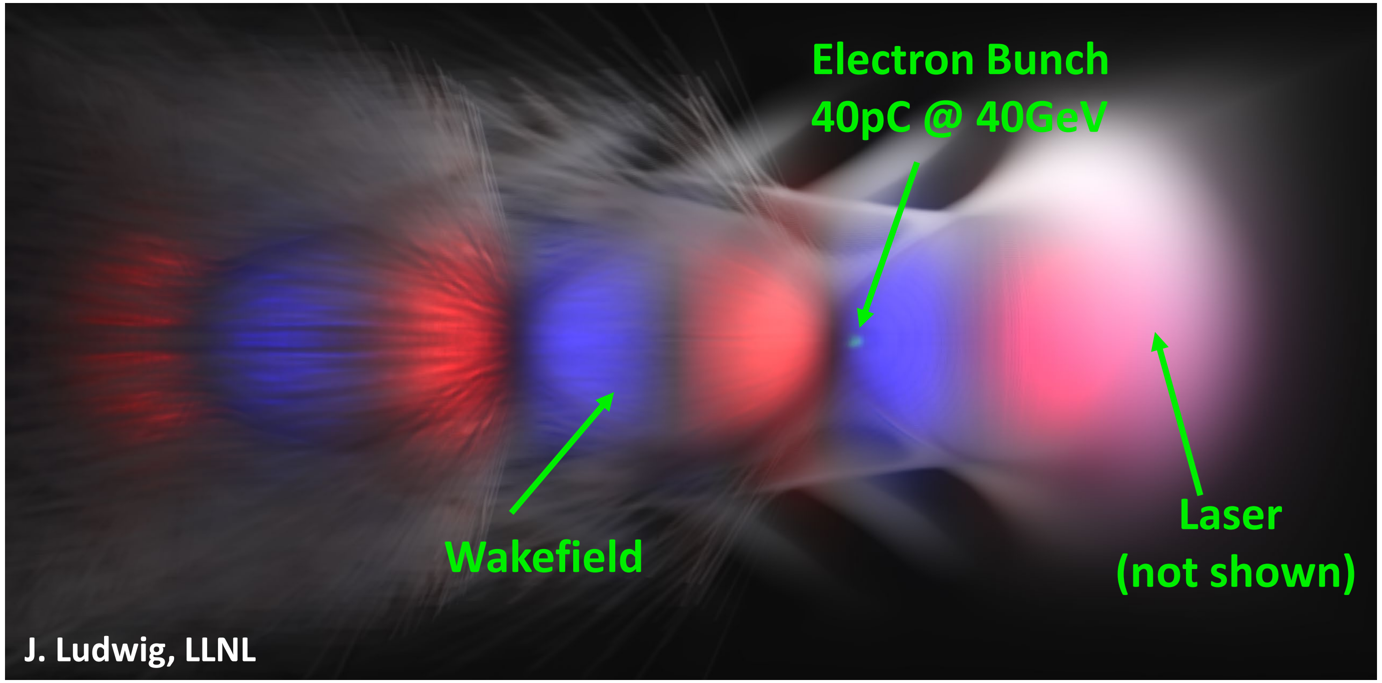
- Construction work at ELI Beamlines
- 2 experimental halls are involved
- New simulations are need (redesign of the control rooms, monitoring system, interlock…)



Thank you for your attention

Laser Wake Field Acceleration and Muon Beams

- Laser Wake Field Acceleration (LWFA)
  - high intensity (PW-class) ultra-short (fs) lasers propagate inside a gas ionizing it and expelling the plasma electrons
  - a wake is created behind the laser in which acceleration gradients of up to **hundreds of GV/m** can be achieved.
  - the high degree of non-linearity in the components of a LWFA complicates the control and the capacity to understand which conditions to aim to



ICMuS2 Collaboration

Colorado State University

~10 GeV LWFA
Muon Detector Development
Initial Muon Production Demo
Plasma Simulations

High Rep. Rate, Model-Driven Plasmas

Lawrence Livermore National Laboratory

LWFA and Muon Models
High Rep Rate Expt
Model-based Expt Direction
ConOp Simulations
Tm:YLF Laser Driver Dev.
Systems Integration

HAPLS 10H PW Laser

eli beamlines

High Energy LWFA
>10 GeV Muon Production Demo
LWFA Theory
Muon Detection

High Ave. Power Lasers

WARP-X LWFA Sims

LWFA

University of Maryland

Waveguides for LWFA
LWFA Experiments and Models

XUV Lasers

Cryo Yb:YAG Laser Driver Dev.

Berkeley Lab

LWFA Simulations and Experiments

Lockheed Martin

System Ruggedization
Tech Transfer

Existing Collaboration

FLUKA

- hadron-hadron and hadron-nucleus interactions
- nucleus-nucleus interactions (including deuterons!)
- photon interactions (>100 eV)
- electron interactions (> 1 keV; including electronuclear)
- muon interactions (including photonuclear)
- neutrino interactions
- low energy (<20 MeV) neutron interactions and transport
- particle decay
- ionization and multiple (single) scattering (including all ions down to 250 eV/u)

- coherent effects in crystals (channelling)
- magnetic field, and electric field in vacuum

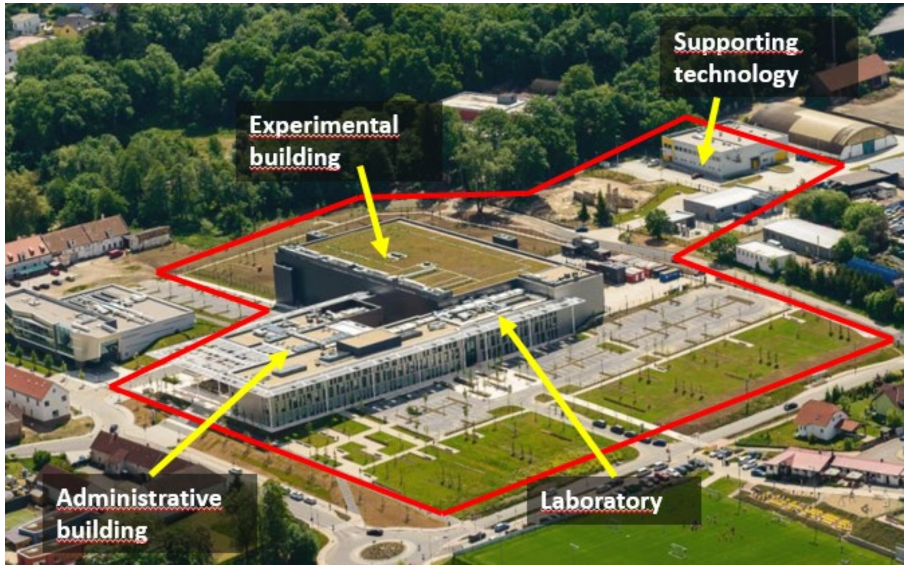
- combinatorial geometry and lattice capabilities
- voxel geometry and DICOM importing
- analogue or biased treatment
- on-line buildup and evolution of induced radioactivity and dose
- built-in scoring of several quantities (including DPA and dose equivalent)

In support of a
wide range of applications

✓Accelerator design
✓Particle physics
✓Cosmic ray physics
✓Neutrino physics
✓Medical applications

✓Radiation protection (shielding design, activation)
✓Dosimetry
✓Radiation damage
✓Radiation to electronics effects
✓ ADS systems, waste transmutation
✓Neutronics

ELI Beamlines



Laser	Energy [J]	Power [TW]	Rate [Hz]
L1 (ALLEGRA)			
(present)	0.03	1.5	10^3
(target)	0.1	5	10^3
L2 (AMOS)	2	10^3	50
L3 (HAPLS)			
(present)	30	333	3.3
(target)	30	10^3	10
L4 (ATON)	$2\cdot10^3$	10^4	0.1

- ELI Beamlines, part of the ELI project, is a laser driven user facility located just south of the city of Prague.
  - It aims at investigating high-field high-density physics, developing high-brightness sources of X-rays, as well as secondary proton, electron, and ion beams, for interdisciplinary applications in physics, medicine, biology, and material sciences
- The experimental building houses four main laser systems labeled L1 (ALLEGRA), L2 (AMOS), L3 (HAPLS), and L4 (ATON)
- Ionizing radiation will be produced in at least 9 experimental stations.

ELI Beamlines Laser Systems

L1 – ALLEGRA

Technology
- OPCPA
- Circular
- Gaussian
- Synchronized probe beam

Parameters

Nominal	Current
100 mJ	55 mJ
1 kHz	1 kHz
15 fs	15 fs

Expected Electron Energy 10-100 MeV

L2 – DUHA

Technology
- OPCPA
- Circular
- Flat-top
- Synchronized mid-IR pulse

Parameters

Nominal	Current
J	WORK
10s Hz	IN
<40 fs	PROGRESS

Expected Electron Energy 0.1-1 GeV

L3 – HAPLS

Technology
- Ti:Sapphire, DPSSL
- Square, 250x250 mm^2
- Flat-top

Parameters

Nominal	Current
30 J	13 J
10 Hz	3.3 Hz
30 fs	30 fs

Expected Electron Energy 1-10 GeV

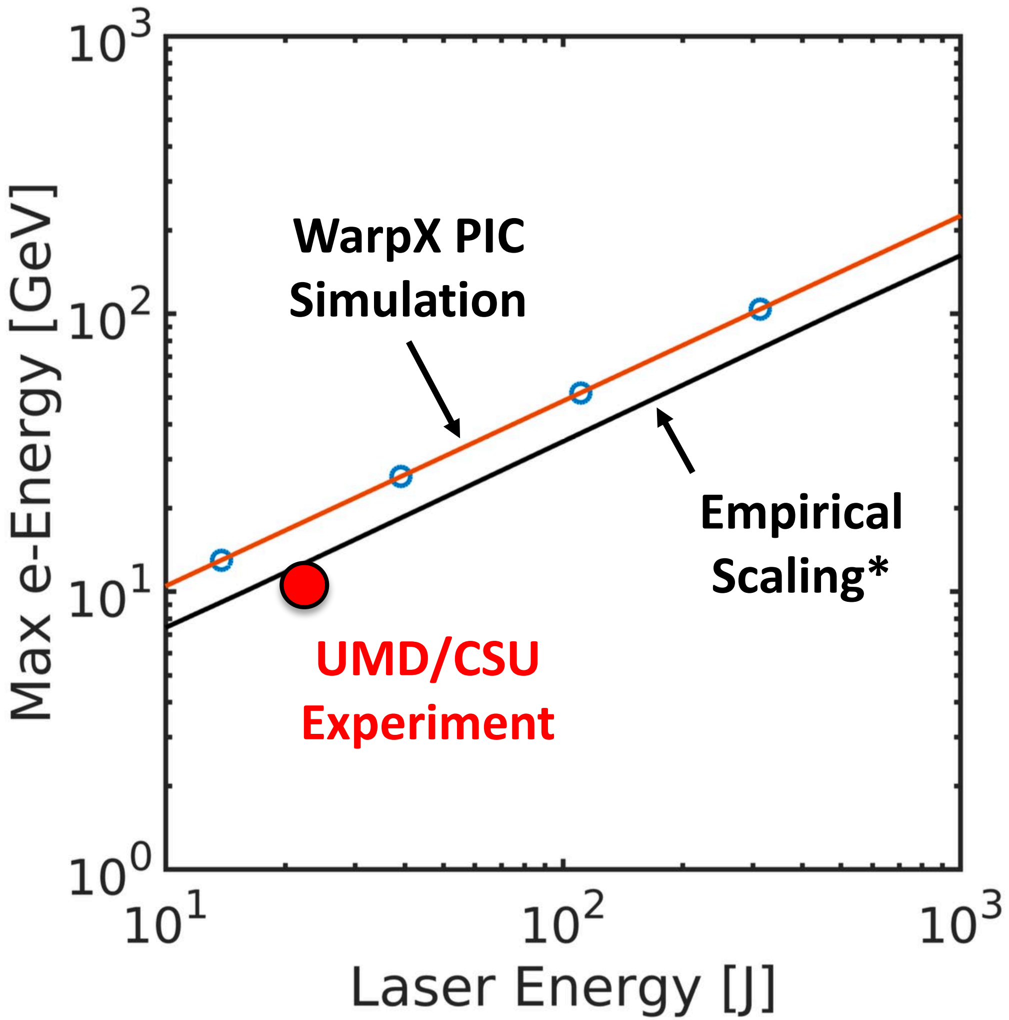
L4 – ATON

Technology
- Nd:glass
- Square, 550x550 mm^2
- Flat-top
- Longer beams (ns and ps)

Parameters

Nominal	Current
1.5 kJ	WORK
1/min	IN
150 fs	PROGRESS

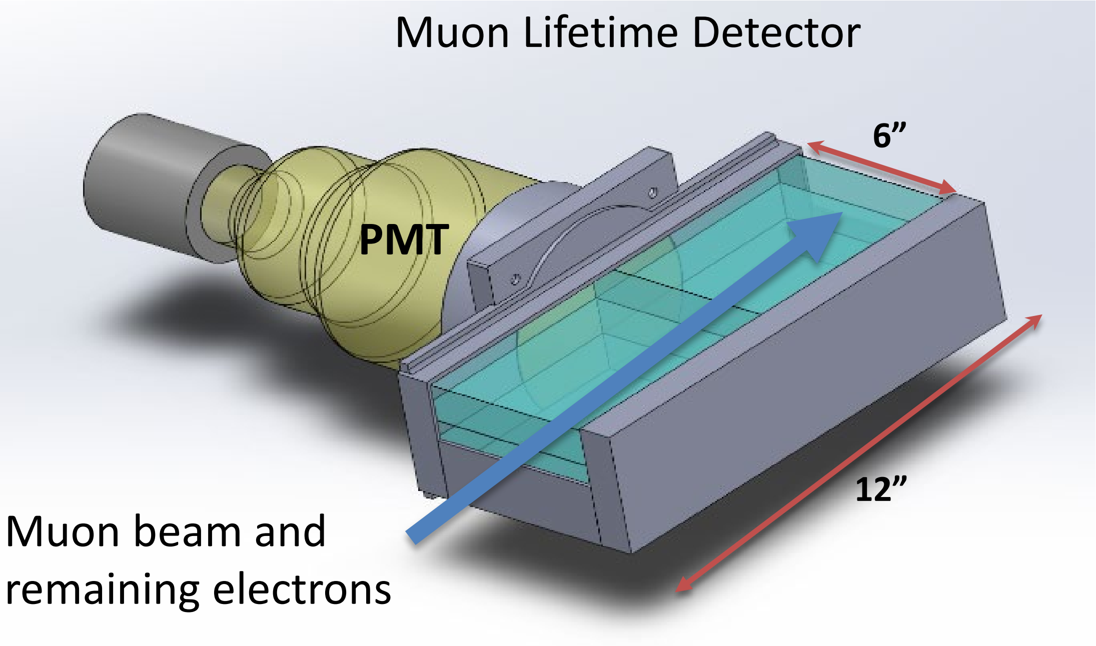
Expected Electron Energy 10-100 GeV



- Simulations show electron acceleration to 100 GeV is achievable within the framework of existing and demonstrated single stage laser wakefield accelerators (LWFA)

*W. Lu, et al. Phys. Rev. ST Accel. Beams **10**, 061301 (2007)

Muon Lifetime Detector

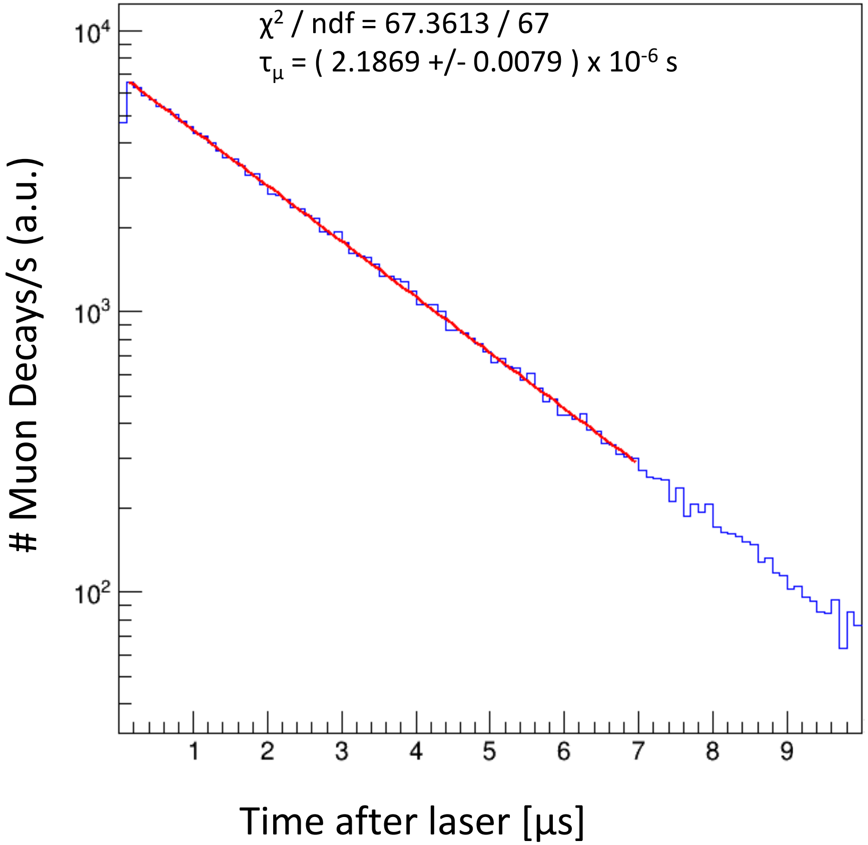


- The e-beam was directed onto either the converter target or the tungsten slit of the magnetic spectrometer, which in this case acts as the converter.
- Downstream of the converter/spectrometer, the beam was attenuated by ~30 cm of lead and directed into the detector which consists of 12” x 6” x 3” scintillating plastic coupled to a photomultiplier tube (PMT).
- Function was verified by exposing the detector to cosmic ray muons and decay signals from stopped muons were seen.
- Signals originating from the main beam and from decays of any muons trapped in the detector were digitized and recorded for the 10 μs following high energy laser shots.

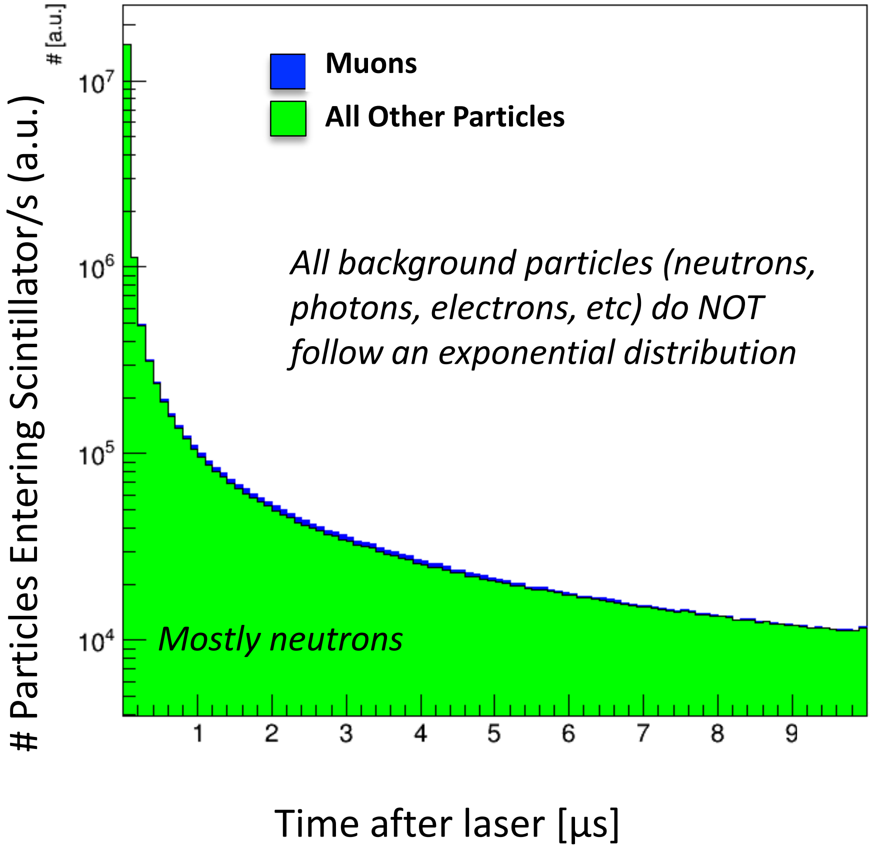
Colorado State University

Monte Carlo FLUKA simulations support conclusion that candidate signal originates from muons and not other particles

FLUKA:Time at which a muon decay is recorded inside scintillator



FLUKA: Time at which any particle enters scintillator volume



ELI Beamlines