MUON SCATTERING TOMOGRAPHY WITH LASER-PLASMA-ACCELERATOR-DRIVEN MUON SOURCE

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Acknowledgements

MPL - Plasma Accelerator and Laser Group at DESY

See out webpage at plasma.desy.de
For a full list of teams and activities

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External Partners

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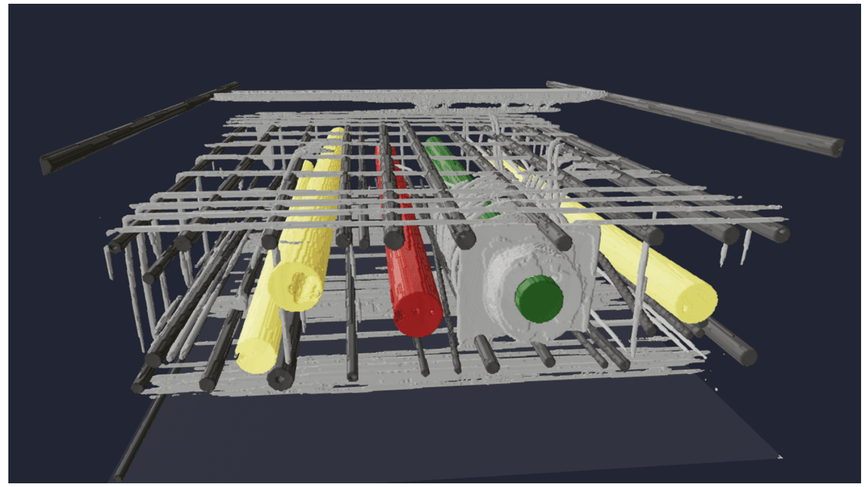
MU-RAY TECH Andi Hektor

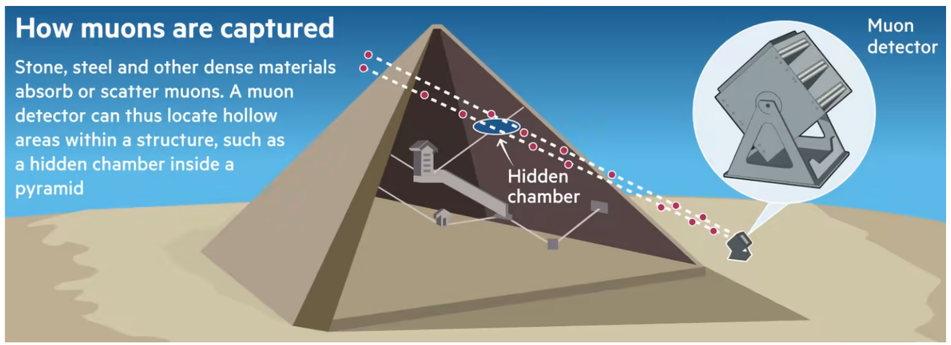
Muons are very powerful tool for imaging

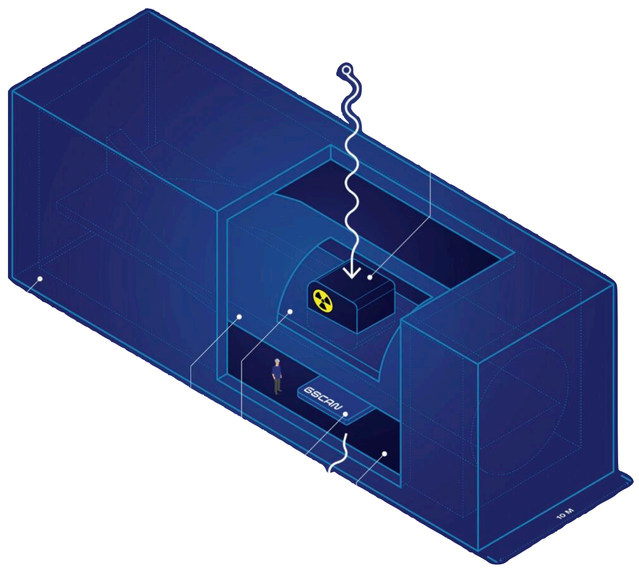
Penetration depths much greater than gamma-rays, while depositing much less dose

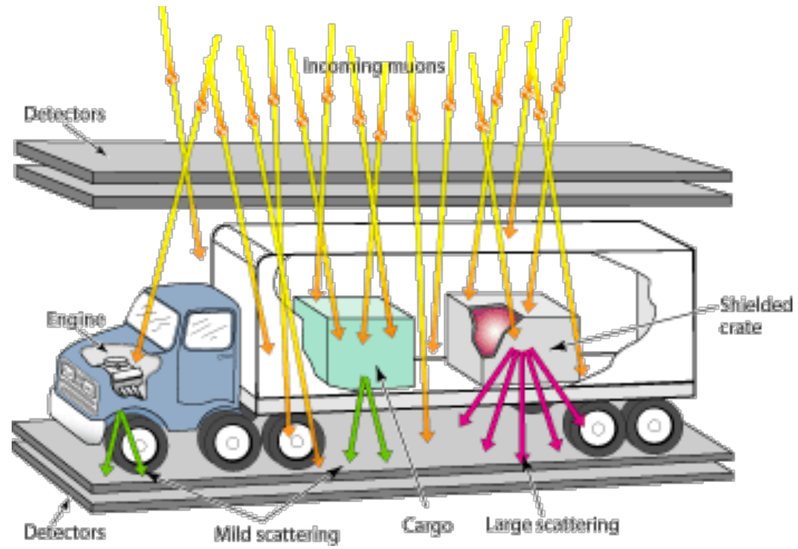
Muons penetrate deep into matter, thereby allowing

- Non-destructive testing of bridges & key infrastructure
- Non-proliferation checks and nuclear decommissioning (e.g. spent fuel casks)
- Cargo scanning (customs)
- Low-dose medical imaging





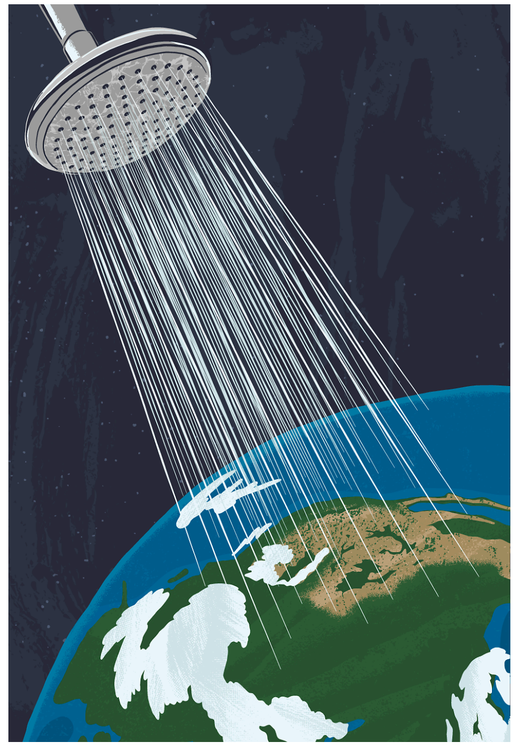




Current muon sources are not suitable for rapid imaging

NDT requirements necessitate a high flux, ideally transportable artificial muon source

- Large-scale artificial sources
  - ISIS (UK), PSI (CH), Osaka (JP), Fermilab (USA), …
  - Specialised in muon spectroscopy: low energies
- Cosmic ray muons
  - Broad energy spectrum peaking ~4 GeV
  - Muons arriving from all hemisphere
  - Low flux 1 muon/minute/cm^2

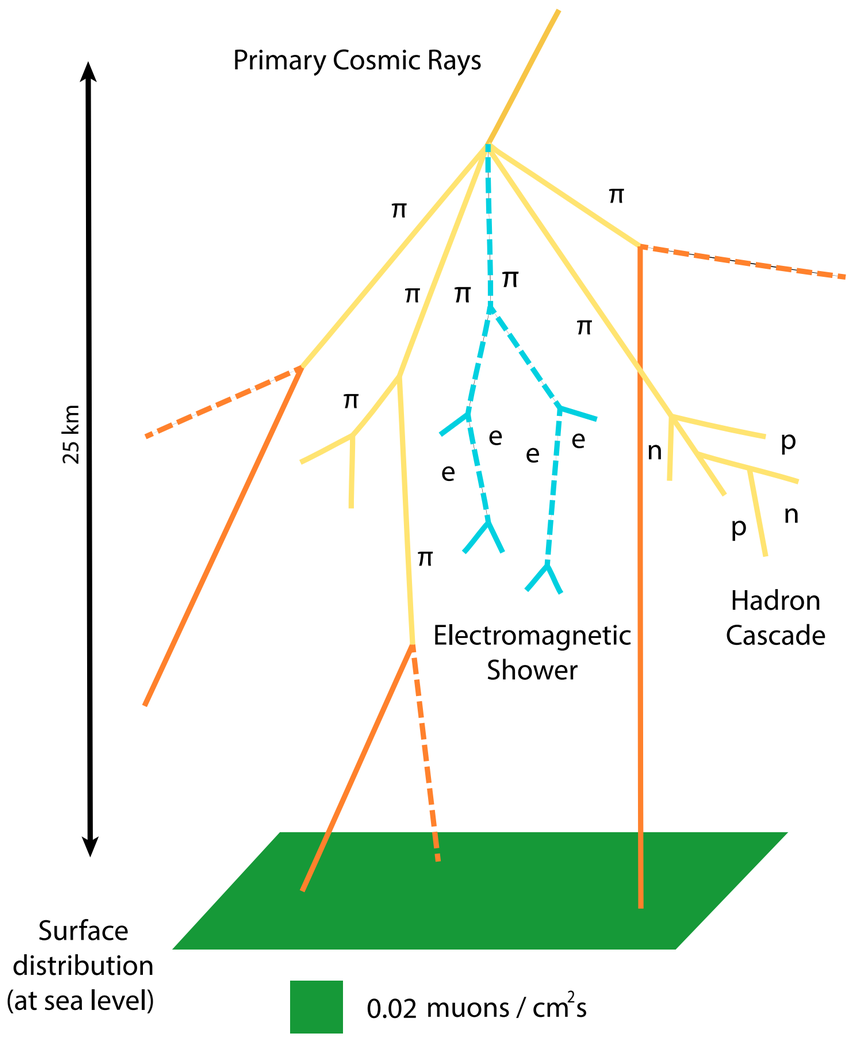


LPAs have potential for huge improvement in flux, energy spectrum and directionality!

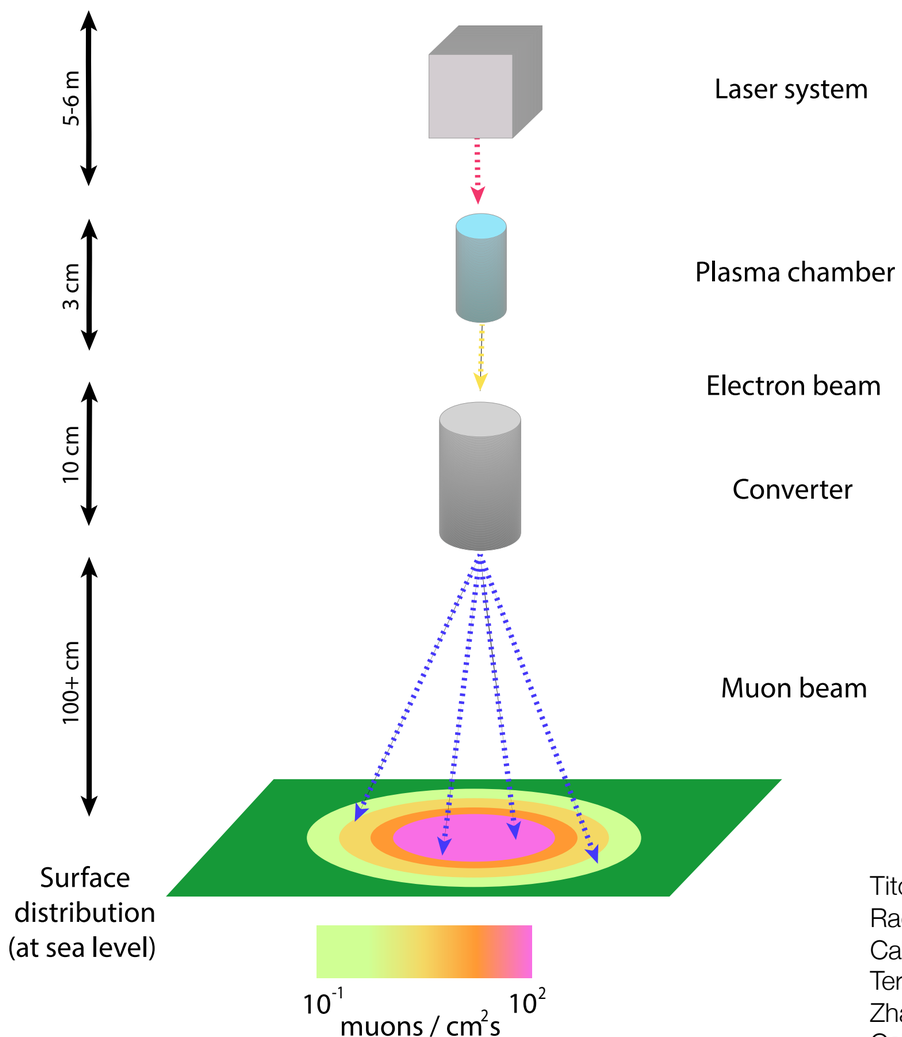
Compact LPA-driven muon sources can provide high flux

GeV-scale electron beams can be converted into large flux of muons

Natural muon flux



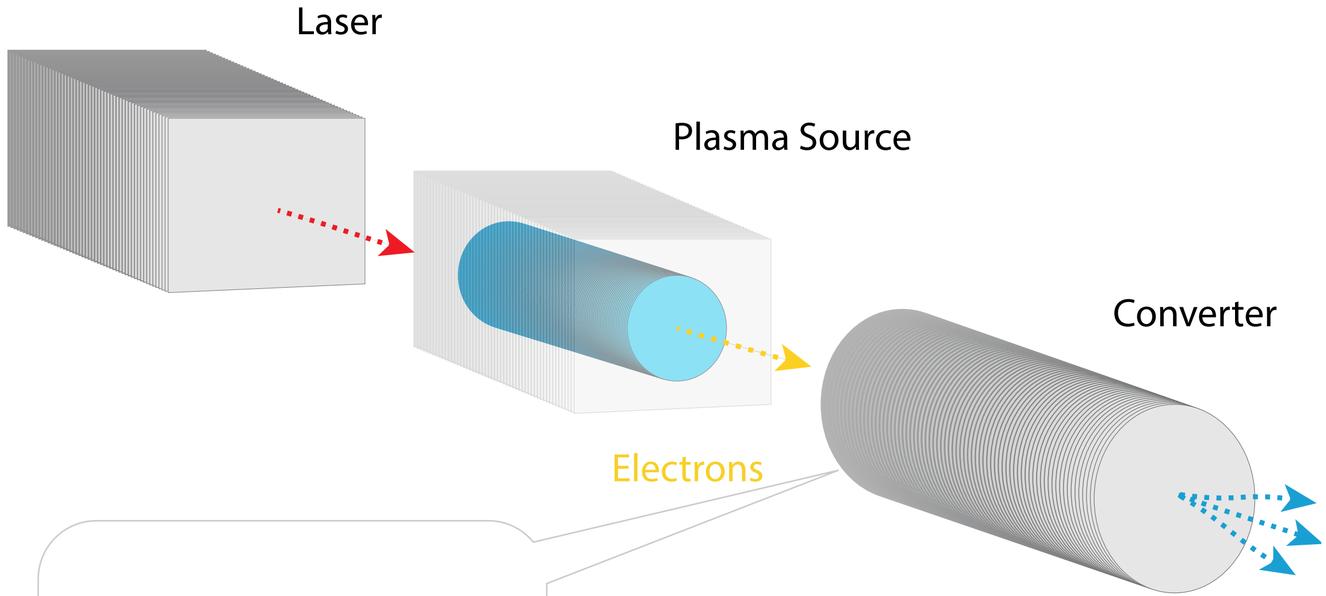
Artificial muon beam

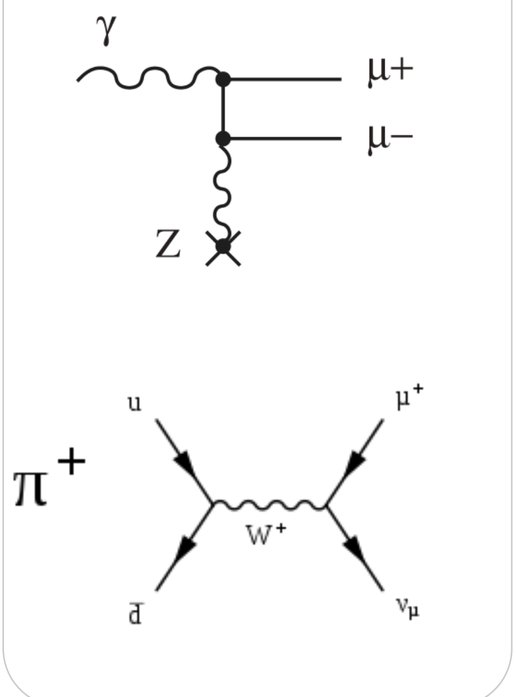


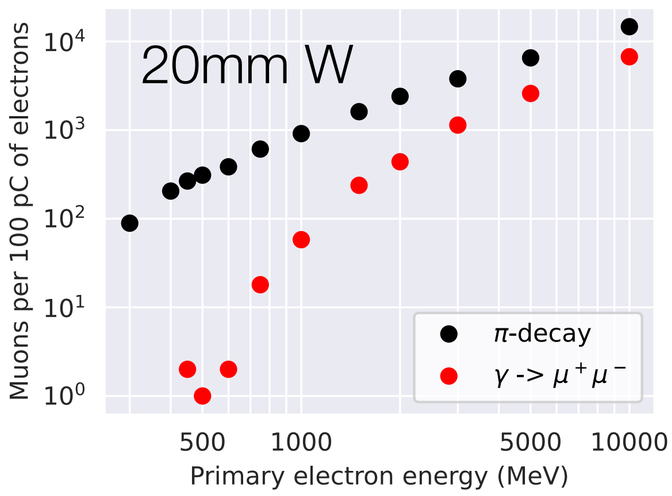
Titov *et al,* PRSTAB **12** (2009)
Rao *et al*, PPCF **60** (2018)
Calvin *et al*, Front. Phys. **11** (2023)
Terzani *et al,* PRAB accepted
Zhang *et al*, Nat. Phys **21** (2025)
Calvin *et al*, arXiv:2503.20904

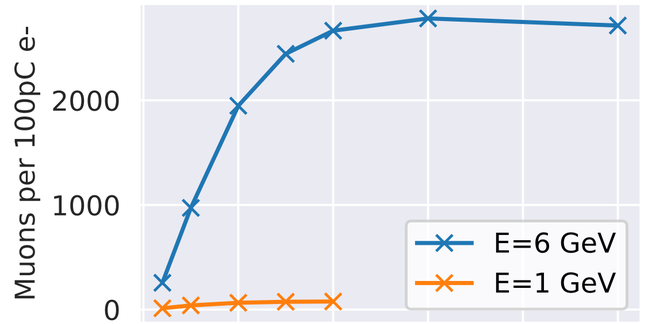
LPA-driven muon sources can provide large flux for imaging

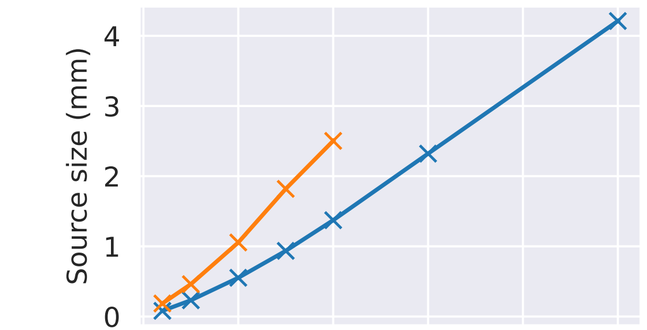
NDT Imaging benefits from high flux and controllable beam shape & spectrum

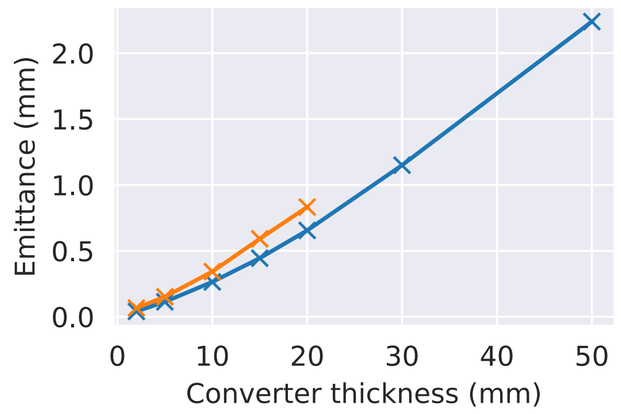








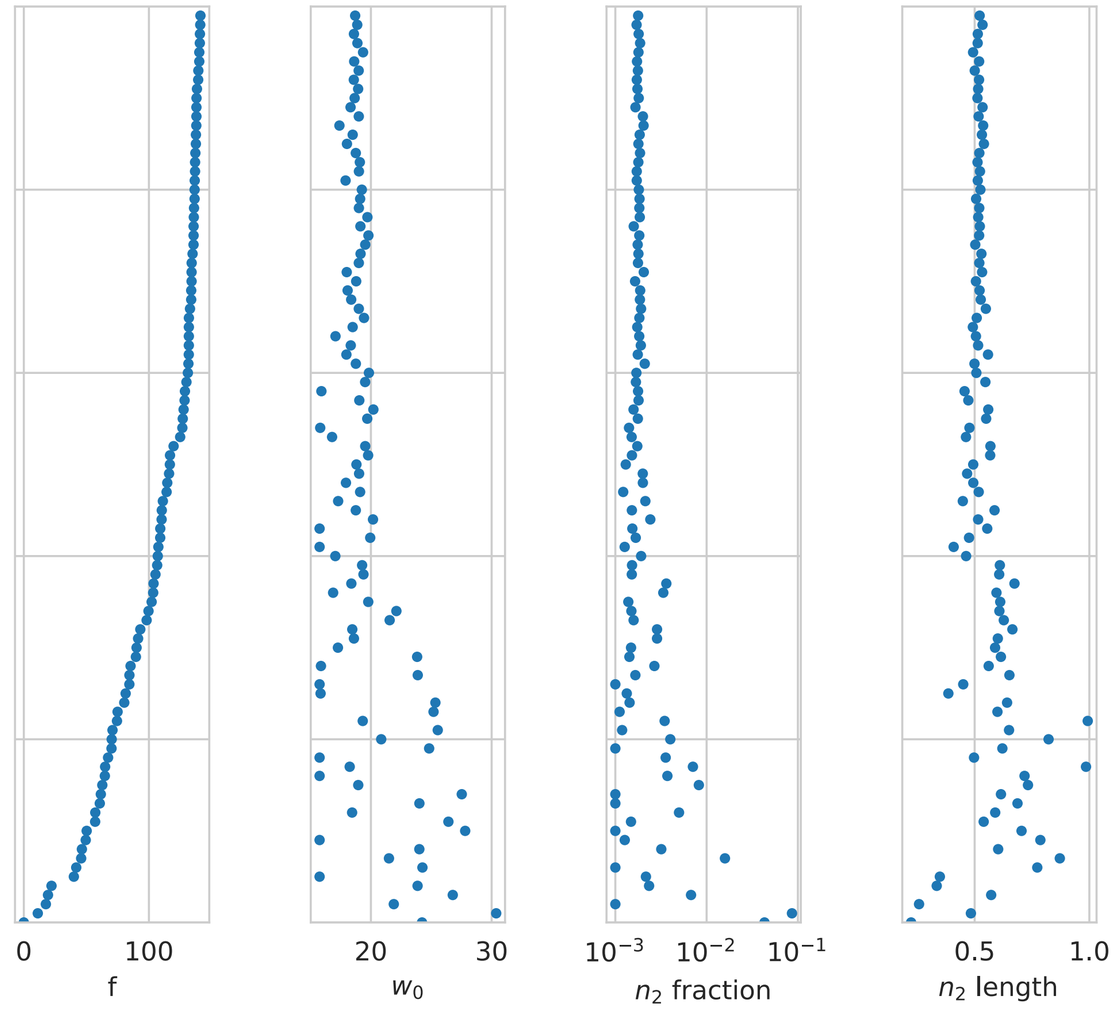




LPAs can be tuned for muon generation

Bayesian Optimisation allows optimising for a particular muon beam property

- 100TW laser pulse focussed into HOFI channel
  - Ionisation injection with nitrogen
  - Varying w_0, n_{N2}/n_e, z_f, l_{ne}
- Muon generation with lookup table
- Fitness function is photomuon count
  - Beam size, emittance etc could also be used



Shalloo *et al*, PRAB **22** 041302 (2019)

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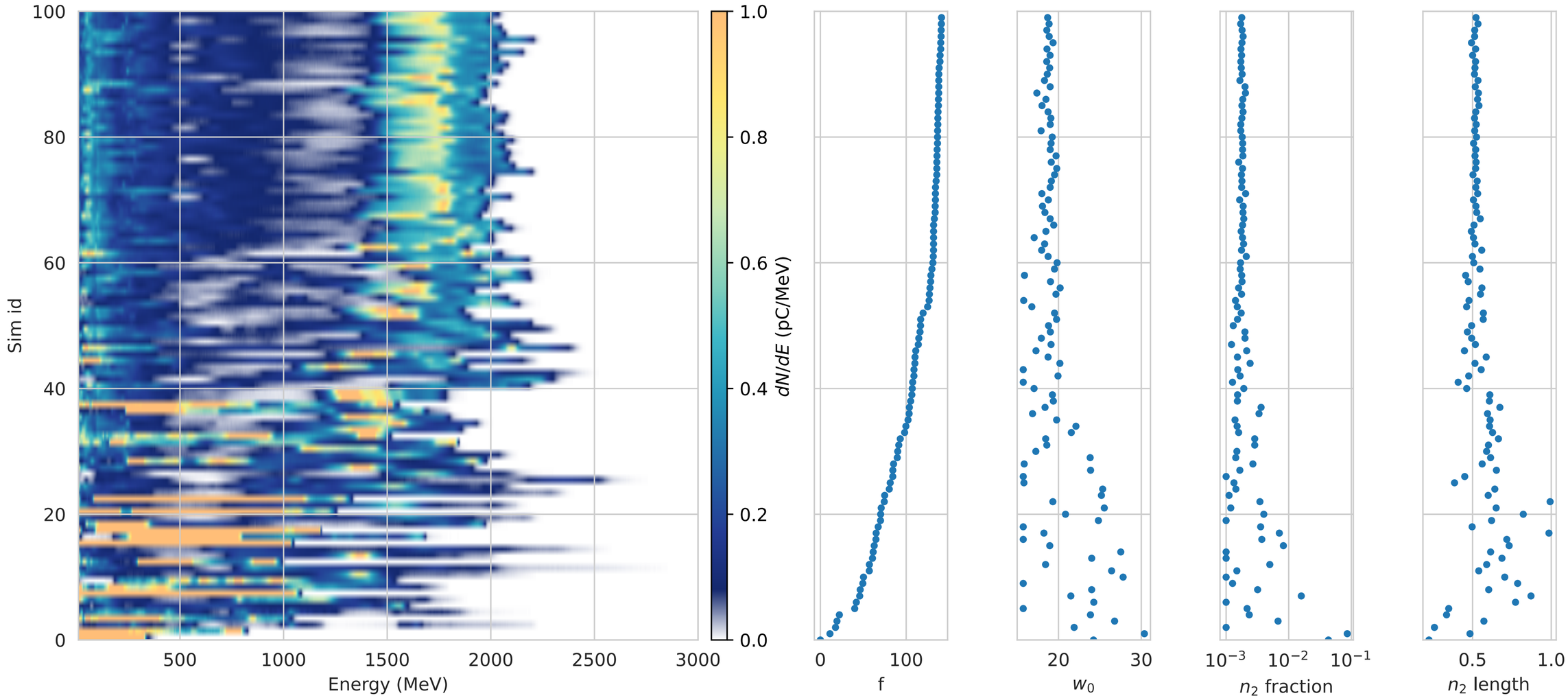
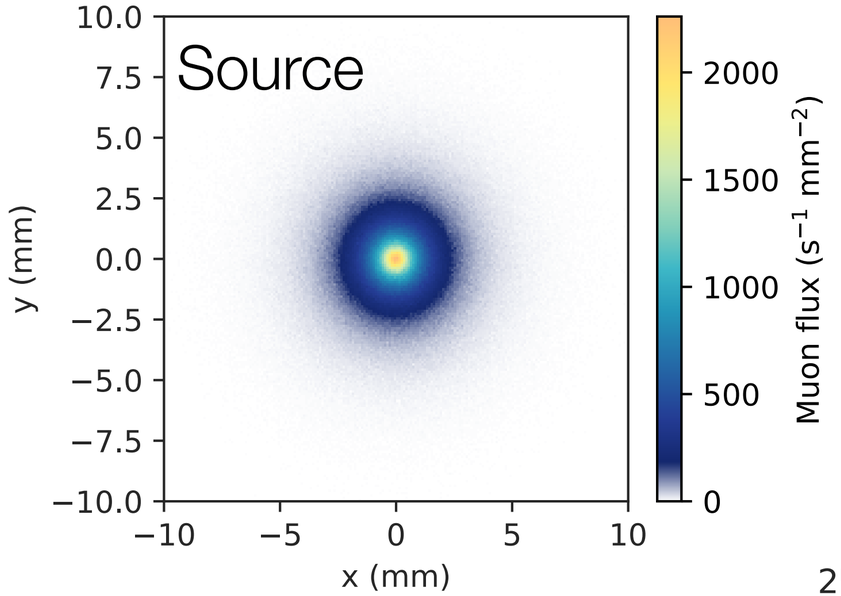


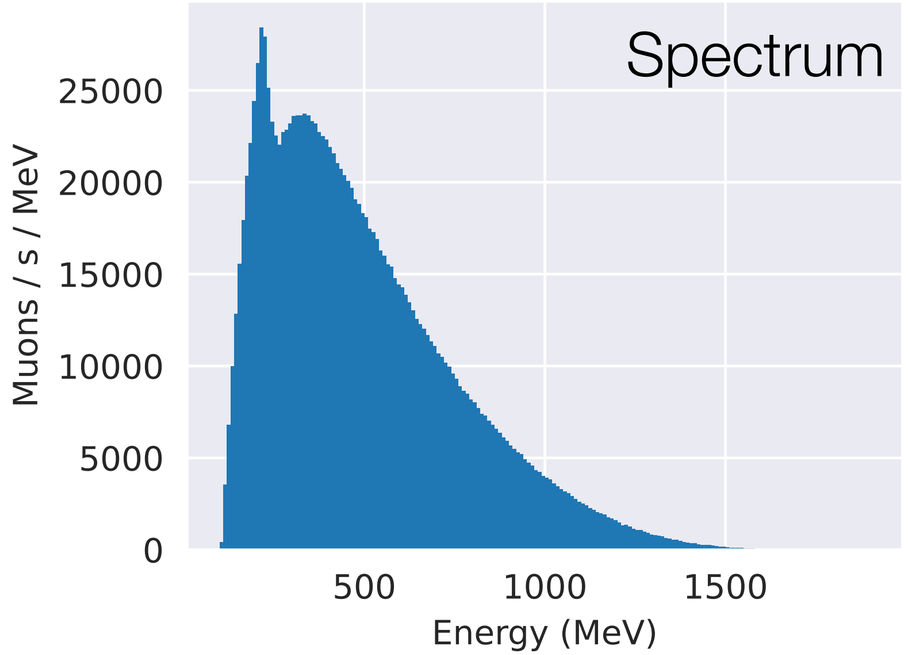
Optimisation results in ~1600 muons per shot

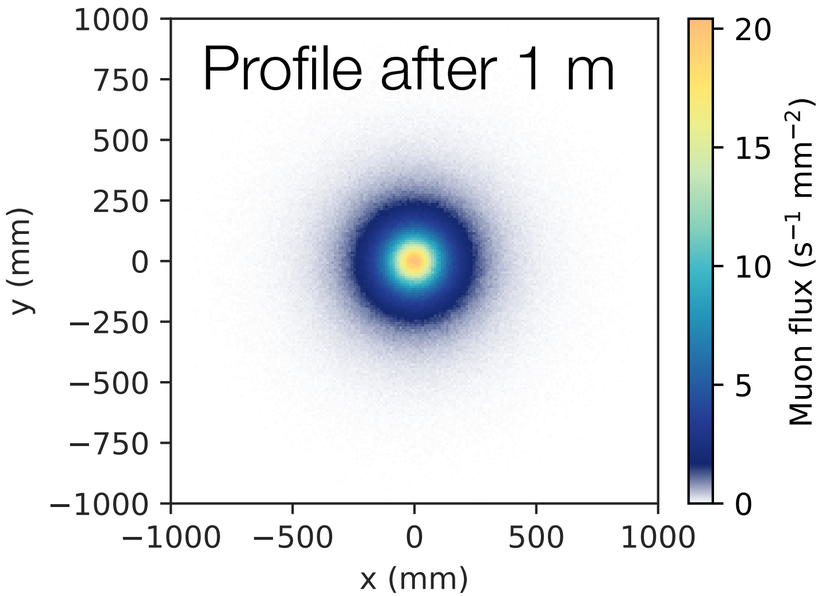
Shalloo *et al*, PRAB **22** 041302 (2019)

LPAs can be optimised for muon generation

100Hz, 100TW-laser-driven bright photomuon beam is highly directional



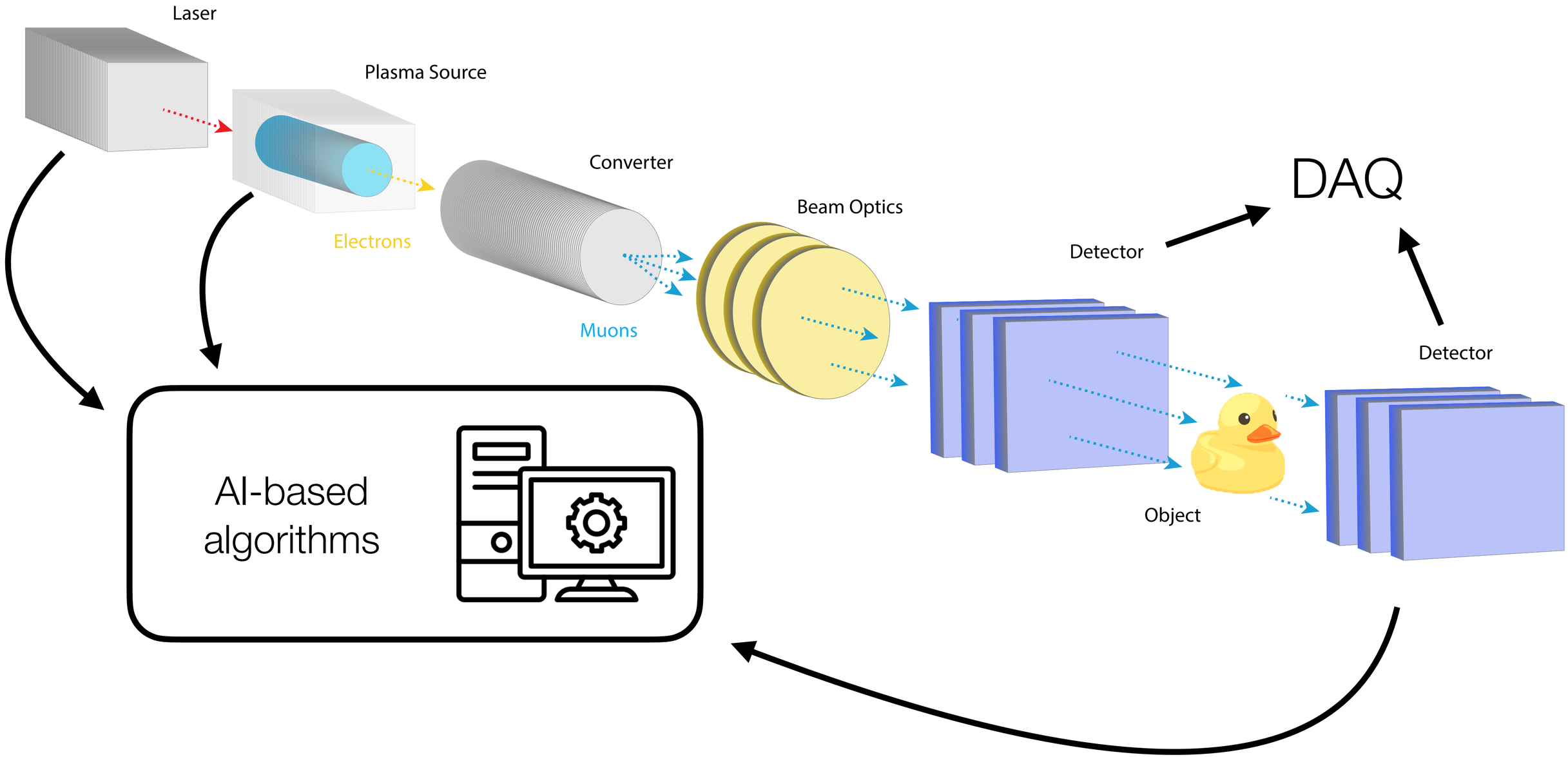




optimas

LPA-driven muon sources enables new imaging applications

Muon-Beam-Imaging: muon scattering tomography with high flux and controllable beam shape



Muon scattering tomography is a powerful imaging method

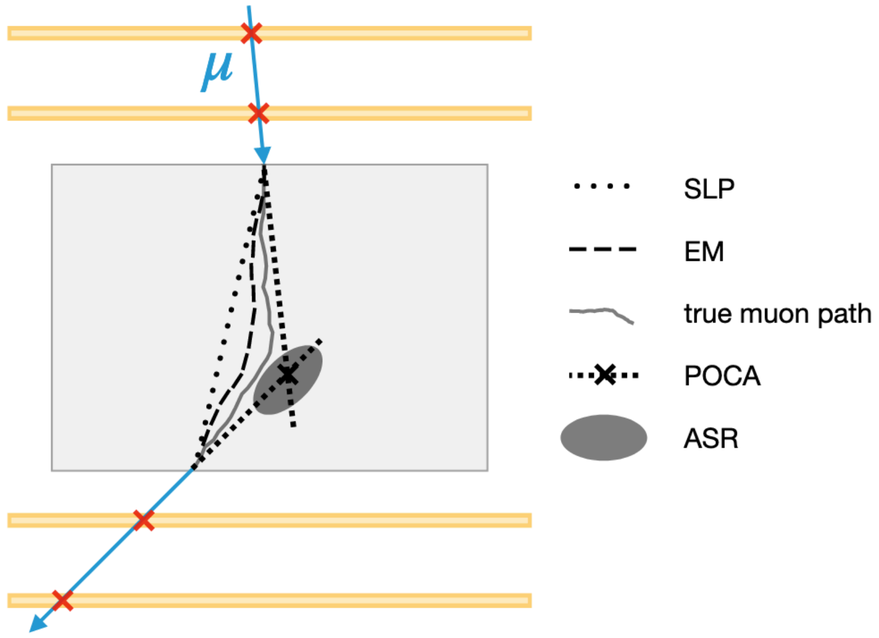
Scattering angle dependence on radiation length allows classification of traversed materials

- Muon deflection mostly caused by multiple scattering

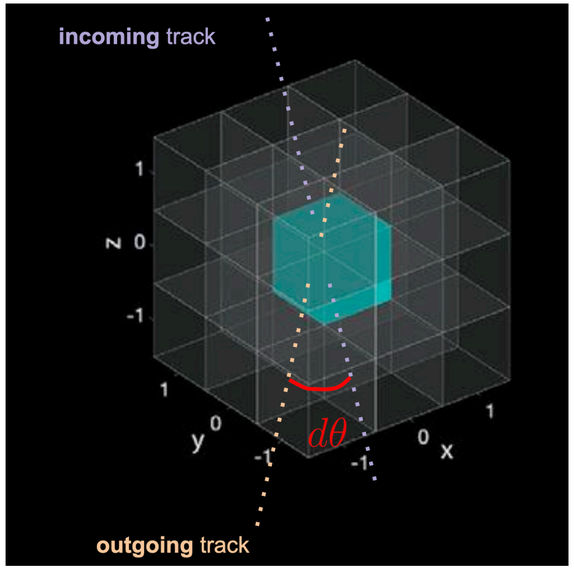
$$\theta_0 = \frac{13.6MeV}{\beta pc}\sqrt{\frac{x}{X_0}}\left(1 + 0.038\ln\frac{x}{X_0}\right)$$

  - Radiation length X_0 scales as

$$X_0 = \frac{716A}{Z(Z+1)\ln(287/\sqrt{Z})}$$



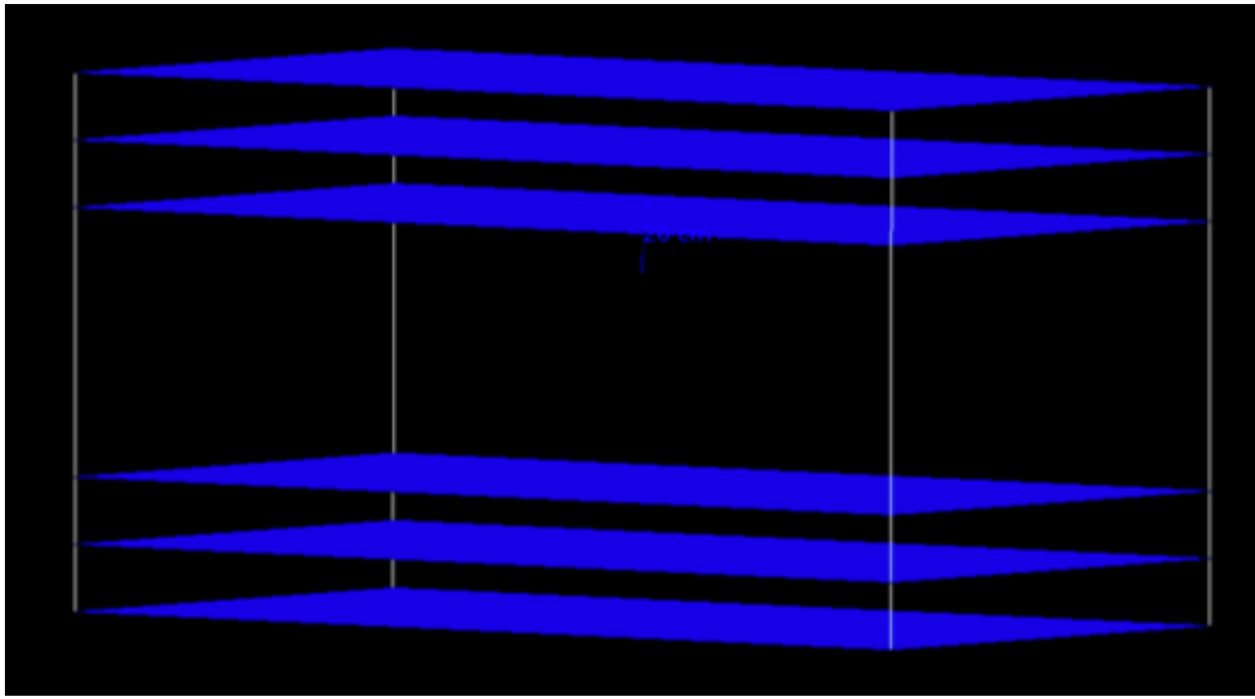
- Measuring muon direction before and after enables reconstructing a 3D density map
- Simplest reconstruction method is point-of-closest-approach
- Density score $s(d\theta) = d\theta$ assigned to each voxel

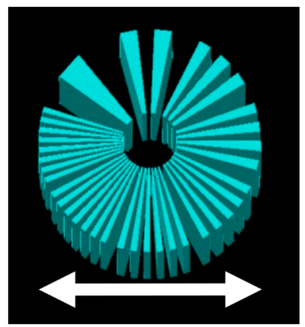


Muon-Beam-Imaging with optimised LPA-based source

100 TW, 100 Hz laser could deliver >10^6 muons/s in a transportable package

- Detector consists of 2 hodoscopes separated by 40cm
- Detector plate area (0.768x1.536) m^2
- 10cm from source to first hodoscope
- Using tungsten wheel to test resolution
- Rounding to nearest 0.25mm to understand detector effects
- Voxels size of 0.25mm for reconstruction
- Simulating 10 million muons
  - Assuming 100 Hz, 100 TW laser
  - Using CRY* for cosmic muons





10 cm

* Hagmann *et al*, IEEE Nuclear Science Symposium Conference Record, **(2)** (2007)

Muon-Beam-Imaging: a disruptive, novel imaging modality

LPA-enabled compactness can enable a transportable MBI source

- Muons are powerful non-destructive imaging tools
- LPAs can generate OoMs more muons than cosmic ray background
  - Muon beams with controllable spectrum, flux and beam shape
- Initial muon-scattering simulations show extremely promising results
  - The high directionality and softer spectrum increase reconstruction efficiency
  - OoMs shorter scan times required
- Potential of muon-beam-imaging for medical imaging to be studied next