GEANT4 SIMULATIONS OF MUON SCATTERING TOMOGRAPHY

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MUON TOMOGRAPHY SIMULATIONS – WHY?

System design and optimization

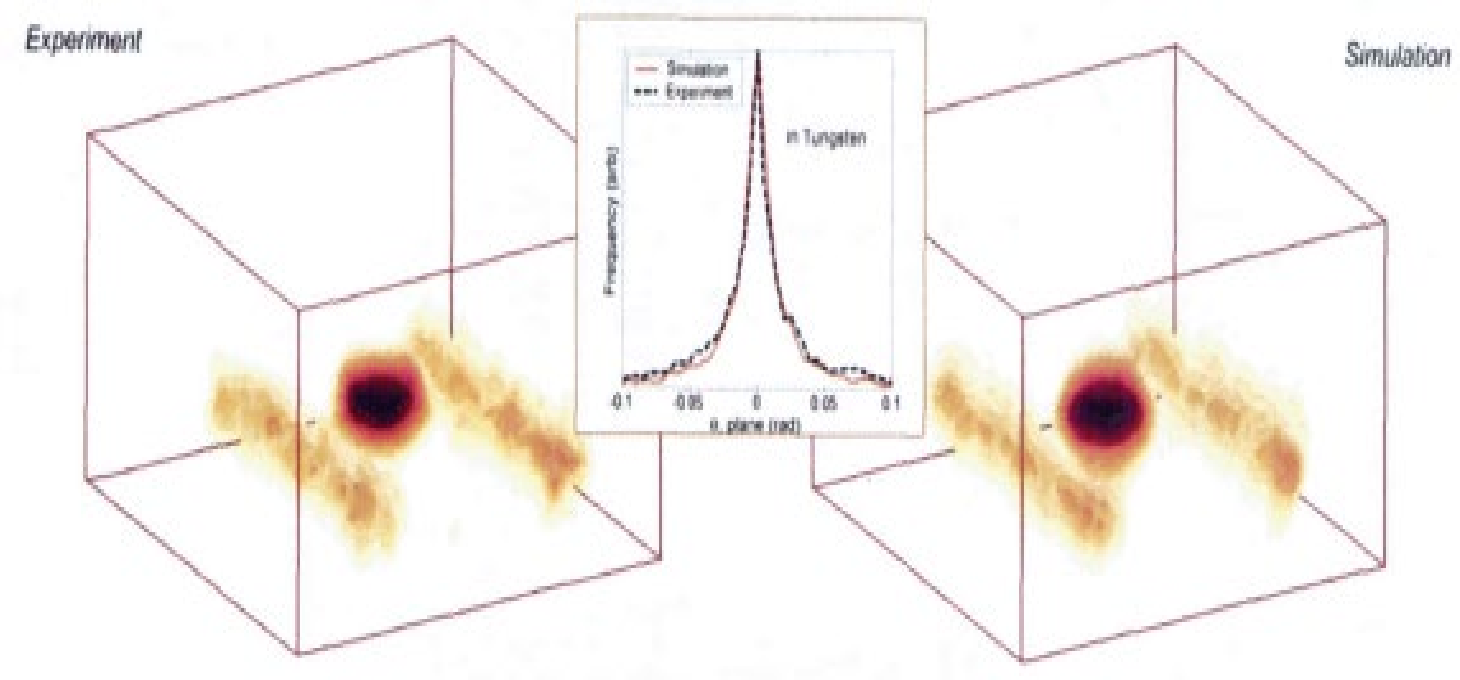
Application-specific feasibility studies

Image reconstruction development

Validation and benchmarking

Machine Learning datasets

FIRST IMAGE



Radiographic imaging with cosmic-ray muons
Konstantin N. Borozdin, Gary E. Hogan, Christopher Morris, William C. Priedhorsky, Alexander Saunders, Larry J. Schultz & Margaret E. Teasdale
Nature 422, 277 (2003)

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Feasibility proof

Image reconstruction

Validation and benchmarking

Radiography without radiation

GEANT4

70s and 80s: GEANT3 FORTRAN-based simulation kit developed at CERN

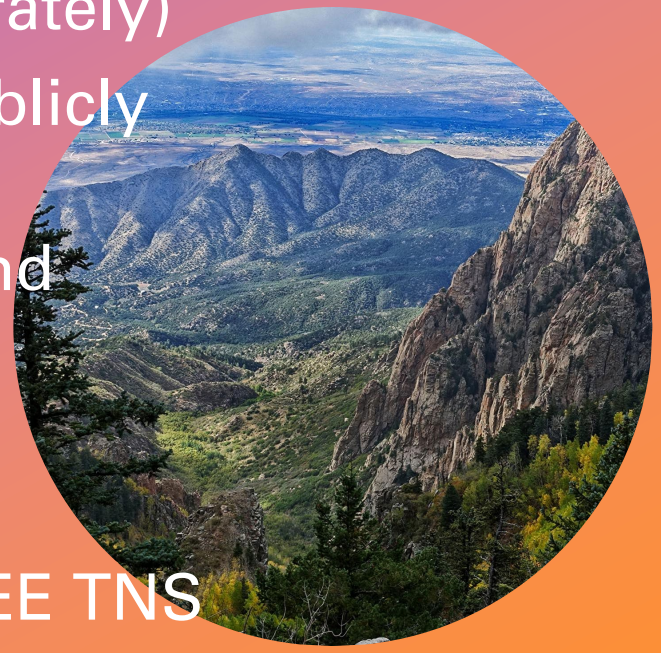
1993-1998: RD44 Project: C++ over FORTRAN, International collaboration, decomposition (physics, geometry, tracking, visualization developed separately)

December 1998: GEANT4 version 1.0 released publicly with open source code available at no charge

Standard simulation toolkit across high-energy and nuclear physics, medical physics, space science, homeland security, astrophysics

Dec 2025: v. 11.4

Agostinelli et al. 2003, NIM; Allison et al. 2006, IEEE TNS



MONTE CARLO

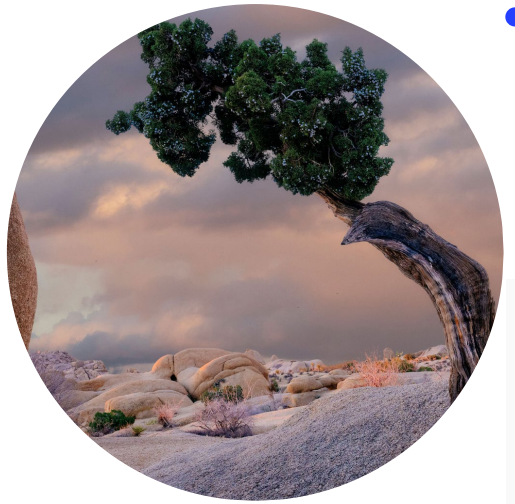
Class of computational algorithms that use repeated random sampling to obtain numerical results (originated by Stanislaw Ulam and Nicholas Metropolis during the Manhattan Project)

Particle transport through matter involves a cascade of stochastic processes, each interaction is fundamentally probabilistic

Simulate one particle at a time, sample each interaction from the appropriate probability distribution, repeat for millions of primary particles

GEANT4 implements MC in the stepping loop (step is the unit of transport, with one particle and one process)

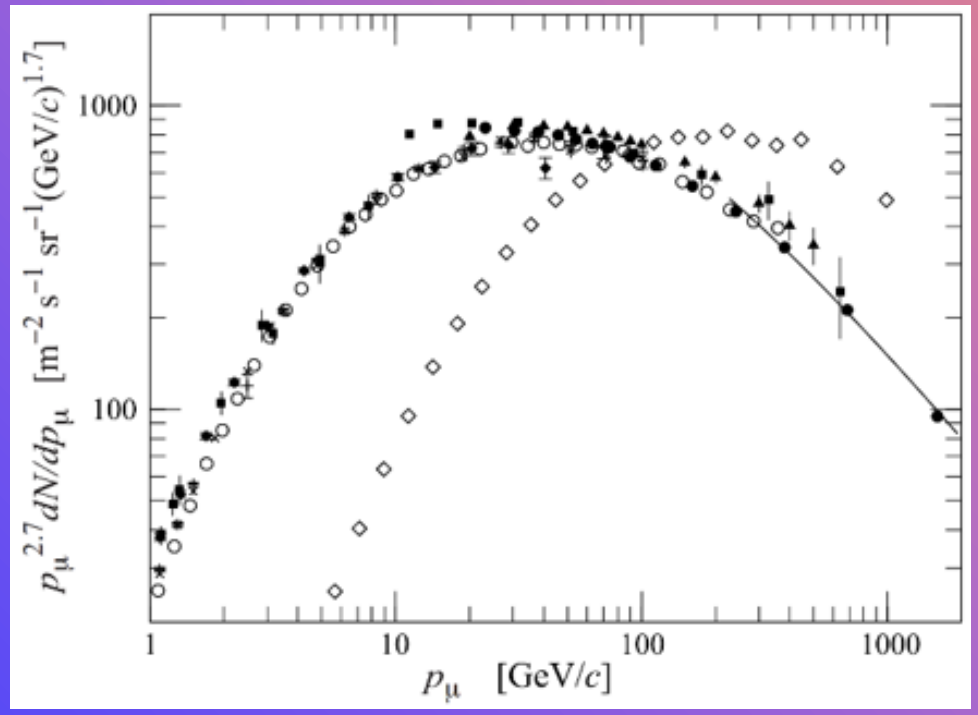
For Multiple Coulomb Scattering all small-angle elastic collisions over a step are condensed into a single net deflection



GEANT4 EXECUTION FLOW

```
main()
  └── RunManager initialized
        ├── DetectorConstruction  → geometry & materials built
        ├── PhysicsList           → processes registered
        └── PrimaryGeneratorAction registered
              └── /run/beamOn N
                    └── [N times] Event loop
                          ├── PrimaryGeneratorAction → generate muon
                          ├── Tracking loop → transport through geometry
                          │     └── SteppingAction called at each step
                          ├── SensitiveDetector → record hits
                          └── EventAction → fill output
```

MUON SOURCE



$$I(p_\mu, 0) = \cos^3(0) I_V(\zeta)$$

K. Hagiwara et al. (Particle Data Group), *Phys. Rev. D* **66**, 010001 (2002)

D. Reyna
arXiv:hep-ph/0604145 (2006)

H. Jokisch et al.
Phys.Rev. D **19,** 1368 (1979)

Implemented as MuonElectronGenerator for GEANT4
https://github.com/kbor-commits/MuonElectronGenerator

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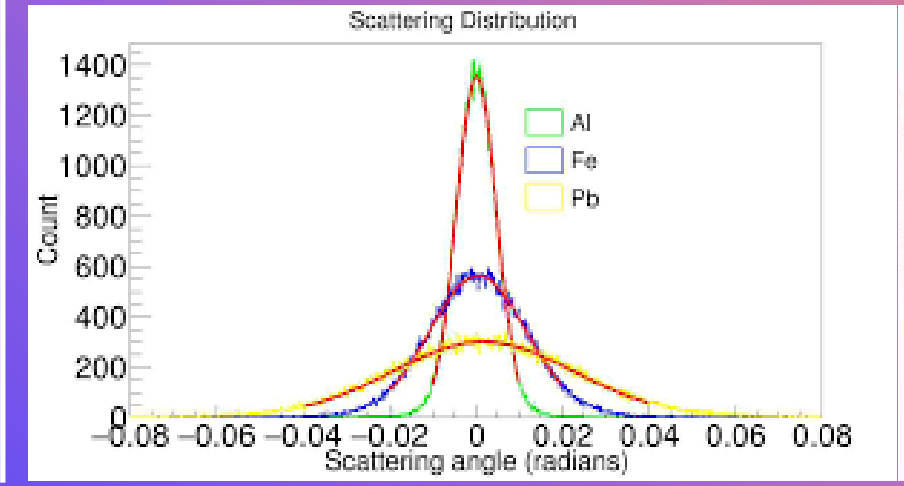
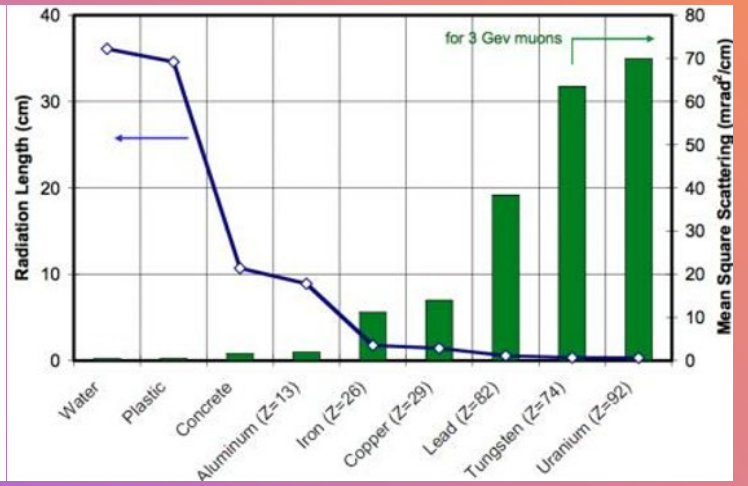
MUON PHYSICS





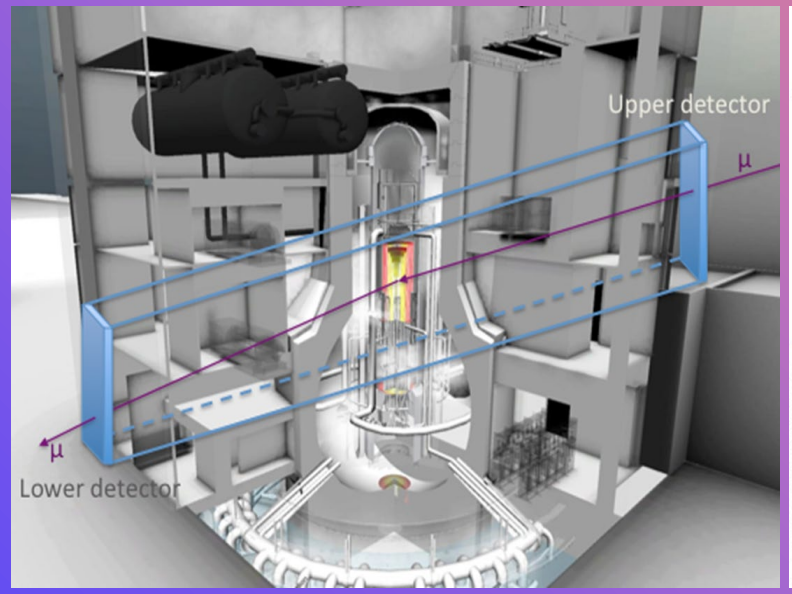
H. Bethe, Phys.Rev. 89, 1256 (1953)

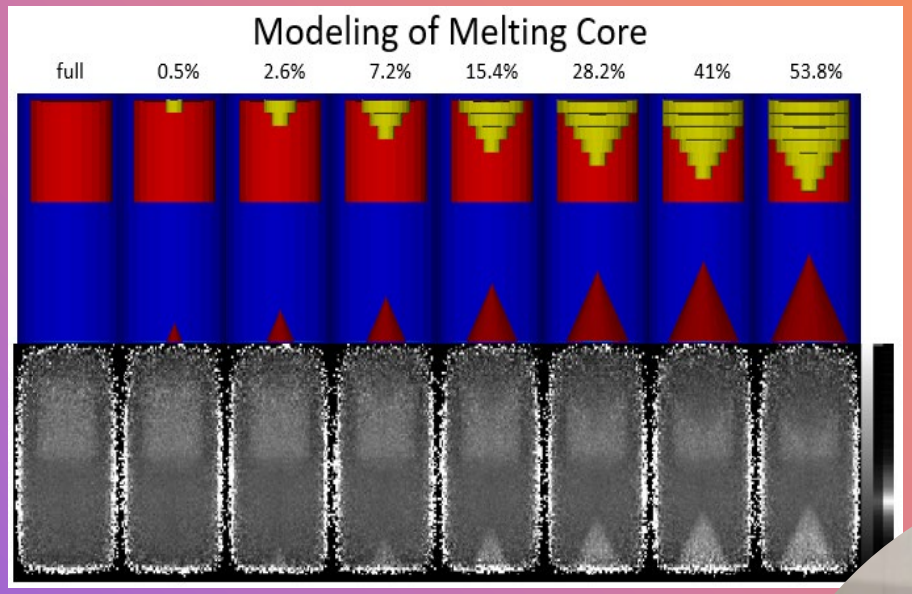
$$\sigma_\theta = \frac{13.6\ MeV}{\beta cp}\sqrt{x/X_0}\,[1 + 0.038\ln(x/X_0)]$$

*V. Highland NIM **129**, 497 (1975)*
*G. Lynch and O.Dahl NIM **B58**, 6 (1991)*

Multiple Coulomb Scattering

FUKUSHIMA





K.Borozdin et al. *Cosmic Ray Radiography of the Damaged Cores of the Fukushima Reactors*, Phys.Rev.Lett. 109, 152501 (2012)
C.Morris et al. *Imaging Fukushima Daiichi Reactors with Muons*, AIP Advances 3, 052133 (2013)

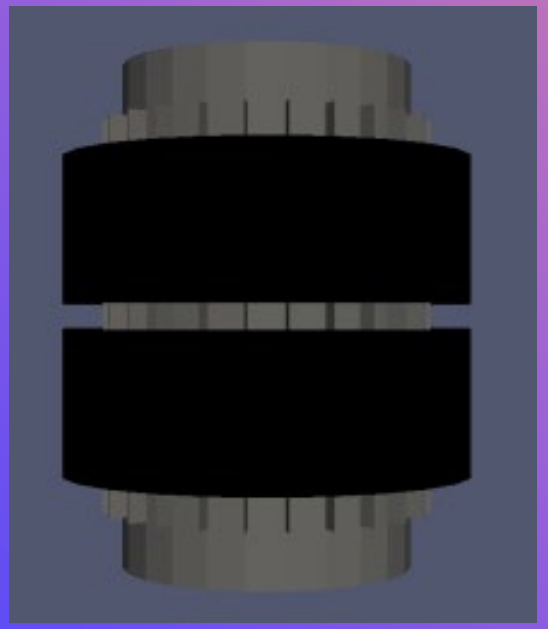
Feasibility of specific application

Detailed simulations of the object

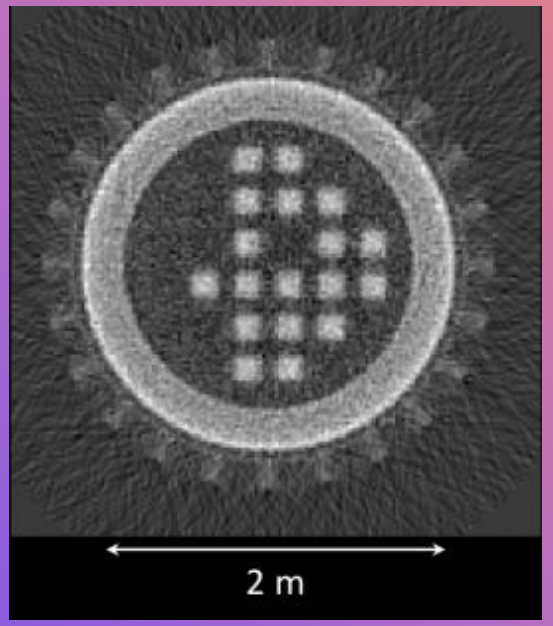
Runs on supercomputer

SPENT FUEL

GEANT4 SIMULATION



RECONSTRUCTED IMAGE



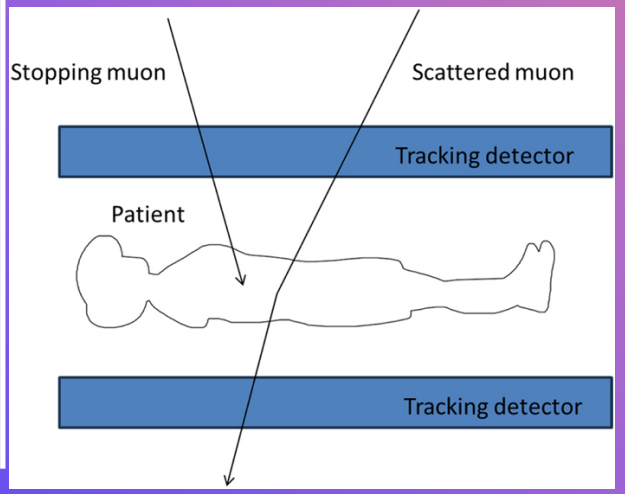
Poulson et al NIM A 842 (2017)

Development of new image reconstruction techniques

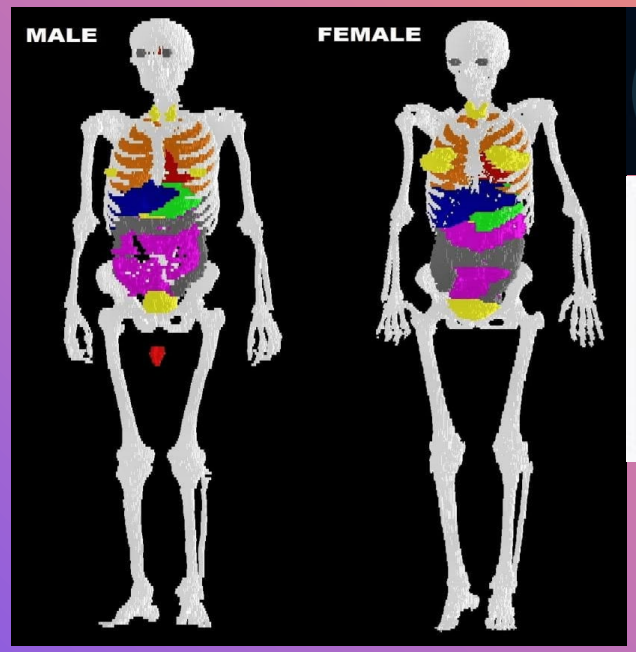
GDML integration

Related work presented in the talks today by Reshma Ughade and Adam Hecht, as well as several talks tomorrow

MEDICAL IMAGING .



C.Morris et al. J. Appl. Phys. 137, 124503 (2025)



MUOTECH

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Feasibility studies

Talk by Noemi Zabari today

NBA Finals start tomorrow

THANK YOU!

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