Towards energy discretization for muon scattering tomography in GEANT4 simulations: A discrete probabilistic approach

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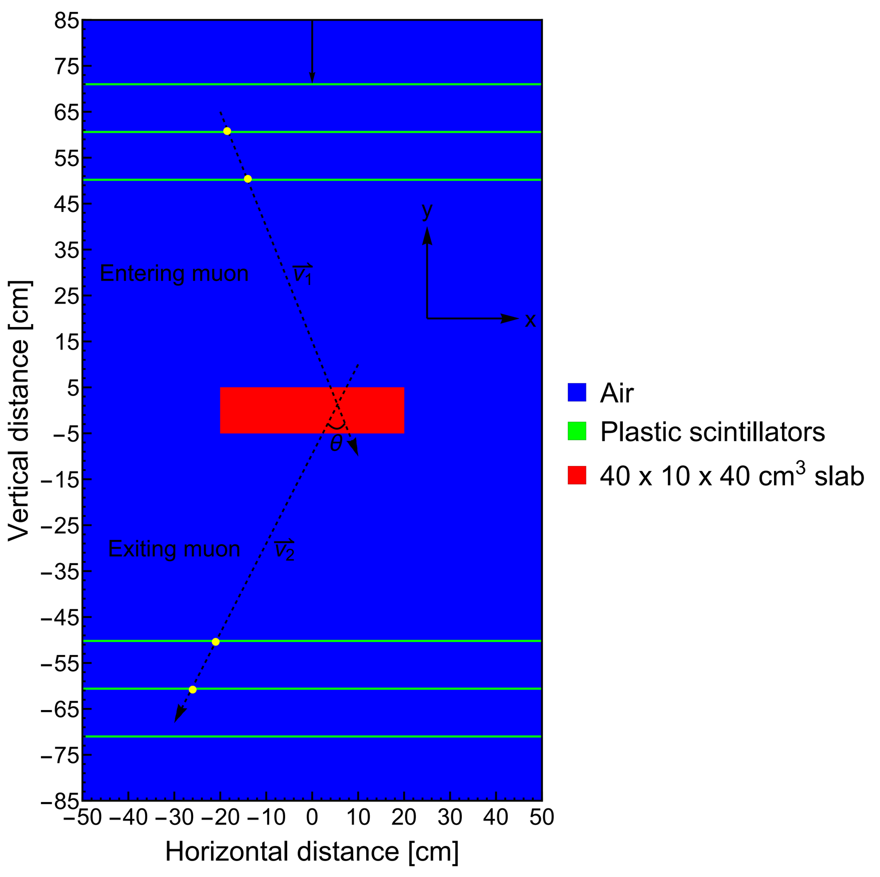
Motivation

In this study, by attempting to eliminate the disadvantageous complexity of the existing particle generators, we present a discrete probabilistic scheme adapted for the discrete energy spectra in the GEANT4 simulations, which grants us the ability to verify as well as to modify the energy spectrum depending on the nature of the information source in addition to the exceptional tracking speed in the course of our muon tomography simulations.

Tomographic setup and basic parameters



Particle	μ^-
Beam direction	Vertical
Momentum direction	(0, -1, 0)
Source geometry	Planar
Initial position (cm)	([-0.5, 0.5], 85, [-0.5, 0.5])
Particle injector	G4ParticleGun
Number of particles	10^5
Energy distribution	Non-linear discrete
Target geometry	Rectangular prism
Target volume (cm^3)	40×10×40
Material database	G4/NIST
Reference physics list	FTFP_BERT

* Average scattering angle and its standard deviation over N number of the non-absorbed/non-decayed muons:

$$\bar{\theta} \pm \delta\theta = \frac{1}{N}\sum_{i=1}^{N}\theta_i \pm \sqrt{\frac{1}{N}\sum_{j=1}^{N}(\theta_j - \bar{\theta})^2} \qquad (1)$$

* Root-mean-square (RMS) of the scattering angle over N number of the non-absorbed/non-decayed muons:

$$\theta^{\mathrm{RMS}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\theta_i^2} \qquad (2)$$

* Number of the absorbed muons within volume-of-interest (VOI):

$$\#^{\mathrm{Capture}} = \#\text{ of muMinusCaptureAtRest in VOI} \qquad (3)$$

Energy discretization and probability grid for GEANT4

Discretization of CRY spectrum

* Number of the non-zero energy bins:

$$\#_{\mathrm{Bins}} = \frac{E_{\mathrm{Max}} - E_{\mathrm{Min}}}{L_{\mathrm{Bins}}} = \frac{8.0 - 0}{0.1} = 80 \qquad (4)$$

* Number of the counts in the bin of E_i (GeV) is computed by incorporating any $E_x \in (E_{i-1}, E_i]$ under the condition of $m_0 = 0$ for $E_0 = 0$:

$$m_i = \sum_{k=1} 1 \text{ if } E_{i-1} < E_x \leq E_i \text{ for i=1, 2, 3,.., 80} \qquad (5)$$

* Total count:

$$\sum_{i=0}^{\#_{\mathrm{Bins}}} m_i = \sum_{i=0}^{80} m_i \qquad (6)$$

* Probability at a given energy bin E_i:

$$p_i = \frac{m_i}{\sum_{i=0}^{80} m_i} \quad \text{with} \quad \sum_{i=0}^{80} p_i = 1 \qquad (7)$$

Utilization of experimental spectra

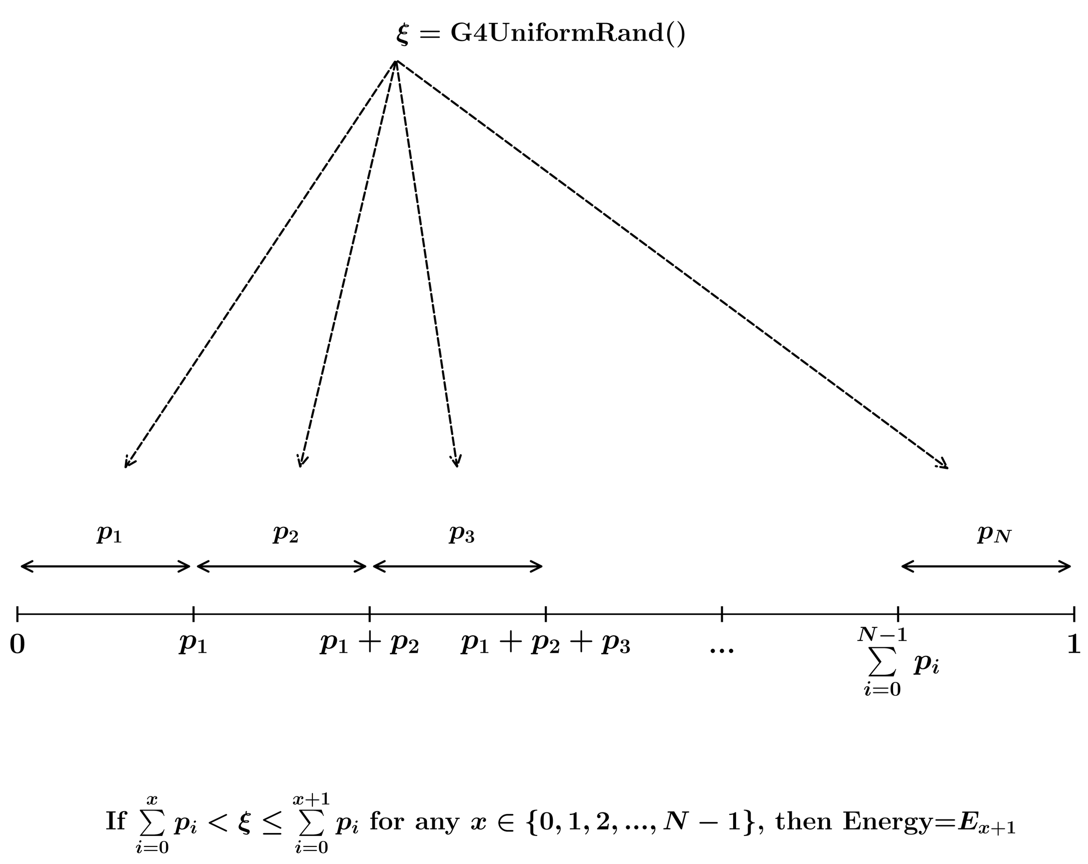
Ratio between the flux values denoted by ϕ_i and the total flux over [0.598, 8.1] GeV according to Haino et al. (2004) with the BESS-TeV spectrometer:

$$p_i = \frac{\phi_i}{\sum_{i=1}^{36} \phi_i} \quad \text{with} \quad \sum_{i=0}^{36} p_i = 1 \qquad (8)$$

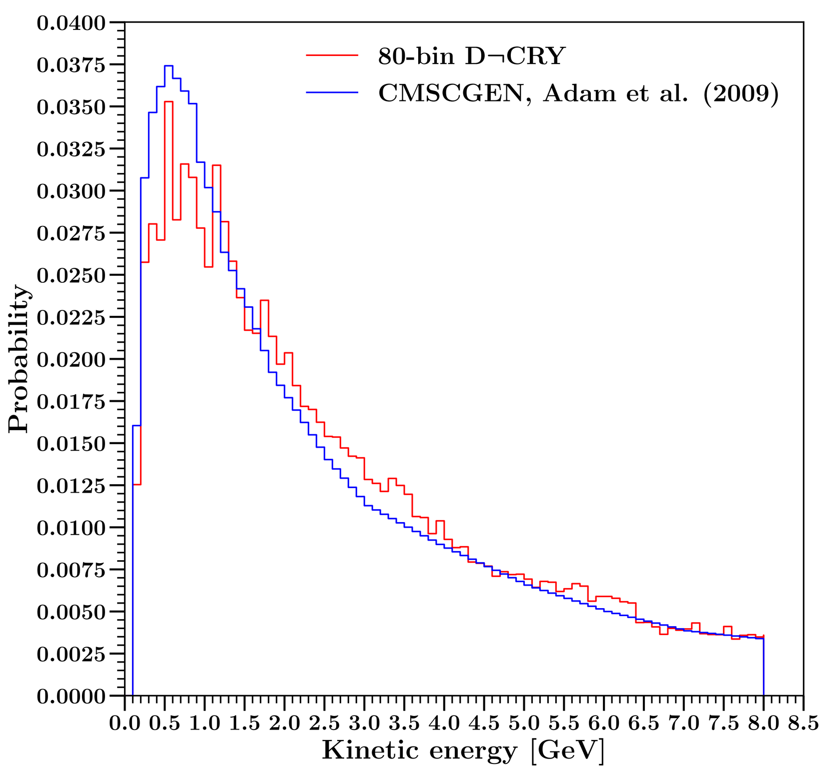
Implementation and comparison

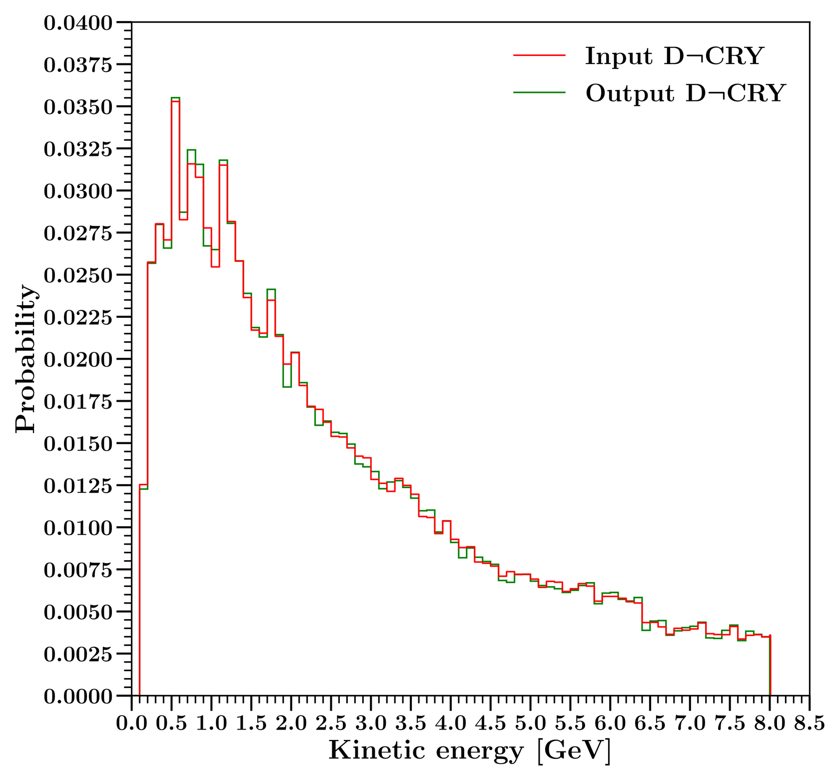
- Our 80-bin discrete CRY spectrum is compared/corroborated with the CMSCGEN distribution from Adam et al., 2009;
- A set of first 36 bins measured by Haino et al., 2004 via the BESS-TeV spectrometer is also employed;
- Our probability grid is verified through input/output;
- We contrast our simulation outcomes with the results of Hohlmann et al., 2009.

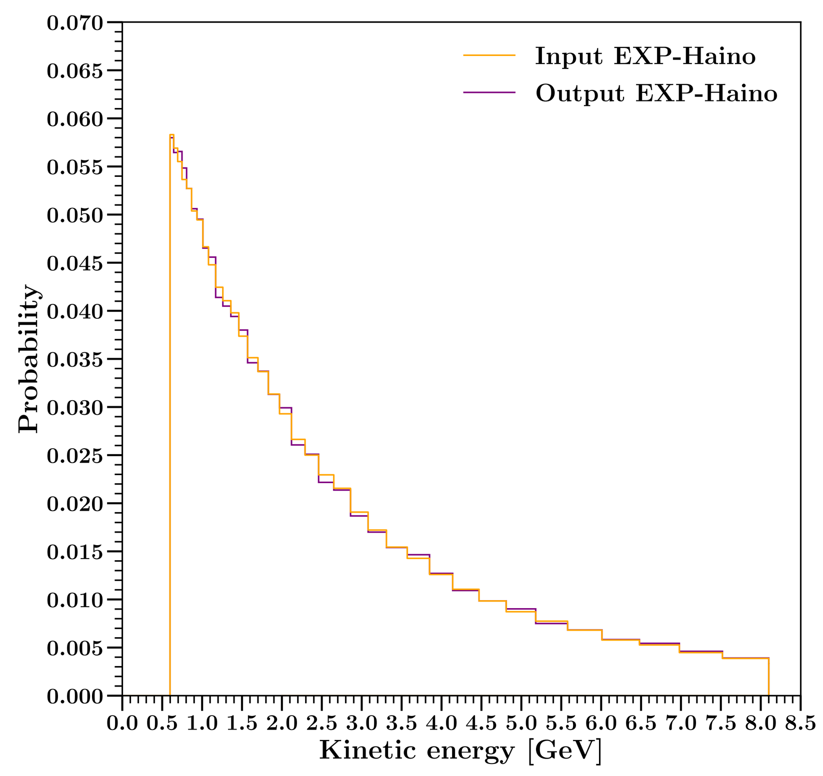
Probability grid



Discrete energy spectra







References

[1] Hagmann and Wright, Cosmic ray shower generator (CRY) for Monte Carlo transport codes, IEEE Nucl. Sci. Symp., 2007.

[2] Hohlmann et al., GEANT4 simulation of a cosmic ray muon tomography system with micro-pattern gas detectors for the detection of high-Z materials, IEEE Trans. Nucl. Sci., 2009.

[3] Haino et al., Measurements of primary and atmospheric cosmic-ray spectra with the BESS-TeV spectrometer, Phys. Lett. B, 2004.

[4] Biallass and Hebbeker, Parametrization of the cosmic muon flux for the generator CMSCGEN, arXiv:0907.5514, 2009.

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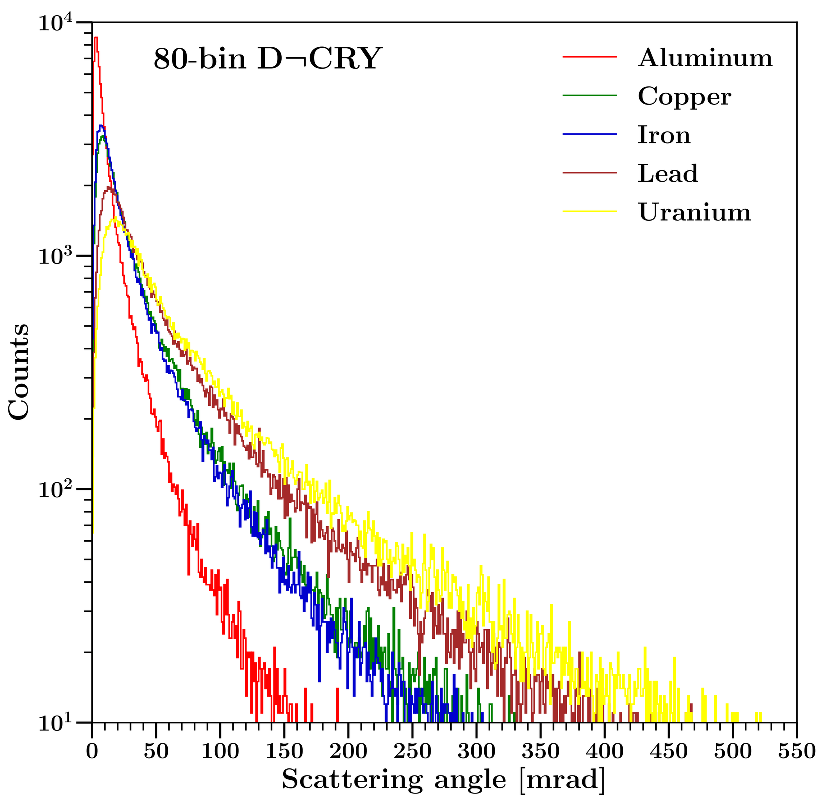
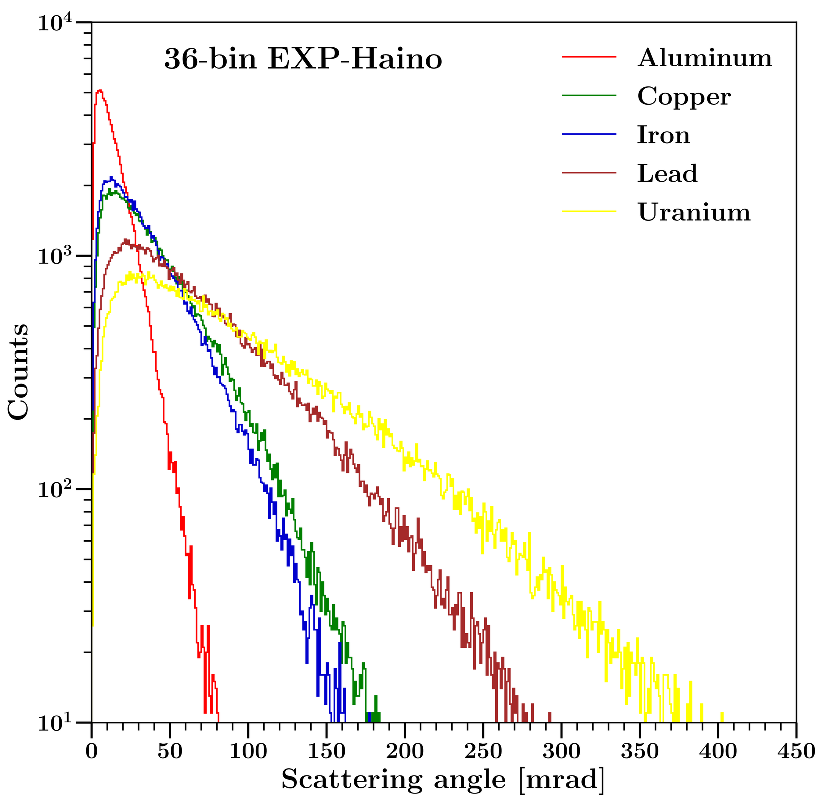
Simulation outcomes





The present study

Material	$\bar{\theta}_{\mathrm{D\neg CRY}} \pm \delta\theta$ [mrad]	$\theta^{\mathrm{RMS}}_{\mathrm{D\neg CRY}}$ [mrad]	$\#^{\mathrm{Capture}}_{\mathrm{D\neg CRY}}$	$\bar{\theta}_{\mathrm{EXP\text{-}Haino}} \pm \delta\theta$ [mrad]	$\theta^{\mathrm{RMS}}_{\mathrm{EXP\text{-}Haino}}$ [mrad]	$\#^{\mathrm{Capture}}_{\mathrm{EXP\text{-}Haino}}$
Aluminum	15.980±27.004	31.378	-	15.036±12.413	19.499	-
Copper	40.638±60.312	72.725	1230	40.759±31.898	51.757	-
Iron	35.824±51.548	62.773	1222	36.200±28.518	46.084	-
Lead	65.325±88.323	109.856	1272	68.138±52.450	85.987	-
Uranium	81.822±100.321	129.457	3836	95.721±75.376	121.836	-

Hohlmann et al. (2009)

Material	$\bar{\theta}_{\mathrm{CRY}}$ [mrad]	$\theta^{\mathrm{CRY}}_{\mathrm{RMS}}$ [mrad]
Aluminum	15.827	33.946
Copper	39.639	65.100
Iron	36.107	61.058
Lead	59.697	84.089
Uranium	76.660	99.007

Concluding remarks

Eventually, our probabilistic methodology implemented in GEANT4 does not only permit us to discretize the continuous energy spectra based on the Monte Carlo generators, but it also gives a unique access to utilize the experimental energy spectrum measured at the distinct particle flux values. To sum up, we gain the capability to control as well as to adjust our energy spectra according to our computational goals apart from the noteworthy computation times.