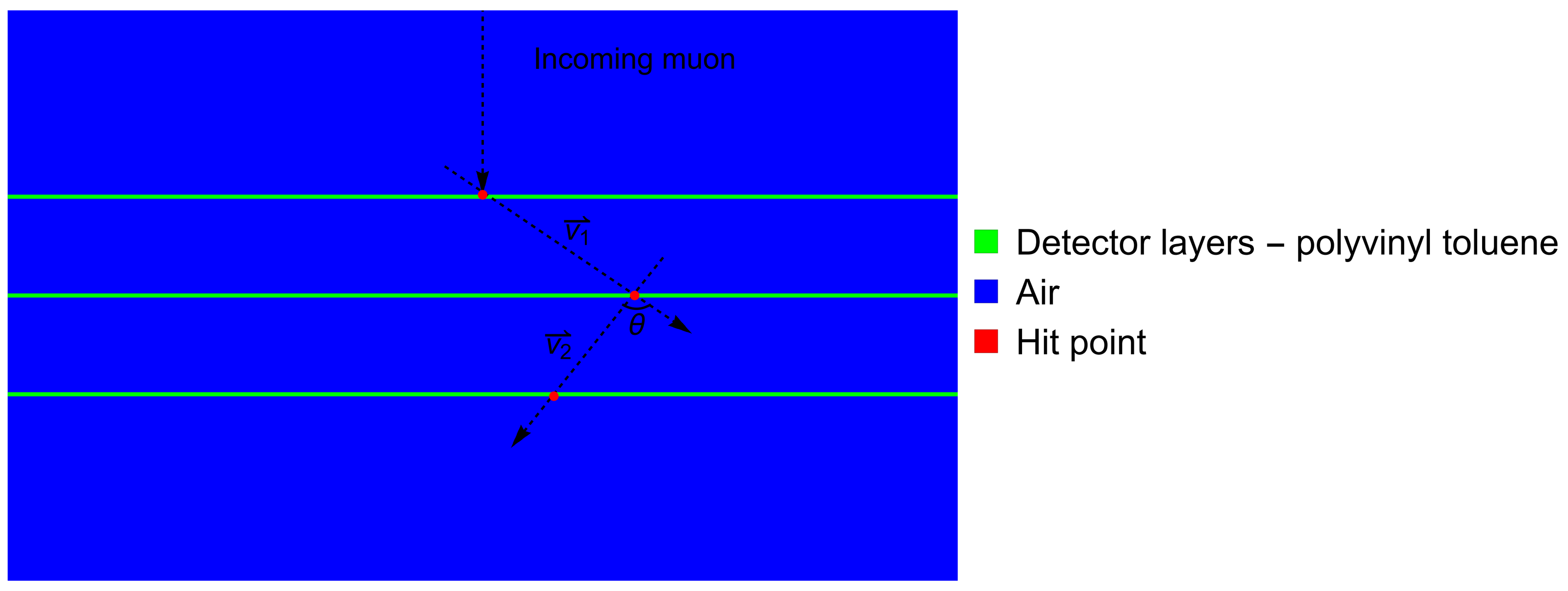
Investigation of deflection angle for muon energy classification in muon scattering tomography via GEANT4 simulations

A. Ilker Topuz[1,2], Madis Kiisk[1,3], Andrea Giammanco[2]
[1] University of Tartu
[2] Université catholique de Louvain
[3] GScan OU

Objectives

In muon scattering tomography, the investigated materials are discriminated according to the scattering angle that mainly depends on the atomic number, the density, and the thickness of the medium at a given energy value. The scattering angles at different initial energies also provide the opportunity to classify the incoming muons into a number of energy groups [1,2]. In this study, by employing the GEANT4 code, we show that the deflection angle exponentially decays with respect to the energy increase, and the numerical values for the current configuration are below the detector accuracy, which is 1 mrad, except the initial energy bins owing to the low-Z, low density, and low thickness of the current plastic scintillators. This implies the necessity of additional components that provoke the muon scattering. Therefore, we introduce stainless steel surfaces into the top and bottom sections in order to amplify the deflection angle as well as to reduce the uncertainty, thereby improving the detector performance.

Average deflection angle and its standard deviation



* Average deflection angle through of a hodoscope at a given energy value over N number of the non-absorbed/non-decayed muons and its standard deviation:

$$\theta = \arccos\left(\frac{\vec{v}_1 \cdot \vec{v}_2}{|v_1|\,|v_2|}\right) \qquad \bar{\theta} = \frac{1}{N}\sum_{i=1}^{N}\theta_i \qquad \delta\theta = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\theta_i - \bar{\theta})^2} \qquad (1)$$

* Average deflection angle of two different hodoscopes (x and y) at a given energy value over N number of the non-absorbed/non-decayed muons and its standard deviation:

$$\bar{\theta}_{\frac{x+y}{2}} = \frac{1}{N}\sum_{i=1}^{N}\frac{\theta_{x,i} + \theta_{y,i}}{2} \qquad \delta\theta = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\theta_{x,i} + \theta_{y,i}}{2} - \bar{\theta}_{\frac{x+y}{2}}\right)^2} \qquad (2)$$

* Coefficient of variation (CV):

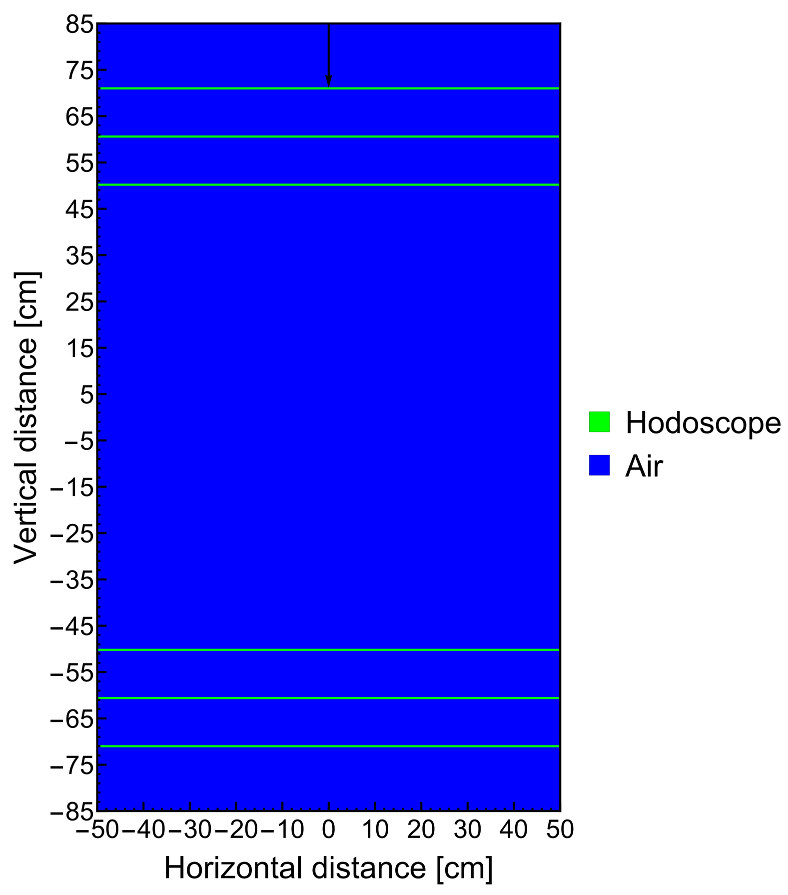
$$\mathrm{CV} = \frac{\text{Standard deviation}}{\text{Average}} = \frac{\delta\theta}{\bar{\theta}} \qquad (3)$$

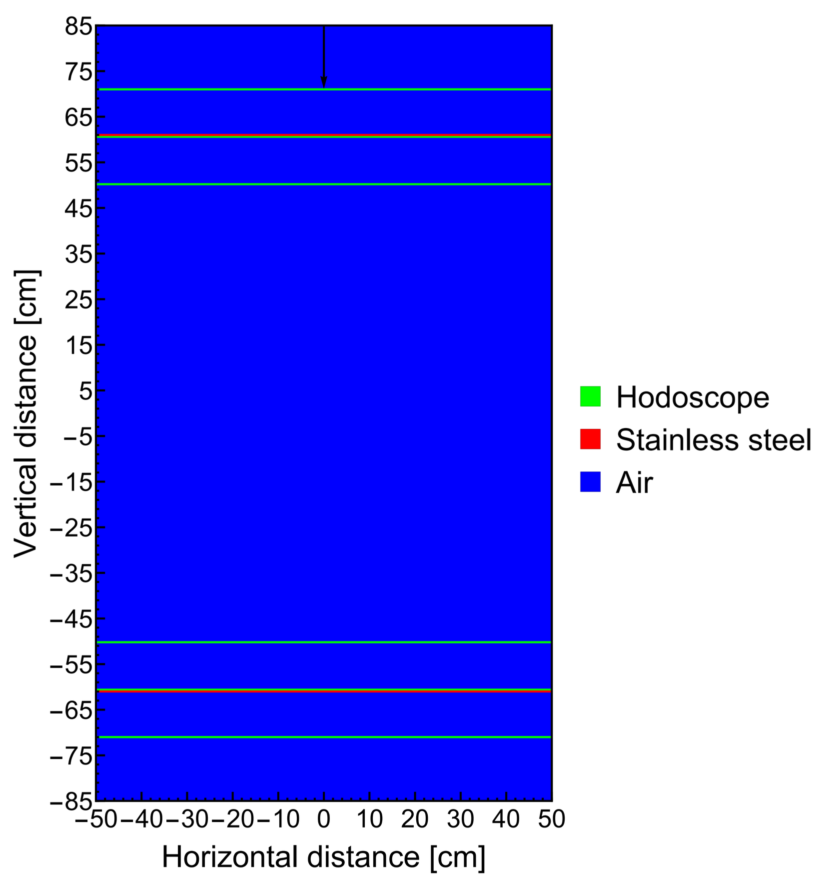
References:

[1] Georgadze et al., Method and apparatus for detection and/or identification of materials and of articles using charged particles, US Patent App. 16/977,293, 2021.

[2] Anbarjafari et al., Atmospheric ray tomography for low-Z materials: implementing new methods on a proof-of-concept tomograph, arXiv:2102.12542, 2021.

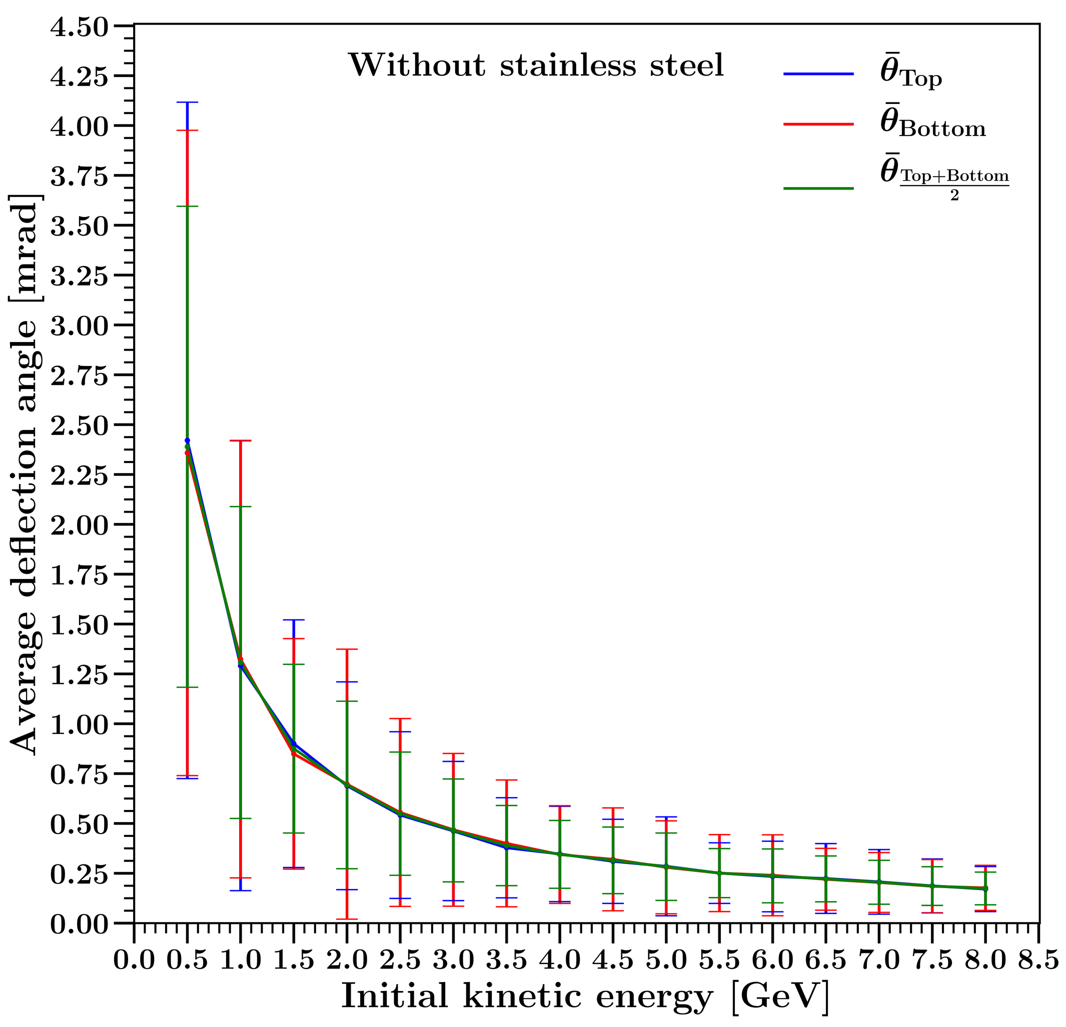
Hodoscope scheme and simulation properties

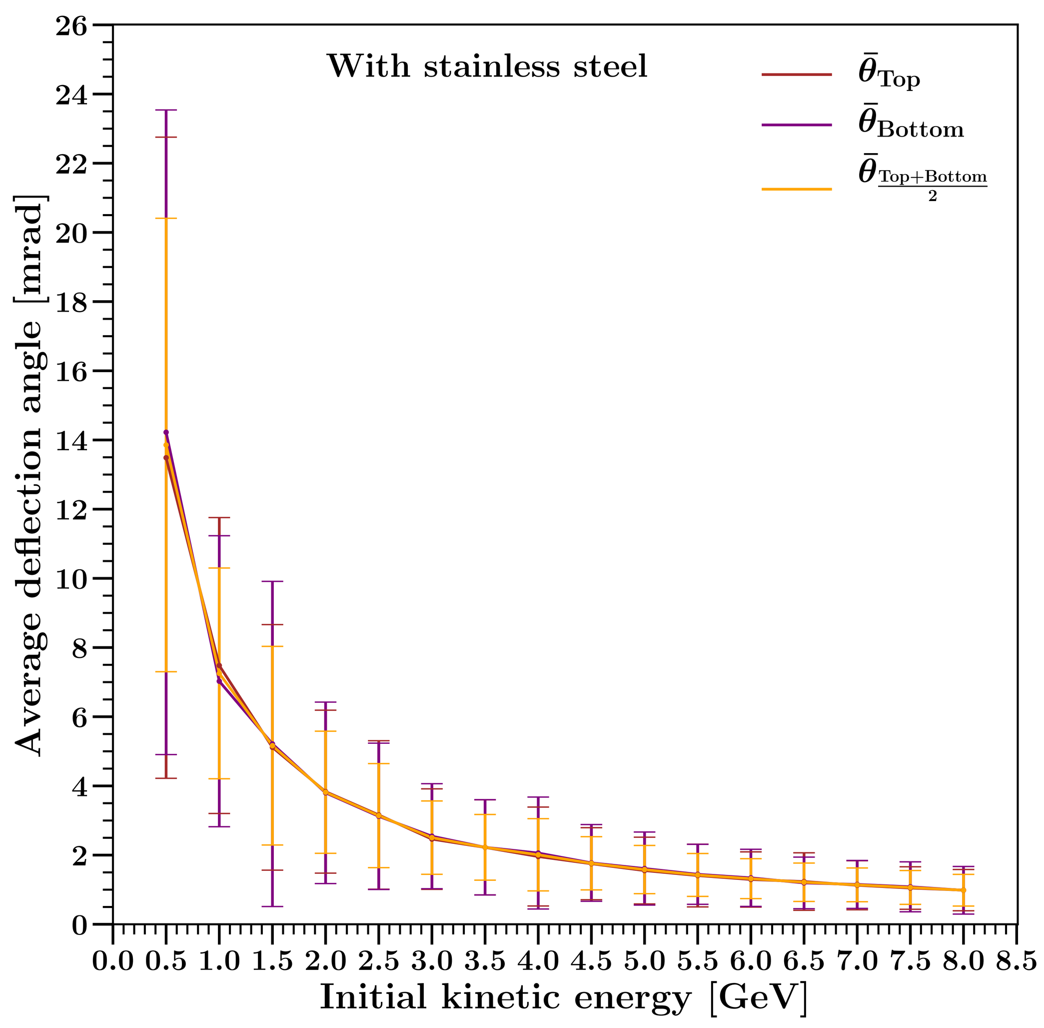


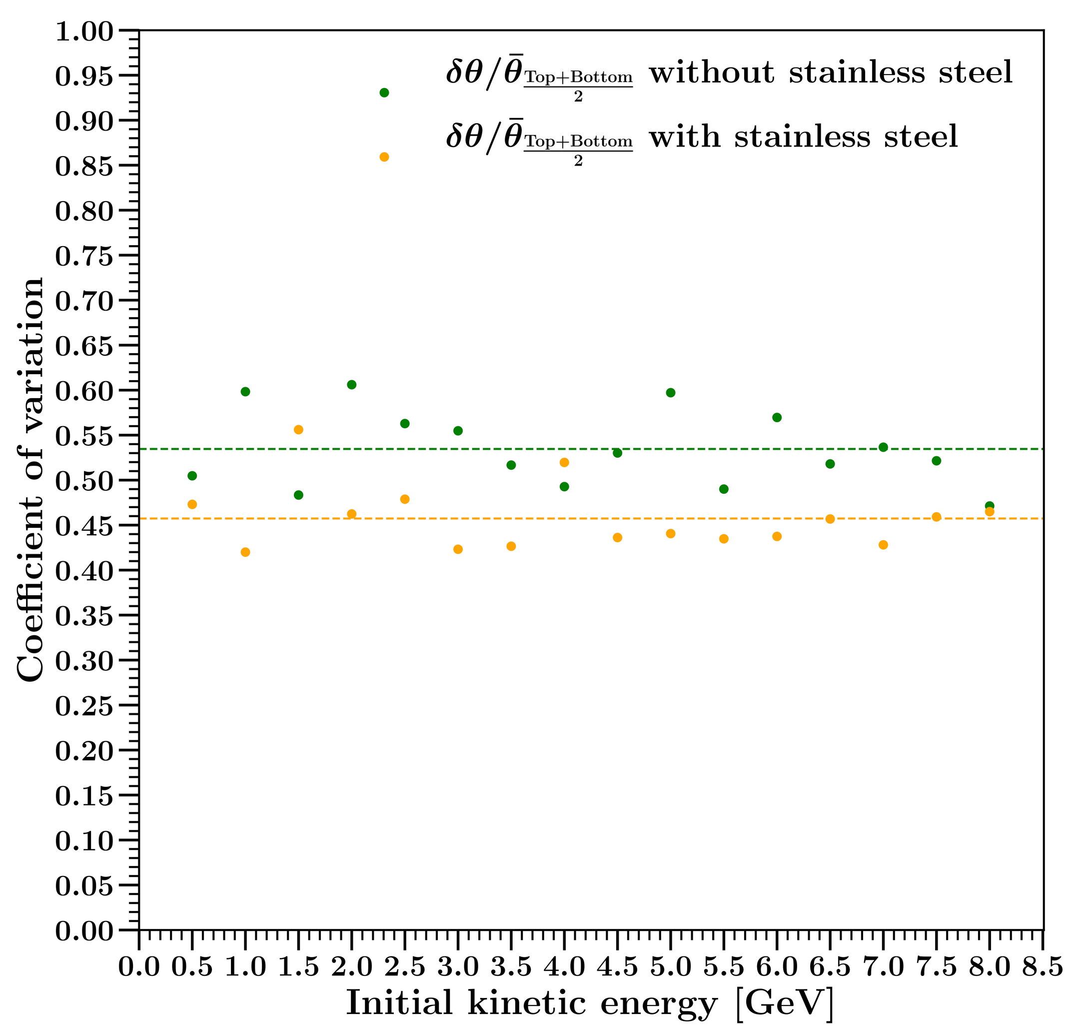


Particle	μ^-
Beam direction	Vertical
Momentum direction	(0, -1, 0)
Source geometry	Point
Initial position (cm)	(0, 85, 0)
Number of particles per bin	1000
Number of beams	Single
Material database	G4/NIST
Energy distribution	Monoenergetic
Reference physics list	FTFP_BERT

Average deflection angles without and with stainless steel layers







Concluding remarks

In this study, the deflection angles due to the plastic scintillators have been investigated. The width of the deflection angle is ameliorated by averaging the outcomes from the top detector layers and the bottom detector layers over the number of the non-absorbed/non-decayed muons. Since the average values are below the current detector accuracy that is 1 mrad, the stainless steel layers are introduced to augment the deflection angles as well as to further diminish the standard deviations.