TomOpt: Investigation into detector scattering

Maxime Lagrange

December 8, 2021

Investigation: Scattering in active detector volume

TomOpt does not take into account muon scattering in active detector volume neither during **muon propagation** simulation nor **scattering inference**.

Question:

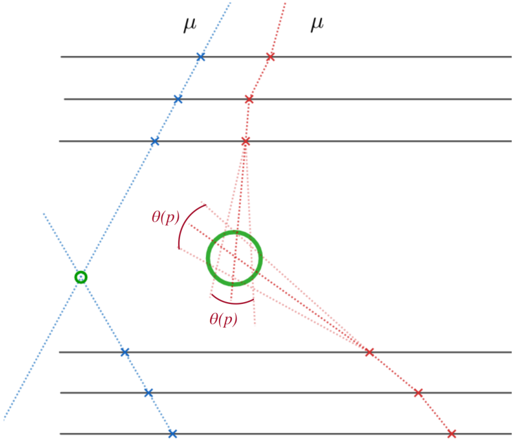
- Is muon scattering in active detector volume a dominant effect ?
- Consequences on tracking efficiency, inference ?

How to anwser:

- **GEANT4 simulation** with several detector configuration using **realistic cosmic muon source**

Qualitative study

- Scattering in planes 3 and 4 induces uncertainties on track inference in the passive volume: θ
- Affect the number of voxels involved during POCA/ML algorithm

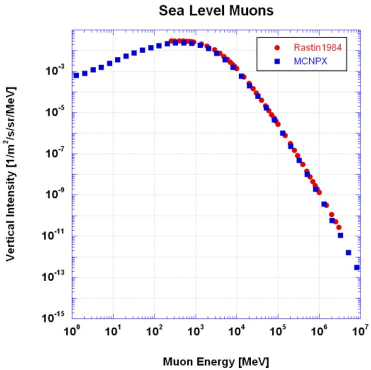


Cosmic muon generation: CRY

Scattering amplitude depends on momentum and path length in the material:

$$\theta_0 = \frac{13.6MeV}{\beta c p} z \sqrt{x/X_0}[1 + 0.038 ln(x/X_0)] \quad (1)$$

- **Need of a realistic muon source:** $\Phi(\theta, \phi, p)$
- CRY generates correlated cosmic-ray particle shower distributions: muons, neutrons, protons, electrons, photons, and pions.
- Realistic energy and angular distributions



Simulation configuration

Scattering amplitude depends on detector configuration: material, plane width, etc...

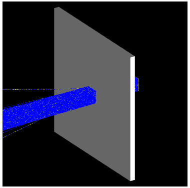
$$\theta_0 = \frac{13.6MeV}{\beta cp} z \sqrt{x/X_0}[1 + 0.038ln(x/X_0)] \quad (2)$$

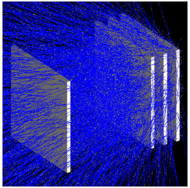
Configuration 1

- Scintillator based detector
- Single plane, simplified muon source

Configuration 2

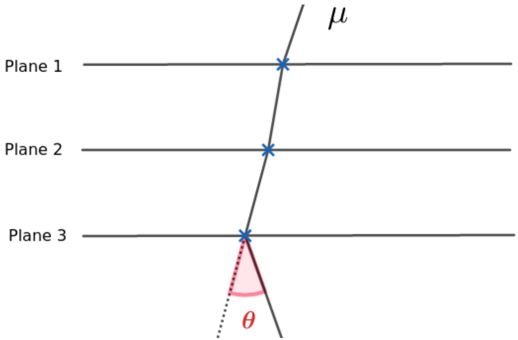
- Scintillator based detector
- 3 planes, plane width = 2, 5 cm, realistic muon source



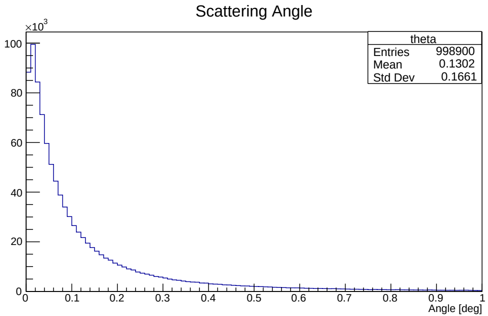


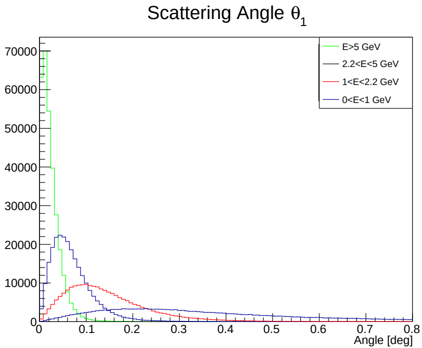
Analysis

- Muon source generated by CRY
- Only **coincident** muons reaching passive volume are considered
- Muons split in 4 categories according to energy range: $E < 1$, $1 < E < 2.2$ $2.2 < E < 5$ and $E > 5$ GeV
- Study of θ distribution



Configuration 1: Simplified setup

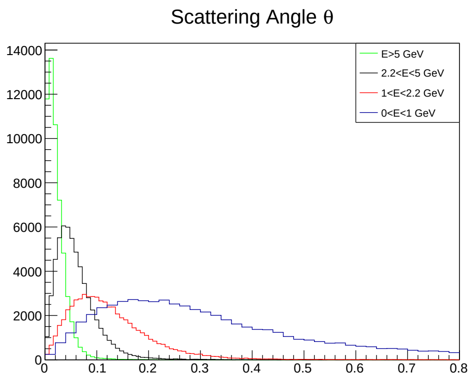




	E< 1	1 <E< 2.2	2.2 <E< 5	E> 5	full range
Relative # of events	22%	22%	25%	31%	/
Mean scattering Angle θ_1	0.55°	0.14°	0.07°	0.02°	0.13°
$P(\theta_1 > 2^\circ)$	3.4%	0.5%	0.2%	0.2%	0.7%

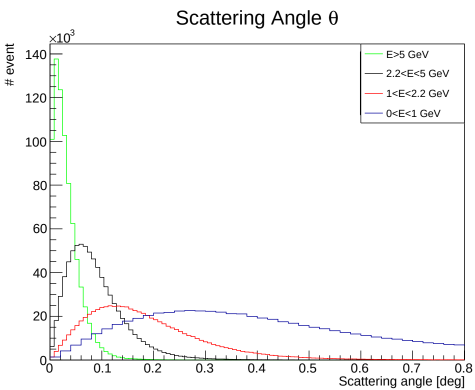
Configuration 2: Realistic setup

Plane width 2cm

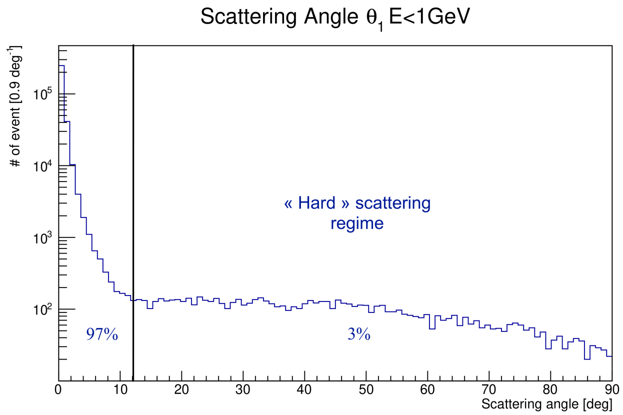


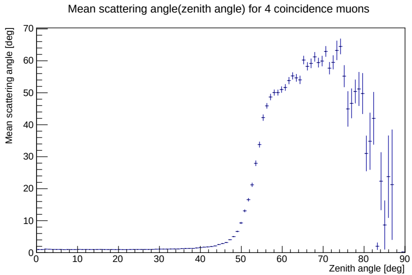
	E< 1	1 <E< 2.2	2.2 <E< 5	E> 5	full range
Relative # of events	26%	25%	25%	24%	/
Mean scattering angle θ	1.4°	1.2°	1.4°	1.8°	1.5°
$P(\theta > 2°)$	5.1%	2.9%	3.3%	4.5%	4.0%

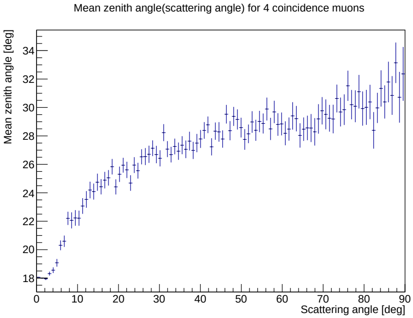
Plane width 5cm



	E< 1	1 <E< 2.2	2.2 <E< 5	E> 5	full range
Relative # of events	26%	25%	25%	24%	/
Mean scattering angle θ	1.7°	1.4°	1.5°	1.9°	1.6°
$P(\theta > 2°)$	7.3%	3.2%	3.6%	4.5%	4.8%


Scattering Angle θ1 E<1GeV
# of event [0.9 deg-1]
« Hard » scattering
regime
97%
3%
Scattering angle [deg]


Mean scattering angle(zenith angle) for 4 coincidence muons
Mean scattering angle [deg]
Zenith angle [deg]


Mean zenith angle(scattering angle) for 4 coincidence muons
Mean zenith angle [deg]
Scattering angle [deg]

Interpretation

- Scattering in active detector volume mainly affects **low-energy muons** $E < 1$ GeV
- **2 regimes** in the distribution: Gaussian ($\tilde{\theta} \approx 0.2^\circ$) + $1/sin^4$ tail ($\tilde{\theta} \approx 1.6^\circ$) for hard scattering
- Depends on **detector geometry**, **muon momentum**
- **Edge** and **coincidence** bias appears when using realistic muon source
- **Hard scattering** dominated by **large zenith angle** muons

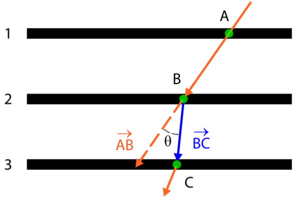
Perspectives: PID

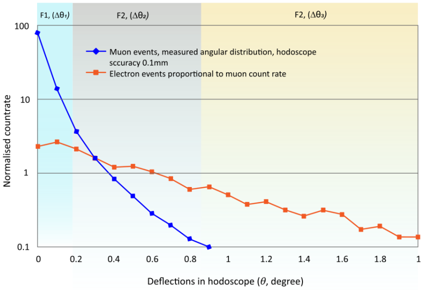
"Atmospheric ray tomography for low-Z materials: implementing new methods on a proof-of-concept tomograph"
arXiv:2102.12542v1

Analysis friendly information

Scattering in active volume provide **partial** but **relevant** information as regards PID and momentum estimation

- Scattering angle spectrum may be divided in 3 regions: one dominated by muons , one by electrons and a mixed regime

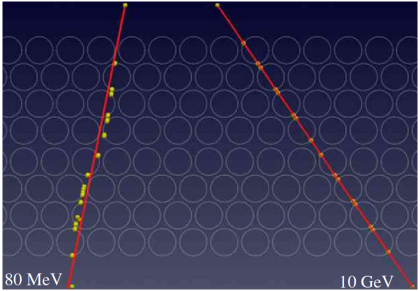


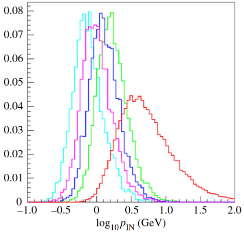


Perspectives: momentum estimation

" *Muography of different structures using muon scattering and absorption algorithms*"
http://dx.doi.org/10.1098/rsta.2018.0051

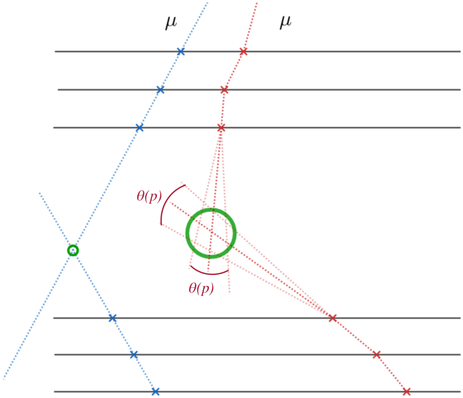
- Instead of raw scattering angle, one can use the χ^2 of the track to infer particle momentum
- Momentum range can be divided into classes according to the average χ^2 value of the track





Consequences for TomOpt

- **Tracking resolution** becomes function of detector parameters (# of plane, plane width)
- X_0 **inference** via likelihood method could benefit from **momentum estimation**
- Consider a **set of tracks** weighted by $\theta(p)$ distribution instead of a single one during POCA algorithm?



Feasibility

Implementation in TomOpt

PROS:

- Adaptation to every geometry

CONS:

- Computation time
- Scattering model accuracy

Use of parametric models obtained from GEANT4 simulation

PROS:

- Computation time
- Scattering model accuracy

CONS:

- Adaptation to every geometry

CRY partgun 0.1m^2 generation surface

Plane width $= 5$cm

	E< 1	$1 <$E< 2.2	$2.2 <$E< 5	E> 5	full range
Relative # of events	22%	22%	25%	31%	/
Mean scattering angle θ	0.55°	0.14°	0.07°	0.02°	0.13°
$P(\theta > 2^\circ)$	3.4%	0.5%	0.2%	0.2%	0.7%

CRY $1m^2$ generation surface

Plane width = 2cm

	E< 1	1 <E< 2.2	2.2 <E< 5	E> 5	full range
Relative # of events	26%	25%	25%	24%	/
Mean scattering angle θ	1.4°	1.2°	1.4°	1.8°	1.5°
$P(\theta > 2^\circ)$	5.1%	2.9%	3.3%	4.5%	4.0%

Plne width = 5cm

	E< 1	1 <E< 2.2	2.2 <E< 5	E> 5	full range
Relative # of events	26%	25%	25%	24%	/
Mean scattering angle θ	1.7°	1.4°	1.5°	1.9°	1.6°
$P(\theta > 2^\circ)$	7.3%	3.2%	3.6%	4.5%	4.8%