PROCEEDINGS OF SCIENCE

The Relevance of Muon Deflections for Neutrino Telescopes

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Large-scale neutrino telescopes have the primary objective to detect and characterize neutrino sources in the universe. These experiments rely on the detection of charged leptons produced in the interaction of neutrinos with nuclei. Angular resolutions are estimated to be better than 1 degree, which is achieved by the reconstruction of muons. This angular resolution is a measure of the accuracy with which the direction of incoming neutrinos can be determined. Since muons can traverse distances of several kilometers through media, the original muon direction can differ from the muon direction inside the detector due to deflections by stochastic interactions and multiple scattering.

In this contribution, a recently published study of muon deflections based on the simulation tool PROPOSAL is presented. Muons with various energies are propagated through different media over several distances. Data-Monte-Carlo comparisons as well as comparisons to the simulation tools MUSIC and Geant4 are performed. Finally, the impact of muon deflections on large-scale neutrino telescopes is discussed.

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1. Introduction

In the universe, neutrino sources are characterized by large-scale neutrino telescopes due to the detection of charged leptons produced in interactions of neutrinos with nuclei in the Earth. The utilization of muons enables the best opportunity to locate these sources since the large propagation distance of muons even in dense media leads to higher angular resolutions in comparison to electrons and taus. Due to the high distance to these sources, their observations require accurate directional reconstructions which are estimated to be better than 1° in current neutrino telescopes [1–5].

In these reconstruction algorithms, a muon propagation along a straight line is assumed and deflections of muons are expected to be lower than the angular resolutions. However, muons with PeV energies are able to propagate kilometers through media like ice and rock while a multitude of individual interactions occur. With every interaction there is a transfer of energy and thus a transfer of momentum, which leads to a small change of direction. All these single deflections accumulate along the track and result in a total deflection θ_{acc} with respect to the initial muon direction. In this proceeding, the impact of this total deflection on the angular resolution of current neutrino telescopes is investigated.

2. Simulation tool PROPOSAL

The simulations are performed with the open-source Monte-Carlo framework PROPOSAL[1] [6, 7], which is written in C++ and also available in Python. This tool propagates charged leptons and photons through media using state-of-the-art parametrizations and cross-sections and it is used in the simulation chain of the IceCube Neutrino Observatory [8], KM3NeT [9] and CORSIKA 8 [10].

For muons, the main interaction types bremsstrahlung, photonuclear interaction, electron pair production, ionization and the decay are provided. An interaction process is sampled by the given cross-sections. The propagation is specified by an initial energy E_{i}, a final energy E_{f}, a propagation distance d, a medium and energy cuts which are described by an absolute energy cut e_{cut} and a relative cut v_{cut}. These energy cut settings define a minimum energy loss $E_{\text{loss, min}}$ by

$$E_{\text{loss, min}} = \min(e_{\text{cut}}, E \cdot v_{\text{cut}}) , \tag{1}$$

with the energy E before the interaction. An energy loss $E_{\text{loss}} \geq E_{\text{loss, min}}$ is treated as a stochastic energy loss, $E_{\text{loss}} < E_{\text{loss, min}}$ as a continuous energy loss. These cuts are needed since energy losses exchanging the massless photon like bremsstrahlung can be arbitrarily small and result in an infinite number of interactions without these cuts. Higher cuts lead to less precise propagations but improved runtime performance.

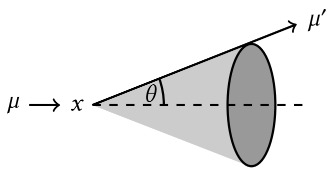

Figure 1: An incoming muon μ is deflected due to an arbitrary interaction x by the angle θ resulting to a new direction of the outgoing muon μ' located on a cone [11].

Deflections along a continuous energy loss are described by multiple scattering. Different multiple scattering parametrizations are available. The deflections caused by stochastic interactions have recently been implemented in PROPOSAL version 7 and are

[1] github.com/tudo-astroparticlephysics/PROPOSAL. The tool can be installed with *pip install proposal* or via CMake.

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available for all relevant muon interaction types [12, 13]. A sketch of a single muon deflection is visualized in Figure 1. Further investigations can be found in [11, 14].

In addition, a scattering multiplier ζ is introduced for all deflection parametrizations and also multiple scattering. This multiplier scales sampled deflection angles θ by

$$\theta_{\mathrm{s}} = \zeta \cdot \theta \, . \tag{2}$$

For each interaction type, a separate multiplier can be chosen. On the one hand, this scaling enables further investigations of upper deflection limits, on the other hand it can be used to perform an analysis in which a deflection can be measured.

A detailed description of PROPOSAL is stated in [6, 7, 15]. For this proceeding, all simulations are performed with PROPOSAL version 7.6.2 using the default parametrizations and multiple scattering described by Molière [16] and an energy cut of $e_{\mathrm{cut}} = 500\,\mathrm{MeV}$ if not stated otherwise.

3. Resulting muon deflections

A single muon deflection depends on the interaction type, the muon energy E and the energy loss E_{loss}. For 1000 muons propagated from $E_{\mathrm{i}} = 1\,\mathrm{PeV}$ to $E_{\mathrm{f}} = 1\,\mathrm{TeV}$ in ice, 95 % of all deflections occur in the interval of $[2.2 \times 10^{-7}\,°, 1.3 \times 10^{-3}\,°]$ with a median deflection of $3.9 \times 10^{-6}°$. The median propagation distance with a 95 % interval is $d = 16.4^{+24.6}_{-7.3}\,\mathrm{km}$ [14].

In the following, the impact of the muon deflection on the angular resolution of muon and neutrino detectors is studied. For this, the accumulated muon deflection θ_{acc} between the initial muon direction and the muon direction after a propagation is simulated. First, 10^6 muons are propagated from $E_{\mathrm{i}} = 10\,\mathrm{PeV}$ to $E_{\mathrm{f}} = 1\,\mathrm{GeV}$ in ice. This is presented in Figure 2. The lower the final muon energy, the larger the accumulated deflection. The profile of the entire distribution has a width of approximately three orders of magnitude. At 1 GeV, the median deflection is about 1°, at very high energies of 1 PeV it is about $10^{-4}°$. Furthermore, angular resolutions of neutrino telescopes are added. At energies above 10 TeV, there is no impact of the muon deflection on the resolution. The resolution of Baikal-GVD [3] which is on the order of 1°, is stated for energies larger than 1 TeV and not affected, similar for ANTARES [17]. However, the reconstruction performance of ARCA [1] and ORCA [2] are both impacted for energies below 10 TeV. This is also the case for Super-Kamiokande [4]. For IceCube [5], the resolution mentioned here might be impacted by some outliers between 1 TeV and 10 TeV. Additionally, the kinematic scattering angle between the neutrino and the produced muon is added, which is larger than the deflection [1].

Furthermore, the deflection is investigated in dependence of the propagation distance d for the same simulation data set. All distances are divided into three intervals that contain an equal number of events. The medians of accumulated deflections are presented for these three intervals and all distances in Figure 3a. At high final energies, large distances do not occur since the muon loses energy continuously during the propagation which results in a maximum distance that can be reached for a specific setting of an initial and final energy. For distances $d < 11\,893\,\mathrm{m}$, the median deflection is shifted to lower angles for energies between 100 GeV and 1 PeV. For distances $d > 21\,147\,\mathrm{m}$, angles are slightly higher in comparison to the median of all events. All in all, there is only a small impact of the propagation distance on the deflection.

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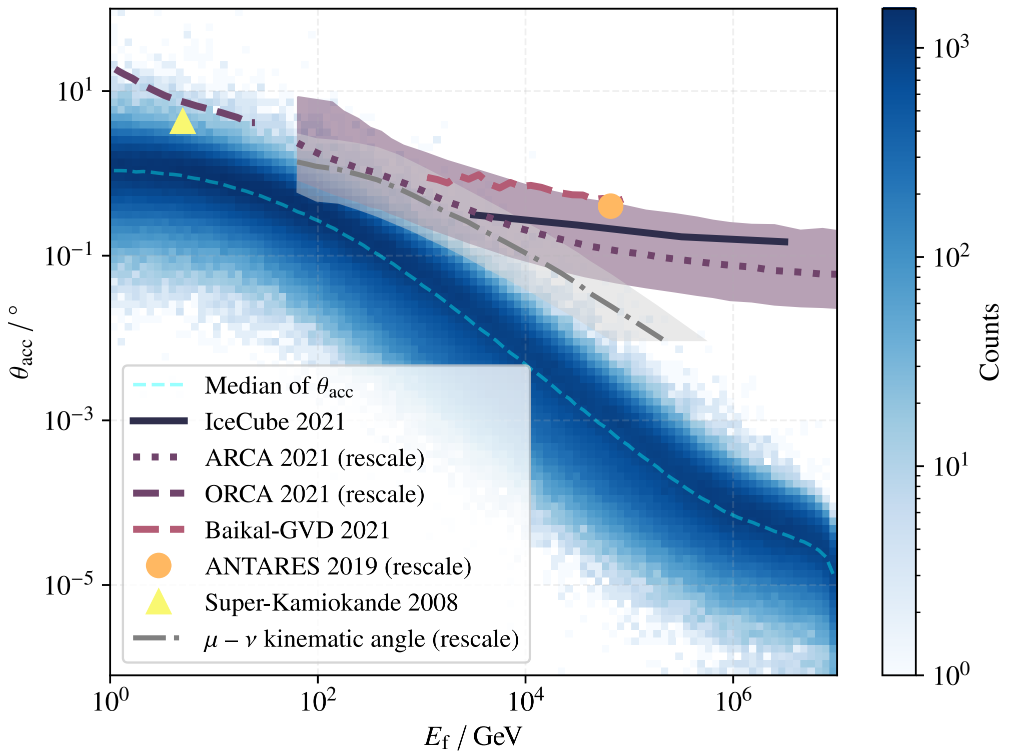

Figure 2: The accumulated muon deflection θ_{acc} is shown in dependence of the final muon energy E_f for 10^6 muons propagated through ice. Angular resolutions of detectors are shown for IceCube [5], ARCA [1], ORCA [2], Baikal-GVD [3], ANTARES [17] and Super-Kamiokande [4]. The kinematic production angle between a neutrino and the produced muon is taken from [1]. Some resolutions are stated as a function of the neutrino energy, to compare these with the muon energy, a rescaling is performed by applying the average energy transfer to the nucleus [18]. The same simulations are performed in water resulting in a deviation of the median deflection of less than 1 %.

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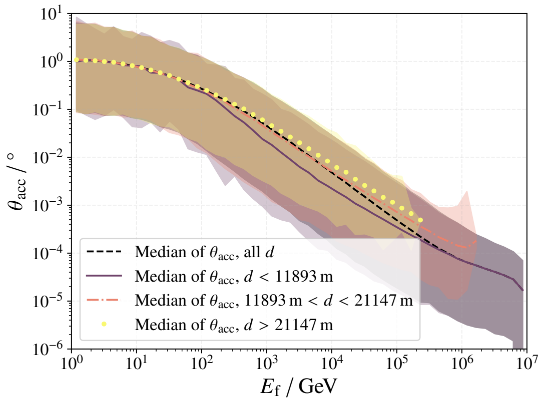
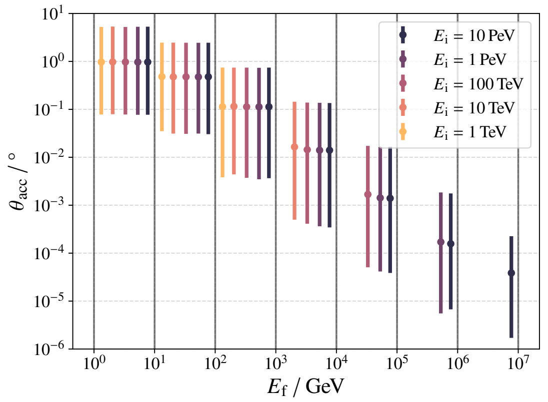
On the experimental side of a neutrino telescope, the initial muon energy is not known. Hence, the deflection is analyzed in dependence of different initial energies. In total, 10^6 muons are propagated through ice for five different initial energies $E_i \in [1\,\text{TeV},\ 10\,\text{TeV},\ 100\,\text{TeV},\ 1\,\text{PeV},\ 10\,\text{PeV}]$. Median deflections and 99 % intervals for seven final energy bins are shown in Figure 3b. All medians per final energy bin and even the intervals are similar. From this follows that the accumulated muon deflection is independent of the initial muon energy.

Additionally, the lateral displacement of the muons is studied in Figure 4a. The $E_i = 1\,\text{PeV}$ simulation data set is used and the final energies are divided into six energy bins. The 99 % contours represent a circular and isotropic distribution of the muon displacements. The lower the final energy, the larger the displacement. This is caused by the fact that larger angles also cause wider displacements. The displacements in the smallest energy interval of $1\,\text{GeV} < E_f < 10\,\text{GeV}$ are smaller than 1 m.

Finally, the accumulated muon deflection depends primarily on the final muon energy. The influence of the propagation distance and the initial muon energy are negligible. This allows using the reconstructed muon energy inside a detector to estimate the muon deflection before the detector

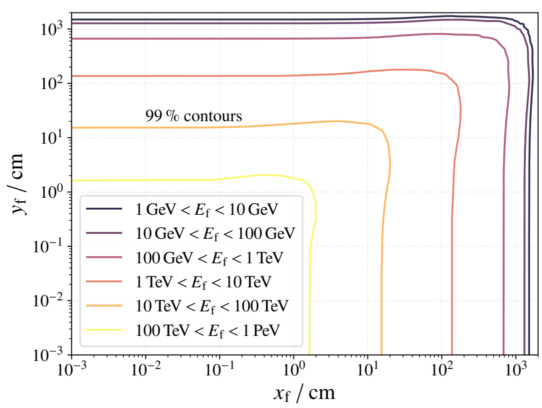


(a) The simulation data set of Figure 2 is divided into three distance quantiles that contain an equal number of events. Presented are four different medians of the accumulated deflection with 99 % . For low distances, lower deflections occur between 100 GeV and 1 PeV. Large distances lead to slightly higher deflections.

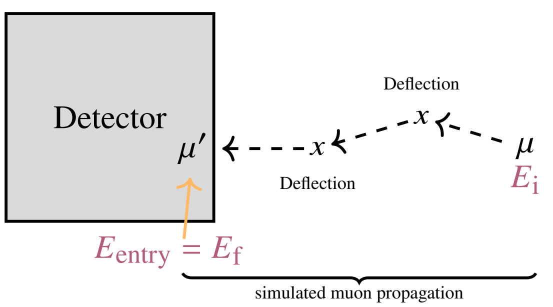


(b) The median deflection θ_{acc} with the 99 % intervals are shown for different initial energies E_i and logarithmic binned final energies E_f. Each simulation set contains 10^6 muons. The grey vertical lines indicate seven intervals of final energies used to determine the medians. Medians and 99 % intervals overlap.

Figure 3: The impact of the propagation distance d and the initial muon energy E_i on the deflection are investigated in dependence of the final muon energy E_f. The distance impacts the deflection only slightly and the initial muon energy has nearly no impact.



(a) 10^6 muons with an initial energy of E_i = 1 PeV are propagated through ice along the z–axis. The 99 % contours of the lateral distributions are presented for different final energies E_f. Since the profiles are circular and isotropic, the absolute values of x_f and x_f are shown. The lower the final energy, the larger the lateral displacement.



(b) The path of a muon to the detector is sketched. The final muon energy E_f corresponds to the entry energy E_{entry}, that can be reconstructed by a detector. Since the muon deflection is nearly independent of the initial muon energy and the distance, E_{entry} can be used to estimate the muon deflection before the detector entry.

Figure 4: The lateral muon profile and a sketch to estimate the muon deflection as a systematic uncertainty for angular reconstructions of muon and neutrino detectors are shown.

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entry. This can serve as an estimation of the systematic uncertainty due to muon deflections for angular reconstruction methods. This principle is sketched in Figure 4b. A parametrization of the median deflection as a function of the final muon energy is given in [14].

4. Summary

Using the simulation tool PROPOSAL, the accumulated muon deflection and its impact on the resolution of angular reconstruction methods in muon and neutrino detectors are investigated. One conclusion is that the lower the final muon energy, the larger is the the resulting deflection. Resolutions of Super-Kamiokande, ARCA and ORCA are affected by outliers of the deflection distributions. Further studies show that the deflection is nearly independent of the initial muon energy and the propagation distance. From this follows that the reconstructed muon energy inside a detector can be used to estimate the deflection of the muon before the detector entry. This can serve as an estimation of a systematic uncertainty in reconstruction algorithms.

In addition, resolutions shown in this proceeding are from 2021 and older. Due to new machine learning techniques, the reconstruction methods improve and lead to more precise angular resolutions. Thus, the impact of the deflection can increase in the future.

5. Discussion: Data-Monte-Carlo Deviations

In recent studies, mismatches between measured data and Monte-Carlo simulations are observed for two different setups [14]. First, the deflection of muons with $E_\mathrm{i} = 199\,\mathrm{MeV}$ passing 109 mm of liquid H_2 is measured and compared to the results of PROPOSAL [19]. Second, muons with $E_\mathrm{i} = 7.3\,\mathrm{GeV}$ passing 1.44 cm of copper are investigated [20]. For $E_\mathrm{i} = 199\,\mathrm{MeV}$, larger angles are underestimated. For $E_\mathrm{i} = 7.3\,\mathrm{GeV}$, larger angles are overestimated. Deviations up to a factor of three are observed. So far, these are the only measurements of muon deflections. For both measurements, simulations have also been performed with the simulation tool GEANT4 [13], which demonstrates similar deviations. The comparisons are displayed in Figure 5.

By now, muon deflections have been measured only for low energies and short distances with respect to neutrino telescopes. Even at these, mismatches occur. Thus, a validation of the simulated muon deflection requires further measurements. These need to be performed at higher energies of TeV to PeV energies and large scale distances on the order of kilometers. The scattering multiplier introduced in Eq. 2 can be used to perform a statistical analysis to measure such deflections. In addition, simulations with applied multipliers can serve to estimate upper limits of the muon deflection to testify, which multiplier would affect a specific angular reconstruction method.

All in all, the resulting muon deflections simulated in this proceeding extend over several orders of magnitude. Hence, possible deviations by a factor of $2-3$ are negligible in first order and the drawn conclusions should remain unaffected.

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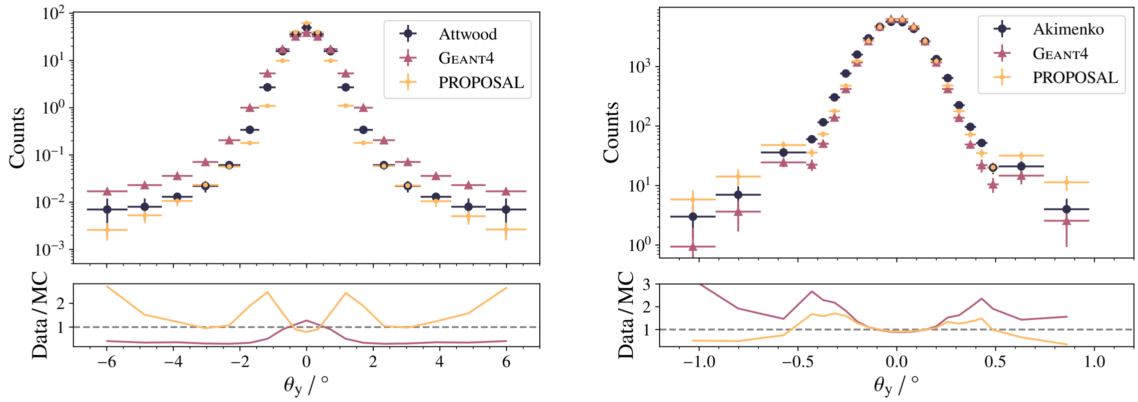

(a) Muons with $E_\mathrm{i} = 199\,\mathrm{MeV}$ propagating through 109 mm of liquid H_2 are shown. Deflections are underestimated by PROPOSAL. Data are taken from [19].

(b) Muons with $E_\mathrm{i} = 7.3\,\mathrm{GeV}$ propagating through 144 mm of copper are shown. Larger deflections are overestimated by PROPOSAL. Data are taken from [20].

Figure 5: Two comparisons between measured data, PROPOSAL simulations and the simulation tool GEANT4 [13] are presented. In PROPOSAL, 100 simulations for each comparison are performed. The means with the standard deviations are shown. A relative energy cut $v_\mathrm{cut} = 10^{-5}$ is used. In both comparisons, deviations between the simulated deflection and the measured data occur. Comparisons are taken from [14].

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