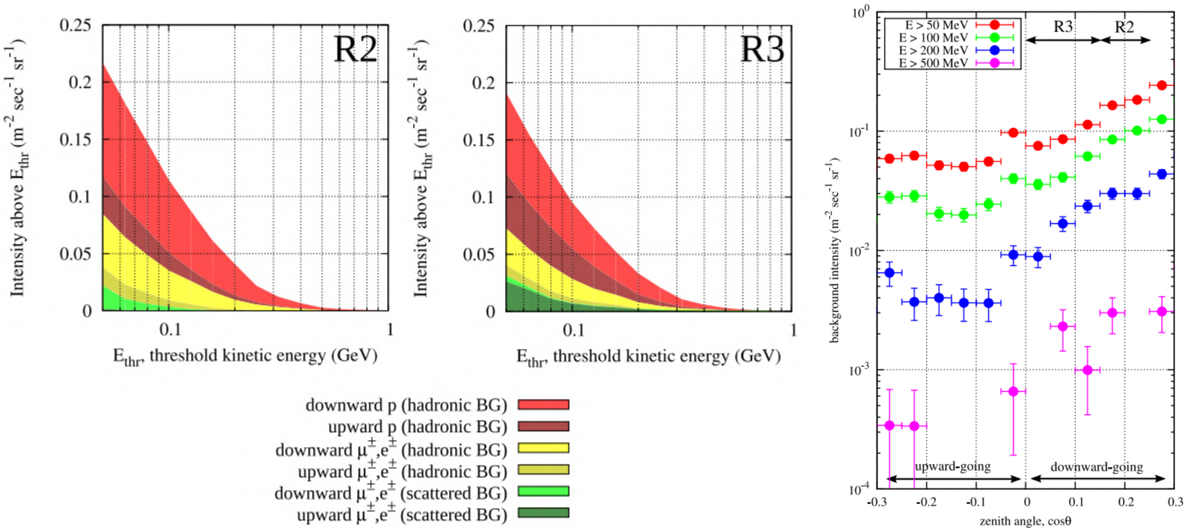
Review answers for Prof. Yoshikazu Nagai

1. **From page 16, the author discusses four major background cases. Which one of the four background categories was the most concerning contribution to your measurement? And what will be your suggestion for the next project to improve that situation?**

Case 2 (combinatorial background) is negligible to our measurements. It can be derived from the applied number of chambers in a detector module, which is around eight. Therefore, the chance for cosmic shower components to mimic a straight line in eight points is improbable. However, it would be reasonable to examine every possible background case with detailed calculations or simulations in a future study.

Case 4, 'backward' (or sometimes called 'upward') scattering has been investigated with Monte Carlo simulations [R. Nishiyama et al. (2016) Geophys. J. Int., 206:1039–1050], which resulted that upward scattering is generally lesser than downward (23-44% at 50 MeV according to the article), and the ratio decreases with energy, see figures below:



Figures: Detailed simulation of background particles from R. Nishiyama et al. Left and middle: Flux of different background sources depending on the energy. Right: Total background flux in different angles around the horizon.

Our surface detectors usually work with energy cut above 1 GeV [L. Oláh et al. Geophys. Res. Lett., 46:17–18, 2019], and from the left figure it can be seen that upward scattering is an order of magnitude lower even at 500 MeV. In any case, it is also true here that it may be worth investigating in more detail for the given measurement.

Case 3 (downward or sometimes called 'forward' scattering of muons), could strongly depend on the topography of the measurement site. H. Gómez [H. Gómez etal *J. Instrum.* **12**: P12018 (2021)] claims, based on simulations, that background can be caused by ‘forward scattering muons’ in certain geometrical cases, which can be relevant even up to 5 GeV muons (before scattering), as shown in figures below.

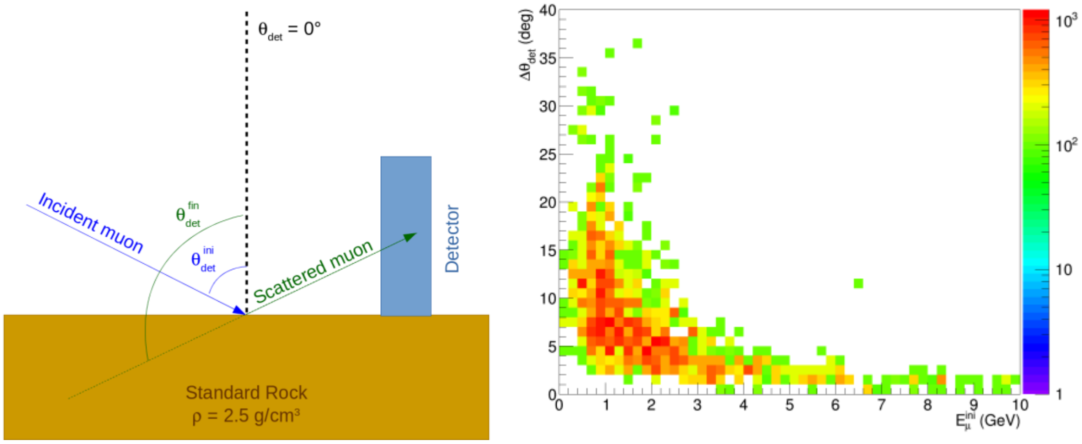
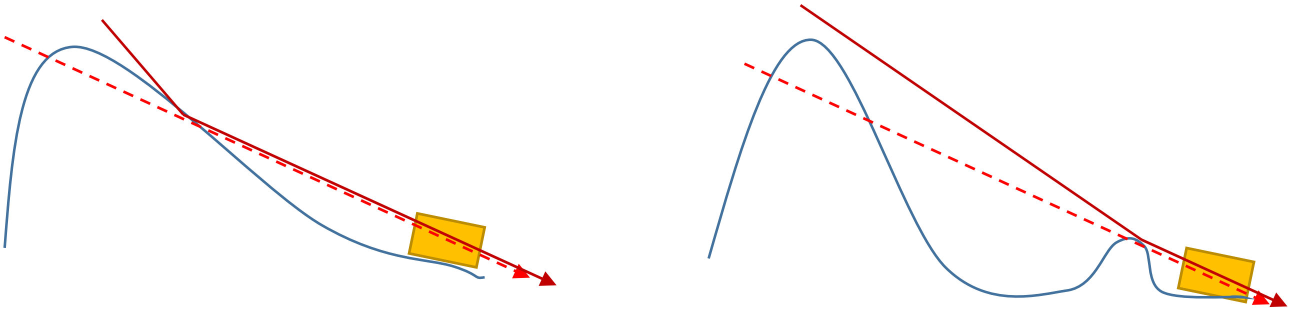


Figure on the left: schematic of scattering of ‘forward’ muons. Right panel shows the muon energy dependency of zenith angle scattering [H. Gómez etal *J. Instrum.* **12**: P12018 (2021)].

This geometrical case can exist for example around the contour of a mountain object with a hill slope close to arriving muon angle, blurring the edge of the mountain image. Alternatively, if significant amount of material located in front of the detector, muons can scatter there, as the schematics shows below:

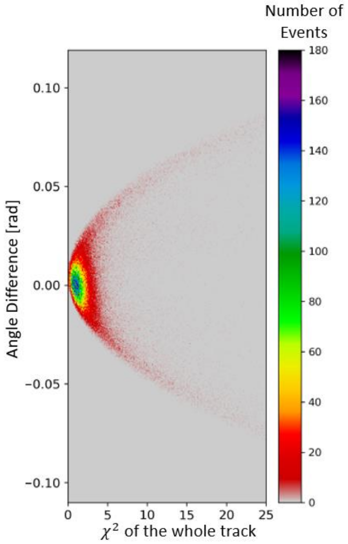


Figures showing possible cases where high energy muon (red) scattering causes background in the detector (yellow rectangle), mimicing signal (dashed).

In a configuration like the cited paper from R. Nishiyama, this case would be also negligible. However, in our Tündérszikla measurement, this component could be a relevant contribution, and therefore it should be investigated in the future.

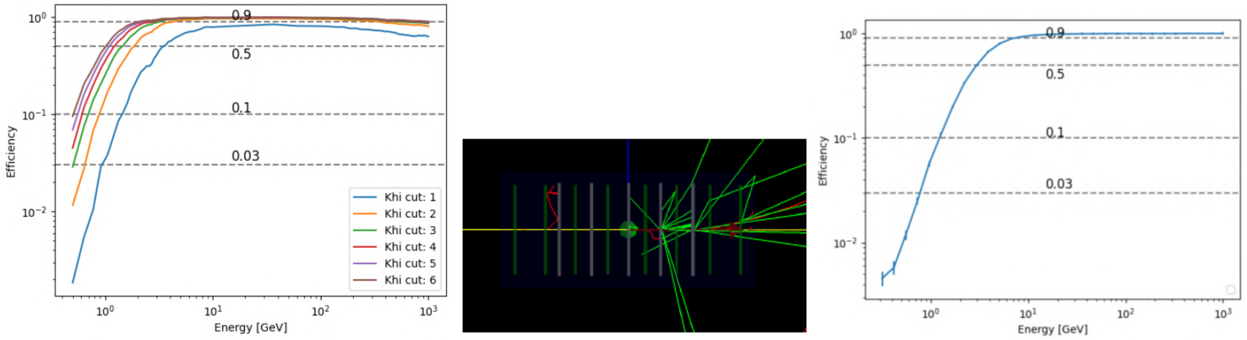
Therefore, the main background contribution in our detector (on surface) is most probably from case 1.

Our background suppression strategy is that, with scattering, we try to filter out every particle below a certain energy level, which affects most background cases (except combinatorial background). There are different strategies reduce background, eg., applying more scattering walls or higher resolution detectors, which both require significant hardware work and cost. Research is also ongoing in various directions to develop the tracking algorithm for better signal-to-noise (and background) ratio in a given detector configuration. My colleagues exploring to extend the χ^2 cut method with examining the angle deviation between different track sections segmented by the lead walls, when there are sufficient number of track points in each section. The idea could be useful not only in background suppression [B. Raboczki, BSc disszertation, ELTE Fizika (2022)], but also in muon scattering tomography [Cs. Botond, OTDK dissertation, ELTE Fizika (2023)]. The former is explained briefly in the figure, right. In this case, there is only one lead wall in the measurement, the angle difference refers to the separately segmented tracking case, and the χ^2 refers to the default tracking (no segmentation). Most of the events, which are the useful signals, are around zero, and the parabolic correlation between the two method is apparent. Research is in progress to apply filtering based on angle deviation, which must be verified by simulation and/or calculations in different muon and background particle energies, angles, and detector configurations.



Comparison of Chi-square and angle deviation in case of a lead scattering wall [B. Raboczki (2022)].

There are also efforts to implement detector simulations to optimise lead wall configurations, and track acceptance. For the latter, figures below show the comparison of traditional χ^2 method with different parameters (left), and a new neural network based method (right) depending on the arriving muon energy.



Figures show the results of Gean4 Monte Carlo simulation on SMO detectors (5 x 2 cm lead walls) for examining the energy cut with different traditional χ^2 cut (left), and teaching machine learning algorithm to predict track acceptance (right) [G. Galgoczi, PhD dissertation 1. thesis point, ELTE (2023)].

2. **From page 87, a case study is shown and results are presented in multiple figures. Could you comment in more detail regarding your systematic uncertainty on this case study about Section 4.1.3? For instance, I could not follow well which systematic uncertainty sources ended up with the dominant (or negligible), as well as how large the statistical uncertainty on the measurement was.**

The statistical uncertainties are expressed in Fig. 4.16 for an arbitrarily chosen slice of data (left panel green error bars, and significance on the right panel), and they are similar for run 1—7 (Fig. 13), since measurement times and density-lengths were approximately the same.

This 'Bayes' method was our first complete tomography solution, including uncertainty calculation propagated from statistical uncertainty, which were successfully applied to real muographic data. The results, presented in 4.2.3 section, do not yet contain systematic uncertainties described in 4.1.3. They were neglected because

- all of the systematic uncertainties were found to be below 3% relative error based on the literature data (values are displayed in 4.1.3), but we aimed to image much larger relative density differences
- most of the systematic uncertainties (first eight point in 4.1.3) cause an absolute baseline-shift on the average density, but we are more interested in relative density difference, hence these uncertainties cancel out in this metric
- some of the systematic uncertainties were corrected (altitude) and minimized by precision measurements (geodesy, detector efficiencies), some of them are negligible due to the measurement configuration: the underground measurements situated under 30—60 m rock which means 15—30 GeV spectrum cut, therefore the solar wind and atmospheric pressure is insignificant.

However, this is one of my research topics now to examine the contribution of systematic uncertainties in specific measurements, estimate the effects, create correction models, test them, and after this, include them into the flux calculation (adds up squarely in Eq. 4.12), which is the input for the inversion algorithm (Eq. 4.17).

3. **From page 57, a novel detector development that combines Thick GEM and CCC (TCPD) is given. To me, it seems a huge potential in addition to the author's primary goal for the detection of Cherenkov light. For instance, it will be very beneficial for future TPC applications to simultaneously detect electron drift charge and primary scintillation UV photons. Many experiments in high energy physics (e.g. neutrino physics, dark matter search) seek simultaneous detection of charge and photon particularly under the high-pressure environment (to maximize gas density or number of target nuclei). I understood from the author's description, for instance, Section 3.1 regarding the mechanical strength of CCC technology and I can imagine that it could be mechanically stronger under over-pressure operation, but an expert's opinion will be very valuable here. Do you have any concerns (or see any benefits) about TCPD technology application under an over-pressure environment (let's say 2-10 bar)?**

The TCPD detector could probably operate in high pressure, but the efficiency must be examined. The optimal detector choice for a given experiment heavily depends on the actual measurable quantities, is it whether particle identification (PID), energy deposition (dE/dx), direction and/or momentum measurement, what are the expected signal sizes, required resolutions, etc.

High pressure TPC detectors, even as active target like the question implied, have also a promising application to obtain the best possible dE/dx resolution in order to maximize the experiment's particle ID capability [High pressure Gas TPCs, talk from Alan Bross], but issues can arise from electron attachment from impurities ($\propto p^2$), how v_{drift} affected (E/p), mechanical implementation in large scale. Efficiency vs pressure dependency is particluraly important to check, since photoelectrons leaving the GEM surface could potentially be pushed back due to high pressure. Latest results from our collaboration allows me to conclude that standard GEM geometries (which have smaller micro-patterns compared to THGEMs) could be potentially better candidates for high pressure operation [Fig. 17 in M. Baruzzo et al. (2020) NIM A **972** 164099,].

Considered separately, measuring electron drifts and photons with the same detector readout could be also highly beneficial for the simplicity of the hardware, and also enticing the same medium for the efficiency of photon detection. However, the latter may raise concerns and should be scrutinized more thoroughly compared to alternatives. This is because the GEM's quantum efficiency is only around 30-50% in the hard UV spectrum when equipped with a gold-plated surface and CsI coating, e.g, in the COMPASS RICH detector which utilizes THGEM (and MicroMegas readout) [J. Agarwala et al. (2019) NIM A **936**, 416-419], or the Hadron Blind Detector (also a Cherenkov detector) for the PHENIX experiment with triple GEM [W. Andreson et al. (2011). NIM A **646**, 35-58]. Also worth noting, that simultaneous electron drift charge and scintillation photon detection is only possible if the created signals are around the same order of magnitude. Further concern, that CsI coating is extremely sensitive to humidity, therefore construction is difficult.

In summary, the suggested operation is possible, as the Leopard system is capable of examining the phenomena. It could serve as an intriguing research topic to combine the aforementioned features, even just for pure detectorphysical pioneering studies, or exploring potential applications, e.g., dual-phase TPC detectors [M. Schumann (2014). JINST **9** C08004], however the application probably must be optimized for the specific task.