Reply to Referees

Ryuichi Nishiyama on behalf of the authors.
19th Feb. 2014.

Thank you for your careful reading, comments and language corrections. Followings are my replies to your comments. This discussion paper consists of two parts. In the former part, we reply to the comments given to some topics from several referees. In the latter part, we answer to the specific comments by each referee.

English problems

> It would certainly benefit from a revision by a native English speaker. Expressions used throughout the text are often incorrect and sentence construction belies very little confidence with the language used **(Referee #1)**.

> I feel that English language should be improved throughout the manuscript. In the following, I give some advices on how to improve some sentences. Anyway, I am not a mother tongue and I urge the author to have the manuscript checked by one of them for linguistic correctness **(Referee #4)**.

Responding to your comments, I already asked a native English speaker for correcting our manuscript. I think linguistic correctness becomes acceptable in the next revision.

Remarks on muography detectors other than emulsion films

> Introduction (1) As stated earlier, it would benefit from a brief overview of what type of detectors have been used so far in this application **(Referee #1)**.

> Furthermore, the authors should provide more detailed discussion on the comparison between the performances of emulsion film detectors and other types of detectors like, for example, those employing plastic scintillators **(Referee #4)**.

> To address this point, a more detailed discussion should be provided about

> advantages and limits of emulsion film detectors, compared with detectors based on different principles **(Referee #4)**.

There are several types of detectors such as scintillation type (Tanaka et al., 2007; Lesparre et al., 2010; Anastasio et al., 2013, etc), gas chamber type (Cârloganu et al., 2013; Barnafoldi et al., 2013, etc) for the application of muon radiography. I will address these precedent works in the next revision. Compared with these types of detectors, the greatest advantages of emulsion detectors are their portability and very high resolution (position resolution: a few microns, angular resolution: a few milli-radians). This work benefited greatly from the high angular resolution, which enables momentum selection. One disadvantage of emulsion is that it does not provide time information of particle arrival. The comparison of the performances should be discussed after we install several detectors at same site. This will be a subject of future study. We will address these issues in the next revision.

Grain density cuts

> Section 5.2.1 The first sentence is incomprehensible. I surmise that the authors cut away events with tracks having grain densities higher than a certain threshold. If this interpretation is correct, the text should be modified accordingly **(Referee #1)**.

> I would suggest replacing "an average grain density (number of AgBr grains on track) higher than threshold. The grain density is" by "grain densities higher than a certain threshold. The grain density is number of silver grains per unit length along the track and is" **(Referee #2)**.

> P656: -l 5: Please rewrite the first sentence which looks strange **(Referee #3)**.

The first sentence in Sec. 5.2.1. in the previous manuscript was strange and misleading. I follow Referee #2's suggestion. Thank you for your careful reading.

Need for more description on experimental conditions

> Fig. 7: How did the authors estimate the shaded histograms in Fig. 7? Why do the tracks recorded during transportation have lower numbers of hits? Were the

> detectors fabricated just before the installation? Better to clarify experimental conditions **(Referee #2)**.

The detectors were fabricated just before the installation. Before the installation, all the OPERA film were refreshed in high temperature and humidity place. We estimate the amount of fake signals by giving misalignment of 500 microns between each film and selected tracks using the same method as employed in the true signal selection. I will address this in the next revision.

> Readers also would like to have an idea of the data taking conditions: environmental parameters effect, humidity/temperature controls in any, fog density in the emulsions etc **(Referee #3)**.

The observation was taken in place in a warehouse without air-conditioning in the midst of winter season in northern part of Japan. We did not monitor temperature or humidity during exposure. According to the Japan Meteorological Agency's report, the maximum temperature is 15.9 degrees in Celsius, and the minimum is – 8.8 degrees around the detector site during the exposure period. Although we did not monitor the humidity, it did not matter to the performance of our detectors, because the films were packed inside of the envelopes. We will try to give specific conditions as much as possible in the next revision.

Reply to each referee's comments

<u>To Referee #1</u>

> "Thus one is left with a paper which in reality describes an improvement (significant) to a standard apparatus used for muon radiography.

I do not get the meaning of this sentence. Could you please give us some explanations if our answers below are not satisfactory to you ?

> I would thus change the title of the paper to reflect the focus on detector improvement and suggest that the authors further develop this aspect in their conclusions, covering feasibility of large area detectors and deployability in the field.

The most important characteristic of emulsion film for muography is that it is very easy to install in the field. The possibility of large area detectors should be discussed along with the current improvement of read-out system (eg. Morishima & Nakano, 2010). I will address these topics in the next revision. However, I do not want to change the title of our paper, because this work focuses on the background source of muography and does not deal with technical aspects of emulsion film itself. In response to your suggestions, we have an alternative title of our paper, which is "Experimental study of momentum of background particles in muon radiography using emulsion film detectors".

> Also it's not clear why the authors suppose straight away that backgrounds to muon radiography are due only to low momenta particles. Could they also be due to high momentum muons coming from behind (scattered on the ground surface) ?

In this paper, we do not exclude the possibility that muons coming from behind the detector could cause background noise. However, we want to emphasize that such muons, which were scattered in the ground are expected to be not so energetic. Please see a revised Figure 1 (below). This histogram shows the distribution of deflection angles of muons after passing through a certain thickness of rock. This figure shows that muons with momenta > 10 GeV c^{-1} (red) are not scattered compared with lower momentum particles (blue and green). Although there are a certain amount of muons which are scattered on the ground surface and come from behind the detector, these well-deflected muons are expected to have low momentum (< 10 GeV c^{-1}). Besides, this type of upward-going muons were reported by another dedicated work using scintillator type detectors and TOF analysis (Jourde et al., 2013). I will discuss these topics furthermore citing this work in the next revision.

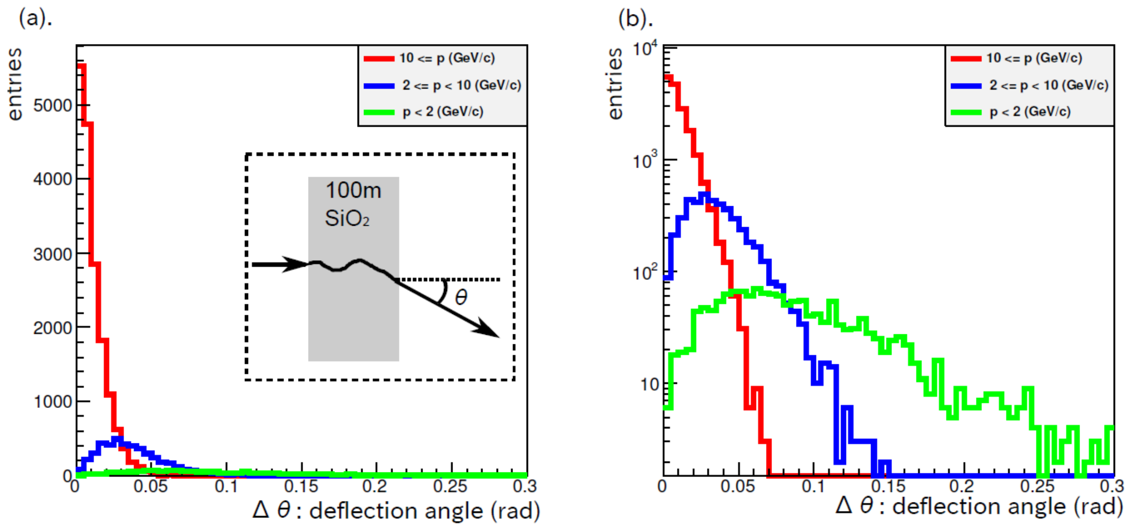

Figure 1 (revised): Deflection angles of CR muons after passing through 100 m thickness of quartz (a: linear scale, b: logarithmic scale). The injection momenta are adjusted to the CR muon momentum spectrum for a zenith angle of 80 degrees. The histogram is divided into three color parts based on the momenta of the ejected muons, green: p_{out} < 2 GeV c^{-1}, blue: 2 GeV c^{-1} < p_{out} < 10 GeV c^{-1}, and red: 10 GeV c^{-1} < p_{out}.

> The comment "Unfortunately there are no sufficient experimental data for the angular dependence of the energy spectrum" referring to the electron component, belies the fact that these are electromagnetic residues from calorimetric showers (the atmosphere being the calorimeter) with an energy of 100 MeV. So what do the authors imply ? Do they expect significant variations with energy ? Do they expect significant deviations from the angular distribution of atmospheric muons ? How would this impact their study ?

While the muon energy spectrum significantly drops due to decay below 1 GeV, the electron spectrum does not drop up to its critical energy in the air (81 MeV). This implies that most of the cosmic electrons at sea level have low energy near 81 MeV and that they have typically large scattering angles in the atmosphere. Thus these well-scattered electrons could hit the detector randomly and are recognized as signals mistakenly. I want to emphasize that these electrons could come from the direction of the mountain, which significantly deteriorates density estimation of the mountain. This is why we think angular distribution of the electron energy spectrum is crucial to muography.

> In fact, are they making a claim that the ECC detector can remove this kind of events ("corrupt muon signals") in a significant and efficient manner ?

Please see again the revised Figure 1. This shows that the probability that muons deflect with more than 0.1 rad is extremely small (Figure 1a) and that most of those muons have momenta less than 2 GeV/c (Figure 1b). Since our ECC module exclude particles with momenta less than 2 GeV/c, we believe ECC detector exclude most of the corrupt muon signals.

> Section 3.2 It is true that one can measure on an event by event basis the momentum of the particle from the measured deflection angles in the detector. This is really applicable though only for very low energy muons and not low energy electrons which suffer Bremsstrahlung. Thus a clarifying statement should be made to how the authors intend to use this information and whether this affects also the electrons traversing the detector.

Do you mean by the second sentence that our method is applicable only for very low energy muons and not applicable for low energy electrons which suffer Bremsstrahlung ? In our analysis, the energy thresholds were calculated for MIP particles. As you have mentioned, this is not in the case of electrons. The electrons deflect with larger angles than muons even if they have the same amount of momentum. But, it does not matter to our purpose since electrons are noise particles for us. If my answer is not satisfactory, please give us detailed explanation for your question.

> Section 5.2.3 It would be interesting to know whether any requirement is made for the ECC detector on possible hits in the first and last layers (i.e. whether a track must be seen "going out" of the detector or not.

There is one requirement which is important but was not written in the previous manuscript. We required tracks in ECC detectors to pass at least five lead plates.

As for the rest of your comments and language corrections, I will follow your suggestions in the next revision. Thank you for your careful reading of our manuscript and valuable questions and comments.

To Referee #2

> Section 3.2: Multiple scattering is known to be well described by Gaussian for small deflection angles, but at larger angles it behaves like Rutherford scattering, having larger tails. The chi-square cut should eliminate tracks in tails. It would be better to mention it here, or at least to add the word “approximately”.

I follow your suggestions. In the next revision, I will give more details of deflection angles and will state that our analysis is based on Gaussian approximation.

> Section 4: The inclination angle theta should be related with theta_x and theta_y by tan(theta) = sqrt{(tan(theta_x))ˆ2 + (tan(theta_y))ˆ2}, not by theta = sqrt{(theta_x)ˆ2 +(theta_y)ˆ2} as given in the paper.

In our analysis, we used the same definition of tan(theta) with your comments. I will change this part in the next revision.

> Section 5.2.2: "An example of the resultant chi-square distribution is shown in Fig. 6." What is this example? Isn’t it data from this experiment? It would be better to specify what it is or to present the real data from this experiment.

This resultant chi-square distribution is from our observation of Mt. Showa-Shinzan. I think the word “example” was misleading. I will change the expression in the next revision.

> Fig. 6: It seems that there are some extra tracks (more than 1 %) in the tail (greater than the upper bound). Are they so called non-signal tracks? It would be worth mentioning.

Due to the error of angular measurement, we have no other way but to regard them as noise tracks although some of the tracks in the tail region are true muon signals. Thus when converting the number of particles into the particle flux, we compensate this effect by multiplying the flux by 100/99. We will mention it in the next revision.

> Section 5.3.1: Are there some tracks which stop inside the ECC detector? If so, don’t they affect the fitting and consequently the efficiency values?

There should be a certain amount of tracks which stop inside the ECC detector. The possible candidates for such tracks are low-momentum cosmic electrons (let's say 100 MeV electrons). However, we could not judge if a particle stops inside our ECC detector or it "looks" stopped due to inefficiency, because the one-film efficiency of current OPERA film is too low (~50% as shown in Fig. 8 green). The efficiency fitting was applied to the high-momentum tracks which survived the severe selection based on scattering angles ($p > 2$ GeV c^{-1}). Since low-momentum cosmic electrons are not selected by our severe selection, the contamination form electrons in the selected tracks is expected to be low enough to affect the resulting efficiency values.

As for the rest of your comments and language corrections, I will follow your suggestions in the next revision. Thank you for your careful reading and valuable questions and comments.

<u>To Referee #3</u>

> Nevertheless one could always suggest other sources of background. For instance there is no mention on the potential effect of ambient radioactivity which is affecting emulsions.

We protected emulsion detectors from ambient radioactive particles with the 3-mm-thickness of steel plates on both sides of the detector (See Tanaka et al. 2007). Figure 9 shows that ambient beta and gamma rays (< a few MeV) are excluded in our analysis. We will address this point in the next revision.

> There are other studies already published on the backward upward-going particle flux which could fake muons coming from the volcano in the absence of time-of-flight analysis (although it seems that there was a significant amount of rock behind the emulsions, please precise).

Jourde et al. (2013) discusses the backward upward-going particles which were found by scintillation type detectors with a dedicated TOF analysis. This type of particles definitely cause noise signals also for emulsion detectors. As you have mentioned, there is a significant amount of rock behind and in front of our emulsion detectors. We think this is why we did not see an excess of the particle flux in the forward or backward directions. We will address this issue in the next revision.

> For instance the authors mention a measurement in underground conditions where soft particles barely penetrate and where the same low-value density was obtained with a "Quartet"-type detector. This looks rather suspicious that such low value may be caused by soft particles. More precisions could help clarifying and assessing the main conclusion of the paper which is otherwise of excellent quality.

I agree with your impression. The noise signals arise not only from soft particles but also from hard particles (muons or pions scattered in the topographic material). I believe the cave measurement will give some constraints on the characteristics of these noise particles. However, details of this work cannot be written here, because it will be published in other place. I will remove this remark on the cave measurement in the next revision, sorry.

> Is it foreseen to couple emulsion detectors with electronic detectors to check instrumental effects with different experimental techniques?

Not yet. But, that sort of study should be conducted near in the future.

As for the rest of your comments and language corrections, I will follow your suggestions in the next revision. Thank you for your careful reading and valuable questions and comments.

To Referee #4

> It seems that emulsion film detectors offer critical advantages with respect to detectors based on different principles and the reader is left with the question of why different detectors were employed in the past to accomplish similar tasks (Tanaka et al., 2011; Lesparre et al., 2012).

There should be several reasons. For example, it is technically difficult for beginners to construct read-out microscope systems. However, we do not know the exact reason why those precedent studies did not use emulsion films.

> As discussed in Sect. 5.3.2, the momentum thresholds of these two detectors are: Why do the authors reveal in advance this information, that is discussed later in the paper?

This is to show the objectives of our comparative study clearly to readers.

> tan_theta_y = 0 horizontal particles: Are the authors sure that they mean horizontal, rather than vertical, particles?

The emulsion detectors were placed perpendicularly to the ground, so the tracks with tan(theta_y) = 0 mean horizontal particles.

As for the rest of your comments and language corrections, I will follow your suggestions in the next revision. Thank you for your careful reading and valuable questions and comments.

References (to be added in the next revision):

Anastasio et al., The MU-RAY detector for muon radiography of volcanoes, Nuclear Instruments and Methods in Physics Research A 732 (2013) 423–426.

Càrloganu et al., Towards a muon radiography of the Puy de Dôme, Geosci. Instrum. Method. Data Syst., 2, 55-60, 2013.

Barnafoldi et al. Portable cosmic muon telescope for environmental applications, Nuclear Instruments and Methods in Physics Research A 689 (2012) 60–69.

Jourde et al. Effects of upward-going cosmic muons on density radiography of volcanoes, arXiv:1307.6758.