The muon content of atmospheric air showers and the mass composition of cosmic rays

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HIRSAP meeting
10.11.22

Structure

On the determination of the muon content

- Muon counting strategy
- Correction of biases in the reconstructed number of muons
- Characterization of the muon lateral distribution function

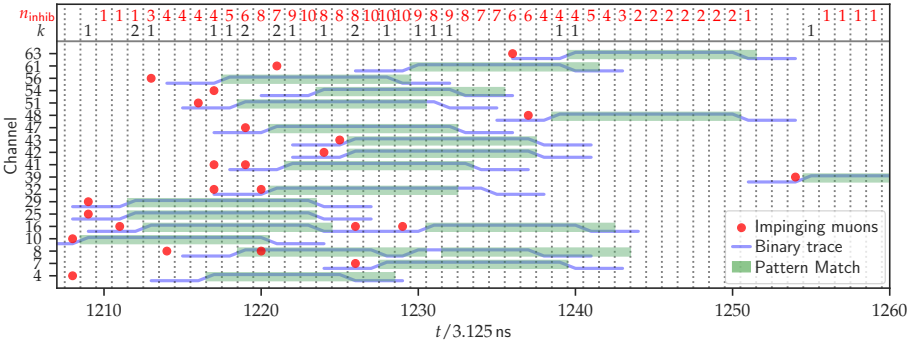
On the composition interpretation of data

- Muon content in air-shower simulations in comparison to:
  - UMD SiPM data
  - AGASA data

Muon counting strategy

[Estimation of the number of counts on a particle counter detector with full time resolution, F. Gesualdi, A.D. Supanitsky, Eur. Phys. J. C 82 (10) 925 (2022)]

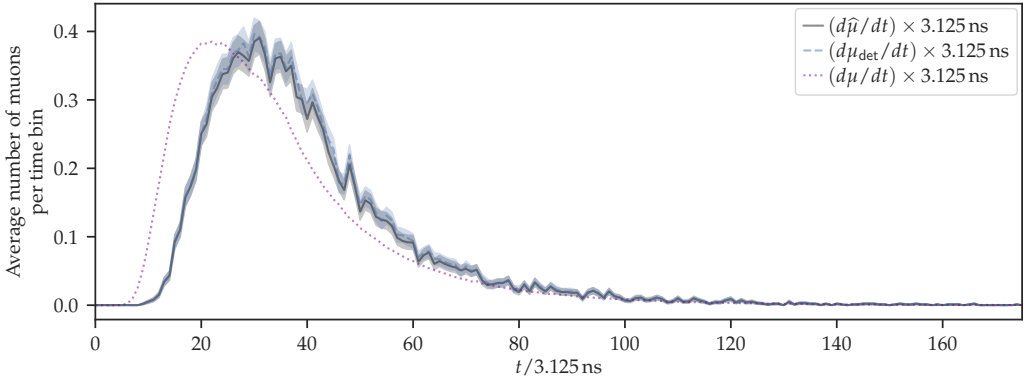
We developed a new counting strategy that accounts for inhibited channels.



$$N_\mu = 24 \qquad \widehat{N}_\mu = \sum_{j=1}^{j=n_w} \underbrace{\frac{n_s}{n_s - n_{\text{inhib},j}}}_{\text{To obtain what would be observed for a const. detector area}} \frac{\ln\left(1 - \frac{k_j}{n_s - n_{\text{inhib},j}}\right)}{\ln\left(1 - \frac{1}{n_s - n_{\text{inhib},j}}\right)} \qquad \Rightarrow \widehat{N}_\mu = 23.1$$

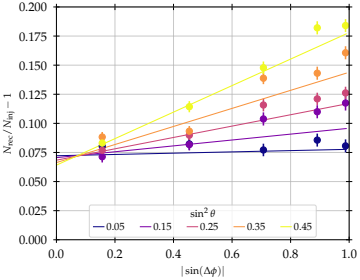
Counting strategies: Muon time structure

With this work's strategy, we are able to reconstruct the muon time structure as seen by the detector to a single time-bin resolution. This can be useful for reconstructing $X^{\mu}_{\max}$.

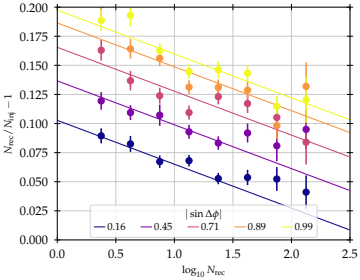


Correction of biases in the reconstructed number of muons

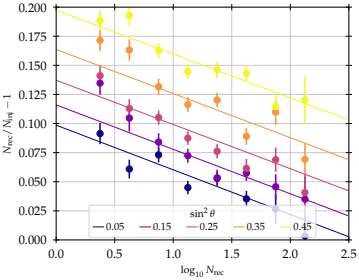
The estimated number of muons are subject to biases, most notably, from corner-clipping muons. Using full detector simulations, we parameterize and correct the bias.



Bias as a function of $|\sin(\Delta\phi)|$ for different $\sin^2\theta$ bins for $1.1 \leq N_\mu \leq 10$.



Bias as a function of $\log_{10} N_\mu$ for different $|\sin(\Delta\phi)|$ bins for $0.4 \leq \sin^2\theta \leq 0.5$.

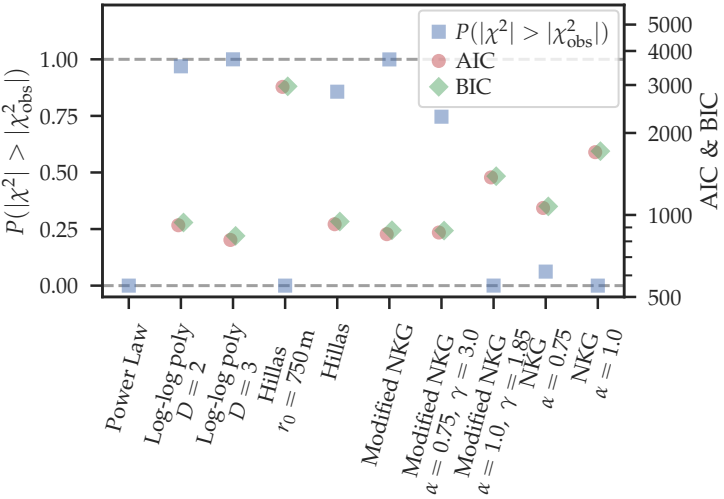


Bias as a function of $\log_{10} N_\mu$ for different $\sin^2\theta$ bins for $76° \leq \Delta\phi \leq 83°$.

Remaining dependencies of the bias are contained within $\pm 4\,\%$.

Characterization of the average muon lateral distribution function

We tested the goodness-of-fit of different models on UMD SiPM data.

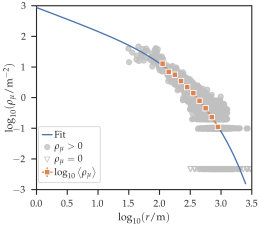


Characterization of the average MLDF: Parameterizations

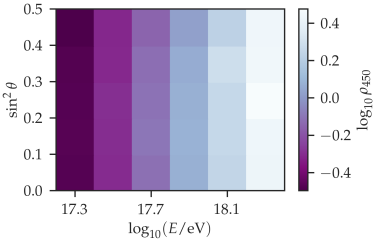
We parameterized the muon LDF using a modified NKG function:

$$\rho_\mu^{\mathrm{mNKG}}(r) = \rho_{r_{\mathrm{opt}}} \left(\frac{r}{r_{\mathrm{opt}}}\right)^{-\alpha} \left(\frac{1 + r/r_0}{1 + r_{\mathrm{opt}}/r_0}\right)^{-\beta} \left(\frac{1 + (r/10r_0)^2}{1 + \left(r_{\mathrm{opt}}/10r_0\right)^2}\right)^{-\gamma},$$

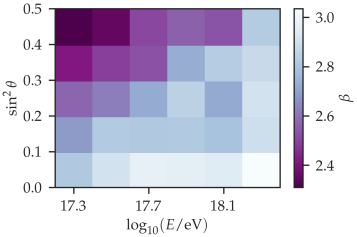
with $r_{\mathrm{opt}} = 450\,\mathrm{m}$, $r_0 = 320\,\mathrm{m}$, $\alpha = 0.75$, and $\gamma = 3$.



Fit to data with $17.6 \leq \log_{10}(E/\mathrm{eV}) < 17.8$, and $27° \leq \theta < 33°$.



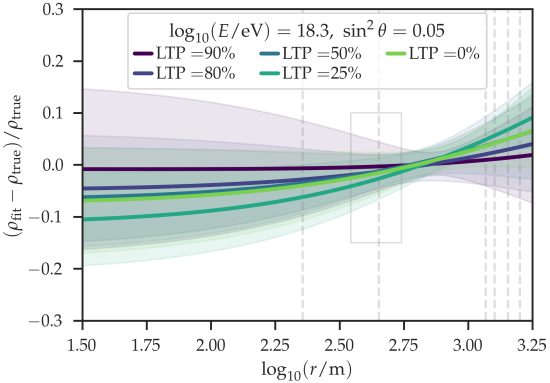
$\log_{10}\rho_{450}$ as a function of $\log_{10}(E/\mathrm{eV})$ and $\sin^2\theta$.

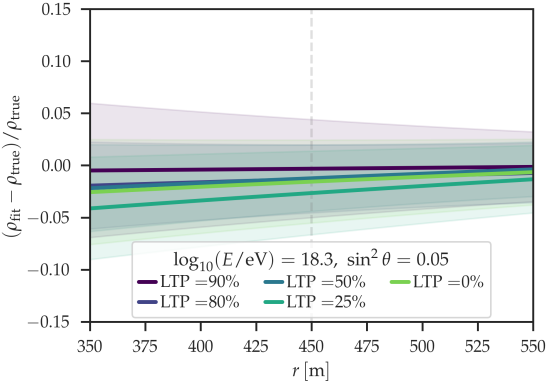


β as a function of $\log_{10}(E/\mathrm{eV})$ and $\sin^2\theta$.

Characterization of the average MLDF: Analysis of systematic uncertainties

Using the parameterizations, we studied the systematic uncertainties of the fits of the average MLDF, introduced by fixing α and γ, and by cutting at a $90\,\%$ lateral trigger probability.

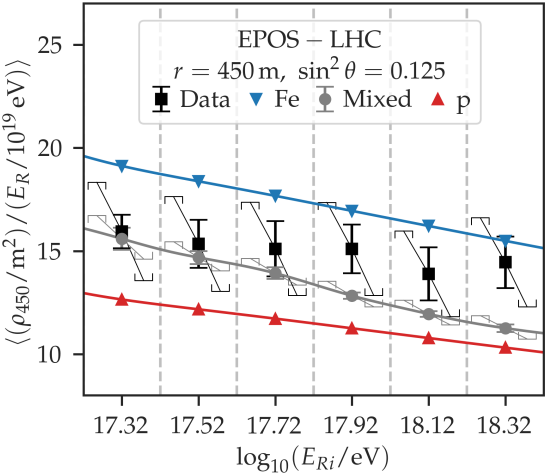


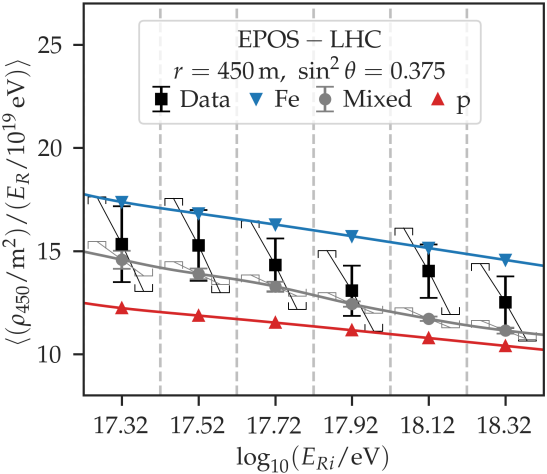


Even when considering the systematic uncertainties from the fits, $450\,\mathrm{m}$ is still an optimal distance.

Muon content in UMD data

We analyzed the muon content in UMD data as a function of the energy, zenith angle, and distance to the shower axis

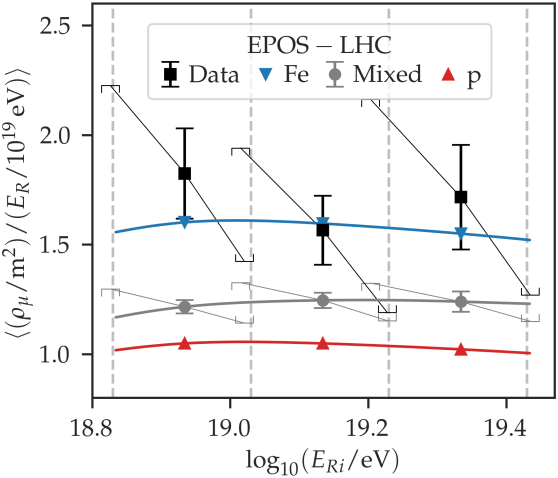




Muon content in AGASA data

We analyzed the muon content in AGASA data as a function of the energy ($\theta < 38°$, $r = 1000\,\mathrm{m}$).

[Muon deficit in air shower simulations estimated from AGASA muon measurements, F. Gesualdi, A.D. Supanitsky, and A. Etchegoyen, Phys. Rev. D **101**, 083025 (2020)]
[Muon deficit in simulations of air showers inferred from AGASA data, F. Gesualdi, A.D. Supanitsky, and A. Etchegoyen, PoS (ICRC2021) 326]

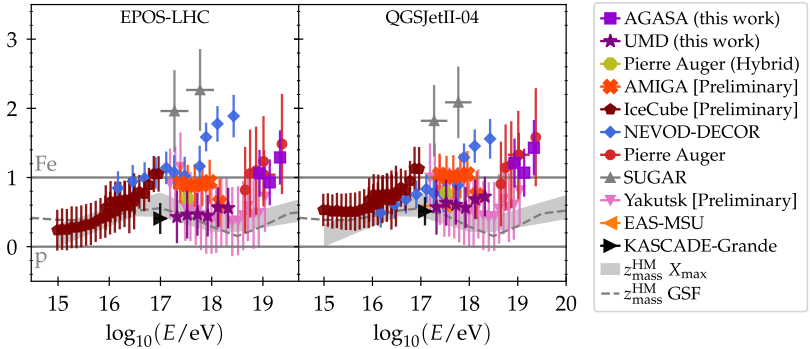


Muon scale as a function of the energy

[On the muon scale of air showers and its application to the AGASA data, F. Gesualdi et. al., PoS (ICRC2021) 473]

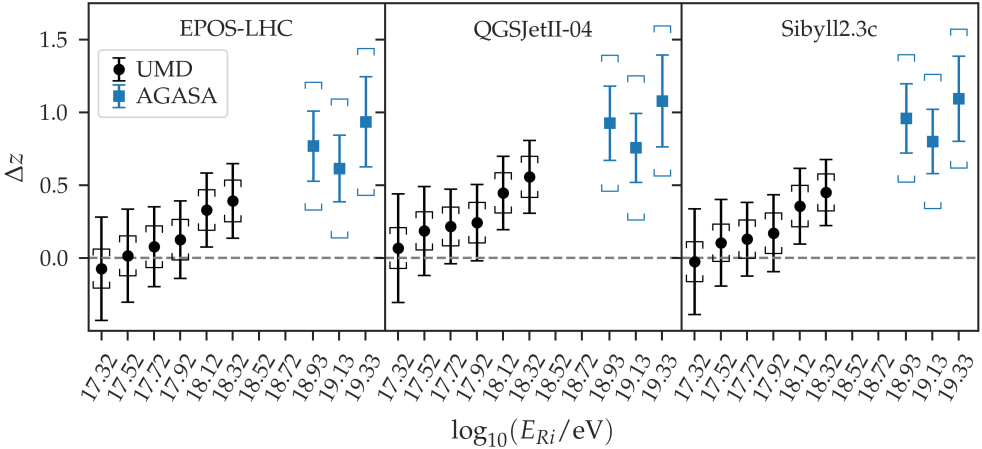
We compared the values of the muon scale z computed from UMD SiPM and from AGASA data to those of other experiments.

$$z = \frac{\ln\langle N^{\text{det}}_{\mu,\,\text{data}}\rangle - \ln\langle N^{\text{det}}_{\mu,\,\text{p}}\rangle}{\ln\langle N^{\text{det}}_{\mu,\,\text{Fe}}\rangle - \ln\langle N^{\text{det}}_{\mu,\,\text{p}}\rangle}$$



Both of our results are consistent with Pierre Auger and Yakutsk array results.

Muon deficit as a function of the energy



Our results, in agreement with other experiments, support the existence of a muon deficit that increases with the energy.

Summary

- New counting strategy
  - → Improves precision in $\hat{N}_\mu$
  - → Allows reconstruction of the muon time structure → Opens the door to X^μ_{max} reconstruction
- Correction of the overall bias
  - → Makes the corrected $\hat{N}_\mu$ accurate to $\pm 4\,\%$
- Characterization of the muon LDF
  - → We provided the parameterizations of the muon LDF using a modified NKG
  - → We concluded that $450\,\text{m}$ is still an optimal distance even when considering the systematic uncertainties due to the fit of the muon LDF ($\pm 2\,\%$).
- Mass composition implications of UMD and AGASA data
  - → The muon content of UMD data is consistent with mixed composition scenarios within total uncertainties, but that of AGASA is not.
  - → Together, they offer a clear picture of a muon deficit that increases with the energy.

List of publications

Reviewed publications

- *Estimation of the number of counts on a particle counter detector with full time resolution*, F. Gesualdi, A.D. Supanitsky, Eur. Phys. J. C 82, 925 (2022), arXiv:2210.09005. Published 18 October 2022.
- *Muon deficit in air shower simulations estimated from AGASA muon measurements*, F. Gesualdi, A.D. Supanitsky, and A. Etchegoyen, Phys. Rev. D 101, 083025, arXiv:2003.03385. Published 22 April 2020.

Unreviewed publications

- *On the muon scale of air showers and its application to the AGASA data*, F. Gesualdi, H. Dembinski, K. Shinozaki, A. D. Supanitsky, T. Pierog, L. Cazon, D. Soldin, and R. Conceição for the Working Group on Hadronic Interactions and Shower Physics. PoS (ICRC 2021) 473, arXiv:2108.04824, 2021.
- *Muon deficit in simulations of air showers inferred from AGASA data*, F. Gesualdi, A. D. Supanitsky, and A. Etchegoyen. PoS (ICRC2021) 326, arXiv:2108.04829, 2021.

List of publications

GAP notes

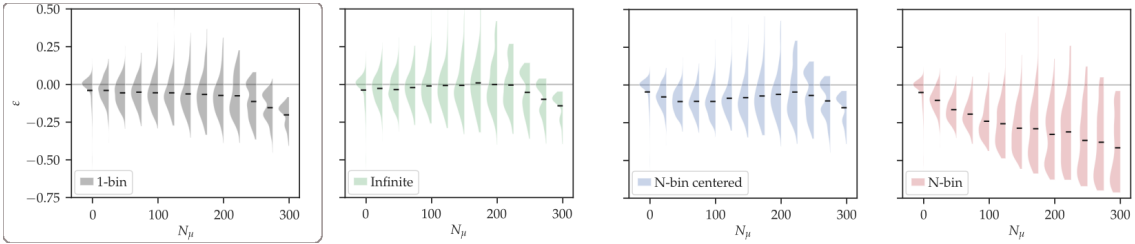
- *A new pile-up correction strategy for the Underground Muon Detector*, F. Gesualdi and A. D. Supanitsky, GAP 2022-001 (2022).
- *Selecting Muon Detector data with the ADST event selection tool in Offline*, F. Gesualdi, M. Roth, D. Schmidt, and D. Veberič. GAP 2021-013 (2021).

Backup

BACKUP SLIDES

Muon counting strategy: Comparison to other strategies

For a realistic comparison, we simulated 7600 $\{\mathrm{p}, \mathrm{Fe}\}$+ EPOS-LHC + UrQMD Corsika simulations (isotropic in $0^\circ \leq \theta \leq 48^\circ$ and uniform in $17.2 \leq \log_{10}(E/\mathrm{eV}) \leq 18.4$) + simulation of electronics



$\varepsilon = \frac{\widehat{N}_\mu - N_\mu}{N_\mu}$ as a function of N_μ for p showers with $18.0 \leq \log_{10}(E/\mathrm{eV}) \leq 18.2$ and $33^\circ \lesssim \theta \lesssim 39^\circ$ ($0.3 \leq \sin^2\theta \leq 0.4$).

Parameterization of the bias in the reconstructed number of muons

The estimated number of muons are subject to biases, most notably, from corner-clipping muons. Using Offline simulations, we parameterize the bias as:

$$f_{\text{bias}}(\theta, \Delta\phi, N_{\mu\,\text{rec}}) = \left\langle \frac{N_{\mu\,\text{rec}}}{N_{\mu\,\text{inj}}} - 1 \right\rangle = a(\theta) + b(\theta)\,|\sin(\Delta\phi)| + c(\theta)\ \log_{10} N_{\mu\,\text{rec}},$$

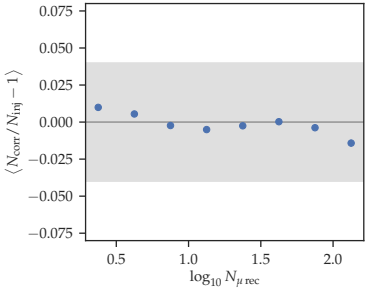
where $a(\theta)$, $b(\theta)$, and $c(\theta)$ are modeled phenomenologically as

$$a(\theta) = a_0 + a_1 \sin^2\theta,$$
$$b(\theta) = b_0 + b_1 \sec\theta,$$
$$c(\theta) = c_0 + c_1 \sin^2\theta,$$

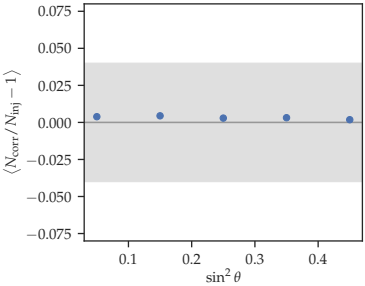
being a_0, a_1, b_0, b_1, c_0, and c_1 parameters of the fit.
We then use the parameterization to correct the estimated number of muons:

$$N_{\mu\,\text{corr}} = \frac{N_{\mu\,\text{rec}}}{1 + f_{\text{bias}}(\theta, \Delta\phi, N_{\mu\,\text{rec}})}.$$

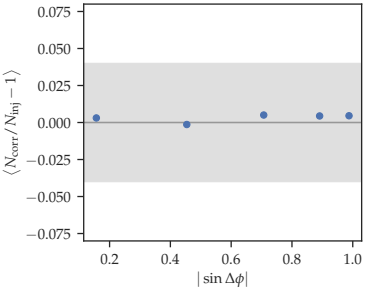
Correction of the bias in the reconstructed number of muons



Bias in the corrected number of muons as a function of $\log_{10} N_{\mu\,\mathrm{rec}}$.

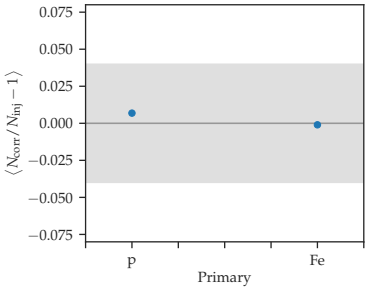


Bias in the corrected number of muons as a function of $\sin^2\theta$.

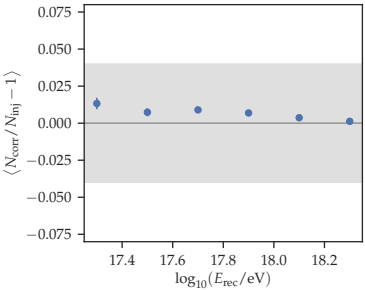


Bias in the corrected number of muons as a function of $|\sin(\Delta\phi)|$.

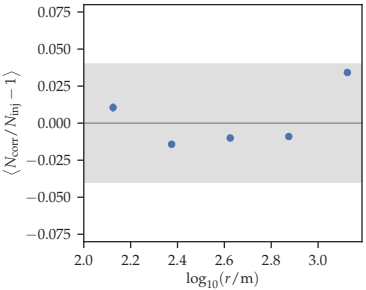
Correction of the bias in the reconstructed number of muons



Bias in the corrected number of muons as a function of the primary type.



Bias in the corrected number of muons as a function of $\log_{10}(E/\mathrm{eV})$.



Bias in the corrected number of muons as a function of $\log_{10}(r/\mathrm{m})$.

The remaining dependencies of the bias-corrected number of muons are contained within $\pm 4\,\%$.

Muon content in UMD data

We analyzed the muon content in UMD data as a function of the energy, zenith angle, and distance to the shower axis