MAP JOINT DOCTORAL PROGRAMMES

Universidade do Minho
Escola de Ciências

LIP

fct Fundação para a Ciência e a Tecnologia

PIERRE AUGER OBSERVATORY

8th LIP/IDPASC PhD Students Workshop

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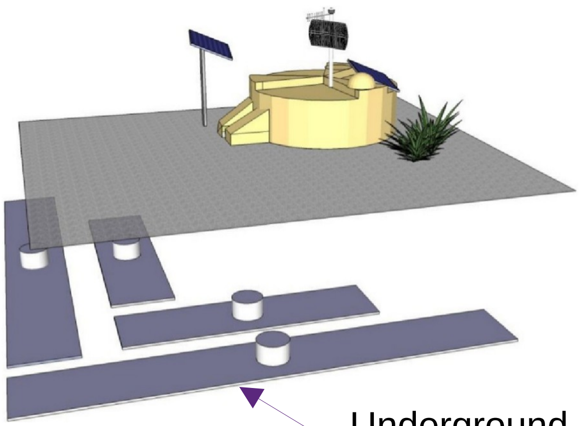
Enhanced Searches with the Pierre Auger Observatory in the Era of Multi-messenger Astrophysics

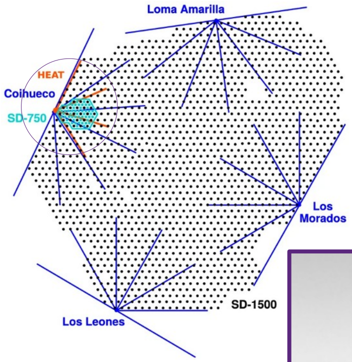
Probing first interaction properties of ultra high energy cosmic rays by measuring the low muon number distribution tail using underground muon detectors

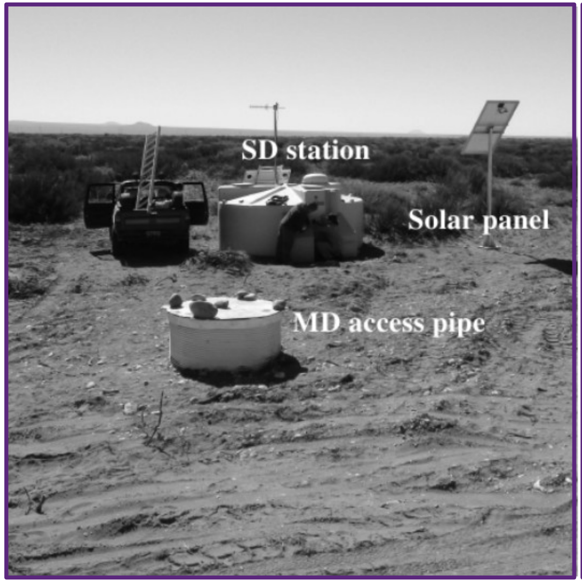
AMIGA

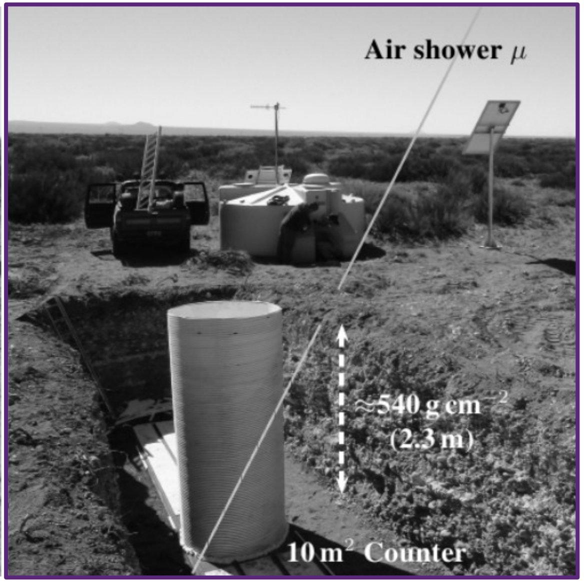
Auger Muons and Infill for the Ground Array



Underground Muon Detector
(UMD)



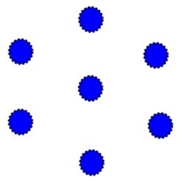


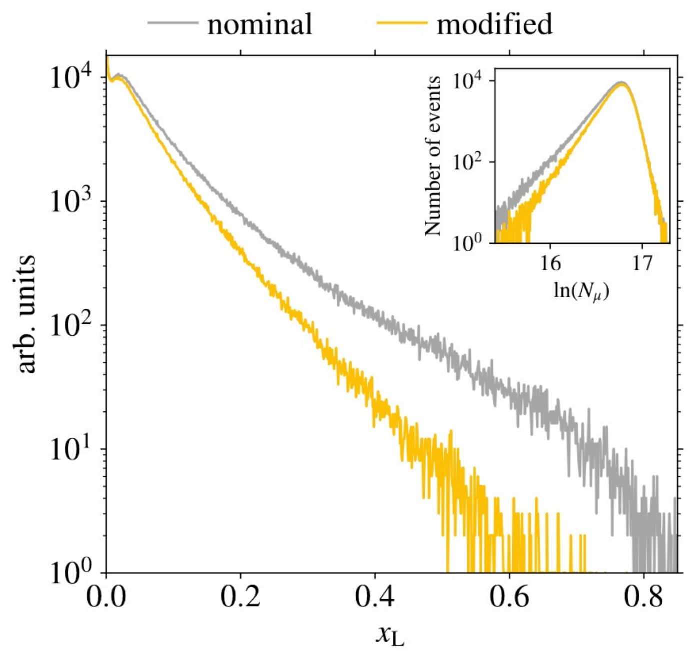


- apart of the Auger Prime Upgrade;
- installed within the infill array;
- direct measurement of muons using buried scintillators;

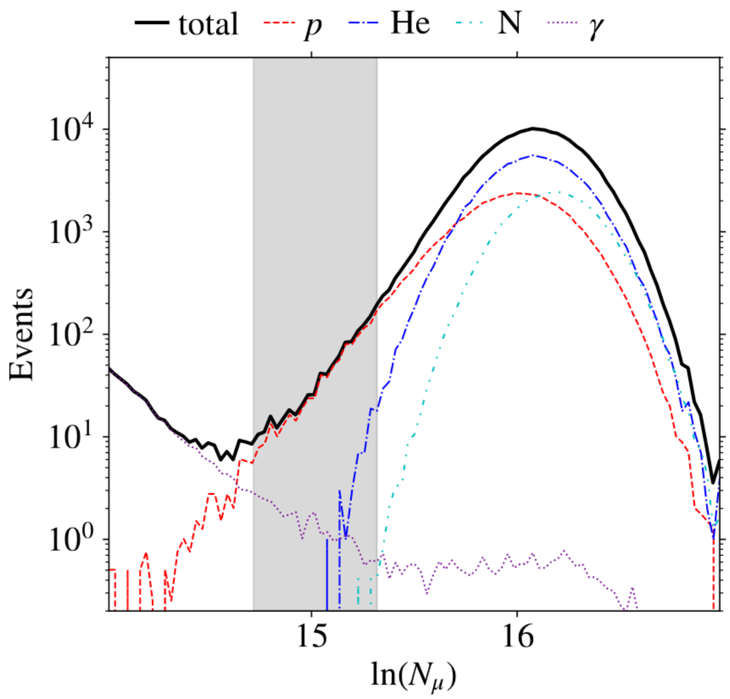
Cazon, L., Conceição, R., Martins, M. A., & Riehn, F. (2021). Physical Review D, 103(2), 022001

Constraining the energy spectrum of neutral pions in ultra–high–energy proton–air interactions





- showers generated using Sibyll 2.3c;
- $\log(E_0/\text{eV}) = 18.7$ and $\theta = 67°$;



The shape of the distribution at **low muon numbers** can be described by an **exponential function** which is sensitive to the properties of multiparticle production in the **first interaction**

Muonic Lateral Distribution Function (LDF)

Modified Nishimura-Kamata-Greisen (NKG) function:

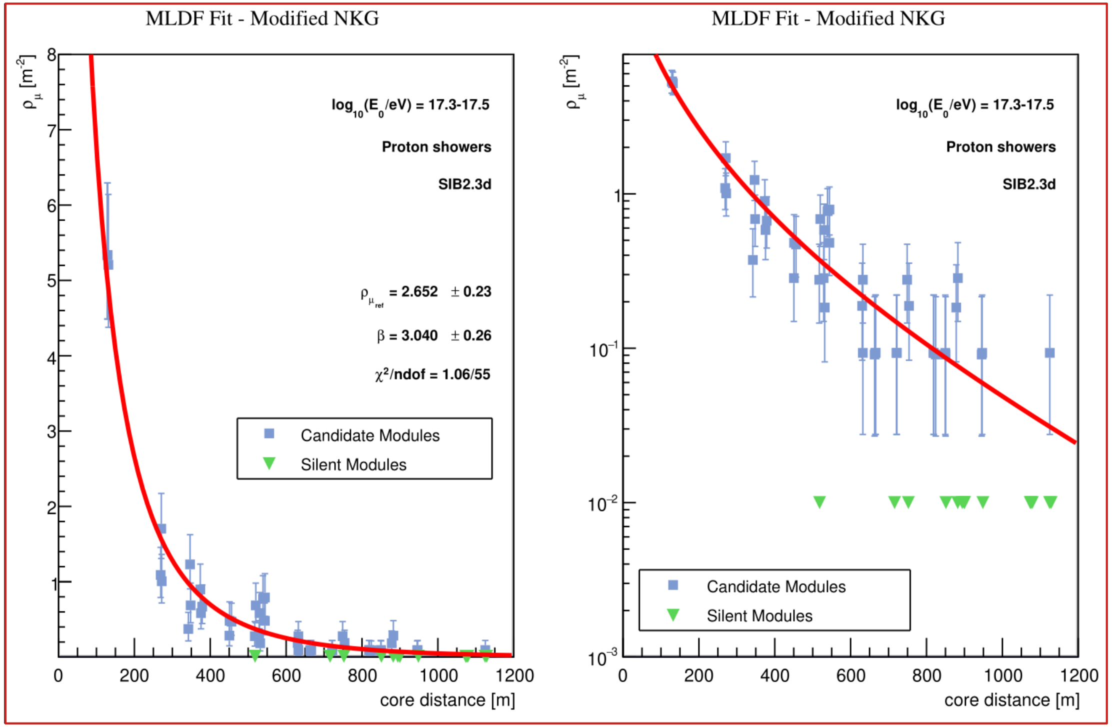
$$\rho_\mu(r) = \rho_{\text{ref}} \times \frac{f_\mu(r)}{f_\mu(r_{\text{ref}})}$$

with,

$$f_\mu(r) = \left(\frac{r}{r^*}\right)^{-\alpha}\left(1+\frac{r}{r^*}\right)^{-\beta}\left(1+\left(\frac{r}{10r^*}\right)^2\right)^{-\gamma}$$

Minimizing -log(Likelihood):

$$\mathcal{L}(\vec{p}) = \prod_{i=1}^{N_{cand}} e^{-\mu(r_i;\vec{p})}\frac{\mu(r_i;\vec{p})^{n_i^{corr}}}{n_i^{corr}!}$$
$$\times \prod_{i=1}^{N_{sat}} \frac{1}{2}\left[1-\mathrm{Erf}\left(\frac{n_i^{\text{sat}}-\mu(r_i;\vec{p})}{\sqrt{2\mu(r_i;\vec{p})}}\right)\right]$$
$$\times \prod_{i=1}^{N_{\text{sil}}} e^{-\mu(r_i;\vec{p})}\left(1+\mu(r_i;\vec{p})+\frac{1}{2}\mu(r_i;\vec{p})^2\right)$$



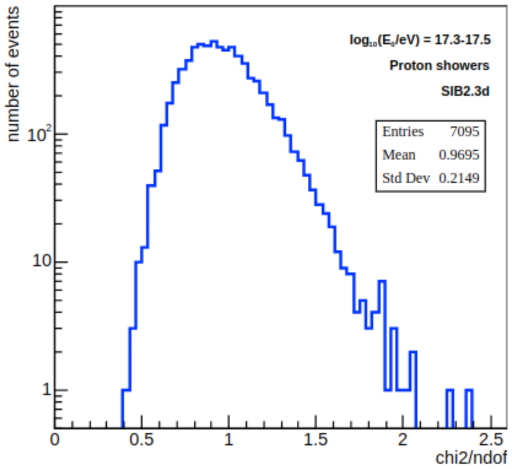
$$r^* = 280\text{m}, \quad \alpha = 0.3 \quad \text{and} \ \gamma = 4.6$$

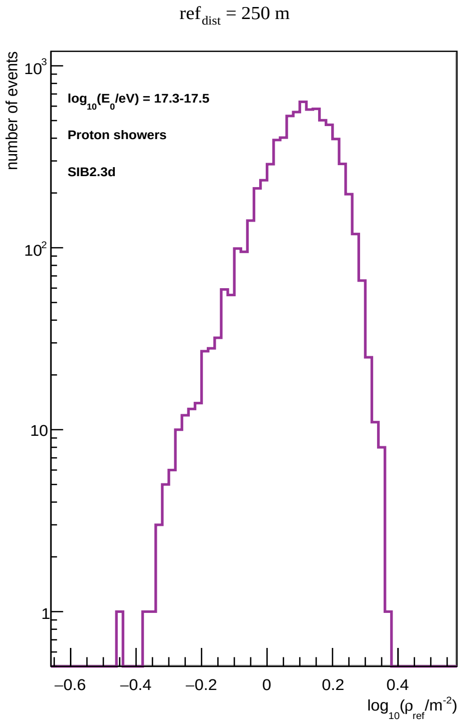
ρ_{ref} as a proxi of the muon content of an air shower

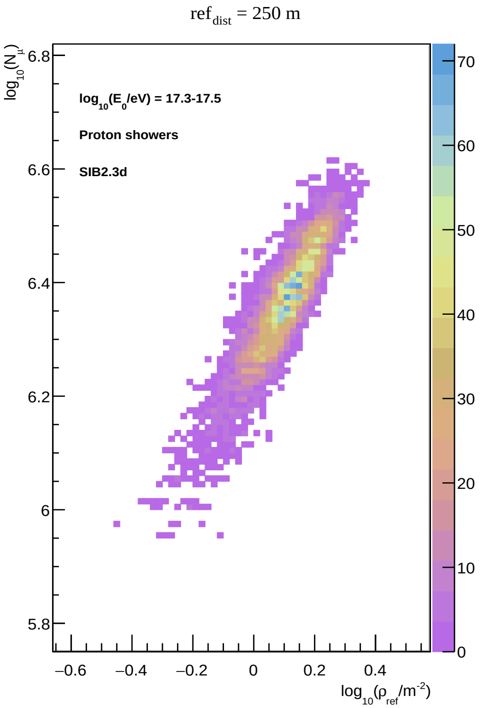
Using the example of the hadronic model:

SIB2.3d

Good quality fits for both models







Good correlation between ρ_{ref} and the total number of muons even when considering a varying core position and detection effects

CORSIKA + Offline simulations

ρ_{ref} as a proxi of the muon content of an air shower

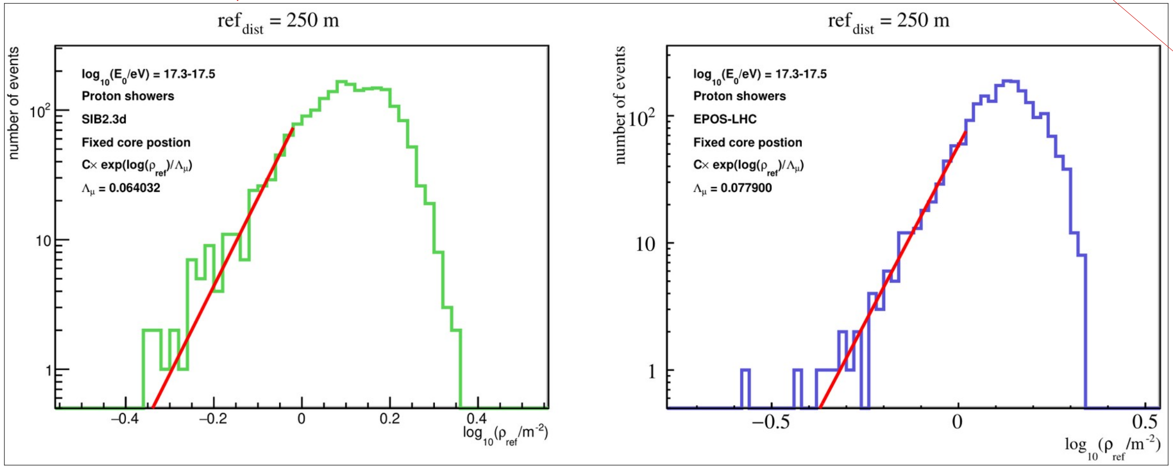
Measurement of Λ_μ by fitting the low muon number tail

Fitting ranges chosen so that the deviation from a pure exponential would not exceed 5%

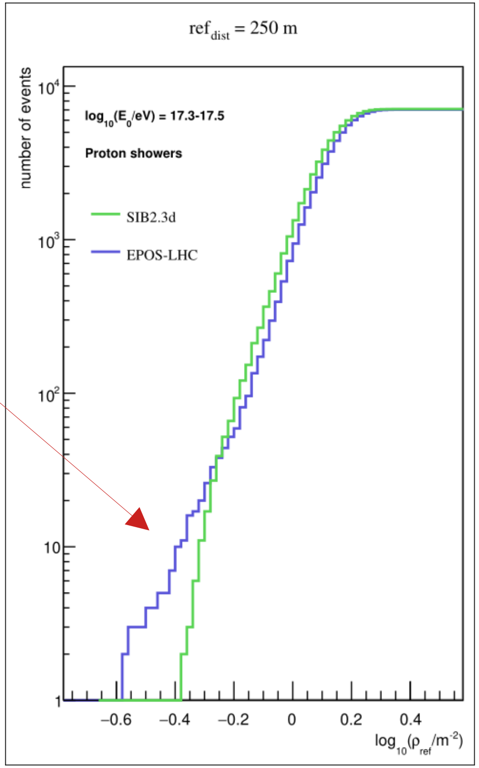
Visible differences between the distribution tails

possibility of testing hadronic models with **data!**

CORSIKA + Offline simulations



Cumulative Distributions



Conclusion

The measurement of can be performed by fitting the muonic LDF directly and using a reference distance, as a good correlation with the total number of muons is achieved regardless of:

- hadronic interaction model;
- core postion;
- properties of the primary;
- detection effects.

The low ρ_{ref} distribuition tails of the two hadronic models tested are visibly different and therefore tests on test first interaction properties for proton-air events are possible.

Current/Next Steps

Performing the measurement using data.

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