A CORSIKA Study on the Influence of Muon Detector Thresholds on the Separability of Primary Cosmic Rays at Highest Energies

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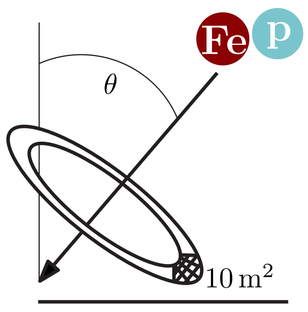
1. Introduction

- **Precise determination of muon number** in extensive air showers crucial to separate mass groups of primary cosmic rays at ultra-high energies
- **Study of expectations on separability** of primaries essential to optimize performance of future muon detectors

2. Simulations

- **115 unthinned air showers** with CORSIKA [1] and EPOS-LHC [2] as high energy interaction model
- **Simulation of ideal muon detector** by calculation of expected muon number for $A_{\mathrm{det}} = 10\,\mathrm{m}^2$ in ring in shower plane



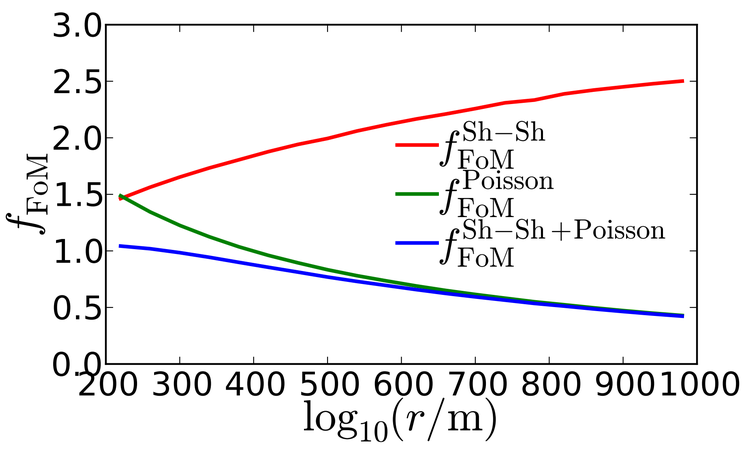
- **Shower features**
  p & Fe primaries
  $E = 3.16 \times 10^{18}\,\mathrm{eV}$
  $\theta = 38°$
  φ random

3. p-Fe Separability

- **Figure of Merit**

$$f_{\mathrm{FoM}} = \frac{N_{\mathrm{Fe}} - N_{\mathrm{p}}}{\sqrt{\sigma_{\mathrm{p}}^2 + \sigma_{\mathrm{Fe}}^2 + N_{\mathrm{p}} + N_{\mathrm{Fe}}}}$$

quantifies separability of p & Fe showers



- **Shower-to-shower fluctuations** dominant at distances below 200 m
- **Poissonian fluctuations** increasingly important for larger r

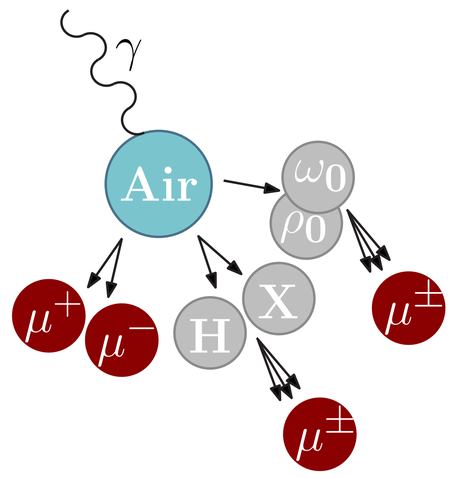
References

[1] D. Heck, J. Knapp, J. N. Capdevielle, G. Schatz, T. Thouw, and Others, *FZKA* **6019** (1998).

[2] K. Werner, F.-M. Liu, and T. Pierog, *Phys. Rev. C* **74** (2006) 044902.

[3] D. Heck and R. Engel, *KIT-SWP* **5** (2009).

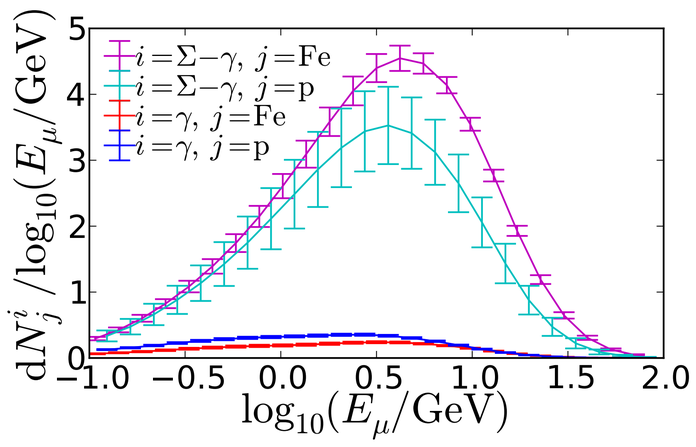
4. Photonuclear Reactions



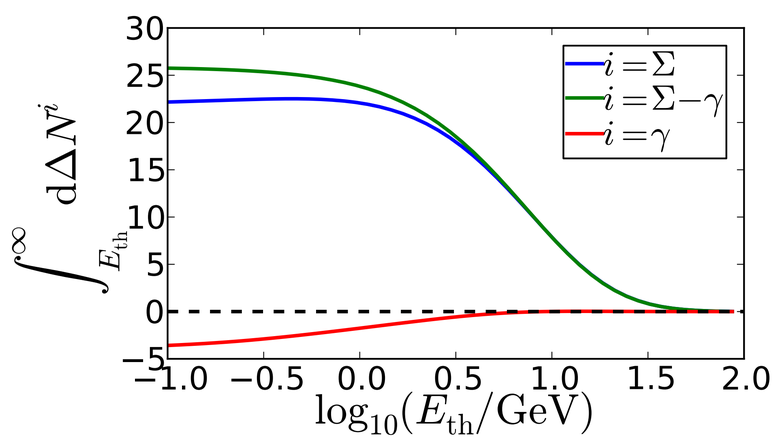
Photon + air
$\rightarrow \mu^+\mu^-$
$\rightarrow$ Hadron + X
$\rightarrow \{\rho^0$ or $\omega^0\}$
+ recoil nucleus

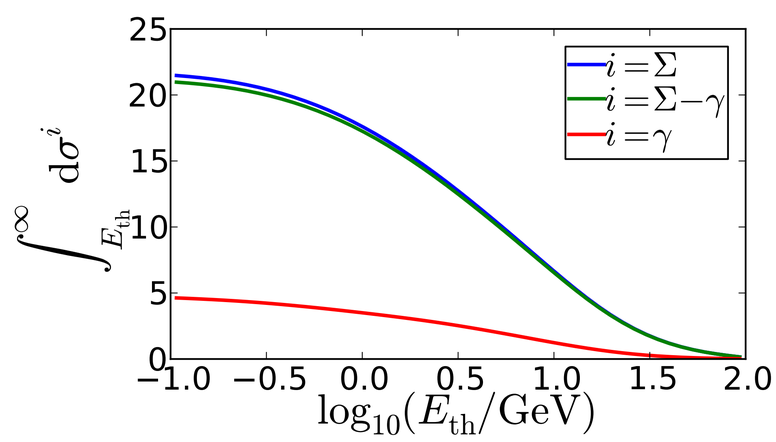
- **Muons of photonuclear origin suppressed** w.r.t. muons from other hadronic processes
- **Distributions approach each other** at low muon energies for $i = \Sigma$ and $i = \Sigma{-}\gamma$

- **Influence of muons from EM shower part** on the figure of merit f_{FoM}?
- **Tag muons from photonuclear reactions** with EHISTORY [3] option in CORSIKA

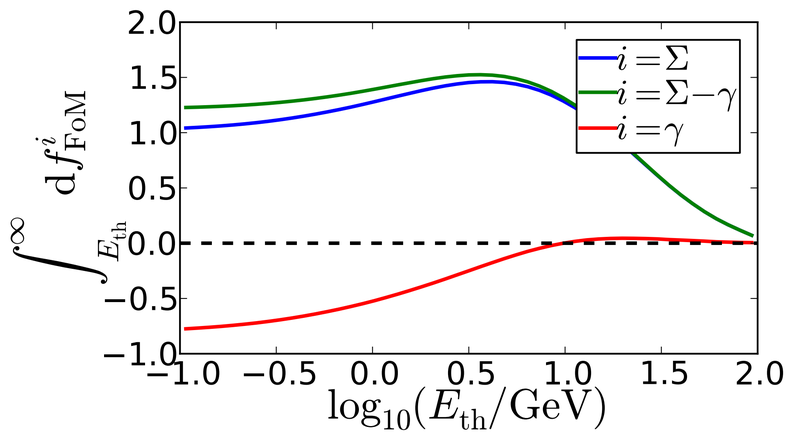


5. Energy Threshold Dependence of f_{FoM}

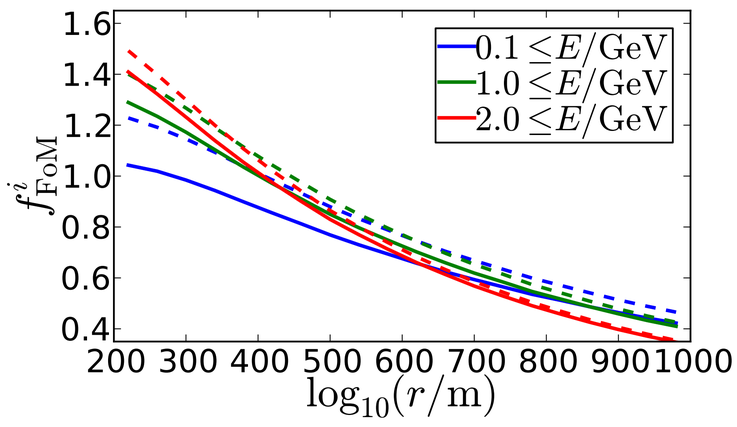


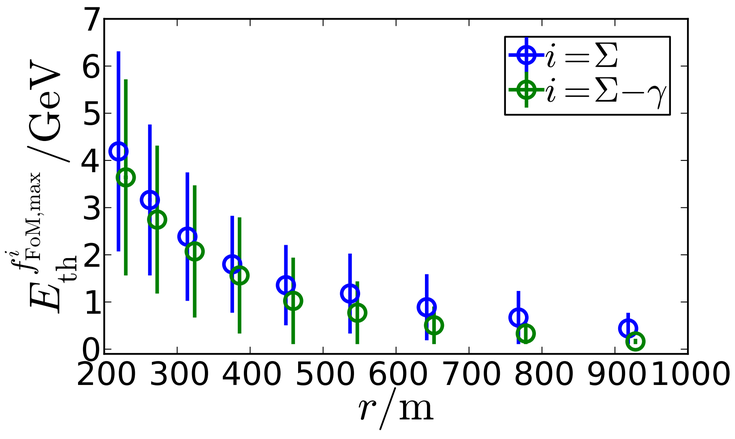


- **Separate analysis of $f_{\mathrm{FoM}}^{\mathrm{i}}$ components** nominator $\int_{E_{\mathrm{th}}}^{\infty} \mathrm{d}\,\Delta N^i$ & denom. $\int_{E_{\mathrm{th}}}^{\infty} \mathrm{d}\,\sigma^i$
- **All muon $f_{\mathrm{FoM}}^{\Sigma}$ lowered w.r.t. $f_{\mathrm{FoM}}^{\Sigma-\gamma}$** i.e. worse separability if muons from photonuclear reactions contribute
- **Increase of $f_{\mathrm{FoM}}^{\Sigma}$ and $f_{\mathrm{FoM}}^{\Sigma-\gamma}$ with E_{th}** up to an optimal r dependent threshold



6. Conclusion: $E_{\mathrm{TH}} \geq 1\,\mathrm{GeV}$ Favored





- **Muons of photonuclear origin reduce f_{FoM}** up to radius dependent muon energy
- **Better separability with increasing energy** detector threshold for both $f_{\mathrm{FoM}}^{\Sigma}$ and $f_{\mathrm{FoM}}^{\Sigma-\gamma}$

- **95% region E_{th} : $f_{\mathrm{FoM}}^{\mathrm{i}} \geq 0.95 \cdot f_{\mathrm{FoM,\,max}}^{\mathrm{i}}$** large for small r, displayed by error bars
- **Optimal energy threshold $E_{\mathrm{th}} \sim 1\,\mathrm{GeV}$** up to 800 m, $E_{\mathrm{th}} \sim 2\,\mathrm{GeV}$ for $r \leq 550\,\mathrm{m}$