VI International Conference on Particle Physics and Astrophysics

Muon puzzle: possible approach to the solution

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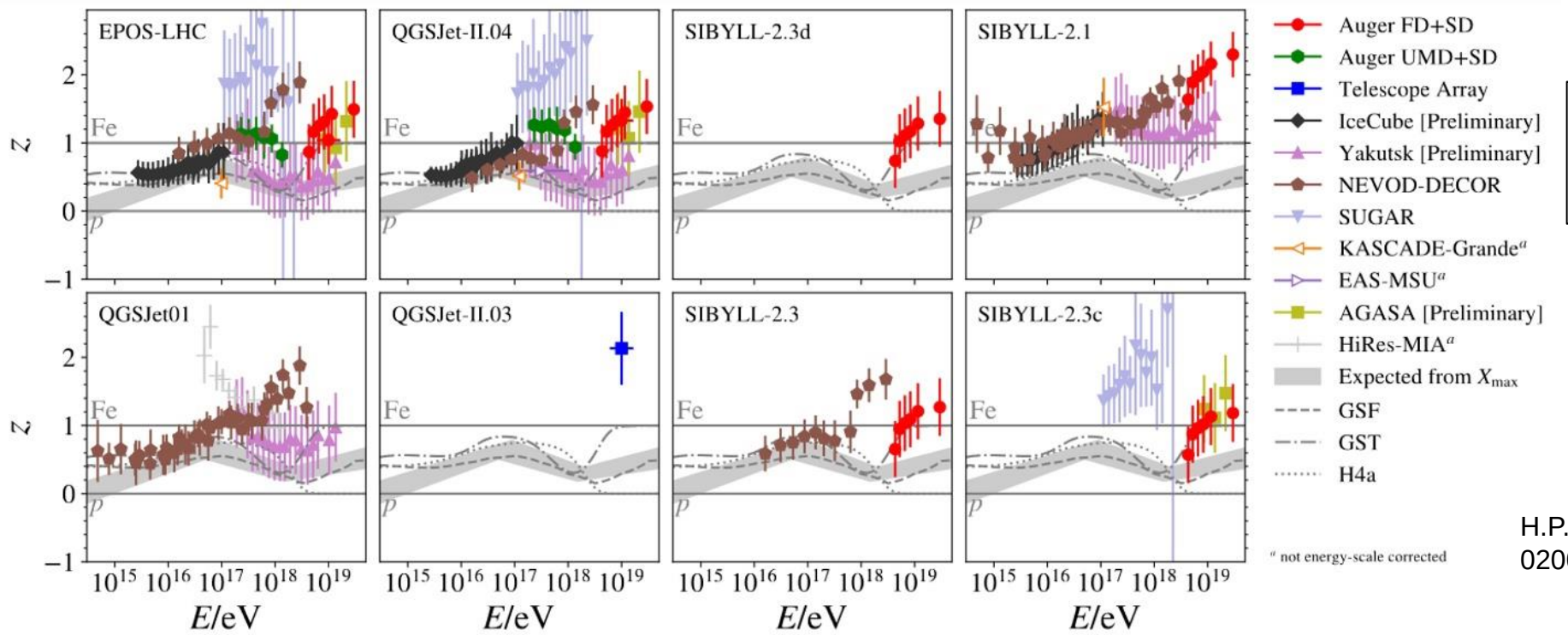
Introduction

The so-called Muon Puzzle is the excess of the events with high multiplicity of cosmic muons in comparison to the MC simulation results.



$$z = \frac{ln\langle N_{\mu}^{det}\rangle - ln\langle N_{\mu,p}^{sim}\rangle}{ln\langle N_{\mu,Fe}^{sim}\rangle - ln\langle N_{\mu,p}^{sim}\rangle}$$

H.P. Dembinski et al. EPJ Web Conf. 210, 02004 (2019).

- Simulation tools include hadron interaction models that use the extrapolation of the experimental data and very different approaches of nucleus-nucleus interactions treatment.

- As a possible solution to the Muon Puzzle, new physical processes in nucleus-nucleus interactions could be introduced.

Models of hadronic and nucleus-nucleus interactions

CORSIKA (COsmic Rays Simulation for KAscade) – program for Monte-Carlo simulation of the generation and development of extensive air showers in the atmosphere.

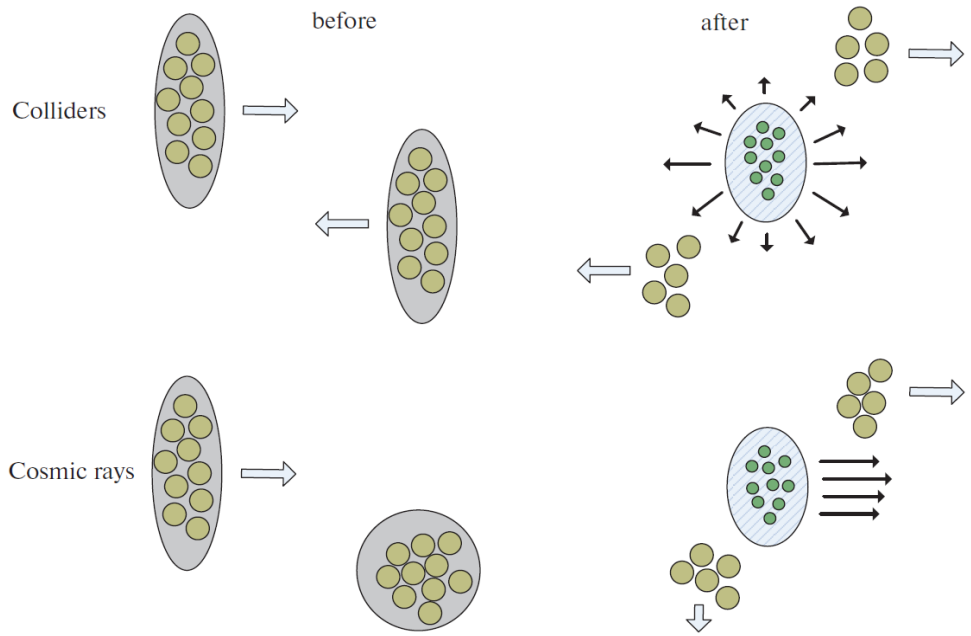
Model	Used in CORSIKA	Spectators fragmentation	Special treatment for A-B int.	Leptons production in first int.	Gamma production in first int.
EPOS-LHC	✓	Intense ($\langle N_{nuc} \rangle = 0.4$)	✓	$\sim 10^{-4}$	$\sim 10^{-1}$
QGSJET-II-04	✓	Moderate ($\langle N_{nuc} \rangle = 1.4$)	✓	—	—
SIBYLL-2.3d	✓	Moderate ($\langle N_{nuc} \rangle = 1$)	Superposition of N-N int.	$\sim 10^{-5}$ (probably Pi decays)	$\sim 10^{-1}$
Pythia8.3 (Angantyr)	—*	— ($N_{nuc} = 2$)	✓	> 1 !	$\sim 10^{2}$

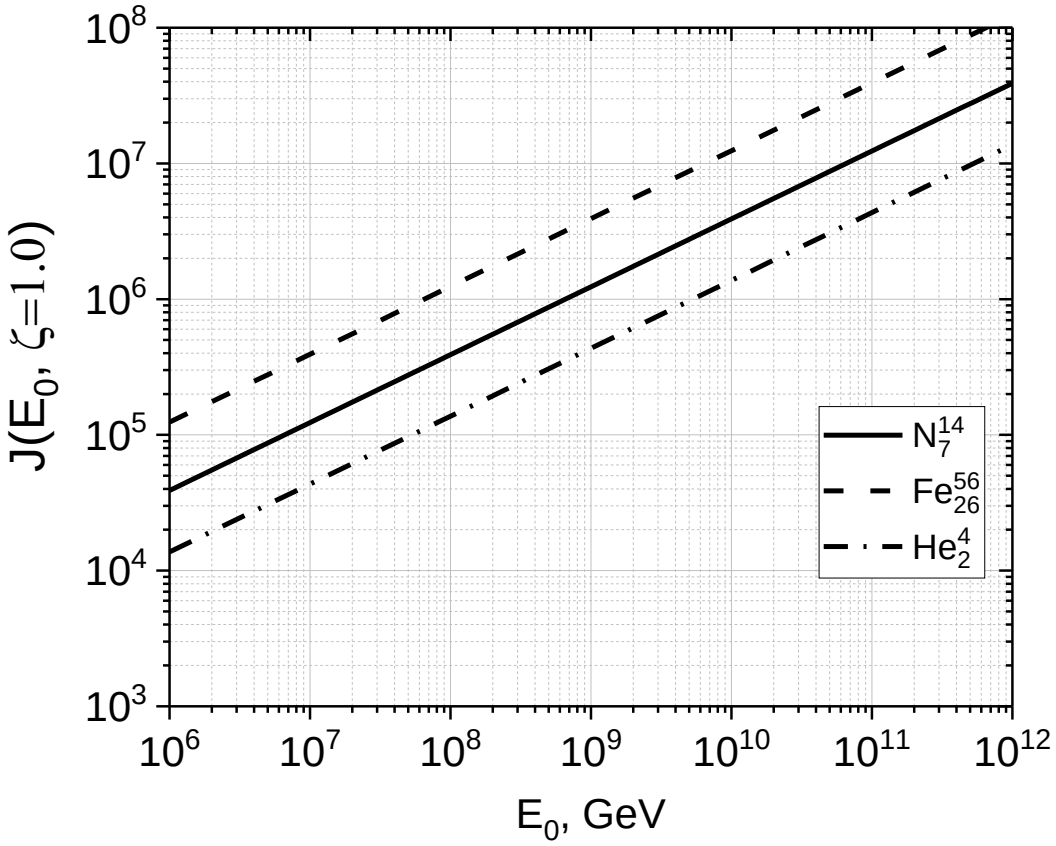
*Pythia6 is used in CORSIKA for decays of charmed particles only

- Energy loss of the nuclei before the first hadronic interaction?
- Collective interactions, QGP, anisotropy …

Quark gluon plasma with high angular momentum

In high energy non-central nucleus-nucleus collisions formation of the quark gluon matter blob (QGMB) with high angular momentum is possible.





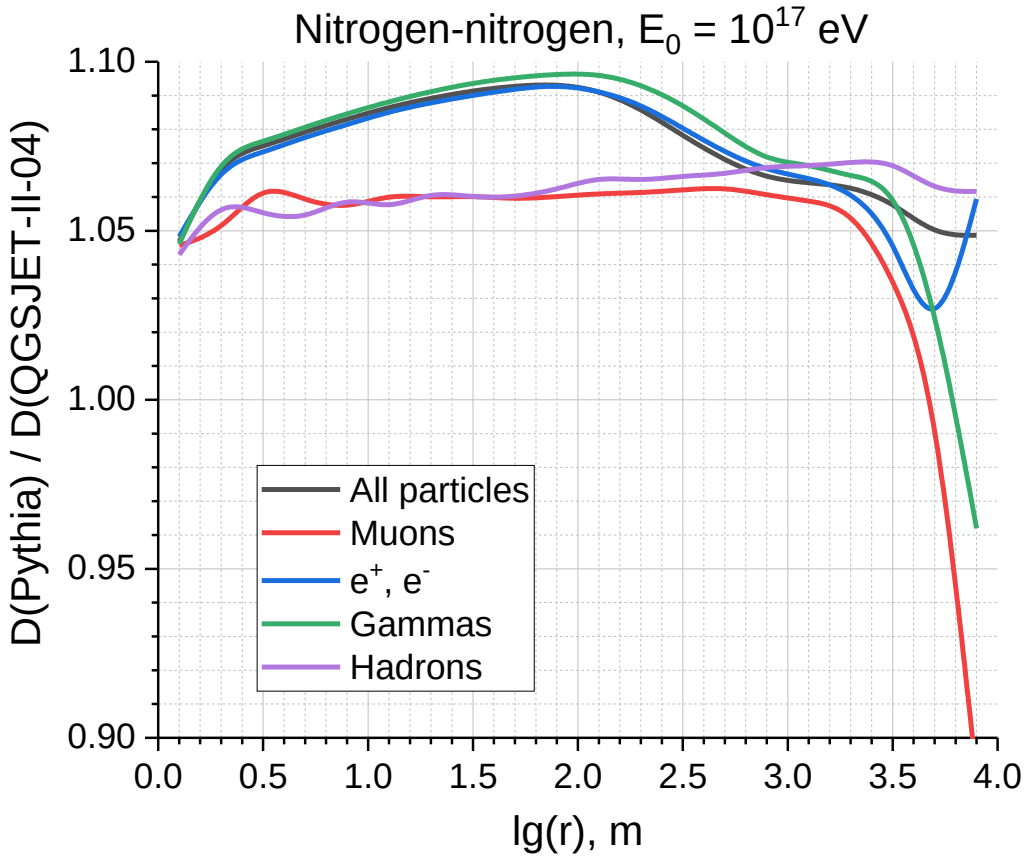
$$J(b) = \frac{1}{2} A \frac{b}{\hbar c} \sqrt{S_{NN}} = \frac{1}{2} A^{4/3} \frac{\zeta}{\hbar c} r_0 \sqrt{S_{NN}}$$

$$V = \frac{\hbar^2 J(J+1)}{2mr^2}$$

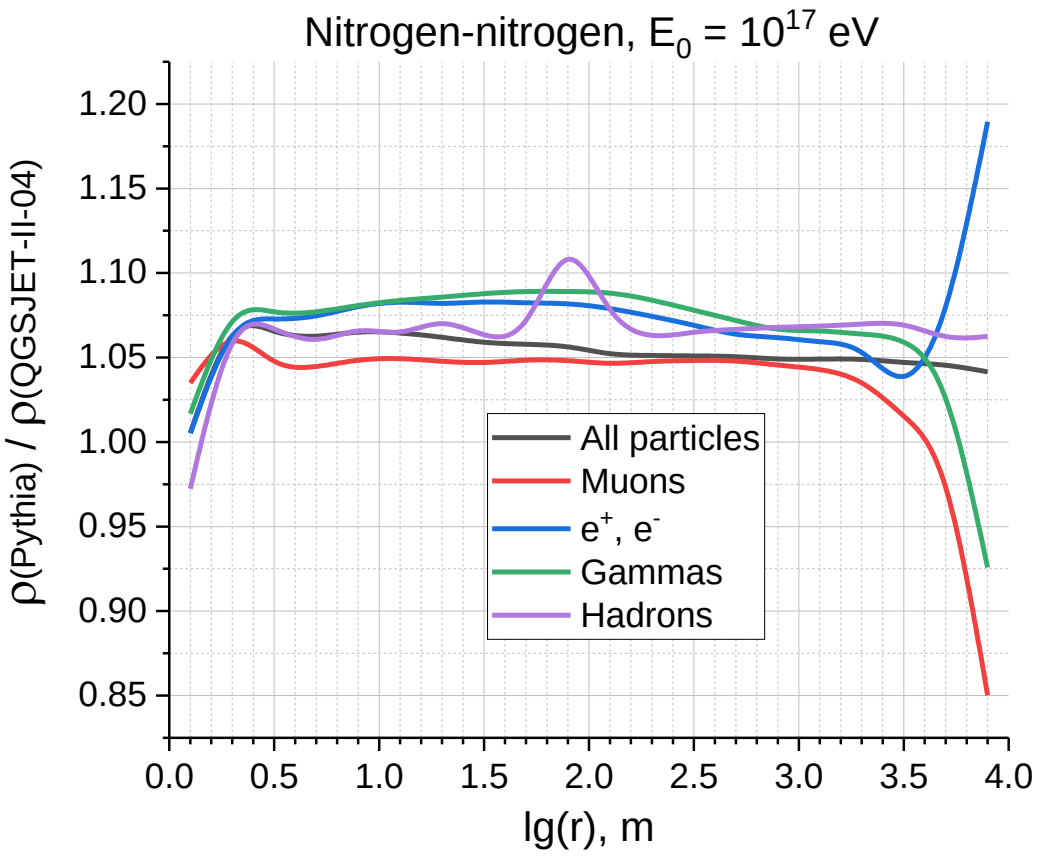
Suppression of light particles production during QGMB expansion

Implementing Pythia8.3 for nucleus-nucleus interactions in CORSIKA

Ratio of the distributions of particles' densities

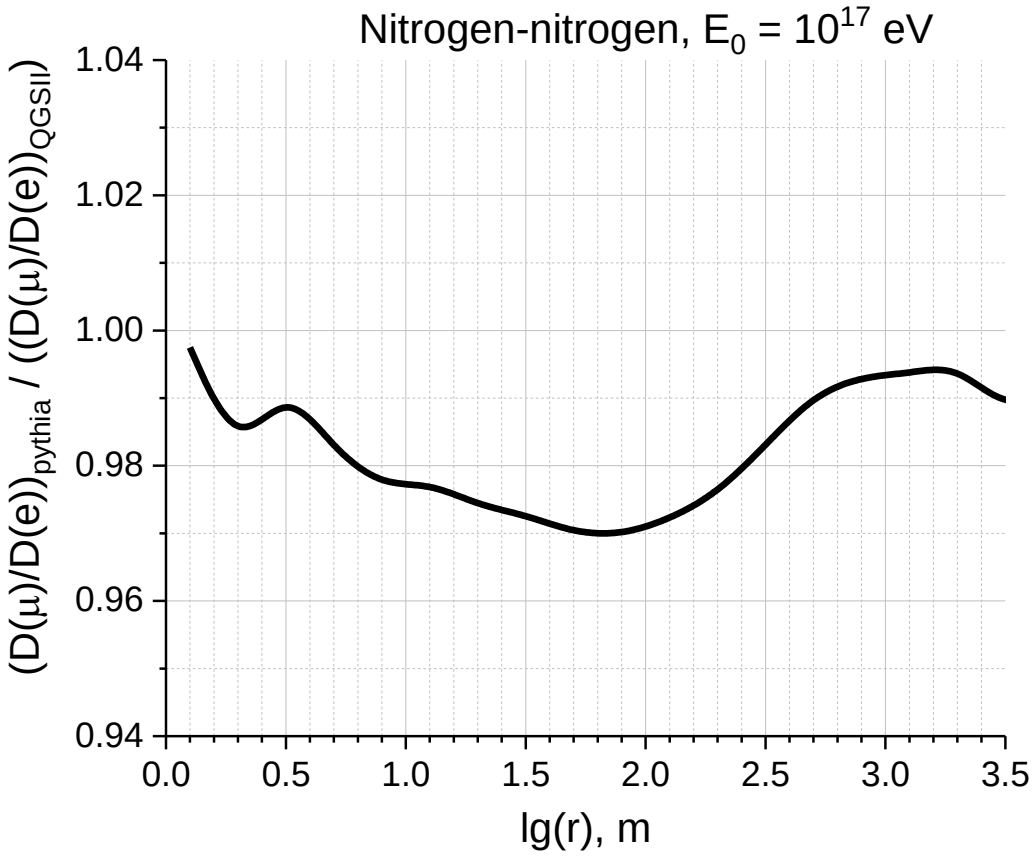


Ratio of the distributions of EAS surface energy

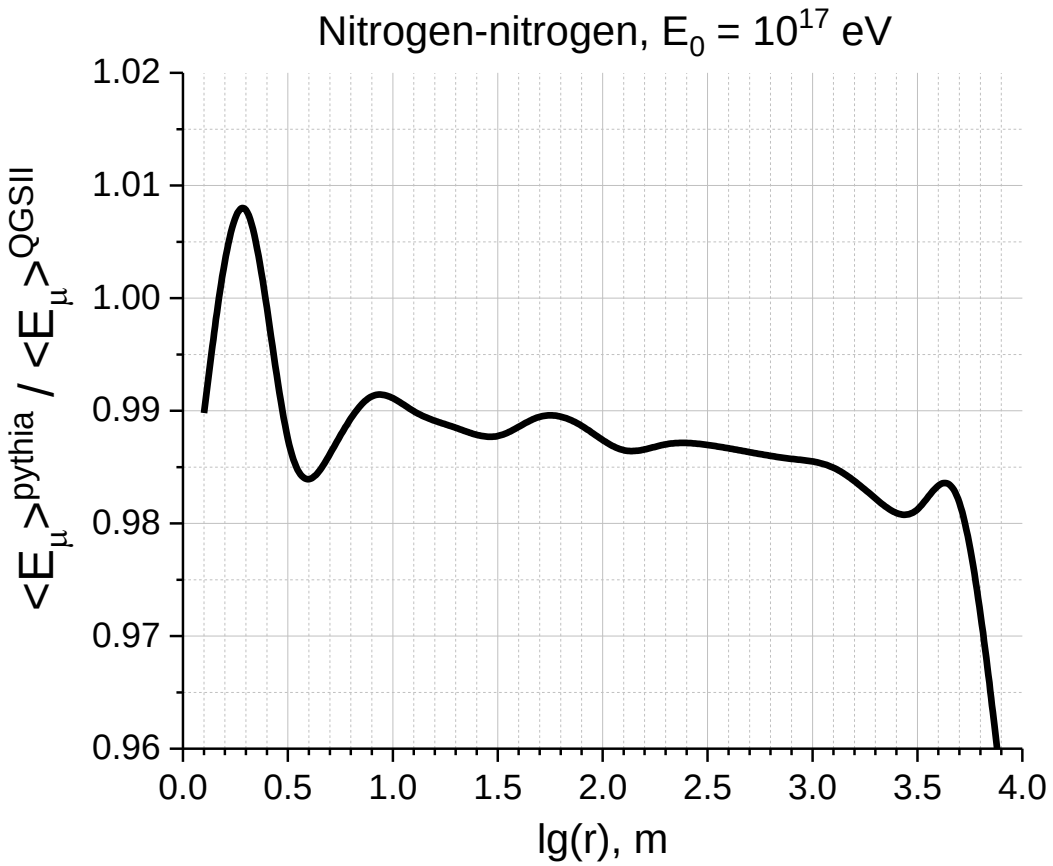


Implementing Pythia8.3 for nucleus-nucleus interactions in CORSIKA

μ/e – ratio comparison with standard QGSJET-II simulation

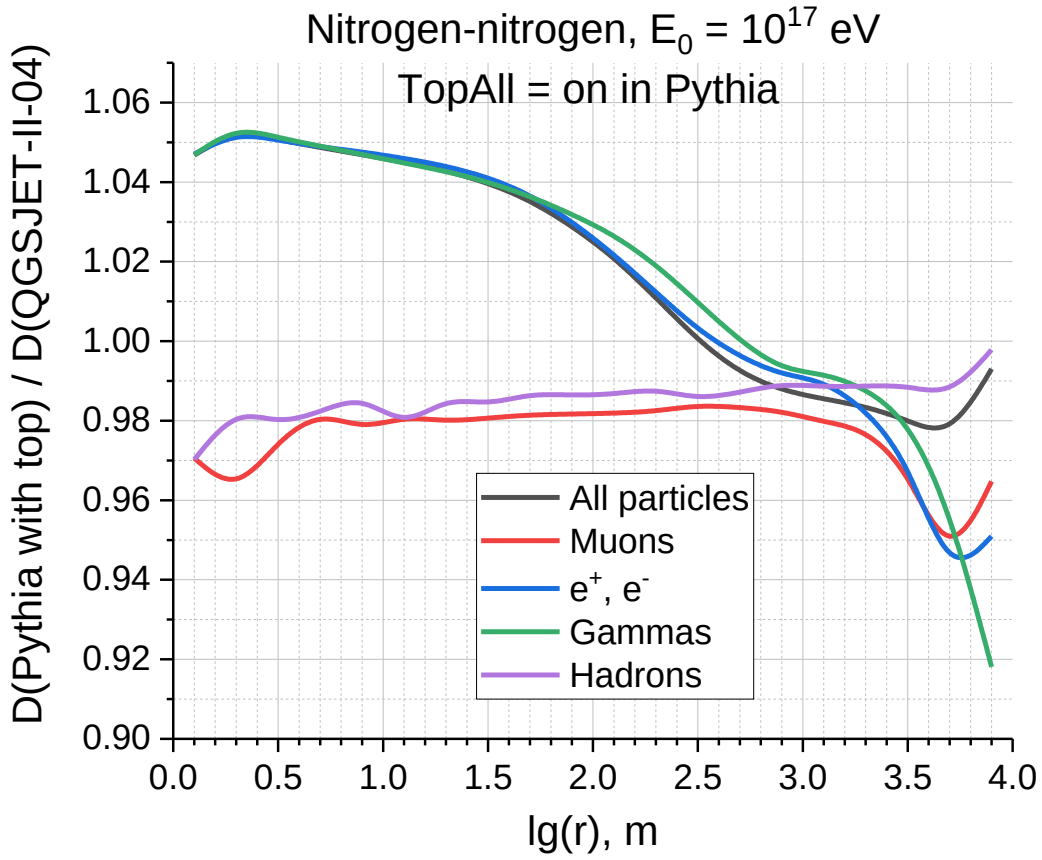


Comparison of the mean energy of EAS muons with standard QGSJET-II simulation

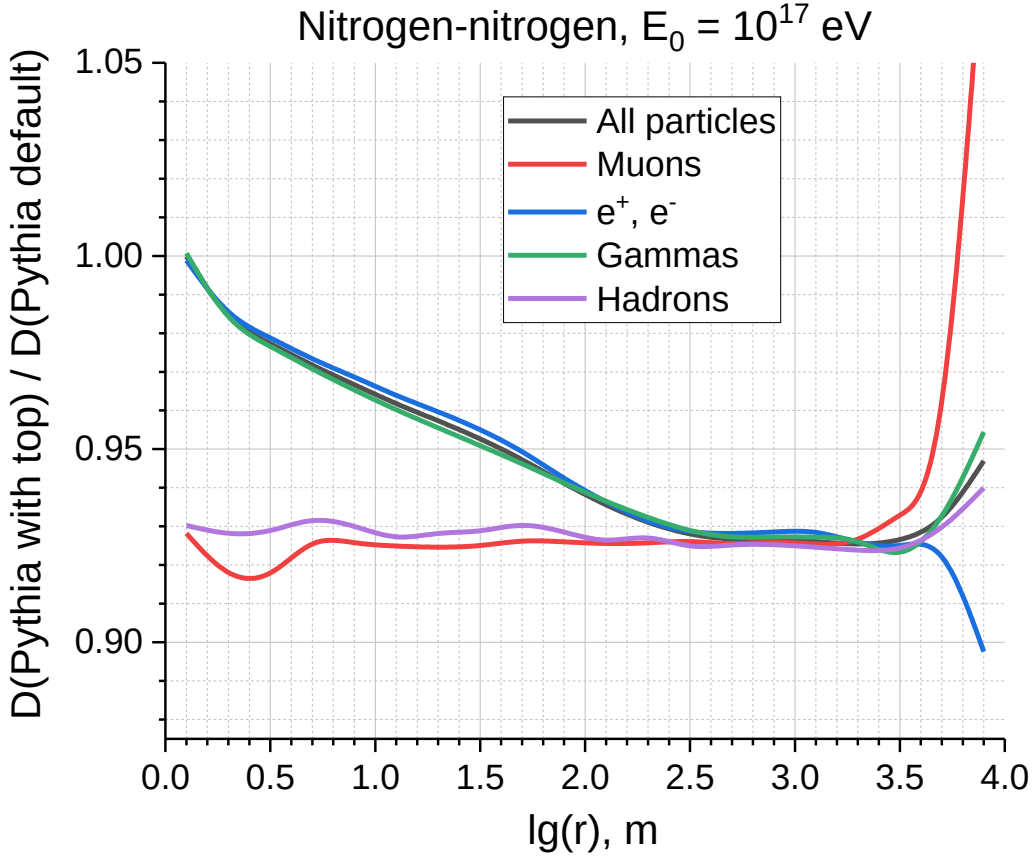


Forcing heavy particles production in the first interaction

Ratio of the distributions of particles' densities (Pythia8 with t-quarks against standard QGSJET-II)

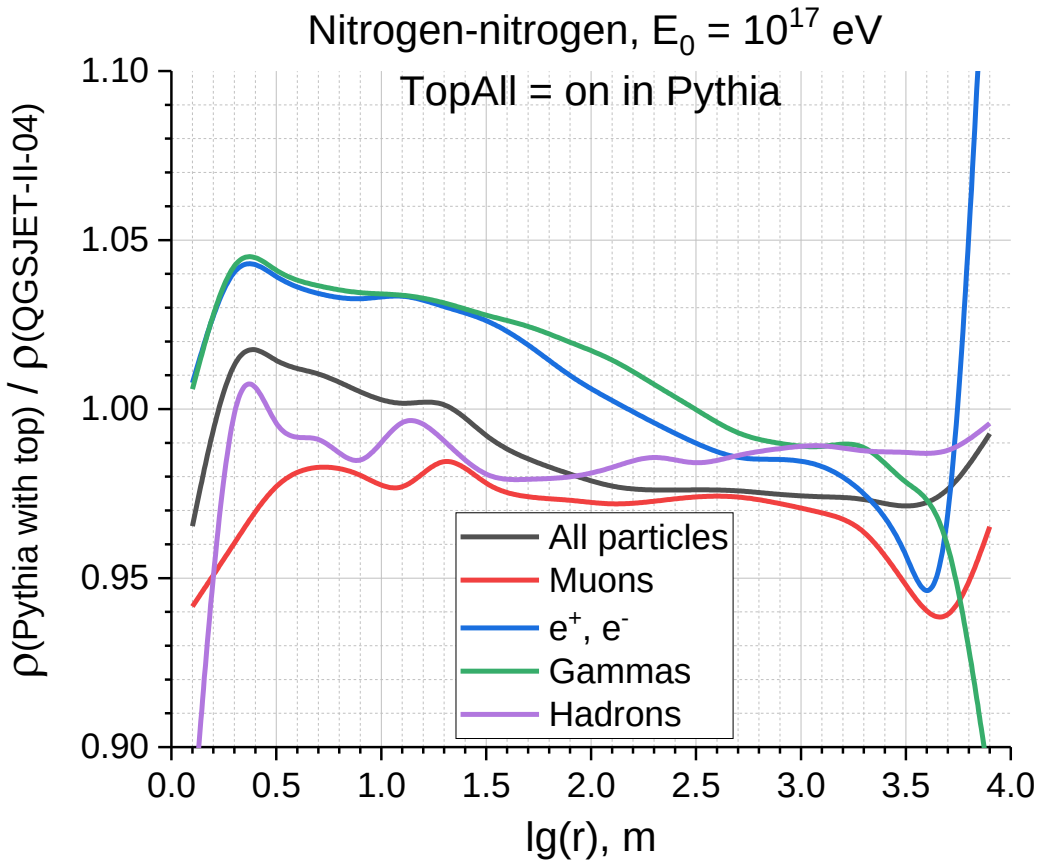


Ratio of the distributions of particles' densities (Pythia8 with t-quarks against default Pythia8)

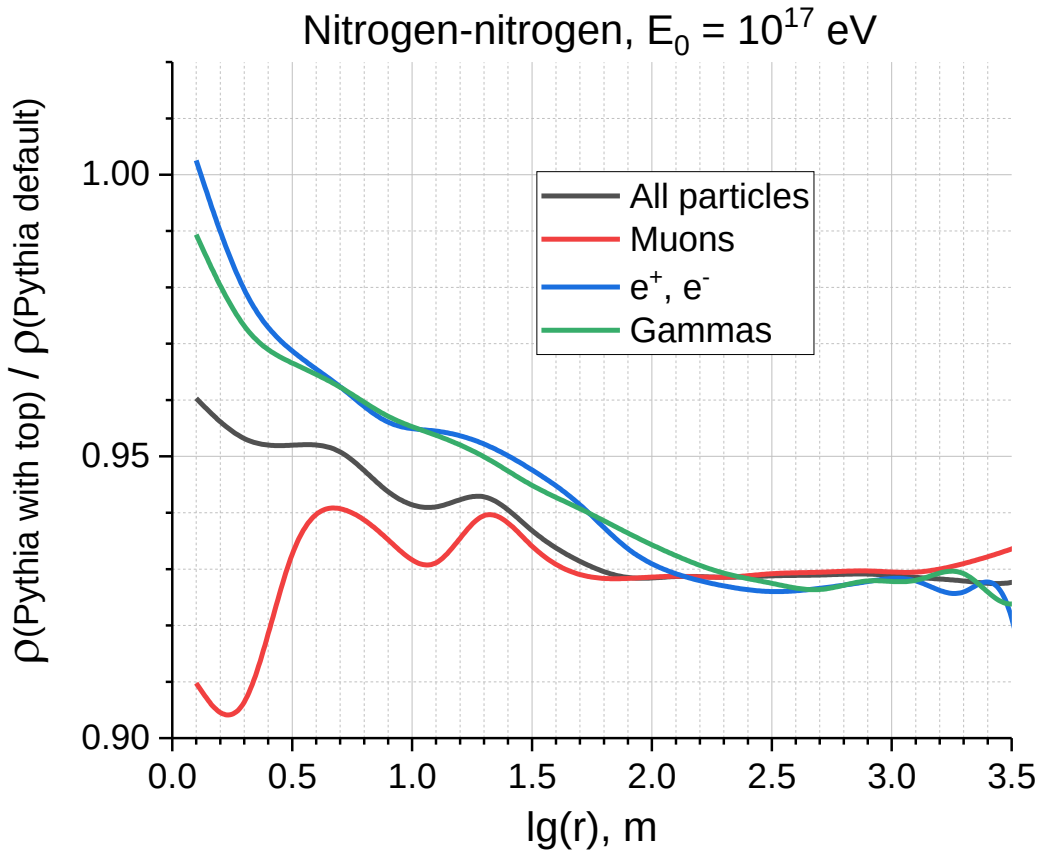


Forcing heavy particles production in the first interaction

Ratio of the distributions of EAS surface energy (Pythia with t-quarks against standard QGSJET-II)

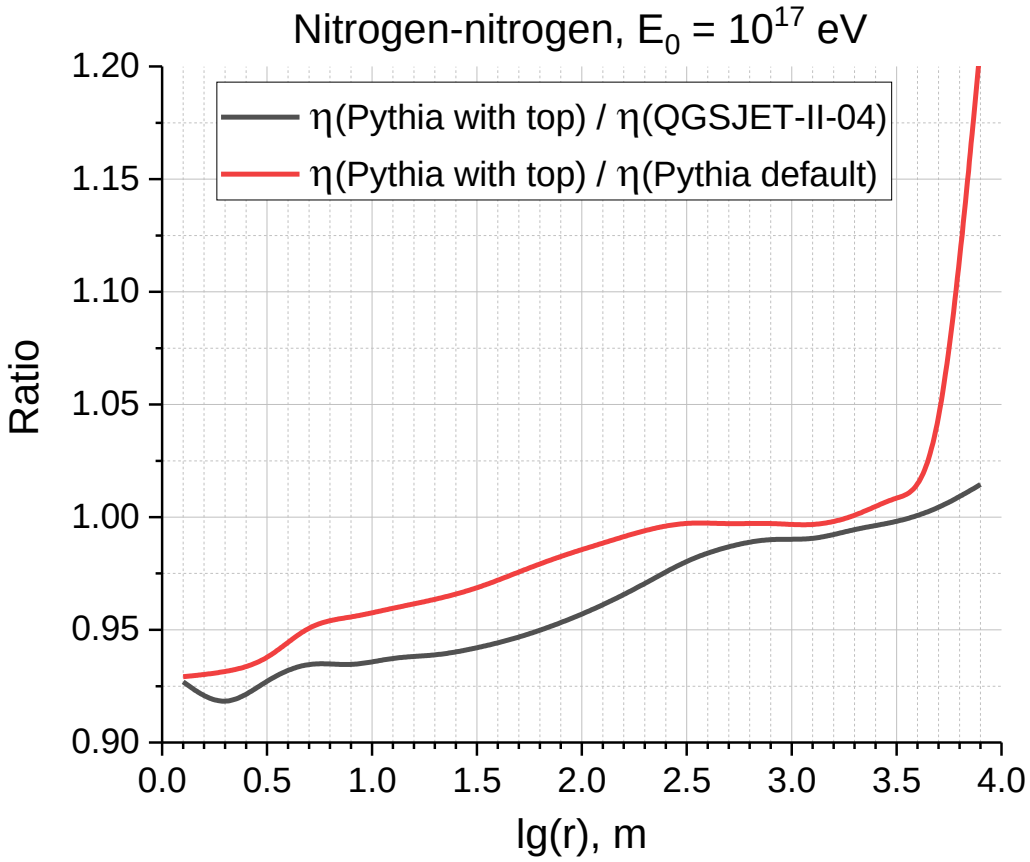


Ratio of the distributions of EAS surface energy (Pythia with t-quarks against default Pythia)



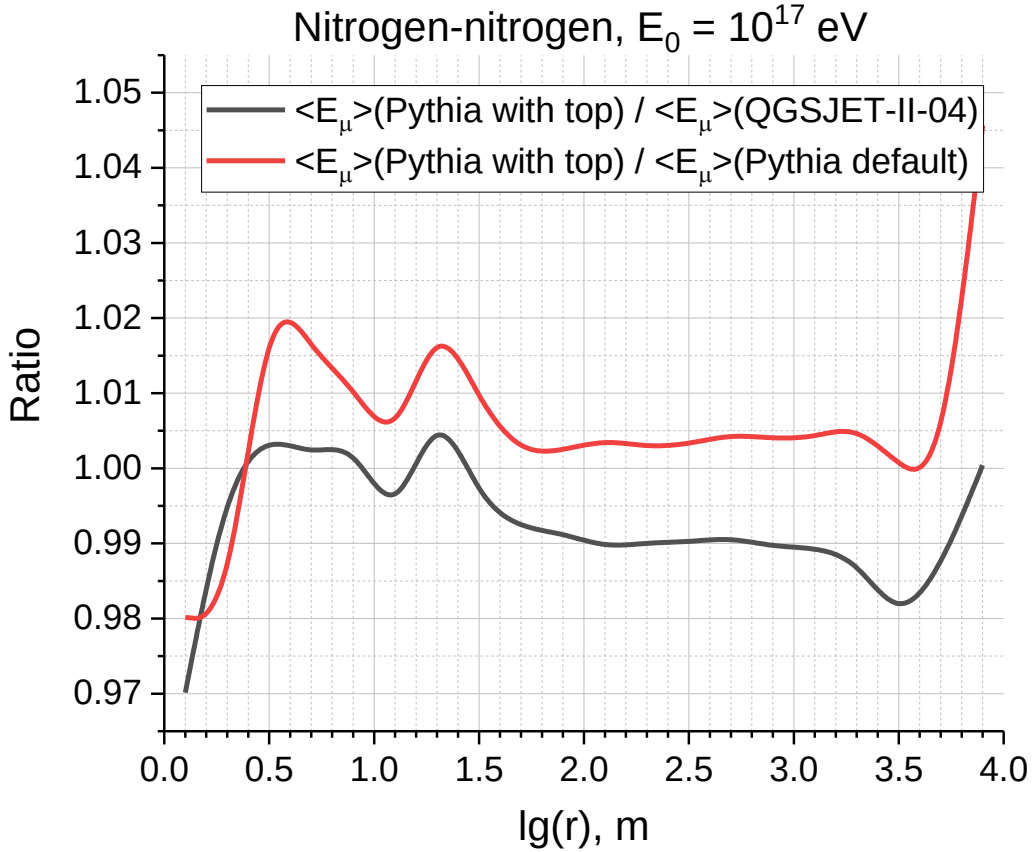
Forcing heavy particles production in the first interaction

μ/e – ratio comparison



$$\eta = D(\mu)/D(e)$$

Comparison of the mean energy of EAS muons



Missing EAS energy

Nitrogen-nitrogen, $E_0 = 10^{17}$ eV

	QGSJET-II-04	Pythia8 (Angantyr)	Pythia8 with top	Ratio Pythia/QGSii, %	Ratio Pythia(top)/ QGSii, %
Total EAS energy [GeV]	$1.71 \cdot 10^7$	$1.69 \cdot 10^7$	$1.8 \cdot 10^7$	98.8	105.2
Total muons energy [GeV]	$9.38 \cdot 10^6$	$9.14 \cdot 10^6$	$9.82 \cdot 10^6$	97.4	104.7
Total electrons energy [GeV]	$2.18 \cdot 10^6$	$2.23 \cdot 10^6$	$2.3 \cdot 10^6$	100.2	105.5
Total gammas energy [GeV]	$3.75 \cdot 10^6$	$3.84 \cdot 10^6$	$4.0 \cdot 10^6$	100.2	106.7
Total neutrinos energy [GeV]	$\sim 5.2 \cdot 10^6$	—	—	—	—
Total hadrons energy [GeV]	$1.82 \cdot 10^6$	$1.72 \cdot 10^6$	$1.87 \cdot 10^6$	94.5	102.7

Conclusion

- Pythia8 with Angantyr model fits well for nucleus-nucleus interactions in EAS simulation. It also has some interesting features (leptons and gamma production, spectator nuclei treatment) that may be useful for cosmic rays studies.

- It is hard to explain the observed excess of muons by implementing models with simply heavier secondary particles spectrum (in the framework of considered models).

- Other consequences of equilibrium state of relativistic matter in nucleus-nucleus collisions should be studied thoroughly: anisotropy of particles momenta, as a mechanism of the variation of spatial distribution functions, more intense gamma production, etc.

Thank you for your attention!