Testing of the QGSJET-01 and QGSJETII-04 models with the help of the atmospheric muons

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Content

Previous result

We are very sorry!

We do apologize for our mistake in input data for the atmosphere!

Previous result was incorrect! (Only the models QGSJET-01, QGSJETII-04, SIBYLL 2.1, EPOS 1.99 are incorrect, other models are correct!)

Improvement

- New parameters of the atmosphere now are properly corresponding to the Yakutsk EAS station.
- Additional calculations with heavy nuclei (N).
- Additional calculation for protons at 10^6 statistics and risen energy thersholds.

Motivation

- Our main goal consists in testing models of hadronic interactions!
- We try to compare a predictions of various models between each other!

Method

- The package CORSIKA 7.4 has ben used to estimate the muon energy spectra $D(E_\mu)$ for models QGSJET-01 and QGSJEETII-04
- Energy gange for muon spectra
- $E_\mu = 10^2 — 10^5$ GeV
- Energy range for primary spectra (p, He, N)
- $E = 10^2 — 10^7$ GeV;
- Statistic N_0 at 10^6 till 10^3 (for the highest energy)
- For muuns in energy interval $(0{,}01\text{-}1)\cdot E_0$ statistic 10^6

Method

Differential energy spectra for prinary cosmic rays [Data: L3+Cosmic, LVD, MACRO]

Muons density distribution functions [CORSIKA 7.4]

$$\left(\frac{dI_p}{dE}\right) \quad S_p(E_\mu, E)\cdot dE_\mu$$

$$\left(\frac{dI_{He}}{dE}\right) \quad S_{He}(E_\mu, E)\cdot dE_\mu$$

$$\left(\frac{dI_N}{dE}\right) \quad S_N(E_\mu, E)\cdot dE_\mu$$

$$\left(\frac{dI_A}{dE}\right)(E) = \frac{dN_A(E)}{dE\cdot dS\cdot dt\cdot d\Omega}$$

$$S_A(E, E_\mu) = \frac{dN_\mu(E_\mu)}{h\cdot N_0}(E)$$

Method of simulations

- We have estimated differential energy spectra of muons as integrals.

$$D_p(E_\mu)\cdot dE_\mu = \int dE \cdot \left(\frac{dI_p}{dE}\right)\cdot S_p(E_\mu, E)\cdot dE_\mu$$

$$D_{He}(E_\mu)\cdot dE_\mu = \int dE \cdot \left(\frac{dI_{He}}{dE}\right)\cdot S_{He}(E_\mu, E)\cdot dE_\mu$$

$$D_N(E_\mu)\cdot dE_\mu = \int dE \cdot \left(\frac{dI_N}{dE}\right)\cdot S_N(E_\mu, E)\cdot dE_\mu$$

$$D(E_\mu) = D_p(E_\mu) + D_{He}(E_\mu) + D_N(E_\mu)$$

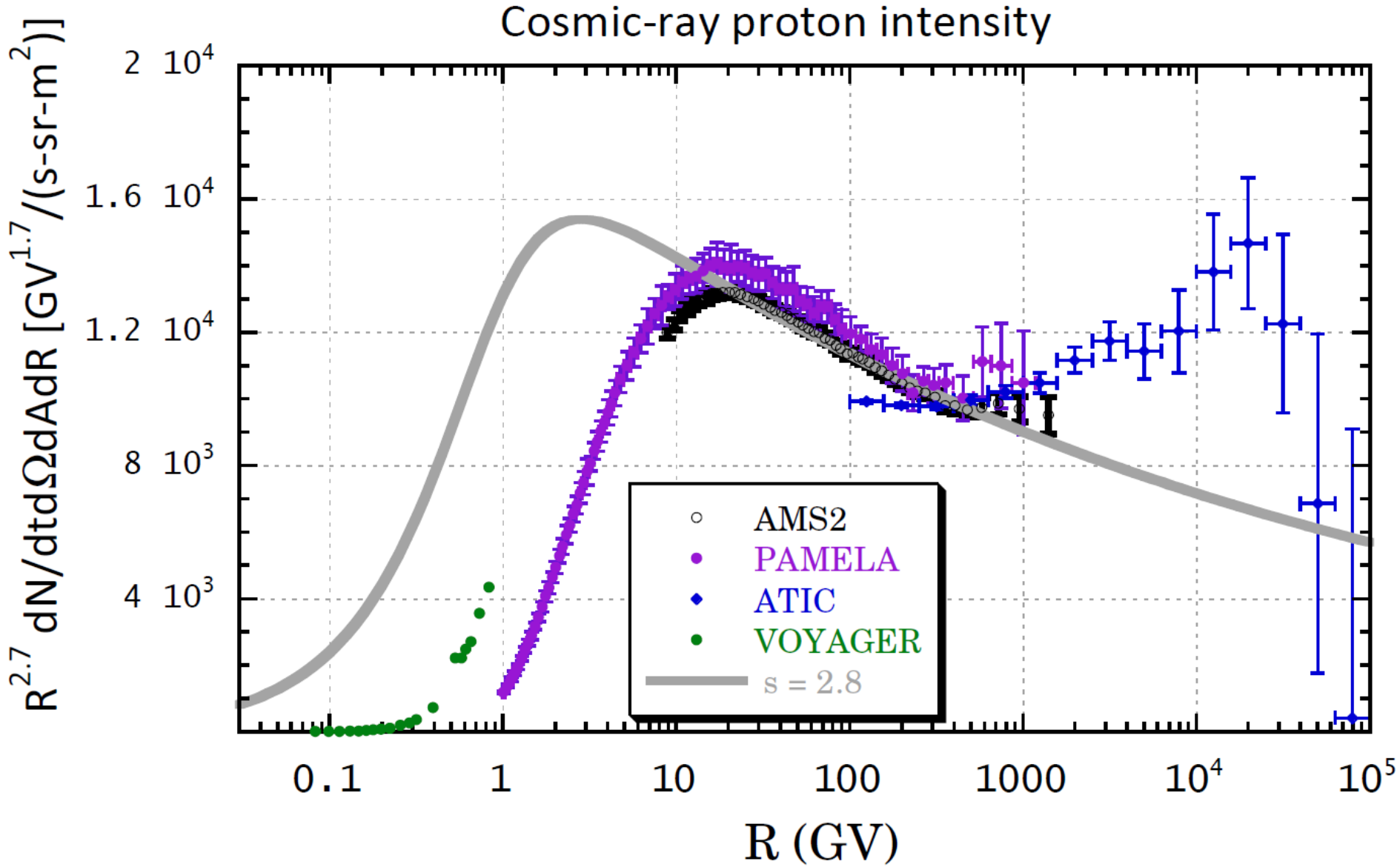
- $D(E_\mu)$ — resulting differential energy spectrum of atmospheric muons [1/(GeV·m²·s·sr)].

Ingredients for calculations (I)

- First we have to choose the primary energy spectra of various primary particles.

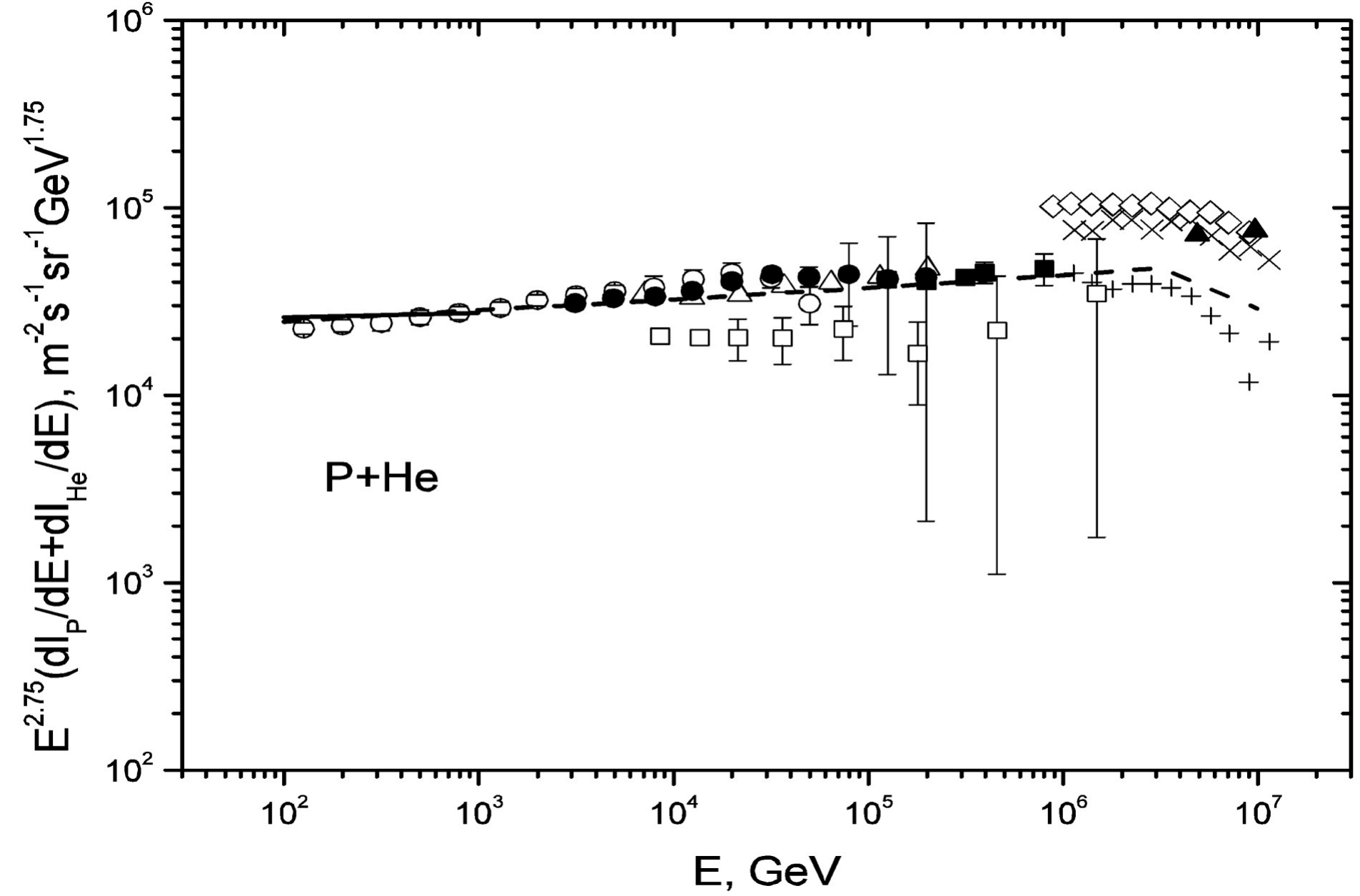
$$\left(\frac{dI_p}{dE}\right) \qquad \left(\frac{dI_{He}}{dE}\right) \qquad \left(\frac{dI_N}{dE}\right)$$

Differential energy spectrum PCR



Charles D. Dermer. Impact of Fermi-LAT and AMS-02 results on cosmic-ray astrophysics. (21 May 2015) arXiv:1505.05757v1

Primary cosmic ray spectrum (p+He)



Data for primary spectra (p + He)

Solid line − AMS02 // Proc. 33-d ICRC, Rio de Janeiro, 2013)

○ - ATIC2, // A.D. Panov et al., Bull. Bull. RAS, Phys.,**73**, 564, 2009

● - CREAM, // H. S. Ahn et al., Astrophys. J. Lett. **714**,L89-L93, 2010

Δ - ARGO, // B.Bartoli et al., Phys. Rev. D, **85**, 092005, 2012

■ - WCFTA, // S.S. Zhang et al., NIM, A, 629,57-65, 2011

× - KASKADE (QGSJET II-03)

+ - KASKADE (SIBYLL 2.1) T. Antoni et al., Astropart. Phys., **24**, 1-25, 2005

□ - RUNJOB, V.A. Derbina et al., ApJ, **628**, L41-L44, 2005

◊ - TUNKA (all particles), V.V. Prosin et al., Proc. 33-d ICRC, Rio de Janeiro, 2013

▲ - SPHERE2 (all particles) R.A. Antonov et al., Proc. 33-d ICRC, Rio de Janeiro, 2013

Approximation Gaisser-Honda for primary cosmic rays.

Gaisser T. K., Honda M. Flux of atmospheric neutrinos // Ann. Rev. Nucl. Part. Sci. 2002. Vol. 52. Pp. 153–199.

K — constant with demension [1/(GeV·m^2·s·sr)];

α, b, c — demensionless constants;

E_k — energy per nucleon [GeV].

$$\frac{dN_A}{dE_k} = K \cdot \left(E_k + b \cdot \exp\left(-c \cdot \sqrt{E_k}\right)\right)^{-\alpha}$$

Nuclei	α	K	b	c
H (1)	2,74	14900	2,15	0,21
He (4)	2,64	600	1,25	0,14
N (14)	2,6	33,2	0,97	0,01

Modified G&H approximation

For values above the critical energy $\mathbf{E_1}$ (for protons $E_1=3\cdot10^6$ GeV; for helium nuclei (^{4}He) for nitrogen nuclei (^{14}N) $E_{2,3}= 6\cdot10^6$ GeV) the modified Gaisser-Honda approximation was used.

1. For the primary protons:

$$(dI_p/dE)_m=(dI_p/dE)_{GH}\cdot(E_1/E)^{0,5}$$

2. For the primary helium nuclei ^{4}He:

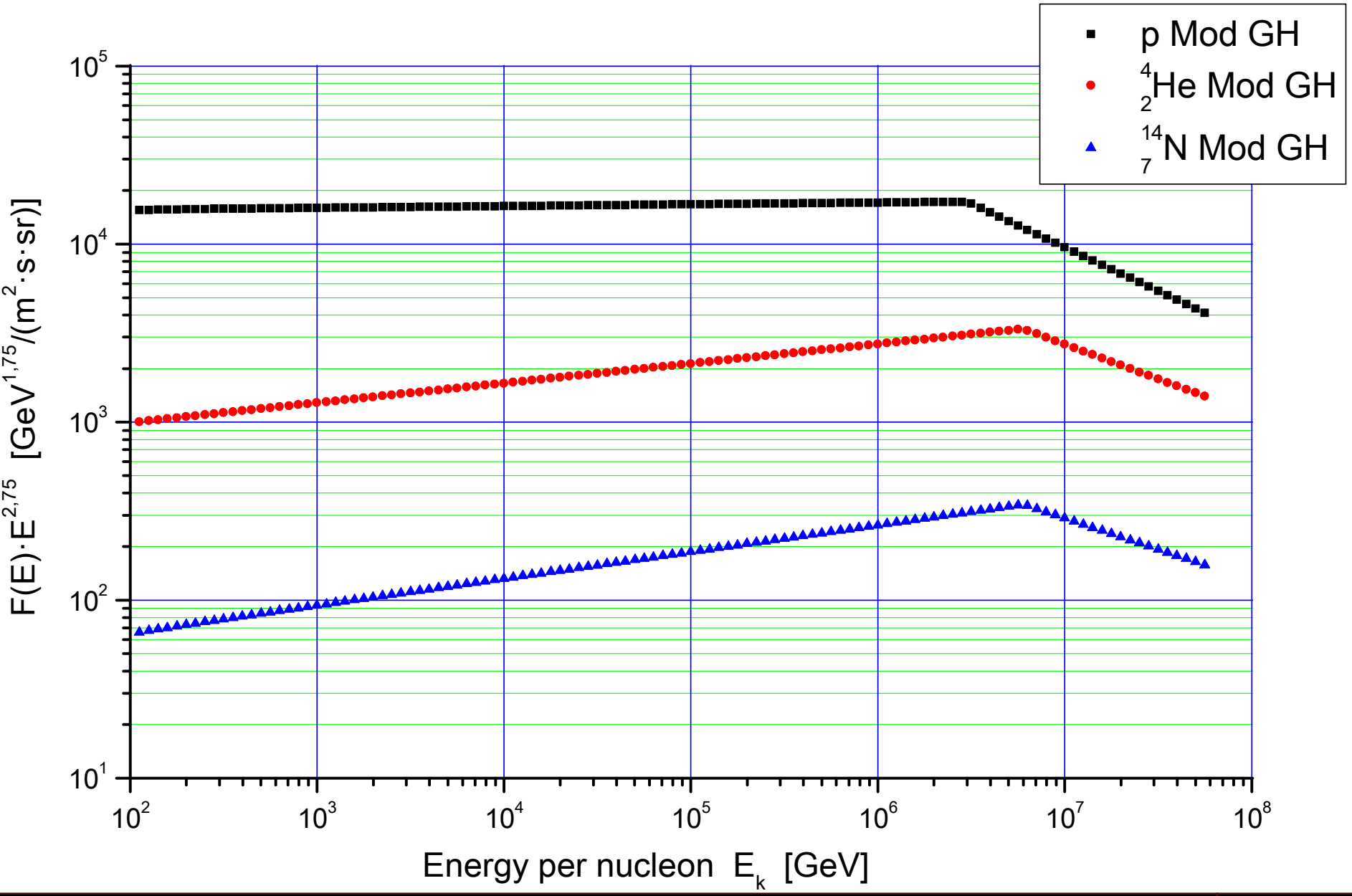
$$(dI_{He}/dE)_m=(dI_{He}/dE)_{GH}\cdot(E_2/E)^{0,5}$$

3. For the primary nitrogen nuclei ^{14}N:

$$(dI_N/dE)_m=(dI_N/dE)_{GH}\cdot(E_3/E)^{0,5}$$

E — energy per nucleon [GeV]; E_1 — critical energy.

Primary spectra



Ingredients for calculations (II)

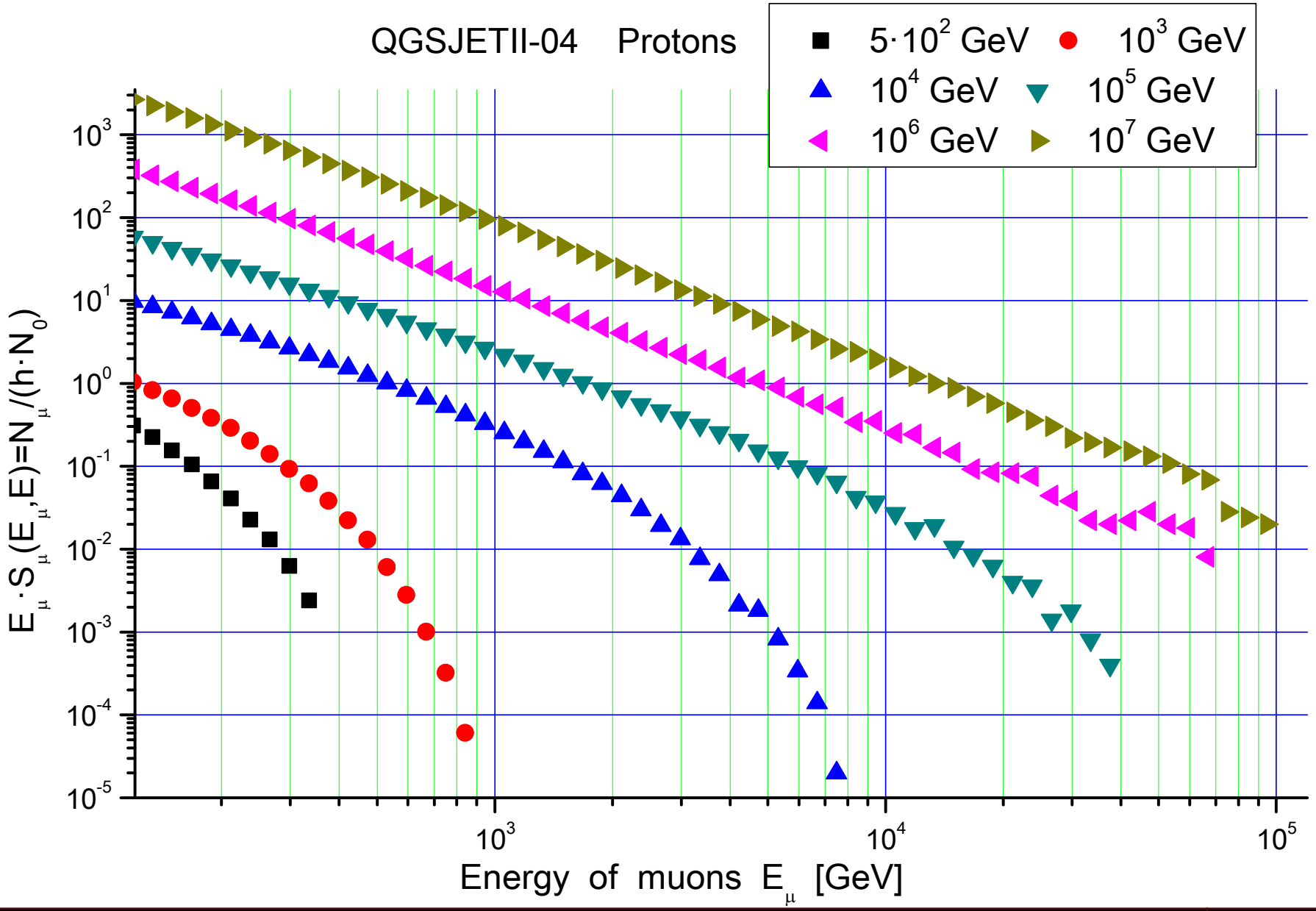
- Second we have to obtain the muon density functions for various primary particles at fixed values of energies (E).

$$S_p(E_\mu, E) \cdot dE_\mu$$

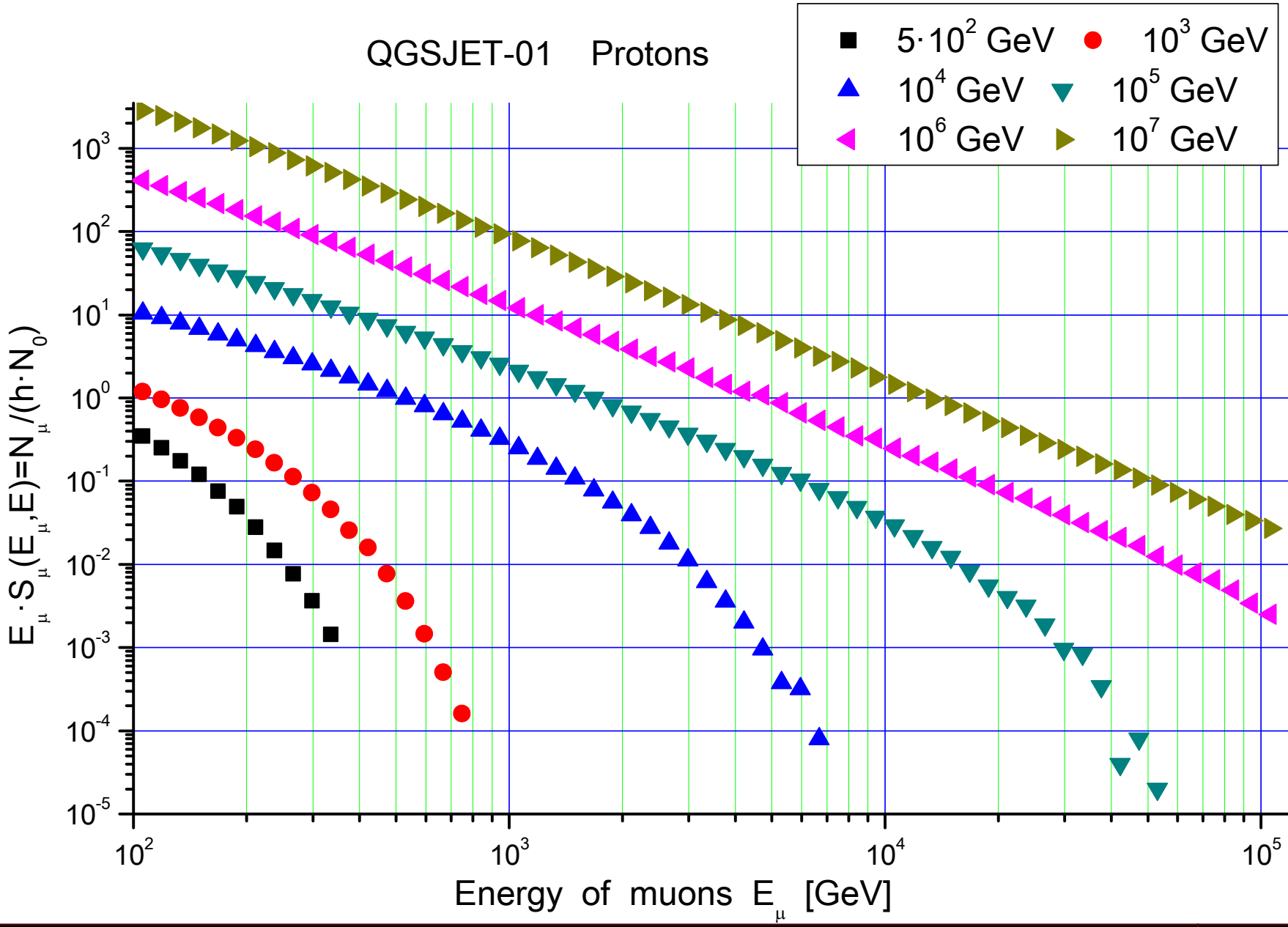
$$S_{He}(E_\mu, E) \cdot dE_\mu$$

$$S_N(E_\mu, E) \cdot dE_\mu$$

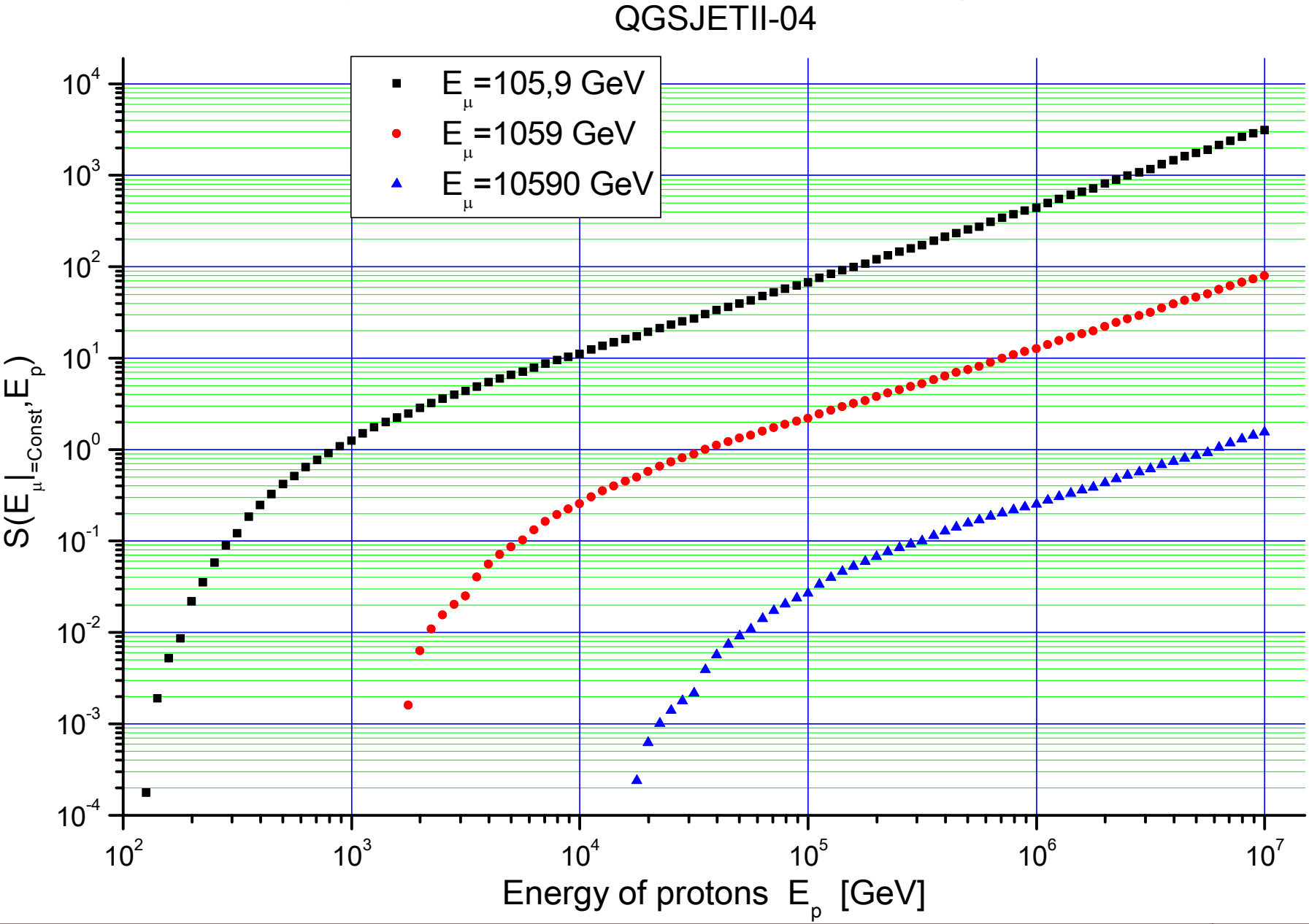
Muons density functions at fixed proton energies



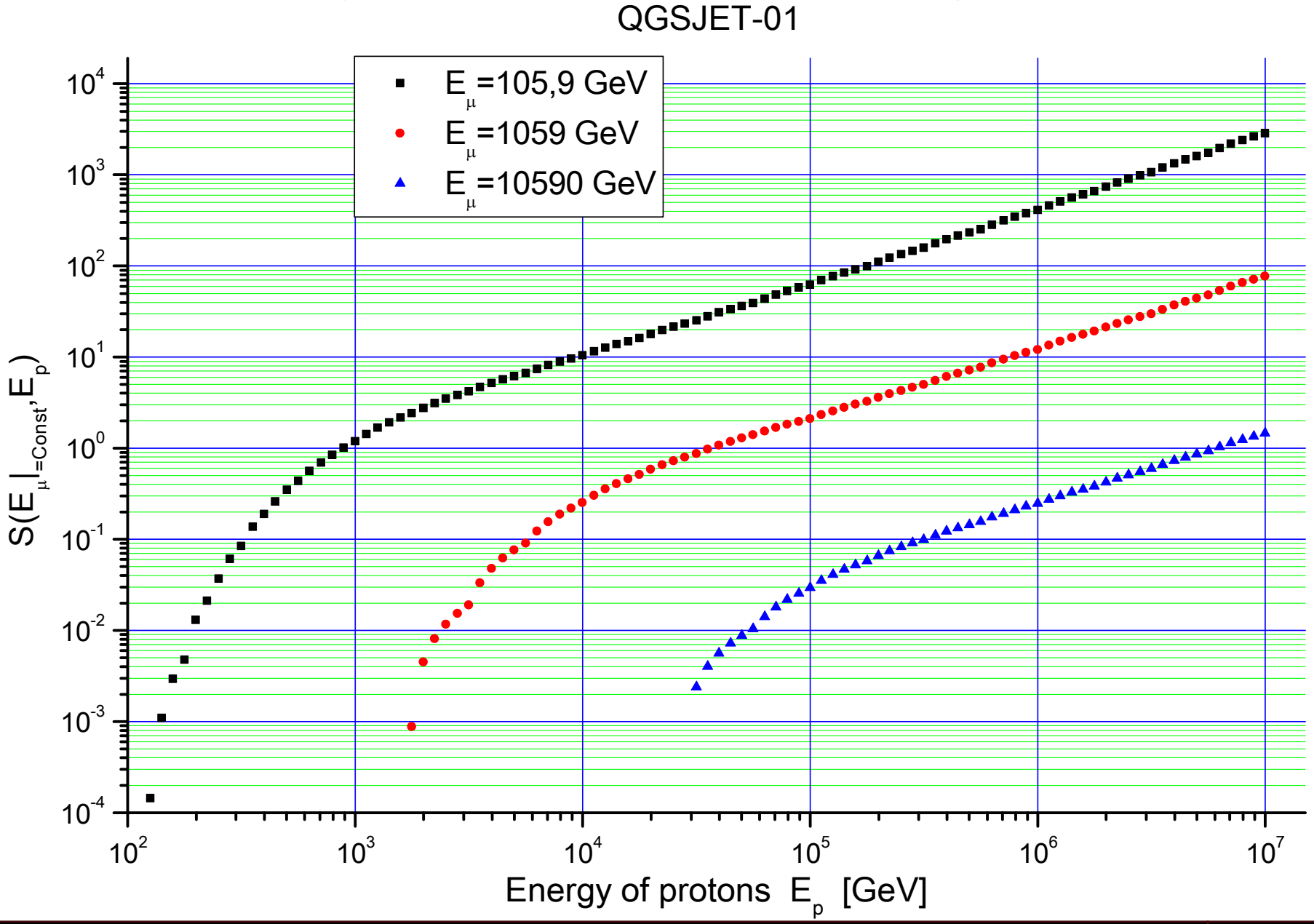
Muons density functions at fixed proton energies



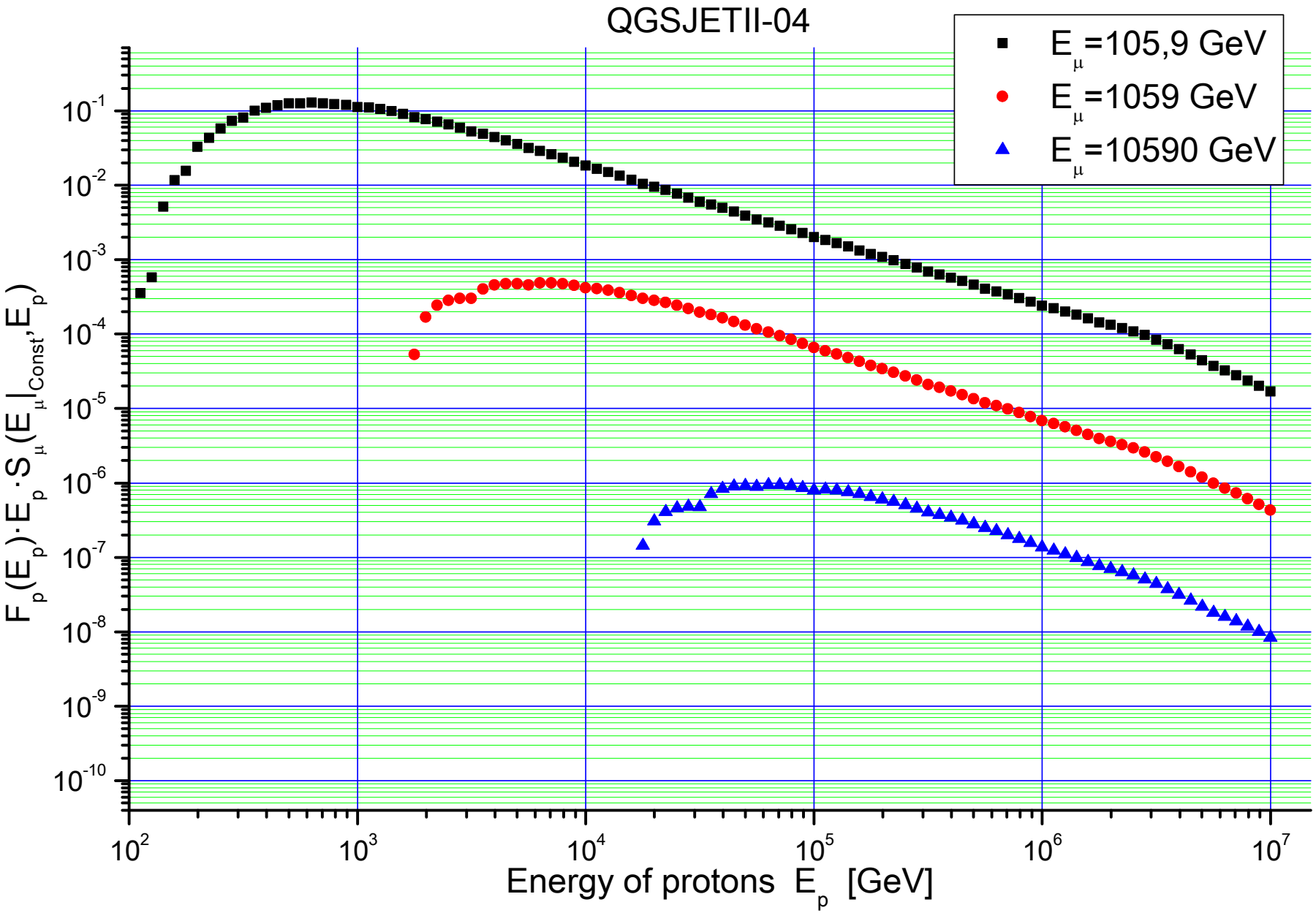
Muons density functions at fixed energies of muons



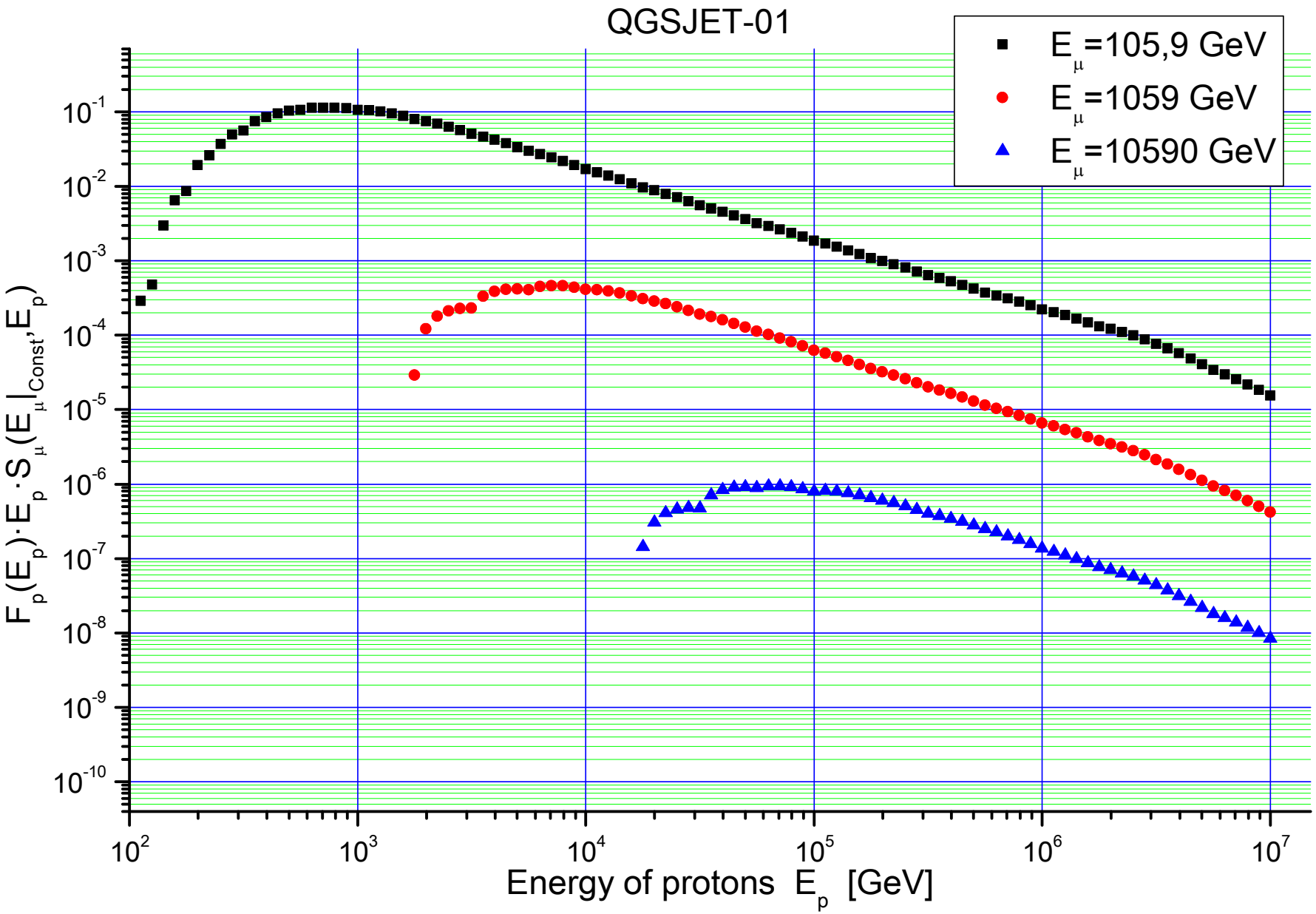
Muons density functions at fixed energies of muons



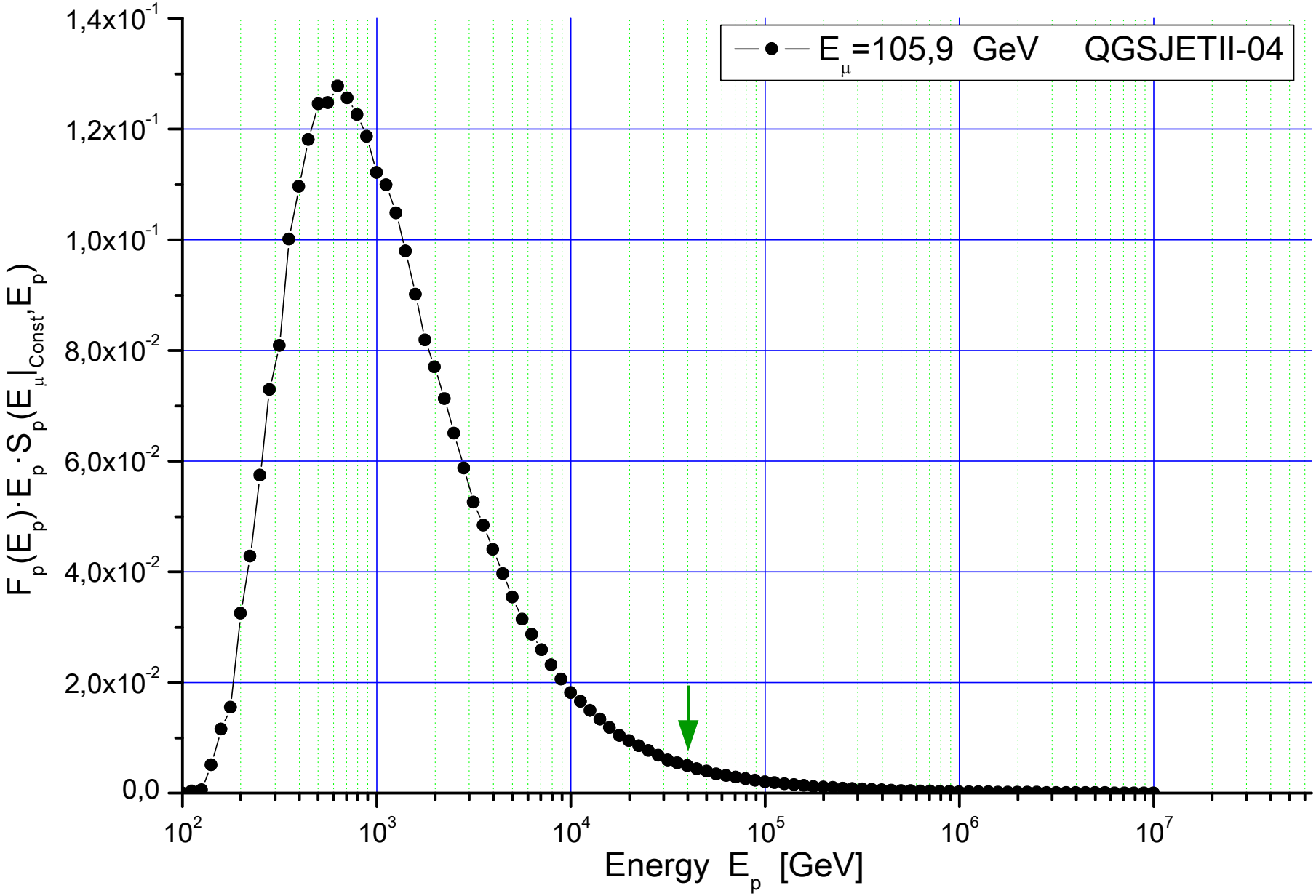
Functions of relative contribution in muons generation



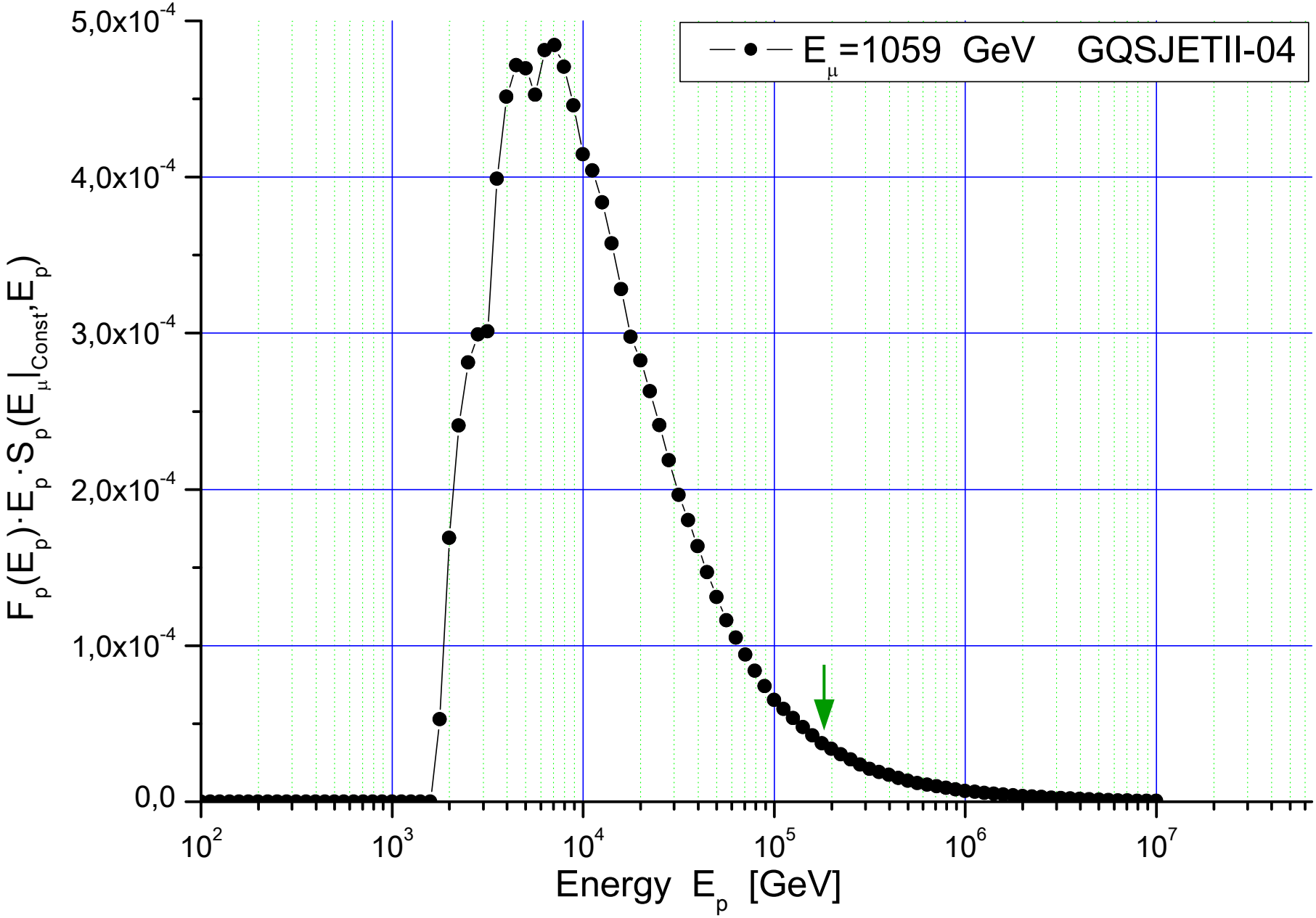
Functions of relative contribution in muons generation



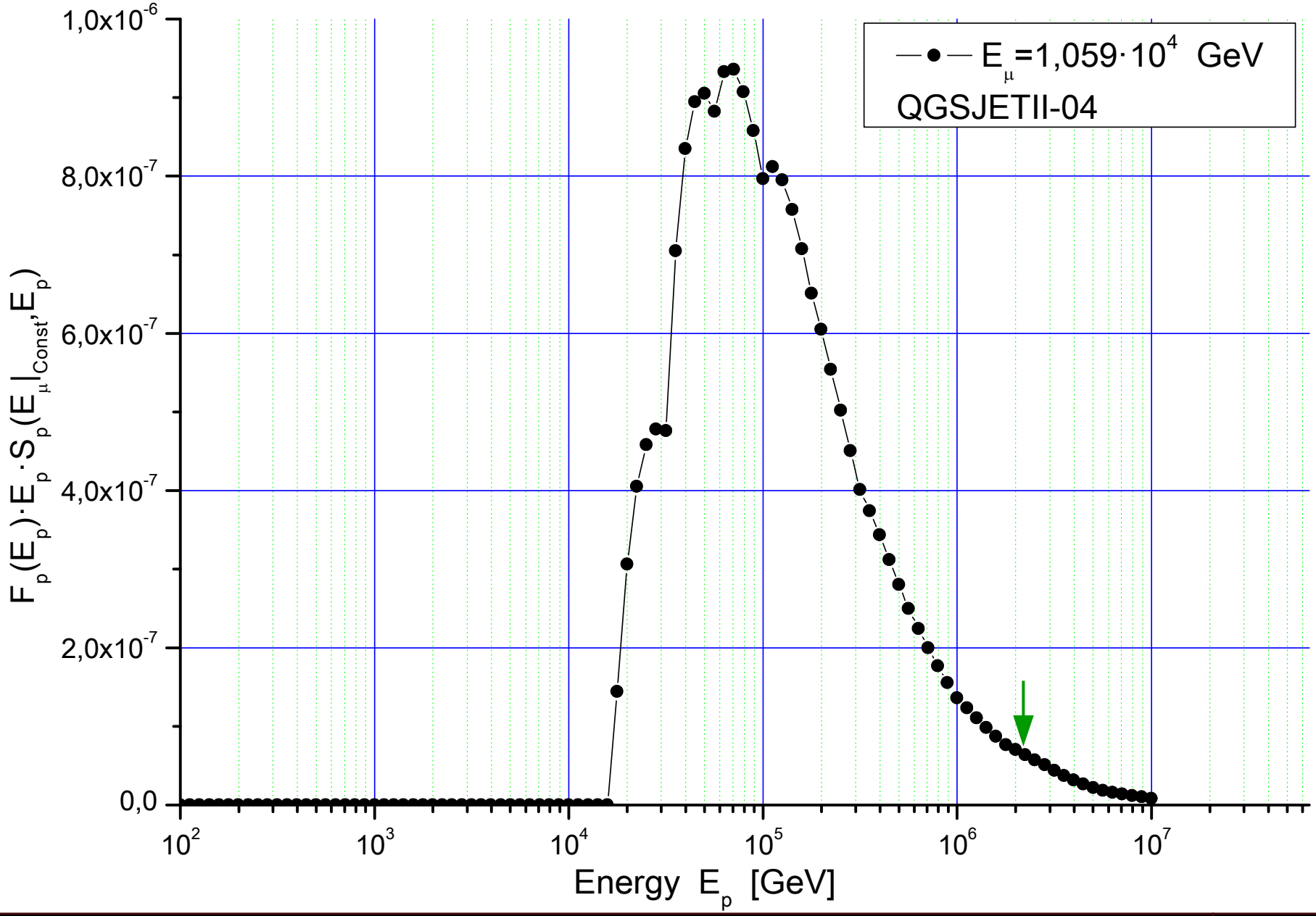
Relative contribution in muons



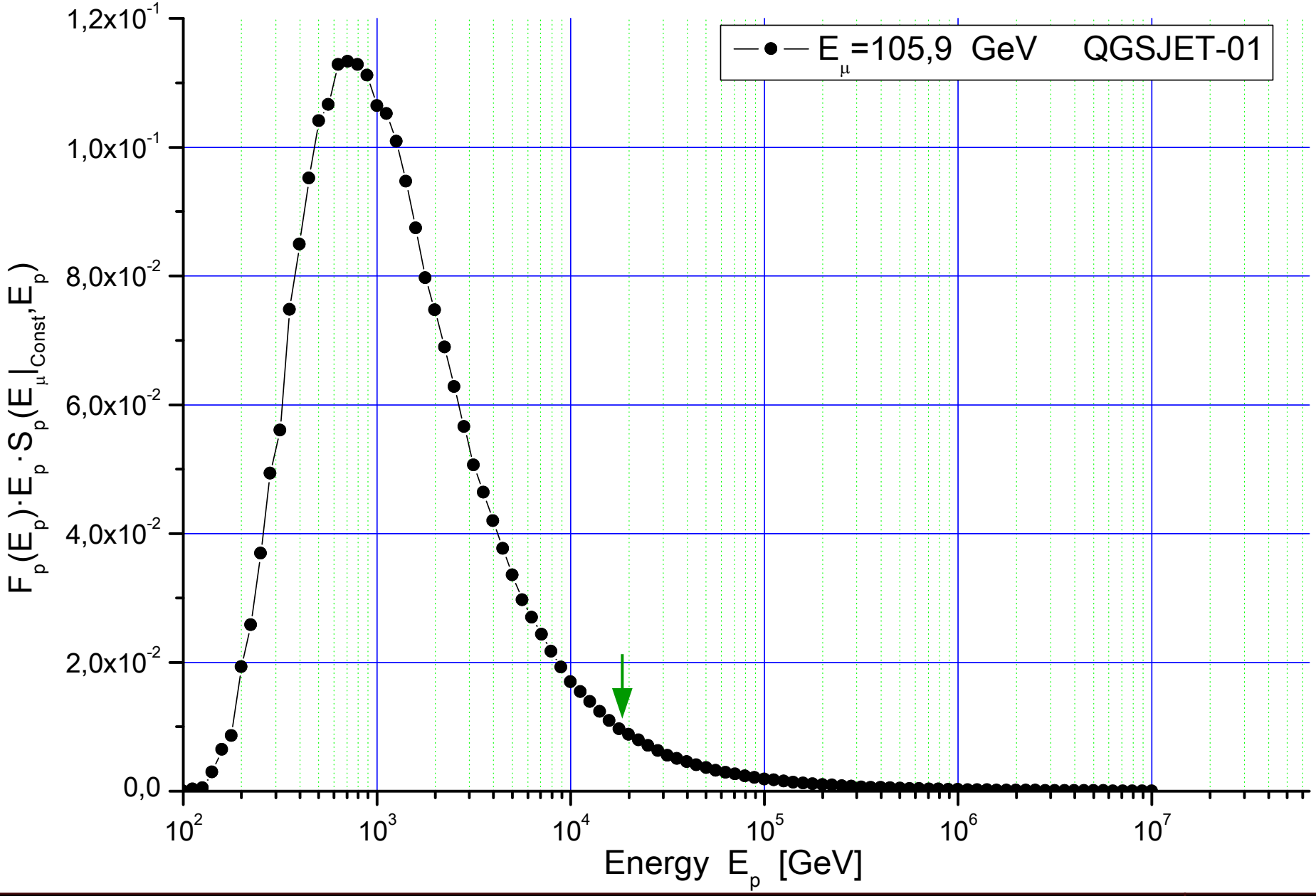
Relative contribution in muons



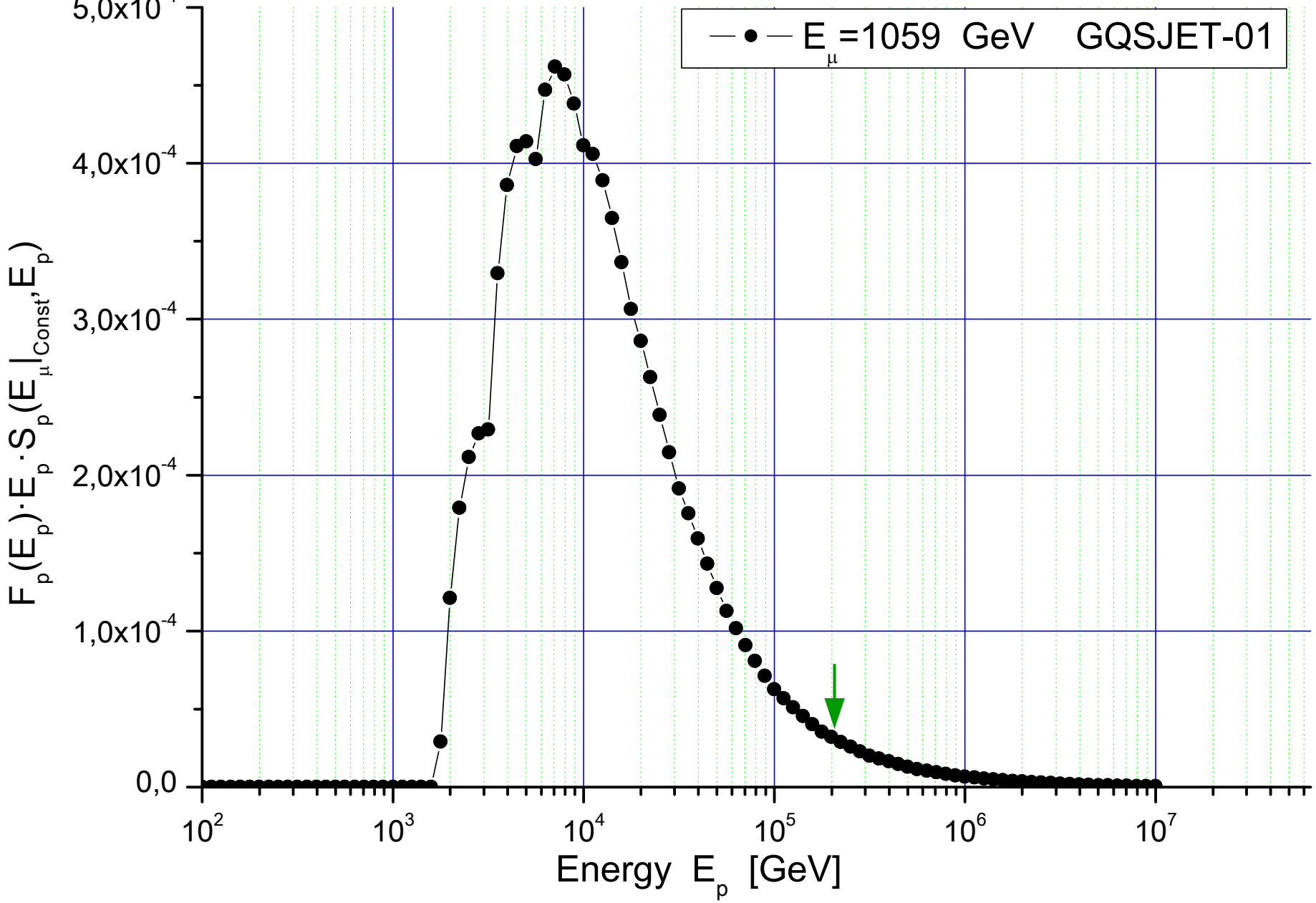
Relative contribution in muons



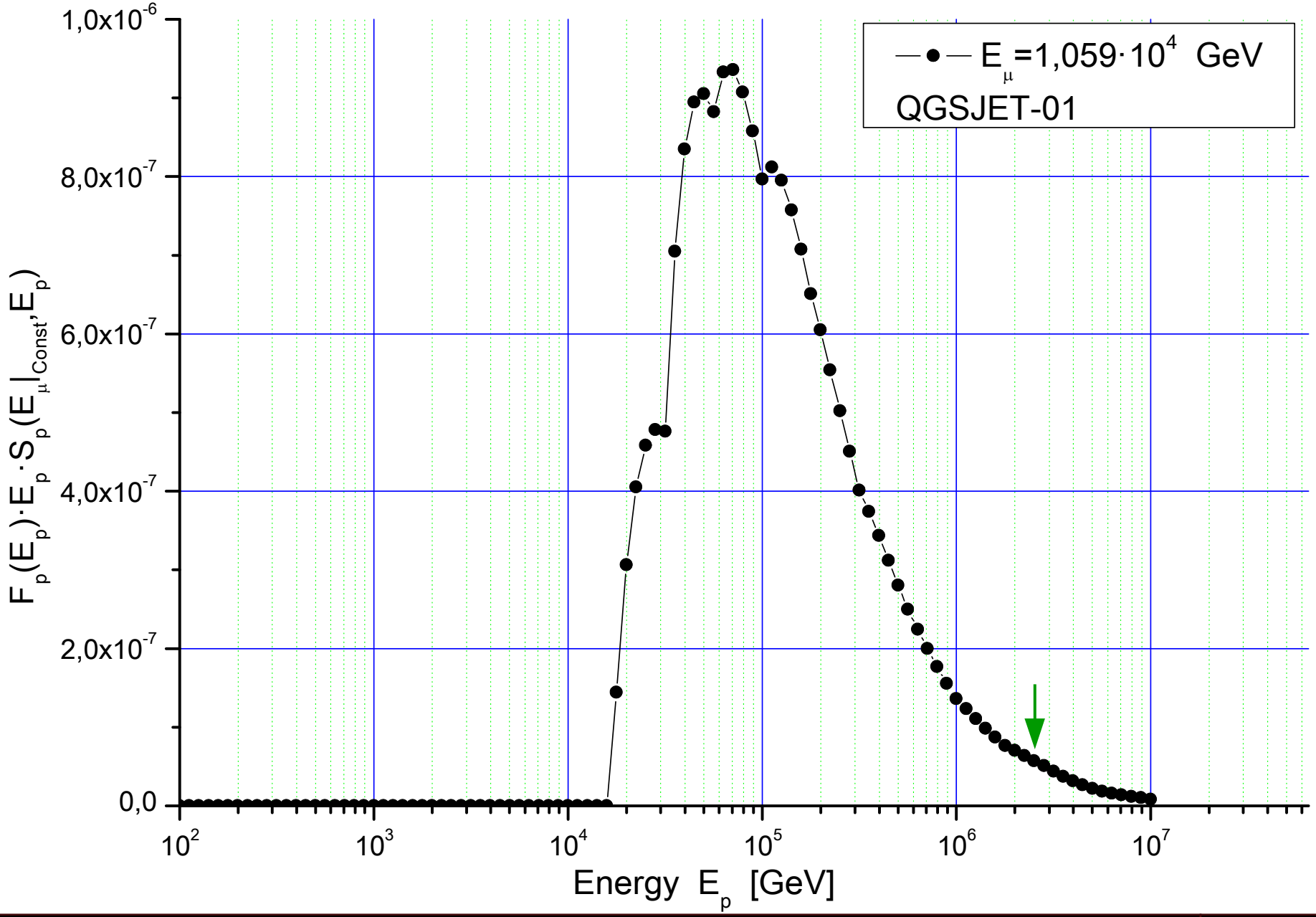
Relative contribution in muons



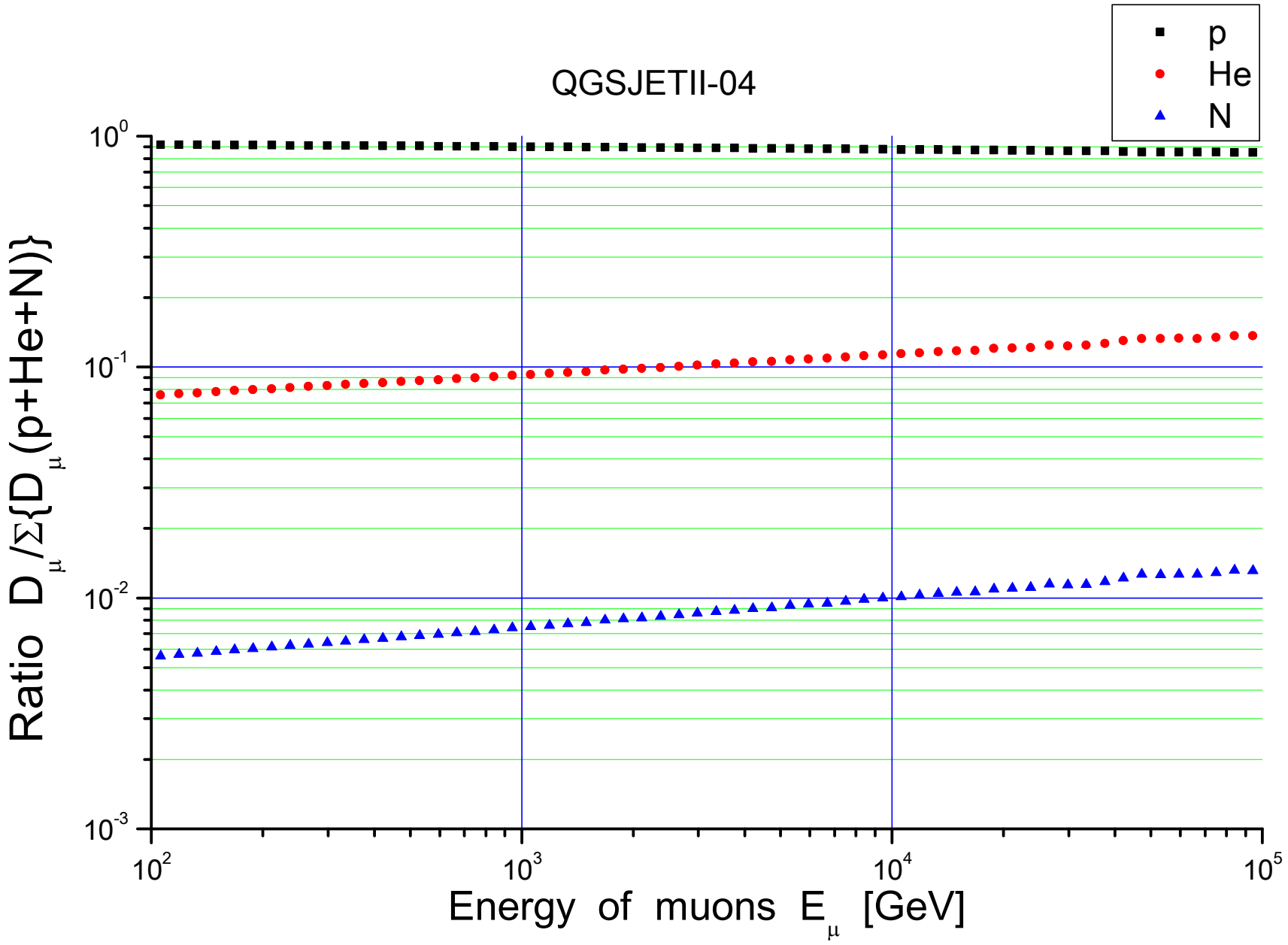
Relative contribution in muons



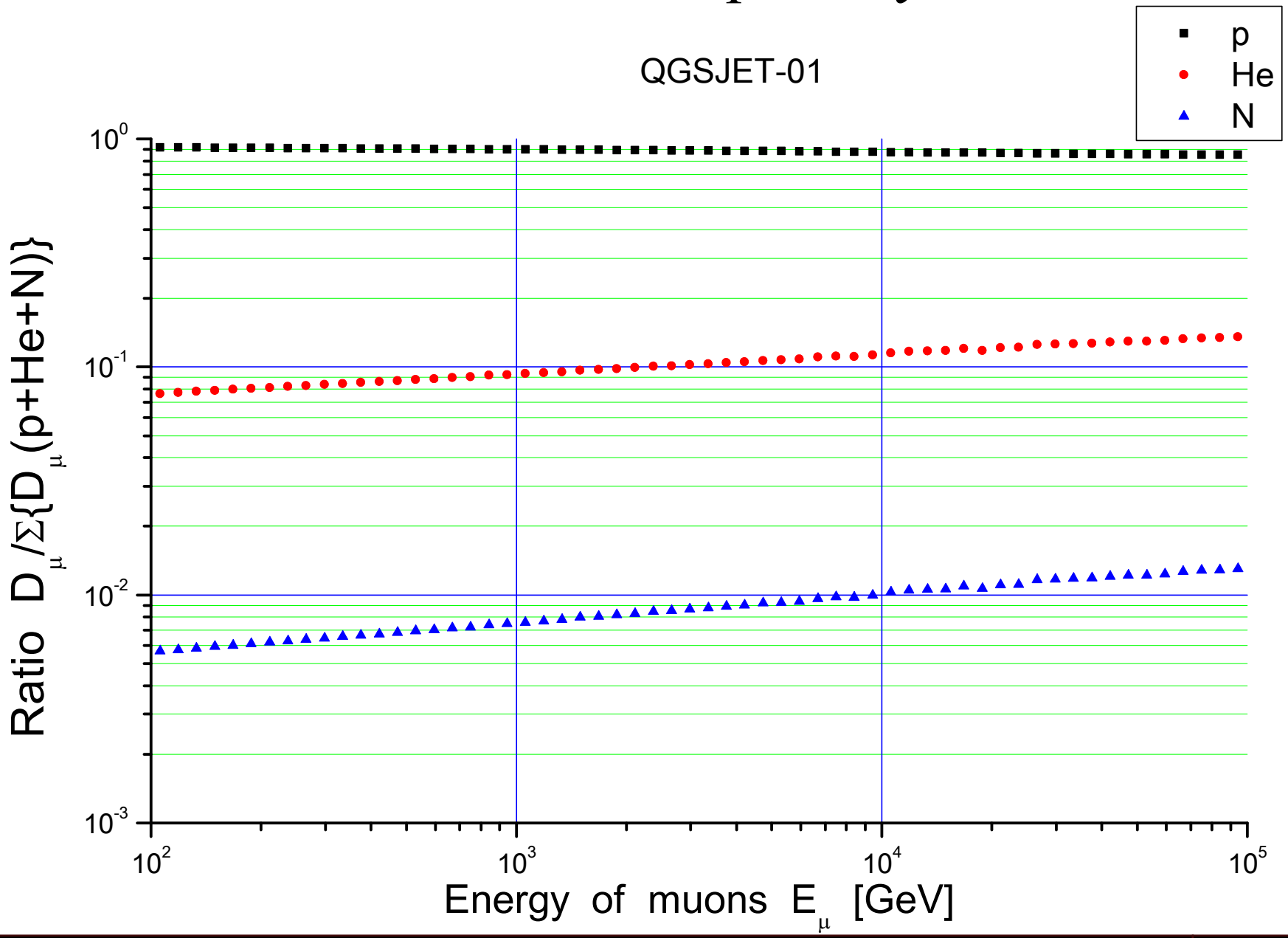
Relative contribution in muons



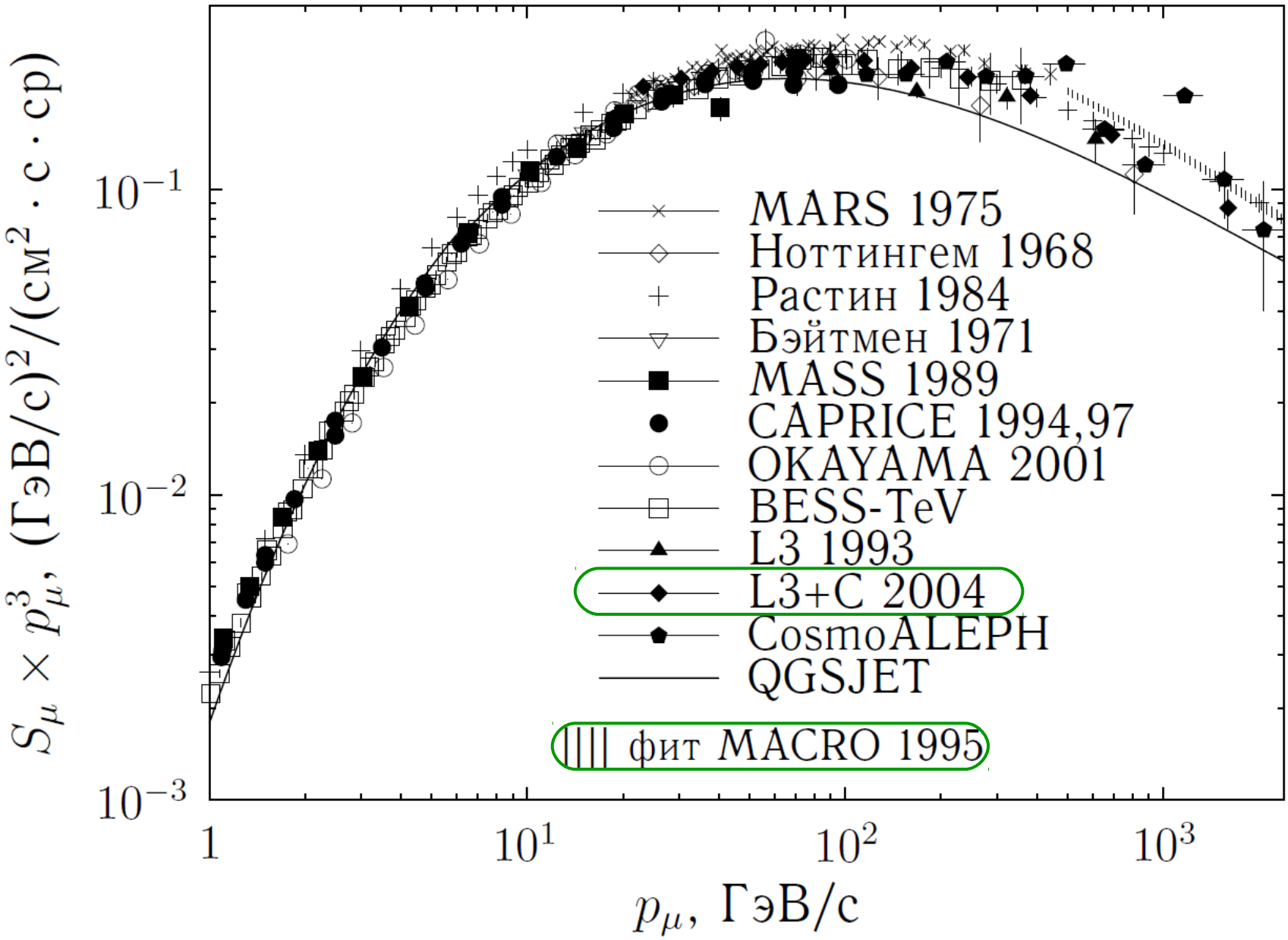
Partial contribution of primary nuclei



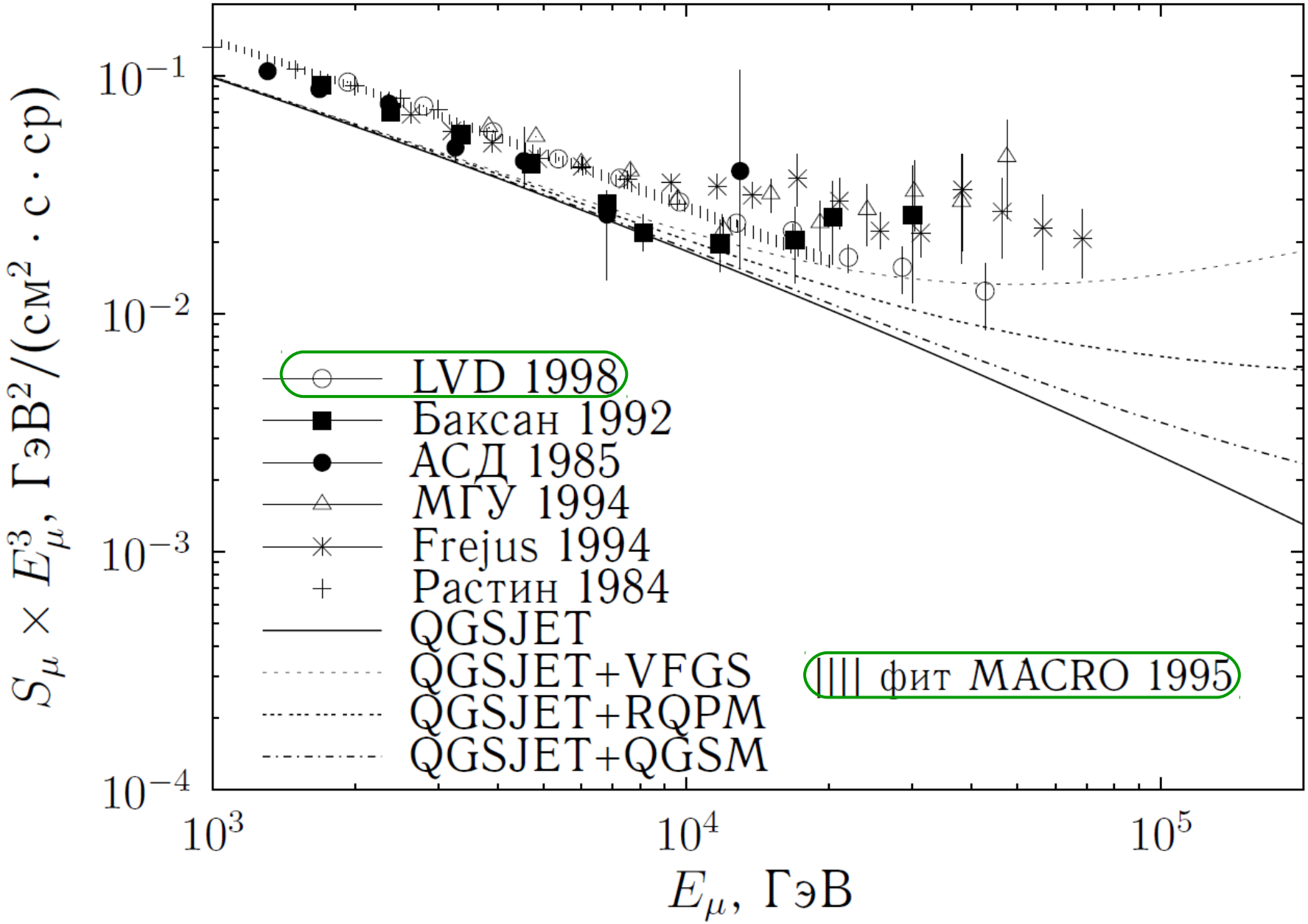
Partial contribution of primary nuclei



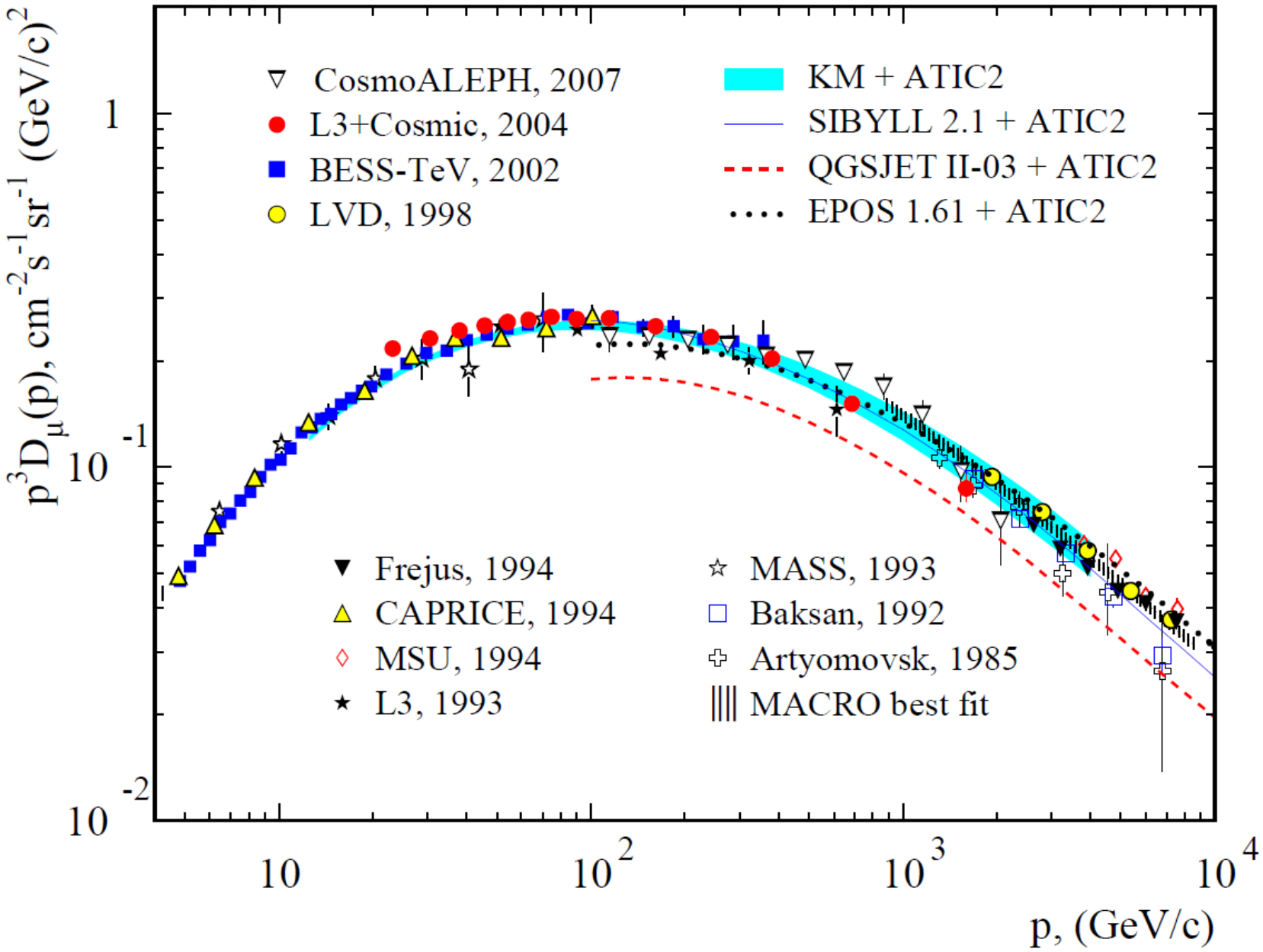
Alexey Yushkov PhD. Thesis



Alexey Yushkov PhD. Thesis



Alexander Kochanov PhD. Thesis



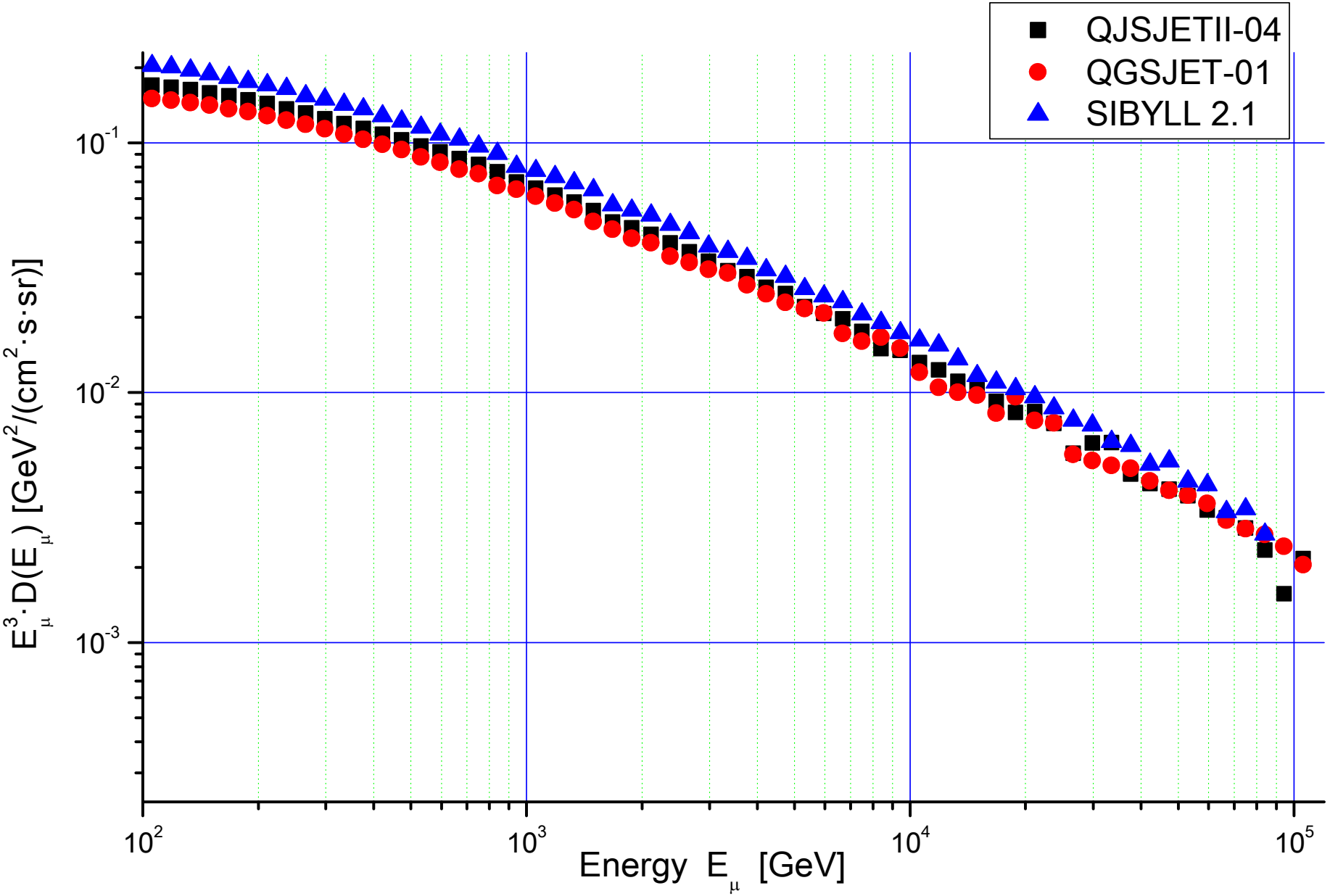
Data of the muon spectra

1) L3+Cosmic: arXiv: hep-ex 0408114v1K (2004)

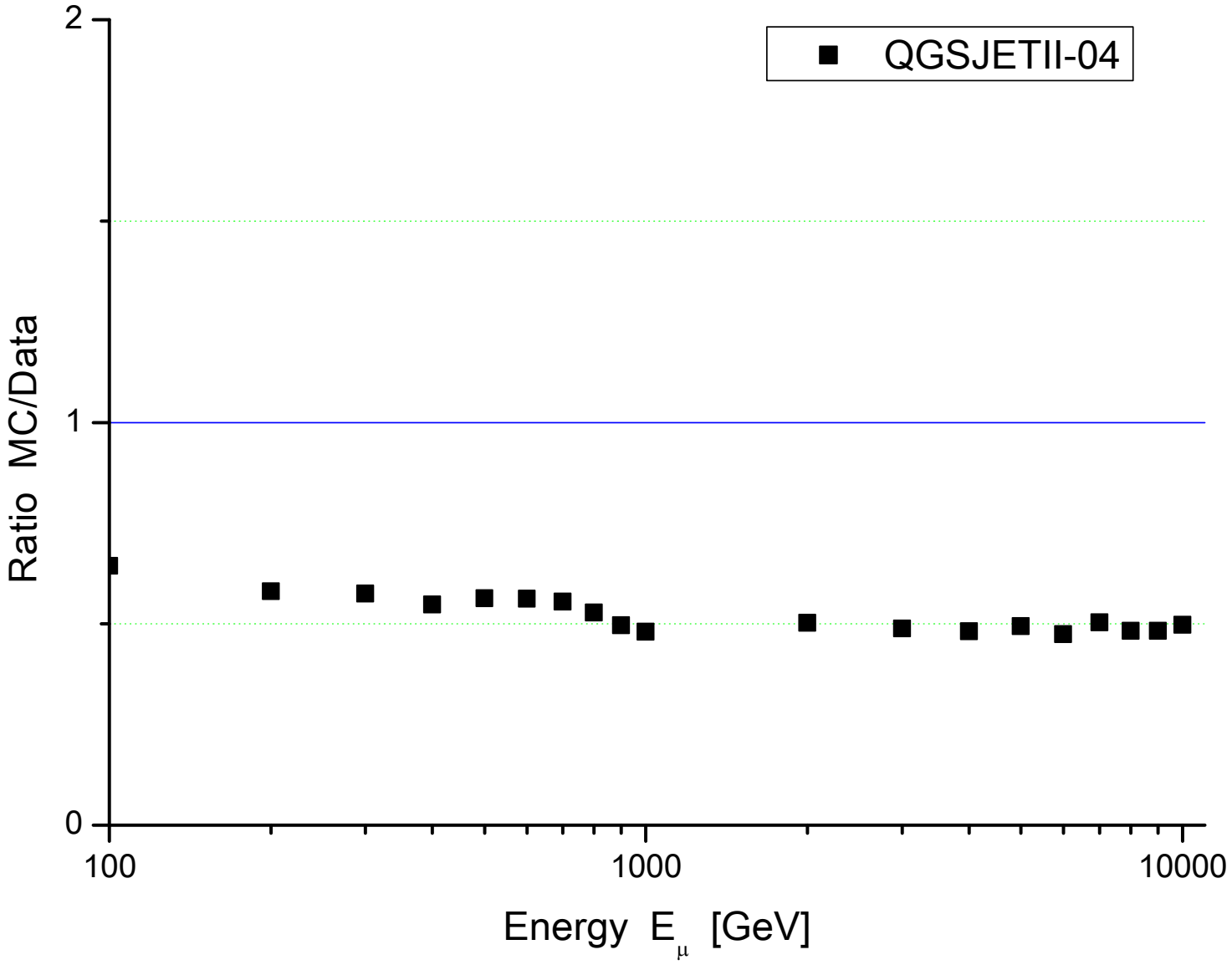
2) MACRO: M. Ambrosio et al., Phys. Rev. D **52**, 3793, (1995)

3) LVD: M. Aglietta et al., arXiv: hep-ex 9806001v1, (1998)

Result of calculations



Result of calculations



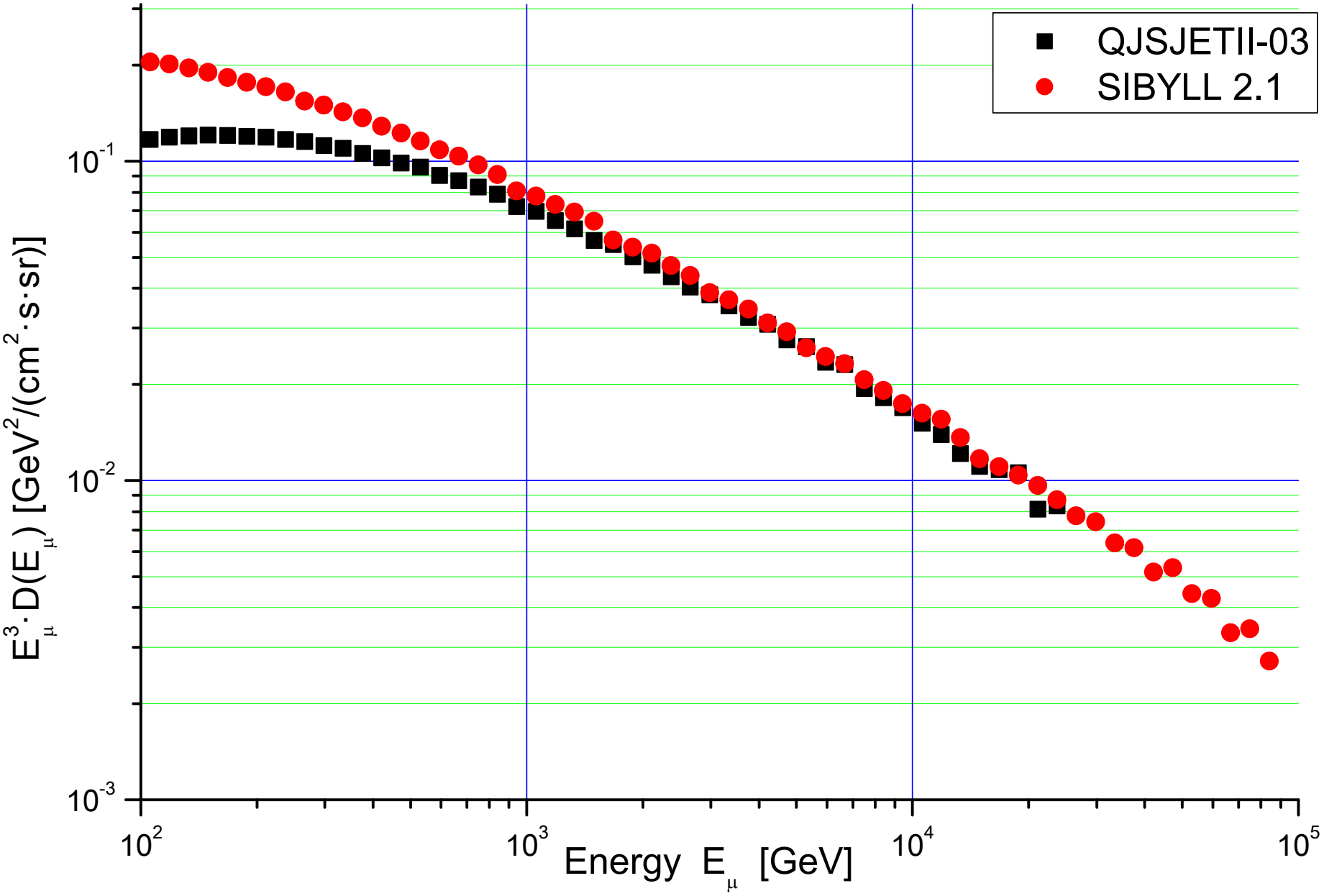
Conclusion

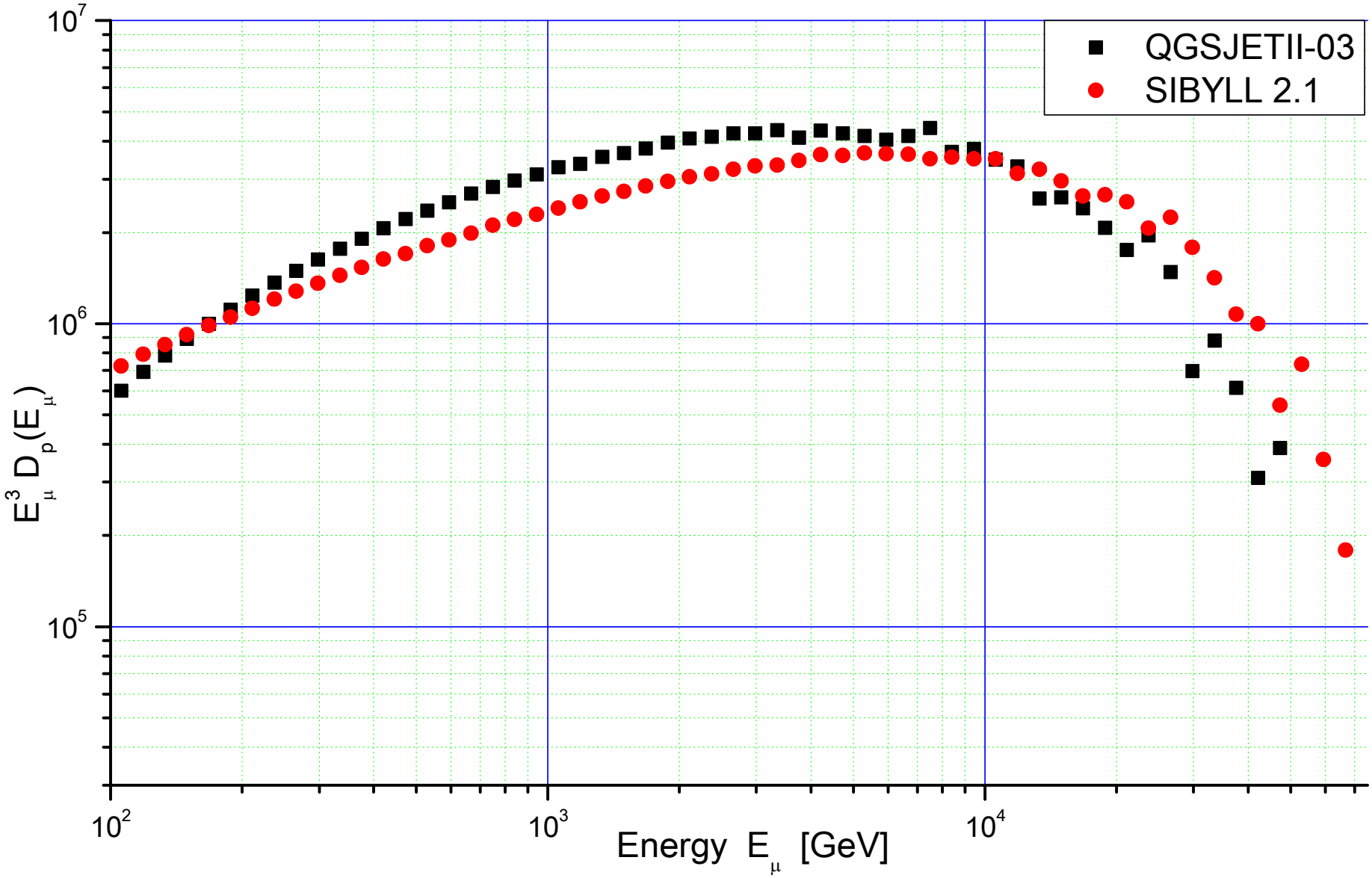
- Primary protons and helium nuclei takes the most significant contribution in muon spectrum.
- The QGSJETII-04 model are shifted below the data by factor ~2.

Acknowledgements

- Authors thanks to Prof. N.N. Kalmykov, pointing to alternative computing with other results and
- Prof. A.A. Lagutin for the important assistance in the validation of the results for the QGSJET-01 model.

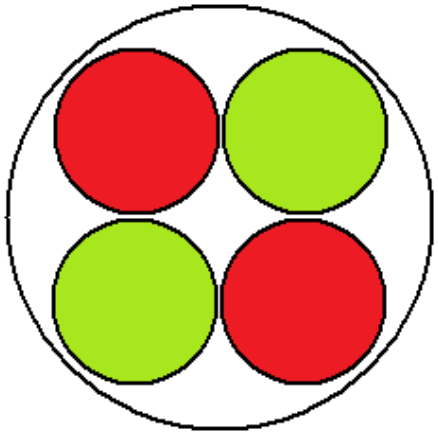
Thank you for attention!

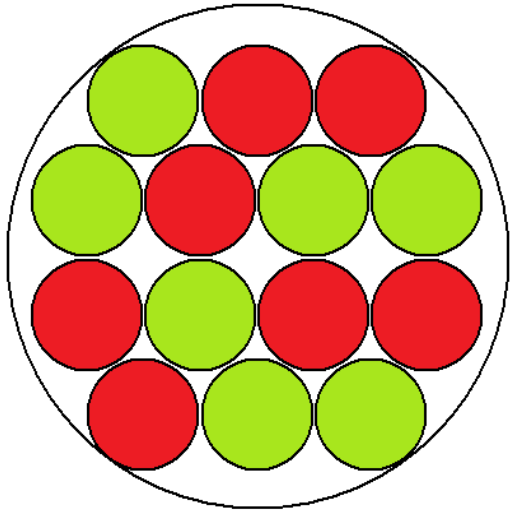

QJSJETII-03
SIBYLL 2.1
$E_\mu^3 \cdot D(E_\mu)$ [GeV^2/(cm^2·s·sr)]
10^{-1}
10^{-2}
10^{-3}
10^2
10^3
10^4
10^5
Energy E_μ [GeV]


QGSJETII-03
SIBYLL 2.1
10^7
10^6
10^5
$E_\mu^3 D_p(E_\mu)$
10^2
10^3
10^4
Energy E_μ [GeV]

Superposition conception

- Helium nuclei (A=4) and nitrogen nuclei (A=14) is a systems of A nucleons.

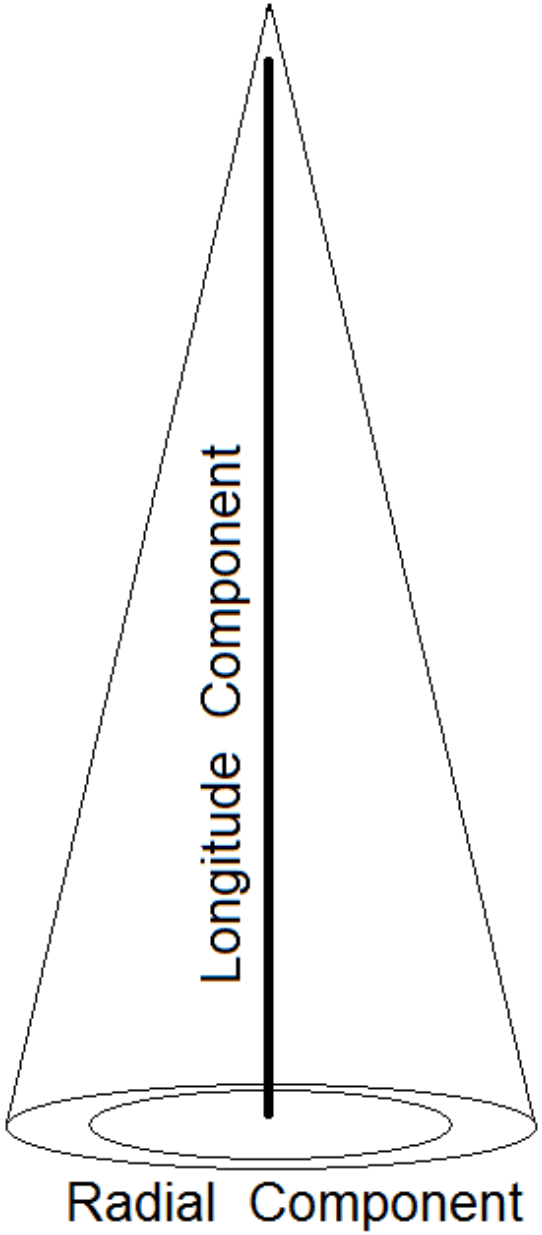




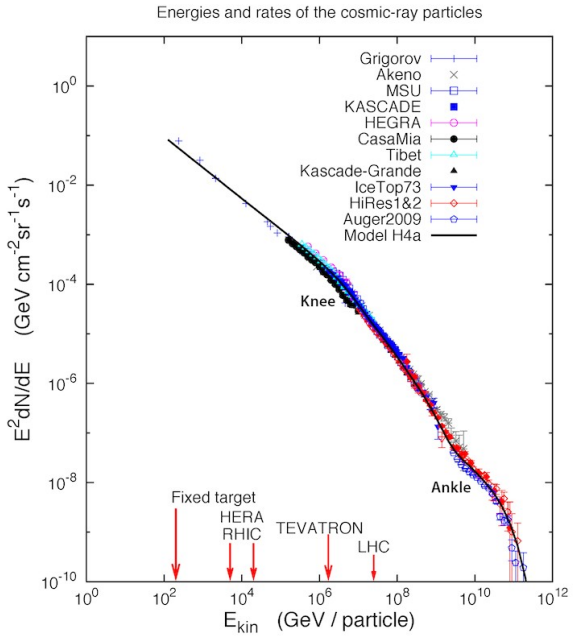
$$S_{He}(E_\mu, E_{He}) \approx 4 \cdot S_p\left(E_\mu, E_p = \frac{E_{He}}{4}\right)$$

$$S_N(E_\mu, E_N) \approx 14 \cdot S_p\left(E_\mu, E_p = \frac{E_N}{14}\right)$$

Intro



Important interlink



$$\left(\frac{dI_p}{dE}\right)$$

Hadronic interaction models

μ