Testing of the DPMJET and VENUS hadronic interaction models with the help of the atmospheric muons.

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Introduction

1) This work is a continuation of the series of testing a hadronic interaction models.

2) DPMJET 2.55, VENUS 4.12, QGSJET-01, QGSJETII-03, QGSJETII-04, SIBYLL 2.1.

3) Our goal is to compare the behavior of different models between each other in the region of maximum energies of the secondary particles.

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 energy spectra of muons $D(E_\mu)$ for models DPMJET and VENUS with energies in the energy range $E_\mu=10^2$ — 10^5 GeV in the atmosphere from the primary protons, He and N nuclei with energies within the interval $E=10^2$ — 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

$N_0 = 10^6$

Method

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

Muons density distribution functions [CORSIKA 7.4]

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

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

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

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

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

Method of simulations

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

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

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

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

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

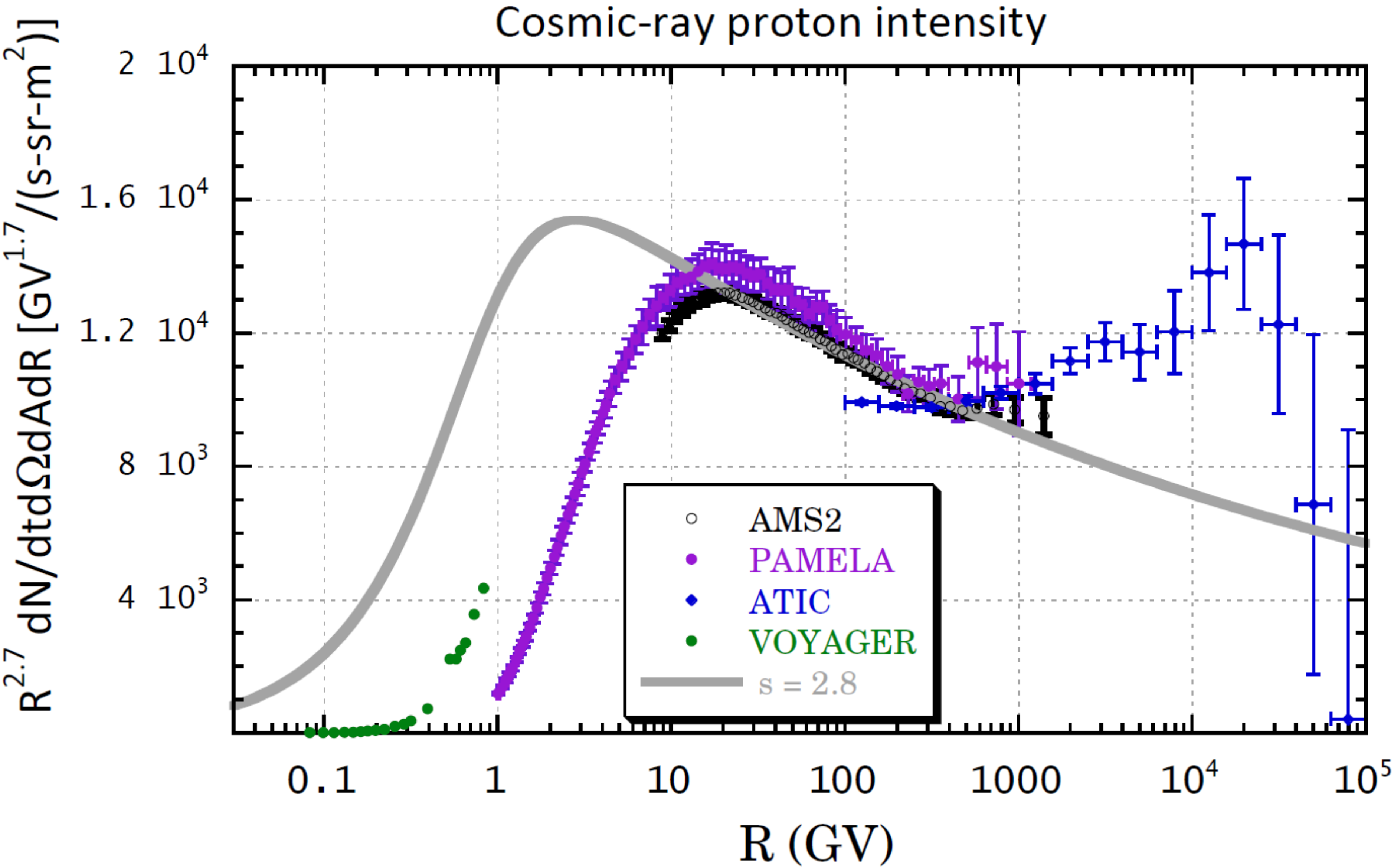
- $D(E_\mu)$ — resulting differential energy spectrum of atmospheric muons [1/(GeV·m²·s·sr)].

Ingredients for calculations (I)

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

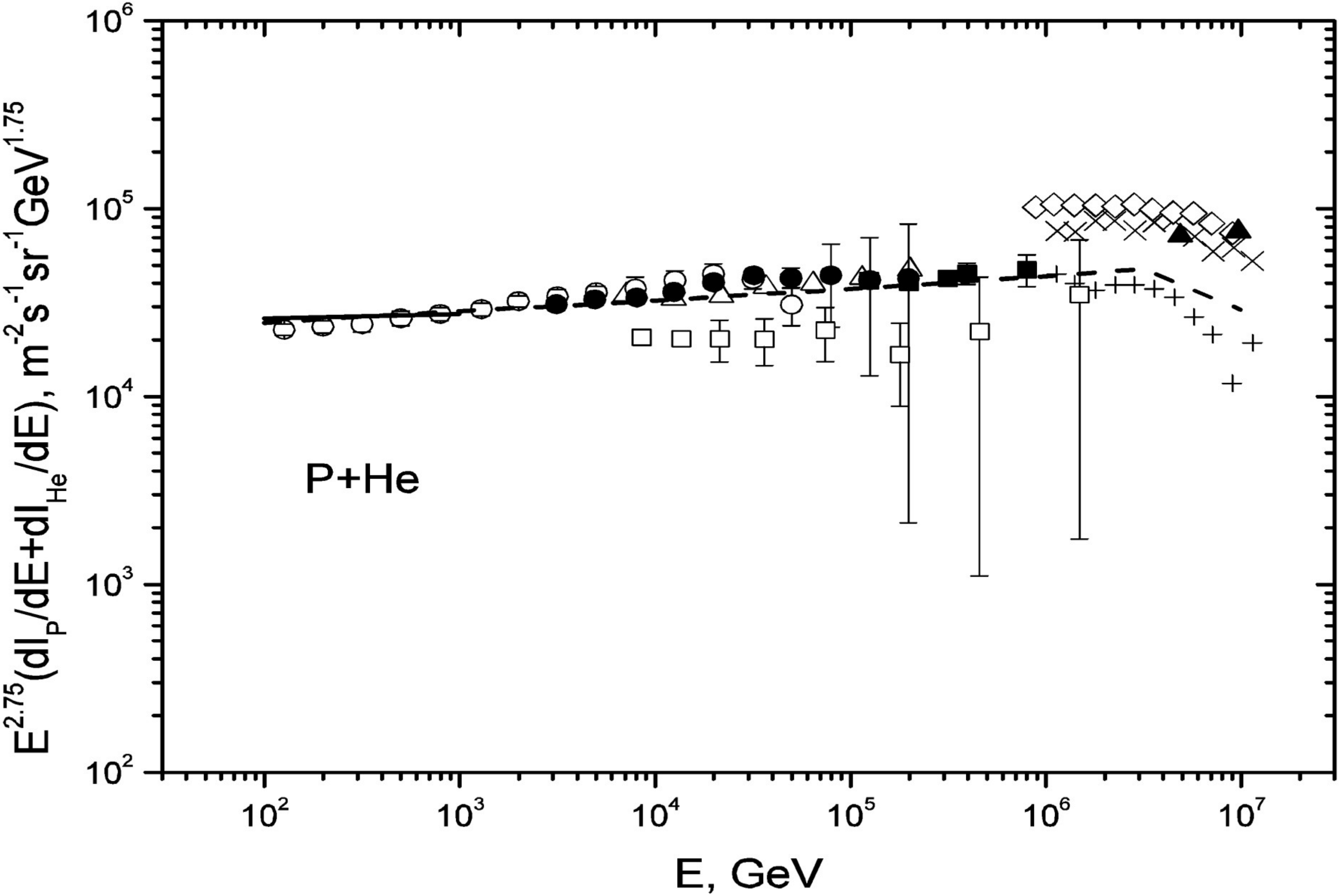
$$\left(\frac{dI_p}{dE}\right) \qquad \left(\frac{dI_{He}}{dE}\right) \qquad \left(\frac{dI_N}{dE}\right)$$

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:

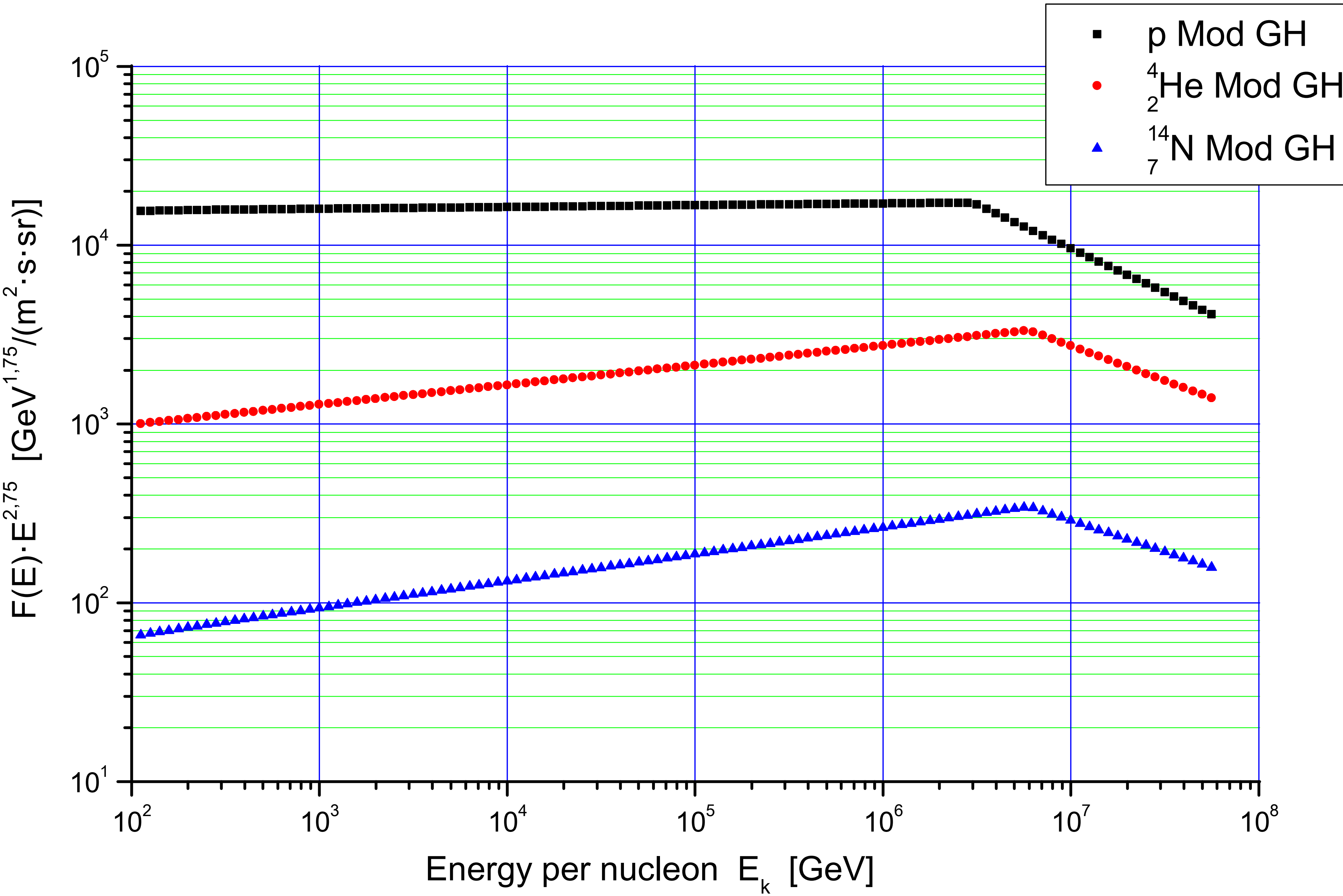
$$(dI_{He}/dE)_m=(dI_{He}/dE)_{GH}\cdot(E_2/E)^{0,5}$$

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)

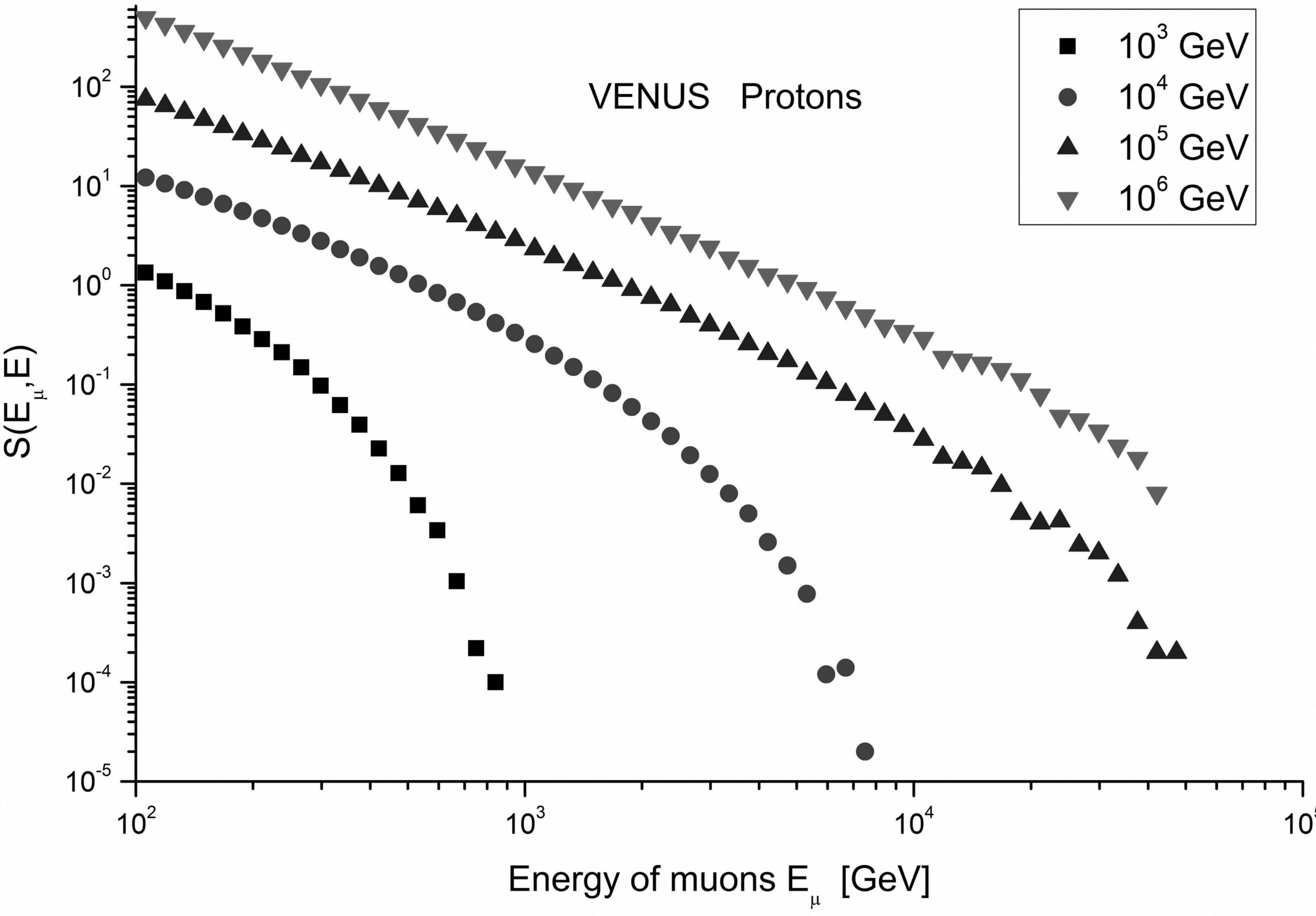
- Second we have to obtain the muon density functions for various primary particles at fixed values of energies (E).

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

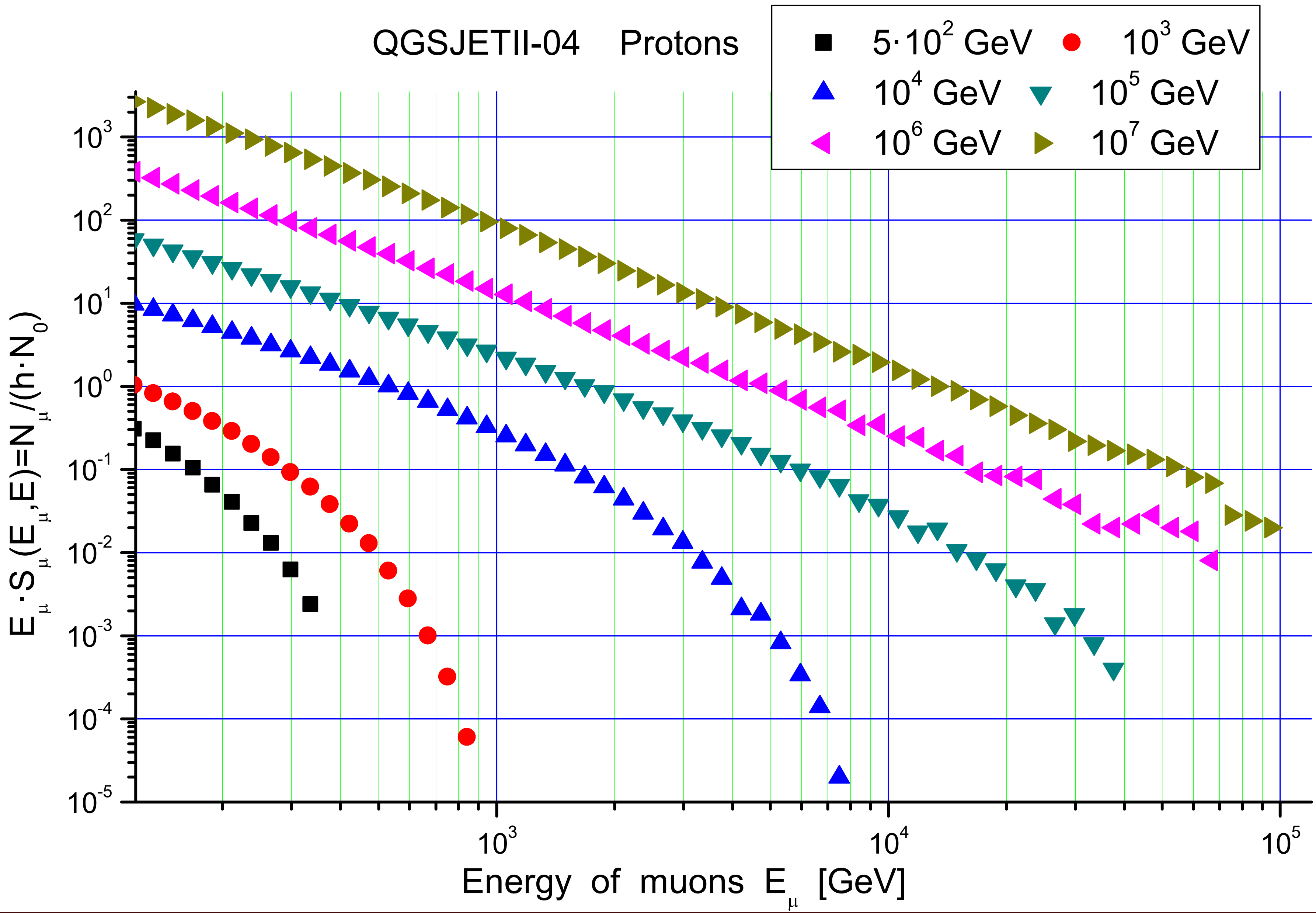
$$S_{He}(E_\mu, E) \cdot dE_\mu$$

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

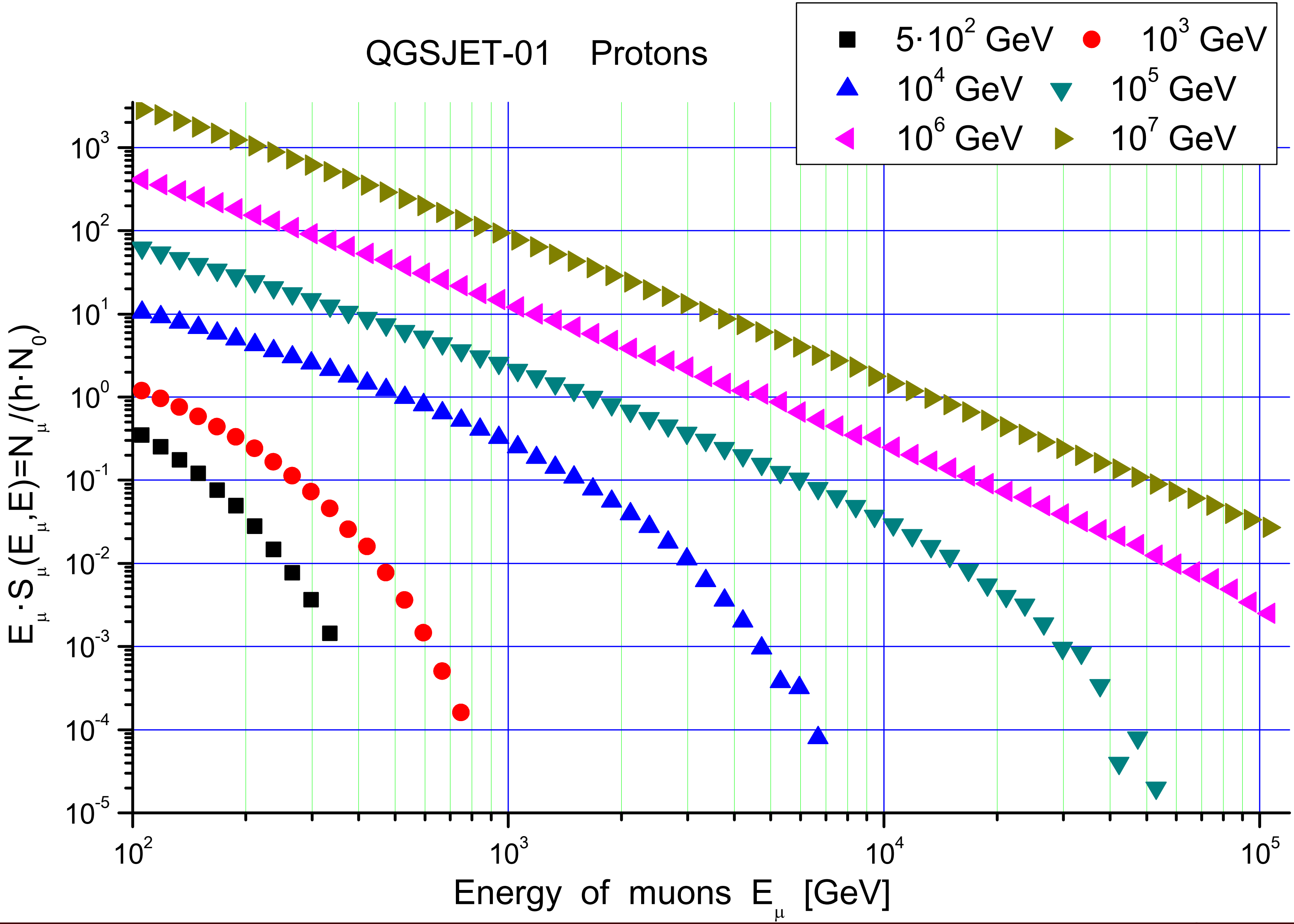
Enegry spectra of muons in showers



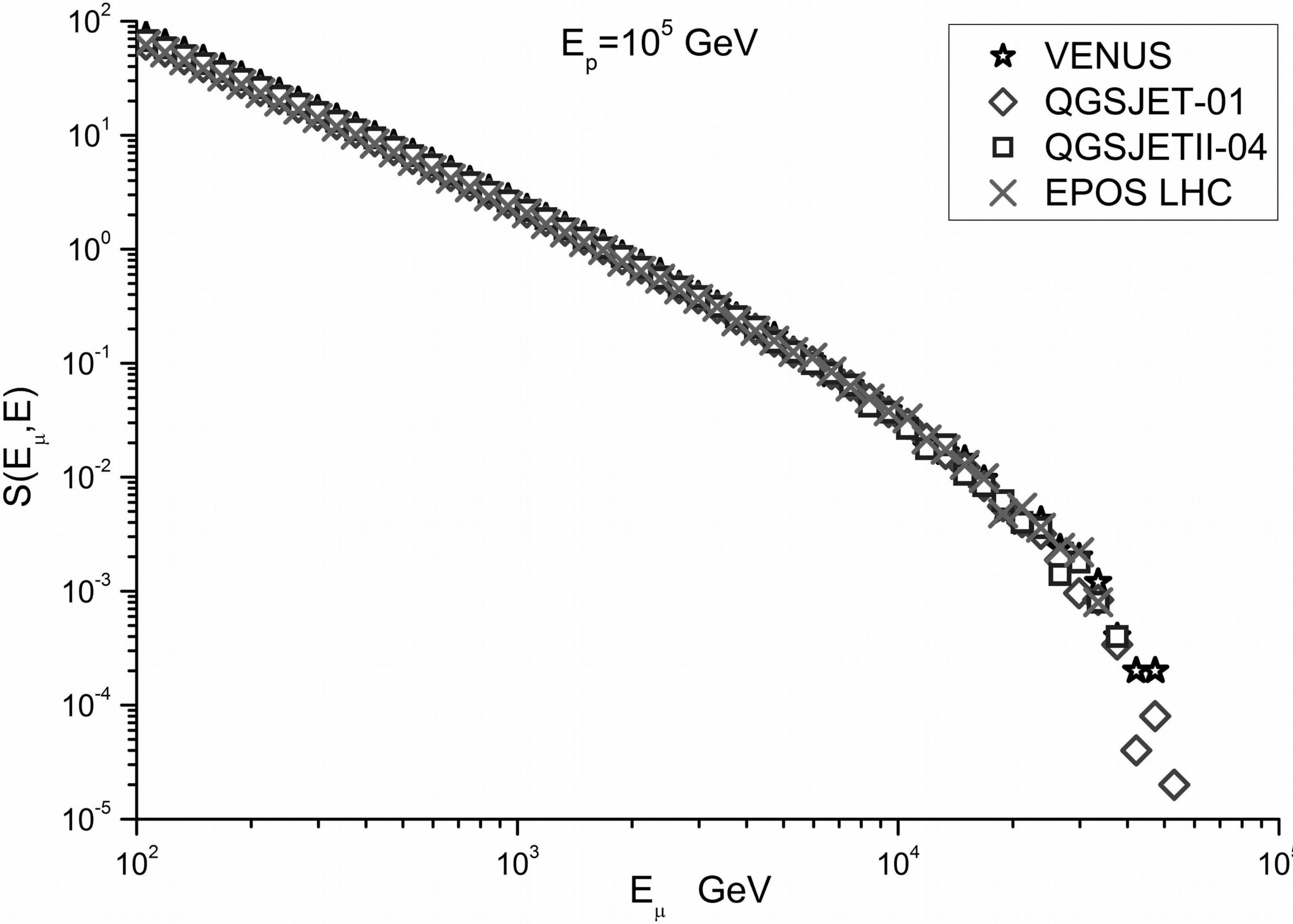
Enegry spectra of muons in showers



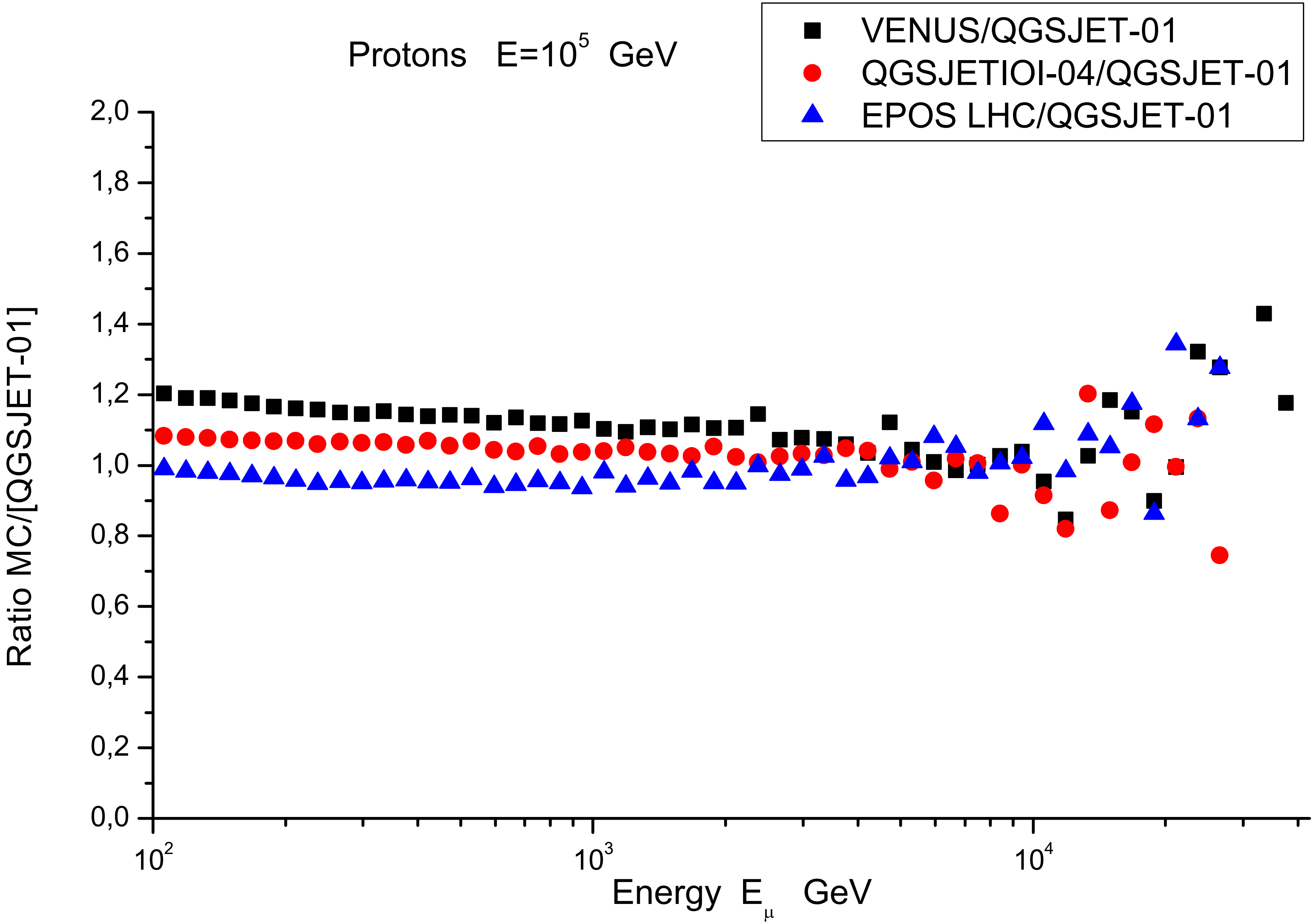
Enegry spectra of muons in showers



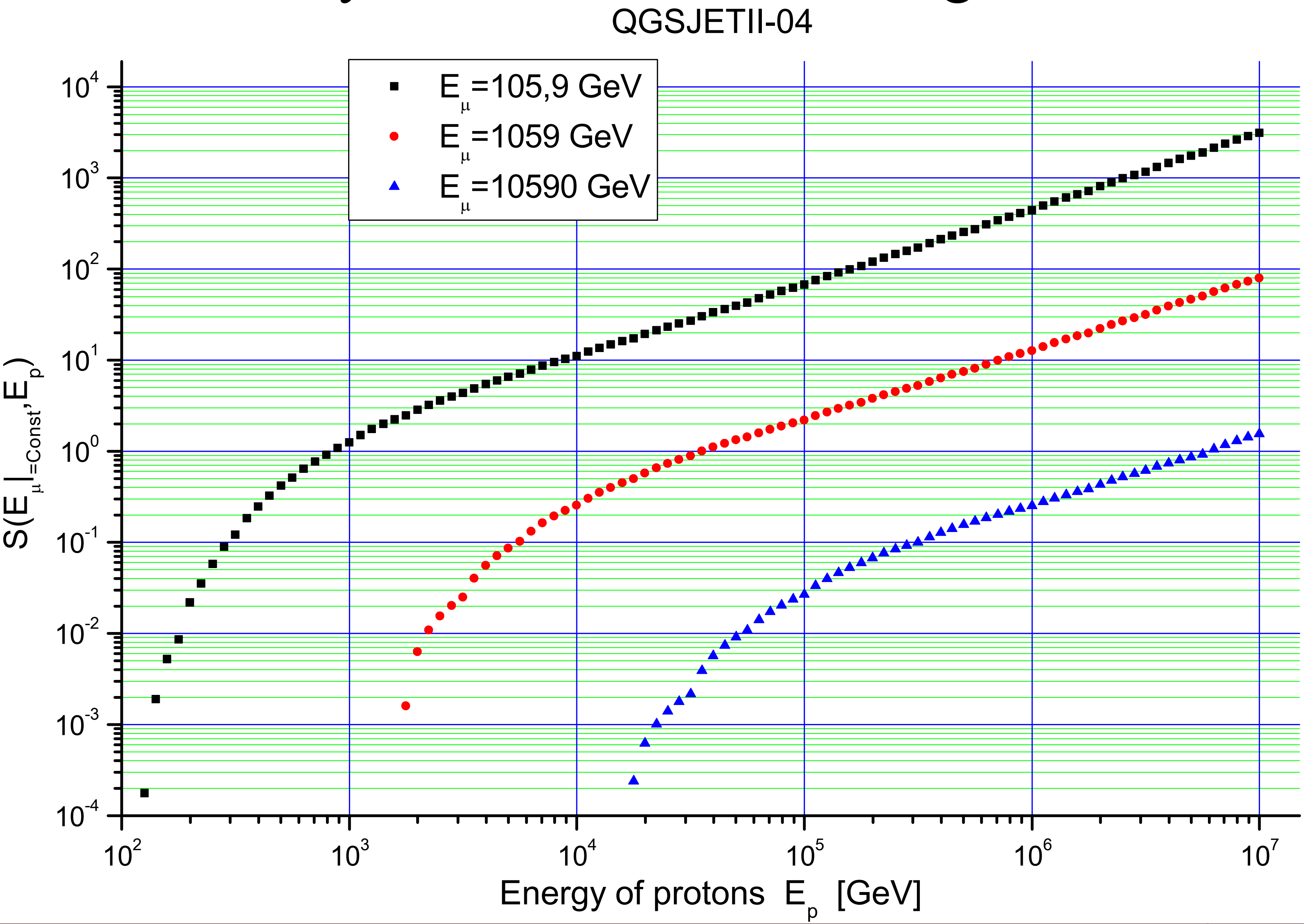
The muon energy spectra induced by the primary protons with energy 10^5 GeV



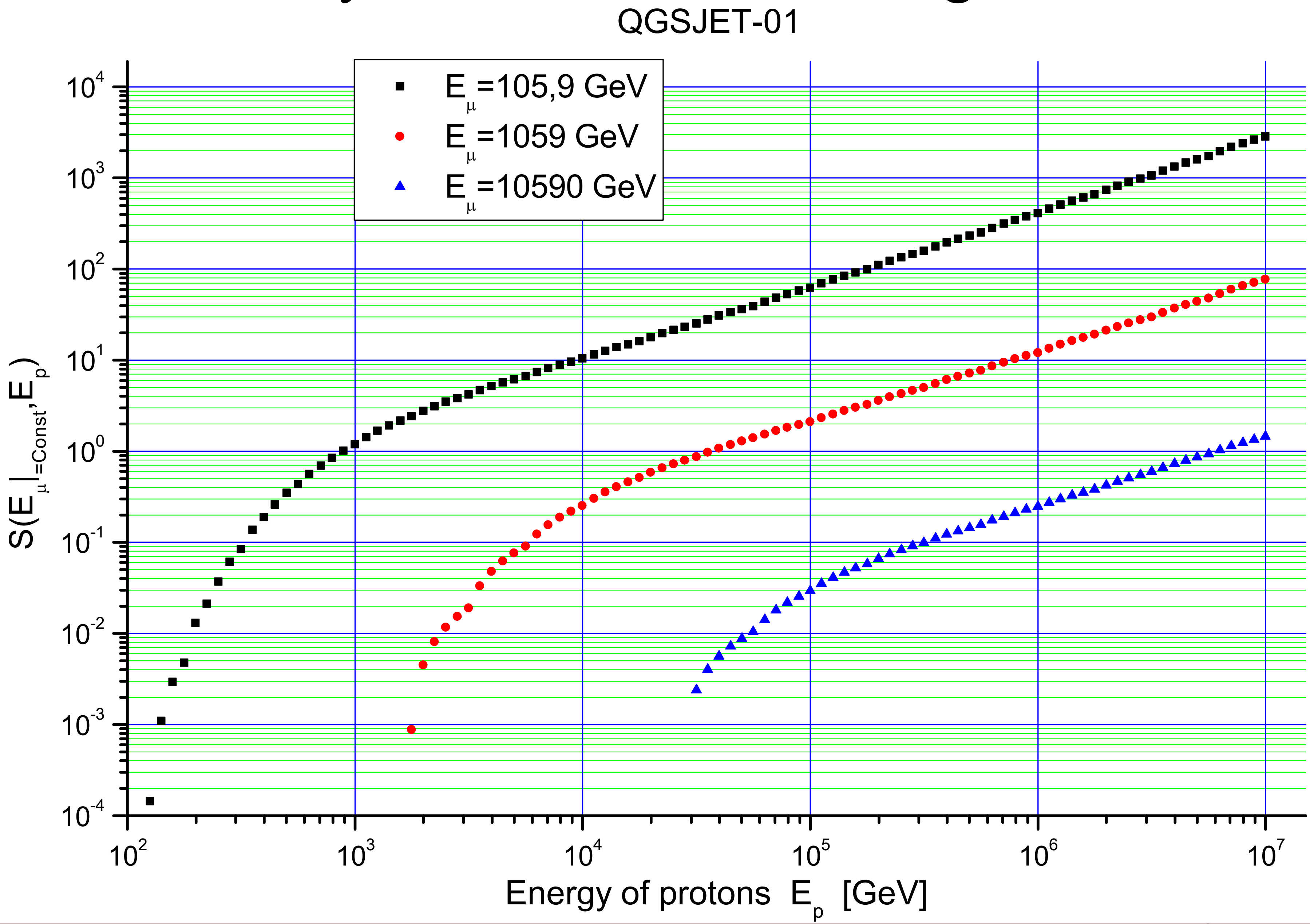
Relation between the models



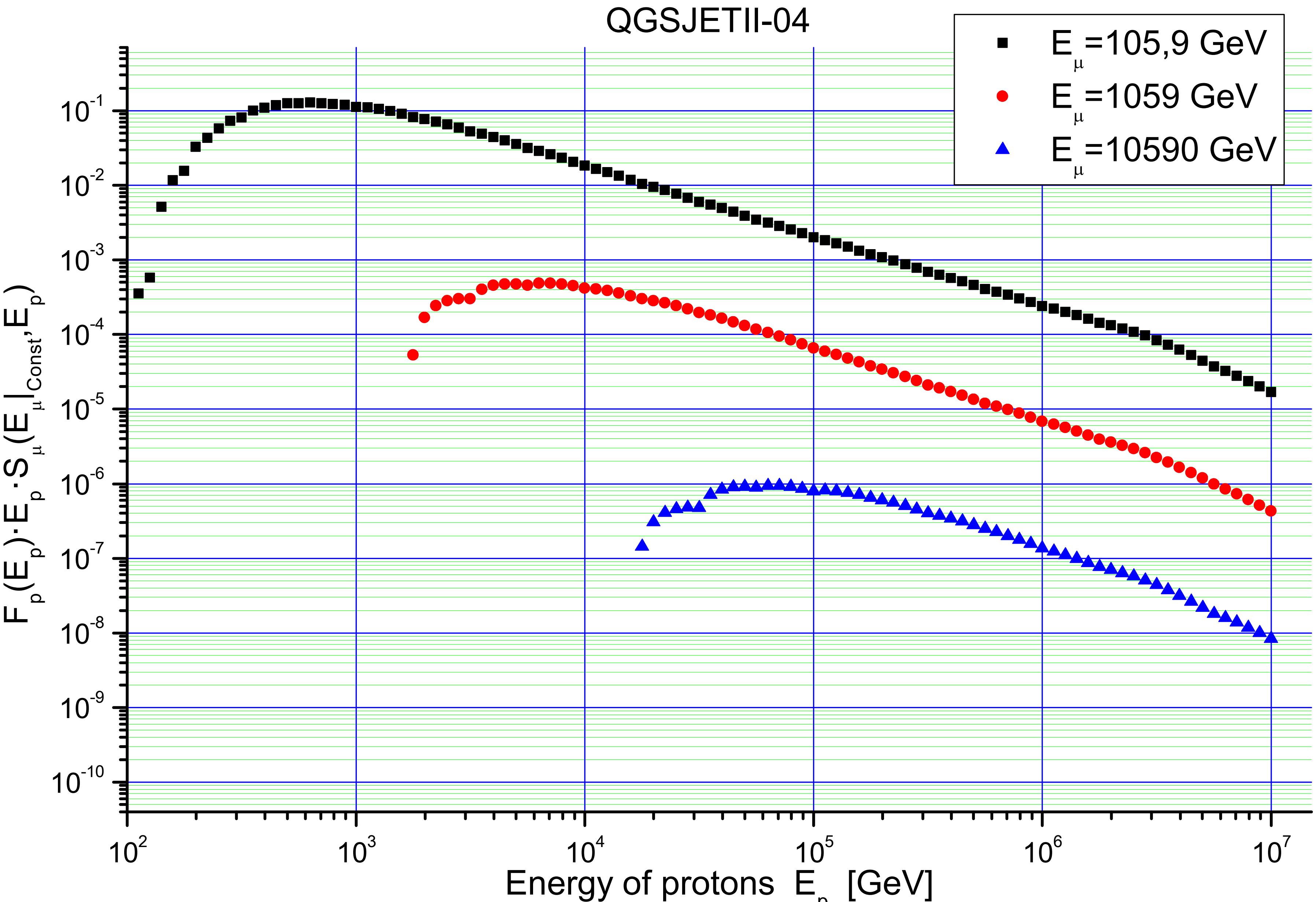
Muons density functions at fixed energies of muons



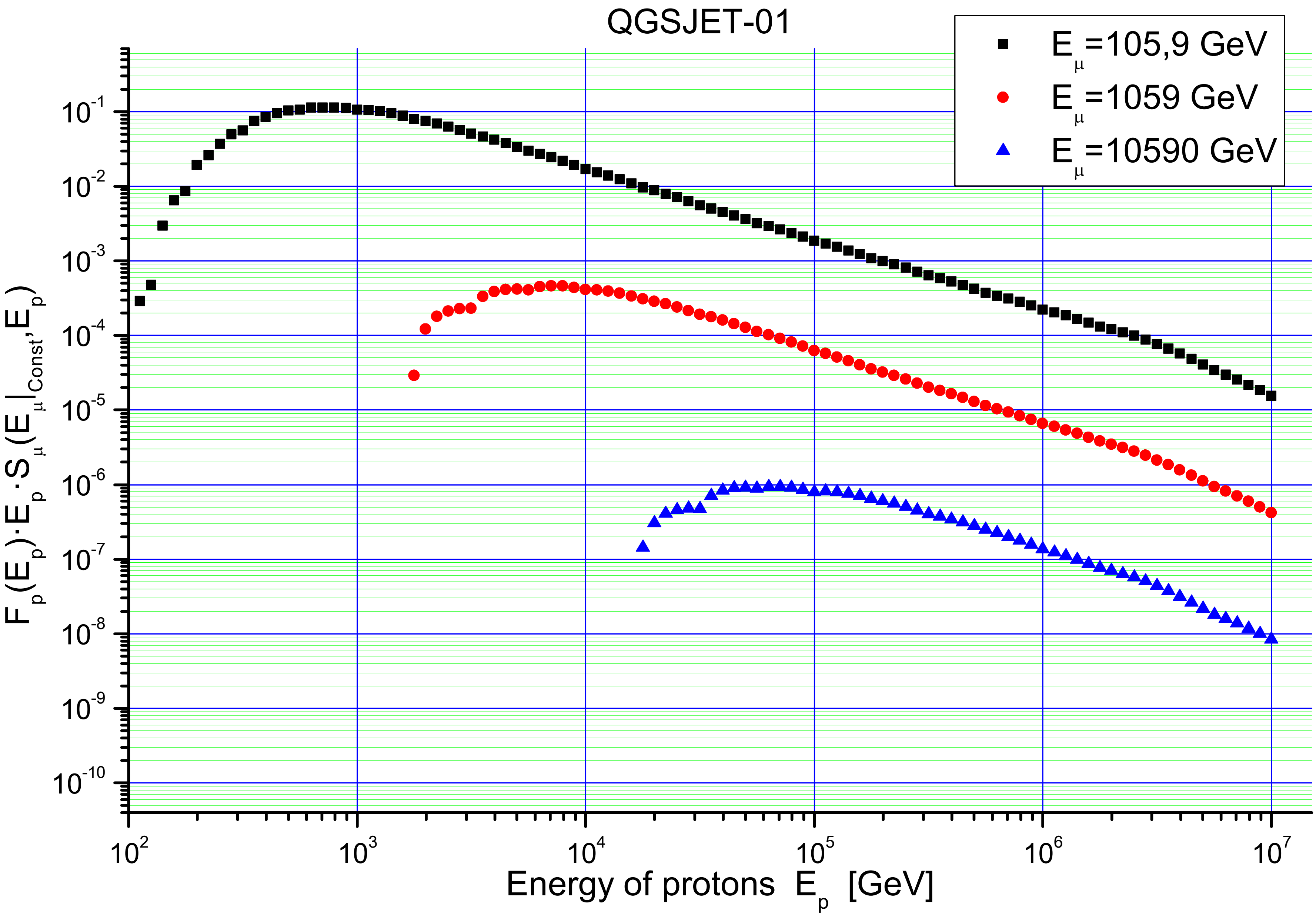
Muons density functions at fixed energies of muons



Functions of relative contribution in muons generation

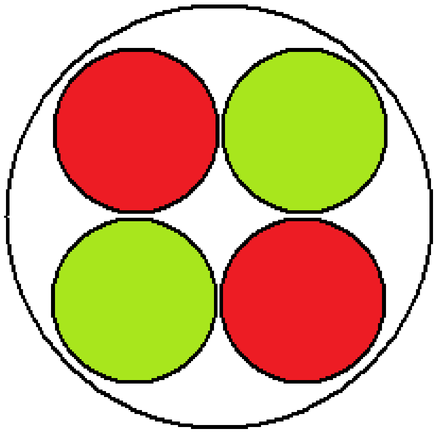


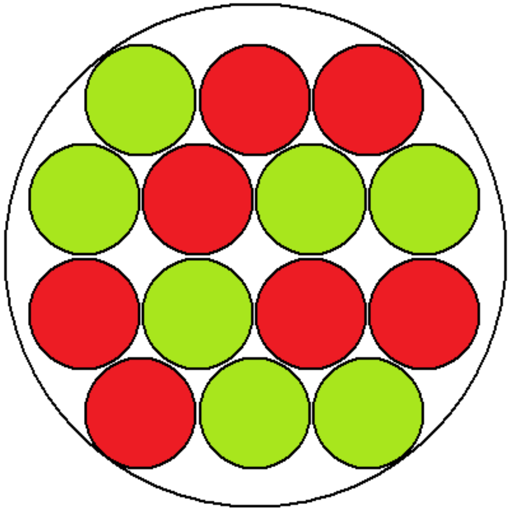
Functions of relative contribution in muons generation



Superposition conception

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

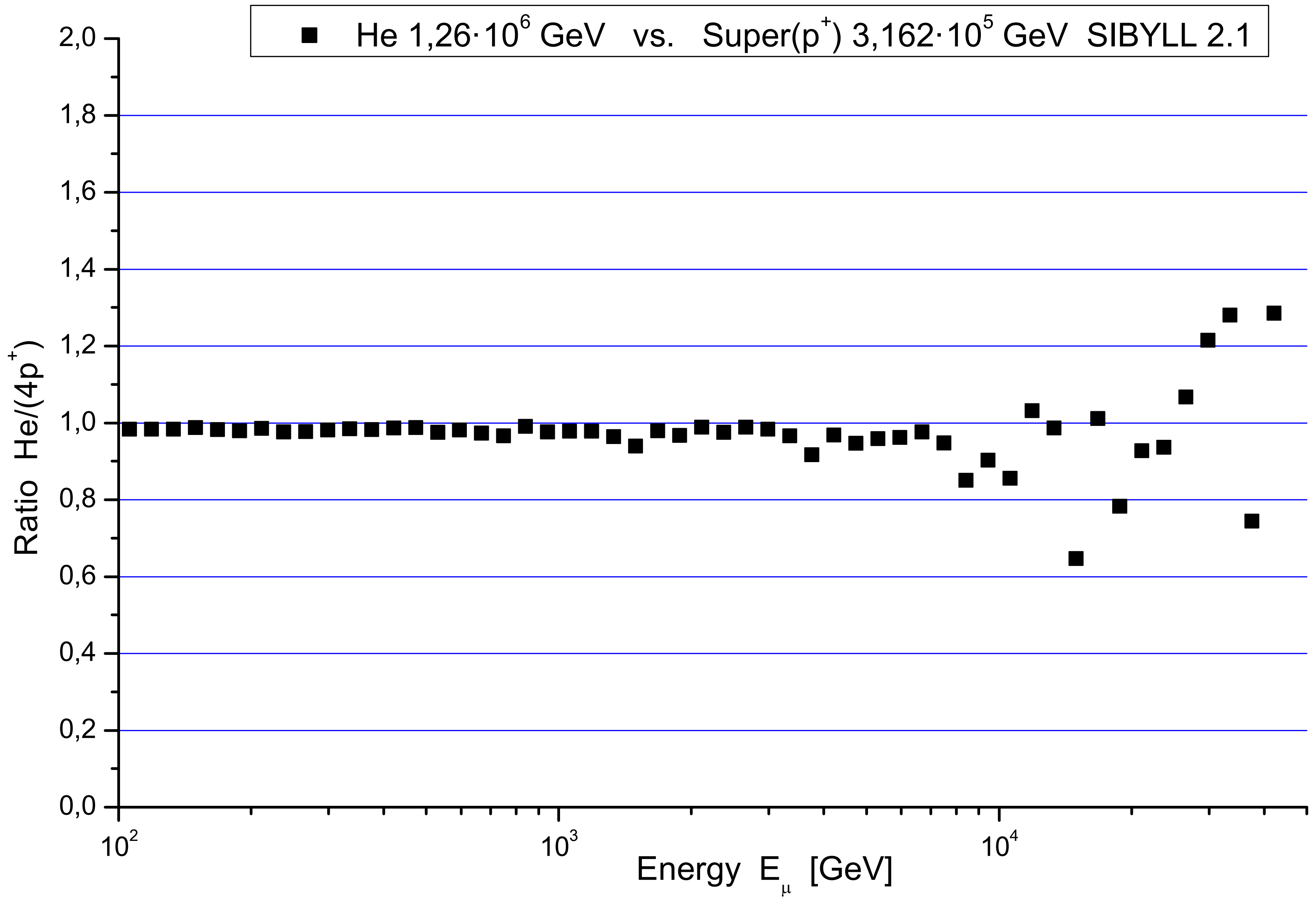




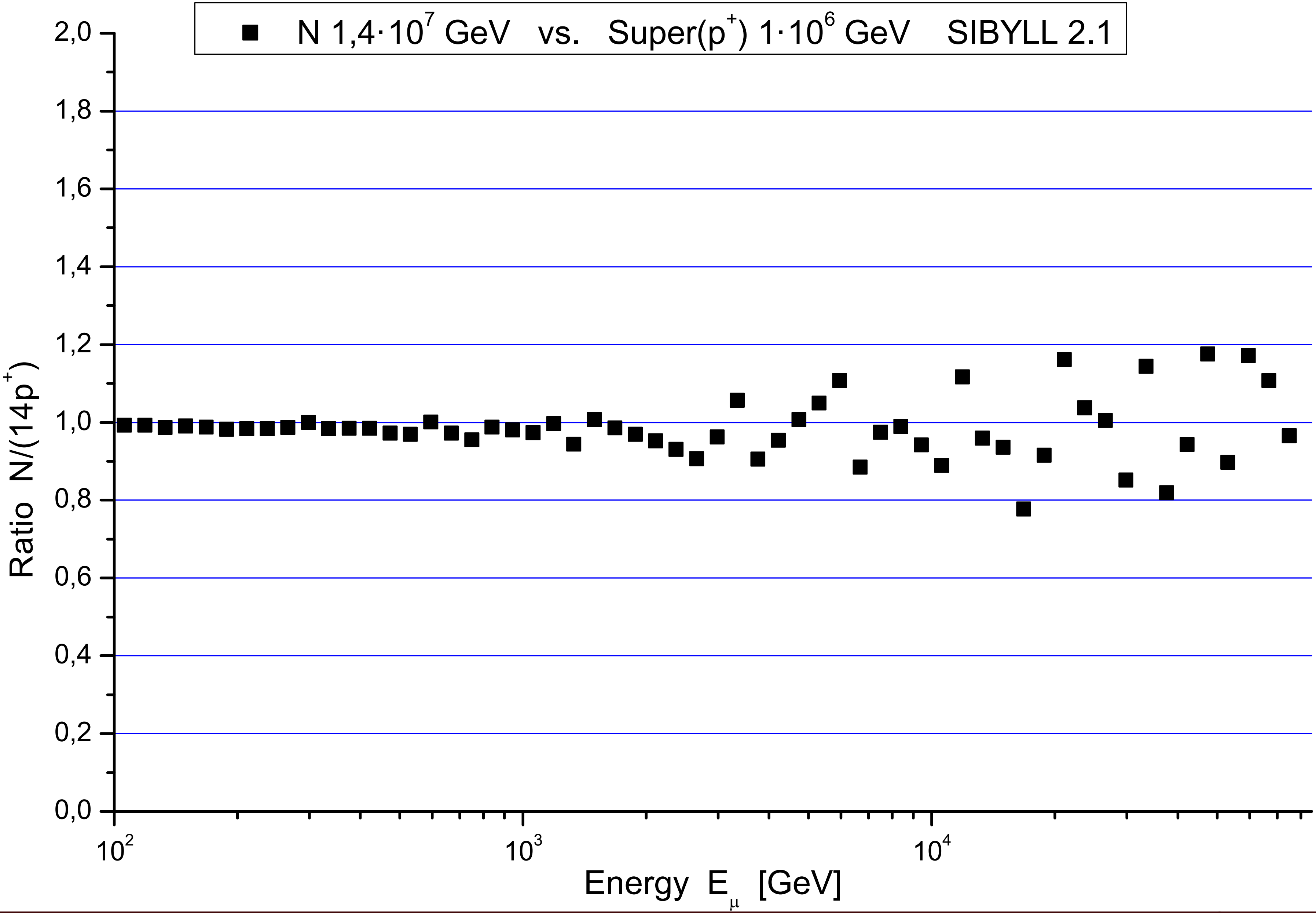
$$S_{He}(E_\mu, E_{He}) \approx 4 \cdot S_p\left(E_\mu, E_p = \frac{E_{He}}{4}\right)$$

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

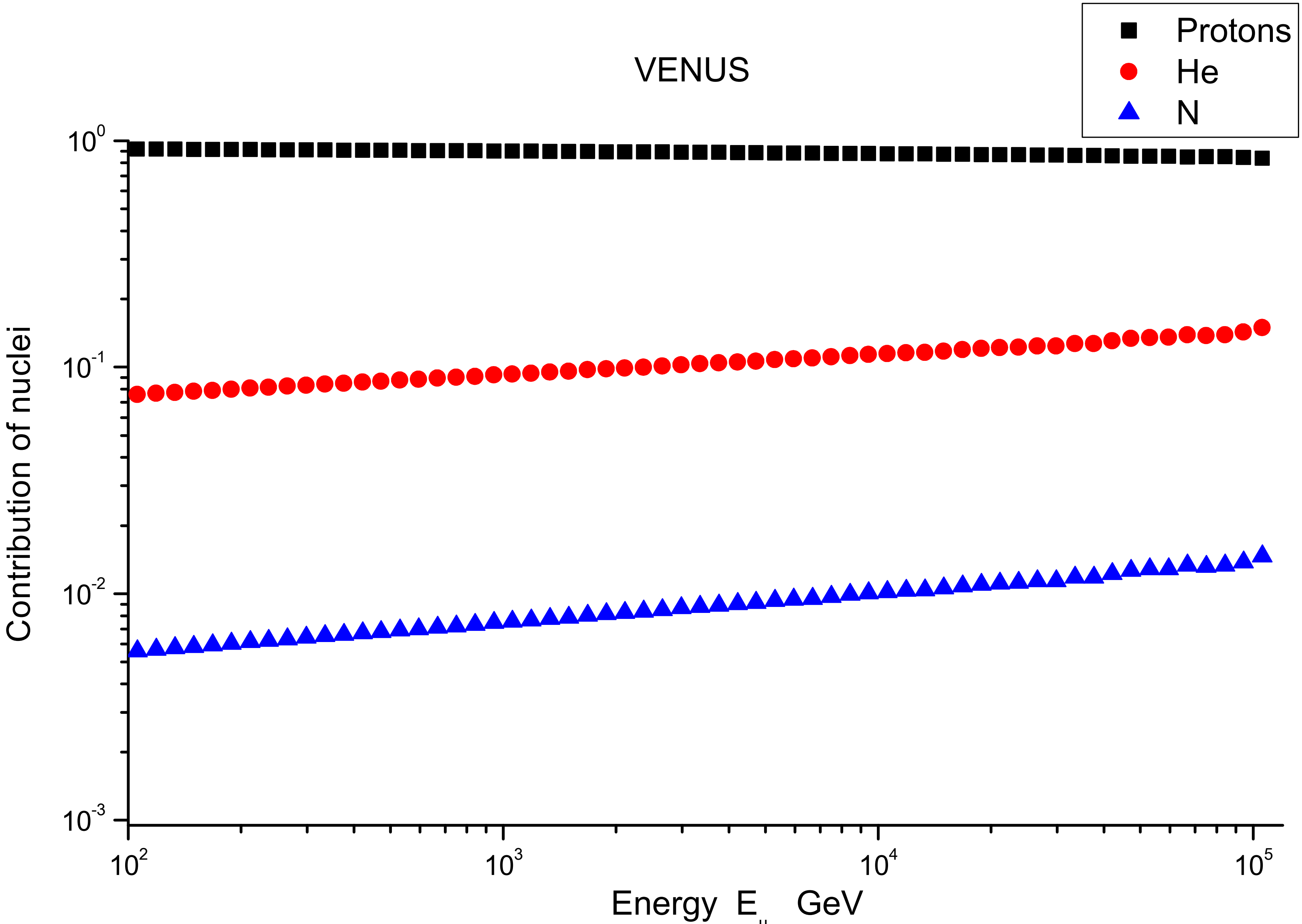
Superposition conception (result for SIBYLL)



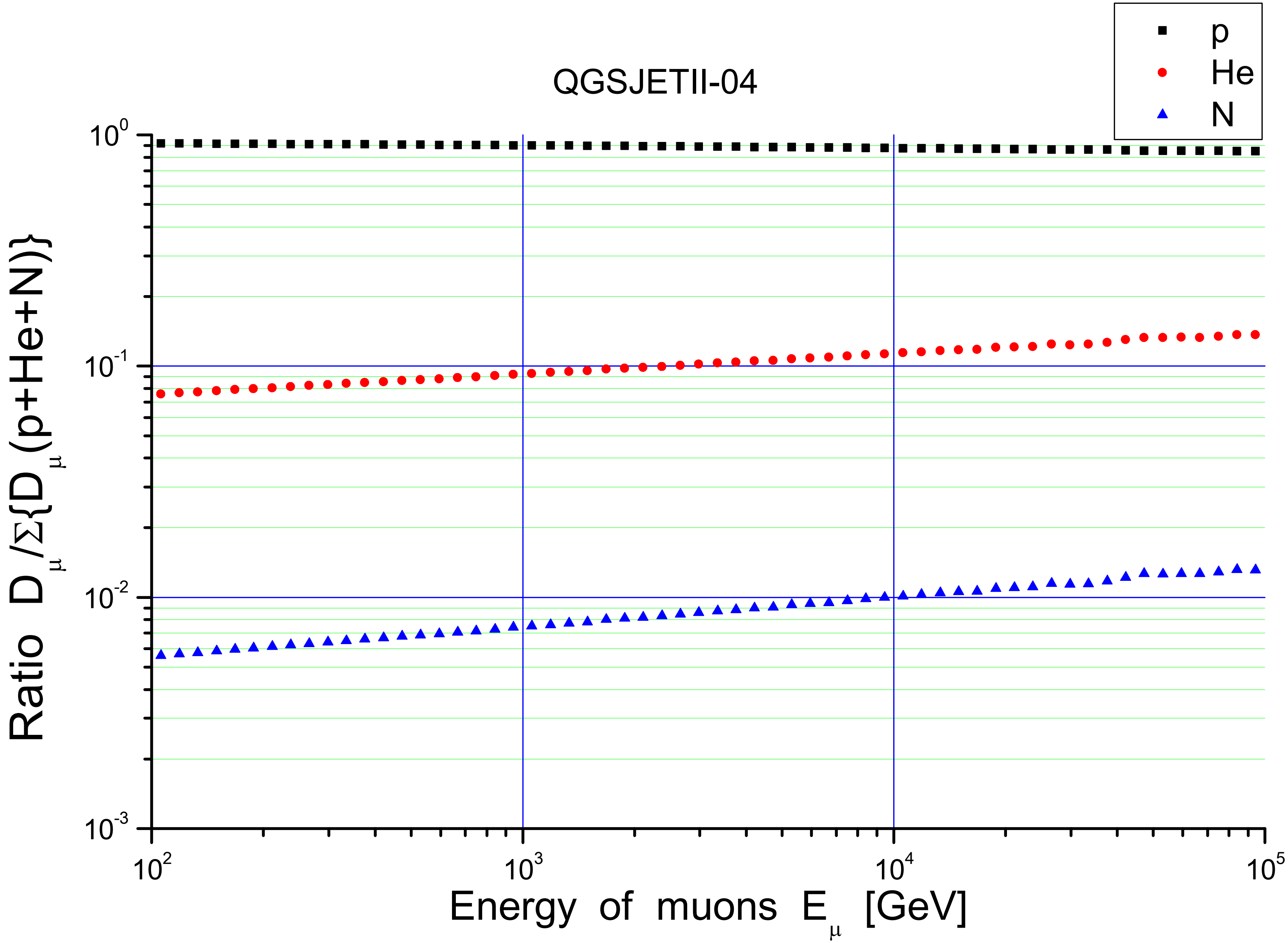
Superposition conception (result for SIBYLL)



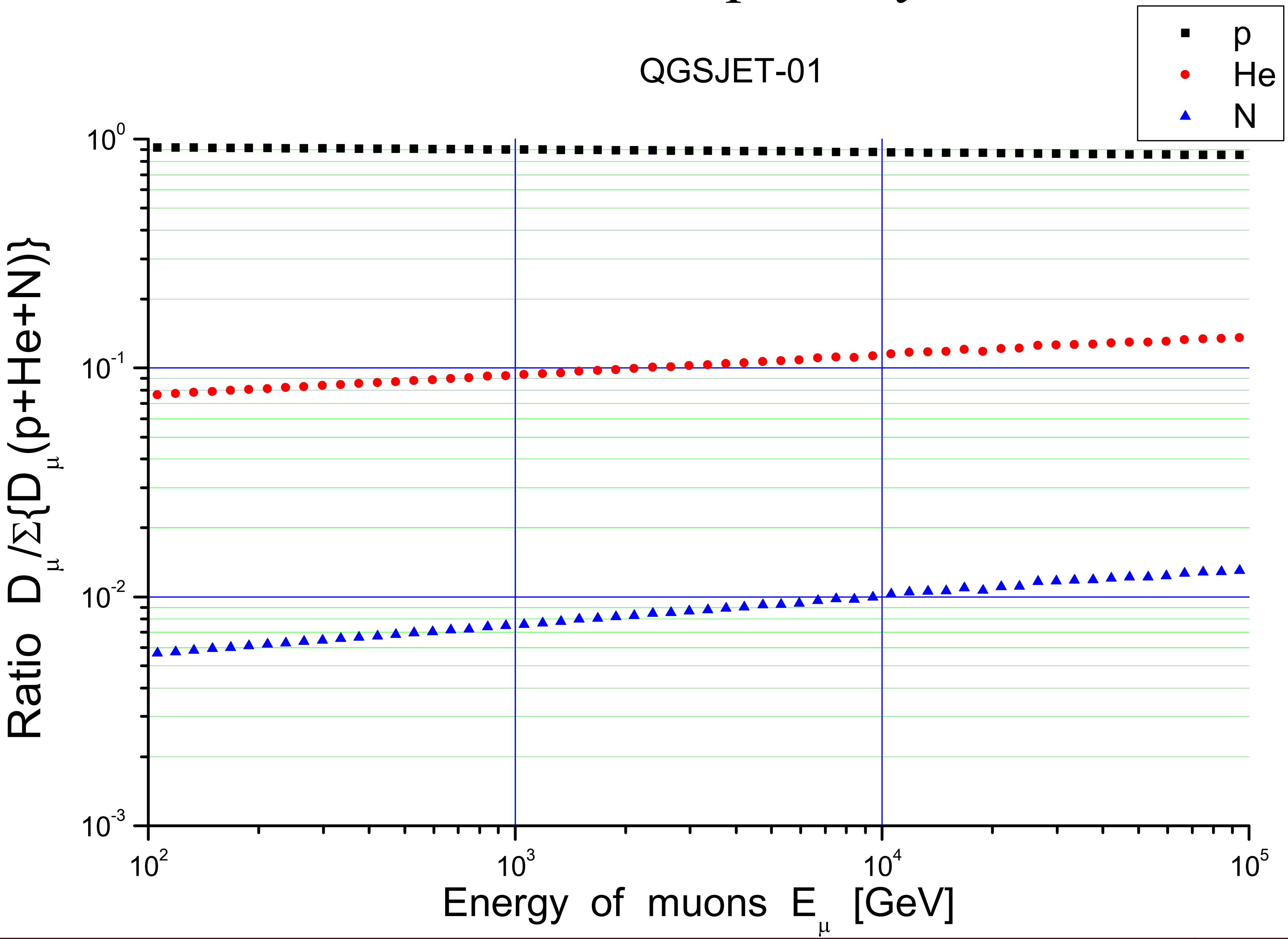
Partial contribution of primary nuclei



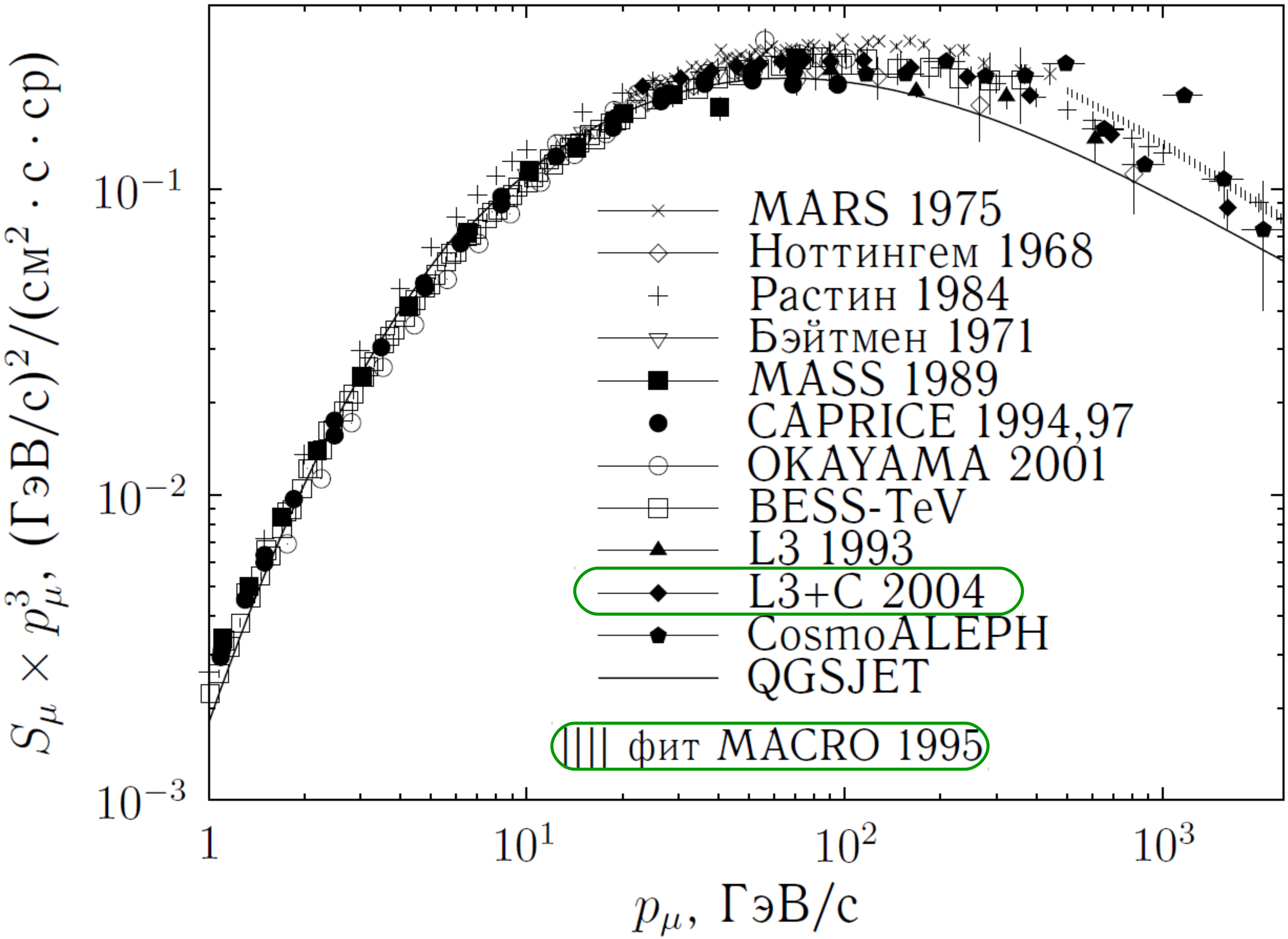
Partial contribution of primary nuclei



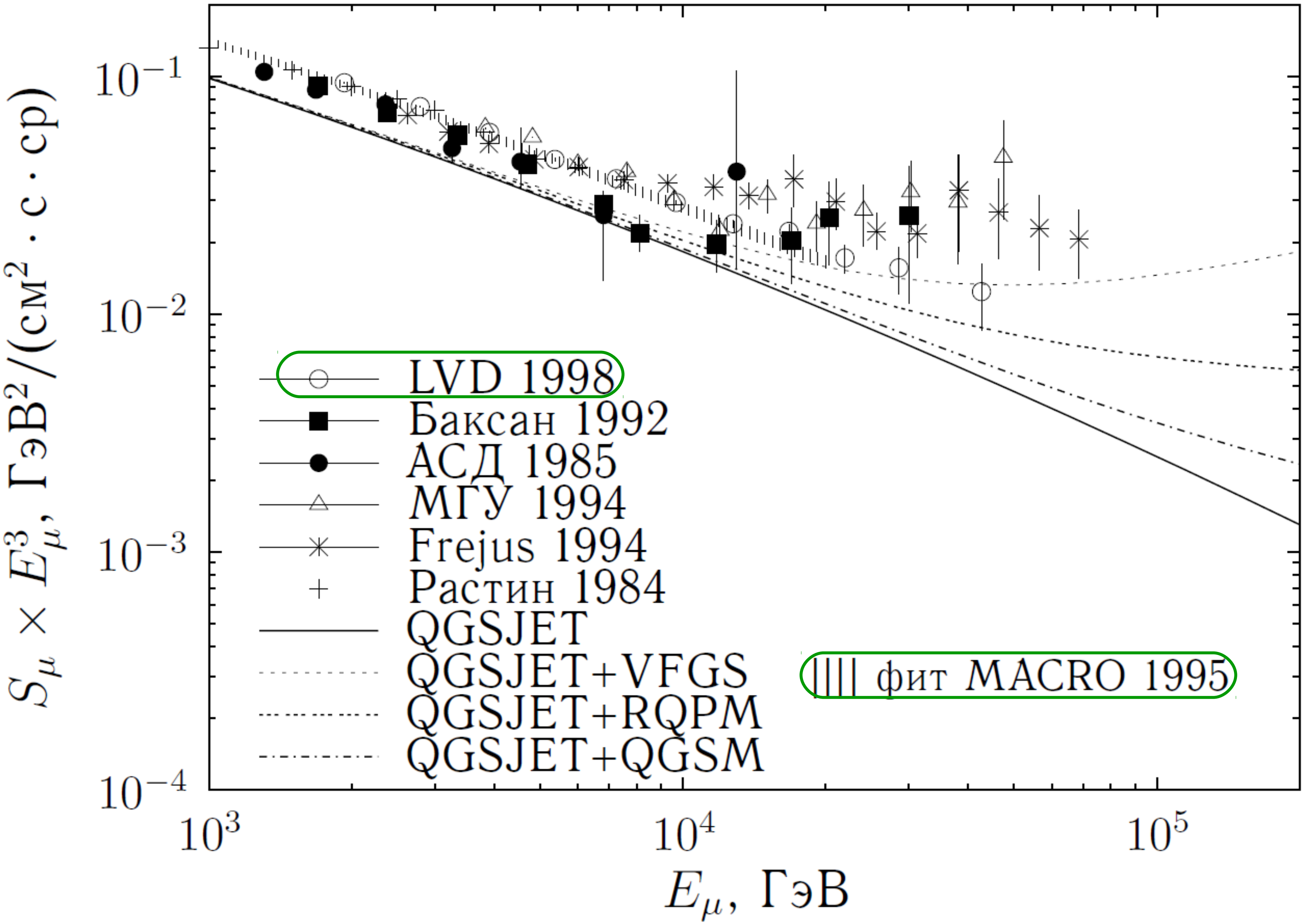
Partial contribution of primary nuclei



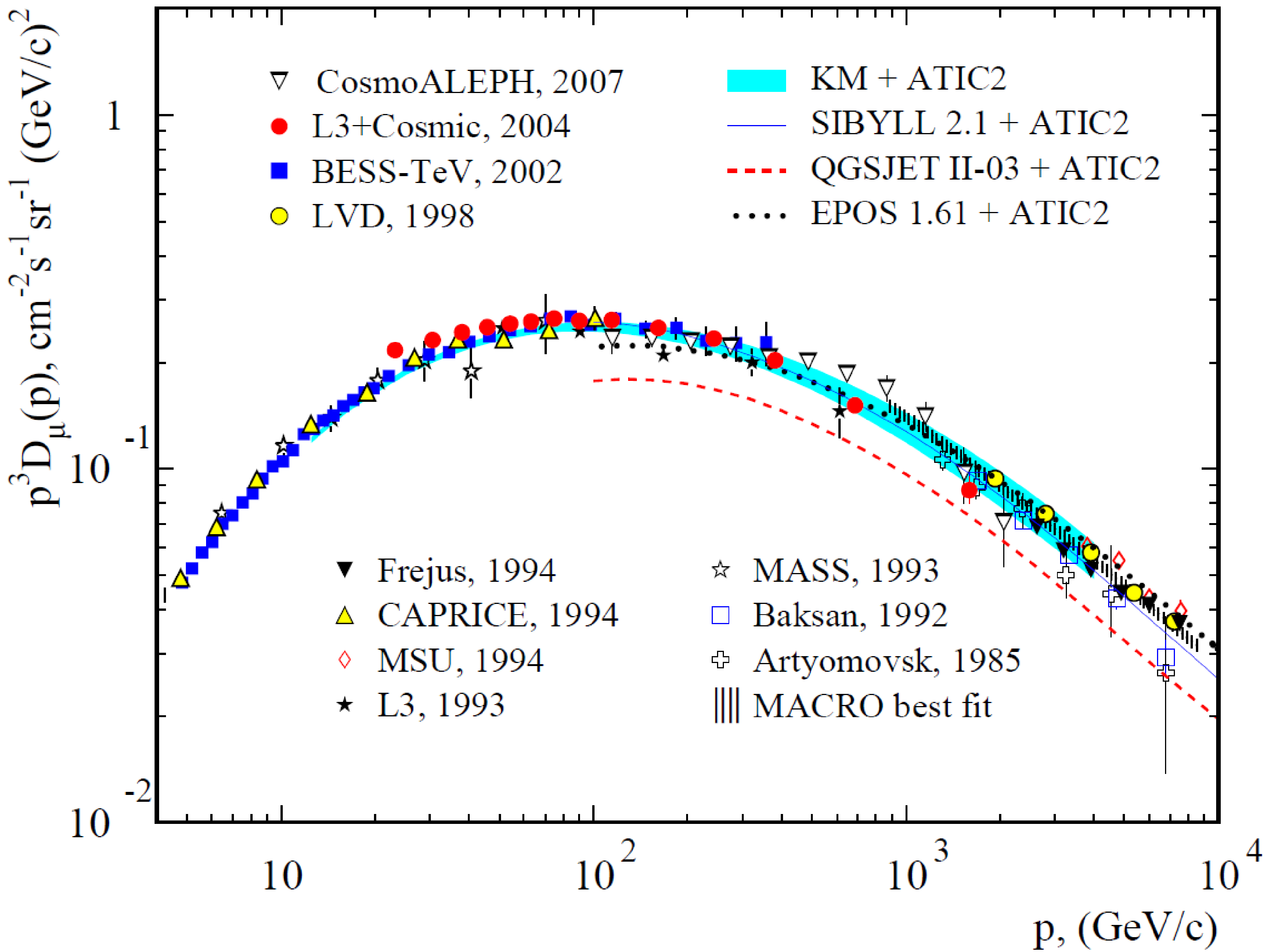
Alexey Yushkov PhD. Thesis



Alexey Yushkov PhD. Thesis



Alexander Kochanov PhD. Thesis



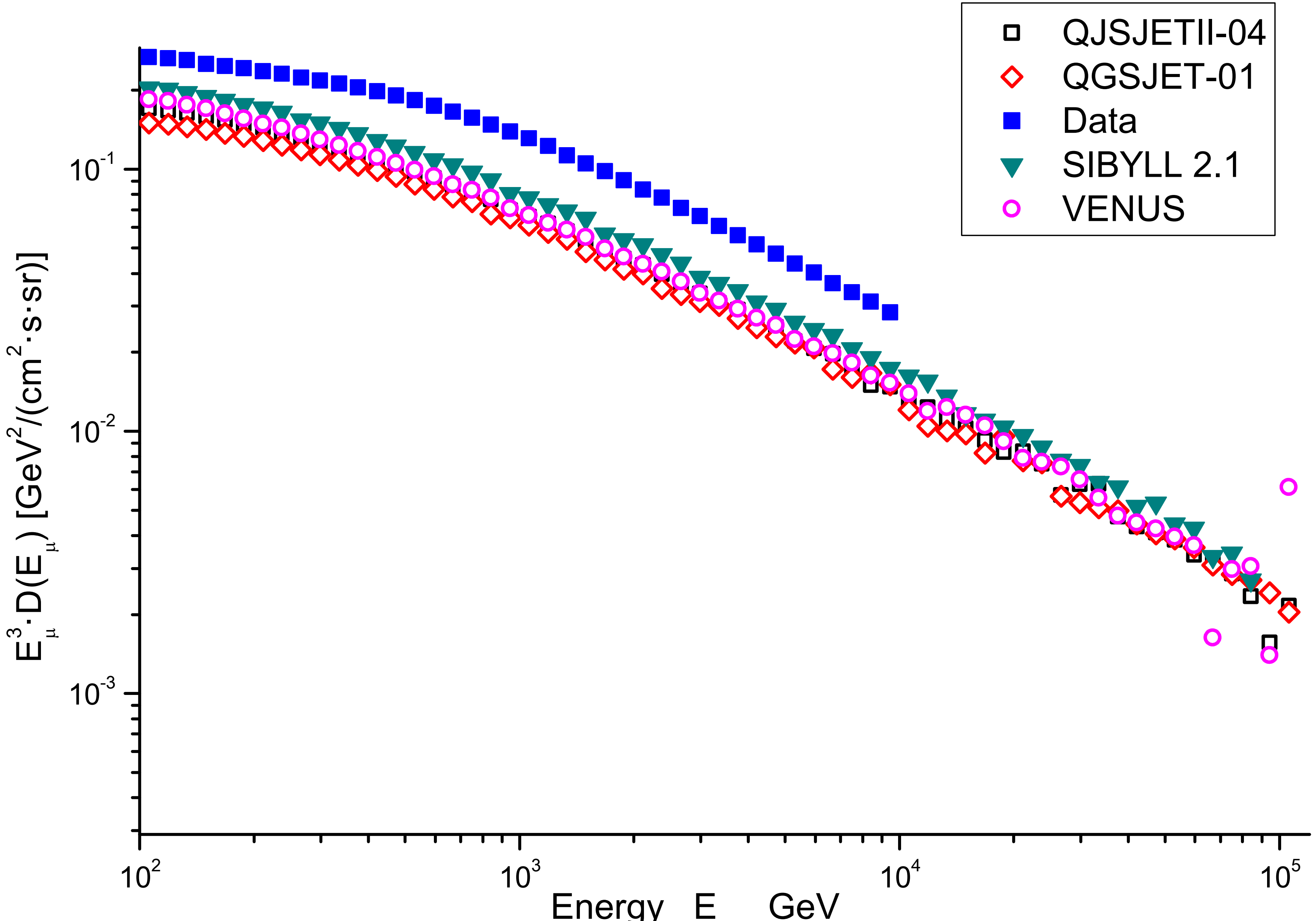
Data of the muon spectra

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

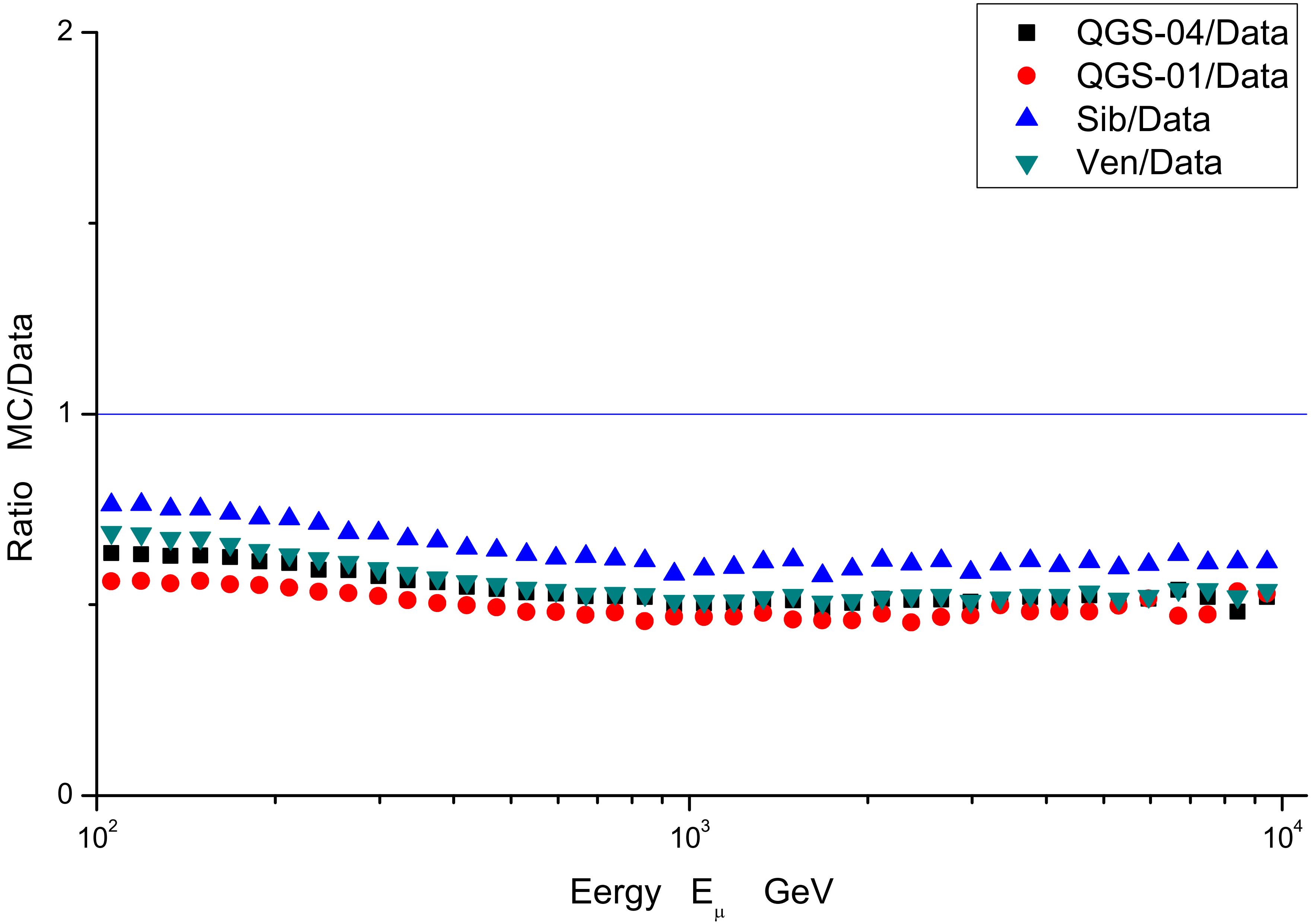
2) MACRO: M. Ambrosio et al., Phys. Rev. D **52**, 3793, (1995)

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

Result of calculations



Result of calculations



Conclusion

- Primary protons takes the most significant contribution in muon spectrum.
- The VENUS model are shifted below the data by factor ~1,42.

Previous result

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!)

Constraints of hadronic interaction models from the cosmic muon observations // EPJ Web of Conferences 99, 10003 (2015)

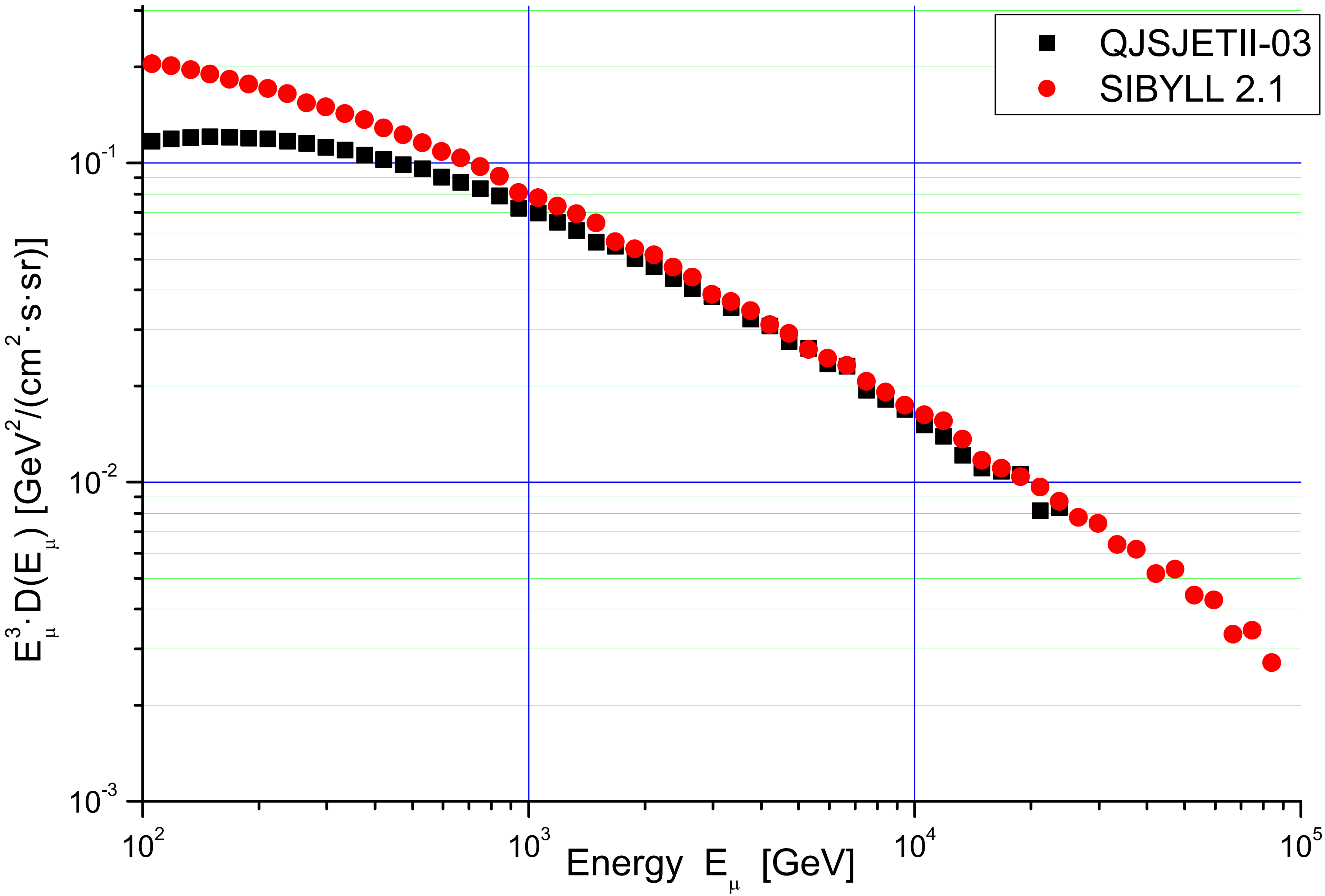
Testing the energy specta of charged secondary particles generated in hadronic interaction models via the atmospheric muon fluxes // J. Nucl. Phys., Vol. *78,* N10 (2015).

Testing of the hadronic interaction models in the most important energy range of secondary particles with help of the atmospheric muons // JETP Lett., Vol. *100,* 4 (2014).

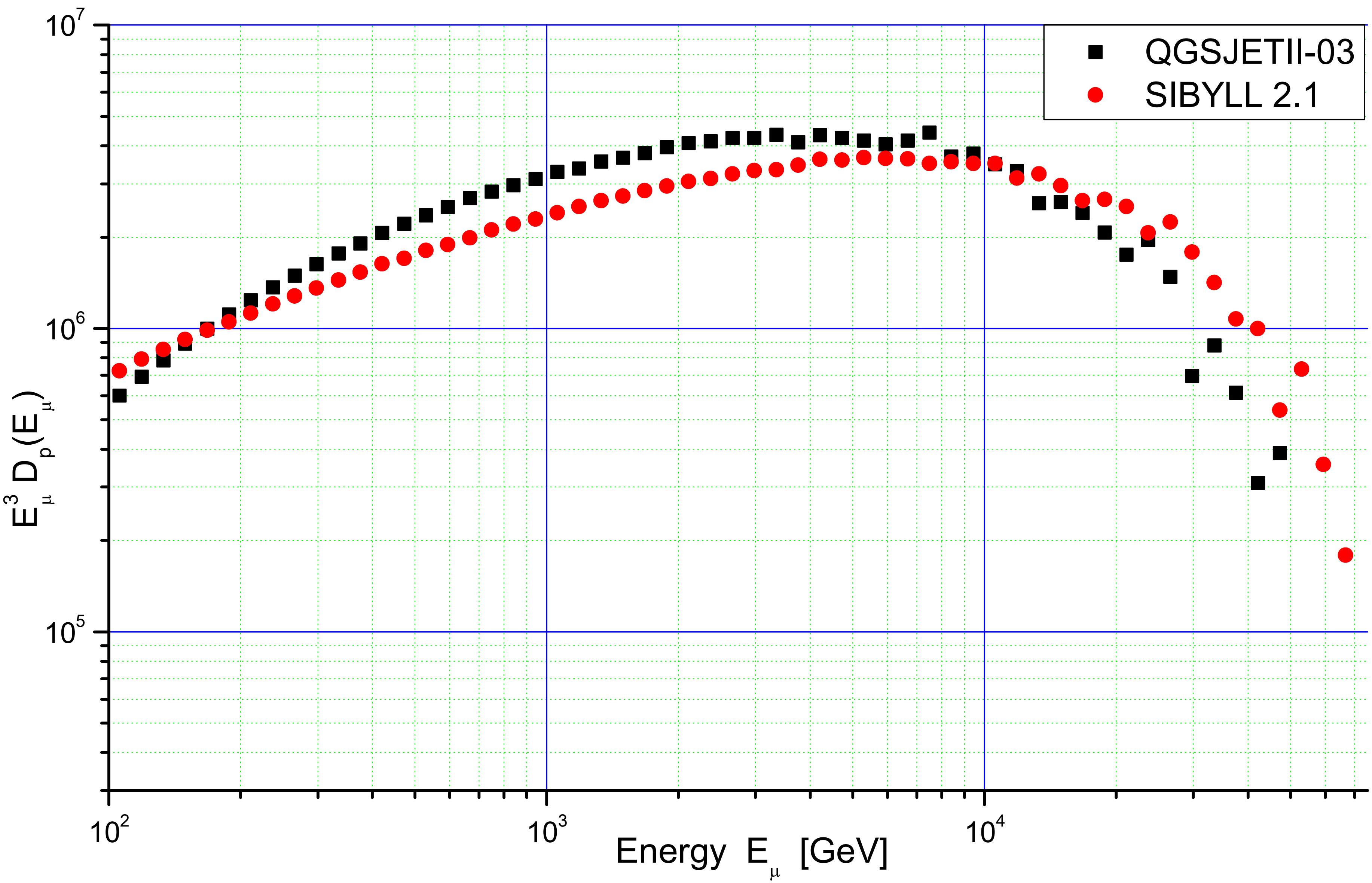
Acknowledgements

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

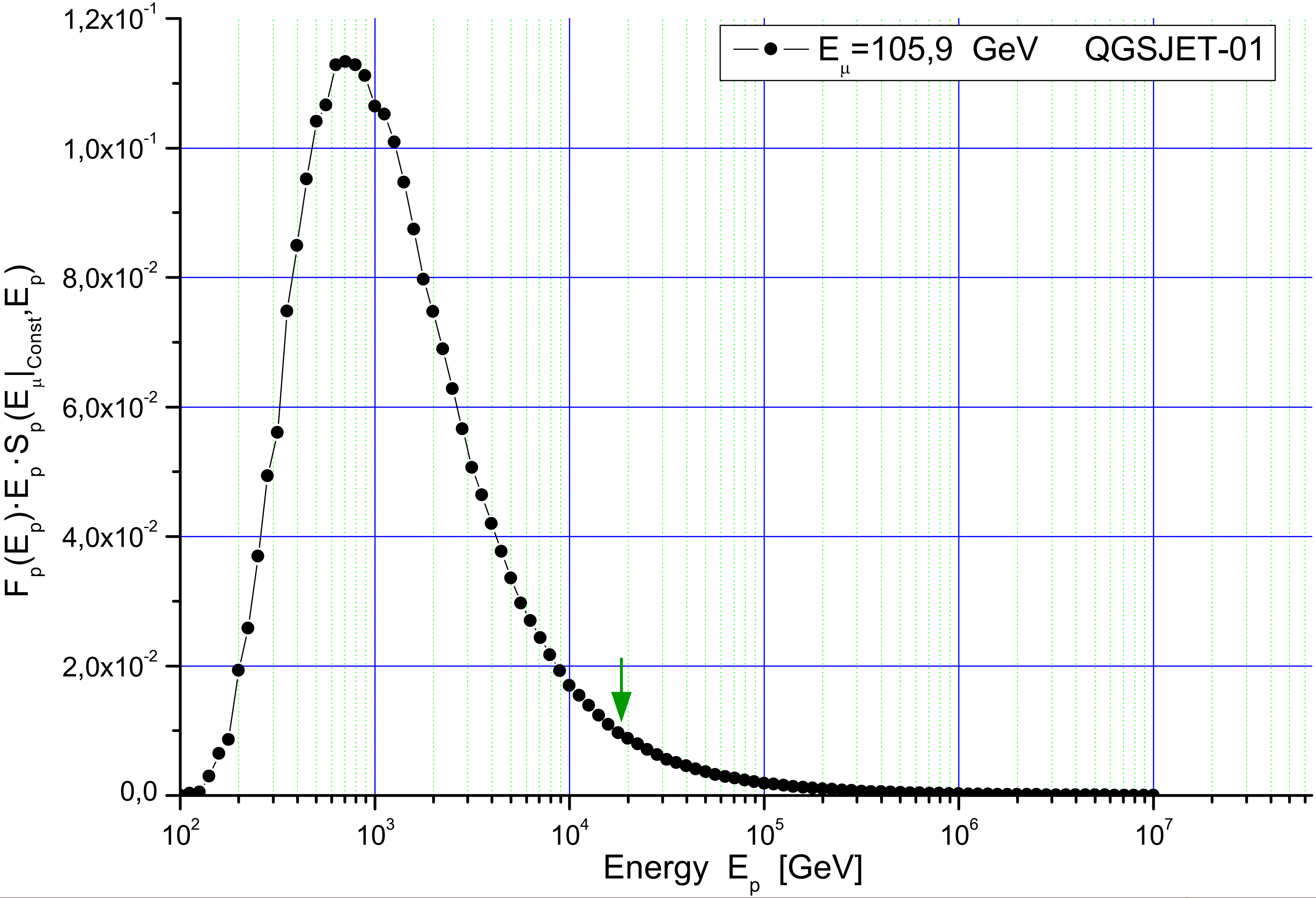
Thank you for attention!



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


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

Relative contribution in muons



Relative contribution in muons