Testing of the VENUS 4.12, DPMJET 2.55, QGSJETII-03 and SIBYLL 2.3 hadronic interaction models via help of the atmospheric vertical muons spectra

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MC models used in Cosmic Rays and HEP

- DPMJET (Dual Parton Model with Jets)
- QGSJET (Quark-Gluon Strig Model with Jets)
- VENUS (Very Energetic NUclear Scattering)
- NEXUS (NEXt generation of Unified Scattering approach)
- EPOS (Energy conserving quantum mechanical multi-scattering approach, based on Partons, Off-shell remnants and Splitting parton ladders)
- SIBYLL (as Sibyl in Greek mythology)
- PYTHIA (as Delphic oracle in Greek mythology)

Improvement

1) Real parameters of the atmosphere now are properly corresponding to the Yakutsk EAS station.

2) Original approximation of primary cosmic rays spectra, based on modern experimental data.

3) Additional MC calculation for protons with statistics of 10^6 and 10^7 events for the high energy tails of distributions.

Motivation

- Our main goal consists in testing models of hadronic interactions!
- We try to compare a predictions of various models for the atmospheric high energy muon fluxes!

Method

- The package CORSIKA has ben used to estimate the muon energy spectra $D(E_\mu)$ for models VENUS 4.12, QGSJETII-03, DPMJET 2.55 and SIBYLL 2.3
- Energy interval for muon spectra
- $E_\mu=10^2$ — 10^5 GeV
- Energy interval for primary spectra (p, He)
- $E=10^2$ — 10^7 GeV;
- Statistics N_0 from 10^6 to 10^3
- Aditional statistics 10^6 in energy interval $(0,01\text{-}1)\cdot E_0$

Method

Differential energy spectra for prinary cosmic rays [Data: AMS-02, PAMELA, CREAM, ARGO, TA, KASCADE, KASCADE-Grande]

Muons density distribution functions [CORSIKA 7.4]

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

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

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

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

Method of simulations

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

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

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

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

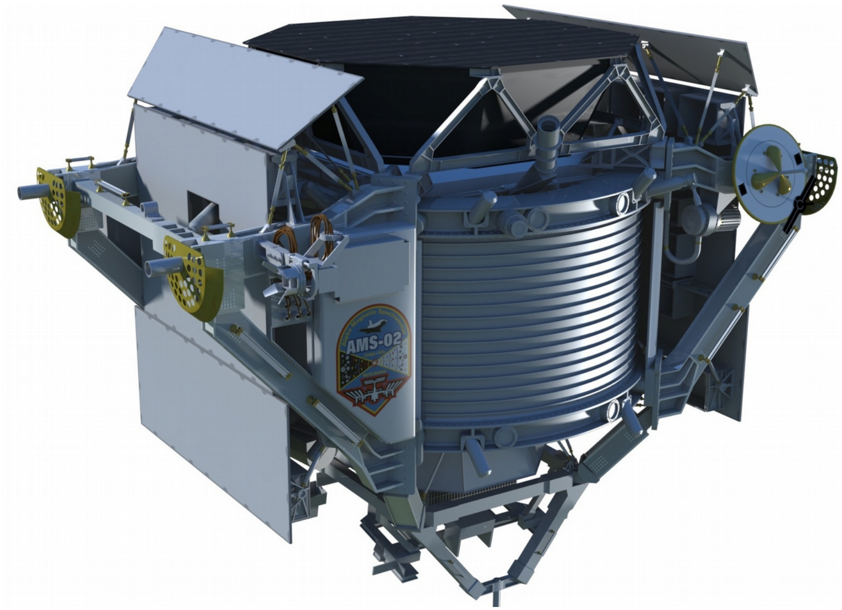
- $D(E_\mu)$ — resulting differential energy spectrum of atmospheric muons [1/(GeV·m^2·s·sr)].

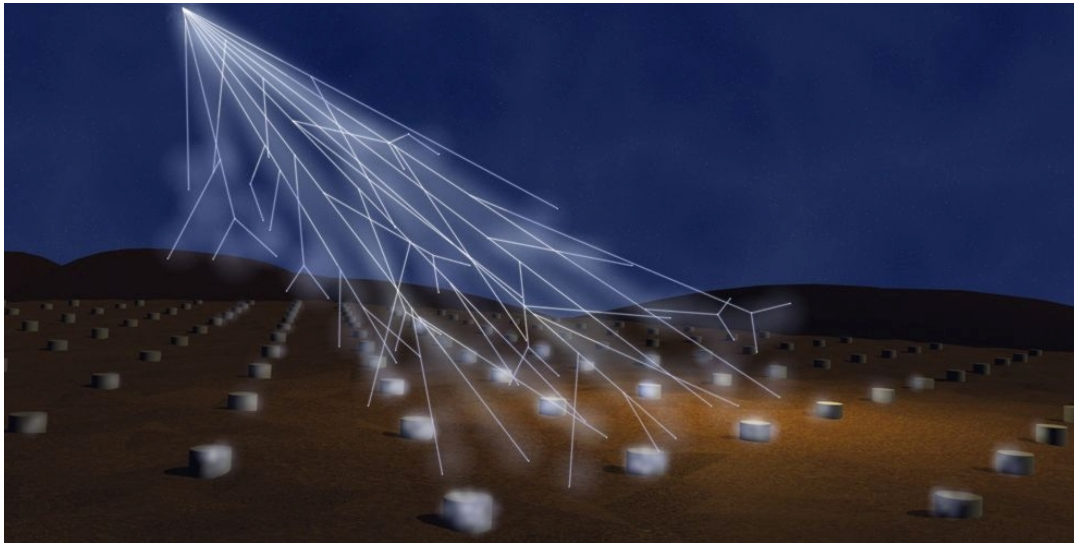
Ingredients for calculations (I)

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

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

Primary cosmic rays data





- AMS-02
- ATIC-2
- CREAM
- PAMELA

- ARGO-YBJ
- ARGO&WCFT02
- KASCADE
- KASCADE-Grande
- PAO
- Telescope Array
- TUNKA

More detail at www.iscra2017.mephi.ru
«Energy spectrum of nucleons of the primary cosmic radiation at energies 0.1–10 000 TeV»

New original approximation (p)

Equation for flux of the primary protons.

$$\frac{d\Phi_p}{dE} = \begin{cases} 0{,}4544 \cdot \left(\frac{E}{45}\right)^{-2{,}849} \cdot \left[1 + \left(\frac{E}{336}\right)^{5{,}5417}\right]^{0{,}024} & E \in \left[10^2 \div 1.8 \cdot 10^4\right] \text{GeV} \\ 8728 \cdot E^{-2{,}7} \cdot \left(\frac{E}{10^4}\right)^{0{,}06} & E \in \left[1.8 \cdot 10^4 \div 10^6\right] \text{GeV} \\ 8728 \cdot E^{-2{,}7} \cdot \left(\frac{E}{10^4}\right)^{0{,}06} \cdot Exp\left[-\frac{E - 10^6}{6 \cdot 10^6}\right] & E \in \left[10^6 \div 10^7\right] \text{GeV} \end{cases}$$

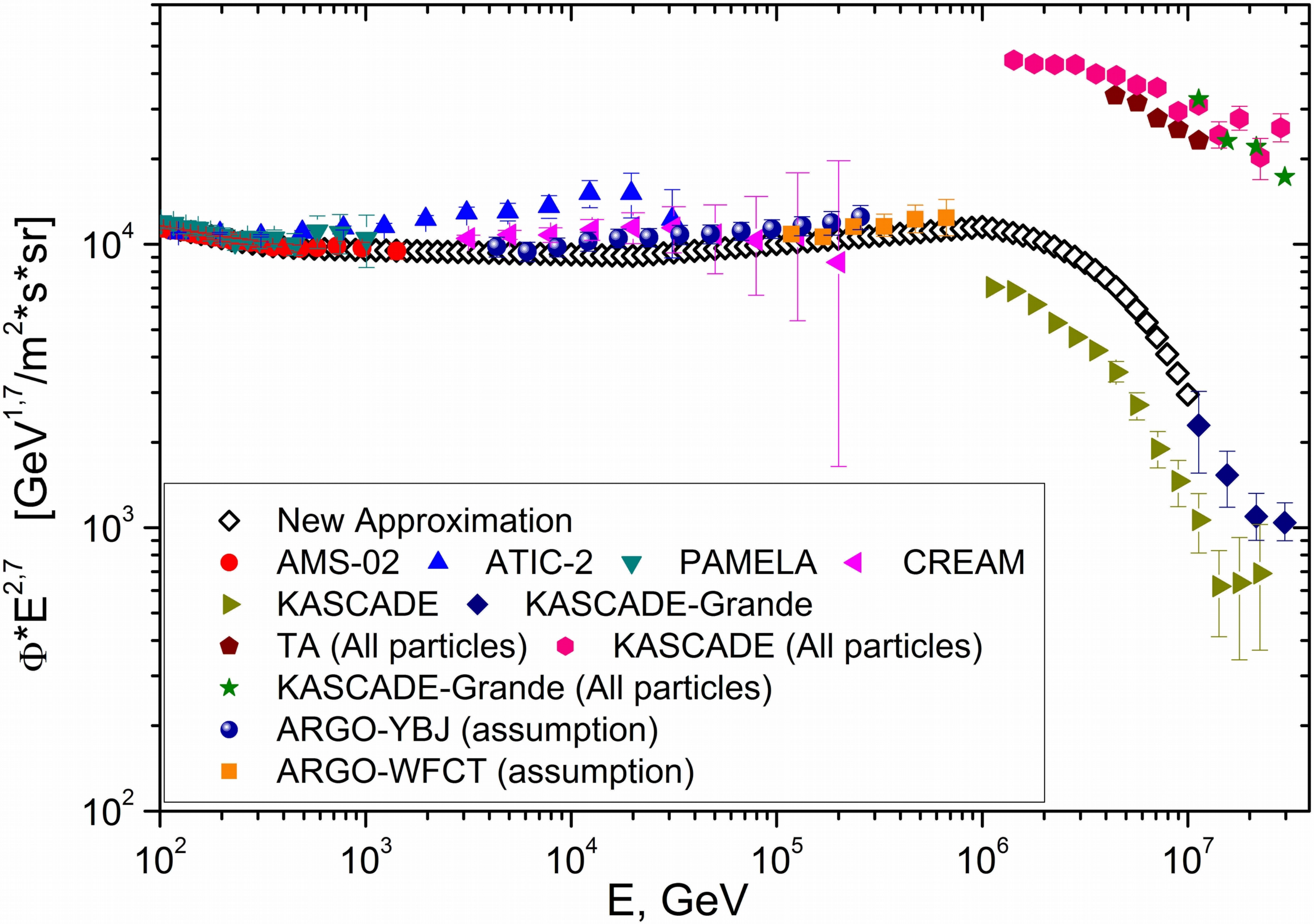
New original approximation (He)

Equation for flux of nucleons of the primary helium nuclei.

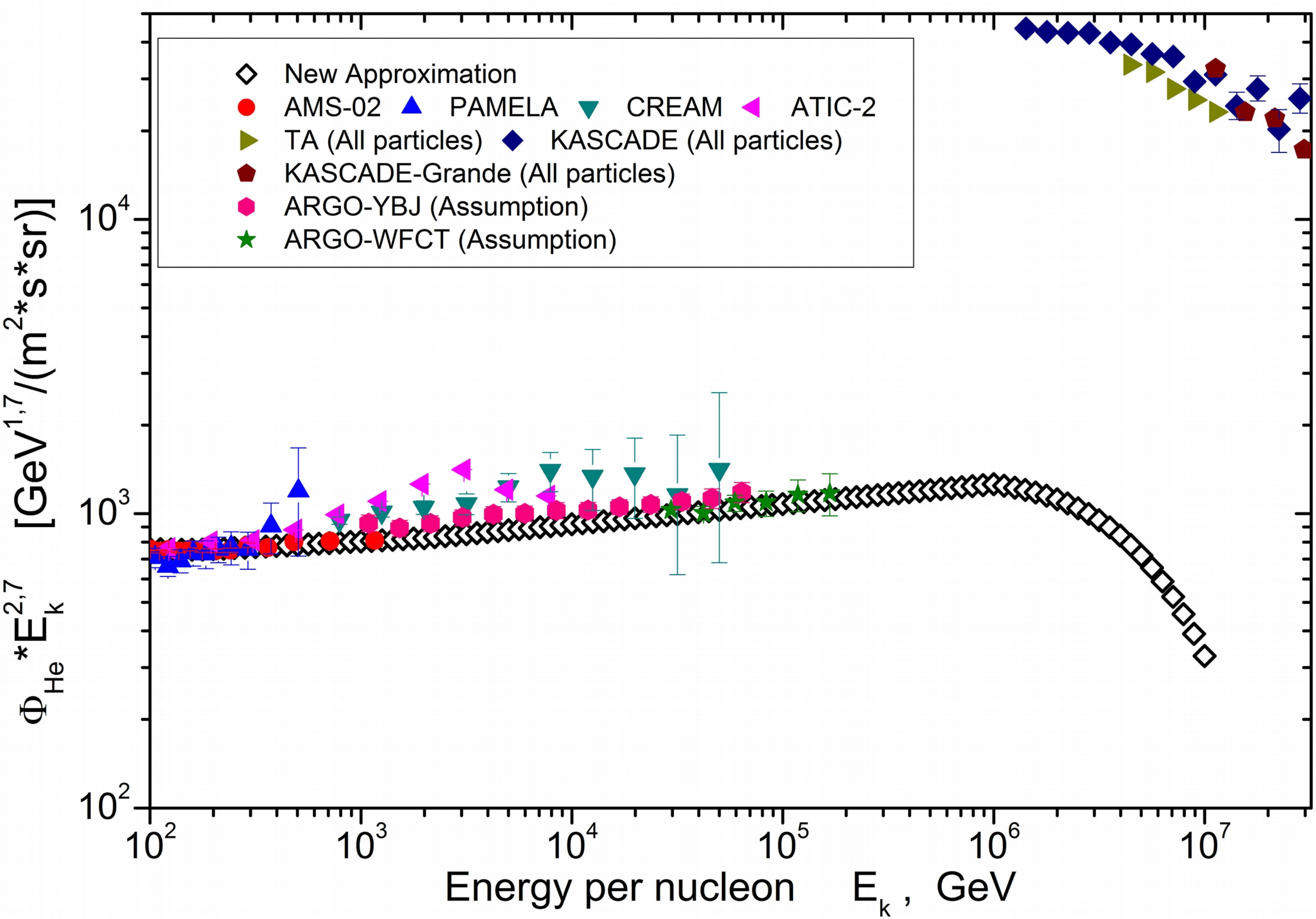
E — energy ner nucleon.

$$\frac{d\Phi_{He}}{dE}=\begin{cases} 0{,}1896\cdot\left(\frac{2\cdot E}{45}\right)^{-2{,}78}\cdot\left[1+\left(\frac{2\cdot E}{245}\right)^{4{,}4074}\right]^{0{,}027} & E\in\left[10^2\div1.8\cdot10^4\right]\text{GeV}\\ 921\cdot E^{-2{,}7}\cdot\left(\frac{E}{10^4}\right)^{0{,}068} & E\in\left[1.8\cdot10^4\div10^6\right]\text{GeV}\\ 921\cdot E^{-2{,}7}\cdot\left(\frac{E}{10^4}\right)^{0{,}068}\cdot Exp\left[-\frac{E-10^6}{6\cdot10^6}\right] & E\in\left[10^6\div10^7\right]\text{GeV}\end{cases}$$

Primary cosmic ray spectrum (p)



Primary cosmic ray spectrum (He)



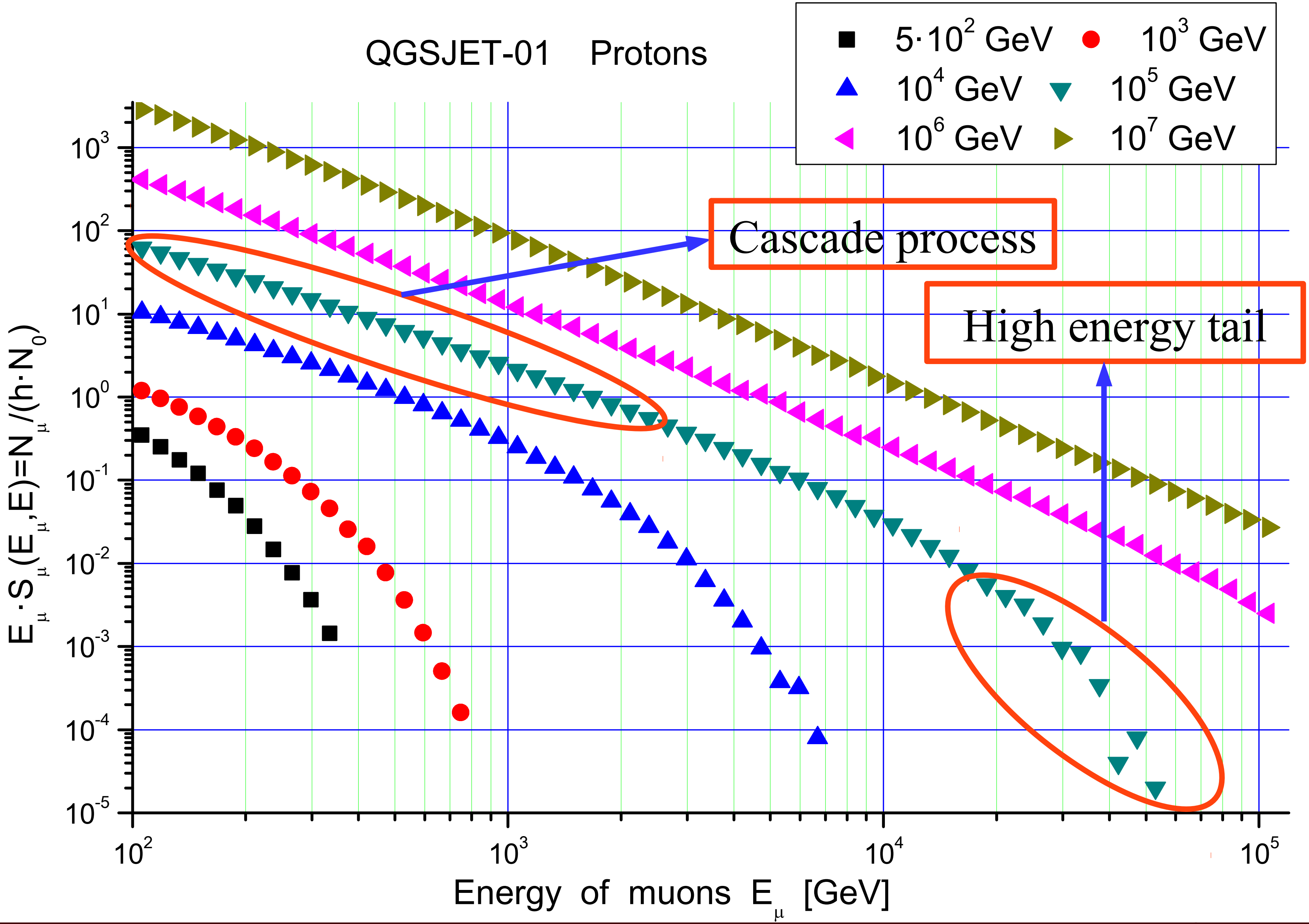
Ingredients for calculations (II)

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

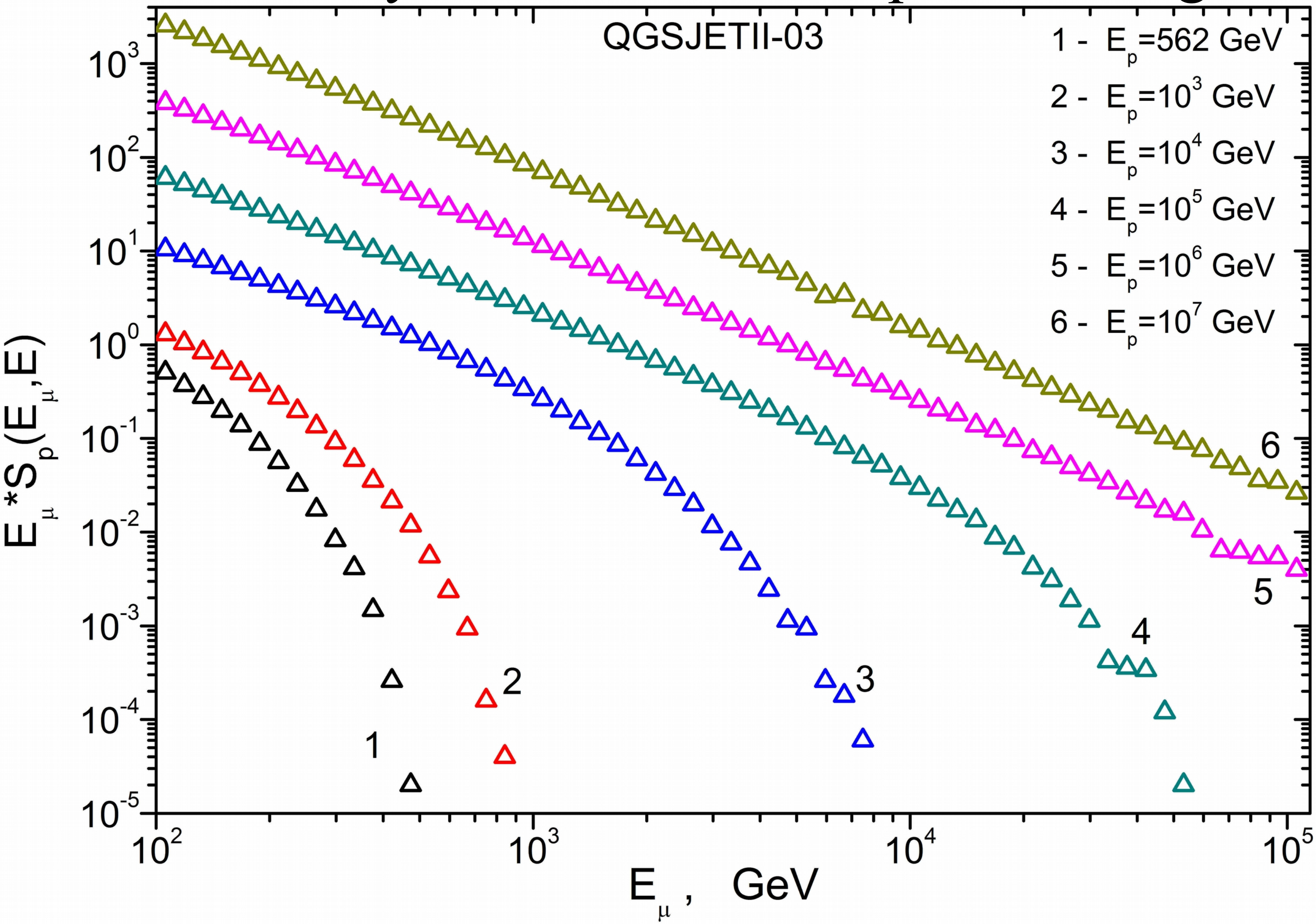
$$S_p(E_\mu, E) \cdot dE_\mu$$

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

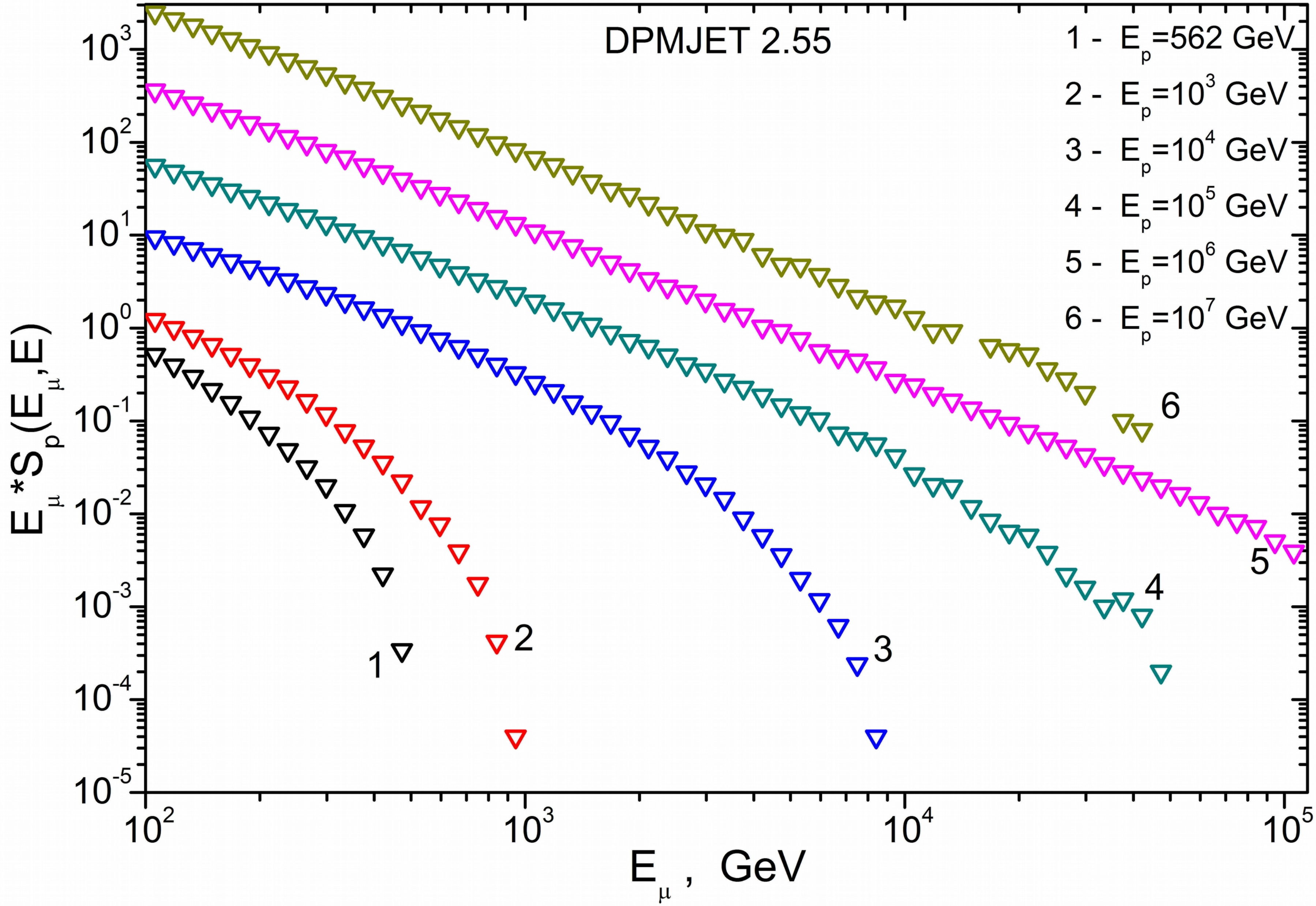
Muons density functions at fixed proton energies



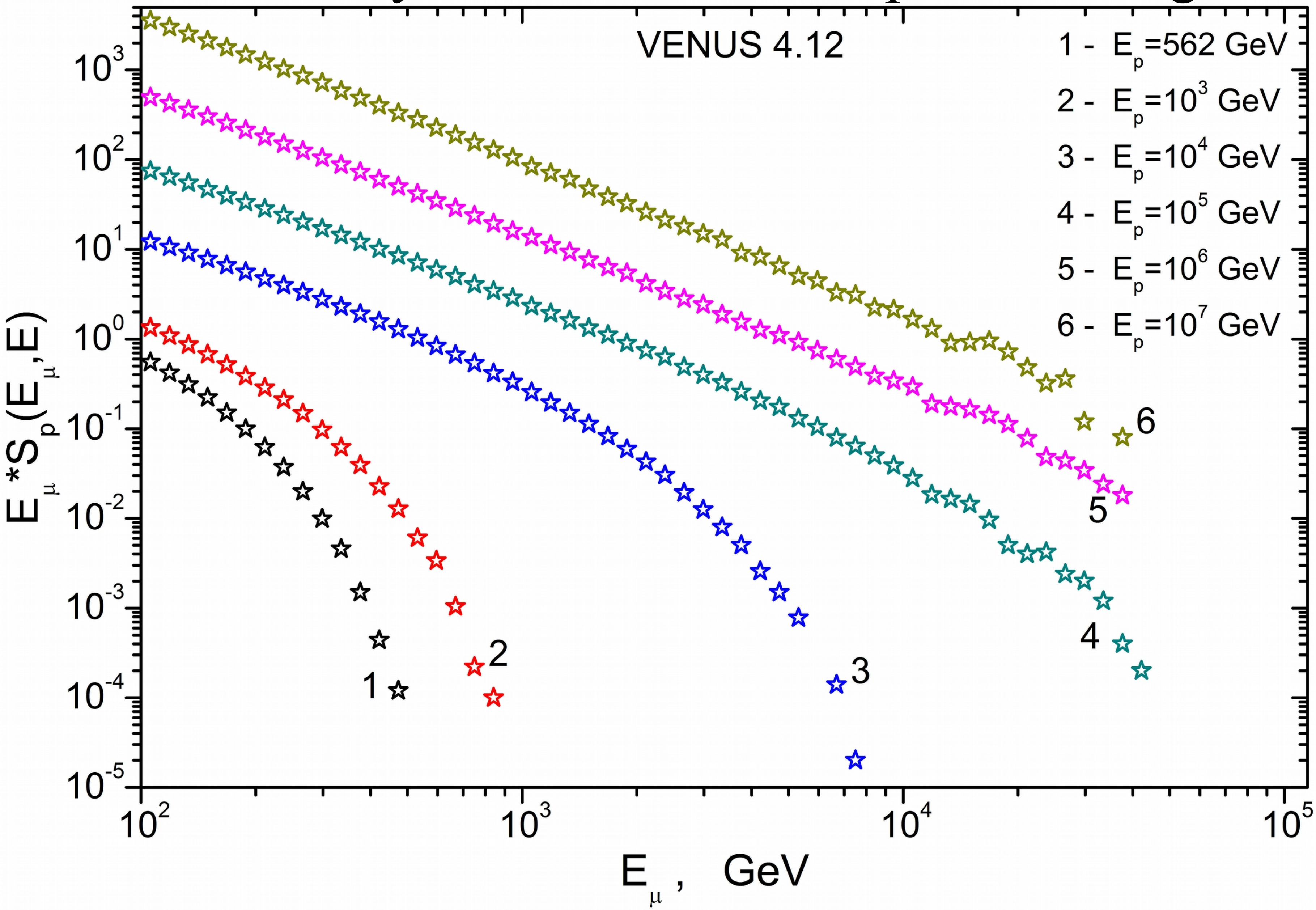
Muons density functions at fixed proton energies



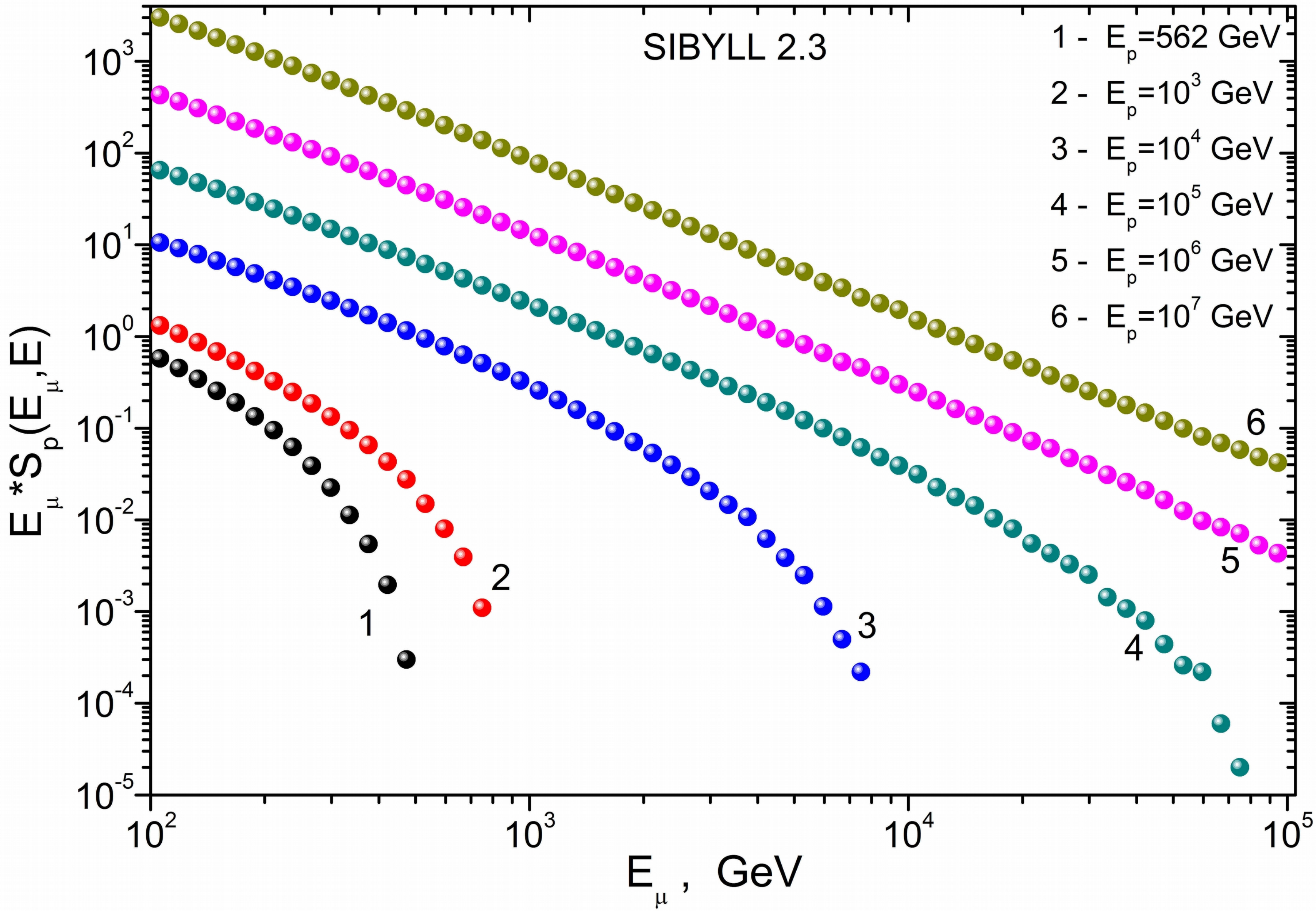
Muons density functions at fixed proton energies



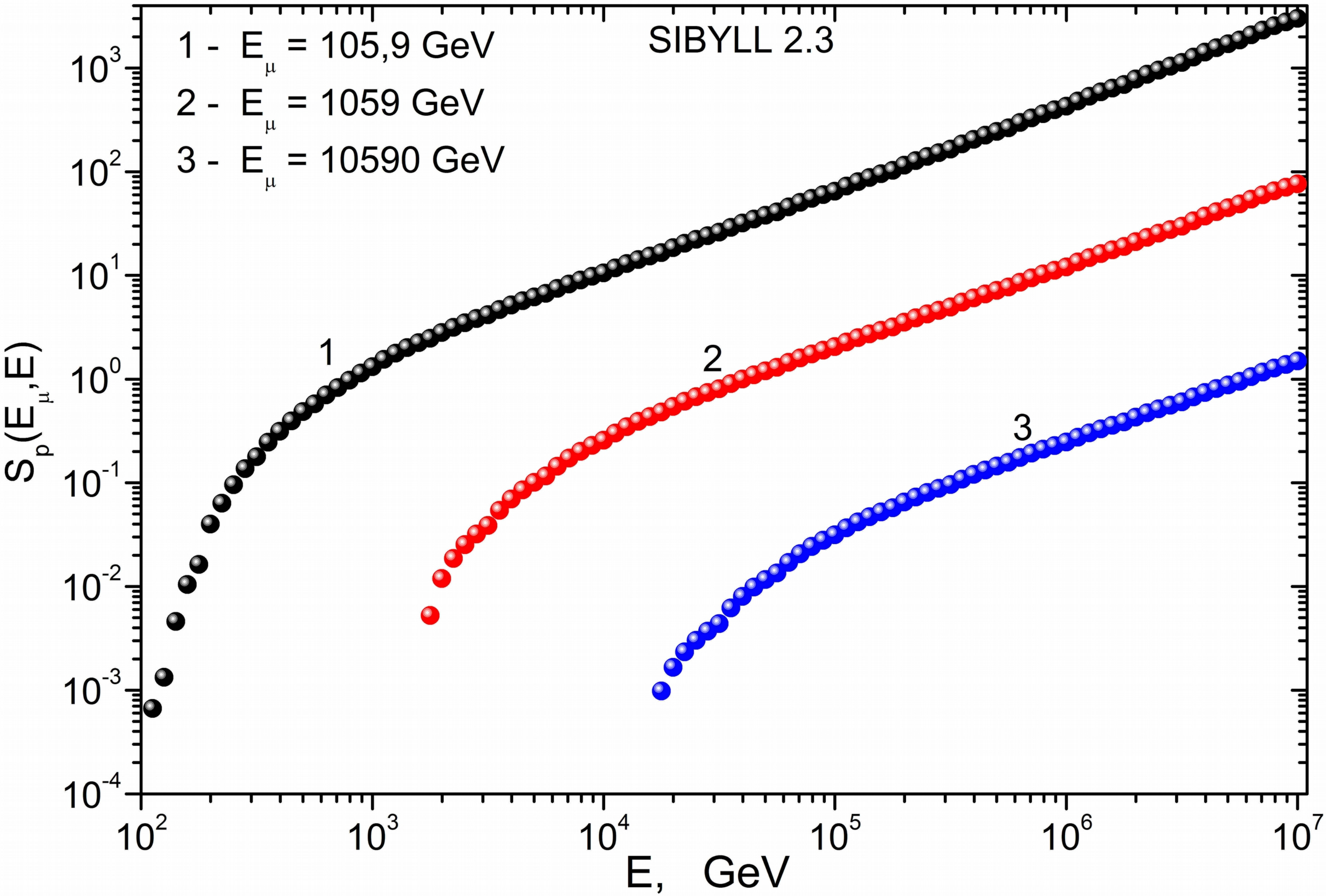
Muons density functions at fixed proton energies



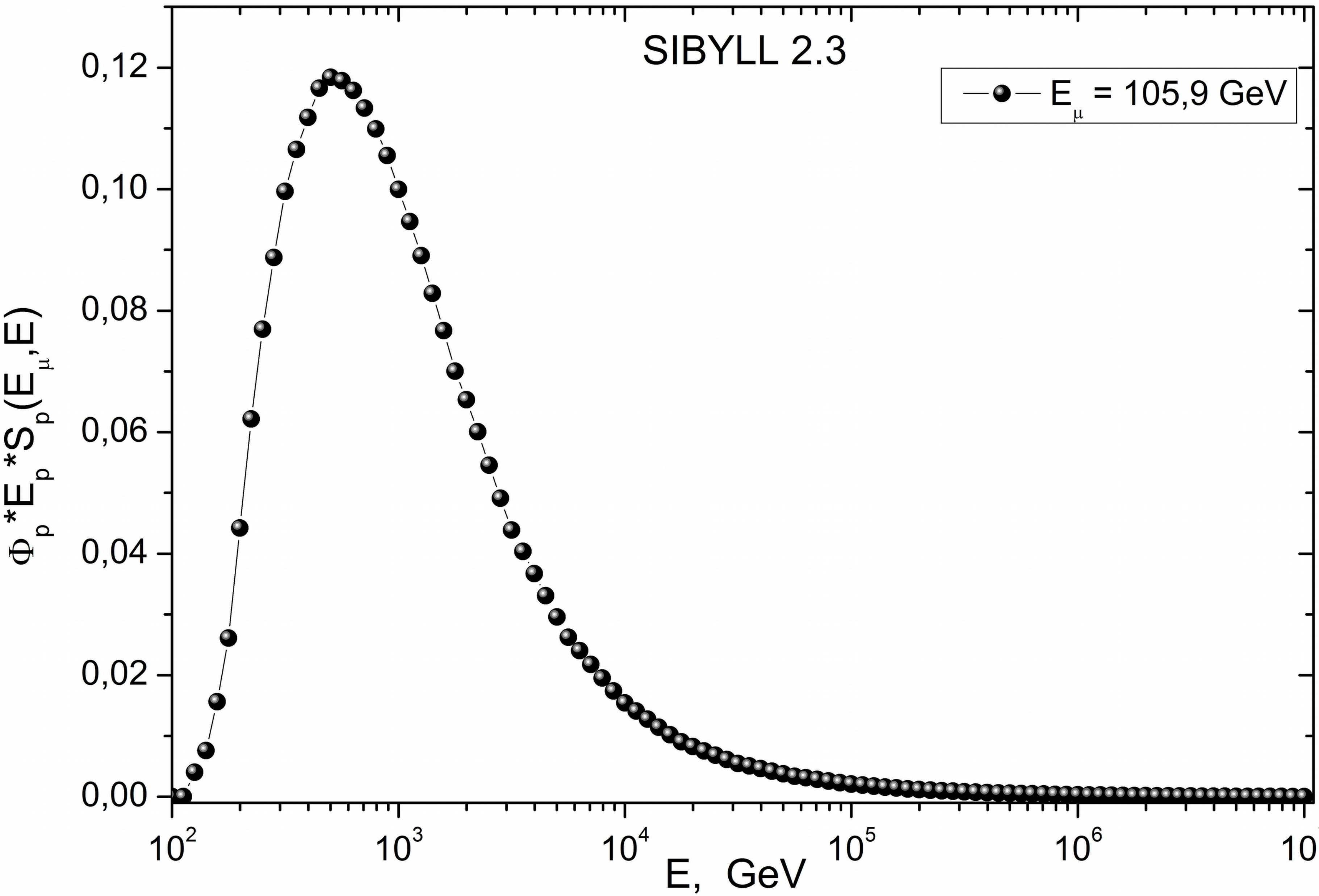
Muons density functions at fixed proton energies



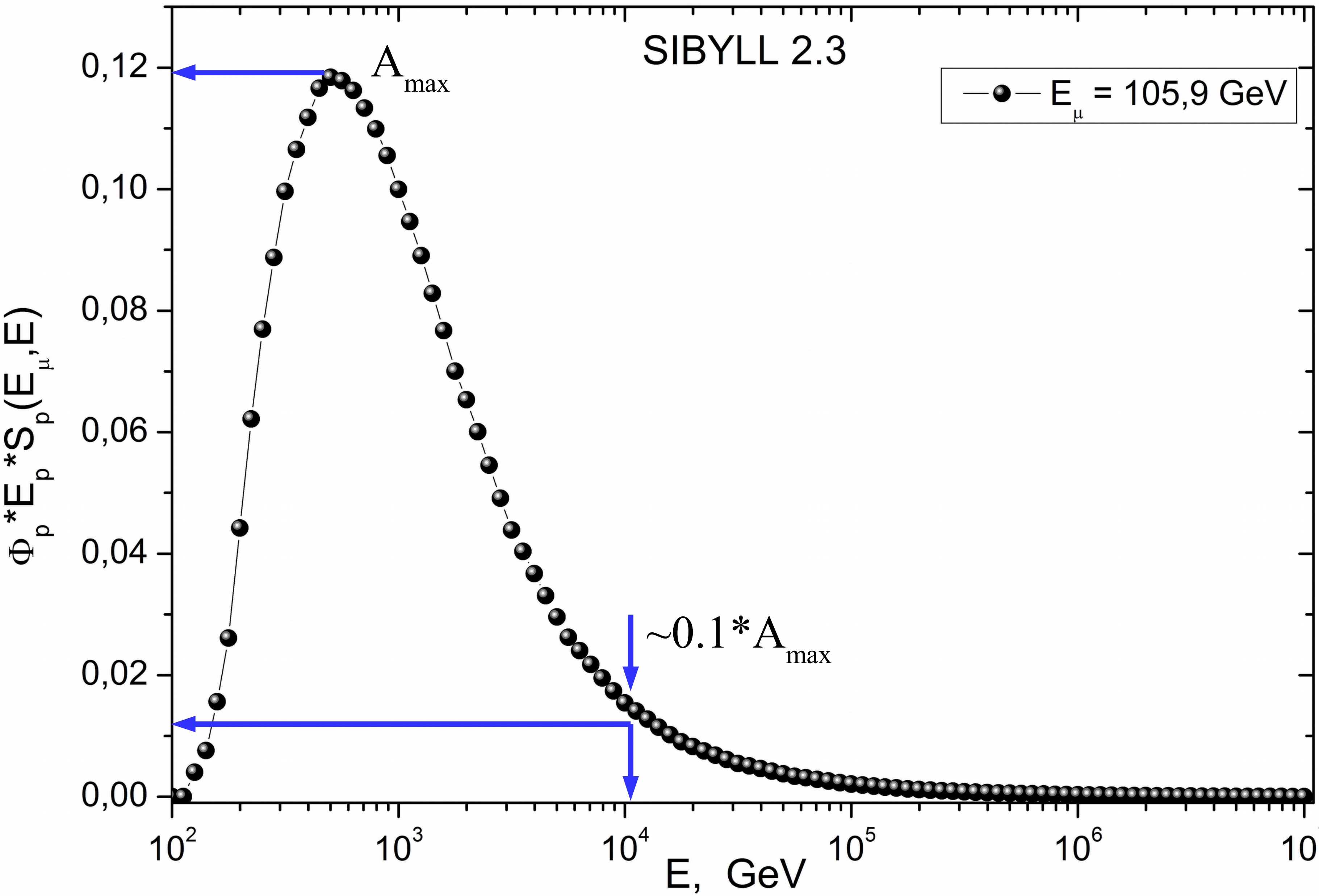
Muons density functions at fixed energies of muons



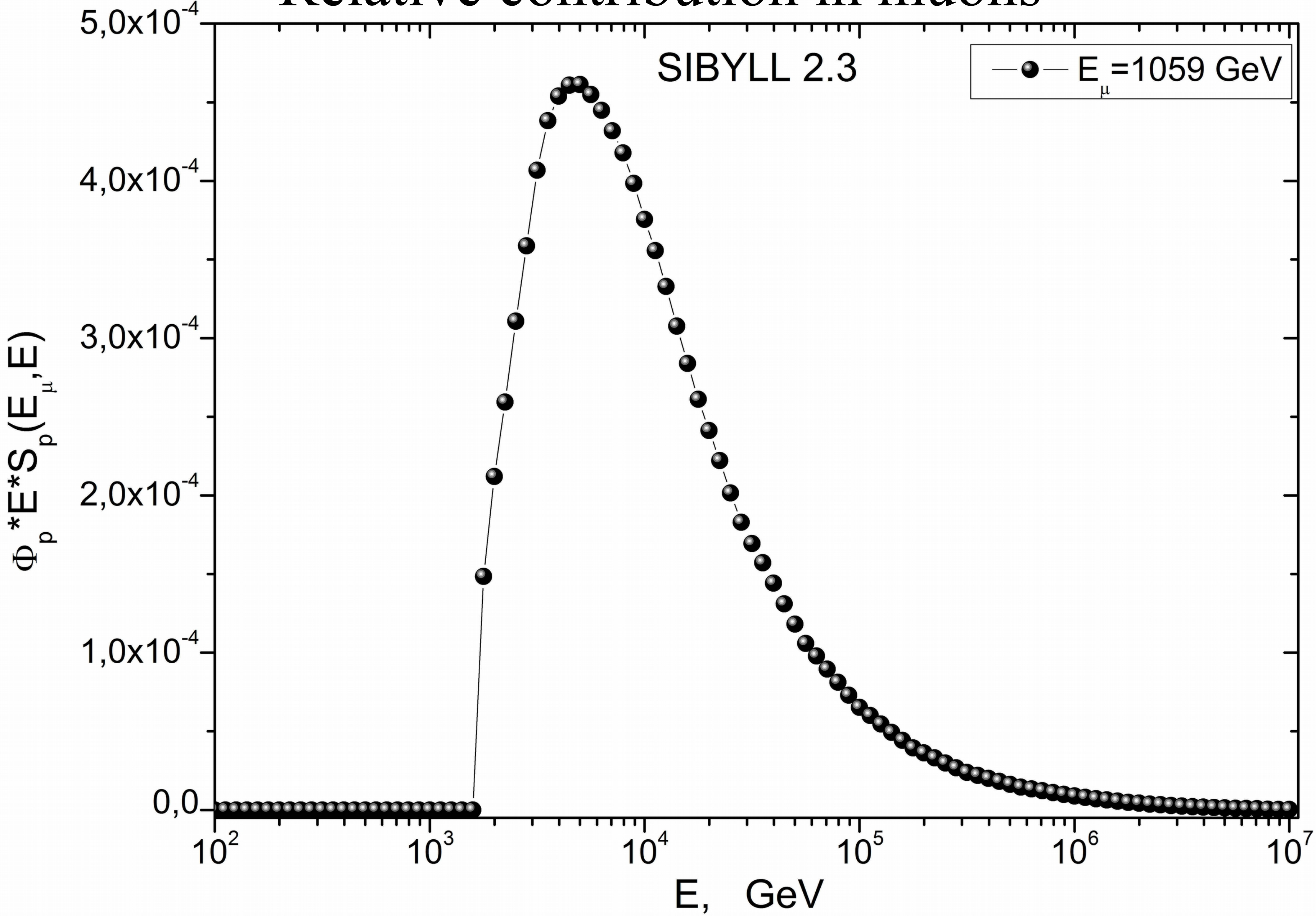
Relative contribution in muons



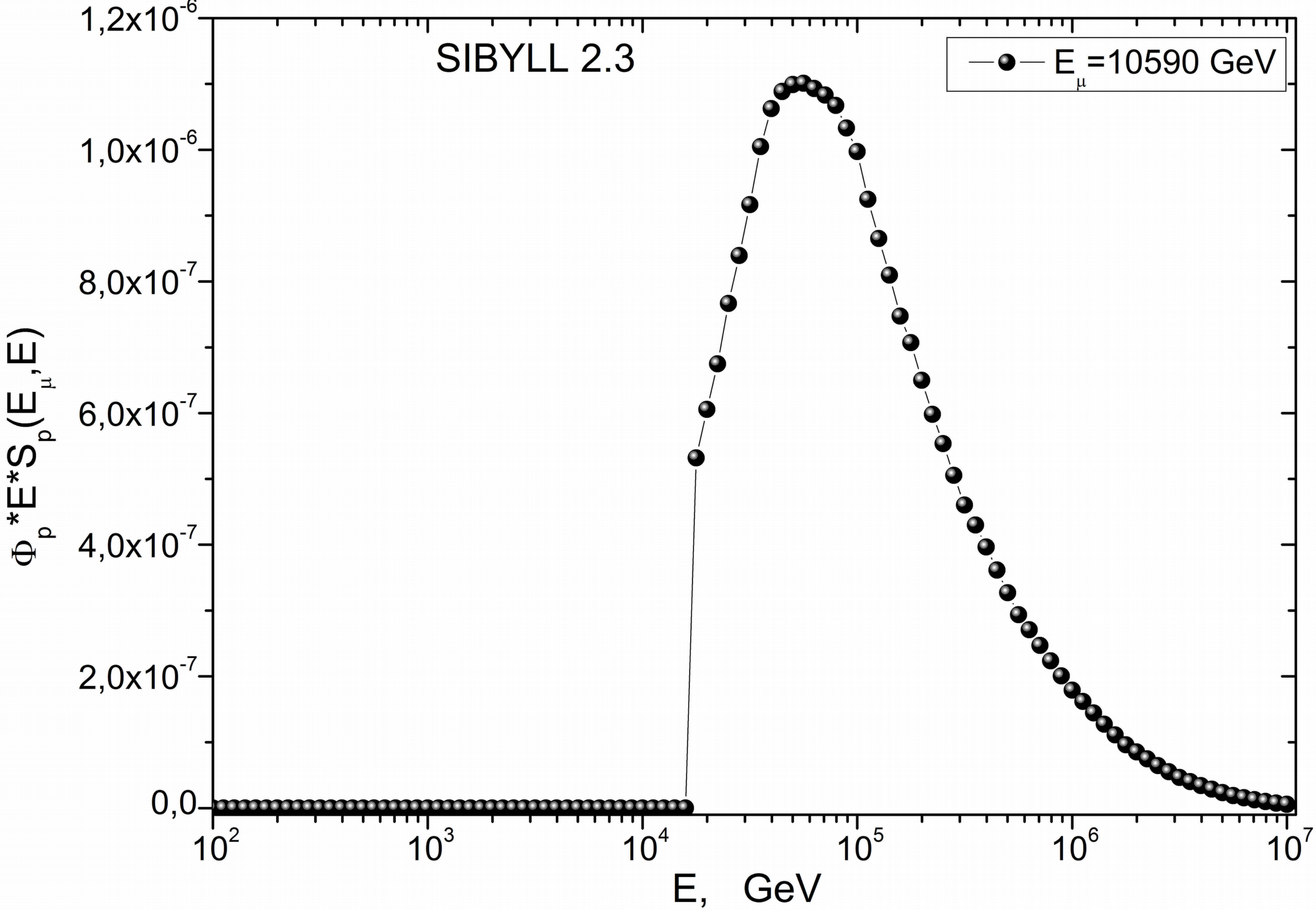
Relative contribution in muons



Relative contribution in muons



Relative contribution in muons



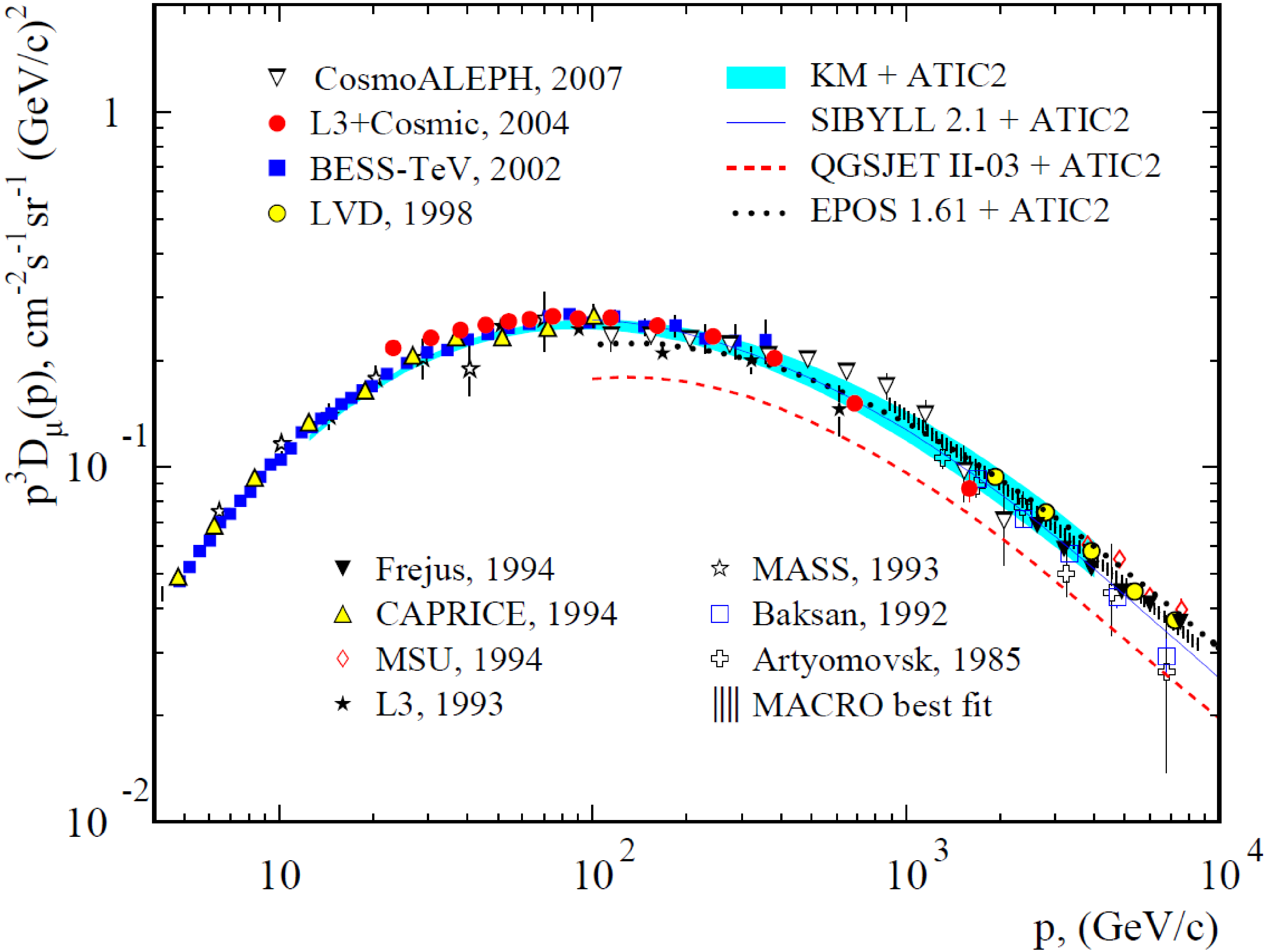
Comparison

- Differential energy spectrum of vertical muons

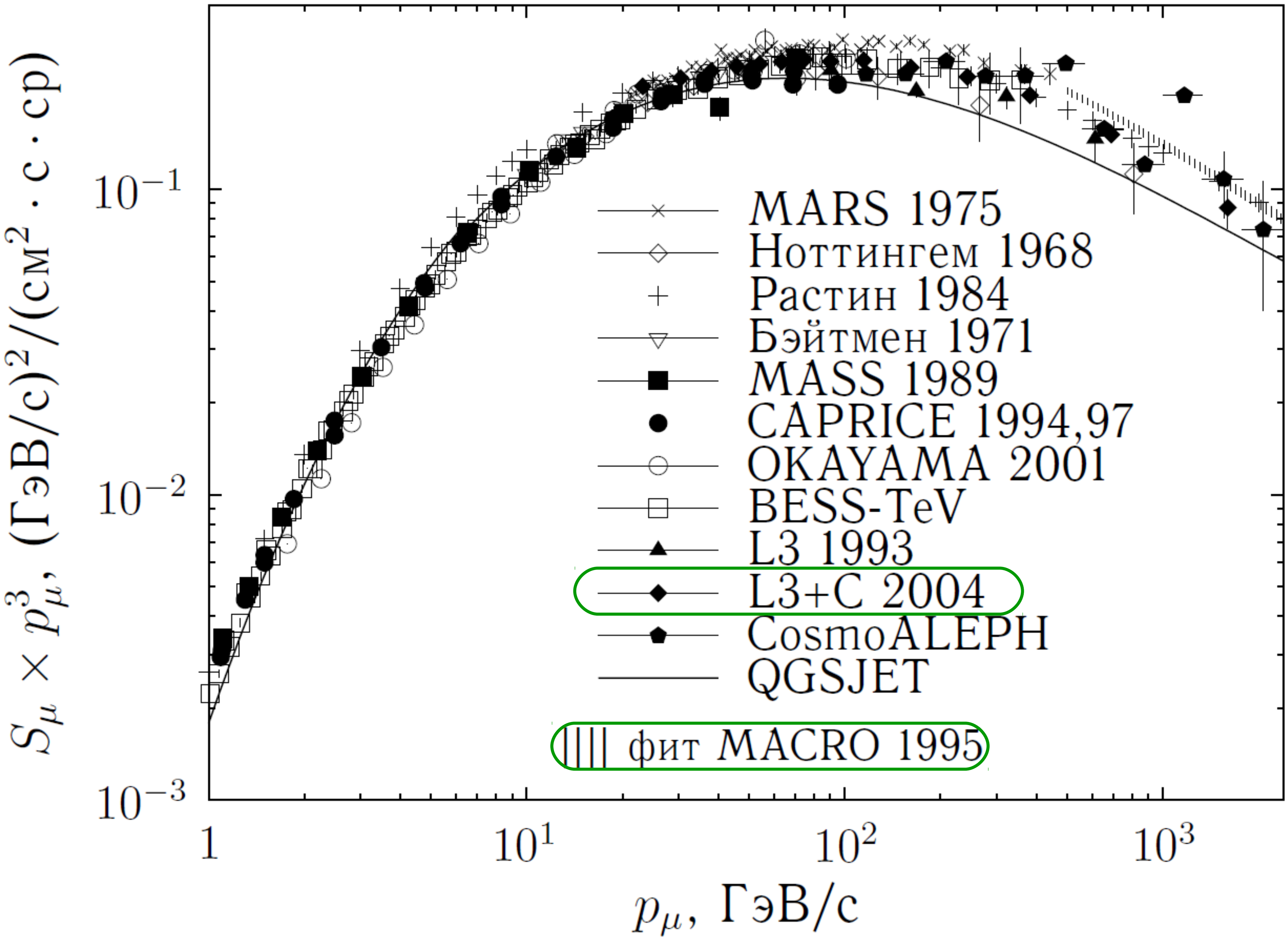
<u>Experimental data:</u>
L3+Cosmic
MACRO
LVD

<u>CORSIKA simulations:</u>
DPMJET 2.55
VENUS 4.12
QGSJETII-03
SIBYLL 2.3

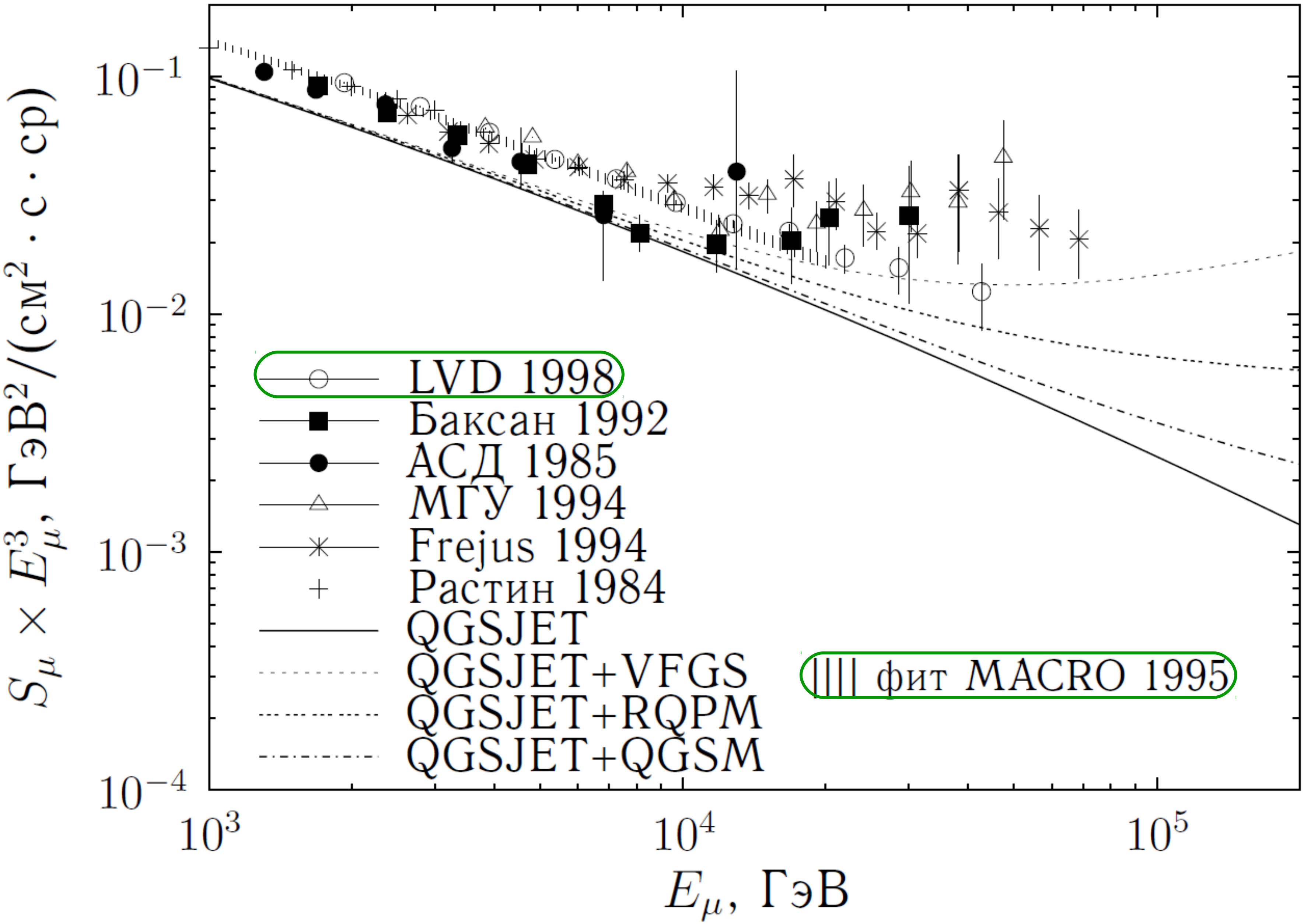
Alex Kochanov PhD. Thesis



Alexey Yushkov PhD. Thesis



Alexey Yushkov PhD. Thesis



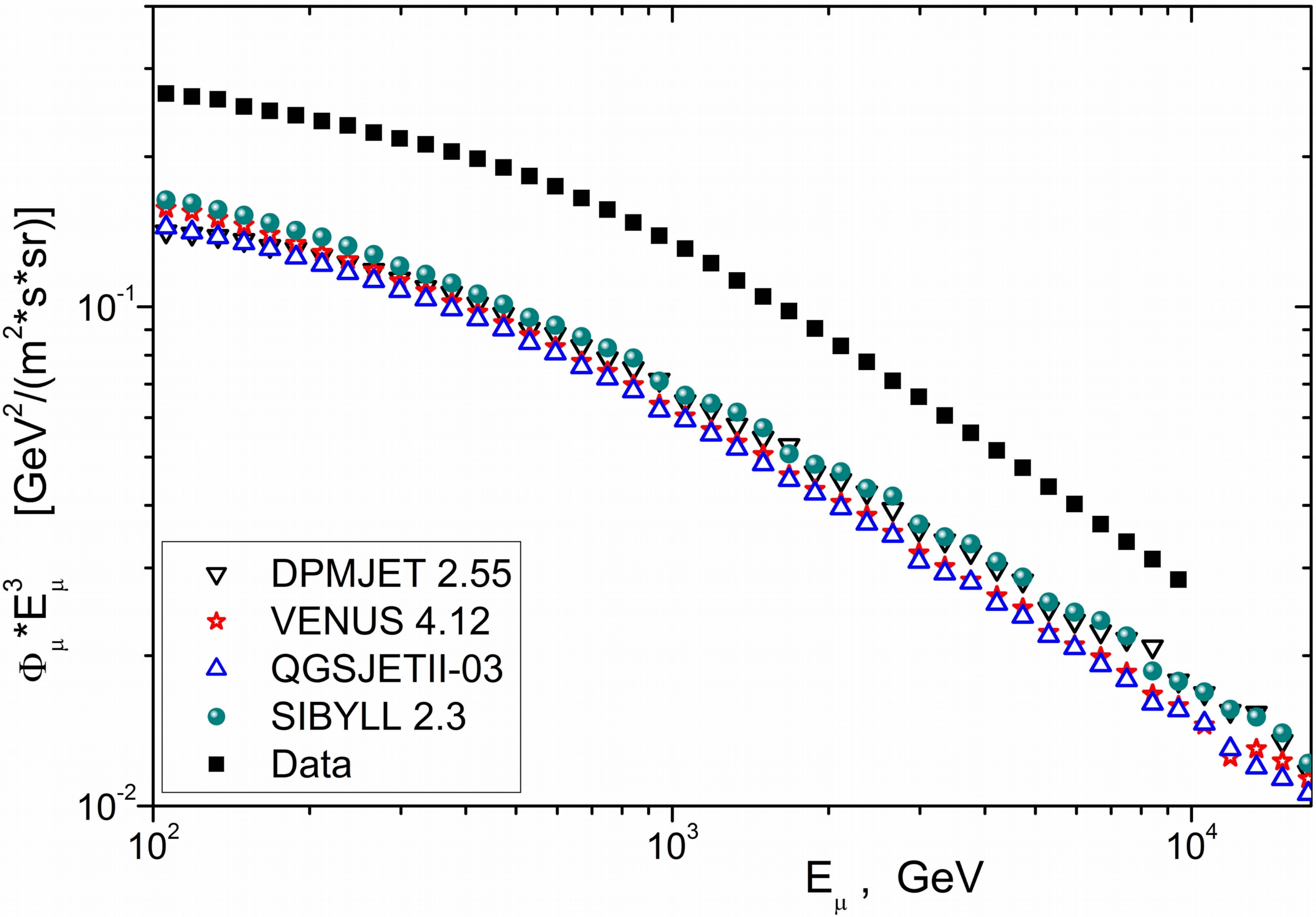
Data of the muon spectra

1) L3+Cosmic: Achard P et al. Phys.Lett. B. 598 15-32 [arXiv:hep-ex 0408114v1] (2004)

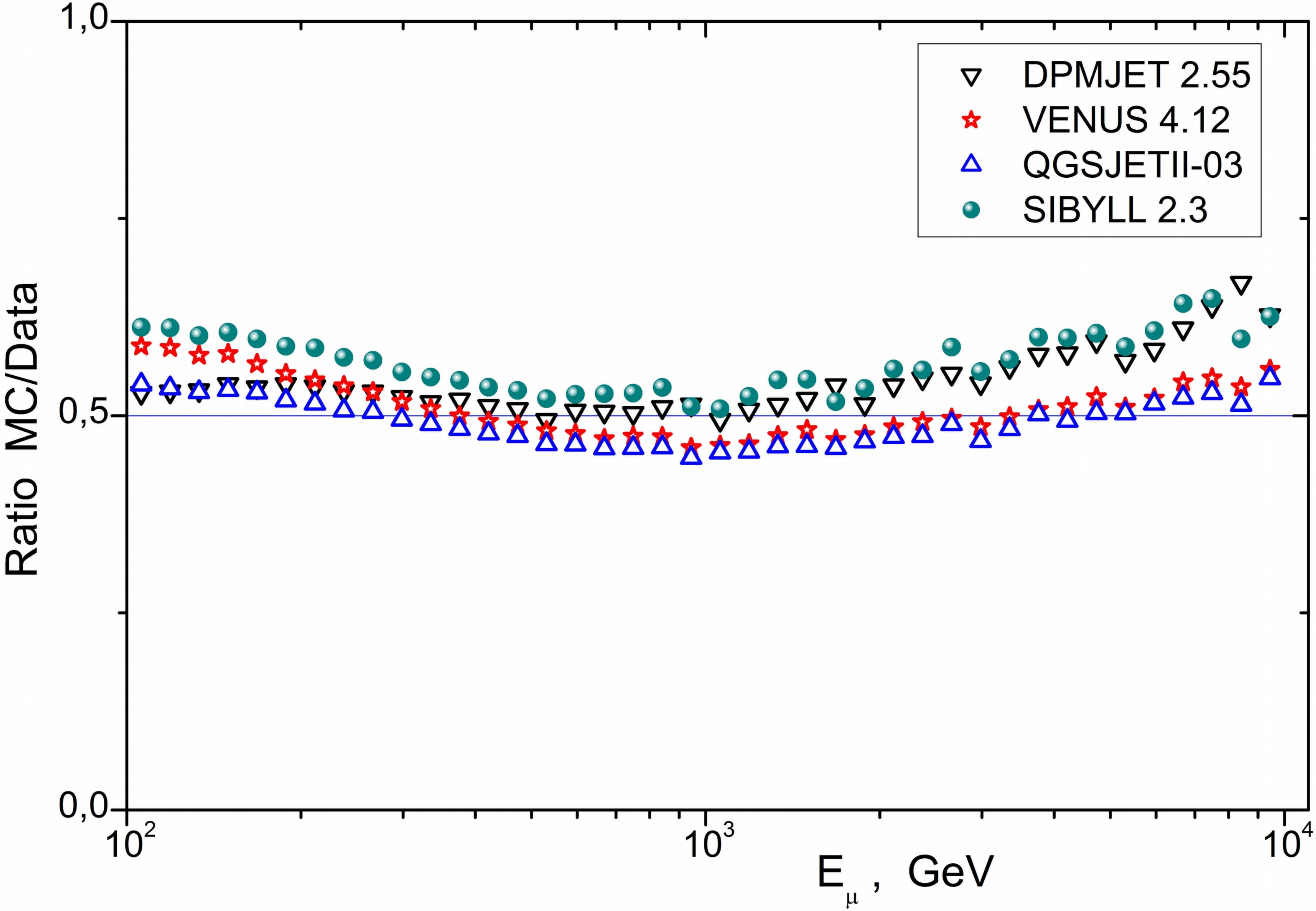
2) MACRO: M. Ambrosio et al., Phys. Rev. D **52**, 3793, (1995)

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 DPMJET 2.55, VENUS 4.12, QGSJETII-03 and SIBYLL 2.3 model are shifted below the data by factor ~2.
- Modern experimental data (primary cosmic ray spectra) only strengthen this discrepancy.

Previous result

We are very sorry!

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

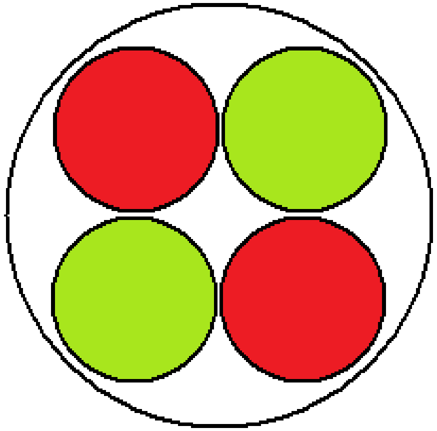
Previous result was incorrect! (Only the models QGSJET-01, QGSJETII-04, SIBYLL 2.1, EPOS 1.99 are incorrect, other models are correct!

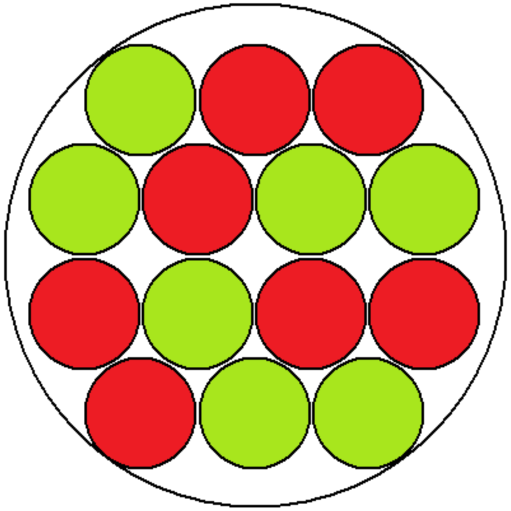
All these works before 2016!)

Thank you for attention!

Superposition conception

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

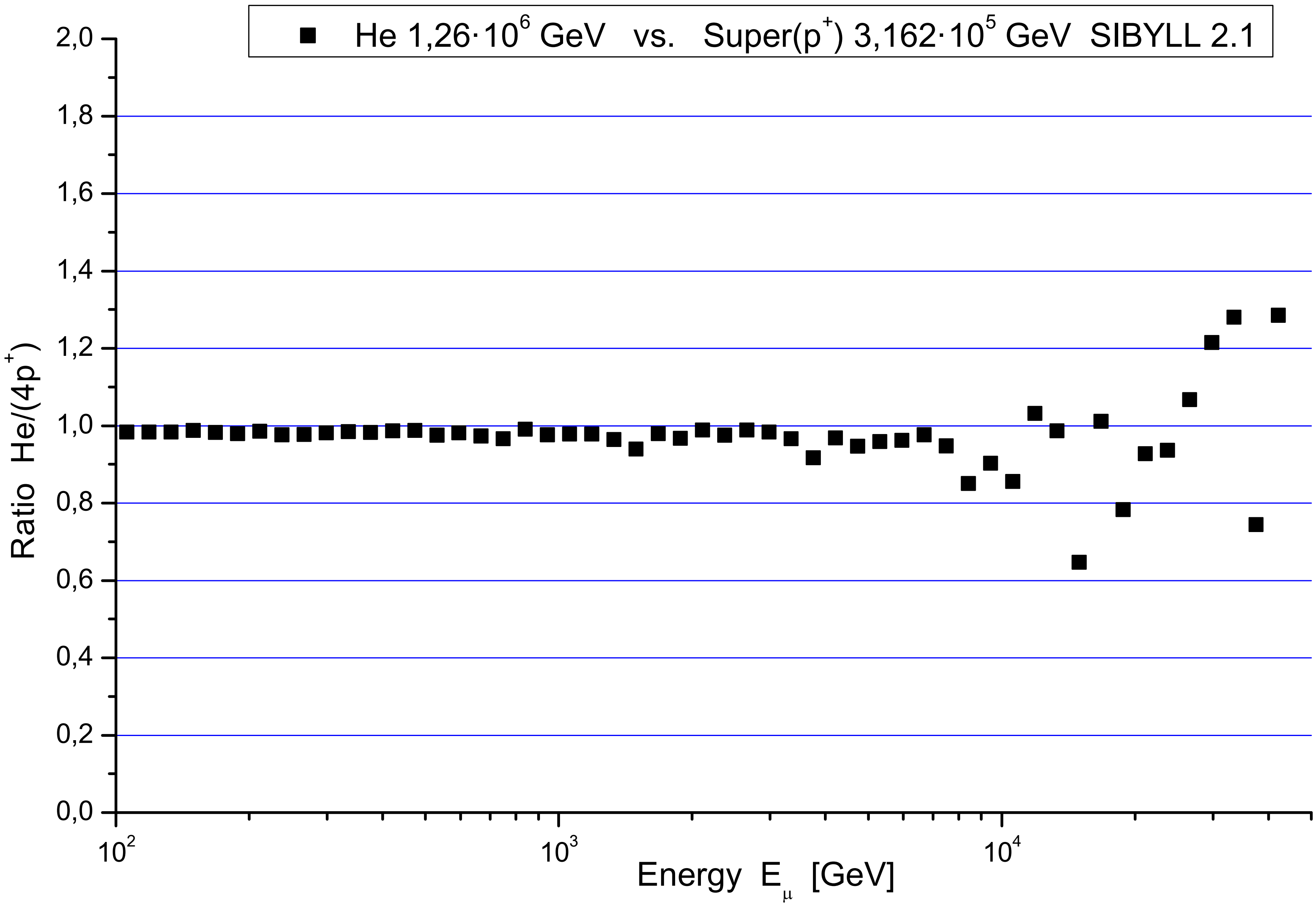




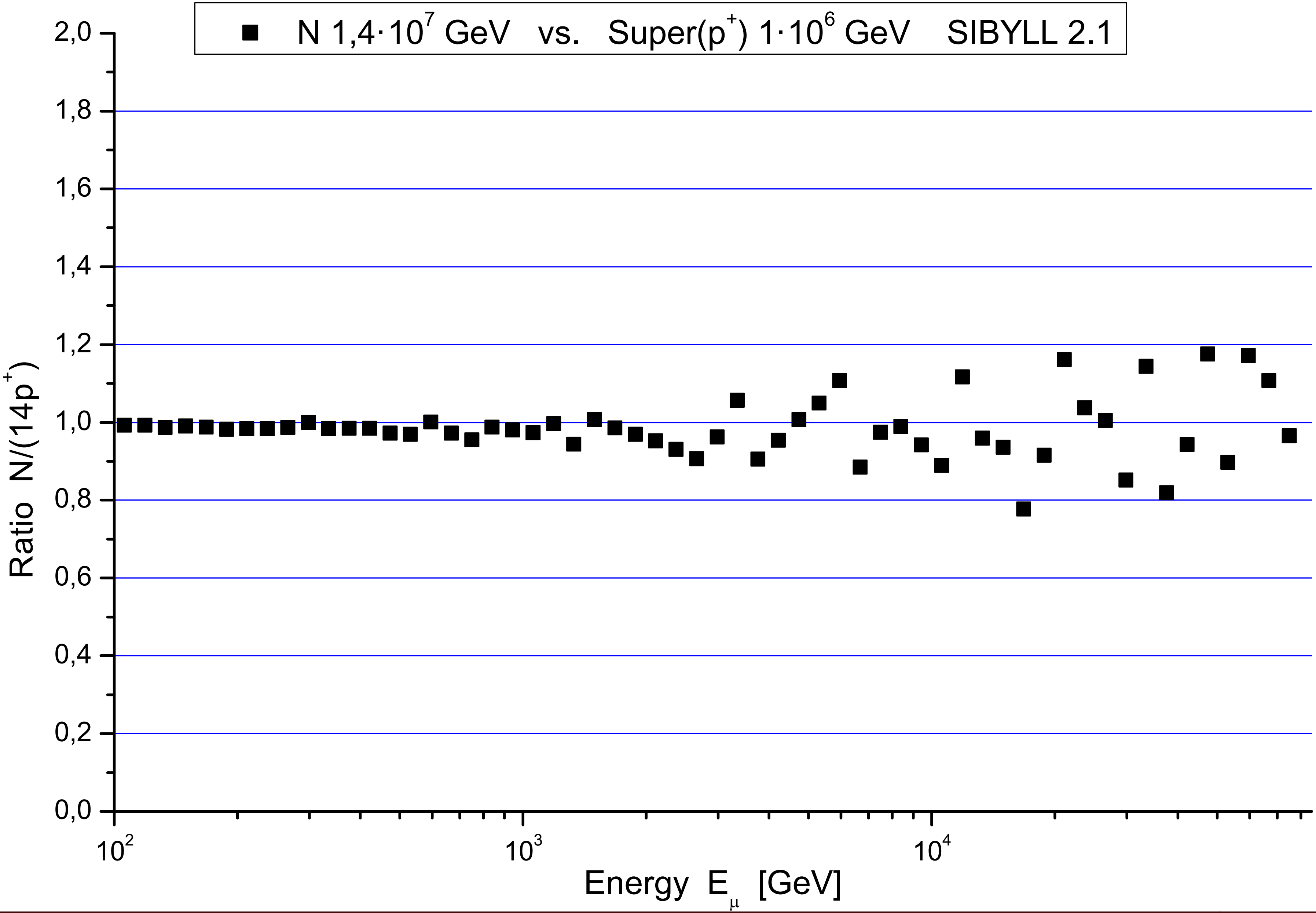
$$S_{He}(E_\mu, E_{He}) \approx 4 \cdot S_p\left(E_\mu, E_p = \frac{E_{He}}{4}\right)$$

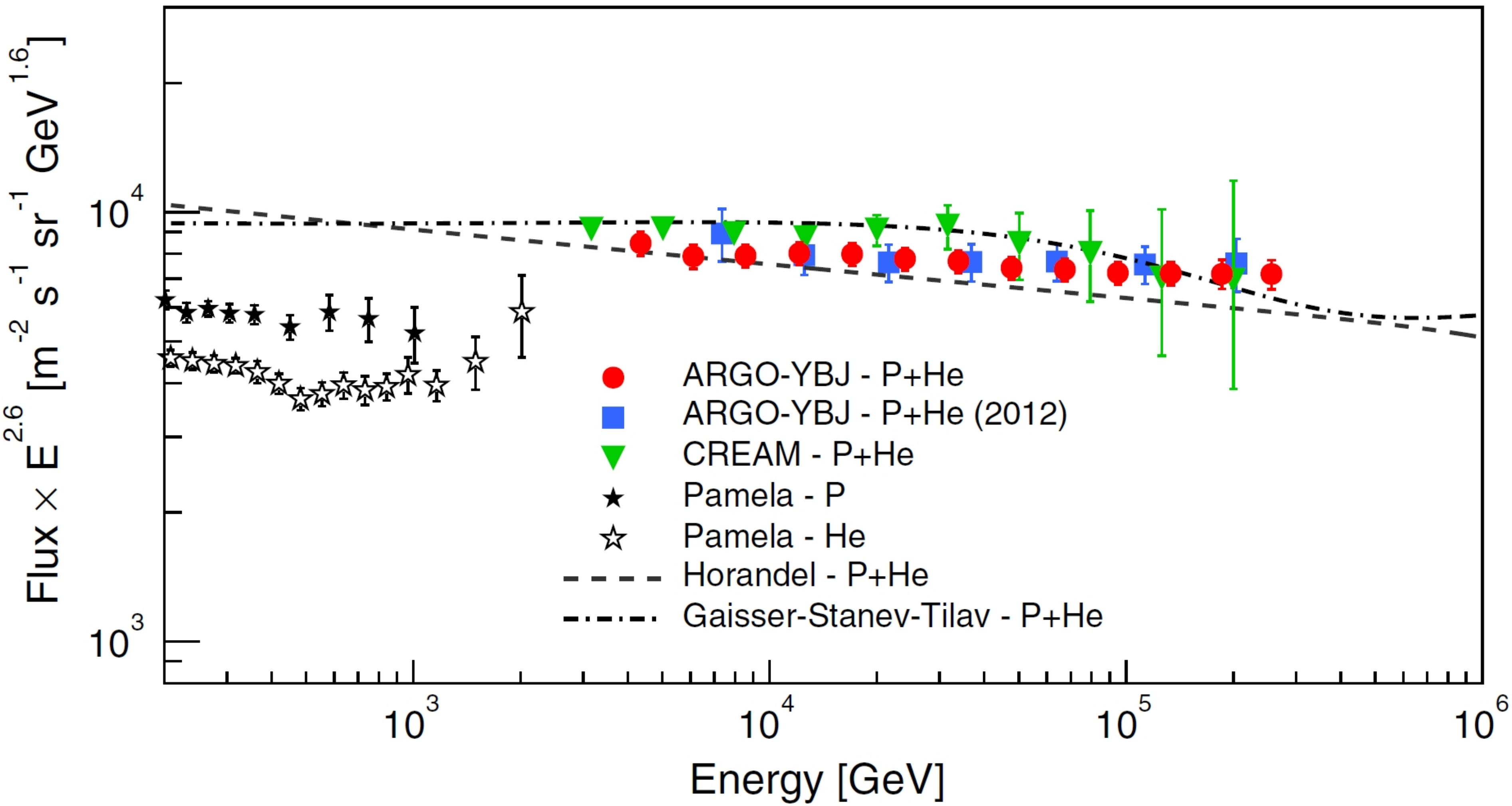
$$S_N(E_\mu, E_N) \approx 14 \cdot S_p\left(E_\mu, E_p = \frac{E_N}{14}\right)$$

Superposition conception (result for SIBYLL)

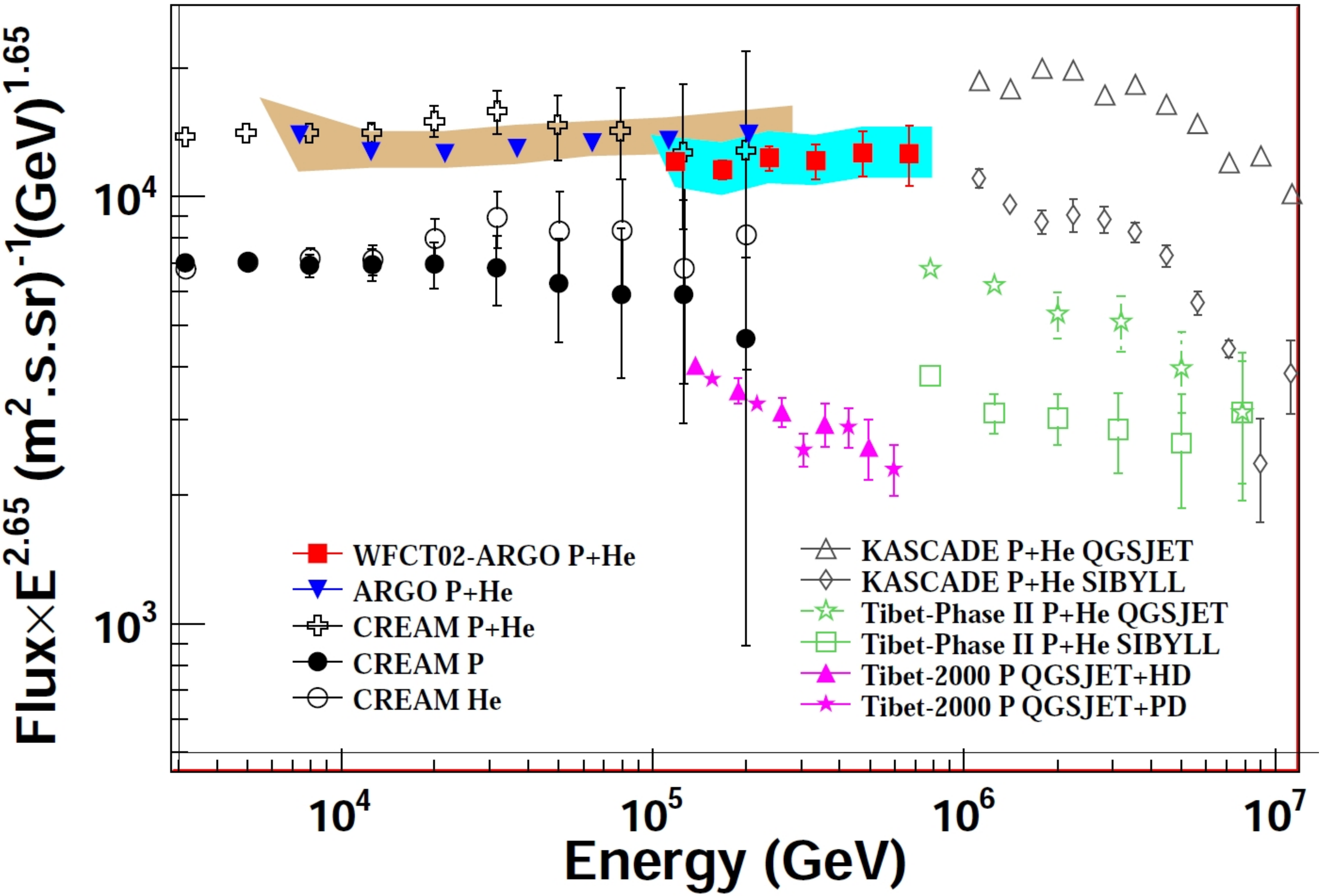


Superposition conception (result for SIBYLL)





Paolo Montini fot the ARGO-YBJ Collaboraion «Cosmic ray physics with ARGO–YBJ» arXiv:1608.01251v1



B. Bartoli et al. (ARGO–YBJ Collaboration) Phys. Rev. D 91, 112017 (2015) «Cosmic ray proton plus helium energy spectrum measured by the ARGO-YBJ experiment in the energy range 3–300 TeV»

Result of calculations