Testing of the high-energy $\pi^{\pm}$ and $K^{\pm}$ meson production by the primary cosmic protons and helium nuclei

Dedenko L.G., Lukyashin A.V., Roganova T.M.

M.V. Lomonosov Moscow State University, Faculty of Physics

Skobeltsyn Institute of Nuclear Physics

National Research Nuclear University «MEPhI» - Moscow Engeniering Physics Institute

Moscow State University NUCLEUS 2022

Content

1. Introduction
2. Motivation
3. Method of testing
4. Primary cosmic rays energy spectra
5. Aproximation of primary spectrum
6. Simulating and calculations
7. Results
8. Conclusion

Hadromic interaction 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)

Improvements

1) Real parameters of the atmosphere are properly corresponding to the standard atmosphere.

2) Original approximation of the primary protons and helium spectra, based on simulations of production of cosmic rays in the SNR and modern experimental data.

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

Motivation

- Our main goal consists in testing the model predictions for the most energetic $\pi^{\pm}$ and $K^{\pm}$ mesons production!
- The predictions may be validated or rejected by comparing the calculated high energy muon fluxes with data.

Method

- The packages CORSIKA 6.9, CORSIKA 7.4 and

  CORSIKA 7.5 has ben used to estimate the muon energy spectra $D(E_\mu)$ induced by the primary protons with fixed energies for models

  EPOS LHC, QGSJET-01, QGSJETII-03, QGSJETII-04, DPMJET 2.55, VENUS 4.12, SIBYLL 2.1 and SIBYLL 2.3.
- The muon energy spectra interval $E_\mu \in 10^2 — 10^5$ GeV
- Energy interval for primary protons and helium nuclei
- $E \in 10^2 — 10^7$ GeV;
- Statistics N from 10^7 to 10^3
- Statistics 10^6 in energy interval $(0,01\text{-}1)\cdot E_0$
- Statistics 10^7 in energy interval $(0,1\text{-}1)\cdot E_0$

Ingredients

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

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

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

Simulations

Muons energy spectra for fixed energies E of nucleons [CORSIKA 6.9, CORSIKA 7.4 and CORSIKA 7.5]

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

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

Method

Ingredients:

1) Approximation of simulations of the primary proton and helium nuclei spectra in supernova remnants.
2) Data: AMS-02, PAMELA, ATIC-2, CREAM, ARGO, TA, KASCADE, KASCADE-Grande, IceCube, Tunka.
3) Muon data: L3+Cosmic, MACRO, LVD.

Simulations:

4) Simulations of the muon energy spectrum by the primary protons and helium nuclei with fixed energies. The superposition model has been used for the helium nuclei.
5) The atmospheric muon energy spectrum as convolutions of the primary cosmic ray spectra with muon energy spectrum at fixed energies.

Method of simulations

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

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

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

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

- $D(E_\mu)$ — 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.

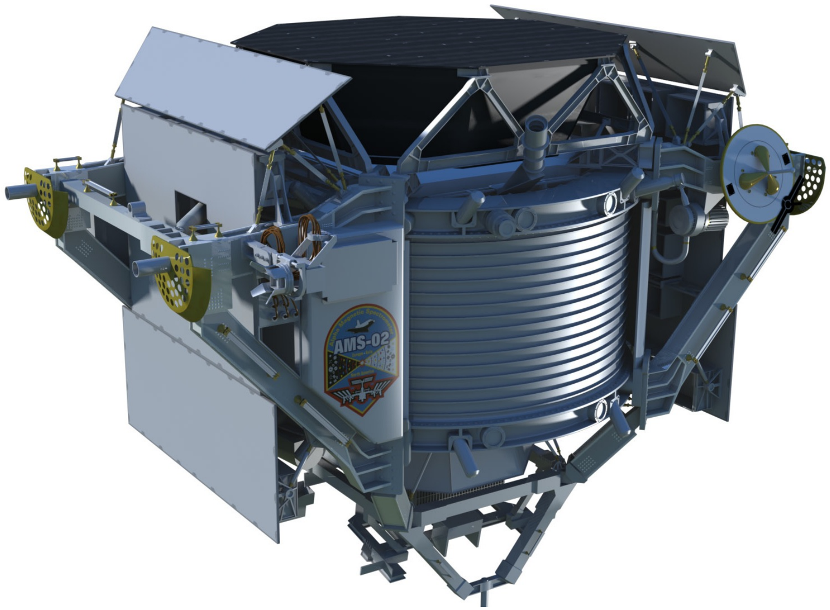
$$\left(\frac{dI_p}{dE}\right) \qquad \left(\frac{dI_{He}}{dE}\right)$$

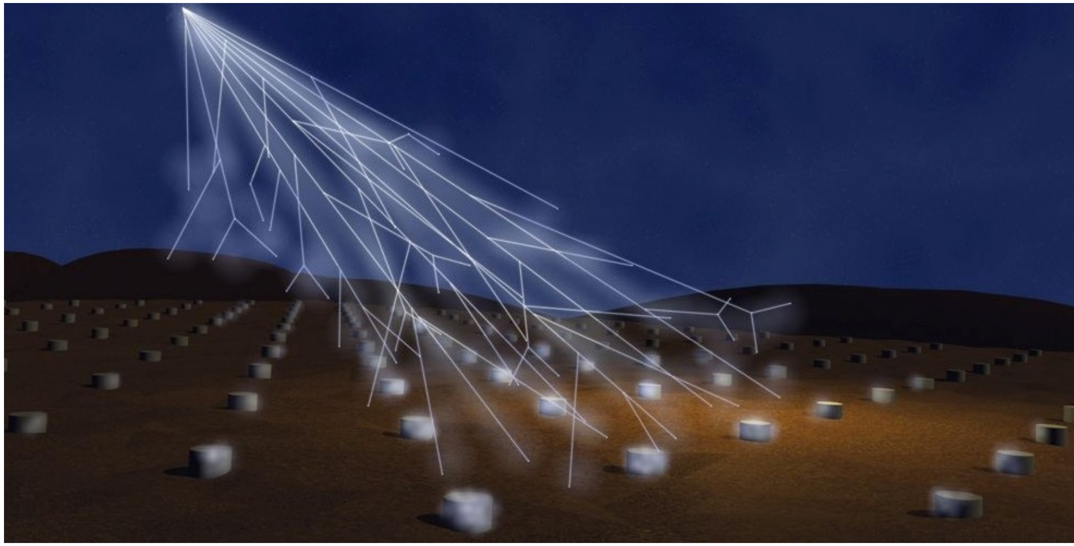
1. Approximations of simulations by Berezhko E.G. have been used.

- Berezhko E.G. and Völk H.J. Astrophysical Journal, 661: L175–L178, (2007)
- Berezhko E.G. Nucl. Phys. B (Proc. Suppl.) Vol. 256 - 257, 2335 (2014)
- Berezhko E.G., Knurenko S.P., Ksenofontov L.T., Astropart. Phys. Vol. 36 3136 (2012).

2. Normalization at 1,8 TeV to the AMS-02 data has been used.

Primary cosmic rays data





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

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

- ARGO-YBJ
- ARGO&FWCTA
- KASCADE
- KASCADE-Grande
- IceCube
- Telescope Array
- TUNKA

Cosmic Rays DataBase

Welcome | Experiments/Data | Data extraction | $\Phi^{NM}(t)$ and J^{TOA} | Links | New data

Database of Charged Cosmic Rays

D. Maurin (LPSC), F. Melot (LPSC), R. Taillet (LAPTh)

If you use this database, please cite Maurin, Melot, Taillet, A&A 569, A32 (2014) [arxiv.org/abs/1302.5525].

New release V3.1 - August 2016
[changelog]
Last code modification: 10/01/2017

Description

This database is a compilation of experimental cosmic-ray data. The database includes electrons, positrons, antiprotons, and nuclides up to Z=30 for energies below the knee. If you spot any errors or omissions, want to contribute, or simply comment on the content of the database, please contact us. We are eager to extend the database to Z>30 and to higher energy ground measurements and any help is welcome.

Warning: several sets of Solar modulation values are provided per sub-experiment. We refer the user to Sect.2.3 of Maurin et al. (2013) for a complete discussion, and only give below a brief description of the different sets of modulation parameters available in the CRDB: [read more]

Current version / Latest data added / Acknowledgements

Structure of the database

This is a mySQL database containing lists of experiments (name, dates of flight, experimental technique in brief, website), the corresponding publications (ref. and link to the ADS database), and all available data points (fluxes and ratios of leptons, nuclides, and anti-protons including their statistical and systematic error whenever available).

Accessing the database

- Experiments/Data: list of experiments, publications, data
- Data extraction: selection by flux/ratio/energy range... (on this web site or via a REST interface)
- Export database content in USINE or GALPROP compliant format (ASCII files)
- Get all bibtex entries and Latex cite (by sub-experiment)

Acknowledgements: this project has been financially supported by the PNHE

Maurin D., Melot F., Taillet R., Astronomy & Astrophysics, 569, A32 (2014). (http://lpsc.in2p3.fr/cosmic-rays-db/)

Approximation of primary cosmic rays

Equations for flux of the primary protons.

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

Approximation of primary cosmic rays

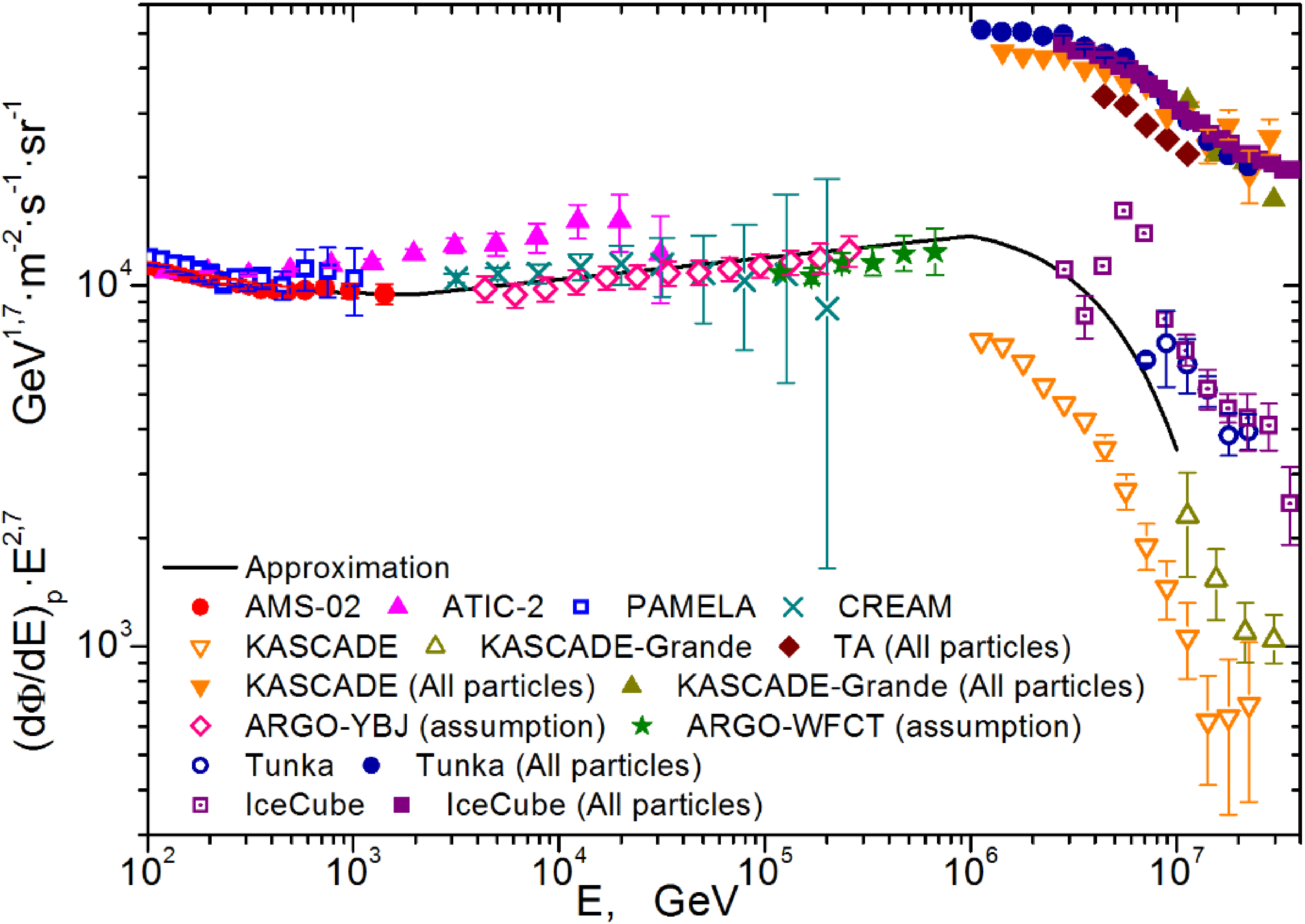
Equations for flux of nucleons of the primary helium nuclei.

E — energy ner nucleon.

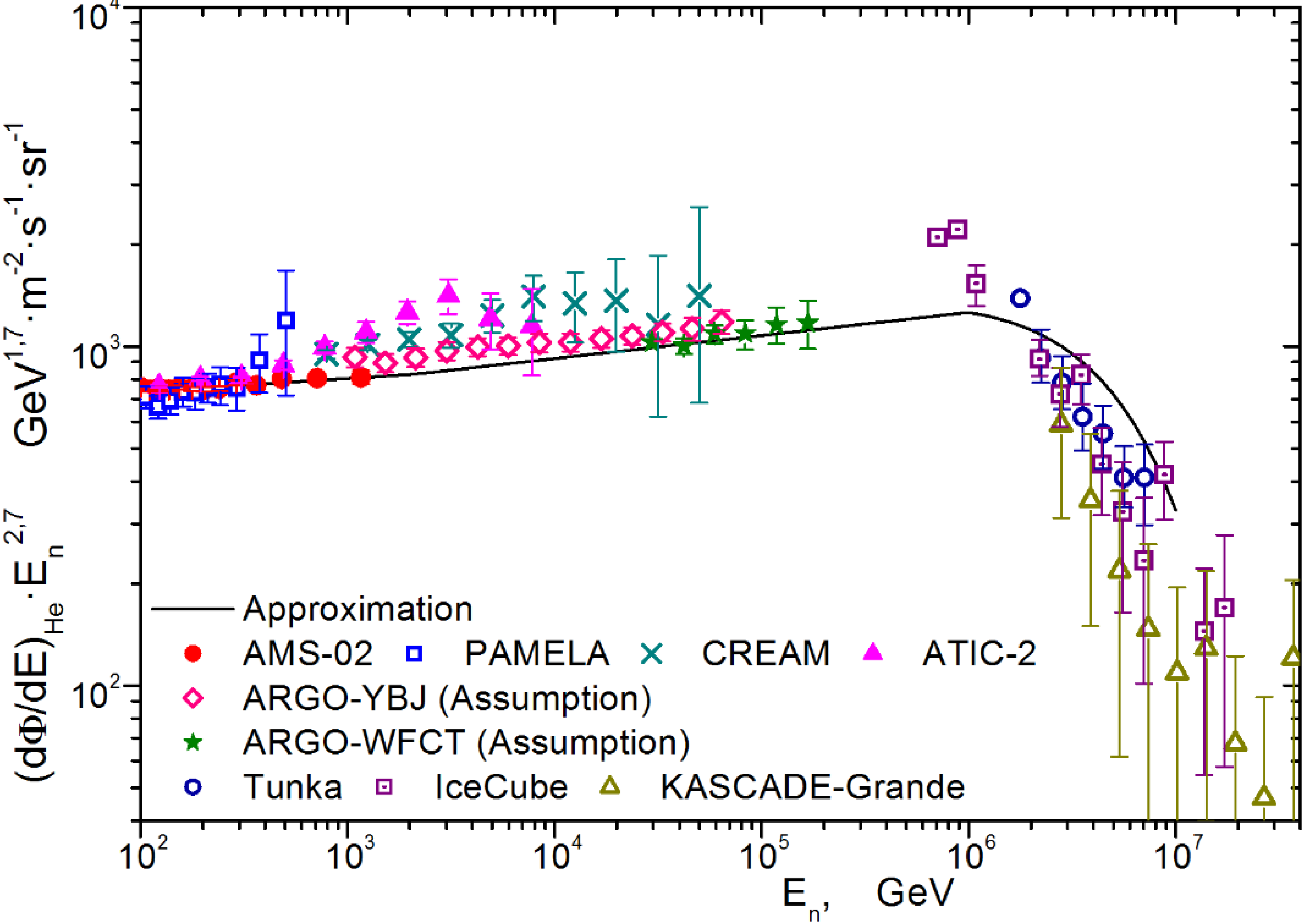
$$\frac{d\Phi_{He}}{dE} = \begin{cases} 0,1896\cdot\left(\frac{2\cdot E}{45}\right)^{-2,78}\cdot\left[1+\left(\frac{2\cdot E}{245}\right)^{4,4074}\right]^{0,027} & E\in\left[10^2\div 1.8\cdot 10^4\right]\text{GeV} \\ 921\cdot E^{-2,7}\cdot\left(\frac{E}{10^4}\right)^{0,068} & E\in\left[1.8\cdot 10^4\div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

As primary protons and helium nuclei contribute to the energy spectrum ~98% we relegate the more havier nuclei.

The primary proton spectrum (approximation and data)



The primary helium nuclei spectrum (approximation and data)



Cosmic Rays Data

- AMS Collab. P.R.Lett. Vol. 114, 171103 (2015); P.R.Lett. Vol. 115, 211101 (2015).
- PAMELA Collab. Advances in Space Research Vol. 51, 219-226 (2013).
- ATIC Collab., Bull. Russ. Acad. Sci. Phys. Vol. 71, 494 (2007); Bull. Russ. Acad. Sci. Phys. Vol. 73, 564 (2009).
- CREAM Collab., , Astrophys.J., 707, 593 (2009).
- ARGO-YBJ Collab. Phys. Rev. D 91, 11, 112017; arXiv:1503.07136 (2015); Chinese Physics C 38, 4, 045001 (2014); Di Sciascio G. et al, J. of Physics: Conf. Series 632, 012089 (2015).
- KASCADE Collab. Astroparticle Physics 24, p. 125 (2005).
- KASCADE-Grande Collab. Astroparticle Physics 47, p. 5466 (2013).
- Tunka Collab. NIM in Physics Research A 756, p. 94101 (2014).
- IceCube Collab. PoS (ICRC2015) 334.
- Telescope Array Collab. PoS (ICRC2015) 349.

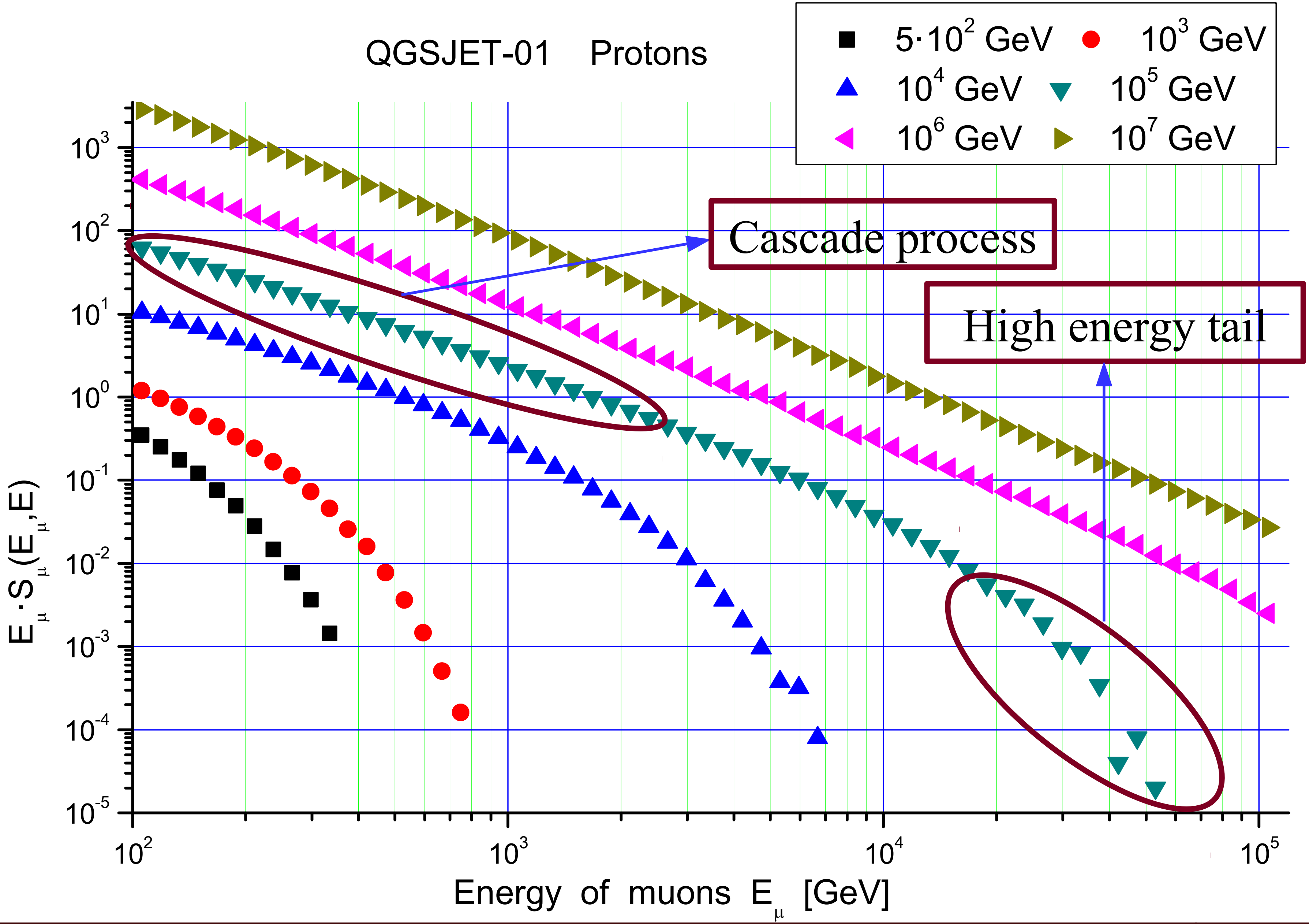
Ingredients for calculations (II)

- We have to obtain the muon muon energy spectra at fixed energies E for various primary particles.

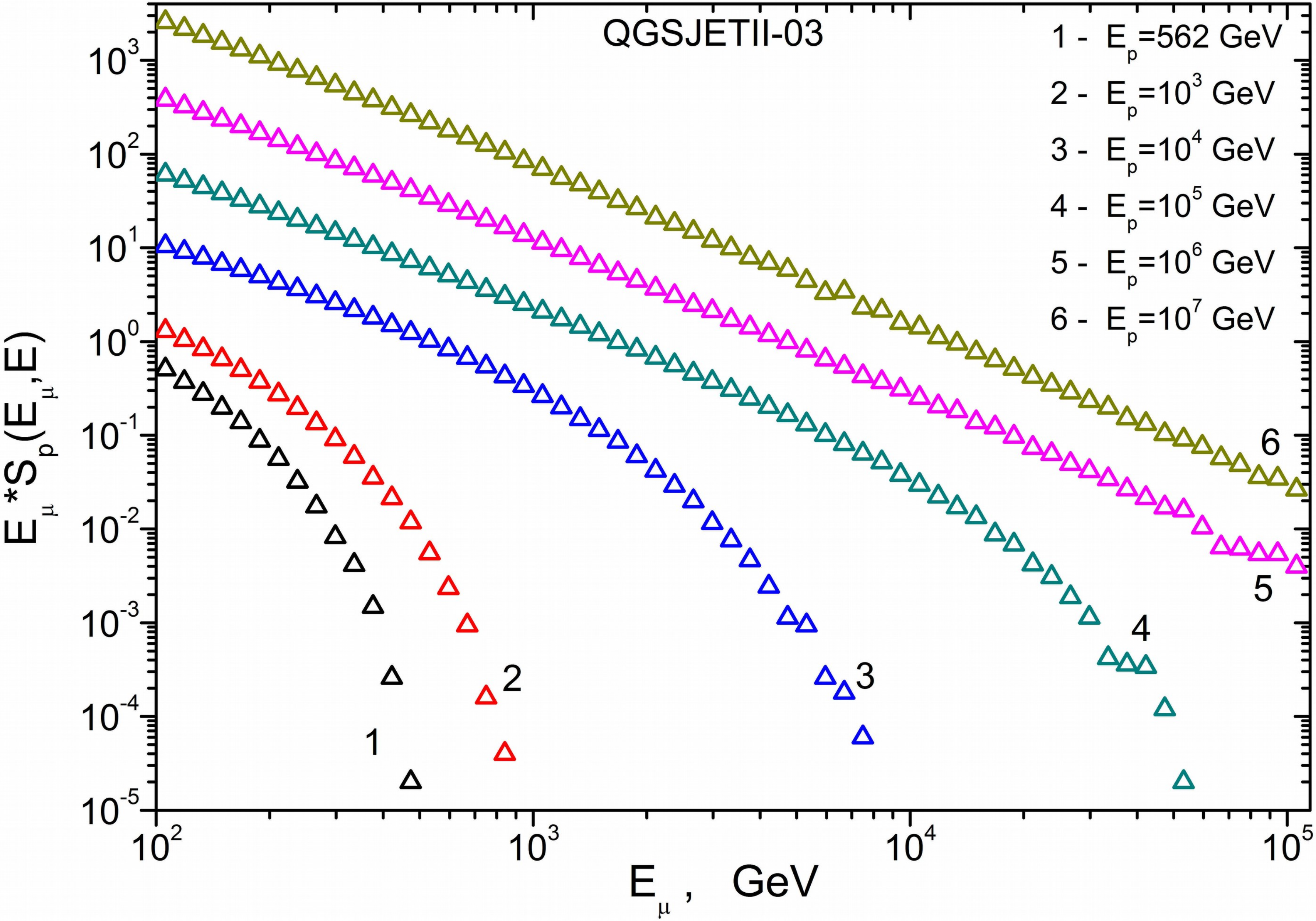
$$S_p(E_\mu, E) \cdot dE_\mu$$

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

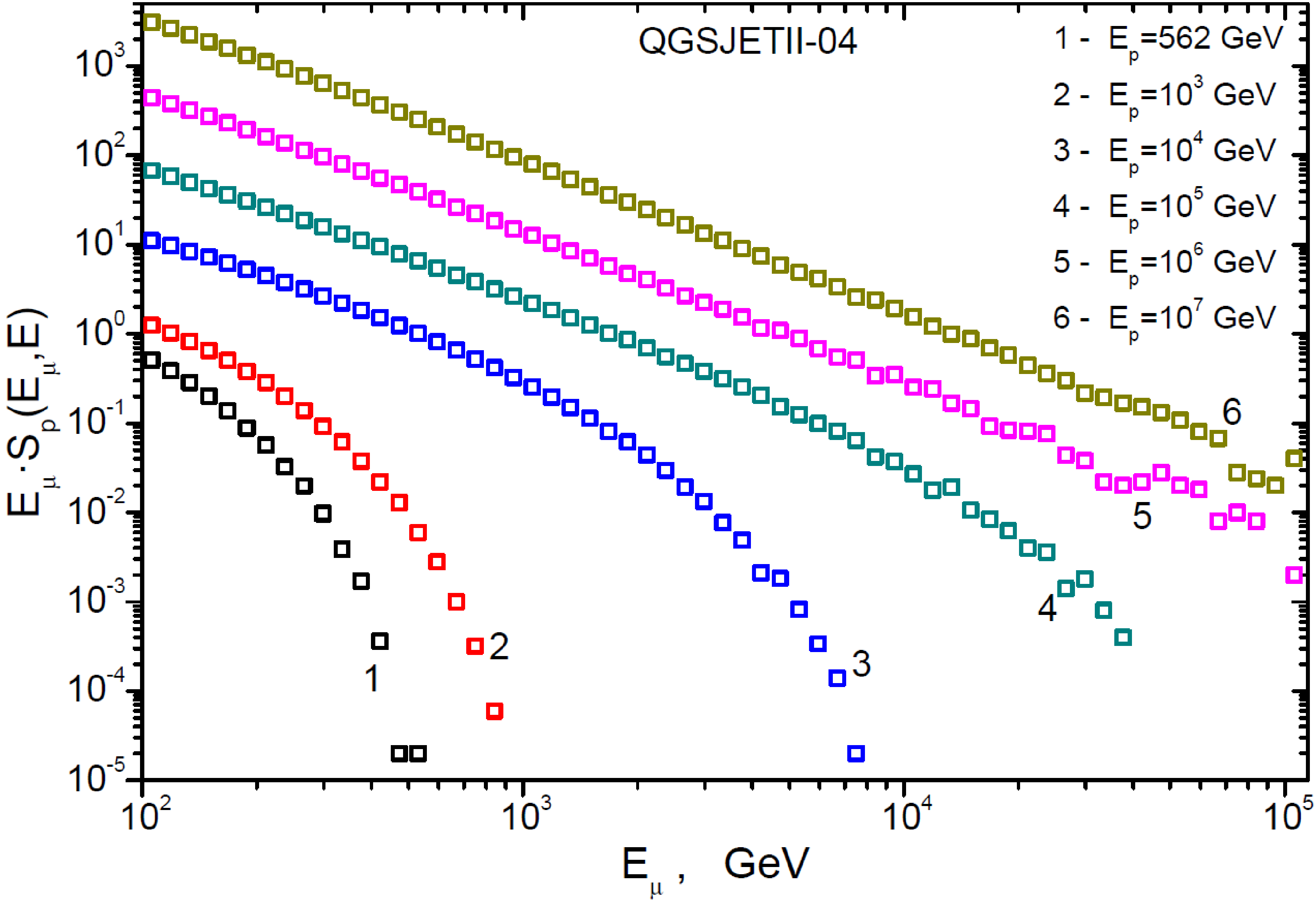
Muon energy spectra at fixed proton energies



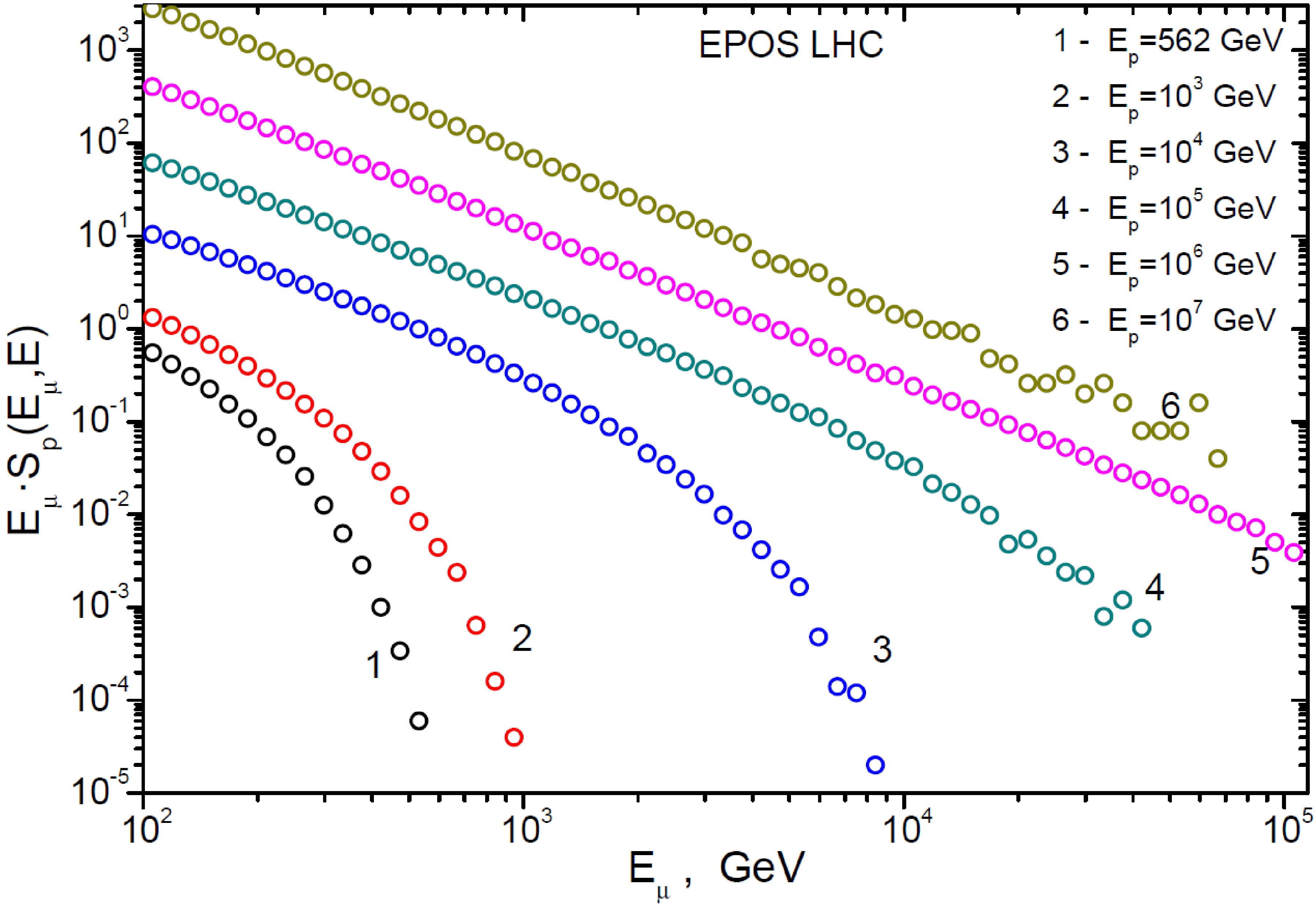
Muon energy spectra at fixed proton energies



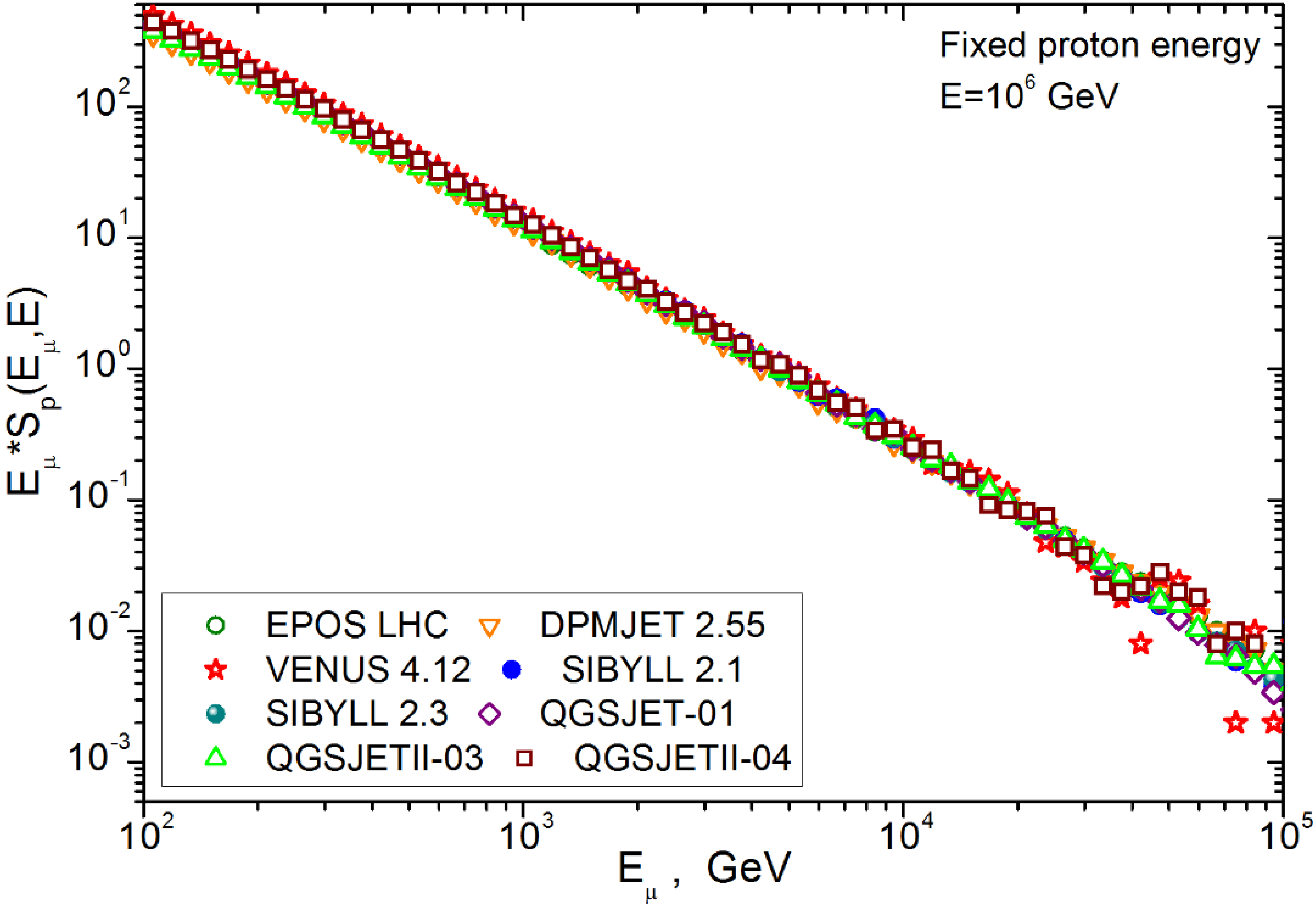
Muon energy spectra at fixed proton energies



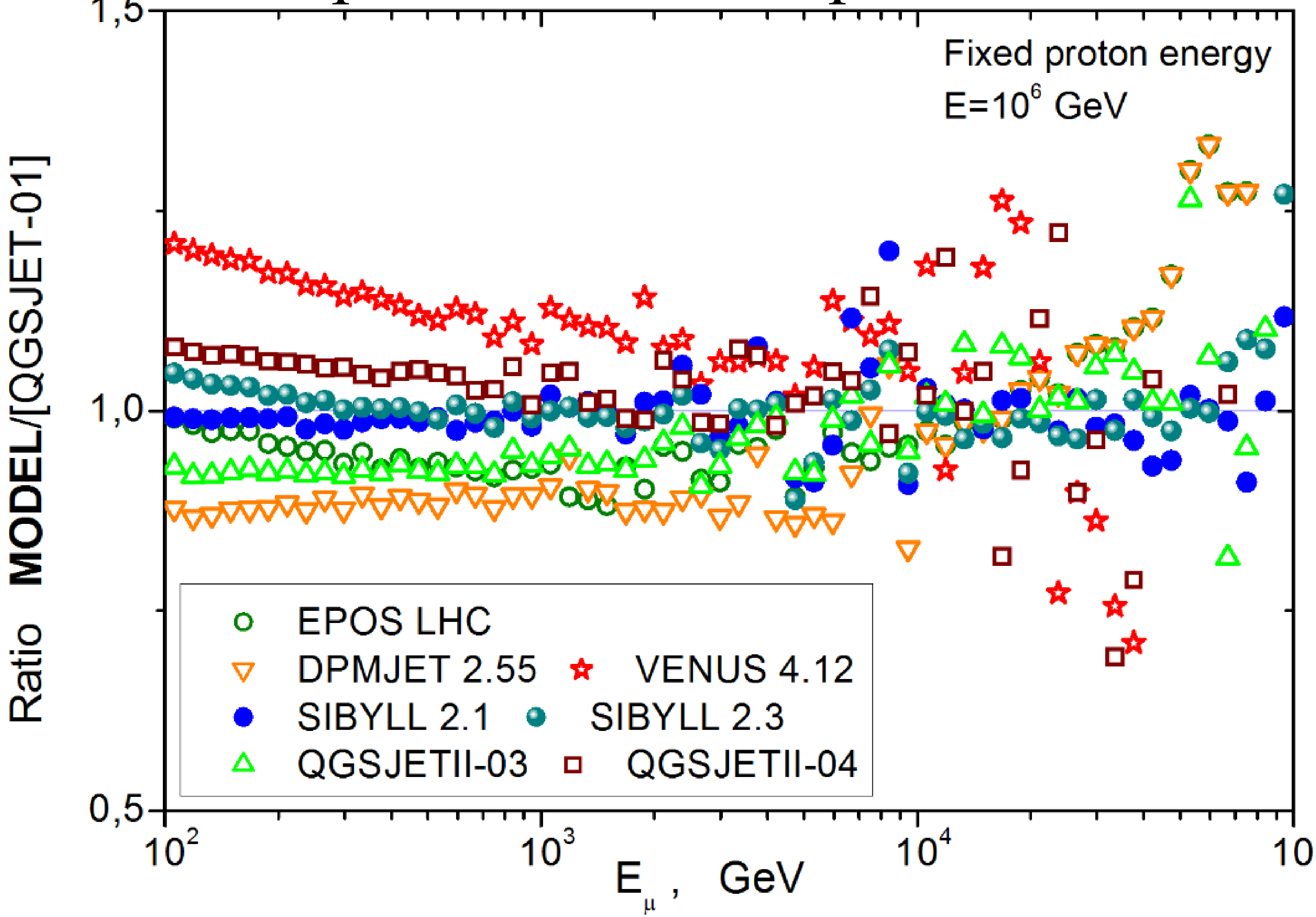
Muon energy spectra at fixed proton energies



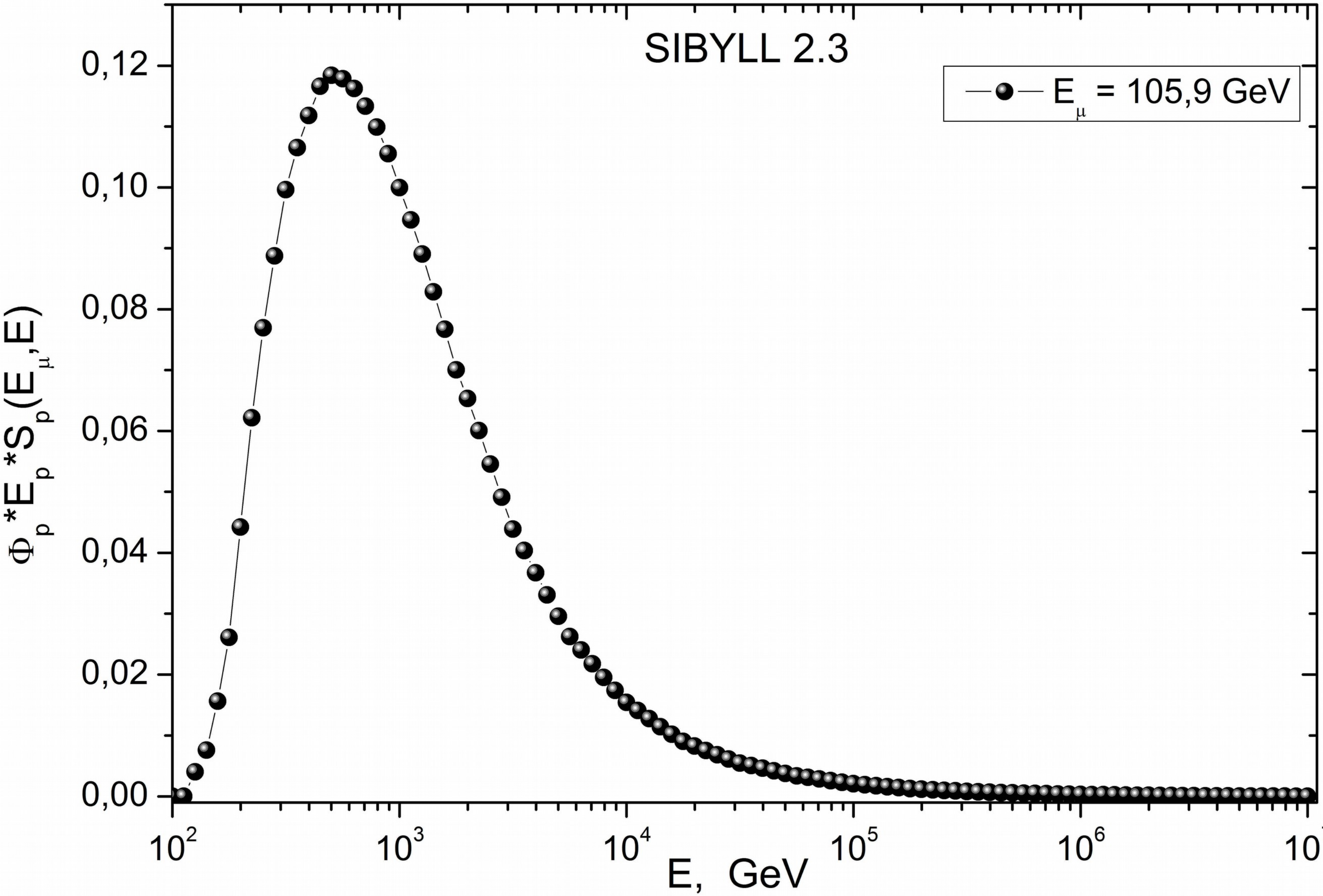
Comparison of model predictions



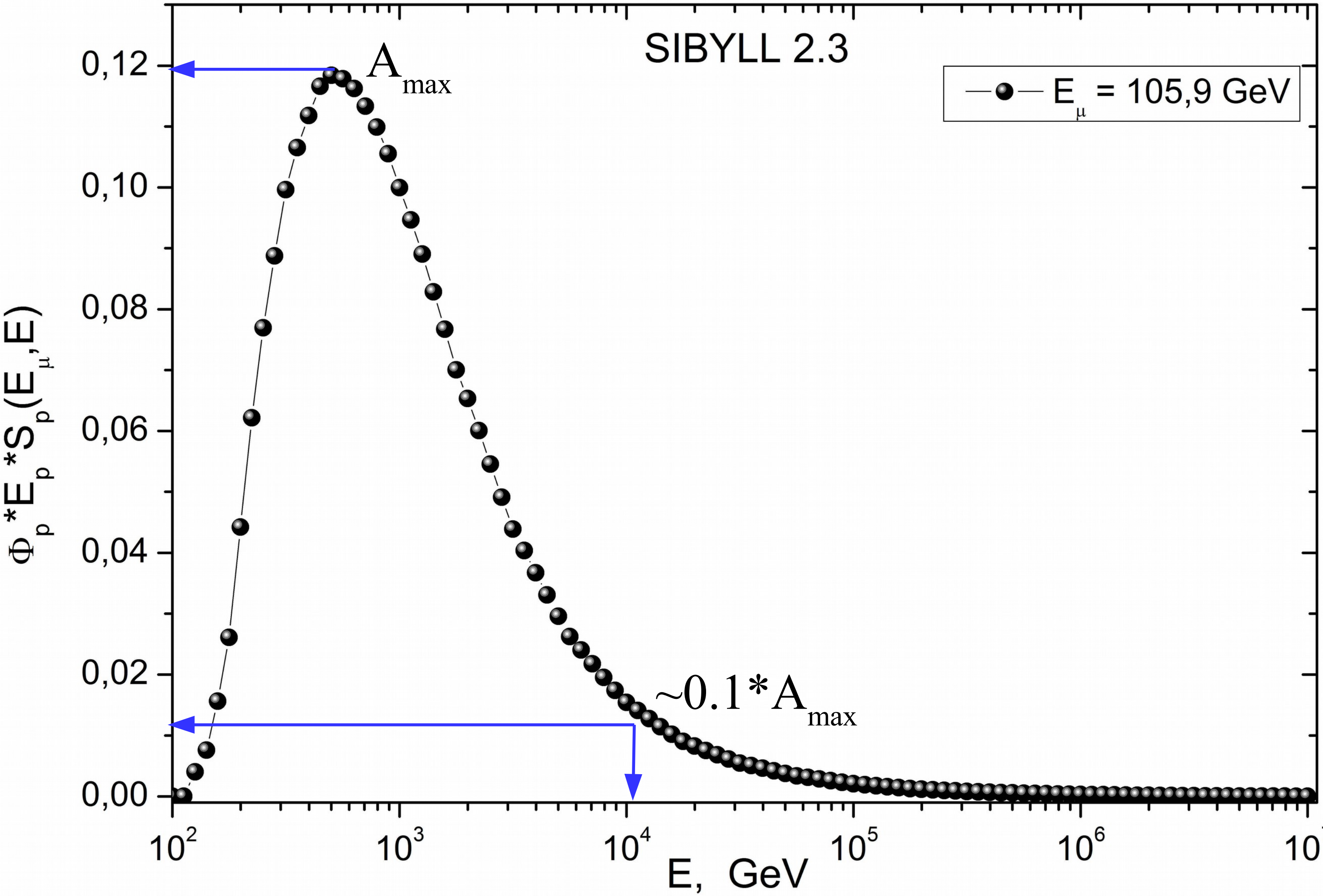
Comparison of model predictions



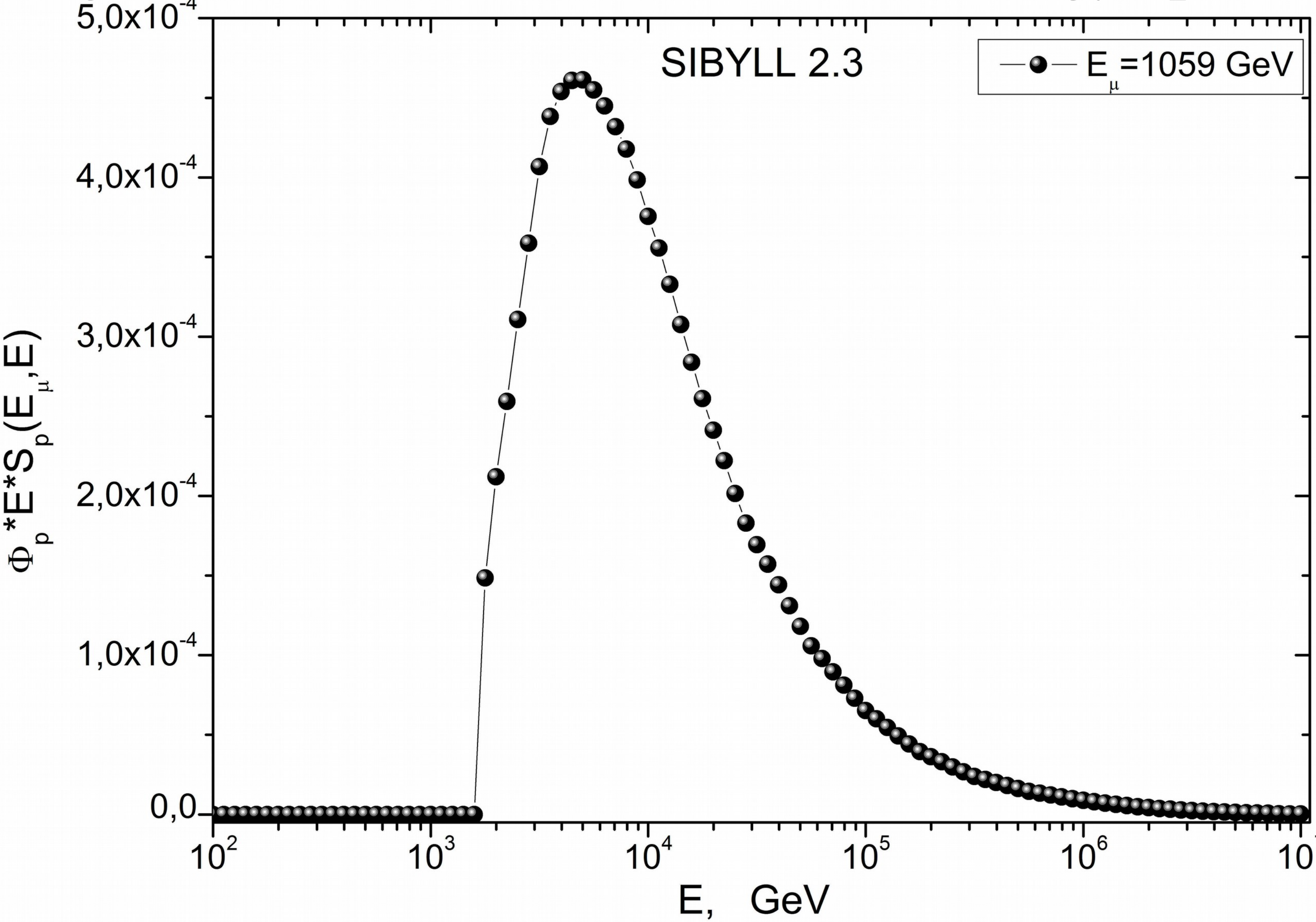
Relative contribution of the primary protons with energies E to the 1-st bin of muon energy spectrum



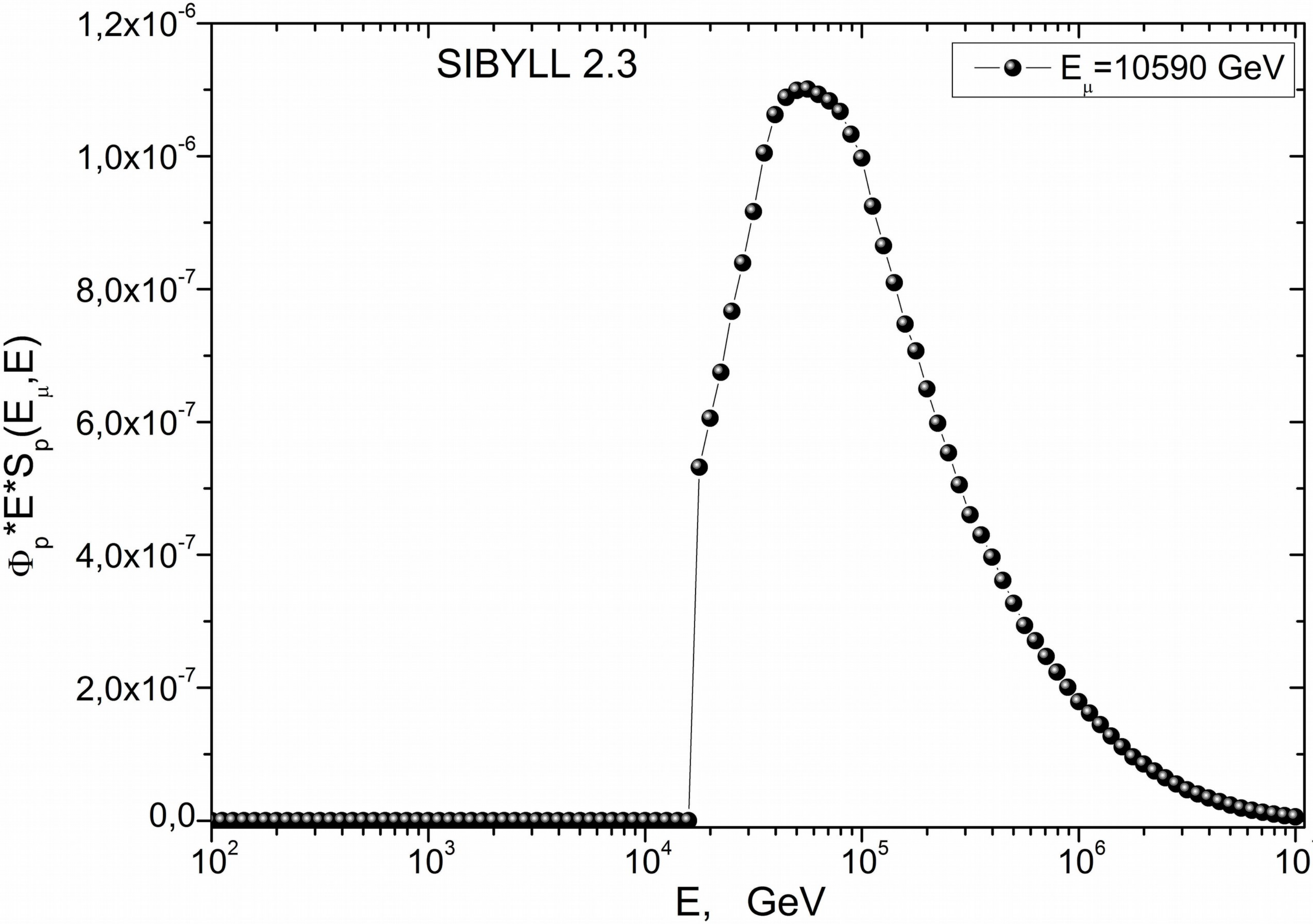
Relative contribution of the primary protons with energies E to the 1-st bin of muon energy spectrum



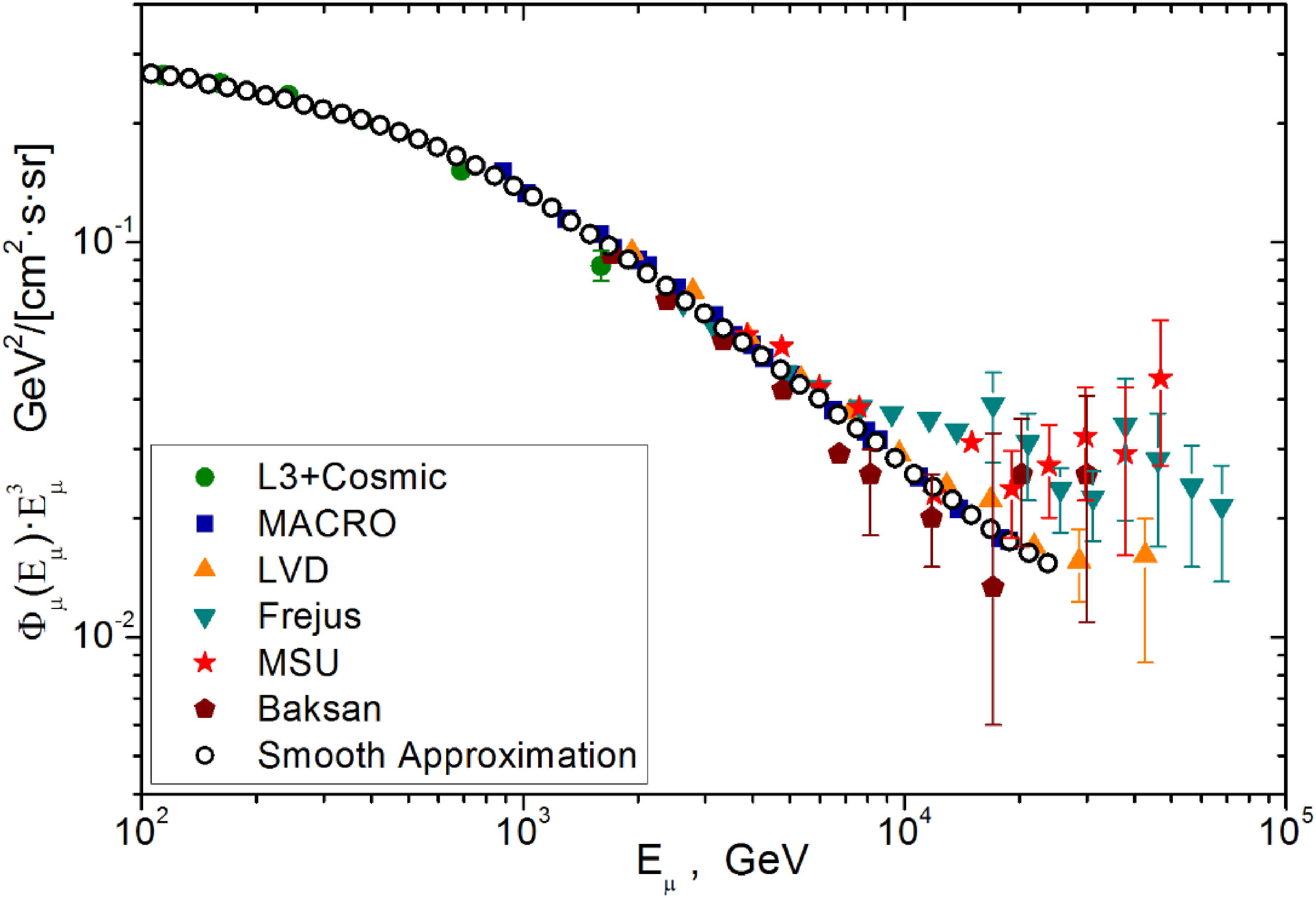
Relative contribution of the primary protons with energies E to the 21-st bin of muon energy spectrum



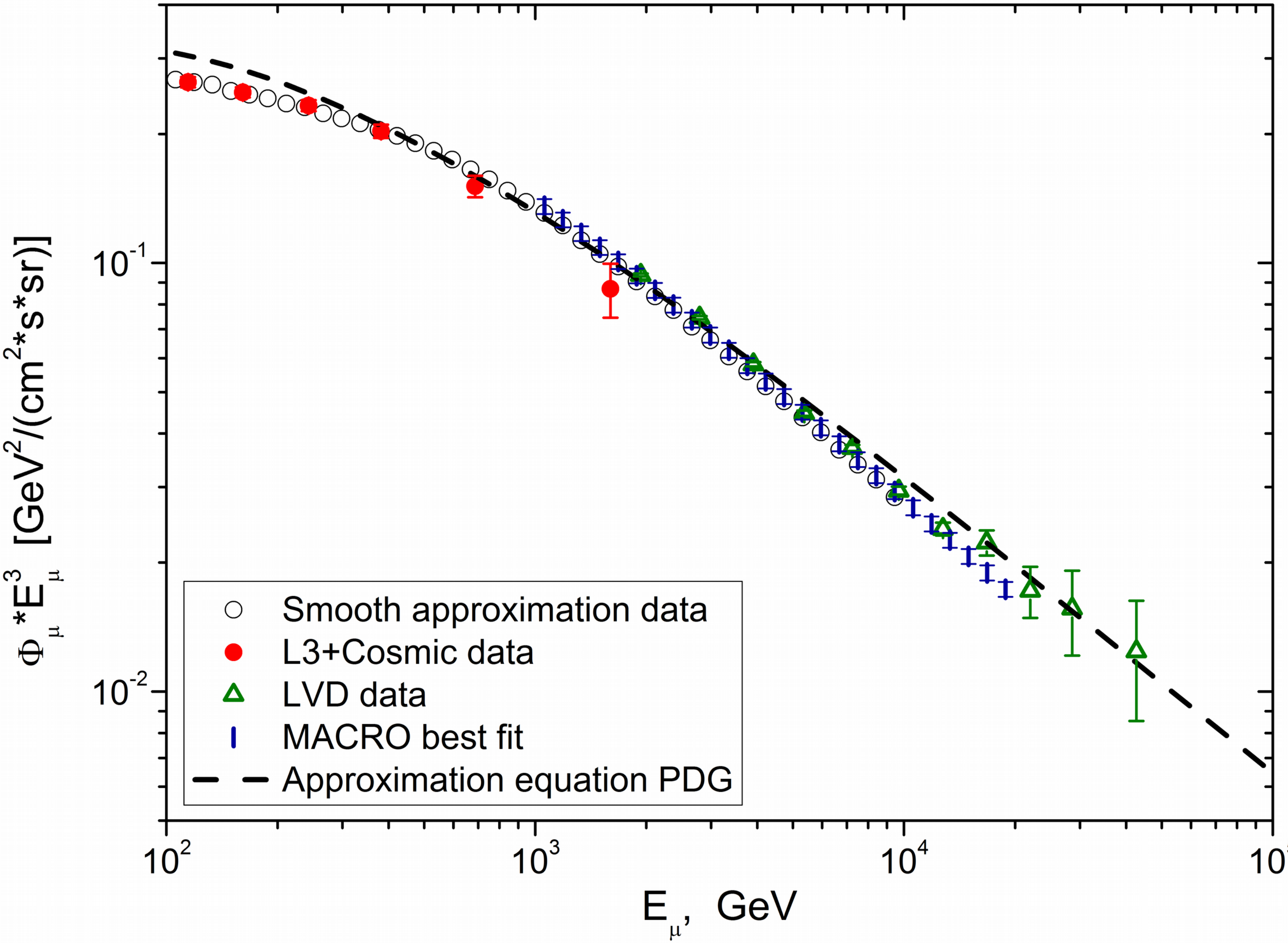
Relative contribution of the primary protons with energies E to the 41-st bin of muon energy spectrum



Muon energy spectrum data



Muon energy spectrum data



Data of the muon spectra

1) L3+Cosmic: Achard P. Adriani O., Aguilar-Benitez M., et al. Phys.Lett. B. **598**, 15-32 [arXiv:hep-ex 0408114v1K] (2004)

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

3) LVD: Aglietta M., Alpat B., Alieva E. D., et al., Phys.Rev. D. **58**, 092005 [arXiv:hep-ex 9806001v1] (1998)

4) Frejus: Rhole W., et al., Nucl. Phys. (Proc. Suppl.) **35**, 250-253 (1994)

5) MSU: Zatsepin G.T., et al. Bull. Russ. Acad. Sci. Phys. **58**, 2050-2052 (1994)

6) Baksan: Bakatanov V.N., et al., Phys. Atom. Nucl. Vol. **55**, 8, pp. 2107-2116 (1992)

Comparison

- Energy spectrum of vertical muons

<u>Smooth approximation</u>

<u>Experimental data:</u>

L3+Cosmic

MACRO

LVD

<u>CORSIKA simulations:</u>

EPOS LHC

QGSJET-01

QGSJET II-03

QGSJET II-04

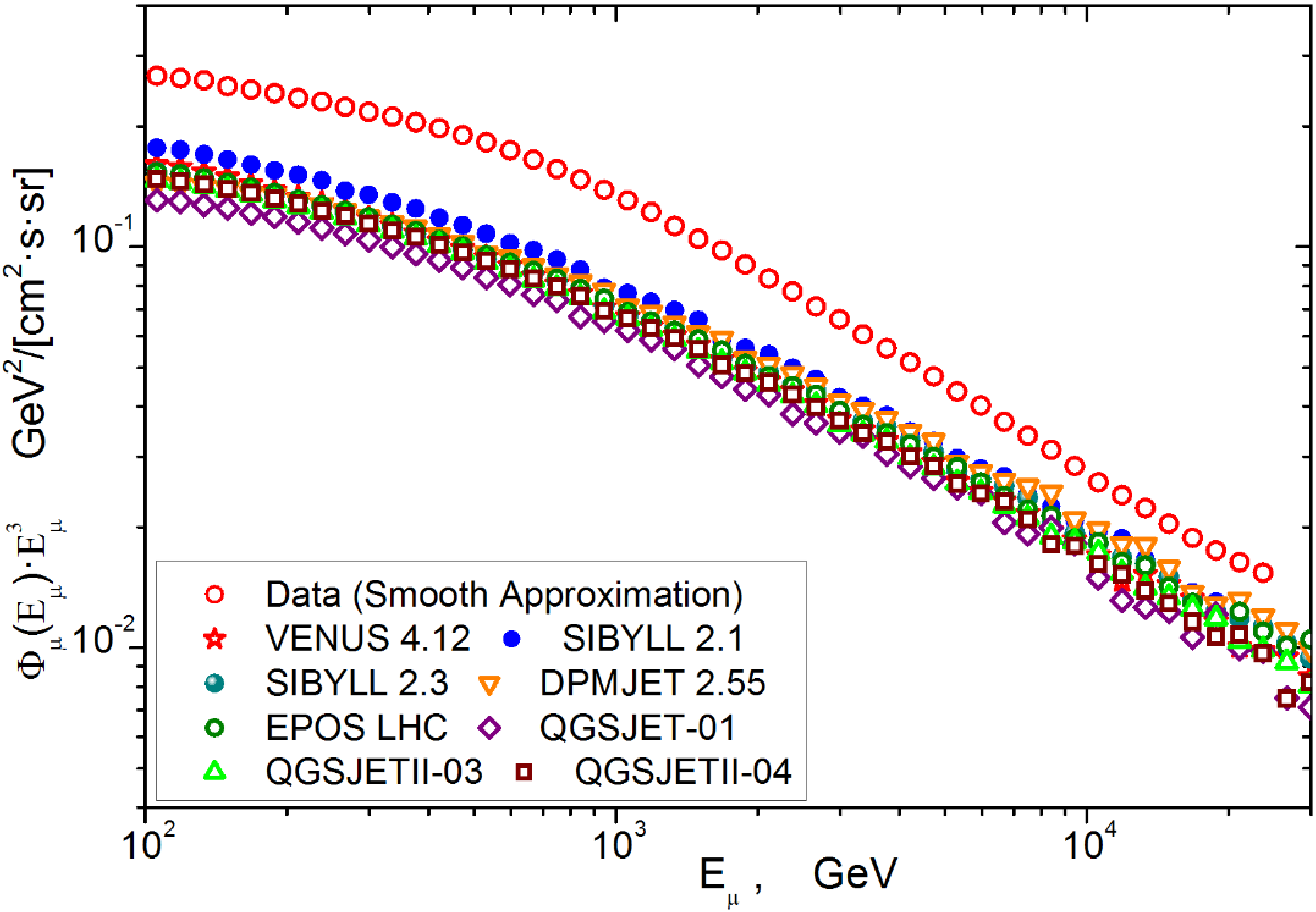
DPMJET 2.55

VENUS 4.12

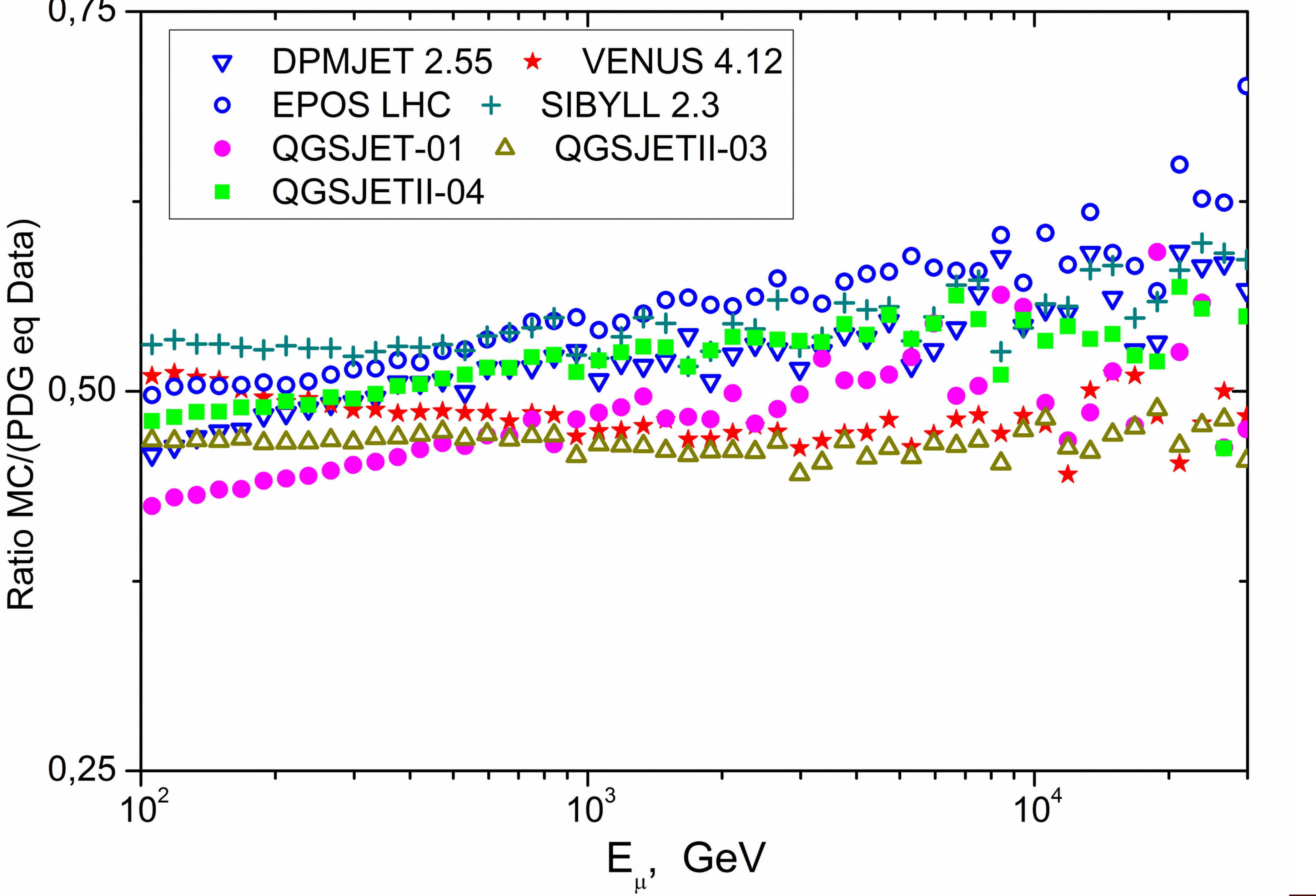
SIBYLL 2.1

SIBYLL 2.3

Muon fluxes (data and simulations)



Result of calculations (MC/Data)



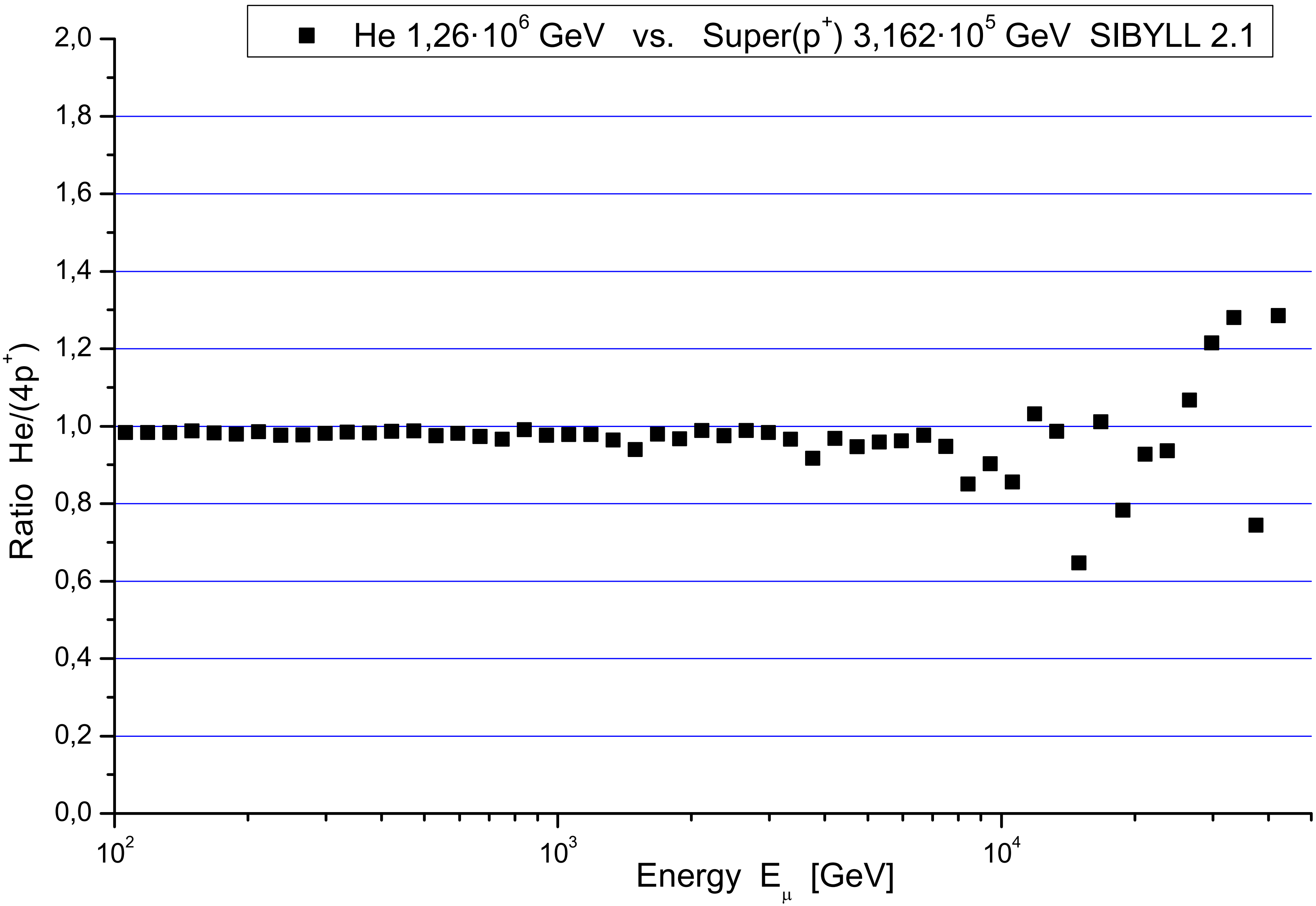
Conclusion

- Prediction of the models EPOS LHC, QGSJET-01, QGSJETII-03, QGSJETII-04, DPMJET 2.55, VENUS 4.12, SIBYLL 2.1 and SIBYLL 2.3 for the muon energy spectrum are below data by a factor of ~1.5-2 (at the range $\sim 10^2$ — 10^4 GeV).
- Model production of the most energetic $\pi^{\pm}$ and $K^{\pm}$ mesons with rapidities $y \in 8$—12 needs to be incresed by ~2 times. (Lomonosov-2022 https://lomonosov-msu.ru/rus/event/schedule/1246)

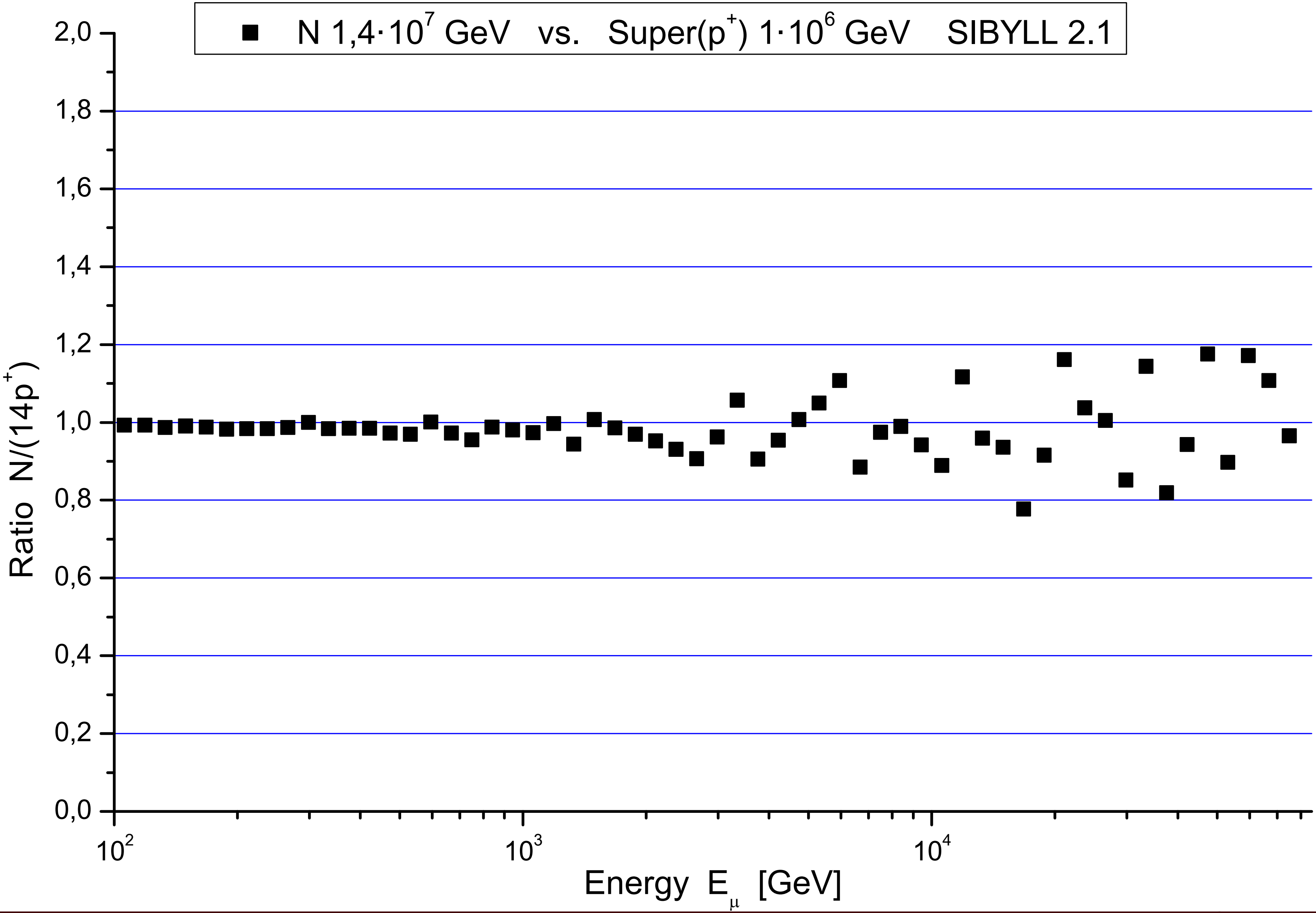
Thank you for attention!

Backup slides

Superposition conception (result for SIBYLL)

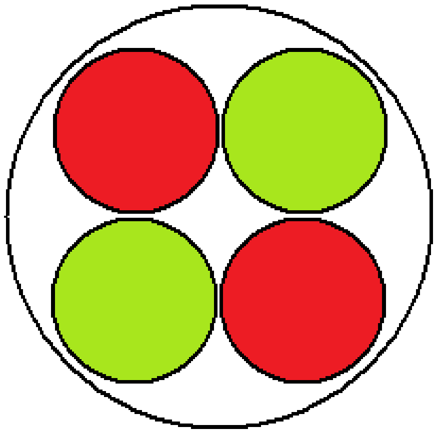


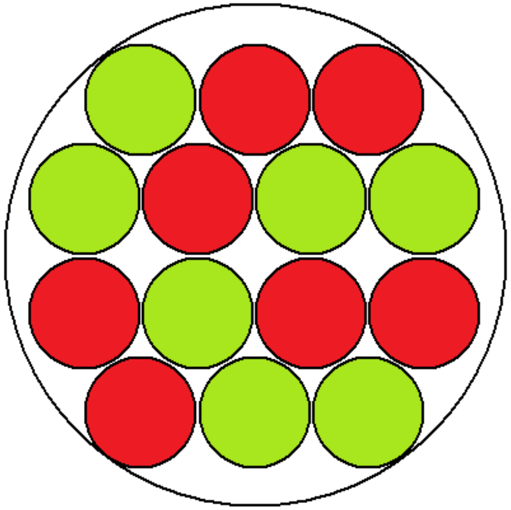
Superposition conception (result for SIBYLL)



Superposition conception

- Helium nuclei (A=4) and nitrogen nuclei (A=14) is a systems of A nucleons.
- Dedenko L.G., Zatsepin G.T., Proceedings of the 6-th ICRC, Moscow, Vol. II, Extensive air showers and cascades process, 201-208 (1960).

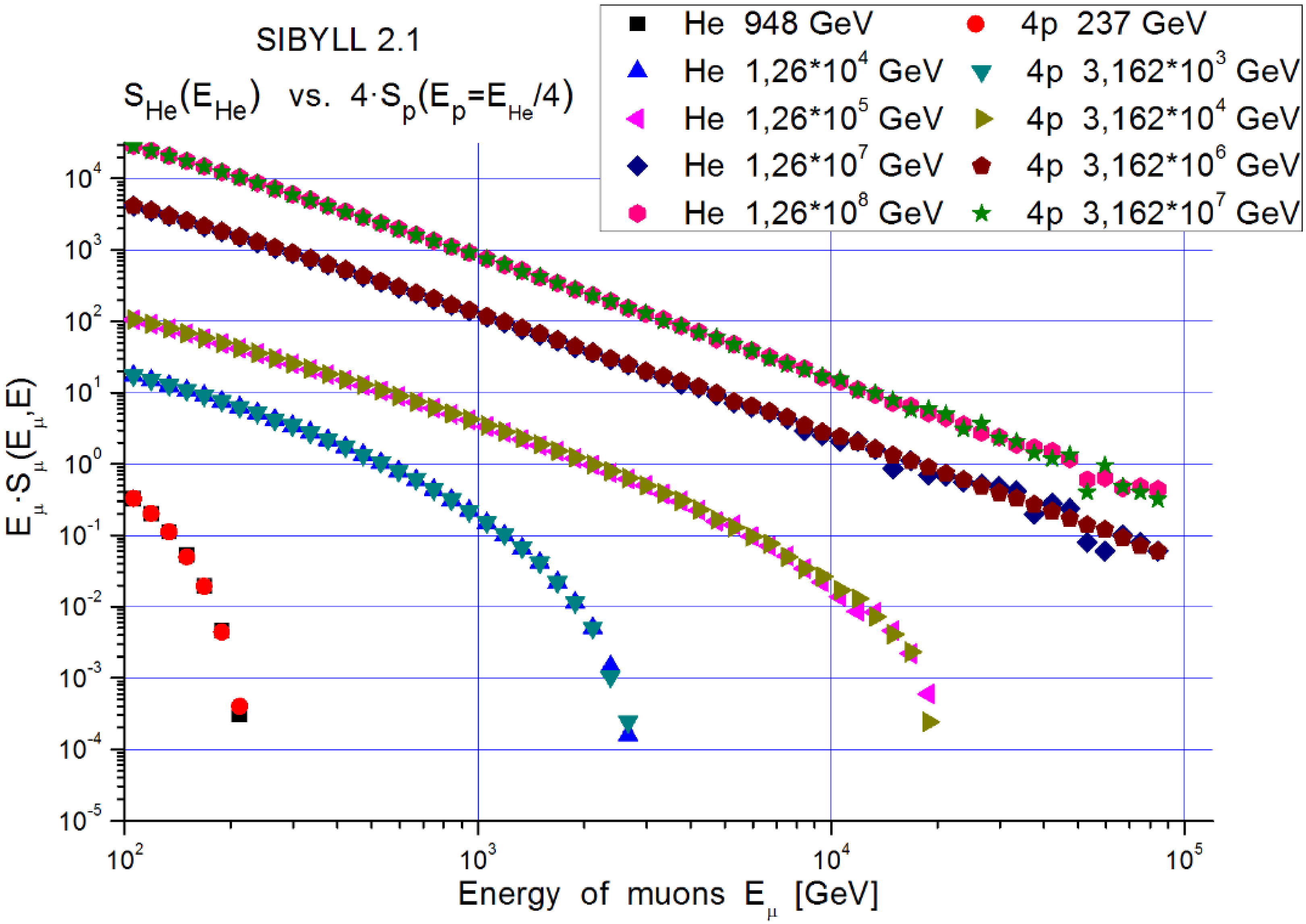




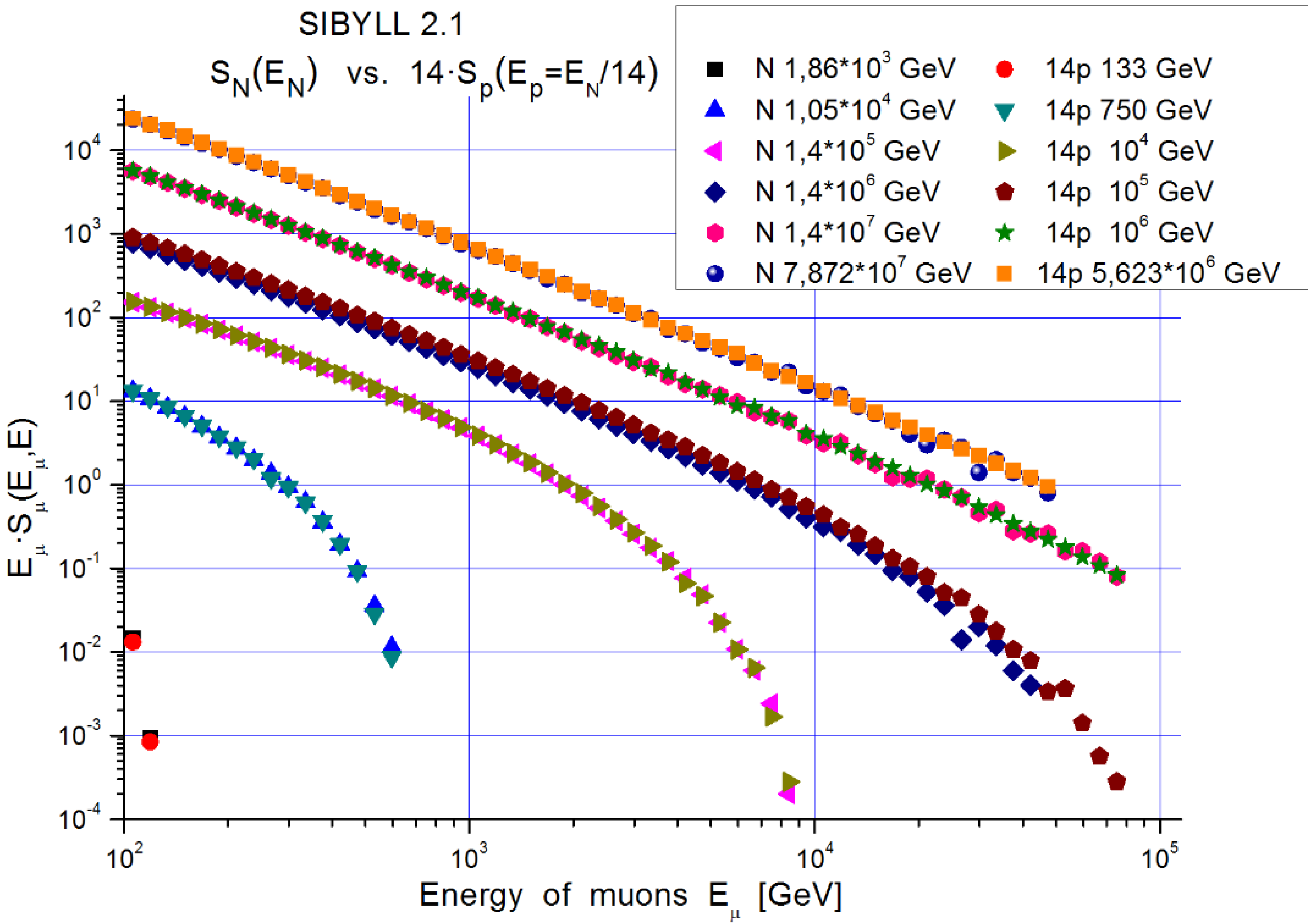
$$S_{He}(E_\mu, E_{He}) \approx 4 \cdot S_p\left(E_\mu, E_p = \frac{E_{He}}{4}\right)$$

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

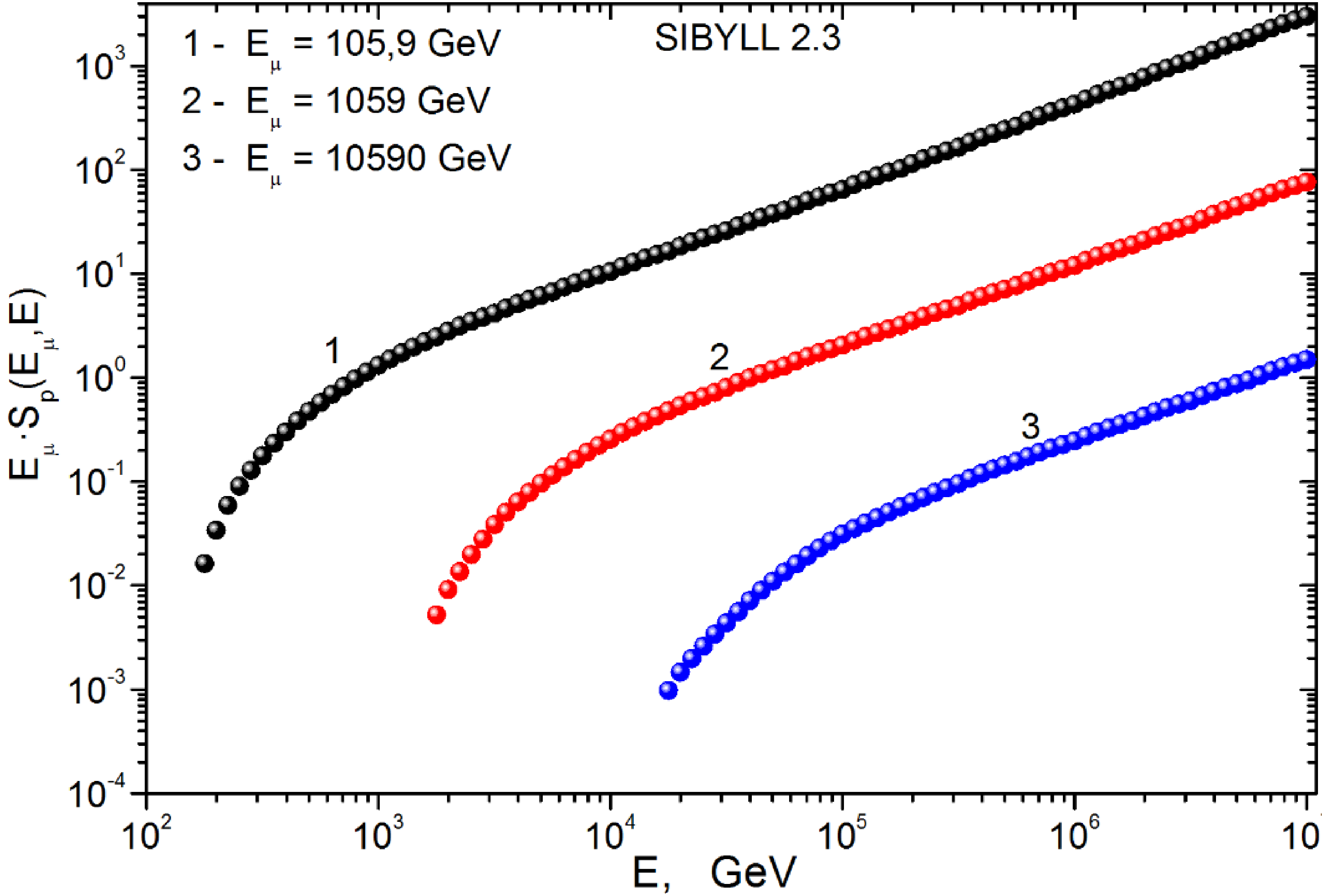
Superposition



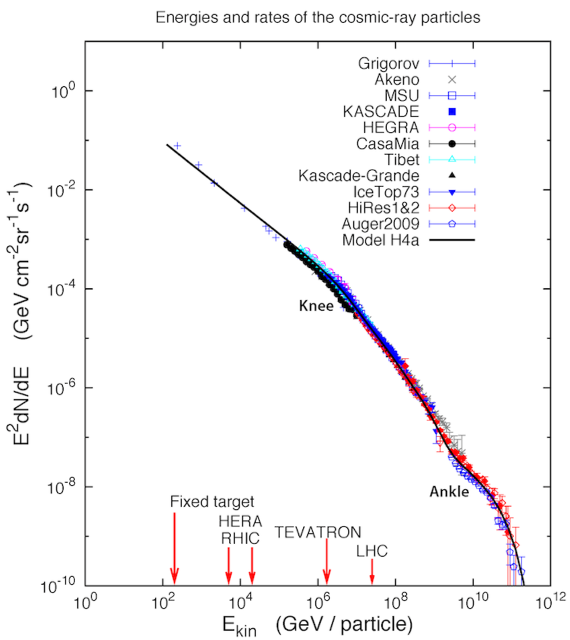
Superposition



Contribution to the muons generation with fixed energies

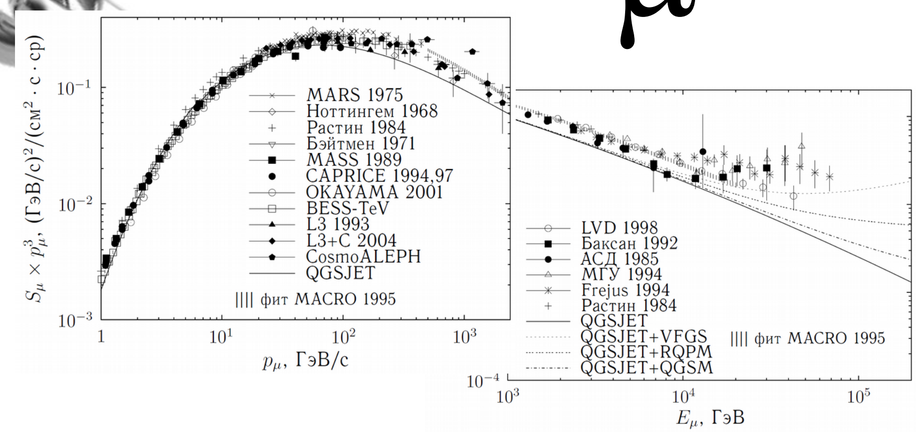


Important interlink



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

μ



Cosmic Rays Data

- Aguilar M., Aisa D., Alpat B., et al, (AMS Collab.) P.R.Lett. Vol. 114, 171103 (2015); P.R.Lett. Vol. 115, 211101 (2015).
- Adriani O., Barbarino G. C., Bazilevskaya G. A., et. al., (PAMELA Collab.) Advances in Space Research Vol. 51, 219-226 (2013).
- Panov A. D., Adams J. H., Ahn H. S. et al. (ATIC Collab.), Bull. Russ. Acad. Sci. Phys. Vol. 71, 494 (2007); Bull. Russ. Acad. Sci. Phys. Vol. 73, 564 (2009).
- Ahn H. S. Allison P., Bagliesi M. G., et al (CREAM Collab.), , Astrophys.J., 707, 593 (2009).
- Bartoli B., Bernardini P., Bi X., et al (ARGO-YBJ Collab.) Phys. Rev. D 91, 11, 112017; arXiv:1503.07136 (2015); Chinese Physics C 38, 4, 045001 (2014); Di Sciascio G. et al, J. of Physics: Conf. Series 632, 012089 (2015).
- Antoni T., Apel W. D., Badea A. F., et al., (KASCADE Collab.) Astroparticle Physics 24, p. 125 (2005).
- Apel W. D., Arteaga-Velazquez J. C., Bekk K., et al., (KASCADE-Grande Collab.) Astroparticle Physics 47, p. 5466 (2013).
- Prosin V. V., Berezhnev S. F., Budnev N. M., et al., (Tunka Collab.) Nuclear Instruments and Methods in Physics Research A 756, p. 94101 (2014).
- Rawlins K., Feusels T., et al., (IceCube Collab.) PoS (ICRC2015) 334.
- Ivanov D., et al., (Telescope Array Collab.) PoS (ICRC2015) 349.

Approximation of primary CR spectra

- Berezhko E.G. Nucl. Phys. B (Proc. Suppl.) Vol. 256 - 257, 2335 (2014);
- Berezhko E.G., Knurenko S.P., Ksenofontov L.T., Astropart. Phys. Vol. 36 3136 (2012).
- Dedenko L.G., Lukyashin A.V., Roranova T.M. and Fedorova G.F., Proceedings of International Symposium on Cosmic Rays and Astroparticles 2017, http://iscra2017.mephi.ru/content/public/files/presentations/June20_Presentation_13_LukyashinAV.pdf

Modern Satelite Experiments

- The DAMPE collaboration (DArk Matter Particle Explorer) http://dpnc.unige.ch/dampe/index.html
- The Fermi-LAT collaboration (The Fermi Large Area Telescope) http://www-glast.stanford.edu/
- The CALET collaboration (CALorimetric Electron Telescope) http://calet.jp/en/
- The ISS-CREAM collaboration (Cosmic Ray Energetics and Mass Experiment for International Space Station) http://cosmicray.umd.edu/iss-cream/collaboration
- The NUCLEON collaboration http://nucleon.sinp.msu.ru/files/index.html