Testing of the EPOS LHC, QGSJET-01, QGSJETII-03 and QGSJETII-04 hadronic interaction models via help of the atmospheric vertical muon spectra

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ITEP NRC «KI»

NRNU «MEPhI»

MEPhI ICPPA 2017

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2. Motivation
3. Method of testing
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5. Aproximation of primary spectrum (original)
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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 normal atmospheric conditions.

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

- It should be noted that for many decades the muon spectrum has been used to restore the primary cosmic ray spectra.
- Now there are very precise measurements of the primary cosmic ray spectrum.
- With give a marveles opportunity to test hadronic interaction model by comparing predictions of muon spectra with data.

Method

- Package CORSIKA and new approximation of primary cosmic rays has ben used to estimate the muon energy spectra $D(E_\mu)$. Models EPOS LHC, QGSJET-01, QGSJETII-03 and QGSJETII-04 has been used.
- 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 $(0{,}01\text{-}1)\cdot E_0$
- The calculations of E.G. Berezhko & H.J. Völk has been exploited for the approximation of primary cosmic rays.

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 $D(E_\mu)$ 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.

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

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).

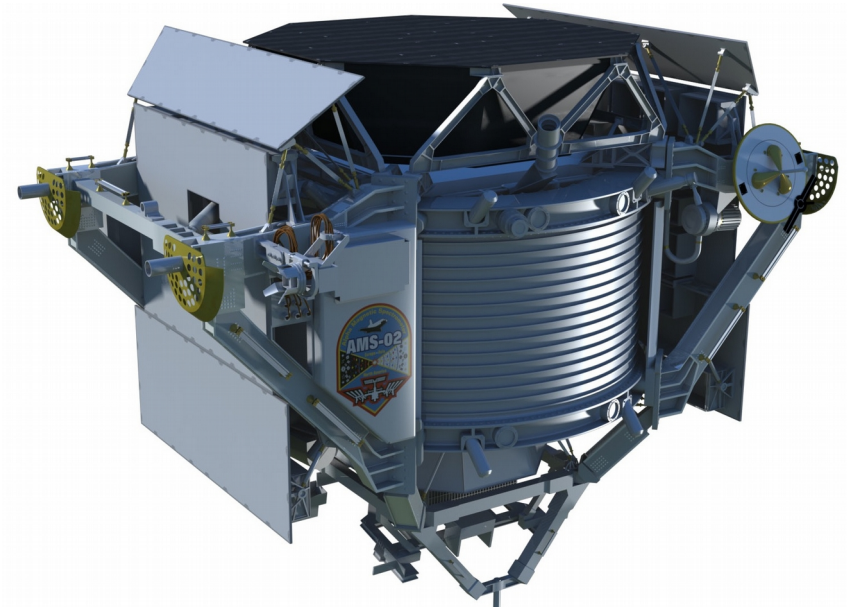
Accessing the database

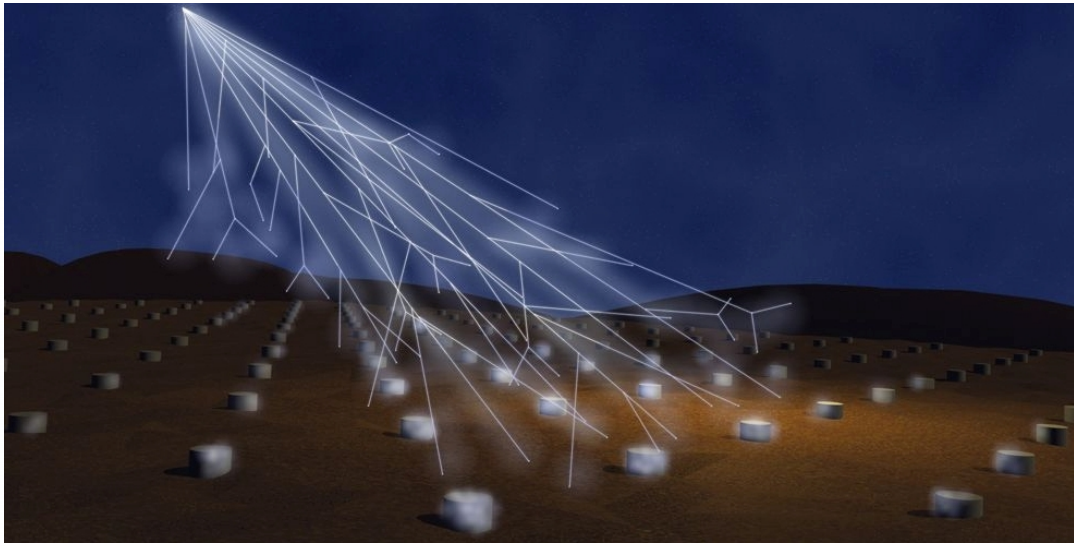
- Experiments/Data: list of experiments, publications, data
- Data extraction: selection by flux/ratio/energy range... (on this web site or via a REST interface)
- Export database content in USINE or GALPROP compliant format (ASCII files)
- Get all bibtex entries and Latex cite (by sub-experiment)

Acknowledgements: this project has been financially supported by the PNHE

Maurin D., Melot F., Taillet R., Astronomy & Astrophysics, 569, A32 (2014).

Primary cosmic rays data





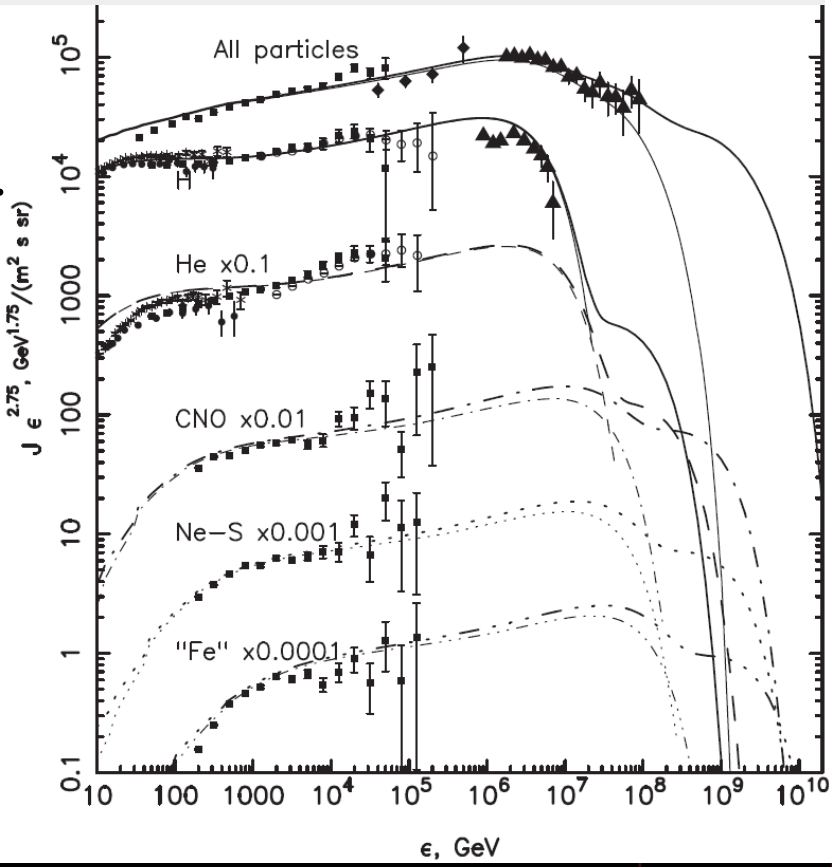
- AMS-02
- ATIC-2
- CREAM
- PAMELA

- ARGO-YBJ
- ARGO&WFCTA
- KASCADE
- KASCADE-Grande
- IceCube
- 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»

Compilation of approximation

1) Direct experiment: lpsc.in2p3.fr/crdb/
2) Calculations by E.G. Berezhko & H.J. Völk: 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)...
3) Take into account the «knee» of CR spectrum.



Approximation (p)

Equation for flux of the primary protons.

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

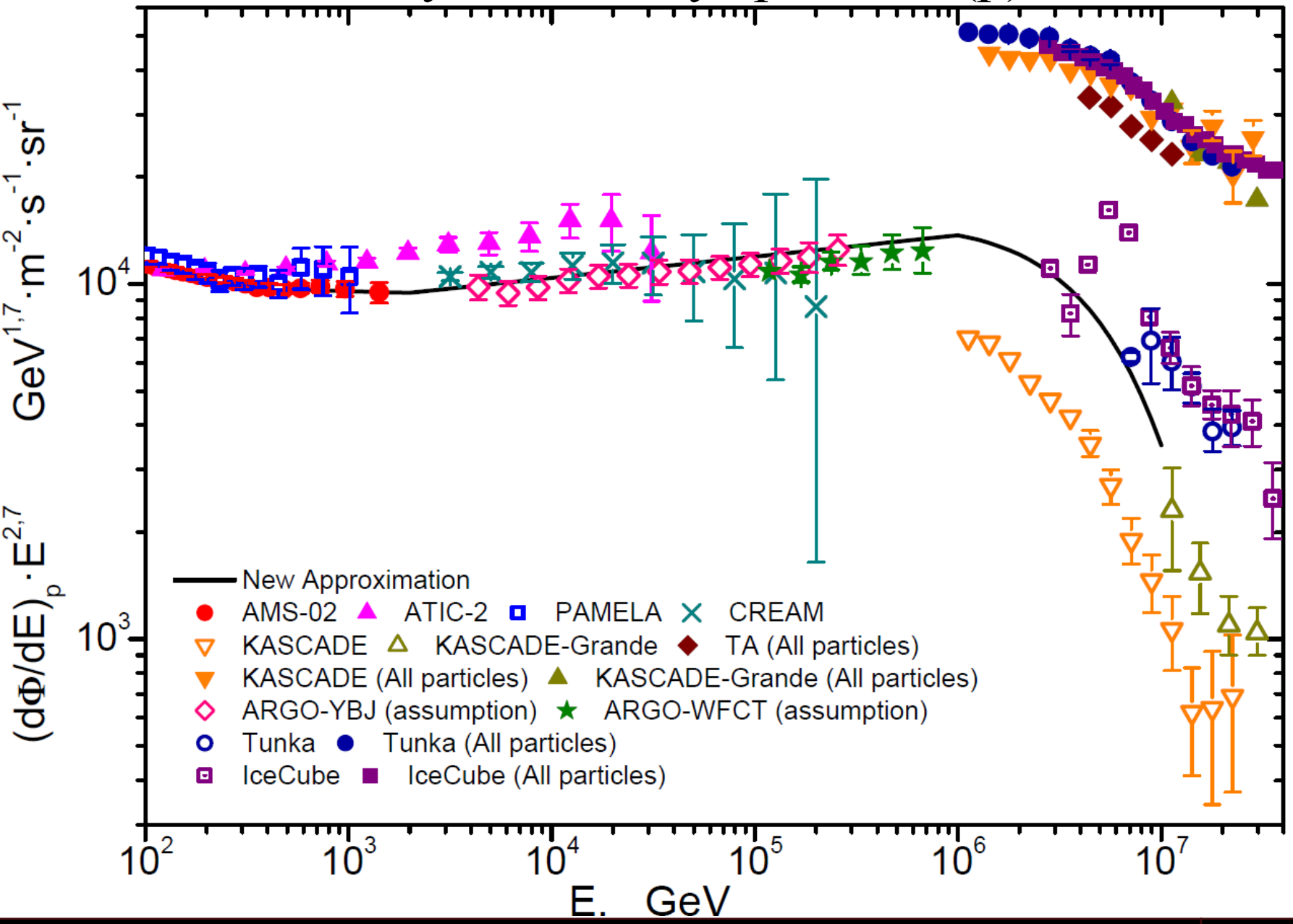
Approximation (He)

Equation for flux of nucleons of the primary helium nuclei.

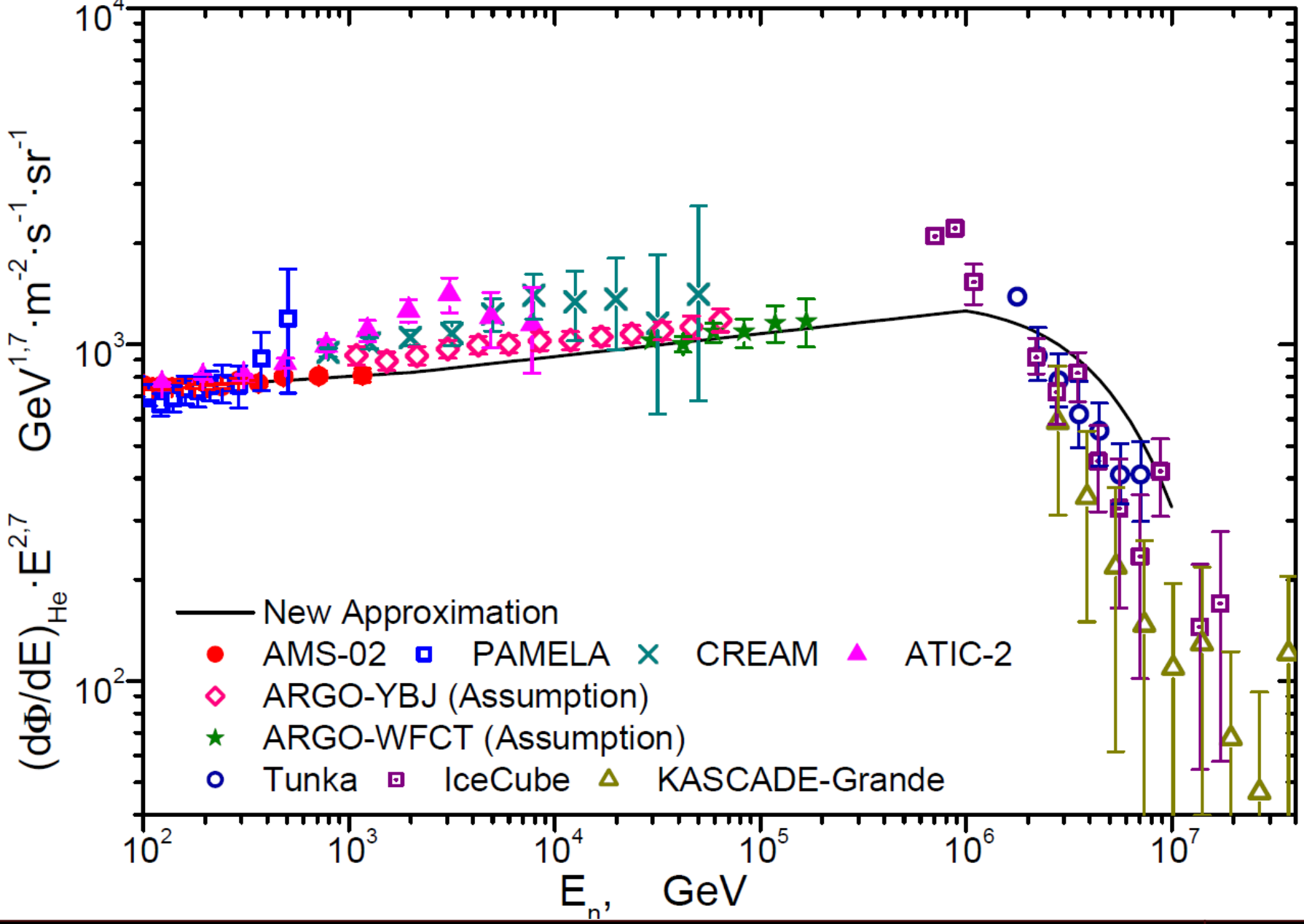
E — energy ner nucleon.

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

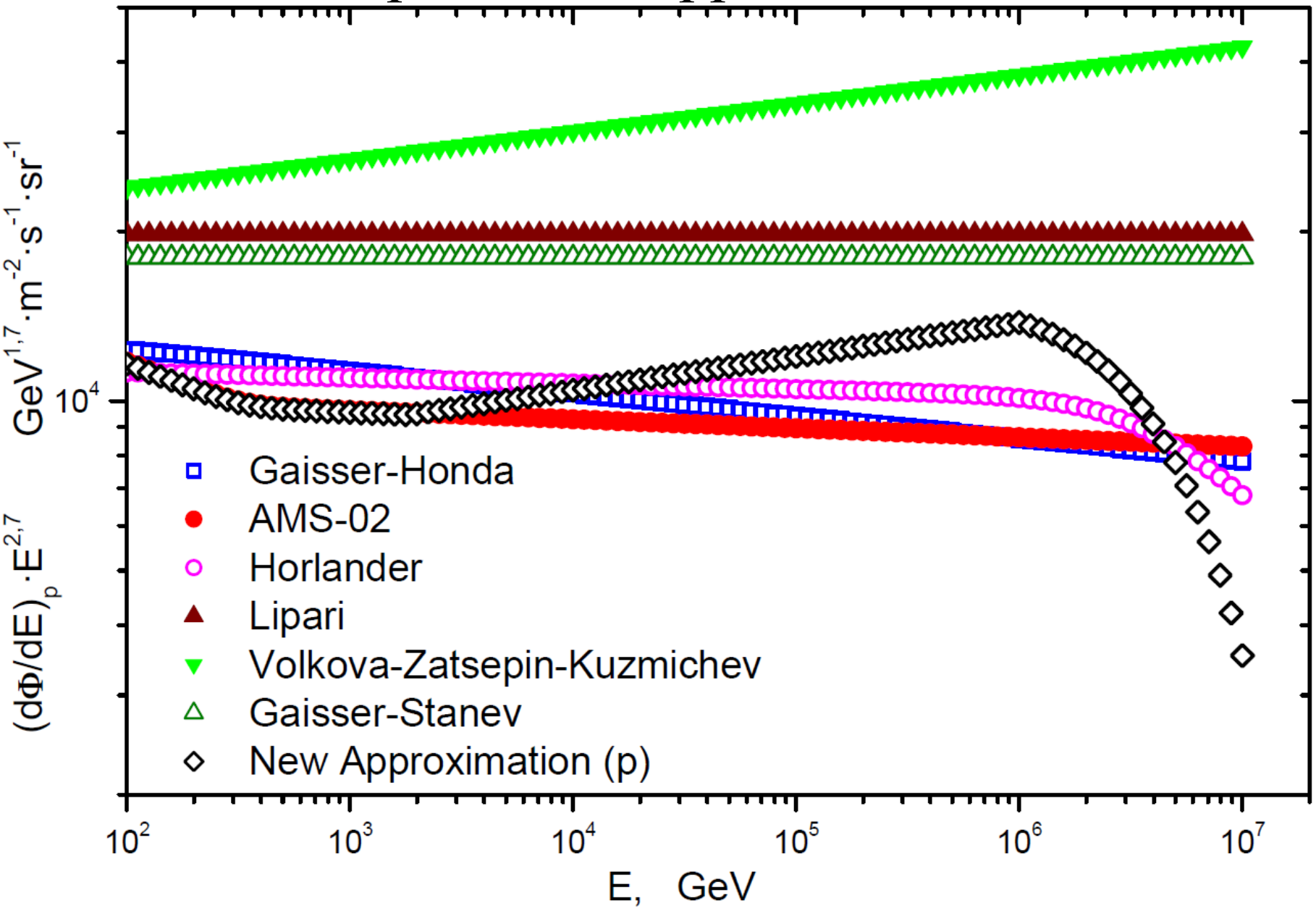
Primary cosmic ray spectrum (p)



Primary cosmic ray spectrum (He)



Comparison of approximations



Data of approximations

- Protons

  ● - Extrapolation of the AMS data: M. Aguilar, D. Aisa, B. Alpat, et al., Phys. Rev. Lett. 114, 171103 (2015).

  ▫ - Gaisser-Honda: T.K. Gaisser, M. Honda, Ann. Rev. Nucl. Part. Sci. 52, 153-199 (2002).

  ○ - Horlander: J.R. Hörlander, Astroparticle Physics 19 Pp. 193–220; astro-ph/0210453v1 (2003).

- Nucleons

  △ - Gaisser-Stanev: G. Barr,T.K. Gaisser, T. Stanev, Phys. Rev. D. 39, 3532 (1989).

  ▲ - Lipari: P. Lipari, Astroparticle Physics 1 Pp. 195–227 (1993).

  ▼ - Volkova-Zatsepin-Kuzmichev: L.V. Volkova, G.T. Zatsepin, L.A. Kuzmichev, Soviet Journal of Nuclear Physics-USSR, 29, N 5, pp. 645-651 (1979).

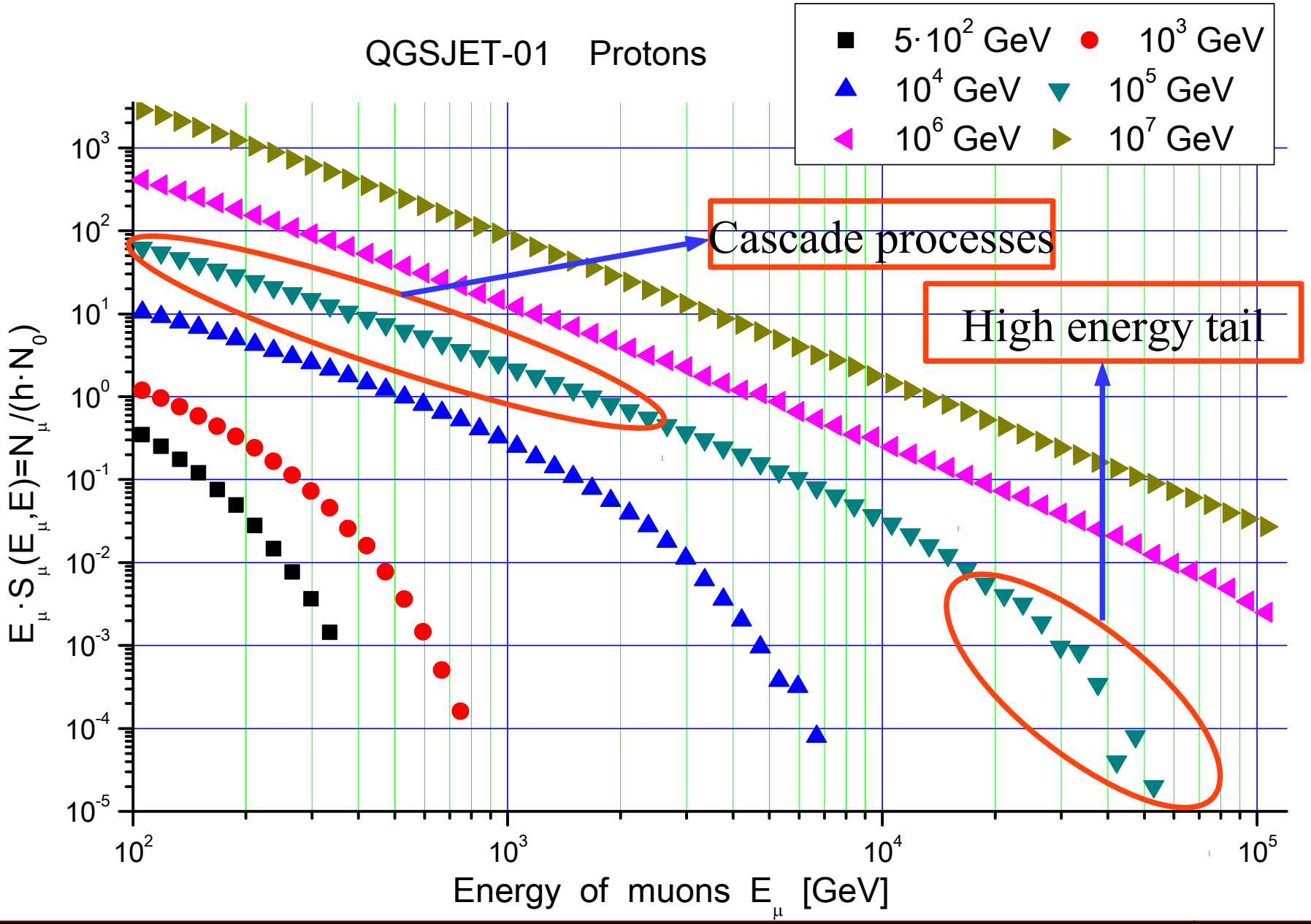
Ingredients for calculations (II)

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

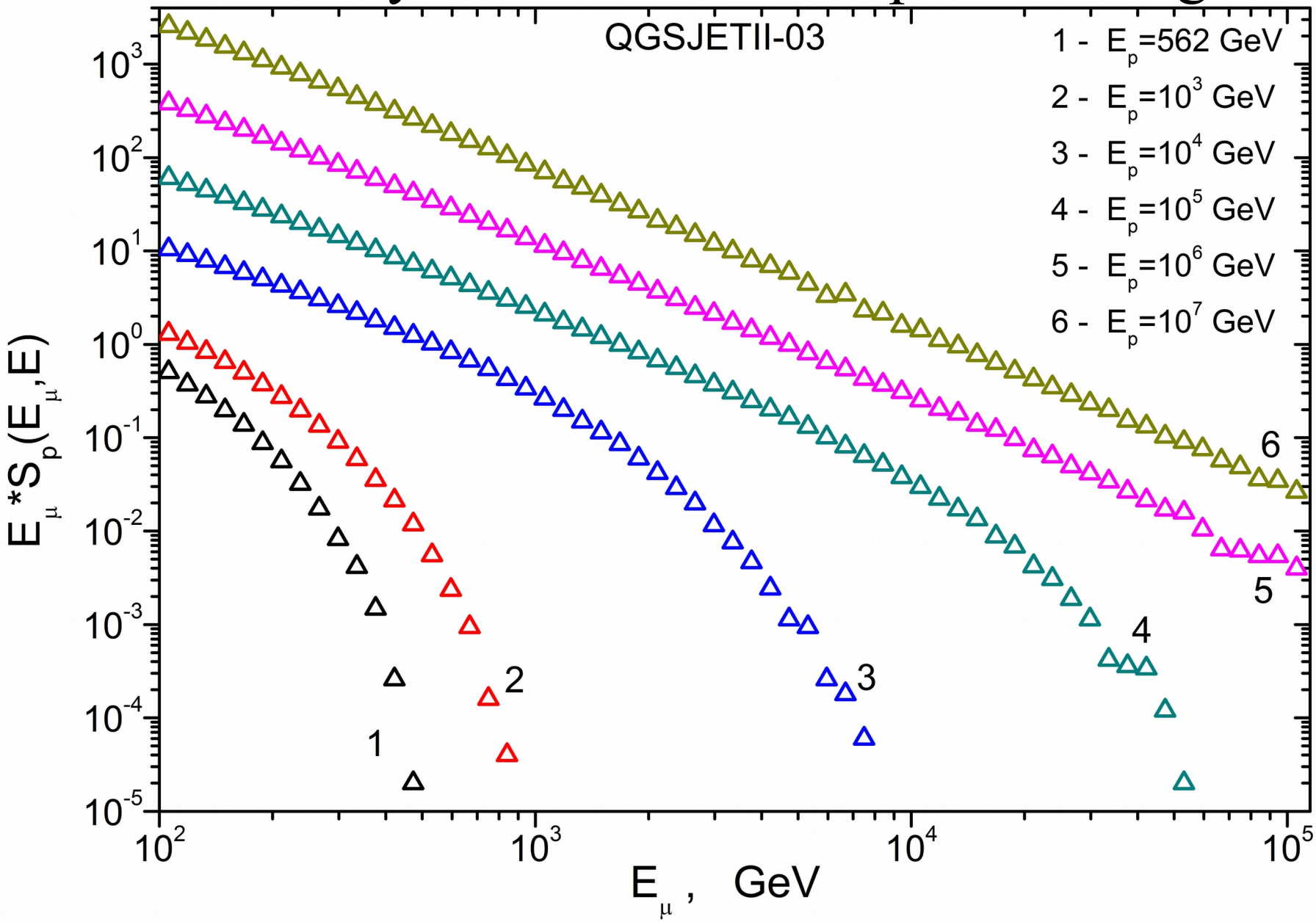
$$S_p(E_\mu, E) \cdot dE_\mu$$

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

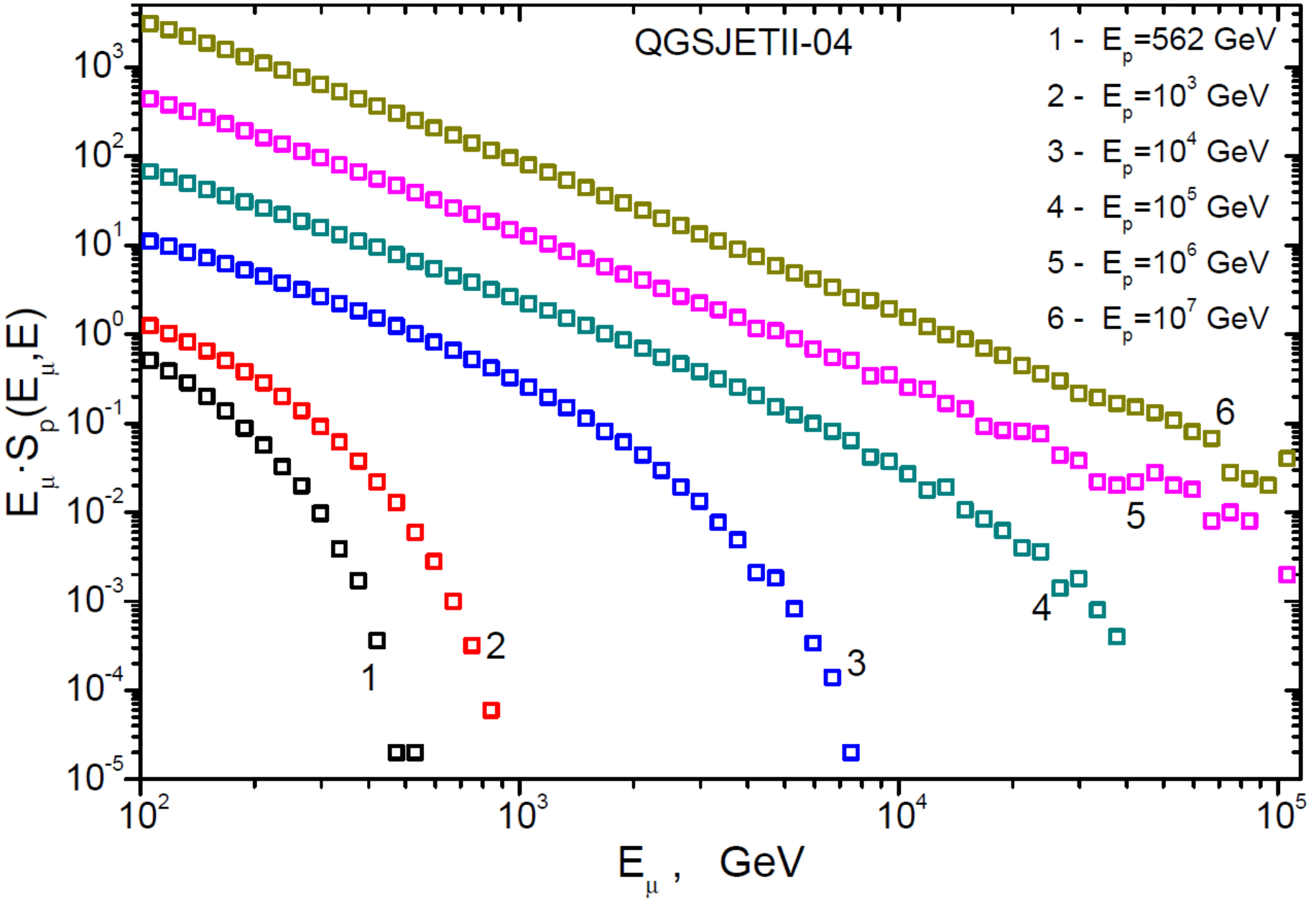
Muons density functions at fixed proton energies



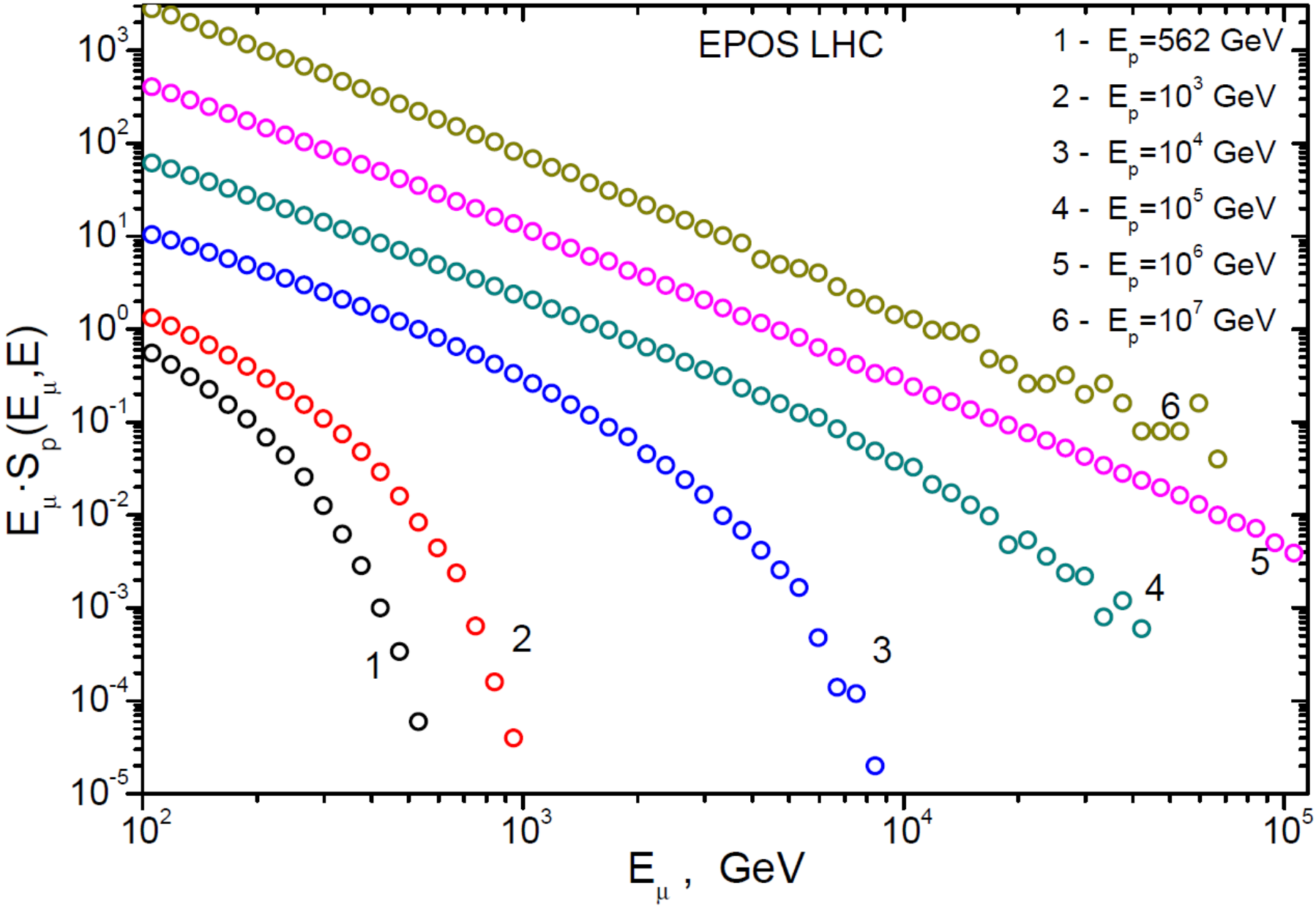
Muons density functions at fixed proton energies



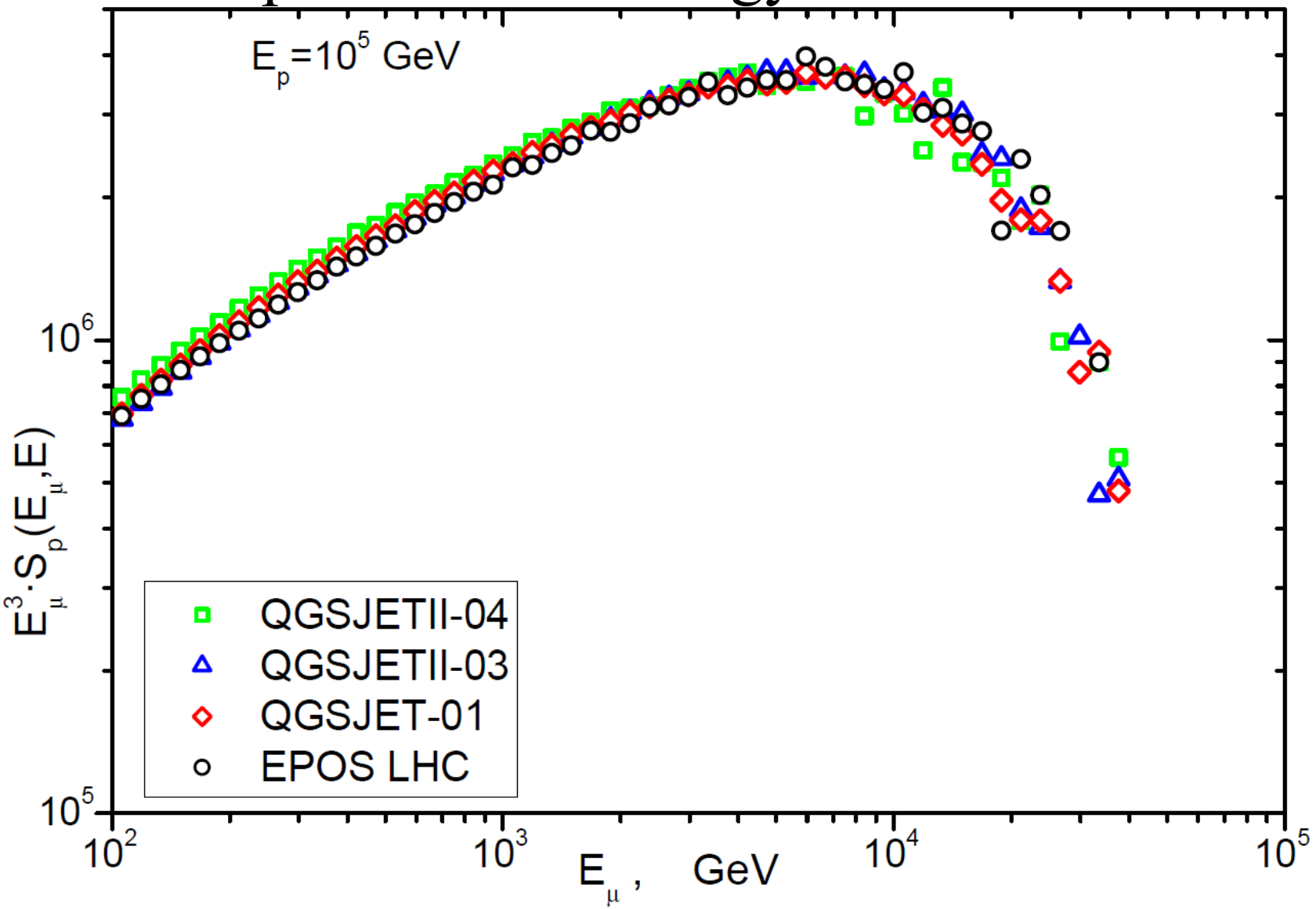
Muons density functions at fixed proton energies



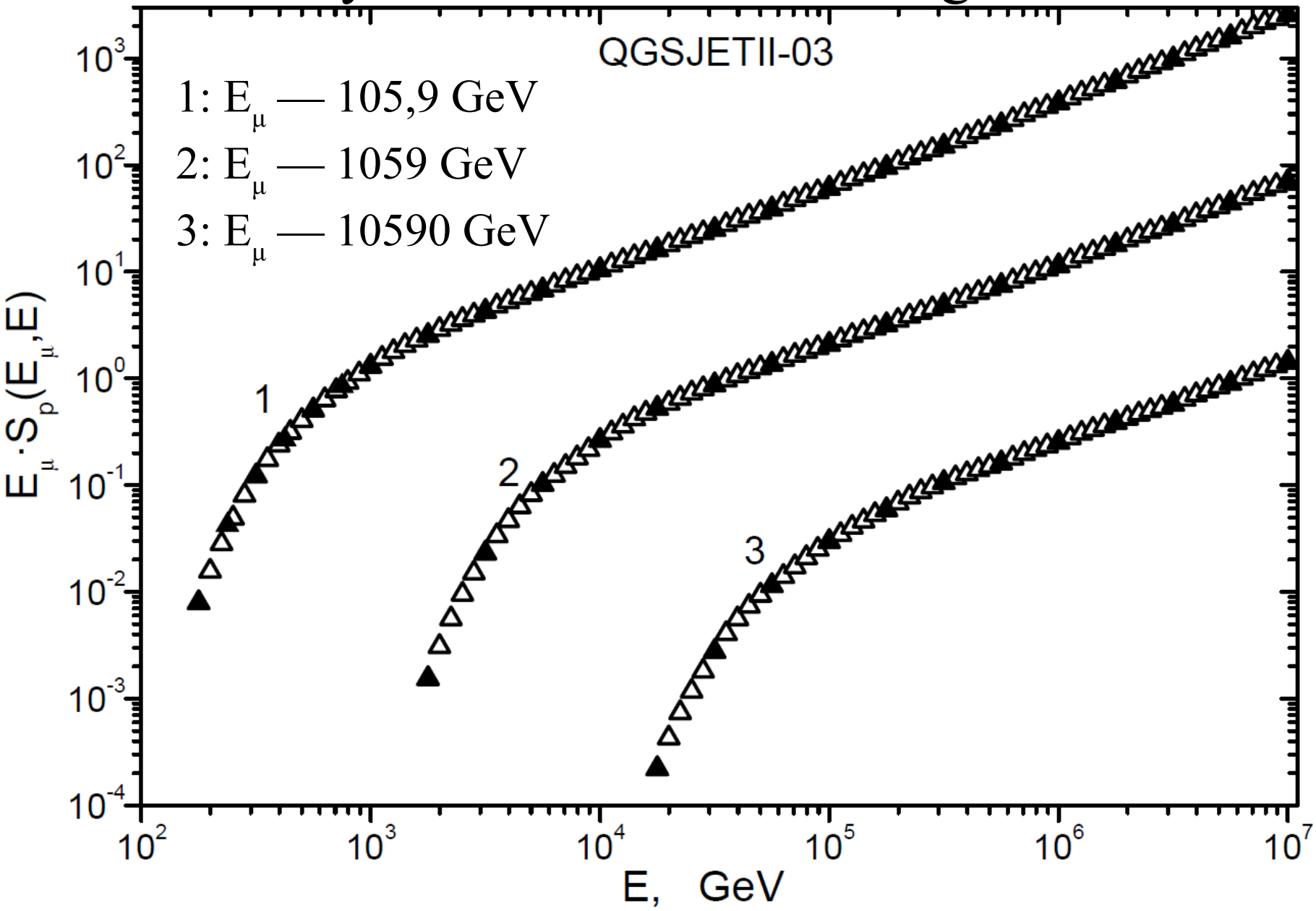
Muons density functions at fixed proton energies



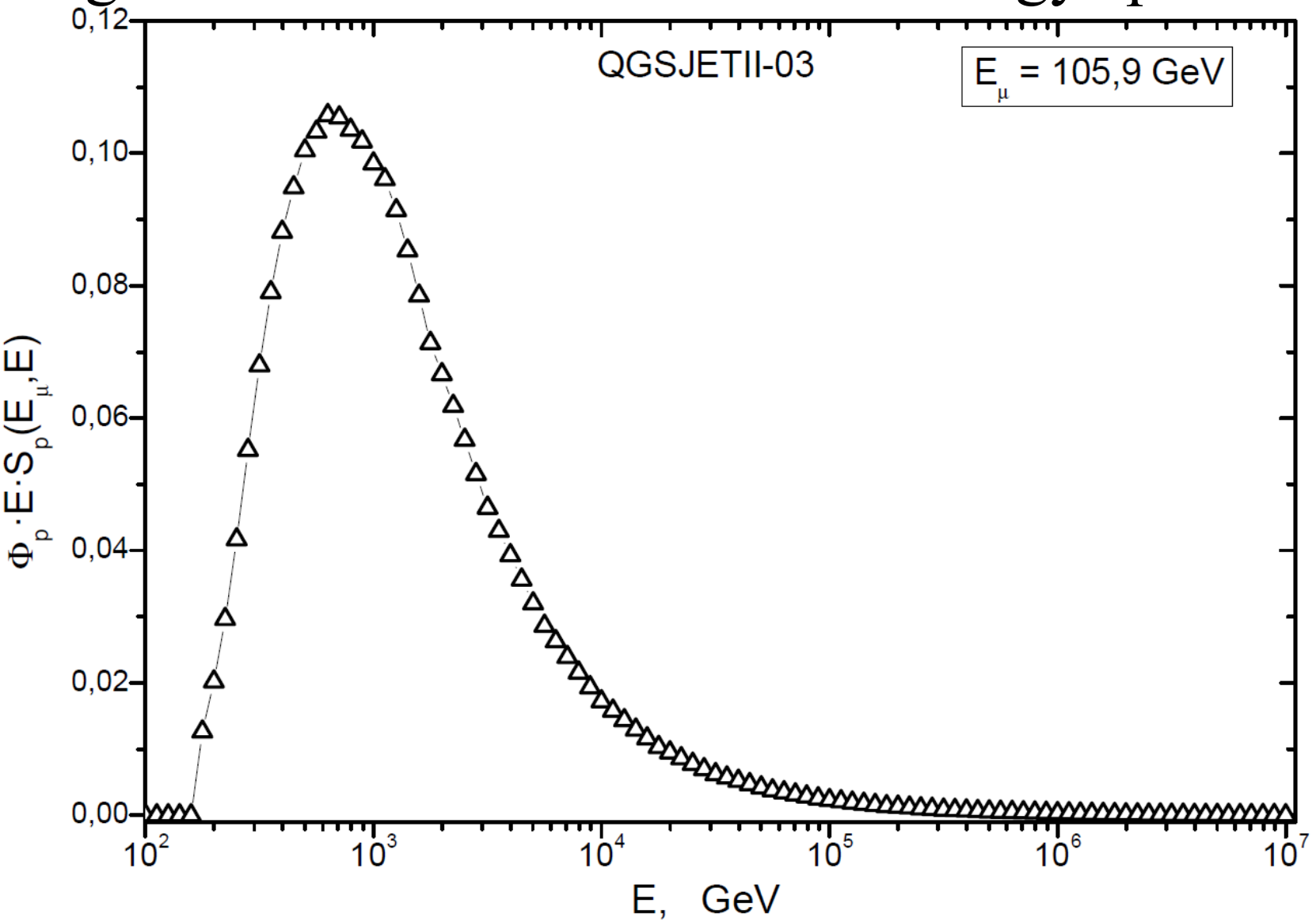
The muon energy spectra induced by the primary protons with energy 10^5 GeV



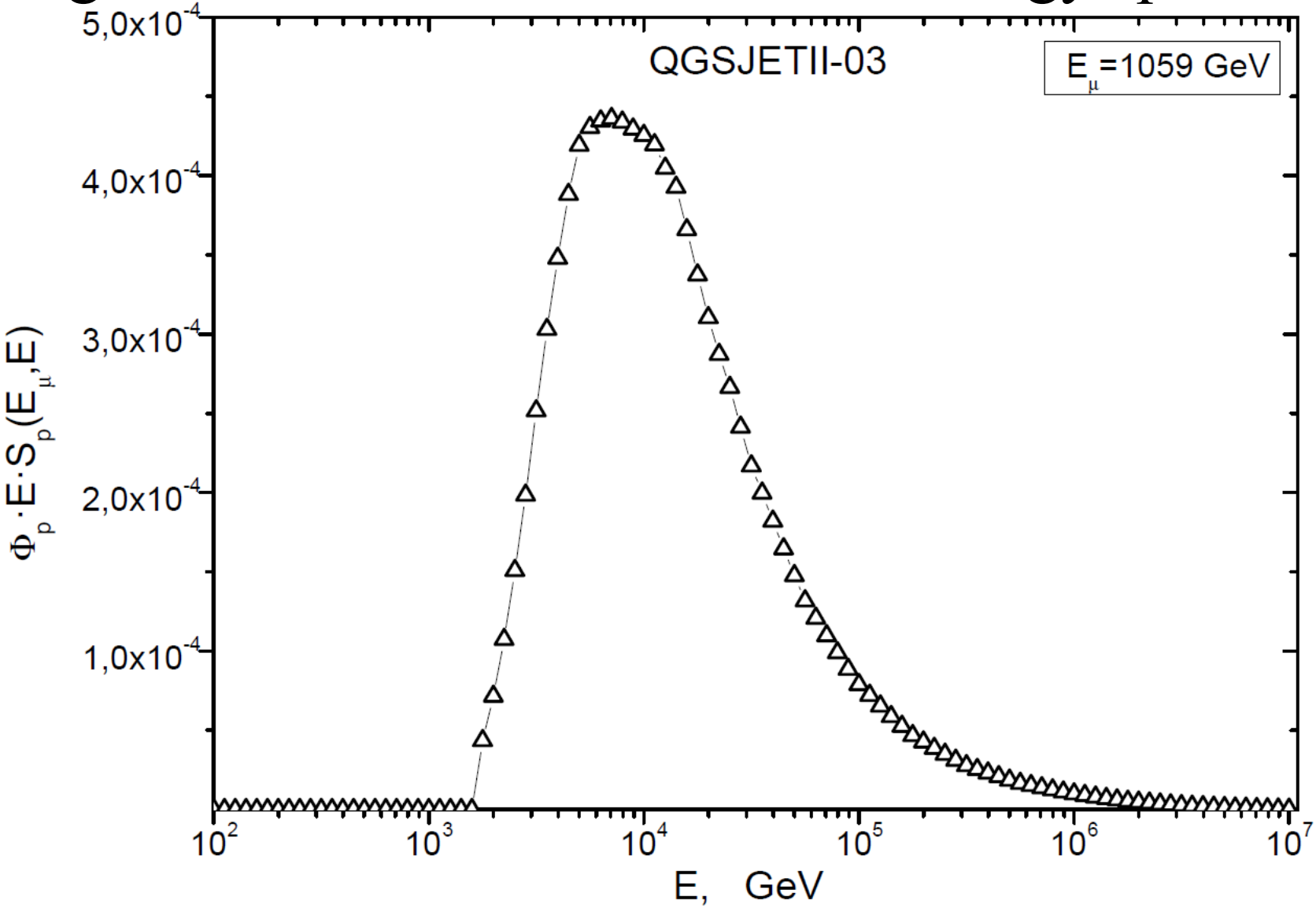
Muons density functions at fixed energies of muons



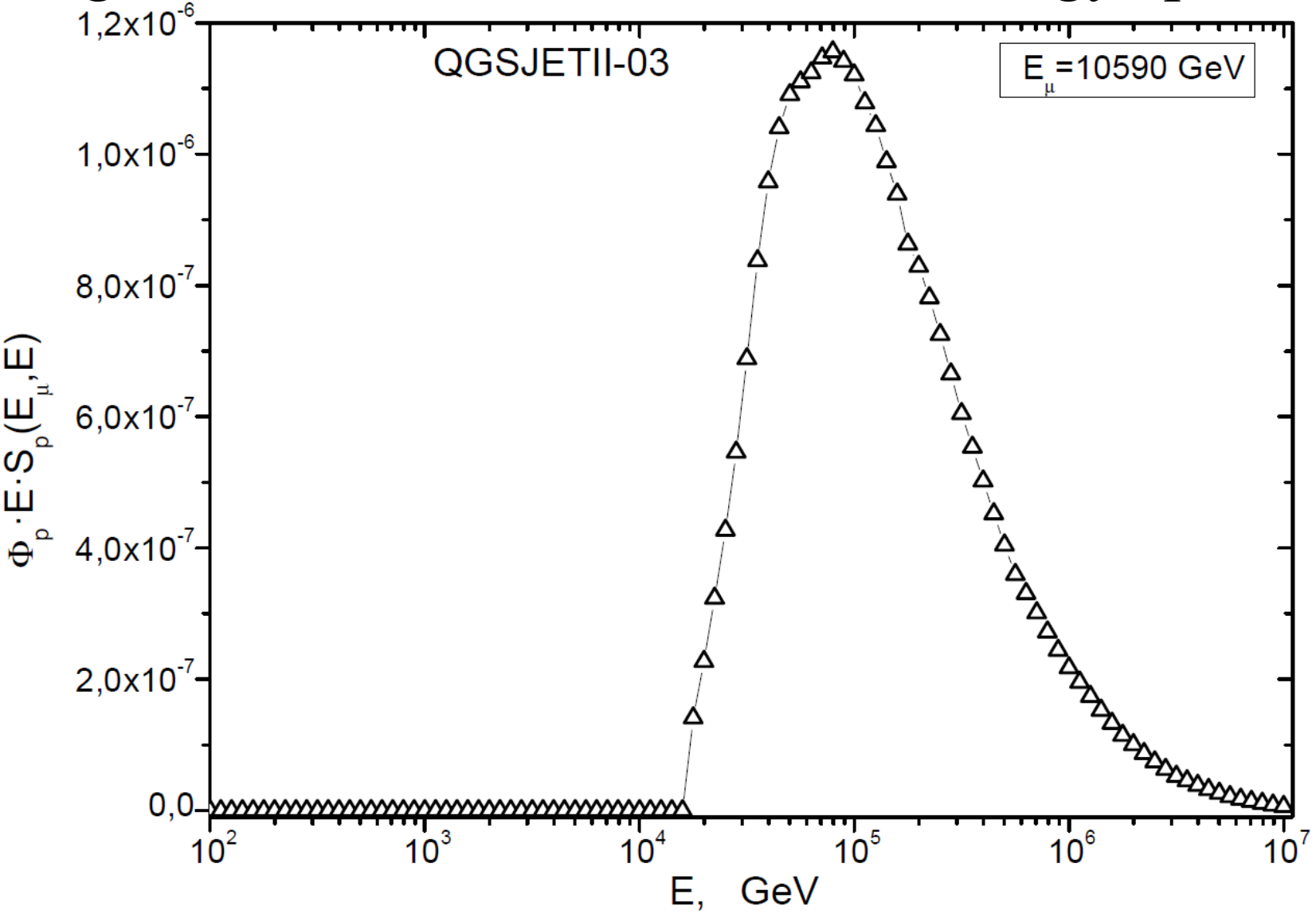
Relative contributions of protons with various energies into the 1-st bin of muon energy spectrum



Relative contributions of protons with various energies into the 21-st bin of muon energy spectrum



Relative contributions of protons with various energies into the 41-st bin of muon energy spectrum



Comparison

- Differential energy spectrum of vertical muons

Experimental data:
L3+Cosmic
MACRO
LVD

CORSIKA simulations:
EPOS LHC
QGSJET-01
QGSJETII-03
QGSJETII-04

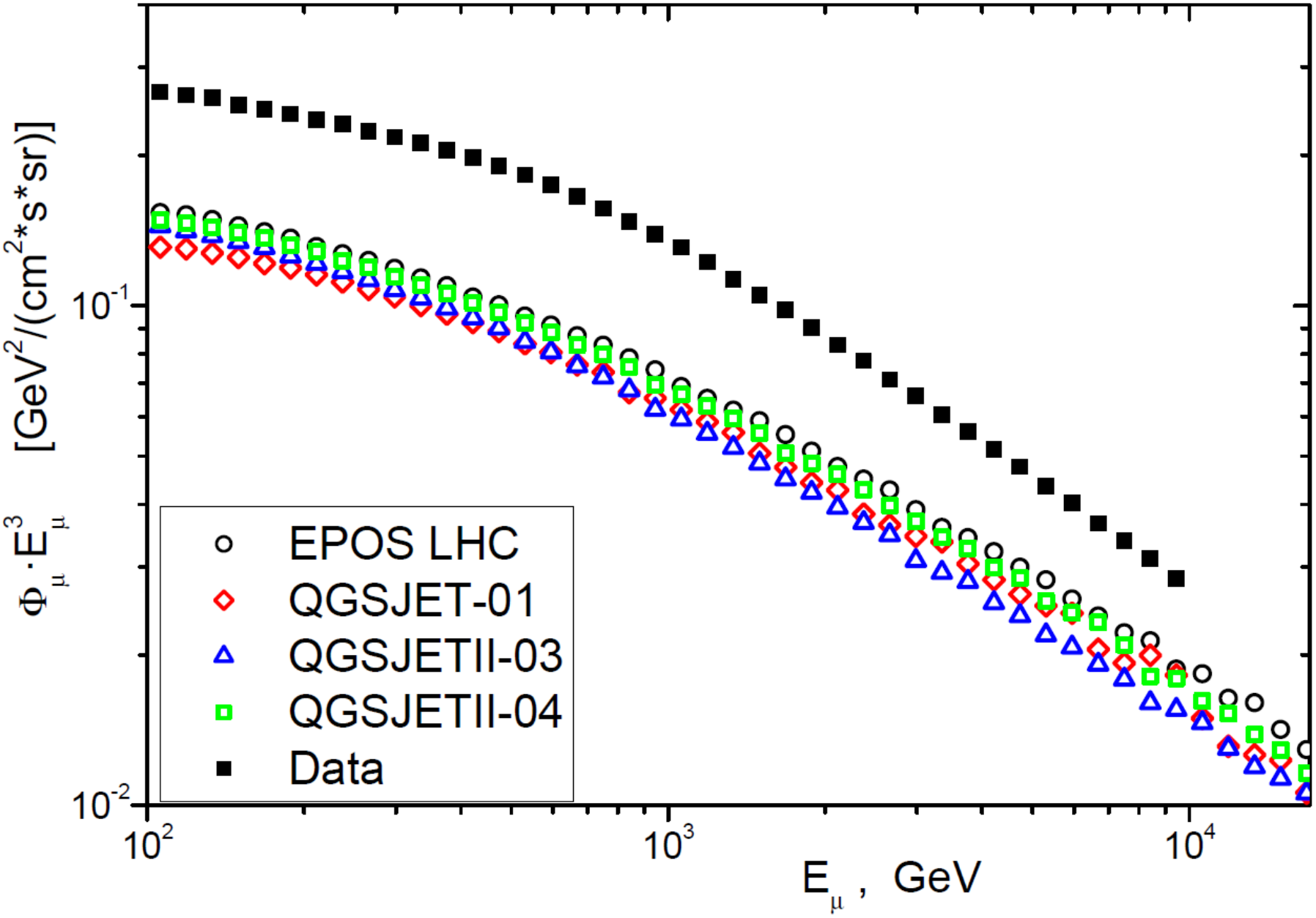
Data of the muon spectra

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

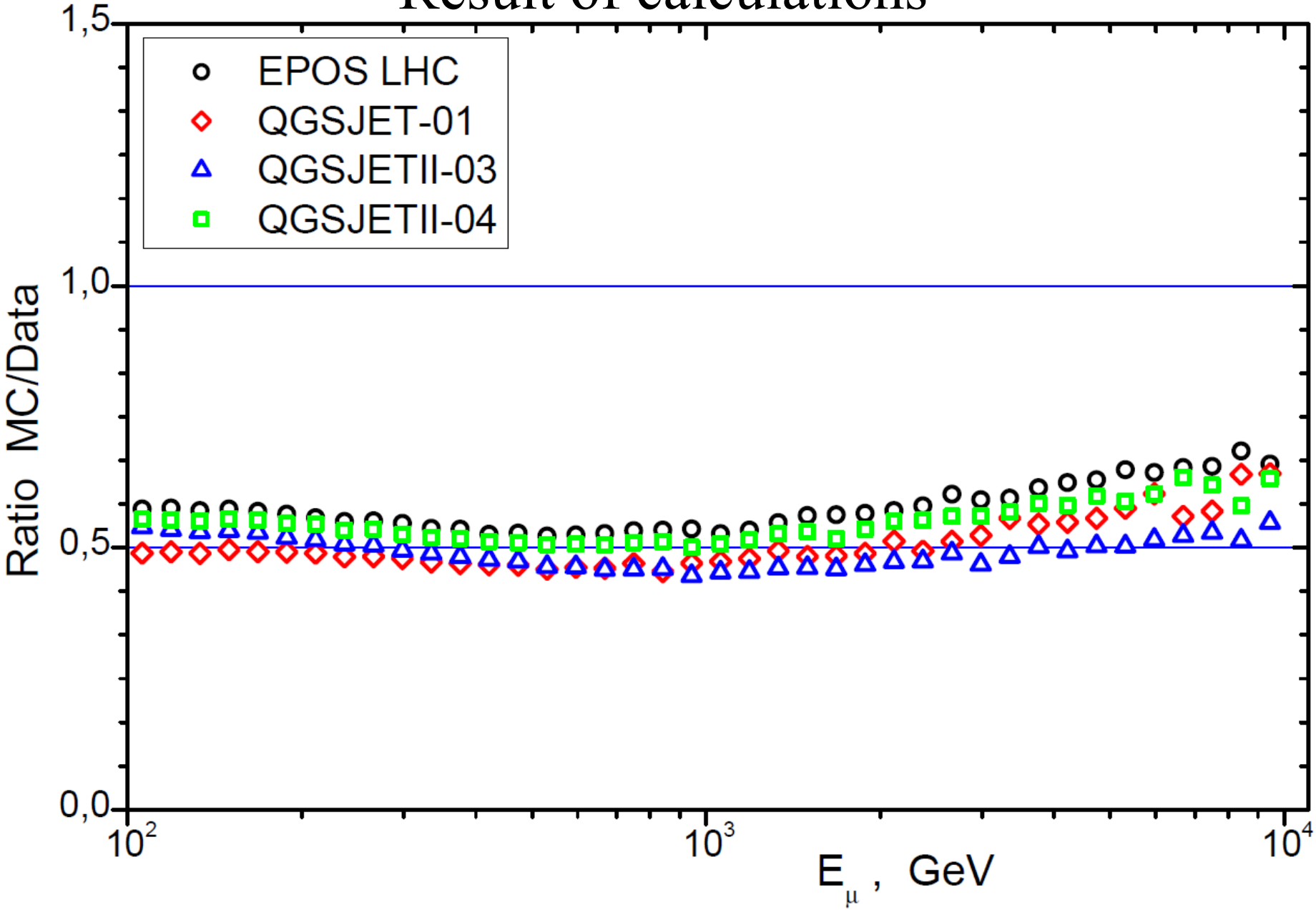
2) MACRO: Ambrosio M., Antolini R., Auriemma G., et al., Phys. Rev. **D**. Vol. 52, 3793 (1995).

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

Result of calculations



Result of calculations



Conclusion

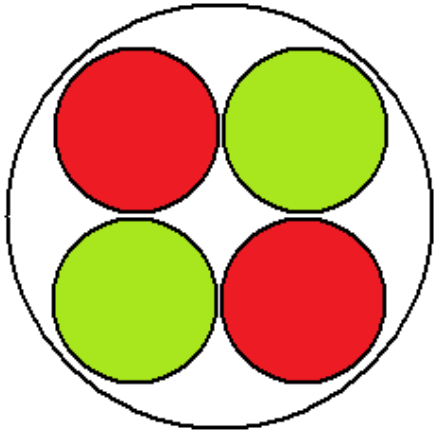
- Primary protons and helium nuclei takes the most significant contribution (~99%) to muon spectrum at energies $E_\mu = 10^2$ — 10^5 GeV.
- The EPOS LHC, QGSJET-01, QGSJETII-03 and QGSJETII-04 models show the deficite of muons by factors ~1,7 — 2 at this region.
- The production of the most energetic $\pi^\pm$ and $K^\pm$ mesons in hadron interactions is suppresed by the same factors.
- All models predict more rapid development of the EAS in the atmosphere.

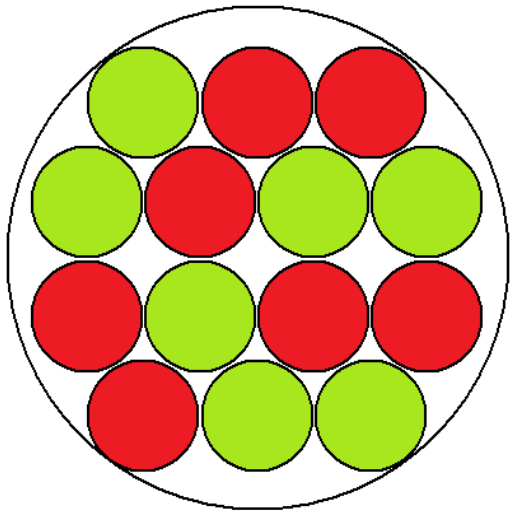
Thank you for attention!

Backup slides

Superposition conception

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

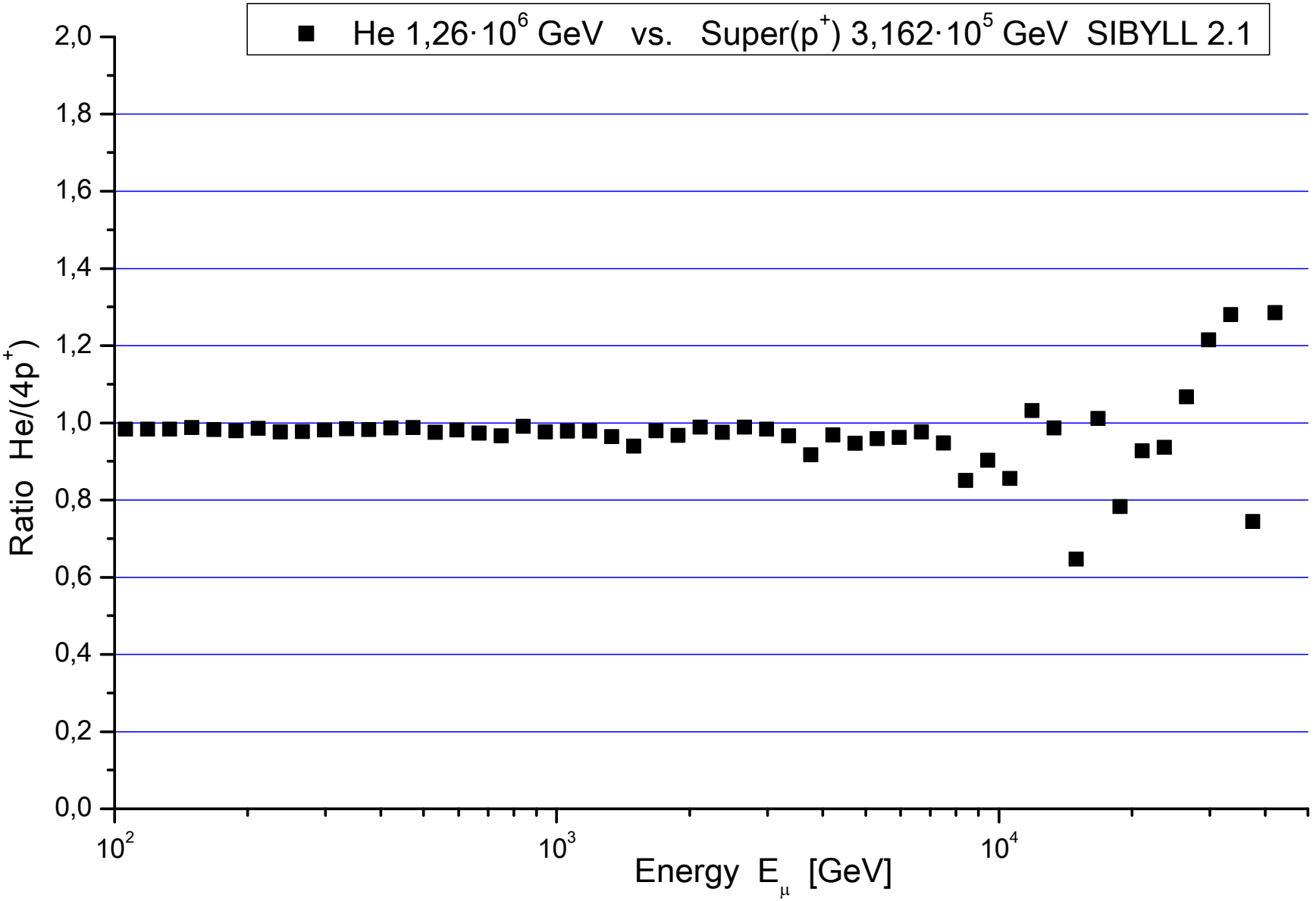




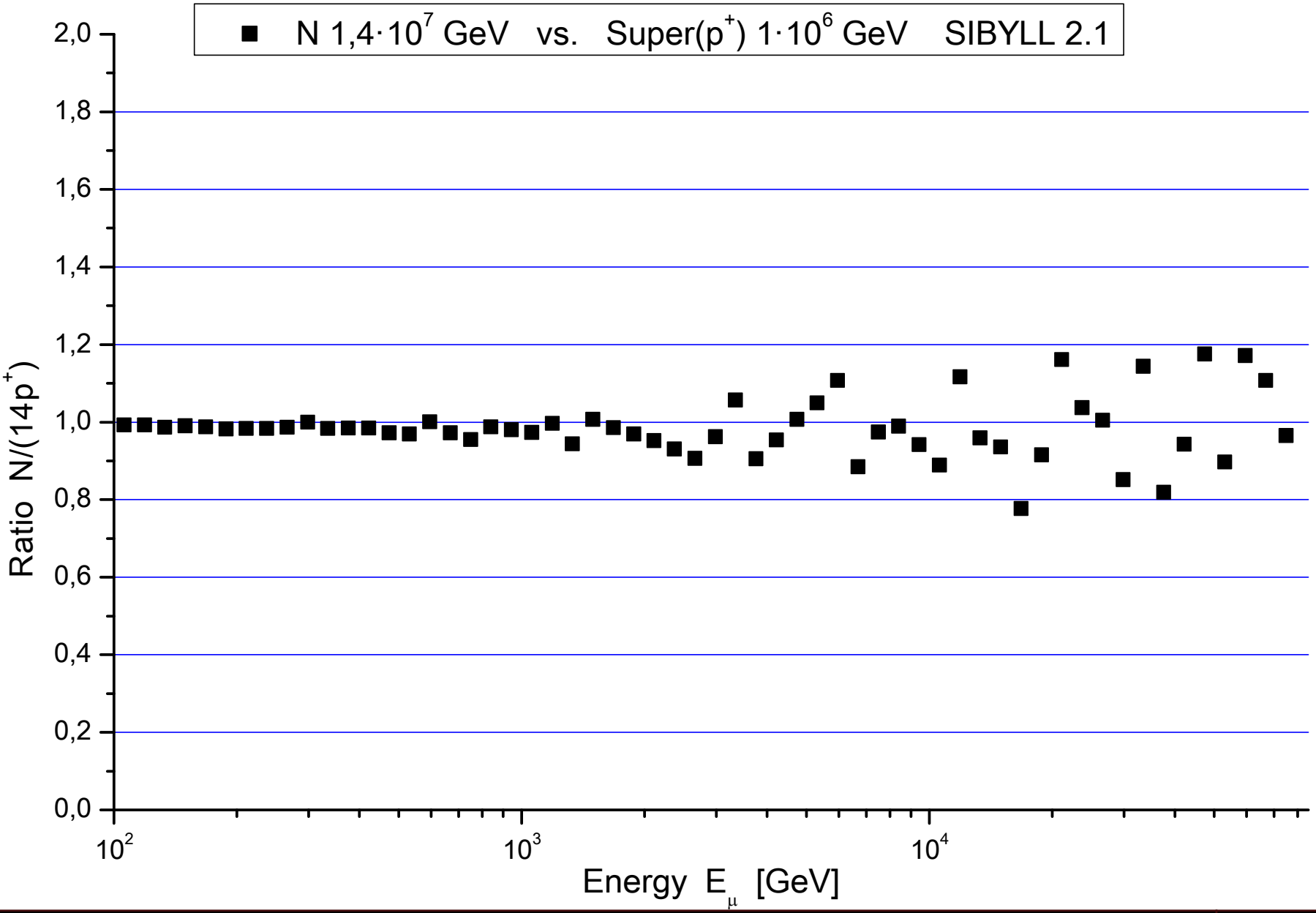
$$S_{He}(E_\mu, E_{He}) \approx 4 \cdot S_p\left(E_\mu, E_p = \frac{E_{He}}{4}\right)$$

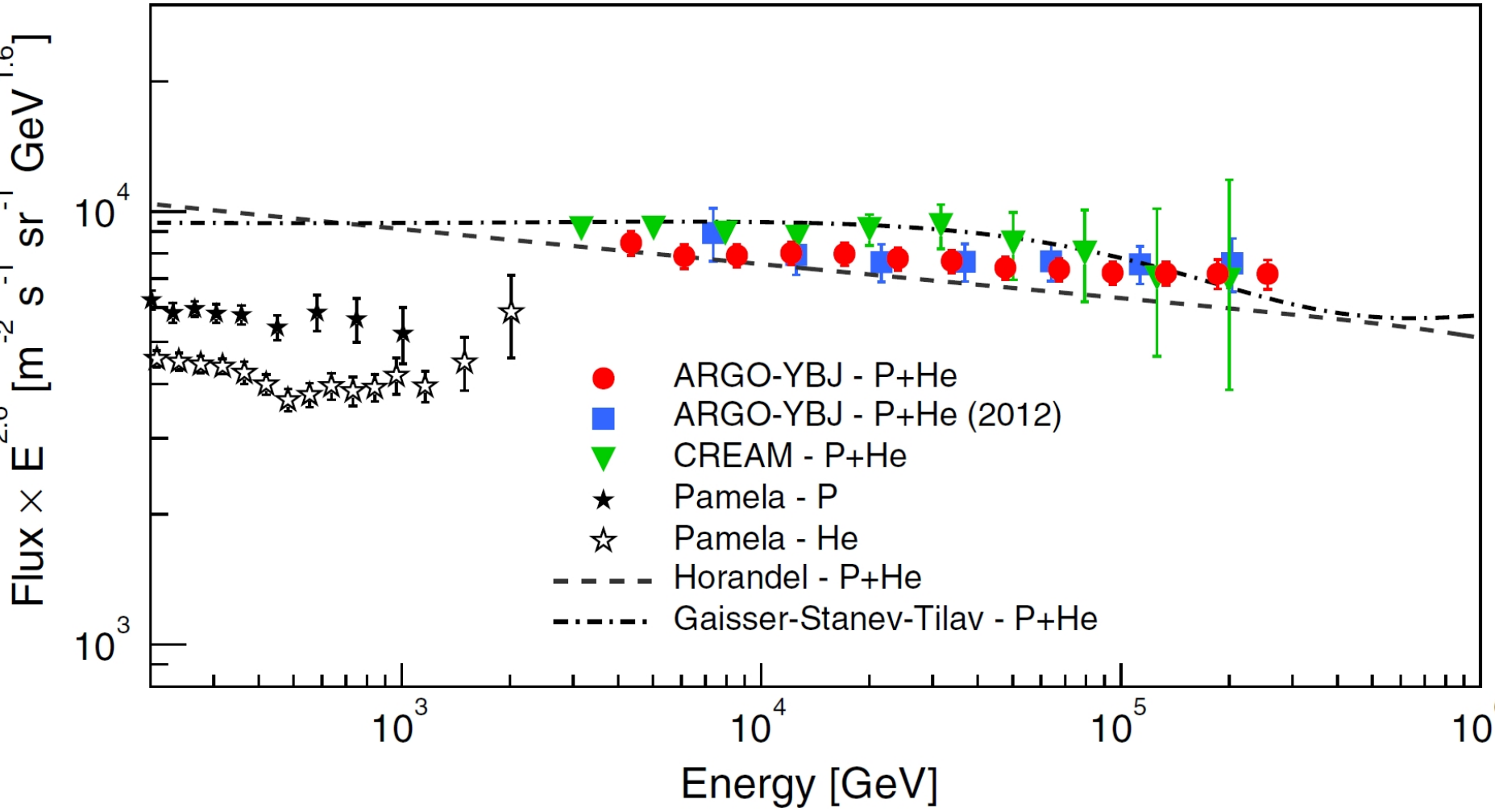
$$S_N(E_\mu, E_N) \approx 14 \cdot S_p\left(E_\mu, E_p = \frac{E_N}{14}\right)$$

Superposition conception (result for SIBYLL)

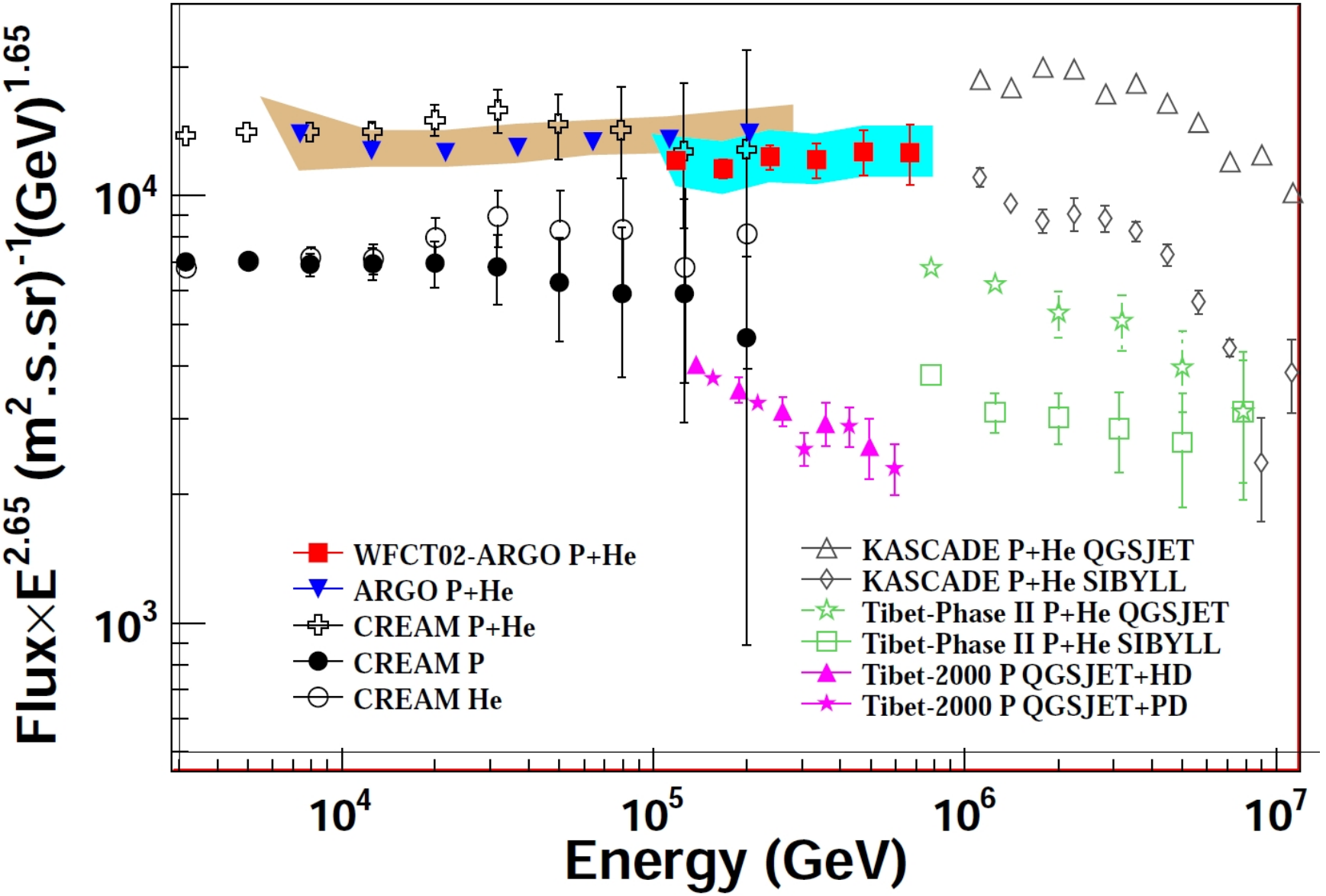


Superposition conception (result for SIBYLL)

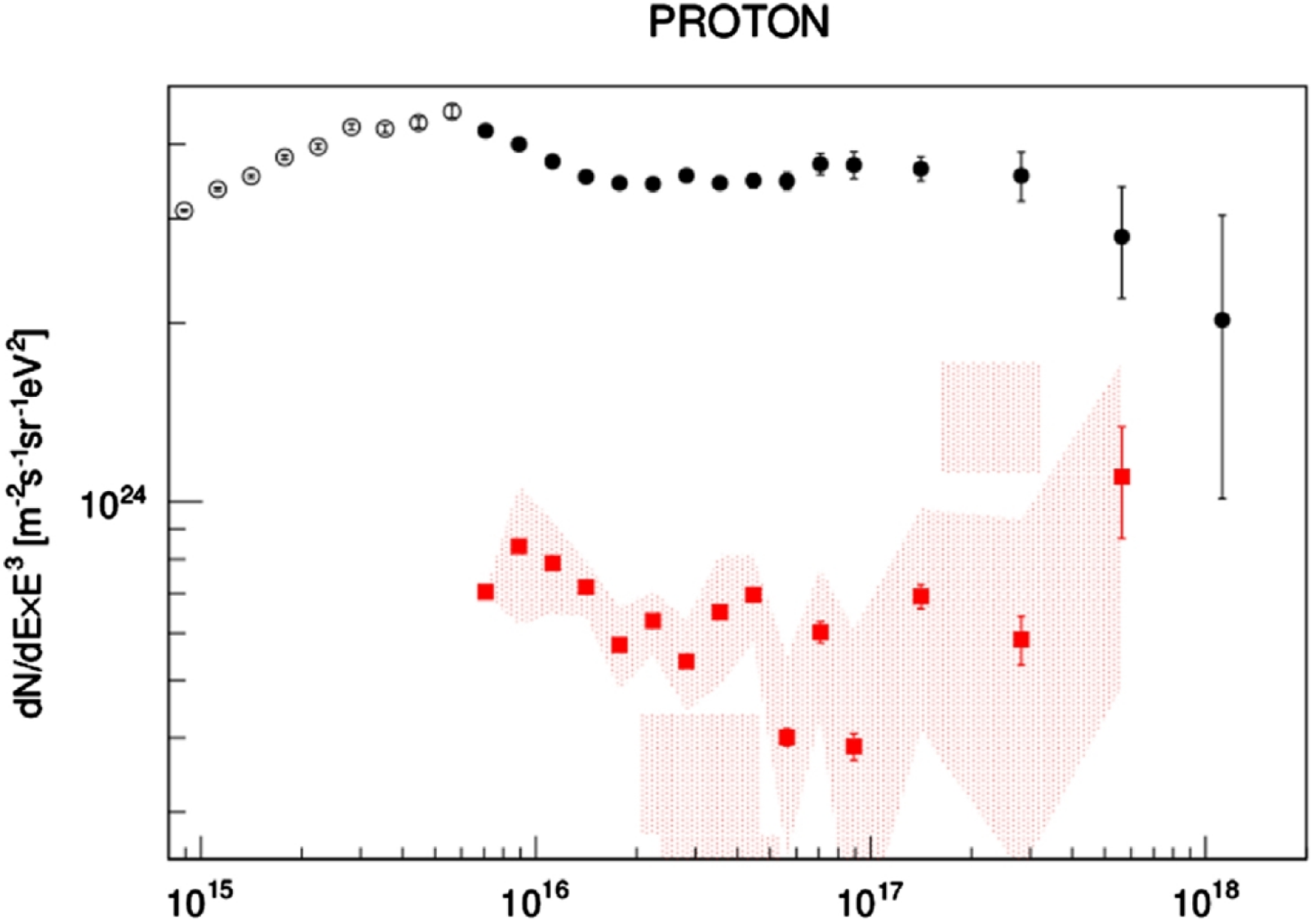




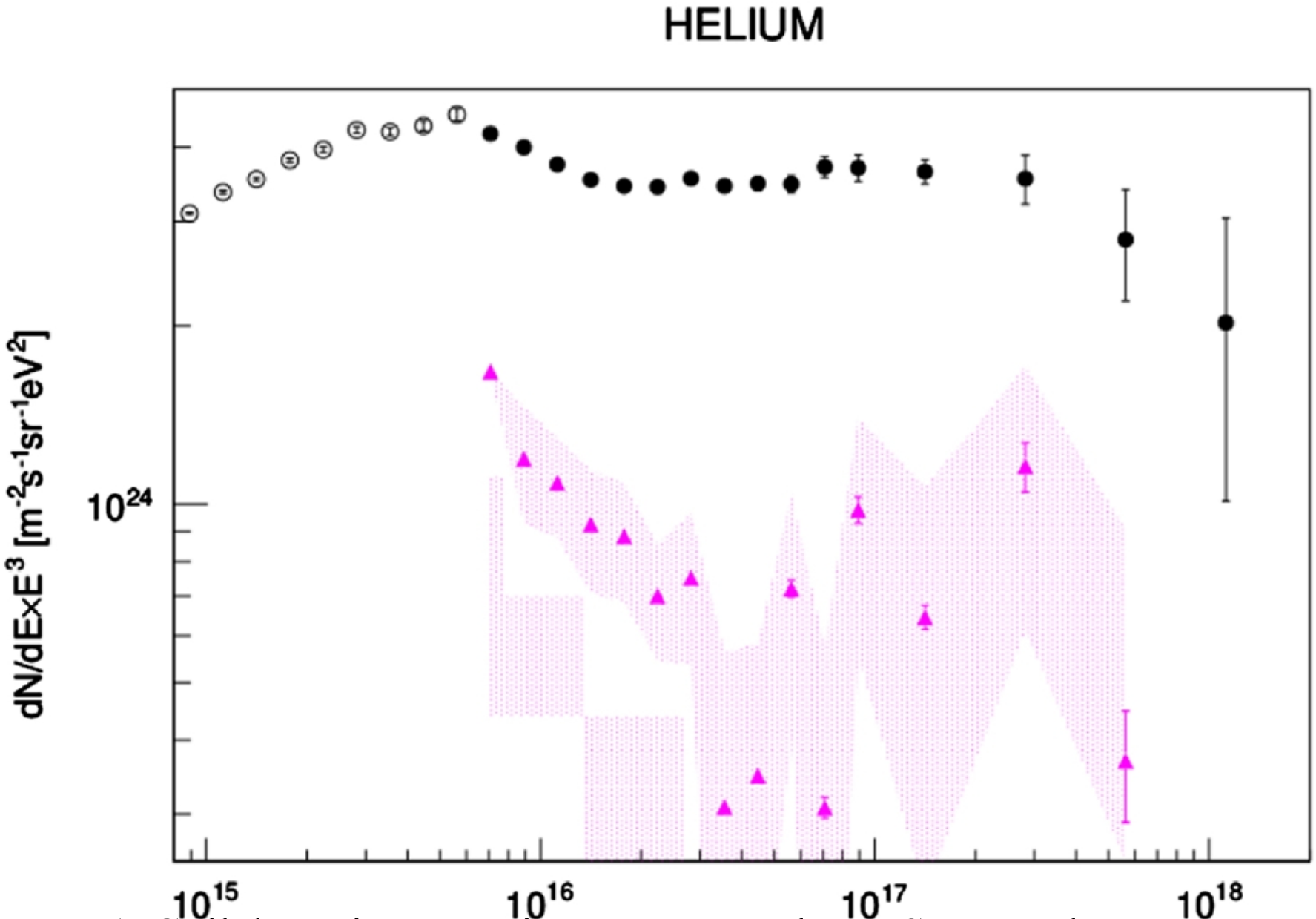
Paolo Montini fot the ARGO-YBJ Collaboraion «Cosmic ray physics with ARGO–YBJ» arXiv:1608.01251v1



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»

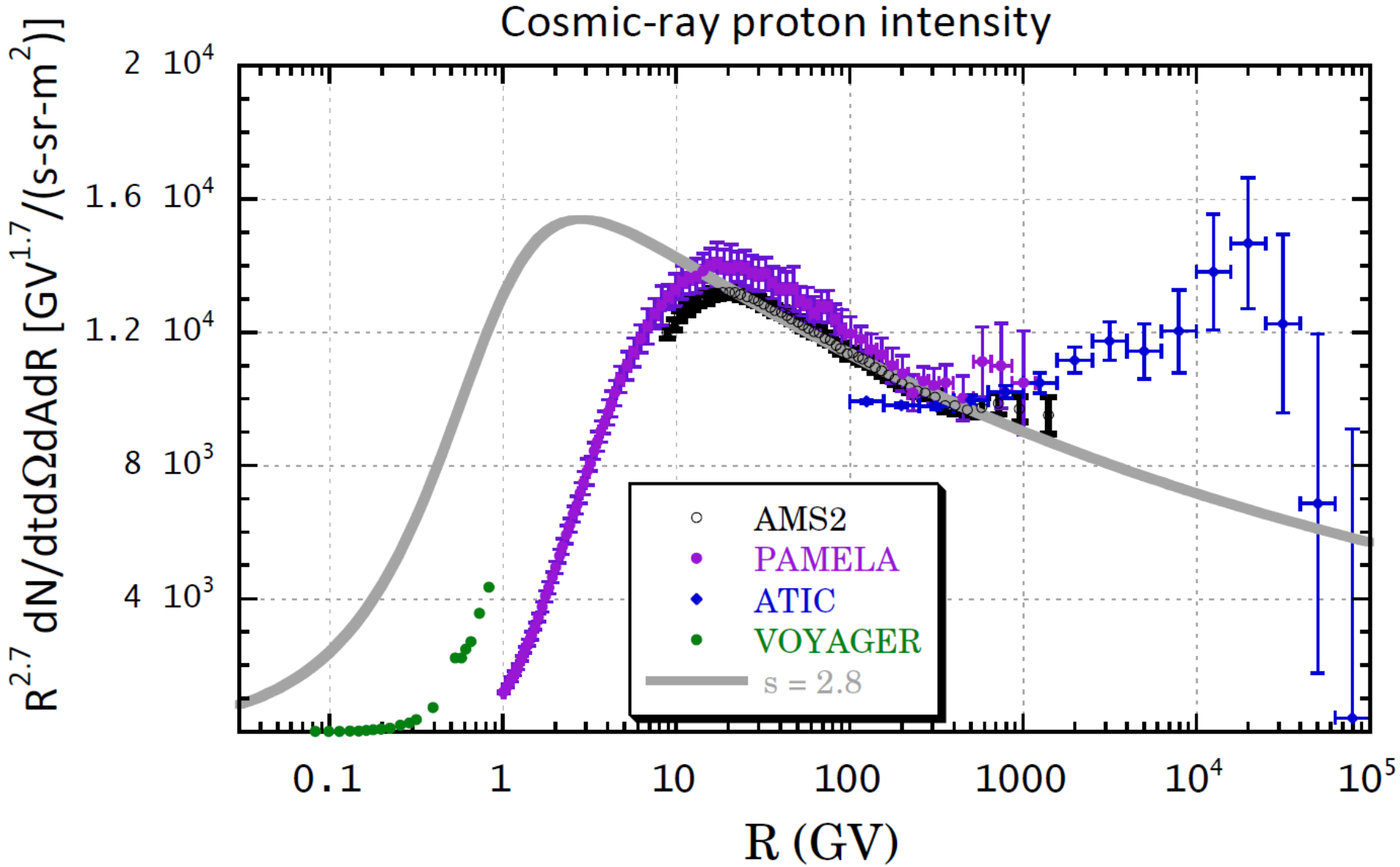


TUNKA Collaboration: Prosin V.V., Berezhnev S.F., Budnev N.M., et al., NIM in Physics Research A 756, p. 94101 (2014).

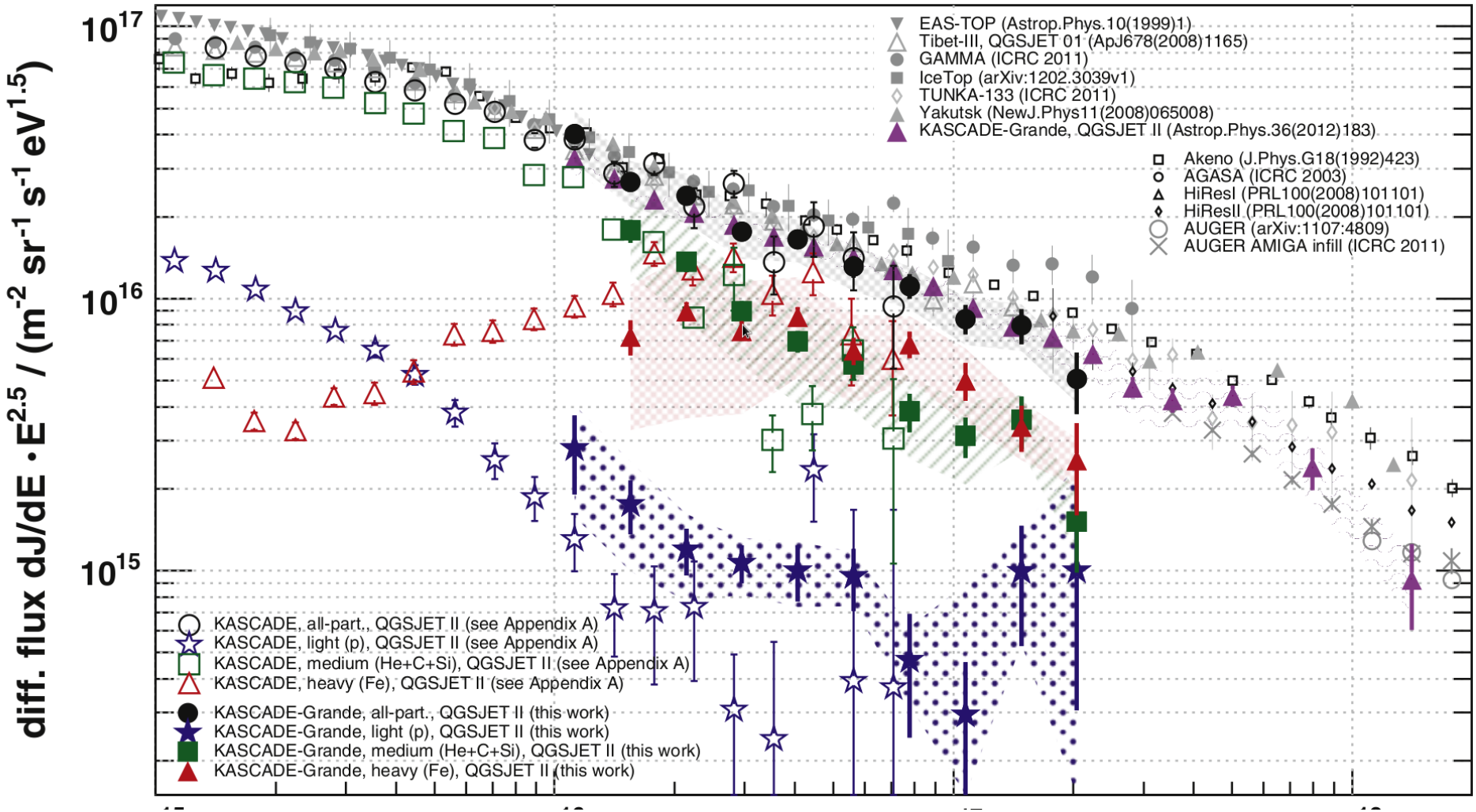


TUNKA Collaboration: Prosin V.V., Berezhnev S.F., Budnev N.M., et al., NIM in Physics Research A 756, p. 94101 (2014).

Differential energy spectrum PCR

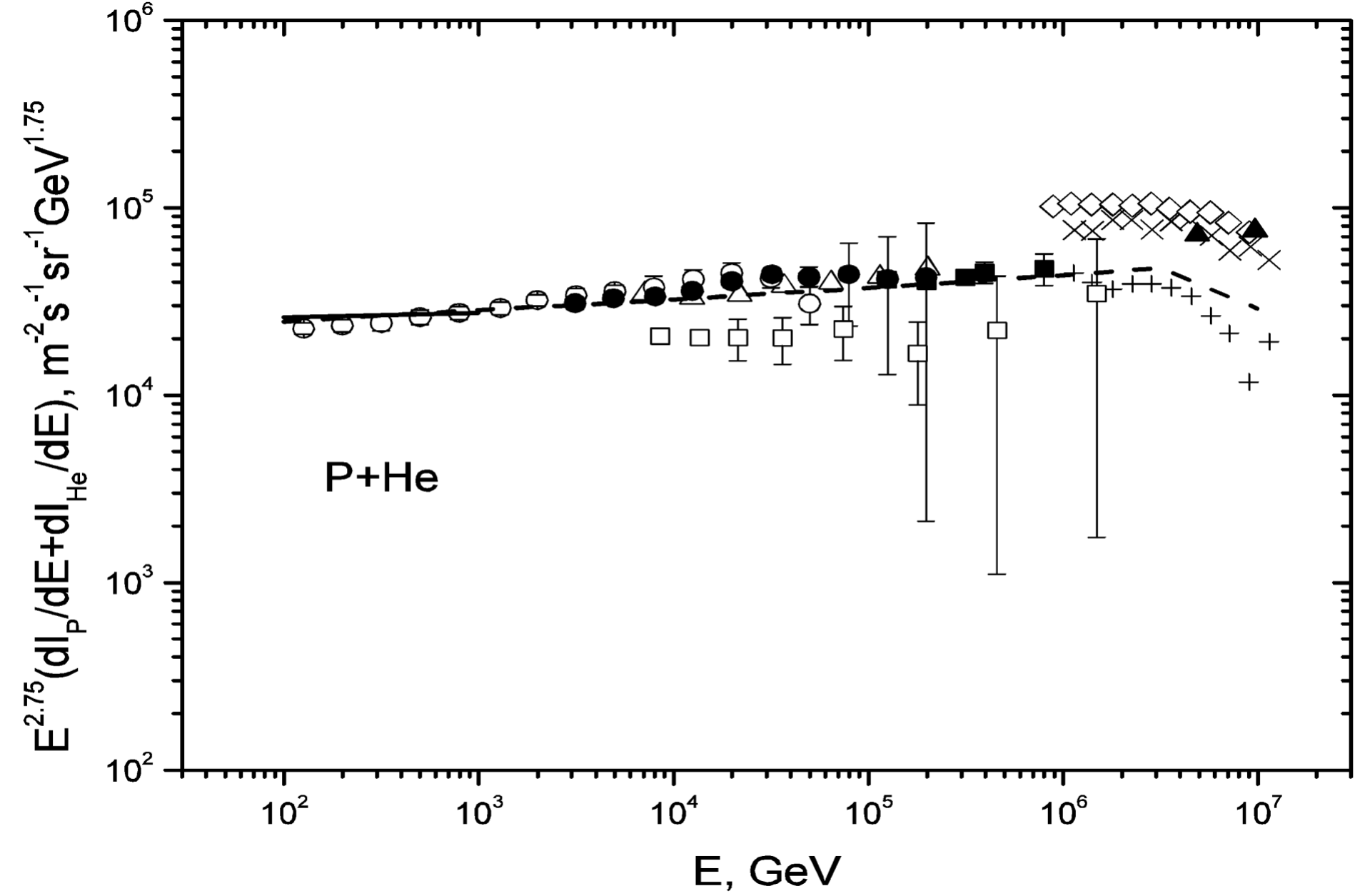


Charles D. Dermer. Impact of Fermi-LAT and AMS-02 results on cosmic-ray astrophysics. (21 May 2015) arXiv:1505.05757v1



KASCADE-Grande Collaboration: Apel W.D., Arteaga-Velazquez J.C., Bekk K., et al.,Astroparticle Physics 47, p. 5466 (2013).

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

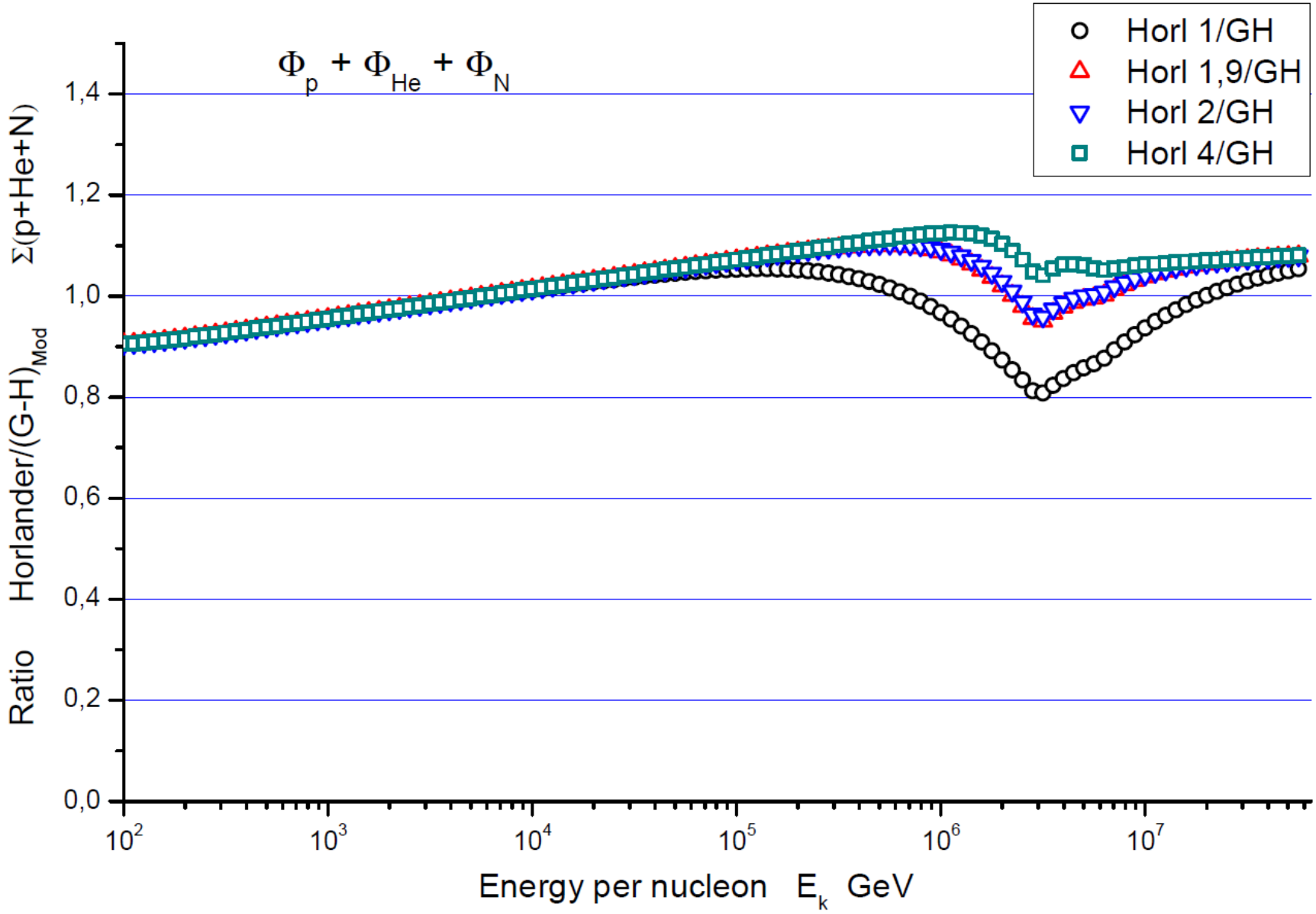
□ - RUNJOB, V.A. Derbina et al., ApJ, **628**, L41-L44, 2005

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

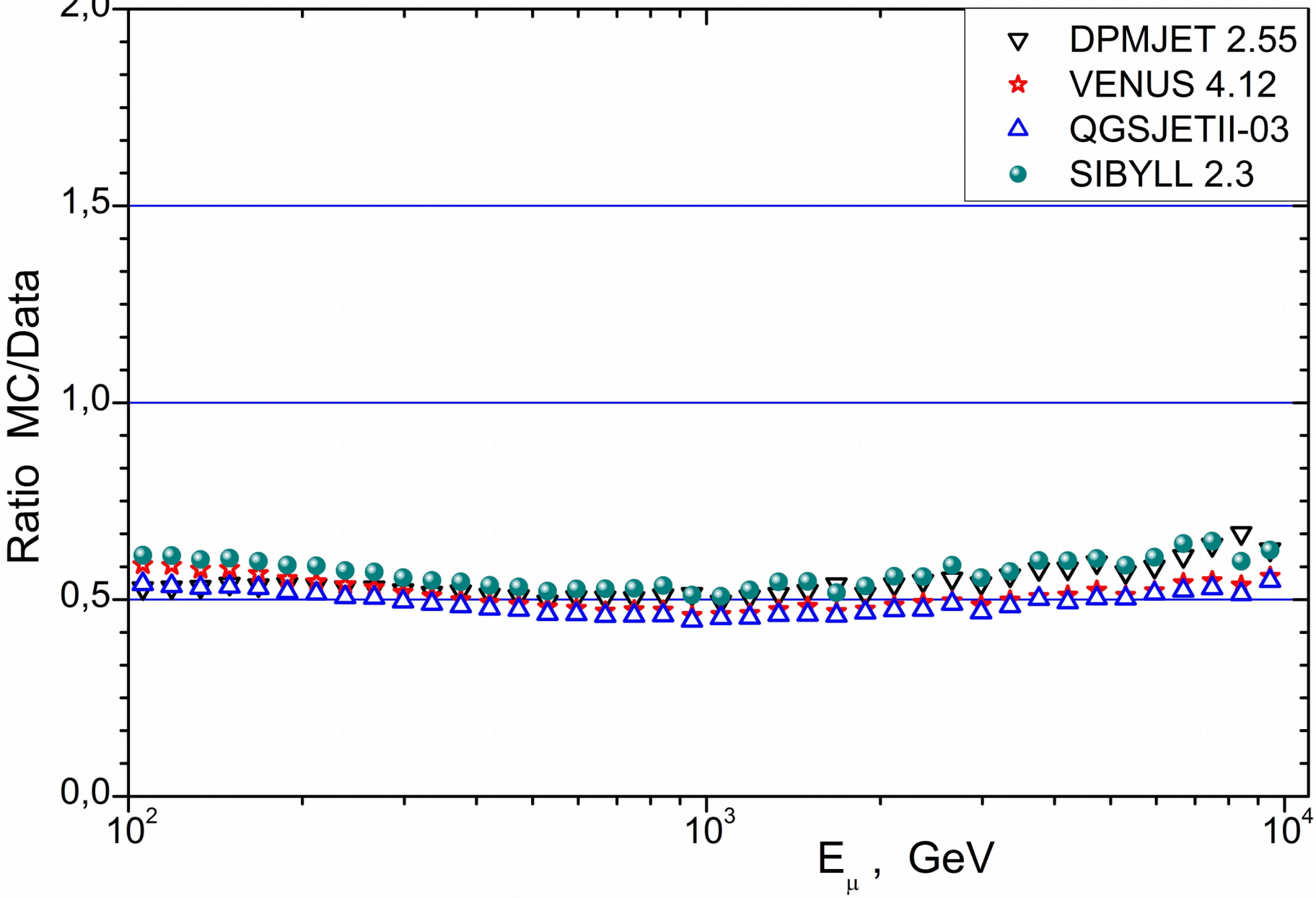
▲ - SPHERE2 (all particles) R.A. Antonov et al., Proc. 33-d ICRC, Rio de Janeiro, 2013

The approximation of results based on calculation Berezhko E.G. and Völk H.J. was exploited with some modification.

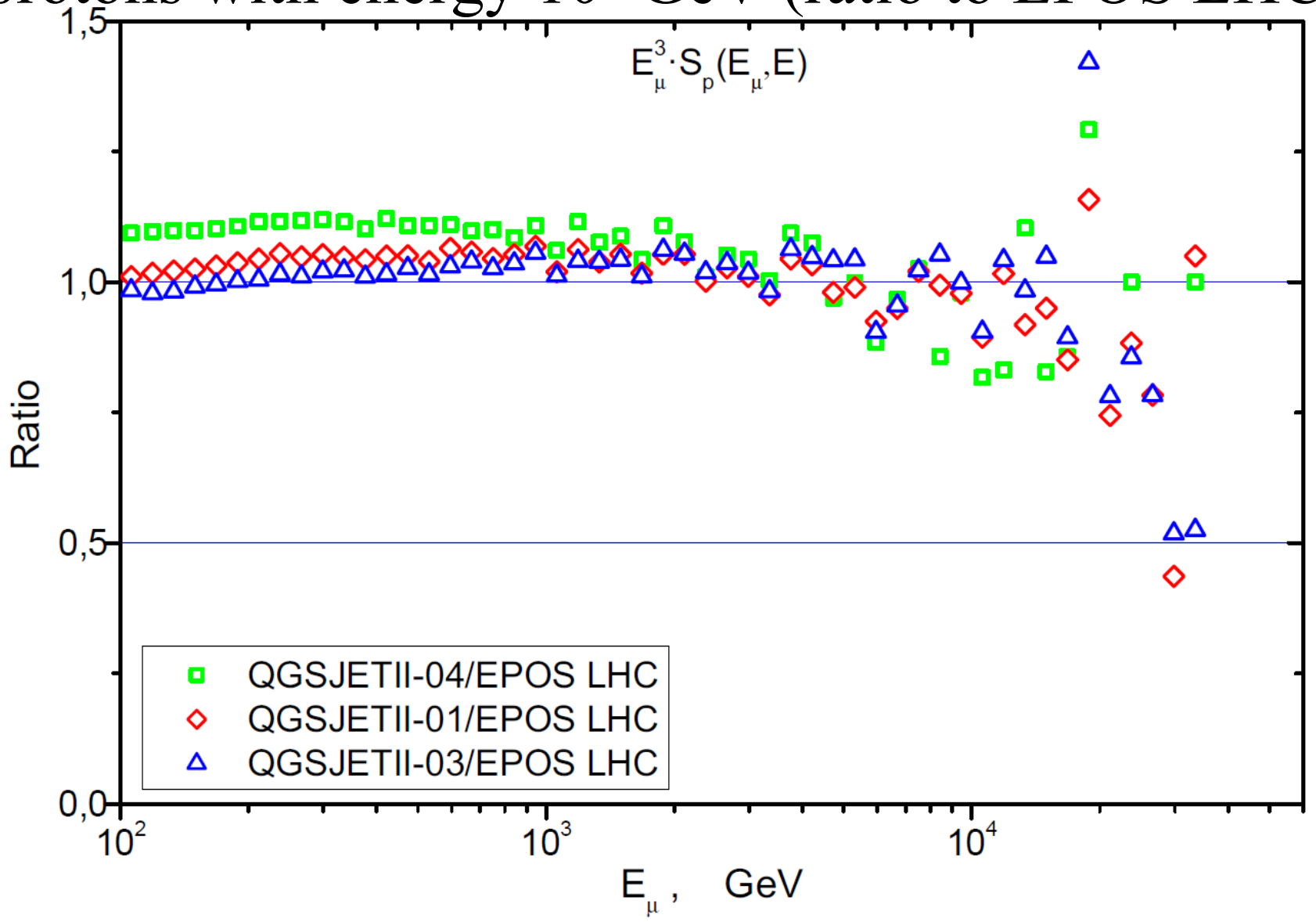
Comparison


Horl 1/GH
Horl 1,9/GH
Horl 2/GH
Horl 4/GH
$\Phi_p + \Phi_{He} + \Phi_N$
Ratio Horlander/(G-H)$_{Mod}$ Σ(p+He+N)
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0,0
10^2
10^3
10^4
10^5
10^6
10^7
Energy per nucleon E_k GeV

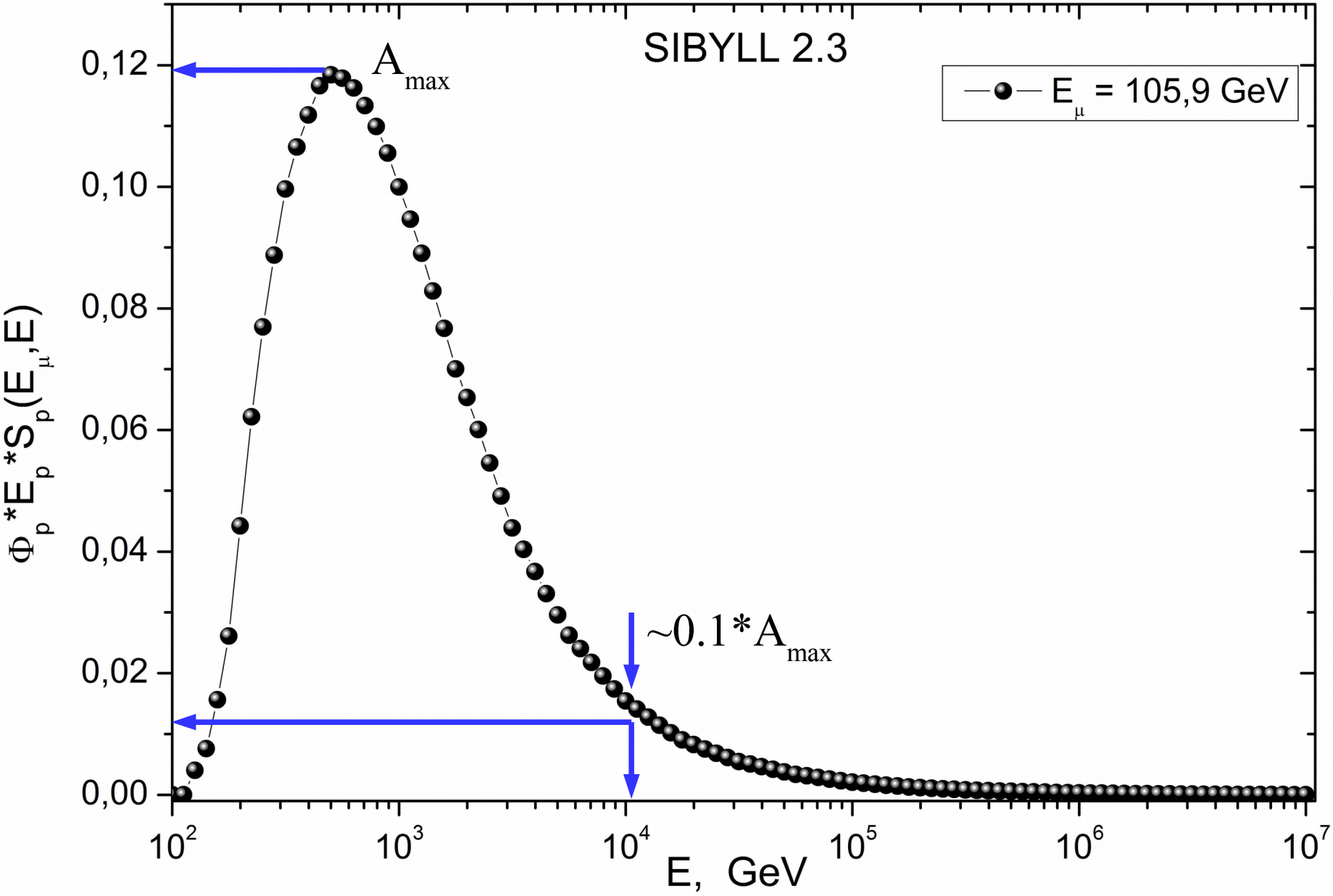
Result of calculations



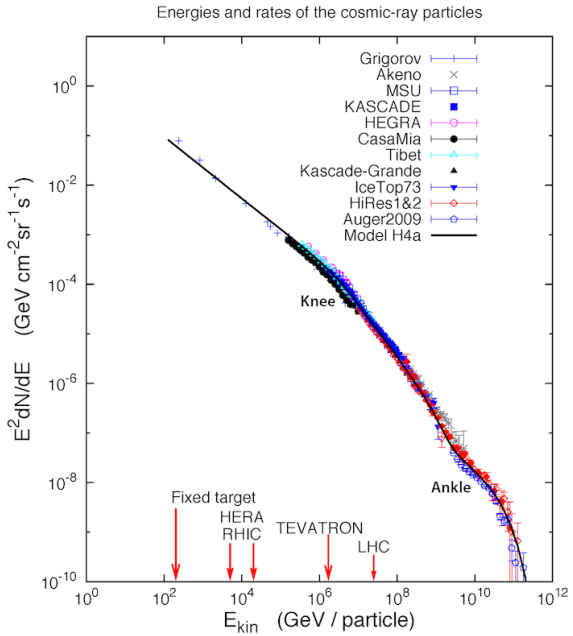
The muon energy spectra induced by the primary protons with energy 10^5 GeV (ratio to EPOS LHC)



Relative contribution in muons



Important interlink



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

Hadronic interaction models

μ