Constraints of hadronic interaction models from the cosmic muon observations.

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CONTENT

1. Introduction (energy range, models, accelerator experiments, importance of testing)
2. Method of testing (atmospheric muon data, estimation the energy spectrum of muons)
3. Results and discussion (comparison and LHC data)
4. Conclusion

Introduction

- The longitudinal development of extensive air showers and, hence, the depth X_{max} of its maximum depends strongly on the rate of the projectile particle energy E degradation. If a probability of secondary particles production in the energy range of
  - $\sim 0.6 \cdot E - 0.01 \cdot E$
- is high then the depth X_{max} is expected to be rather large. And contrary, in case of the severe energy degradation the length of a shower and the depth X_{max} of its maximum will be small.

Introduction

- Number of high energy muons in a shower is also determined by the secondary particles produced in the energy range of ~0.6·E – 0.01·E
- This energy interval is the most important for the extensive air shower development.
- The study of the secondary particle production with the most considerable energies is also of importance for understanding of particle interactions.
- The extensive air shower data are interpreted in terms of some models of hadronic interactions.
- In this report we consider the QGSJET II-03 and the QGSJET II-04 models.

Introduction

- Usually models are tested at the accelerator experiments (e.g., LHC, LHCf and TOTEM)
- We suggest to test also the most popular models of hadronic interactions with the atmospheric muon data, measured with rather high accuracy.
- This testing is of the primary importance for the study of composition of the primary particles.

Energy spectrum and composition of the primary particles

- All features of the energy spectrum and composition of the primary particles are of importance to understand the origin of cosmic rays, their possible sources and a transport of particles in magnetic fields on their ways to the Earth.

Energy spectrum and composition of the primary particles

- Study of composition.
- Standard approach:
- The depth X_{max} of shower maximum vs. E

Alternative approach

- THE FRACTION OF MUONS

- The ratio of signals in the underground and the surface detectors at a distance of 600 m from the shower core:

$$\alpha = s_{\mu}(600)/s(600)$$

Importance of model testing

- All hadronic interaction models should be tested!

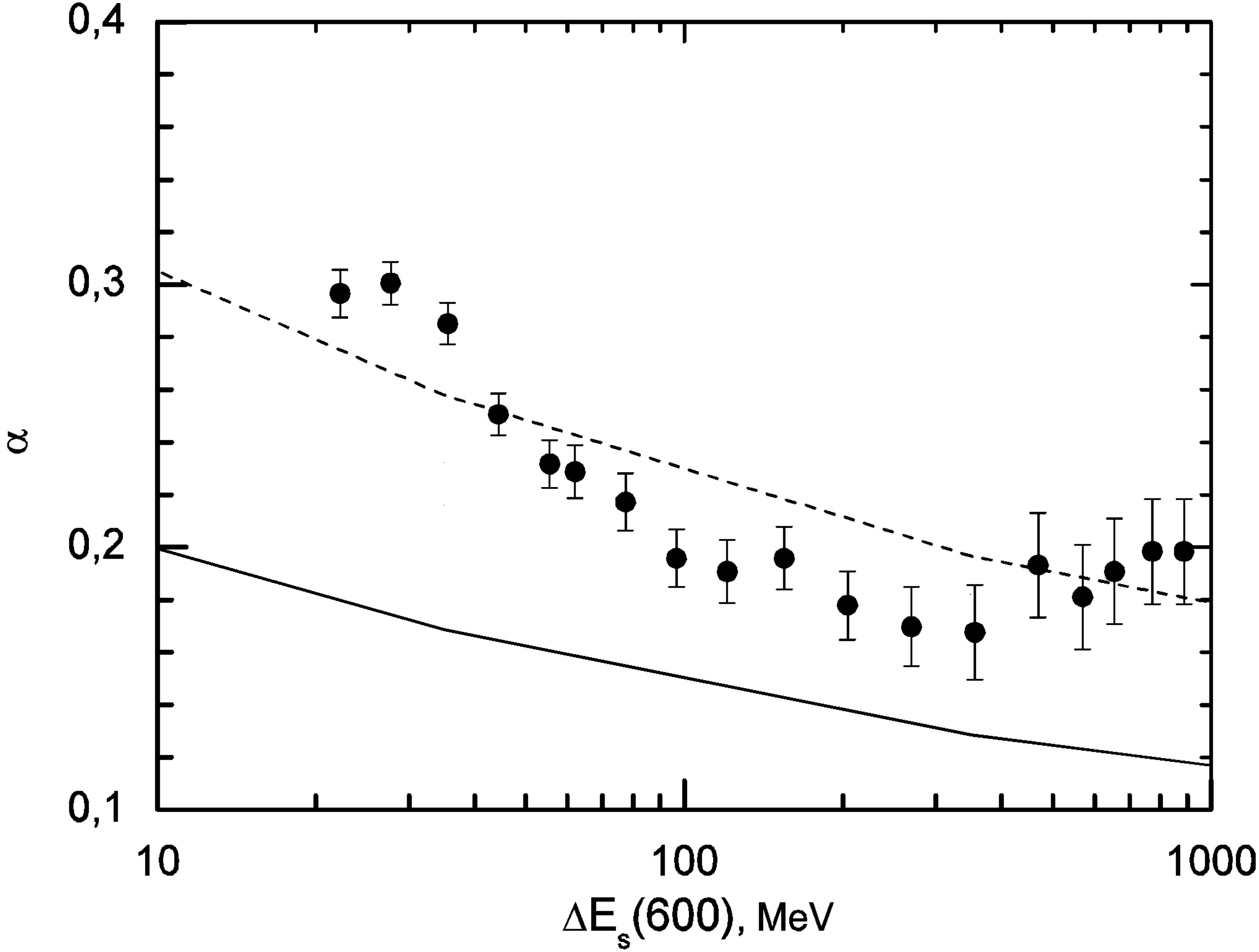
Importance of model testing

- The Yakutsk array data interpreted in terms of the same model QGSJET II-03 gave

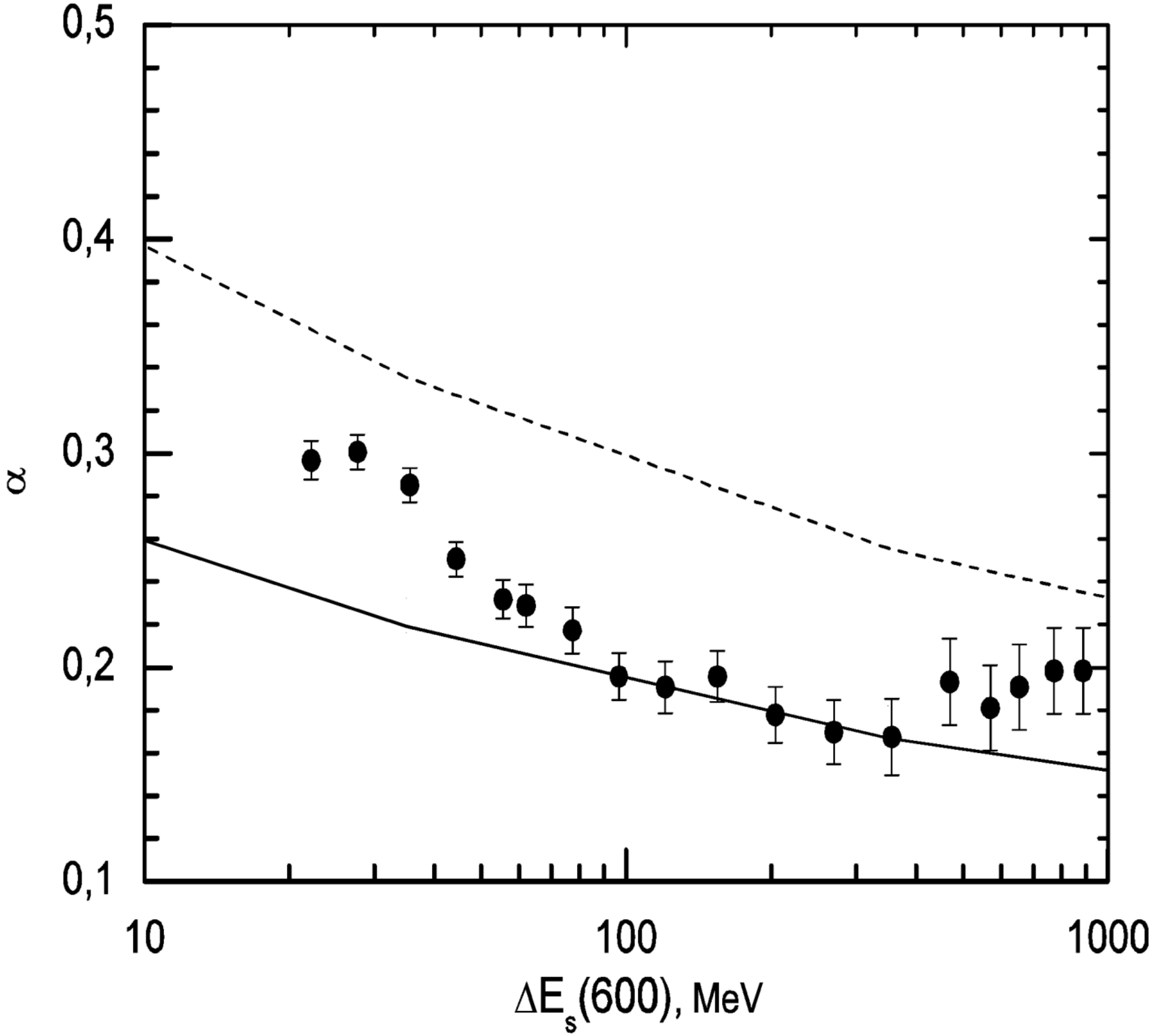
1) Heavy composition – no testing

2) Light composition – with testing

- *L.G. Dedenko, G.F. Fedorova, T.M. Roganova et al., 2012, J. Phys. G: Nucl. Part. Phys.**39** 095202-095212*

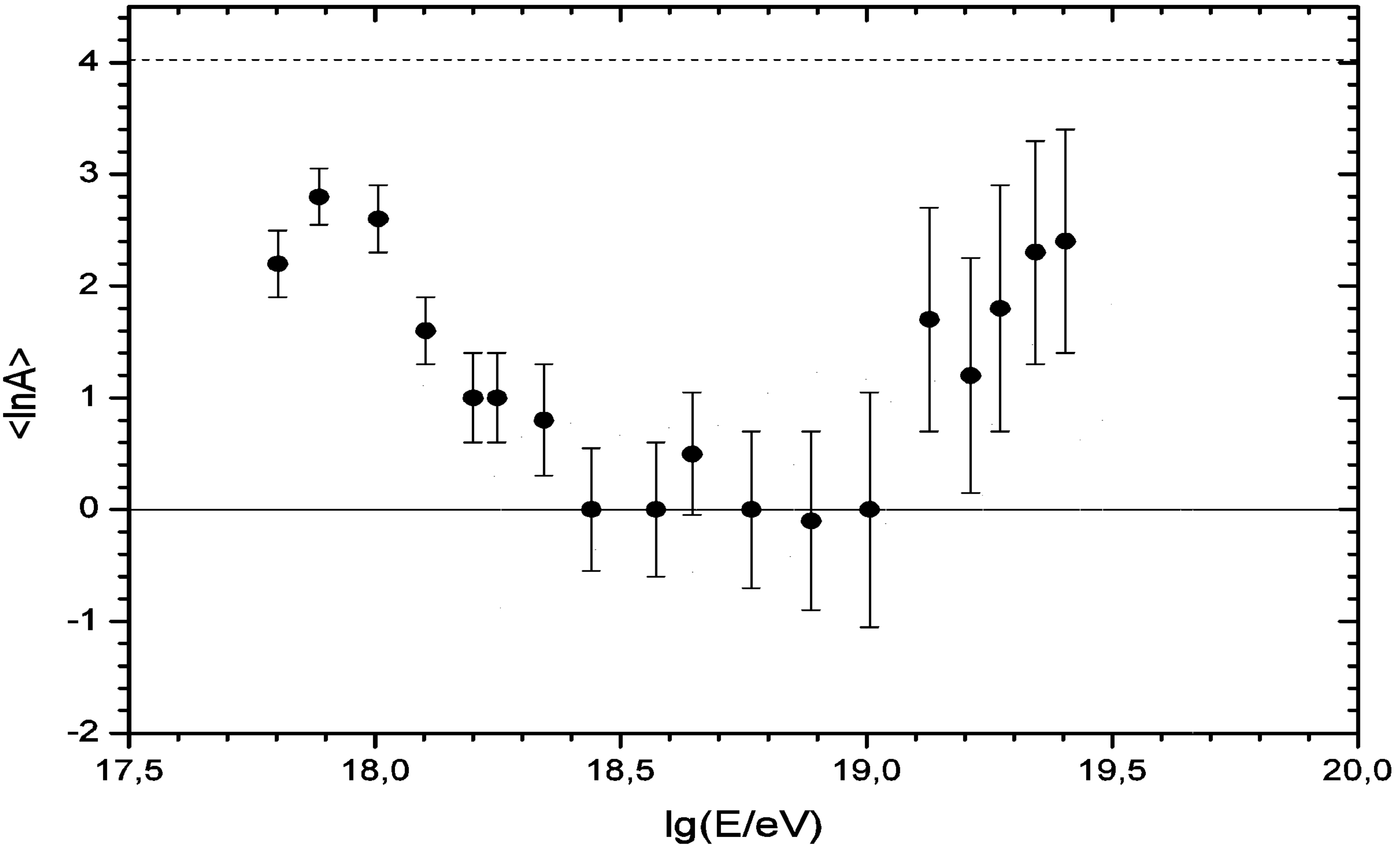


The fraction α of muons calculated in terms of the QGSJET II-03 model for the primary protons (solid line) and the primary iron nuclei (dashed line) and the Yakutsk array data vs. the signal $\Delta E_s(600)$ in the SD. *NO TESTING*



The fraction α of muons calculated in terms of the QGSJET II-03 model for the primary protons (solid line) and the primary iron nuclei (dashed line) vs. the signal $\Delta E_s(600)$. *WITH TESTING*

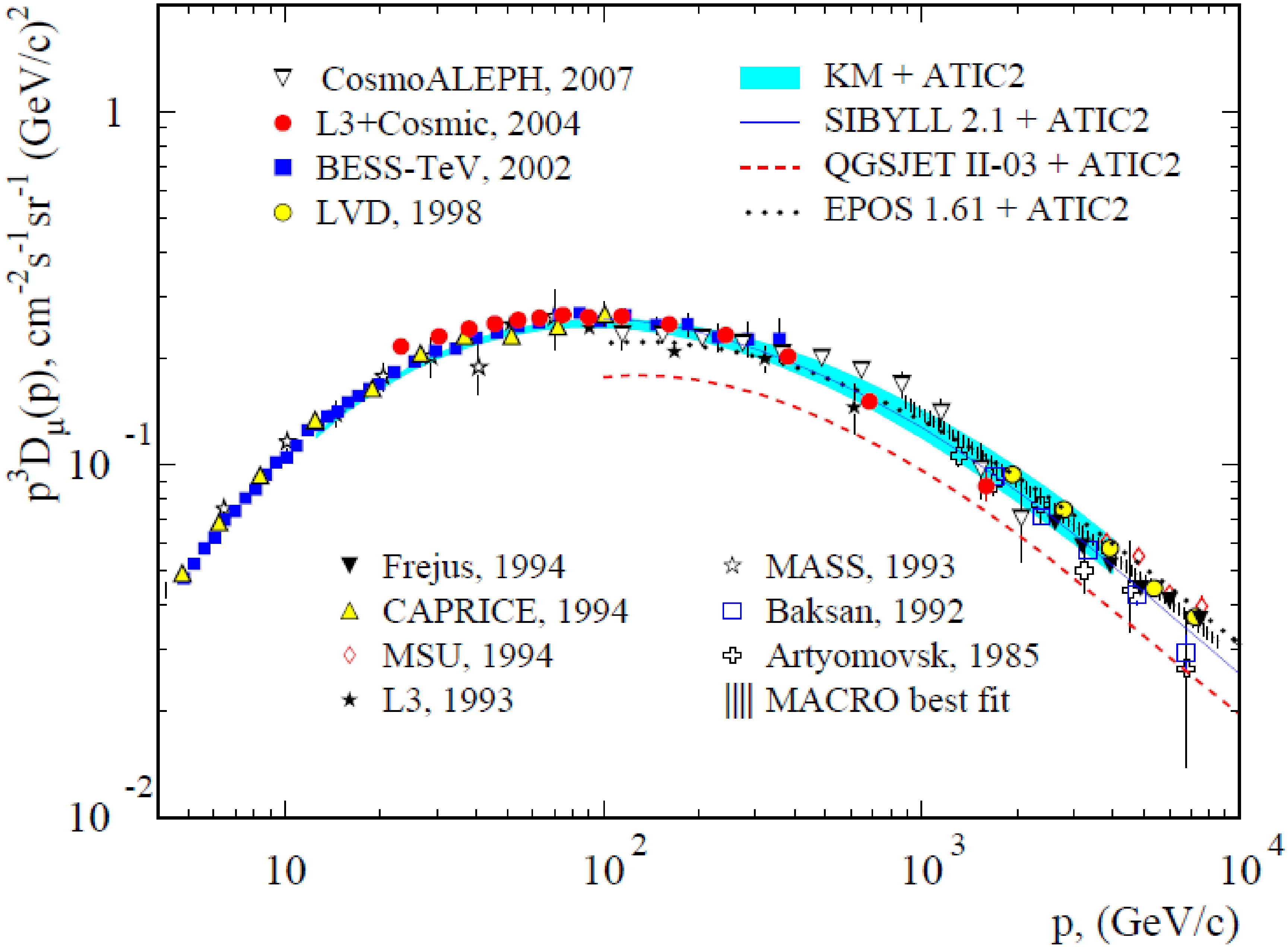
Composition with testing



Main idea of testing

- Using transport equations Kochanov had found in terms of the QGSJET II-03 model and the ATIC 2 primary particle spectrum the atmospheric muon energy spectrum which is by a factor 1.5 lower than data.
- We suggest the very simple method to simulate the muon energy specrum to test any hadronic interaction models.

A. Kochanov, PhD Thesis



Transport equations

- A. Kochanov had used the transport equations to estimate the muon energy spectrum.
- Many papers used the same method:

References

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- Lipari P. Lepton spectra in the Earth’s atmosphere // Astropart. Phys.1993. Vol. 1. pp. 195–227.
- Bugaev E. V. et al. Atmospheric muon flux at sea level, underground and underwater // Phys. Rev. 1998. Vol. D58. pp. 054001; hep–ph/9803488.

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- Volkova L. V. Fluxes of high and ultrahigh-energy cosmic ray muons // Bull. Russ. Acad. Sci. Phys. 2007. Vol. 71. Pp. 560–563.
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- Kochanov A.A., Sinegovskaya T.S., Sinegovsky S.I., Calculation of the atmospheric muon flux // Astropart. Physics, 30, p.219, 2008

Suggestion

- We suggest to test the models of hadron interactions with the atmospheric muon data.
- We suggest the very simple simulations to calculate this spectrum in terms of various models.

Simulations

- The package CORSIKA 7.4 had been used to estimate the energy spectra of muons $D(E_\mu)$ with energies in the energy range of 10^2 - 10^5 GeV in the atmosphere from the primary protons and He nuclei with energies within the interval 10^2 - 10^7 GeV in terms of the
- QGSJET II- 03, QGSJET II-04
- models with statistics $10^6 - 10^2$ events.

Simulations

- To estimate the energy spectra of muons $D(E_{\mu})$ with energies in the energy range of 10^2 - 10^5 GeV in the atmosphere
- we need to know

1) the energy spectra dI_p/dE and dI_{He}/dE of the primary protons and He nuclei with energies within the interval 10^2 - 10^7 GeV

2) the energy spectra of muons $S_p(E_{\mu},E)$ and $S_{He}(E_{\mu},E)$ calculated from the primary H and He nuclei with the fixed energies E in terms of the QGSJET II- 03, QGSJET II-04 models.

Simulations of the energy spectra of muons

- *From the primary protons*:

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

- *From the primary He nuclei*:

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

- *The sum*

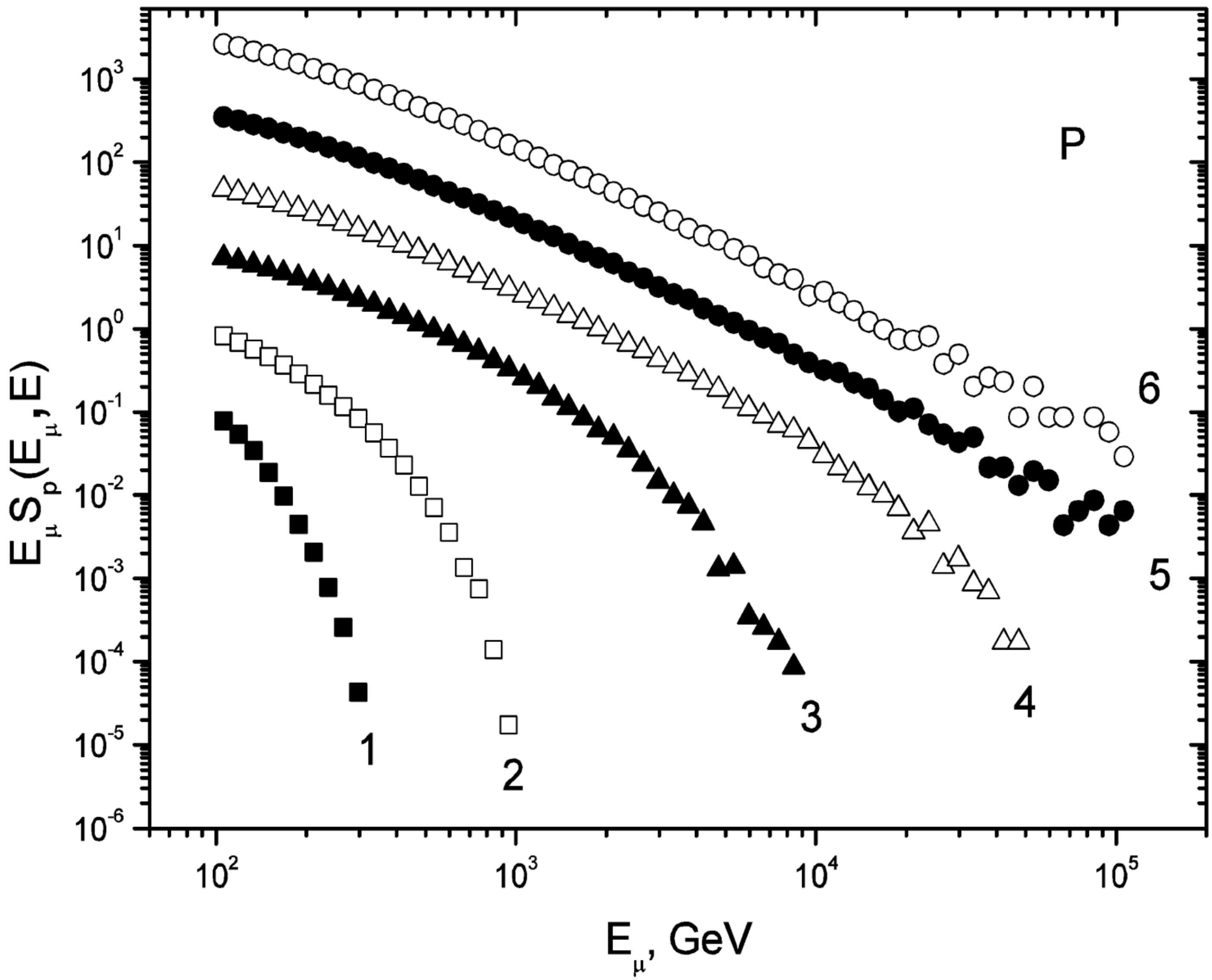
$$D(E_\mu) = \left(D_p(E_\mu) + D_{He}(E_\mu)\right)$$

Spectra of muons

- *Spectrum of muons from the primary protons with fixed energy E*
- $S_p(E_\mu,E)\cdot dE_\mu$

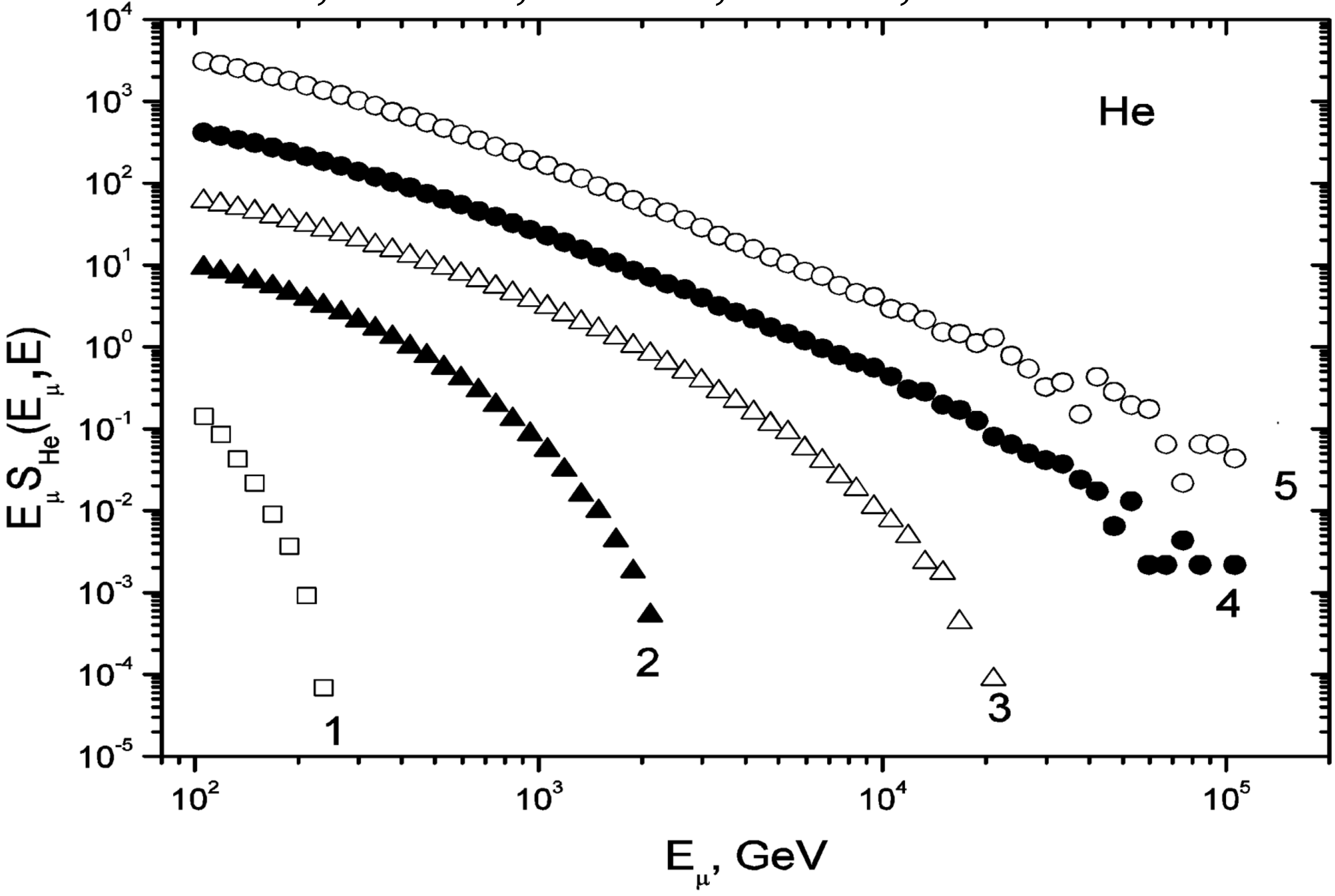
- *Spectrum of muons from the primary He nuclei with fixed energy E*
- $S_{He}(E_\mu,E)\cdot dE_\mu$

The energy spectra of muons generated by the primary protons with various energies E (QGSJET II-04):
1 - $3.162 \cdot 10^2$, 2 - 10^3, 3 - 10^4, 4 - 10^5, 5 - 10^6, 6 - 10^7 GeV;



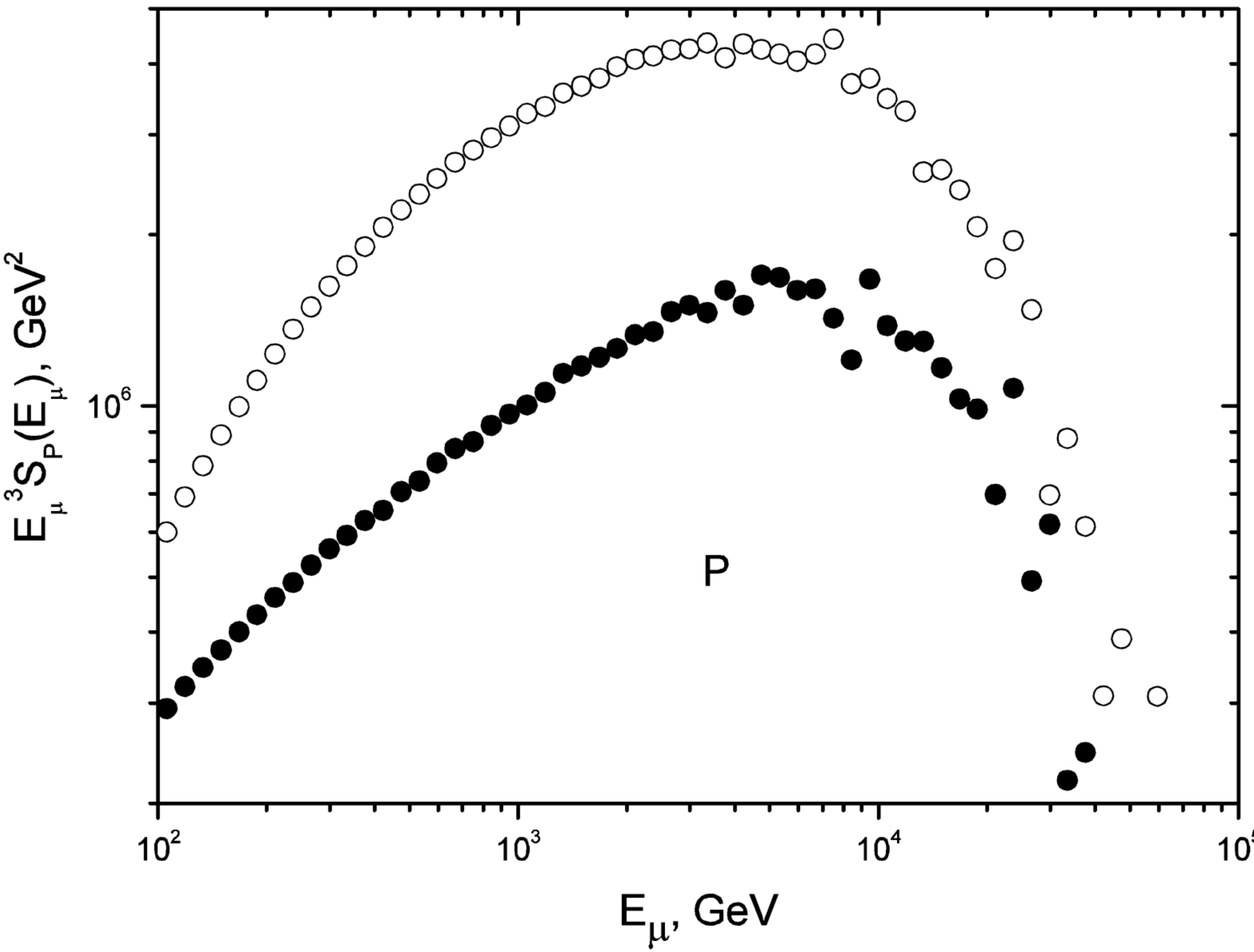
The energy spectra of muons generated by the primary He nuclei with various energies E (QGSJET II-04):

1 - 10^3, 2 - 10^4, 3 - 10^5, 4 - 10^6, 5 - 10^7 GeV.



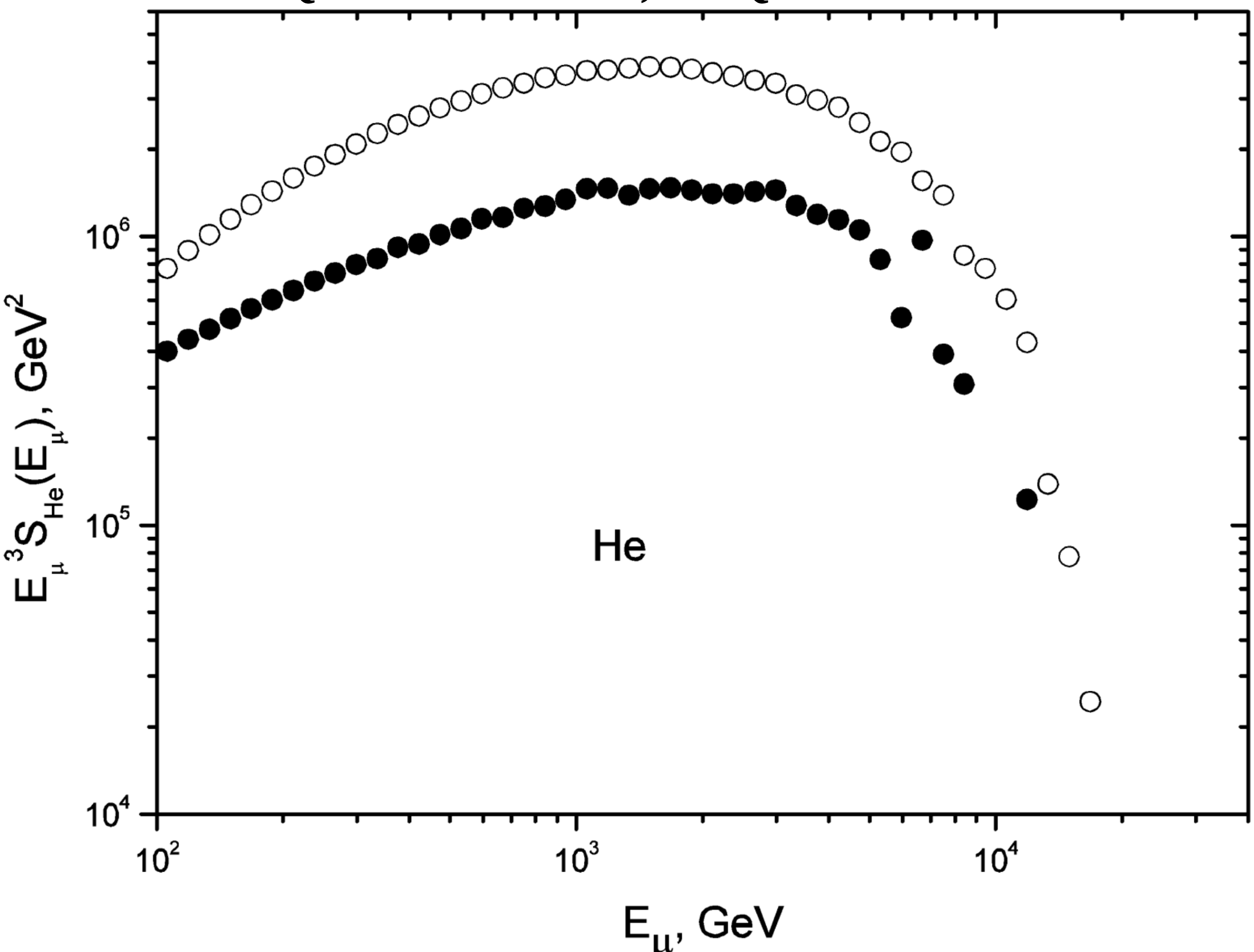
Muon spectrum for the primary protons with the energy $E=10^5$ GeV in terms of the various models

● QGSJET II-03, ○ QGSJET II-04



Muon spectrum for the primary He nuclei with the energy E=10^5 GeV in terms of the various models

● QGSJET II-03, ○ QGSJET II-04



Testing

- Models
- QGSJET II- 03, S.S. Ostapchenko, Phys. Rev. D**74**, 014026, 2006
- QGSJET II-04, S.S. Ostapchenko, Phys. Rev. D **83**, 014018, 2011
- *are tested with the help of the atmospheric muon data.*

Atmospheric muon data

- The smooth approximation of the atmospheric muon data observed by the collaborations:

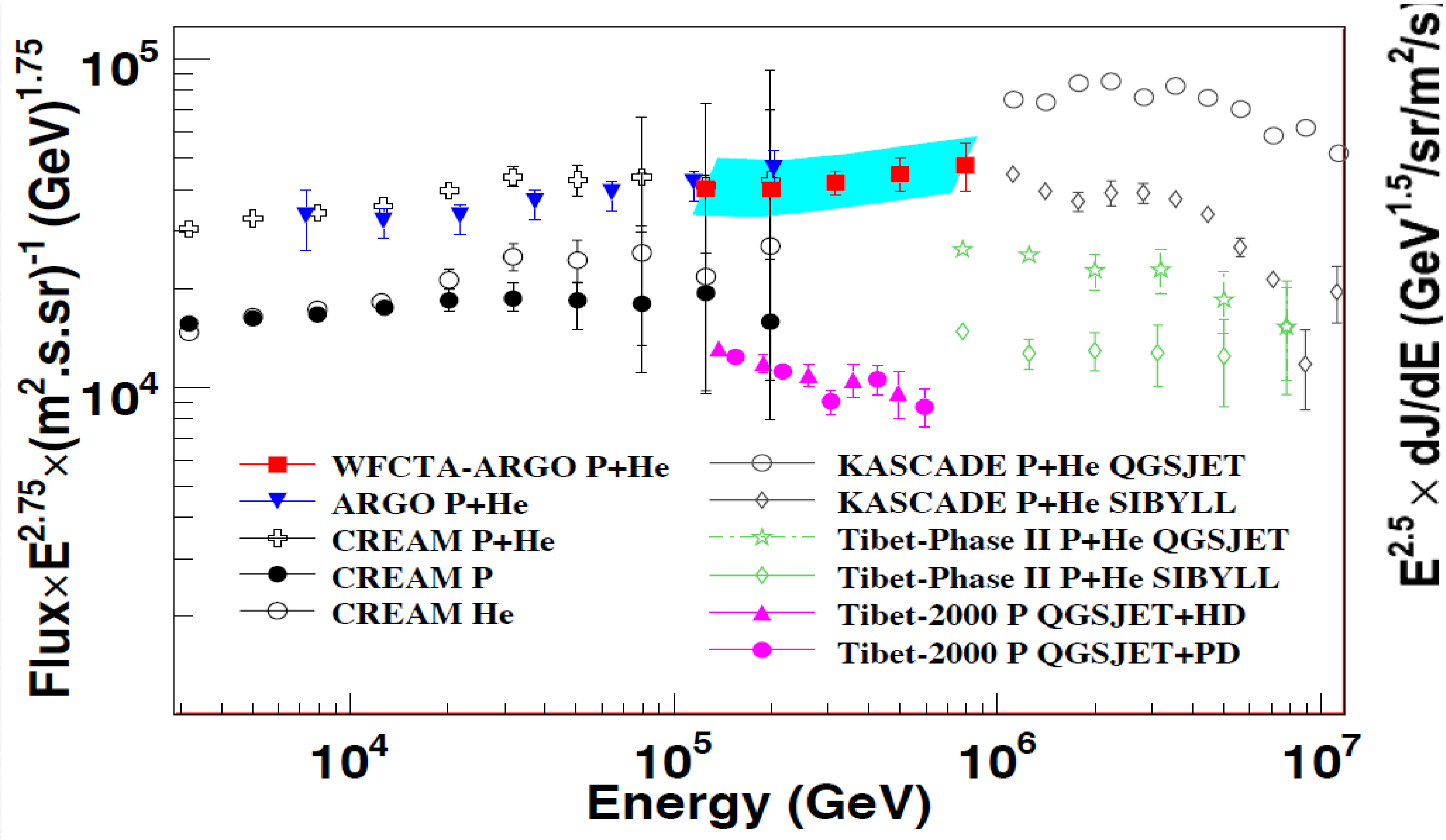
1) L3+Cosmic: arXiv: hep-ex 0408114v1K (2004)
2) MACRO: M. Ambrosio et al., Phys. Rev. D **52**, 3793, (1995)
3) LVD: M. Aglietta et al., arXiv: hep-ex 9806001v1, (1998)

- had been used for comparison with results of simulations.

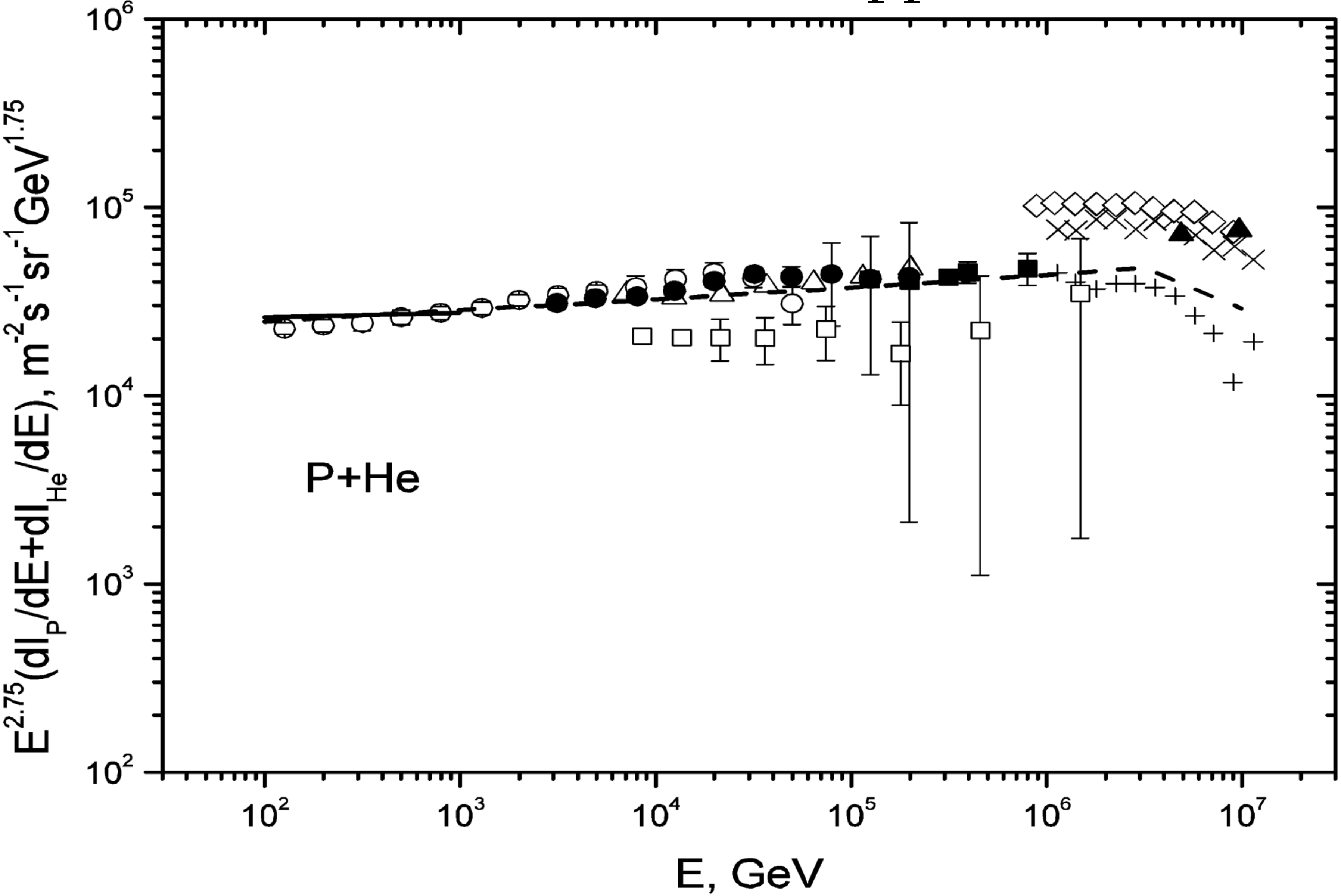
Method of simulation

- The energy spectra and the primary particles composition:
- As the energy per nucleon of importance only the energy spectra of the primary protons and He nuclei should be taken into account.

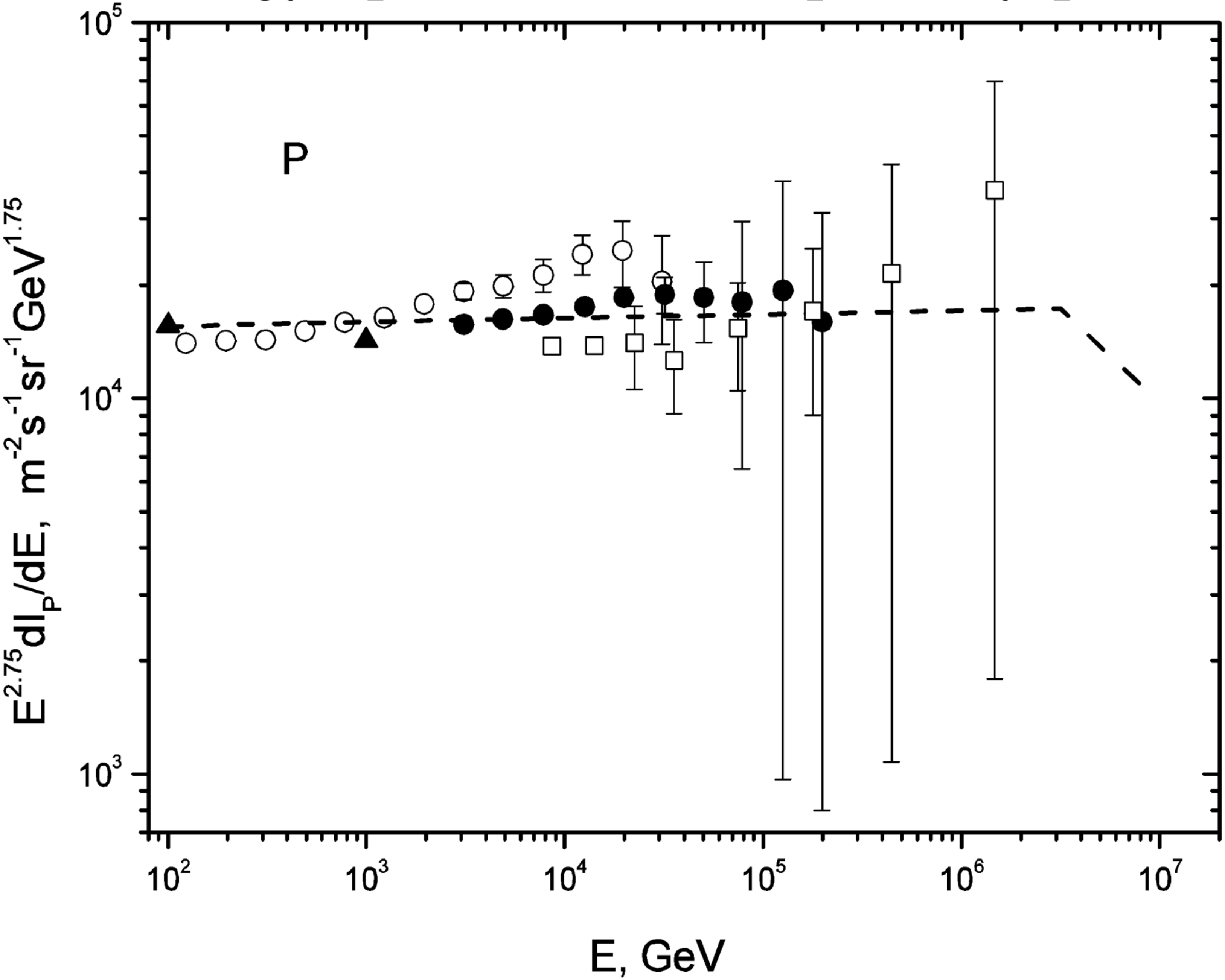
Energy spectra of the primary protons and He nuclei.
Yoshiki Tsunesada, *Tokyo Institute of Technology*, July 09 2013
Rapporteur Talk at 33-d ICRC 2013, Rio de Janeiro



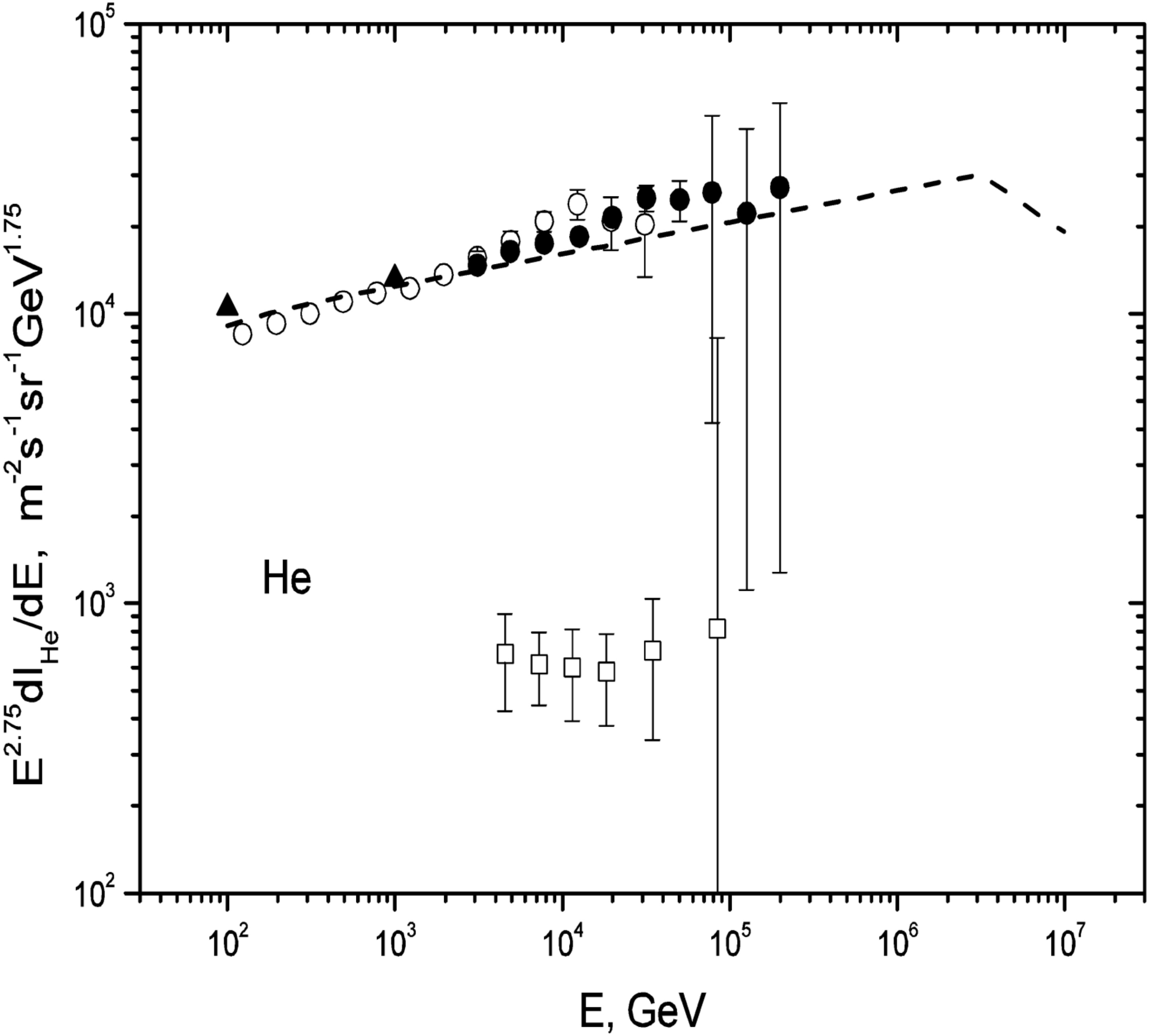
The primary spectrum of (p+He). Dashed line – modified Gaisser-Honda approximation



The energy spectrum of the primary protons



The energy spectrum of the primary He nuclei



Approximation G&H for the primary protons and He nuclei

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

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

Nuclei	α	K	b	c
H (1)	2.74	14900	2.15	0.21
He (4)	2.64	600	1.25	0.14

- We will use G&H as $(dI_p/dE)_{GH}$ and $(dI_{He}/dE)_{GH}$

Modified G&H approximation of the energy spectra of the primary particles

- 1. For the primary protons:
- $(dI_p/dE)_m = (dI_p/dE)_{GH} \cdot (E_1/E)^{0.5}$
- 2. For the primary He nuclei:
- $(dI_{He}/dE)_m = (dI_{He}/dE)_{GH} \cdot (E_1/E)^{0.5}$
- where $E_1 = 3 \cdot 10^6$ GeV.
- Modified G&H will be used at energies above E_1.

The primary spectrum of (p+He)

- Dashed line – the G&H and the modified Gaisser-Honda approximation.
- Solid line – AMS02, ○ - ATIC2, ● - CREAM,
- Δ - ARGO, ■ - WCFTA,
- × - KASKADE (QGSJET II-03) and
- \+ - KASKADE (SIBYLL 2.1)
- □ - RUNJOB,
- ◊ - TUNKA (all particles),
- ▲ - SPHERE2 (all particles)

The primary spectra of (p, He)

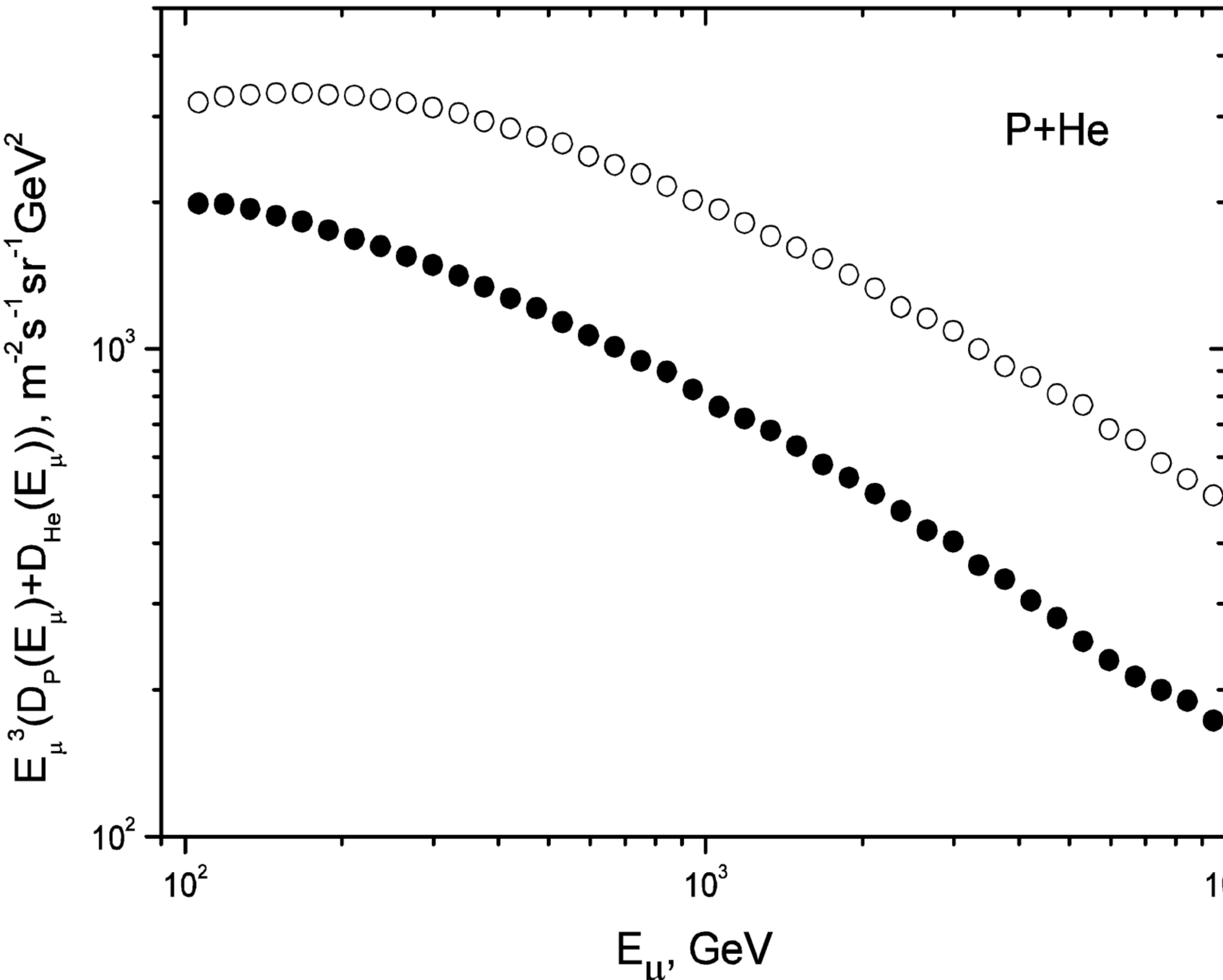
- AMS02: Proc. 33-d ICRC, Rio de Janeiro, 2013
- ATIC2: A.D. Panov et al., Bull. Bull. RAS, Phys.,**73**, 564, 2009
- CREAM: H. S. Ahn et al., Astrophys. J. Lett. **714**,L89-L93, 2010
- ARGO: B.Bartoli et al., Phys. Rev. D, **85**, 092005, 2012
- WCFTA: S.S. Zhang et al., NIM, A, 629,57-65, 2011
- × 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

Results

- The simulated muon spectra in terms of the
- ● QGSJET II-03 and
- ○ QGSJET II-04 models.
- At energies above B~100 GeV, the simulated spectra are steepened.
- (the decay constant for the charged π mesons)

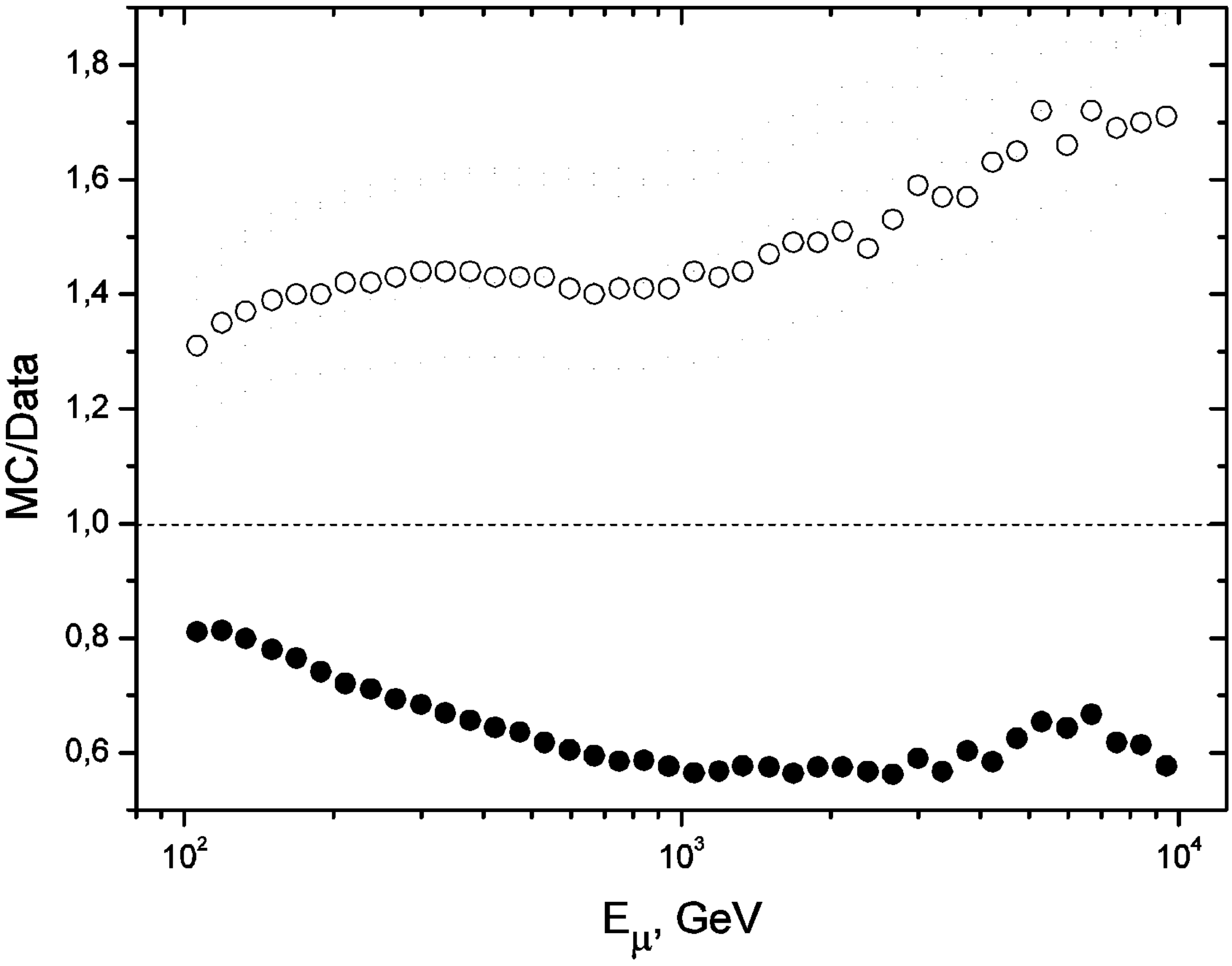
The calculated spectra of near vertical muons

● QGSJETII-03, ○ QGSJETII-04



Comparison with the atmospheric muon data

MC/DATA: ● QGSJET II-03, ○ QGSJET II-04



Comparison with the atmospheric muon data MC/DATA:

● QGSJET II-03, ○ QGSJET II-04

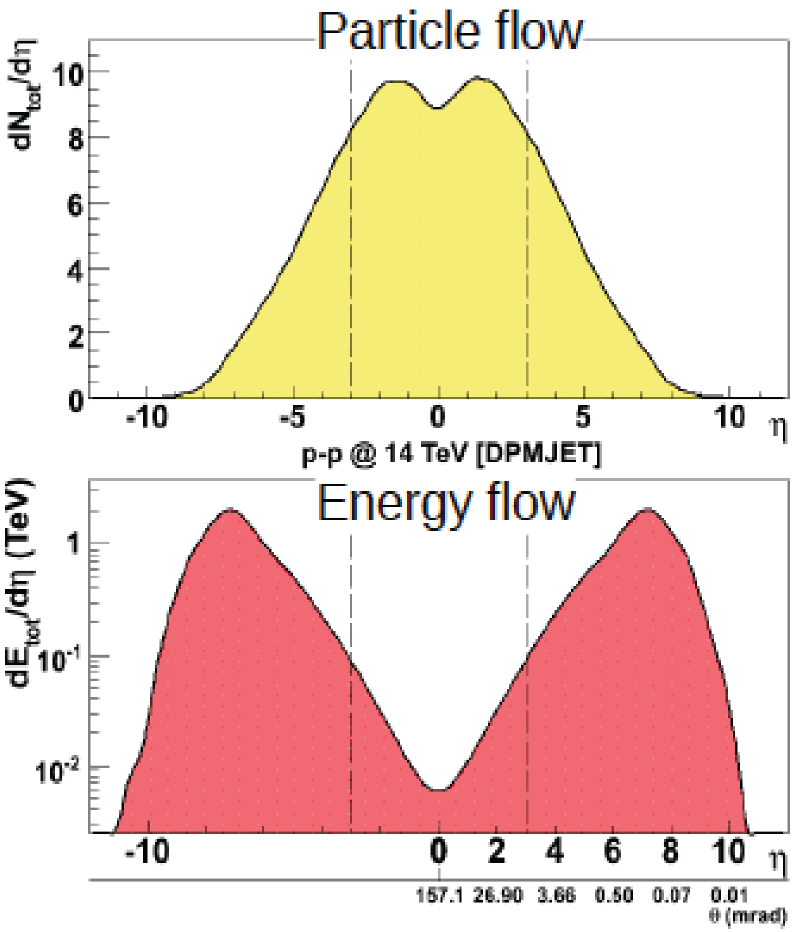
- At energy $E_\mu=10^4$ GeV the calculated muon spectra are by a factor (f)
- f=1.7 above the data for QGSJET II-04
- f=1.5 below the data for QGSJET II-03
- Strain (shift) for these series!

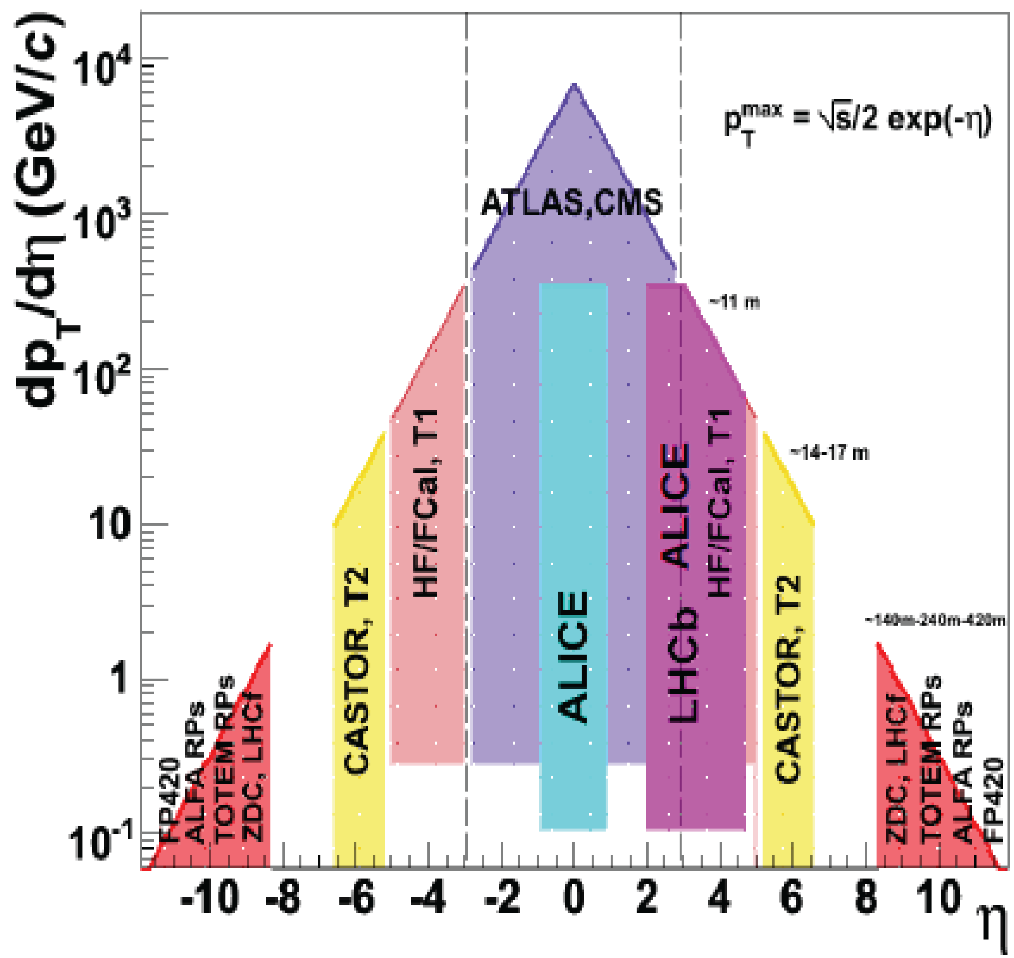
The LHC data

- Experiments:
- LHCf
- TOTEM

James L. Pinfold
The University of Alberta
Report at 33-d ICRC 2013, Rio de Janeiro

p-p @ 14 TeV





Summary of Physics Results from the TOTEM Experiment, Giuseppe Latino, arXiv:1302.2098v1 8 Feb 2013

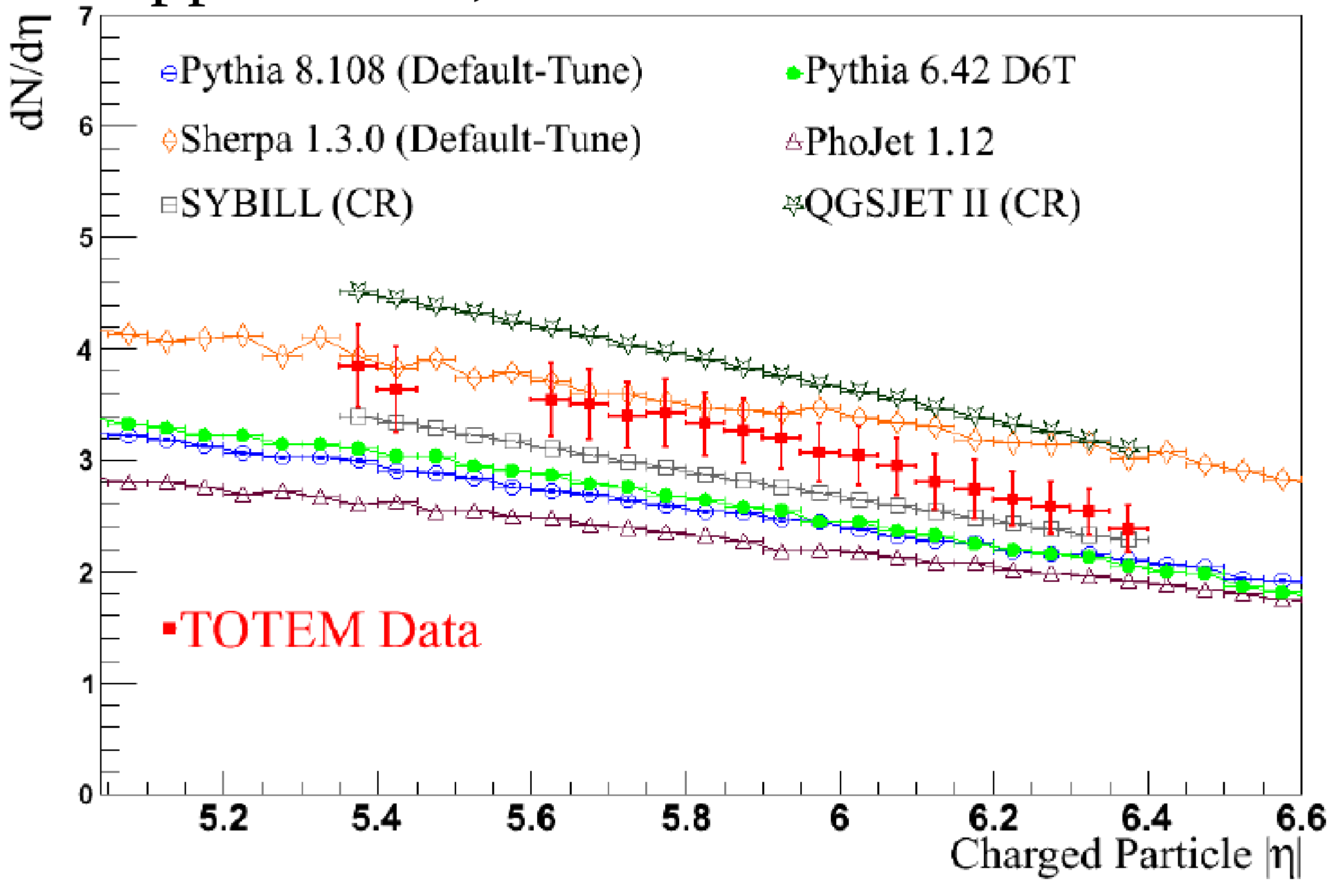
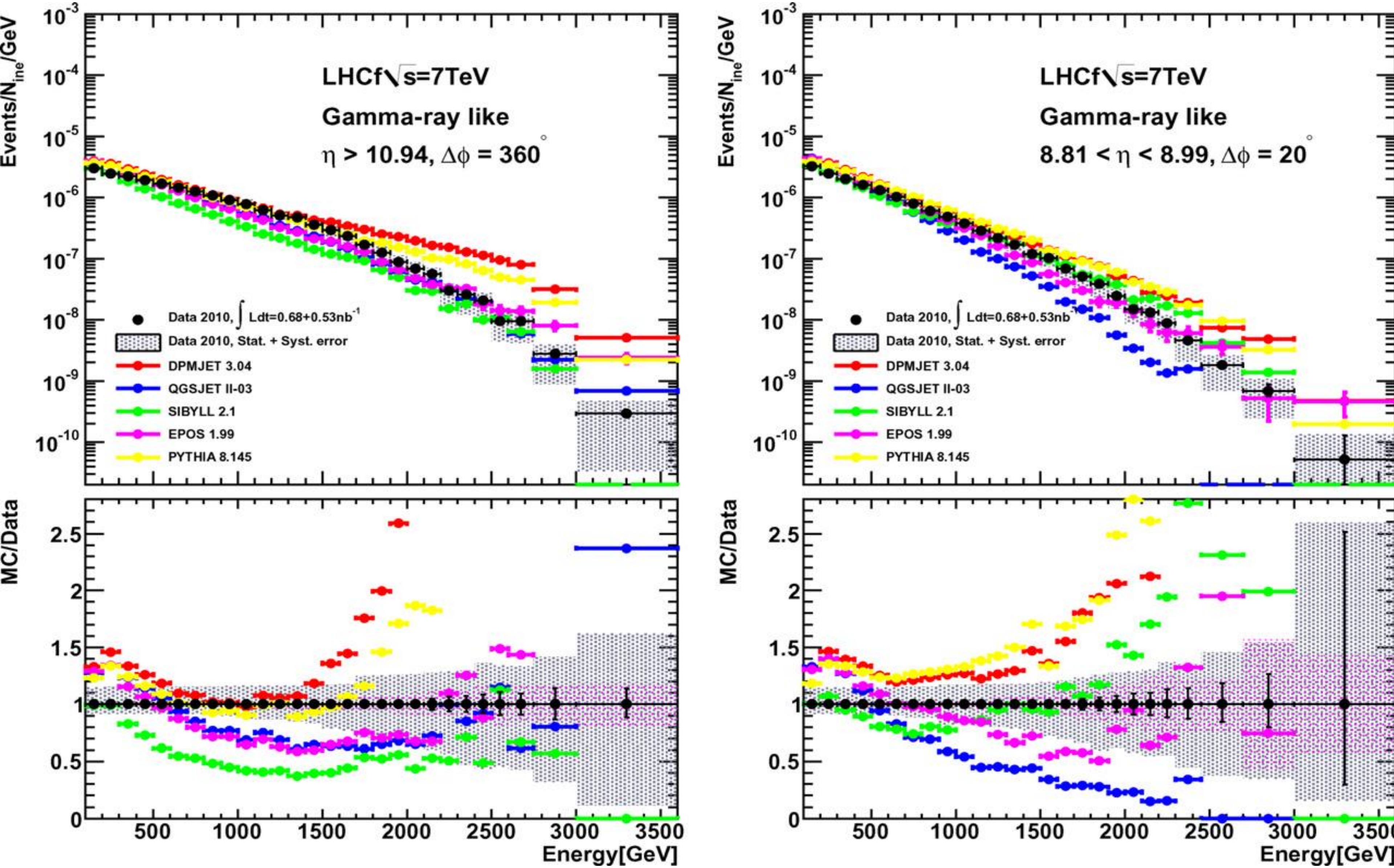


Figure 6. $dN_{ch}/d\eta$ distribution measured by Totem. The experimental results (red squares), obtained as the average of the four T2 quarters, are reported with the error bars including both statistical and systematic errors. The predictions from some MC generators are reported for comparison.

LHCf: forward photon production $pp \to \gamma X$



- Forward photon energy spectrum at LHC 7 TeV p–p collisions measured by LHCf, Nuclear Instruments and Methods in Physics Research A 692 (2012) 224–227

CONCLUSION

At energy $E_\mu=10^4$ GeV the calculated muon spectra are strain by a factor

- f=1.7 above the data for QGSJET II-04
- f=1.5 below the data for QGSJET II-03

Models of hadron interaction should be updated at very high energies of secondary particles.

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Thank you

for attention!