Vulcano 2014

Are IceCube PeV neutrino events extraterrestrial or can be of atmospheric origin?

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Content

Introduction - 1

Cascade showers with energies near PeV in IceCube which could be induced only by neutrinos were observed.

PRL 111, 021103 (2013)

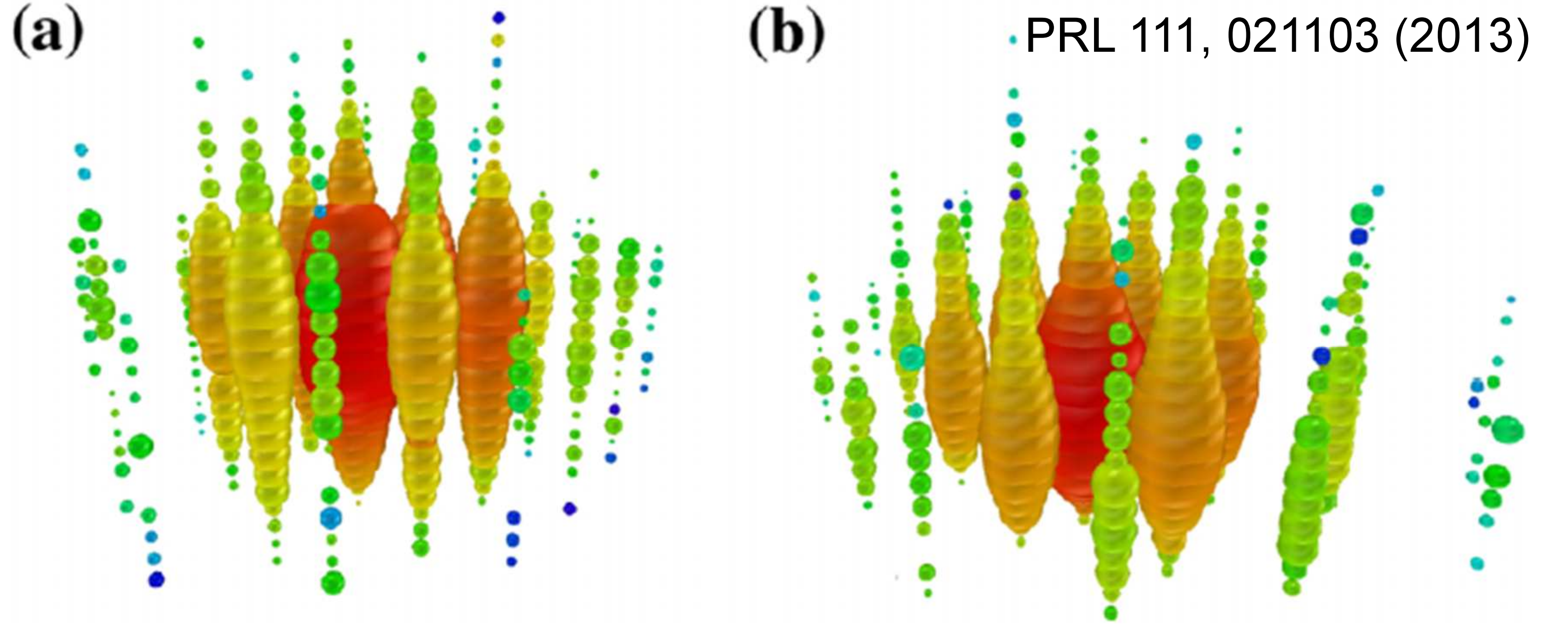
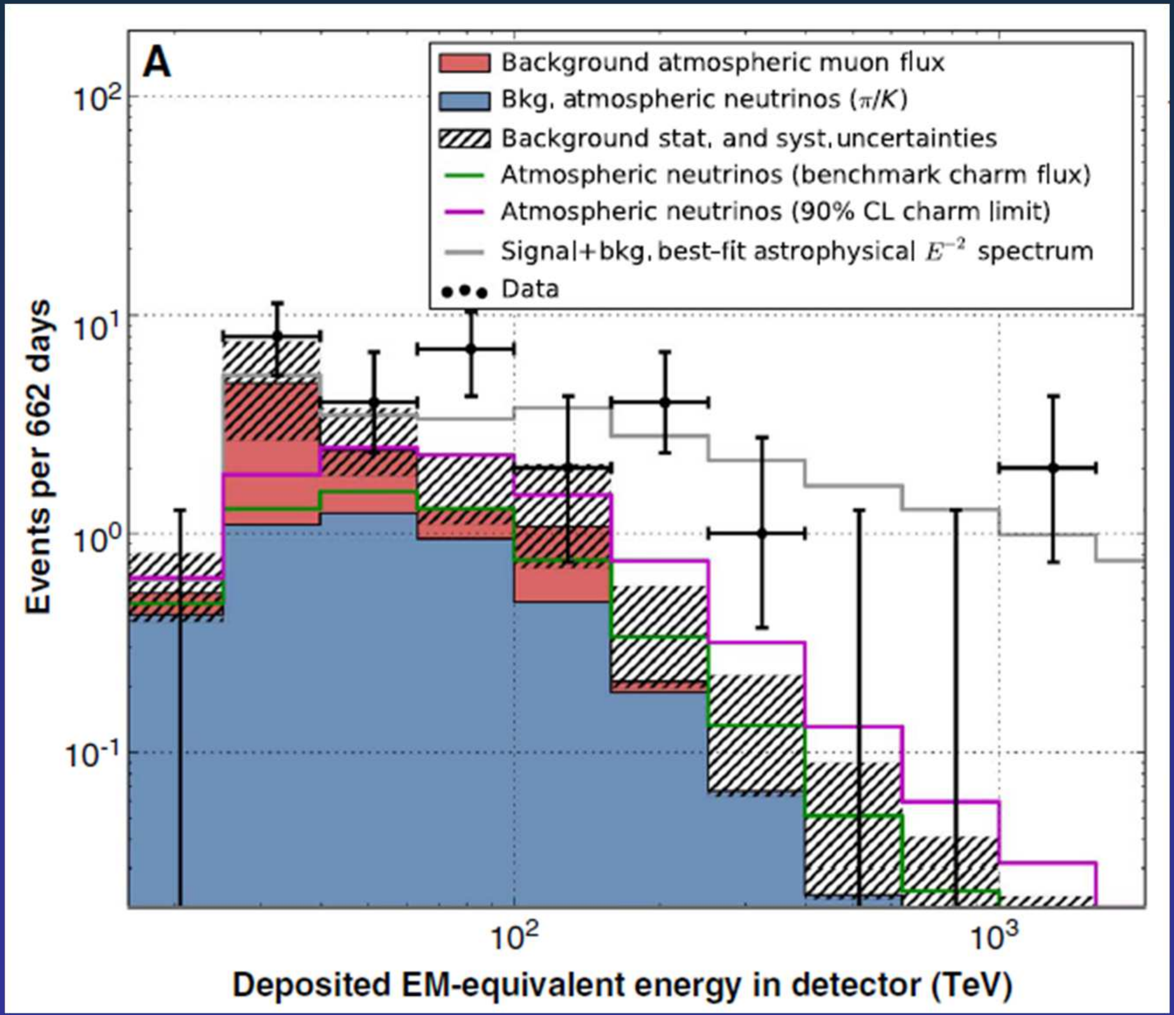


FIG. 4 (color online). The two observed events from (a) August 2011 and (b) January 2012. Each sphere represents a DOM. Colors represent the arrival times of the photons where red indicates early and blue late times. The size of the spheres is a measure for the recorded number of photoelectrons.

Introduction - 2

The flux of atmospheric neutrinos at such energies is very small to observe such events.

Science 342 (2013) 1242856



The difference is several tens times.

Explanation

IceCube Collaboration believes that these neutrinos are extraterrestrial, since to explain observed events by atmospheric neutrinos, it is necessary to increase their flux at PeV energies in several tens times.

Is it possible? My answer is ‘yes’.

In principle, the observed neutrino events give an additional contribution to a big list of unusual phenomena, which is permanently increasing and is discussed many years.

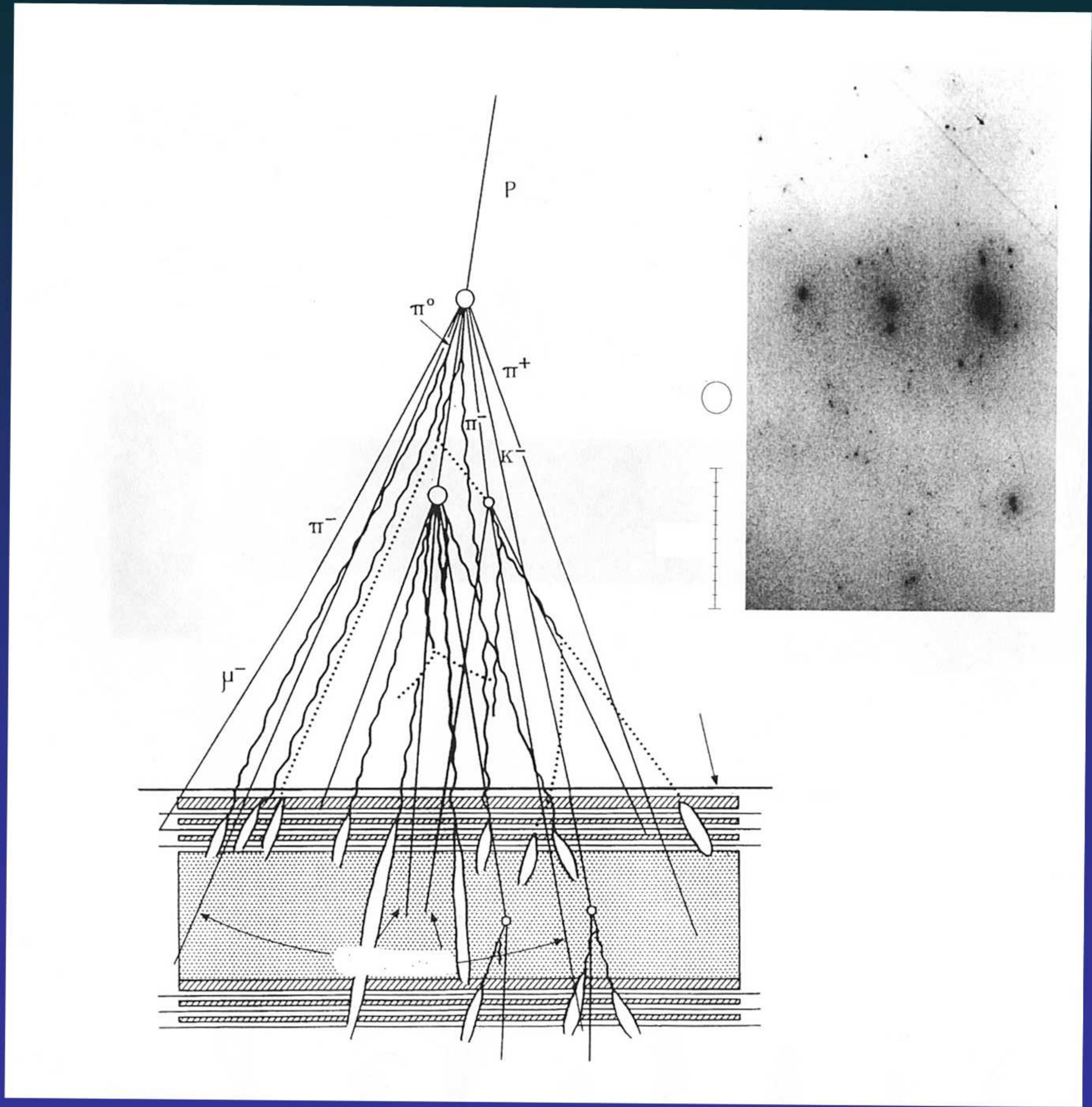
I would like to remind you that unusual events are observed in other components of cosmic rays: hadrons, muons and EAS in different experiments including IceCube.

List of unusual events

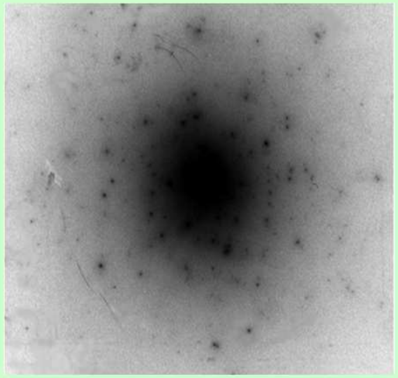
- In **hadron** experiments:
  - Halos,
  - Alignment,
  - Penetrating cascades,
  - Centauros.
- In **muon** experiments:
  - Excess of muon bundles,
  - Excess of VHE (~ 100 TeV) single muons.
- In **EAS** investigations:
  - Increase of the energy spectrum slope,
  - Changes in N_μ / N_e - ratio dependence.

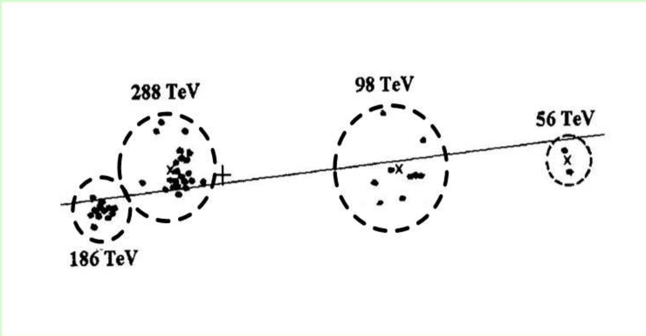
Important: Unusual events appear at PeV energies of primary particles.

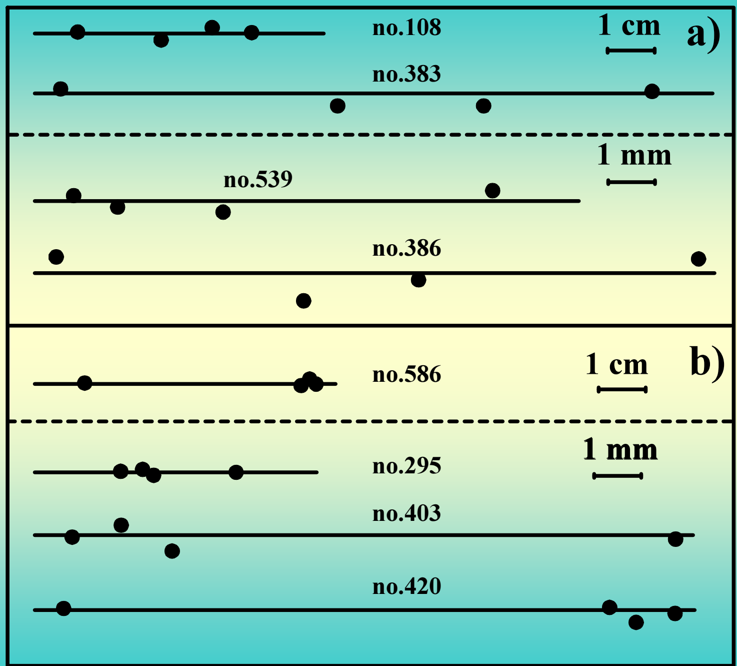
Experiment Pamir



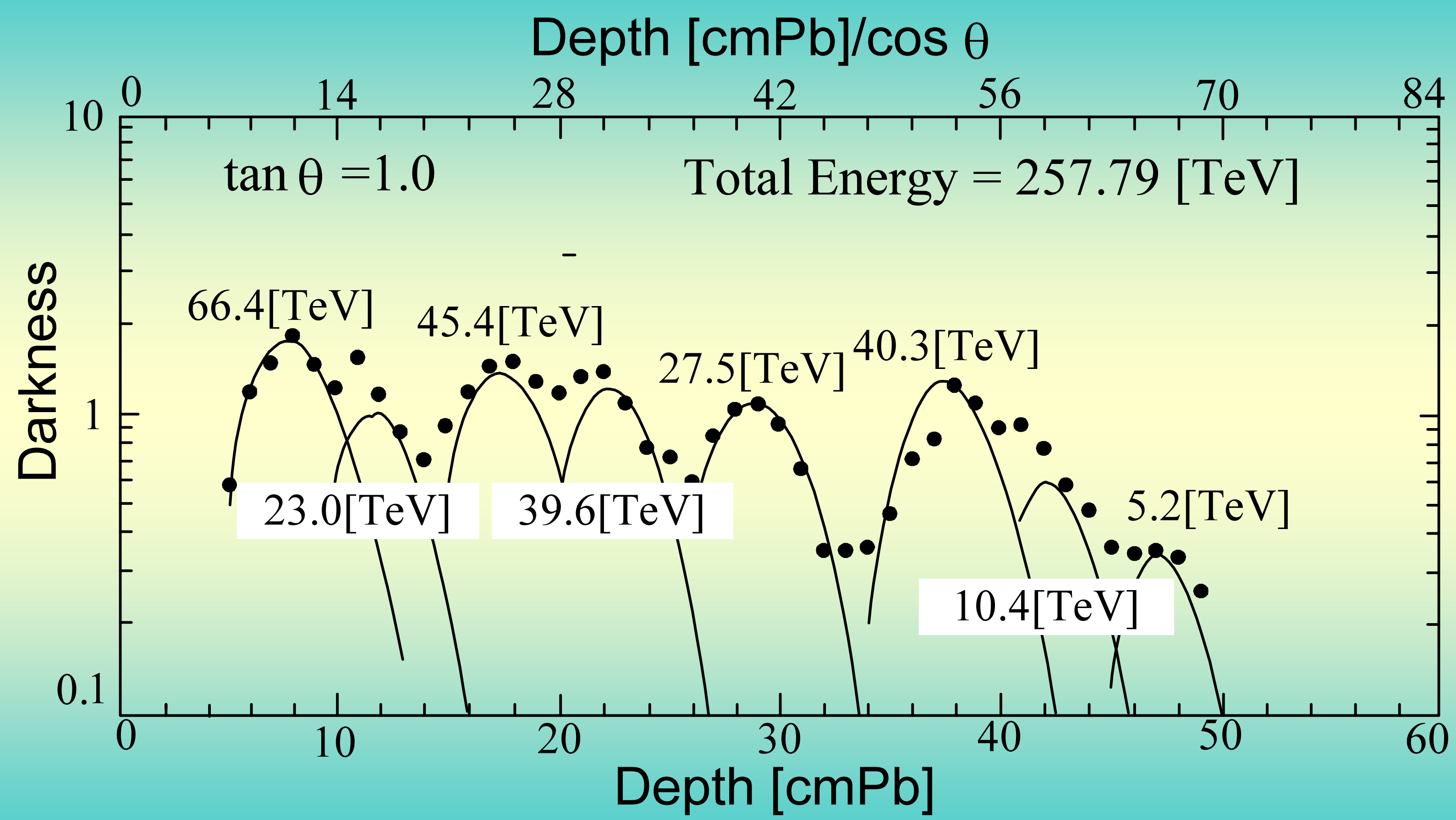
Halo and alignment



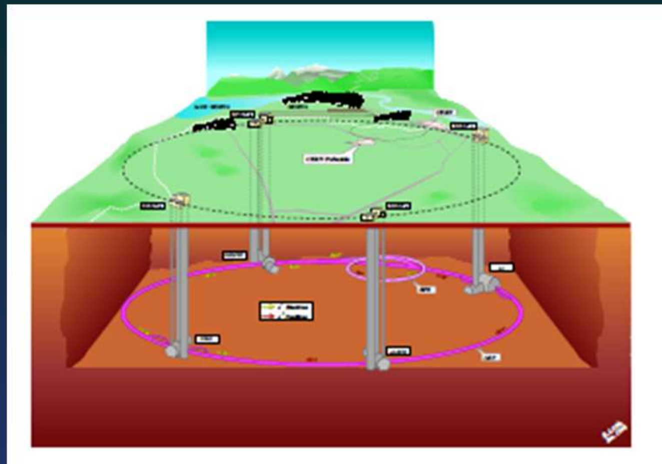


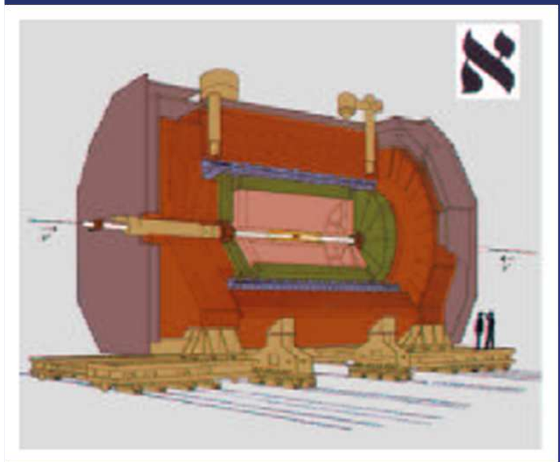


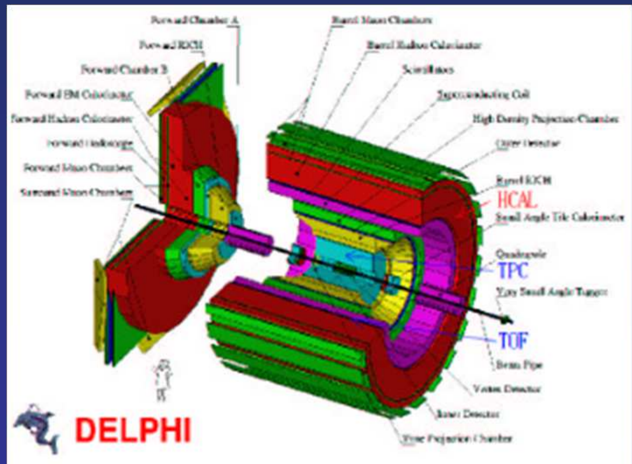
Penetrating cascades

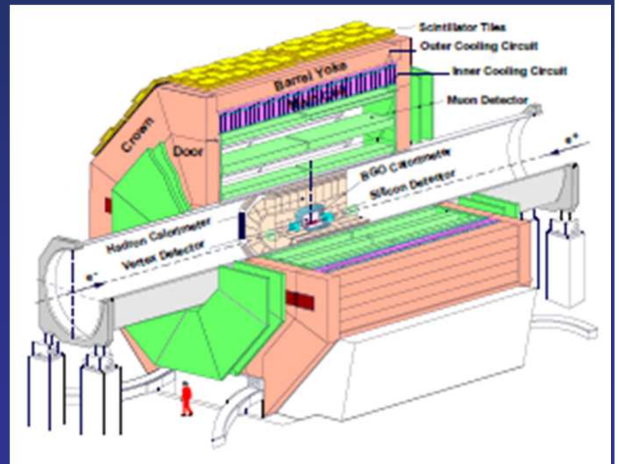


LEP Detectors (CERN)









ALEPH

130 m depth ($E_{\mu} > 70$ GeV)
Hadron calorimeter, TPC
5 scintillator stations

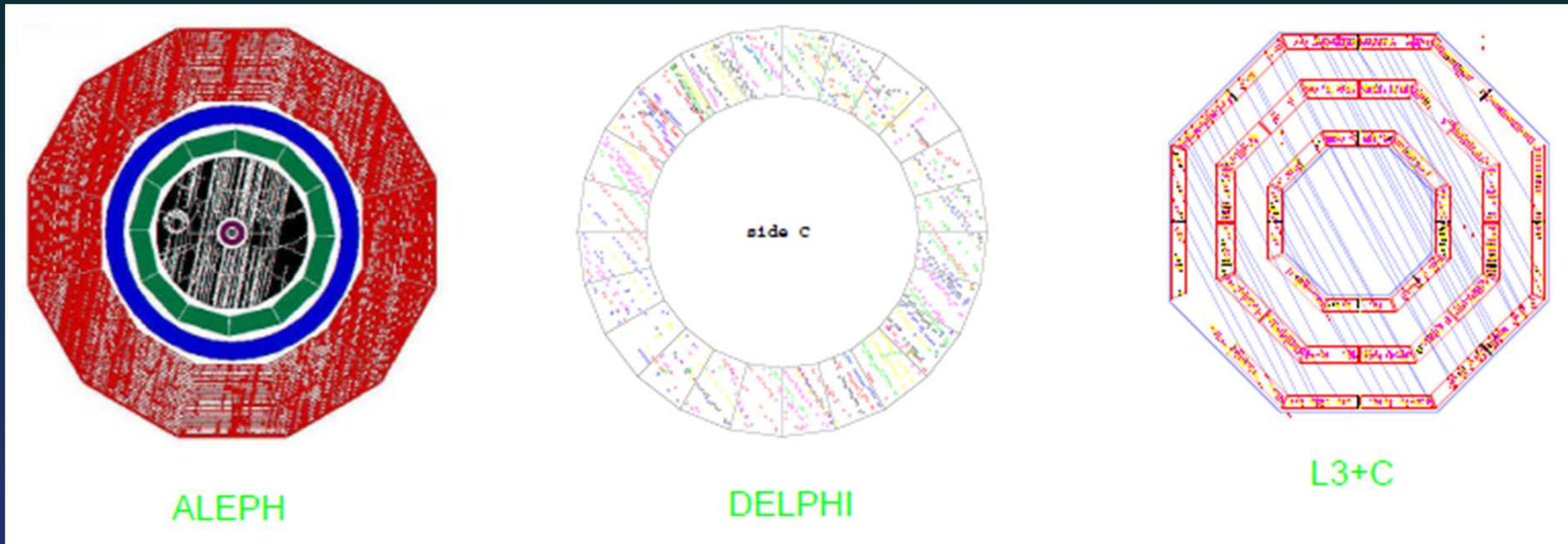
DELPHI

100 m depth ($E_{\mu} > 50$ GeV)
Hadron calorimeter, TPC, TOF

L3

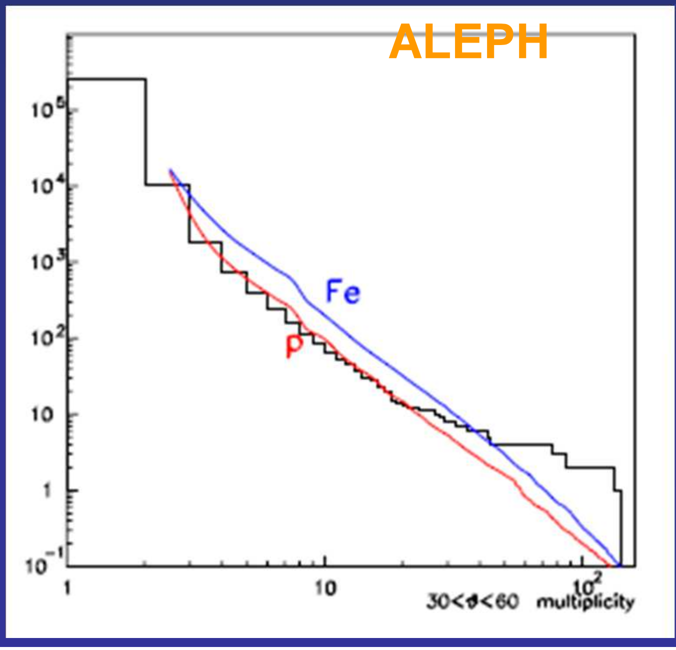
40 m depth ($E_{\mu} > 15$ GeV)
Drift chambers, timing scintillators, surface EAS array

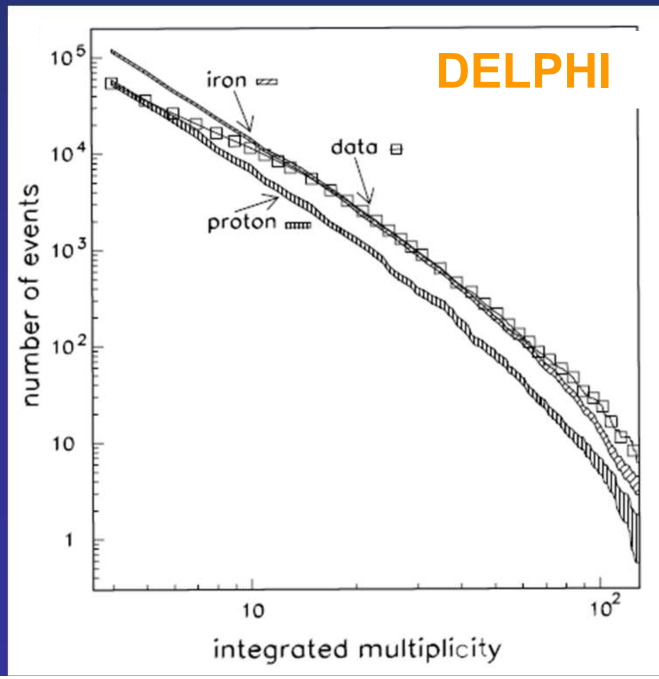
Multi-muon events (muon bundles)



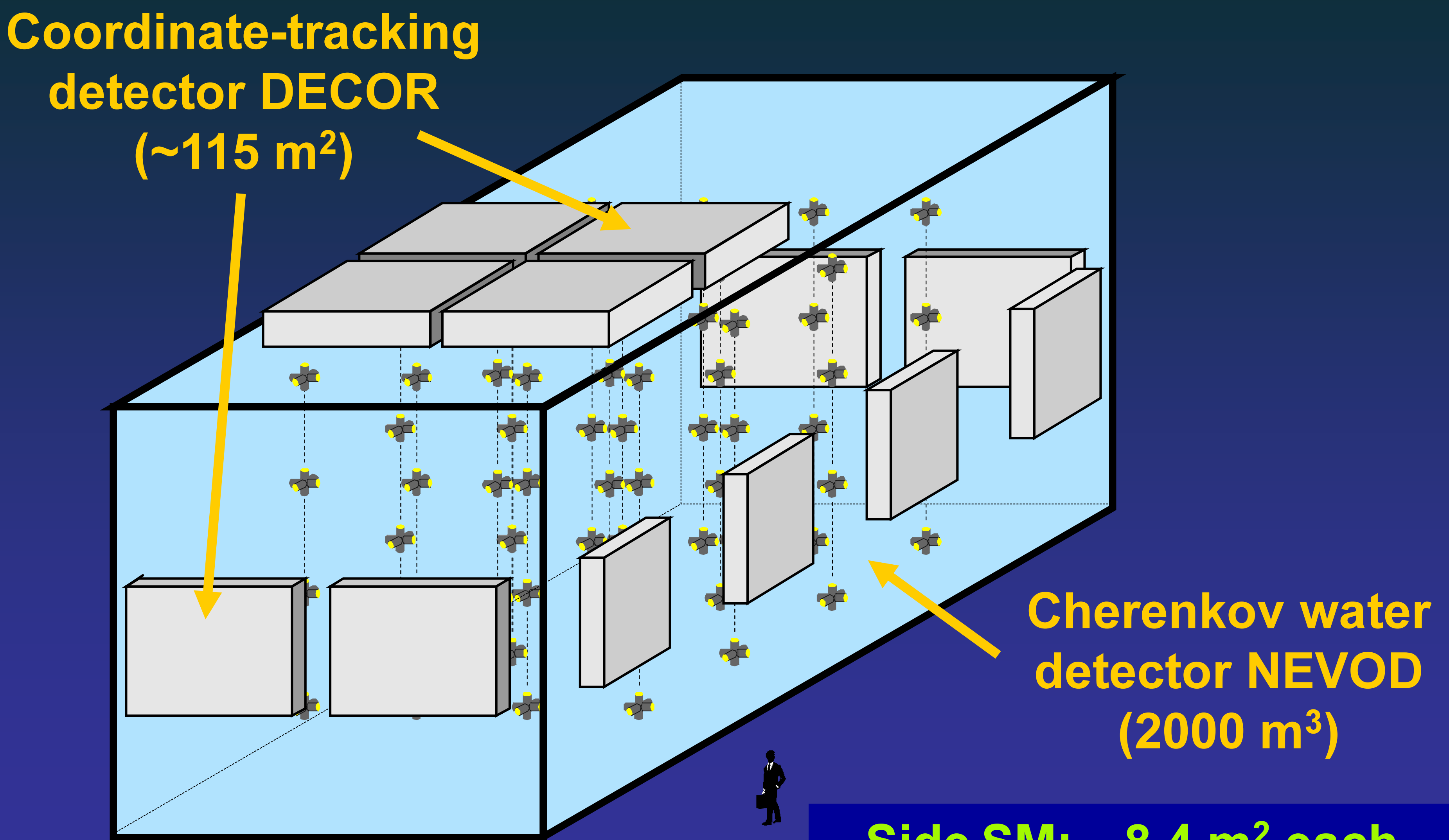
C. Grupen et al., Nuclear Physics B (Proc. Suppl.) 175-176 (2008) 286.

J. Abdallah et al., Astroparticle Physics 28 (2007) 273.



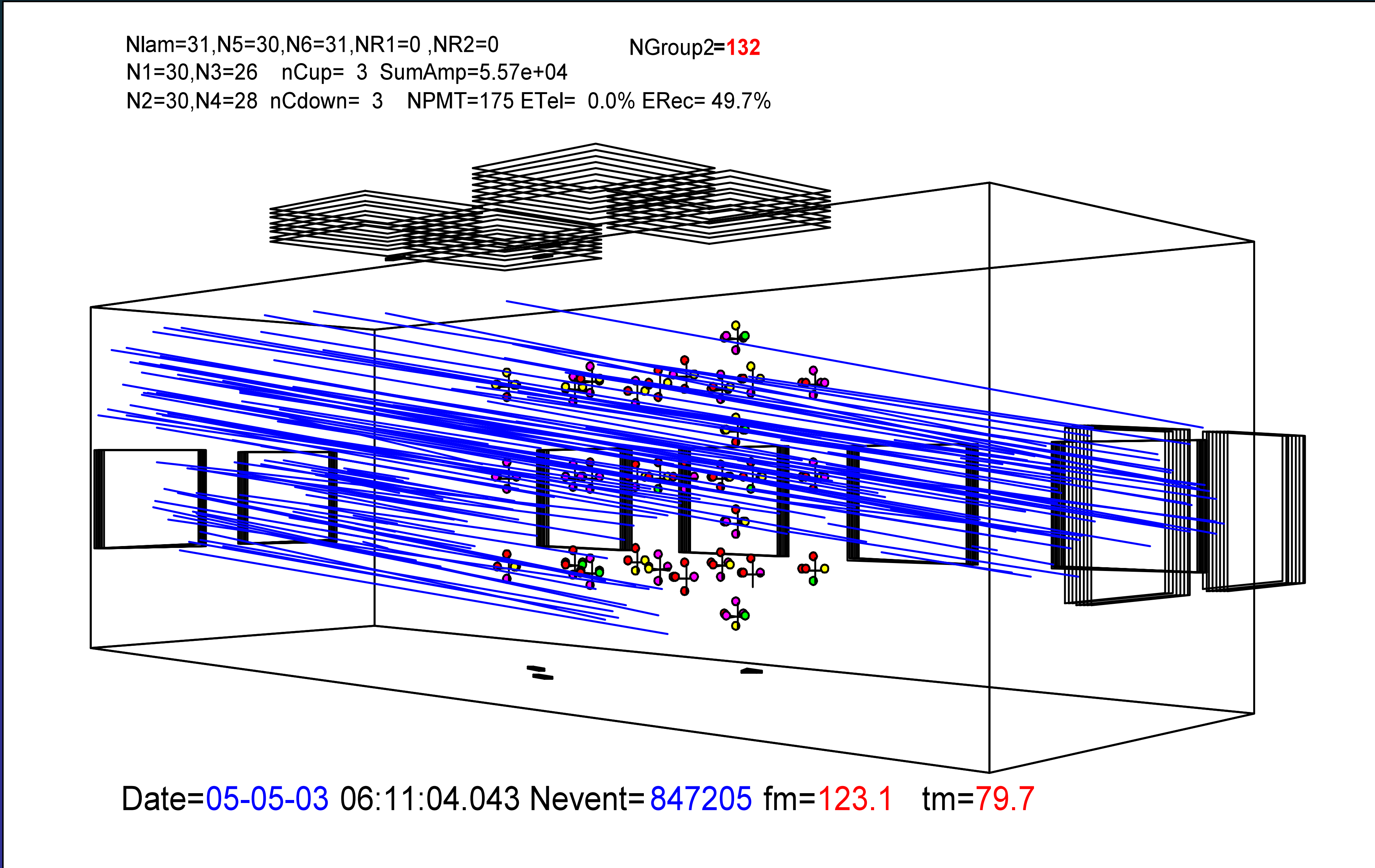


General view of NEVOD-DECOR complex
(Russian-Italian experiment)

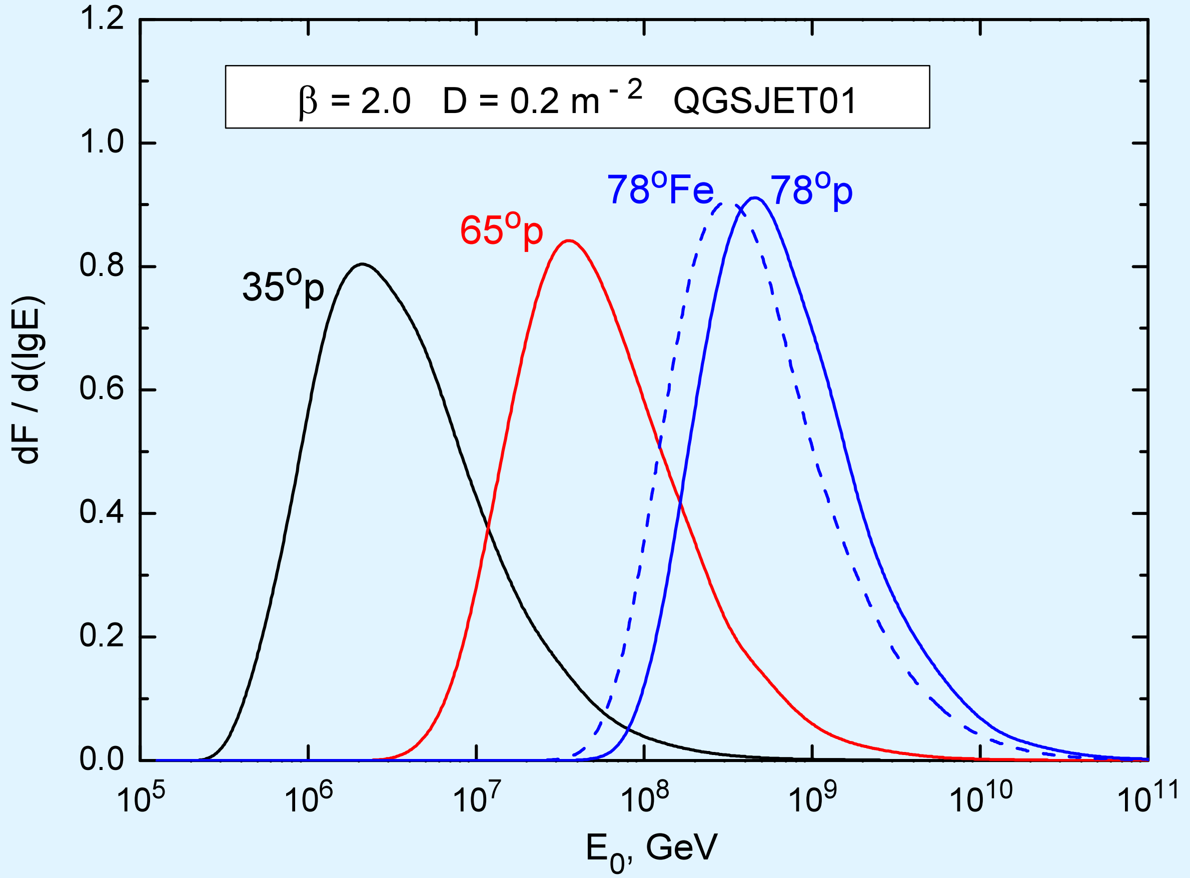


Side SM: 8.4 m^2 each
- $\sigma_x \sim 1$ cm; $\sigma_\psi \sim 1°$

Muon bundle event (geometry reconstruction)

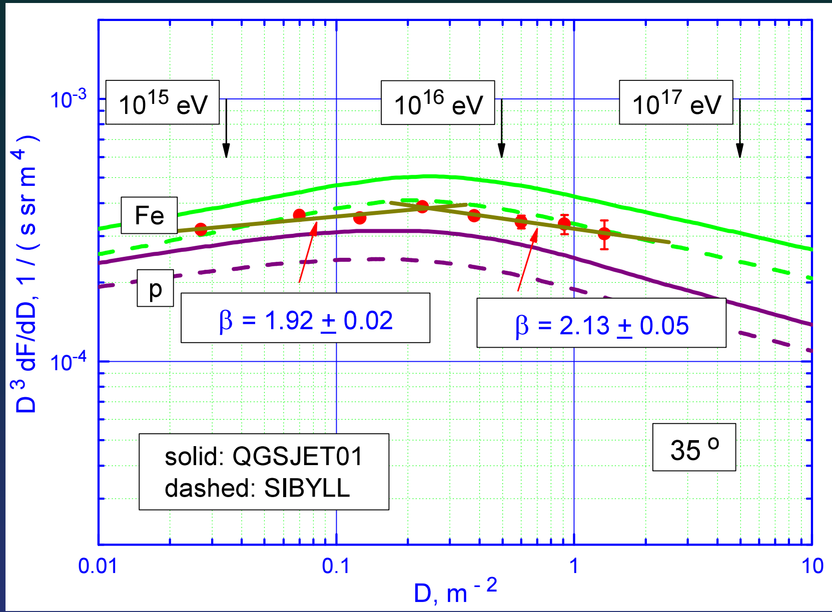


Contribution of primary energies at different zenith angles

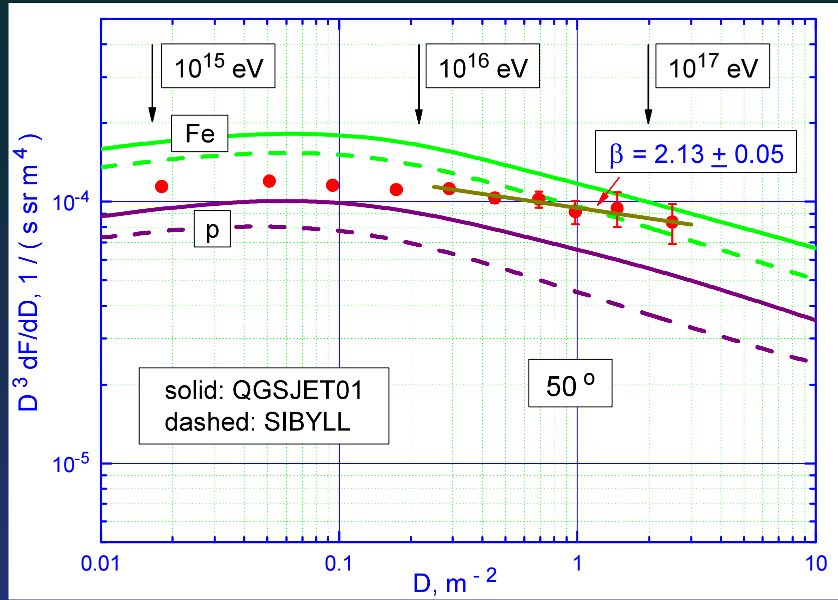


Wide angular interval – very wide range of primary energies !

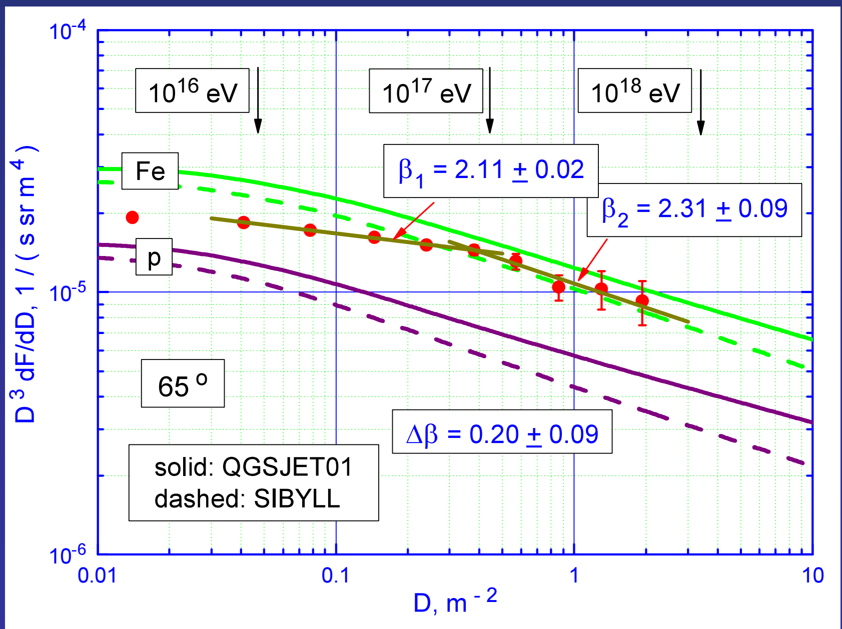
Low angles: around the “knee”



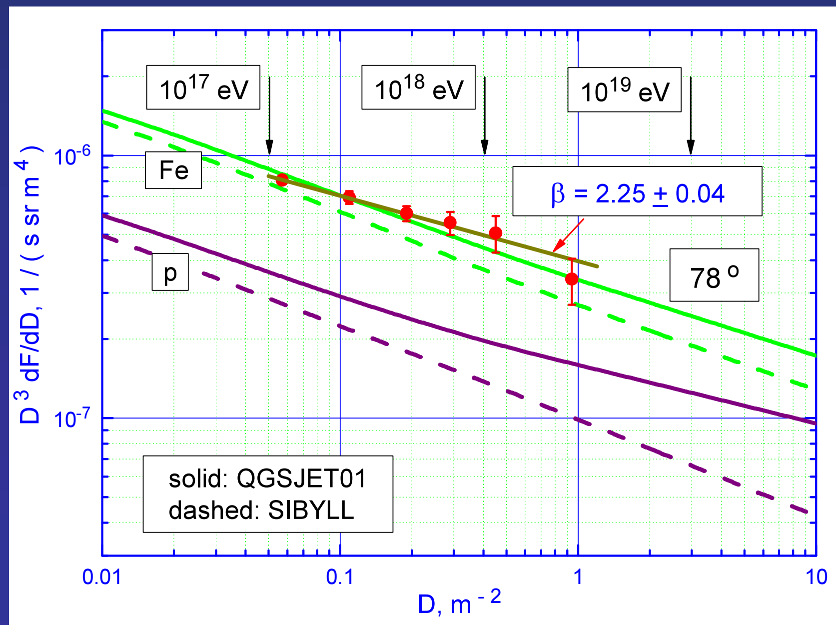
$\theta = 50^o$: $10^{15} - 10^{17}$ eV

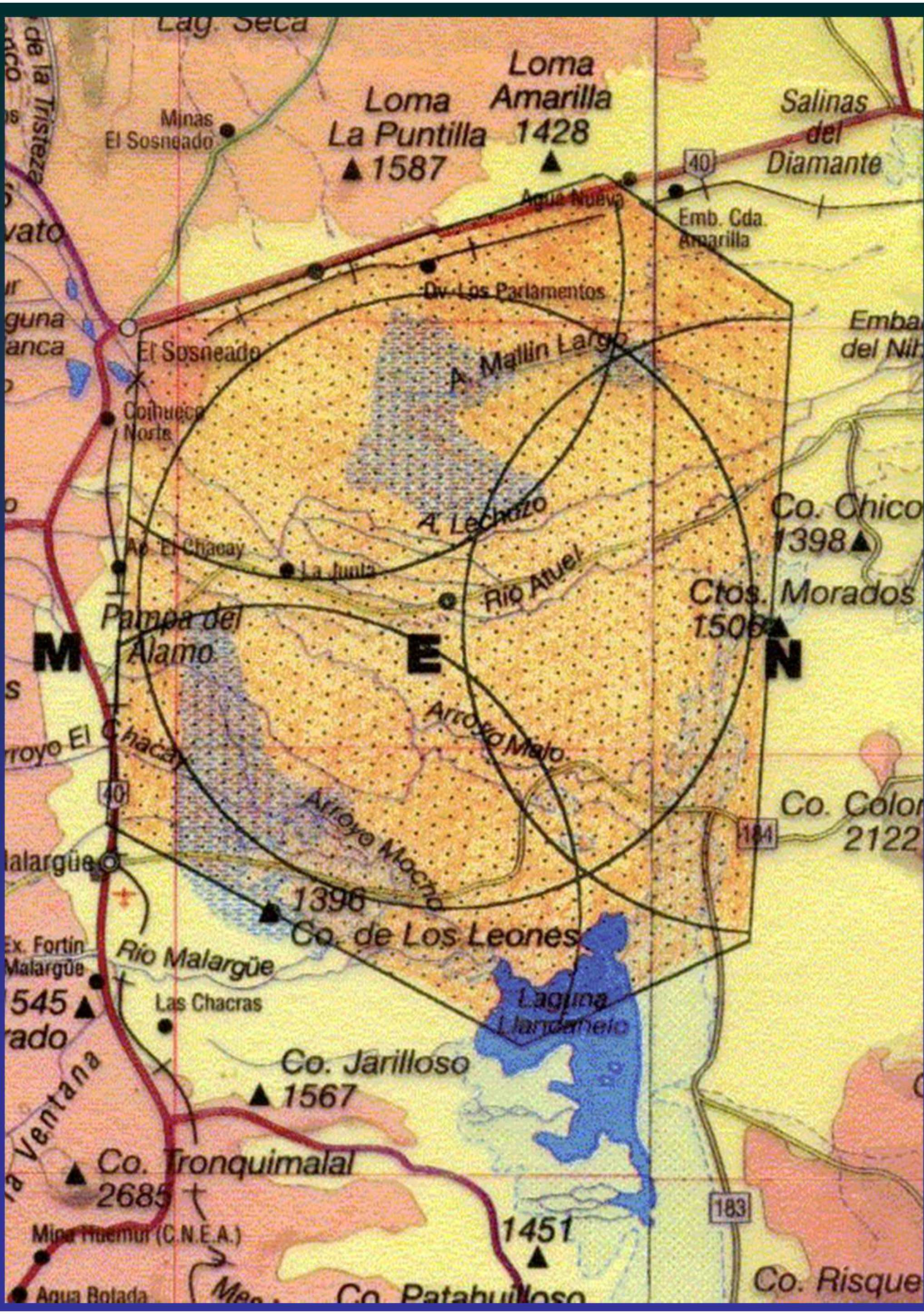


$\theta = 65^o$: $10^{16} - 10^{18}$ eV



Large angles: around 10^{18} eV





Pierre Auger Observatory

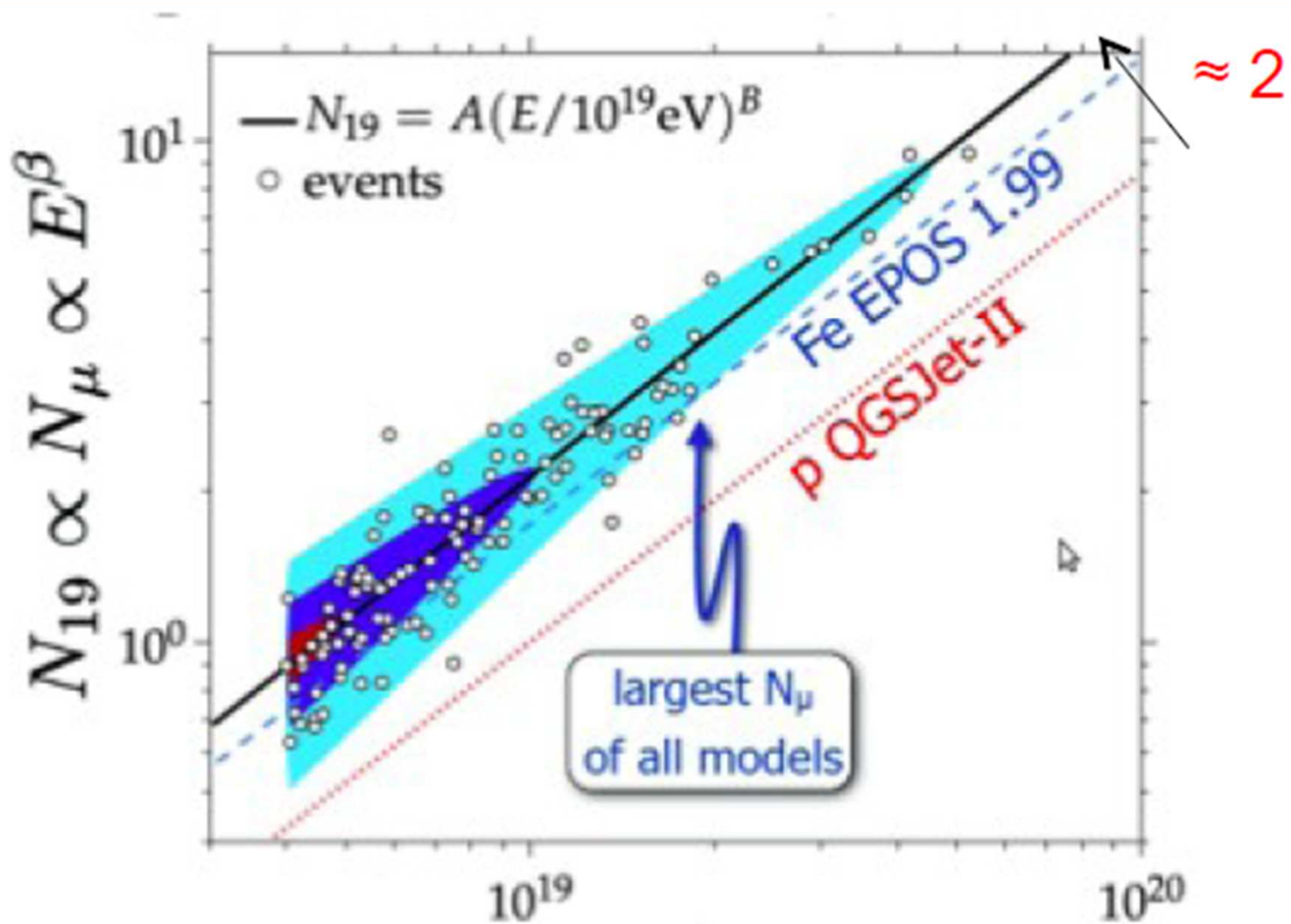
Area - 3000 km^2

Number of detectors - 1600

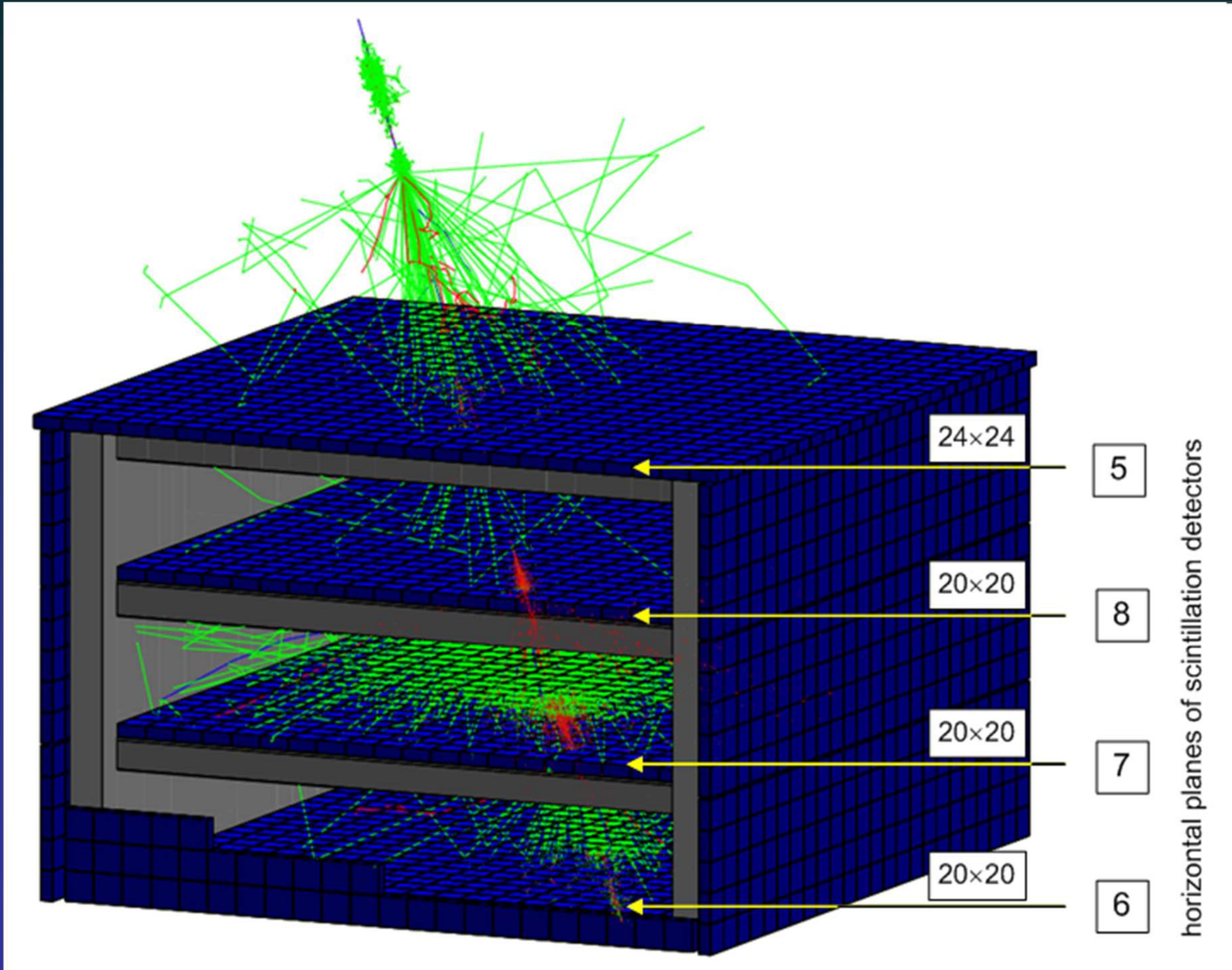
Detector size - 12 m^3

The distance between detectors - 1500 m.

Muons in Auger

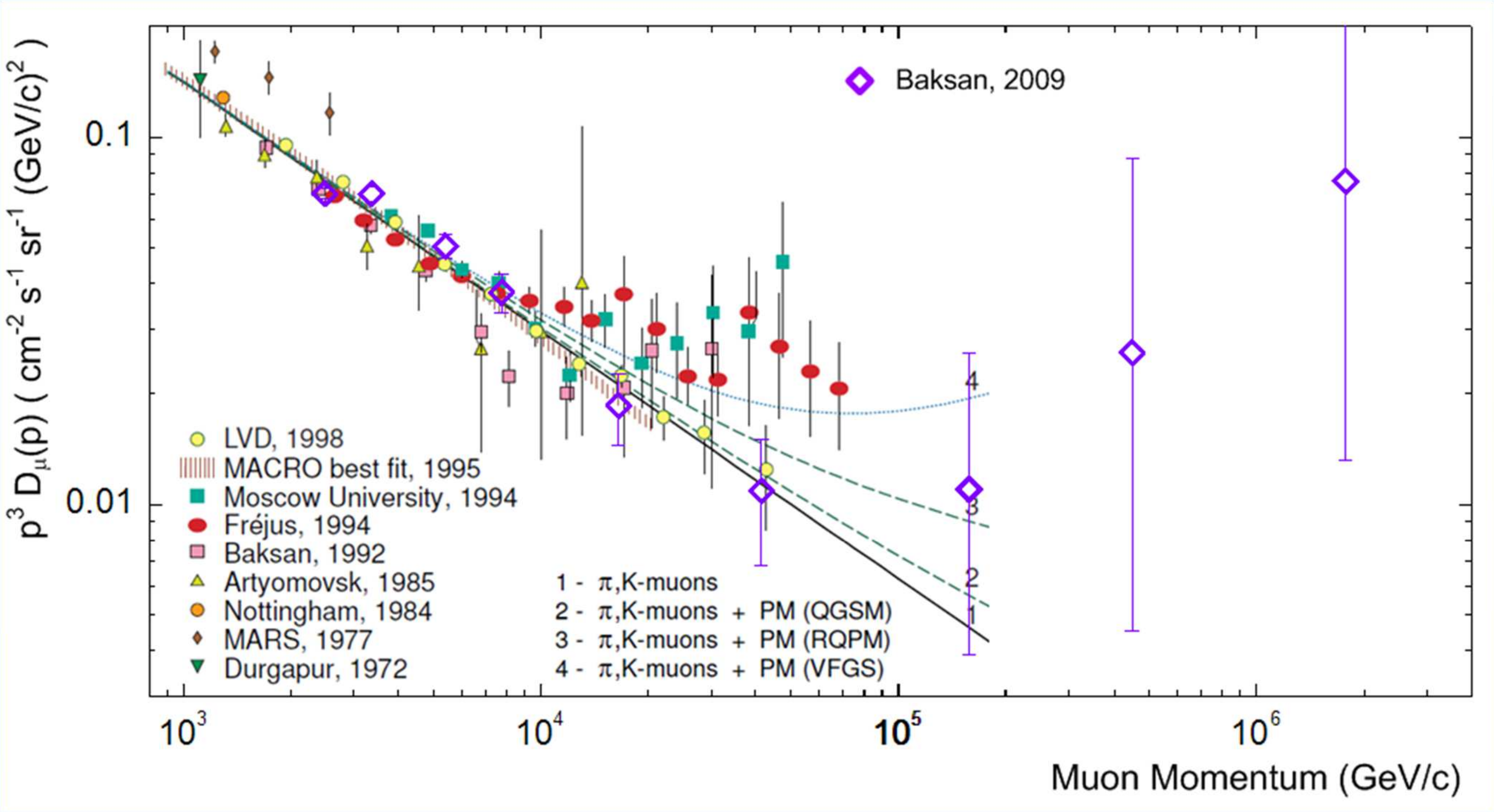


Baksan underground scintillation telescope

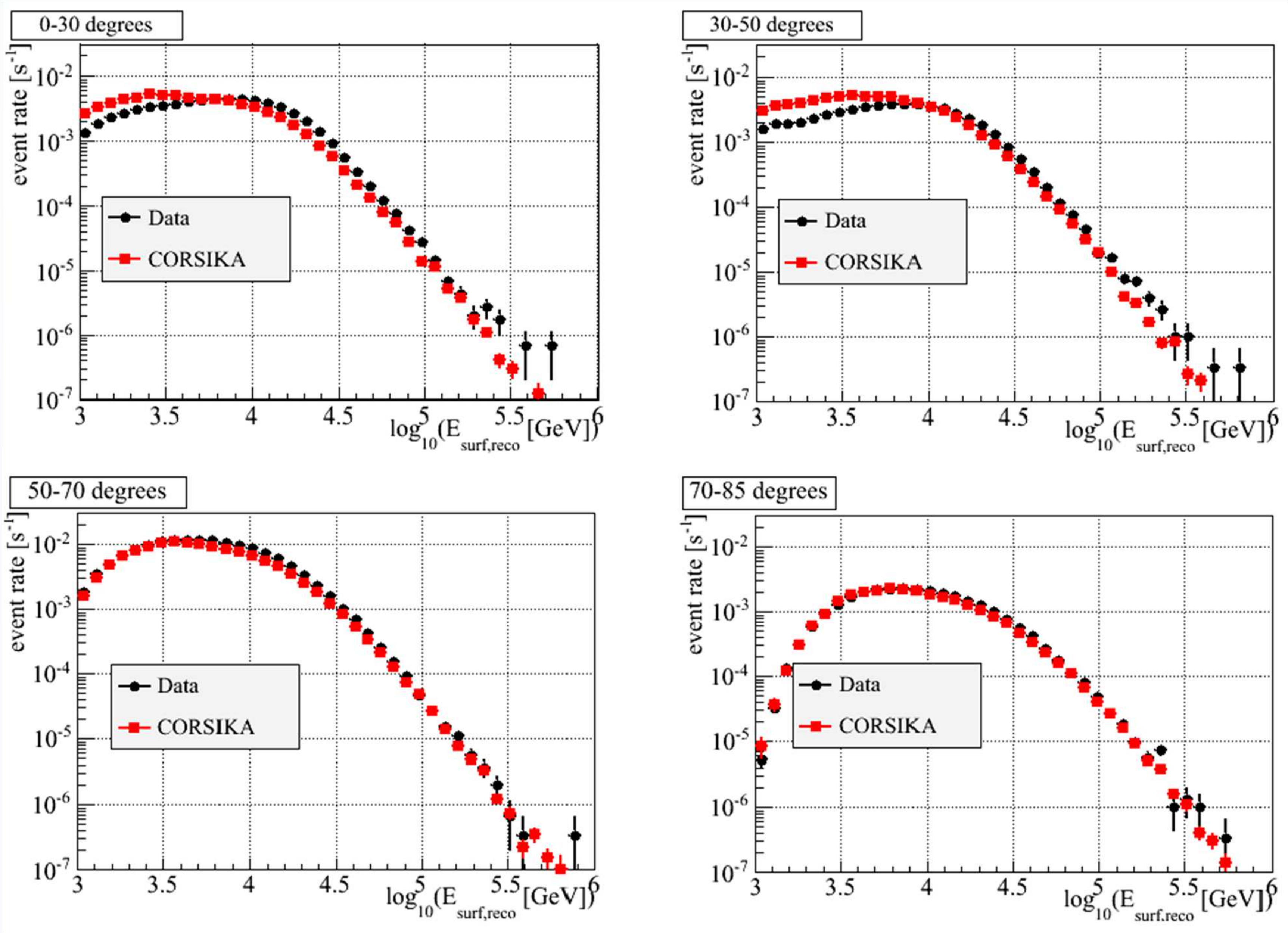


Results of muon energy spectrum investigations in Baksan Underground Scintillation Telescope (BUST)

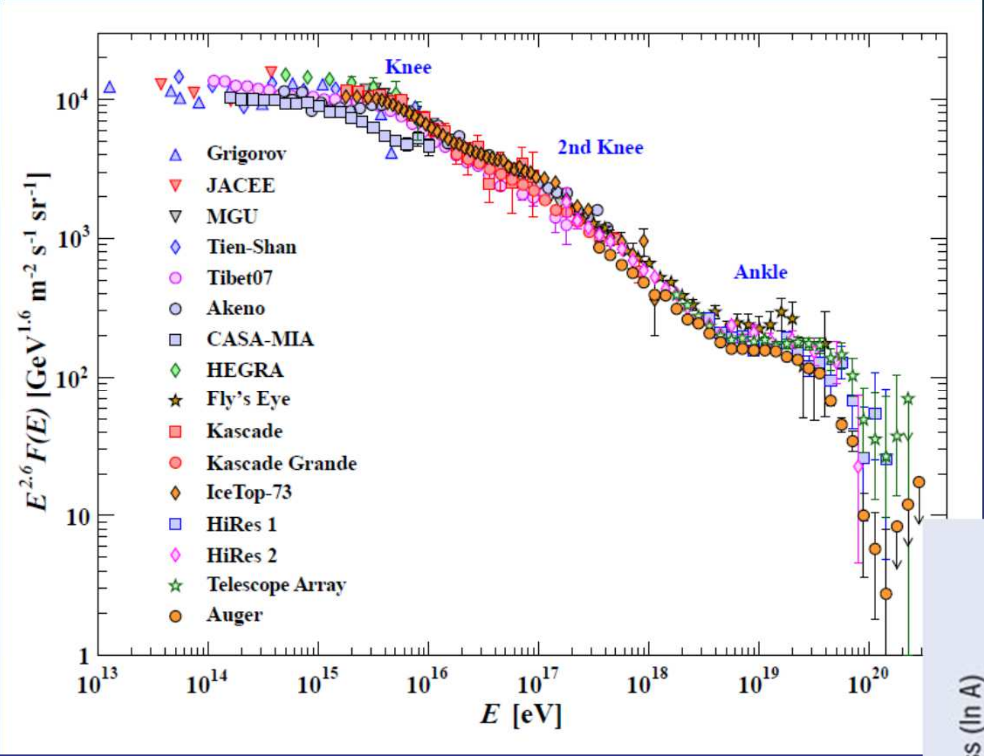
Astroparticle Physics, 2012, 36, 224-236.

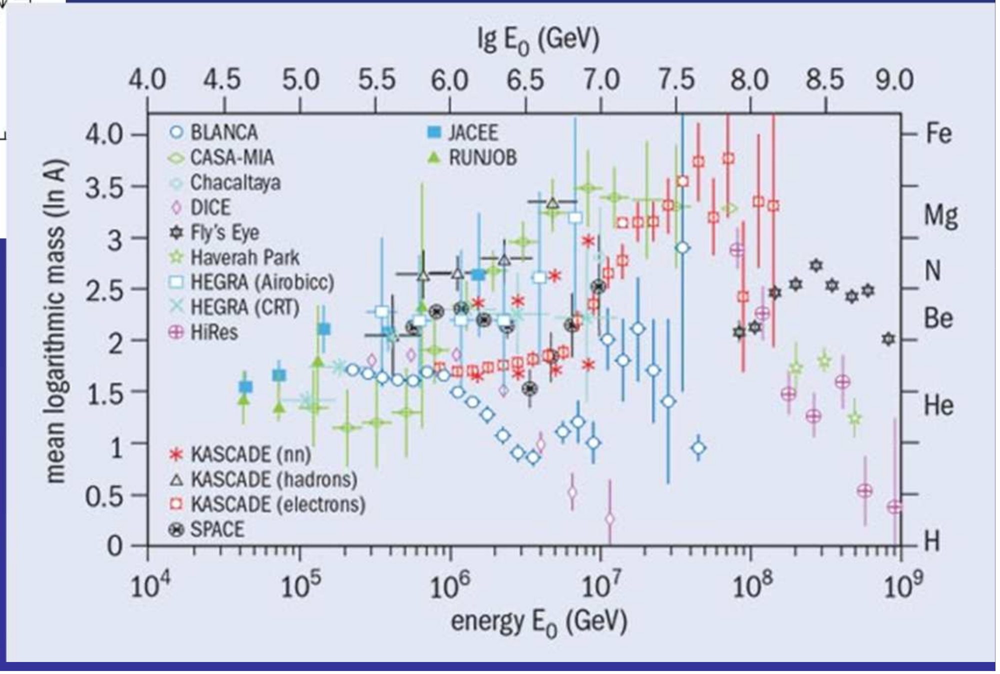


Muon energy spectrum - 2011



The energy spectrum and composition of primary cosmic rays according to EAS data





What do we need to explain all unusual data?

Model of hadron interactions which gives:

1. Threshold behaviour (unusual events appear at several PeV only).
2. Large cross section (to change EAS spectrum slope).
3. Large orbital momentum (alignment).
4. Large yield of VHE leptons (excess of VHE muons, muon bundles, penetrating cascades).
5. The change of EAS development and, as a consequence, increasing N_μ / N_e ratio.

Possible variants

- Production of new heavy particles.
  In this case geometrical cross-section will be very small.

$$\sigma = \pi\lambda^2, \quad \lambda \quad 1/m$$

- Production of blobs of quark-gluon plasma (QGP) (possibly it is better to speak, in general, about quark-gluon matter - QGM).

We consider the last model, since it allows demonstrably explain the inclusion of new interaction features, and with relatively big probability it is correct.

Quark-gluon matter

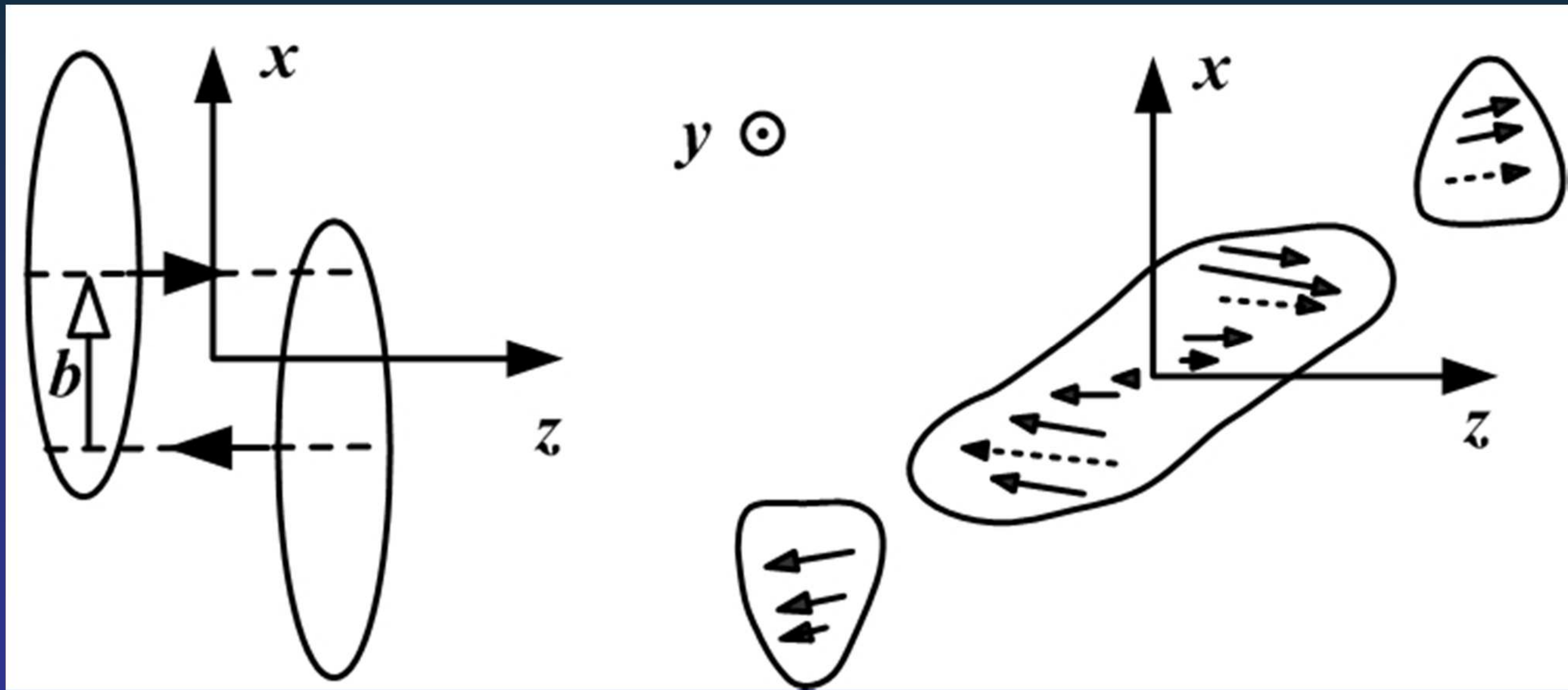
1. Production of QGM provides two main conditions:
   - threshold behavior, since for that high temperature (energy) is required;
   - large cross section, since the transition from quark-quark interaction to some collective interaction of many quarks occurs:

$$\sigma = \pi \bar{\lambda}^2 \rightarrow \sigma \approx \pi R^2$$

where R is a size of quark-gluon blob.

2. But for explanation of other observed phenomena a large value of orbital angular momentum is required.

Orbital angular momentum in non-central ion-ion collisions

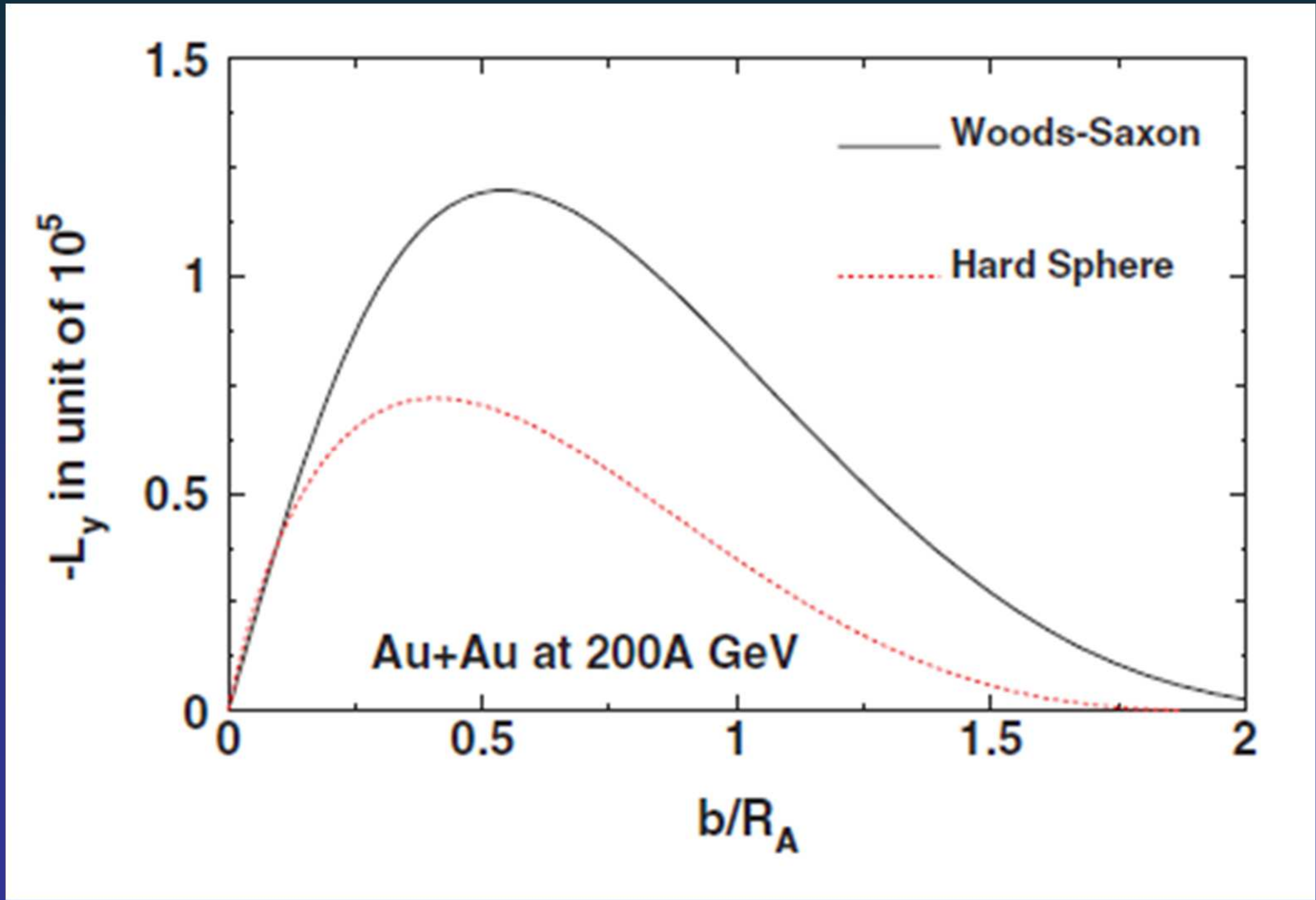


This momentum is increasing with energy $L \quad \sqrt{s}$.

Zuo-Tang Liang and Xin-Nian Wang,
PRL 94, 102301 (2005); 96, 039901 (2006)

The value of orbital angular momentum

Jian-Hua Gao et al., Phys. Rev. C 77 (2008) 044902



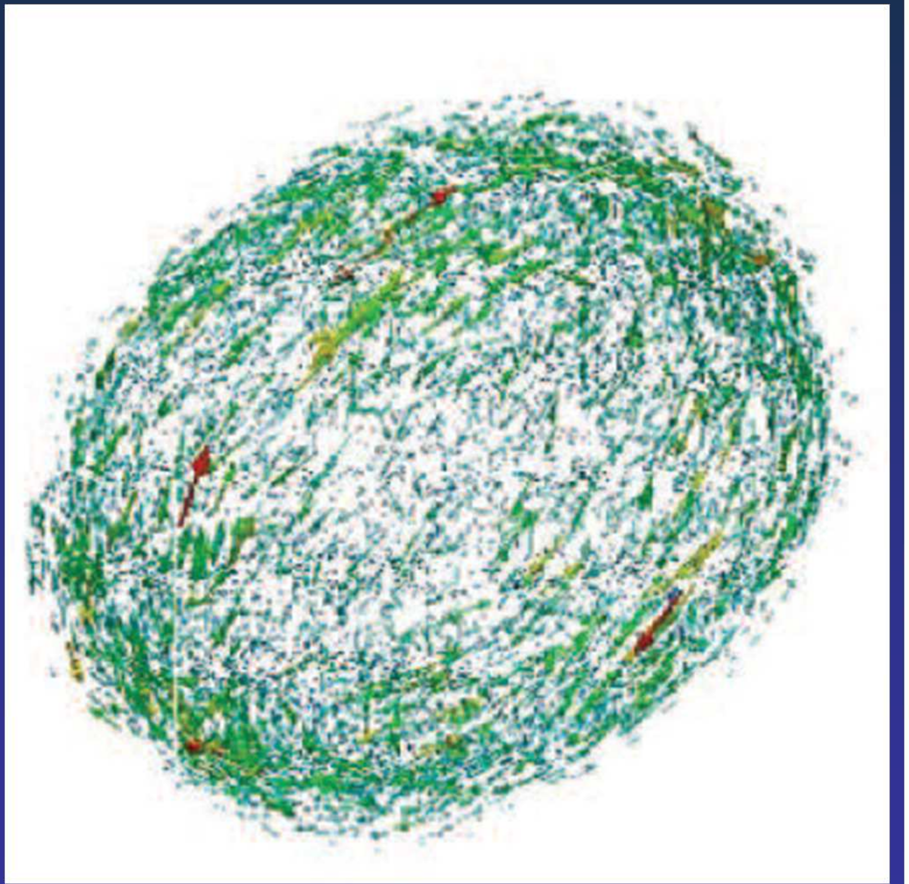
Total orbital angular momentum of the overlapping system in Au+Au collisions at the RHIC energy as a function of the impact parameter b.

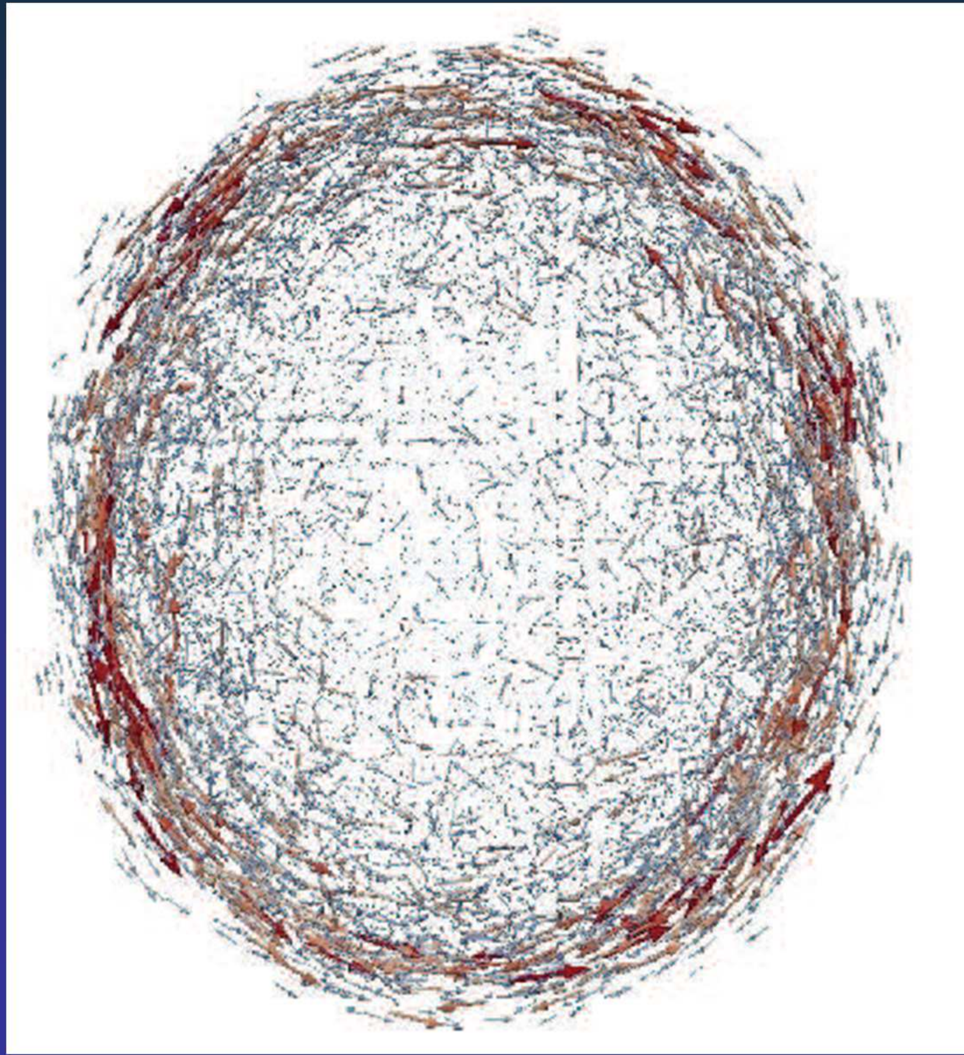
Centrifugal barrier

1. A blob of a globally polarized QGM with large orbital angular momentum can be considered as a usual resonance with a large centrifugal barrier.
2. Centrifugal barrier $V(L) = L^2 / 2mr^2$ will be large for light quarks but less for top-quarks or other heavy particles.
3. Though in interacting nuclei top-quarks are absent, the suppression of decay into light quarks gives time for the appearance of heavy quarks.

Helicity separation in Heavy-Ion Collisions

Mircea Baznat, Konstantin Gudima, Alexander Sorin and Oleg Teryaev
arXiv:1301.7003 [nucl-th]





How interaction is changed in frame of a new model?

1. Simultaneous interactions of many quarks change the energy in the center of mass system drastically:

$$\sqrt{S} = \sqrt{2m_p E_1} \rightarrow \sqrt{2m_c E_1}$$

where $m_c \approx nm_N$. At threshold energy, n ~ 4 (α - particle).

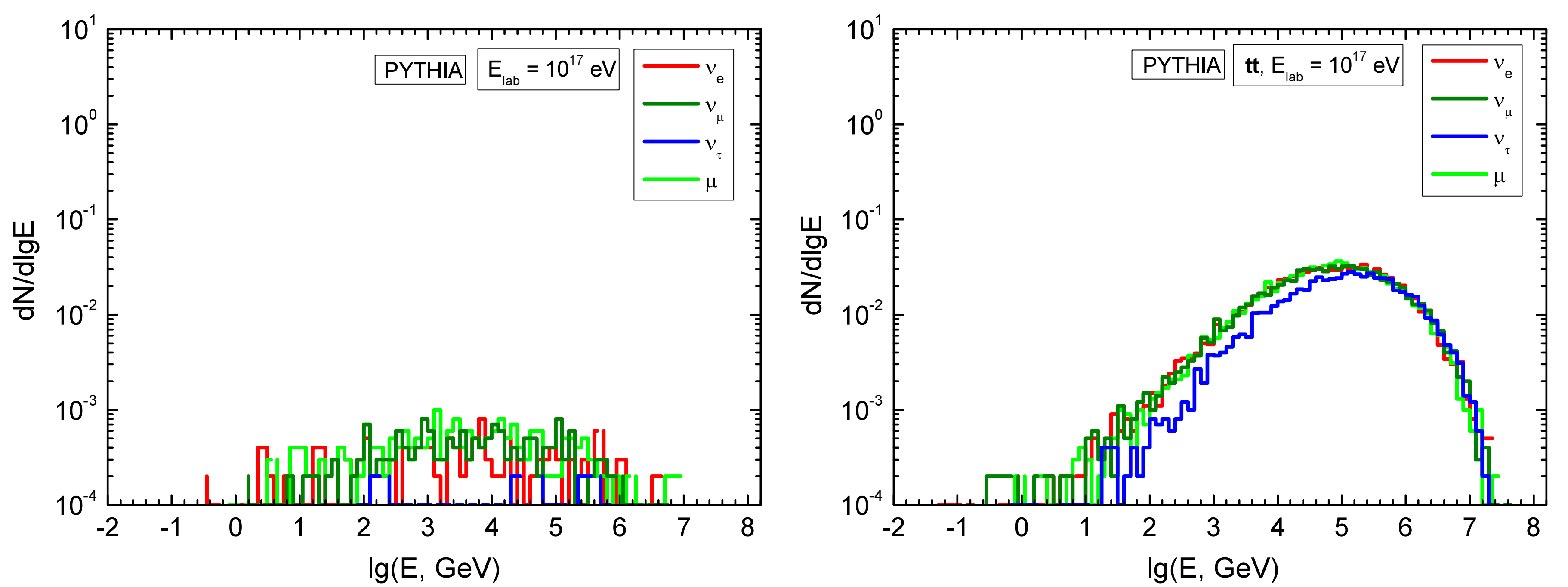
2. Produced $t\bar{t}$-quarks take away energy $\varepsilon_t > 2m_t \approx 350$ GeV, and taking into account fly-out energy $\varepsilon_t > 4m_t \approx 700$ GeV in the center of mass system.

3. Decays of top-quarks: $t\left(\bar{t}\right) \rightarrow W^+\left(W^-\right) + b\left(\bar{b}\right)$;

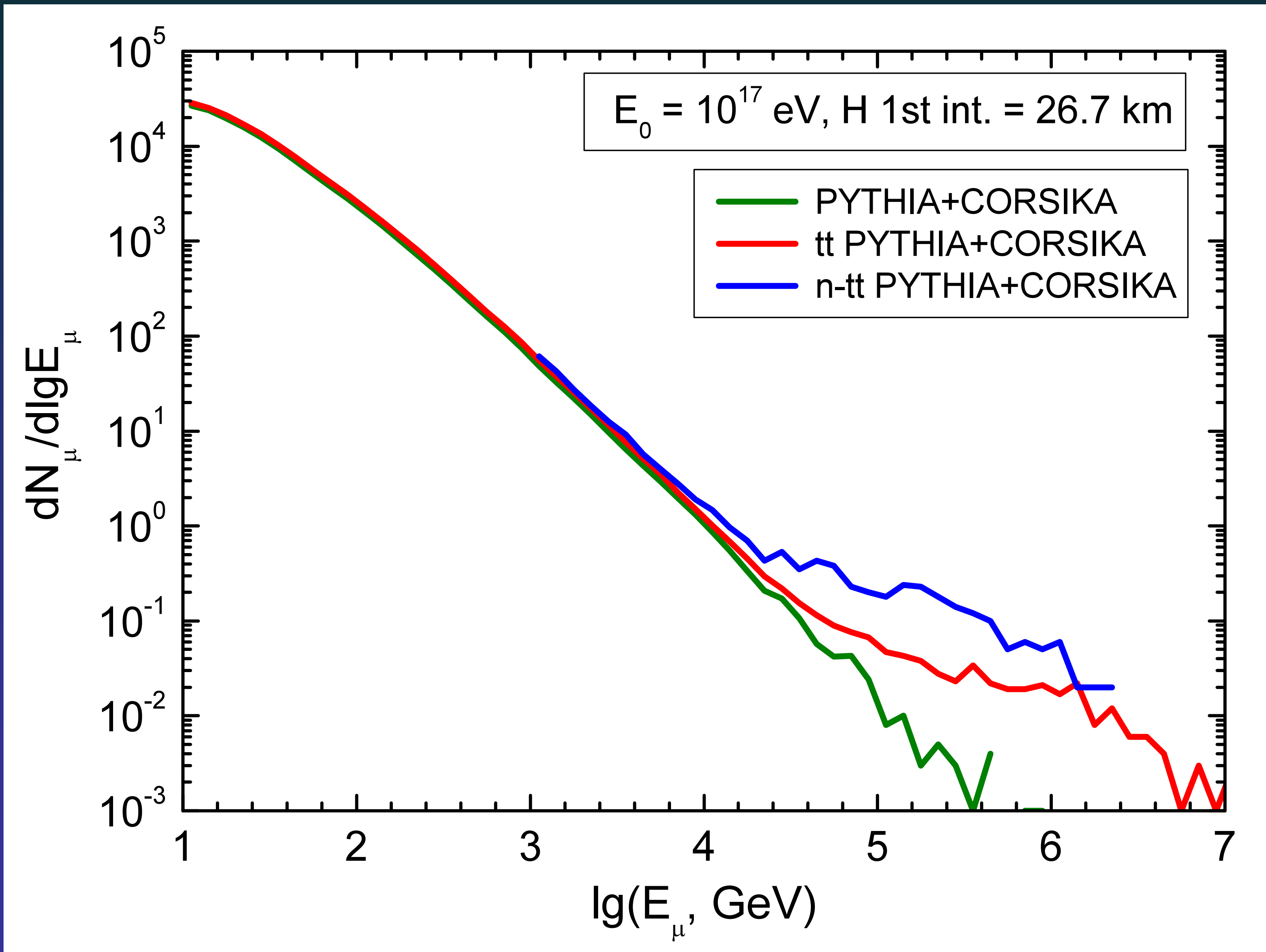
W –bosons decay into leptons (~30%) and hadrons (~70%);

$b \rightarrow c \rightarrow s \rightarrow u$ with production of muons and neutrinos.

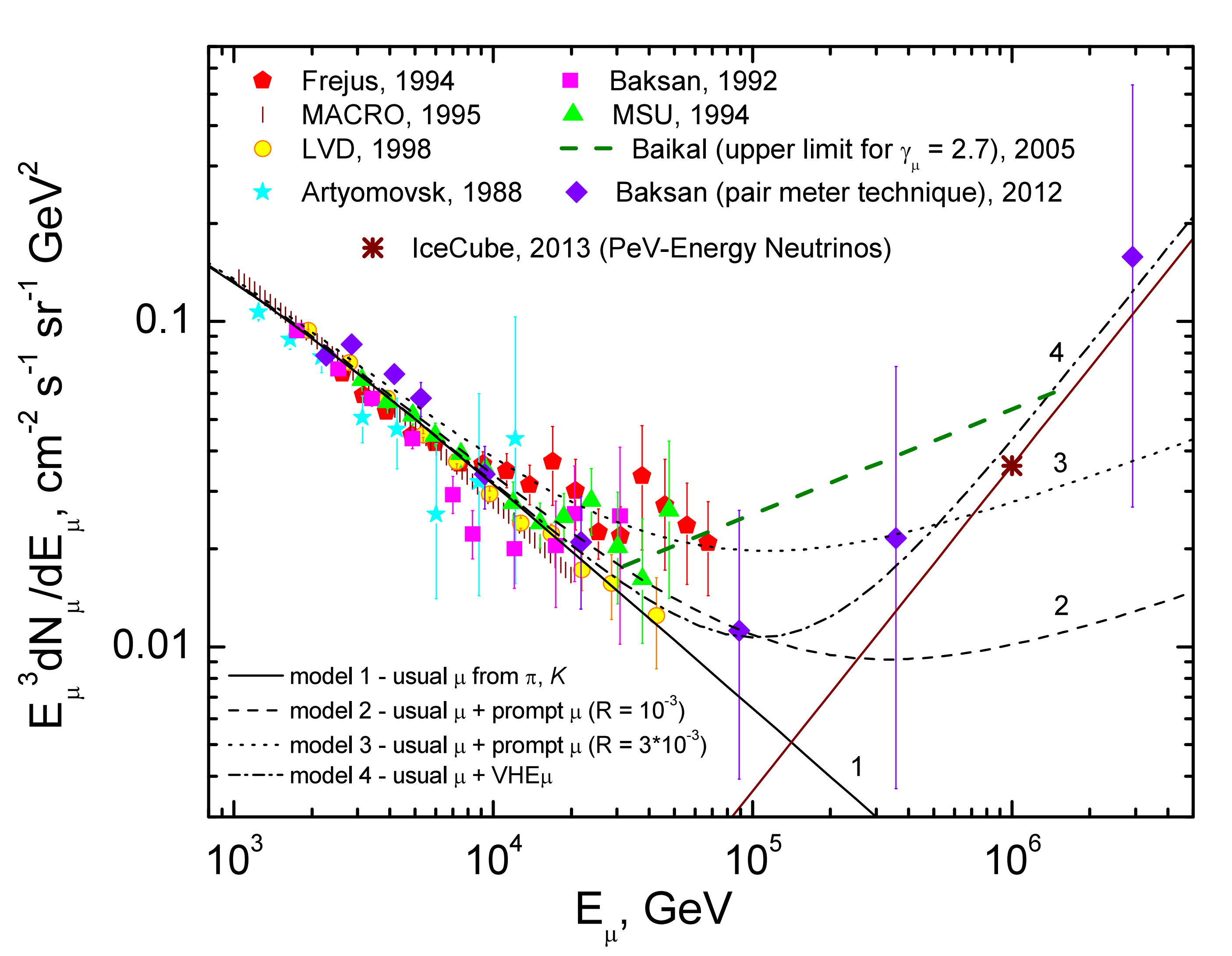
Influence of top-quarks on neutrino production



Changes of lepton spectrum



Differential muon energy spectra



The curves correspond to different spectrum models:

1. Usual muon spectrum from π-, K-decays in the atmosphere.

2. Usual spectrum with addition of prompt muons at the level of $R = 1\times10^{-3}$.

3. Usual spectrum with addition of prompt muons at the level of $R = 3\times10^{-3}$.

4. Usual spectrum with inclusion of VHE muons ($3.5\times10^{-8}\ E_\mu^{-2}$).

How to get the final conclusion in favour of new approach at PeV energies directly in IceCube?

If neutrinos with PeV energies have atmospheric origin, the muons with the same energies must exist.
Neutrinos can be astrophysical, but muons not!

How to measure muons with such energies?
There are two methods:

- detection of big cascade showers generated by bremsstrahlung of muons;
- detection of consecutive small cascade showers generated by pair production of muons.

Both techniques allow to evaluate muon energies up to PeV region. I hope that this analysis will be done.

Conclusion

The neutrino results of IceCube Collaboration can be considered as confirmation of

extraterrestrial neutrino detection

or

new state of matter existence.

I do not know what is more important.

Thank you for attention!

Cosmic ray experiments

• LHC energies 1-14 TeV correspond to the interval $10^{15} – 10^{17}$ eV in laboratory system for *pp*-interactions.

• But in CR experiments:

- targets are nuclei of nitrogen and oxygen;
- most part of CRs are nuclei.

Thus in CRs we investigate mainly nucleus-nucleus interactions.

Particles	*Z*	*<A>*	Energy per nucleon	Energy per nucleus
Protons	*1*	*1*	*92 %*	*40 %*
α – particles	*2*	*4*	*7 %*	*21 %*
Light nuclei	*3 – 5*	*10*	*0.15 %*	*1 %*
Medium nuclei	*6 – 10*	*15*	*0.5 %*	*18 %*
Heavy nuclei	*≥11*	*32*	*0.15 %*	*18 %*

How to check the new approach in LHC experiments?

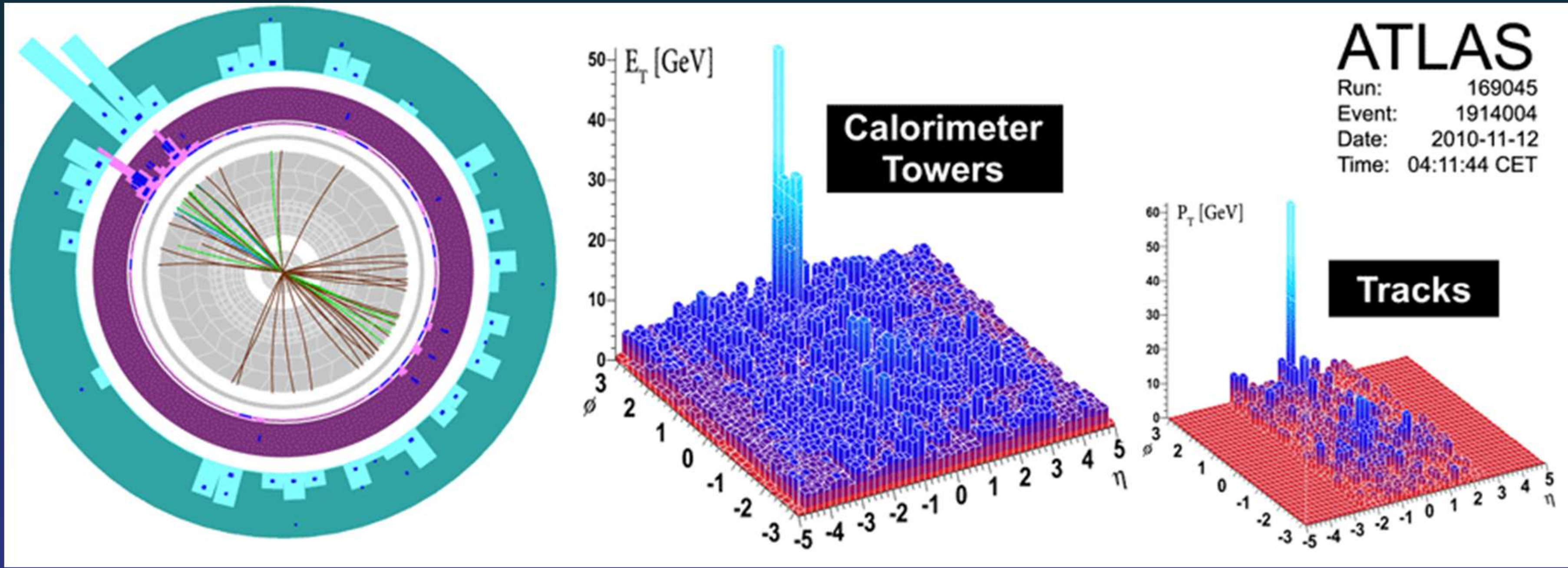
There are several possibilities to check the new approach in LHC experiments, since QGM with described characteristics (excess of *t*-quarks, excess of VHE muons, sharp increasing of missing energy, etc.) doubtless can be observed.

However these results unlikely can be obtained in *pp*-interactions even at full energy 14 TeV, which corresponds to 10^{17} eV in cosmic ray experiments (for *pp*-interaction), since for that collisions of sufficiently heavy nuclei are required.

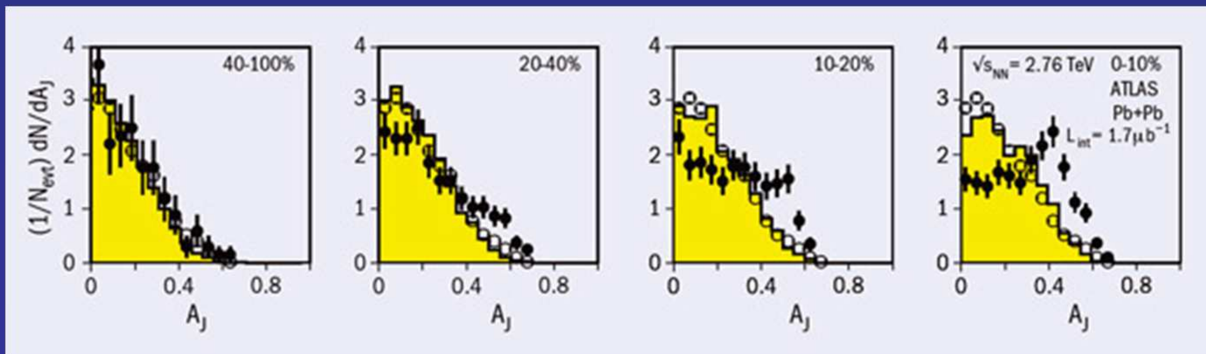
Apparently, some evidences of observation of the effects predicted by new model were yet obtained in A-A interactions.

ATLAS observes striking imbalance of jet energies in heavy ion collisions

(CERN Courier, January/February 2011)



Highly asymmetric dijet event



Dijet asymmetry distributions

How to explain the ATLAS result in frame of the considered approach?

$$t \to W^+ + b$$

In top-quark center-of-mass system:

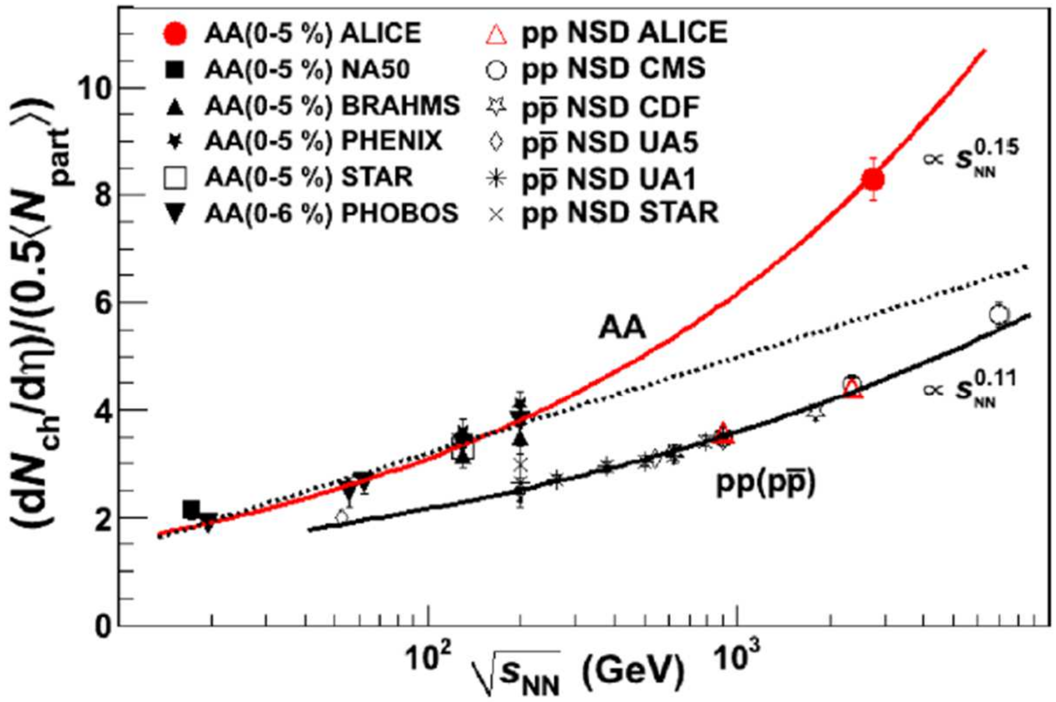
$$T_b \sim 65 \text{ GeV}, \qquad T_W \sim 25 \text{ GeV}.$$

If to take into account fly-out energy, T_b can be more than 100 GeV.

In the case if b gives a jet and $W \to \sim 20\ \pi$, the ATLAS experiment's picture will be obtained.

Charged Particle Multiplicity

most central collisions: ~ 1600 charged particles per unit of η



ALICE: PRL105 (2010) 252301

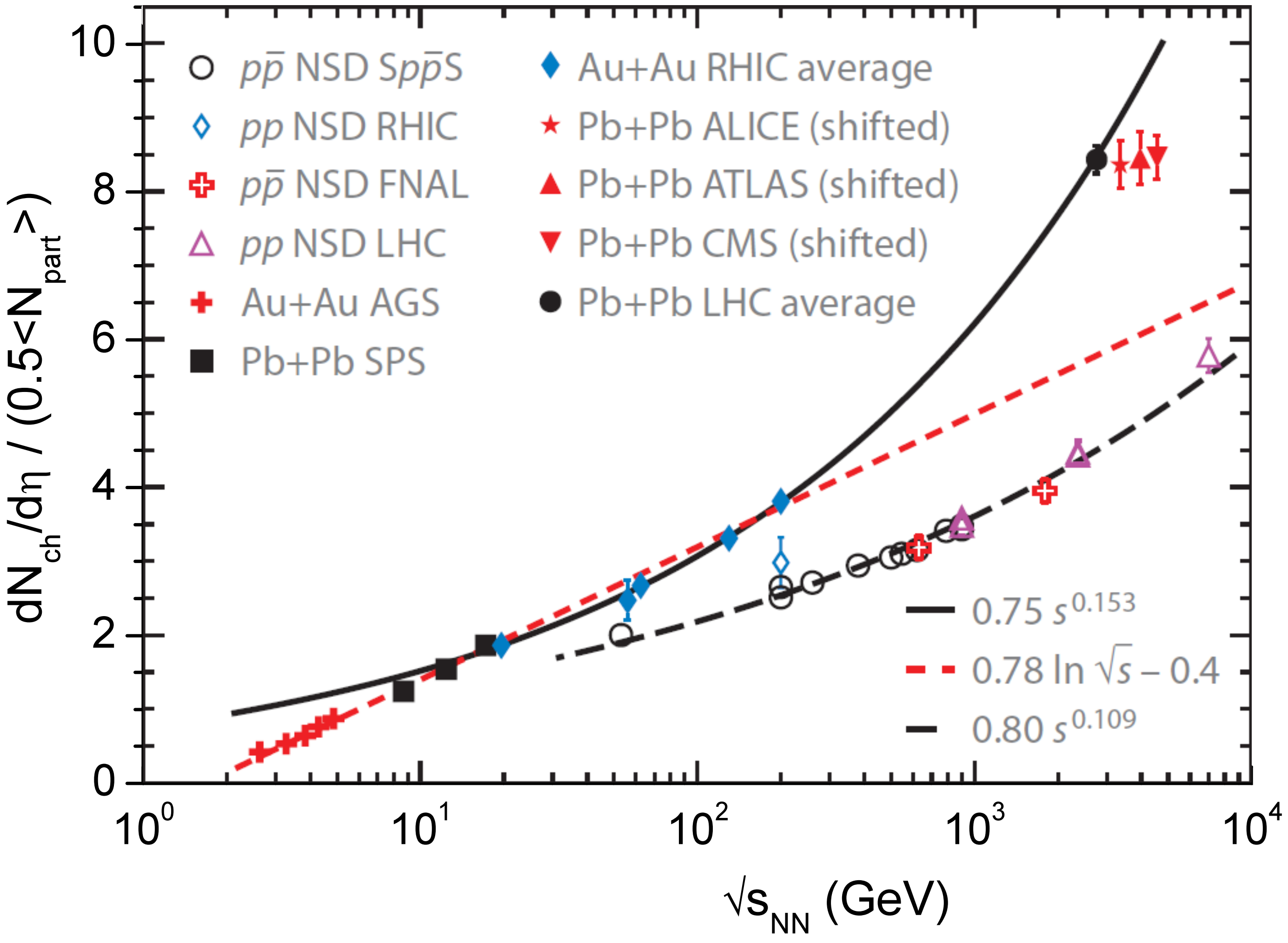
$\sqrt{s_{NN}}$=2.76 TeV Pb+Pb, 0-5% central, |η|<0.5

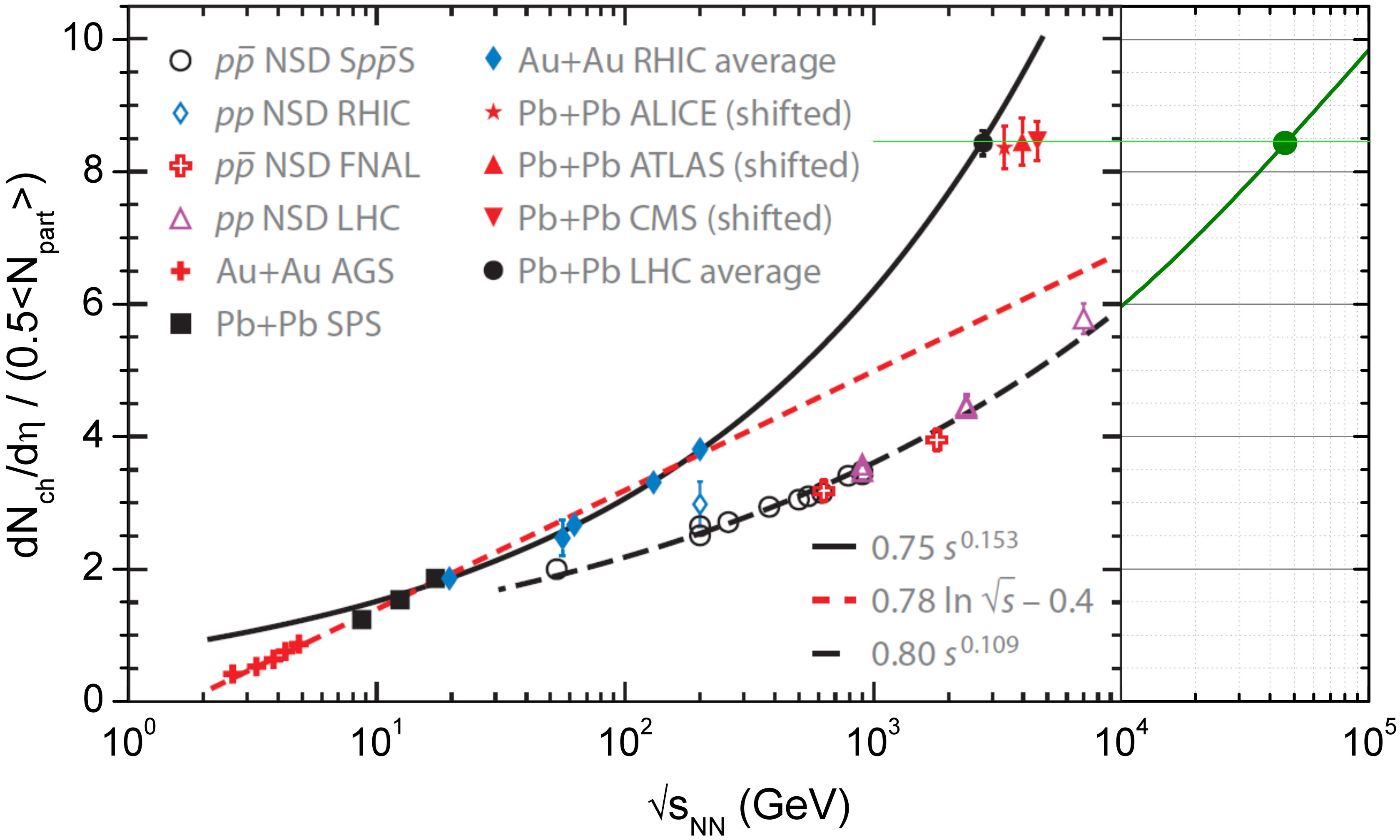
2 dNch/dη / <Npart> = 8.3 ± 0.4 (sys.)

log extrapolation fails (finally!)

2.2 x central Au+Au
($\sqrt{s_{NN}}$=0.2 TeV)

1.9 x pp (NSD)
($\sqrt{s_{NN}}$=2.36 TeV)


pp̄ NSD Spp̄S
pp NSD RHIC
pp̄ NSD FNAL
pp NSD LHC
Au+Au AGS
Pb+Pb SPS
Au+Au RHIC average
Pb+Pb ALICE (shifted)
Pb+Pb ATLAS (shifted)
Pb+Pb CMS (shifted)
Pb+Pb LHC average
0.75 s^0.153
0.78 ln √s – 0.4
0.80 s^0.109
dN_ch/dη / (0.5<N_part>)
√s_NN (GeV)
0
2
4
6
8
10
10^0
10^1
10^2
10^3
10^4



$p\bar{p}$ NSD $Sp\bar{p}S$
pp NSD RHIC
$p\bar{p}$ NSD FNAL
pp NSD LHC
Au+Au AGS
Pb+Pb SPS
Au+Au RHIC average
Pb+Pb ALICE (shifted)
Pb+Pb ATLAS (shifted)
Pb+Pb CMS (shifted)
Pb+Pb LHC average
$0.75\, s^{0.153}$
$0.78 \ln \sqrt{s} - 0.4$
$0.80\, s^{0.109}$
$dN_{ch}/d\eta \;/\; (0.5\langle N_{part}\rangle)$
$\sqrt{s_{NN}}$ (GeV)
0
2
4
6
8
10
10^0
10^1
10^2
10^3
10^4
10^5

The remark about QGP blob size

In usual interpretation the experimental point corresponds to $\sqrt{S_{NN}}$ = 2.76 TeV (for A-A interaction).

In frame of new model $\sqrt{S_{NN}}$ must be larger.

If take into account that $\sqrt{S_{NN}}$ cannot be more than $\sqrt{S_{NN}}$ for pp-interaction it is possible to evaluate number of nucleons in QGP blob.

$$n_N < \frac{50\ \text{TeV}}{3.5\ \text{TeV}} \approx 14$$

Conclusion

If the considered approach to explanation of CR results is correct, than in LHC experiments it is necessary to search new physics in nucleus-nucleus interactions, and, apparently, in collisions of light nuclei (nitrogen, oxygen), for which the threshold energies will be lower, but secondary particle multiplicity is not so big as for heavy nuclei.

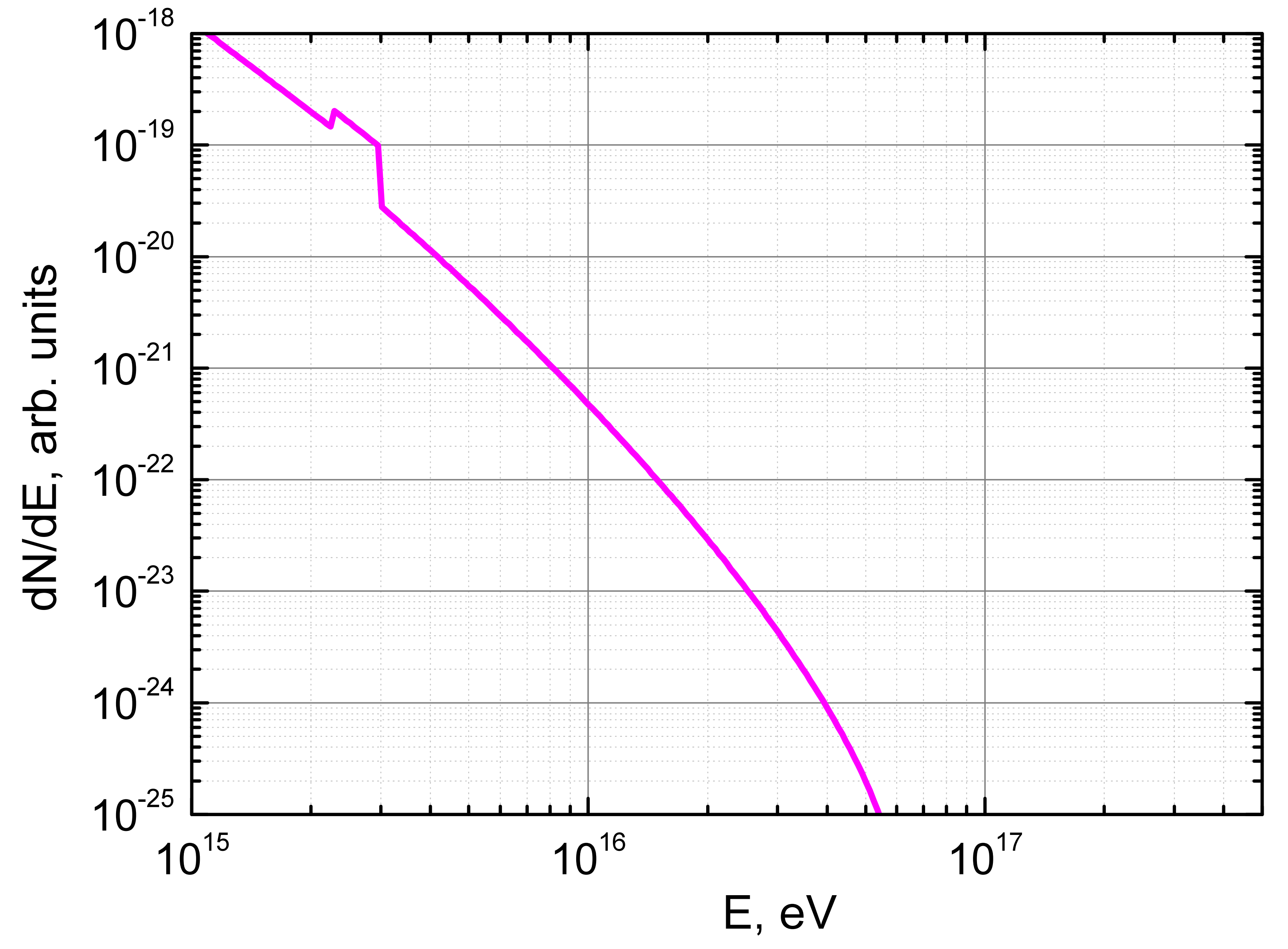
How the CR energy spectrum is changed?

1. One part of t-quark energy gives the missing energy (ν_e, ν_μ, ν_τ, μ), and another part changes EAS development, especially its beginning, parameters of which are not measured.

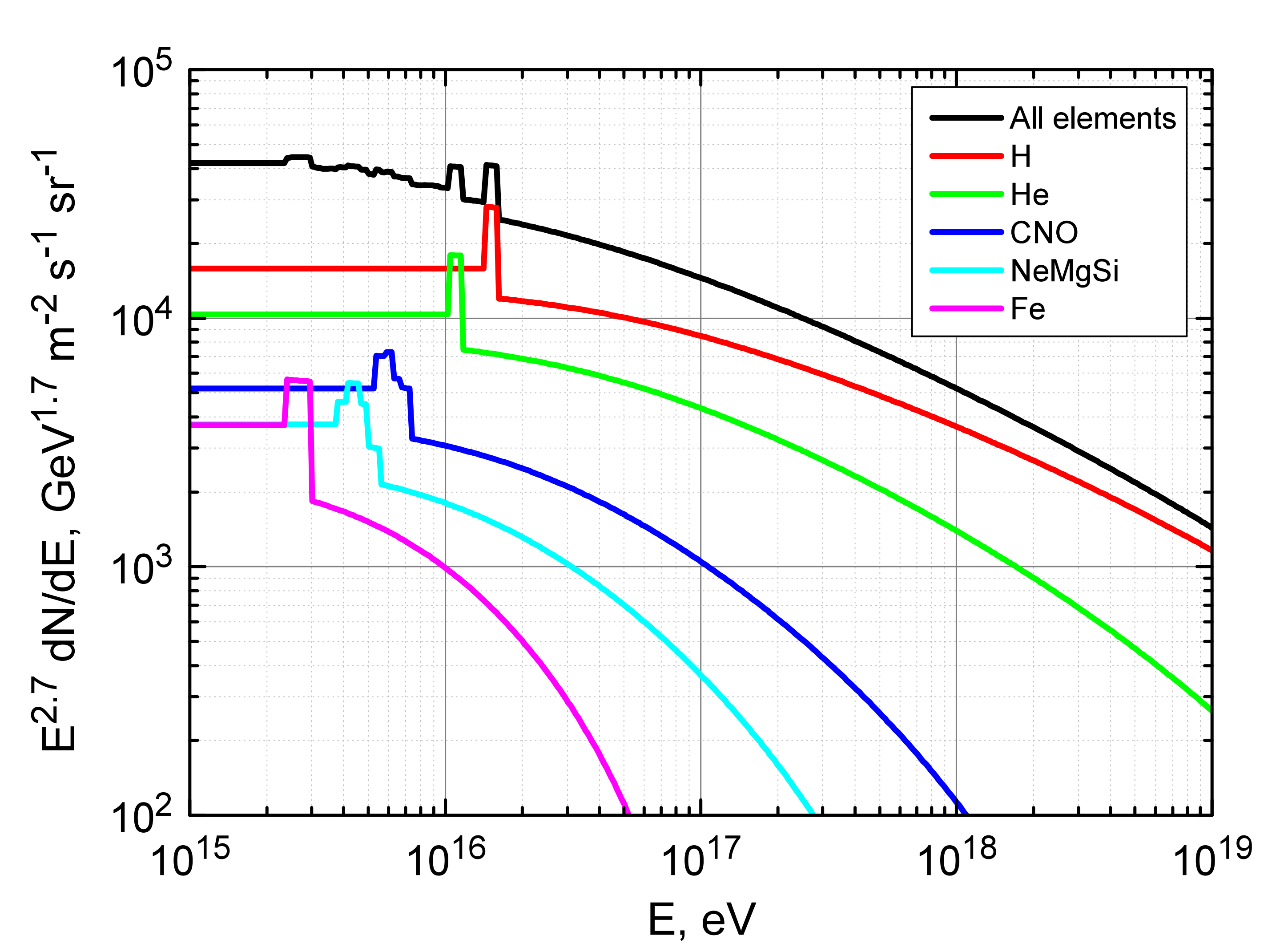
2. As a result, the measured EAS energy E_2 will not be equal to primary particle energy E_1 and the measured spectrum will be different from the primary spectrum.

3. Transition of particles from energy E_1 to energy E_2 gives a bump in the energy spectrum near the threshold.

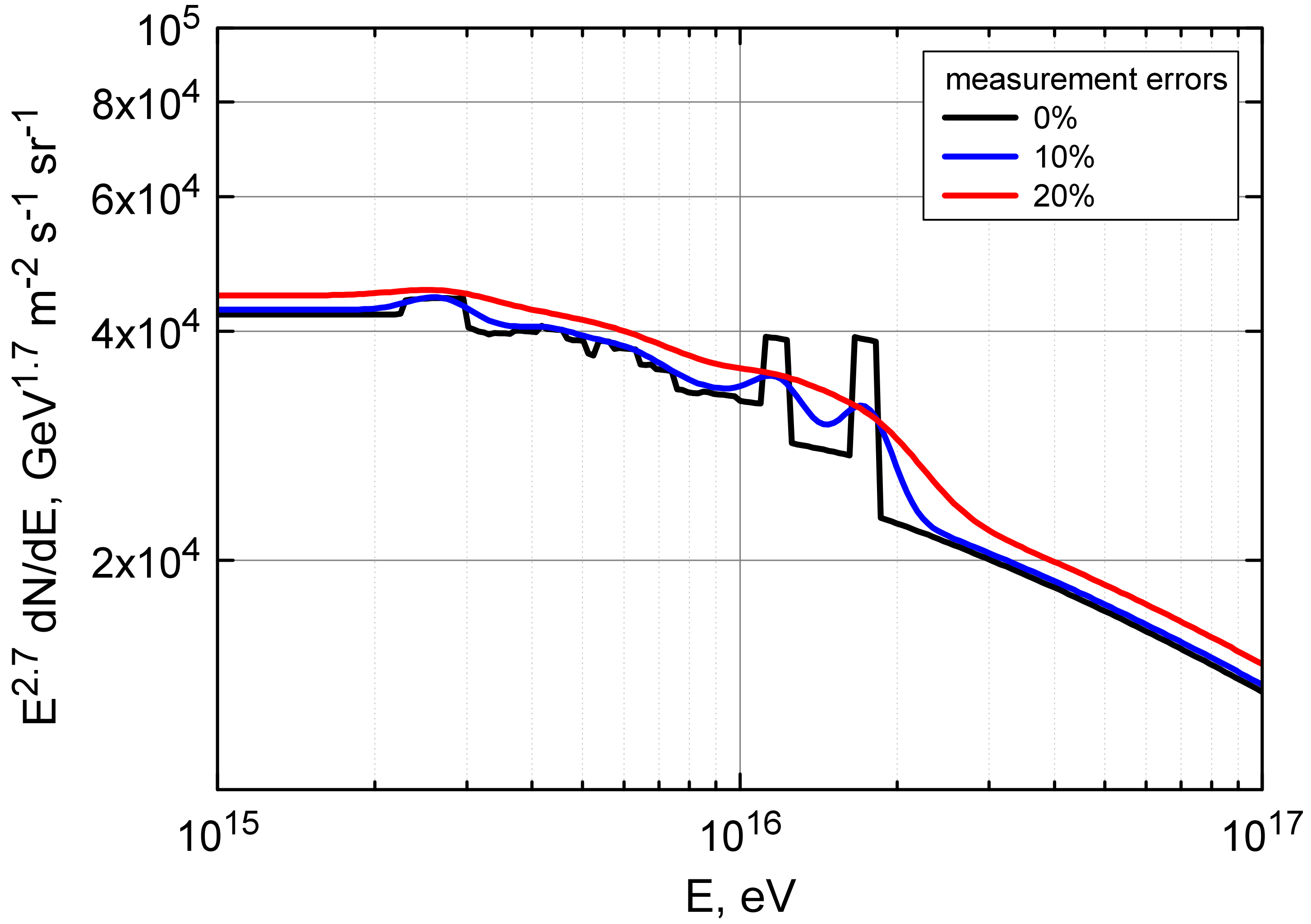
Change of primary energy spectrum



Measured spectra for some nuclei and spectrum of all particles



Influence of energy straggling



Comparison with experimental data

(with 10% straggling)