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# Nucleus-Nucleus interactions at LHC and in cosmic rays around and above the knee

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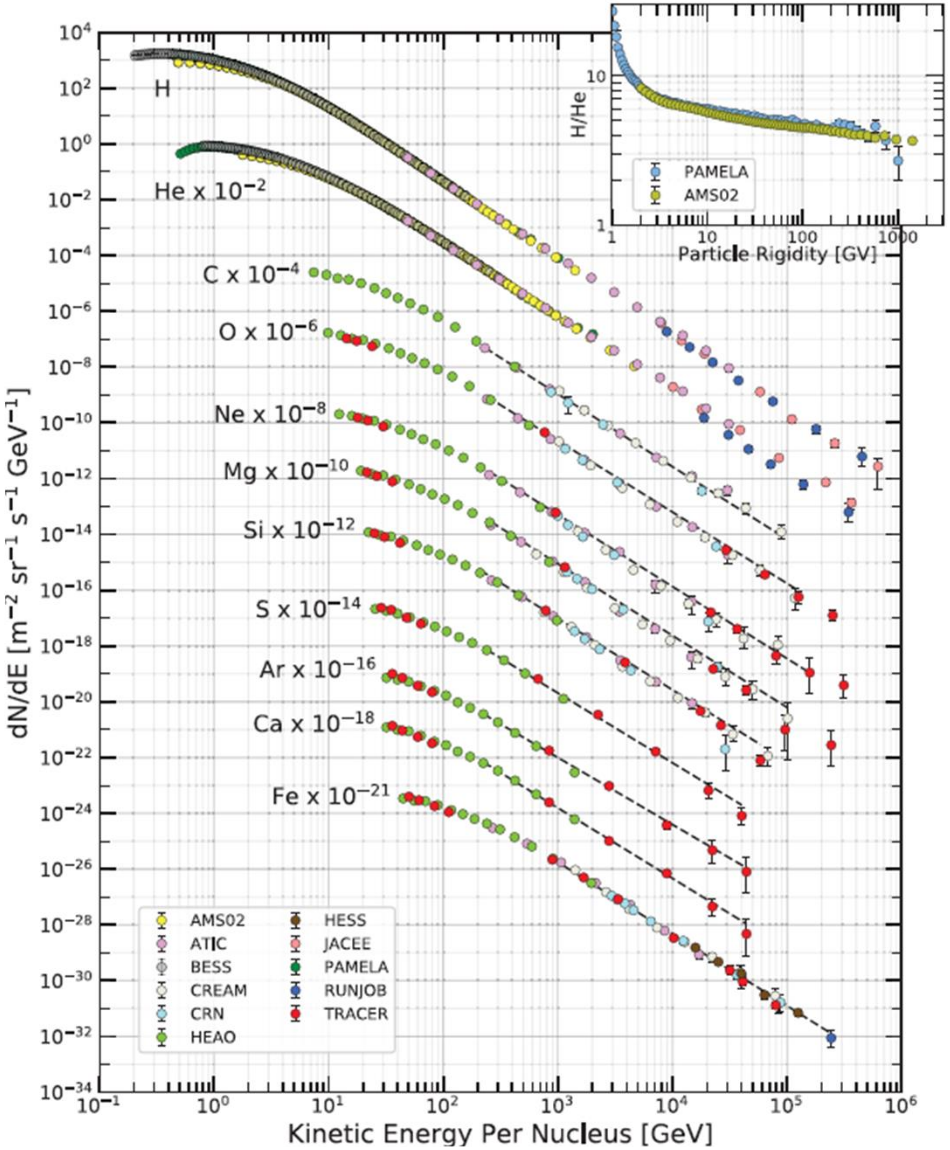
- Why nucleus – nucleus interactions?
- Why a new model  of A – A – interaction is required?
- A possible new model of nucleus – nucleus interactions.
- How to check the new model at LHC and in CR.
- Conclusion

# Why nucleus – nucleus interactions?

- Cosmic rays  bellow the knee consist mainly (~60%) of nuclei.
- Above the knee cosmic ray spectrum is changed and the fraction of nuclei is increased.
- Many unusual events and phenomena in cosmic ray experiments at energies above the knee were observed (Halos, Alignment, Penetrating cascades, Centauros et al.).
- In the last years so called “muon puzzle” in EAS investigations is appeared (excess of muon bundles and very high energy muons (>~ 100 TeV) compared with calculations).
- In nucleus – nucleus collisions at LHC more large increasing of secondary particle flux compared to proton – proton collisions was observed too.

# CR energy spectrum and mass composition

*C. Patrignani et al. (Particle Data Group)*
*Chin. Phys. C, 40, 100001 (2016) and 2017 update*




For CR energies < $10^{15}$ eV

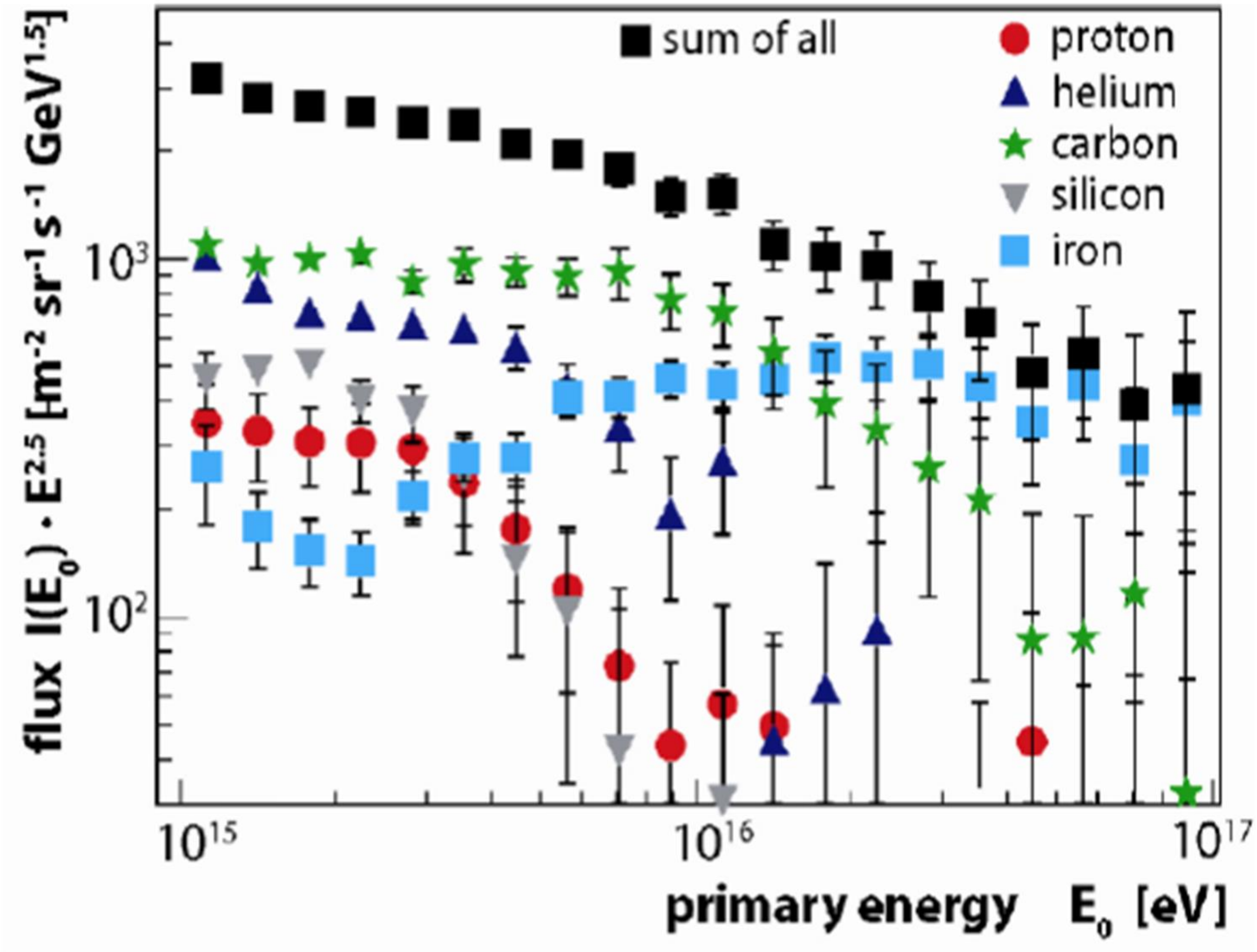
$dN/dE \sim E^{-\gamma}$ ; $\gamma \approx 2.7$

$\langle \ln A \rangle \approx 1.5$

| Particles | Z | <A> | Energy per nucleon | Energy per nucleus |
|---|---|---|---|---|
| Protons | 1 | 1 | 92 % | 42 % |
| $\alpha$-particles | 2 | 4 | 7 % | 21 % |
| Light nuclei | 3-5 | 10 | 0.15 % | 1 % |
| Medium nuclei | 6-10 | 15 | 0.5 % | 18 % |
| Heavy nuclei | $\geq$ 11 | 32 | 0.15 % | 18 % |

# Spectra of Individual Mass Groups

**KASCADE**




*Donghwa Kang*, Sven Schoo for the KASCADE-Grande Collaboration,*
*Combined analysis of KASCADE and KASCADE-Grande,*
*35th International Cosmic Ray Conference, 12-21 July, 2017, Busan, Korea*

# List of unusual events

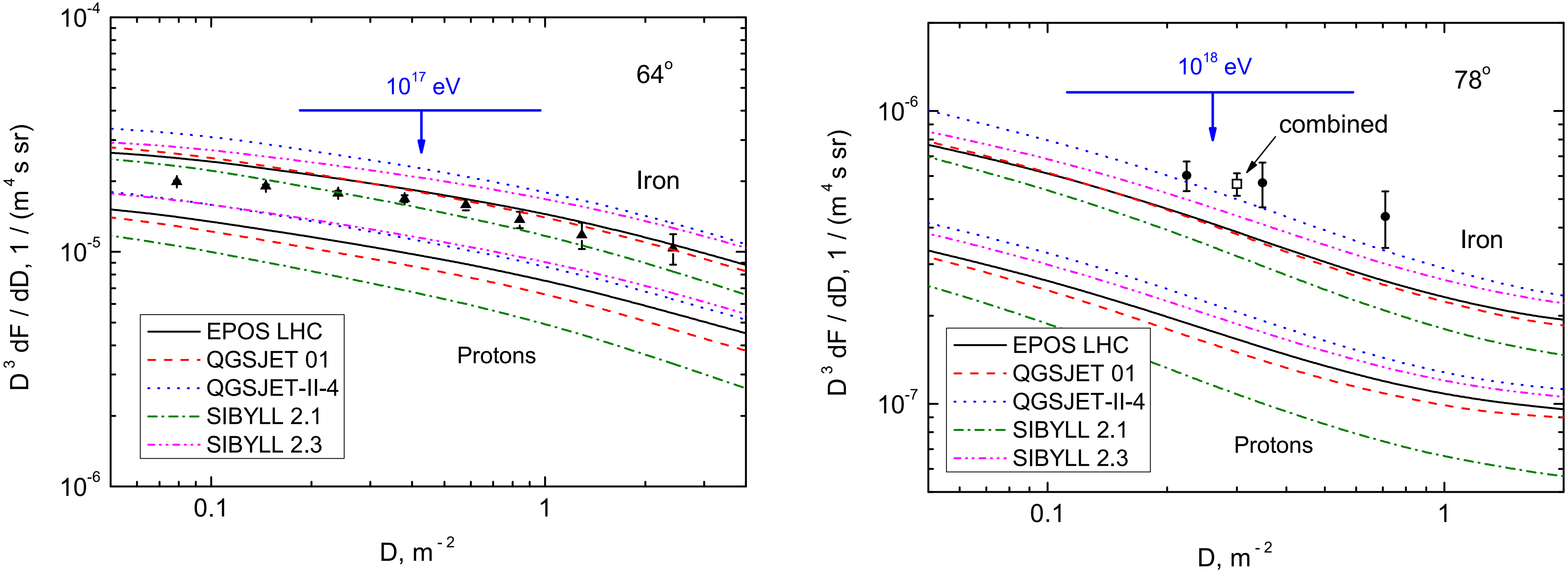
- In hadron experiments (mainly Pamir-Chakaltaya):
  - Halos, Alignment, Penetrating cascades, Centauros.
- In muon experiments (so called "Muon puzzle"):
  - Excess of muon bundles (CERN, NEVOD-DECOR, Auger);
  - Excess of VHE (~ 100 TeV) single muons (BUST, IceCube).
- In EAS investigations (in this approach, we can consider):
  - change of EAS energy spectrum, which now is interpreted as a change of the primary energy spectrum.
  - changes of behavior of $N_\mu(N_e)$ and $X_{max}(N_e)$ dependences, which now are explained as the changes of composition.

Important:

1. Unusual events appear at PeV energies of primary particles.
2. Cosmic rays consist mainly of nuclei, which interact with nuclei of the atmosphere.

# Excess of muon bundles intensity from DECOR data

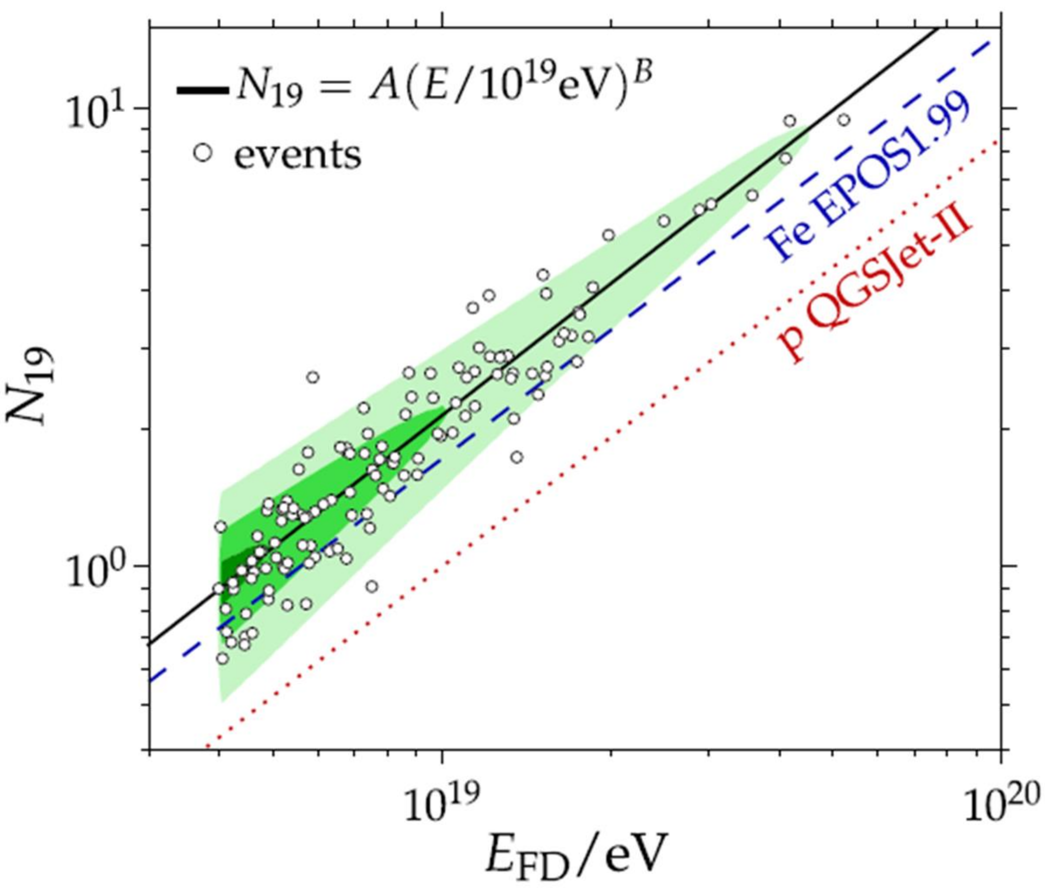
*A.G. Bogdanov et al., Astroparticle Physics 98 (2018) 13*




Reconstructed muon density spectra at 64° and 78° zenith angle (dark circles) and expected spectra calculated for protons and iron nuclei as primary particles (lower and upper groups of the curves respectively) with five different hadron interaction models. The open square represents a combined estimate based on all events with muon multiplicity m ≥ 10 in the respective angular bin. The arrow indicates the positions ($10^{17}$ and $10^{18}$ eV) effective primary energies.

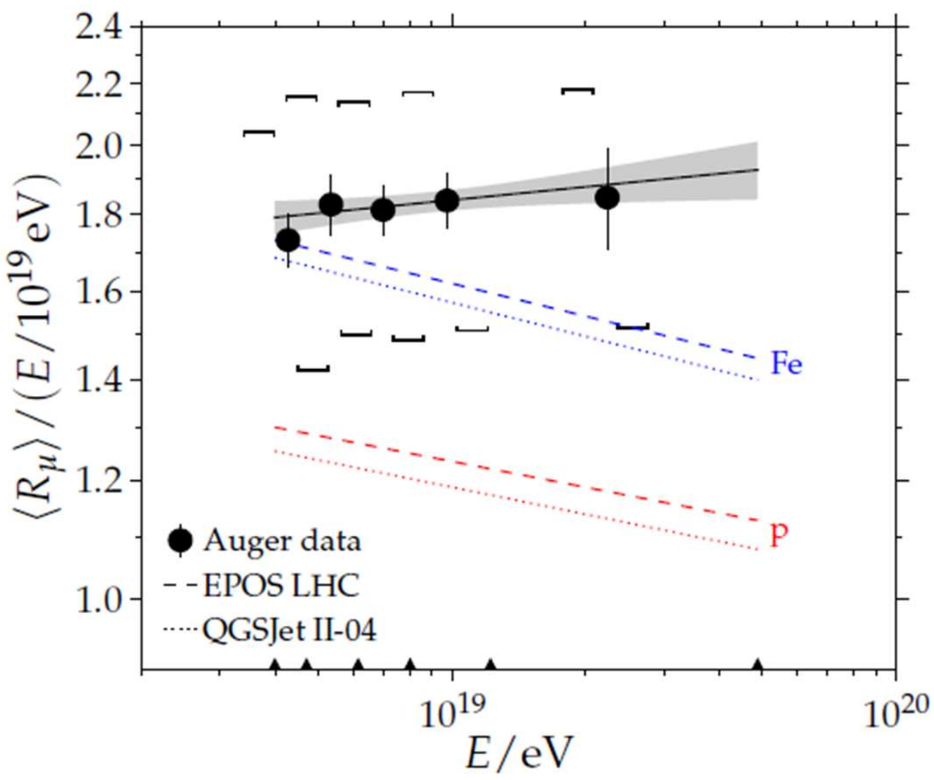
# Excess of the number of muons in highly inclined EAS from Pierre Auger Observatory data

*G. Rodriguez, EPJ Web of Conf. 53 (2013) 07003*




*The number of muons as a function of energy.*

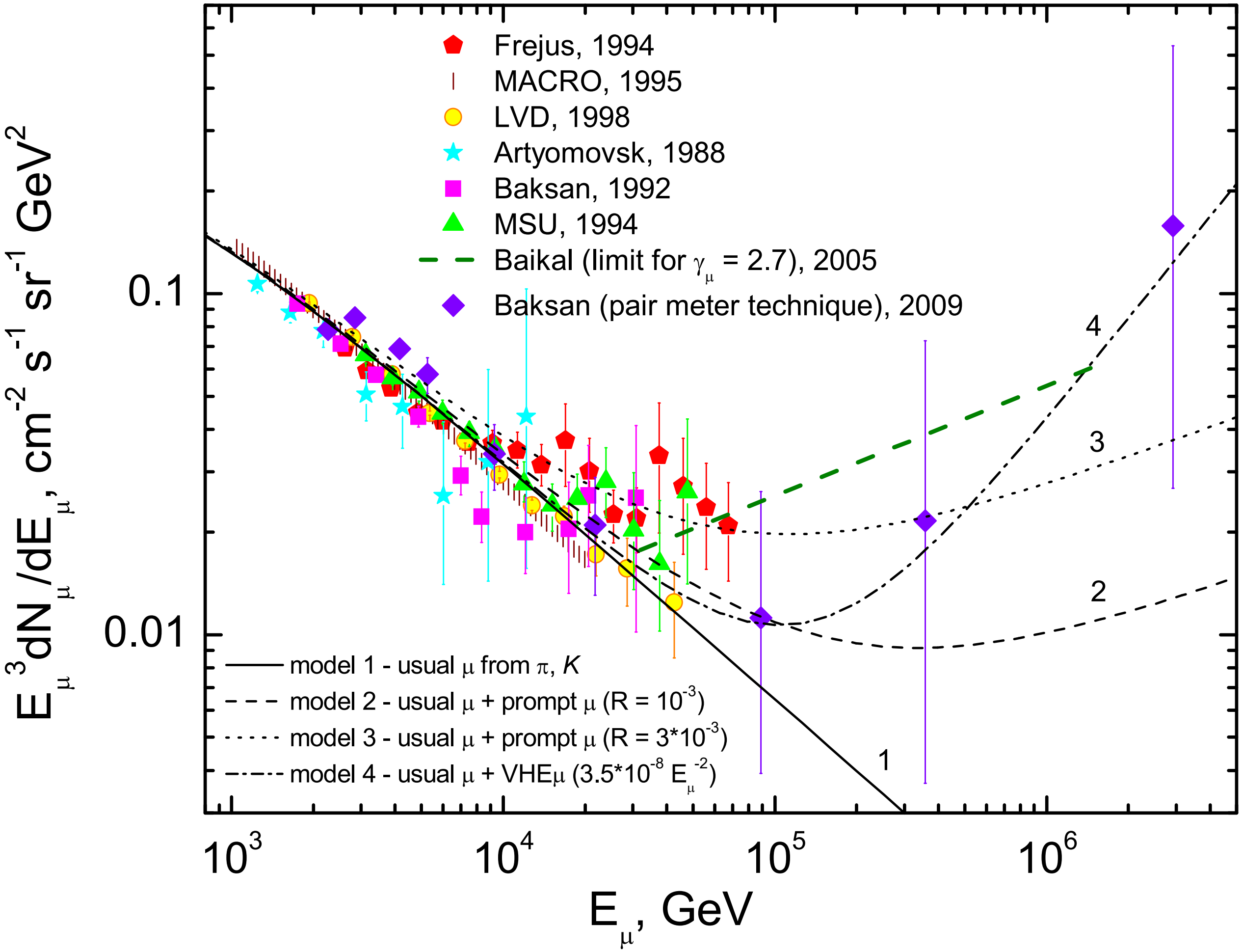
*A. Aab et al., Phys. Rev. D 91 (2015) 032003*




*Average muon content $\langle R_\mu \rangle$ per shower energy E as a function of the shower energy E in double logarithmic scale.*

# Excess of VHE muons from Baksan data

*A.G. Bogdanov et al., Astroparticle Physics 36 (2012) 224*

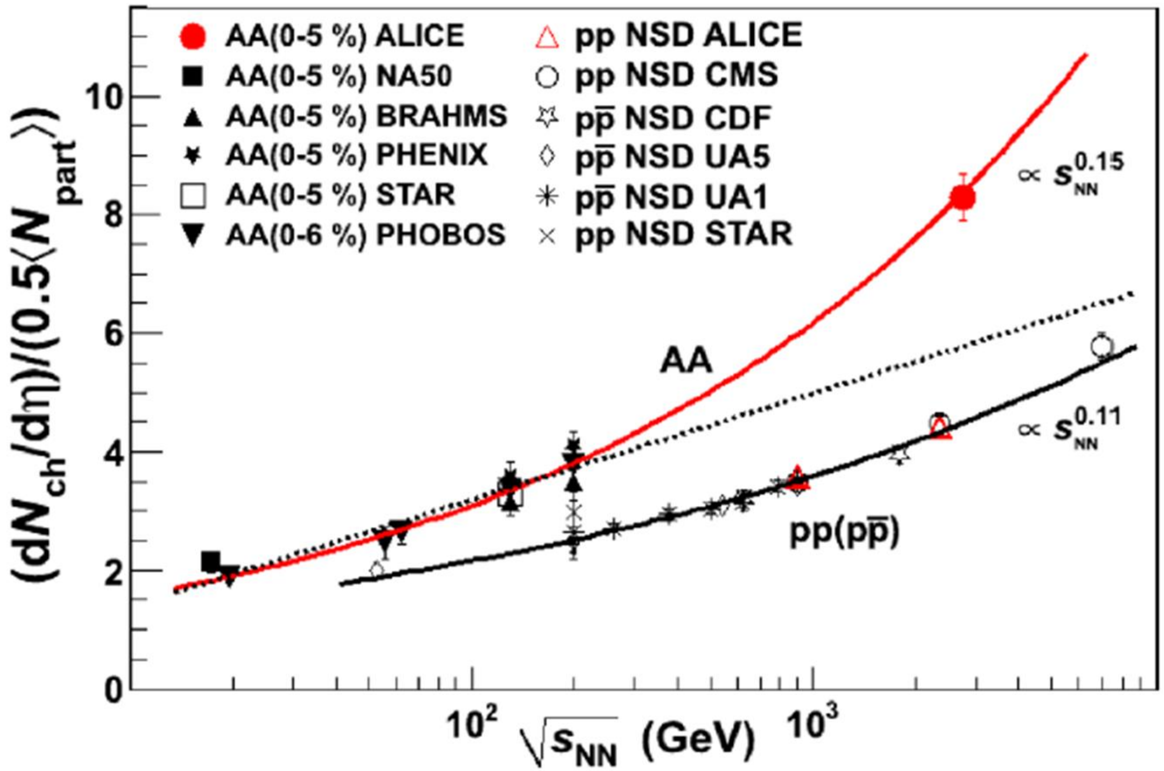



*Differential muon energy spectra for vertical direction measured in various experiments*

Such excess of VHE muons was obtained by means of multiple interaction method. The curves correspond to different spectrum models.

# Charged Particle Multiplicity

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




log extrapolation fails (finally!)

2.2 x central Au+Au

($\sqrt{s_{NN}}$=0.2 TeV)

1.9 x pp (NSD)

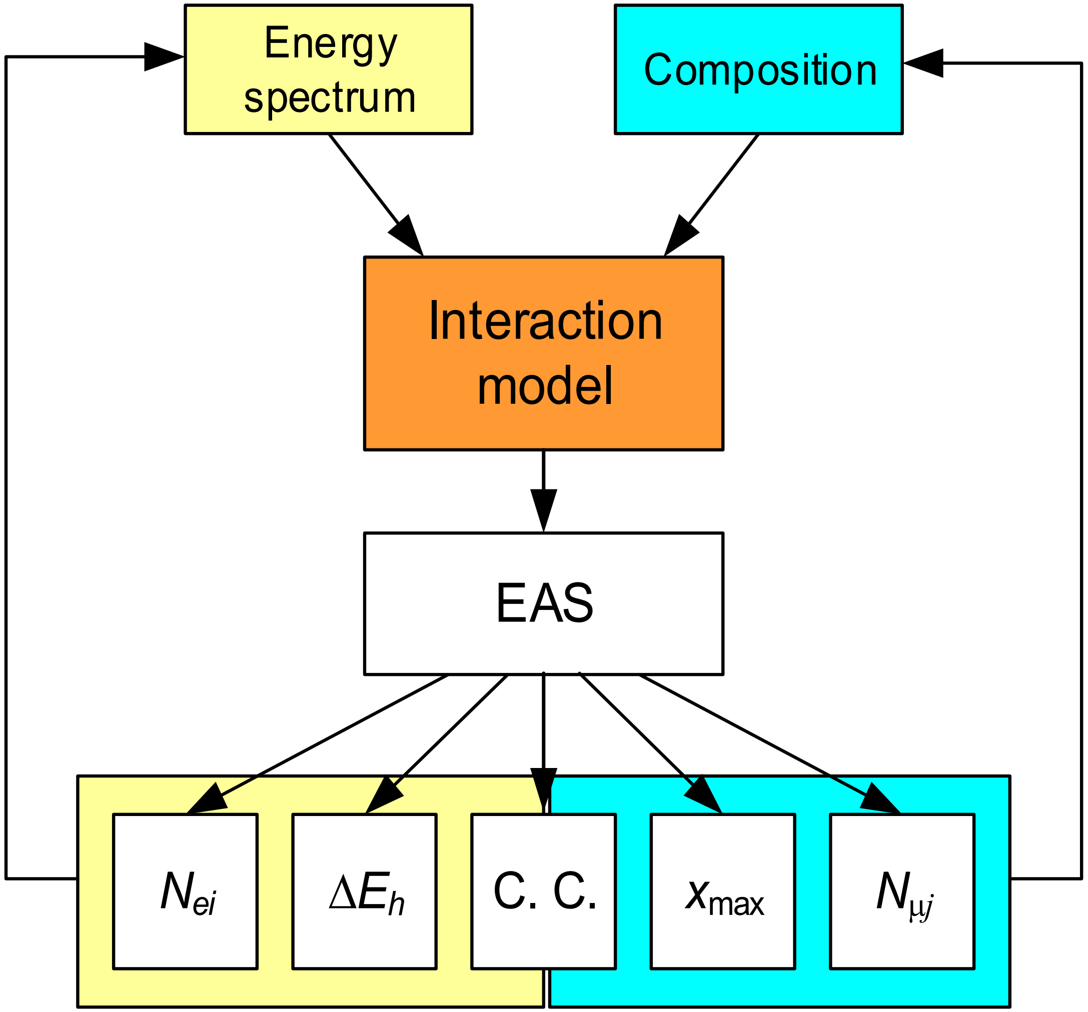
($\sqrt{s_{NN}}$=2.36 TeV)

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.)

# Existing approach to EAS analysis




If to suppose that there are no changes of interaction model, the following results can be obtained

# Comments to this approach

In this approach it is supposed that:

EAS energy is equal to energy of primary particle.

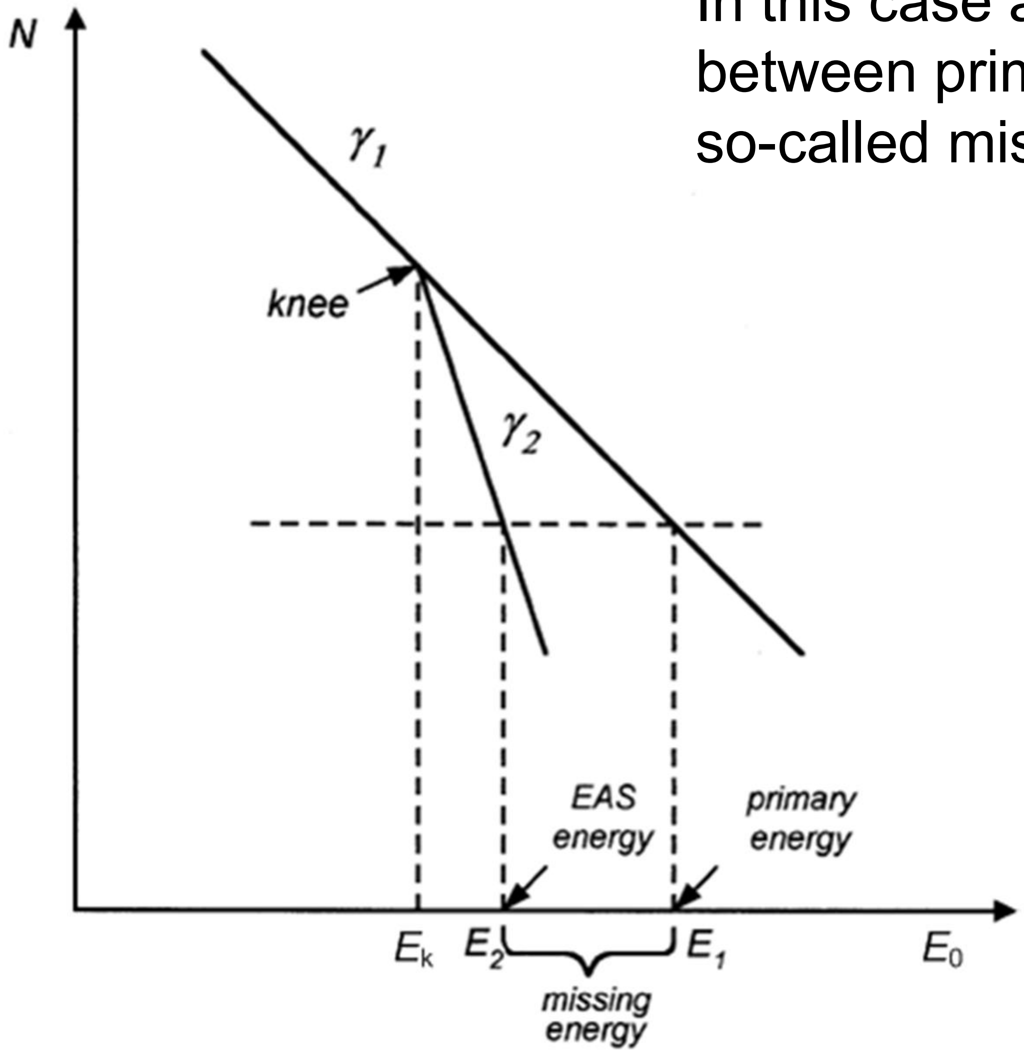
All changes of EAS characteristics in dependence on energy are results of energy spectrum or/and composition changes only.

The reasons of such changes:

Primary cosmic rays at least up to $10^{17}$–$10^{18}$ eV have galactic origin.

Their acceleration and keeping in Galaxy are determined by their charge *Z* or/and mass *A*.

# The knee as a result of the interaction change




In this case a difference between primary and EAS energies, so-called missing energy, appears

Appearance of very high energy muons and correspondingly neutrinos can explain this missing energy

# What do we need to explain all unusual data?

Model of hadron interactions which gives:

1. Threshold behavior (unusual events appear at several PeV only).
2. Large cross section (to observe unusual events in CR).
3. Large orbital momentum (alignment).
4. Large yield of HE leptons (excess of muon bundles, penetrating cascades).
5. The change of EAS development and, as a consequence, a missing energy appearance and increasing $N_\mu$ / $N_e$ ratio.

# Possible variants

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

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

- 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 explain the inclusion of new interaction features, and with relatively big probability it is correct.

# Quark-gluon matter

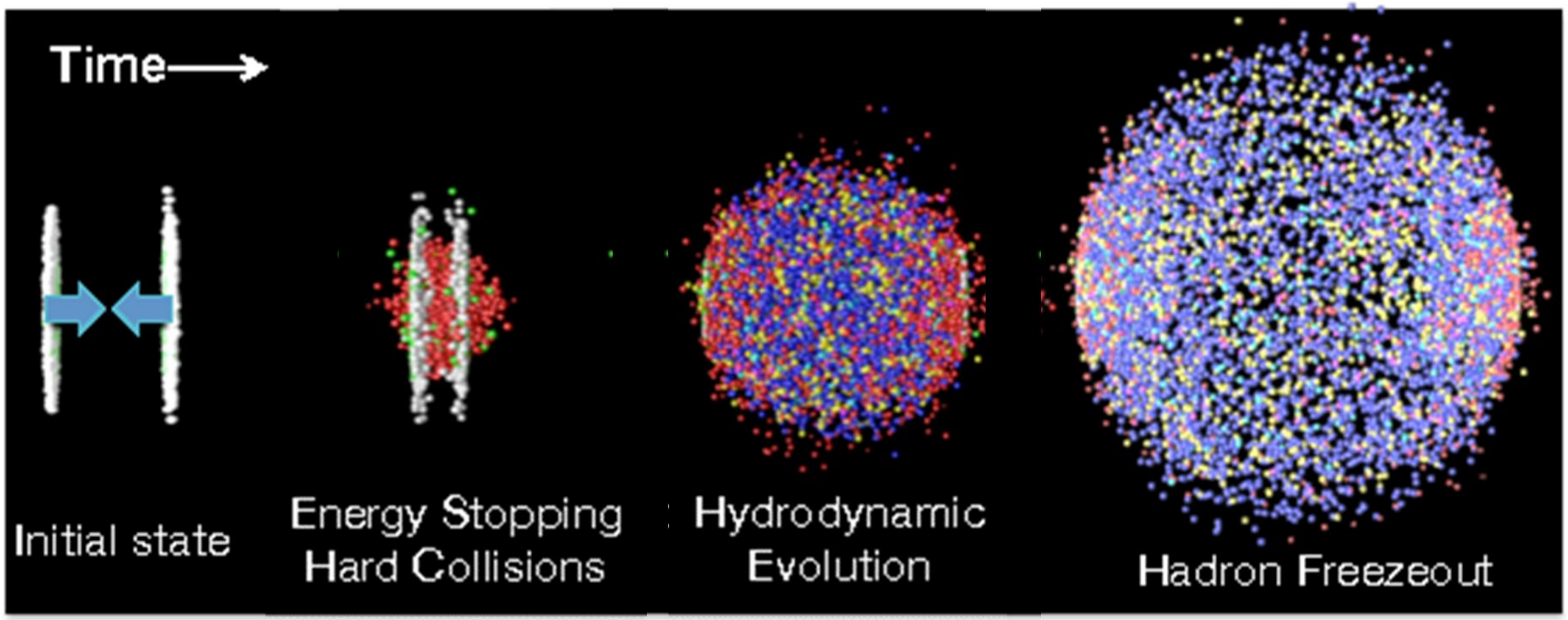
1. Production of QGM provides two main conditions:
   - threshold behavior, since for that high temperature (energy) is required;
   - large cross section, since the transition from quark-quark interaction to some collective interaction of many quarks occurs:

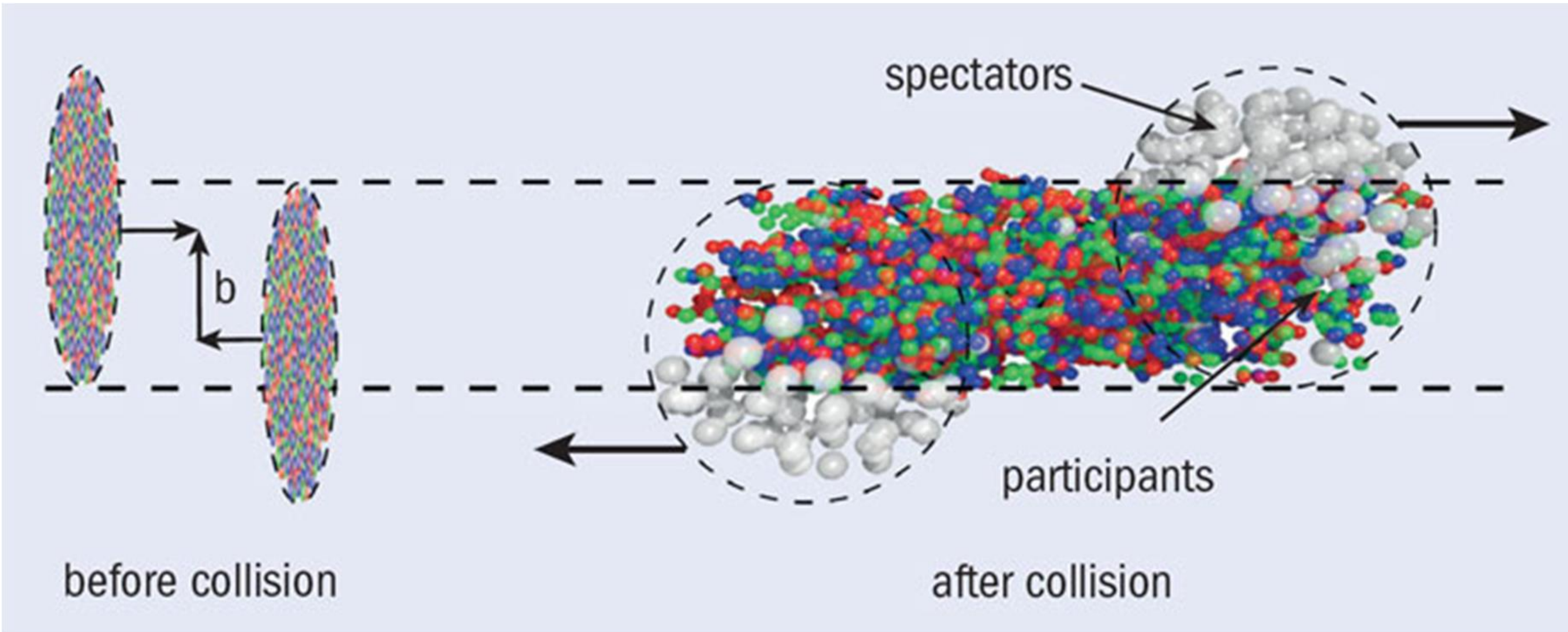
$$\sigma = \pi D^2 \rightarrow \sigma \sim \pi R^2$$

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.

Tapan K. Nayak, Pramana 79 (2012) 719-735

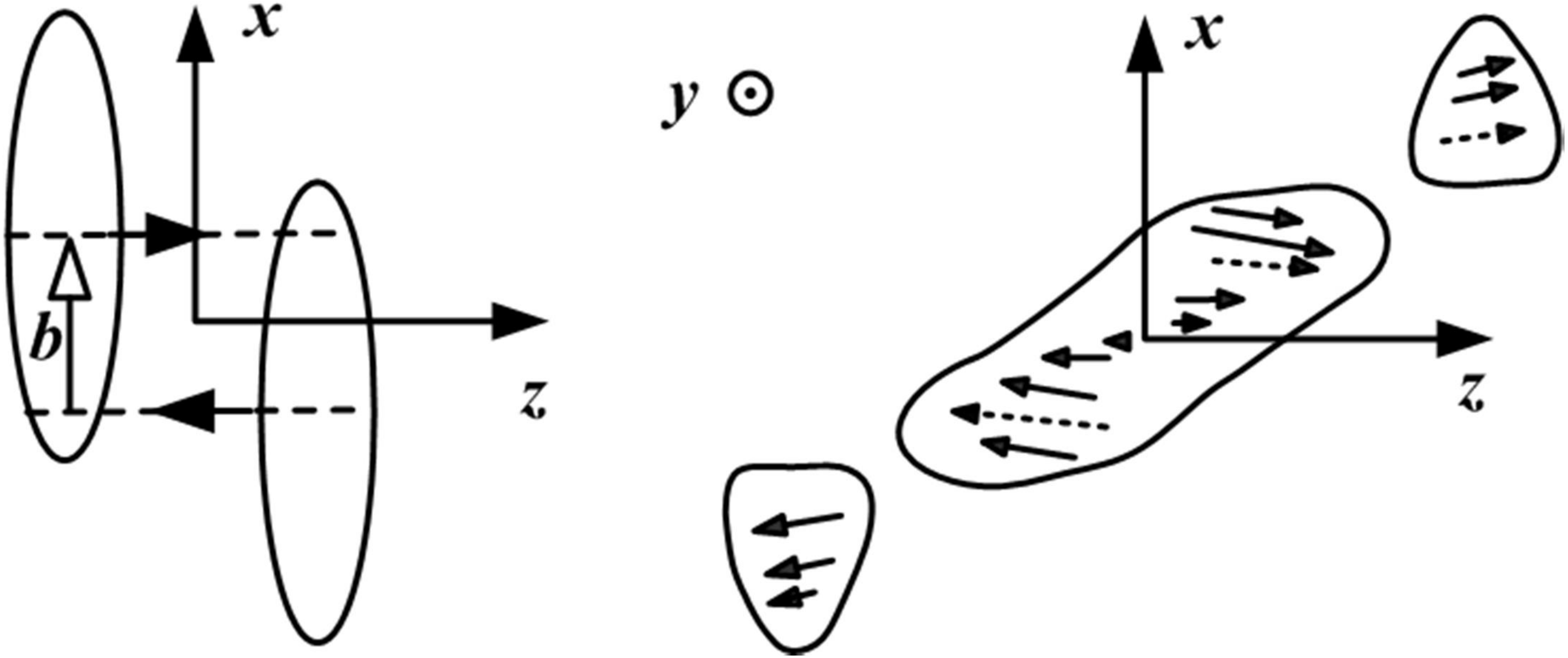



Alberica Toia, CERN COURIER, Apr 26, 2013

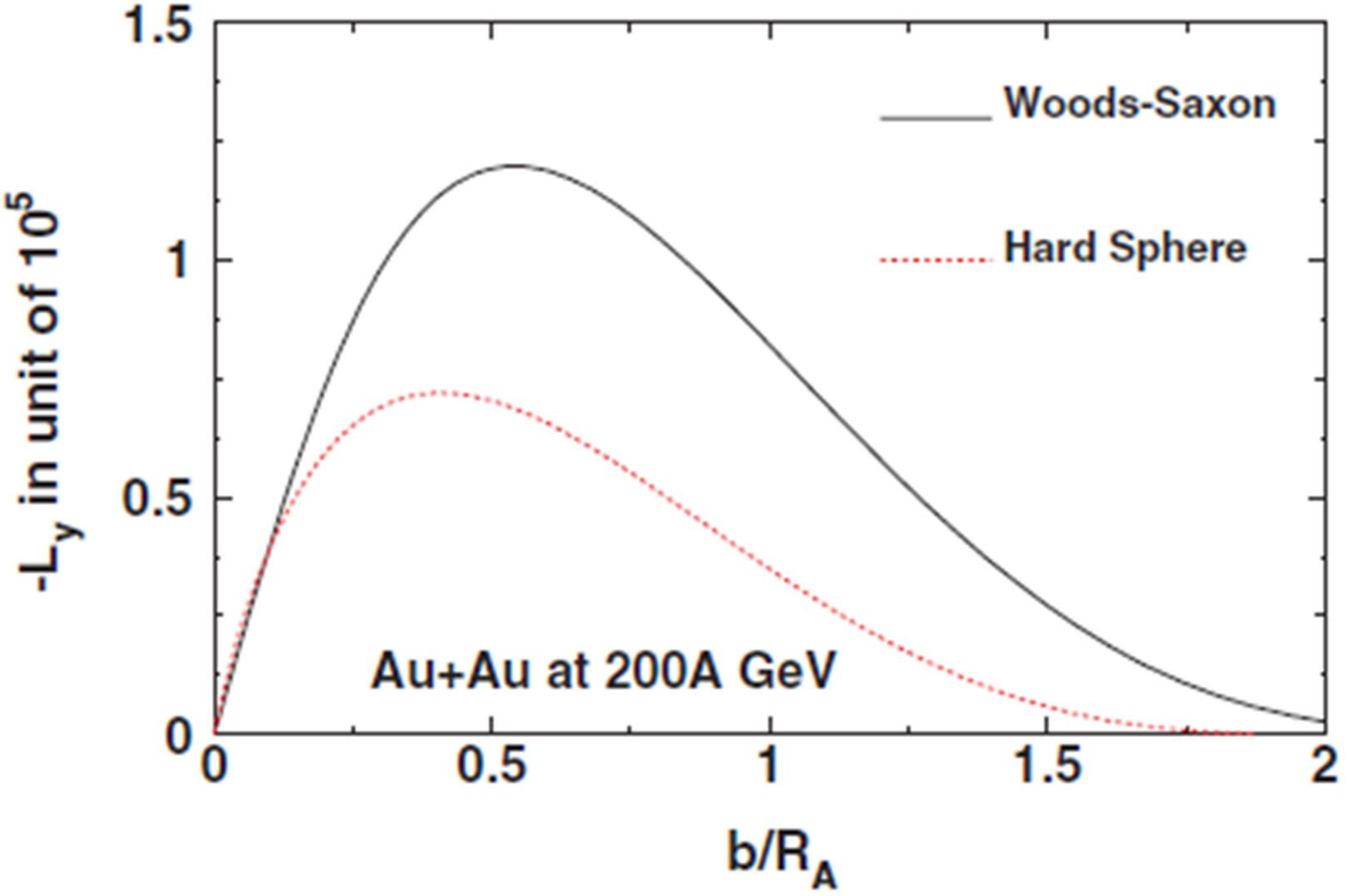
# Orbital angular momentum in non-central ion-ion collisions

*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 much less for top-quarks or other heavy particles.

3. Though in interacting nuclei top-quarks are absent, the suppression of decays into light quarks gives time for the appearence of heavy quarks.

[redacted]

# 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, $n \approx 4$ ($\alpha$ - 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: $t(\bar{t}) \rightarrow W^+(W^-) + b(\bar{b})$

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

*b*-quarks produce jets which generate multiple pions decaying into muons and neutrinos.

# What can explain the new model?

Short answer: Practically all.

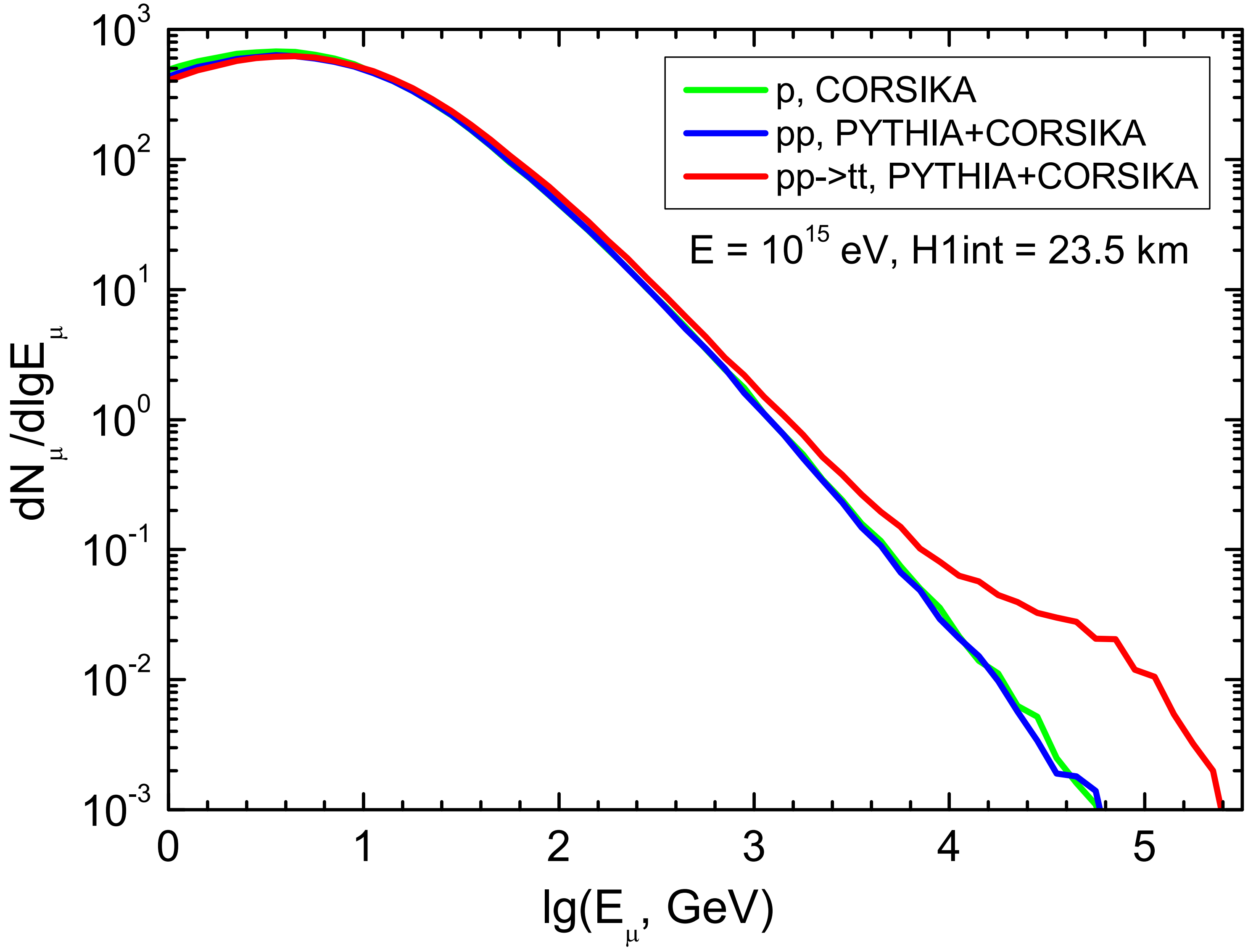
1. "Muon puzzle"
   - Decays of W-bosons into muons and neutrinos explain excess of VHE muons with energy above 100 TeV and appearance of penetrating cascades.
   - Decays of W-bosons into hadrons (mainly pions , on average ~ 20) explain the increasing muon number (muon bundles) with increasing of energy.

2. Behavior of EAS energy spectrum.

   Now the transition from measured data to the EAS energy does not take into account a missing energy which is carried away by VHE muons and three types neutrinos, and a change of EAS development due to a change of interaction model.

3. All unusual events (alignment, halos, Centauros etc.)

# Predicted muon energy spectrum from *W*-boson decays



# How to check the new approach?

Possibilities to check the new approach in CR experiments:

- study of energy deposit of muon bundles (NEVOD);
- study of muon energy spectrum above 100 TeV (IceCube and HAWC).

Possibilities to check this approach in LHC experiments:

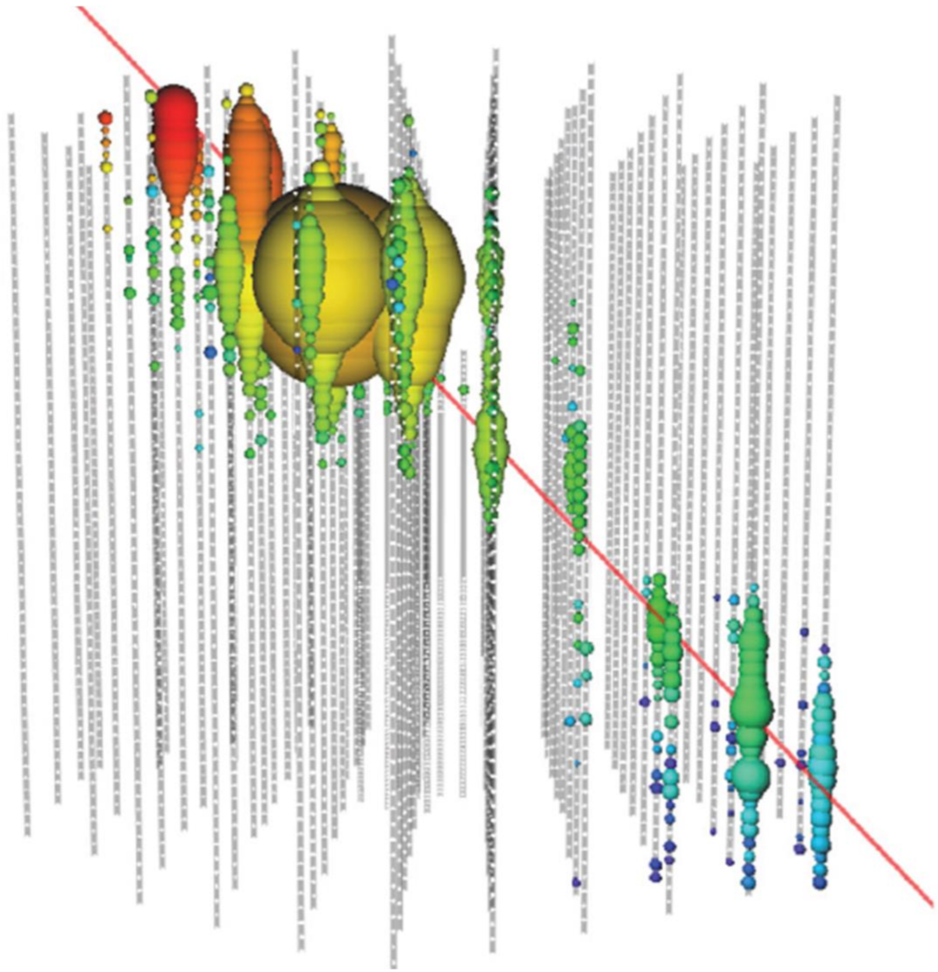
excess of *t*-quarks, excess of *W*-bosons, sharp increasing of missing energy, etc.

For these searches it is better to use *A*-*A* interactions (as in cosmic rays) but not *p*-*p* interactions.

And apparently, some observations of the effects predicted by new model were yet obtained in *A*-*A* interactions.

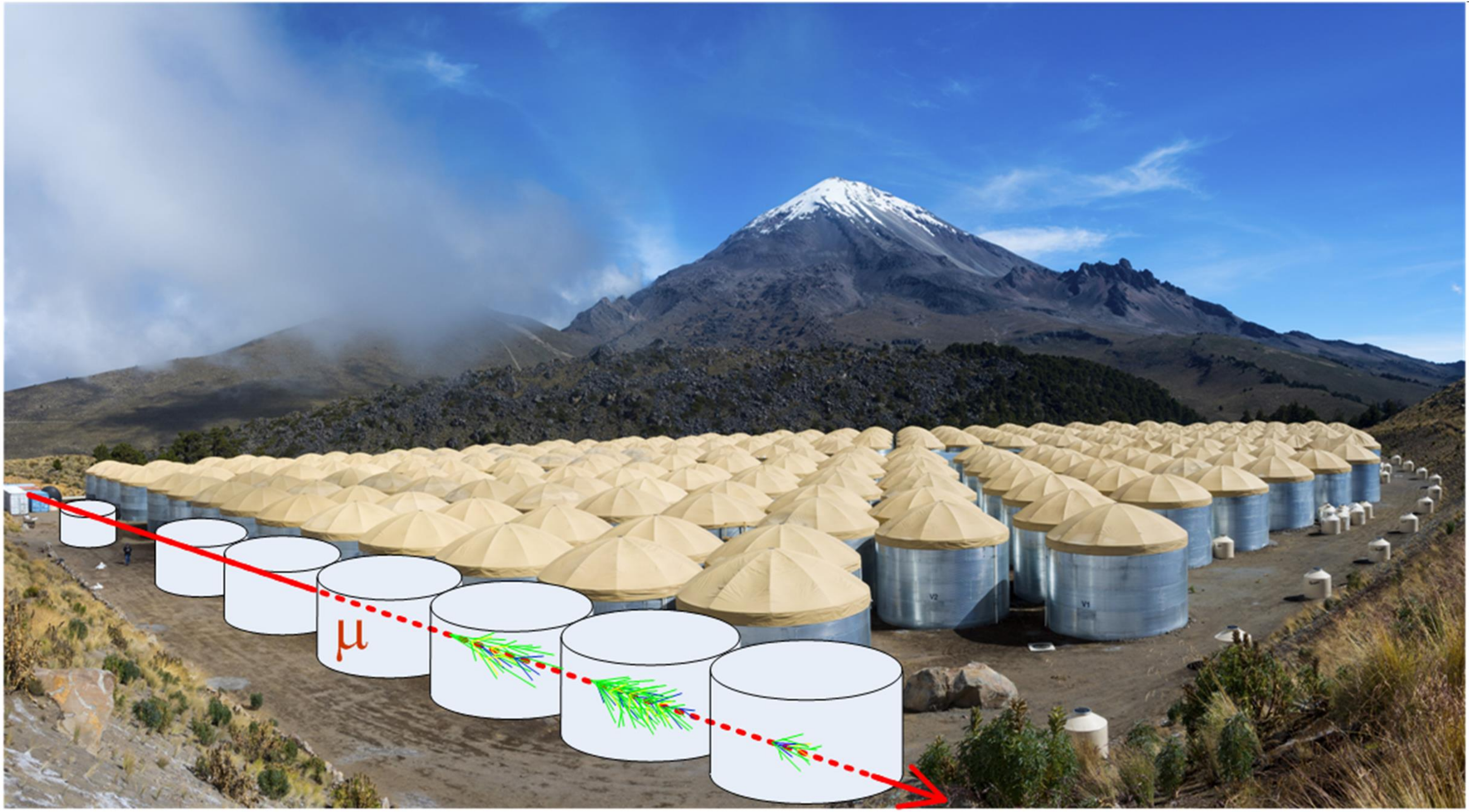
# IceCube and HE muon

*M.G. Aartsen et al., Astroparticle Physics 78 (2016) 1*



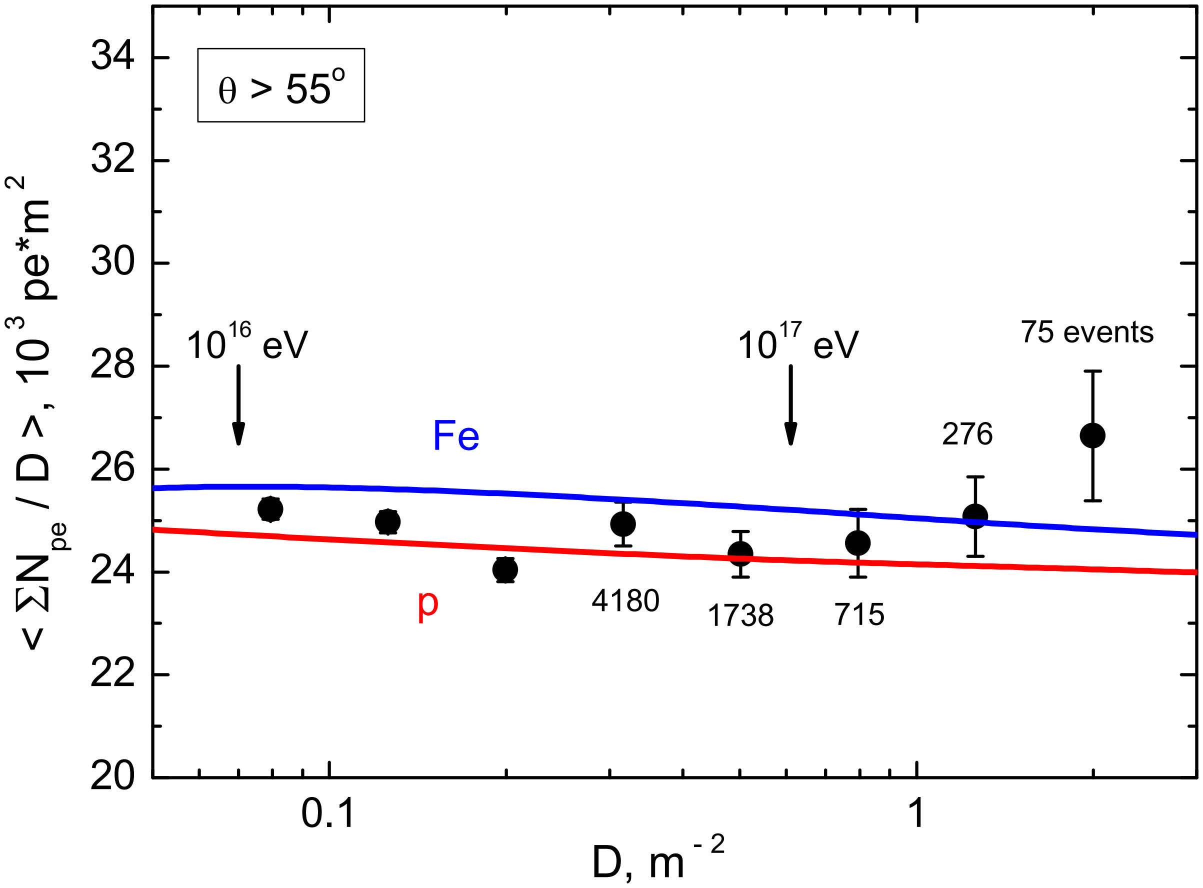
Example of in high-energy muon candidate event found in experimental data. Reconstructed event parameters are: $E_{loss}$ = 550 TeV , $E_{\mu,\ surf}$ = 1.03 PeV , $\theta = 45^{\circ}$.

# HAWC and VHE muon



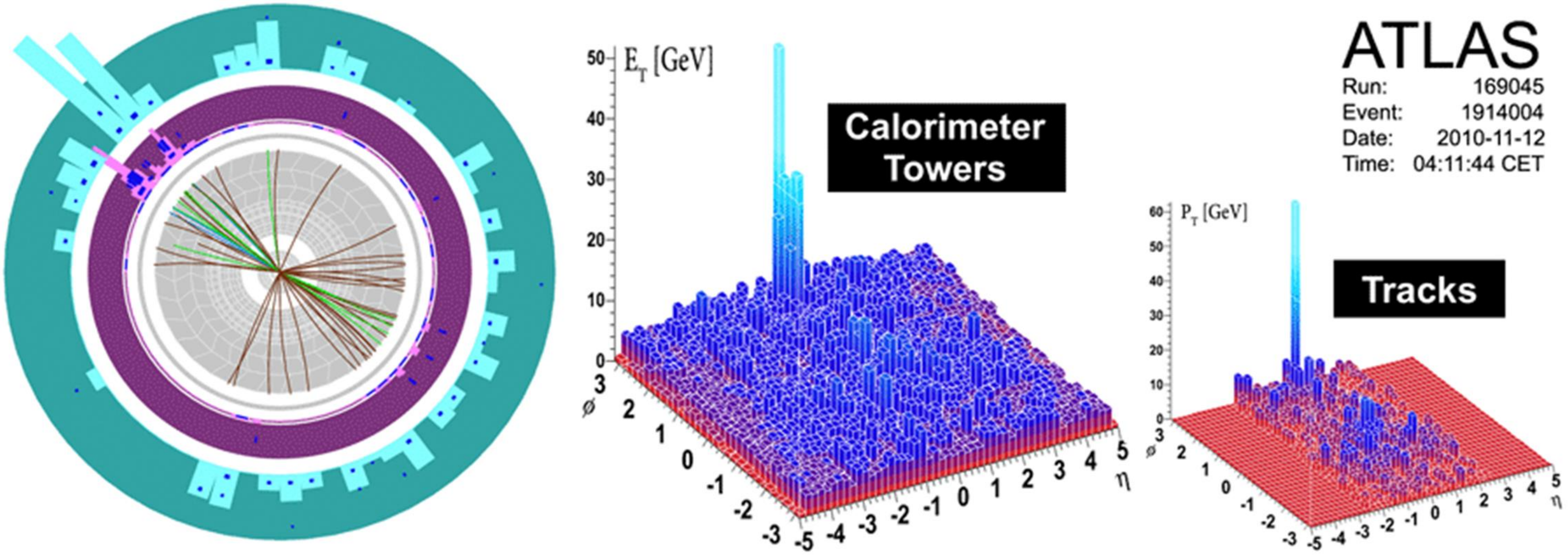
# Dependence of average specific energy deposit on muon density (NEVOD+DECOR data)

In fact (for a fixed range of zenith angles), this is a measurement of the dependence $<\Sigma N_{pe} / D>$ on the energy of primary particles.

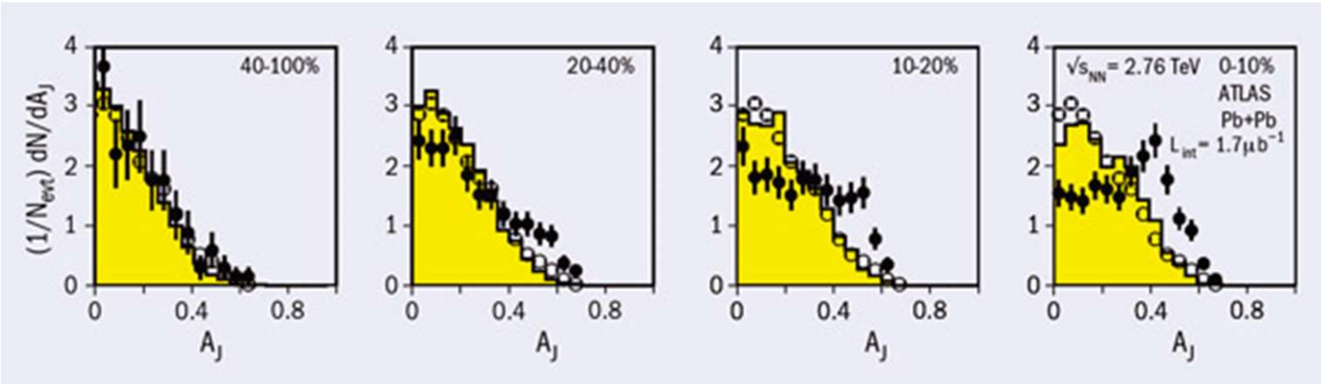



Simulation results show a tendency to a slow decrease of muon energy in the bundles with the increase of primary energy. In contrast, data indicate some increase of the average specific energy deposit at high muon densities (corresponding to effective primary particle energies more than $10^{17}$ eV).

# 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?

In nucleus-nucleus interactions top-quark is generated.
It decays

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

In top-quark center-of-mass system kinetic energy:

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

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 $W$ decays to ~ 20 $\pi$,
the ATLAS experiment's picture will be obtained.

# Conclusion

If the considered approach is correct, it can be investigated at LHC. But it is necessary to search for the new state of matter in detail at LHC not in *proton-proton* interactions but in *nucleus-nucleus* interactions.

Method of the investigation is the search of an excess top-quark production, but this is a very difficult task, since muon energy from W-decay is about 40 GeV and it will be difficult to find it among other numerous particles with similar energy.

In cosmic rays these muons will have energies above 100 TeV, detection of which is not so complex task, if to have acceptable experimental setup, f. e. HAWC, IceCube, Baikal, KM3Net

As result, in the first time for the long period a new state of matter can be observed in CR before than at accelerators!

**Thank you very much for your attention!**