TAUP, September 7-11, 2015

New approach to cosmic ray investigations above the knee

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Contents

Introduction

Energy region about 10^{15} eV is very interesting and important.

Firstly, it separates two main methods of CR particle energy measurements:

- direct measurement at satellites;

- EAS investigations.

Secondly, namely above this energy basic characteristics of CR: energy spectrum (the knee) and mass composition (more heavy) are changed.

Now all changes of the energy spectrum and mass composition are explained by cosmophysical reasons.

Why a new approach is required?

1. *The knee was firstly observed almost 60 years ago. But no exhaustive and accepted description for this long period was supposed.*

2. *Many unusual events in cosmic ray experiments at energies above the knee during this period were observed.*

3. *Additionally, in the last years, so-called "muon puzzle" in EAS investigations appeared.*

List of unusual events

- In **hadron** experiments (mainly Pamir-Chacaltaya):
  - Halos, Alignment, Penetrating cascades, Centauros, etc.

- 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 frame of new approach):
  - change of EAS energy spectrum, which is now interpreted as a change of the primary energy spectrum.
  - changes of behavior of $N_\mu(N_e)$ and $X_{max}(N_e)$ dependences, which are now explained as the changes of composition.

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

Background of a necessity of a new model

There is no model, which could describe all observed unusual phenomena from a single point of view.

All existing models of strong interactions are based on extrapolation of accelerator results to higher energies.

But good accelerator data were obtained for p-p-interactions only.

In cosmic rays most part of interactions are nucleus-nucleus (~ 60%) and proton-nucleus (~ 40%).

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 (for measurements in CR).
3. Large orbital momentum (to explain the alignment).
4. Large yield of VHE leptons (excess of VHE muons and muon bundles, penetrating cascades).
5. The change of EAS development and, as a consequence, change of N_μ / N_e ratio and $X_{max}(N_e)$ behavior.

Possible variant

Since muons cannot be produced in hadron interactions directly, it is necessary to suppose that at the knee energy (about 3 TeV in the center-of-mass system) some new state of matter with effective mass ~ TeV appears and then decays through t-quarks and W, Z – bosons into leptons.

Quark-gluon plasma (QGP) model is very suitable for that.

Better to speak about quark-gluon matter (QGM), since:

- usual plasma is a gas;
- quark-gluon plasma is some kind of liquid.

Quark-gluon matter

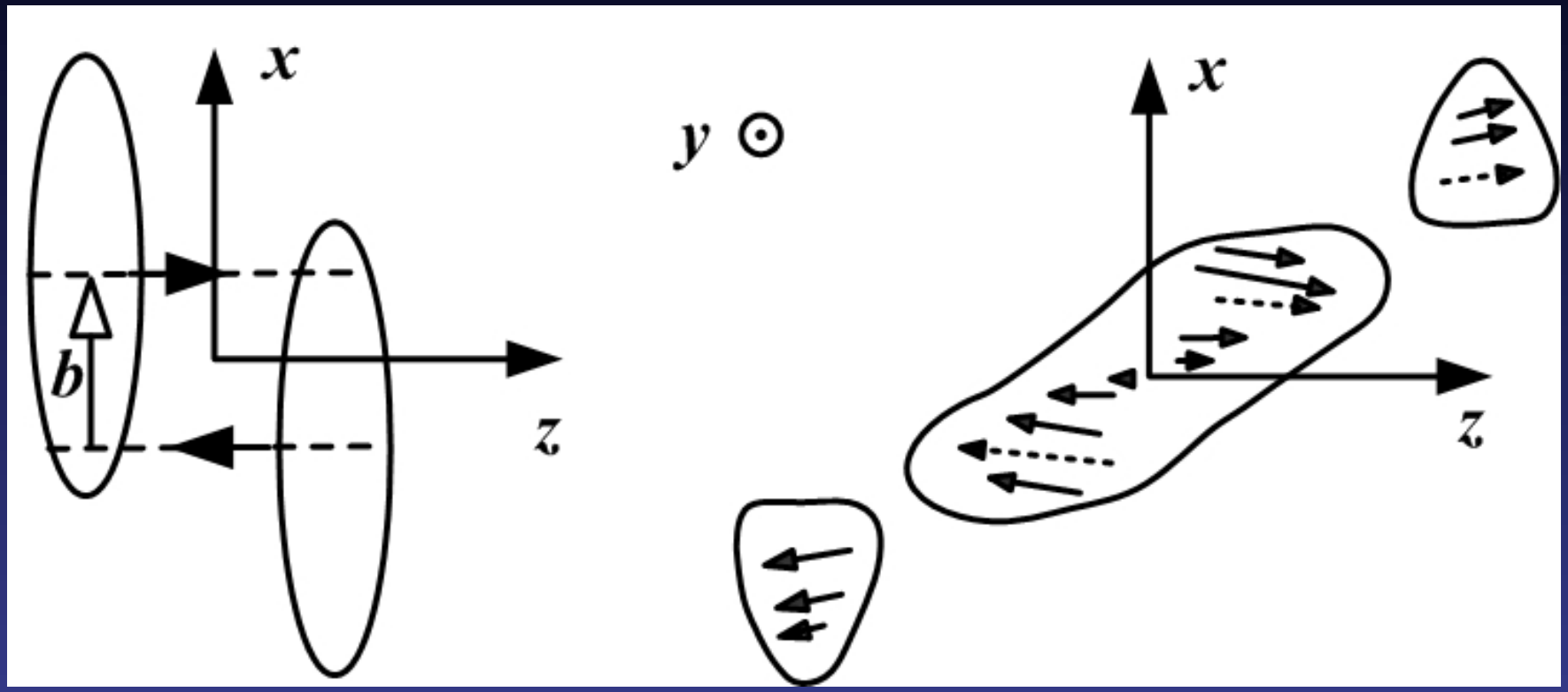
1. Production of QGM provides two main conditions:
   - threshold behavior, since for that high temperature (energy) is required;
   - large cross section, since the transition from quark-quark interaction to some collective interaction of many quarks and gluons occurs:

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

   where R is a size of quark-gluon blob.

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

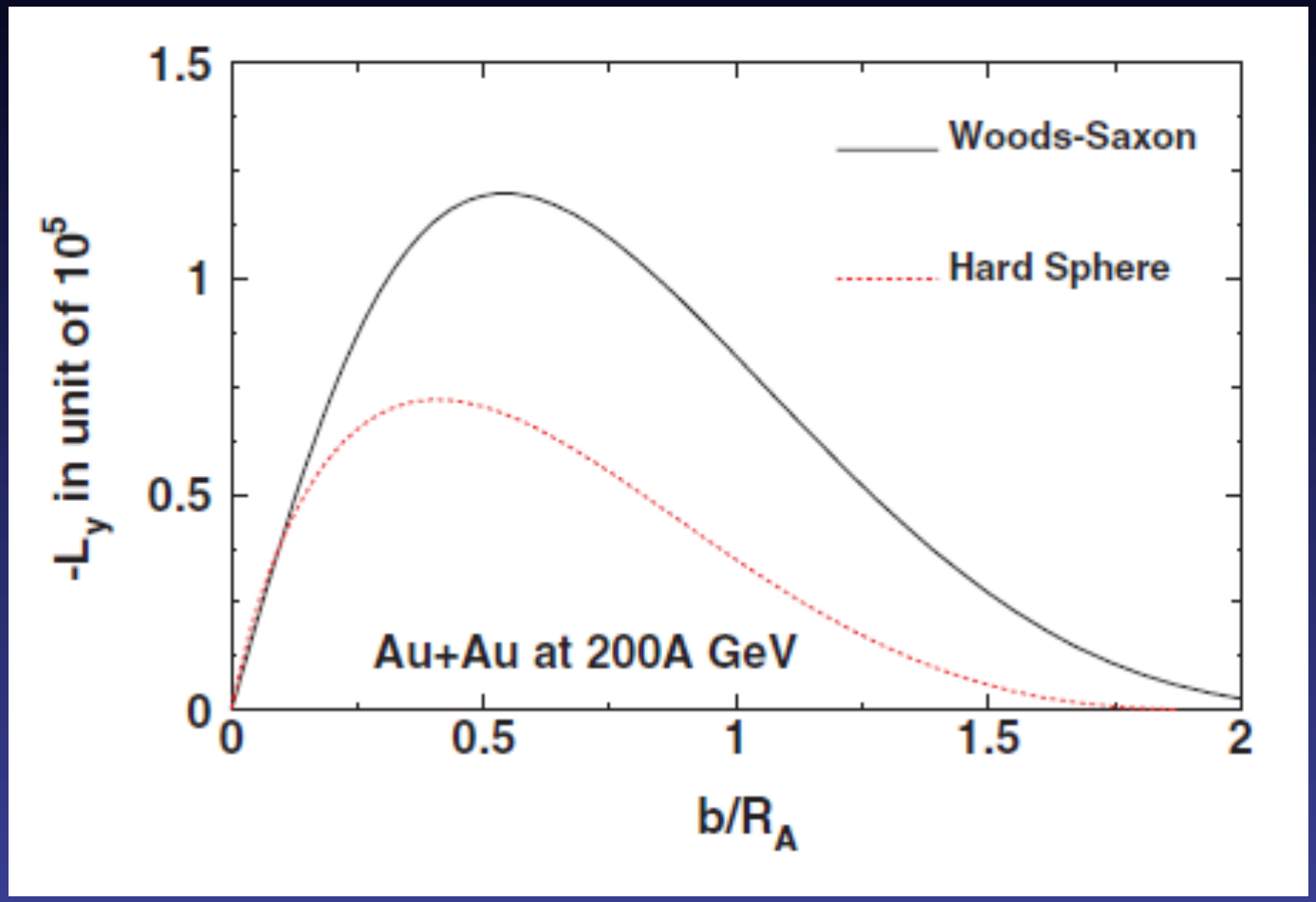
Orbital angular momentum in non-central ion-ion collisions



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

Orbital momentum value

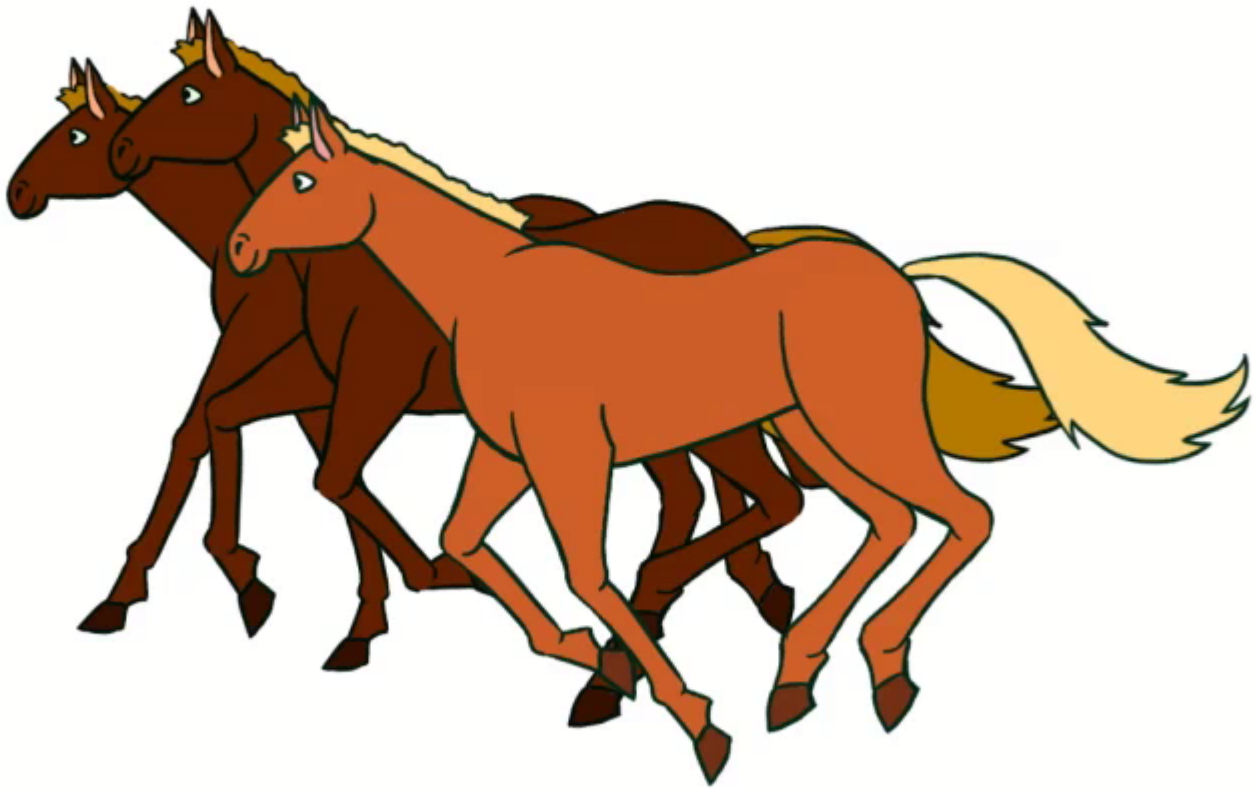
Jian-Hua Gao et al., Phys. Rev. C 77 (2008) 044902



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 the top-quarks are absent in interacting nuclei, the suppression of decays into light quarks gives time for the appearance of heavy quarks in very hot QGM.



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 $t(\bar{t}) \rightarrow W^+(W^-) + b(\bar{b})$

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

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

What can explain the new model?

Short answer: Practically all.

1. All unusual events (alignment, halo, Centauros etc.).

2. "Muon puzzle"

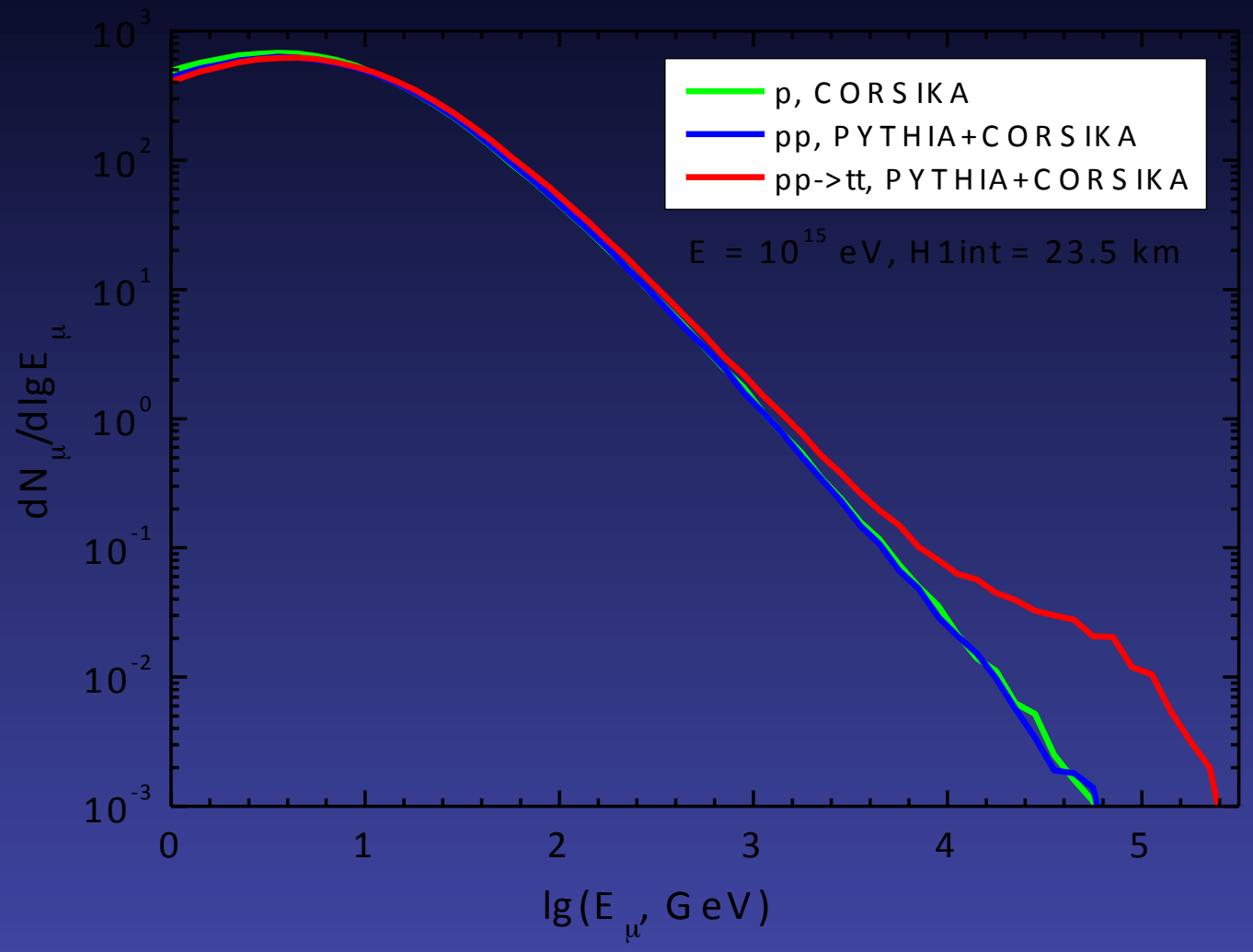
   - Decays of W-bosons into muons and neutrinos explain the excess of VHE muons (and neutrinos too) with energy above 100 TeV.

   - Decays of W-bosons into hadrons (mainly pions – in average ~ 20) explain the increasing number of muons (muon bundles) with the increase of energy.

3. Behavior of the EAS energy spectrum.

   Now the transition from the measured data to EAS energy does not take into account a possible change of EAS development due to a change of the interaction model.

Inclusive muon energy spectrum



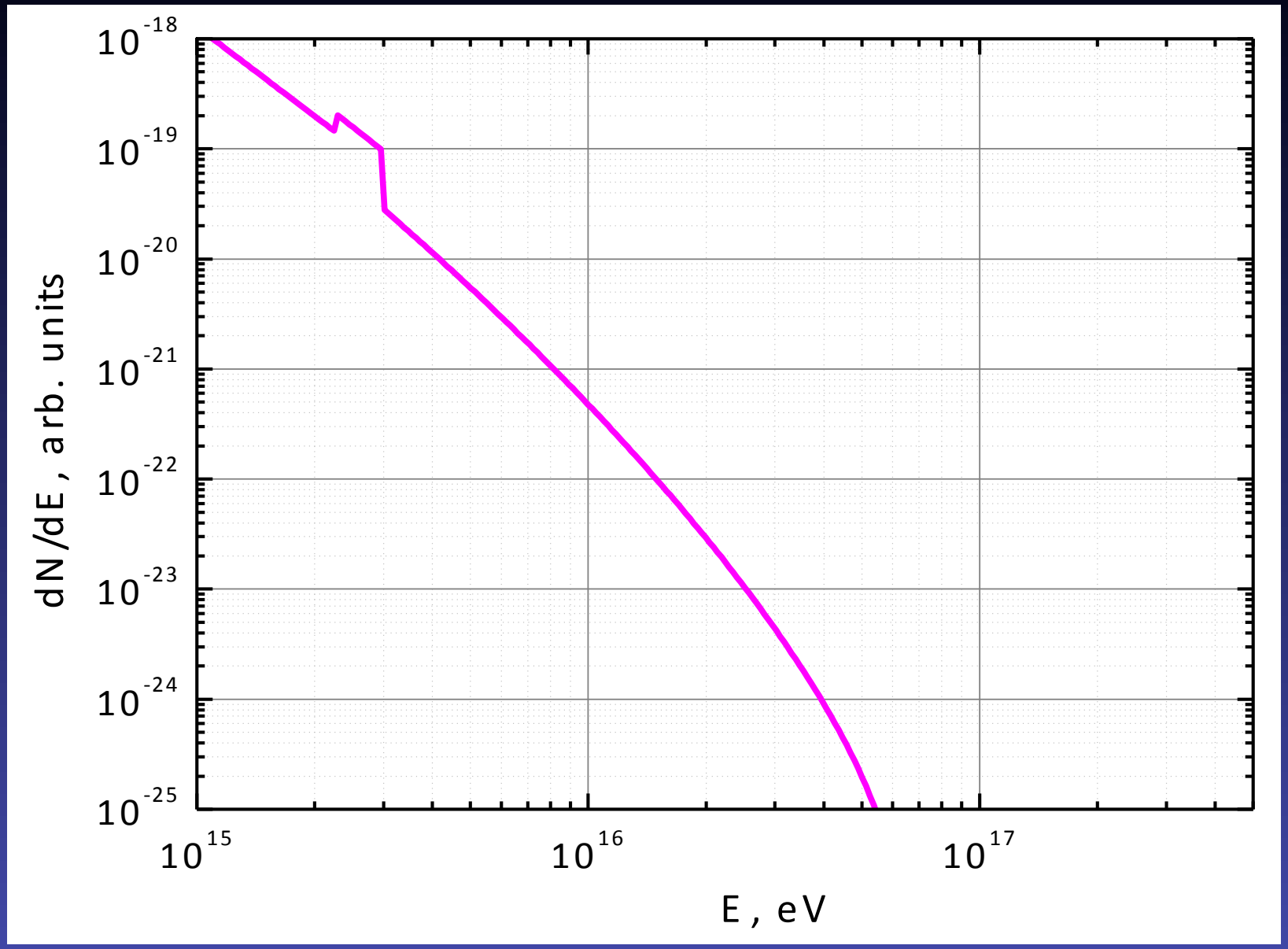
How CR energy spectrum is changed?

1. One part of t-quark energy gives the missing energy (ν_e, ν_μ, ν_τ, μ), and another part changes the EAS development due to increasing multiplicity of secondary particles.

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 differ from the primary spectrum.

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

Change of the primary energy spectrum



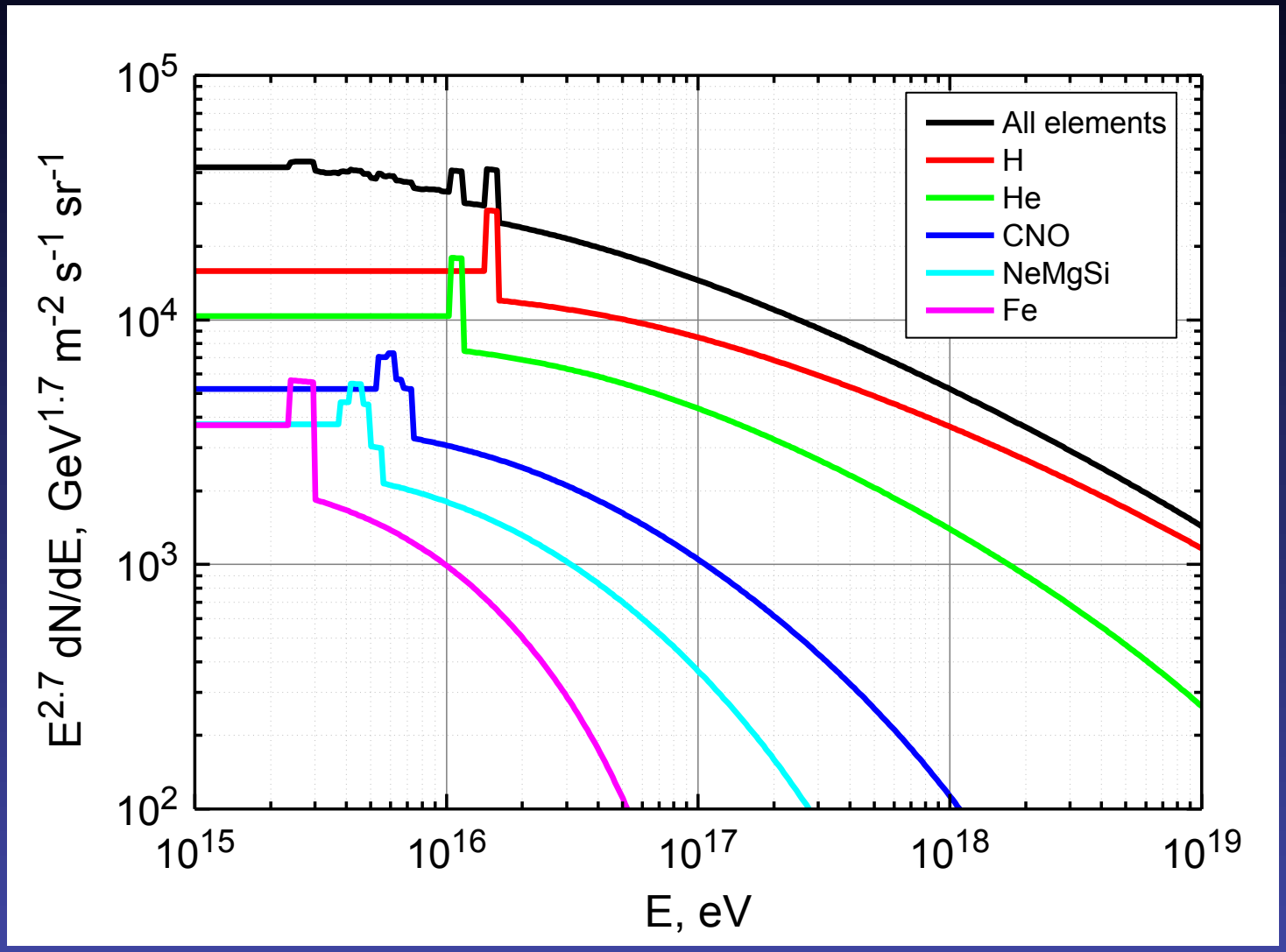
How measured composition is changed in frame of the new approach

Since for QGM production not only high temperature (energy) but also high density is required, threshold energy for production of new state of matter for heavy nuclei will be less than for light nuclei and protons.

Therefore heavy nuclei (e.g., iron) spectrum is changed earlier than light nuclei and proton spectra!!!

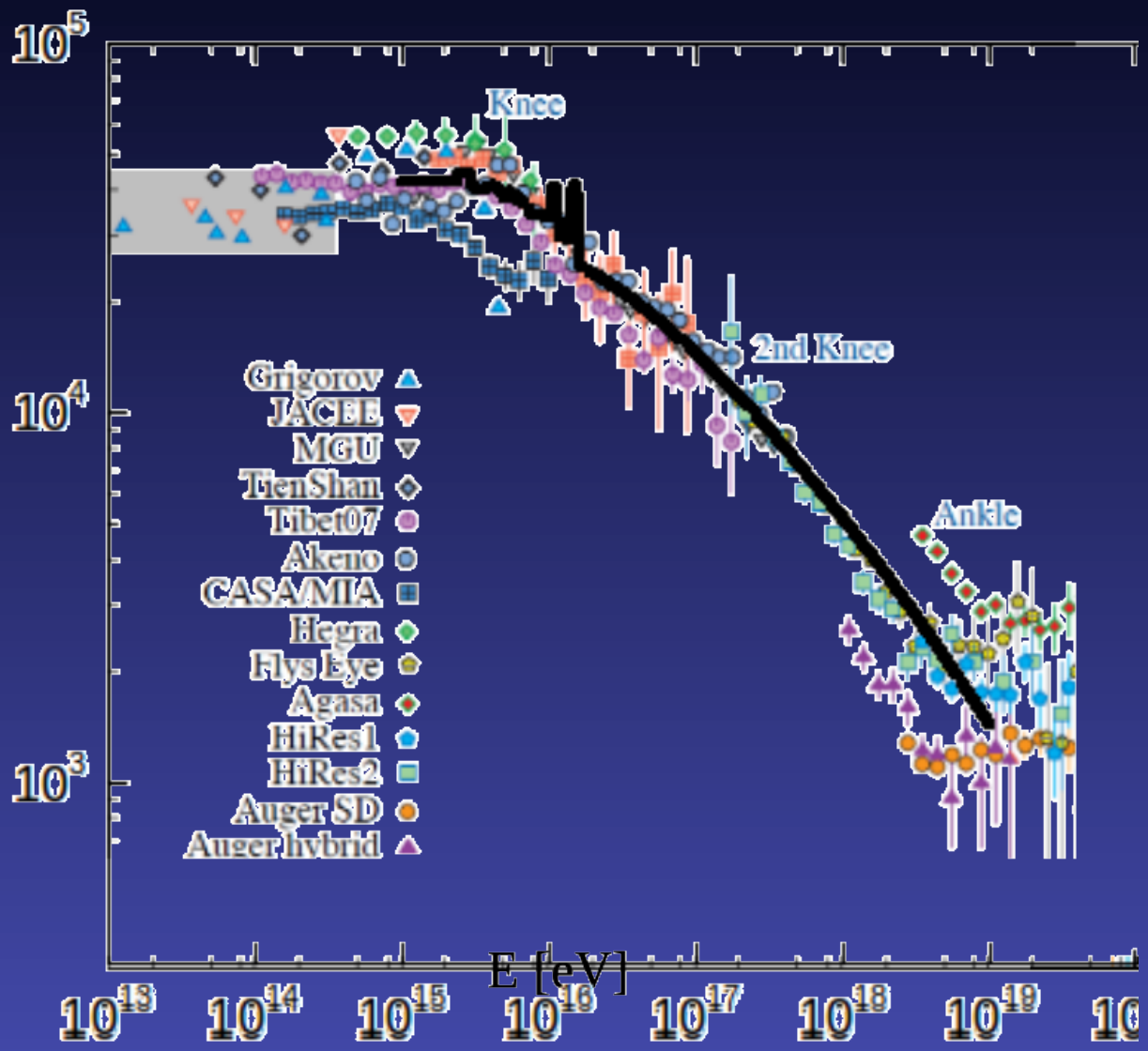
Measured spectra for different nuclei will not correspond to the primary composition!!!

Measured spectra for some nuclei and spectrum of all particles



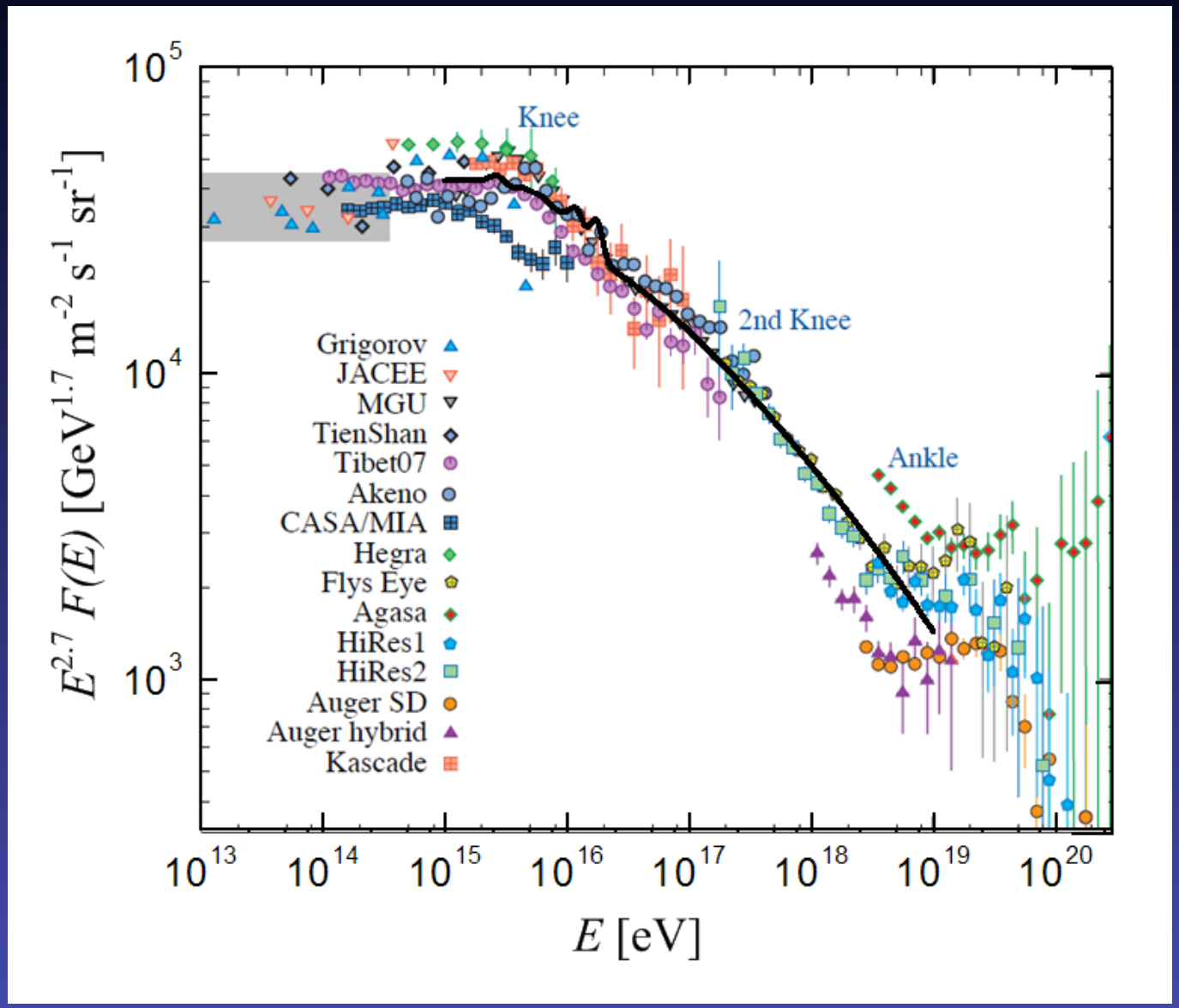
Comparison with experimental data

(without energy measurement straggling)

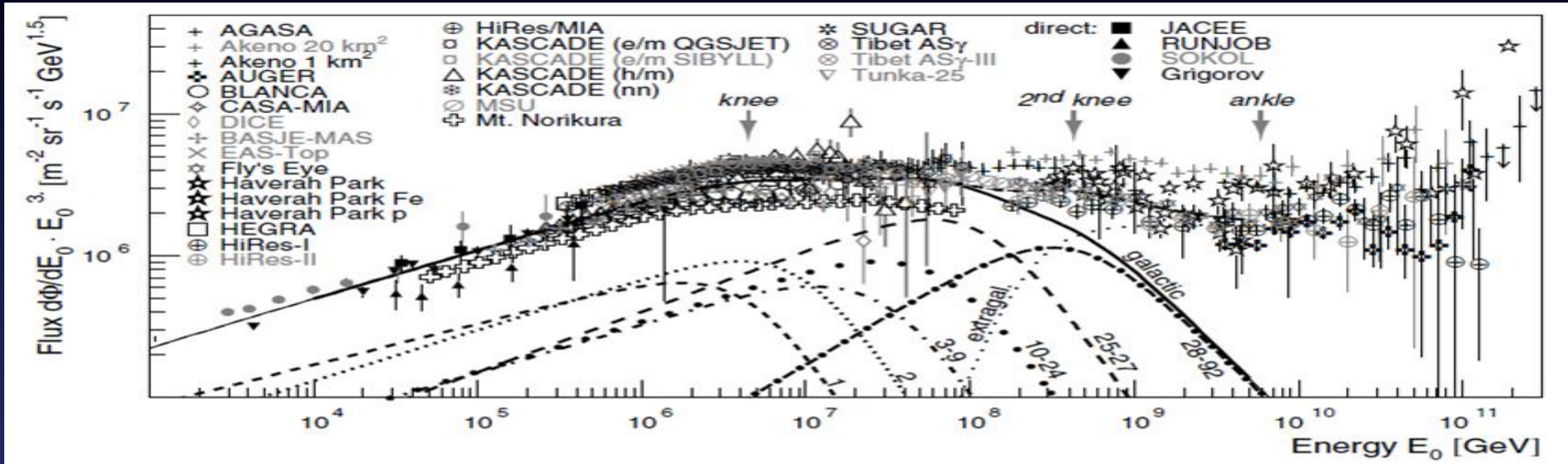


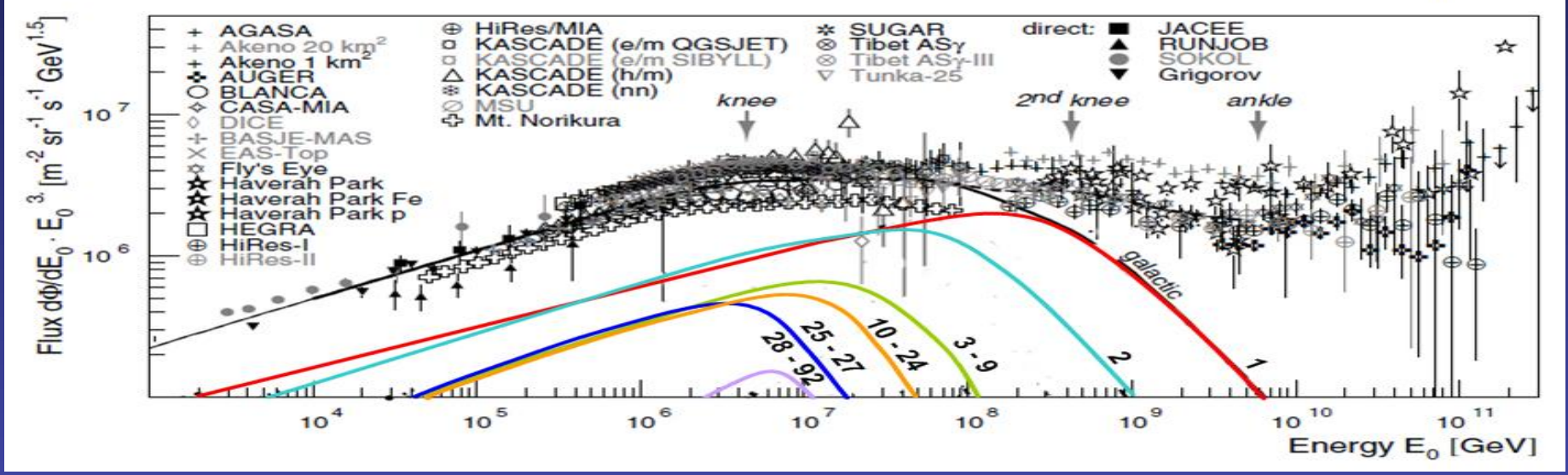
Comparison with experimental data

(with 10% energy straggling)



CR composition in two approaches





Discussion of results

1. Energy spectrum obtained in frame of this model surprisingly well describes experimental data.

2. Changes of measured composition are explained:
   - a sharp increase of the average mass at detection of EAS from heavy nuclei,
   - and then a slow transition to proton composition.

3. So-called “muon problem” (“muon puzzle”) is explained, too. Number of muons is increased not as a result of muon production in EAS initiated by heavy nuclei but through decays of massive particles into pions with large multiplicity.

How to check the new approach?

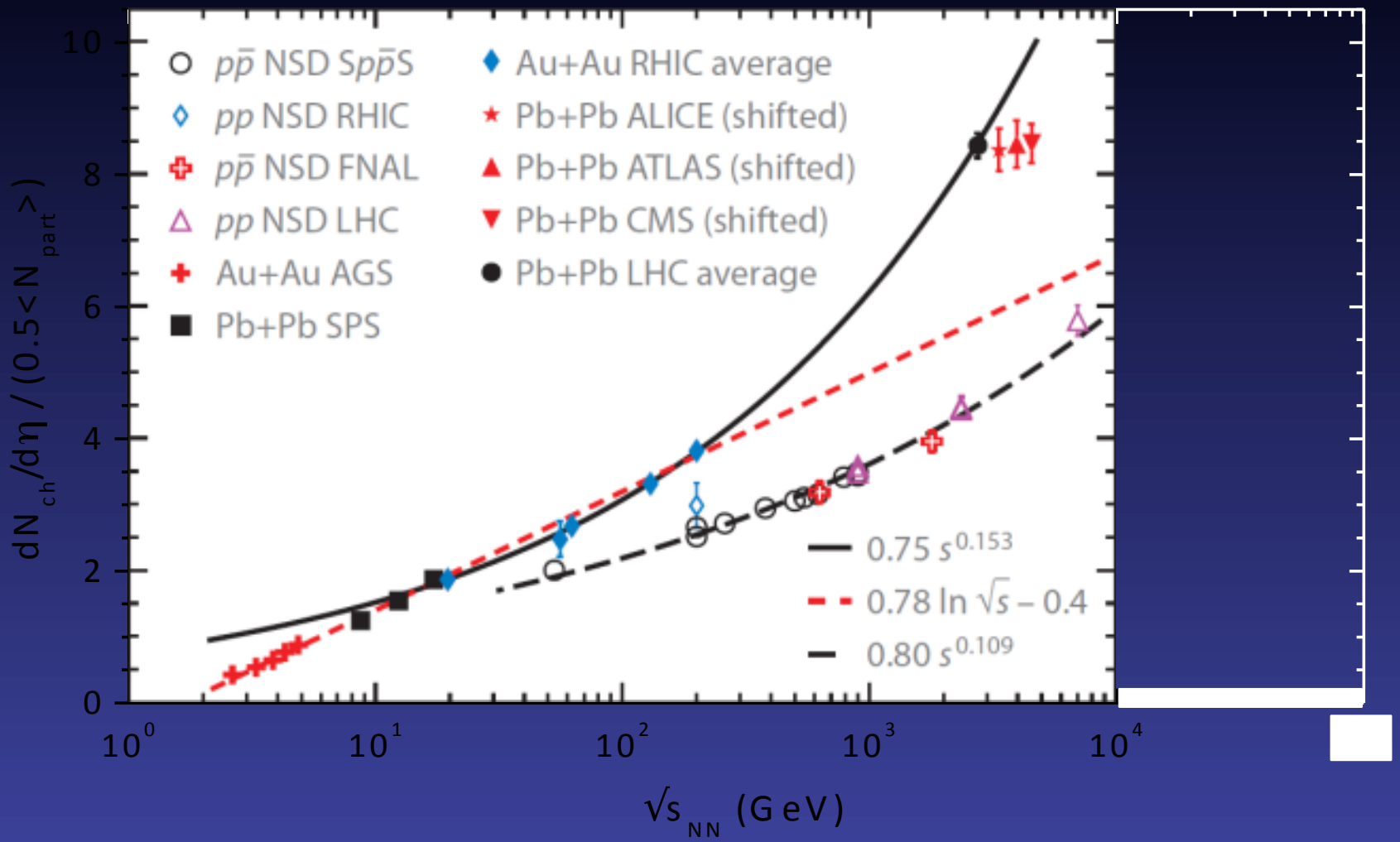
Possibilities to check the new approach in CR experiments:

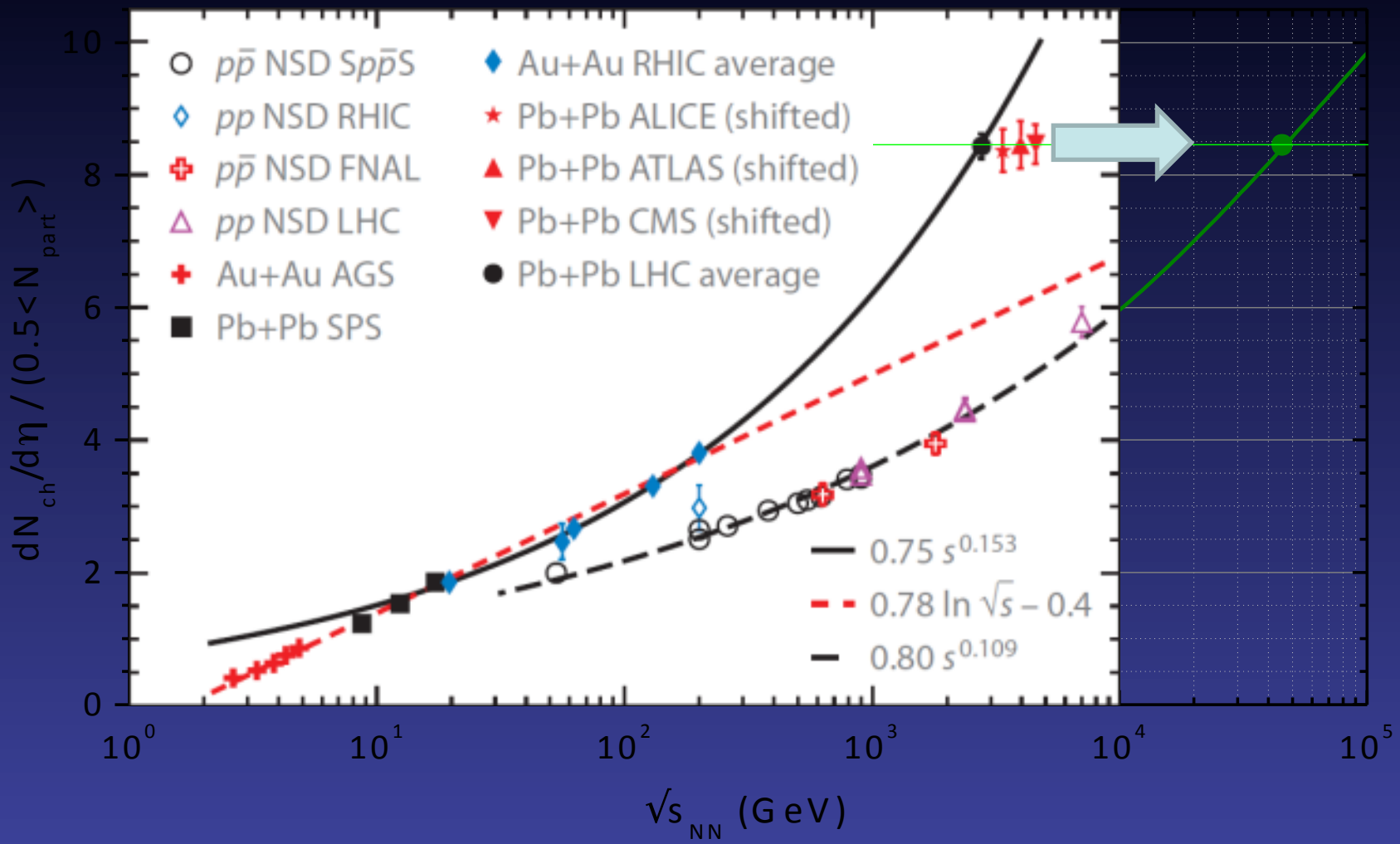
- study of the energy deposit of muon bundles (NEVOD);
- study of muon energy spectrum above 100 TeV (IceCube).

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 necessary to use *A-A* interactions (as in cosmic rays) but not *p-p*-interactions.

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


$p\bar{p}$ 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
$0.75\ s^{0.153}$
$0.78 \ln \sqrt{s} - 0.4$
$0.80\ s^{0.109}$
$dN_{ch}/d\eta\ /\ (0.5 < N_{part} >)$
$\sqrt{s_{NN}}$ (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
$0.75\ s^{0.153}$
$0.78 \ln \sqrt{s} - 0.4$
$0.80\ s^{0.109}$
$dN_{ch}/d\eta\ /\ (0.5 < N_{part} >)$
$\sqrt{s_{NN}}$ (GeV)
0
2
4
6
8
10
10^0
10^1
10^2
10^3
10^4
10^5

A remark about QGP blob size

In usual interpretation the experimental point corresponds to $\sqrt{S_{NN}} \approx 3$ TeV (for *A-A* interaction).

In frame of the new model $\sqrt{S}$ must be larger.

If to take into account that $\sqrt{S}$ in *A-A* interactions cannot be more than $\sqrt{S_{NN}}$ for pp-interaction, it is possible to evaluate the upper limit for the number of nucleons in QGM blob.

For *Pb-Pb*-interaction $$\sqrt{n_N} < \frac{40-45 \ \ \text{TeV}}{3 \ \ \text{TeV}} \approx 14$$

It means that up to half of total number of nucleons (n ~ 200) can be included in a blob of QGM.

Conclusion

The considered approach to interpretation of results of EAS measurements allows to solve problem of primary cosmic ray energy spectrum and mass composition changes and to explain all unusual events.

Possibilities of searching of a new state of matter exist:

in LHC: measurements of excess of t-quarks and W-bosons;

in CR: study of the energy deposit of muon bundles (NEVOD) and muon energy spectrum above 100 TeV (IceCube).

I hope that unique possibility to prove the existence of a new state of matter in CR before accelerators will be realized!

Small remark to the conclusion

Some excess of W-bosons (~ 30 %) in p-p interactions by ATLAS and CMS was already observed:

- *ATLAS Collaboration, arXiv: 1210.2979:*
- *CMS Collaboration, arXiv: 1301.4698.*
- *CMS Collaboration, arXiv: 1306.1126.*

But cross section of the order of pb was measured.

In frame of the new model, its value in A-A interactions must be of the order of mb.

Thank you!

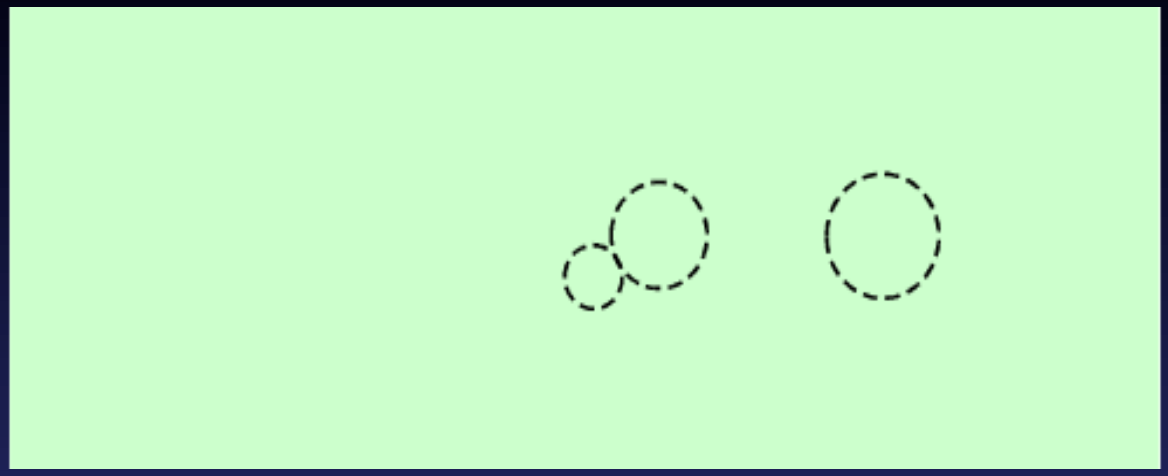
Cosmic ray composition

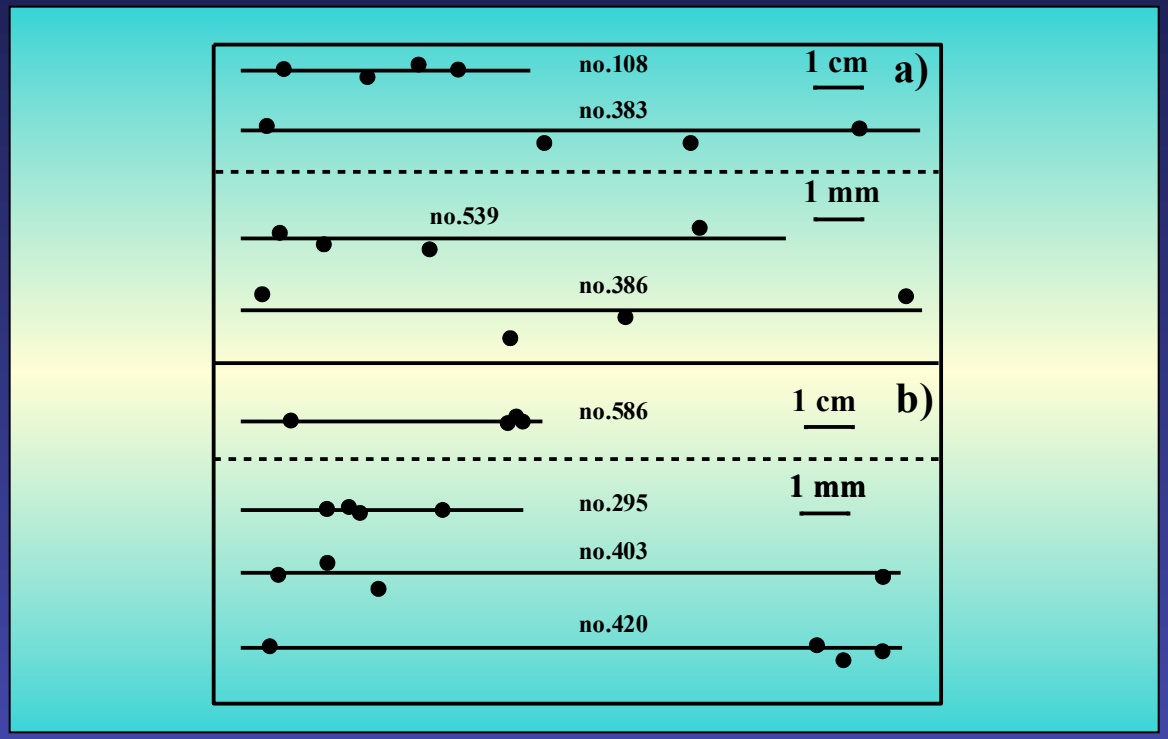
- Composition of CR at low energies:

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 %*

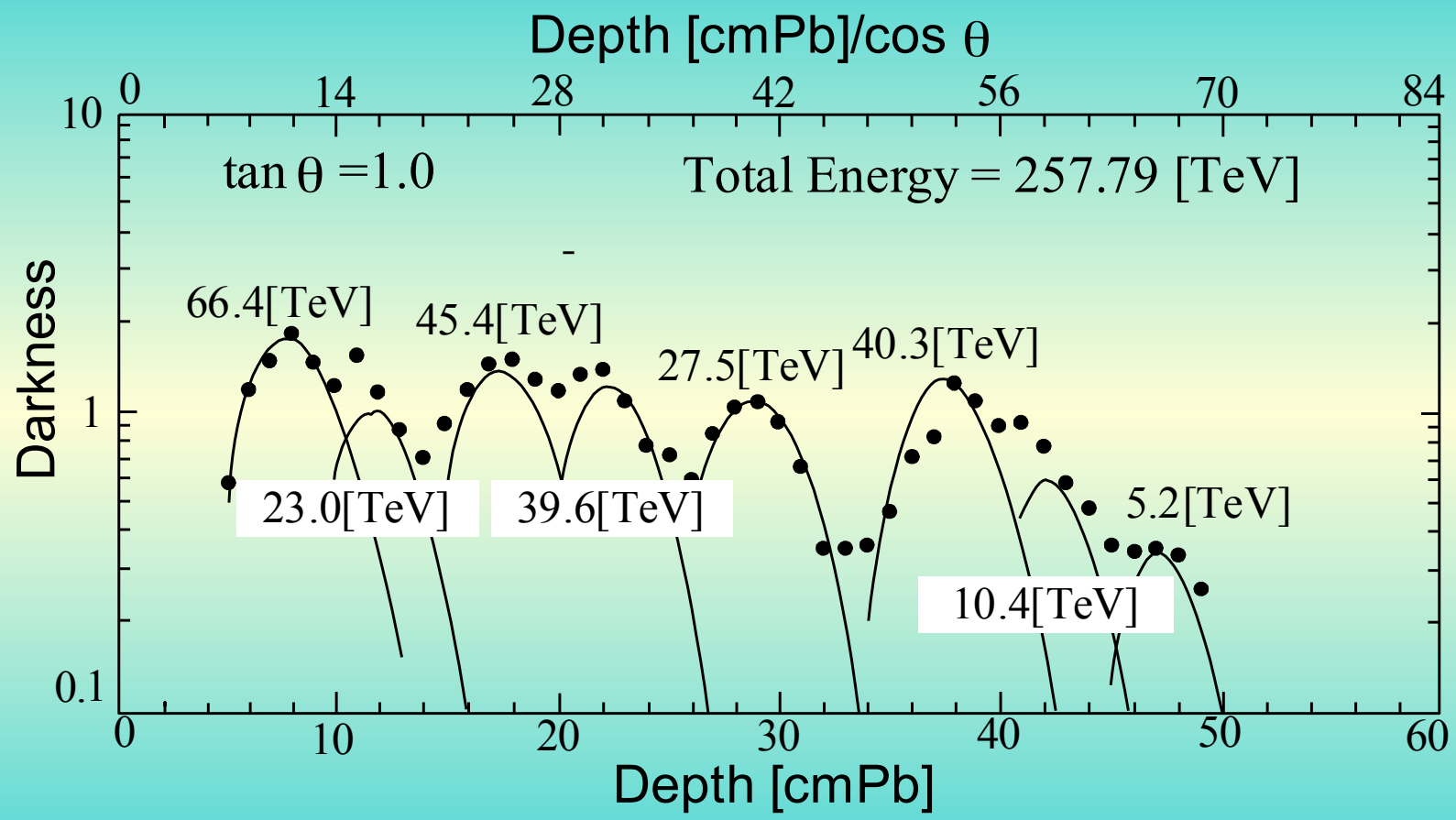
With increasing CR primary energy ratio of nuclei to protons is increased too. Thus in CRs we investigate mainly interactions of nuclei with nuclei. And namely in interactions of CR nuclei with nuclei of air (oxygen and nitrogen) many unusual events and phenomena are observed.

Halo and alignment

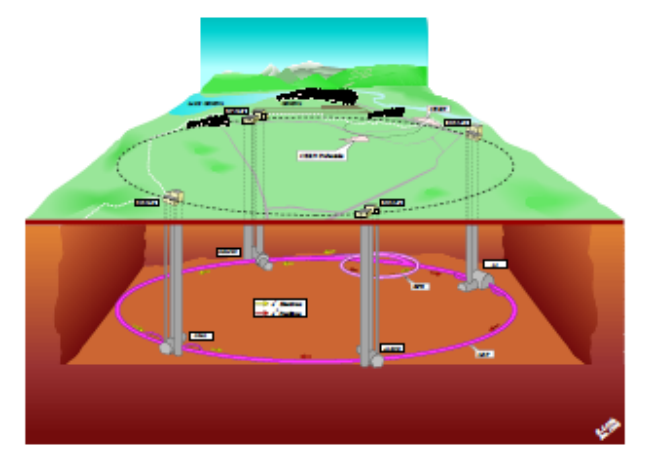


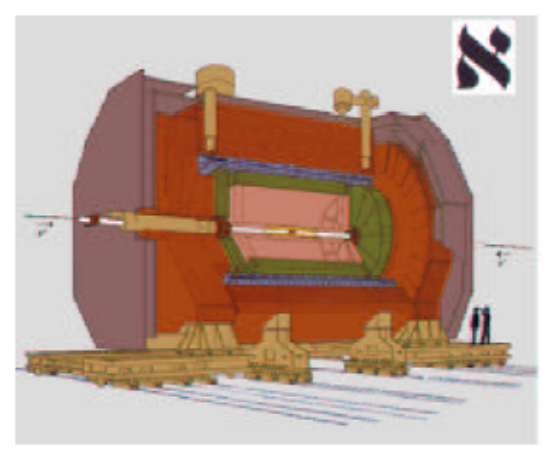


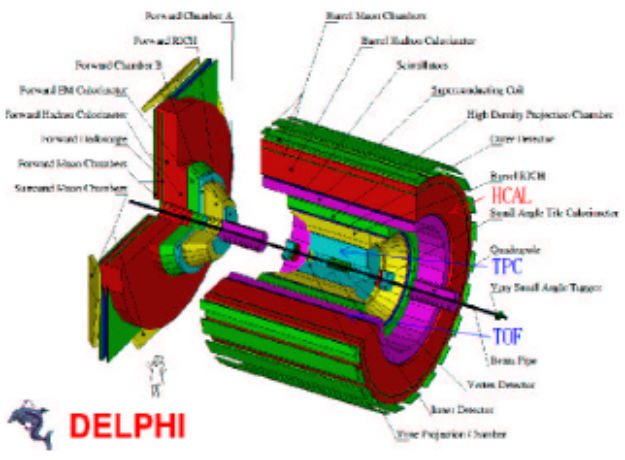
Penetrating cascades

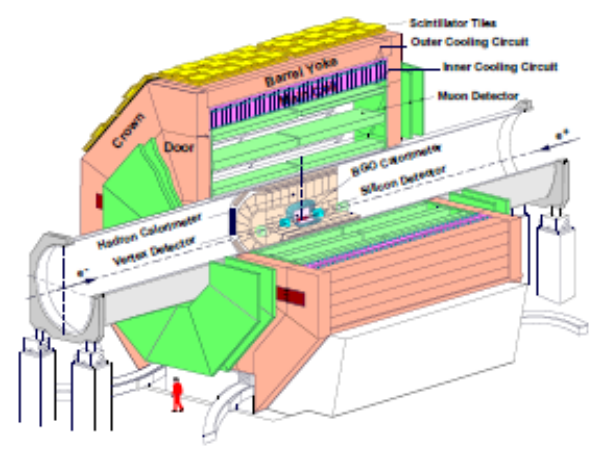


LEP Detectors (CERN)









ALEPH

130 m depth (E_μ > 70 GeV)
Hadron calorimeter, TPC
5 scintillator stations

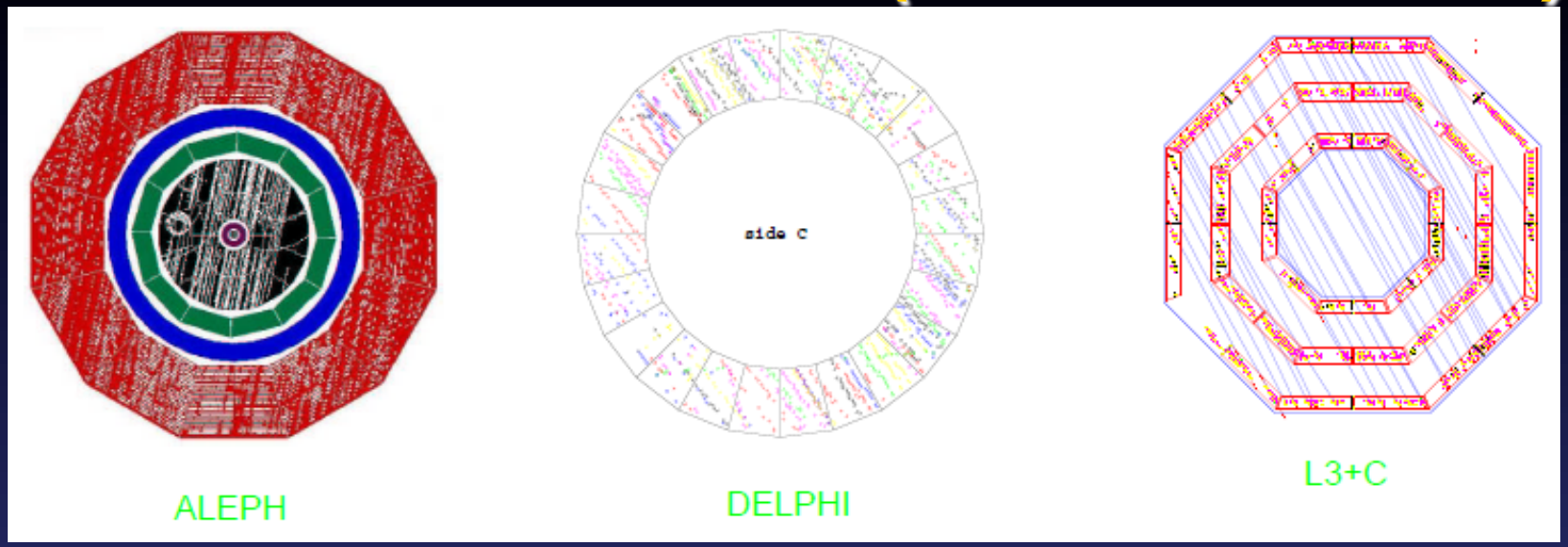
DELPHI

100 m depth (E_μ > 50 GeV)
Hadron calorimeter, TPC, TOF

L3

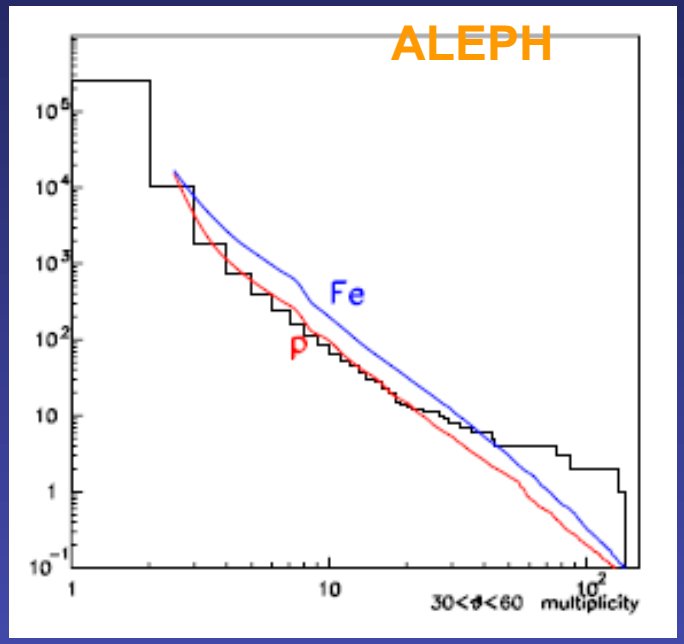
40 m depth (E_μ > 15 GeV)
Drift chambers, timing scintillators, surface EAS array

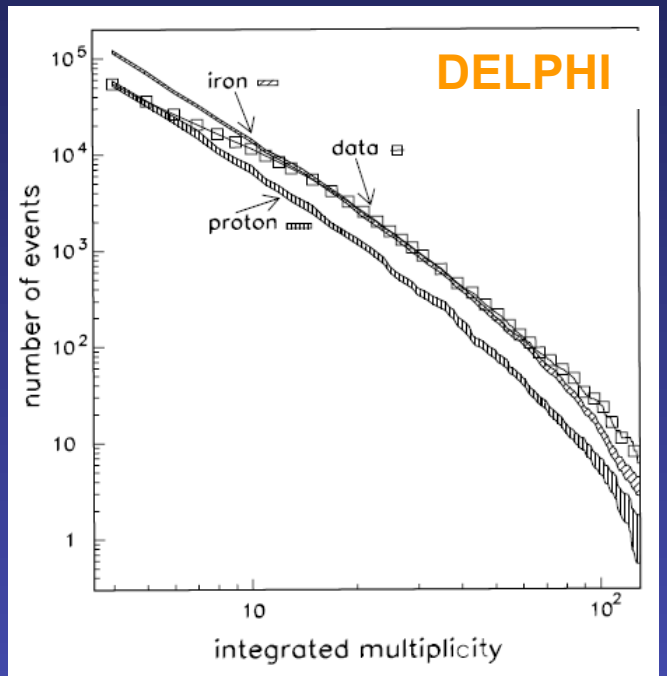
Multi-muon events (muon bundles)



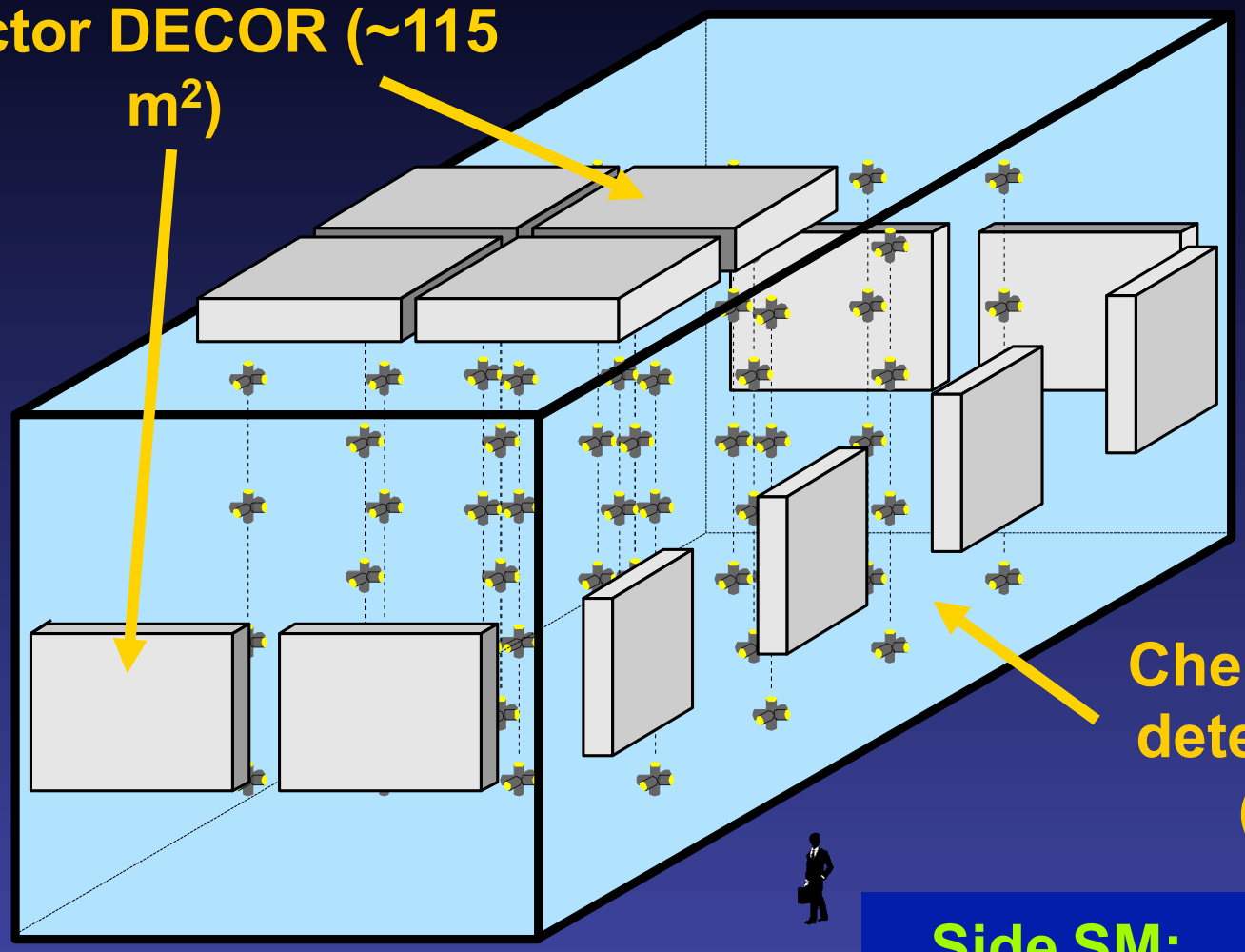
C. Grupen et al., Nuclear Physics B (Proc. Suppl.) 175-176 (2008) 286.

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





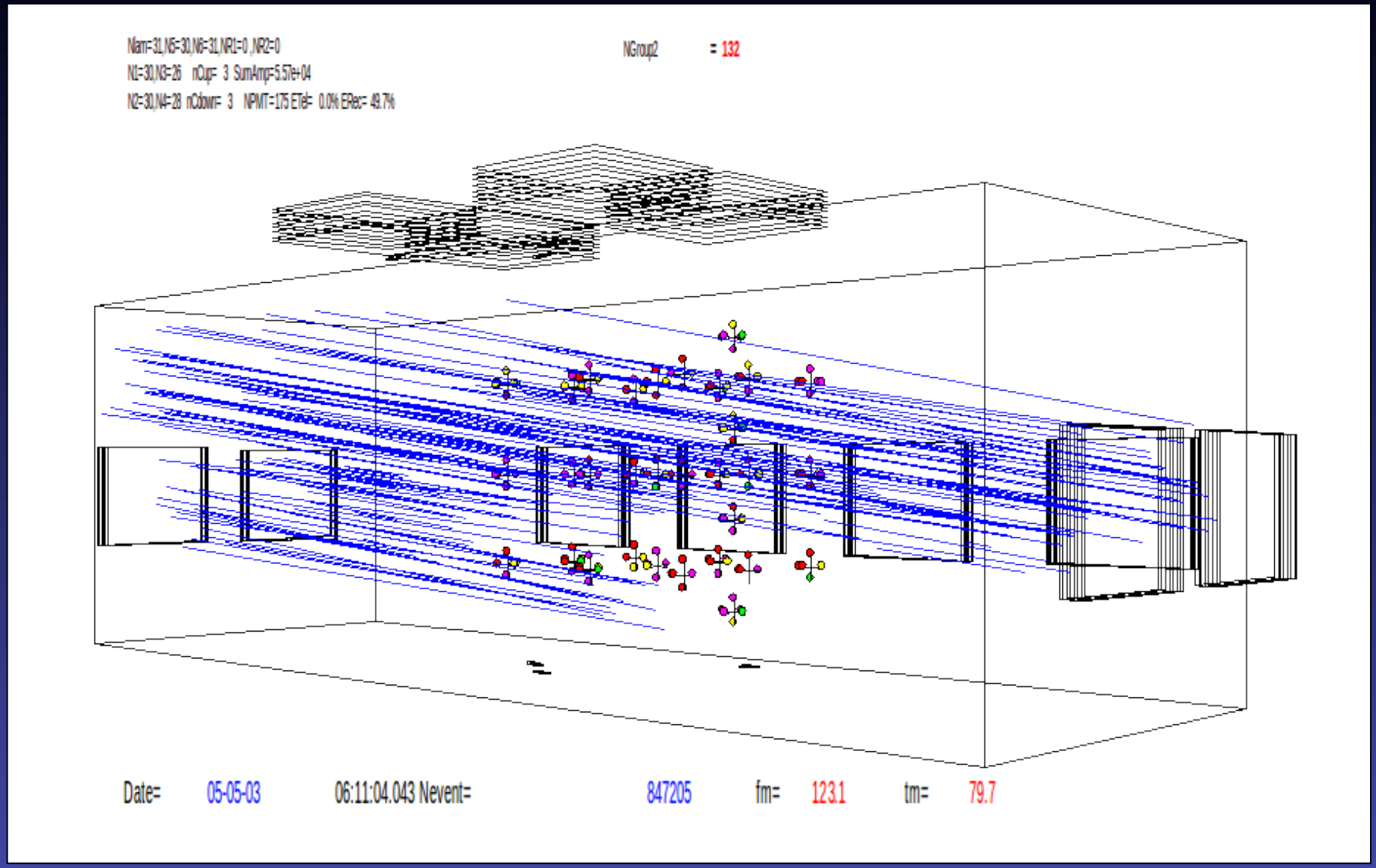
General view of NEVOD-DECOR complex



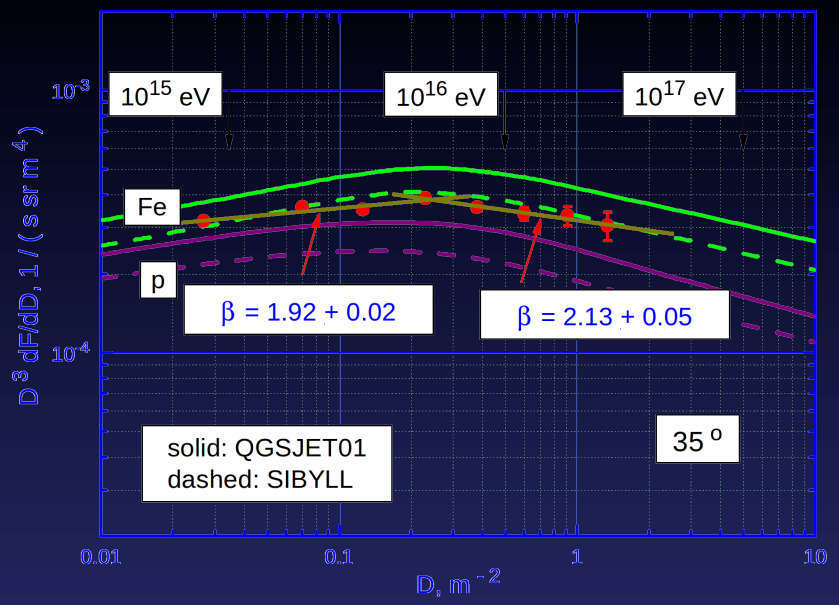
Side SM: 8.4 m^2 each

- $\sigma_x \sim 1$ cm; $\sigma_\psi \sim 1°$

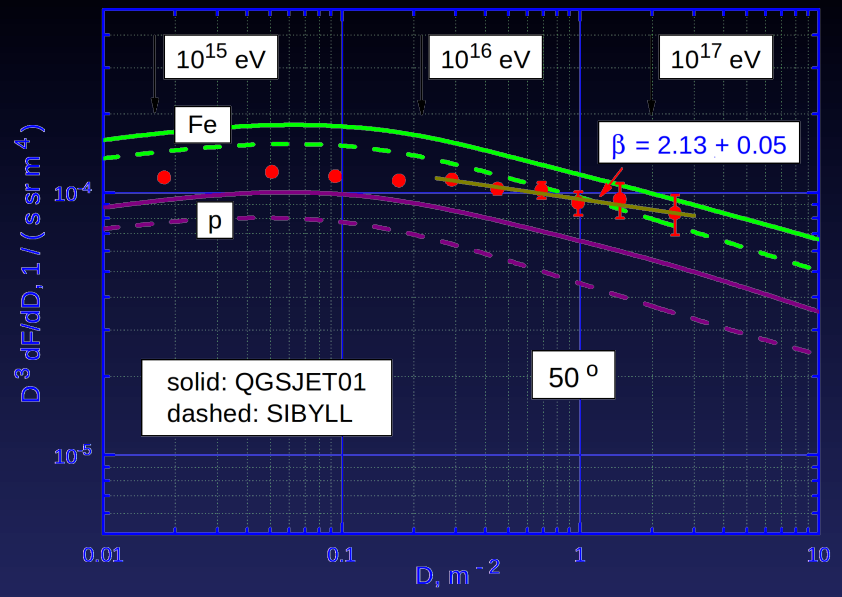
Muon bundle event (geometry reconstruction)



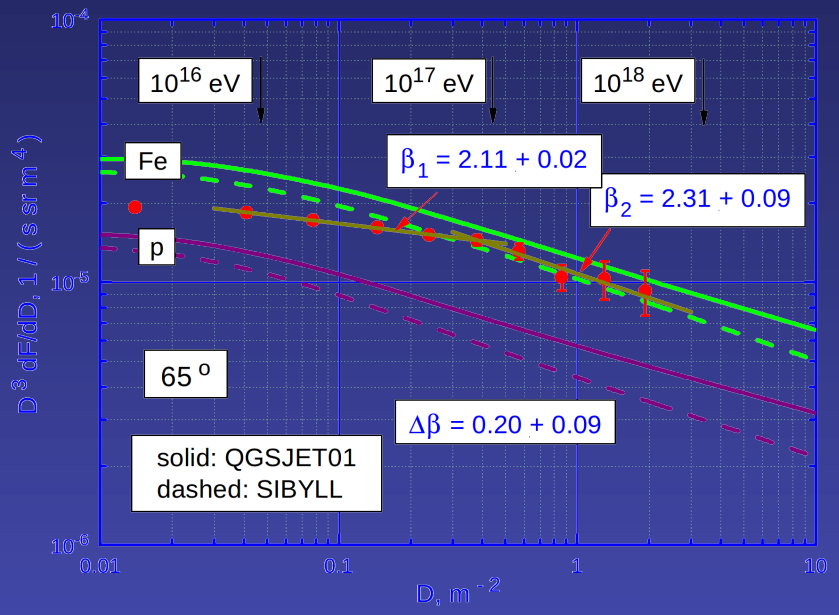
Low angles: around the “knee”



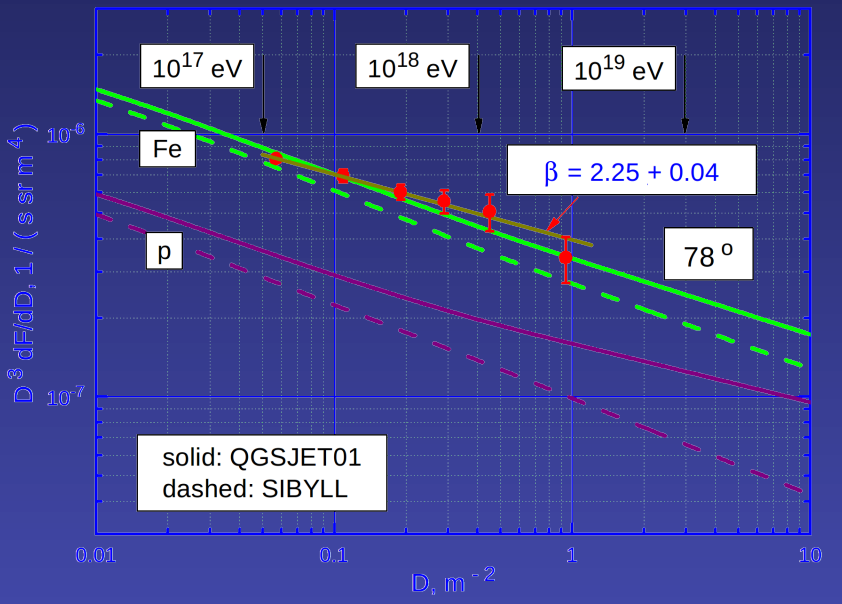
θ = 50° : 10^{15} – 10^{17} eV

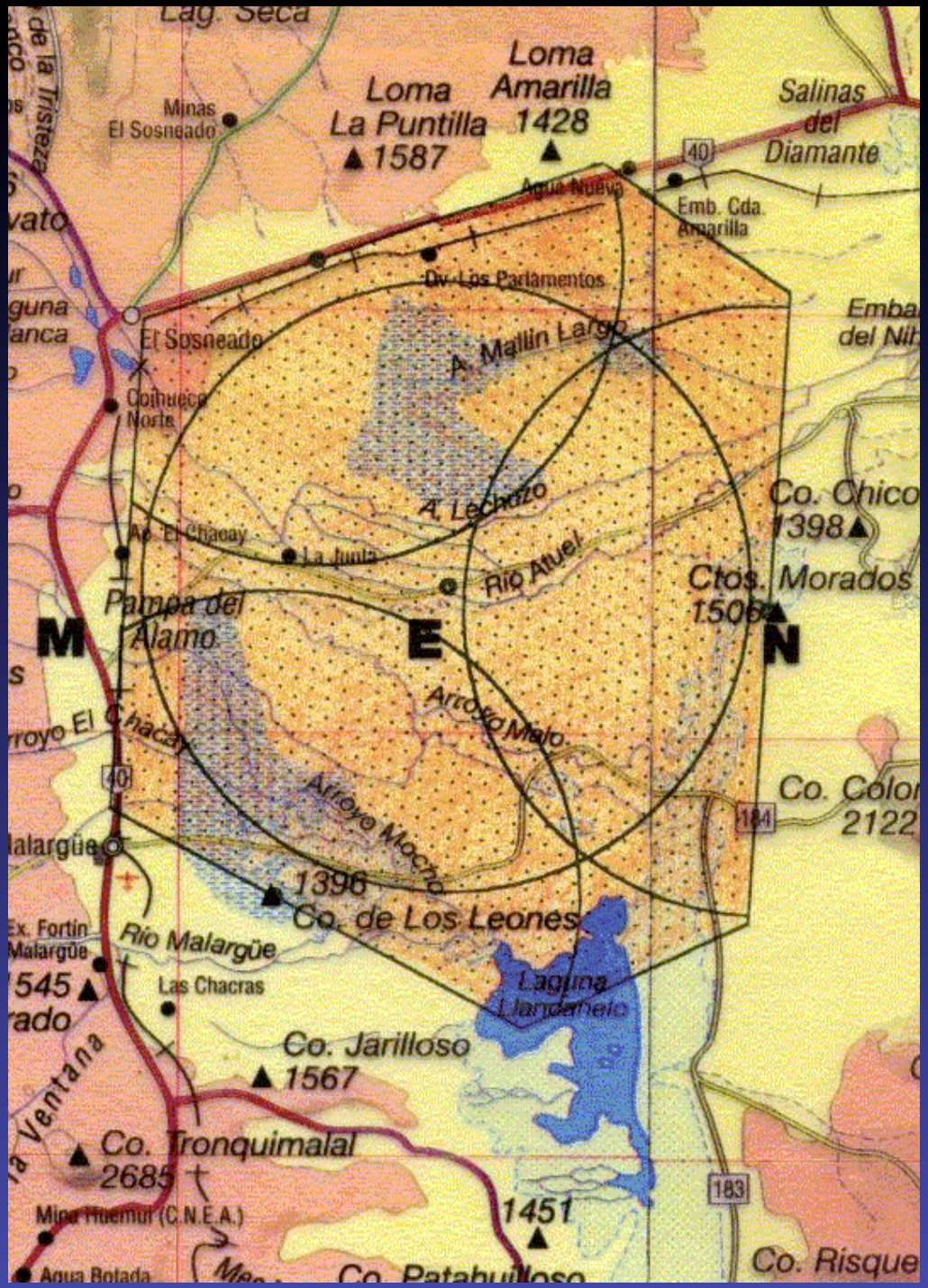


θ = 65° : 10^{16} – 10^{18} eV



Large angles: around 10^{18} eV





Pierre Auger Observatory

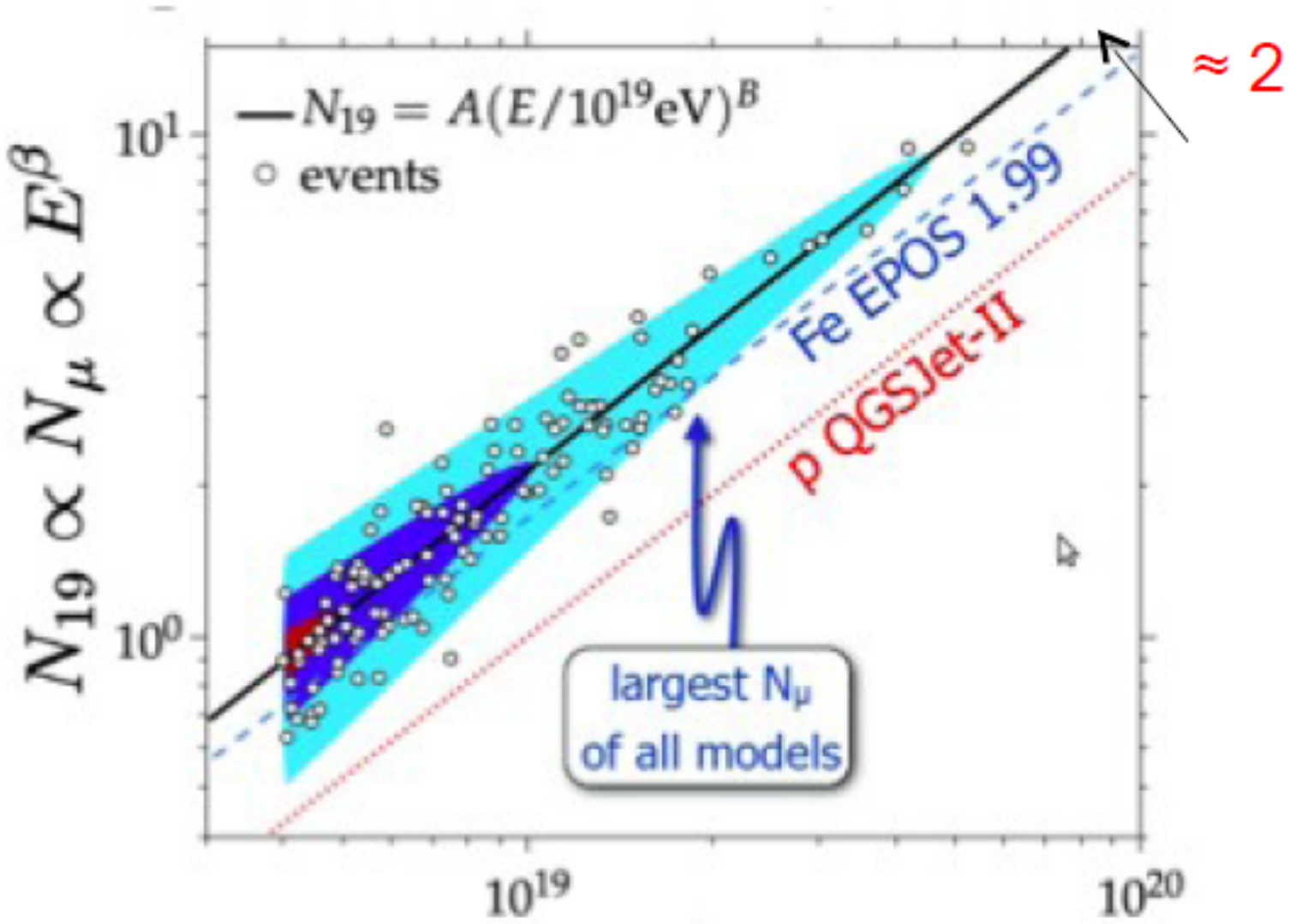
Area - 3000 km^2

Number of detectors - 1600

Detector size - 12 m^3

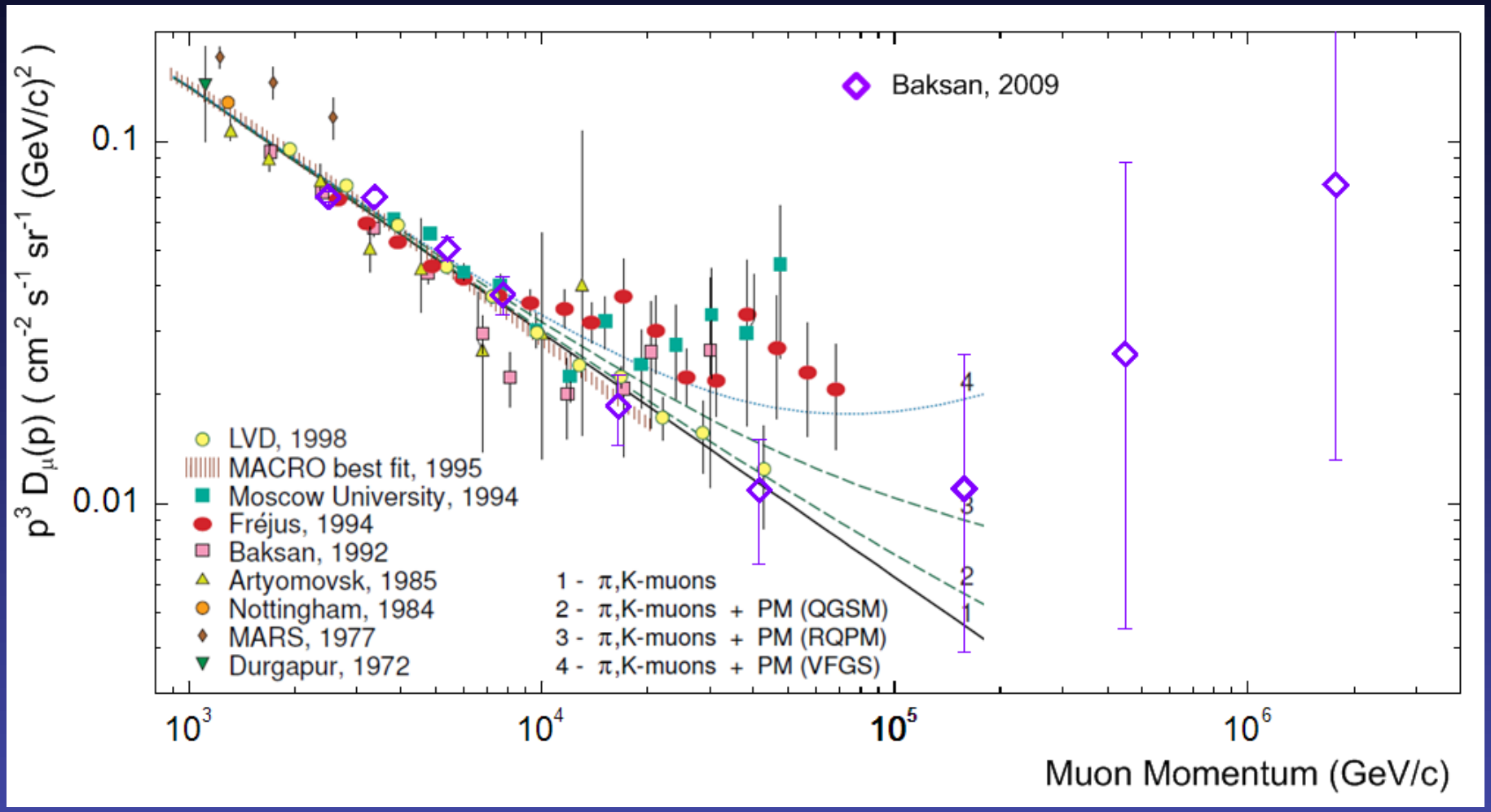
The distance between detectors - 1500 m.

Muons in Auger

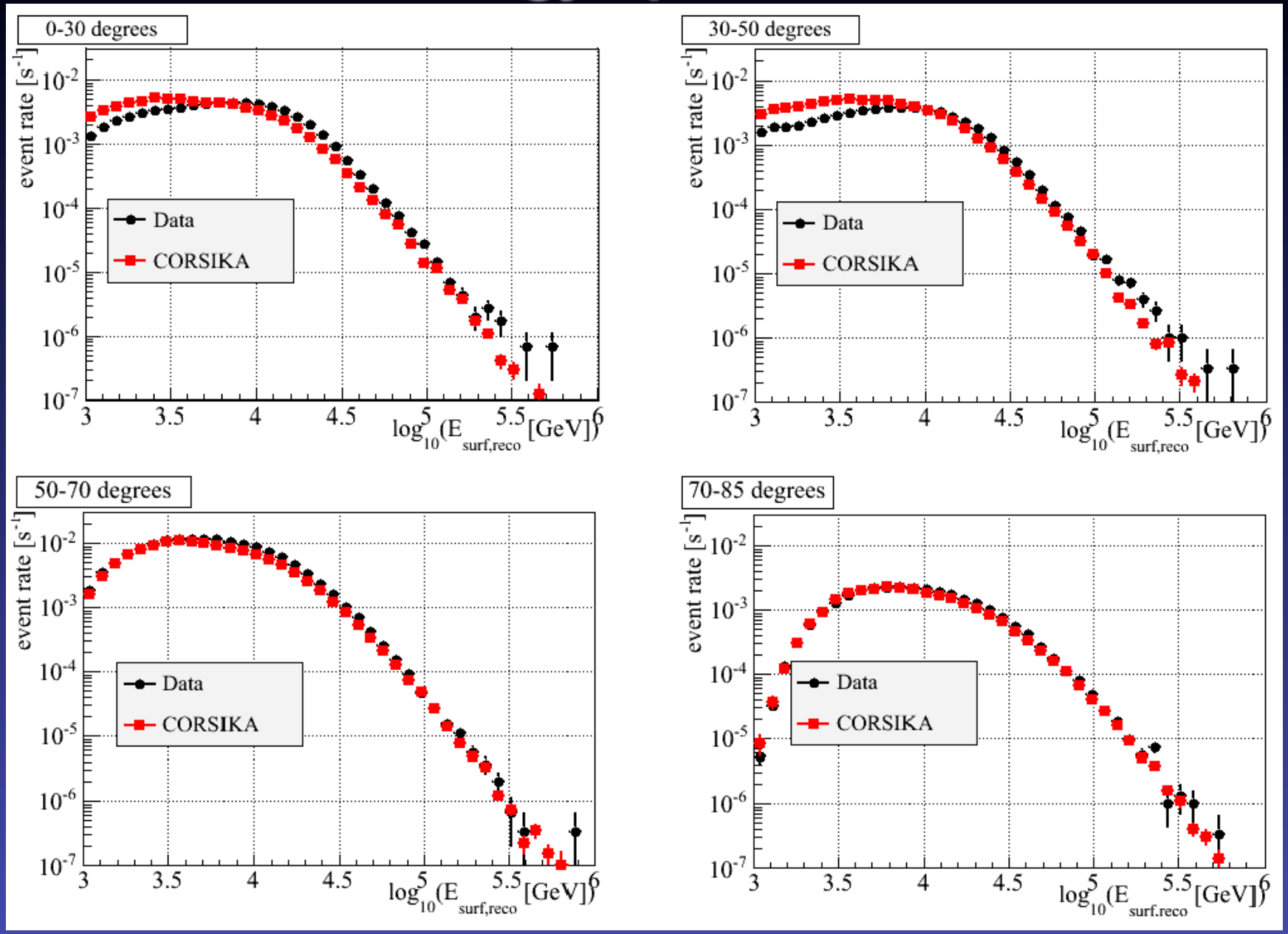


Results of muon energy spectrum investigations in Baksan Underground Scintillation Telescope (BUST)

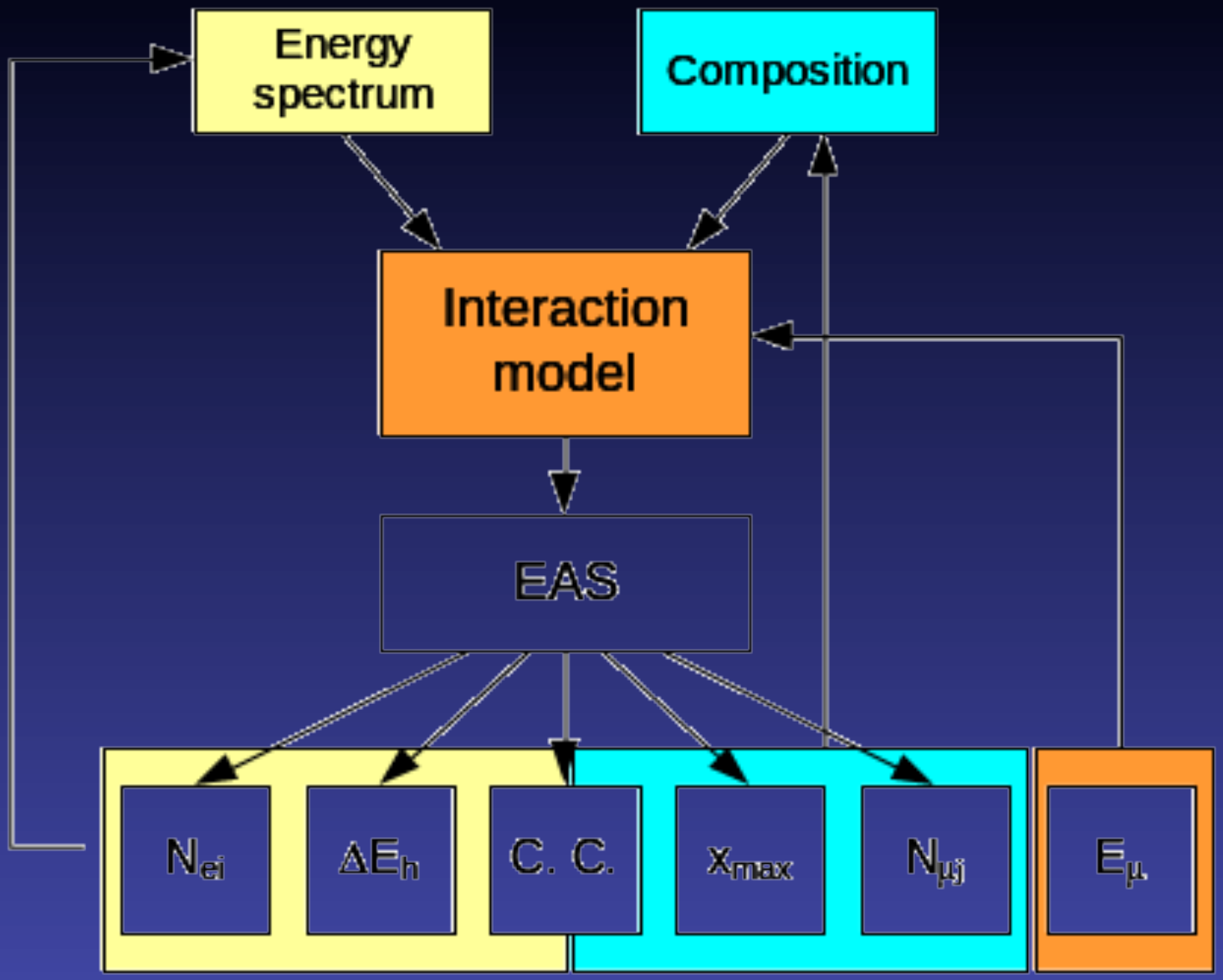
Astroparticle Physics, 2012, 36, 224-236.



Muon energy spectrum - 2011

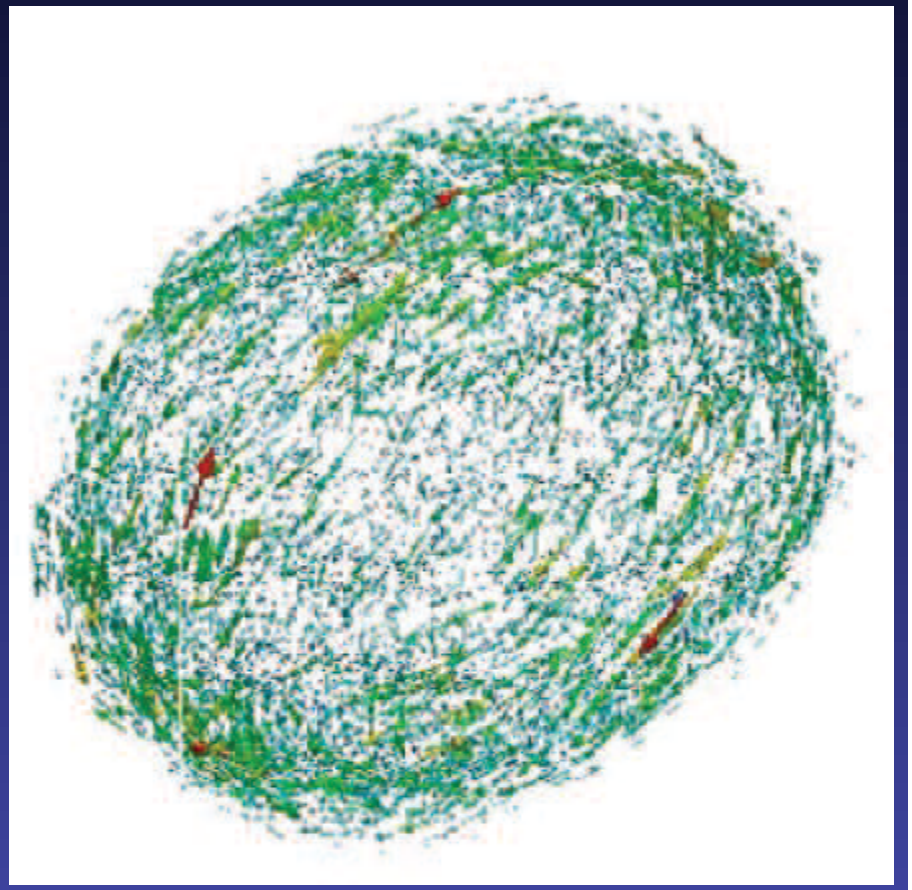


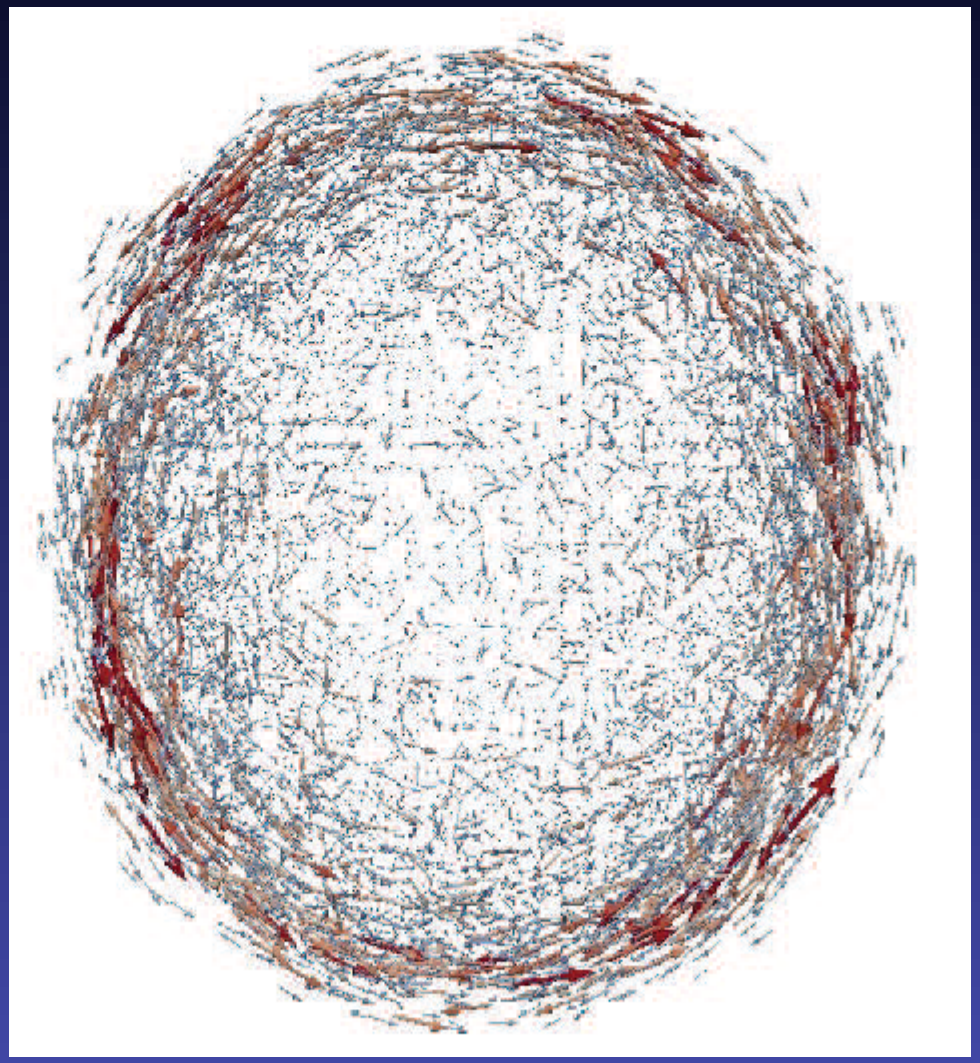
New approach to EAS analysis



Helicity separation in Heavy-Ion Collisions

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





Relation between primary energy E_1 and measured energy E_2

$$E_2 = \frac{\left[\sqrt{2m_c E_1} - \varepsilon_t\left(E_1, A_i\right)\right]^2}{2m_c}$$

where ε_t is total energy of top-quarks in the center-of-mass system.

Threshold energy E_{th}, above which QGM blobs are produced, is determined by nucleus mass number A_i.

In principle, compound mass m_c may depend on A_i and E_1 , too.

Simplest model

$$\varepsilon_t = 4m_t\sqrt{\frac{E_1}{E_{th}}}\ln\left(1.7+\frac{E_1}{E_{th}}\right)$$

where ln takes into account the increase of the top-quark multiplicity and square root provides transition into the center-of-mass system.

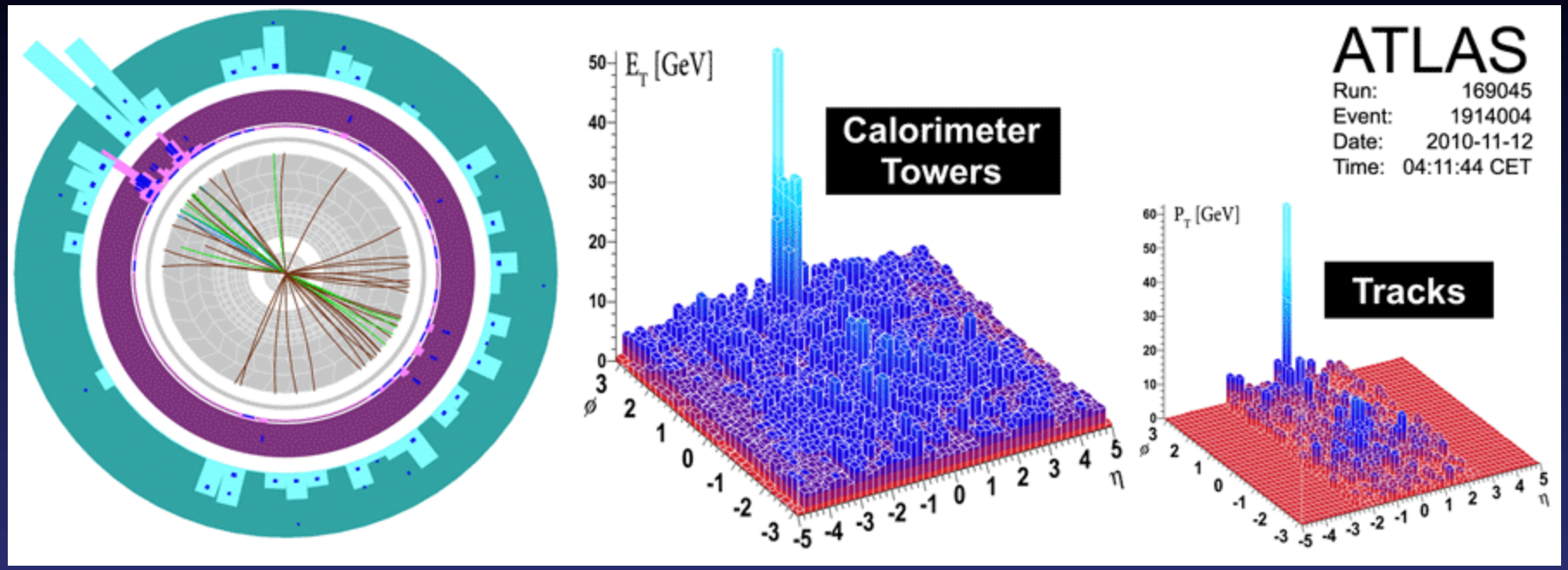
$$E_{th} = m_c 10^6\left(\frac{56+n}{A_i+n}\right)^{2/3}, \ \text{GeV}$$

m_c = constant = nm_N. $n = 4$

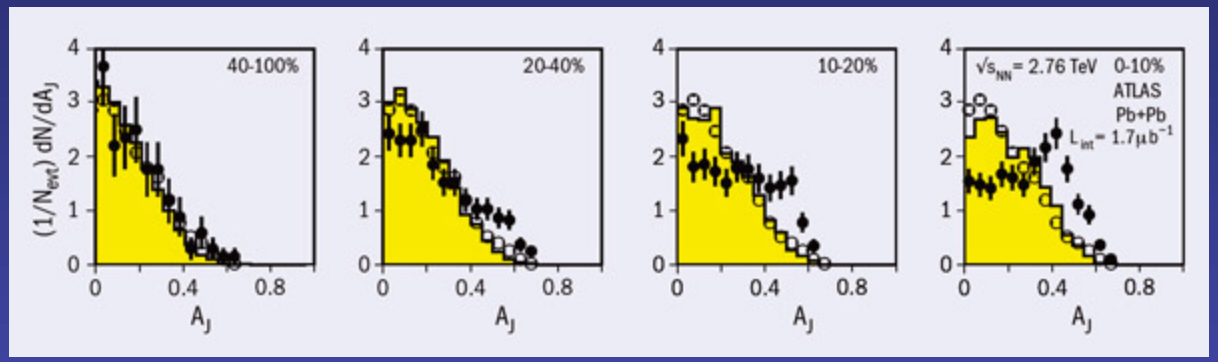
Spectrum $dN/dE = N_0 E_1^{-(\gamma+1)}$ *without the knee is calculated, but obtained values are related to energy* E_2.

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?

$$t \rightarrow W + b$$

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 $W \rightarrow \sim 20\ \pi$, the ATLAS experiment's picture will be obtained.