Vulcano 2016

TeV energy physics at LHC and in cosmic rays

Anatoly Petrukhin

National Research Nuclear University
MEPhI (Moscow Engineering Physics Institute), Russia

Many physicists dream and hope to find a new physics at TeV energies.
However this new physics can be not so new, but unusual.
In my talk I would like to discuss one of such possibilities.

Introduction

TeV energy region in the center-of-mass system is investigated:

- in CR more than 50 years; - at LHC more than 5 years.

LHC interval of energies 1 -14 TeV corresponds to the energy interval of CR $10^{15} – 10^{17}$ eV for *p*-*p*-interactions.

CR consist of nuclei (~ 60%) and protons (~ 40%) at energies < 10^{15} eV. At higher energies, the fraction of protons decreases.

In CR and LHC experiments some deviations from existing models of interaction were observed.

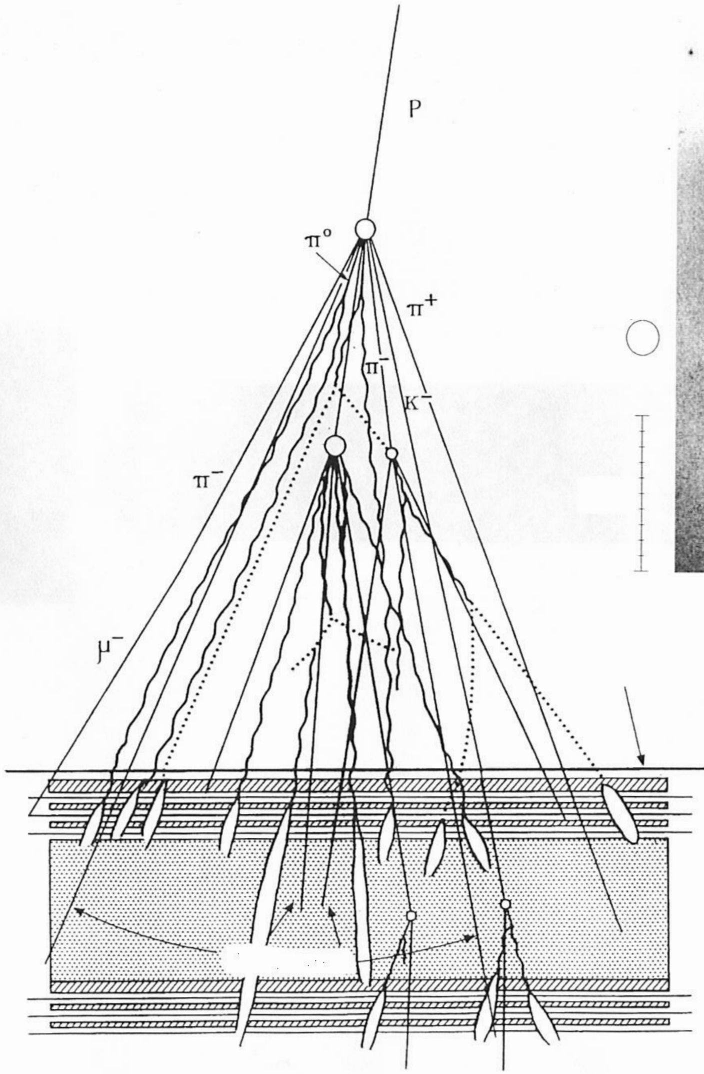
The purpose of my talk is to compare these results and to discuss possible their explanation.

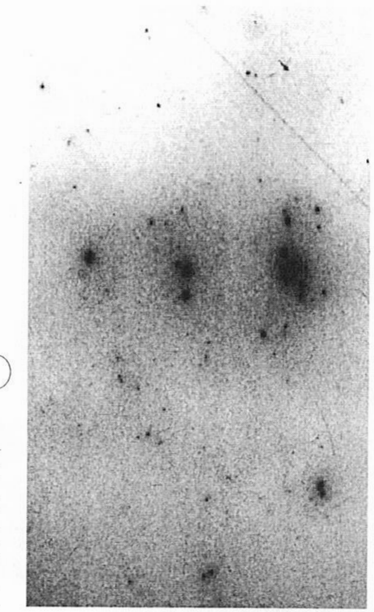
List of unusual events in CR

- In **hadron** experiments (mainly in Pamir experiment):
  - Halos,
  - Alignment,
  - Penetrating cascades,
  - Centauros.
- In **muon** experiments:
  - Excess of muon bundles (so-called "muon puzzle"), which was observed as at CR so at accelerator detectors.
- In **EAS** investigations:
  - Increase of energy spectrum slope.
  - Changes in N_μ / N_e - ratio dependence.

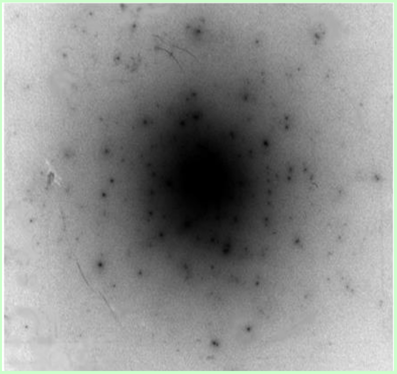
Important: Unusual events appear at PeV energies of primary particles (at TeV energies in the center-of-mass system).

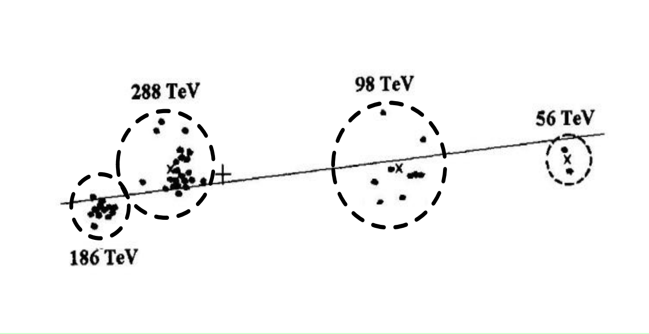
Pamir Experiment

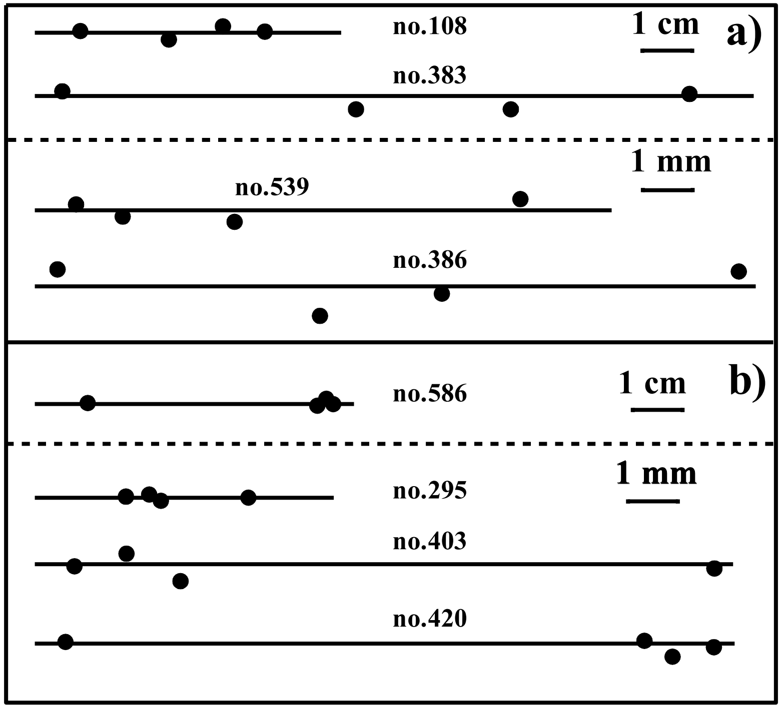




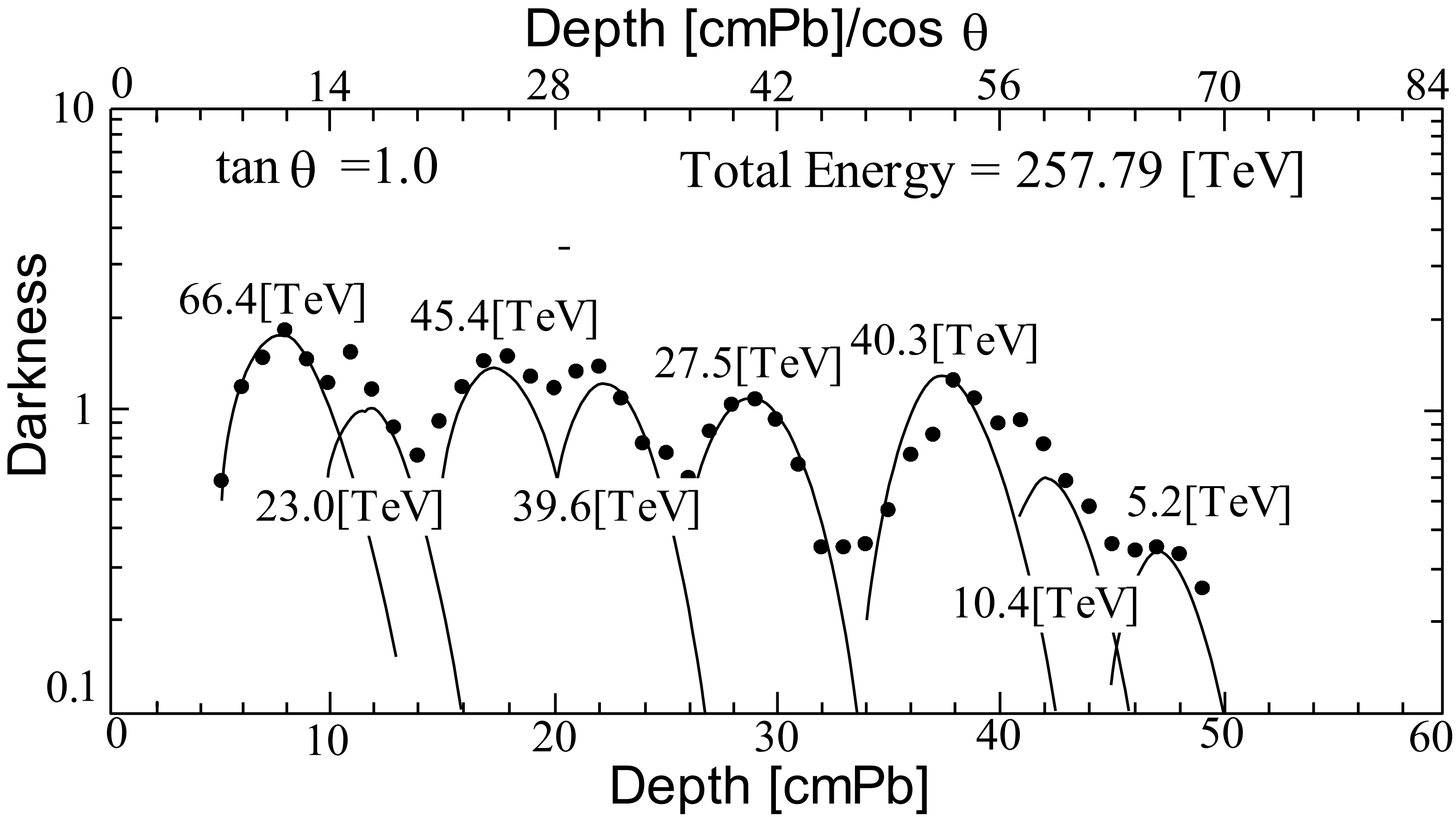
Halo and alignment





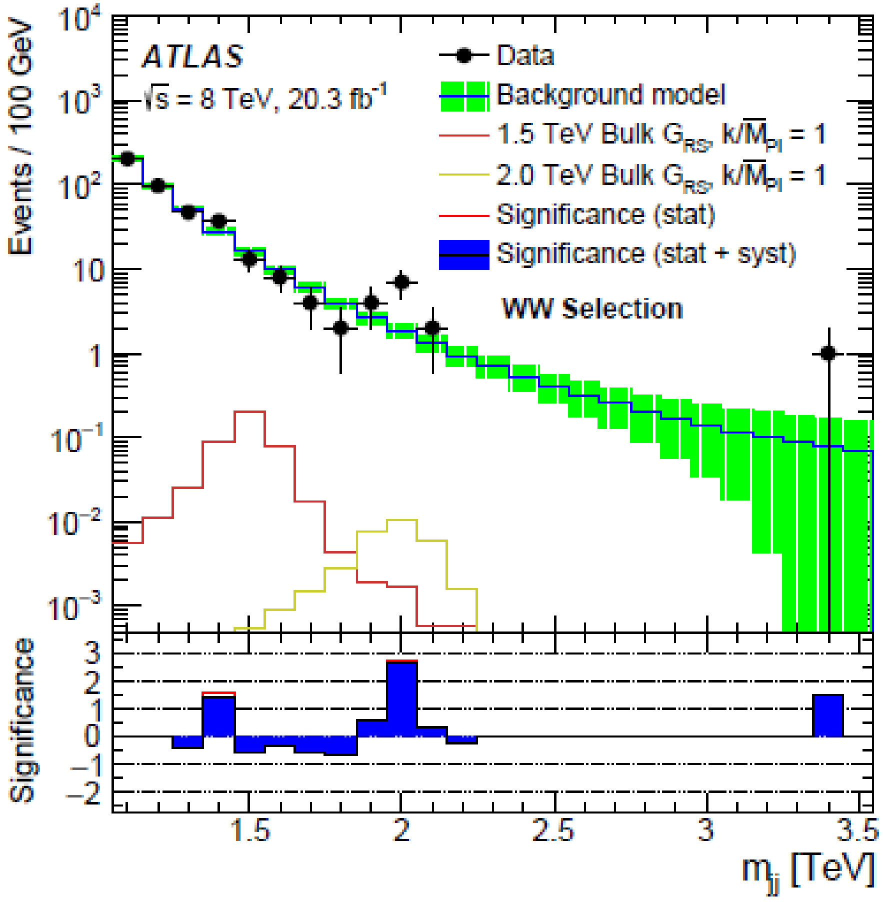


Penetrating cascades



2 TeV mass resonance in ATLAS

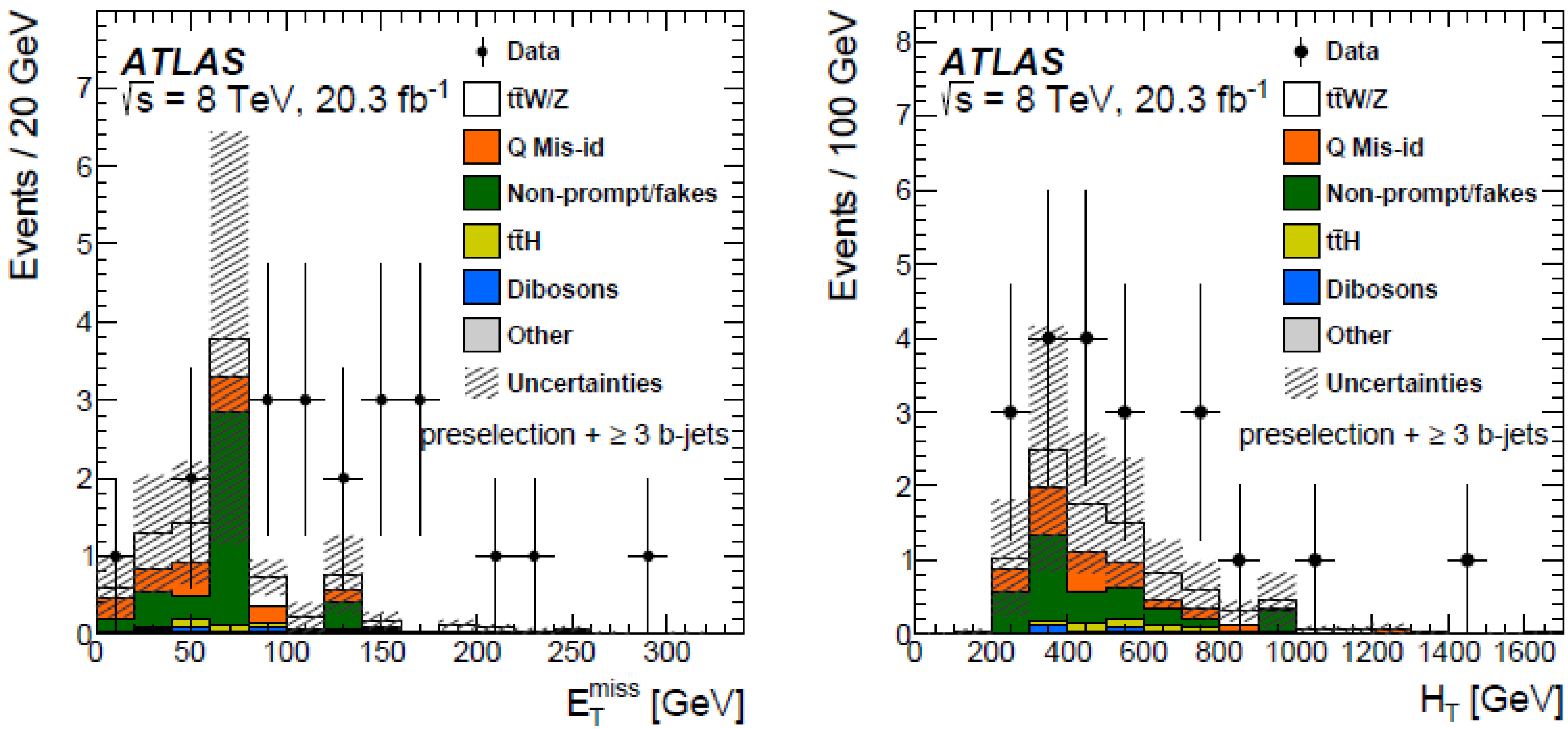
Search for high-mass diboson resonances with boson-tagged jets in proton-proton collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector, arXiv:1506.00962v3 [hep-ex] 22 Jan 2016



Background-only fits to the dijet mass (m_{jj}) distributions in data after tagging with the *WW* selection.

Excess of missing energy and transverse momenta

Analysis of events with b-jets and a pair of leptons of the same charge in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector, arXiv:1504.04605v2 [hep-ex] 29 Oct 2015

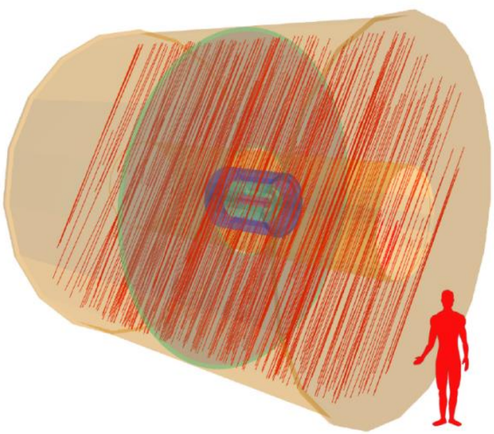


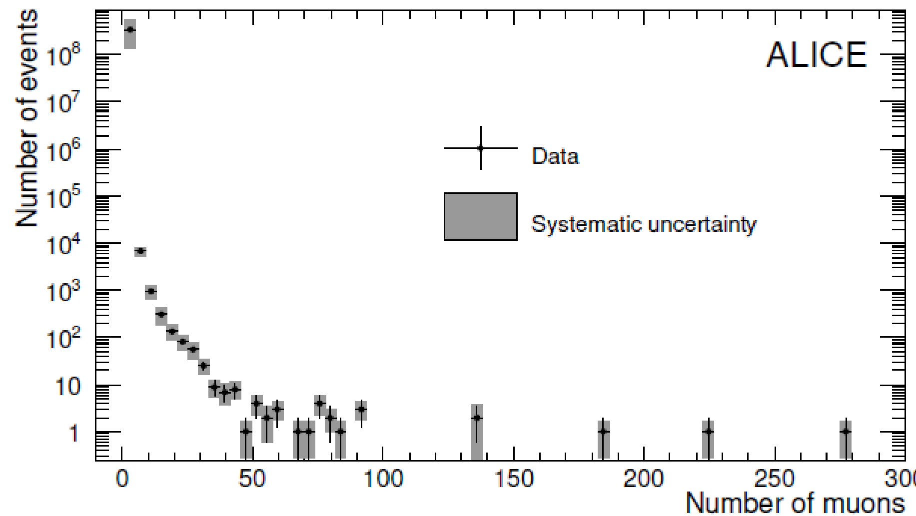
Distributions of the missing transverse momentum E_{missT} and scalar sum of jet and lepton transverse momenta H_T after applying the preselection criteria, for events with one, two, or more than two *b*-tagged jets.

Muon bundles in ALICE

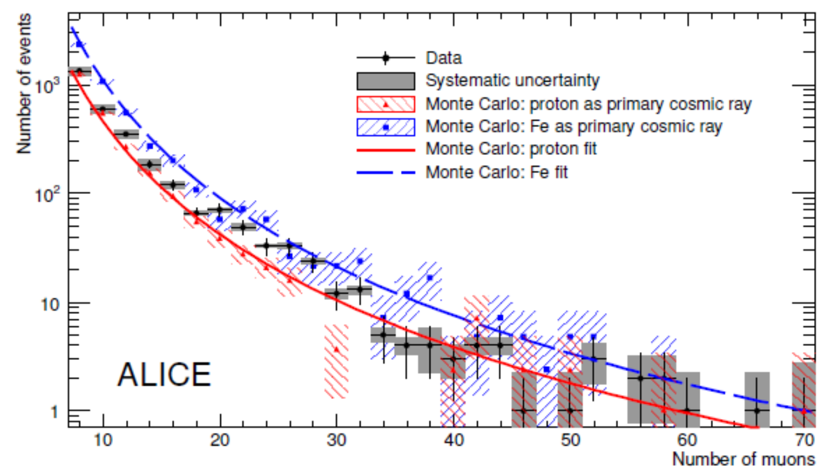
Study of cosmic ray events with high muon multiplicity using the ALICE detector at the CERN Large Hadron Collider, ALICE collaboration, JCAP01 (2016) 032

Muon multiplicity distribution of the whole sample of data (2010-2013) corresponding to 30.8 days of data taking.

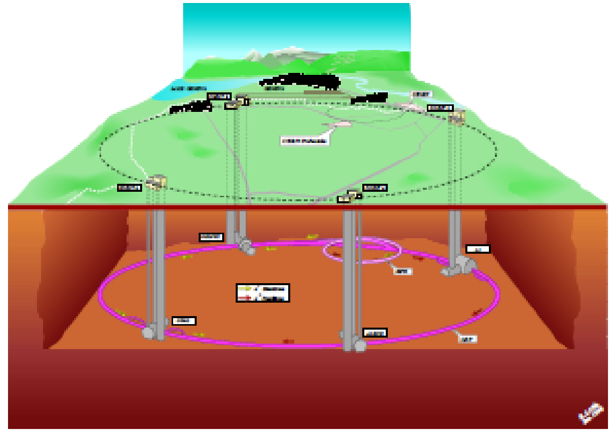


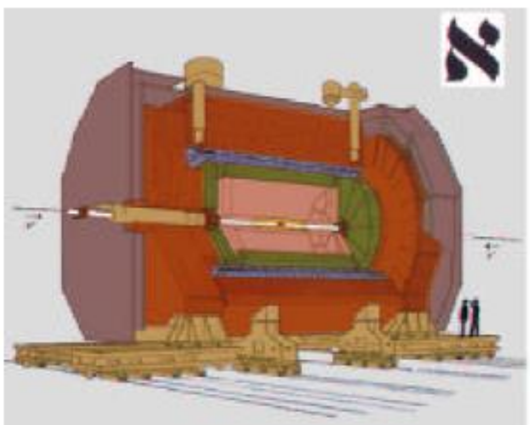


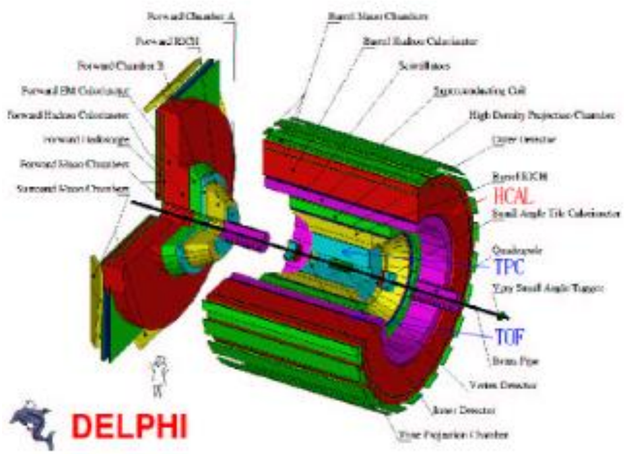
The measured muon multiplicity distribution compared with the values and fits obtained from CORSIKA simulations with proton and iron primary cosmic rays for 30.8 days of data taking.

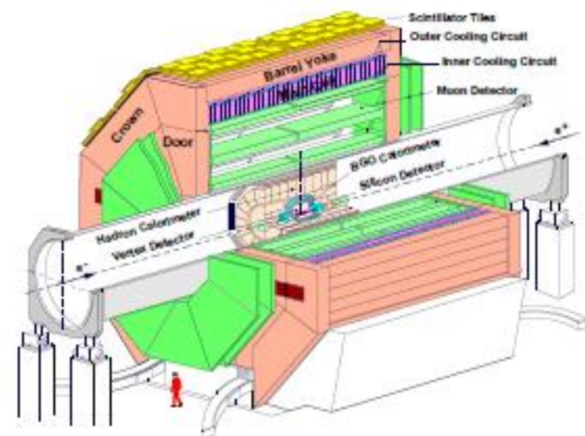


LEP Detectors (CERN)









ALEPH

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

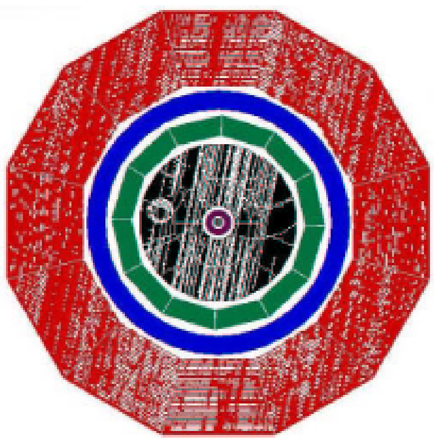
DELPHI

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

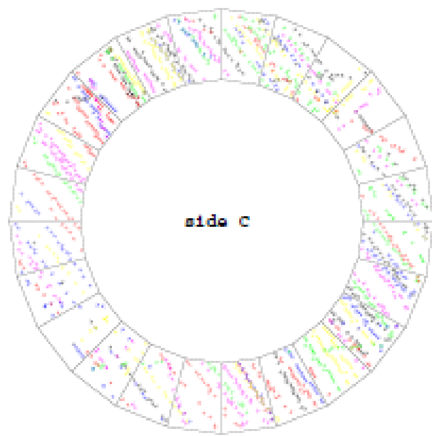
L3

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

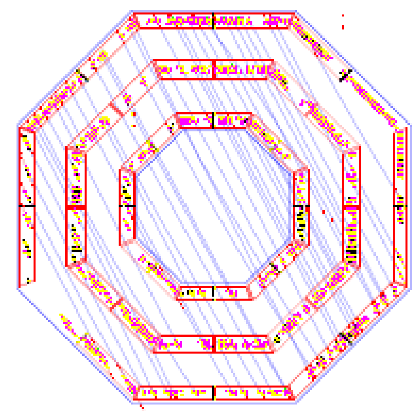
Multi muon events (muon-bundles)



ALEPH



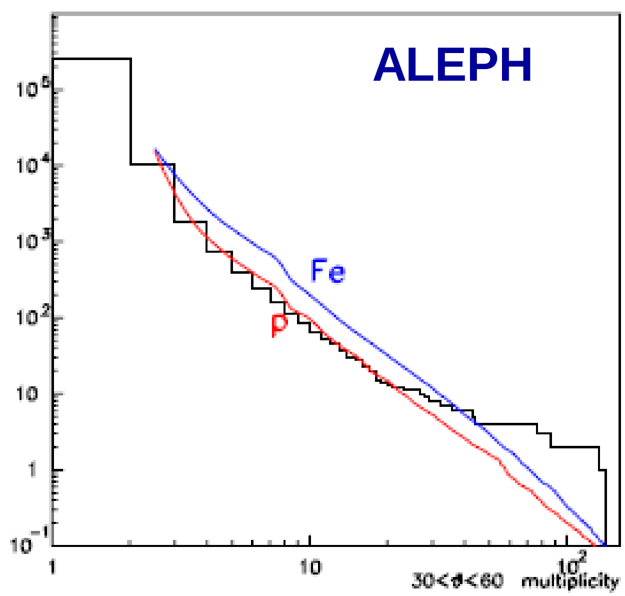
DELPHI

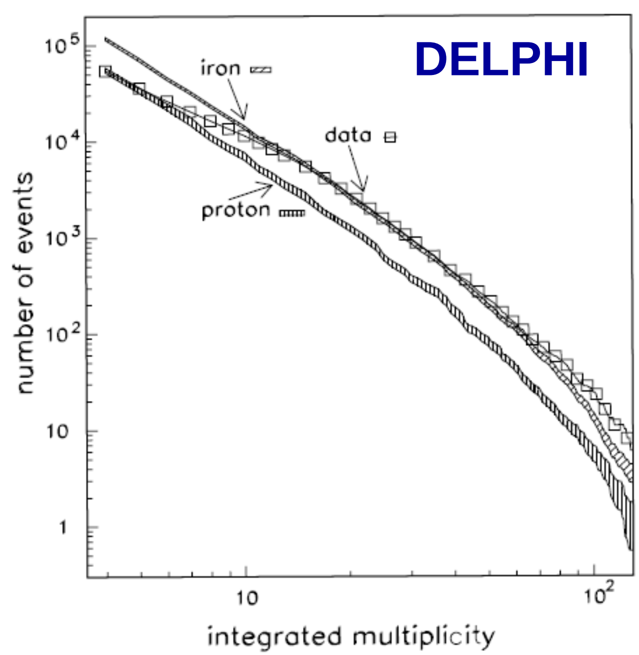


L3+C

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

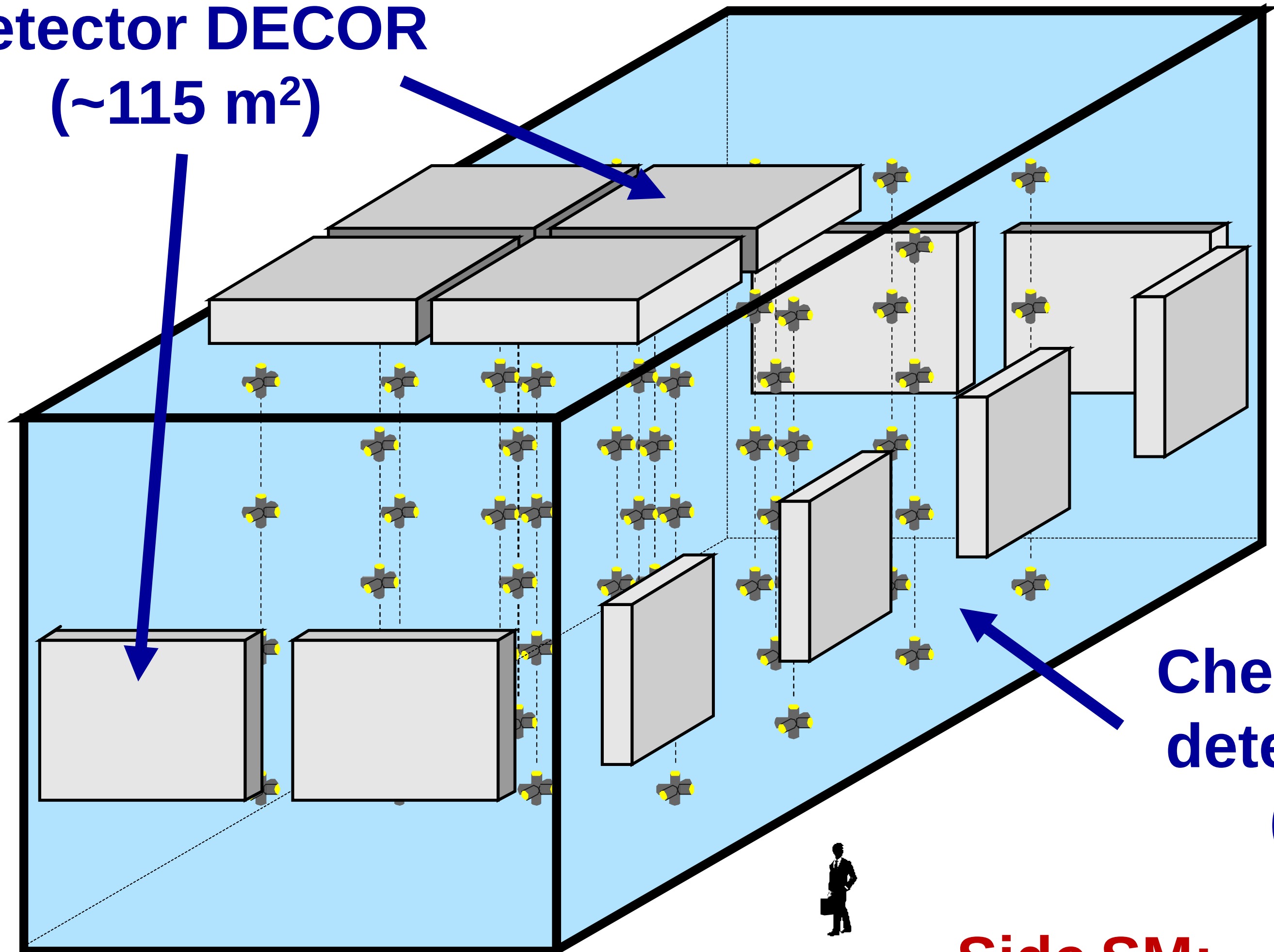
J. Abdallah et al., Astroparticle Physics 28 (2007) 273.





Russian-Italian NEVOD-DECOR experiment

Coordinate-tracking detector DECOR ($\sim$115 m^2)

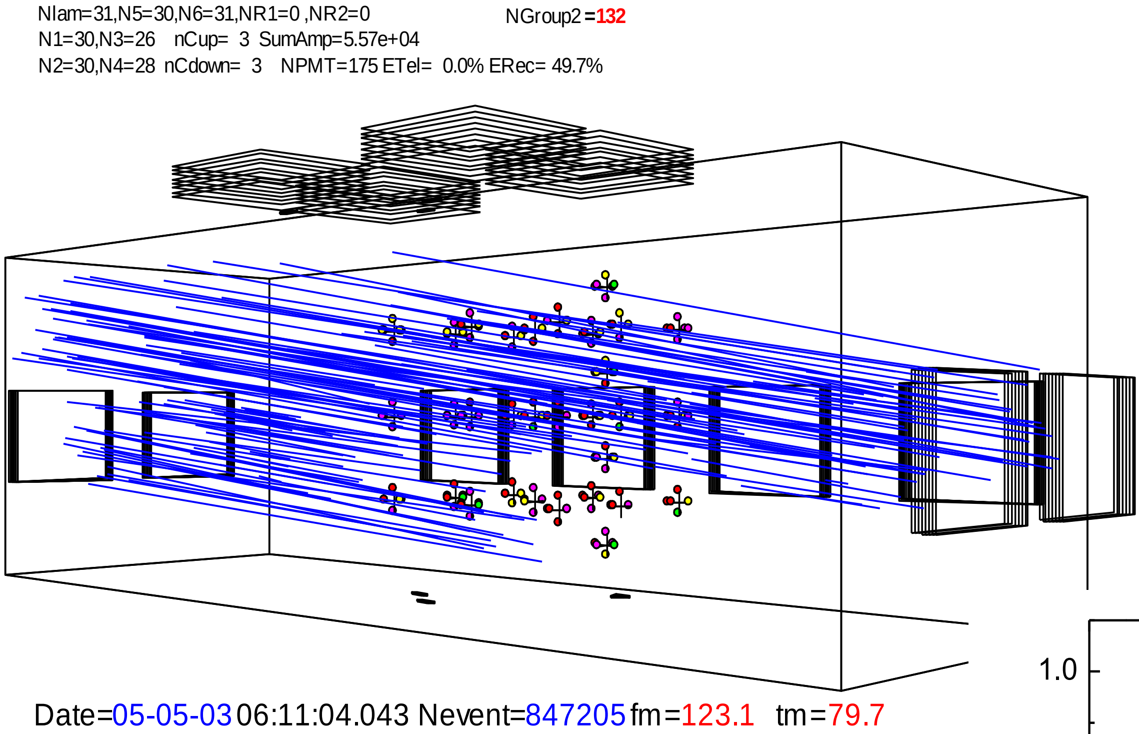


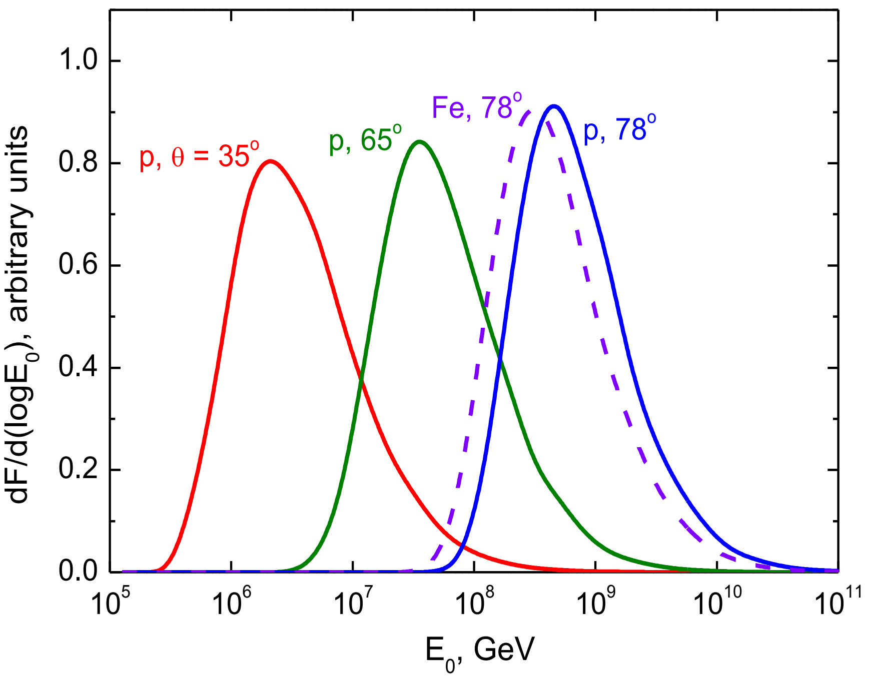
Cherenkov water detector NEVOD (2000 m^3)

<u>Side SM:</u> 8.4 m^2 each

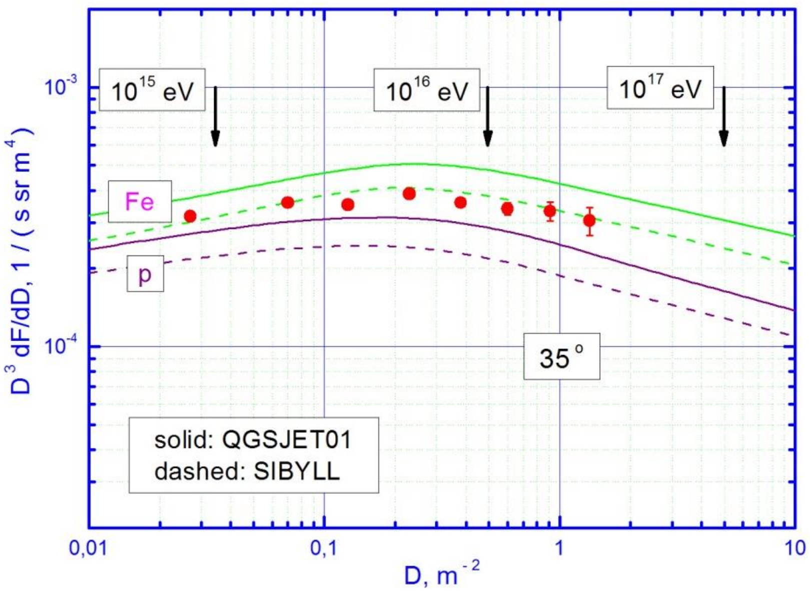
- **$\sigma_x \sim 1$ cm; $\sigma_\psi \sim 1°$**

Muon bundle event (geometry reconstruction)

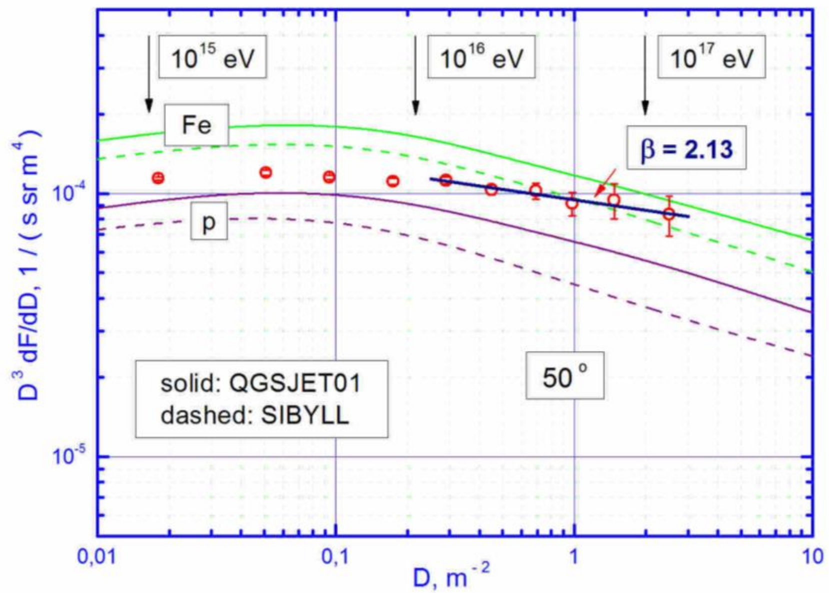




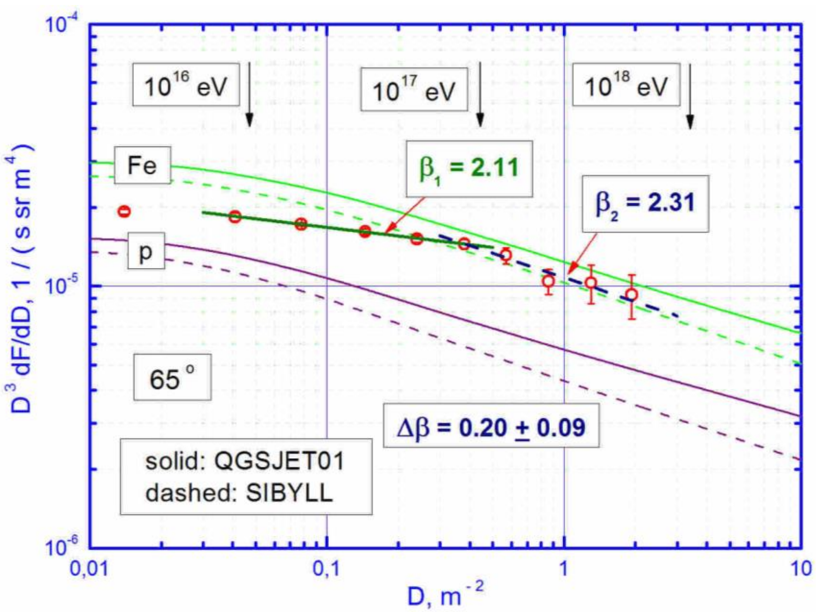
Low angles: around the “knee”



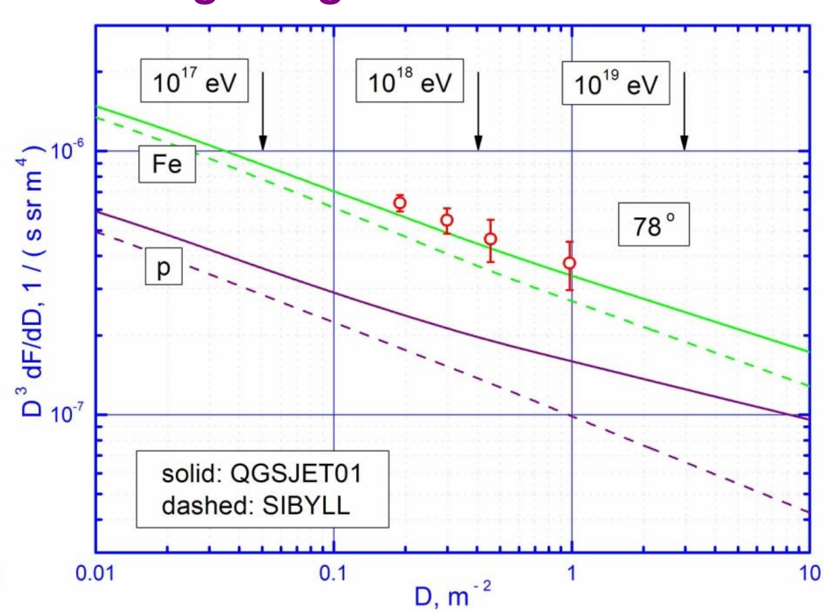
$\theta = 50^o$: $10^{15} – 10^{17}$ eV



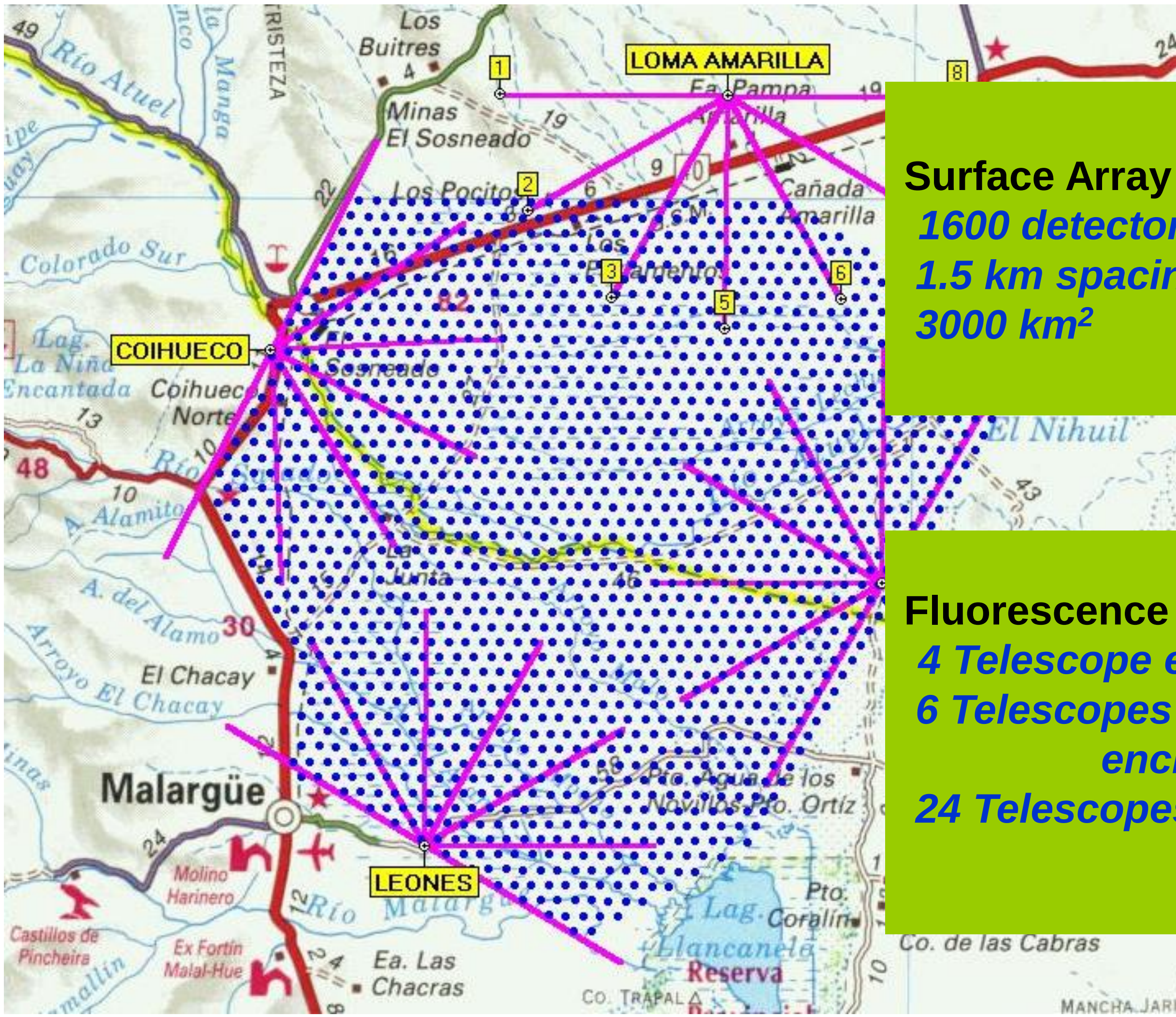
$\theta = 65^o$: $10^{16} – 10^{18}$ eV



Large angles: around 10^{18} eV



Pierre Auger Observatory



Surface Array

1600 detector stations

1.5 km spacing

3000 km^2

Fluorescence Detectors

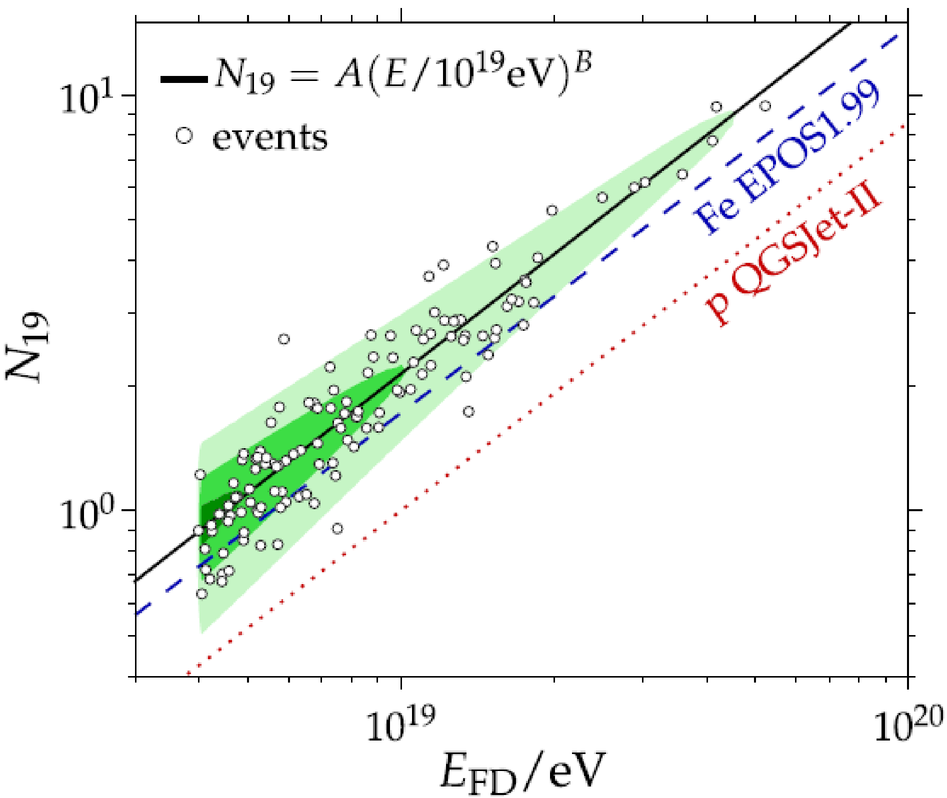
4 Telescope enclosures

6 Telescopes per enclosure

24 Telescopes total

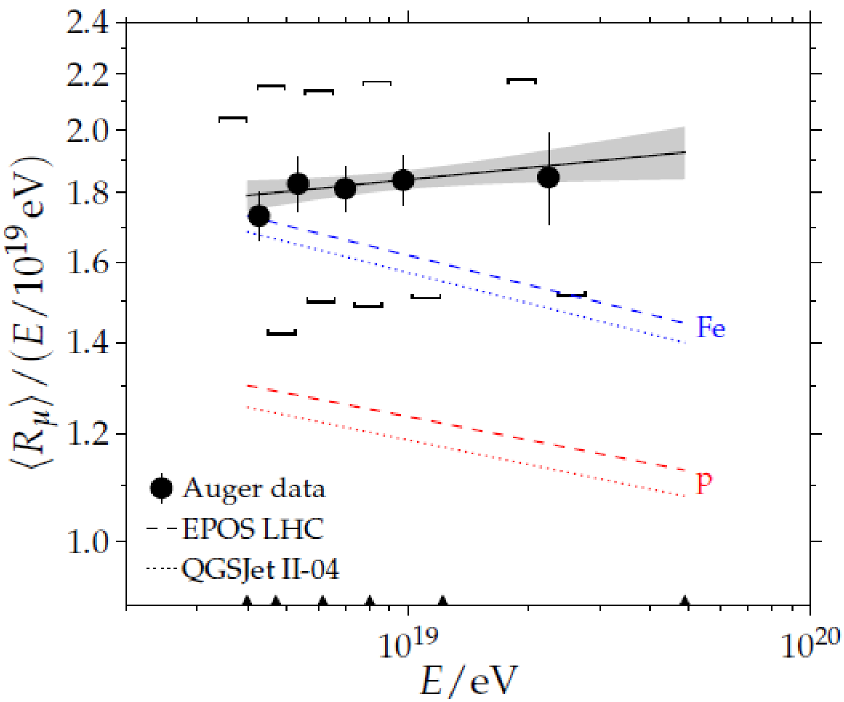
Excess of the number of muons in highly inclined EAS from Pierre Auger Observatory data

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, 032003



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

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 observe unusual events in CR).
3. Large orbital momentum (alignment).
4. Large yield of HE leptons (excess 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.

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

- 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

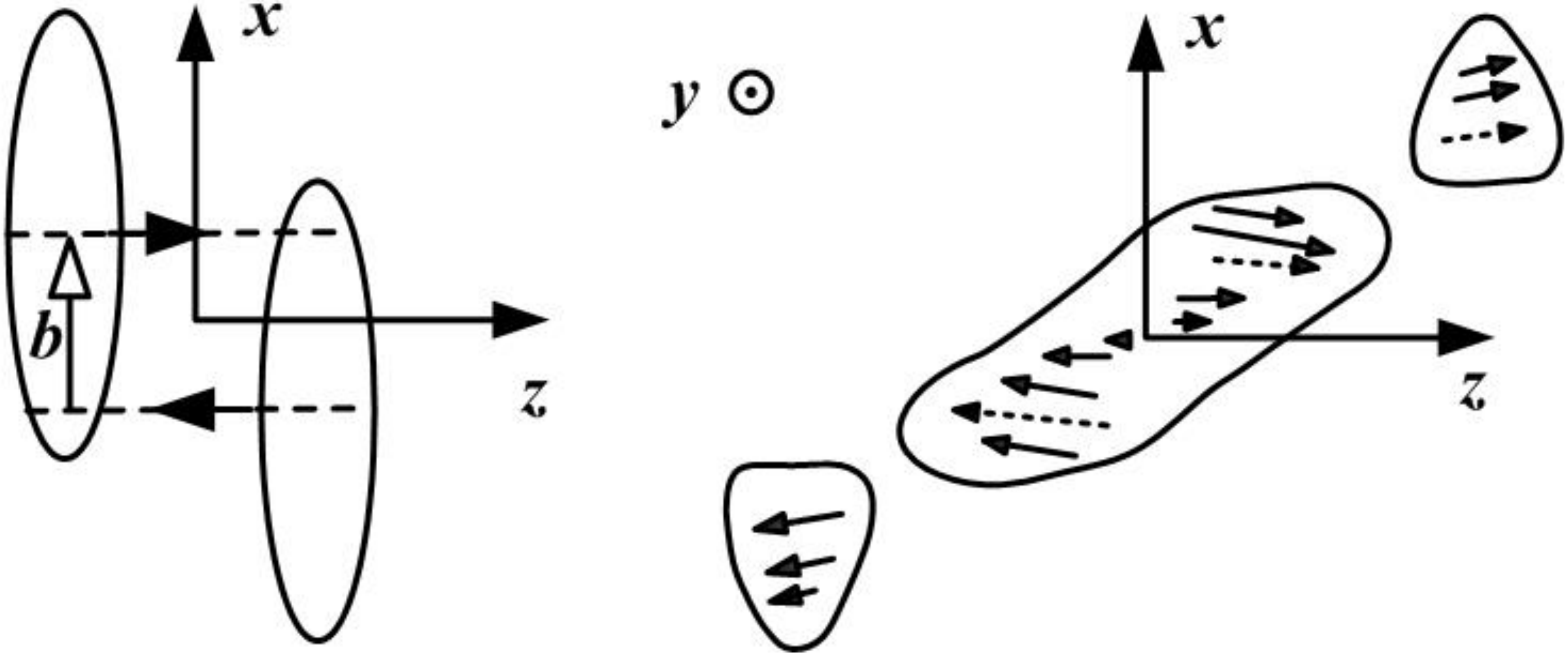
1. Production of QGM provides two main conditions:
   - threshold behavior, since for that high temperature (energy) is required;
   - large cross section, since the transition from quark-quark interaction to some collective interaction of many quarks occurs:

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

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.

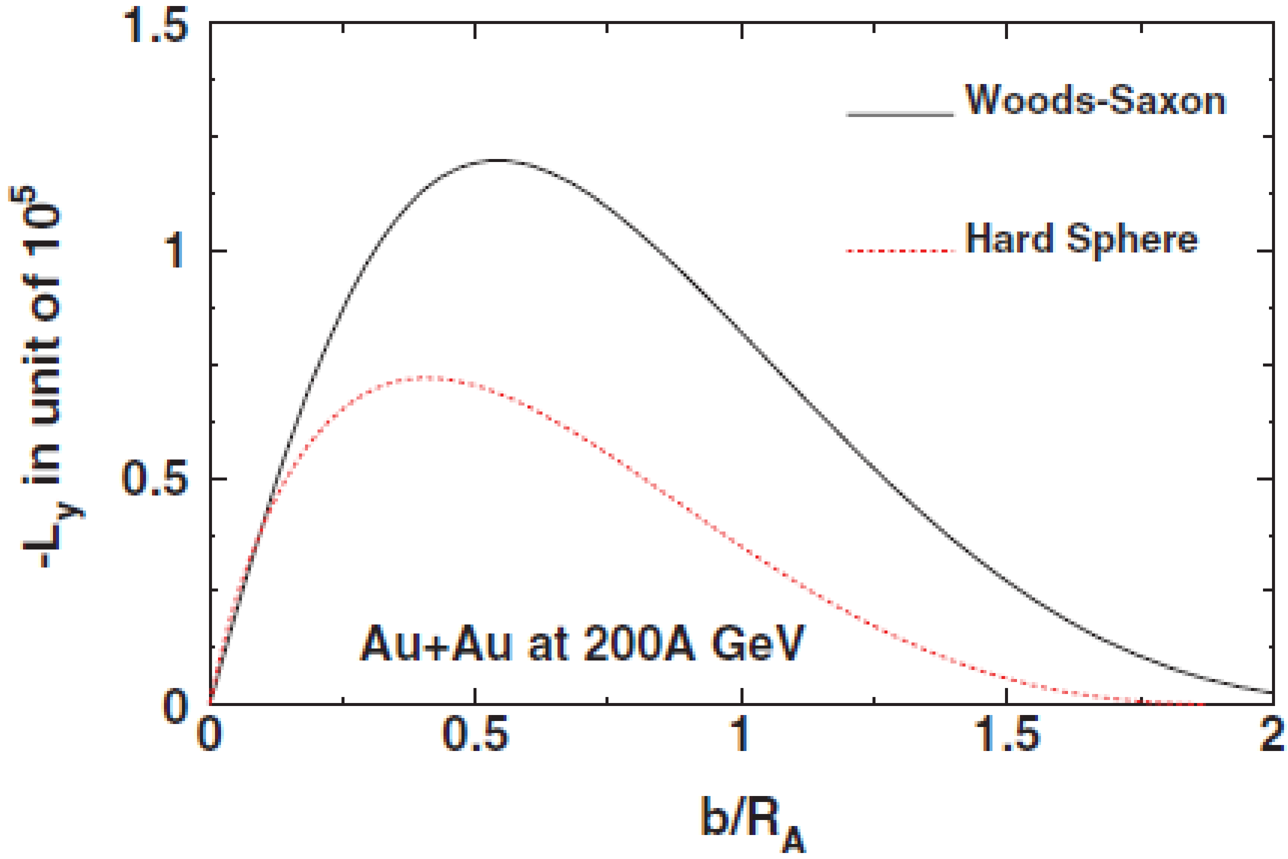
Orbital angular momentum in non-central ion-ion collisions



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.

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, $n \sim 4$ (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 – 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.

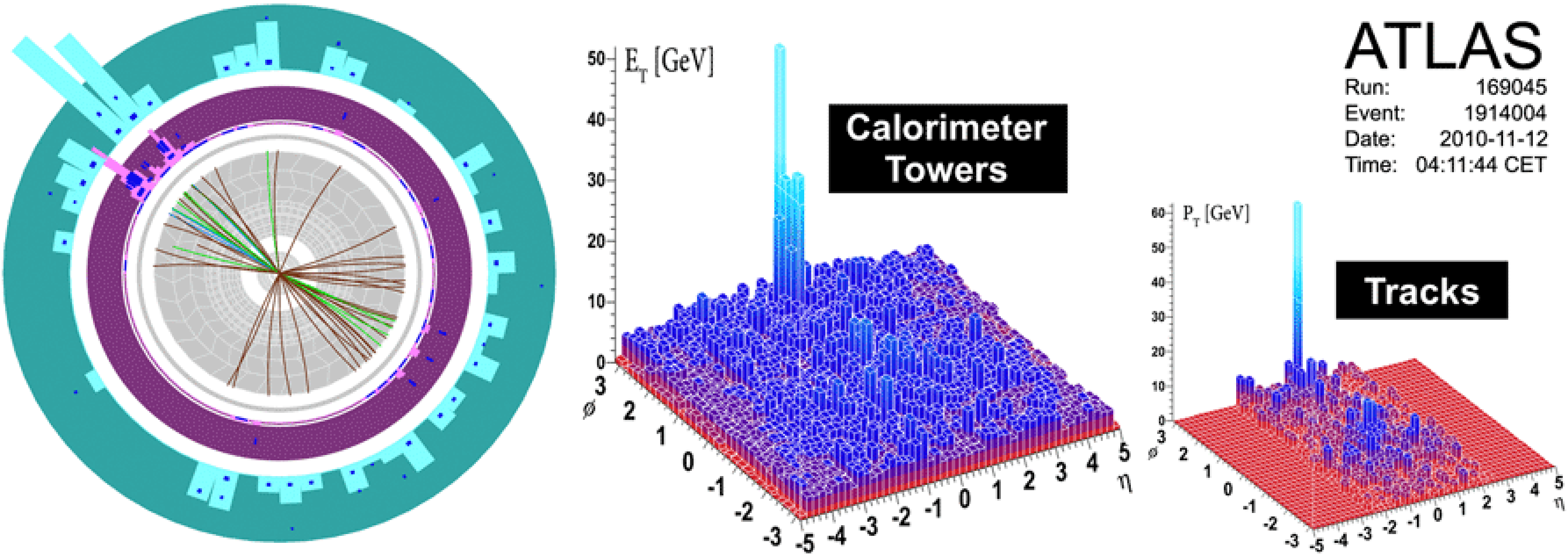
- Decays of W-bosons into hadrons (mainly pions – in average ~ 20) explain the increasing muon number (muon bundles) with increasing of energy.

2. Behavior of EAS energy spectrum.

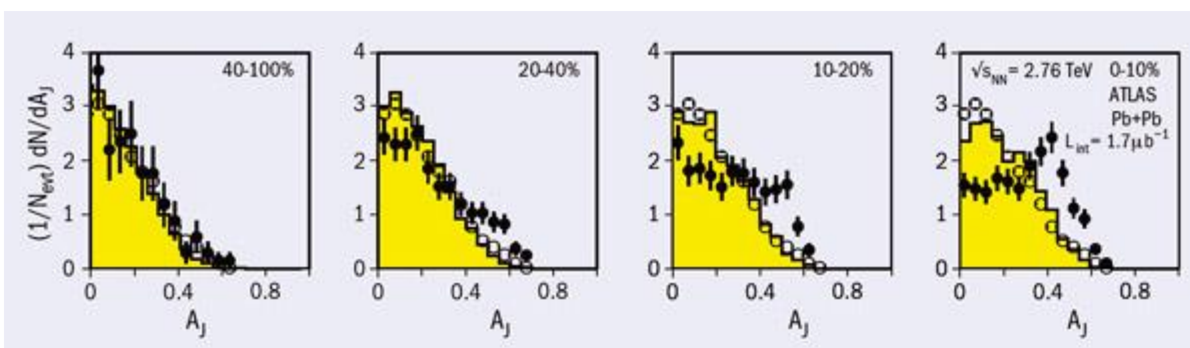
Now the transition from measured data to the EAS energy does not take into account a missing energy which is carried away by three VHE neutrinos, and a change of EAS development due to a change of interaction model.

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

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:

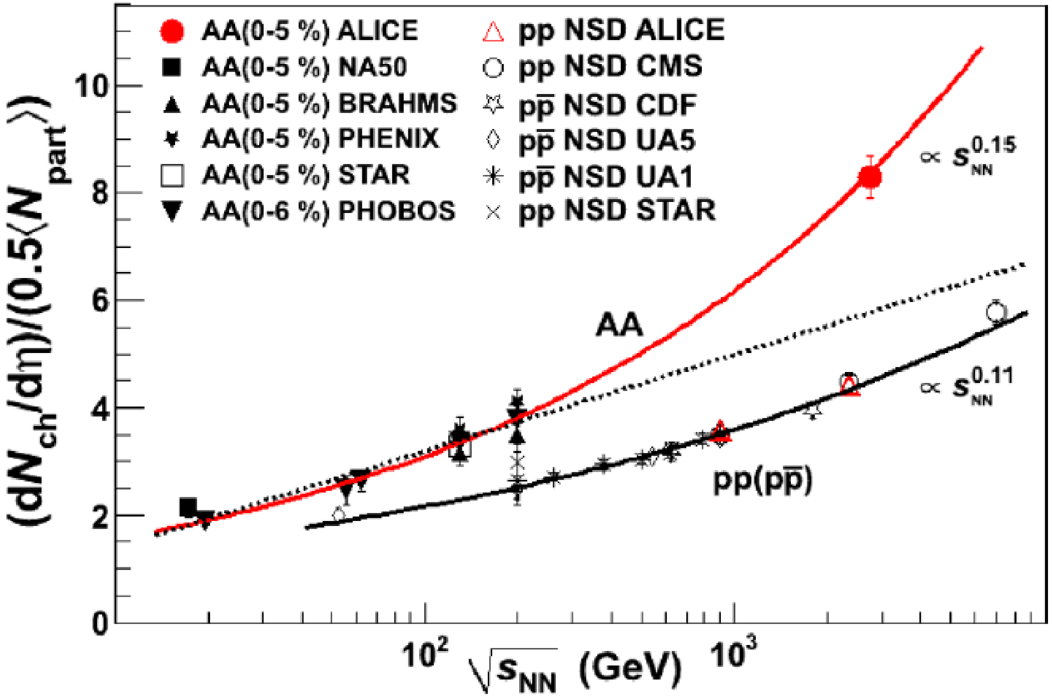
$$T_b \sim 65\ \text{GeV}, \qquad T_W \sim 25\ \text{GeV}.$$

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



log extrapolation fails (finally!)

2.2 x central Au+Au

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

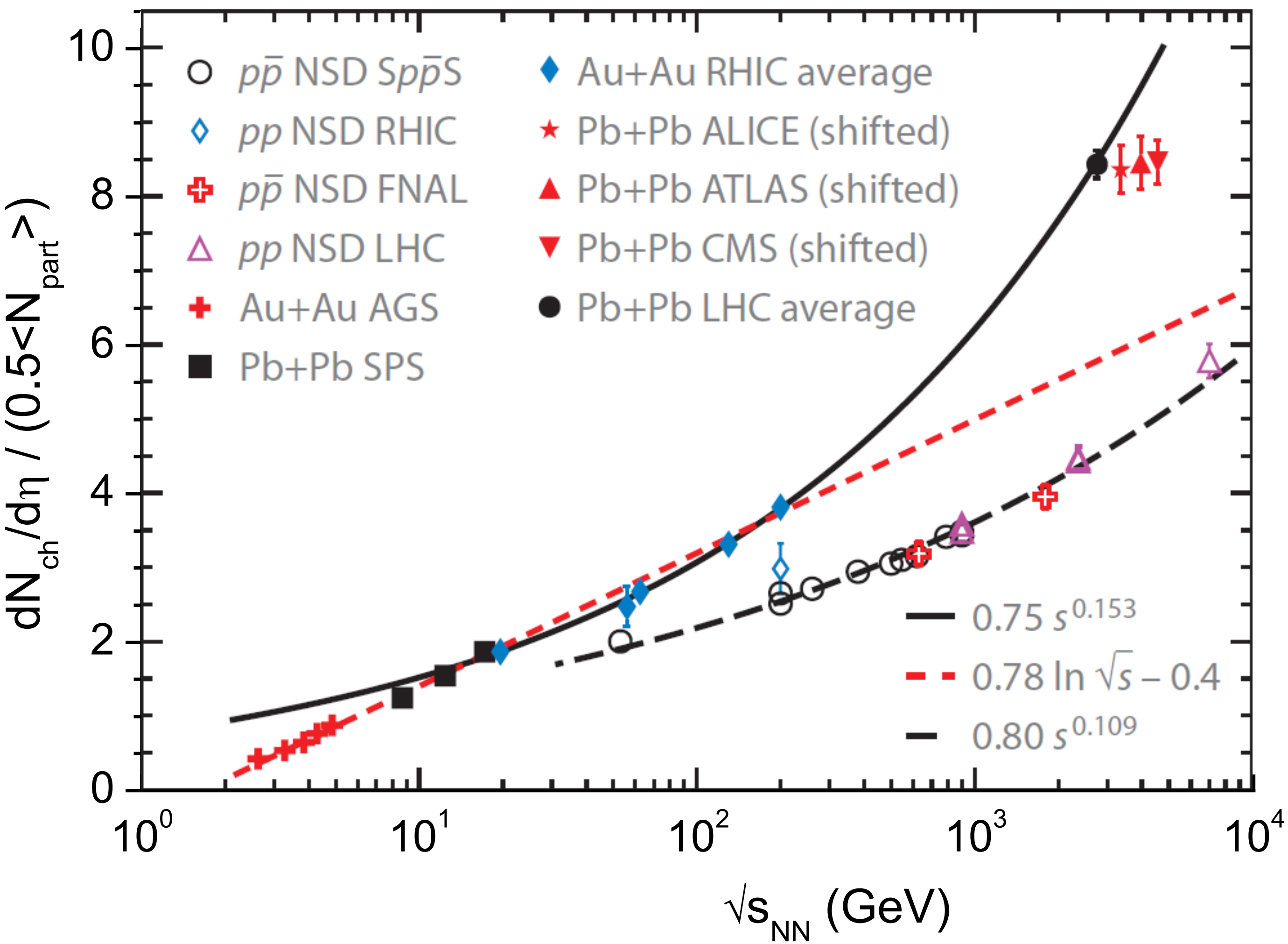
1.9 x pp (NSD)

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

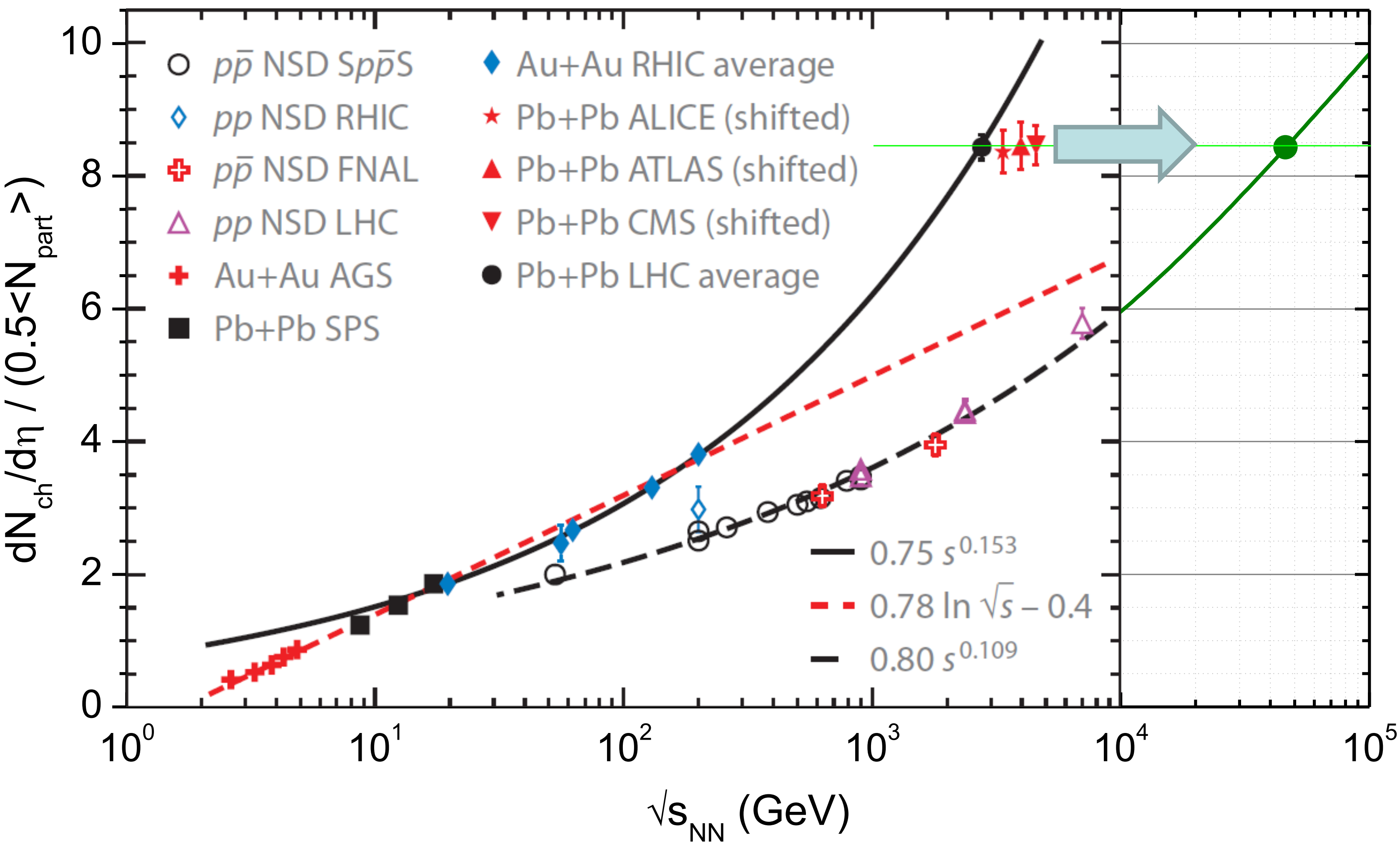
ALICE: PRL105 (2010) 252301

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

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



$p\bar{p}$ 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



pp̄ NSD Sp p̄S
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
dNch/dη / (0.5<Npart>)
√sNN (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 a new model $\sqrt{S}$ must be larger.

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

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

So, in Pb-Pb collisions up to a half of nucleons can be considered as a target mass.

Conclusion

If the considered approach to the explanation of the results obtained at the LHC and in cosmic rays is correct, it is better to search for the new state of matter in detail at LHC not in *proton-proton* interactions but in *nucleus-nucleus* interactions of light nuclei (nitrogen, oxygen), for which the multiplicity of secondary particles is not so large compared to *Pb-Pb* or *Au-Au*

Thank you!