PAPC, June 27, 2013

What can we learn from nuclei-nuclei interactions at LHC?

Anatoly Petrukhin

National Research Nuclear University MEPhI, Moscow, Russia

Outline

1. Introduction.
2. Some results of CR investigations.
3. Their possible explanation.
4. Consequences for LHC experiments.
5. Conclusion.

Introduction

- Discovery of Higgs boson was the main task for LHC and its investigations will be continued.
- Of course, investigations of known processes and phenomena in new energy region will be continued, too.

What are the next tasks?

- Of course, there are many various theoretical ideas: supersymmetry, dark matter, etc.

- The purpose of my talk is to pay attention to another possibility which follows from results of CR investigations.

Cosmic ray experiments

- LHC energies 1-14 TeV correspond to the interval $10^{15} – 10^{17}$ eV in laboratory system for *pp*-interactions and namely at these energies many interesting and sometimes unusual results were obtained.

- But in CR experiments:

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

  Thus in CRs we investigate mainly nuclei-nuclei interactions.

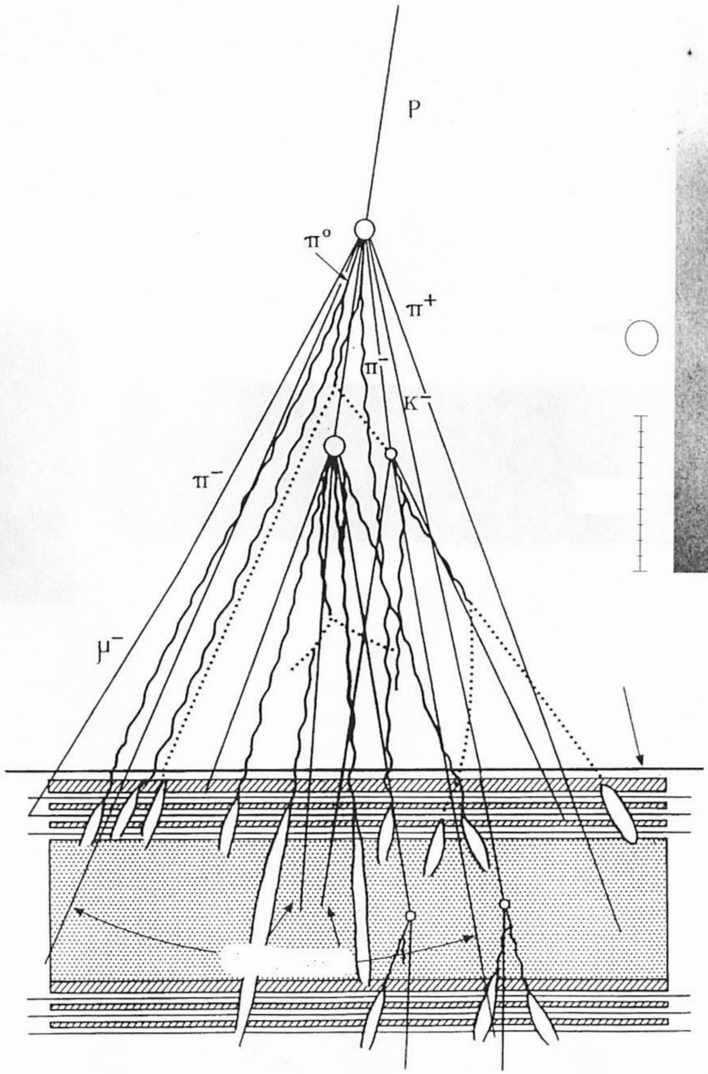
Particles	*Z*	<*A*>	Energy per nucleon	Energy per nucleus
Protons	*1*	*1*	*92 %*	*40 %*
α *– particles*	*2*	*4*	*7 %*	*21 %*
Light nuclei	*3 – 5*	*10*	*0,15 %*	*1 %*
Medium nuclei	*6 – 10*	*15*	*0,5 %*	*18 %*
Heavy nuclei	$\geq$*11*	*32*	*0,15 %*	*18 %*

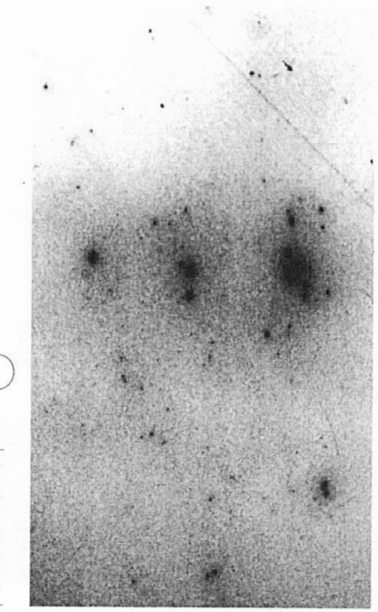
List of unusual events

- 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 energy spectrum slope.
  - Changes in N_μ / N_e - ratio dependence.

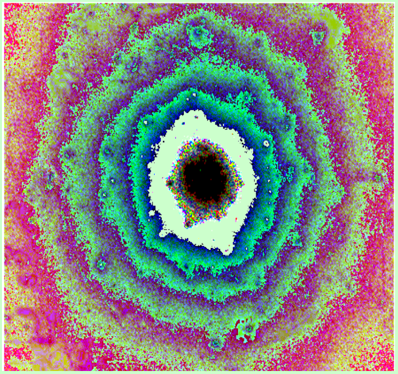
Important: Unusual events appear at PeV energies of primary particles.

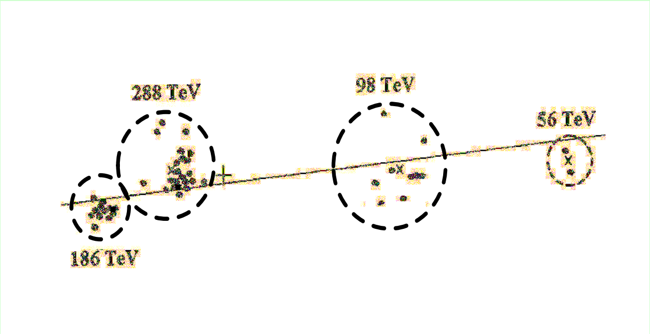
Experiment Pamir

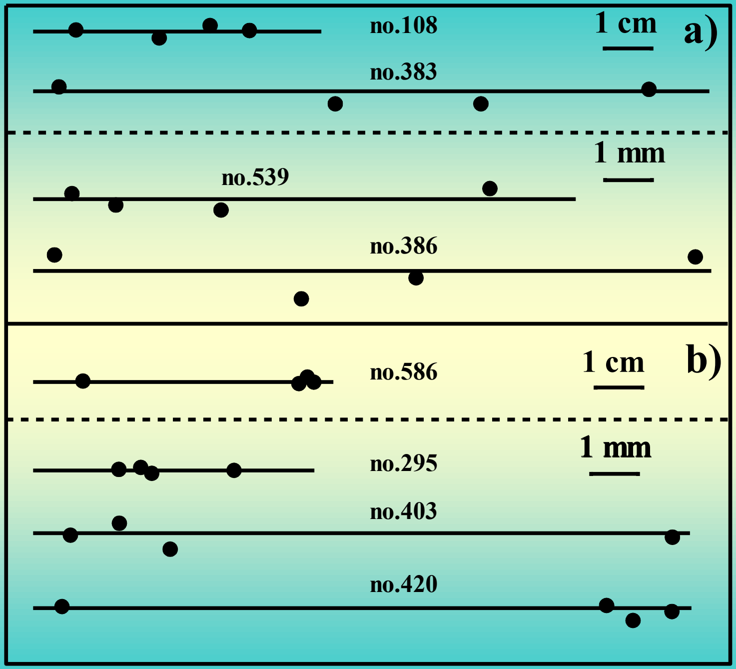




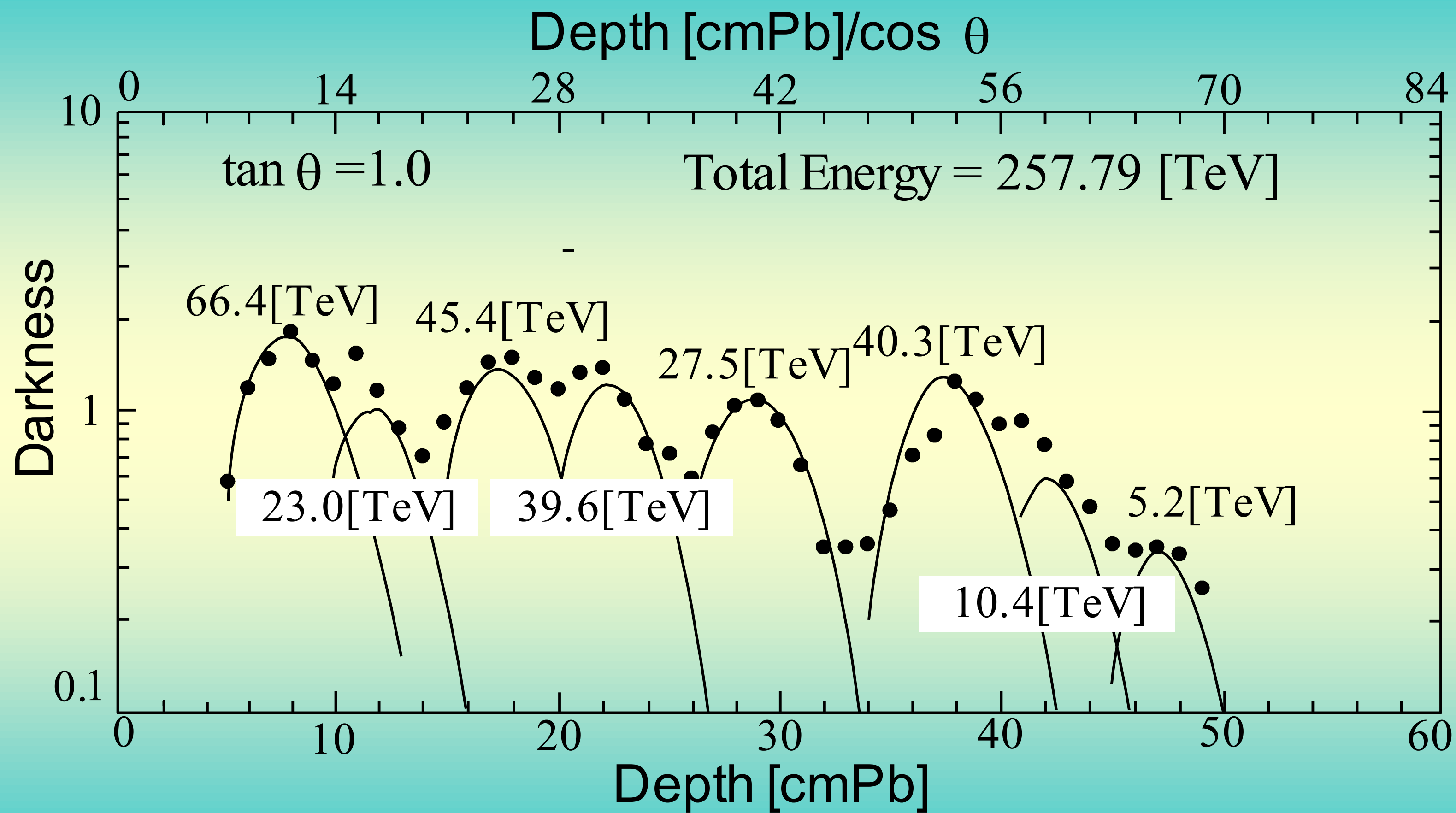
Halo and alignment



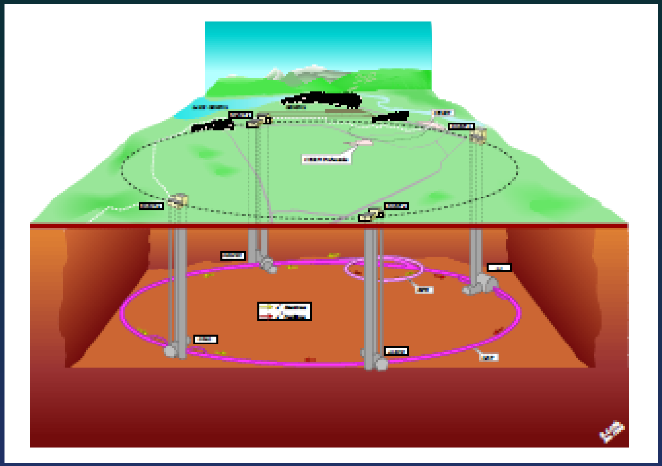


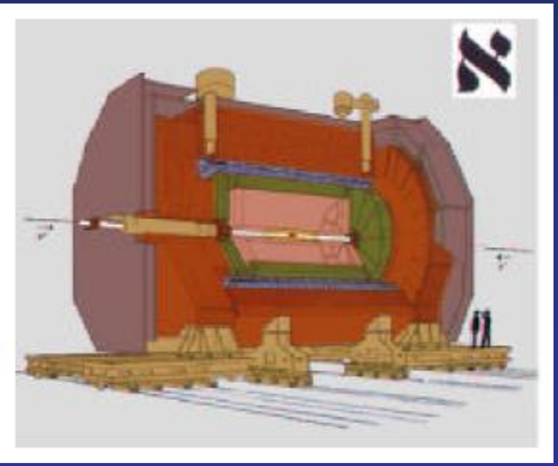


Penetrating cascades

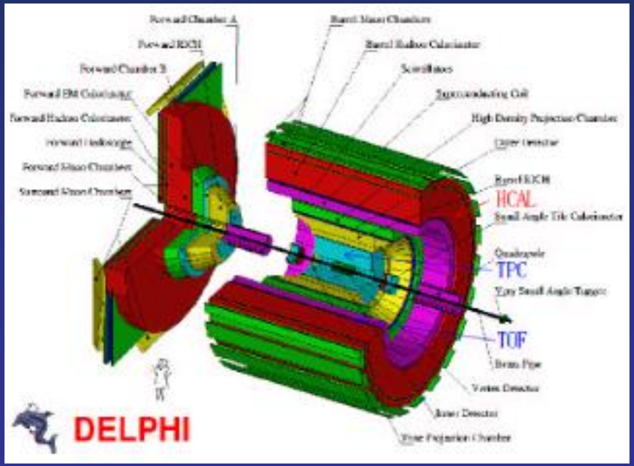


LEP Detectors (CERN)

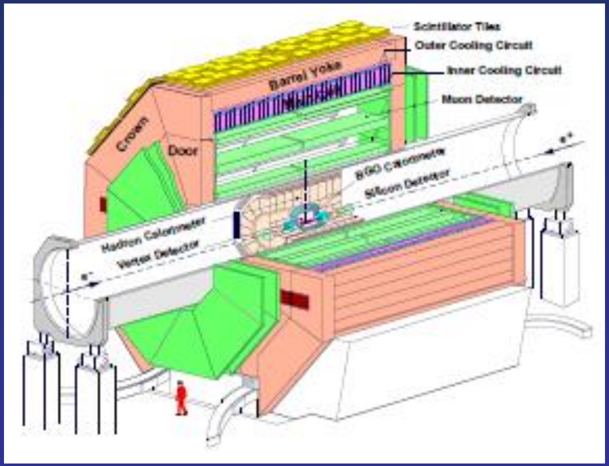




ALEPH



DELPHI



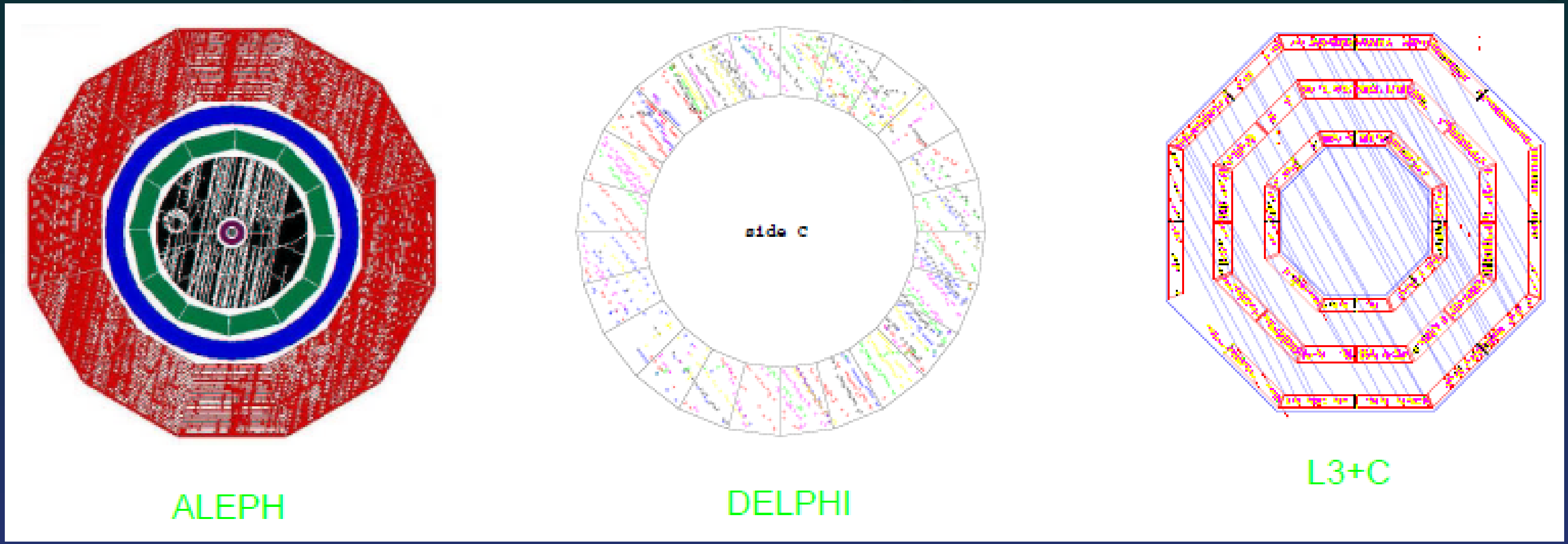
L3

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

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

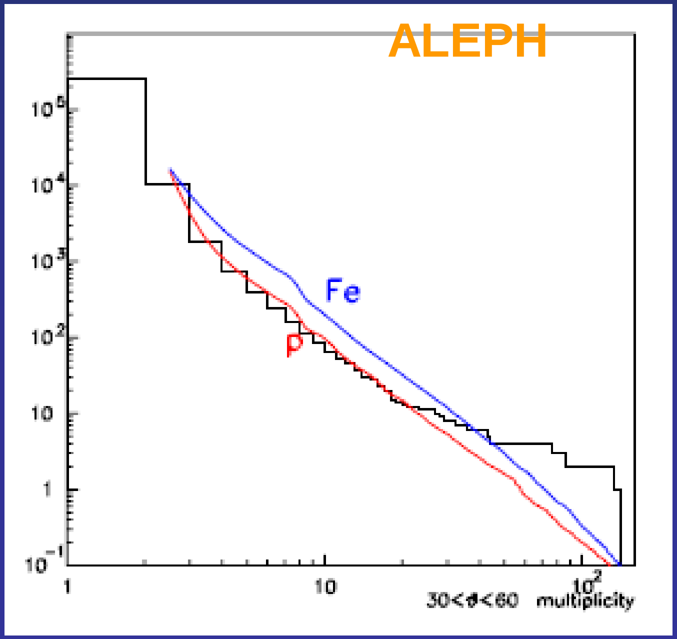
40 m depth ($E_\mu > 15$ GeV)
Drift chambers, timing scintillators, surface EAS array

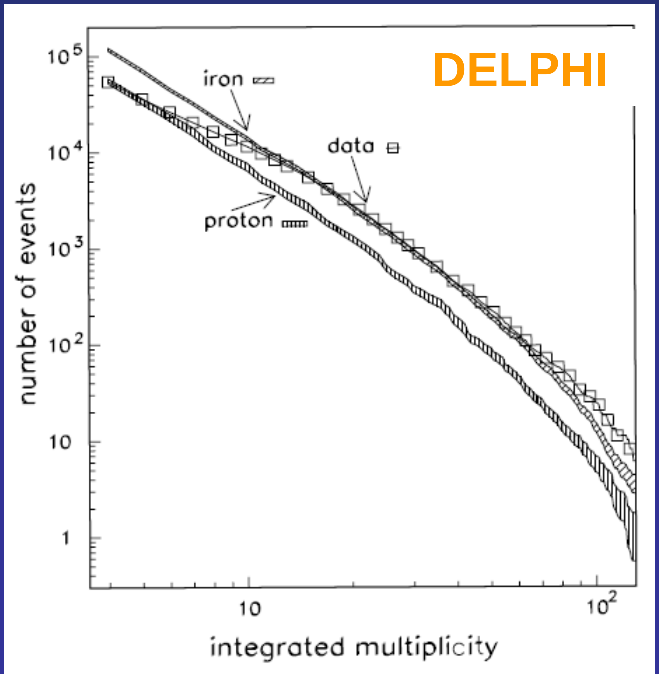
Multi-muon events (muon bundles)



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

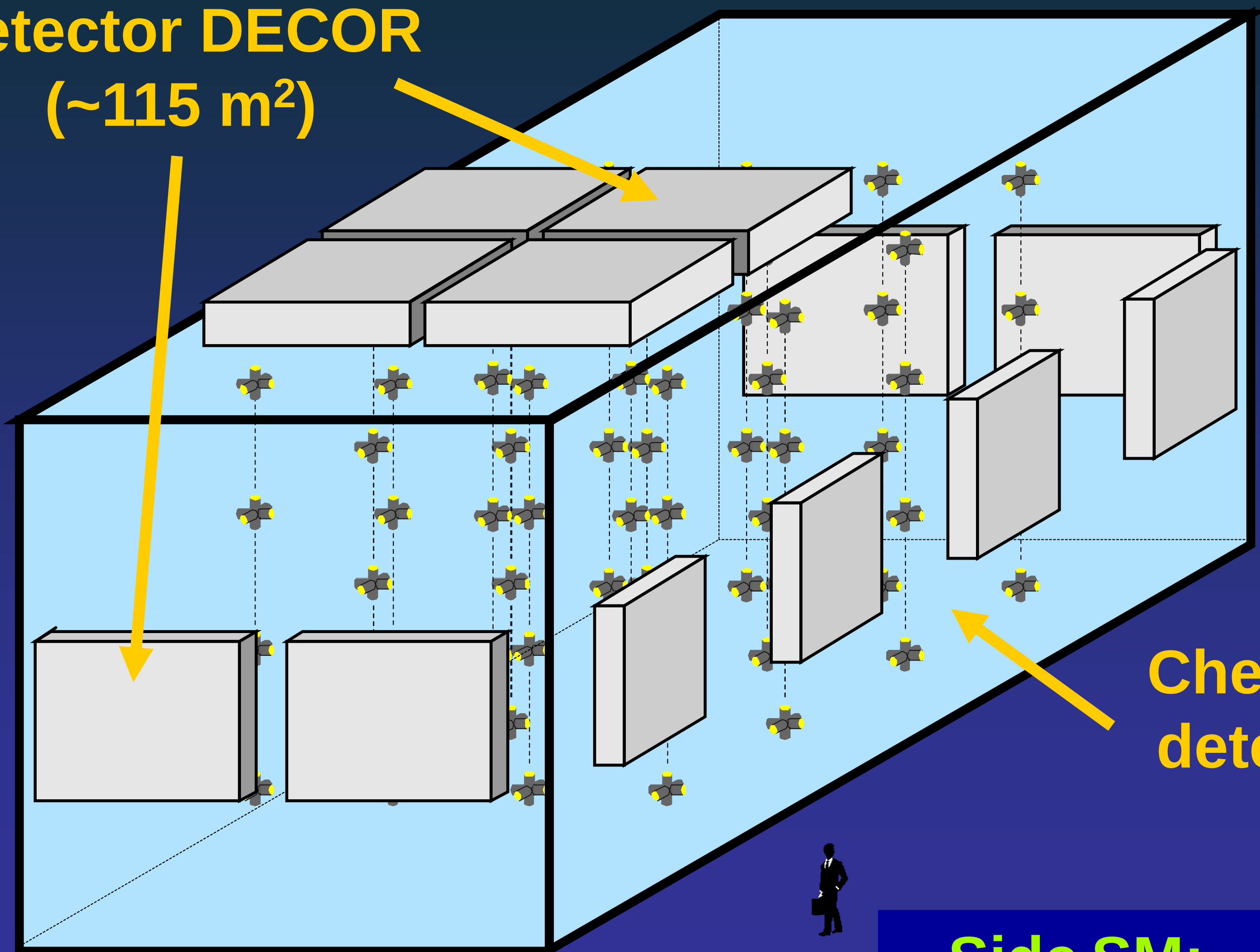
J. Abdallah et al., Astroparticle Physics 28 (2007) 273.





General view of NEVOD-DECOR complex

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

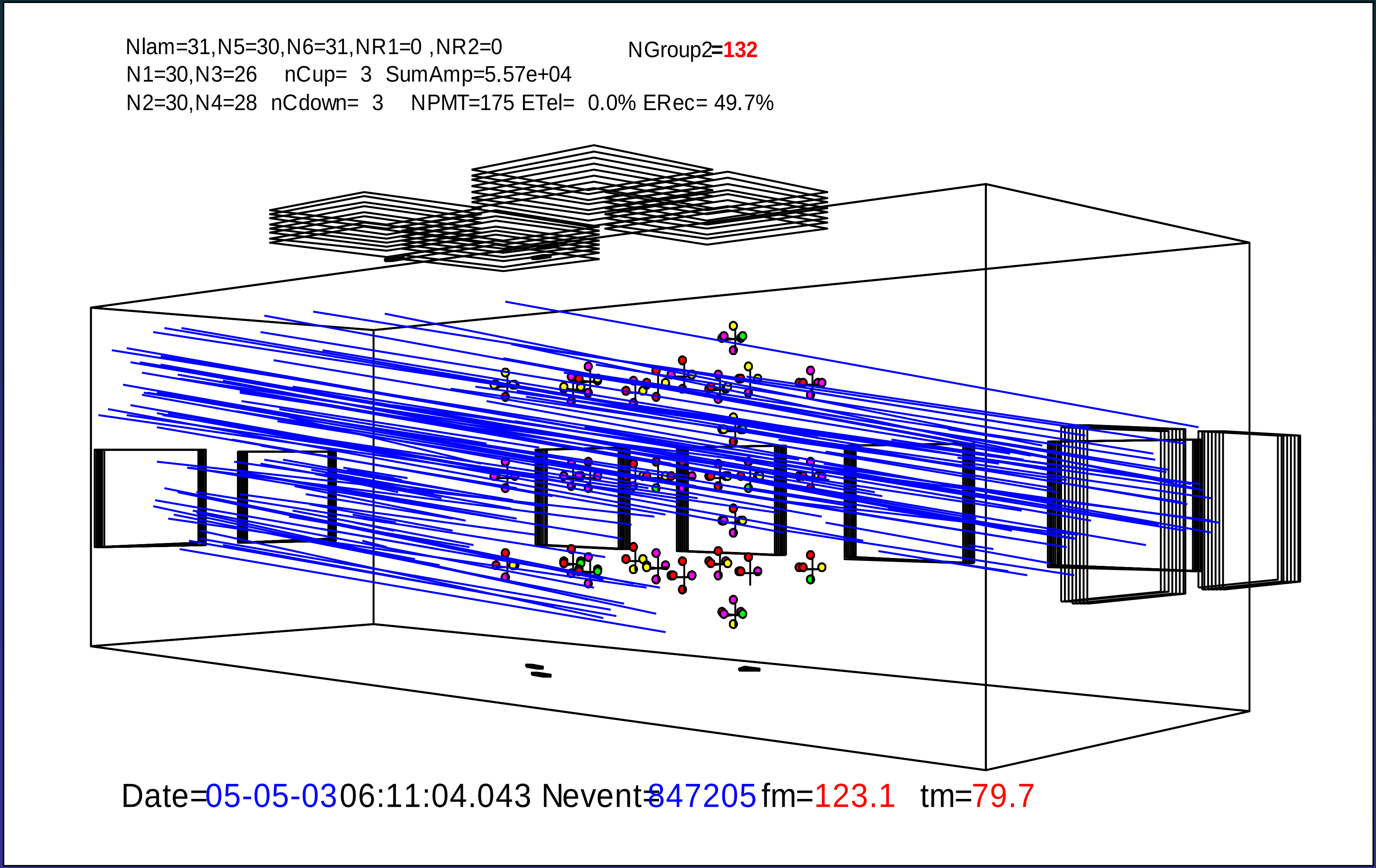


Cherenkov water detector NEVOD (2000 m^3)

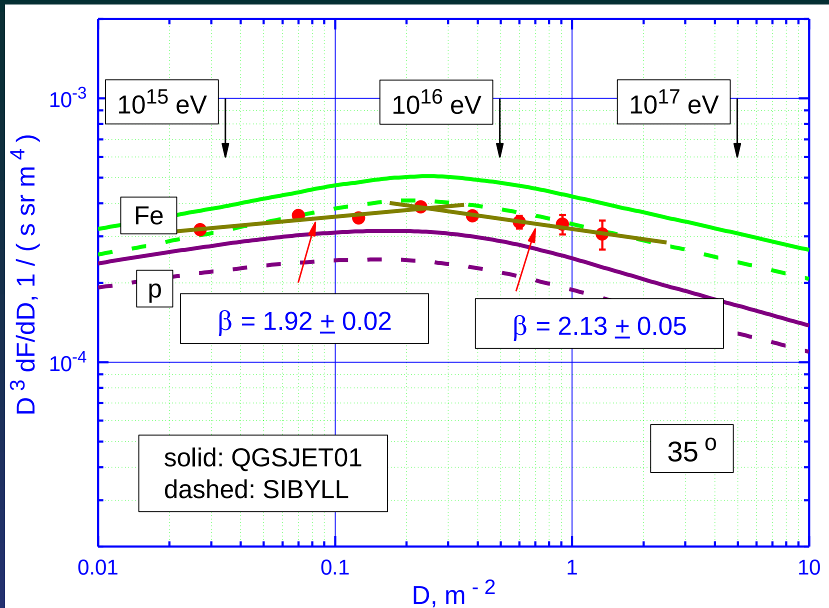
Side SM: 8.4 m^2 each

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

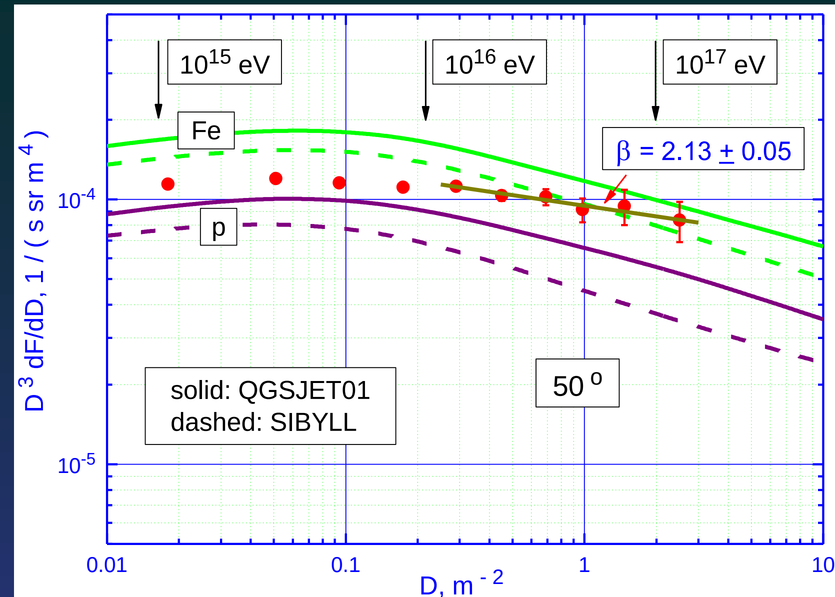
Muon bundle event (geometry reconstruction)



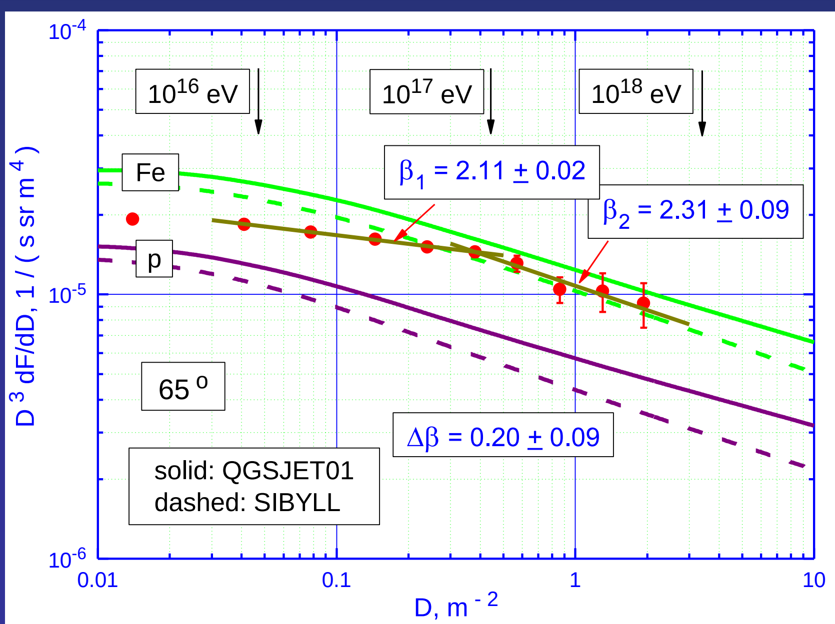
Low angles: around the “knee”



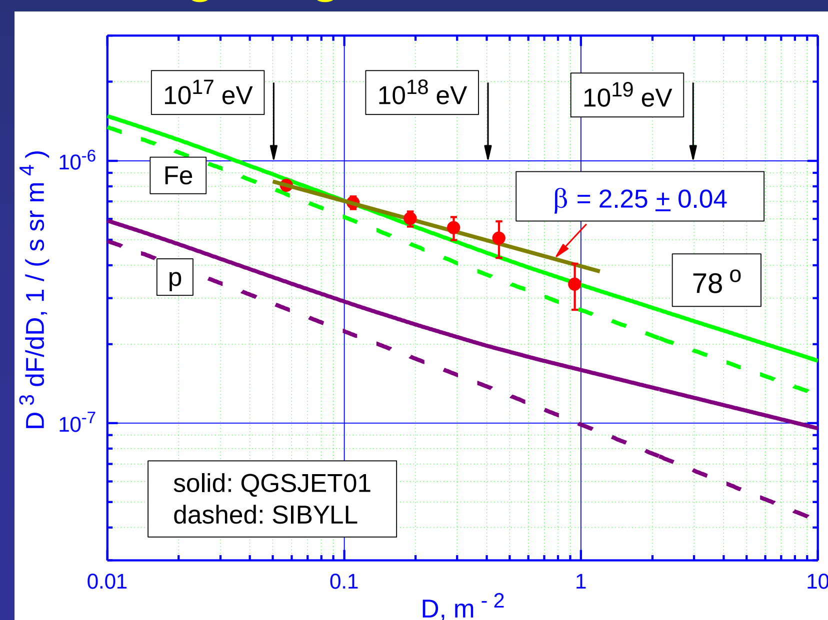
$\theta = 50^o$: $10^{15} – 10^{17}$ eV

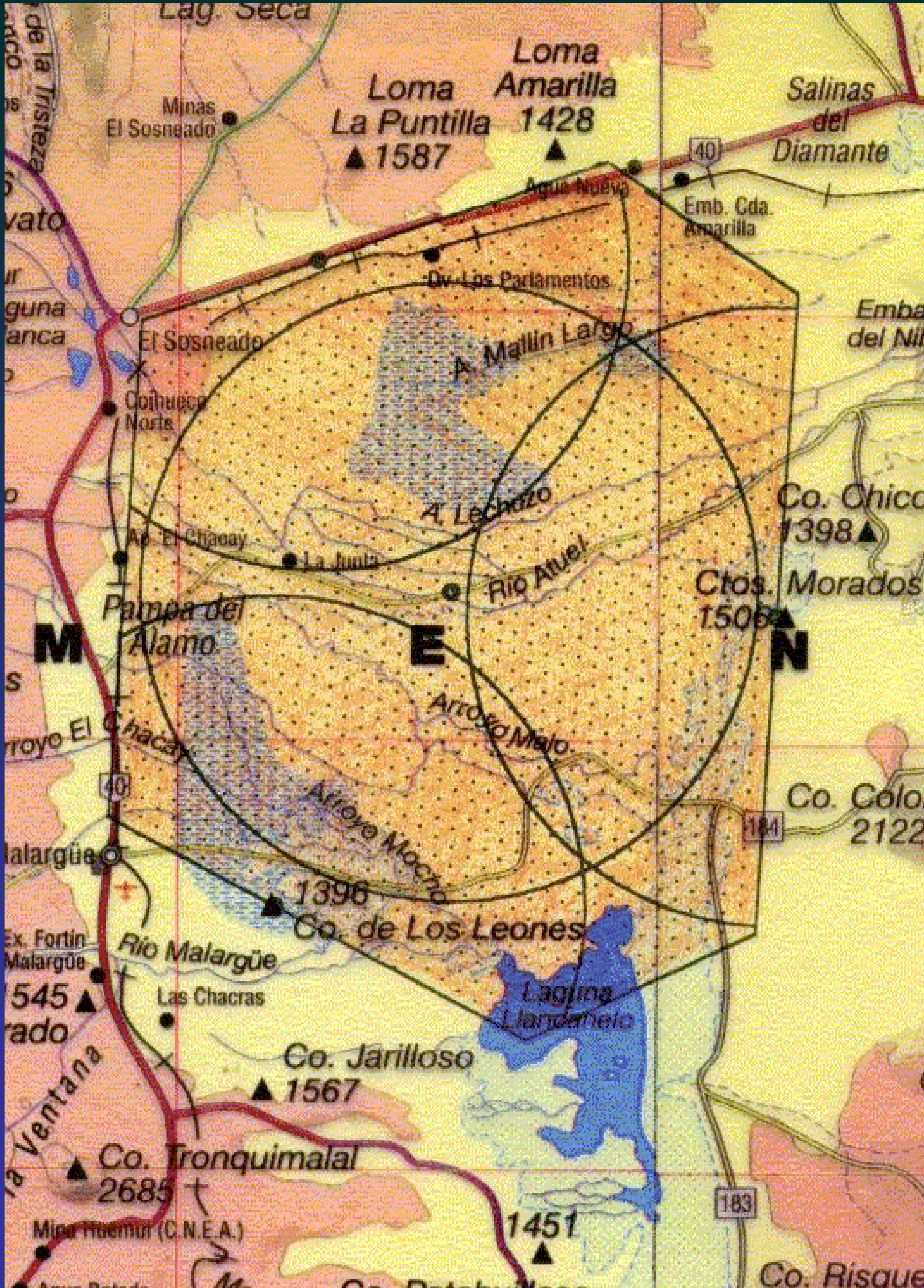


$\theta = 65^o$: $10^{16} – 10^{18}$ eV



Large angles: around 10^{18} eV





Pierre Auger Observatory

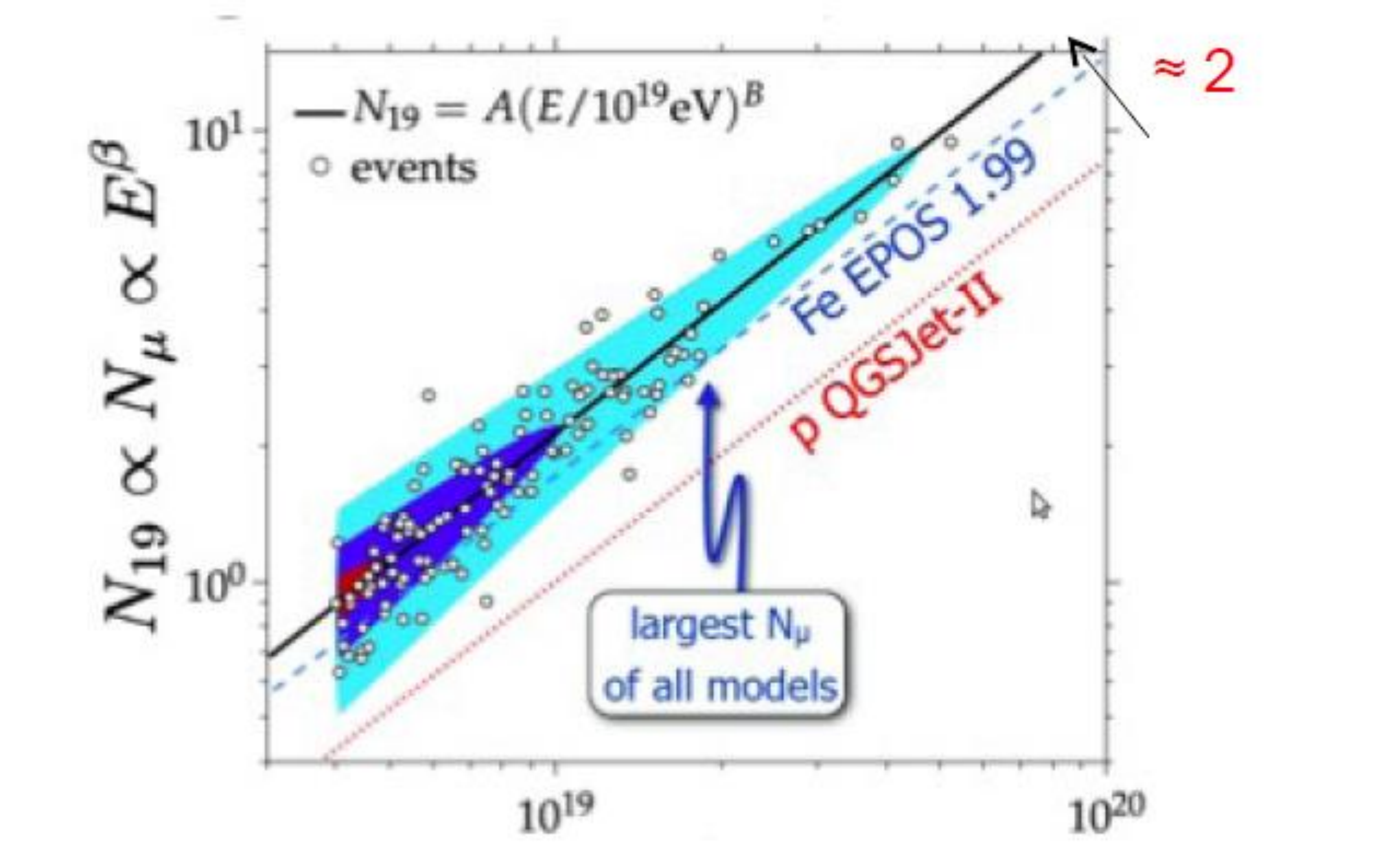
Area - 3000 km^2

Number of detectors - 1600

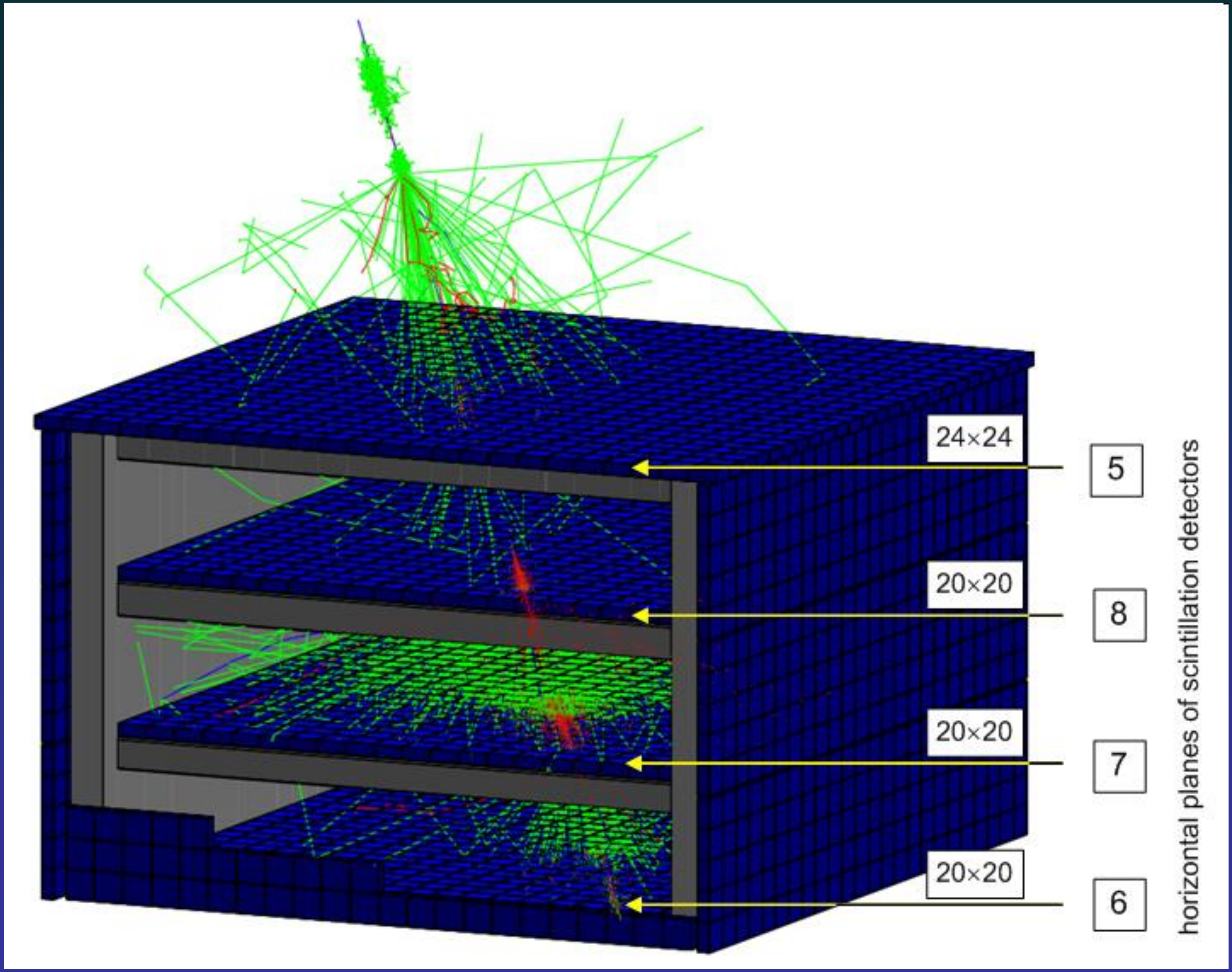
Detector size - 12 m^3

The distance between detectors - 1500 m.

Muons in Auger

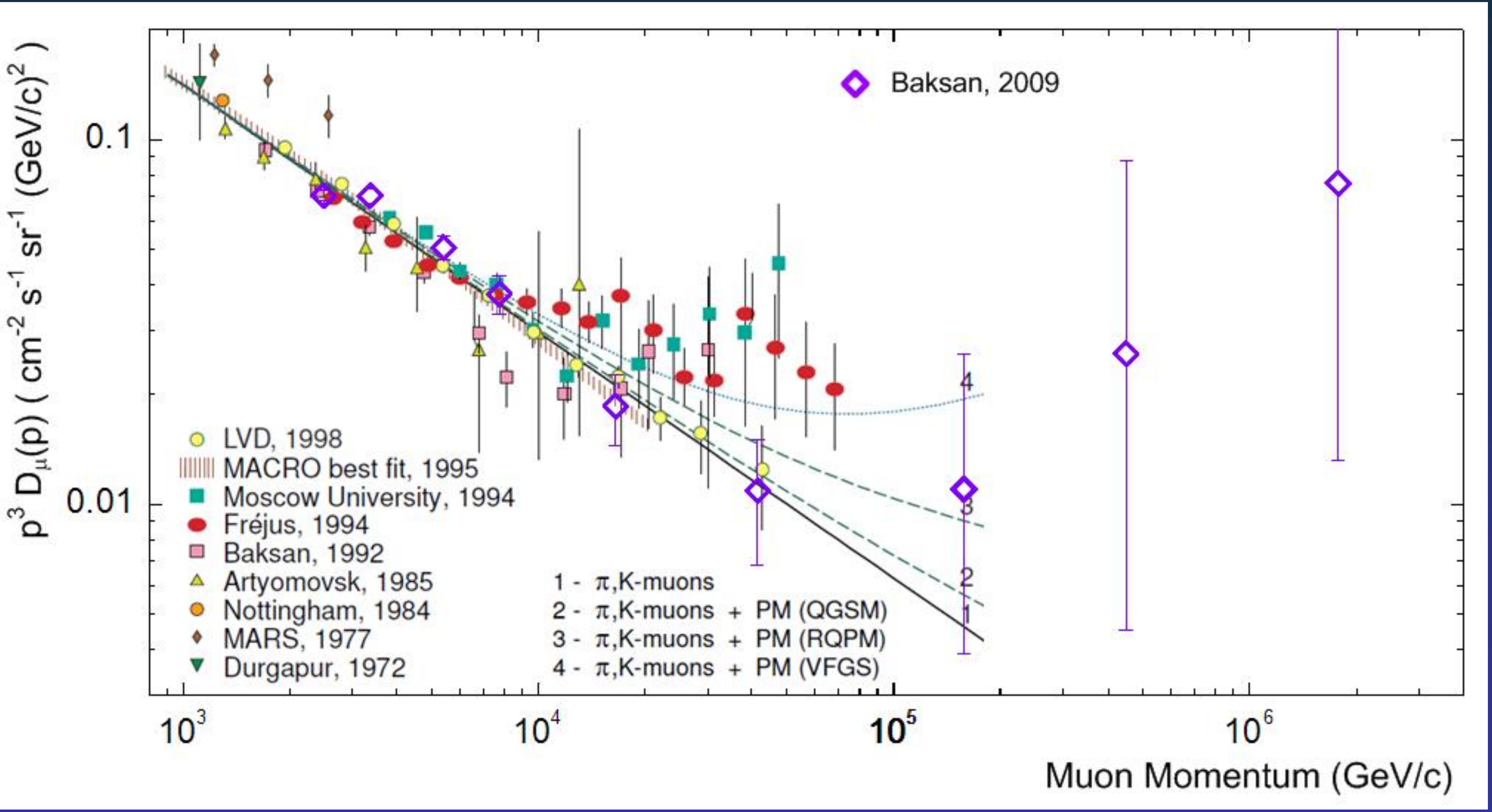


Baksan underground scintillation telescope

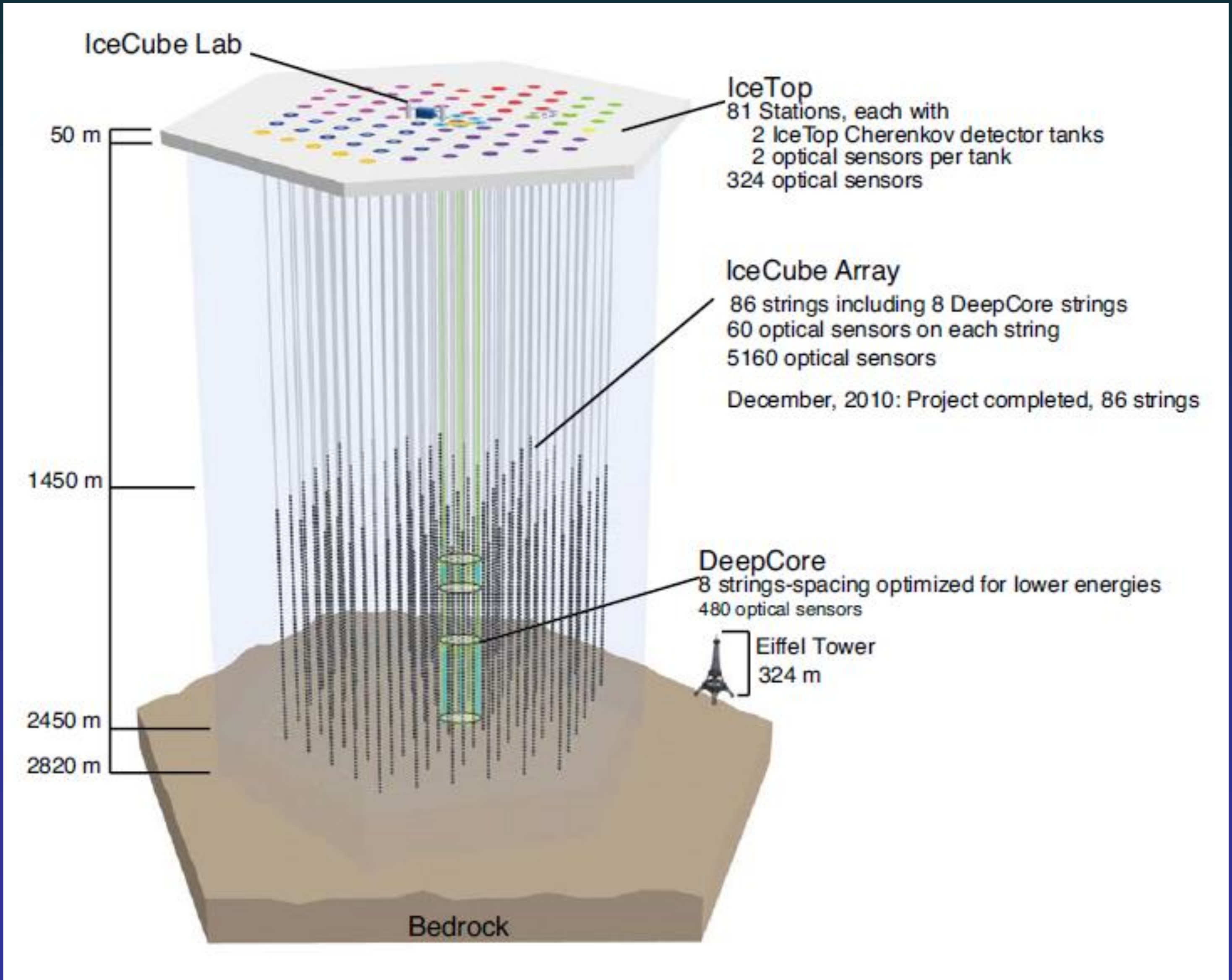


Preliminary results of muon energy spectrum investigations in Baksan Underground Scintillation Telescope (BUST)

Astroparticle Physics, 2012, 36, 224-236.

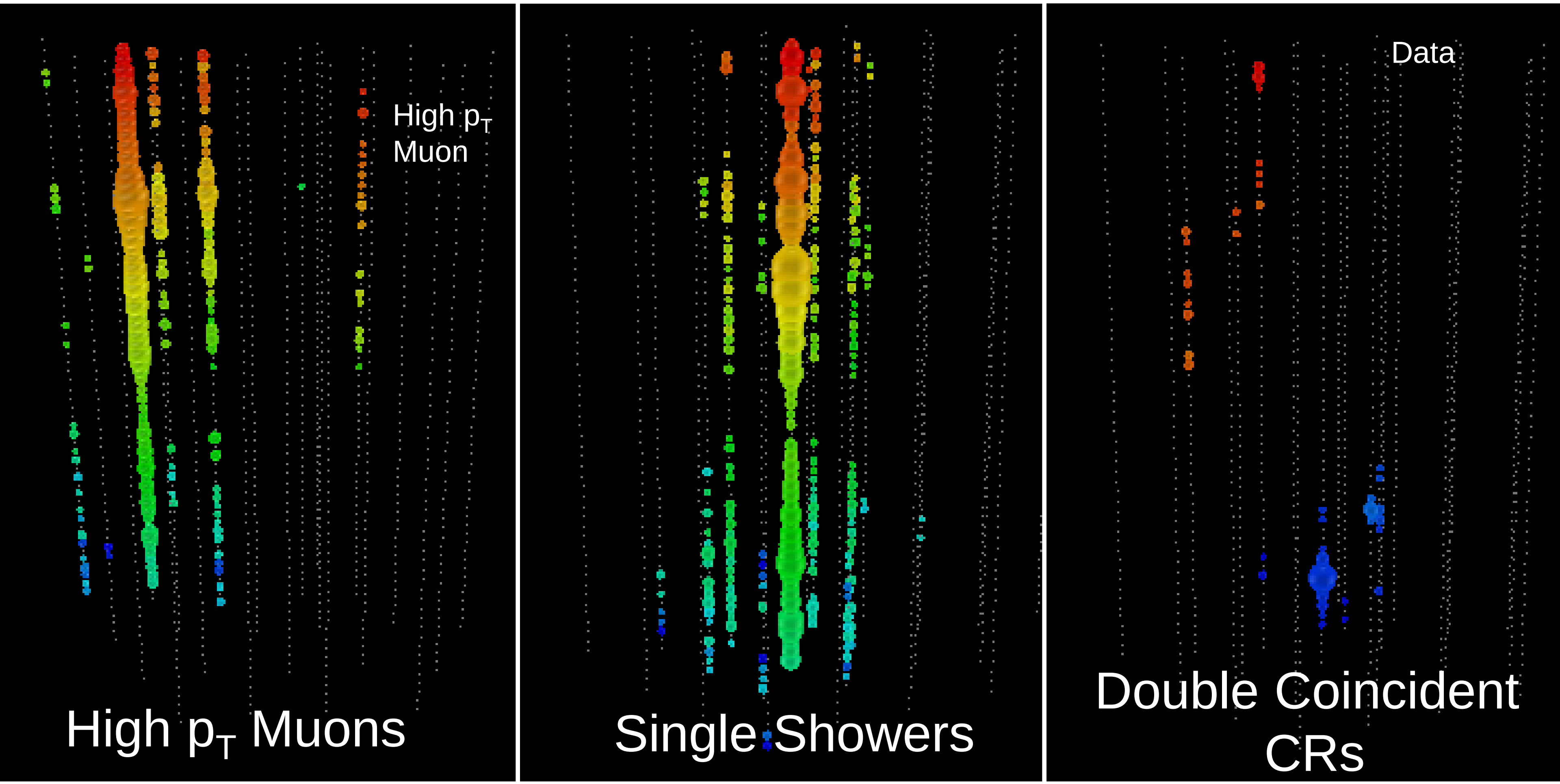


IceCube

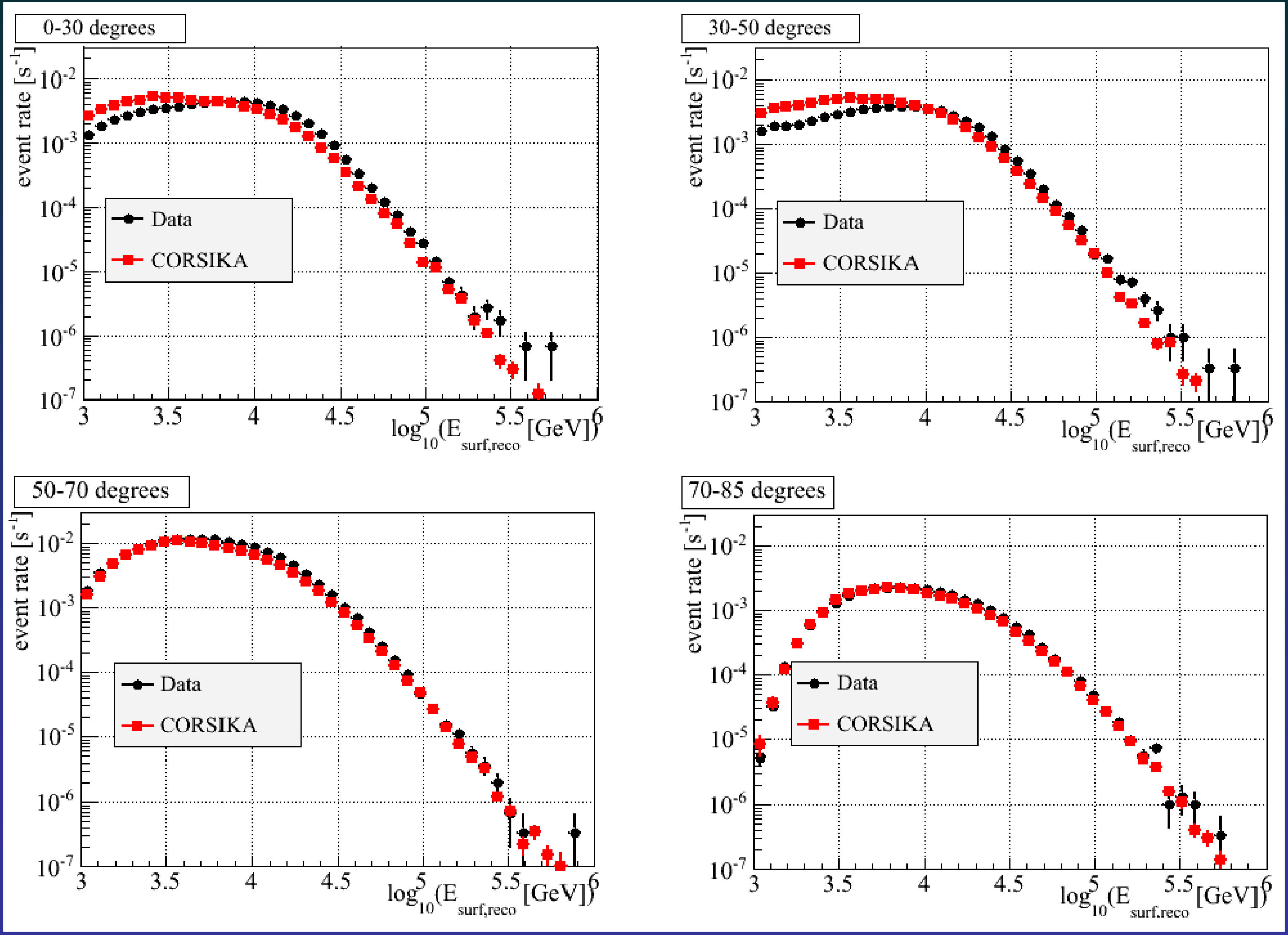

IceCube Lab
IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors
December, 2010: Project completed, 86 strings
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m
Bedrock

IceCube results

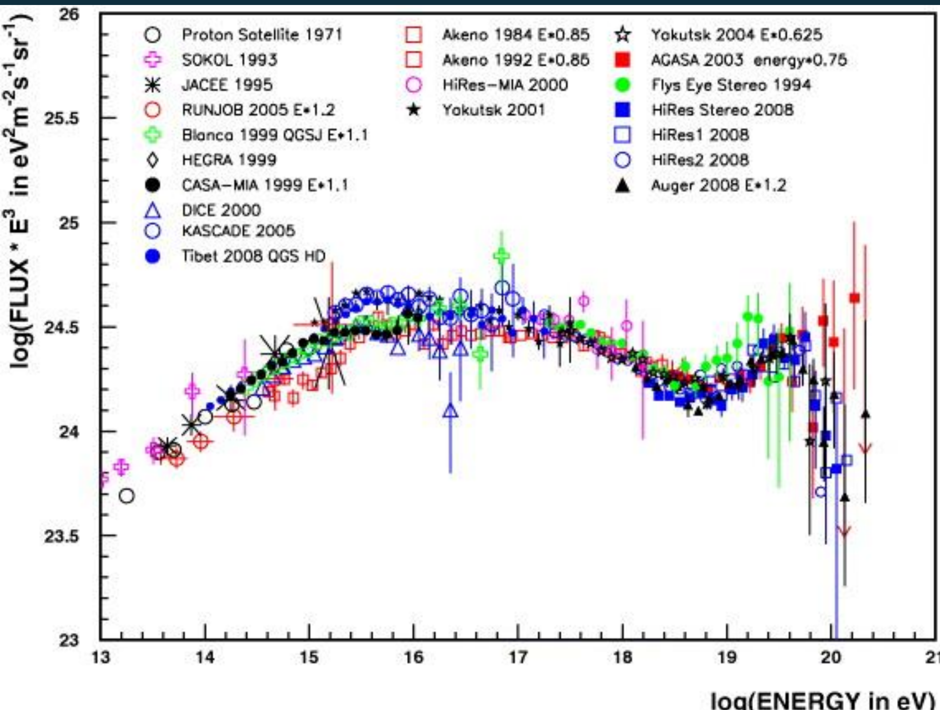
Bundle

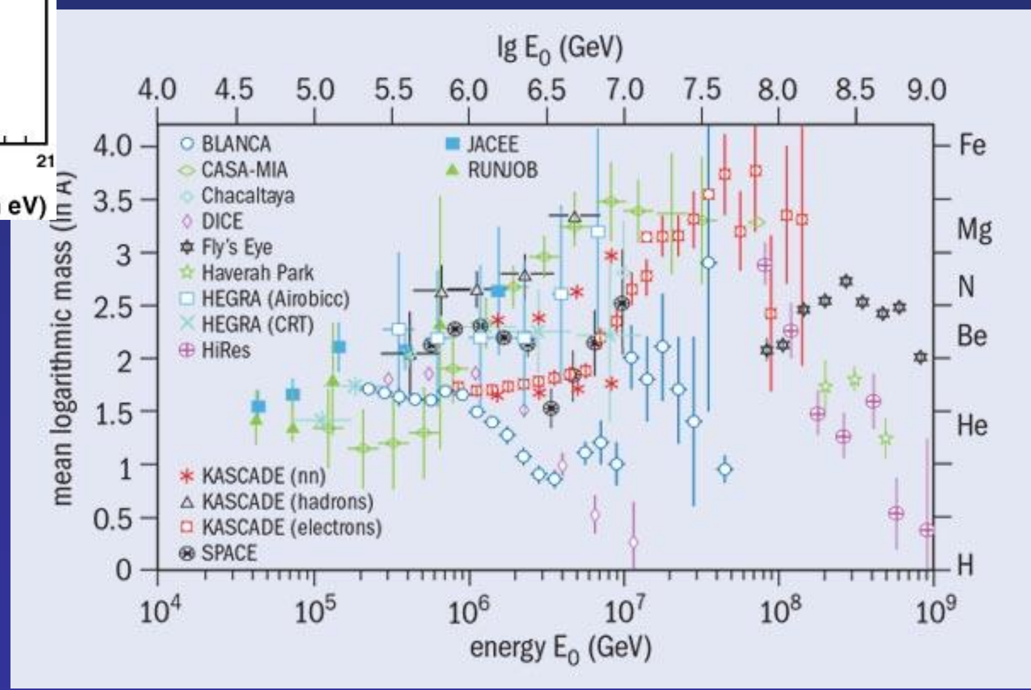


Muon energy spectrum - 2011



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.

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

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

Quark-gluon matter

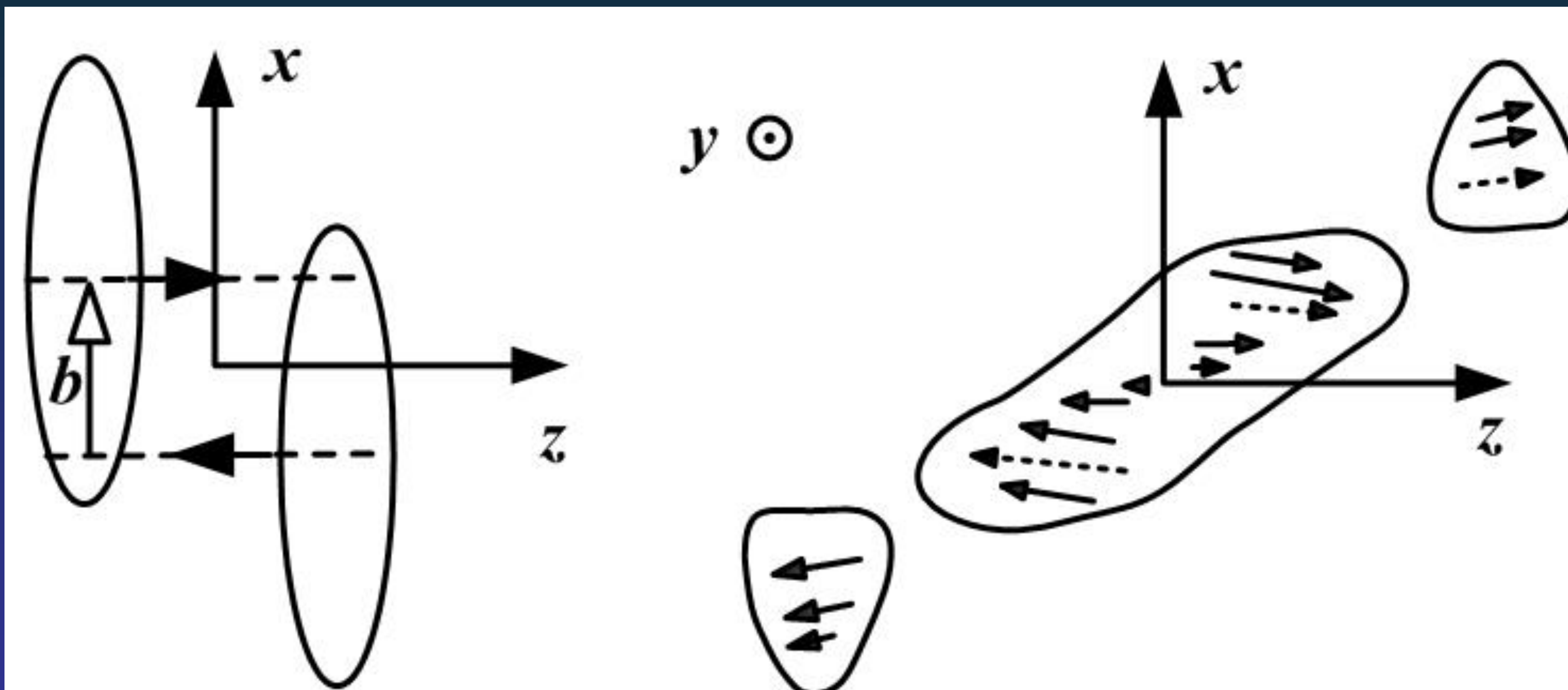
1. Production of QGM provides two main conditions:
   - threshold behavior, since for that high temperature (energy) is required;
   - large cross section, since the transition from quark-quark interaction to some collective interaction of many quarks occurs:

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

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

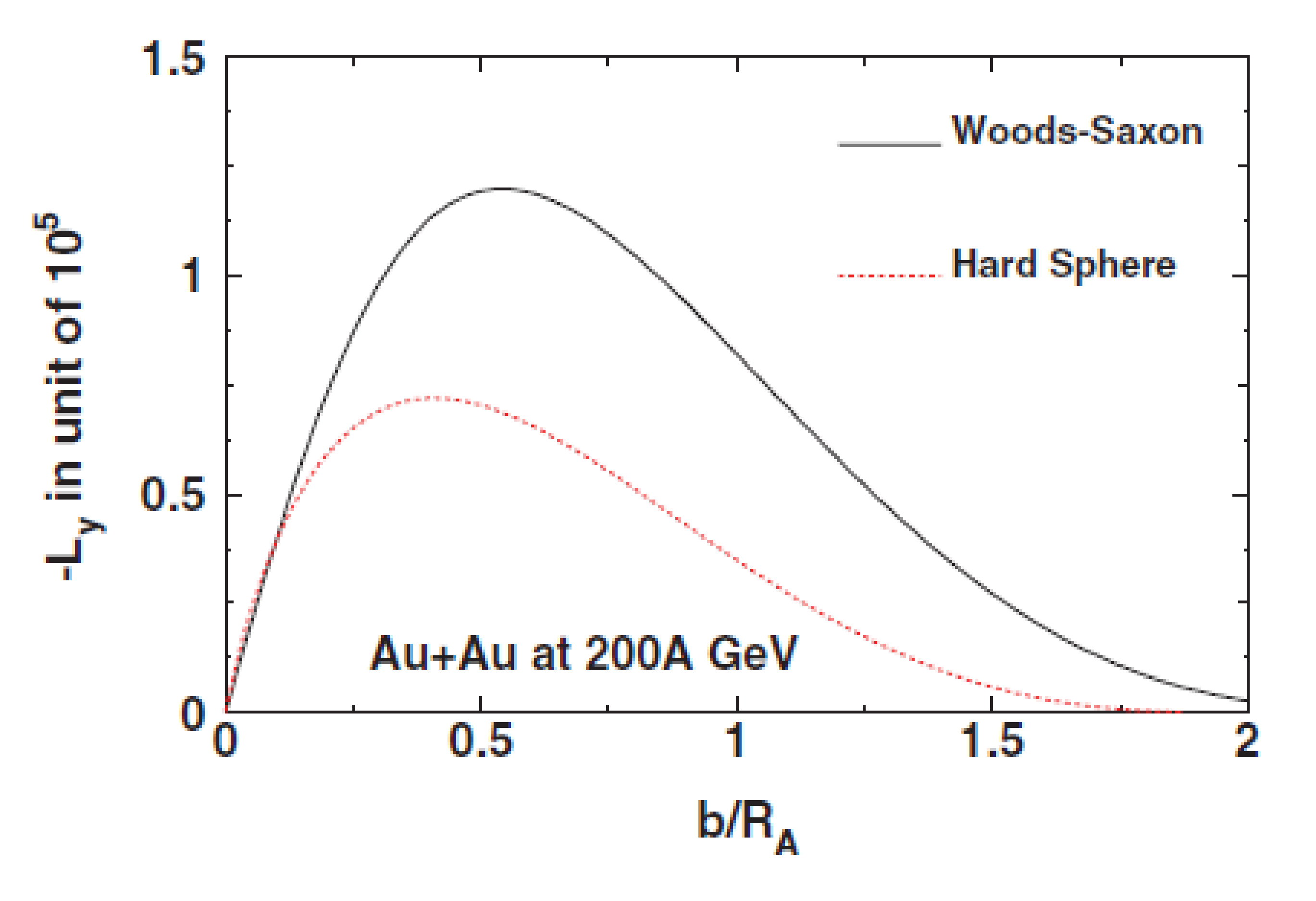


This momentum is increased with energy $L \sim \sqrt{s}$.

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

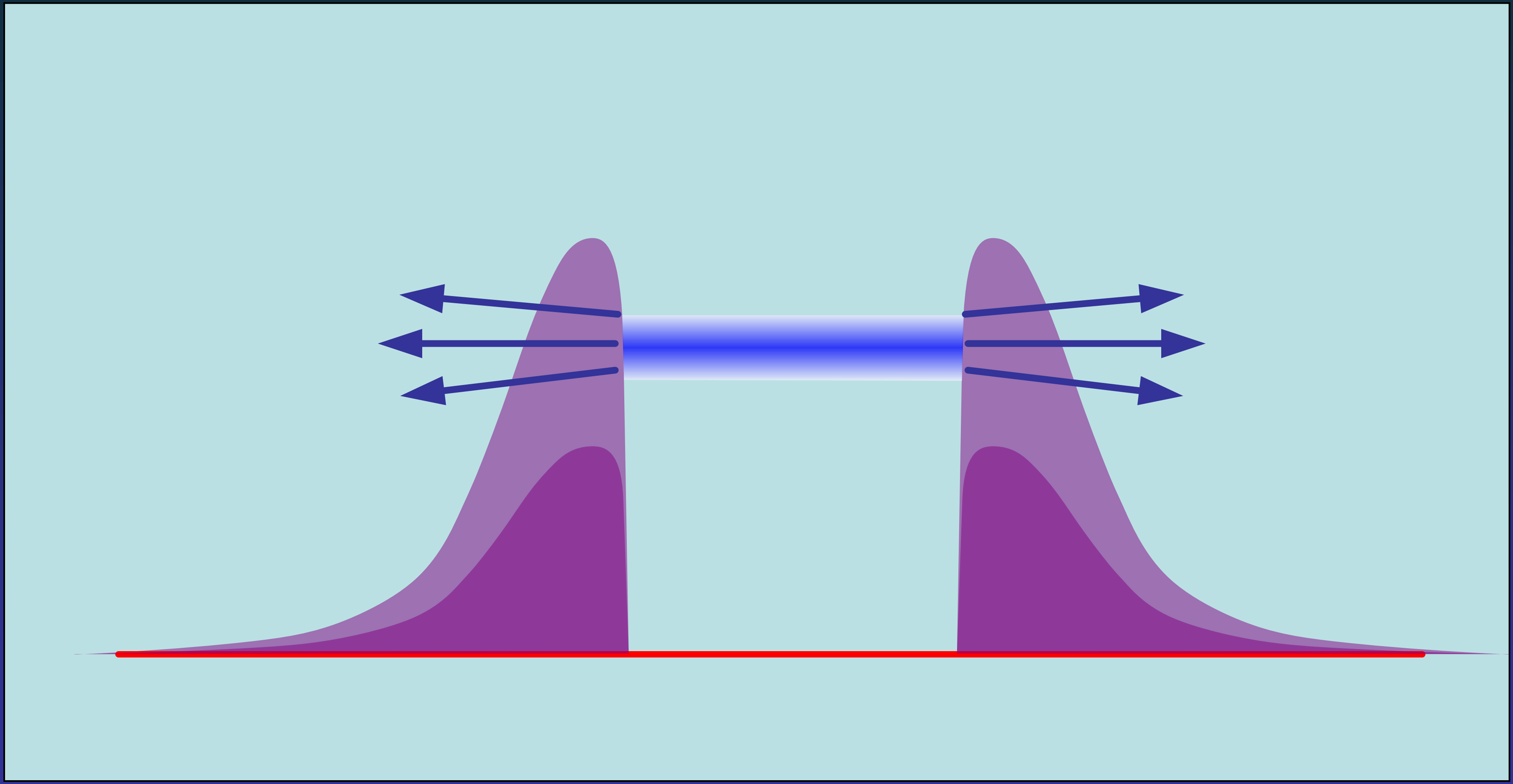


Total orbital angular momentum of the overlapping system in Au+Au collisions at the RHIC energy as a function of the impact parameter b.

Centrifugal barrier

1. A blob of a globally polarized QGP 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.

Centrifugal barrier for different masses



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%);

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

How to check the new approach?

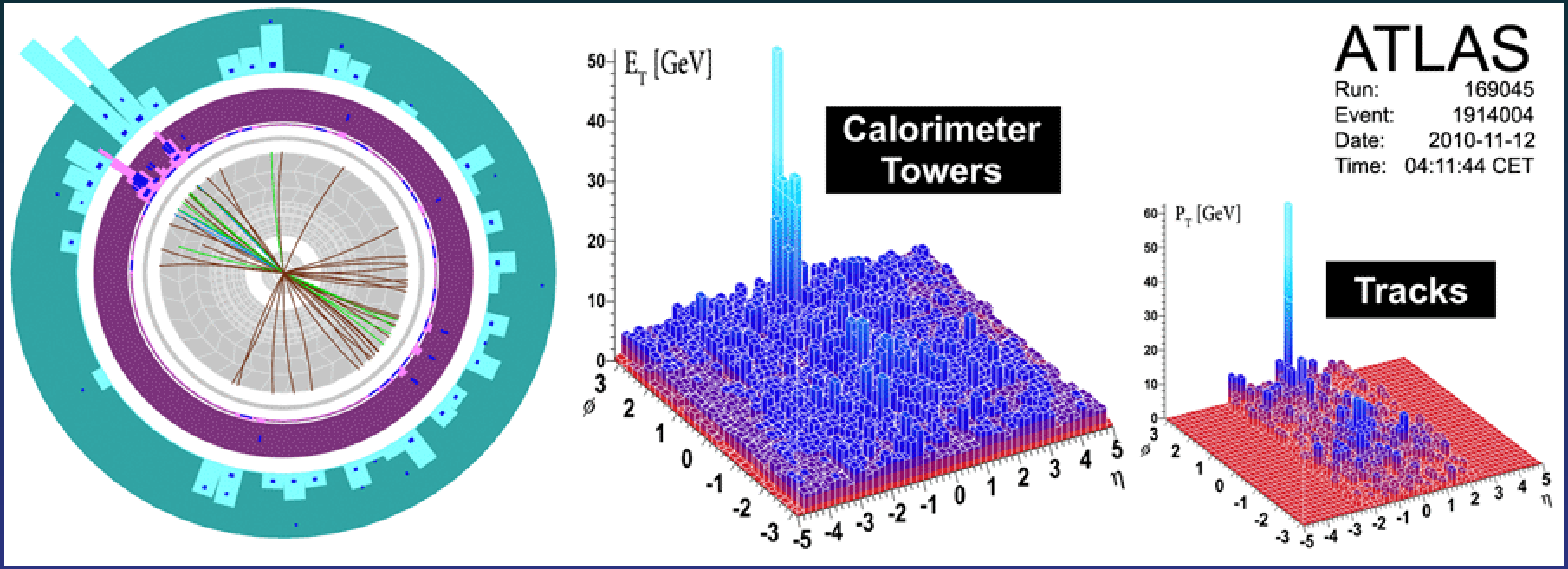
There are several possibilities to check the new approach in LHC experiments, since QGM with described characteristics (excess of *t*-quarks, excess of VHE muons, sharp increasing of missing energy, etc.) doubtless can be observed.

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.

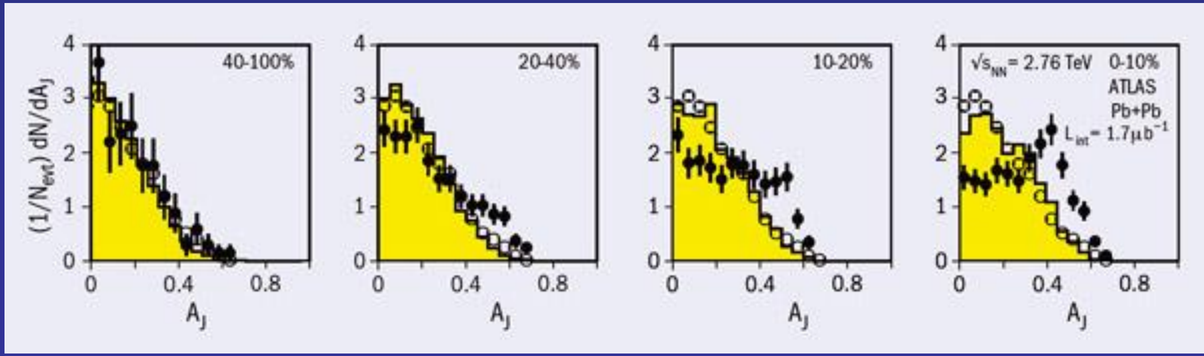
Apparently, some evidences of observation of the effects predicted by new model were yet obtained in A-A interactions.

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:

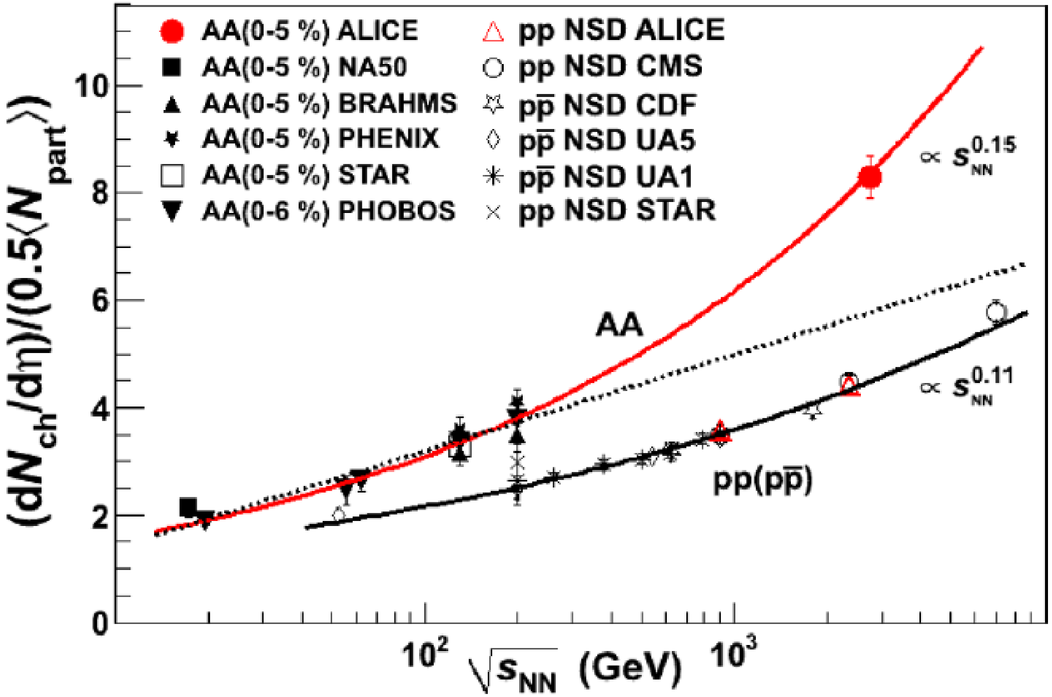
$$T_b \sim 65 \text{ GeV}, \qquad T_W \sim 25 \text{ GeV}.$$

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.)

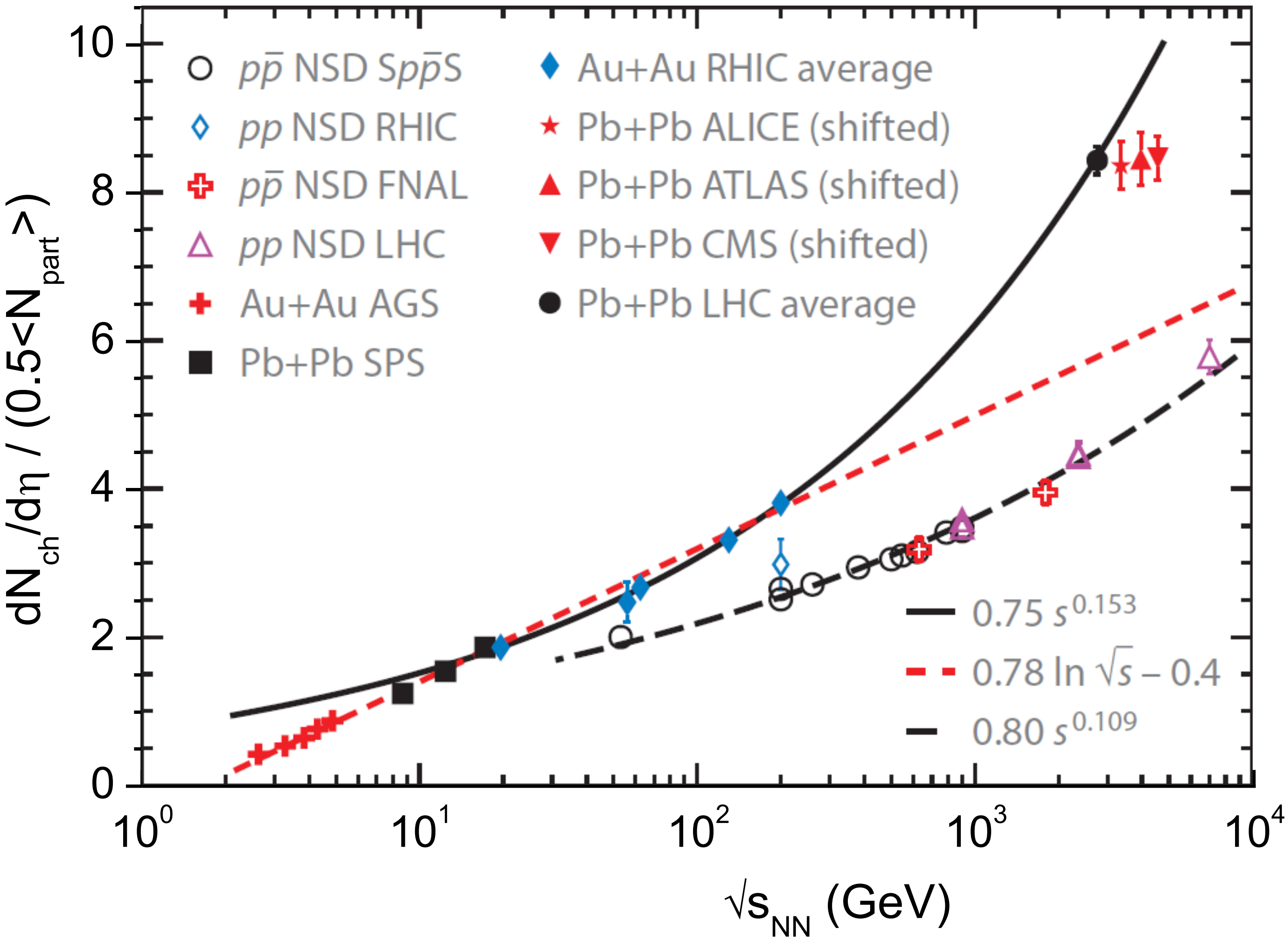
log extrapolation fails (finally!)

2.2 x central Au+Au

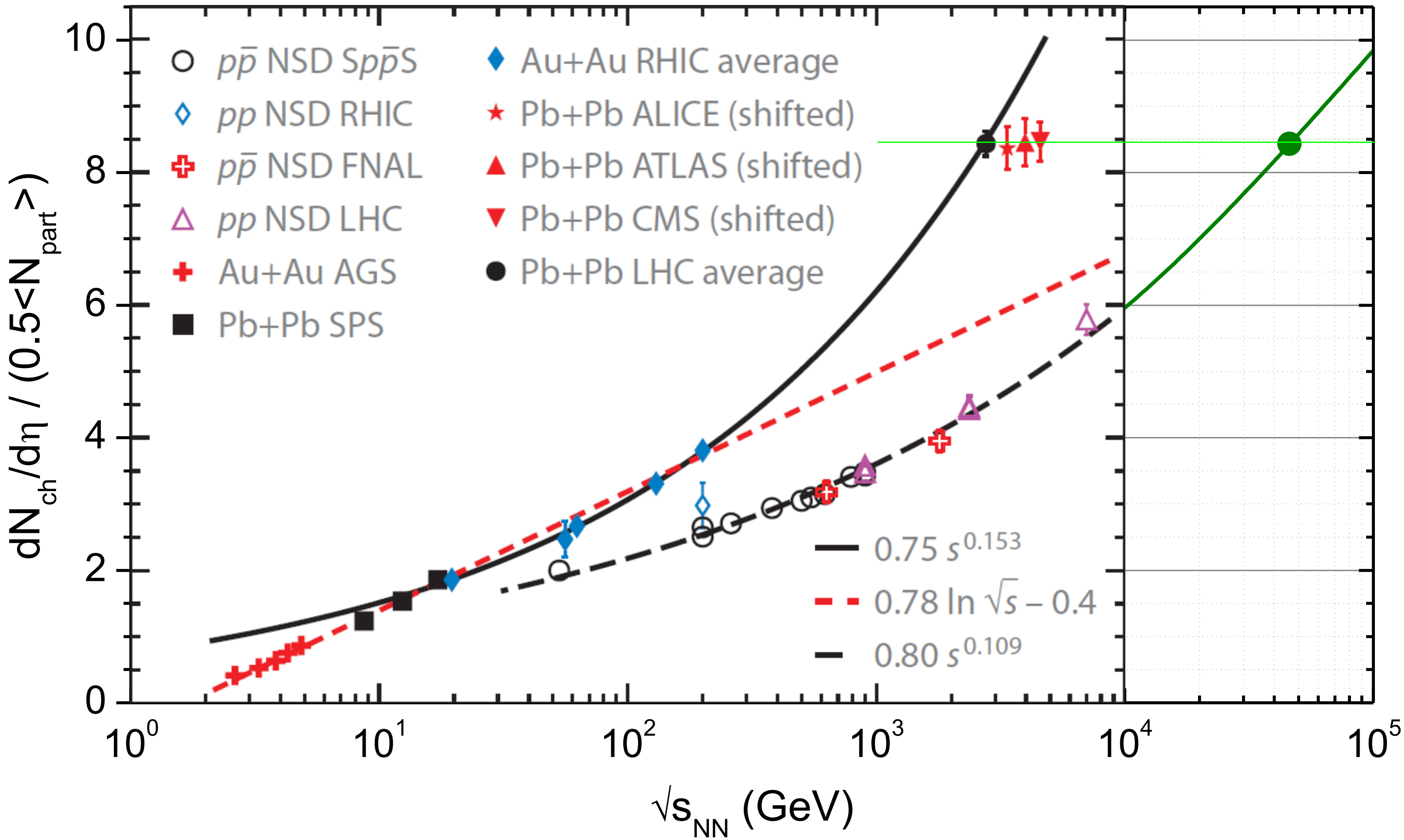
($\sqrt{s_{NN}}$=0.2 TeV)

1.9 x pp (NSD)

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



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



$p\bar{p}$ 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.

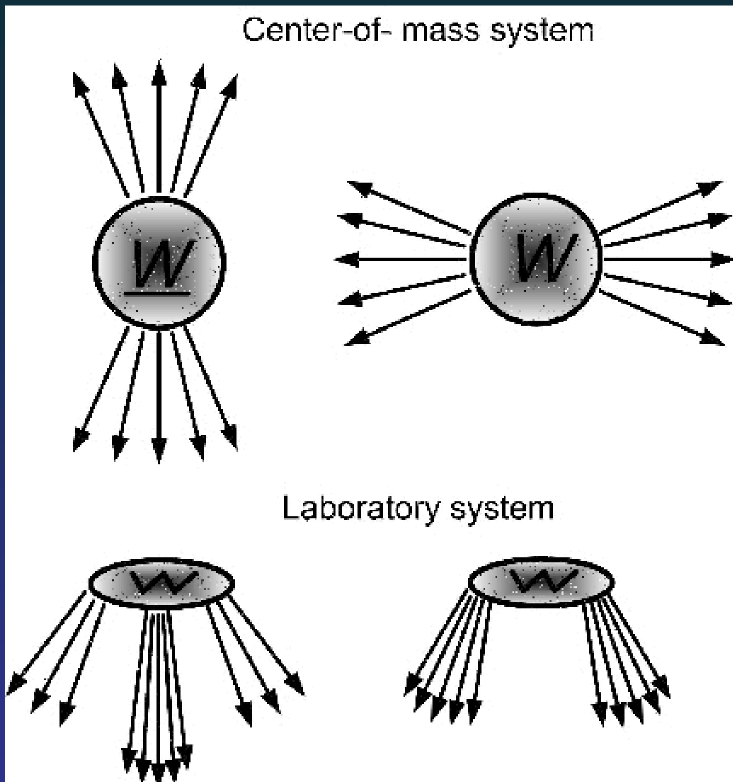
If take into account that $\sqrt{S_{NN}}$ cannot be more than $\sqrt{S_{NN}}$ for pp-interaction it is possible to evaluate number of nucleons in QGP blob.

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

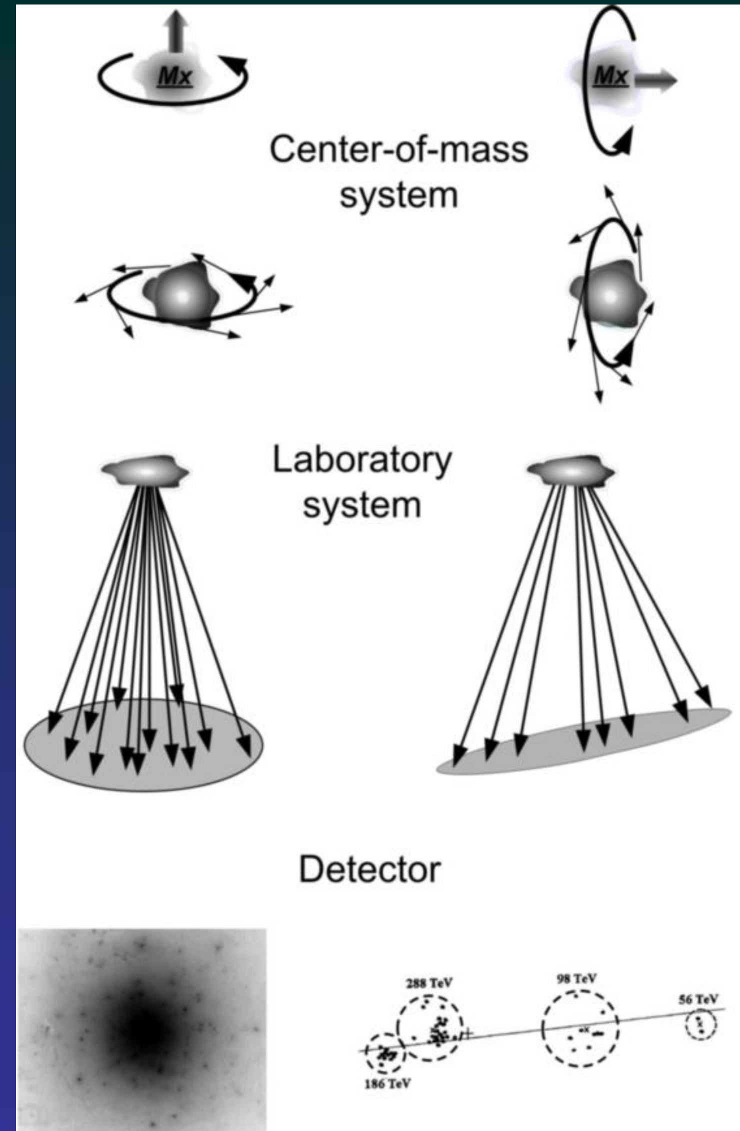
Conclusion

If the considered approach to explanation of CR results is correct, than in LHC experiments it is necessary to search new physics in nuclei-nuclei 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.

Thank you for attention!



Production of families
and events with large p_t



Halo and alignment production
in decays of resonance state
with large spin