LHC on the March
22 November 2012

Consequences for LHC from cosmic ray experiments

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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.

But what are the next searches of new physics?

- 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-interaction and namely at these energies and above many interesting and sometimes unusual results were obtained in CR investigations.

- Of course, cosmic ray experiments have many drawbacks. As a rule, in experiments are unknown: type of particles, their energy and direction, full flux, place and time of interaction.

- Upper limit of direct measurements of CR energies is about 10^{15} eV. For higher energies, evaluations of EAS energies are possible only, but they depend on measurement methods and simulation models.

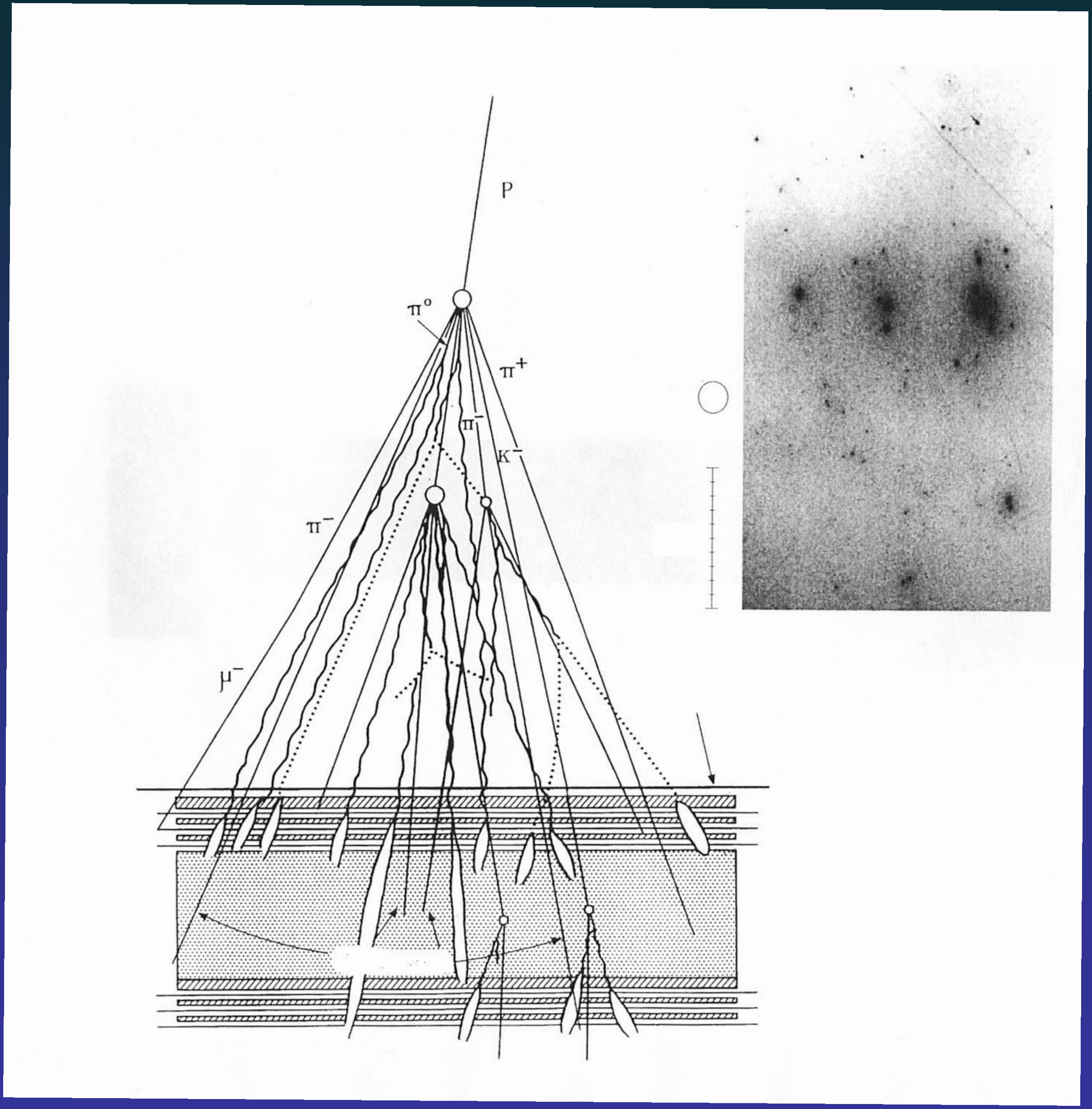
List of unusual events

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

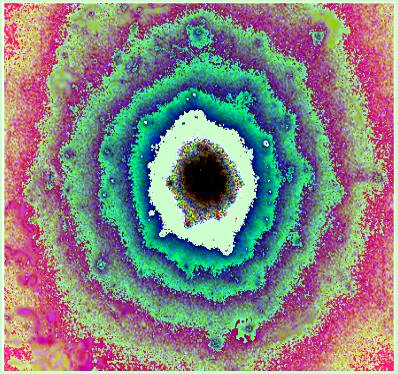
Important: Unusual events appear at PeV energies of primary particles, where the slope is changed.

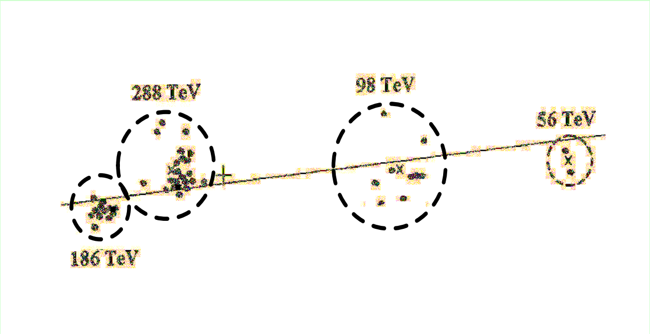
Hadron events

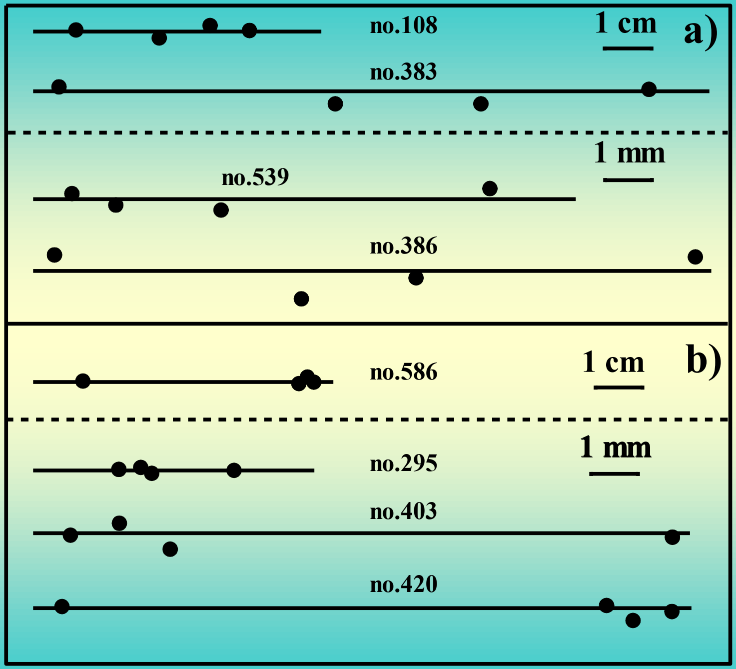
Experiment Pamir



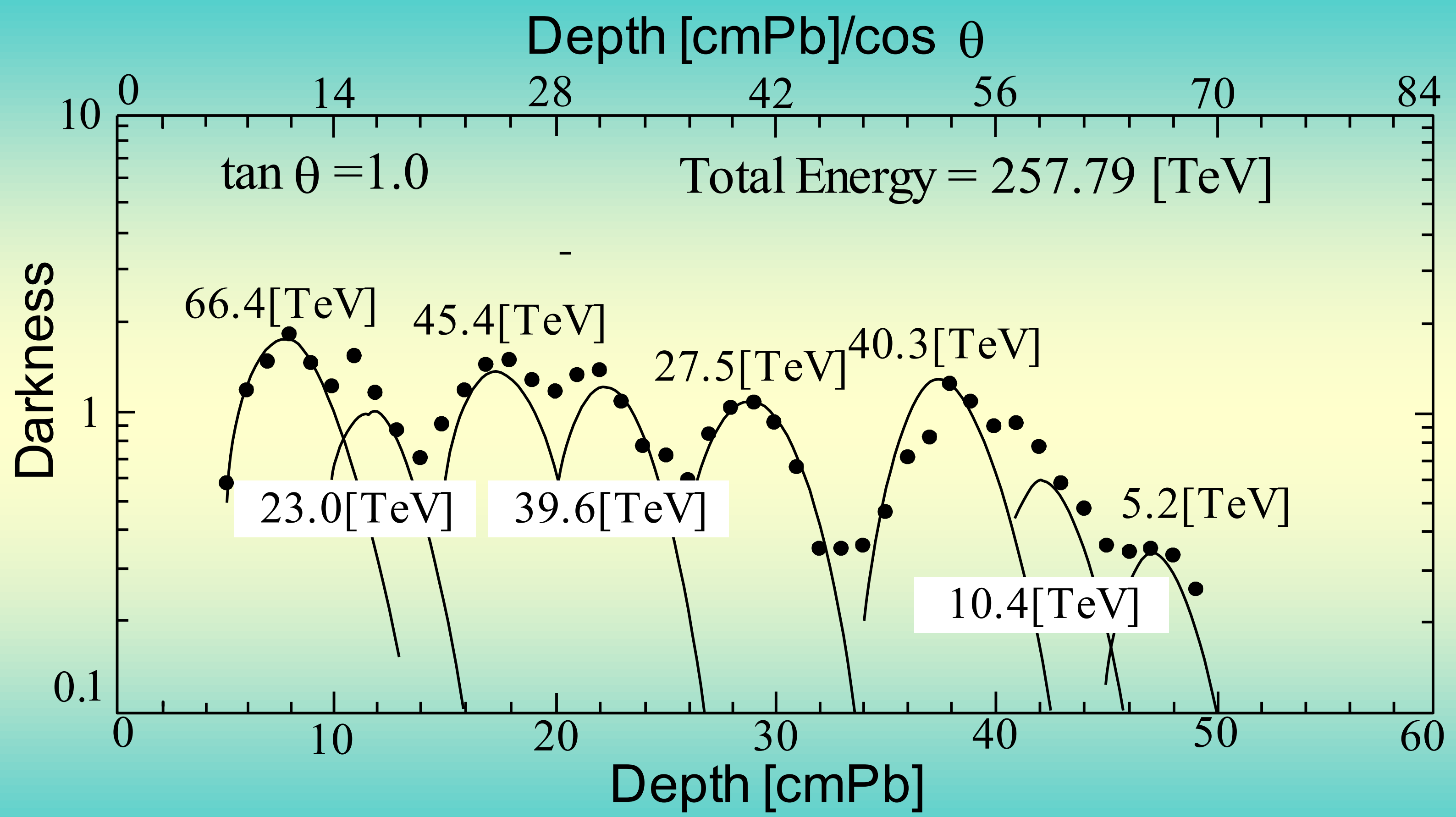
Halo and alignment





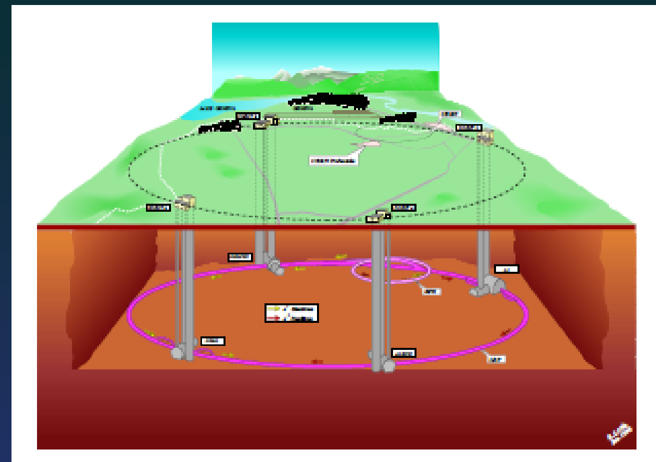


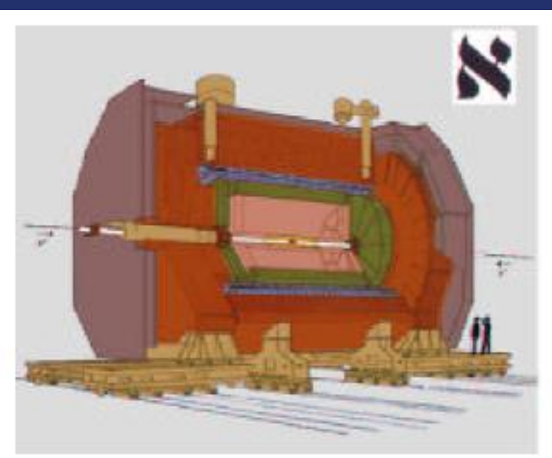
Penetrating cascades



Muon bundles

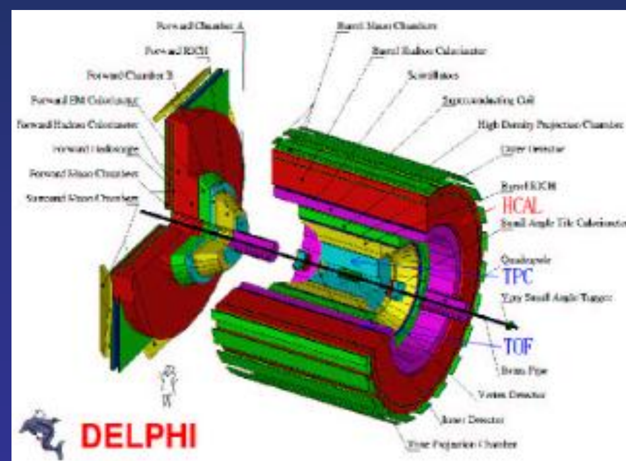
LEP Detectors (CERN)





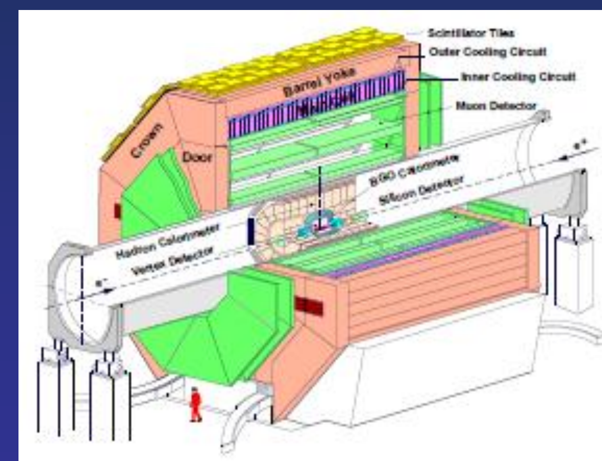
ALEPH

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



DELPHI

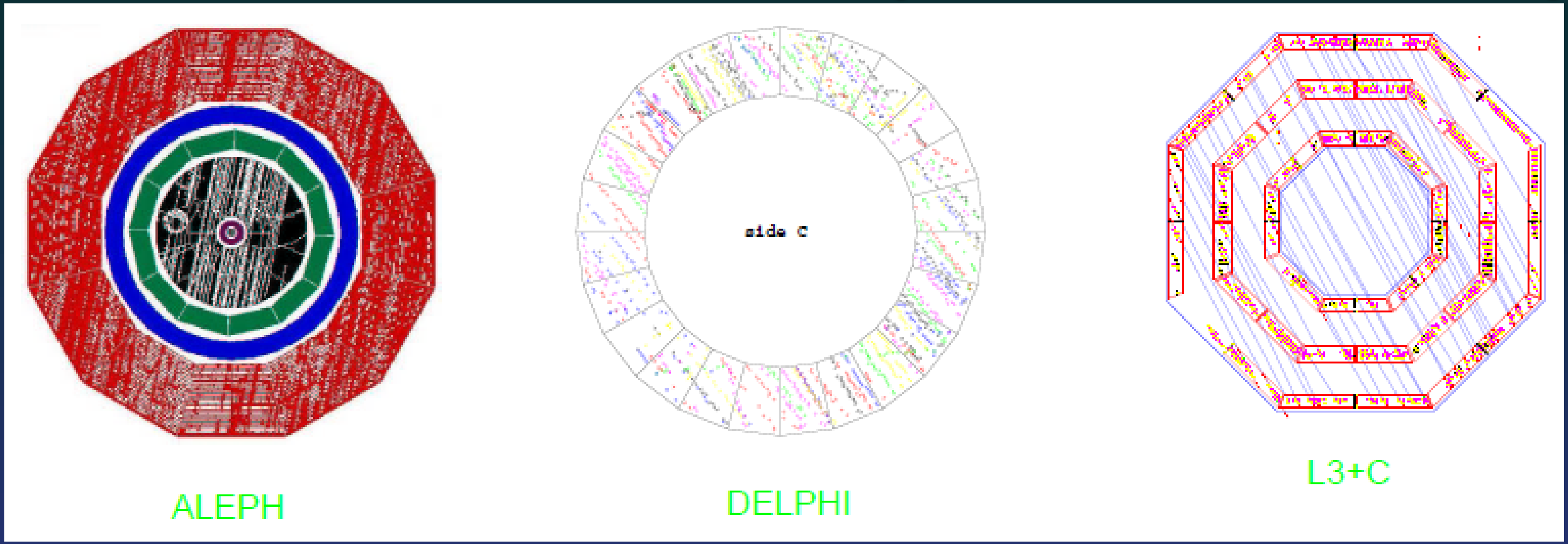
100 m depth ($E_\mu > 50$ GeV)
Hadron calorimeter, TPC, TOF



L3

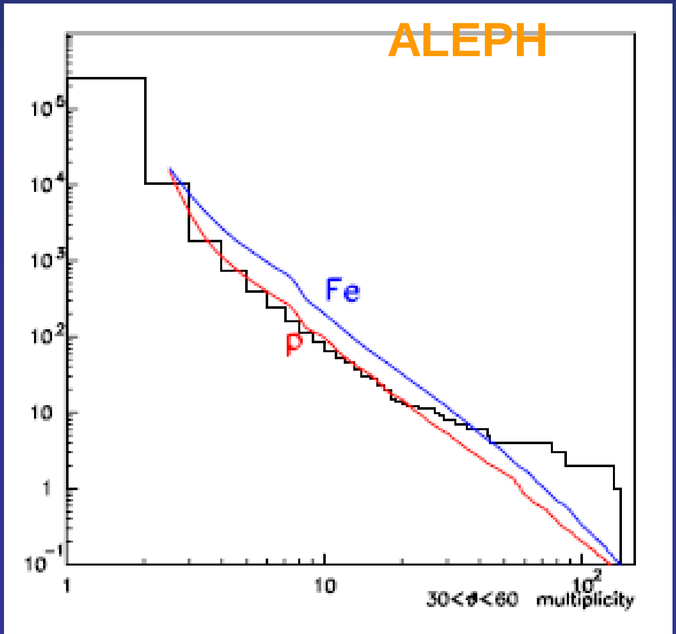
40 m depth ($E_\mu > 15$ GeV)
Drift chambers, Timing
scintillators EAS surface array

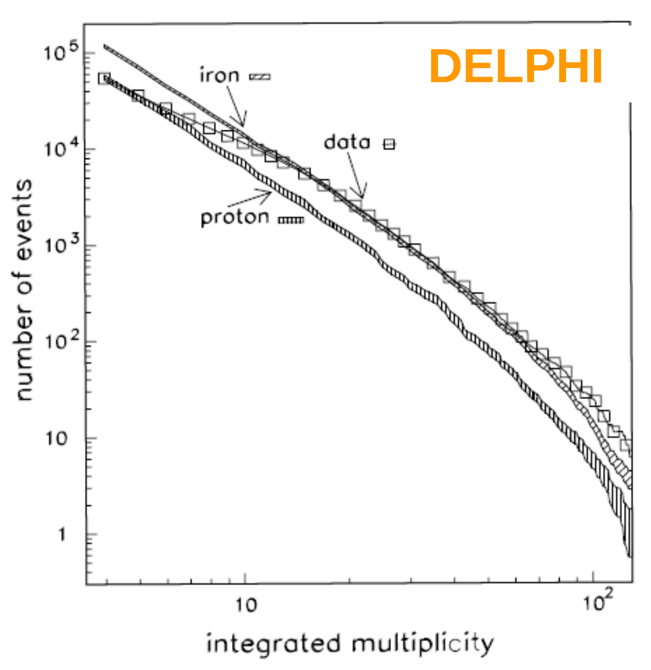
Multi muon events (muon-bundles)



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

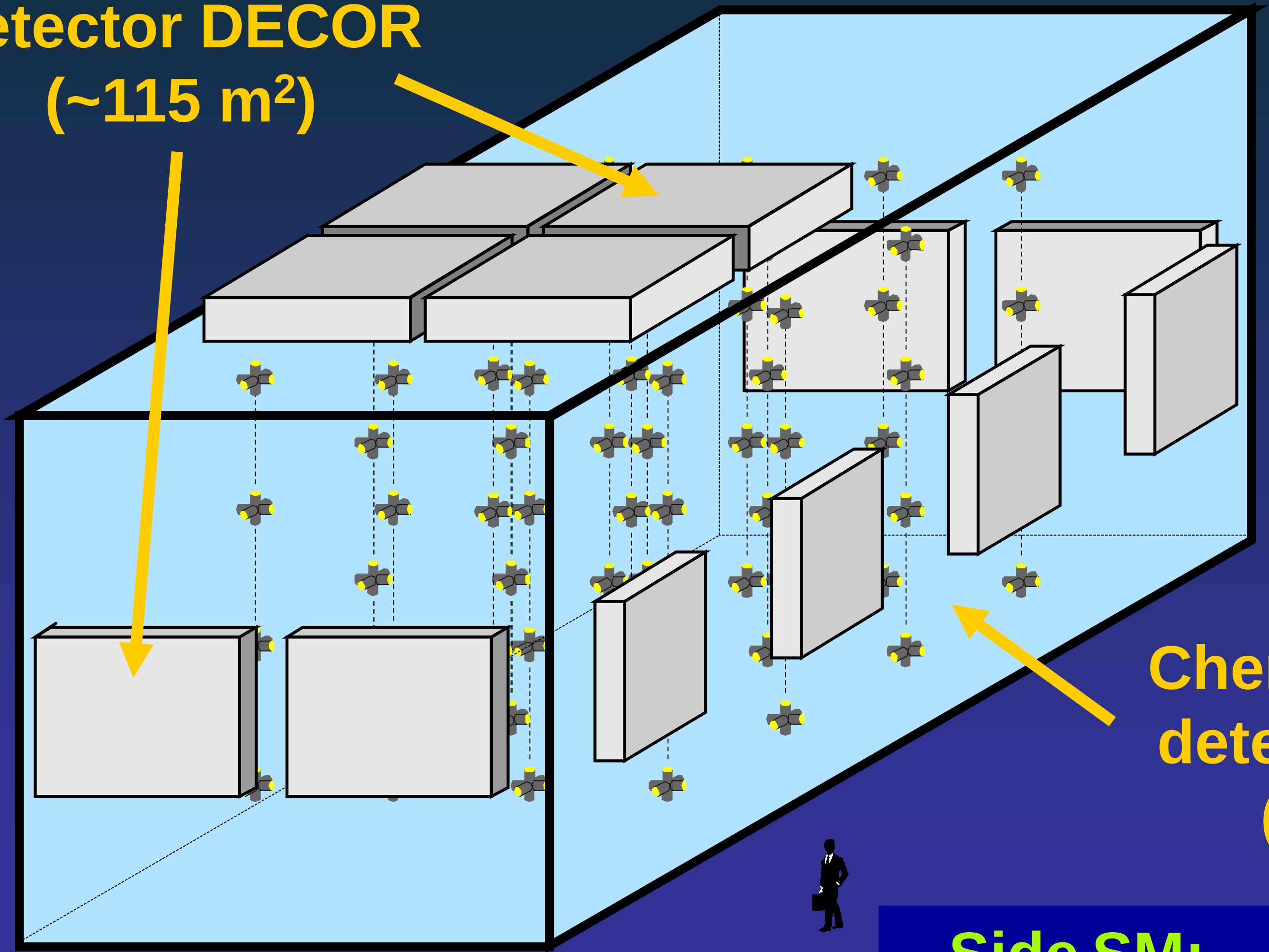
J. Abdallah et al., Astroparticle Physics 28 (2007) 273.





General view of NEVOD-DECOR complex

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

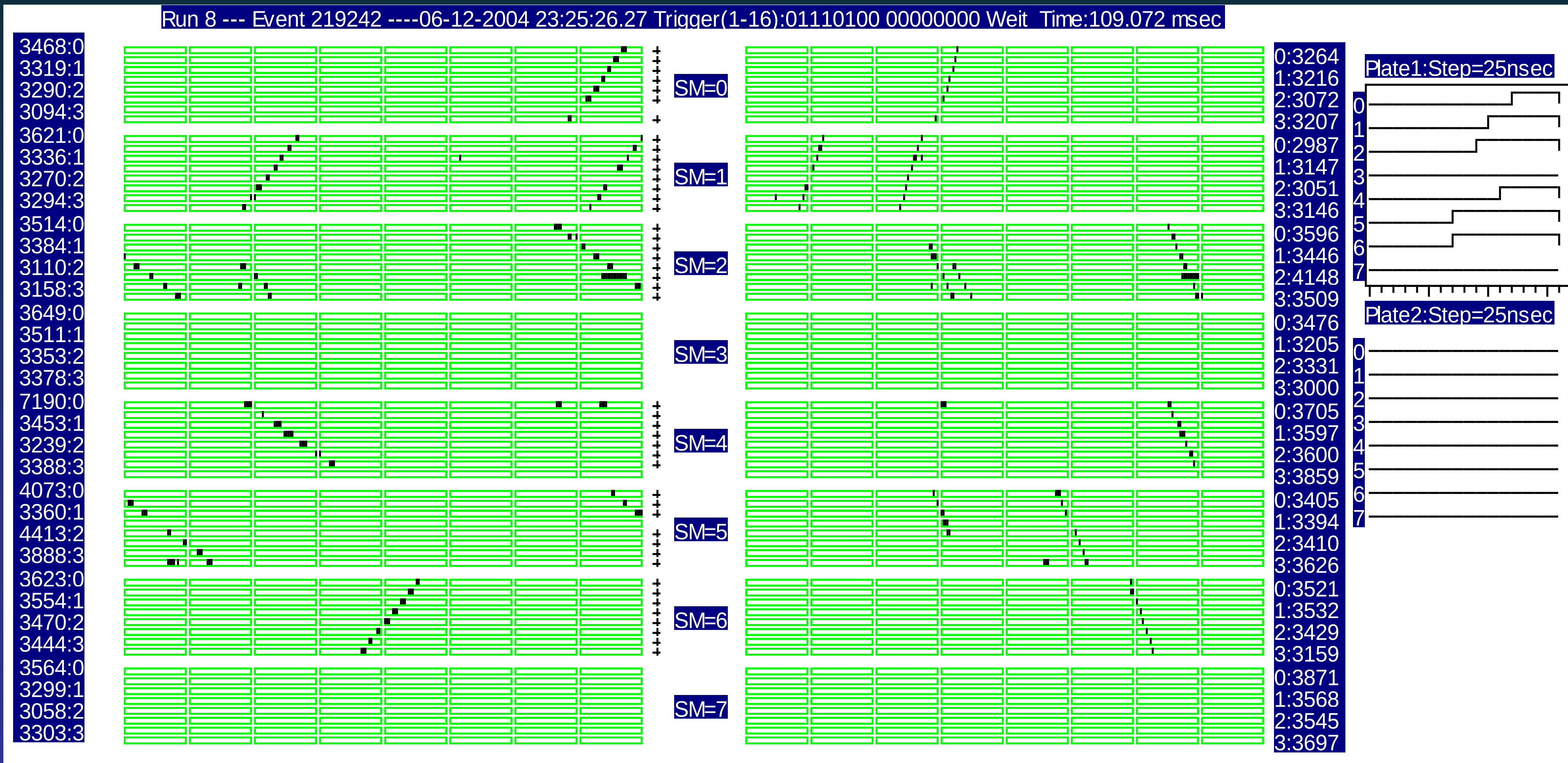


Cherenkov water detector NEVOD ($2000\ m^3$)

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

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

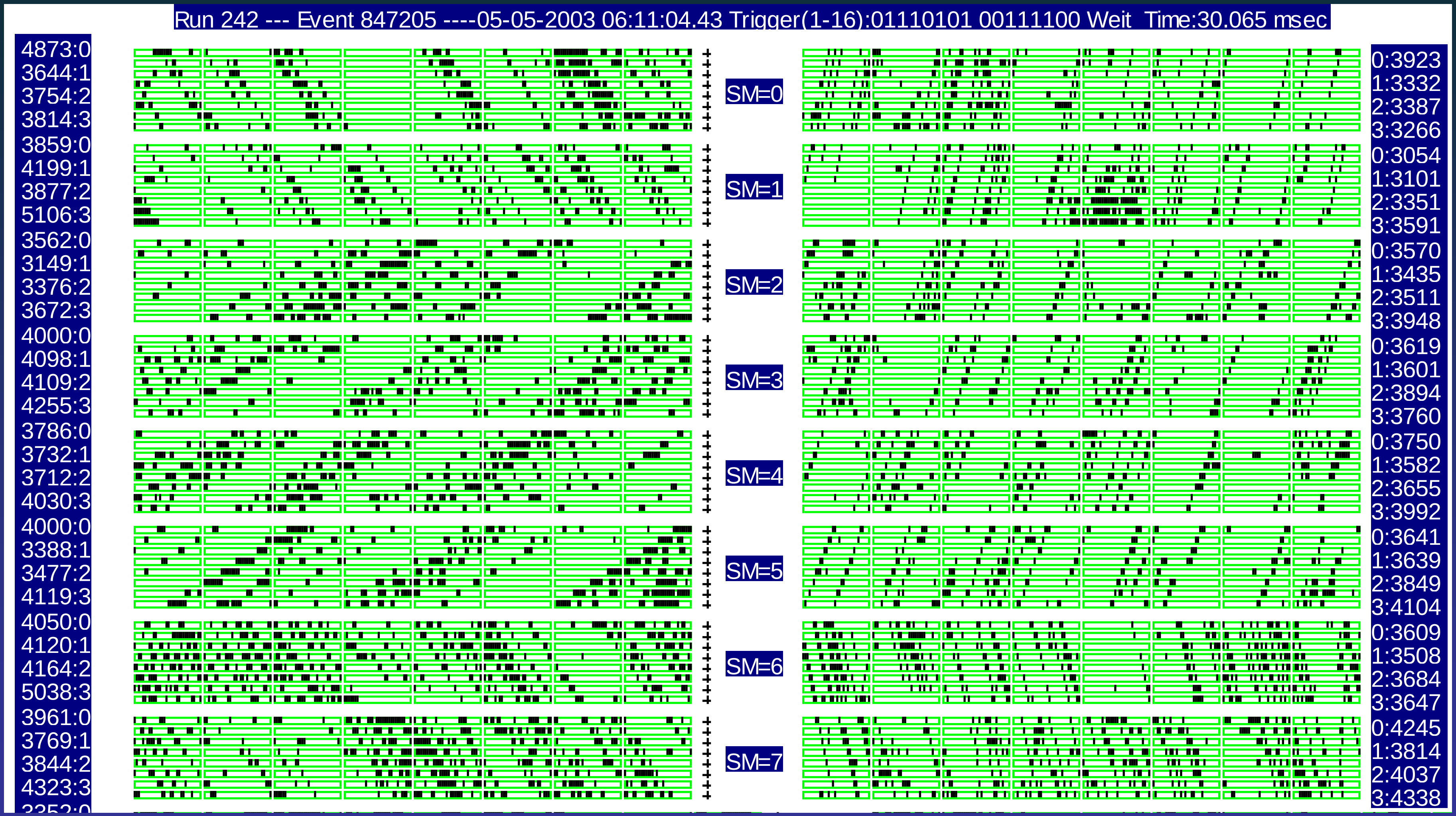
A typical muon bundle event in Side DECOR
(9 muons, 78 degrees)



Y-projection

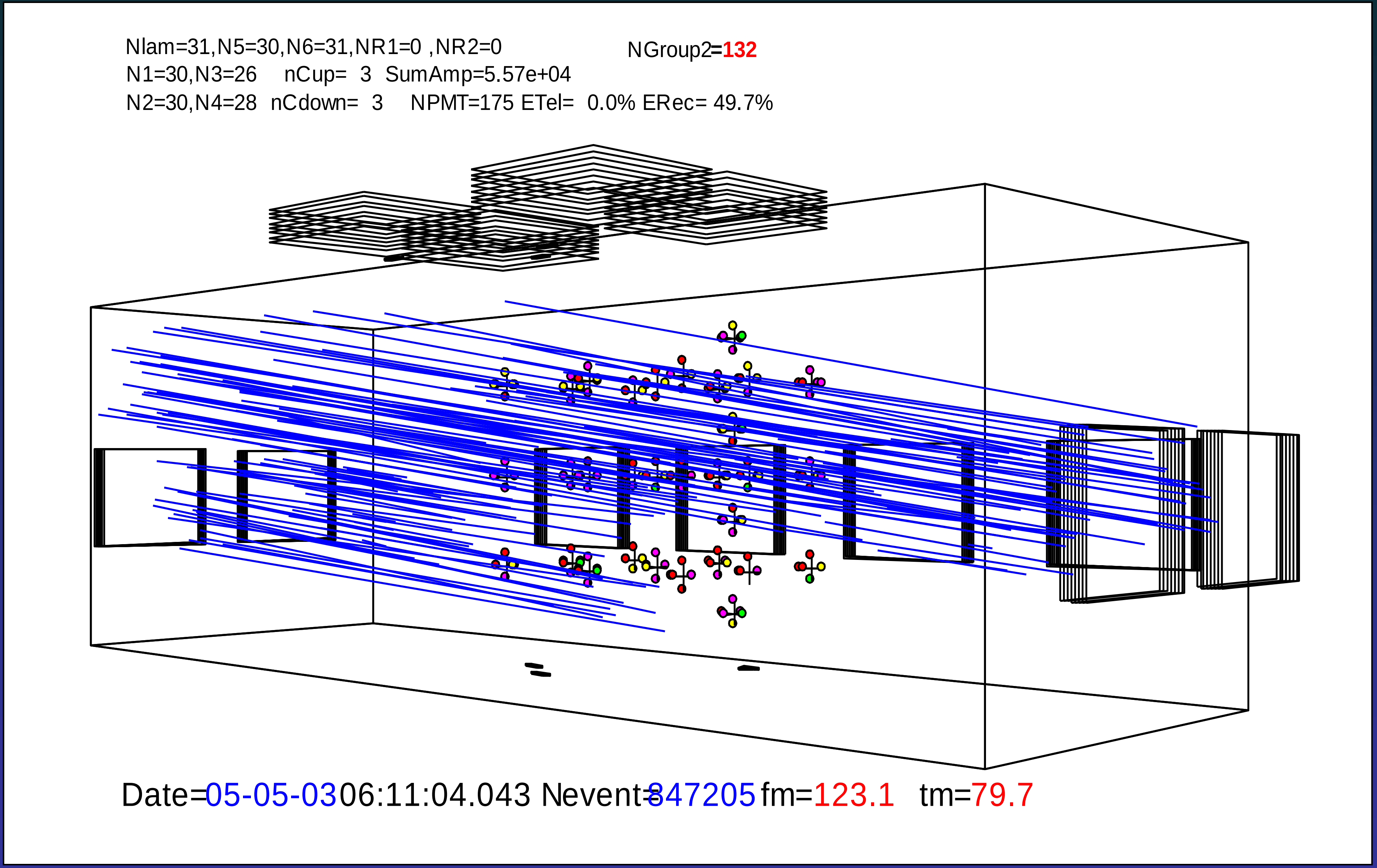
X-projection

A “record” muon bundle event

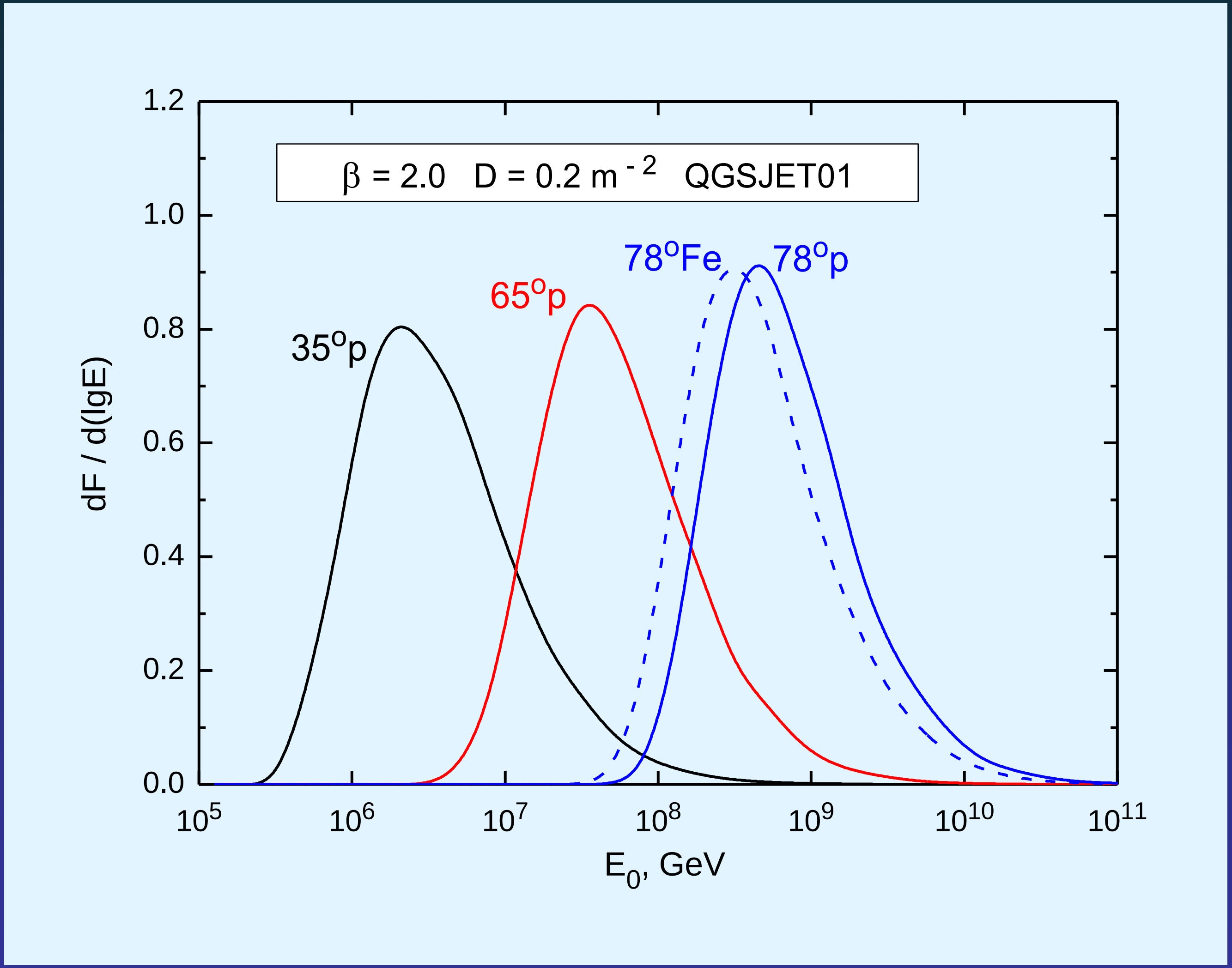


Y-projection **X-projection**

Muon bundle event (geometry reconstruction)

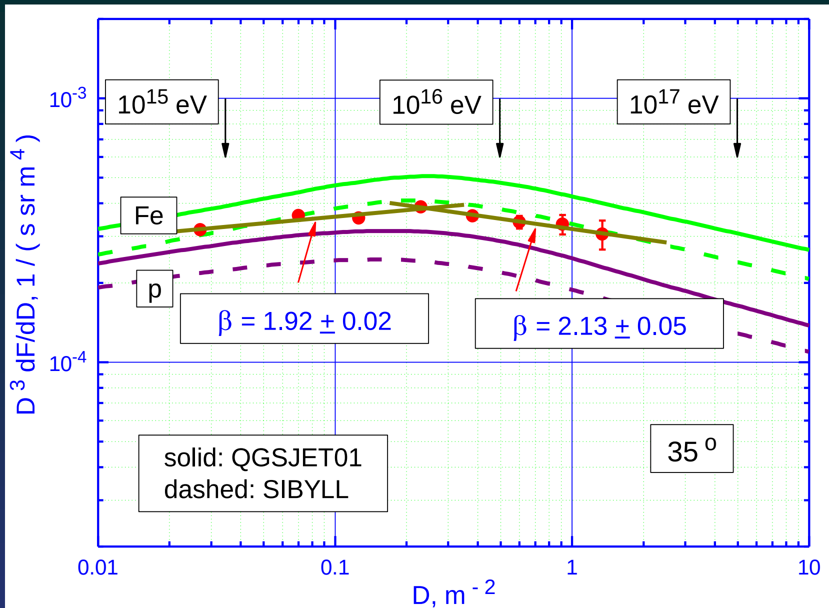


Contribution of primary energies at different zenith angles

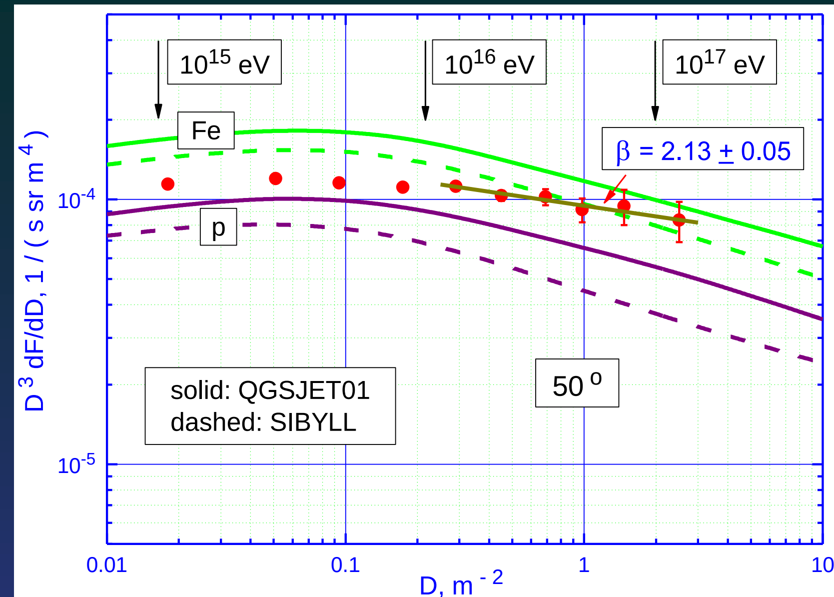


Wide angular interval – very wide range of primary energies !

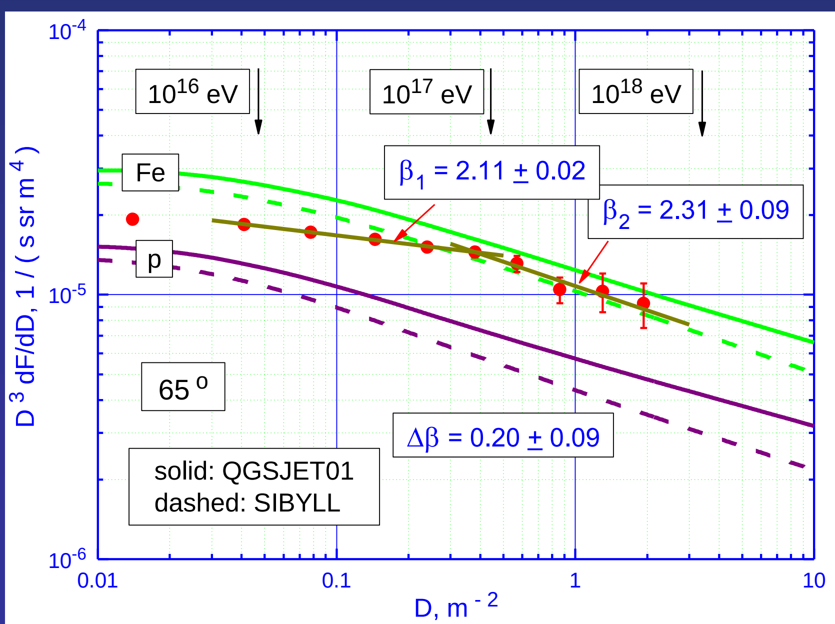
Low angles: around the “knee”



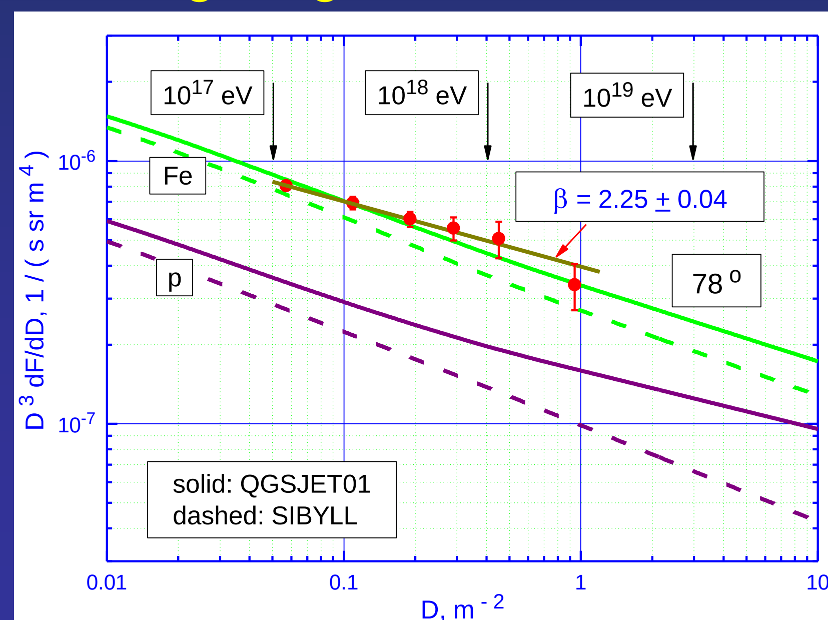
θ = 50° : 10^{16} – 10^{17} eV



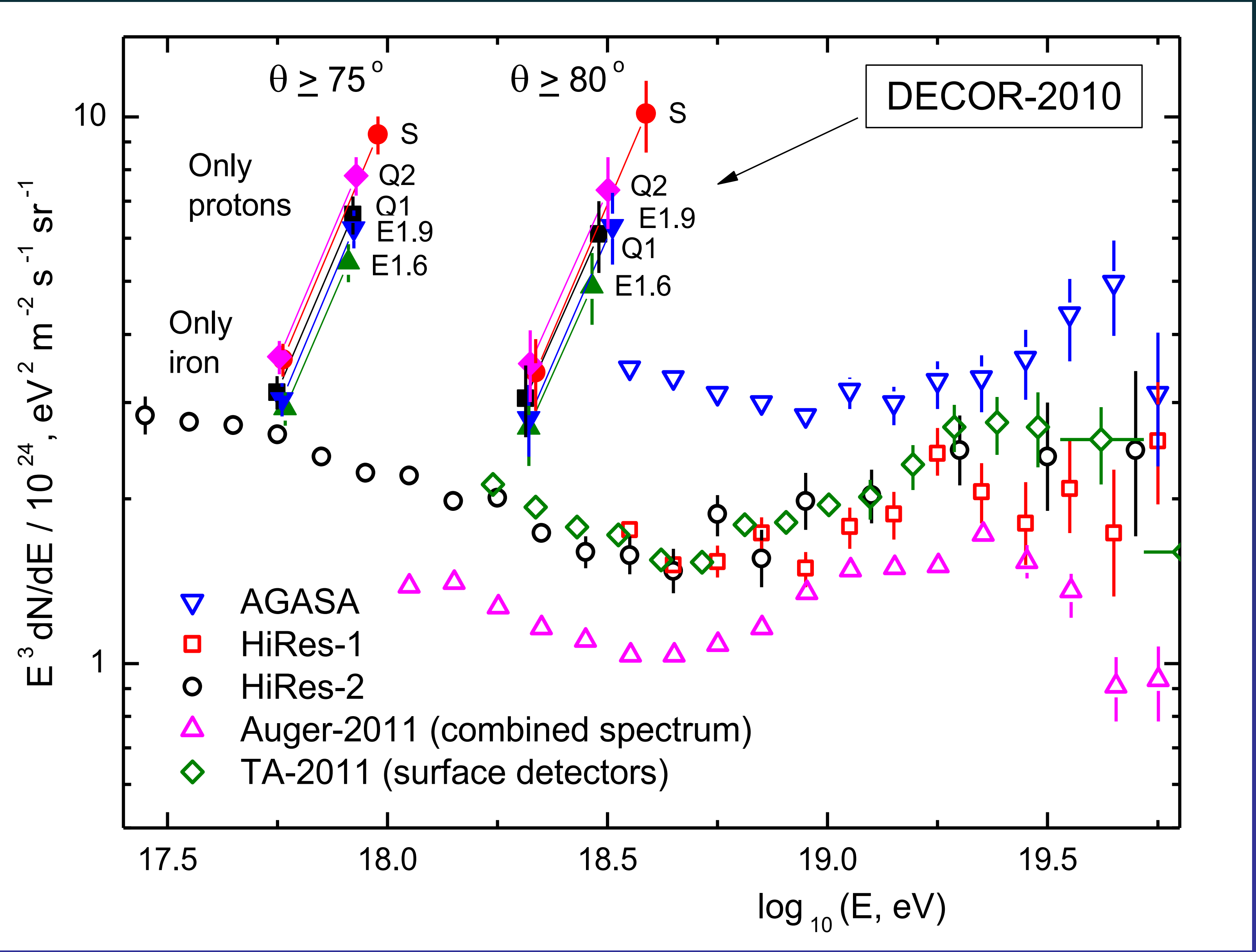
θ = 65° : 10^{16} – 10^{18} eV

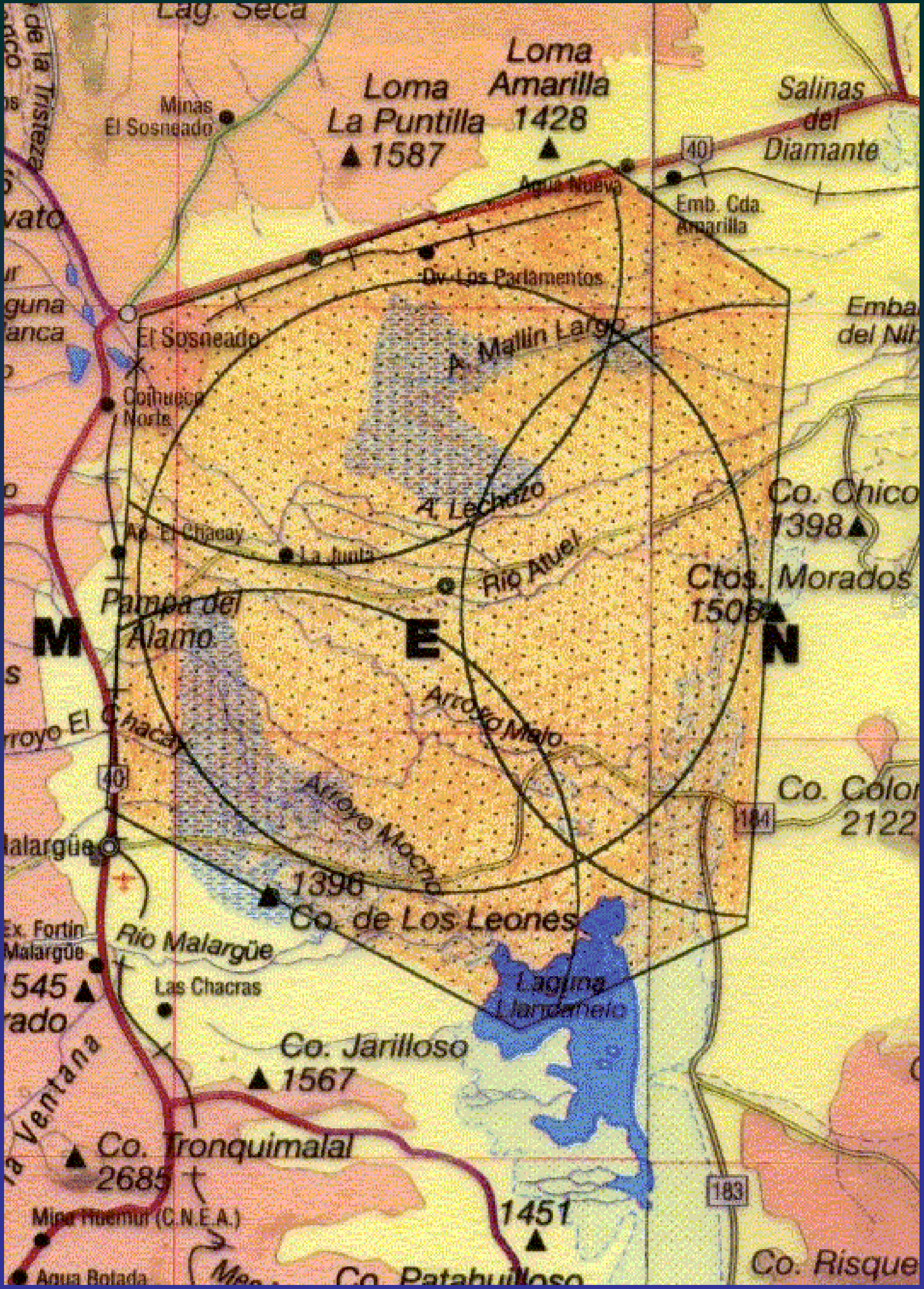


Large angles: around 10^{18} eV



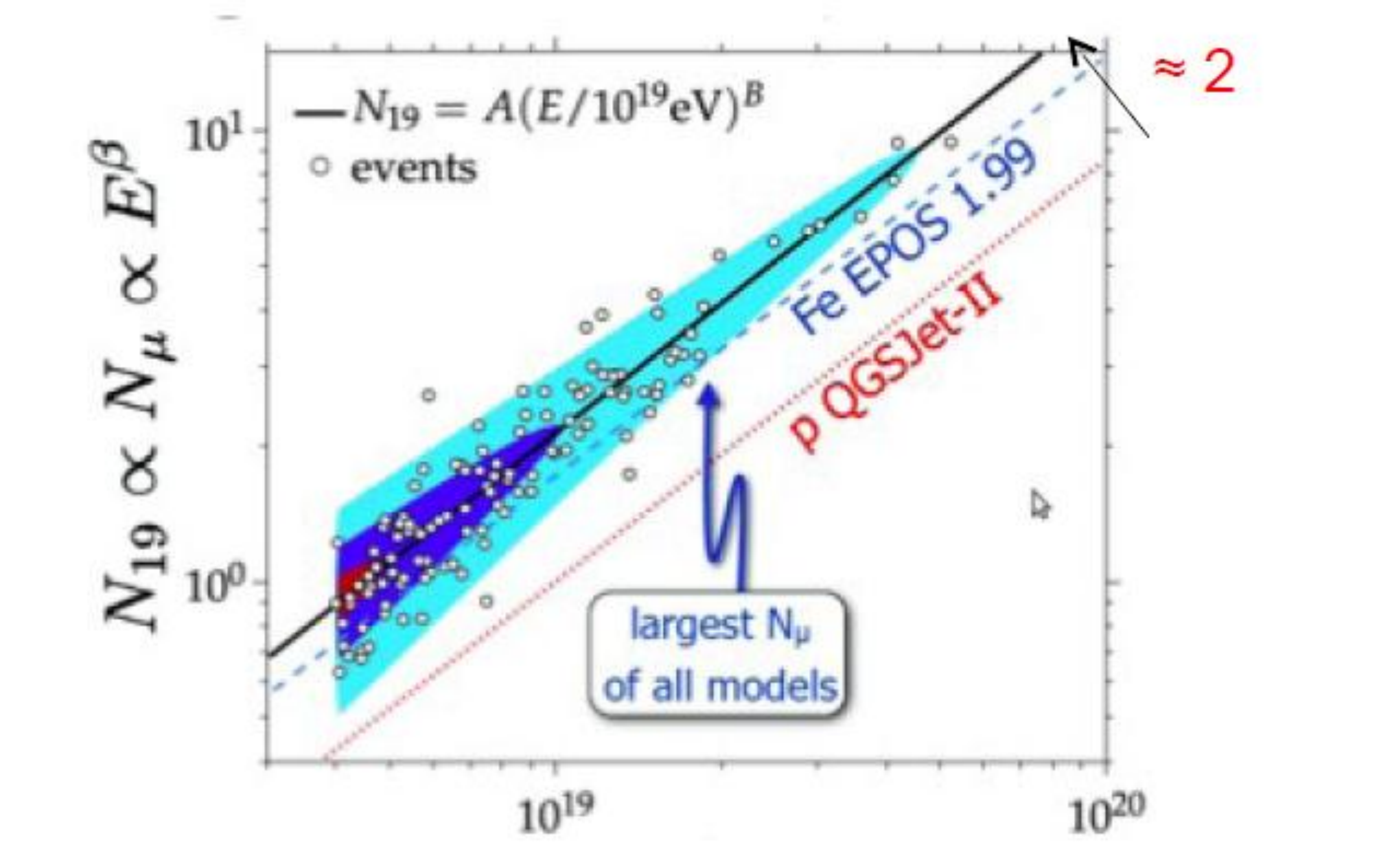
Comparison with other data





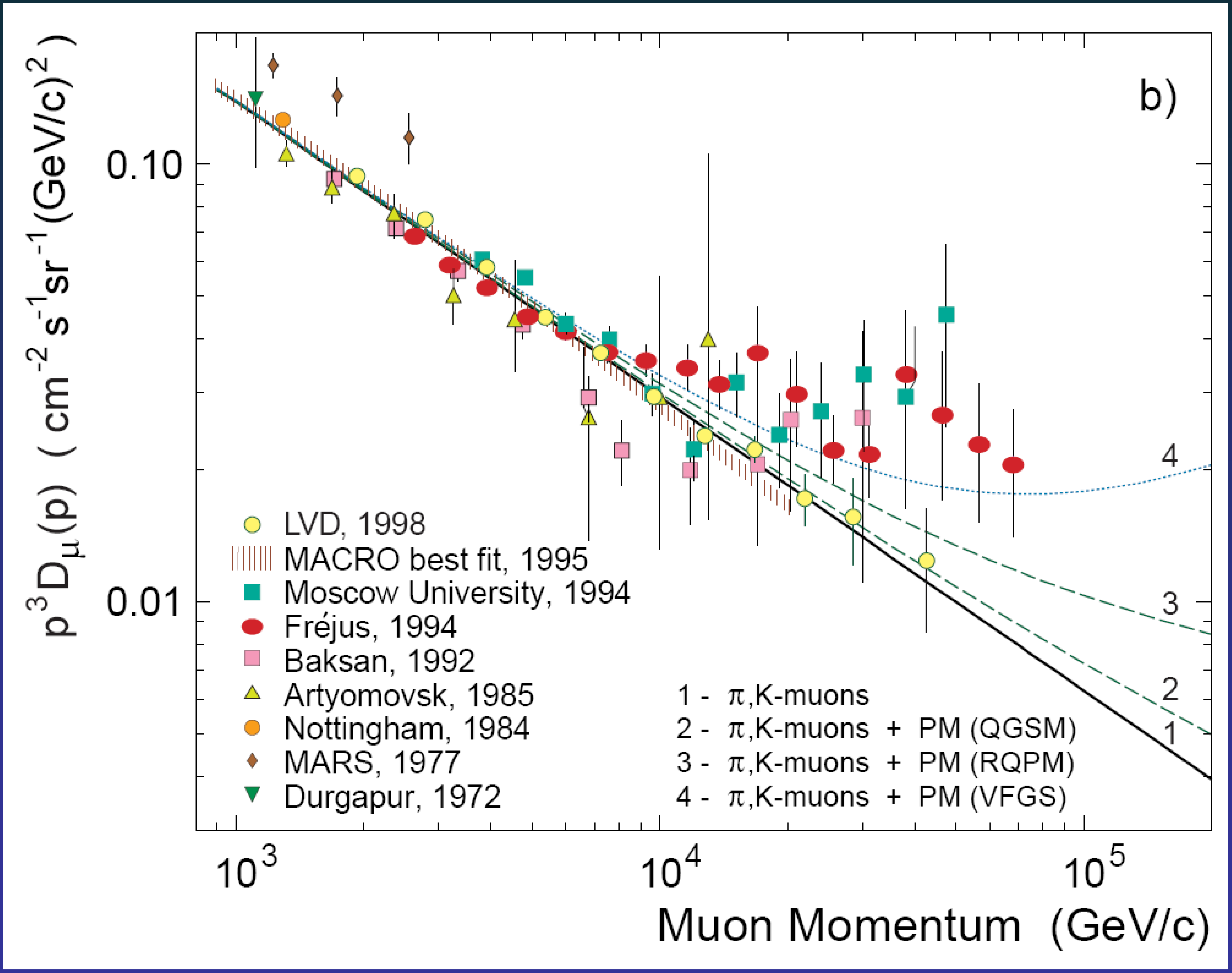
Pierre Auger Observatory

Muons in Auger

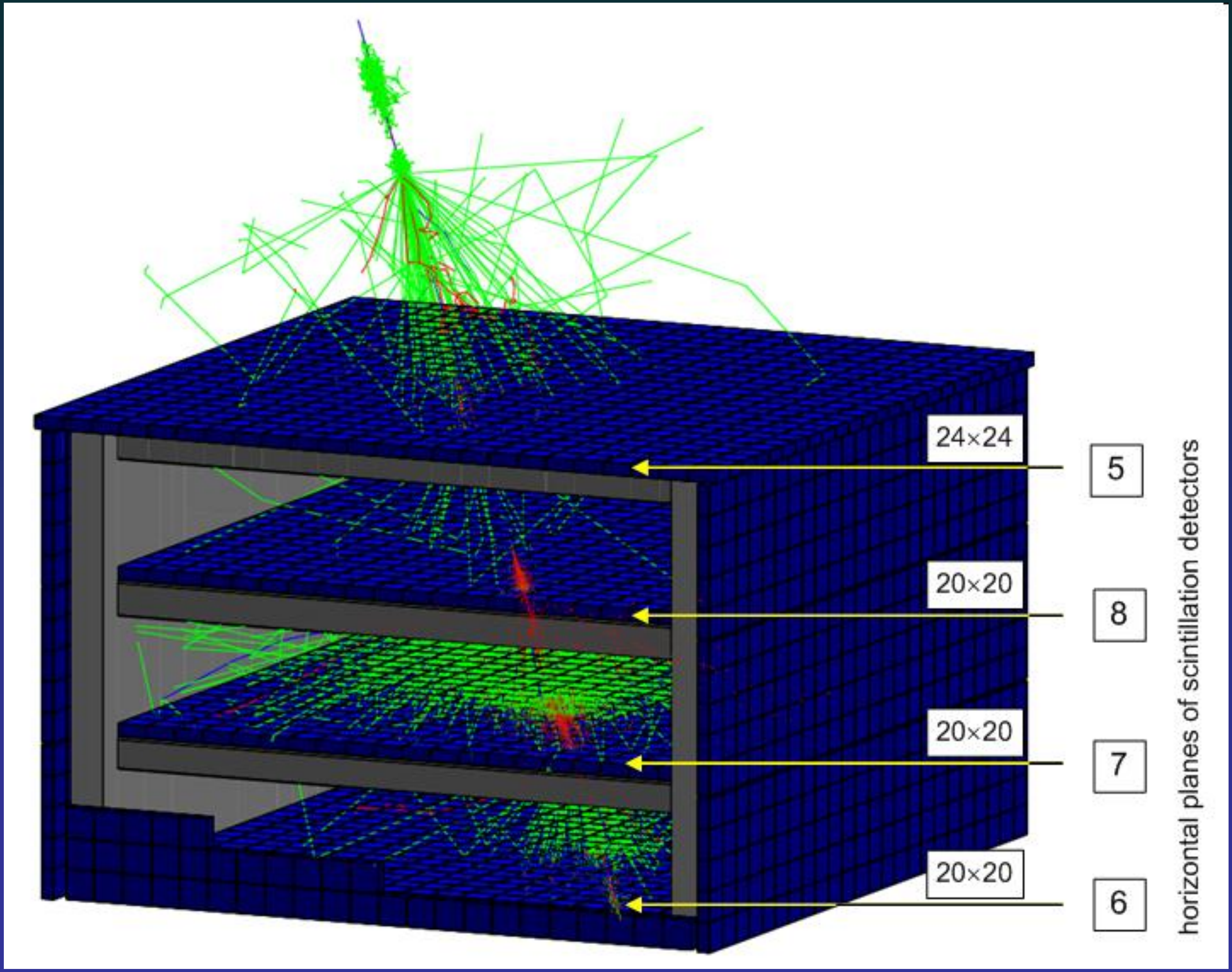


Muon energy spectrum

CR muon energy spectrum

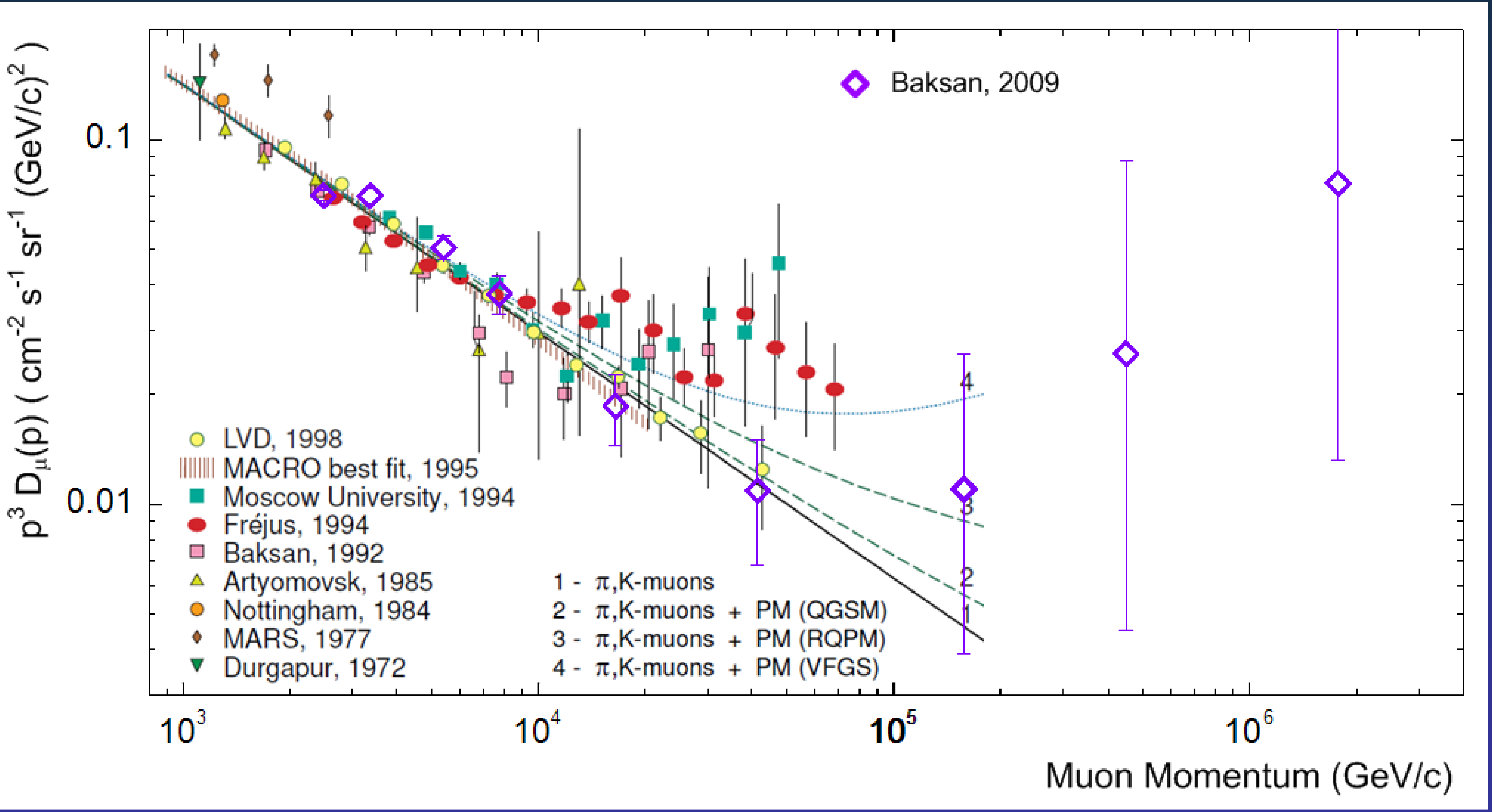


Baksan underground scintillation telescope

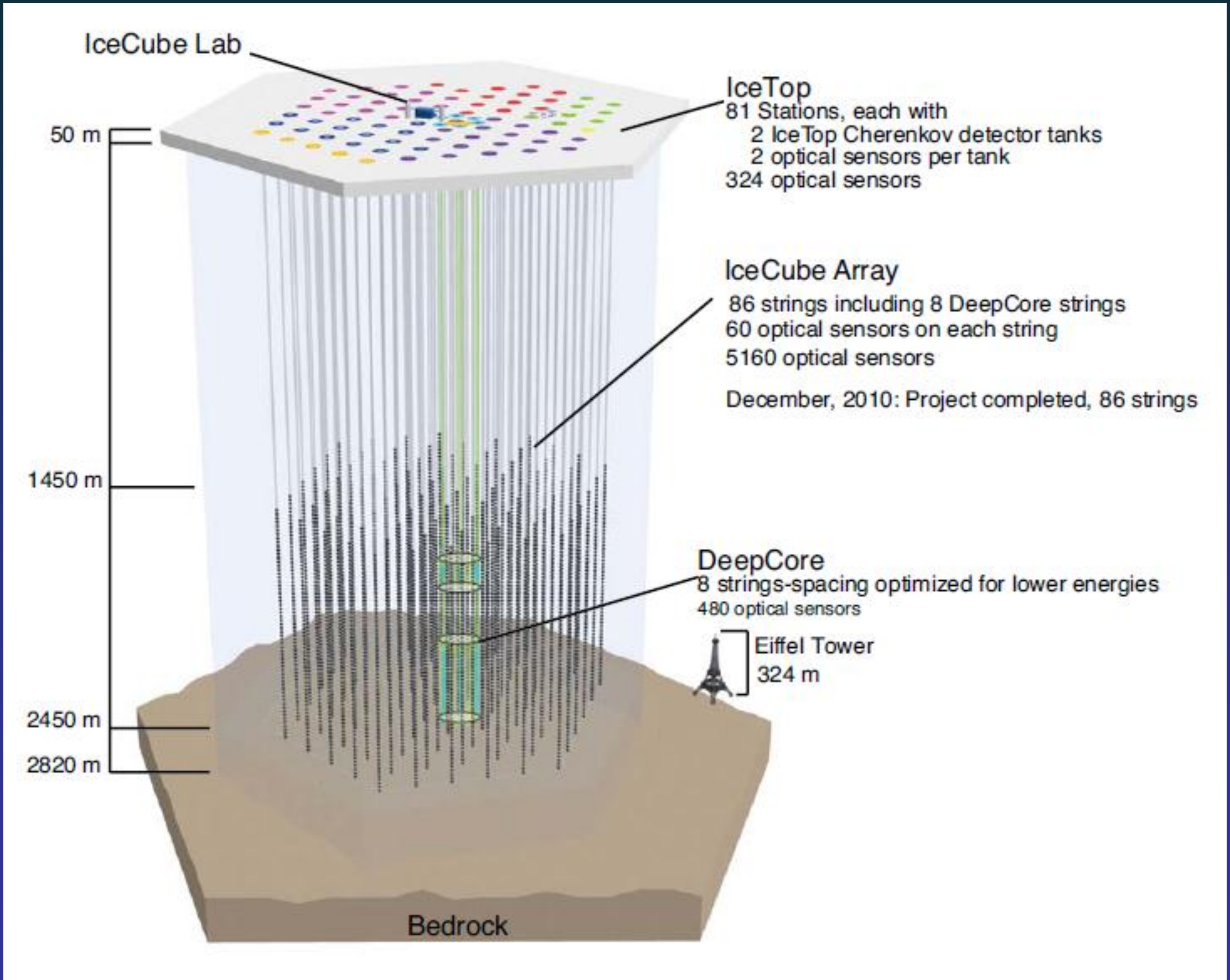


Preliminary results of muon energy spectrum investigations in Baksan Underground Scintillation Telescope (BUST)

http://arxiv.org/pdf/0911.1692

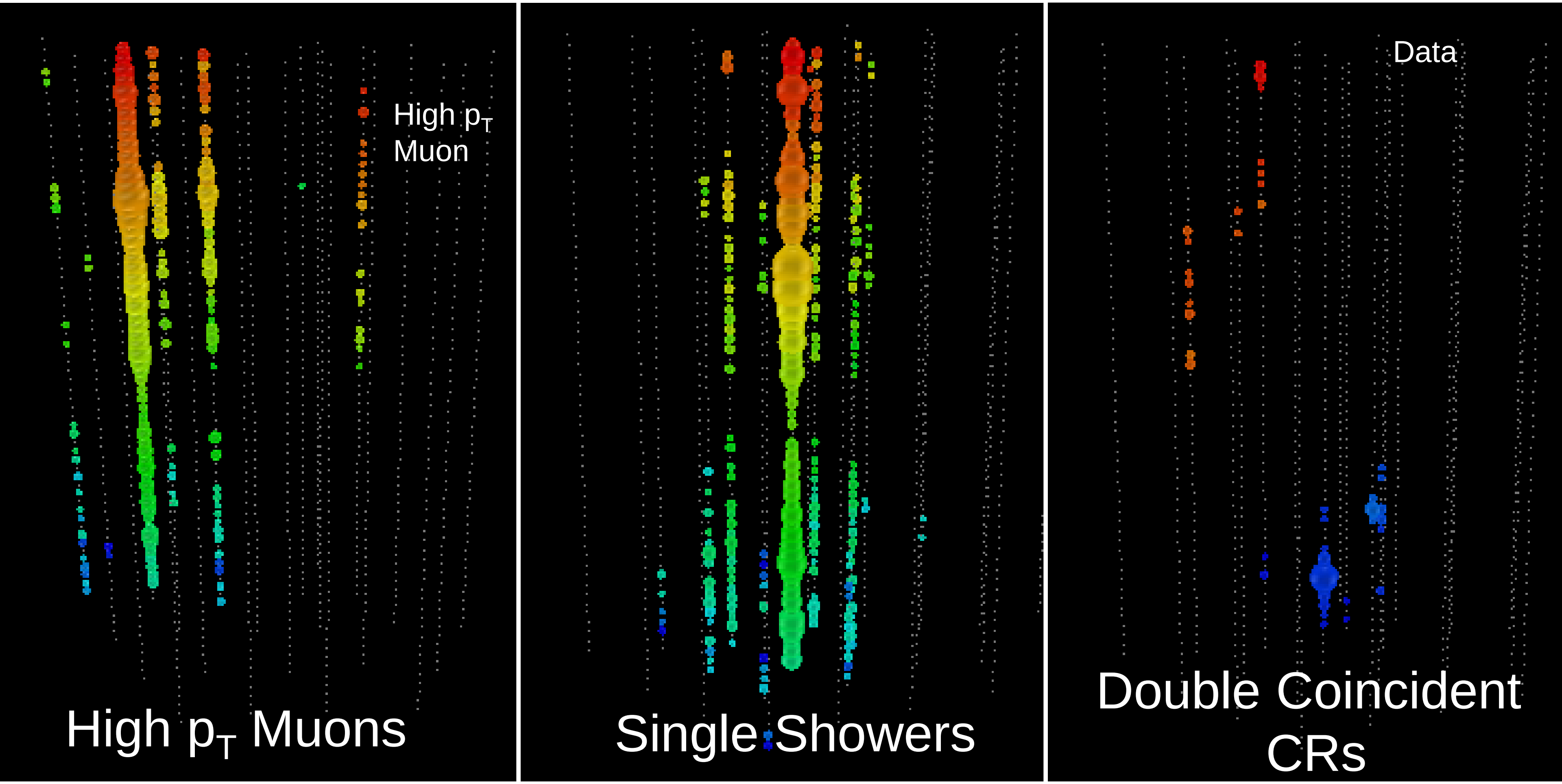


IceCube


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

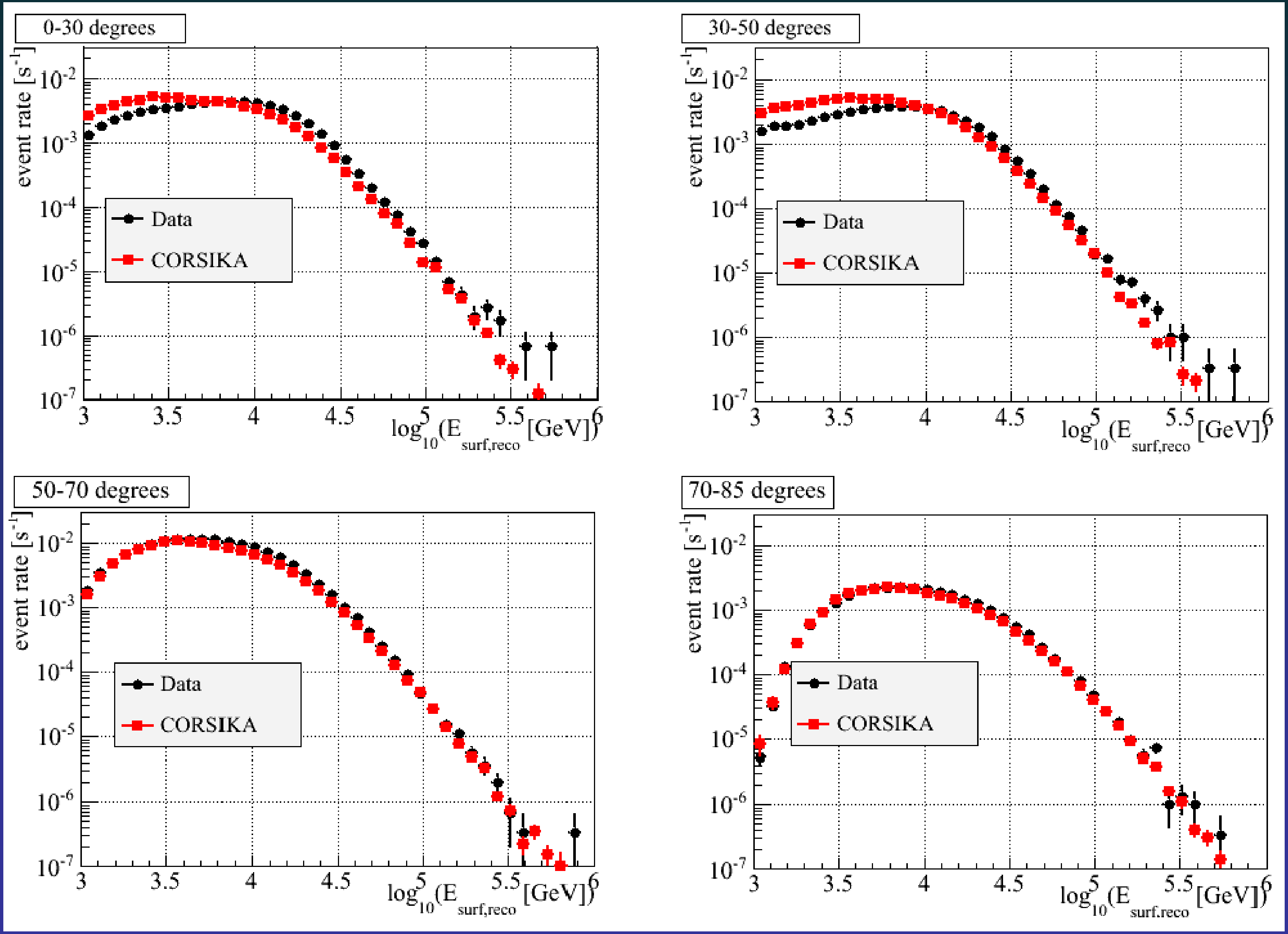
IceCube results

Bundle



Patrick Berghaus, Chen Xu, 32nd ICRC, 2011, Beijing

Muon energy spectrum - 2011



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 yield of VHE leptons (excess of muons, penetrating cascades).
4. Large orbital momentum (alignment).
5. More quick development of EAS (for increasing N_μ / N_e ratio and muon bundle excess).

Possible variants

- Inclusion of new (f.e., super-strong) interaction.
- Appearance of new massive particles (supersymmetric, relatively long-lived resonances, etc.)
- Production of blobs of quark-gluon plasma (QGP) (better to speak about quark-gluon matter - QGM, since usual plasma is a gas but quark-gluon matter is a liquid).

We considered the last model since it allows demonstrably explain the inclusion of new interaction.

Model of QGM production

Quark-gluon matter

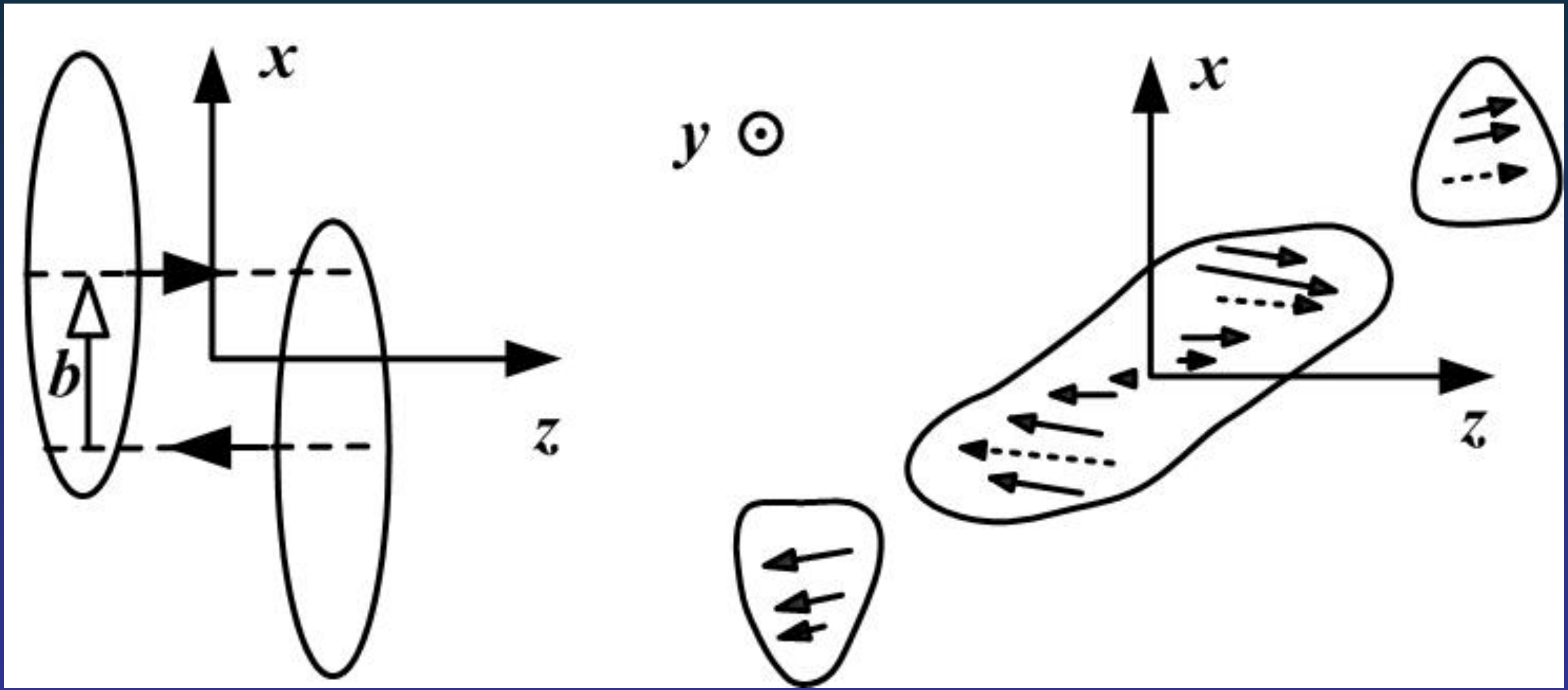
1. Production of QGM provides two main conditions:
   - threshold behavior, since for that high temperature (energy) is required;
   - large cross section, since the transition from quark-quark interaction to some collective interaction of many quarks occurs:

$$\sigma = \pi \bar{\lambda}^2 \rightarrow \sigma \approx \pi\left(\bar{\lambda} + R\right)^2 \; or \; \pi\left(R_1 + R_2\right)^2$$

where R, R_1 and R_2 are sizes of quark-gluon blobs.

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

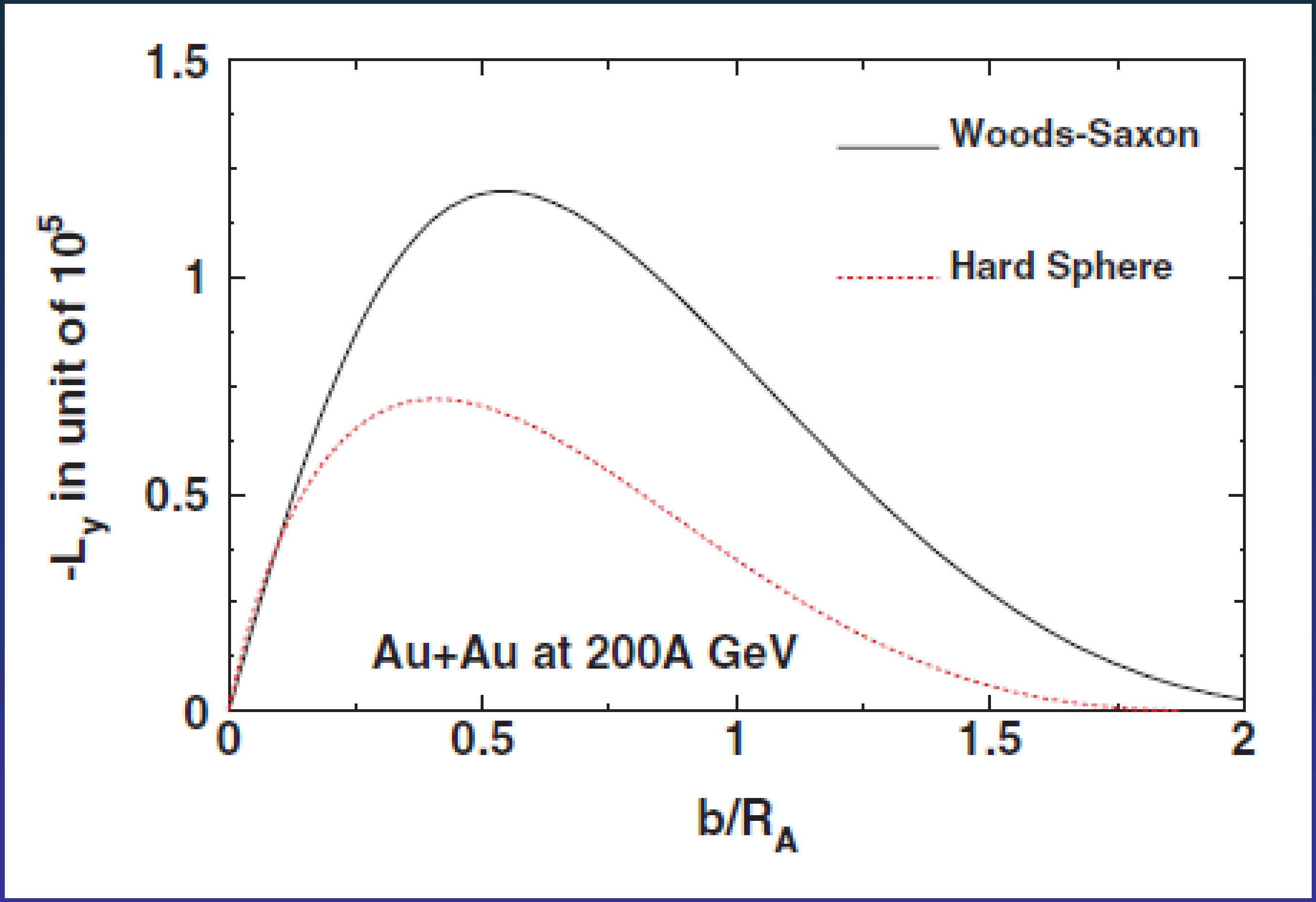
Orbital angular momentum in non-central ion-ion collisions



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

The value orbital angular momentum

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

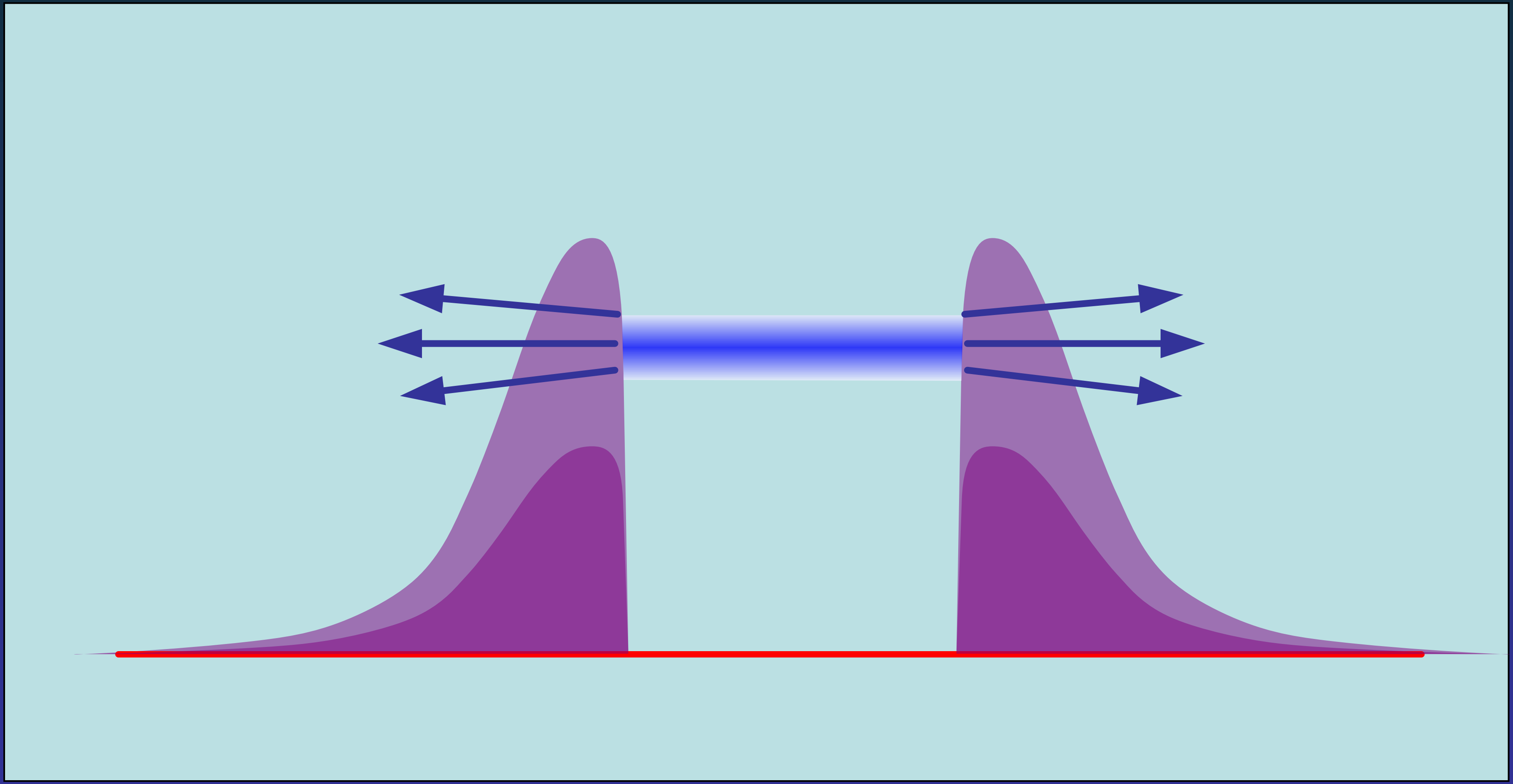


Total orbital angular momentum of the overlapping system in Au+Au collisions at the RHIC energy as a function of the impact parameter b.

Centrifugal barrier

1. As was shown by Zuo-Tang Liang and Xin-Nian Wang, in non-central collisions a globally polarized QGP with large orbital angular momentum which increases with energy $L \sim \sqrt{s}$ appears.
2. In this case, such state of quark-gluon matter can be considered as a usual resonance with a large centrifugal barrier.
3. Centrifugal barrier $V(L) = L^2 / 2mr^2$ will be large for light quarks but less for top-quarks or other heavy particles.

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.

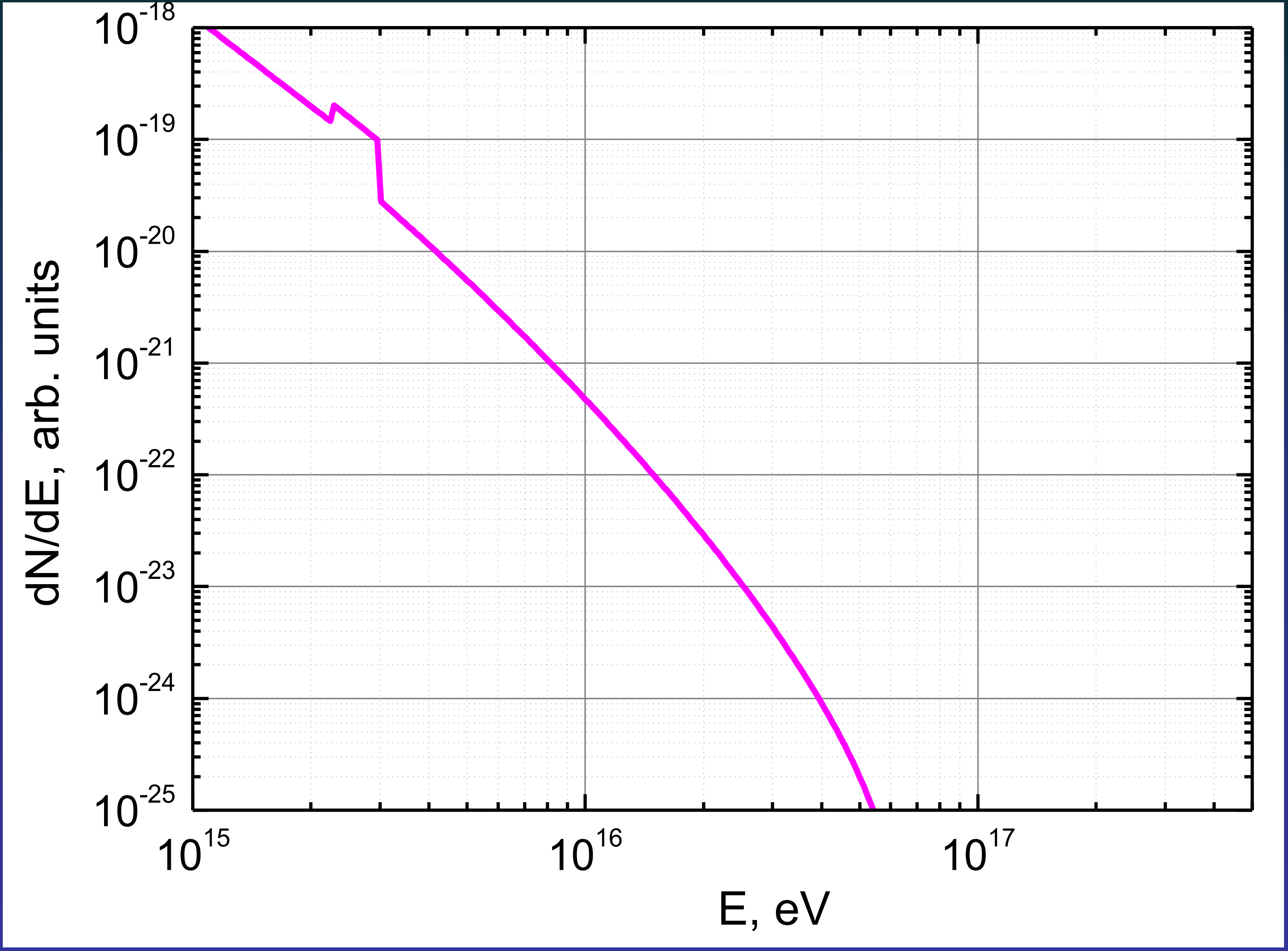
How the energy spectrum is changed?

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

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



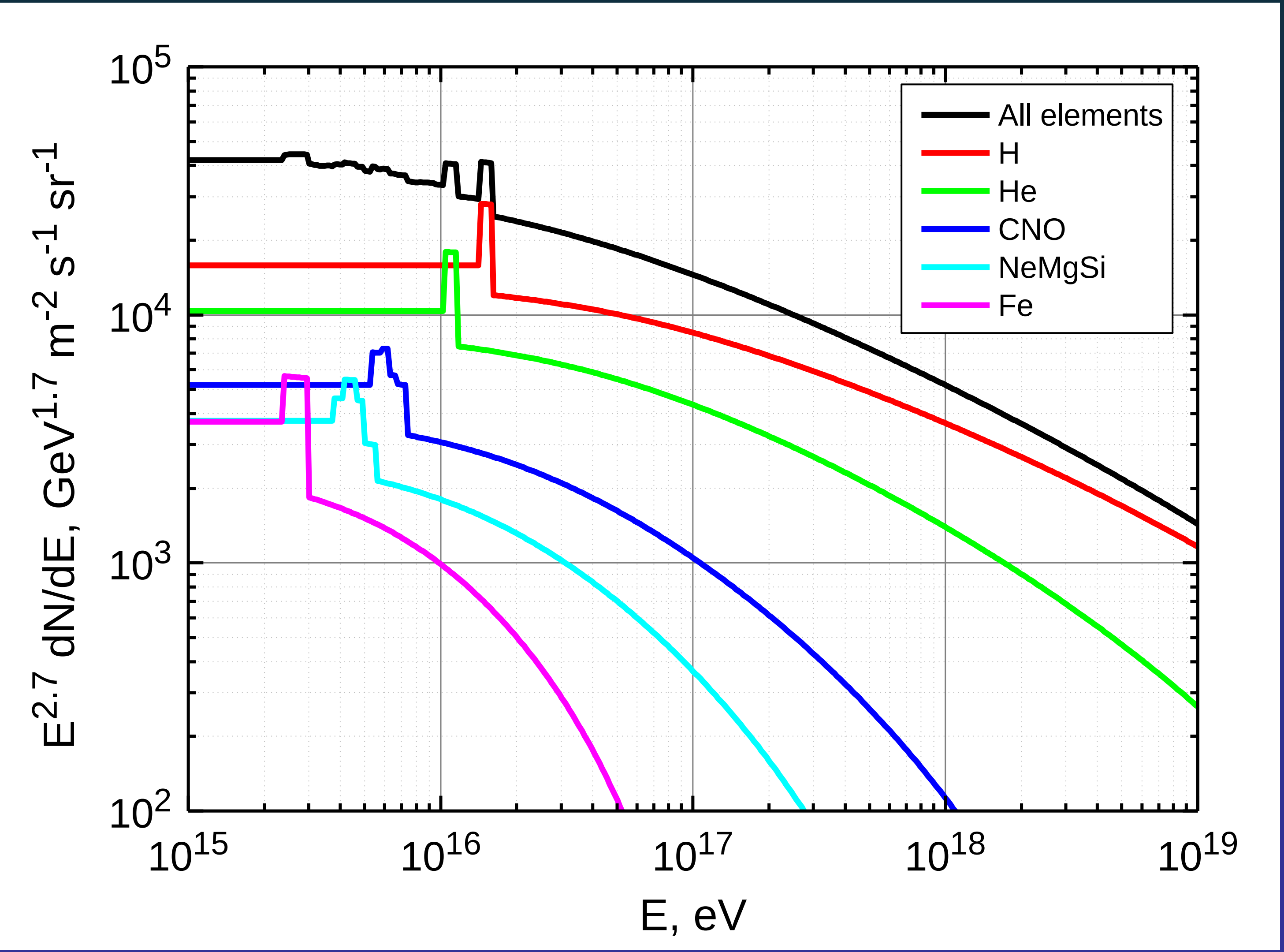
How measured composition is changed in frame of the new approach

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.

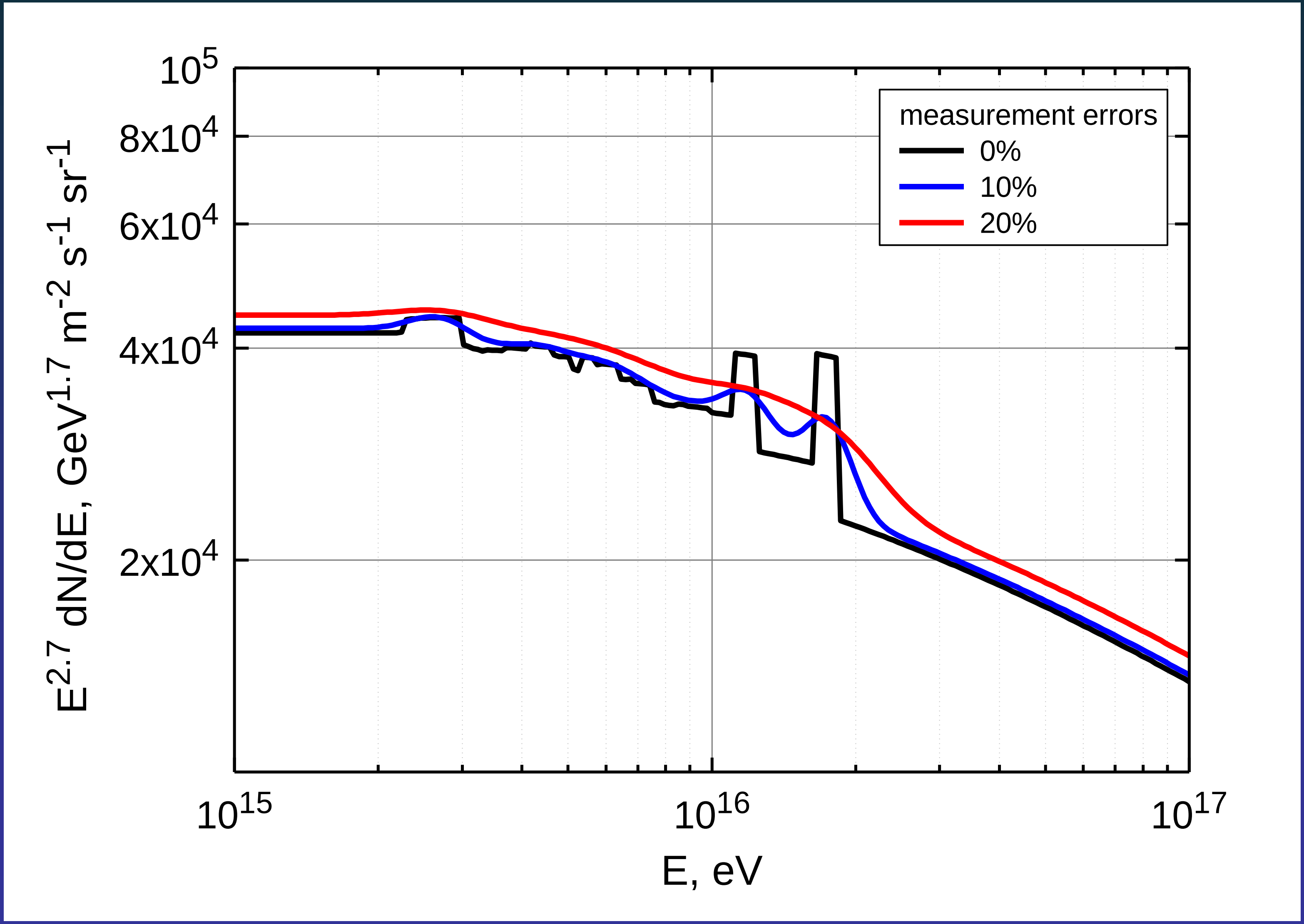
Therefore heavy nuclei (f.e., iron) spectrum is changed earlier than light nuclei and proton spectra!!!

Measured spectra for different nuclei will be not equal to primary composition!!!

Measured spectra for some nuclei and spectrum of all particles

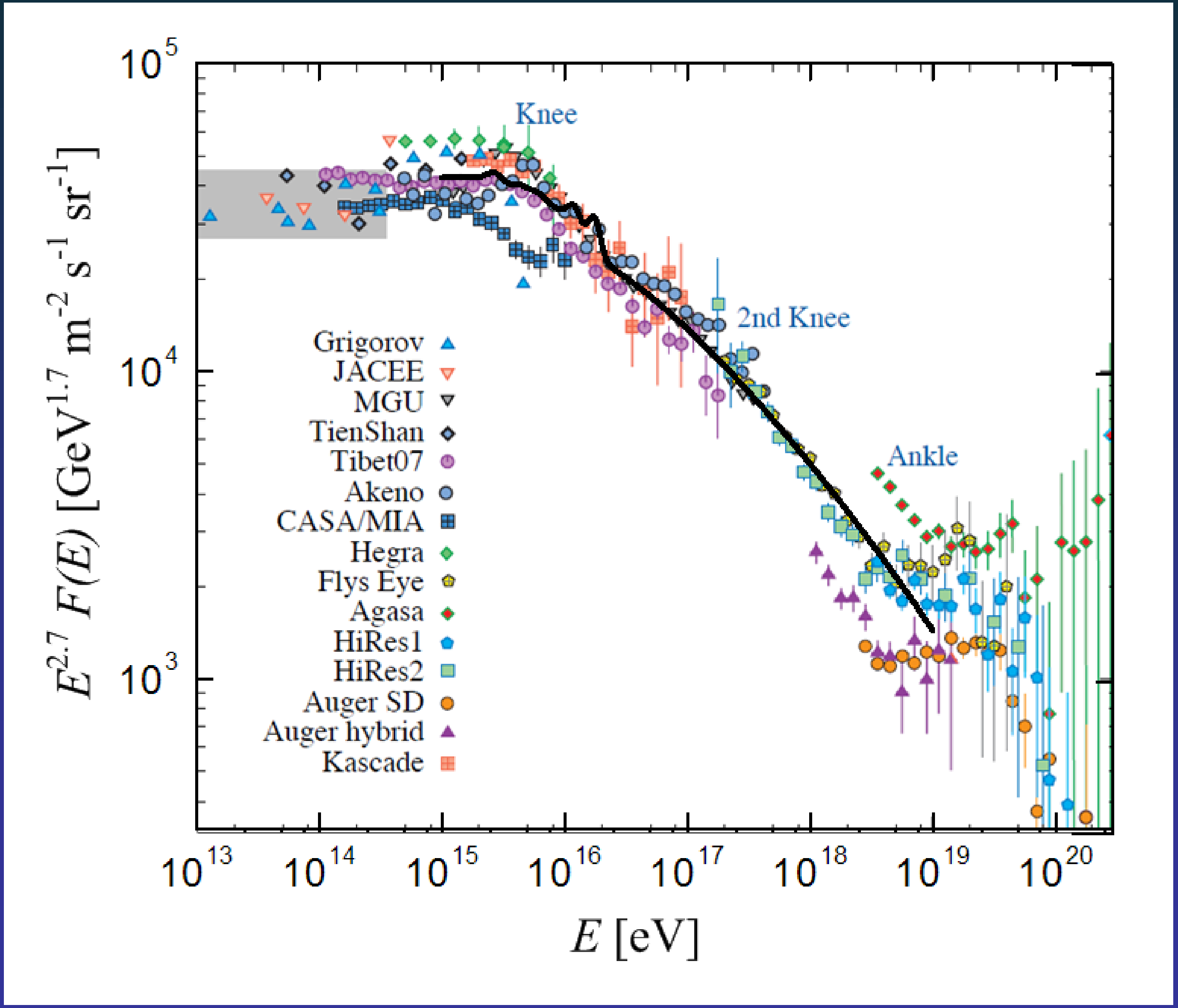


Influence of energy straggling



Comparison with experimental data

(with 10% straggling)



Discussion of results

1. Considered approach allows explain all unusual results obtained in cosmic rays.
2. Simplest model of energy spectrum surprisingly well describes experimental data.
3. Observed changes of composition are explained:
   - a sharp increase of average mass at the expense of detection of EAS from heavy nuclei,
   - after that, slow transition to proton composition.

Possibilities of new model check

How to check the new approach?

There are several possibilities to check new approach in LHC experiments.

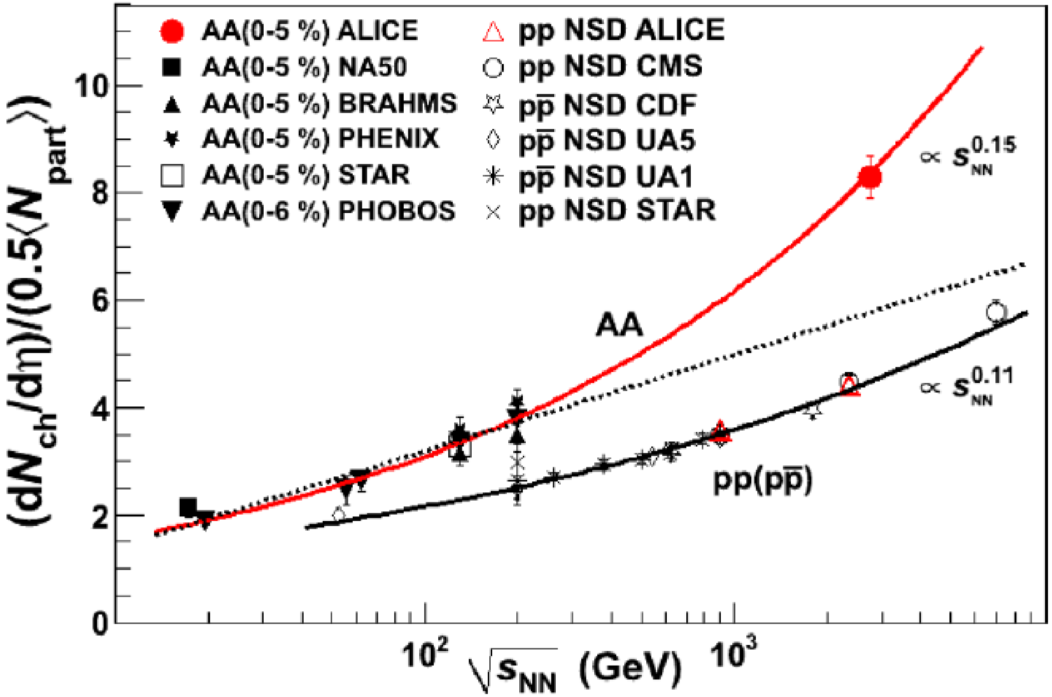
Of course, the most convincing results can be obtained in LHC experiments, since QGM with described characteristics (excess of *t*-quarks, excess of VHE muons, sharp increasing of missing energy, etc.) doubtless will be observed.

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.

Some LHC results evident in the favor of considered model.

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)

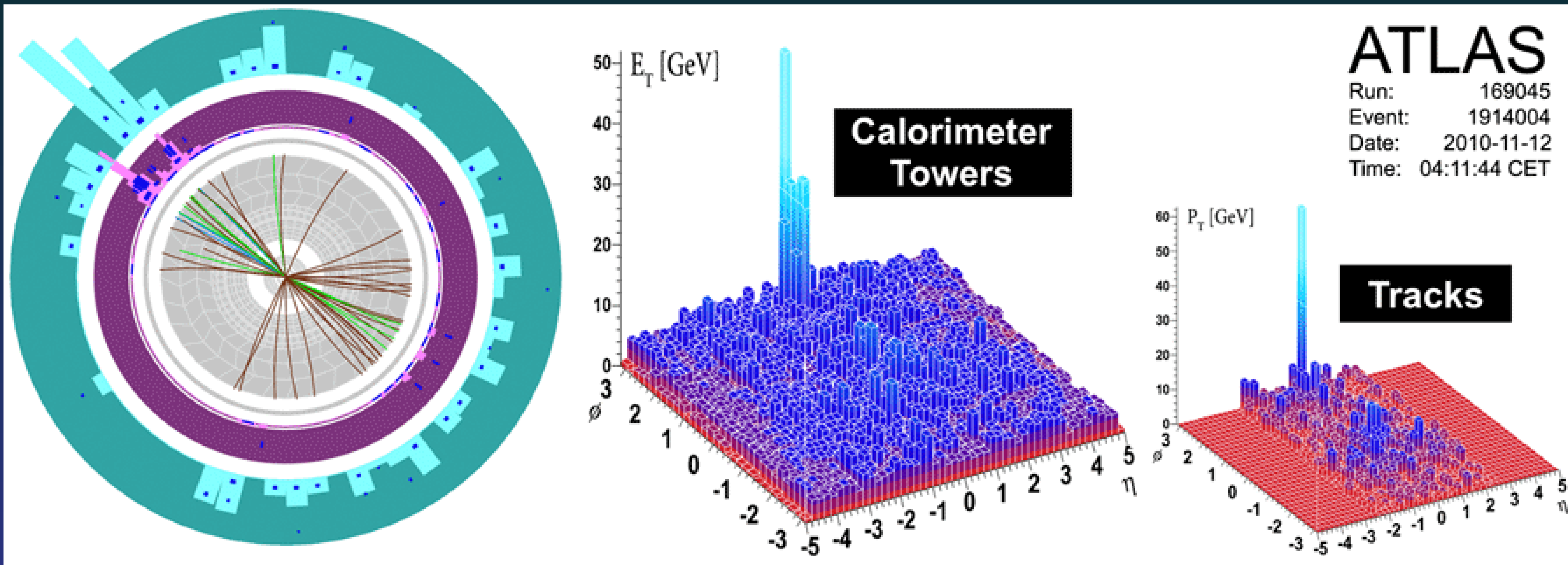
ALICE: PRL105 (2010) 252301

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

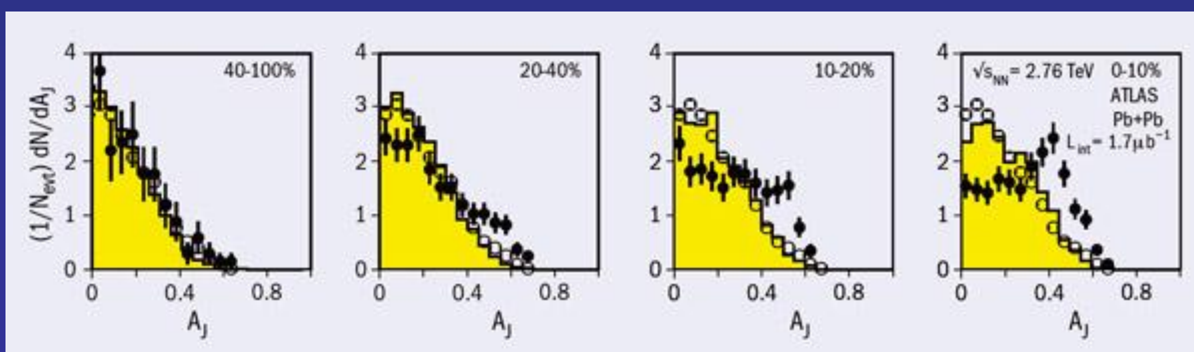
2 dNch/dη / <Npart> = 8.3 ± 0.4 (sys.)

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 results in frame of considered approach?

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

In the 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.

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.

Thank you for attention!