The puzzle of cosmic ray muons

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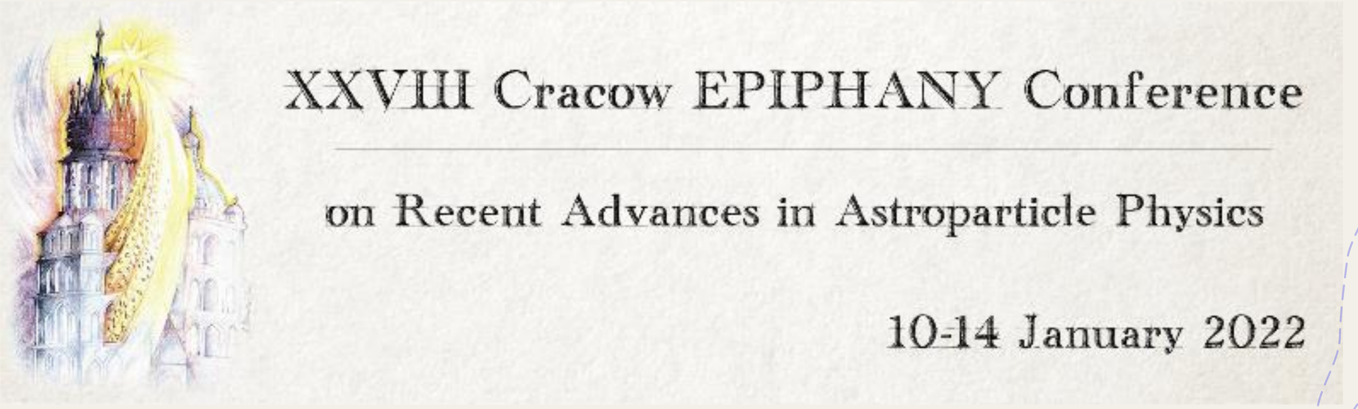
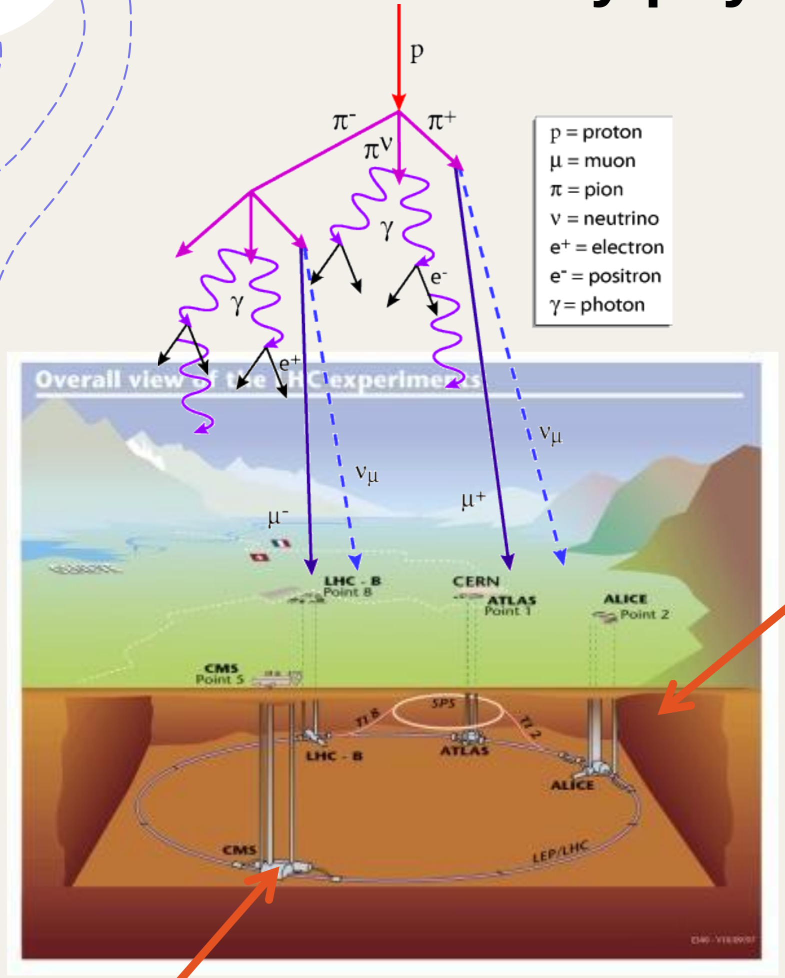
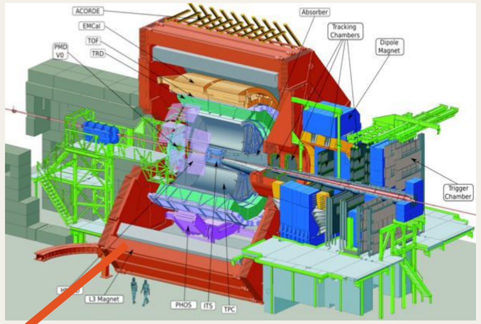
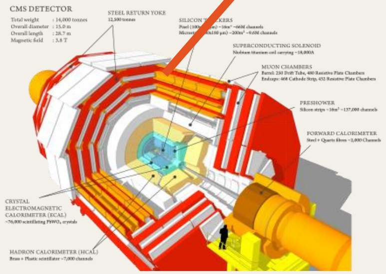


Cosmic-ray physics with CERN experiments





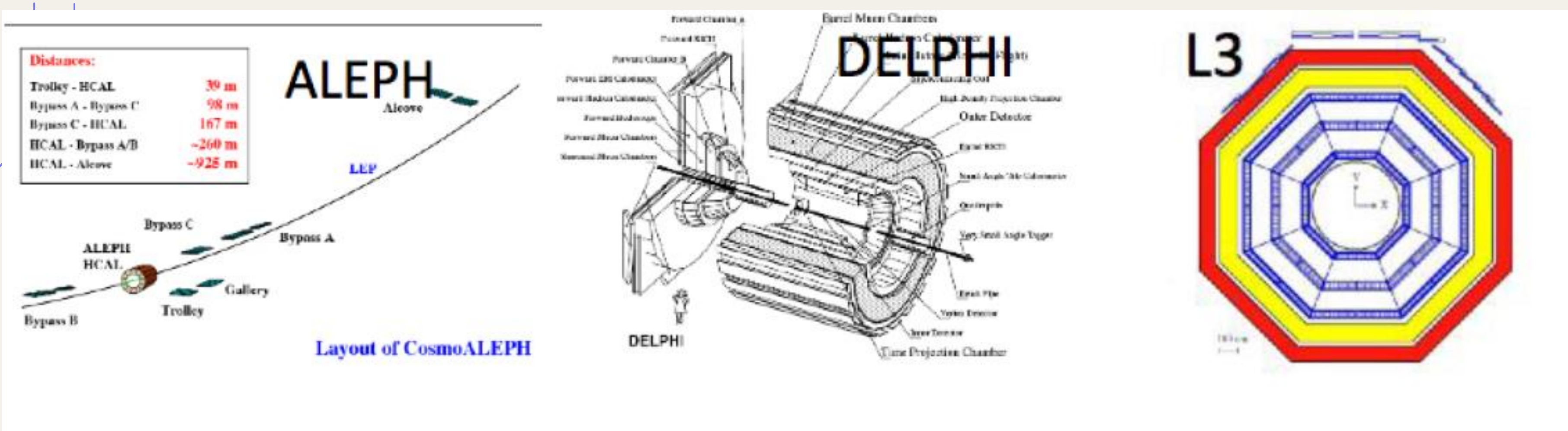


✓Small detectors with respect to EAS experiments
✓ Low underground
✓ Detection of muons (only!) crossing the rock
✓ Short time of data taking

These detectors are not designed to cosmic ray physics!

Advantages:
- Detectors with very high performance
- Presence of magnetic field

Detection of CR by CERN LEP experiments



ALEPH: 130 m of rock, momentum muon threshold p > 70/cosθ

Underground scintillators, HCAL (horizontal area ~ 50 m^2),
TPC projected area ~ 16 m^2

DELPHI: 100 m of rock, momentum muon threshold p > 52/cosθ

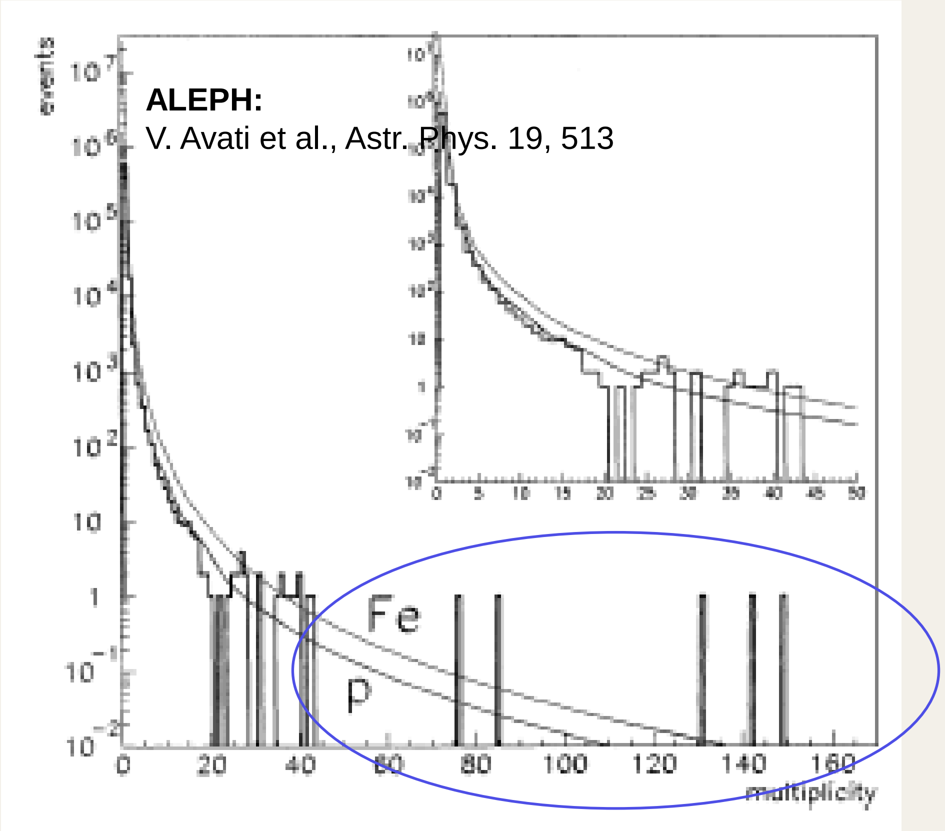
Hadron calorimeter (horizontal area ~ 75 m^2),
muon barrel, TPC, ToF and outer detectors

L3+C: 30 m of rock, momentum muon threshold p > 20/cosθ + surface array

Scintillator surface array (200 m^2),
trigger, muon barrel (100 m^2), hadron calorimeter, etc.

COSMIC RAY ENERGY COVERAGE FROM 10^{14} – 10^{18} eV

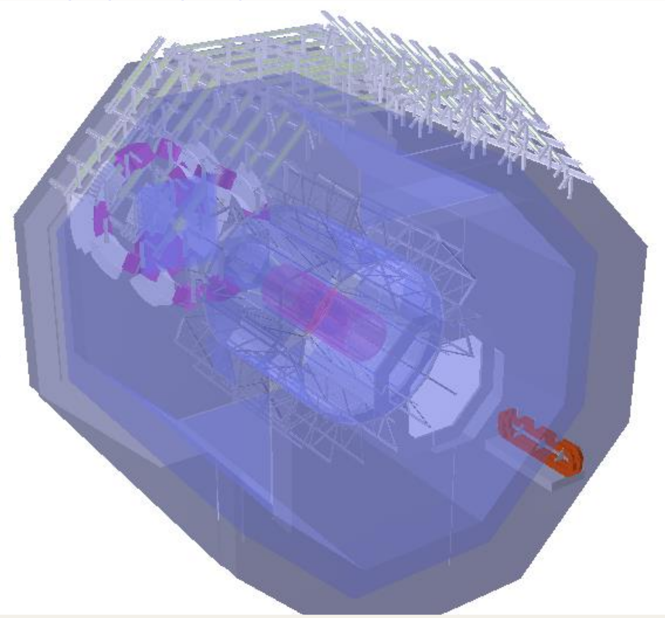
LEP results: muon multiplicity spectra

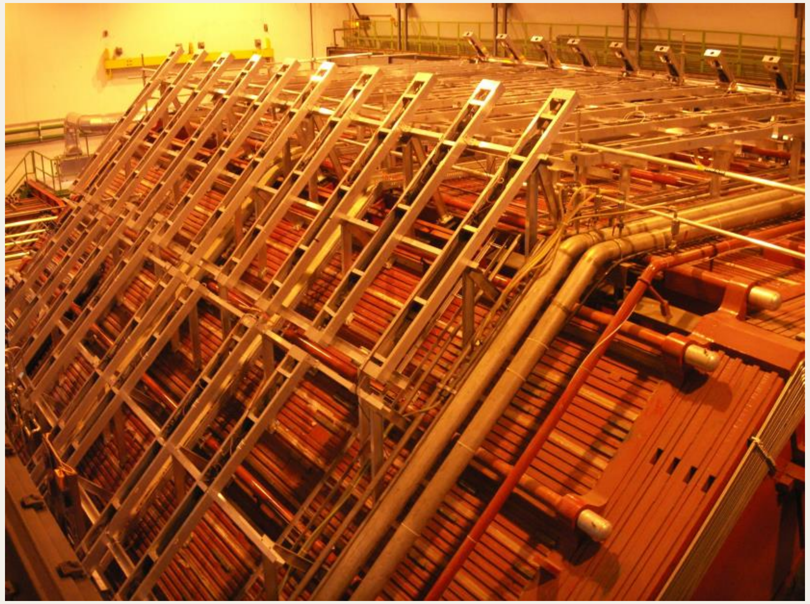


- ✓ These muon bundles are not well described (more than an order of magnitude above the simulation)
- ✓ Data indicates that heavier component is needed to explain higher multiplicity muon bundles
- ✓ Even the combination of extreme assumptions of highest measured flux value and pure iron spectrum, fails to describe the abundance of high multiplicity events.
- ✓ The conclusions of DELPHI and L3+C are similar to ALEPH

The only LEP result not consistent with the standard hadronic interaction models was the observation of the 'anomalous' number of high-multiplicity muon bundles.

Detection of CR by the LHC ALICE experiment



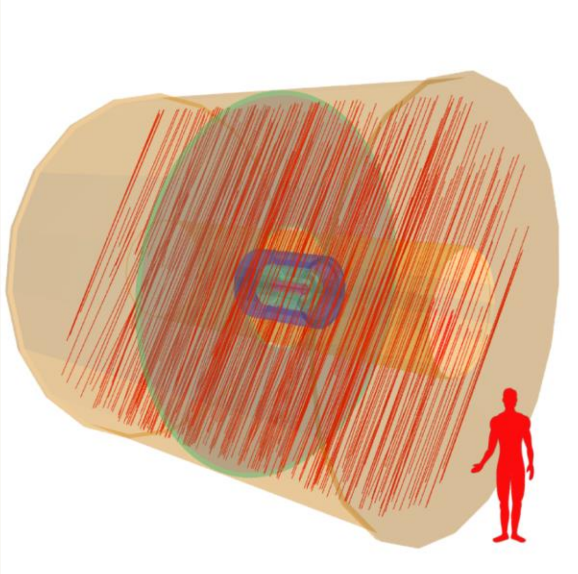


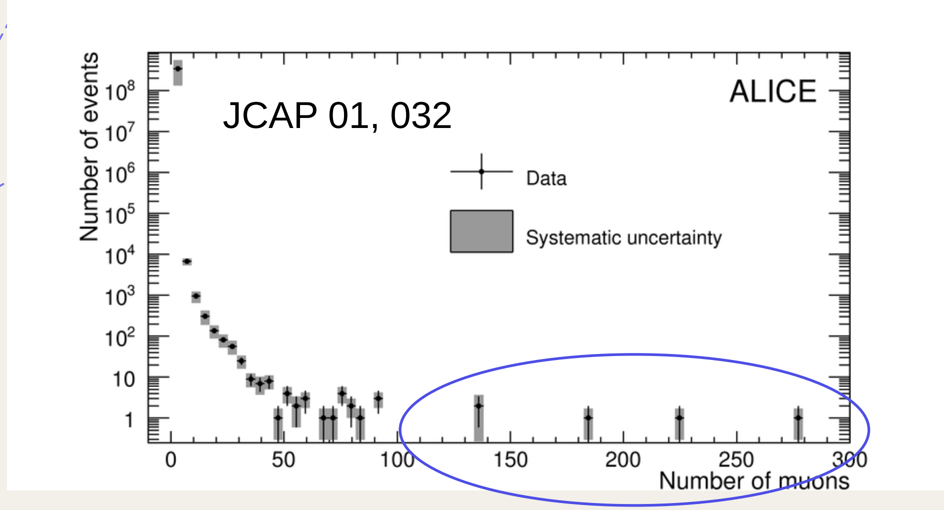
ALICE configuration for cosmic-ray physics:

- ✓ Cylindrical multi-gap resistive-plate chamber array
- ✓ TOF covers a cylindrical surface of polar acceptance in the theta range 45 ≤ Θ ≤ 135
- ✓ Modular structure: 18 sectors in azimuthal angle
- ✓ Time resolution less than 100 ps
- ✓ Efficiency around 95%

Detection of CR by the LHC ALICE experiment

Recently the ALICE experiment has been used to perform studies that are of relevance to astro-particle physics.

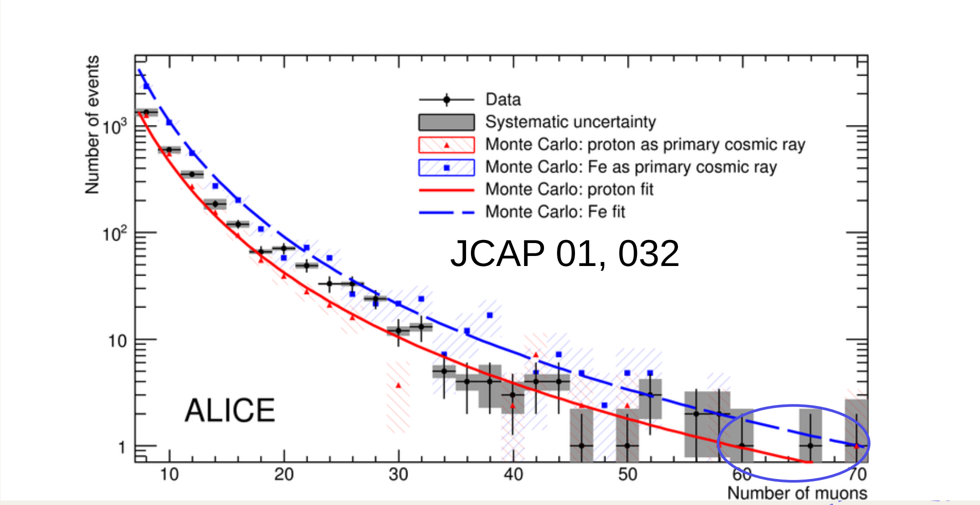




$0° < \Theta < 50°$

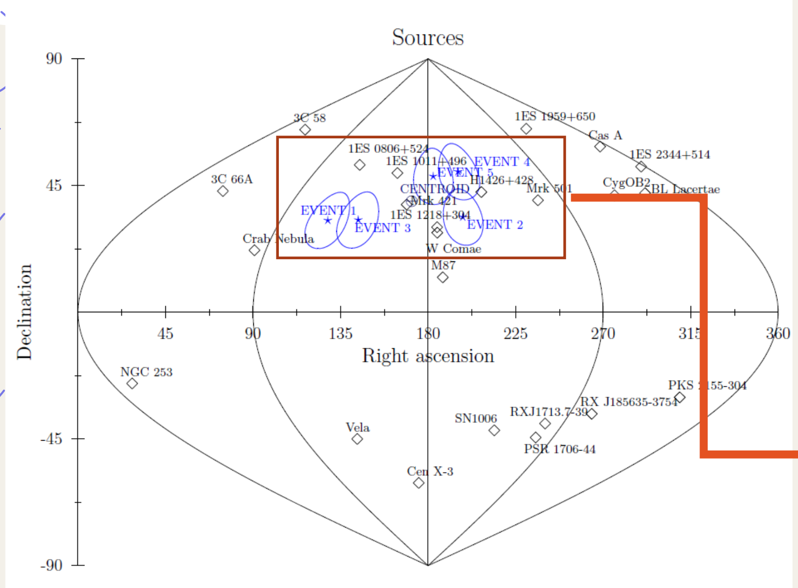
$E_\mu > 16$ GeV$/\cos\Theta$

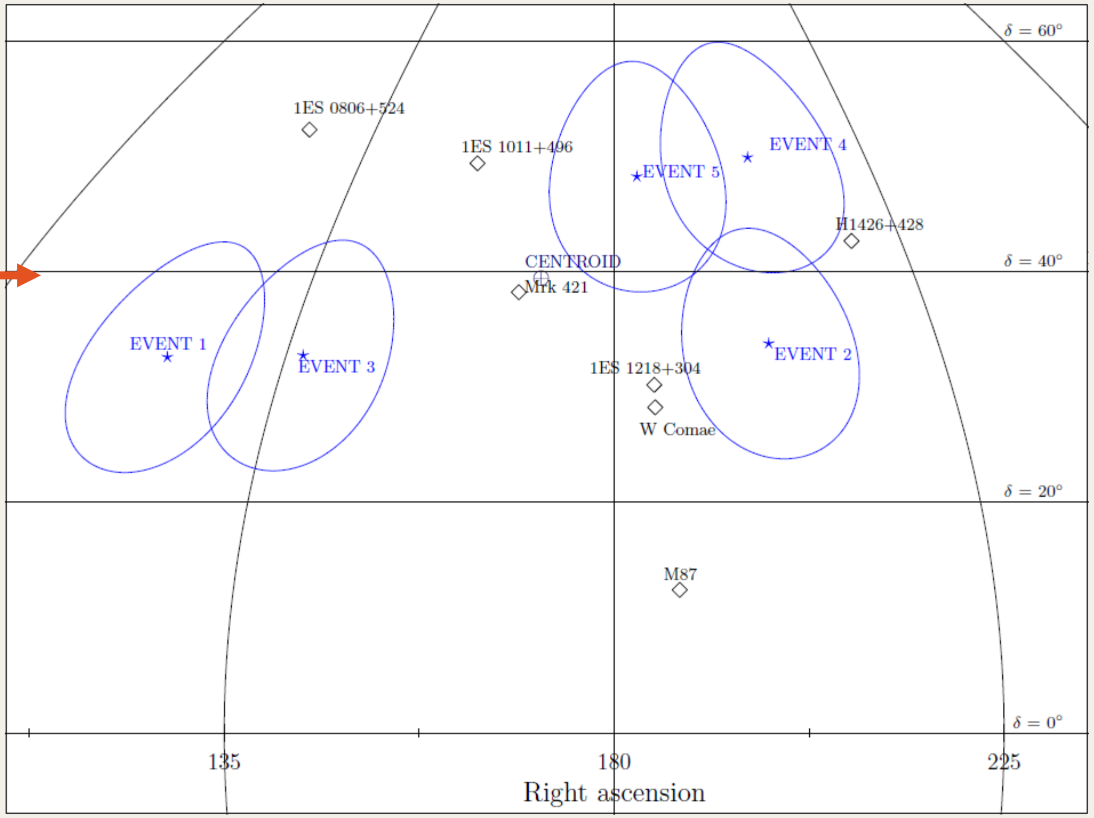
Total time of data taking: 30.8 days



ALICE experiment registered the presence of large groups of muons produced in EAS by cosmic ray interactions in the upper atmosphere.

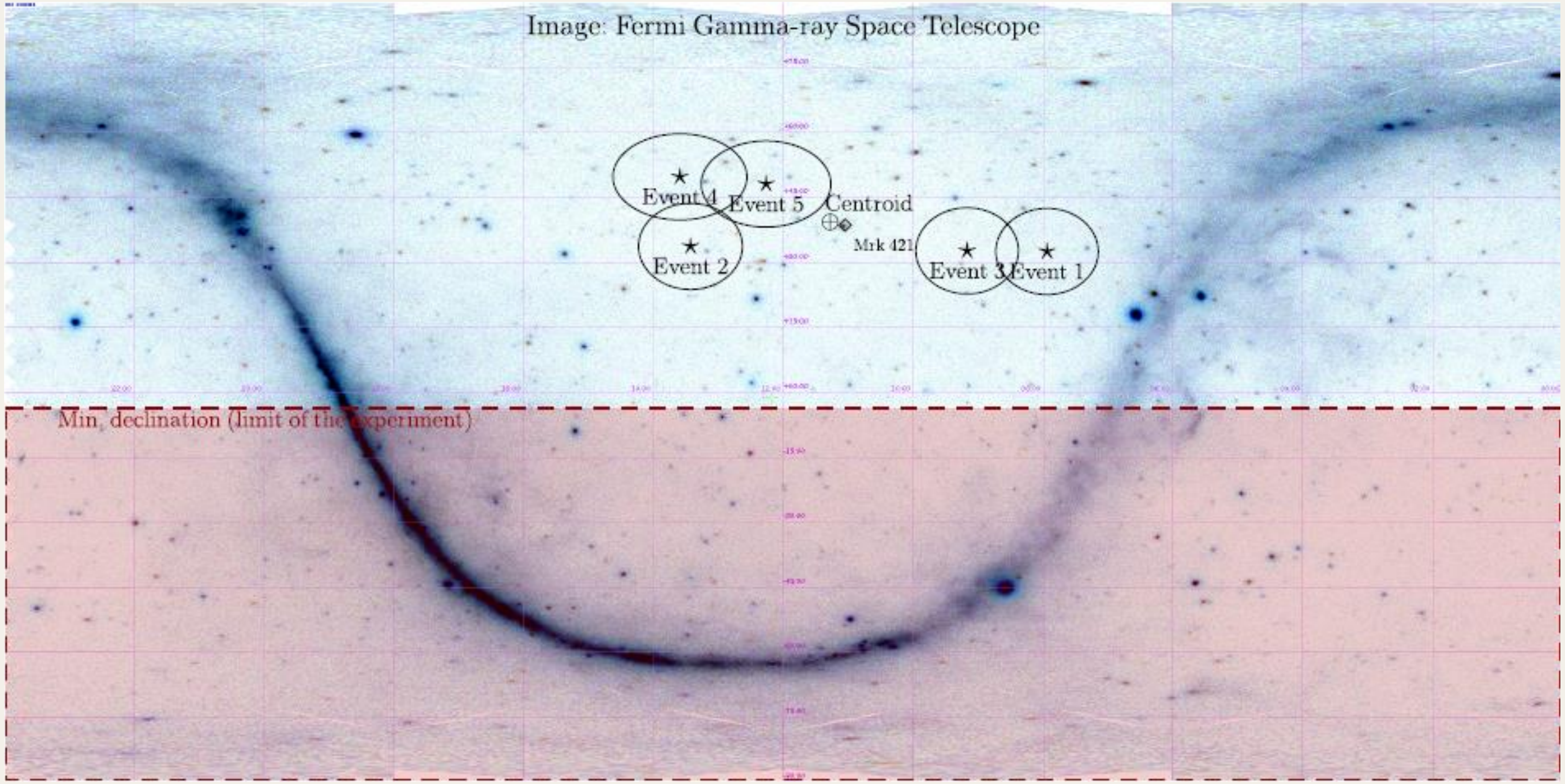
Anisotropy of arrival directions





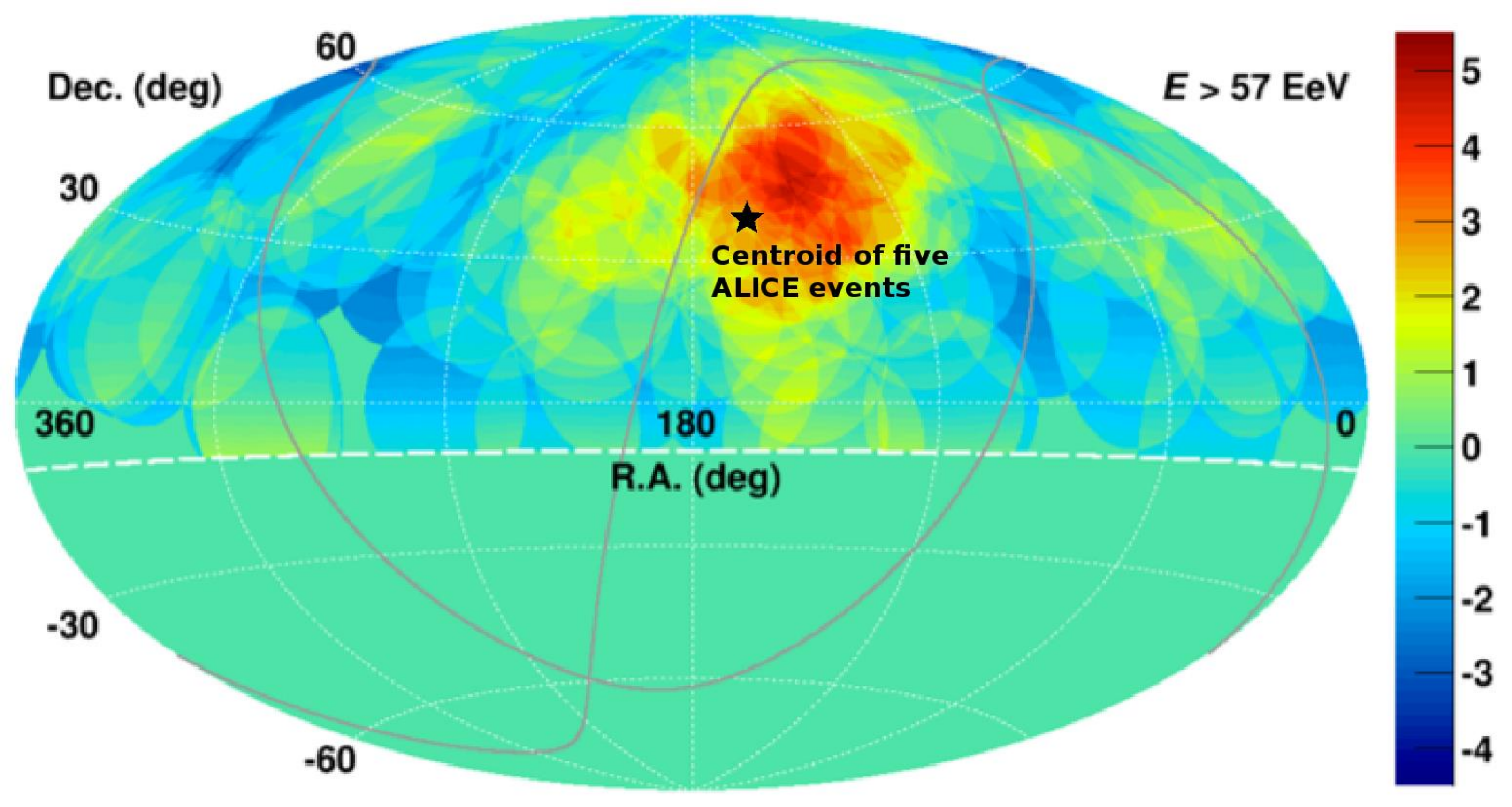
ALICE five high-multiplicity muon events in the equatorial reference frame (α, δ).
Most known extragalactic TeV Sources (blazars, SNRs, radio galaxies) in the sky
[Horan and Weekes, New Astr. Rev. 48, 527], [Turley et al., ApJ 833, 117] are also shown
(note that **the Mrk 421 blazar** is the source located very close to the centroid of the five considered events).

Anisotropy of arrival directions



ALICE five high-multiplicity muon events. All events are located close to the galactic pole (far from the galactic plane). Background: Inverted (negative) image of the Fermi telescope mosaic. The minimum declination limit (due to the restricted zenith angle in the experiment) is marked by a horizontal line. The area in the southern sky not covered by the experiment is marked by a rectangle (filled).

Anisotropy of arrival directions



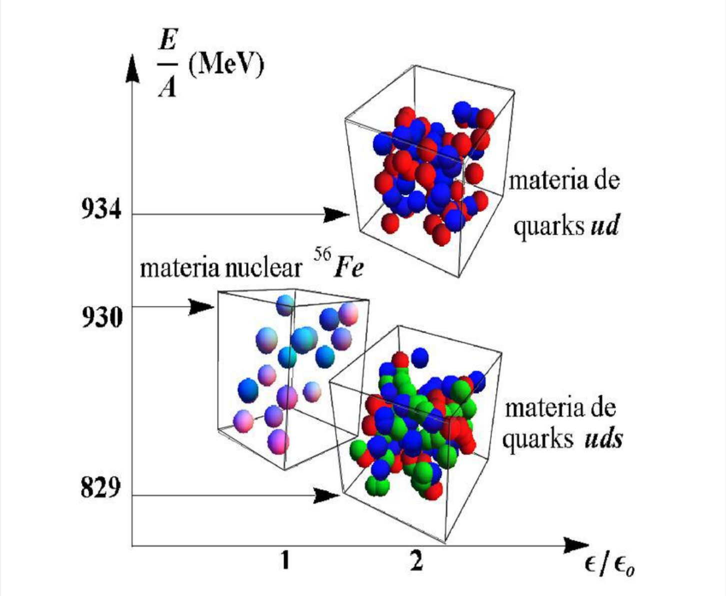
Aitoff projection of the UHECR map in equatorial coordinates taken from Telescope Array Collaboration data [ApJL 790, L21]

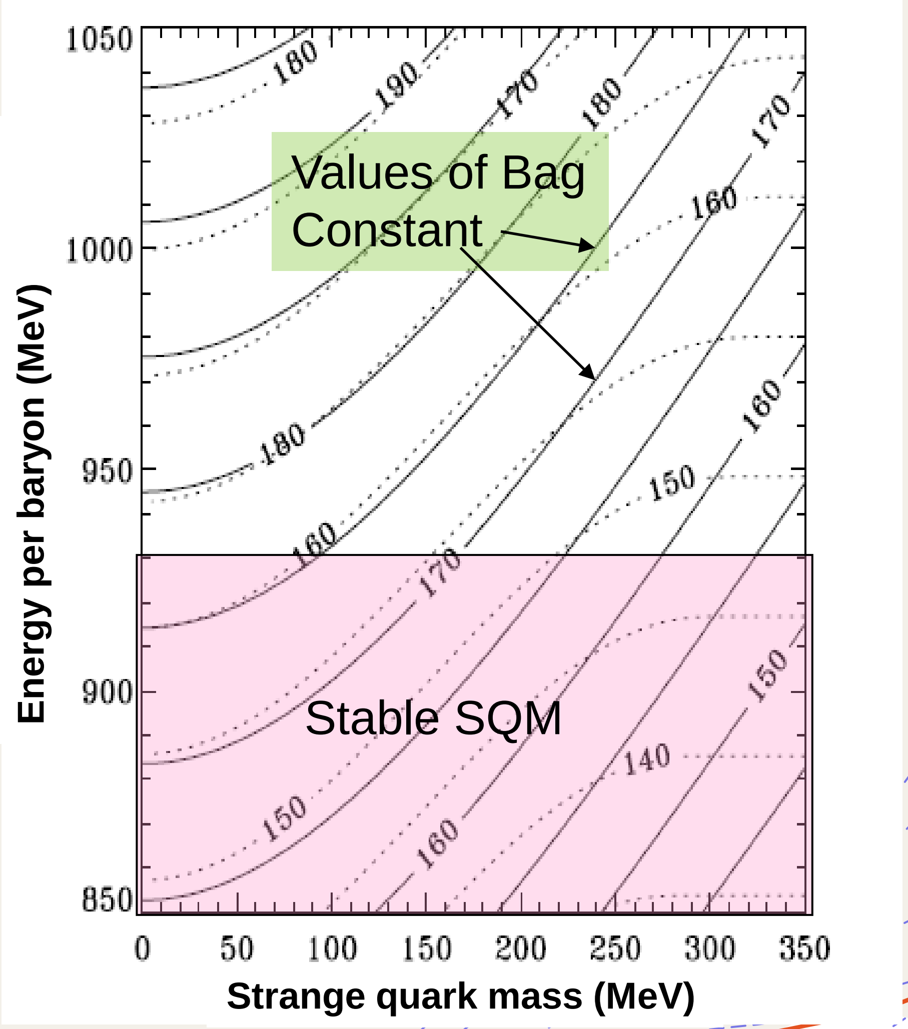
The possible source of high-multiplicity muon groups: Strange Quark Matter

Witten [Phys. Rev. D 30, 272] proposed that SQM could even be the ground state of nuclear matter and could exist in bulk as remnants of the Big Bang

[J. Madsen, Phys.Rev. Lett. 87, 172003]

Ground state of nuclear matter?



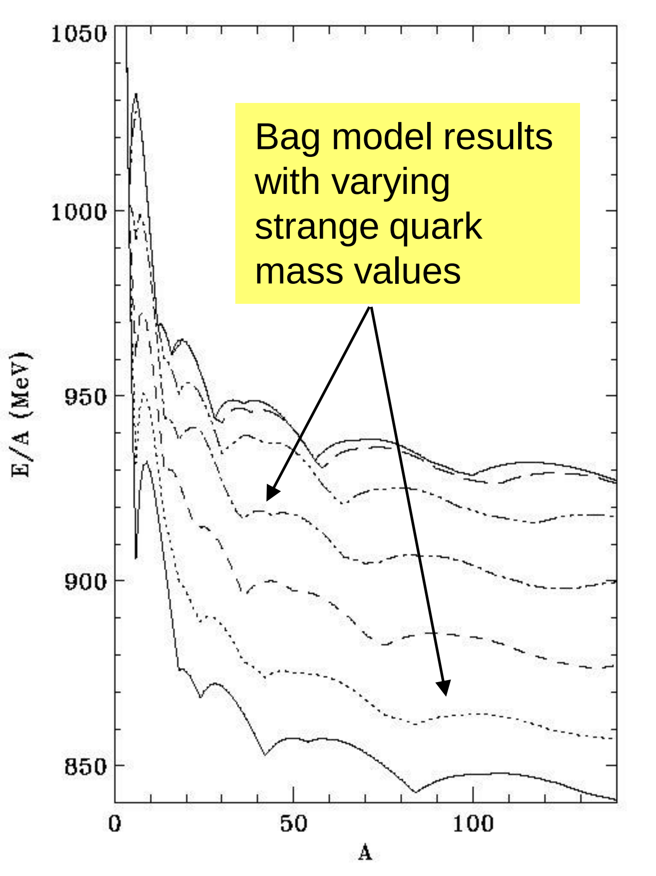


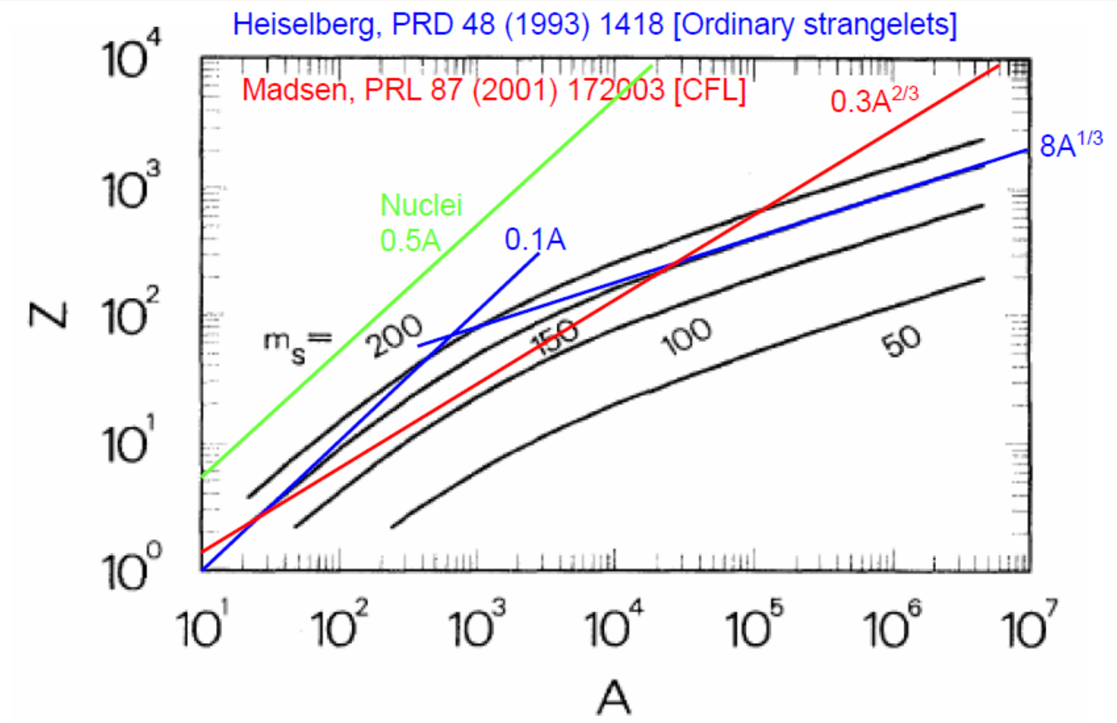
Stability can not be calculated in QCD, but is addressed in phenomenological models (MIT Bag Model, Color Flavor Locking…).

For a large part (~half) of available parameter space, these models predict that SQM is absolutely stable in bulk.

Strange Quark Matter

Roughly equal numbers of u, d, s quarks in a single 'bag' of cold hadronic matter.



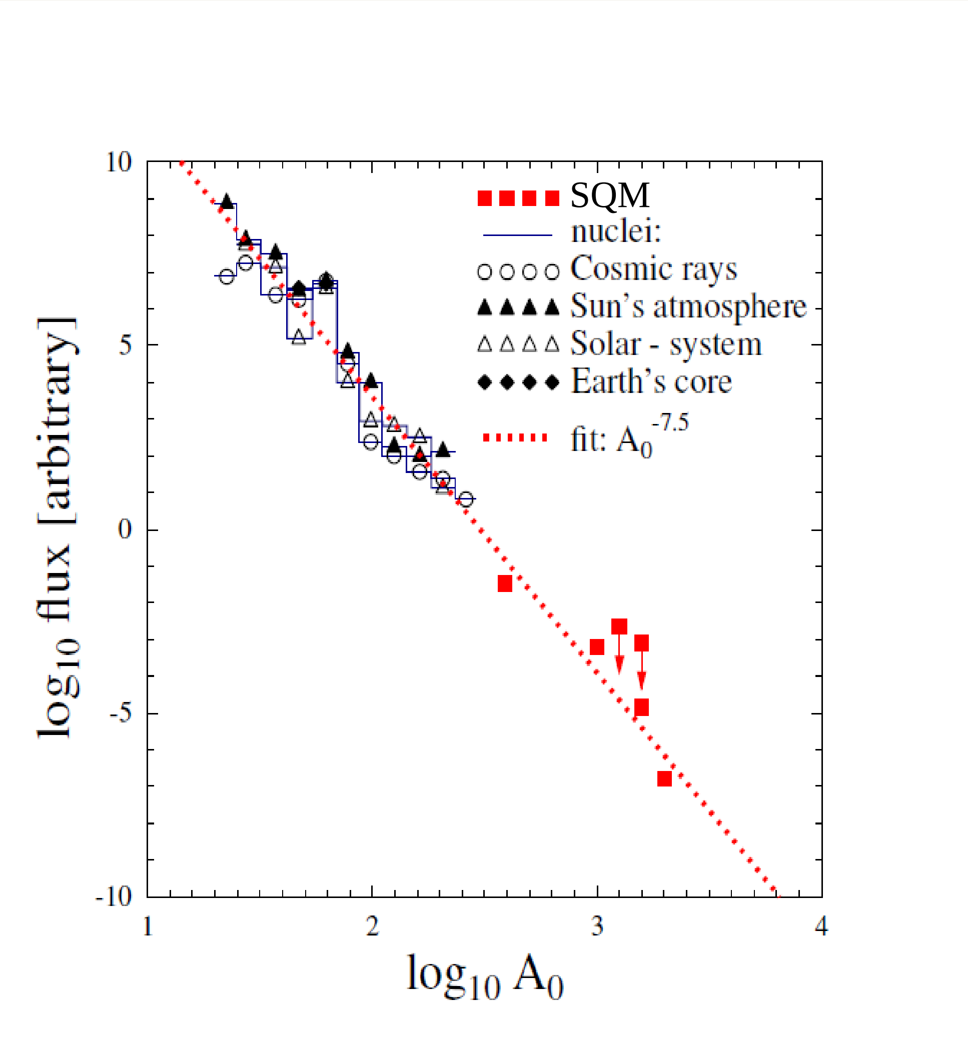


SQM is less stable for lower baryon number (A < ~100)

Strange Quark Matter have low Z/A

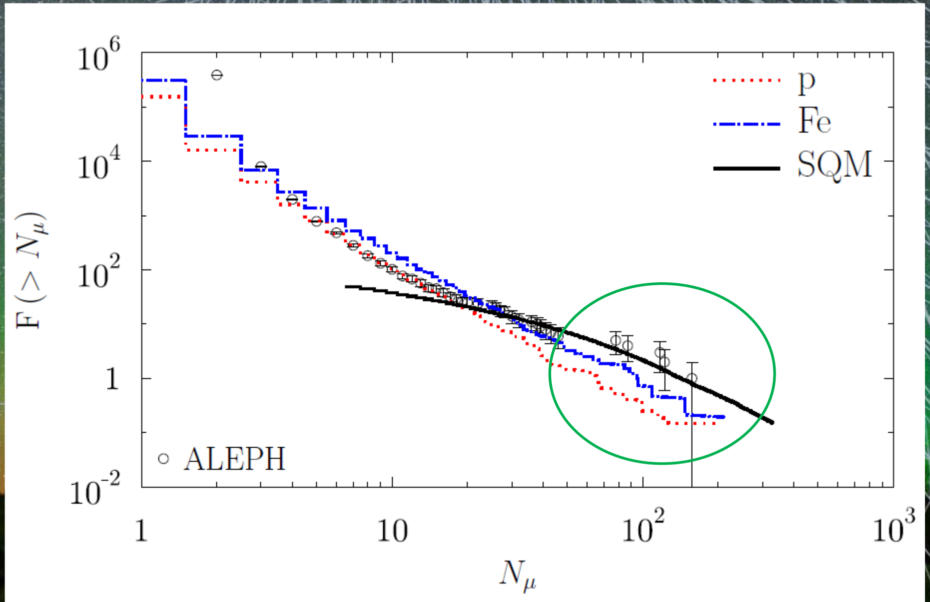
[E. Farhi, R.L. Jaffe, Phys. Rev. D 30, 2379]
[C. Alcock and E. Farhi, Phys. Rev. D 32, 1273]

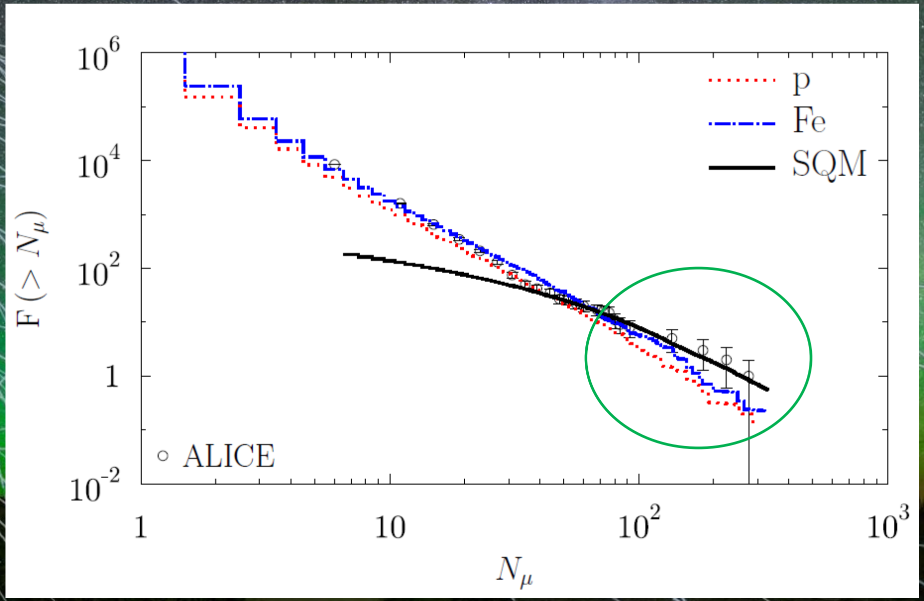
Abundances of elements in the Universe



[G.B. Zhdanov, Usp. Fiz. Nauk 111, 109]
[G.B. Zhdanov, Sov. Phys. Usp. 16, 642]
[M. Rybczyński, Z. Włodarczyk, G. Wilk, Acta Phys. Polon. B 33, 277]

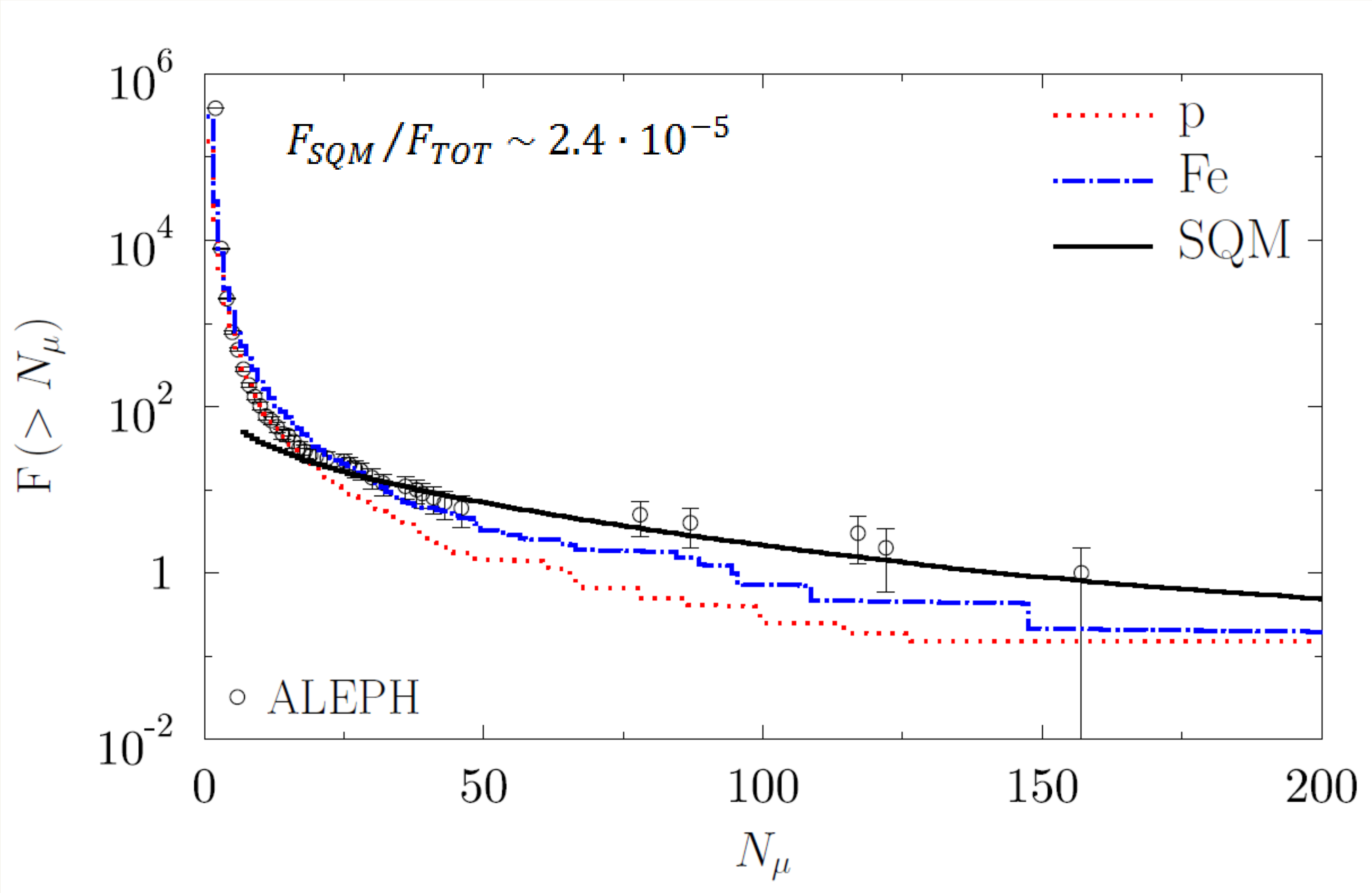
High-multiplicity muon bundles from SQM





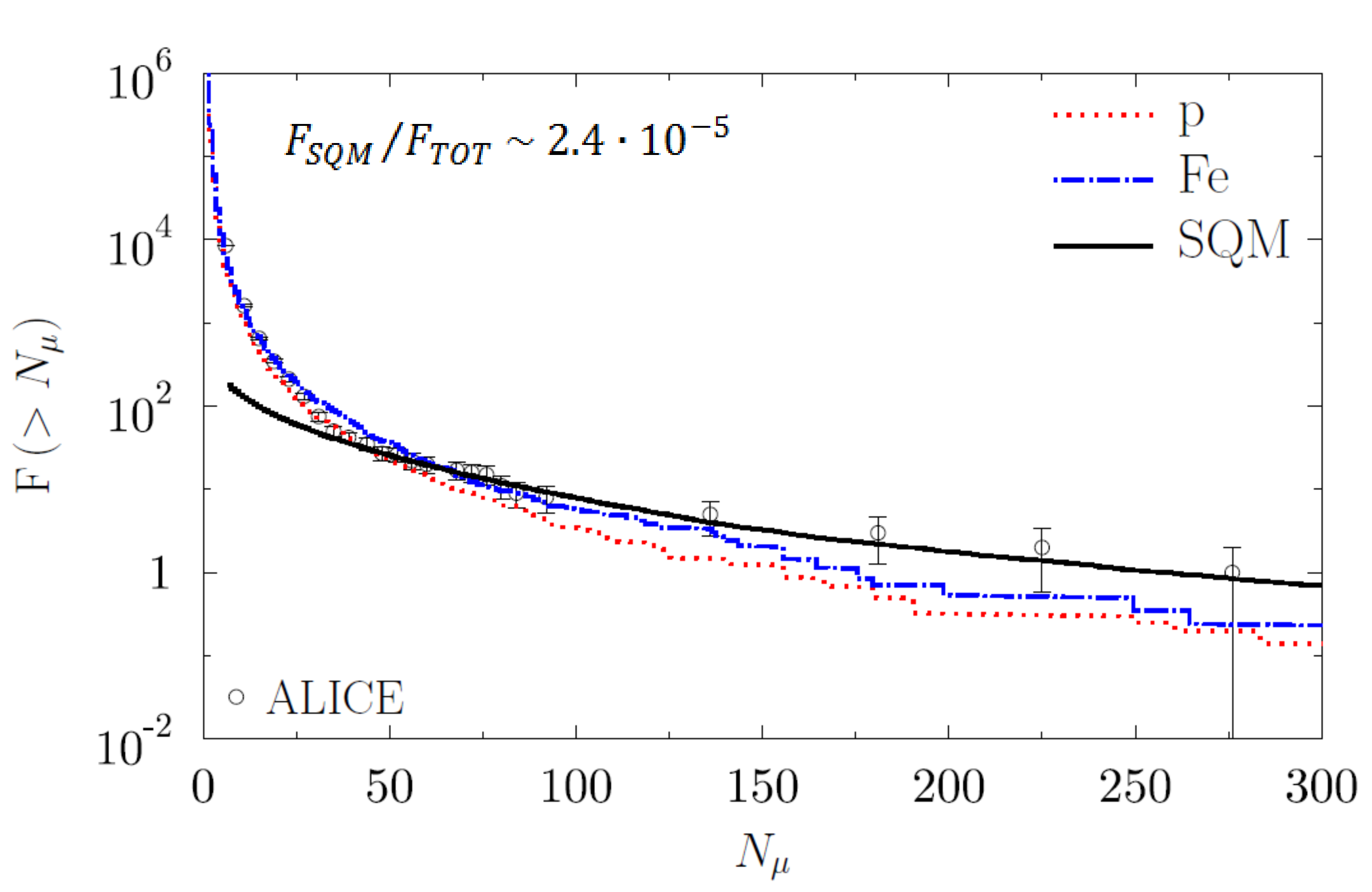
[P. Kankiewicz, M. Rybczyński, G. Wilk, and Z. Włodarczyk, **ApJ 839, 31** [1612.04749 [hep-ph]]

High-multiplicity muon bundles from SQM



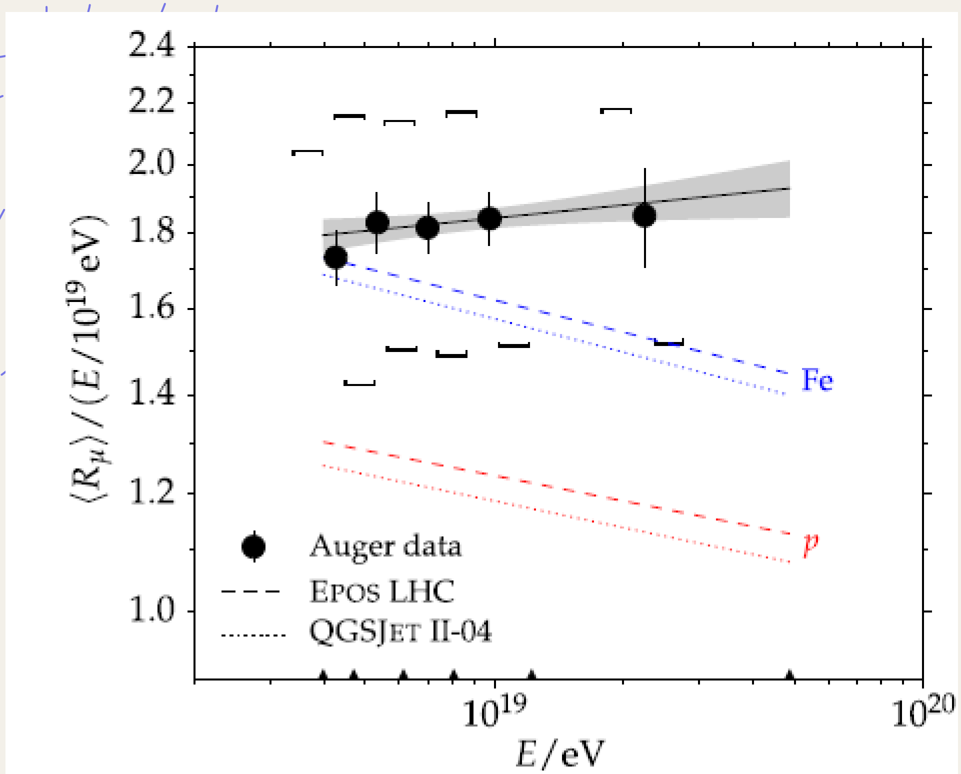
Integral multiplicity distribution of muons the ALEPH data (circles) published in [Astr. Phys. 19, 513]. Monte Carlo simulations for primary protons (dotted line); iron nuclei (dashed dot line) and primary strangelets with mass A taken from the $A^{-7.5}$ distribution (full line) with abundance of the order of $2 \cdot 10^{-5}$ of the total primary flux at 10 GeV.

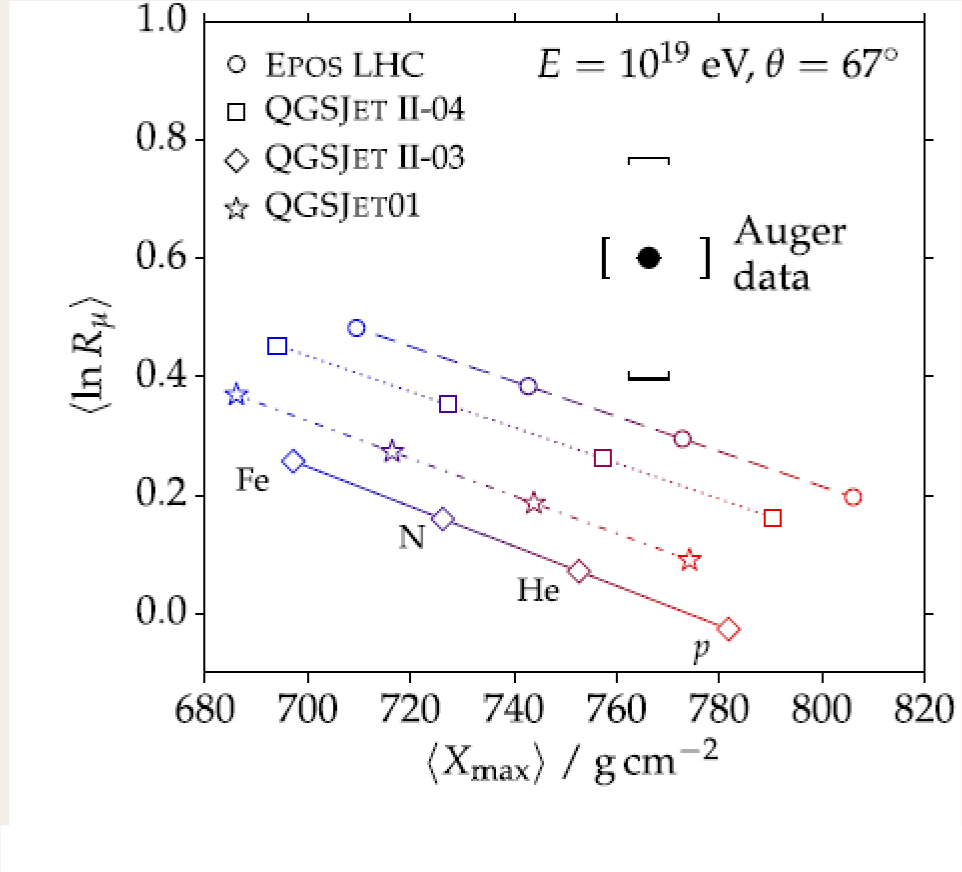
High-multiplicity muon bundles from SQM



Integral multiplicity distribution of muons for the ALICE data (circles) published in [JCAP 01, 032]. Monte Carlo simulations for primary protons (dotted line); iron nuclei (dashed dot line) and primary strangelets with mass A taken from the $A^{-7.5}$ distribution (full line) with abundance of the order of $2 \cdot 10^{-5}$ of the total primary flux at 10 GeV.

Muon excess in EAS





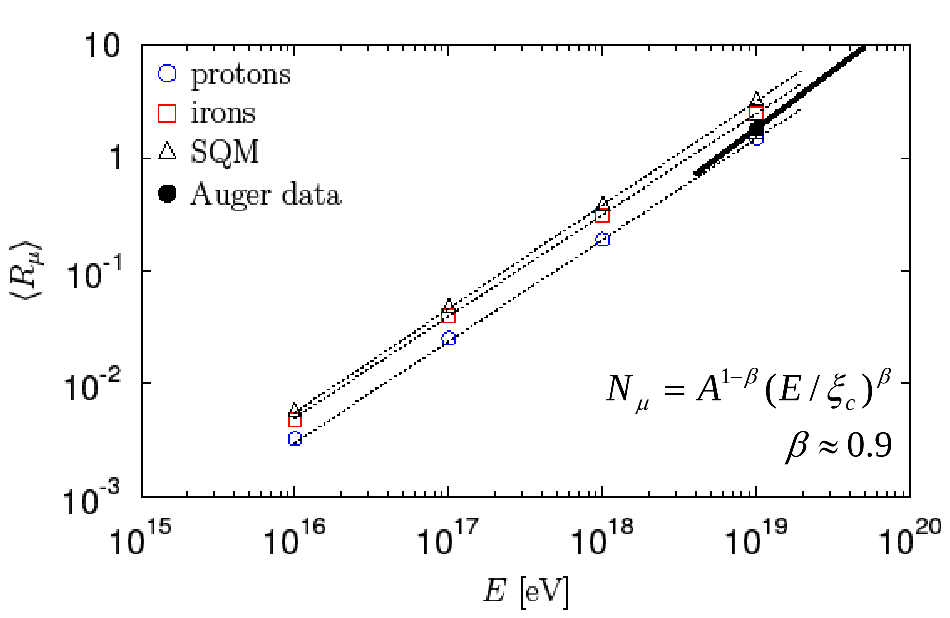
[Aab A et al. (Pierre Auger Collaboration), Phys. Rev. D 91, 032003, Erratum: Phys. Rev. D 91, 059901]

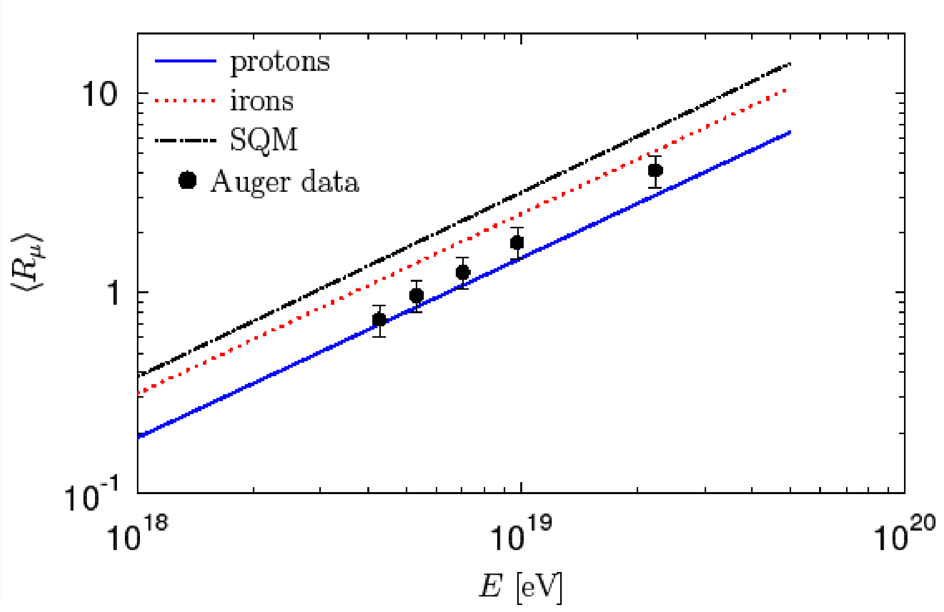
$$R_\mu = N_\mu / N_{\mu,19}$$

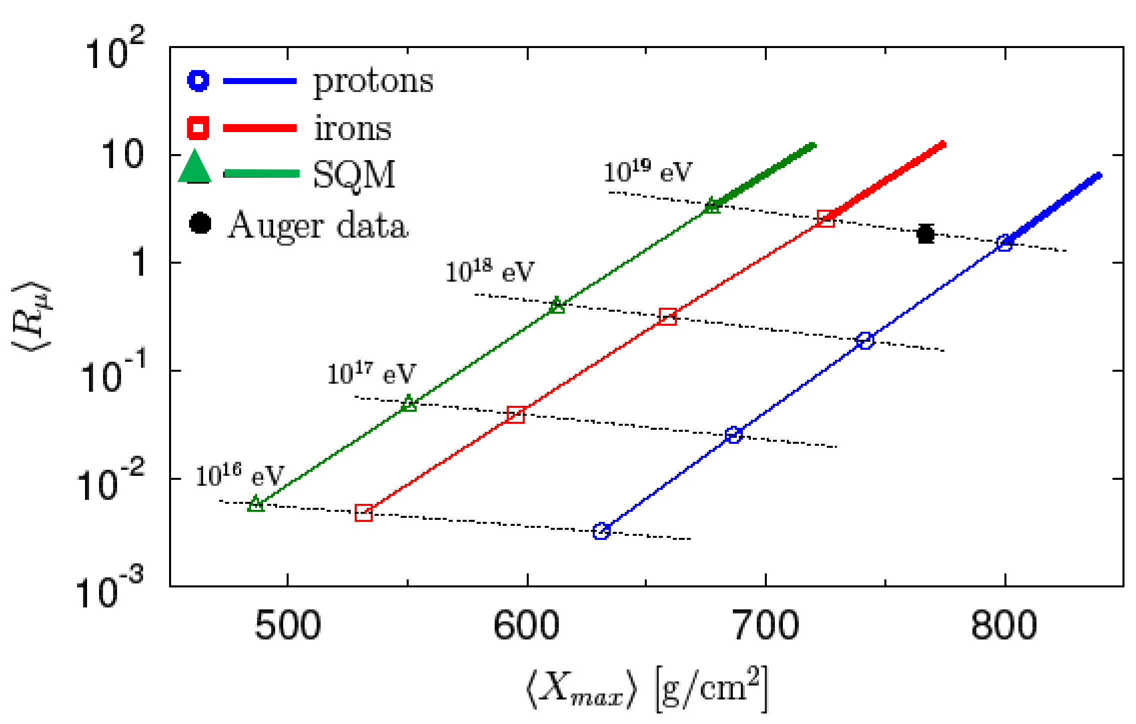
At zenith angle $\Theta = 67^0$ the muon content

$R_\mu = 1$ corresponds to $N_\mu = 1.455 \cdot 10^7$ muons at the ground with energies above 0.3 GeV

Muon content in EAS

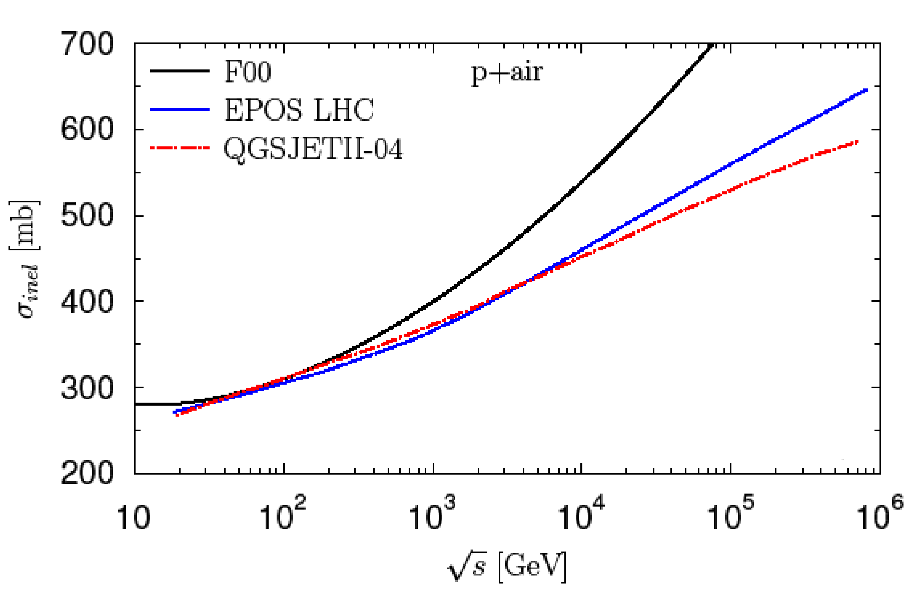


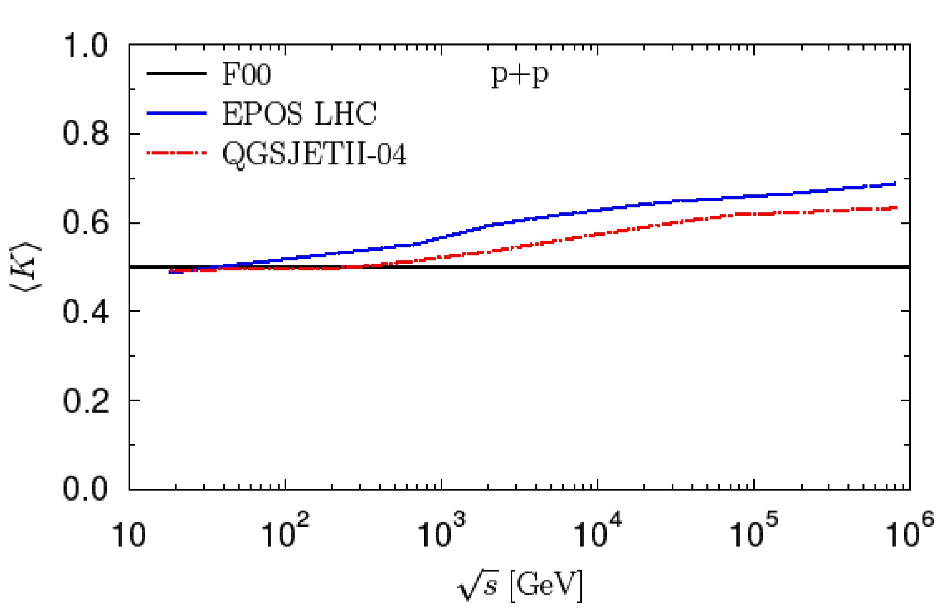


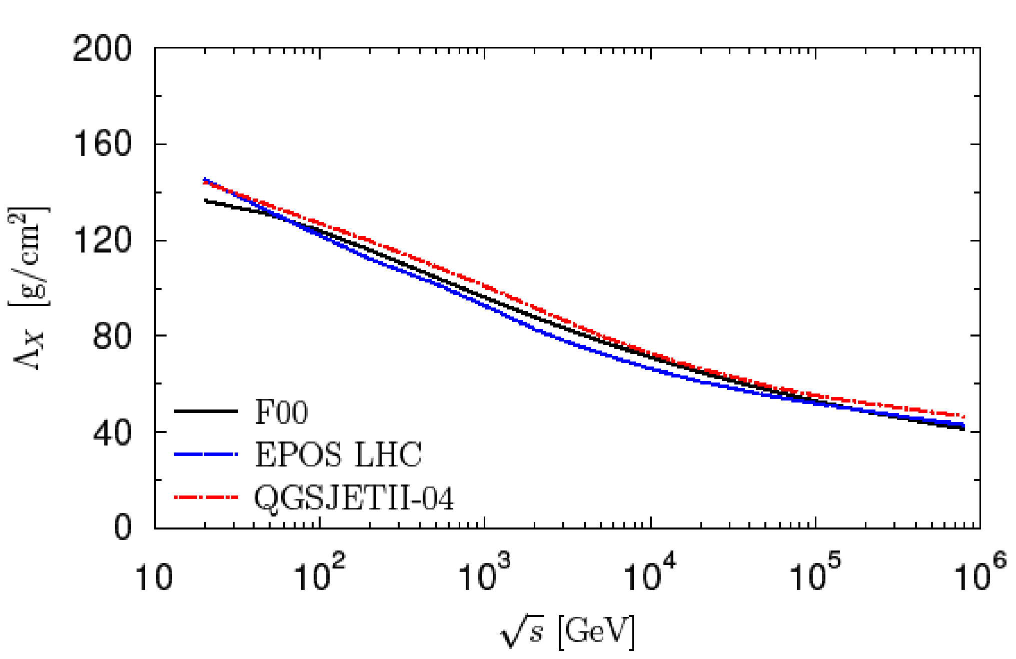


A rough agreement between the simulations and the data for ordinary nuclei **without any contribution of SQM** in primary flux of cosmic rays

F00 model (from the SHOWERSIM modular software)







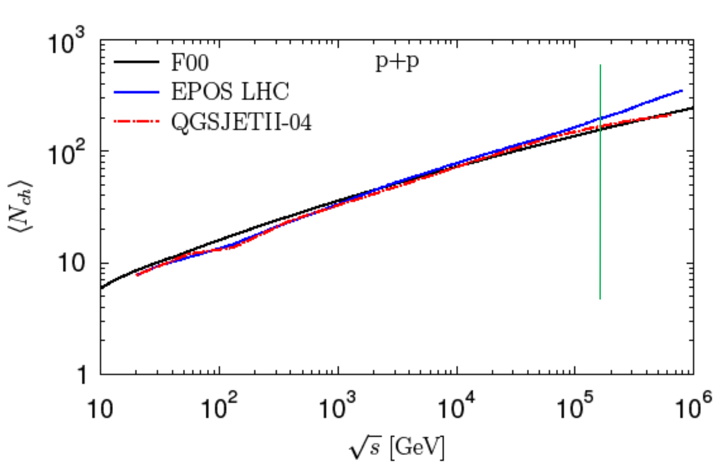
The deep tail of maximum distribution

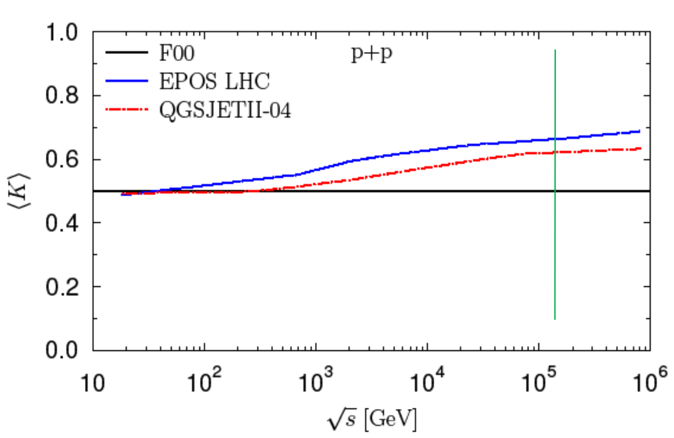
$$\frac{dN}{dX_{\max}} \propto \exp\left(-\frac{X_{\max}}{\Lambda_X}\right)$$

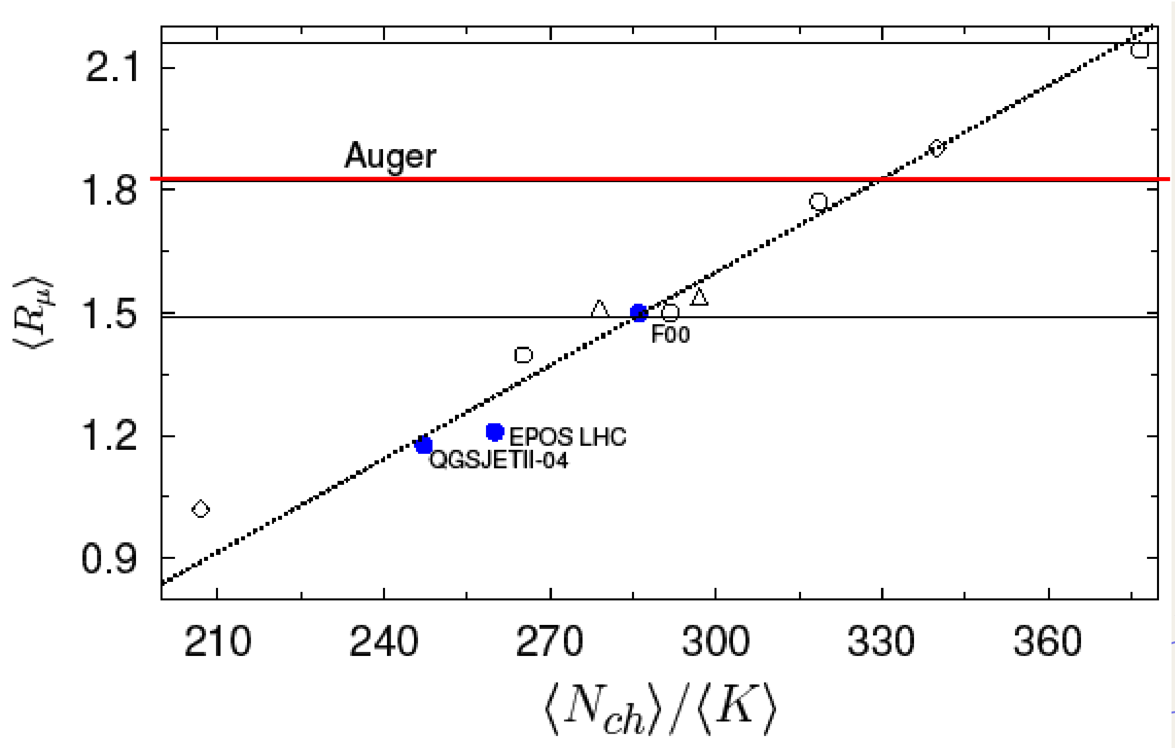
depends on shower maxima attenuation length

$$\Lambda_X \cong 0.8 \frac{2.4 \cdot 10^4 \, g/cm^2}{< K > \sigma_{inel}}$$

F00 model (from the SHOWERSIM modular software)







[M. Rybczyński, Z. Włodarczyk, **Int. J. Mod. Phys. D 28, 1950097** [1902.09988 [hep-ph]]

Concluding Remarks

Accelerator apparata can be suitable for cosmic-ray physics. Recently CERN ALICE experiment, in its dedicated cosmic ray run, observed muon bundles of very high multiplicities confirming similar findings from the LEP era at CERN (in the Cosmo-LEP program: ALEPH, DELPHI and L3)

The measured by the CERN ALICE experiment low multiplicity muon groups favor light nuclei as primaries, medium multiplicities show tend to heavier primaries.
In the case of high-multiplicity muon groups, the common interaction models fail to describe muon bundles. **SQM allows to reproduce the high muon multiplicity groups**.

The arrival directions of the observed high-multiplicity muon groups suggest their **extragalactic origin**.

Ordinary nuclei, without any contribution from strange quark matter in the primary flux of cosmic rays can describe muon content in EAS. Even if SQM contribute with a small amount in the primary flux and generate high-multiplicity muon bundles, their influence on the average muon content $\langle R_\mu \rangle$ in EAS is negligible.

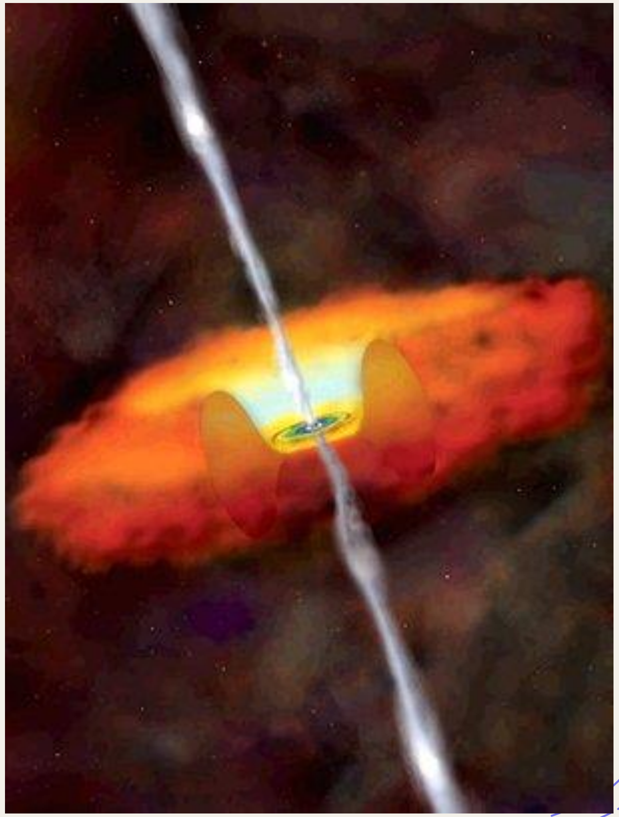
Additional slides

The Mrk 421 blazar

Blazars are a subgroup of a very bright active galaxies (called Active Galactic Nuclei, AGN). Radiation emitted by blazars extends across the entire range of the electromagnetic spectrum, from radio frequency up to high-energy gamma radiation.

Specifically, to be classified as a blazar an AGN must be observed with one of the following properties:

- ✓ high radio-brightness accompanied by flatness of the radio spectrum
- ✓ high optical polarization,
- ✓ strong optical variability on very short timescales (less than few days).



Markarian 421 (Mrk 421) is located in the constellation Ursa Major at redshift z = 0.03 (roughly equivalent to 115 Mpc or 370 million light-years).
It is one of the brightest objects in its class, thus often monitored by different instruments.

Anisotropy of Arrival Directions

ALICE highest-multiplicity muon bundles

Event	N_μ	Φ [°]	θ [°]	Date (JD)	Az [°]	h [°]	α_{2000}	δ_{2000}
1	181	212.4	40.4	2455247.53666	268.5	49.6	7 h 54 m	32° 36′
2	136	170.2	16.6	2455256.64166	226.3	73.4	13 h 25 m	33° 49′
3	276	192.9	26.0	2455708.26792	249.0	64.0	9 h 08 m	32° 45′
4	225	235.7	23.5	2456044.54870	291.8	66.5	13 h 35 m	49° 57′
5	136	264.8	2.6	2456052.38119	320.9	87.4	12 h 14 m	48° 18′

ALICE result: highest-multiplicity reconstructed

Event with 276 atmospheric muons