COSMIC RAY INSPIRED SEARCHES AT THE LHC*

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New experimental findings and theoretical trends concerning the cosmic ray exotic phenomena are reviewed. Motivation and possibilities of their searches at LHC experiments are discussed.

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1. Introduction

Ultra-high energy cosmic ray events [1, 2] reveal many unexpected features and could be signs of new states of matter. The new accelerator experiments should incorporate the exotic phenomena (*e.g.* Centauro-related anomalies, strongly penetrating component, ring-like events possibly connected with the Cherenkov gluons emission, magnetic monopoles *etc.*) into the list of investigated ones. We proposed to search for unusual events from the first days of preparation of physics motivation for the LHC collider [2, 3, 4], suggesting that they could be signs of the phase transition from a Quark Gluon Plasma (QGP) to a hadronic phase and a manifestation of extreme fluctuations expected in the vicinity of the critical end-point. The start of the LHC collider is a suitable time to refresh these ideas. Motivation comes as well as from some new results of cosmic ray experiments, theoretical ideas and also from the first LHC data. In particular, the ALICE Collaboration found that the charged particle multiplicity of events produced in pp collisions at $\sqrt{s} = 0.9$, 2.36 and 7 TeV (what corresponds to $E_{\rm lab} \simeq 4 \times 10^5$, 2.8×10^6 and 2.5×10^7 GeV, respectively) [5] is following a simple power law in energy. Two cosmic ray physicists, Erlykin and Wolfendale, noticed [6] that the power law exponent, observed at LHC, is

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the same as $\alpha = 0.11$ found at $E_{\rm lab} \simeq 1.5 \times 10^3$–$1.5 \times 10^5$ GeV, and close to $\alpha = 0.13$, found in the lower energy range $E_{\rm lab} \simeq 10$–1.5×10^3 GeV. The confirmation of the old multiplicity results should trigger interest of the LHC community in searching for and studying also exotic phenomena observed in cosmic ray experiments.

2. Centauros — present status, experimental puzzles and new theoretical trends

Status of Centauros was rather clear until 2003. Reasonable statistics of Centauro-like events (Centauros, mini-Centauros, Chirons) revealing surprising features, such as: abnormal hadron dominance, high transverse momentum of produced particles, existence of mini-clusters, frequent accompaniment by a strongly penetrating component, has been published (see review [2]). It has been shown that they cannot be explained by fluctuations in usual hadron interactions and in the development of electromagnetic cascades. Many models, based on different scenarios (*e.g.* isospin violation, Quark Gluon Plasma (QGP), Disoriented Chiral Condensates (DCC), Strange Quark Matter (SQM) formation) satisfactorily explained the hadron-rich composition of Centauros [2]. Our model of SQM fireballs decaying into baryons and strangelets [7] offers simultaneous explanation of both hadron-rich events and a strongly penetrating component which is assumed to be produced by strangelets [8]. More recently, the new explanations of Centauros, based on Mini Black Holes (MBH) [9] and R-hadrons scenarios [10] have been proposed. In 2003, however, some embarrassment with Centauro I happened.

2.1. Centauro I puzzle

Centauro I is the first and the most spectacular event of this type. It was found in 1972, in the two-storey Chacaltaya chamber. According to the original analysis [1], the event consisted of two groups of showers: one group of 7 showers was observed in the upper chamber and the other one of 43 showers was found in the lower chamber. The fuss has been made [11, 12] when more recently, two groups of physicists reexamined the Centauro I event and discovered differences in angles between the cascades registered in the upper and lower blocks. The remeasurement could indicate as well as the trivial apparatus effects or just the ultra-exotic nature of the event, much more surprising behaviour as it has been thought before. The interpretation and conclusions done by the two groups are different.

Kopenkin, Fujimoto and Sinzi stated [12] that the event observed in the lower chamber could be the air family passing through a gap between blocks in the upper detector. On the contrary, Ohsawa, Shibuya and Tamada [11] presented a lot of arguments against the "passing gap hypothesis". According to [11] the probability that the event passed through a gap is as low as ~ 0.5–3×10^{-4} and also other features of the event cannot be described by the gap-passing hypothesis. Centauro I passed the detector leaving no (or a single) showers in the upper block, so the event seems to be even much more surprising than before. It could be explained by a SQM scenario.

Another solution of Centauro I puzzle could be the Mini Black Holes scenario. MBHs production and evaporation could be possible in space with extra dimensions in which the fundamental Planck scale would be in the TeV range. MBHs would decay thermally via Hawking radiation, with equal probabilities to all Standard Model degrees of freedom. The resulting photon/hadron ratio should be lower than that for ordinary hadronic interactions and Centauros could be the result of evaporation of MBHs [9]. Because of very high temperature [9] the appearance of particles with high transverse momenta is expected. Standard elaboration of the experimental material from mountain emulsion chambers causes that very high p_{T} particles could be interpreted as flying at different arrival angles and not recognised as the family members [13].

It should be stressed that Centauro I is not a sole hadron-rich event. Besides Centauro I there is the rich statistics of other hadron-rich events detected in various chambers, as well as by Chacaltaya, Pamir and Pamir-Joint-Chambers collaborations [2]. Their hadron-rich composition cannot be explained by apparatus effects and questioned.

2.2. Centauros in the ALICE experiment at the LHC

Centauros can be searched for in the LHC experiments via looking for extreme event-by-event fluctuations [2, 3, 4].

To study the ability of LHC experiments in searching for Centauro-related phenomena we generated the usual central $\mathrm{Pb}+\mathrm{Pb}$ events (by HIJING) and Centauros (by our CNGEN generator [14]), assuming energy densities up to $\epsilon \simeq 30$ GeV/fm^3 and the nuclear stopping $\Delta y_{\mathrm{stop}} \sim 2$–$3.5$, in accordance with HIJING and VENUS model predictions and with BRAHMS experimental results. Strangelets are always flying in the very forward direction. Pseudorapidity distributions of other Centauro decay products depend on characteristics of Centauro fireballs. They occupy preferably forward rapidity regions, where higher values of quark chemical potential μ_q are expected, but sometimes distributions extend almost to the central rapidity region. Fig. 1 shows pseudorapidity distribution of Centauro decay products and strangelets generated at the temperature $T = 300$ MeV, and a fireball stopping $\Delta y_{\mathrm{fb}} = 1.5$. Geometrical acceptance of some ALICE components [15], suitable to study Centauros has been sketched.

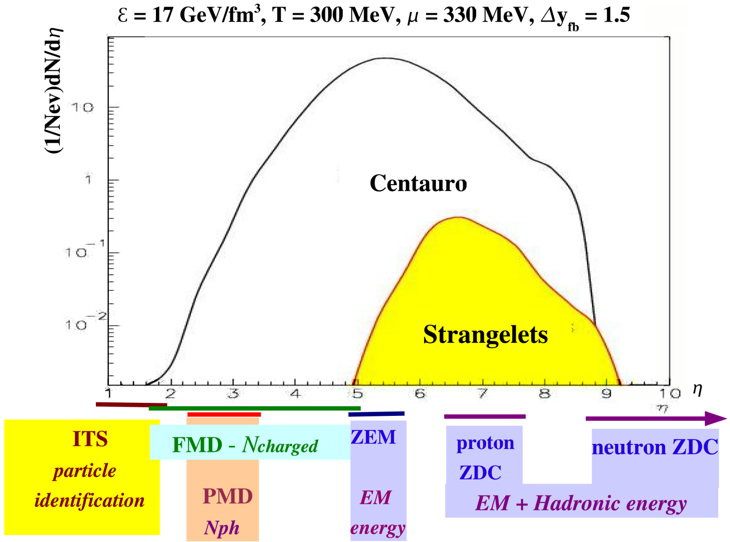

Fig. 1. Pseudorapidity distribution of Centauro decay products and strangelets, generated by CNGEN program for Pb + Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV. Geometrical acceptance of several ALICE detectors has been sketched.

The Forward Multiplicity (FMD) detector, consisting of three Si detection planes, covering the region $1.7 < \eta < 5.09$ at one side of the interaction point, and two Si planes, covering $1.7 < \eta < 3.4$ at the second side, could be used for Centauro searches via multiplicity fluctuation studies. Anomalous composition of Centauro decay products, within the geometrical acceptance of the FMD detector, is compared with HIJING predictions in Fig. 2. Total multiplicities of Centauro events ($\langle N_{\text{tot}} \rangle = 64$) are apparently lower than multiplicities of usual events ($\langle N_{\text{tot}} \rangle = 19441$). Multiplicities of usual events are dominated by mesons and gammas, while in Centauros mainly baryons are produced.

Photon Multiplicity detector (PMD) will detect photons and charged particles in the pseudorapidity range $\sim 2.3 < \eta < 3.5$. It consists of the VETO plane for vetoing charged particles and the Preshower plane, placed behind the $5X_0$ thick Pb converter, for photons. Centauro events, if produced within the PMD acceptance could be recognized by imbalance between photon and hadron component. The typical observable used in cosmic ray experiments is a number of hadrons *versus* the ratio of hadron multiplicity to total multiplicity. Our simulations showed [16] that the simplest ALICE observable could be a scatter-diagram N_{veto} *vs.* $N_{\text{veto}}/N_{\text{presh}}$ where N_{veto} and N_{presh} are numbers of tracks in the veto and preshower planes respectively. Centauros could be searched for among events characterized by high values of both N_{veto} and $N_{\text{veto}}/N_{\text{presh}}$. After hadron and photon identifica-

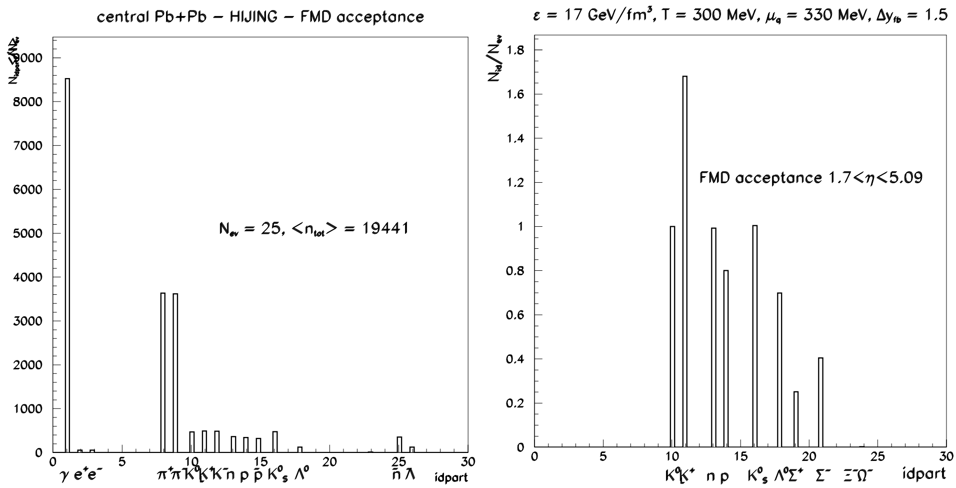

Fig. 2. Multiplicity and composition of particles produced in Pb + Pb central collisions at $\sqrt{s_{NN}} = 5.5$ TeV, within geometrical acceptance of ALICE FMD. HIJING and Centauro events are shown in left and right plots respectively.

tion we could search for Centauros at the upper right corner of the plot N_{h} *vs.* $N_{\mathrm{h}}/(N_{\mathrm{h}} + N_{\mathrm{ph}})$, far from $N_{\mathrm{h}}/(N_{\mathrm{h}} + N_{\mathrm{ph}}) \simeq 0.5$, where usual events are grouped. Anti-Centauros should be placed at the lower left corner of that plot (at $N_{\mathrm{h}}/(N_{\mathrm{h}} + N_{\mathrm{ph}}) \simeq 0$ and at low, close to zero, N_{h}) (top panel of Fig. 3).

Central ALICE detectors (TPC and ITS) allow for detection and identification of charged particles in the midrapidity range $-1.5 < \eta < 1.5$ ($|\eta| < 0.9$ for full-length TPC tracks). Cosmic ray Centauros are characterized by anomalous ratio of hadronic to electromagnetic component. Using cosmic ray emulsion chambers, it is impossible, however, to define the nature of the hadronic component. So, the Centauro phenomenon could be the result of a baryon fireball decay (with strong suppression of meson production) or alternatively the result of the isospin violation in events in which π^+ and π^- are produced without π^0 component. In the last case, the Centauro search in the central ALICE detectors will be possible by using the conversion method for π^0 identification. In the first case, baryonic fireballs can be recognised by baryon identification. Centauros should be grouped at the right upper corner of the scatter diagram showing the number of protons and anti-protons, N_{pr}, *versus* the ratio of protons and anti-protons to the total multiplicity $N_{\mathrm{pr}}/N_{\mathrm{tot}}$. Usual events, generated by Pythia, are characterized by a low value of N_{pr} and $N_{\mathrm{pr}}/N_{\mathrm{tot}} < 0.5$ [16].

The bottom panel of Fig. 3 shows the scatter-diagrams of the number of charged pions *vs.* the number of protons and anti-protons N_{pr} (left plot) and the sum of protons and kaons $N_{\mathrm{pr}} + N_{\mathrm{K}}$ (right plot), generated by Pythia.

Only events with the number of tracks $N > 60$ are shown. According to our Centauro model [14] an enhancement in the sum multiplicity of baryons and kaons is expected. Centauros should be looked for at the lower right corner of these plots.

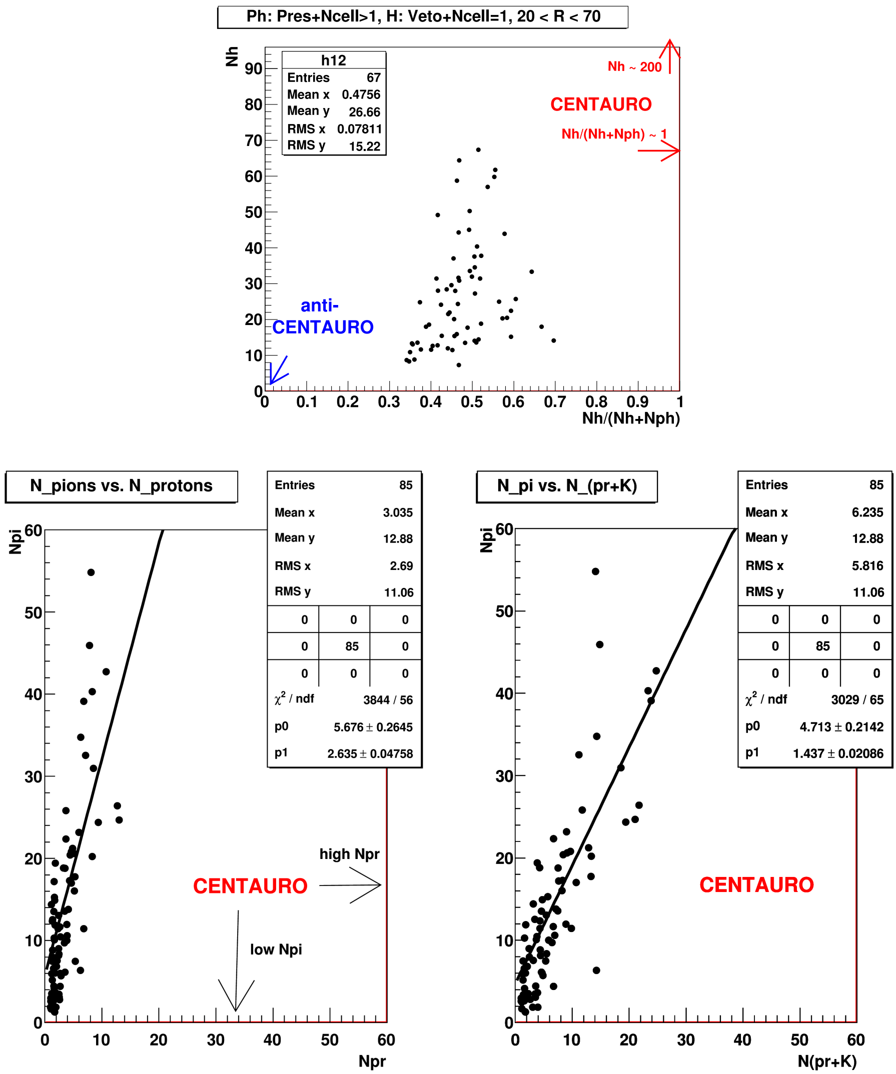

Fig. 3. Top panel: number of charged hadrons $N_{\rm h}$ in the VETO plane *vs.* $N_{\rm h}/(N_{\rm h}+N_{\rm ph})$, where $N_{\rm ph}$ is number of photon clusters in the preshower plane of PMD. Bottom panel: number of charged pions N_π *vs.* number of protons and anti-protons $N_{\rm pr}$ (left plot); number of protons, anti-protons and charged kaons (right plot). Particles have been generated by Pythia in *pp* collisions at $\sqrt{s} = 7$ TeV.

3. Strongly penetrating component

Centauro-like events are very frequently connected with the so-called *strongly penetrating component*. It has been observed in the apparatus in the form of long flying single cascades, clusters of showers or the so-called *halo*. This phenomenon manifests itself by the characteristic energy deposition pattern revealed in shower development in deep chambers (calorimeters) indicating the slow attenuation and many maxima structure. We have presented the first such event in 1980 [17]. Other penetrating mini-clusters and long many-maxima cascades, observed as well as by the Chacaltaya and the Pamir Collaboration we have reviewed in [2]. A many-maxima structure can appear when passage of any object through the matter is connected with emission of lepton(s) or hadrons in the process of successive decays or inelastic collisions. We have proposed and checked by simulations the hypothesis that exotic many-maxima cascades observed in cosmic ray experiments could be produced by strangelets [2, 8]. We proposed *the energy deposition pattern in deep calorimeters with fine longitudinal segmentation* as the new signature of novel states of matter [18] and it has been shown [4] that not only strangelets, but also other unusual objects, such as Centauros and narrow neutral or charged pion clusters (DCC), should produce characteristic transition curves. The analysis of such observables as: fluctuations of electromagnetic to hadronic energy ratio, longitudinal extent of the signal, many–maxima structure, azimuthal asymmetry, and concentration of the energy in a small phase space volume will allow not only to distinguish between "normal" and "unusual" events, but also to distinguish between different scenarios. We expect that also other objects, such as for example magnetic monopoles, R-hadrons *etc.*, could be responsible for the unusual development of cascades and could be detected in the deep CASTOR-like calorimeters.

3.1. Strangelets

3.1.1. Embarrassment with strangelets

Previous searches for SQM resulted in low limits for strangelets but on the other hand some observations could be understood by assuming the presence of strangelets in cosmic rays [4]. Recent experimental results are also confusing. On the one hand, two SQM candidates have been found during the AMS prototype flight [19]. On the other hand the negative results of strangelet searches have been published by the STAR Collaboration at the RHIC collider [20].

This result can be understood on the basis of our model of strangelet production via distillation of s quarks in the SQM (Centauro) fireball [7]. Fig. 4 shows pseudorapidity distributions of strangelets possibly produced in central Au + Au collisions, at RHIC conditions. Our simulations indicate the pseudorapidity region $\sim 4 < \eta < 6$ as the most suitable place for strangelet production. It is outside searches done by the STAR Collaboration in $\sim 6.5 < \eta < 8.0$ range of the ZDC calorimeter. Another explanation, proposed by Norbeck and Onel, could be the formation of strangelets from modified spectator matter [21]. In this case, strangelets produced in nucleus–nucleus collisions should be looked for *not in central* but *in peripheral* collisions.

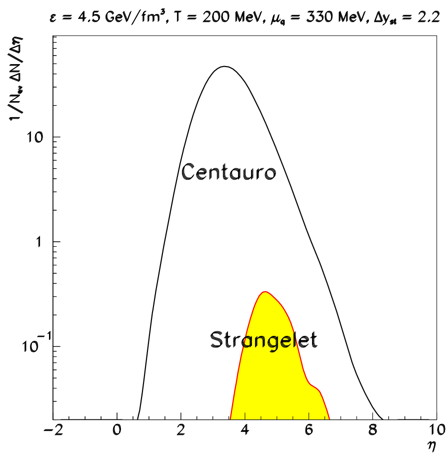

Fig. 4. Pseudorapidity distribution of strangelets, simulated by CNGEN generator [14], in central Au + Au collisions at RHIC.

3.1.2. Hunting for strangelets in the ALICE experiment at the LHC

The ALICE experiment gives some opportunities to search for strangelets, if produced at midrapidity or at very forward region. In the first case, strangelets could be looked for in the central detectors [22]. Long-lived strangelets could be recognised via the characteristic energy deposit in the TPC and the time of flight, measured in the TOF detector. Short-lived strangelets could be searched for by the characteristic decays [22].

Strangelets flying in the very forward rapidity region or just in the fragmentation region [21], could be searched for in the Zero Degree Calorimeters (ZDCs) of ALICE [16], CMS and ATLAS experiments. They should produce unexpectedly high signal in ZDCs, higher than that expected from the impact parameter value, determined by other methods. The most suitable seem to be the ALICE ZDC calorimeters. ALICE has proton P1ZDC and neutron N1ZDC calorimeters, located at both sides of the outgoing beam line. Usually, a nearly constant ratio of signals from neutron and proton spectators should be expected. A deviation from this ratio could indicate a strangelet.

The division of ALICE zero degree calorimeters into 4 towers will allow to localize a strangelet more precisely and distinguish it from "usual" signals. The ratio of signals in individual towers of the neutron N1ZDC to the sum of signals in both calorimeters (EN1 + EP1) extends up to 1, in the case of $p+p$ collisions, generated by Pythia [16]. It means that in pp collisions there are produced events, in which a big fraction of projectile energy, sometimes almost whole energy, is deposited in one tower of the neutron or proton calorimeter. It is different picture from that in Pb + Pb collisions, generated by HIJING, where this ratio is always less than 0.2 and energies carried by fragments of the spectator matter are distributed almost uniformly among the towers of the neutron N1ZDC [16]. Finding Pb + Pb event with the investigated ratio close to 1, could indicate that some strange object (*i.e.* strangelet), characterized by strong concentration of energy in a small region of phase space, has been produced.

3.1.3. Hunting for strangelets in the CASTOR detector for CMS

The CASTOR (Centauro And STrange Object Research) tungsten–quartz calorimeter, originally proposed for the ALICE experiment and finally built as the subsystem of the CMS experiment [23], is the unique experimental device dedicated to explore the baryon-rich forward rapidity region ($5.2 < \eta < 6.5$). We have shown [2, 4, 18] that high depth (760 mm of tungsten, *i.e.* $\sim 10.3\lambda$) and fine azimuthal (16 sectors) and longitudinal sampling (14 readout units) make CASTOR the sensitive tool for a study of longitudinal profiles of cascade showers, and thus for detection of strongly penetrating objects, in particular, as well as stable and unstable, charged and neutral strangelets. Showers produced by strangelets reveal very long extent and characteristic attenuation pattern with many hump structure, so they can be easily distinguished from conventional events.

3.2. Magnetic monopoles

Up to now, only *slow monopoles* have been searched for in accelerator experiments, by signatures based mainly on their *high ionization losses* and *characteristic trajectories in the magnetic field* [24].

Theoretical predictions concerning masses of magnetic monopoles are undefined, ranging from quite small values $M_{\mathrm{mon}} = 2.56\ m_{\mathrm{p}}$, where m_{p} is a proton mass, up to enormously large masses, near the Planck mass, $M_{\mathrm{mon}} \sim 10^{16}$–$10^{17}$ GeV. LHC energies will be much higher than those available at the previous accelerators, so there is a chance to produce here more massive and faster monopoles, and searching for *relativistic monopoles* should be also taken into account. For relativistic magnetic monopoles, not only ionization, but also other processes, such as successive emission of high energy bremsstrahlung photons or electron pairs creation will be important [25]. We expect that for some combinations of monopole masses and charges the bremsstrahlung is a dominant process. Using formulas from [25] we see that the ratio of bremsstrahlung to ionization loss is:

$$(dE/dx)^{\rm brem}_{\rm mon}/(dE/dx)^{\rm ioniz}_{\rm mon} \sim (ng)^2 Z\gamma/M_{\rm mon}\,, \tag{1}$$

where Z is the charge of nucleus absorber, g is a magnetic charge of Dirac monopole. So, energy loss by bremsstrahlung will be stronger for monopoles with higher magnetic charges, lower masses and traversing heavier absorbers. As the example, we plotted the ratio of bremsstrahlung to ionization energy loss *versus* gamma factor γ for monopole masses $M_{\rm mon} = 10$ GeV and 100 GeV and monopole charges $ng = 1g, 2g, 3g$ (Fig. 5). Replacing $ze \to ng$ we adapted for monopoles the formula given by Ahlen in [26] for electrically charged particles with $\gamma \gg 1$

$$(dE/dx)^{\rm brem}_{\rm mon}/(dE/dx)^{\rm ioniz}_{\rm mon} \sim \frac{4}{3\pi}\frac{(ng)^2 Z}{137}\frac{m_e}{M_{\rm mon}}\gamma\frac{\ln\left(\lambda 192 M_{\rm mon}/m_e Z^{1/3}\right)}{L}\,, \tag{2}$$

where $L = \ln(2m_ec^2\beta^2\gamma^2/I) - \beta^2$, I is the mean ionization potential, $\lambda \simeq 1$. It is seen that bremsstrahlung energy loss increases with γ and n, and decreases with monopole mass $M_{\rm mon}$. For $M_{\rm mon} < 100$ GeV (1 TeV), $\gamma > 100$ and $n \geq 1$ ($n > 1$), bremsstrahlung dominates ionization energy loss. Bremsstrahlung energy loss is proportional to the 4-th power of the magnetic charge and inversely proportional to the monopole mass what is the reason that in some cases the monopole radiation length $X_{\rm mon}$ can

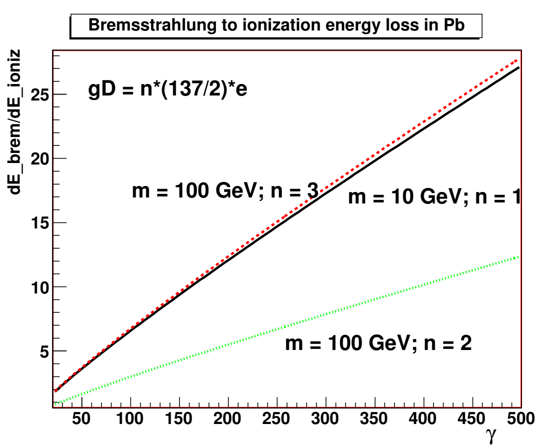

Fig. 5. Ratio of bremsstrahlung to ionization energy loss *vs.* monopole gamma factor γ.

be longer than that for an electron X_e. It results in different longitudinal shape of monopole showers than those produced by usual particles in deep calorimeters. In particular the many-hump structure could appear.

From formulas for bremsstrahlung energy loss for electrically charged particles and for magnetic monopoles [27,28], we get the ratio of radiation length of a monopole to that for an electron

$$X_{\rm mon}/X_e = (dE/dx)_e/(dE/dx)_{\rm mon} \simeq \tfrac{1}{2}\left(\frac{e}{ng}\right)^4\left(\frac{m_g}{m_e}\right)^2 . \qquad (3)$$

It is illustrated in Fig. 6. For some combinations of masses and magnetic charges, a monopole could emit gamma quanta in the bremsstrahlung process with frequency low enough to produce many individual humps seen in the cascade transition curve. The mean distance between humps, observed in the exotic long cascades in cosmic ray experiments, is about 10 X_e [2,17]. Such picture could be produced by bremsstrahlung, if the radiation comes from an object with the radiation length of about 10 times longer than that for an electron. It could be for example a magnetic monopole with $M_{\rm mon} \simeq$ 10 GeV and $g = 1 \times 137/2$ or $M_{\rm mon} \simeq 43$ GeV and $g = 2 \times 137/2$.

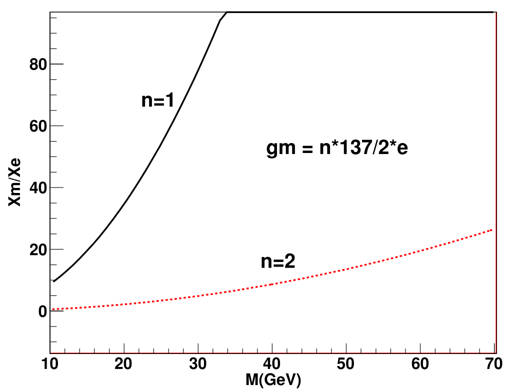

Fig. 6. Ratio of a monopole to an electron radiation length $X_{\rm mon}/X_e$ *vs.* monopole mass M.

3.3. R-hadrons

A few of the current SUSY theories predict the existence of R-hadrons, which are essentially colorless and originate through confinement of long-lived gluinos (or squarks) with quarks, anti-quarks and gluons.

Standard methods of searching for R-hadrons, developed in the LHC experiments depend on their lifetime. *Unstable R-hadrons* will decay before reaching the first sensitive layers of detectors and they could be recognized by the secondary vertex technique, especially in the pixel detectors. *Metastable* *or stable R-hadrons* traversing a detector could be detected by using *time delay* relative to ultrarelativistic usual particles or by *anomalously high ionization losses*. In the ALICE central detectors a striking difference between R-hadrons and ordinary particles is expected [29].

We propose *a new method of R-hadrons detection*. The stable component of R-hadrons (*e.g.* gluino) could be the reservoir of kinetic energy, allowing it to penetrate far in the matter. Successive interactions or decays of *ordinary* ingredients (standard quarks) would initiate an ensemble of subshowers along the trajectory of the leading particle and to carve a characteristic structure on the transition curve observed in the calorimeter. It has been shown [10] by simulations, that the flat longitudinal profile of the R-hadron initiated cascade is expected in the air. We should note, however, that this is neither general nor qualitative statement, because the shape of a resulting shower strongly depends on both, properties of a projectile and *properties of an absorber matter*. We estimated, for example, that the mean interaction length of an R-hadron in lead should be about 15.9 X_0, and about 14.3 X_0 in a tungsten absorber. In such absorbers, cascades from consecutive interactions should be separated and structures in the longitudinal development of the resulting shower could be investigated.

4. Ring-like events as inspiration for Cherenkov gluon radiation

The present renaissance [30, 32, 32] of the old idea [33] that in analogy to electromagnetic forces, strong interactions could induce such collective effects as Cherenkov gluons and Mach waves, is caused by deeper knowledge of matter structure, experimental findings in cosmic ray experiments and super high-energy accelerators. Cherenkov gluons are predicted to be emitted by partons born in hadron collisions and moving in nuclear medium, provided the nuclear index of refraction n exceeds 1. They would be emitted at the cone angle θ with respect to the momentum of the parton-emitter in the rest system of the infinite medium defined by: $\cos\theta = 1/\beta n$.

Cherenkov gluons should produce ring-like two-dimensional distributions, in the plane perpendicular to the momentum of the primary parton. The first high energy event ($E_0 \sim 10^{16}$ eV) [31], described by Cherenkov gluon emission has been found in a detector exposed during the stratospheric balloon flight. To the list of events, analysed in the context of Cherenkov gluons emission [30, 32], we would like to add our events, found in the X-ray film thick Pb chamber of the Pamir experiment. These eight high energy events (the total visible energy $\Sigma E_{\rm vis} \approx 10^{15}$ TeV) [34] reveal peculiar characteristics, such as two-maxima structure, seen as well as in lateral and transverse momenta distributions of showers. The mean transverse momentum of showers from the second maximum was about 5.2 times higher than that in the first maximum. Lateral distributions for four Pamir families are shown in Fig. 7. The second maximum, observed at lower pseudorapidites and characterized additionally by high transverse momenta of produced secondaries could arise by the Cherenkov gluon radiation. In that case, as it should be expected, the refraction index is close to one, $n = 1/\cos(\theta_{\rm Ch}) \approx 1.0000015$, indicating a high nuclear transparency at these high energies. The first maximum, observed in more forward pseudorapidity region, could be a result of an usual jet fragmentation.

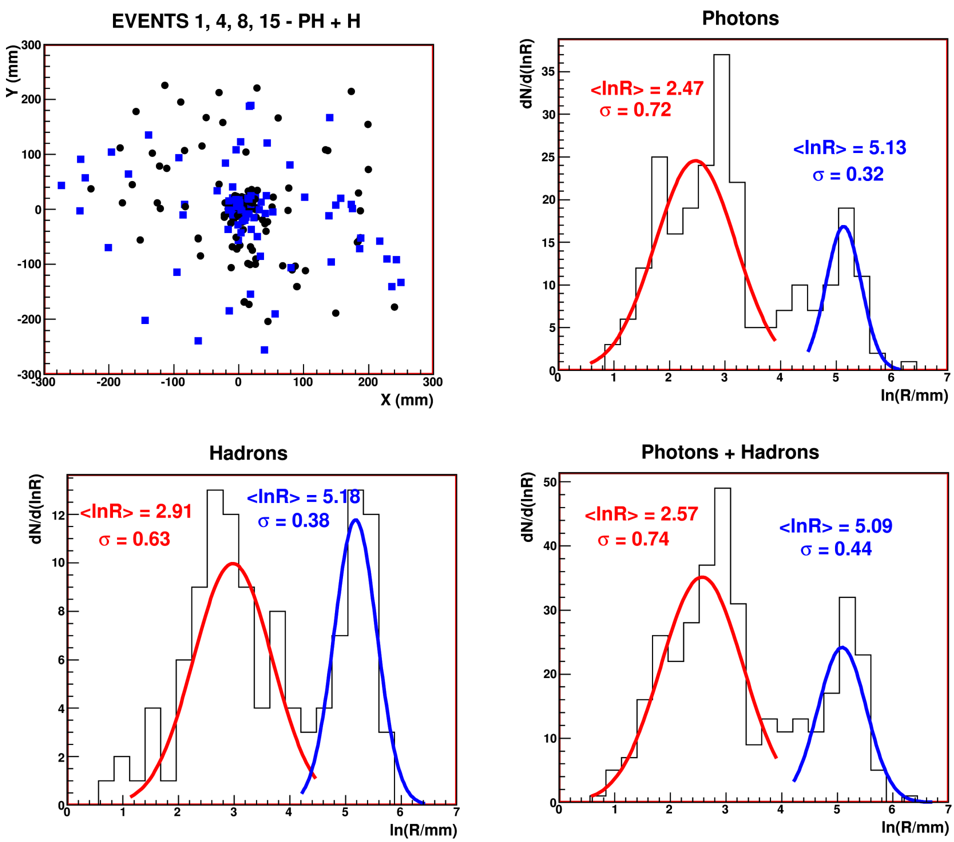

Fig. 7. Lateral distribution of photon and hadron cascades for the four families found in the Pamir thick Pb chamber. The upper left panel shows the target diagram in the plane perpendicular to the collision axis.

These events encourage one to search for similar phenomena at the LHC where Cherenkov gluons are proposed as a diagnostic tool of the partonic properties of matter [30]. The method has been tested at RHIC energies [32]. Two-bump structures of angular distributions of hadrons belonging to the so-called companion (away-side) jets seen in central Au + Au collisions by the STAR and PHENIX experiments allowed to estimate some features of the produced nuclear medium [30, 32]. In particular, the refractive index $n \approx 2.5$–3, what indicates high density medium. The cosmic ray data indicate that at LHC energies, we could expect a higher nuclear transparency, and refraction index only a little higher than 1.

5. Conclusions

The question of Centauro-related phenomena and other cosmic ray anomalies is still open and it should be solved by LHC experiments. Centauros could be searched for via looking for extreme event-by-event fluctuations in the ratio of electromagnetic to hadronic component, multiplicity and transverse momentum of produced particles. Strangelets, if produced at midrapidity, were proposed to be searched for in the ALICE central detectors. If produced beyond midrapidity, they could be searched for in the CASTOR-CMS experiment, and also in the ZDCs (ALICE, CMS). We suggest that also other exotic objects, such as DCC clusters, SUSY long-lived particles (R-hadrons) and magnetic monopoles could be detected and recognized in the CASTOR-type, thick and longitudinally segmented calorimeters. The energy deposition pattern in such calorimeters could be the new signature of novel states of matter. The additional confirmation of the existence of ring-like events, inspiring the idea of Cherenkov gluon emission has been presented.

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REFERENCES

[1] C.M.G. Lattes, Y. Fujimoto, S. Hasegawa, *Phys. Rep.* **65**, 151 (1980).

[2] E. Gładysz-Dziaduś, *Phys. Part. Nucl.* **34**, 285 (2003) and references therein.

[3] J. Bartke *et al.*, ALICE Internal Note, PHYS/93-12.

[4] E. Gładysz-Dziaduś [CASTOR Group], *Nuclear Theory '21*, ed. V. Nikolaev, Heron Press, Sofia 2002, pp. 152–175; *Acta Phys. Pol. B* **37**, 153 (2006).

[5] K. Aamodt *et al.* [ALICE Collaboration], *Eur. Phys. J.* **C68**, 345 (2010); *Eur. Phys. J.* **C68**, 89 (2010).

[6] A.D. Erlykin, A.W. Wolfendale, Letters, CERN Courier, June 7, 2010.

[7] M.N. Asprouli, A.D. Panagiotou, E. Gładysz-Dziaduś, *Astropart. Phys.* **2**, 167 (1994); E. Gładysz-Dziaduś, A.D. Panagiotou, Intern. Symp. on SQM, Crete (1994), World Scientific, Singapore, 1995, eds. G. Vassiliadis *et al.*, p. 265; A.D. Panagiotou *et al.*, *Phys. Rev.* **D45**, 3134 (1992).

[8] E. Gładysz-Dziaduś, Z. Włodarczyk, *J. Phys. G: Nucl. Part. Phys.* **23**, 2057 (1997).

[9] A. Mironov, A. Morozov, T. Tomaras, *Int. J. Mod. Phys.* **A24**, 4097 (2009).

[10] L.A. Anchordoqui *et al.*, *Phys. Rev.* **D77**, 023009 (2008).

[11] A. Ohsawa, E. Shibuya, M. Tamada, *Phys. Rev.* **D70**, 074028 (2004).

[12] V. Kopenkin, Y. Fujimoto, T. Sinzi, *Phys. Rev.* **D68**, 052007 (2003).

[13] E. Gładysz-Dziaduś, `hep-ph/0405115`; E. Gładysz-Dziaduś, Z. Włodarczyk, in *Trends in Black Hole Research*, ed. P.V. Kreitler, Nova Science Publishers, 2006, p. 163, ISBN 1-59454-475-1.

[14] S. Sadovsky *et al.*, *Phys. At. Nucl.* **67**, 396 (2004).

[15] K. Aamodt *et al.* [ALICE Collaboration], *JINST* **3**, S08002 (2008).

[16] E. Gładysz-Dziaduś, ALICE Internal Note, ALICE-INT-2011-001.

[17] Z. Buja *et al.*, presented by E. Gładysz at the 17th ICRC, Paris 1981, Conf. Proc. Vol. 11, p. 104.

[18] A.L.S. Angelis, J. Bartke, E. Gładysz-Dziaduś, Z. Włodarczyk, *EPJdirect* **C9**, 1 (2000); A.D. Panagiotou, P. Katsas, *Nucl. Phys.* **A782**, 383c (2007).

[19] M. Aguilar *et al.* [AMS Collaboration], *Phys. Rep.* **366**, 331 (2002).

[20] B.I. Abelev *et al.* [STAR Collaboration], *Phys. Rev.* **C76**, 011901 (2007).

[21] E. Norbeck, Y. Onel, *J. Phys. Conf. Ser.* **230**, 012044 (2010).

[22] ALICE TP, 1995; J. Coffin *et al.*, *J. Phys. G: Nucl. Part. Phys.* **28**, 1707 (2002); J. Coffin, C. Kuhn, *J. Phys. G: Nucl. Part. Phys.* **23**, 2117 (1997).

[23] A.L.S. Angelis *et al.*, *Nucl. Phys. Proc. Suppl.* **B122**, 205 (2003); P. Gottlicher [CMS-CASTOR Collaboration], *Nucl. Instrum. Methods. Phys. Res.* **A623**, 225 (2010).

[24] G. Bauer *et al.*, *Nucl. Instrum. Methods. Phys. Res.* **A545**, 503 (2005).

[25] S. Wick *et al.*, *Astropart. Phys.* **18**, 663 (2003).

[26] S. Ahlen, *Rev. Mod. Phys.* **52**, 121 (1980).

[27] E. Amaldi *et al.*, CERN 63-13, 1963.

[28] B. Cabrera, W.P. Trower, *Found. Phys.* **13**, 195 (1983).

[29] A. Dobrin [ALICE Collaboration], *AIP Conf. Proc.* **1200**, 730 (2010).

[30] I.M. Dremin, *Int. J. Mod. Phys.* **A22**, 3087 (2007); *Acta Phys. Pol. B Proc. Suppl.* **1**, 641 (2008).

[31] A.V. Apanasenko *et al.*, *JETP Lett.* **30**, 145 (1979).

[32] I. Dremin, *Nucl. Phys.* **A785**, 365 (2007); *Phys. At. Nucl.* **74**, 487 (2011) [`arXiv:0910.0099v3 [hep-ph]`].

[33] D. Ivanenko, V. Gurgenidze, *DAN SSSR* **67**, 997 (1949); W. Czyz, S. Glashow, *Nucl. Phys.* **20**, 309 (1960).

[34] Z. Buja *et al.*, presented by E. Gładysz at the 17th ICRC., Conf. Proc., Paris, 1981, Vol. 11, p. 108.