Coplanar emission near the LHC energy range (observed with XREC in the stratosphere)

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***Abstract*— The alignment of very high energy secondary cosmic rays was observed at both stratospheric and mountain altitudes by several X-ray emulsion chamber experiments. Extensive simulation with CORSIKA demonstrates that such phenomena can be explained by fluctuations with standard physics. However, in the case of two events observed in the stratosphere, specific features contradicts such explanation. According to the properties of those events with a minimal cascading, we explore the hints of new physics which could explain the alignment in terms of relativistic strings and diquark breaking. One description of the consequent coplanar emission expected in colliders is proposed.**

I. INTRODUCTION

Two decades ago the alignment of secondary particles has been observed in X ray emulsion chambers (XREC) exposed at mountains such as Pamir [1], [2], [3] and Kanbala [4], or boarded in a plane like Concorde [5], [6], or else during Siberian Balloon Flights (SBF) such as RUNJOB [7]; γ-ray families exhibiting clear geometrical alignments have also been registrated.

The coplanar emission appears significantly above a threshold energy of about 10 PeV at mountain altitude [8] and a similar threshold is ascertained also in the stratosphere [9].

We have pointed out from extensive simulations with CORSIKA [10] that the aligments can result from fluctuations in a context of standard physics. In contrast, several common features between the two events collected in the stratosphere (JF2AF2 in Concorde, STRANA on a balloon flown by FIAN) belies this last conclusion and the present work is concentrated again on new elements suggesting some hints of new physics in terms of valence diquark breaking and stretching of relativistic strings at very high tension.

Our paper is outlined as follows: the geometric characterization of the alignment is reviewed in section 2 and the properties of JF2AF2 and STRANA are considered in section 3, after a detailed presentation of the experimental data and the simulation results. Section 4 is devoted to the methodological approaches of the origin of the interaction, the effect of the experimental energy threshold in XREC's. The last sections concern the new theoretical propositions explaining the coplanar emission and the description of the coplanar emission which might be expected in colliders at energies exceeding $\sqrt{(s)} = 3000$ GeV.

II. GEOMETRICAL AND STATISTICAL CHARACTERIZATION OF THE COPLANAR EMISSION

The asymmetry of the geometrical structure of detected particles (hadrons or electrons and photons) can be characterized by the linear correlation coefficient r determined by fitting to a straight line by the least-squares method the coordinates derived from the tracks (or dark spots) left on the sensitive plates [5]:

$$r = \frac{\sum_i^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i^n (x_i - \bar{x})^2}\sqrt{\sum_i^n (y_i - \bar{y})^2} \qquad (1)$$

where n is the number of particles under consideration, (x_i, y_i) the coordinates of the i^{th} particle and $(\bar{x}, \bar{y})$ the average values. The degree of alignment can also be described by the parameter λ_n introduced by Pamir Collaboration [2] and defined as:

$$\lambda_n = \frac{\sum_{i \neq j \neq k}^n \cos 2\varphi_{ij}^k}{n(n-1)(n-2)} \qquad (2)$$

where φ_{ij}^k is the angle between the straight lines joining the i^{th} and j^{th} particles to the k^{th} one ($0 \leq \varphi_{ij}^k \leq \pi$). If all the n points are perfectly aligned along a straight line, $r = \pm 1$ and $\lambda_n = 1$; both tend respectively to 0 and $-\frac{1}{n-1}$ in case of an isotropic distribution. When $\lambda_n \geq 0.8$, the event is considered as *aligned* or *elongated*. This corresponds for more than 90% of the events to $|r| \geq 0.94$.

III. A PAIR OF COPLANAR EVENTS IN THE STRATOSPHERE, JF2AF2(CONCORDE) AND STRANA (BALLOON)

Among stratospheric experiments, only ECHOS-Concorde [5], [6] and the earliest FIAN SBF [11] experiments reported the observation of coplanar emission. The events registrated in Concorde above 1 PeV are non contained events, under the form of γ-ray families, resulting mainly from the primary hadronic interaction. Strictly speaking, that are "near direct events" that we have sorted in the category of "direct observations". It must be emphasized that in the experimental emulsion chamber terminology, the symbol γ's denotes all particles generating electromagnetic cascades in the chamber, i.e. photons, electrons and positrons.

A. ECHOS-Concorde experiment

During more than two decades, 8 X-ray emulsion chambers were flown with the supersonic aircraft *Concorde* connecting Paris to New York to achieve different measurements: very high energy cosmic ray jets, stratospheric γ-ray families, γ-ray flux [12], [13], [14], [15], hyperstrange baryonic matter [16] and dosimetry. Regular Atlantic flights provide indeed a *plateau exposure* of more than 2 hours. Hence, the same X-ray emulsion chamber, boarded a hundred times, can be exposed during at least 200 hour (the supersonic flights at an average altitude of 17 km, corresponds to an atmospheric depth of about 100 g cm^{-2}). The thickness of all the detectors, except for the last one, was large enough to measure the energy of secondary γ-rays (γ+e$^{\pm}$) at least up to 1000 TeV, allowing the collection of valuable information on the hadronic multiproduction in the energy range lying between the limits of the present colliders and the future LHC. However, because of the limited weight resulting from the compromise between area, aperture and time of exposure, the chamber was not thick enough to measure the energy of secondary hadrons. Three events were observed above 1 PeV; two of them, near 10^6 GeV, exhibit respectively a multicluster structure and hints of nuclear fragments.
The most energetic event, arrived under a zenith angle of 52° with a deposited energy of 1600 TeV by the e.m. component, approaching a primary energy of 10 PeV.
This exceptional event shows a perfect alignment of the most energetic γ-rays (γ+e$^{\pm}$) on the X-ray film [5]. The photography of this event, named JF2af2, visible to the naked eyes on the X-ray film, is reproduced on figure 1. The 211 γ-rays (above 200 GeV) composing this event are identified by their respective coordinates and energies. Their analysis, focused on multiclustering and planarity, following the information of the emulsion sheets scanned after superposition of the X-ray film, indicating the passage of the cascades, suggests a multijet structure [15]. When sorted in order of decreasing energy, it comes out that the most energetic γ-rays stand along a perfect geometrical straight line. The topology of JF2af2 is displayed as a *lego-plot* on figure 2 for the 4 most energetic γ-rays (above 50 TeV). The linear correlation factor r determined by fitting to a straight line the coordinates of the 4 aligned γ-rays is equal to 0.9993 ($\lambda_4 = 0.9972$). Moreover, r remains close to unity (0.992) for the 38 most energetic γ-rays containing 808 TeV, i.e. 51% of all the visible energy.

In order to examine the relevance of this remarkable event, we have carried out a special set of simulations (10^4 events) under the same experimental conditions. Among all individual events simulated, we have selected for a complete analysis those with a linear correlation factor $|r|$ larger than 0.94. An event virtually identical with JF2af2 in this sample shows a nice alignment of 23 γ-rays (figure 3a). The similarity of clusters (γ-rays above 10 TeV) to those of figure 1 is especially interesting. Tracing back the genetics of this event, it comes out that it arises from a normal non-single diffractive (NSD) primary interaction with a high multiplicity. The altitude of the

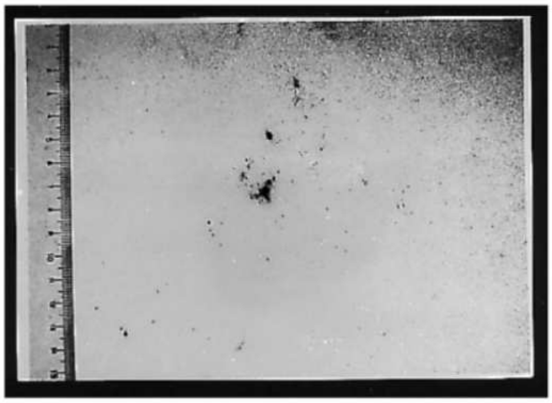

Fig. 1. JF2af2 event as it appears to the naked eye on the X-ray film.

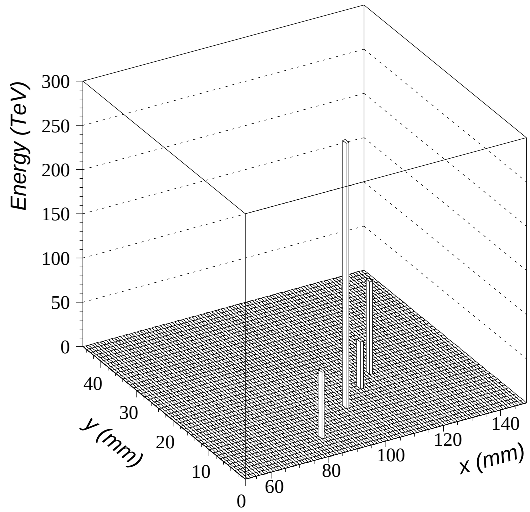

Fig. 2. Lego-plot of the central part of the event JF2af2.

first collision is about 40 km and the linear correlation factor for the 23 γ-rays (above 10 TeV) is 0.991; the total energy deposited is about 964 TeV. Figure 3b shows another aligned event with similar characteristics obtained with a second set of simulations. In this case, the first interaction takes place at an altitude of 28 km and the linear correlation factor for the 18 aligned γ-rays above 10 TeV forming this event is equal to 0.999.

The main features producing the alignment, here, are the high multiplicity and the large geometrical distance between the chamber and the first collision. Both circumstances combine as follows: the probability to get a large transverse momentum $p_{\rm t}$ is enhanced in high multiplicity events and this large $p_{\rm t}$ can be assigned to a high energy γ-ray. The rest of the cluster is displayed in the opposite direction ($p_{\rm t}$ conservation) and the maximal separation between γ-rays appears in the horizontal plane (the emulsion or X sheets) with a characteristic gap.

Table I shows the calculated fraction (%) of events with

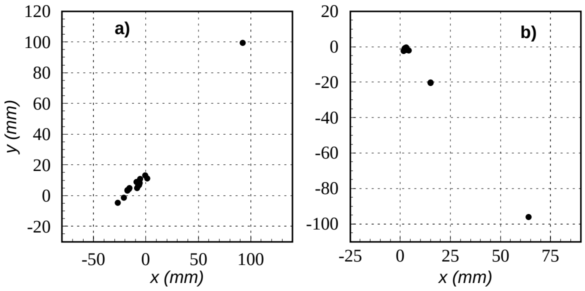

Fig. 3. Examples of 2 simulated events similar to JF2af2 with 23 (a) and 18 (b) aligned γ-rays (γ+e$^{\pm}$) above 10 TeV.

TABLE I
CALCULATED FRACTIONS (%) OF THE ALIGNED EVENTS WITH AT LEAST 4 γ-RAYS (γ+E$^{\pm}$) ABOVE 10 TEV FOR WITH $|r| \geq 0.94$ (FIRST ROW) AND $\lambda_4 \geq 0.8$ (SECOND ROW) FOR DIFFERENT HIGH ENERGY HADRONIC INTERACTION MODELS.

	DPMJET	HDPM	QGSJET	SIBYLL	VENUS
$\|r\| \geq 0.94$	0.7	1.5	0.6	0.5	0.9
$\lambda_4 \geq 0.8$	7.4	8.0	7.4	7.4	7.1

at least 4 γ-rays (γ+e$^{\pm}$), i.e. four e.m. cascades in a family (each above 10 TeV) for which $|r| \geq 0.94$ (first row) and $\lambda_4 \geq 0.8$ (second row) for different hadronic interaction models. We reproduce hereafter in table II the typical structure of JF2af2 with 3 dominant clusters, Jet A, Jet Ap and Jet B with respective characteristics, $\sum(E_\gamma)$ (visible energy), X, Y (coordinates of individual energy weighted centers), N_γ, average radius R and average $< ER >$ factor ; distances X, Y, R are in millimeters, E energy of individual γ's are in TeV.

B. SBF and RUNJOB experiments

The RUssian-Nippon JOint Balloon (RUNJOB) experiment consists in a balloon-borne X-ray emulsion chamber flown at an average altitude of about 30 km ($\sim$ 10 g cm^{-2}) since 1995 [17]. We emphasize here that the event STRANA was registrated earlier in similar conditions during a preliminary flight and that the alignement was ascertained during a recent analysis. The design of this detector gives the opportunity to study the geometry of secondary particles after the interaction of primary cosmic rays in a target module. The energy range covered by RUNJOB lies between the limits of the present accelerators and the very high energy cosmic rays. The data of four balloon flights performed during 1995 and 1996 were analyzed in order to search for alignments in the electromagnetic component [7].

TABLE II
3 MAIN CLUSTERS IN JF2AF2.

	$\sum(E_\gamma)$	X	Y	N_γ	R	$< ER >$
Jet A	331.	81.3	7.1	60	8.62	35.8
Jet Ap	455.4	100.5	11.2	10	0.49	13.1
Jet B	610.6	114.	22.	77	10.26	75.6

TABLE III
TOTAL ENERGY DEPOSITED FOR JF2AF2 AND STRANA (E.M. COMPONENT

	$\sum(E_\gamma)$	N_γ	$E_{\rm th}$
JF2AF2	1586.	211	0.2
STRANA	1400.	76	2.

In order to estimate the situation of balloon flights measurements we have simulated 100 sets of stratospheric γ-ray families, each set containing exactly the same number of events (170) as observed, under the same RUNJOB experimental conditions. That is a carbon nucleus as target (Lucite target), a primary energy ranging from 10^{13} to 10^{15} eV and a detection threshold energy of 100 GeV. The primary particle is assumed to be in turn a proton, an α-particle ($^4_2$He), a carbon ($^{12}_6$C) nucleus, a magnesium ($^{24}_{12}$Mg) nucleus and in the end an iron ($^{56}_{26}$Fe) nucleus. Besides, the simulated events satisfy the requirement of falling within the fiducial area of the detector (0.4 m^2). The zenith angle is chosen at random in the range 0–70° and the first interaction of the primary cosmic particle is fixed at an altitude of 30 km ($\sim$ 10 g cm^{-2}). The observation level lies 20 cm below.
The asymmetry parameter λ_n is calculated for the 3 and 4 most energetic secondary γ-rays (γ+e$^{\pm}$). Figure 4 shows the average fractions of the aligned events with $\lambda_3 \geq 0.8$ (a) and $\lambda_4 \geq 0.8$ (b) for the different hadronic interaction models as a function of the mass number A of the primary particle. The error bars are purely statistical and represent one standard deviation. It is clear that all the models give values very close to each other and, within the error bars, independently of the type of primary particle . These fractions equal on average (22 ± 2) for the events with $\lambda_3 \geq 0.8$ and (7 ± 1) for $\lambda_4 \geq 0.8$. Our simulation at RUNJOB level provided also accidental alignments [10] and a situation similar to table I (as shown in figure 4).

In the case of the earliest SBF, the calorimeter was deep enough to collect the energy deposited also by the secondary hadrons with one general energy threshold for γ's and hadrons of 2 TeV. In the case of the XREC of Concorde, it was not possible to follow the hadronic contribution, but the energy threshold for γ's of 0.2 TeV provided a better resolution.

C. JF2AF2 and STRANA

Taking into account the different energy thresholds of the XREC's used for both events, respectively 200 GeV for JF2af2 and 2 TeV for STRANA [18] , we observe first that the visible energy deposited in γ rays is very similar, as shown in table III.

In the case of STRANA, the hadronic accompaniement is observed for the central jet with 30 hadrons depositing a total energy of 2500 TeV.

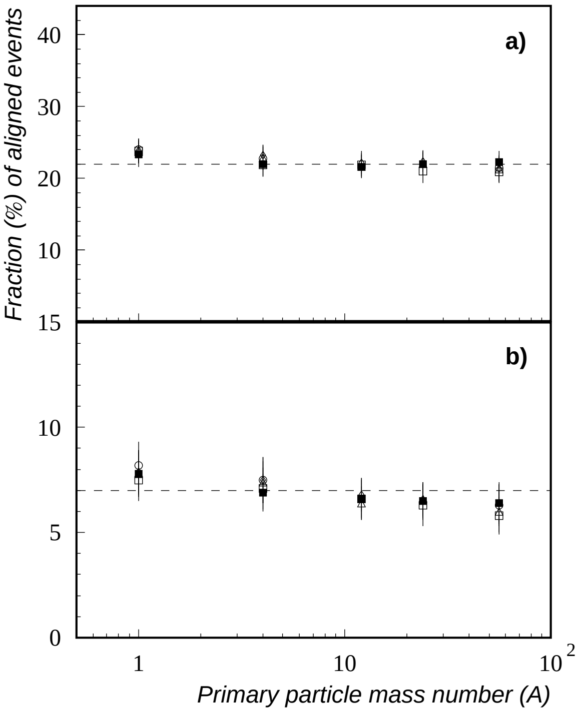

Fig. 4. Calculated fractions (%) of the aligned events with $\lambda_3 \geq 0.8$ (a) and $\lambda_4 \geq 0.8$ (b) for RUNJOB experimental conditions obtained by different hadronic interaction models: DPMJET (open circle), HDPM (open triangle), QGSJET (full square), SYBILL (open square) and VENUS (open diamond). The dashed line represents in both cases the average value.

IV. Approach of the origin of the interaction

For non contained events, the tracks appears parallel as far as the distance to the vertex exceeds more than 50 m and the geometrical convergence measurements are no more valid. The height of the primary collision can be obtained by the invariant mass method, assuming that the γ's originates mainly from neutral pion decay, by the $< ER >$ factor assuming an average transverse momentum of 0.2 GeV/c for γ's and by the best fit of pseudo-rapidity distribution for a given height.

A. The invariant mass method

The invariant pseudo-rapidity distributions have been determined for JF2af2 [15] for the total event as well as for the individual jets A, Ap, B and we have repeated those calculations, obtaining from the maxima of the histograms respective heights around 80 m (for total), 65 m, 75 m. Those values are however submitted to large uncertainties (η meson production, an error of 10-20% on coordinates and energy measurements, proportion of γ's of 1st generation, but they suggest that the γ's of the 3 major jets are generated at less than 300 m above the chamber.

B. The $< ER >$ factor

We observe on table II that the $< ER >$ factor indicates an origin of 325 m for Jet B, instead of an origin of 175 m for Jet A and 65 m for Jet Ap. In the case of STRANA, the invariant mass method and the other approaches suggested also different values from 100 m up tp 1000 m in the case of pseudo rapidity distribution fitted for an α primary. We have not the coordinates of the particles of STRANA, but we note that the central Jet Ap in JF2af2 is very concentrated, suggesting an interaction close from the chamber and could be followed by a hadronic cascade developed under the XREC.

TABLE IV

Effect of the energy threshold of the XREC on transverse momentum, N_γ, K_γ averaged on 1000 proton collisions of 10 PeV. N_γ, K_γ are respectively 81 and 0.26 for $E_{\rm th} = 0$ TeV. $z = 2$ is the KNO factor and the last line illustrates the case of fluctuations in case of high multiplicity.

	$p_{\rm t\gamma}$	$p_{\rm t\pi^0}$	N_γ	K_γ
$E_{\rm th} = 0.2$	0.233	0.534	43	0.259
$E_{\rm th} = 2.0$	0.249	0.541	29	0.257
$E_{\rm th} = 2.0$ $(z = 2)$	0.294	0.654	66	0.324

C. Effect of the energy threshold of the XREC

Our simulation to check the limits of validity of the vertex determination are in progress and we started to appreciate the effect of the XREC threshold; some discrepancies with the so-called Bristol convention (relation of transverse momenta from γ's to neutral pions) appears as other consequences on N_γ and inelasticity K_γ shown on table IV.

We observed also that the KNO variable z has to be taken into account in any interpretation by fitting the pseudo rapidity.

V. Theoretical hypothesis for the coplanar emission

A. Earliest conjectures

This intriguing phenomenon motivated several theoretical investigations [19], [20]. Specific interaction features such as the breakdown of linear strings, due to the production of gluon jets in the main interaction [21], or the double inelastic diffraction [22] were discussed as a possible origin of the alignment. Other works proposed new physical processes such as the coplanar diffractive production of strange baryons not far from the chamber [23].

B. Strings between valence quark and valence diquark breaking

Following the proposition of one of us [9], we introduce here the combination of the valence diquark and the breakdown of relativistic strings as a possible explanation of the coplanar emission 5.

According to the simplified presentation of Wong [24], one pair $q - \bar{q}$ is created when the distance L separating both valence quarks exceeds a threshold value. The string fragmentation corresponds to a tension $\kappa = 1/2\pi\alpha'$ of about 1 GeV/fm, α' being the Regge slope. The transverse momentum

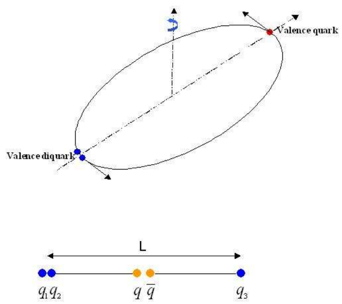

Fig. 5. Valence quarks and diquarks, string tension.

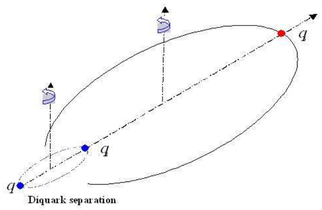

Fig. 6. Maximal tension for a threshold excitation energy, stretching of a high tension string between valence quarks of the diquark, diquark breaking.

of the quarks emitted is related to the tension by the relation (3):

$$\sqrt{< p_\mathrm{t} >^2} = \sqrt{\frac{\kappa}{\pi}} \qquad (3)$$

Such relation provides the classical values of $p_\mathrm{t} = 0.2$ GeV/c for quarks and 0.4 GeV/c for the pions where the pairs $q - \bar{q}$ are recombined.

Above an energy threshold of about 200 GeV (in CMS) per valence quarks (corresponding to a proton projectile of 10 PeV in the Laboratory system, a new string appears between the partners of the valence diquark (6). The tension increases with the distance and the breakdown happens s soon as the minimal energy of excitation required is available; the maximal distance between the valence quarks associated to this minimal energy is obtained when the 3 quarks are aligned.

Such circumstance excludes the classic recombination of the leading cluster (one valence diquark with one quark of the sea giving a pilot proton, a neutron or a Δ resonance); this could explain why the penetrating power of the cosmic air showers appears to level off in the ”knee” energy range. Following this assumption, at energies more close to the LHC, the fragmentation of 3 separated valence quarks will still be observed, but the alignment will be smeared out, the energy required for the rupture being available for all geometrical configurations. The most simple recombination for the 3 valence quarks of the projectile will happen with antiquarks of the sea giving the emission of 3 energetic hadrons. Around the threshold energy, the coplanar emission will result in the emission of one characteristic collimated trident, of 3 charged pions, for example.

VI. Coplanar emission and colliders

Coming back to JF2af2 and STRANA, the assumption of the emission of 3 hadrons could have several advantages, explaining in both cases the electromagnetic and hadronic components, as well as the original transverse momenta. In the case of JF2af2, the external jets ($< ER >$) factor and some secondary peaks at the largest values of the invariant mass indicate a maximal distance of the primary collision at 2.2 km above the chamber. We notice that 3 coplanar charged pions carrying the e.m. energy deposited in A, Ap and B interacting respectively at about 175, 60 and 320 m above the chamber are able to reproduce the structure observed and require a primary energy of about 5 PeV (reduced by 50% when compared to normal hadronic collision); this energy is very close of the ”knee” of the primary energy spectrum and in better agreement with the number of high energy events expected with the modest exposures on Concorde and on SBF. The transverse momenta required for those pions at the emission would be 10.0, 3.3 and 6.5 GeV/c, comparable to the values required for STRANA. Such circumstance indicate a maximal tension of the string concerning the diquark of 20-30 GeV/fm instead of 1 GeV/fm.

The transformation in Center of mass system could give a crude description of a possible coplanar emission in colliders.

- characteristics coplanar tridents collimated (emitted inside 0.3–1.5°);
- pseudo-rapidities between 4.3 and 5.8, energies between 0.4 and 0.7 TeV;
- p_t's around 3–10 GeV/c;
- energy threshold $\sqrt{s} = 3000$ GeV (an energy reachable by Fermi collider working in pulse mode) corresponding to valence quarks with individual energies above 200 GeV.

VII. Discussion

We have investigated in this work the physical relevancy of some experimental data concerning the phenomenon of alignment observed for secondary particles in high energy cosmic ray interactions. The standard collider physics can explain the alignment via fluctuations and accidental large transverse momenta of very energetic secondaries. Some contradiction however remains (height of the primary collision, multicluster structure, very high p_t, energy distribution).

The frequency of occurrence of the coplanar emission at high energy is another point worth discussing. Let us take, for instance, the event JF2af2 observed by ECHOS-Concorde experiment assuming that it is the outcome of a coplanar interaction at an altitude of 17 km of a 10^7 GeV primary nucleon with an atmospheric nitrogen. Taking into consideration the total primary integral energy spectrum [25], the area of the exposed detector, and an aperture of $60°$, the total exposure would have to be multiplied by 20 to collect one event of 10^7 GeV. The energy of the primary particle is usually estimated from the so-called *visible energy*, i.e. the energy of the electromagnetic component of the considered interaction assuming that an average of one third of the available energy is allocated to this channel with a total inelasticity near 0.5. However this assumption which results from standard physics at low energy is in actual fact extrapolated to very high energy. Some theoretical work have recently proposed new unconventional processes that contradict this hypothesis. For instance the Concorde events with γ-inelasticity factor of 0.53 would correspond to the primary energy of 3 10^6 GeV requiring just to increase the expected exposure time by 50%.

Among the new ideas to explain the coplanar emission, the diquark breaking mechanism combined with relativistic strings fragmentation leads to a reduction by about a factor 2 of the primary energy when converted from the visible energy, which results in an enhancement of the frequency of occurrence of coplanar emission; it may also explain the reduction of the penetrating power of the cosmic ray cascades near the energies of the cosmic ray knee [26]. It may also be connected with the decrease of high energy secondaries in the fragmentation region suggested by hybrid EAS-γ families experiment. The collimated coplanar tridents could be a simple signature to recognize or eliminate with collider experiments and more generally , it could be useful to present the remarkable cosmic ray events in Center of Mass for systematic comparisons.

An experiment at low luminosity in the LHC, measuring the secondaries in the very forward region [27], could probably clarify the question of coplanar emission, as well as the extension of the present emulsion chamber experiments, as it is now planned in Pamir. Another possibility could be to use the test flights of the Airbus A380 with an arrangement of emulsion bricks (like in the Opera neutrino experiment) on both decks of the airliner.

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