COSMIC RAY OBSERVATIONS RELEVANT TO THE PHYSICS EXPLORED WITH FELIX

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1 Overview

1.1 Forward Physics and Energy Flow

The dominant focus of research with hadron colliders has been on the central region of rapidity space. Thus the ISR and the SPS at CERN and the Fermilab Tevatron have used detectors which explored particle production down to within about 2 degrees of the beam directions, i.e. over the range of pseudorapidity corresponding to $|\eta| < 4$. However the most forward protons in these collisions have rapidities, y, of 7.6 at the Tevatron and will have y=9.6 at LHC energies. To be sure, the central region includes over 99% of the total solid angle and also the range of the highest secondary particle density per unit of pseurapidity ($dN/d\eta$).

Cosmic ray observations, on the other hand, are dominated by the energy flow in nucleon-nucleon collisions, as detectors of nuclear and electromagnetic cascades are critical in triggering and analyzing cosmic ray data. Particular detectors or analysis strategies may trigger, for example, on a total "visible" energy (in a defined, small area) of 100 or 500 TeV, and may have thesholds for individual particle detection of between 2 and 10 TeV. The energy flow, in turn, very strongly weights the most forward-produced particles. It can be easily shown that the number distribution as a function of pseudorapidity η (in effect equivalent to rapidity y), $dN/d\eta$, when weighted by energy ($EdN/d\eta$) is approximately $e^y dN/d\eta$, for transverse momentum distributions independent of η or y. In the cosmic ray case, of course, the Tevatron energy of 1.8 TeV c.m. is equivalent to about 2 PeV (2×10^{15} eV) for a cosmic ray proton incident on a stationary nucleon, corresponding to a rapidity range between 0 and 15.2. And the LHC energy of 14 TeV c.m. corresponds to a cosmic ray of about 100 PeV (10^{17} eV), with rapidity ranging up to 19.2 for forward nucleons.

Even at the proton-proton and proton-antiproton colliders, the energy flow is badly sampled by the typical 4π detectors. Wlodarczyk estimates, for example, that the fraction of the total energy in secondary particles carried by those produced within an angle of 28 mr to the circulating beams (corresponding to $|\eta| > 4.25$) increases from 60% at the SPS and 80% at the Tevatron to 95% at the LHC.

1.2 Energy Range and the Character of Cosmic Ray Observations

The flux of cosmic rays falls very rapidly with energy; the differential flux dN/dE falling approximately as E^{-3} above a PeV [1]. This flux is shown in Figure 1. Direct observations of interactions of primary cosmic rays via balloon or satellite payloads have been limited to exposures measured in square meter-days, and hence to energies below a PeV. Our knowledge of strong interactions from cosmic rays of energies greater than this comes primarily from mountain top observations, under 5 to 7 nuclear interaction mean free paths of atmospheric overburden, and from observations of the electromagnetic component (air showers) and muon components at about sea level or (for muons) underground. Mountain top observations include hadron calorimeters, often coupled with other detectors, and emulsion chambers; layers of nuclear emulsion and/or X-ray film stacked between layers of lead and sometimes other absorber. These emulsion chambers can be placed at over 5000 meters elevation and exposed for about a year at a time; each chamber comprising 30 to 100 square meters of sensitive area. The observed cascades in the emulsion chamber can be interpreted in terms of the electromagetic energy deposited, and the angular resolution can permit extrapolation to interaction vertices in the atmosphere up to over a kilometer above the chamber. A nucleon interaction mean free path at these mountain elevations (e.g. 5200 m.) is about 1200 m.

One difficulty in interpreting the data from mountain elevations is the primary composition of cosmic rays. Up to about 10^{14} eV the composition is known from balloon and satellite direct observations.. At 100 TeV the relative intensities are: protons (A=1) 20%, He (A=4) 36%, C-N-O

(<A>=14) 19%, Ne-S (<A>=24) 12%, and Fe group (<A>=56) 13% [2]. The fraction of protons is reported to decrease further so that at 370 TeV there may be only 12% protons [3]. Protons and He are dominant, but significant fractions of heavier nuclei up to iron are also present (Figure 2). However above this energy, perhaps in the vicinity of the "knee" in the spectrum between one and 10 PeV, there is evidence for a change in the spectrum, with heavier primaries becoming more abundant. Flys Eye data above 10^{17} eV has been interpreted as indicating that the composition again becomes dominated by protons as energies increase to and above 10^{18} eV. For the mountain top elevations, this primary composition uncertainty is perhaps less a problem than might first be guessed. Heavy nuclei of these energies are Coulomb-dissociated into their constituent nucleons in the first tens of g/cm^2 of the atmosphere so that, with the steeply-falling primary spectrum for all values of A, the all-nucleon flux exceeds the proton flux by only 20% for any given energy window [4].

2 Centauros and Anti-Centauros

The Centauro phenomenon is perhaps the longest-standing puzzle in cosmic ray emulsion chamber observations. Several events have been reported from the Brazilian-Japanese Collaboration, first about 25 years ago, wherein an interaction in the air 50 to about 500 meters above the detector gave rise to a large number of charged hadrons and zero or very few γs (or electrons). The separation between the electromagnetic component (γs and electrons) and charged hadrons is quite clean, based on the depth of initiation of the electromagnetic cascade in the lead of the chamber [5]. In Figure 3, a particularly striking Centauro event is reproduced. Table I is a listing of several of these Centauro candidate events. Note that the emulsion chamber technique only records the energy in electromagnetic cascades (by quantifying the densities in successive layers of emulsion separted by lead), so the "observed" energy of hadrons is probably of the order of 20% - 40% of their total energy. Hence the events tabulated probably result from the interactions of nucleons of a PeV energy or greater. The Chacaltaya site where the exposures containing these events was made is at 5200 m elevation, corresponding to a depth in the atmosphere of about 550 g/cm^2. The cross section for Coulomb dissociation in the atmosphere is great enough so that the initiating particle of these events is almost certainly a nucleon. These events are not common; an estimate of the probability of producing a Centauro in an interaction of one PeV or above is about 1% or less. While evidence for Centauros is reported from the Brazil-Japanese collaboration and the Russian and Russian-Japanese collaborations (from emulsion chambers exposed at 4300 m in the Pamirs), no Centauros are reported from the Japanese group working at Mt. Fuji (3750 m) or the Japanese-Chinese collaboration exposures on Mt. Kanbala in Tibet (5500 m). The Chacaltaya group ascribes this to differences in the emulsion chamber configuration between the Fuji - Kanbala chambers and those at Chacaltaya and the Pamirs.

The groups reporting Centauro events have made a broader, if less definitive, study of possible evidence for this phenomena by studying a statistically larger group of events wherein the incident γs and hadrons in a "family" are identified. Here, a "family" is defined as a group of EM cascades in the emulsion chamber within a radius of several cm. which appear substantially parallel, and thus are consistant with secondaries from interactions of a primary hadron in the air above the chamber, together with possible subsequent secondary interactions. They have plotted the number of hadrons seen vs. the energy fraction of a family in the hadron component and compared these distributions with Monte Carlo simulations. The experimental data shows a significant excess of large hadron numbers and a large energy fraction in the hadrons when compared with a model based on a binomial distribution of produced pions (in the interactions). However a 30% addition of Disoriented Chiral Condensates to the forward production in the simulations shows much better agreement with the data [6] (Figure 4). Note that this 30% may not be unreasonably high in view of the high energies involved, the extreme forward angles, and the fact that the interaction is on an air nucleus and not a free nucleon. Thus the fact that Centauro events have not been reported from accelerator experiments thus far is not *a priori* in contradiction with these observations and conclusions.

Inelastic interactions of nucleons or pions in the atmosphere an interaction length or greater above the detector would be expected to produce neutral pions, whose decay γs would initiate showers in the upper layers of the chamber. Secondary charged hadrons, however, have less than a 100% probability of converting in the chamber, hence it is not surprizing to see events with E-M cascades at the top of the chamber but few identified charged hadron cascades at a greater depth. However, the Japanese-American Cooperative Emulsion-chamber Experiment, JACEE, has flown smaller emulsion chambers with balloons near the top of the atmosphere. Here they are able to observe the incident cosmic ray particle; from the ionization of its track in the emulsions, they also know the nuclear charge. This experimental program has provided the firmest data to date on the primary composition of cosmic rays up to energies of about 100 TeV per nucleus. Of course interactions are also seen, and the energies of the resulting E-M cascades, from γs produced at the interaction vertex as well as from hadrons interacting at a greater depth in the emulsion and lead stack, are determined. Note that many of the JACEE interactions studied involve heavier primary cosmic ray nuclei (He - Fe) rather than incident protons.

Among other interesting results from the JACEE group, at least two events have been observed which have been referred to as "Anti-Centauros". Here a region of $\eta - \phi$ phase space is seen containing an anomalous number of γ-induced showers and a dirth of charged particles. One such event is shown in Figure 5, wherein 32 γ cascades are observed within a circle of radius 0.7 in $\eta - \phi$ space with only 1 charged track. Another event, reported in 1993, is presented in Figure 6, where (11-η) is represented as the radial coordinate in a polar plot. Again, 27 γs are seen with $\eta > 6$ (and these from conversions in only 0.8 radiation lengths), while only 6 charged tracks fall in the same kinematic range [7].

These Centauro and Anti-Centauro events have been interpreted as manifestations of Disoriented Chiral Condensates.

3 Anomalous Mean Free Path, the Long Flying Component

The Russians have operated a lead/ionization chamber calorimeter of 36 square meters area and 850 grams per square cm of lead in thickness (together with other detectors) at a mountain station on Tien-Shan at an elevation of 3340 meters. Ion chambers were in 15 layers distributed through the lead absorber. A high-energy cosmic ray hadron entering the calorimeter will interact at some depth; neutral pions produced in this interaction will initiate EM cascades resulting in a prompt build-up of ionization and permitting identification of the initial interaction depth. Secondary hadrons then interact at greater depths, each initiating its own EM and hadronic cascade. The resulting ionization vs. depth is then a peak followed by an (approximately) exponentially falling ionization with depth, where the slope is a function of the interaction mean free path and the inelasticity of the produced secondaries. From calculations and models, this exponential slope should be only a weak function of the energy of the incident hadron.

The obserations of the Russian group are that the exponential characterizing the ionization *vs* depth of the cascade from a cosmic ray hadron becomes flatter (the attenuation length greater) as the incident hadron becomes more energetic, for energies above about 10 TeV [8]. A compilation of results of attenuation length vs incident energy is in Figure 7. The group argues that the explanation for this phenomenon could be the anomalous production of charmed hadrons in the forward direction at high energies. With the plausible assumption that the inelasticity of charmed hadrons is considerably smaller than that for the u and d quark hadrons (due to their large mass and flavor conservation in strong interactions), they conclude that the data could be explained by forward (high-x) production of charmed hadrons with a probability of 30% per interaction above about 10 TeV. At lower energies, the charmed particle decay length is short compared to the characteristic cascade development, and there is little effect on cascades. However, for energies well above 10 TeV, the charmed hadron decay length becomes comparable to the depth of a Pb calorimeter, and this would lead to the observed lengthening of the cascade profile and large energy depositions deep in the calorimeter. At still higher energies, (above the energies represented by the data on Figure 7) the charmed hadrons would escape the calorimeter before decaying, resulting in a cascade development similar to the low energy case, but with a systematic under-sampling of the incident energy. The Russian-Japanese emulsion chamber group working at the Pamirs site has published data from their chambers supporting the Tien-Shan results [9].

4 Anomalous Heavy Flavor Production

There have been many suggestions that the production of heavy flavors (charm and bottom quark states) are enhanced at high energies in the far forward direction. The strongest evidence for this comes from the JACEE collaboration. In recent publications [10], they report the analysis of 15 events with incident energies of over a TeV per nucleon wherein the number of secondaries was less than 50 per event (at energies of tens of TeV, a heavy primary cosmic ray may produce hundreds of secondaries in a collision with an emulsion nucleus). Within these 15 events, they observed 64 secondary vertices (kinks, vees, 3-prong vertices, etc.) within their chamber. At these energies, these decay lengths are too short for strange particles, and the authors suggest many or most may be decays of c or b quark mesons or baryons. Sequential decays are seen, wherein a track displays two kinks, corresponding to b to c to u or d quark decays. Two events are especially striking, each showing a kink (decay in flight) of a secondary with 4 gamma vertices pointing back to the kink. As the chambers are only a fraction of a radiation length in depth, the observed gammas are compatible with a total of about 10 gammas produced at each vertex. The observed gammas do not pair to fit π^0s. These decays do not match any known charm or bottom hadrons. A diagram of the relevant tracks from one of the events is shown in Figure 8.

Yakovlev [9] argues that there are many other less direct observations which are also compatible with increasing heavy flavor production at energies above a PeV. He notes that one can interpret the break in the primary cosmic ray spectrum at a few PeV, for example, as due to heavy flavor production. This would be because the small inelasticity of the heavy c and b hadrons and their increasing decay mean free path with energy would lead to a decrease in the fraction of the primary energy appearing in air showers at energies above some energy. This would indeed simulate a break in the spectrum.

Alan White, in fact, goes further. He suggests that at energies above the knee (above a few PeV) the production of heavy objects could explain many apparently anomalous cosmic ray observations. For example, air showers at large zenith angles are reported from the Russian Tien-Shan air shower experiment to be asymmetric in azimuthal angle (around the shower axis), and the shower number vs. zenith angle for a fixed integrated number of observed electrons falls sensibly for lower energies, but displays an anomalous number of events for showers of $2.5 - 4.0 \times 10^6$ electrons (corresponding to energies of over several PeV). White also cites multimuon distributions as reported from underground detectors and air shower electron distributions in support of heavy particle production. He has developed a theory of color sextets, which suggests the existance of new, unstable massive baryons; he argues that many of these cosmic ray observations are compatible with this idea [11]. In this context, it is interesting to note that Starkman, et al. have noted the observational windows for strongly interacting dark matter (SIMPS); candidate objects to solve the astrophysical dark matter problem [12].

Perhaps the most unusual interpretation in support of the production of odd massive objects is the Chinese interpretation of an event seen in a cloud chamber that they had operated during the 1970s [13]. They have correlated this with observations which had been reported by the Kolar Gold Fields experiment and by the LVD detector in the Gran Sasso Tunnel. The event they observed was a track of energy too great to detect bending but of apparently minimum ionization; from the absence of relativistic rise in ionization, they deduce that this track must have been from a particle of rest mass greater than about 10 GeV/c^2. The events reported by the KGF experiment and by LVD appear to be decays of neutral, very massive particles moving isotropically (at least not vertically) in or near the detector. They postulate that their information is compatible with the production of weakly-interacting charged particles of rest mass greater than 40 GeV/c^2 in primary cosmic rays, that these particles may charge-exchange scatter or decay to neutral particles of comparable mass, and that these massive neutral particles, moving with $\gamma \leq 2.5$, are observed to decay in the deep underground detectors. Since their report was circulated, it has been learned that "isoburst" events had been observed in the IMB proton decay experiment, which are indeed compatible with the KGF and LVD events, but suggesting an energy release of perhaps 300 GeV or more [14].

5 Chirons, Halo Events, and Mini-Clusters

For some years the Brazilian-Japanese collaboration, working with emulsion chambers on Mt. Chacaltaya, have reported a class of events they refer to as "Chirons" [15]. The two best examples are events where the event vertex is found by triangulation to be in the air within 500 meters above the chambers. These events are characterized by clean hadronic cascades (not clustered among E-M cascade from atmospheric showering of γs in the intervening atmosphere) with average transverse momenta of 2 - 3 GeV/c. This is interesting in itself. Even more unusual is the fact that about half of these hadronic cascades are seen, on close inspection, to contain two or more internal cascades; clearly identified as initiated by hadrons. The relative transverse momenta within each minicluster is anomalously small; 20 or 30 MeV/c. One may speculate that these arise from the decay of a massive, unstable object from the primary interaction, or perhaps from unusual jets produced in that interaction. There seems to be no easy explanation for them. The total energy in these Chiron events is estimated to be well above a PeV, perhaps over 10 PeV (10^{16}eV). Chirons are stated to be more abundant than Centauros. They are also said to have an anomalously high hadron/γ ratio.

Events are also often observed which are characterized by a dense blackening of the emulsion over a small area (due to an electromagnetic cascade which had begun development in the air above the chamber) containing within it several hadronic cores, again spaced very closely together. These authors suggest again that the relative transverse momenta of the hadrons within these miniclusters are in the 20 - 30 MeV/c range, as in the Chirons. These are called "Halo" events [16].

The cosmic ray emulsion chamber community has been very intrigued with the observation that in many of these multi-halo events, the halos associated with a given family are very often aligned. They argue that this alignment is present to a much greater degree, especially at energies above a PeV, than can be accounted for by jet production [17]. Halzen, on the other hand, argues that it is in fact quite consistant with hard quark-quark scattering and QCD predictions [18]. Often only two (substantially parallel) cores are seen, as would be expected from a forward-scattered quark jet and its parent nucleon fragments both stiking the detector. Ding and others at IHEP have examined these "Geminion" data and compared them with QCD predictions. They find a significant disagreement, with the data corresponding to a significant excess of large transverse momenta jets [19]. Note that the cosmic ray energies from which these observations are taken, 10^4 - 10^5 TeV, are well above the Tevatron collider energy. There is a report that the Tevatron jet data, for the highest momentum transfers, were also in excess of QCD predictions, perhaps suggesting quark substructure. More recent interpretations of those data ascribe this effect as due to the gluon component of the nucleon structure function [20].

6 Anomalous Attenuation of Secondary Hadrons

The Chacaltaya - Pamir Collaboration has reported that the hadrons within families (as defined in 2. above) of cosmic ray events display an anomalously short mean free path in their emulsion chambers [21]. The interaction length, ΔT, is defined as the distance between the top of the chamber and the initiation of an E-M cascade (deeper than 6 radiation lengths into the chamber) which signals the vertex of a hadronic interaction. ¿From the study of γ-initiated cascades, the group can determine the distance between the observed maximum of the E-M cascade and its initiating vertex. The distribution of ΔT is then exponential. However the slope of this exponent is significantly greater than that for single unaccompanied hadrons seen in the same chambers and corresponds to a cross section in lead much larger than known from accelerator experiments. A compilation of data from this collaboration is shown in Figure 9. The attenuation length they report for family hadrons is $170g/cm^2$, whereas unaccompanied hadrons show an attenuation length of $252g/cm^2$. The unaccompanied hadrons in this data sample have a visible energy in gamma rays of 6 TeV and greater; data from families are recorded for total visible (E-M) energies of over 700 TeV and visible energy in each E-M cascade core of at least 10 TeV. There is some possibility that the apparent interaction length reported in these observations is a consequence of two or more hadrons in tight cores (as in Chirons). This might result in unresolved cascades, wherein the interaction of a second hadron in a core would be interpreted as part of the cascade from an earlier interaction of the first hadron in the same core.

7 Energy Fraction of Air Showers in Emulsion Chamber Families

The Japanese emulsion chamber group working at Mt. Chacaltaya has reported that, for extensive air showers produced by incident cosmic rays of over 10 PeV, the energy visible in families in their emulsion chambers is not proportional to the incident energy as determined by the air shower array (for events wherein the core of the shower lies within the emulsion chamber array) [22]. They show that the visible energy in E-M cascades (from incident electrons and γs as well as incident hadrons) increases less rapidly than the total number of electrons in the air shower, where families include events with a visible energy exceeding 10 TeV. Their results are summarized in Figure 10, where results from the Russian HADRON experiment at Tien-Shan, which reached the same conclusions, are also presented [23].

A caution should be noted in evaluating many of these papers, however. Halzen and others have independently Monte Carlo'd similar problems and find that QCD with scaling and a slowly rising inelasticity together with a composition increasing in average atomic weight with energy fits several sets of emulsion chamber data very well [24]. While they do not present exactly the same plots, they do compare the integral flux of all particles and of the E-M component and hadron component separately vs. energy for the Mt. Fuji and the Mt. Kanbala data. They conclude that a value of $<A>$ of 7.3 provides a very good fit to the data. Clearly the details of the Monte Carlo simulations are critical,

Table 1: Summary of Properties of Five Centauro Candidates from the Brazil-Japan Mt. Chacaltaya Emulsion Chambers [5]

Centauro interaction event number	I	II	III	IV	V	
Height of interaction (m) above emulsion chamber	50	80	230	500	400	
Estimated number of jets originating in the atmosphere above the chambers	3	5	13	32	18	
Number of hadrons produced in the primary interaction (estimated)	74	71	76	90	63	
Total energy (TeV)	330	370	350	340	350	
Number of electrons and gammas produced in the primary interaction (estimated)	0	0	0	4	0	

and it is important that there be both improvements in simulations and in global communication within this community. In this context, meetings such as the IX International Symposium on Very High Energy Cosmic Ray Interactions (held in Karlsruhe in 1996), where a day was devoted to Monte Carlo simulations of high energy cosmic ray interactions, are very important and timely. Nevertheless, particle physics is on very thin ice in extrapolating forward physics data from energies of less than a TeV where distributions are known to energies above 10 PeV (4 or 5 orders of magnitude).

In this context, it may be noted that there is a significant disagreement over the inelasticity of a nuclear interaction as a function of energy. The inelasticity, K, is defined as one minus the fraction of the incident hadron's energy carried by the most energetic final state hadron ($K =< 1 - E/E_0 >$). From careful studies of the cosmic ray data, Ohsawa [25] and (independently) Wlodarczyk [4] conclude that the inelasticity is falling with increasing energy from its low energy value of about 0.5. Halzen et al. [24] and others, on the other hand, argue that it rises with energy, based on the increasing cross section for minijet production and QCD, and (as noted above) they contend that this also agrees with the cosmic ray data.

8 Summary Comments

The arguments over inelasticity are not uncommon in the attempts of cosmic ray physicists to understand elementary particle interactions at energies which will be studied by the LHC. The problems of uncertain primary composition, the depth of the large detectors in the atmosphere (5 to 7 interaction mean free paths) and the character of the information on each event available all limit the certainty of interpretation of the results, in spite of truly heroic work by those active in this area. It is also possible that cosmic ray experimentalists are fascinated by the challenge of seeing new and unexpected phenomena, and they may be somewhat reluctant to accept a conventional explanation for their observations. However, even with the limitations noted, most of the observations cited above have not found an explanation based on physics understood today. The cosmic ray community goes further: a statement heard often at conferences [26] and repeated in the conclusions of several of their papers in different words is that "There is persuasive evidence that there is a fundamental change in the character of strong interactions above 10^{16}eV". Certainly, to date, there is no hard data to contradict that statement!

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