FELIX:
THE COSMIC RAY CONNECTION

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Summary

We here draw attention to the fact that FELIX, a full acceptance LHC detector with the capability of observing complete events, can significantly contribute to the resolution of important issues in cosmic ray astrophysics. Modeling of particle interactions has, unfortunately, become an integral part of operating a cosmic ray detector because direct experimental observations are often only available at much lower energies, much smaller rapidities, and for proton rather than nuclear targets and projectiles. Felix is unique in covering the energy and rapidity range explored by high energy cosmic ray detectors. Acquiring the relevant data on particle and nuclear interactions has gained a new urgency with the construction of new facilities such as HIRES in Utah and the Auger air shower array. FELIX can make a critical contribution to the search for the cosmic accelerator(s) of the highest energy cosmic rays, a problem so puzzling that the decay of topological defects has been researched as a credible mechanism for their origin. Thus a long-standing astrophysics enigma may be relevant to aspects of gauge theories which cannot be probed directly with accelerators. Also, unlike conventional central detectors, FELIX can search for a variety of unusual phenomena associated with the production of very forward particles in cosmic ray interactions with collision energy in excess of 10^{14}–10^{15} eV, i.e. $\sqrt{s}$ larger than 1 TeV.

1 A full acceptance detector FELIX: Connections to Particle Astrophysics

The goal of the FELIX collaboration, very much inspired by the SSC's Full Acceptance Detector philosophy[1], is to develop an instrument that, like an old-fashioned bubble chamber, can view complete LHC interactions. While not the main motivation for building such a detector, its capability to cover far-forward/backward rapidity space will allow FELIX to gather data of importance to cosmic ray physics[2]. We will show how FELIX can indirectly contribute to the resolution of the question of where and how the highest energy cosmic rays are accelerated. Because the detector has the capability to cover the energy and rapidity range explored by the highest energy cosmic ray detectors, it can, furthermore, scrutinize the claims of "anomalies" associated with the production of very forward particles above a threshold of 10^{14}–10^{15} eV. "Centauro" events constitute one of several unusual phenomena which we will review.

Above energies where the flux is large enough to be studied directly by satellite or balloon experiments, our information on cosmic rays and their interactions is indirect. The nature and energy of the incident cosmic particles must be derived from observations of air cascades at depths where they are roughly 10 atmospheric interaction lengths removed from the primary interaction. The development of the air shower is controlled by the physics of particle and nuclear interactions at energies beyond the reach of existing accelerators and, to make matters worse, by the physics of very large Feynman x, a region of phase space not even covered by the latest generation of high energy collider experiments. In order to extract information on the primary interaction, e.g. its energy, and whether the primary is a proton or a nucleus, one relies on modeling the particle physics dictating the development of the air showers. Often the relevant data on the production of secondaries in proton-nucleus interactions does not exist above center-of-mass energies of $\sqrt{s} \simeq 10\,\mathrm{GeV}$, four or more orders of magnitude below the $\sqrt{s} > 140\,\mathrm{TeV}$ interaction energies of the highest energy cosmic rays[3].

It is informative to recall that the muon and pion were born as anomalies in air cascades before being identified as particles in individual events. All quarks and leptons, with the exception of τ, top and bottom, were discovered in the cosmic ray beam. In 1971 Niu et al. discovered[4] long-lived particles among the secondaries of cosmic ray events recorded in emulsion chambers. These were readily interpreted[5] as charm by a group of Japanese theoreticians. The discovery was ignored by the particle physics community. A common criticism from the few who paid attention was that there are background processes faking long-lived particles. This criticism was valid and it was, unfortunately, not until after the discovery of the J/Ψ that it was shown[6] that the rate of fake events was less than 10^{-4} per event, a fact subsequently confirmed by accelerator experiments using emulsion targets to study charm. Another criticism was that neutral particles (gaps) had a longer average lifetime than the charged ones (kinks). This "inconsistency" anticipated the different lifetime of neutral and charged D's! This story should encourage us not to routinely ignore cosmic ray anomalies. This being said, let me draw attention to the event[7], shown in Fig. 1, which exhibits five heavy quark signatures, including a cascade decay. It has so far defied interpretation.

One must appreciate that this, as well as any other cosmic ray events, must be produced with characteristic millibarn cross sections which makes exotic explanations such as WW production followed by $t\bar{b}$ decay totally irrelevant. In fairness to cosmic ray physicists it must be pointed out that exaggerated claims or experimental mistakes have rarely been the source of cosmic ray anomalies. The possible fates of an anomaly are that: i) it is the first hint of new physics, such as charm, ii) it is eventually understood in terms of known physics (puzzling observations are scattered over the cosmic ray literature which, after their identification at accelerators, were understood as manifestations of parton jets), or iii) it reflects an insufficient understanding of the measurements which are often very indirect. One of the most persistent anomalies are Centauro events, i.e. excess production of neutral pions, and anomalous "halo"

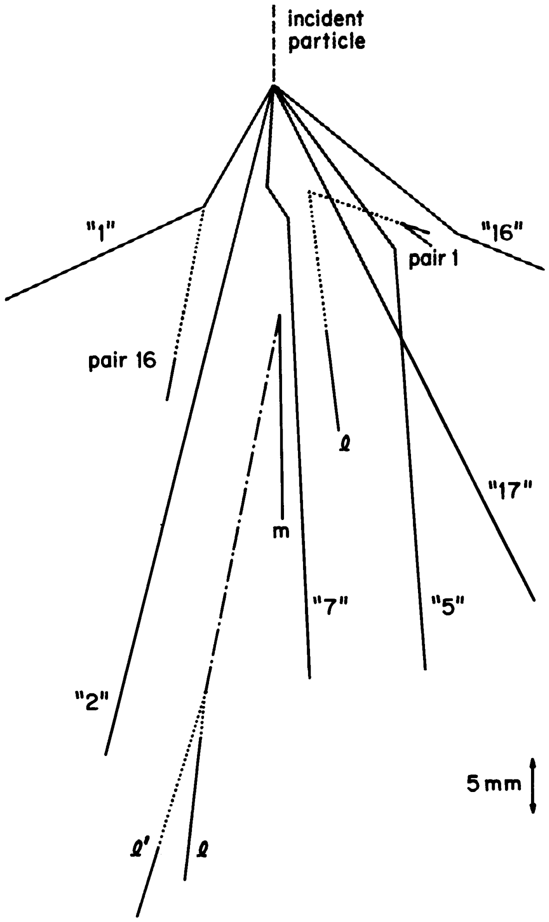

Figure 1: Emulsion chamber observation of the associated production of 5 heavy quarks. One of the quarks, presumably a b, undergoes a $b \to c$ cascade decay.

events with characteristic transverse momenta of only 20 MeV. Because of the characteristic millibarn cross sections associated with "anomalies", confirming evidence should require about 1 microsecond of FELIX data taking.

2 The Origin of Cosmic Rays: Who Cares?

Cosmic rays form an integral part of our galaxy. Their energy density is qualitatively similar to that of photons, electrons and magnetic fields. It is believed that most were born in supernova blast waves. Their energy spectrum can be understood, up to perhaps 1 PeV (1000 TeV), in terms of acceleration by supernova shocks exploding into the interstellar medium of our galaxy. Although the slope of the cosmic ray spectrum abruptly increases at this energy, particles with energies in excess of 10^{20} eV have been observed and cannot be accounted for by this mechanism. The break in the spectrum, usually referred to as the "knee," can be best exhibited by plotting the flux multiplied by an energy dependent power $E^{2.75}$; see Fig. 2.

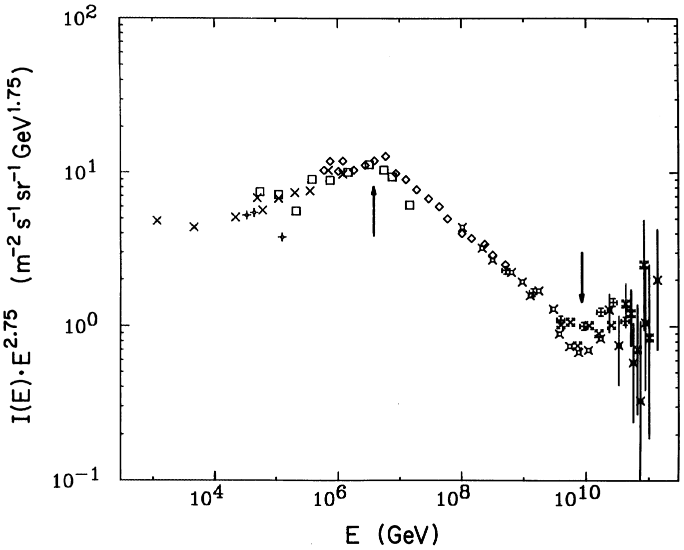

Figure 2: Flux of high energy cosmic rays after multiplication by a factor $E^{2.75}$. Arrows point at the structure in the spectrum near 1 PeV, the "knee', and 10 EeV, the "ankle".

The failure of supernovae to accelerate cosmic rays above 1000 TeV energy can be essentially understood on the basis of dimensional analysis:

$$E = BRc\,, \tag{1}$$

where B and R are the magnetic field and the radius of the accelerator and c is the speed of light. Equation (1) yields a maximum energy

$$\left[\frac{E_{\rm max}}{10^5\,{\rm TeV}}\right] = \left[\frac{B}{3\times 10^{-6}{\rm G}}\right]\left[\frac{R}{50\,{\rm pc}}\right] c\,, \tag{2}$$

and therefore particles moving at the speed of light c reach energies up to a maximum value $E_{\rm max}$ which must be less than 100 PeV for the typical values of B and R for a supernova shock. Realistic modeling introduces inefficiencies in the acceleration process and yields a maximum energy which is typically two orders of magnitude smaller than the value obtained by dimensional analysis. One therefore identifies the "knee" with the sharp cutoff associated with particles accelerated by supernovae.

Where cosmic rays with energy in excess of 1 PeV are accelerated undoubtedly represents the most urgent problem in cosmic ray astrophysics and one of the oldest unresolved puzzles in astronomy. In order to beat the dimensional argument just presented, one has to accelerate particles over larger distances R or identify higher magnetic fields B. This leads to a variety of speculations[3]. The large B-fields in pulsars, near black holes and in the cores of active galactic nuclei (AGNs), where they extend over large distances, have been exploited in models where the highest energy cosmic rays originate in point sources. All we really know at this point is that cosmic rays of $10^3 \sim 10^9$ TeV do exist. We do not know whether they are protons or iron nuclei or, something else. The failure to produce convincing models for the acceleration of charged particles of lower energy, has inspired speculations where the highest energy cosmic rays are produced in a "top-down" mechanism, e.g. the decay of X-particles[3]. Sources of these particles would be topological defects formed in the early universe at the time of GUT phase transitions. Energy is no longer a problem: the characteristic energy scale associated with such a scenario is the GUT scale (10^{13} TeV).

Topological defects illustrate how cosmic ray experiments may probe aspects of particle physics which cannot be addressed using accelerators. So, who cares about high energy cosmic rays? We do. It is, in fact, reasonable to argue that the question of the origin of the highest energy particles in the universe is of sufficient importance to deserve the support of accelerator experiments, whether their sources are GUT defects or not. FELIX, more than any other collider detector, has the capability to provide measurements supporting the analysis of cosmic ray experiments such as energy determination and, more importantly, identification of the nature of the primary.

3 Particle Physics Beyond the Reach of Accelerators: Understanding Cosmic Ray Interactions

With our fascination for puzzling aspects of isolated cosmic ray events, an important message is often lost: there is no compelling evidence that the dynamics of average particle interactions cannot be understood, all the way to 10^9 TeV, on the basis of anything more than the simplest dynamics embodied, for instance, in "QCD-inspired" models[8].

Evidence on individual particle interactions in or near the LHC energy range has been predominantly collected in exposures of large, high altitude emulsion chambers to the cosmic ray beam[9]. The experiments have a typical single-particle threshold of 4 TeV and they therefore observe interactions in the 10^3–10^6 TeV energy range. Only electromagnetic showers are detected, but showers penetrating the chambers to more than 4 to 7 cascade units are classified as hadrons. Many chambers have a 2 story structure with the top (bottom) emulsion chambers basically acting as electromagnetic (hadronic) calorimeters. The largest of these experiments is the USSR-Poland-Brazil-Japan experiment in the Pamir mountains which exposed a total emulsion area of $10^5\,\mathrm{m}^2$ year collecting order 100 events with LHC energy.

All air shower and emulsion data can be accommodated on the basis of the simplest assumptions on particle production in the very forward direction: Feynman scaling and energy-independent inelasticity[10]. These assumptions are guided by the features of QCD-inspired models which indeed exhibit approximate Feynman scaling in the fragmentation region and predict an inelasticity which varies slowly with increasing energy. The rapidity density of secondary charged pions is parametrized as

$$\frac{dN}{dy} = x\frac{dN}{dx} = a\frac{(1-x)^n}{x} \ , \tag{3}$$

where y is the rapidity of the secondaries and the Feynman variable x is given by the ratio of the energy E of the secondary particle to the incident energy E_0. This simple picture is consistent with the little information one can extract from accelerator results on the production of particles in the very forward direction[11]. With $a = 0.12$ and $n = 2.6$ ($n = 3$ is expected on the basis of counting rules) the overall features of single events detected in emulsion chambers are quantitatively reproduced. For illustration, we present in Fig. 3 the hadronic integral spectrum of two events detected by the Brazil-Japan Collaboration at Mt. Chacaltaya, Bolivia (atmospheric depth 540 g/cm^2) [12, 13], which are successfully described by the most straightforward assumptions [14]. The overall features of the very high-energy interactions recorded with emulsion chambers, rapidity and transverse momentum distribution of the secondaries, can be quantitatively reproduced. (This is somewhat surprising after numerous claims in the literature that the same data implied large scaling violations or new dynamics.)

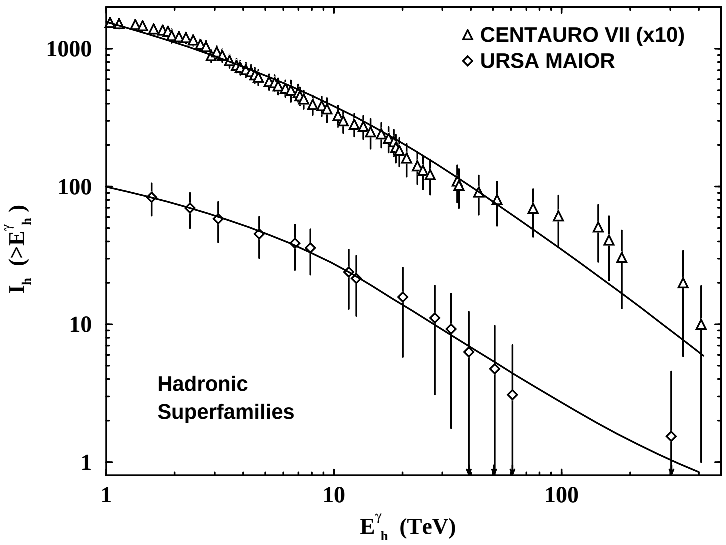

Figure 3: Integral energy spectra of hadronic secondaries detected at Mt. Chacaltaya[12, 13]. Ursa Maior event ($\Diamond$) and Centauro VII data ($\triangle$), are compared to the calculation of Ref. [10] (solid line), using the x-distribution of Eq. (3). For illustrative purposes, the data of Centauro VII have been shifted by a factor 10.

The same assumptions can be used to calculate both the hadronic and electromagnetic integral spectra (rather than individual events) produced by cosmic rays in the atmosphere and detected, at mountain altitude, in large emulsion chamber experiments. Starting with the measured all-particle primary spectrum at the top of the atmosphere, particle showers are propagated down to the mountain altitude detection level and the total electromagnetic and hadronic flux can be predicted. The results not only depend on the interaction dynamics discussed above, but also on the (unknown) composition of the primary cosmic radiation. All mountain altitude spectra can be reproduced[10] if we assume a heavy nuclear component of primary cosmic rays above the "knee" in the spectrum with average mass number $\langle A \rangle = 7.3 \pm 0.9$; see Fig. 4.

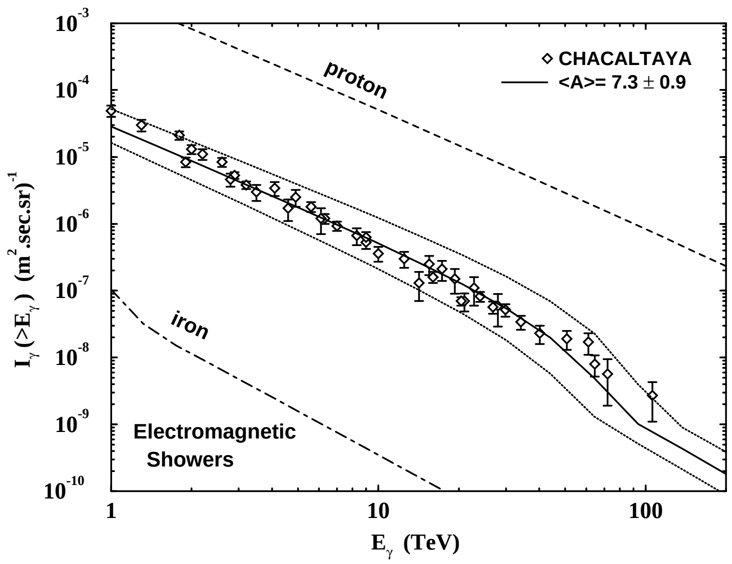

Figure 4: Integral energy spectra of electromagnetic showers ($\Diamond$) detected at Mt. Chacaltaya[15] compared to the calculation using the x-distribution of Eq. (3). Dashed lines: $\langle A \rangle = 1$ (proton) and 56 (iron); solid line: $\langle A \rangle = 7.3 \pm 0.9$, dotted lines: calculated from uncertainties in A and γ.

Although the simplest assumptions for the dynamics of particle production at high energies clearly allow us to understand the fluxes of hadrons and photons at mountain altitudes, as well as the structure of individual events, we cannot describe *some* of the Centauro events: see Fig. 5. This convincingly suggests that these events are anomalous, independently of their well-advertised unusual features such as the absence of neutral secondaries.

A prominent feature of emulsion chamber events is that a large fraction of the events contain "halos" which appear as spots of extremely high optical density on the X-ray film. In a recent analysis of 50 high energy events, 8 contained 3 and 1 event 4 halos[9]. It is safe to say that this cannot be a freak observation as other groups also

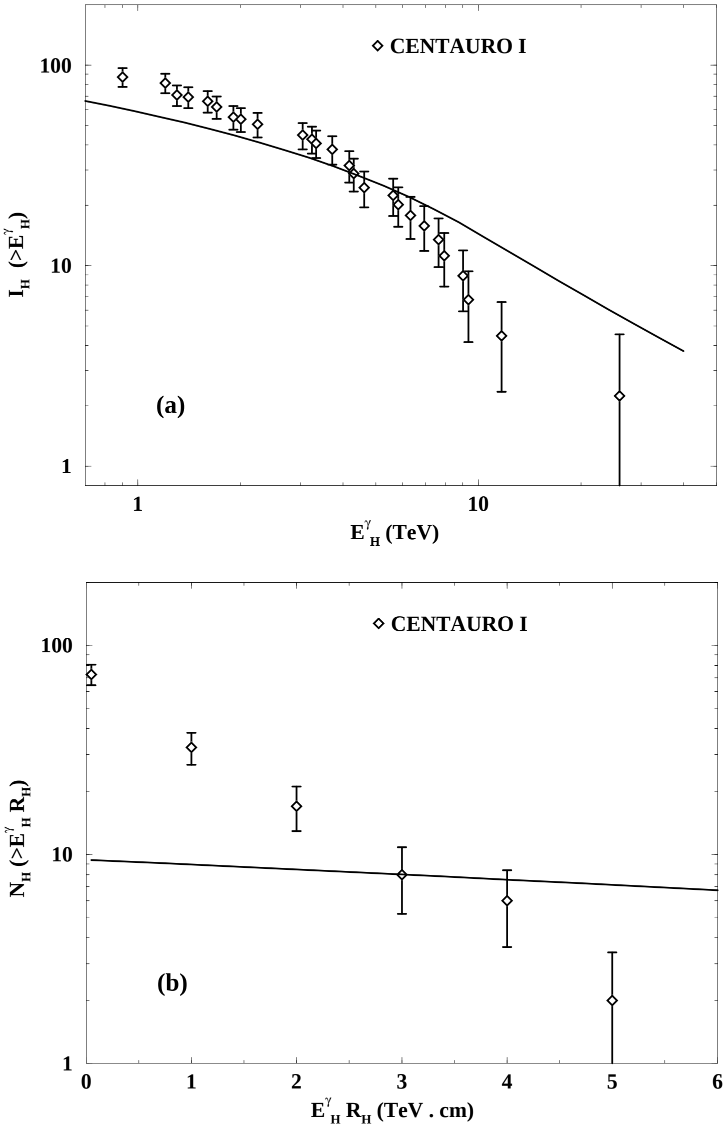

Figure 5: Investigation of the Centauro I (◇) event, detected at Mt. Chacaltaya [16, 17]: (a) Integral energy spectrum, (b) energy-weighted lateral spread of secondary particles in the event. Solid lines are the analytical calculations.

observe the phenomenon and no analysis is involved; the picture tells the story. A most intriguing fact is that the halos in each event are aligned to a remarkable degree. Careful statistical analysis shows isotropic production to be unlikely. The alignment in the observation plane means that the multiple halos, produced on average in collisions 1 km above the detector, are highly coplanar.

This bizarre observation might have the following most conventional explanation[18] Halos are electromagnetic showers produced by the most energetic π^0 in jets. In a two-jet event the produced jets and the projectile/target fragments form, by momentum conservation, a plane which will intersect the emulsion thus defining a line along which the fragmentation products of both jets as well as those from the colliding hadrons will line up. This picture naturally explains the alignment of 3 halos. In accelerator language events with 4 halos are three-jet events. It is a fact of QCD that also the additional jet is preferentially produced in the plane of the first two. This leads to the alignment of 4 halos. Detailed Monte Carlo simulation supports this straightforward picture. The characteristic transverse momentum of the jets is given by the quantity

$$p_T h = E\, r_{\min}\ , \tag{4}$$

which is measured to be of order $10^3\,\mathrm{GeV\,m}$. Here $r_{\min}$ is the spacing of the jets on the X-ray film, h is the height of interaction and E is the energy of the jet. So p_T is of order a few GeV for $r_{\min} = 1\,\mathrm{mm}$, h $= 1\,\mathrm{km}$, and E of order a few 1000 TeV. An accelerator physicist would classify these events as mini-jet events and the Pamir collaboration has indeed measured a jet cross section with $p_T > 3\,\mathrm{GeV}$ consistent with the QCD energy extrapolation of the UA1 observations[19]. If in 8 out of 50 events jets are visible to the naked eye, it is reasonable to assume that most high energy events are jet events.

Monte Carlo generators such as PYTHIA[20] and SYBILL[21] have been developed on the basis of the mini-jet model which embodies the features of cosmic ray interactions just described. The event generators have been fine-tuned to describe accelerator data and are subsequently used to model cosmic ray experiments.

4 On the Importance of FELIX Data

How critical is particle dynamics to particle astrophysics experiments operating beyond the phase space covered by accelerators? The electromagnetic part of the showers can always be modeled with great confidence and can be exploited to yield a robust lower limit on particle energies deduced from air shower measurements. This is not to imply that modeling of the electromagnetic cascades will not present us with challenges such as the calculation of the interaction of the particles with the earth's magnetic field and the evaluation of coherent interactions of very high energy particles with more than a single atom, the Landau-Pomeranchuk-Migdal effect. The less tractable problem is however associated with the first few generations of interactions in the air cascade, where the center-of-mass energy greatly exceeds that of accelerators. The footprint of the incident particle (proton, nucleus or anything else) is therefore shielded from direct experimental observation by several cascade interactions involving unknown particle dynamics. So, the problem is primarily associated with the determination of the composition of the beam.

Extrapolations of direct measurements of the composition below 100 TeV hint at the possibility of an abundant iron component in the cosmic ray beam. This would exclude the extra-galactic origin of the cosmic rays because heavy nuclei inevitably disintegrate on 3K cosmic photons before reaching earth. If, on the other hand, active galaxies are the accelerators of the high energy cosmic rays, only protons can escape the acceleration site, which is characterized by high densities of photons and large magnetic fields. The cosmic rays are, in fact, the decay products of neutrons escaping the source. The question of composition is clearly primordial. It has been extensively researched using a wide variety of techniques. The failure to find totally conclusive answers can be readily identified with the indirect nature of air shower information. In order to extract information on primary composition from the observations one must have a complete understanding of the particle physics that dictates the early development of the cascade. Identifying the composition seems as impossible as solving a single equation (the observation) with two unknowns (the composition and the particle interaction dynamics). A LHC detector sensitive to all, including very large, rapidities will provide the critical particle physics information required to directly extract the cosmic ray composition from air shower experiments. FELIX can thus make a critical step in resolving the riddle of the origin of the highest energy cosmic rays.

The development of air cascades is primarily dictated by three features of particle production: i) the amount of collision energy transferred to the leading proton, ii) the inclusive cross section and transverse momentum of particles produced in the very forward direction, and iii) the nuclear effects of the projectile interacting with nitrogen or oxygen in the atmosphere. Conversely, data on cosmic ray cascades contains indirect information on these aspects of particle production. This information is unfortunately clouded by the fact that we do not know the composition of the beam. Our previous calculation of the frequency of showers observed in mountain altitude detectors nicely illustrates the problem. The showers are the debris at mountain altitude of cascades initiated by the primary cosmic ray flux at the top of the atmosphere. Fitting the data requires making assumptions on the particle model and the composition. An uncontroversial result is that the assumption that all high energy cosmic rays are protons, combined with particle production dictated by Feynman scaling, cannot accommodate this data; see Fig. 4. Such a model does not dissipate the energy fast enough to match the observations. So, faster dissipation in the atmosphere must be achieved by subdividing the energy between the nucleons of heavy nuclear primaries, or by abundant particle production violating Feynman scaling. This is a specific example of the dilemma introduced in the beginning. Any conclusions depend on particle physics beyond the reach of present laboratory experiments.

Our calculation in the previous section, using scaling, required indeed that $\langle A \rangle = 7.3 \pm 0.9$. QCD-inspired models do actually violate scaling because an increased fraction of the collision energy goes into the production of jets. Most of the partons producing jets are soft, therefore jet production and the associated violation of scaling is mostly a feature of central interactions. By momentum conservation, the energy transferred to jet production is not available to the leading particle. In cosmic ray language this means that the inelasticity increases with energy. I.e. with higher energy an increasing fraction of the energy goes into particle production, leaving necessarily a decreasing fraction for the leading particle. The latter conclusion is important as it implies violation of Feynman scaling in the forward direction and, therefore, a faster dissipation of the energy in the showers. Their penetrating power is diminished at higher energy. The violation of scaling is however very weak for reasons that are qualitative and easy to understand. Although the violation of Feynman scaling near $x = 0$ is quite dramatic, only a modest fraction of the leading-particle energy is required to supply the energy for this effect which is characterized by the production of mostly soft particles. The QCD models are therefore essentially scaling models and produce results consistent with our simple calculations presented in the preceding section. When combined with the type of data shown in Fig. 4, one will conclude that the high energy cosmic ray beam must contain heavy nuclei. If one's theory favors a proton-rich cosmic ray beam one can blame the fast dissipation of shower energy on abundant particle production as predicted, for instance, by statistical models. At very high energy the number of particles produced in these models becomes so large that the inelasticity has to be artificially reduced, i.e. more energy must be transferred to the leading particle. This seems a bit pathological; the best way to settle the issue, however, is to do accelerator experiments.

The above discussion ignores the added ambiguities associated with nuclear effects. They are usually finessed by using the superposition model: the interaction of a nucleus with A constituents and energy E, is modeled as A independent nucleon collisions, each with energy E/A. Whereas the model is likely to adequately reproduce average properties of the shower, it almost certainly underestimates fluctuations. The LHC has the possibility to accelerate nuclei and provide the relevant data to resolve a problem that covers physics interesting in its own right.

5 Heavy primaries or new particle threshold?[22]

With the UA7 experiment providing evidence against a radical departure from scaling, one may think at this point that a consensus has developed around a heavy composition of the cosmic ray beam. Emulsion experiments typically indicate a composition with over 40% Fe and 20% protons. Intermediate nuclei make up the remainder. Measurements counting underground muons as a signature for $< A >$ usually find a somewhat lighter composition consistent with the one derived in the preceding section. Things are not that simple and the alternative possibility is of interest to particle physics. The Brazil-Japan and Pamir collaborations argue a proton-rich beam can accommodate the same data by arguing that the dynamics of particle interactions changes in the vicinity of 100–1000 TeV threshold energy. Below that energy they agree that QCD-inspired models are adequate. So, here is the dual choice again: i) a change of composition to mostly Fe above the "knee," a conclusion which would, for instance, instantly invalidate active galaxies as cosmic accelerators of PeV cosmic rays, or ii) the appearance of a new threshold in particle physics. FELIX will not only decide the issue, but will elucidate the message of the cosmic ray data, whatever it is. The proponents of the new particle threshold do have a collection of unusual phenomena or so-called "anomalies", to bolster their claim. We briefly review them next.

6 Anomalous cosmic ray interactions: a brief overview[9, 23]

The well-advertised Centauro events are characterized by the production of a large multiplicity of charged particles accompanied by very few photons. The original Centauro event is still the most dramatic example, with a multiplicity of 100 charged secondaries and no, or at least no more than three, π^0's. As previously discussed, we cannot describe some of the Centauro events with the same assumptions that allow us to quantitatively all other features of the emulsion data. The unusually broad transverse momentum and steep rapidity distribution suggest that these events are anomalous, independently of the unusual charge distribution of the secondaries.

We already discussed the halo phenomenon. Halos are a common feature of very high energy events, 1000 TeV or more. Our previous discussion omitted the important fact that the electromagnetic shower development within the halo is anomalous. This is very interesting as we are studying the highest energy pions/photons ever observed. The much publicized Geminion event, which in the picture presented earlier would be a routine two-jet event, consists of two halos with a relative p_T of a few GeV. The real challenge in understanding halos is that they contain hadrons, i.e. penetrating showers, and that the transverse momentum of the particles within the clusters is typically 1% of that of the clusters relative to one another. The p_T-distribution[9] of particles inside a cluster is shown in Fig. 6. This is an interesting observation. As is clear from Eq. (9), p_T depends on the height of interaction which is not directly measured in the experiment. In the Geminion event and others like it, one can change one's model-dependent guess of the height of interaction in order to modify the value of p_T. It is, however, clear that if one decreases the height of interaction by a factor 10 in order to increase the $\langle p_T \rangle$-value inside the mini-cluster to the usual 300 MeV, then the relative transverse momentum between the clusters (jets) themselves is increased to large values incompatible with QCD expectations. One cannot adjust height to make both the relative p_T of the jets as well as the relative p_T of particles within the jet fall in line with expectations. The most conventional interpretation may be that the relative p_T of the jets is indeed 2 GeV and a new phenomenon characterized by an average p_T of order 20 MeV is responsible for the particle production in halos. Bjorken[1] has suggested chiral condensates as an explanation for both the Centauro and low-p_T particle production phenomena.

As a last example of anomalies we discuss the long-flying component[24]. A calorimeter built as a sandwich of scintillator and lead plates has been used to measure the attenuation of high energy cosmic ray showers. The data suggest the appearance of a penetrating component of showers with energies in excess of 100 TeV. The abun-

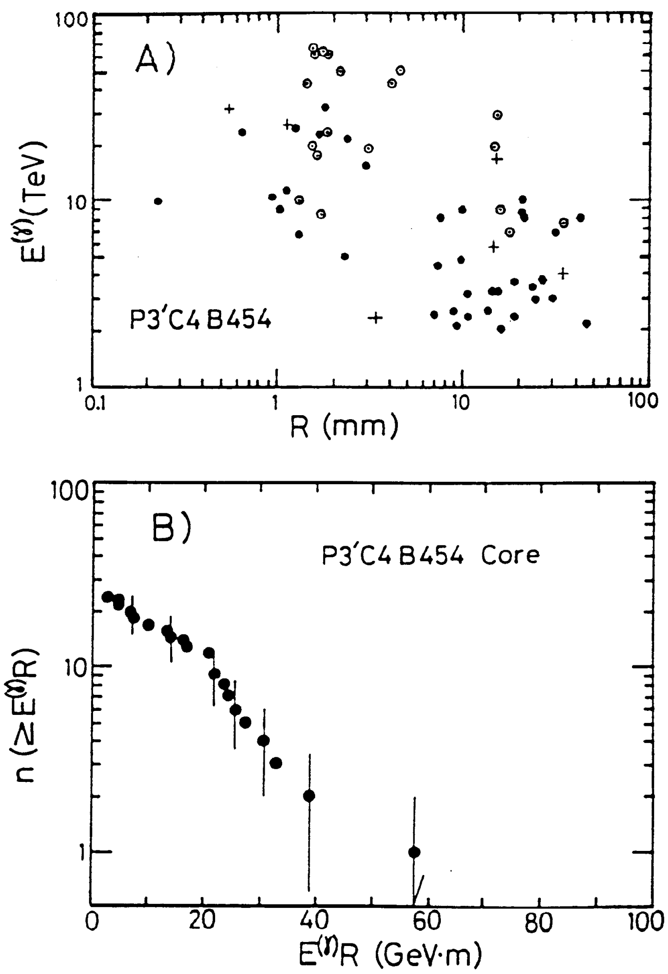

Figure 6: Inclusive p_T-distribution of particles inside a minicluster of halo. The enhancement occurs for $ER < 20\,\mathrm{GeV\,m}$, which corresponds to a p_T of 20 MeV for an average interaction height of 1km above the detector; see Eq. (4).

dant production of charm quarks has been invoked as the origin of the observations. Charmed secondaries will interact in the calorimeter with relative small inelasticity and thus be the origin of a penetrating and narrow component in the shower. Heavy quarks can scatter forward without losing a large fraction of their energy to particle production. It would be interesting to study this phenomenon with FELIX because, if real, it can have important implications beyond charm physics. It might affect the development of TeV showers in LHC calorimeters in a way not modeled by standard Monte Carlos. It has also been claimed that it affects the development of air showers by the fact that the relation between the number of electrons observed at a given depth of atmosphere and the energy of the shower is affected as a result of the penetrating component.

This list of anomalies is incomplete. The important point is that they are all associated with very high energy and very far forward phenomena. The FELIX detector is the only instrument that can debunk or elucidate the observations. Because the target, or possible both beam and target particles, are nuclei, there is also the possibility that cosmic ray anomalies are associated with nuclear effects, e.g. the formation of quark-gluon plasma.

Acknowledgments

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References

[1] J. D. Bjorken, SLAC-PUB 5616 (1992).

[2] The material in this document relied on T. K. Gaisser, *Phys. Lett.* **B100**, 425 (1981); T. K. Gaisser, *Cosmic Rays and Particle Physics*, Cambridge University Press (1991), *Proceedings of the 21st International Cosmic Ray Conference* in Adelaide, Australia, Invited/rapporteur talks by A. Erlykin, F. Halzen, R. Holinski and Y. Muraki, *Proceedings of the 22nd International Cosmic Ray Conference* in Dublin, Ireland, rapporteur talk by T. Yuda.

[3] For recent review, see *The Pierre Auger Project Design Report*, Fermilab report (1995) and therein.

[4] K. Niu et al., Prog. Theor. Phys. **46**, 1644 (1971).

[5] T. Hayashi et al., Prog. Theor. Phys. **47**, 280 (1972).

[6] T. K. Gaisser and F. Halzen, Phys. Rev. **D14**, 3153 (1976).

[7] S. Kuramata et al., *13th International Cosmic Ray Conference* (Denver) **3**, 2239 (1973).

[8] For a review see M. Block et al., Nucl. Phys. B (Proc. Suppl.) 12A, 238 (1990) and Phys. Rev. **D45**, 839 (1992).

[9] L. J. Baradzei et al., Nucl. Phys. **B370**, 365 (1992).

[10] C. G. S. Costa, F. Halzen and C. Salles, Phys. Rev. D **52**, 3890 (1995); Phys. Rev. D **54**, 5558 (1996).

[11] E. Pare et al., Phys. Lett. **B242**, 531 (1990).

[12] J.A. Chinellato, Ph.D Thesis, Universidade Estadual de Campinas, Brazil (1981).

[13] Brazil-Japan Collaboration, J.A. Chinellato *et al.*, in *Proc. of the 21st International Cosmic Ray Conference*, Adelaide, Australia, ed. by R.J. Protheroe (Graphic Services, Northfield, 1990), Vol. 8, p. 259.

[14] These results can be obtained using analytic shower theory.

[15] Brazil-Japan Collaboration, C.M.G. Lattes *et al.*, Prog. Theor. Phys. Suppl. **47**, 1 (1971); and in *Proc. of the 13th International Cosmic Ray Conference*, Denver, USA, (Colorado Associated Univ. Press, Boulder, 1973), Vol. 3, p. 2219.

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

[17] C.E. Navia *et al.*, Phys. Rev. D **40**, 2898 (1989).

[18] F. Halzen and D. A. Morris, Phys. Rev. **D52**, 1435 (1990).

[19] G. Arnison et al., Phys. Lett. **B118**, 167 (1992); T. Alexopoulos et al., Phys. Rev. Lett. **64**, 991 (1990).

[20] H. Bengtsson And T. Sjöstrand, Comput. Phys. Commun. **46**, 43 (1987) and **43**, 367 (1987).

[21] R. S. Fletcher, T. K. Gaisser, P. Lipari and T. Stanev, Phys. Rev. D **50**, 5710 (1994).

[22] For a detailed discussion, see T. Yuda in Reference 2.

[23] E. M. G. Lattes et al., Phys. Rep. **65**, 151 (1980).

[24] V. Yakovlev, in the *7th International Symposium on Very High Energy Cosmic Rays*, L. Jones, editor, World Scientific, Singapore (1993).