A COMPARISON OF COSMIC RAY PHYSICS WITH LATEST ACCELERATOR DATA

J.G. Rushbrooke^(*)
CERN, Geneva, Switzerland

Abstract. - A comparison is made of existing cosmic ray results with the latest accelerator data, mainly from the CERN pp Collider. Topics in hadron physics covered include: total cross section, scaling violations in the central and fragmentation regions, increase of mean transverse momentum, the multiplicity of particle production, kaon and baryon-antibaryon production. A search for Centauro events, the possibility of an energy threshold for such unusual events, and the evident need for higher machine energy is discussed.

Invited talk presented at the XXI International Conference on
High Energy Physics, 26-31 July 1982, Paris, France

(*) Visiting Scientist from Cambridge University, Cambridge, England.

Résumé. - Une comparaison est établie entre les résultats provenant des rayons cosmiques et les dernières données venant des accélérateurs, principalement du Collider du CERN. Les sujets abordés sont: la section efficace totale, la violation d'échelle dans les régions centrale et de fragmentation, l'augmentation de la quantité de mouvement transverse, la multiplicité de production des particules, la production de kaons et de paires baryon-antibaryon. On discute également la recherche d'événements Centauro, l'existence possible d'un seuil en énergie pour la production de ces événements rares, et la nécessité manifeste d'une augmentation de l'énergie des machines.

1. INTRODUCTION

Up to now our knowledge of particle physics at energies above the highest ISR energy has relied upon an ability to extract useful information from cosmic ray experiments [1]. The interpretation of such experiments has in turn relied upon a knowledge of certain energy-dependent physical quantities - total cross sections, inclusive differential cross sections, the fraction of kaon and baryon production - which would require an extrapolation of accelerator data beyond the ISR range. These cosmic ray experiments suffer from several further difficulties: firstly the problem of low flux, since the total rate of primaries at the top of the atmosphere is less than one per m^2 per hour for laboratory energy $E_0 > 100 \text{ TeV}$, and less than one per m^2 per day for $E_0 > 1000 \text{ TeV}$: uncertainty as to the exact energy dependence and nuclear composition of the primary spectrum, both of which are important astrophysical questions: and the problem of relating pp cross sections to p-air cross sections when considering cascade development in the atmosphere.

An important development over the past twelve months has been the successful operation of the CERN $p\bar{p}$ collider and hence the arrival of $p\bar{p}$ data at $\sqrt{s} = 540 \text{ GeV}$, equivalent to $E_0 = 155 \text{ TeV}$. An average luminosity of a few $10^{26} \text{ cm}^{-2}\text{s}^{-1}$

has been achieved during runs in late 1981, giving ~ 20 events per second, so that up to $\sim 10^6$ events have by now been accumulated for study by the experiments UA1, 2, 4, 5 together.

This review will attempt to relate these first collider measurements of cross sections and particle production to earlier cosmic ray estimates. Fig. 1 shows the range of energies involved. The possibility of scale breaking in inclusive cross sections has arisen previously at the ISR for the central region, and it will be shown that the collider data now put this beyond doubt and suggest a violation of Feynman scaling in the fragmentation region as well. A change in transverse momentum distributions is also a form of scale breaking and this will be referred to. Evidence relating to the proportion of kaons and baryons produced at collider energy will be discussed. Finally, there remains the perplexing question of the existence of a weird class of events - Centauros, mini-Centauros, Geminions, and now Chirons - suggested by mountain-based cosmic ray experiments. Searches for Centauros at the Collider have been carried out. The question of an energy threshold and the likely energy dependence of the yield of these cosmic ray events will be considered to see what the chances are of observing these phenomena at accelerators.

Fig. 1 : Cosmic ray and collider experiments.

2. TOTAL CROSS SECTION

A preliminary measurement of the $p\bar{p}$ total cross section at the CERN Collider has been made by UA4 and reported elsewhere in this conference [2]. Their value of 66 ± 7 mb is derived from the slope in t of the elastic differential cross section and the rates for inelastic and elastic events. Attempts to deduce σ_{pp}^{tot} from cosmic ray data are summarized in fig. 2, taken from Tonwar [3]. Measurements of the cosmic ray flux surviving at mountain altitudes give values up to 50 TeV in good agreement with either power law in s or $\ln^2 s$ extrapolations of the ISR data of Amaldi et al. [4]. The UA4 result is likewise in agreement with either. Estimates above $E_0 = 100$ TeV based on the flux of extensive air showers (EAS) are, however, subject to very large systematic errors, mainly because of the possible presence of a significant fraction of heavy primaries, such as Fe

nuclei. From a more recent analysis of cosmic ray gamma-families Gaisser [5] guesses a value $\sigma_{pp}^{\text{tot}} = 70 \pm 10 \text{ mb}$ at CERN collider energy.

Clearly one must be looking for a definitive measurement from UA4, which one hopes will be made by the end of this year.

Fig. 2 : Variation of total proton-proton cross section with laboratory energy. The measurement of UA4 at the $p\bar{p}$ Collider is shown.

3. SCALING OF INCLUSIVE CROSS SECTIONS

3.1 Central and fragmentation regions

The scaling of the invariant inclusive cross section for produced secondaries of a given type means that it can be written

$$\frac{1}{\sigma_{\text{inel}}} \frac{2E}{\sqrt{s}} \frac{d^2\sigma}{dx dp_T^2} = f(x, p_T) \quad (1)$$

where $x = p_L / (1/2 \sqrt{s})$ is the Feynman scaling variable, and p_L is the cms longitudinal momentum. This form is taken to hold at finite energy, though in the strict Feynman sense it is a prediction for infinite energy only. The fact that eq. (1) is violated over the ISR energy range for secondaries produced in the central region is already well known and has been confirmed in the Collider results [6] of UA5. This is shown in fig. 3, which is a plot of $1/\sigma d\sigma/d\eta|_{\eta=0}$ versus $\sqrt{s}$, η being the cms pseudorapidity ($\eta = -1/2 \ln \tan \theta/2$). The UA5 result is for non-single diffractive events only: on correcting for a single-diffractive component^(*) one obtains the lower value indicated, which is consistent with an overall trend from ISR energies like $\ln s$ or $s^{0.1}$.

(*) Measured as $\sim 18\%$ of the inelastic cross section by UA4 [2].

Fig. 3 : Central region pseudorapidity density for charged particles as a function of c.m. energy.

Whether scaling holds also in the fragmentation region ($x \gtrsim 0.05$) has been questioned by Wdowczyk and Wolfendale [7], who suggested an empirical approach, taking as scaling variable $x_1 = p_L / (1/2 \sqrt{s})^{1-2\alpha} = x (\sqrt{s}/2)^{2\alpha}$, where the parameter α can be expected to lie between zero for Feynman scaling and about 0.22 for maximum scale breaking. The invariant cross section then takes the form

$$\frac{1}{\sigma_{inel}} \frac{2E}{\sqrt{s}} \frac{d^2\sigma}{dx dp_T^2} = \left(\frac{s}{s_0}\right)^\alpha f\left\{x\left(\frac{s}{s_0}\right)^\alpha, p_T\right\} \quad (2)$$

which predicts that the observed x -distribution will fall in the fragmentation region and rise in the central region as s increases.

These authors also claimed that the accelerator data up to ISR energy offers some support for eq. (2), and estimated a value for α of 0.13 ± 0.02 . They also showed [8] that analysis of cosmic ray data for $E_0 \sim 10$ -100 TeV gave $\alpha = 0.20 \pm 0.05$, and that a value $\alpha \sim 0.25$ could explain the EAS data up to the highest energies, $E_0 \sim 10^6$ TeV, though systematic uncertainties could conceivably depress α to 0.1. It would therefore seem that violation of scaling was not a transition effect up to ISR energies but persisted up to the highest energies.

The CERN Collider now offers an opportunity to investigate this hypothesis over a much wider range of s than hitherto possible from accelerator data. Fig. 4 presents the rapidity density, plotted against $\eta_{lab} \equiv \eta - y_{target}^*$, where $y_{target}^* = -1/2 \ln s/m_{target}^2$, for data obtained in the UA5 detector at the Collider and the ISR. Exact fragmentation region scaling means that the data points should overlay one another for $|x| \gtrsim 0.05$, equivalent to y_{lab} less than $\sim 2 - 2 1/2$ units. However, there is probably a systematic displacement indicating a scaling violation in this region, which we now investigate more quantitatively.

Transforming eq. (2) into rapidity and p_T variables, assuming that the invariant cross section factorizes in these variables, and noting that in the

Fig. 4 : Pseudorapidity distributions as a function of laboratory frame rapidity measured at ISR and CERN Collider.

target fragmentation region shown in fig. 4 one may write $x \sim (e^{-\eta}/\sqrt{s}) \sqrt{p_T^2 + m^2}$, one has on integrating over p_T an expression of the form

$$\frac{1}{\sigma} \frac{d\sigma}{d\eta} = \left(\frac{s}{s_0}\right)^\alpha F \left\{ e^{-\eta} \left(\frac{s}{s_0}\right)^{\alpha-1/2} \right\}, \quad (3)$$

It follows that equal values of the scaled rapidity density $1/\sigma \, d\sigma/d\eta \div (s/s_0)^\alpha$, i.e. F , will occur when

$$e^{-\eta} s^{\alpha-1/2} = \text{constant}$$

i.e.

$$-\eta + (\alpha-1/2) \ln s = \text{constant.}$$

or

$$y_{\text{lab}} = \alpha \ln s + \text{constant.} \quad (4)$$

To check eq. (4) against the data we have taken $\alpha = 0.1$ as suggested by the central region data of fig. 3, and found the values of y_{lab} at different s for which F takes the chosen value 0.8, the result being plotted in fig. 5. With the big range in s a clear trend is now visible, though too strong to be consistent with the value $\alpha = 0.1$ indicated by the straight line. However, the collider point in fig. 5 is uncertain because of the exclusion of the single diffractive component by the trigger. One may thus conclude that the accelerator data suggest an indication of scaling violation in the fragmentation region, but a quantitative understanding must await a better Collider measurement.

3.2 Transverse momentum distributions

Turning to average transverse momentum the data points for cosmic rays are shown in fig. 6, taken from ref. [8]. The straight lines are extrapolations from lower energy accelerator data for $\pi^\pm$, $K^\pm$, $\bar{p}$ and for all charged particles, taken from the review of Rossi [9]. The Collider values obtained by UA1 [9], UA2 [11] and UA5 [12], are seen to be in fair agreement with the trend of accelerator data, indicating that the cosmic ray values are perhaps overestimated as suggested in ref. [8]. However, measurements of neutral particle decays in the UA5 streamer

Fig. 5 : Experimental test of fragmentation region scaling in terms of eq. (4) using ISR and $p\bar{p}$ Collider data.

chamber experiment [13] show considerably higher values for the mean transverse momenta for kaons and hyperons, as shown in fig. 6. One might tentatively infer from the Collider measurements so far that $\langle p_T \rangle$ for pions is ~ 360 MeV/c, in line with the trend of lower energy data, while $\langle p_T \rangle$ for kaons and baryons has increased to perhaps $\sim 600 - 650$ MeV/c.

Fig. 6 : Average transverse momentum versus primary particle energy for cosmic ray and accelerator data from ref. [9]. Recent estimates from CERN Collider experiments are added as crosses.

4. AVERAGE PARTICLE MULTIPLICITIES: KAON AND BARYON/ANTIBARYON PRODUCTION

Fig. 7 shows the s -dependence of the mean charged multiplicity from hadronic interactions. The UA5 Collider measurement for non-single diffractive events gives $\langle n_{ch} \rangle = 28.5 \pm 1.0$, which can tentatively be corrected [14] for the single-diffractive component to give a value 25 ± 2 for the inelastic charged multiplicity. This is plotted in fig. 7 and is seen to lie on an extrapolation of the quadratic fit in $\ln s$ to the ISR data. A cosmic ray balloon experiment point [15] for $\sqrt{s} \sim 250$ GeV is also on the curve. One can also look at the C-jet data from the Brazil-Japan emulsion chamber, corresponding to an average incident energy of ~ 100 TeV, close to the Collider energy. The resulting values (see ref. [16] for details) are in rough agreement with the UA5 result.

Fig. 7 : Comparison of $\langle n_{ch} \rangle$ from accelerators with values estimated from cosmic ray experiments.

No sign has appeared from data up to Collider energy therefore, of the energy dependence stronger than $\ln^2 s$ suggested by cosmic ray data at much higher energies, collected in fig. 8 [8].

Fig. 8 : The average multiplicity versus primary particle energy.

From measurements of the multiplicities of charged particles, photons and neutral strange particles produced at the Collider, the UA5 experiment has been able to estimate [14,17] the average multiplicities of various types of produced particles. The result is summarized in table 1. One sees that in a "typical" event at Collider energy about 42.7 "stable" particles (i.e. including the products of strongly decaying resonances) are produced. Of these $\sim 12\%$ are kaons and $\sim 9\%$ are baryon/antibaryons, indicating a definite rise from the ISR values of $\sim 9\%$ and 5% respectively. A measure of the kaon and baryon fraction is given by the charged-to-neutral hadron ratio (C/N) defined as

$$\frac{C}{N} = \frac{\pi^{\pm} + K^{\pm} + B^{\pm}/\bar{B}^{\pm}}{K^0/\bar{K}^0 + B^0/\bar{B}^0}$$

The ISR values and the UA5 estimate (equal to $25.2 \div 4.7 = 5.4$ from table 1) are plotted against E_0 in fig. 9(a) together with various model calculations described in ref. [18]. Of particular interest is the dotted curve, inferred [19] from measurements shown plotted in fig. 9(b) of the C/N ratio at the bottom of high energy EAS. The important thing is the dramatic fall in measured values of C/N just above Collider energy, which if correct would imply $C/N \rightarrow 1$ in the dotted curve, consistent with a dominant baryon-antibaryon production.

Fig. 9 : Ratio C/N as a function of laboratory energy (a) for primary hadron-hadron interaction, and (b) as measured in EAS

In fig. 10 is shown the total transverse energy, ΣE_T , of produced hadrons from C-jet data [16]. A rough Collider estimate (for non-single diffractive events) can be made as

$$\Sigma E_T = \langle n_{ch} \rangle * \frac{n_{total}}{n_{ch}} * \langle E_T \rangle$$

Using $\langle n_{ch} \rangle = 28.5$ and $n_{tot}/n_{ch} \sim 42.7/25.5$ (table 1) from UA5, and taking $\langle E_T \rangle \sim 0.45 \text{ GeV}^{(*)}$ we arrive at the value plotted in the figure. The overall result is in reasonable agreement with the trend from lower energies, and shows that the Collider and C-jet data are compatible.

(*) Estimated using the values mentioned in sect. 3.2 together with the results of table 1.

Fig. 10 : Comparison of the estimated ΣE_T from C-jet data with the CERN Collider result. SPS and ISR values are likewise shown.

5. UNUSUAL EVENTS

At least four categories of unusual events have been reported as seen among cosmic ray families produced in the atmosphere. Their properties are summarized [20], [21] in table. 2. The most spectacular of these, the so-called Centauro events, should have been clearly visible at the Collider if produced as the result of a $\sqrt{s} = 540$ GeV hadronic collision.

The UA5 search^(*) for such events has already been published [22], and the reader is referred there for details. One can summarize the result in fig. 11, which gives histograms of observed charged multiplicity n_{ch}^{obs} for different n_{γ}^{obs} , measured in the pseudorapidity range $\eta > 2$ (or $\eta < -2$) chosen to reproduce the sensitive range of the emulsion chamber detector. Analysis of the Centauro events described in the literature suggested that these should have at least 30-40 charged secondaries and a number of secondary photons consistent with zero. Such events would populate the dashed region of fig. 11, and no cases are seen amongst 3600 minimum bias events.

Fig. 11 : Distribution of n_{ch}^{obs} ($|\eta| > 2$) as as obtained by UA5 experiment at CERN Collider.

(*) A search has also been carried out by the UA1 Collaboration, but this and other results of UA1 were to be reported elsewhere at the Conference.

This negative result may not be too surprising since the CERN $p\bar{p}$ Collider has an equivalent laboratory energy $E_0 = 155$ TeV, whereas the 5 Centauros reported had observed ΣE_γ in the range 300-400 TeV, corresponding to a mean $E_0 \sim 1700$ TeV. Could there be a threshold over the range 155-1700 TeV i.e. $\sqrt{s} = 540$ -1800 GeV?

To try and shed light on this possibility the integral energy spectrum [20] of all families, known to be of the form (writing $E = \Sigma E_\gamma$)

$$N(> E) = cE^{-1.34}, \quad (E \geq 100 \text{ TeV}),$$

has been used, together with the energy of each of the events counted in table 2. The efficiency for finding such families is $\sim 100\%$. The result is presented in fig. 12 as the fraction of all events that these unusual events, taken together, would represent as a function of primary laboratory energy. Several important points can be made:

Fig. 12 : Estimate of fraction of unusual events from Brazil-Japan cosmic ray data compared with UA5 limit as a function of laboratory energy. The curve is merely to guide the eye.

1. No unusual events have been reported amongst the 196 C-jet events of the Brazil-Japan Collaboration, representing a limit of $\sim 5 \cdot 10^{-3}$ for $\langle E_0 \rangle \sim 80$ TeV.
2. With the same detector, the proportion of unusual events seen amongst atmospheric families seems to be rising from $\sim 7\%$ to perhaps $\sim 40\%$ over the range of E_0 from 300 to 3000 TeV. It is important to note that the technique of scanning X-ray plates for these atmospheric families means that Centauros could not have been found below 300 TeV.

3. The UA5 result would imply a fairly steep threshold above present Collider energy if Centauros are produced.

The question of the existence of such unusual events is of considerable importance for hadron physics. Up to $\sqrt{s} = 540$ GeV there are no apparent inconsistencies between cosmic ray and Collider data. Almost doubling the CERN Collider energy to $\sqrt{s} = 900$ GeV, as has been suggested [23], should yield unusual events at the 5-10% level if fig. 12 is to be believed, and so settle the question in the near future. Eventually the 2 TeV Tevatron Collider ($E_0 = 2130$ TeV) is likely to give the answer.

A variety of other explanations for the Centauro phenomenon have been given [24], [25], for example suggesting that a collision of a heavy nucleus such as Fe with $E_0 \gtrsim 100$ -1000 TeV has formed a metastable colourless cluster of quarks, a "glob", which could have penetrated ~ 500 g cm⁻² of atmosphere down to mountain level and decayed, preferably into baryons/antibaryons, above the detector. The observed fraction of unusual events would require a heavy component at the $\sim 10\%$ level, with important astrophysical implications.

Such quark matter could be produced in high energy heavy ion collisions. Could it not be produced observably in $p\bar{p}$ Colliders? There appears to be a strong case for raising the energy of hadron-hadron colliders to search for such phenomena.

6. CONCLUSION

This comparison of latest accelerator data with cosmic ray data is summarized in table 3.

Acknowledgements

I am grateful to Professor Hasegawa for illuminating discussions concerning the cosmic ray data from the Brazil-Japan Collaboration. It is a pleasure to thank my colleagues in UA5 for their advice, help and encouragement.

TABLE 1

UA5 Experiment: Summary of estimates of average particle multiplicities at $\sqrt{s} = 540$ GeV

	Type	Mean No. ($ \eta < 5$)
	$\pi^{\pm}$	20.2
	π^0	10.1
	η	3.5
	$K^{\pm}$	2.5
	$K^0/\bar{K}^0$	2.7
	$p/\bar{p}$	1.5
	$n/\bar{n}$	1.5
	$\Lambda/\bar{\Lambda}$	0.5
	$\Sigma^{\pm}/\bar{\Sigma}^{\pm}$	0.25
	Total $ \eta < 5$	42.7
Monte-Carlo estimate	$ \eta > 5$	3 (of which 2 are leading baryon/antibaryon)

$$\frac{K}{\text{all}} \sim 12\%$$

$$\frac{B/\bar{B}}{\text{all}} \sim 9\%$$

TABLE 2

Unusual event species reported [20] in cosmic ray atmospheric families
(Brazil-Japan Mt Chacaltaya emulsion chamber experiment)

Type	N_{hadrons}	$\langle p(\gamma) \rangle$ (MeV/c)	No. cases observed	Other features
Centauero	100 ± 20	0.35 ± 0.10	5	$n_{\gamma} \sim 0$
mini-Centauero	15 ± 2	0.35 ± 0.10	13	$n_{\gamma} \sim 0$
Chiron	16 ± 4	2.0 ± 0.5	14	see ref. [21]
Geminion	2	2.0 ± 0.3	21	

TABLE 3

Topic	CERN $p\bar{p}$ Collider ($\sqrt{s} = 540$ GeV)	Cosmic ray experiments (E_0 is incident primary laboratory energy)
σ_{tot}	prelim. result 66 ± 7 mb	estimated 70 ± 10 mb at $\sqrt{s} = 540$ from A-jets
Scaling Violations	central region $\frac{1}{\sigma} \frac{d\sigma}{d\eta} \sim \ln s$ or $s^{0.1}$. fragmentation region possibly $\frac{E}{\sigma} \frac{d^3\sigma}{dp^3} = \left(\frac{s}{s_0}\right)^\alpha F\left[x\left(\frac{s}{s_0}\right)^\alpha, p_T\right]$ with $\alpha \sim 0.1 - 0.2$	Implications for modelling cascades and primary composition. Shower maxima gave $\alpha = 0.2$ and EAS data $\alpha \sim 0.25$
$\langle n_{\text{ch}} \rangle$	$\sim a + b \ln s + c \ln^2 s$ up to Collider energy	Consistent with balloon and C-jet data. Steeper than $\ln^2 s$ above $E_0 \sim 1000$ TeV?
Transverse momentum	$\langle p_T \rangle \sim 400$ MeV/c for pions, higher for K's and baryons	$\langle p_T \rangle$ increasing rapidly with energy and with multiplicity (C-jets).
Particle production	Increase in fraction of K's and baryons from ISR to Collider	Confirms trend of C/N. Does $\frac{C}{N} \rightarrow 1$, suggesting dominant $B\bar{B}$ production?
Unusual Events	Centauros, < 1 in 3600 minimum bias events Conclusion: need higher energy (CERN Collider, Fermilab Tevatron Collider)	Unusual events at $\sim 10\%$ level for $E_0 \gtrsim 300$ TeV Globs? Heavy primaries?

REFERENCES

- [1] T.K. Gaisser and G.B. Yodh, Ann. Rev. Nucl. Sc. (1980) 475;
T.K. Gaisser, Cosmic rays and particle physics, Comments on nuclear and particle physics (to be published).
- [2] R. Battiston et al., UA4 Collaboration, CERN/EP 82-111, 21 July 1982.
- [3] S.C. Tonwar, J. Phys. G, : Nucl. Phys. 5 (1979) L 193.
- [4] U. Amaldi et al., Phys. Lett. 66B (1977) 390;
U. Amaldi et al., Nucl. Phys. B145 (1978) 367.
- [5] T.K. Gaisser, Proc. Conf. on Proton-Antiproton Collider Physics 1981, p. 571.
- [6] K. Alpgard et al., Phys. Lett. 107B (1981) 310
- [7] J. Wdowczyk and A.W. Wolfendale, Nuovo Cimento 54A (1979) 433.
- [8] J. Wdowczyk, Proc. Int. Seminar on Cosmic Ray Cascades, Sofia 1980, p. 185;
J. Wdowczyk and A.W. Wolfendale, Proc. Conf. on Proton-Antiproton Collider Physics 1981, p. 578.
- [9] A.J. Rossi et al., Nucl. Phys. B84 (1975) 269.
- [10] G. Arnison et al., UA1 Collaboration, Submitted to the Paris Conference.
- [11] M. Banner et al., UA2 Collaboration, Submitted to the Paris Conference.
- [12] A.R. Weidberg, Ph. D. Thesis, University of Cambridge, 1982.
- [13] K. Alpgard et al., Phys. Lett. B115 (1982) 65.
- [14] D.R. Ward, Proc. "Physics in Collision II", June 1982, Stockholm.
- [15] S. Tasaka et al., Univ. of Tokyo, Inst. of Cosmic Ray Research preprint, ICR 93-81-9.
- [16] N. Yamdagni, Proc. "Physics in Collision II", June 1982, Stockholm.
- [17] P. Carlson, Contribution to the Paris Conference, July 1982.
- [18] T.K. Gaisser and P. Rudolf, J. Phys. G.: Nucl. Phys. 2 (1976) 781.
- [19] R.H. Vatcha and B.V. Sreekantan, J. Phys. A.: Math., Nucl., Gen 6 (1973) 1050, 1067, 1078.
- [20] C.M.G. Lattes, Y. Fujimoto and S. Hasegawa, Phys. Rep. C65 (1980) 151.
- [21] J. Chinellato et al., "Chirons", paper to the Paris Conference, July 1982.
- [22] K. Alpgard et al., Phys. Lett. B115 (1982) 71.
- [23] J.G. Rushbrooke, CERN/EP 82-6, January 1982.
- [24] J.D. Bjorken and L. McLerran, Cosmic Rays and Particle Fields 1978, ed. T.K. Gaisser, (AIP New York 1979), D. Sutherland ibid;
J.D. Bjorken and L. McLerran, Phys. Rev. D20 (1979) 2353.
- [25] F. Halzen and H.C. Liu, Phys. Rev. Lett. 48 (1982) 771.