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KNO SCALING VIOLATIONS AND THE APPEARANCE
OF THE THREE GLUON COUPLING AT THE COLLIDER

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KNO scaling violations are discussed in a soft gluon bremsstrahlung model for particle production with quarks as well as gluons as their sources. Both ISR and recent collider data can be reasonably accounted for in this scheme.

The problem of understanding the shape of the hadronic multiplicity distribution and of its approximate scaling in the variable $z = n/\langle n \rangle$ still represents an outstanding question in strong interaction physics. In 1972 Koba, Nielsen and Olesen [1] predicted, on the basis of Feynman scaling and the approximate logarithmic growth of the mean multiplicity, $\langle n(s) \rangle \approx \ln s$, that the function

$$\Psi(z,s) = \langle n \rangle \sigma_n(s) \Big/ \sum_n \sigma_n$$

should be just a function of z, hence that its shape remain approximately constant with changes in energy. As is well known, this prediction has been found to be approximately true from $\sqrt{s} = 1.5$ GeV up to the ISR energy $\sqrt{s} = 63$ GeV [2]. Present measurements of the multiplicity distribution at the CERN proton–antiproton collider [3], have rekindled the interest in this problem. Indeed, the shape of the KNO function has been obtained in a variety of models with rather different theoretical inputs, for instance the uncorrelated cluster model of de Groot [4], geometric models [5], quark parton model [6], dual parton model [7,8], the three fireball model [9], stochastic-dynamical model [10] and QCD models [11,12]. Recently, the UA5 collaboration has reported violations of KNO scaling in the hadronic multiplicity distribution at $\sqrt{s} = 540$ GeV [13]. It appears that at large multiplicity, $n \simeq 2-3\langle n \rangle$, there is an excess of events over the asymptotic KNO fit at lower energies. Although the fraction of "abnormal" events is relatively small, the effect is very conspicuous when the higher moments of the KNO function are compared at different energies. From $\sqrt{s} = 1.5$ GeV up to ISR energies, the moments are approximately constant [13], thus indicating that the shape of the curve does not change, i.e. that KNO scaling holds. However after the ISR energies, the higher moments, which are more sensitive to the larger multiplicity region, drastically change. This might indicate a new production mechanism which becomes significant at the collider energy and which is characterized by a higher mean multiplicity. This hypothesis

is consistent with the discrepancy between the value of $\langle n(s) \rangle$ observed at $\sqrt{s}$ = 540 GeV and the value extrapolated from lower energy data using the best fit [14]

$$\langle n(s) \rangle = a + b \ln s + c(\ln s)^2, \tag{1}$$

with a = -0.25 ± 0.11, b = 0.94 ± 0.05, c = 0.090 ± 0.004. As is well known, the extrapolated curve lies lower than the collider value, $\langle n(s) \rangle$ = 29.1 for the UA5 collaboration [13], although the data do not completely rule out the behaviour given by eq. (1).

In this paper we suggest that the new mechanism is related to the appearance of gluon initiated processes, which were quite negligible in the ISR range but which start showing up at the collider, most noticeably in jet production. Indeed, there are three observations, concerning jet production, which are relevant to this discussion: (i) at the CERN collider the energy is high enough to allow for hard scattering between many low-x partons, leading to the production of mini-jets, i.e. jets around and below the lowest detectable threshold, (ii) at low x the dominant QCD subprocess in jet production is gluon–gluon scattering, (iii) measurements by the UA1 collaboration show that the multiplicity of the background accompanying the jets, what has been called the "jet floor" in a multiplicity versus rapidity plot, is more than twice the minimum bias multiplicity and is independent of the transverse energy of the trigger jet, remaining high ($\simeq 2\langle n(s) \rangle$) down to rather low values of the trigger [15].

We shall now study the hypothesis of a two component model of multiparticle production, one related to quark initiated processes and characterized by a mean multiplicity $\langle n_q(s) \rangle$ and one related to gluon processes, with mean multiplicity $\langle n_g(s) \rangle$. In bremsstrahlung models, the ratio of the two values is given by

$$\langle n_q(s) \rangle / \langle n_g(s) \rangle \simeq c_F/c_A = \tfrac{4}{9},$$

where c_F and c_A are the colour factors associated with gluon emission from a quark or from a gluon.

In a previous paper [12], we described the hadronic multiplicity distribution in the central region as arising from a mechanism of soft gluon bremsstrahlung from the interacting partons. By summing over the soft gluon distributions and averaging over the hadronic matter coordinates, we had obtained

the following expression for the KNO function:

$$\Psi(z,s) = \langle n(s) \rangle \sigma(n,s)/\sigma_{inel}(s)$$

$$= \beta \int \frac{dt}{2\pi} \exp\left(i\beta zt - \beta \int_0^1 \frac{dk}{k} (1 - e^{ikt}) \right), \tag{2}$$

with $z = n/\langle n \rangle$ and where β is a measure — on the average — of the QCD soft radiation spectrum. The shape of the KNO function is completely determined by the spectrum β. Thus, if we treat β as a parameter, we can obtain the shape at lower energies and, changing β, at higher energies. Let the moments of the KNO function be defined as

$$C_k = \langle z^k \rangle = \int z^k \Psi(z,s) \, dz.$$

Then, the folloqing expressions can be easily obtained through successive partial integrations, from eq. (2):

$$\langle z^2 \rangle = 1 + 1/2\beta, \tag{3a}$$

$$\langle z^3 \rangle = 1 + 3/2\beta + 1/3\beta^2, \tag{3b}$$

$$\langle z^4 \rangle = 1 + 3/\beta + 25/12\beta^2 + 1/4\beta^3, \tag{3c}$$

$$\langle z^5 \rangle = 1 + 5/\beta + 95/12\beta^2 + 35/12\beta^3 + 1/5\beta^4. \tag{3d}$$

Fixing the value of β from C_2, we obtain the values shown in table 1 for the moments at lower energy, i.e. up to $\sqrt{s}$ = 63 GeV, and in table 2 for the moments at higher energies, i.e. at the CERN proton–antiproton collider.

The agreement between the experimental and the theoretical values for C_3, C_4 and C_5 points to the validity of the description of the multiplicity distribution in terms of a Fourier transform of an exponentiated bremsstrahlung spectrum of the type $(\beta/k) \, dk$. At the same time, we notice that the rise in the higher

Table 1

Theoretical values are obtained from eq. (3) fixing C_2 = 1.2 (β = 2.5). $\sqrt{s}$ = 63 GeV.

C_k	Model predictions	ISR data [14]
C_2	1.2 (fixed)	1.20 ± 0.01
C_3	1.653	1.67 ± 0.03
C_4	2.55	2.60 ± 0.08
C_5	4.46	4.43 ± 0.20

Table 2
Theoretical values are obtained from eq. (3) fixing $C_2 = 1.31$
($\beta = 1.61$). Data are from the UA5 collaboration. $\sqrt{s} = 540$
GeV one-component model.

C_k	Model predictions	UA5 data [13]
C_2	1.31 (fixed)	$1.31 \pm 0.01 \pm 0.03$
C_3	2.06	$2.12 \pm 0.03 \pm 0.11$
C_4	3.72	$4.05 \pm 0.10 \pm 0.30$
C_5	7.87	$8.8 \pm 0.4 \pm 0.9$

moments from ISR to collider energies is quantitatively accounted for with a decrease in the effective β from $\beta_{ISR} = 2.5$ to $\beta_{collider} = 1.61$. The soft gluon model exposed in ref. [12], does not explain a decrease in the effective gluon spectrum. If there were no new production mechanisms between lower energies and the collider, β should grow, albeit slowly, $\approx \ln \ln s$. Thus a decrease in the effective β must signal some new production mechanism (jets, mini-jets, multipartons [16], etc.) with a threshold around the ISR energy and with a smaller cross section and higher multiplicity. A simple two-component model which illustrates this idea and utilizes the soft gluon bremsstrahlung mechanism, gives the following KNO function:

$$\Psi(z,s) = \frac{P_0(z,s) + r(s)P_1(z,s)}{1 + r(s)} \int_{-\infty}^{\infty} \frac{dt}{2\pi} e^{izt} \frac{1}{1+r}$$

$$\times \left[\exp\left(-\beta_0 \int_0^{\langle n_0 \rangle / \beta_0 \langle n \rangle} \frac{dk}{k} (1 - e^{-ikt}) \right) \right.$$

$$\left. + r(s) \exp\left(-\beta_1 \int_0^{\langle n_1 \rangle / \beta_1 \langle n \rangle} \frac{dk}{k} (1 - e^{-ikt}) \right) \right], \quad (4)$$

where

$$r(s) = \sigma_1(s)/\sigma_0(s),$$

with σ_0 and σ_1 the cross sections for the two different production processes, $\sigma_1 \simeq 0$ up to ISR energies. The two distributions $P_0(z,s)$ and $P_1(z,s)$ are the appropriate QCD radiation functions which "dress" the interacting partons with a cloud of soft gluons and whose respective β factors and fraction of total multiplicity $\langle n_{0,1} \rangle / \langle n \rangle$, are characteristic of the specific production process. β is proportional to α_s and to the colour factor c_F or c_A according as to whether the (exponentiated) soft gluons have been emitted by a quark or by a gluon leg.

From eq. (4), we obtain

$$\langle n(s) \rangle = [\langle n_0(s) \rangle + r(s)\langle n_1(s) \rangle] / [1 + r(s)], \quad (5)$$

where, according to the previous discussion,

$$\langle n_1(s) \rangle / \langle n_0(s) \rangle \simeq c_A/c_F \simeq \beta_1/\beta_0. \quad (6)$$

Making use of eq. (6), we can rewrite eq. (4), as follows:

$$\Psi(z,s) = \bar{\beta} \int_{-\infty}^{\infty} \frac{d\tau}{2\pi} e^{i\bar{\beta}z\tau} \frac{1}{1+r}$$

$$\times \left[\exp\left(-\beta_0 \int_0^1 \frac{dk}{k} (1 - e^{-ik\tau}) \right) \right.$$

$$\left. + r(s) \exp\left(-\beta_1 \int_0^1 \frac{dk}{k} (1 - e^{-ik\tau}) \right) \right], \quad (7)$$

with

$$\bar{\beta}/\langle n \rangle \simeq \beta_0/\langle n_0 \rangle \simeq \beta_1/\langle n_1 \rangle.$$

We now turn to compute C_k for the two-component model. The results are shown in table 3. To obtain the values shown in table 3, we have scaled β_0 according to the asymptotic freedom formula

$$\beta_0(\sqrt{s} = 540 \text{ GeV})$$

$$= \beta_0(\sqrt{s} = 63 \text{ GeV}) \frac{\ln \ln(540/\Lambda)^2}{\ln \ln(63/\Lambda)^2} \simeq 2.78,$$

and have used the approximate relation given by eq. (6), and set $\Lambda = 100$ MeV. The table shows that this two component model can quantitatively account for the observed scaling violations in the collider region. Moreover, the slight excess in the observed mean multiplicity above the asymptotic IRS fit, eq. (1), is also explained in this picture in the following way. The non-diffractive data below the collider energy have

Table 3
Two-component model $r = 0.12$.

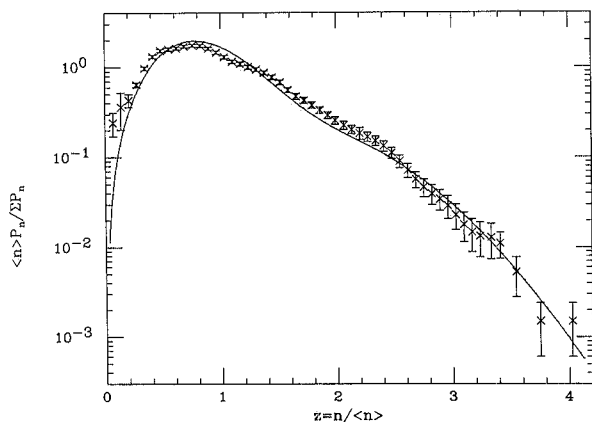| C_k	Model predictions	UA5 data [13]
C_2	1.275	$1.31 \pm 0.01 \pm 0.03$
C_3	2.014	$2.12 \pm 0.03 \pm 0.11$
C_4	3.822	$4.05 \pm 0.10 \pm 0.30$
C_5	8.524	$8.8 \pm 0.4 \pm 0.9$

Fig. 1. Corrected multiplicity data from 1981 and 1982 run at the CERN SppS collider. Data are from the UA5 Collaboration [13]. The continuous curve is obtained from the two-component soft QCD bremsstrahlung model described in the text.

been parametrized as in eq. (1). At the collider energy ($\sqrt{s}$ = 540 GeV) this fit gives $\langle n_0 \rangle$ = 25.83. For r = 0.12, which is the value used in computing table 3, we find from eq. (5)

$$\langle n \rangle = 29.3,$$

to be compared with the experimental value 29.1 $\pm$ 0.3 $\pm$ 0.9 obtained by the UA5 collaboration [13].

Using the above parameters, β_0 = 2.78, β_1 = $\frac{9}{4}\beta_0$ and r = 0.12, we show in fig. 1 a plot of $2\Psi(z)$ versus z and its comparison with the recent UA5 data. Clearly, the fit could be improved by freely varying the parameters, but then the one-component model would be just as acceptable as the present one. On the other hand, the approximate agreement between the data and the theoretical curve may lead the way to correctly incorporate scaling violations in QCD models. It should also be noted that very similar results have been obtained in the dual parton model [17].

The conclusion we can draw from this simple picture is that indeed a new production mechanism is operative, with an average multiplicity which is (at least) a factor 2 higher and with an overall cross section which is $\approx \frac{1}{10}$ of the basic cross section. The phenomenological analysis presented here suggests this new component to be gluon initiated with the observed scaling violations due to the presence of the three gluon vertex.

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