Collective behaviour in nuclear interactions and shower development

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Abstract

In a high energy nucleus nucleus collision the intense color fields can increase the stopping power of the leading baryons. This effect could modify significantly the shower development and the muonic content of nucleus induced showers.

1. Introduction

In cosmic ray physics, it is usually assumed that the nucleus nucleus collision occurs as an independent combination of nucleon nucleon interactions. This approximation is useful in that allows to obtain scaling relations for shower properties like shower maximum and the muon content, which are approximately obeyed.

This approximation is not justified at high energies. A beam nucleon may interact several times with different target nucleons: this will invalidate the approximation trivially. A more interesting possibility would be the formation of new nuclear phases during the collision, like quark-gluon plasma. Indeed some evidence for a violation of mass scaling has already been observed at RHIC [2].

Here we will investigate the effects of collective behaviour on the development of high energy cosmic ray showers. Collective behaviour may affect shower development in two different ways. First, it is generally expected that any collective behaviour would reduce the total multiplicity due to shadowing. This would affect the shower development only if the multiplicity reduction can be carried over the whole cascade process [1,3]. Alternatively collective effects may affect the secondary particle spectrum, in particular in the large Feynman x region, thereby modifying the inelasticity of the collision. This may have important consequences in shower development as we will show below.

We will concentrate on this last possibility. It has been suggested recently by Mishustin and Kapusta [2] that in the central region at high energies strong chromo electric fields are formed. They will attract the forward and backward particles, reducing considerably the rapidity of the fast moving, leading, secondaries. For high energy collisions it is expected that this effect can increase the

pp. 1619–1622 ©2003 by Universal Academy Press, Inc.

inelasticity even for peripheral collisions.

2. Deceleration of fast particles

In the center of mass frame a nuclear collision can be viewed as two thin slab of nucleons colliding with each other. After the collision the two slabs will move fast and in the central region a strong coherent field may form. The back reaction of this field on the slabs will decelerate the slabs increasing the stopping power. The situation resembles the movement of charged capacitor plates on the electric field. This deceleration will continue until the field lines stretch so much that they decay into quark-antiquark pairs and gluons produced from the vacuum via the Schwinger mechanism, which will eventually neutralize the chromo electric fields.

The resulting slab will have a final gamma factor given by, see [2]

$$\gamma^* = \cosh y^* = \gamma_0 \left(1 - \frac{\tau_0}{\lambda}\left(v_0\sqrt{1+\frac{\tau_0^2}{4\lambda^2}} - \frac{\tau_0}{2\lambda}\right)\right), \tag{1}$$

where γ_0, v_0 are the original gamma factor and velocity of the slab and τ_0 is the time from the start of the collision up to the end of the acceleration process. λ is the characteristic deceleration length

$$\lambda = \frac{\epsilon\rho_0}{\varepsilon_f}\, l, \tag{2}$$

where ϵ is the initial energy per baryon, ε_f is the energy density of the chromo electric field, l is the slab thickness, and ρ_0 is the nuclear density. Following reference [2] we parameterize the energy density on the chromo electric field by

$$\varepsilon = \varepsilon_0 (\frac{s}{s_0})^{\alpha/2} (\frac{N_p N_t}{N_0^2})^{\beta}, \tag{3}$$

where $\alpha \sim 0.3$ given by the low-x structure function behaviour. s is the total center of mass energy squared and s_0 is a reference energy squared. $N_{p,t}$ is the participant nucleon density of projectile and target and $N_0 \sim 0.4$ fm^{-2}. The amount of stopping power depends on the initial energy and also on the impact parameter. It is expected that ε will be proportional to the number of binary parton collisions, which here is parameterized through the dependence on $N_{p,t}$. For uncorrelated collisions $\beta \sim 1$, while in the case of strong correlations (like those assumed in the percolation of strings) one expects $\beta \sim 0.5$

For central collisions in Au-Au at 65 GeV per nucleon one gets a final center of mass energy of 3.5 GeV per baryon. This could explain the strong stopping power already observed at RHIC [2].

3. Implementation and Results

We have implemented this increasing of the stopping power in Aires [4]. In a given nucleus air interactions, the impact parameter is chosen randomly and the stopping power is calculated according to eq. 1. The collision is generated with a conventional Monte Carlo generator (QGSJET and Sibyll are implemented in Aires). The energy, and momentum, of the leading particles obtained in the collision is reduced to match the stopping power predicted, and this energy taken is redistributed between the non leading particles. For the rest of the showering process the collisions are calculated normally, so that only the first nucleus nucleus collision is modified.

For very high energy, $E > 10^{17}$ eV, and small impact parameters $b < 6$ fm the inelasticity increase is so high that the first collision is indistinguishable from a proton air collision, in terms of inelasticity. This has the effect of modifying slightly the $X_{\max}$ of the shower and the total number of muons.

Although the average value of $X_{\max}$ does not change much, the distribution gets wider, mainly depending on the dependence of the strength of the elasticity suppression on the impact parameter. In fig. 1. we can see the correlation between the $X_{\max}$ and the impact parameter for collisions. At very low impact parameters this fields are large and the stopping power is large, making the shower develop faster. At very large impact parameter the effect of the field is irrelevant and the result with and without the modified stopping power is the same.

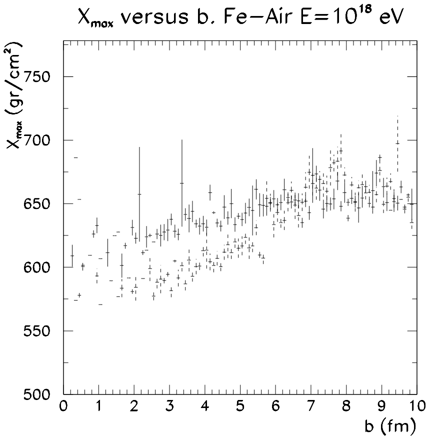

Fig. 1. Correlation between first interaction impact parameter, b, and shower maximum $X_{\max}$ for 10^{18} eV iron initiated showers for the QGSJET model (continuous points) and of stopping power enhancement (dashed points).

Finally in fig. 2. we show the muon number distribution at ground. Here a dramatic effect is observed with showers suffering from this effect or not, the number of muons will resemble those of a proton shower or a regular iron shower.

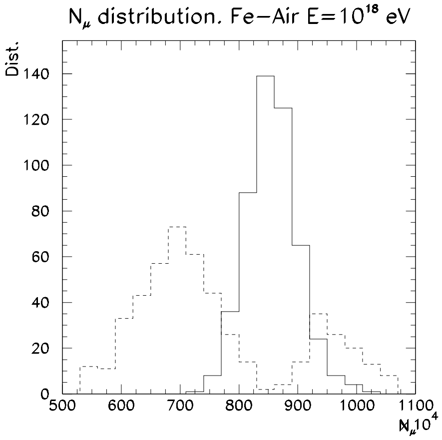

Fig. 2. Muon number distribution at ground for 10^{18} eV iron initiated showers without (continuous line) and with (dashed line) the effect discussed.

This effect may have important implications in the composition measurements and separation of proton induced from iron induced showers.

This work is supported by Xunta de Galicia (PGIDT00PXI20615PR), by CICYT (AEN99-0589-C02-02), and by MCYT (FPA 2001-3837). R.A.V. is supported by the "Ramón y Cajal" program. We thank the "Centro de Supercomputación de Galicia" (CESGA) for computer resources.

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