Application of Thermodynamical Description of Hadron Production at High Energies of EAS

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Abstract

Data from $p-p$ collision, e^+e^- annihilation and deep inelastic scattering are used to check the most popular microdynamic models and thermodynamic description of hadron production. The effect of different models for interpretation of EAS data is discussed in aspect of the chemical composition of primary cosmic rays.

1 Introduction

A pending problem in cosmic rays study at high energies is the interpretation of EAS data in aspect of the chemical composition of primaries. It depends essentially on the description of multihadron production. No uniform and satisfactory description is achieved, for high p_t production perturbative calculations are made, while in the case of low p_t hadronization there are used a lot of models which can not explain all data (Popova, 1997).

Here we present an alternative statistical description of the universal features of hadron production. It allows to derive a simple thermodynamic equation of hadron spectra which is easy to apply in EAS study.

2 Universal Features of Hadronization

First the universality of hadronization features has been observed by Zichichi group (Basile et al, 1980). They show that all momentum spectra from $p-p$ collisions, e^+e^- annihilation and deep inelastic scattering (DIS) are similar when the effect of leading particle is taken into account.

Apparent widening of $x-$ spectra and their shift closer to $x=0$ is seen with increasing energy. Starting from $10GeV$ hadron spectra in all experiments reveal a clear trend to Boltzmann type distribution.

Here we present a simple formula that could express the universal features of hadron production in accelerator experiments and explains the gross features of EAS up to the highest cosmic ray energies.

3 Thermodynamic Description of Hadronization Processes

In early FNAL and ISR experiments an exponential function has been used for approximation of meson spectra (on Feynman variable)

$$\frac{2Ed\sigma}{\sqrt{s}\sigma_{in}dx_F} = A\exp(-Bx_F) \tag{1}$$

If one neglects $\frac{4(m^2+p_t^2)}{s}$ in respect to x_F^2 at high energies (1) could be transformed in Boltzmann type energy distribution

$$probability = \frac{1}{E}\exp(-\beta E) \tag{2}$$

It is reasonable to expect Boltzmann statistics for many hadrons. More precisely, it means that the probability for a state of energy E is $P = f(E)exp(-\beta E)$, where $\beta = 1/<E>$. The density of microstates $f(E)$ in our case is $f(E) = 1/E$ (in unisotropic phase space corresponding to the rapidity distributions of hadrons). One could qualify Boltzmann statistics by the standard method since P_{f_1}/P_{f_2} is a pure exponent independent of $f(E)$. It means that the energy distribution of hadrons 2 is invariant in respect to the statistical scaling variable $x_s = E/ < E >$.

Assuming power law dependence of multiplicity, $< n >\sim (s/s_0)^{\alpha/2}$, a thermodynamic equation of state $< E >\sim s^{(1-\alpha)/2}$ is derived (Popova, 1997). Using these relations one can replace x_s by Wdowczyk and Walfendale variable $x_{WW} = x_F(s/s_0)^{\alpha/2}$. Thus, the longitudinal momentum spectrum of hadrons (1) turns to

$$\frac{x_F d\sigma}{\sigma_{in} dx_F} = A(s/s_0)^{\alpha/2} \exp[-B(s/s_0)^{\alpha/2} x_F] \tag{3}$$

This formula is a simplification of a general thermodynamical equation (Buccella & Popova, 1999) which is convenient for the present analysis.

4 Model Fit to Accelerator Data

First, the value of statistical parameter α is estimated on the basis of $p-p$ (Alner et al, 19985), (Slattery, 1973), e^+e^- (Abe et al, 1994), (Althoff et al, 1984), (Zheng et al, 1990), and DIS (Basile et al, 1988) data for the average number of charged mesons. We find that the empirical formula $< n_{ch} >= -7 + 7.2(\sqrt{s}/\sqrt{s_0})^{\alpha}$, $(s_0 = 1GeV)$ derived in the range of SPS and TEVATRON energies (Abe et al, 1994) for $p-p$ collisions is valid at lower ISR energies with the same value of $\alpha = 0.254$. A similar formula $< n_{ch} >= -7.3 + 8.586(\sqrt{s}/\sqrt{s_0})^{0.254}$ fits e^+e^- and DIS data. It implies a constant value of the average coefficient of inelasticity in proton collisions, $k_{in}^{p-p} = 0.5$, in the interval from $\sqrt{s} = 10GeV$ to $900GeV$ being confirmed at higher energies by cosmic ray data (Barroso et al, 1997). The parameter α keeps a constant value in all the processes and in the entire energy interval.

Second, we define $\alpha = 0.30 \pm 0.04$ by using the equation of state (avoiding assumptions for k_{in}) on the basis of e^+e^- data (Althoff et al, 1984) by the method of maximum likelihood (m.m.l.).

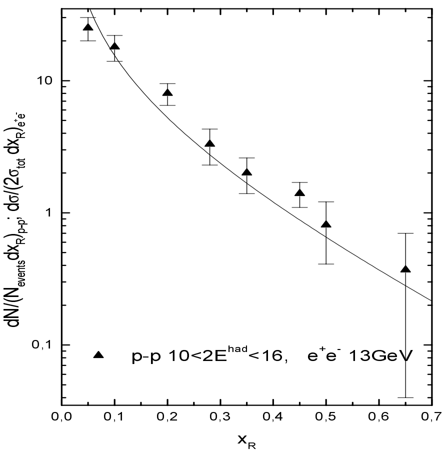
Third, the differential cross sections in vicinity of $x = 0$ for $p-p$ (Capiluppi et al, 1974) and e^+e^- collisions (Basile et al, 1988) have been used to estimate α from 10 to the highest ISR energy, $63GeV$. Applying m.m.l. it was obtained $\alpha = 0.26$.

At last, we apply the same method and determine $A = 1.764$ and $B = 3$ in (3) using x_R-spectra ($x_R = E^h/E_{tot}$) in e^+e^- and $p-p$ collisions (Basile et al, 1988), (Capiluppi et al, 1974) in the entire range of ISR energies. The compiled data from annihilation of electrons and positrons at $\sqrt{s} = 13GeV$ with p-p collisions for $10 < 2E_{tot} < 16GeV$ are shown on Fig.1. Similar compilation of data for $\sqrt{s} = 27.4 \div 31.6GeV$ and $28 < 2E_{tot} < 32GeV$ is presented on Fig.2.

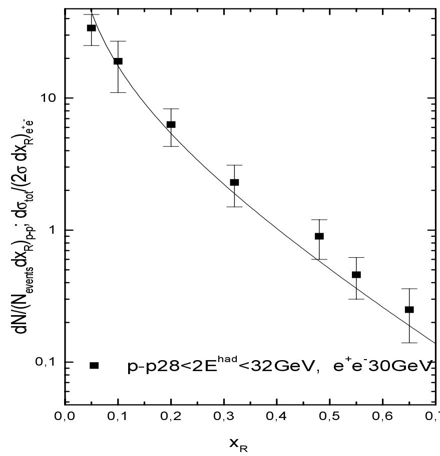
In the both figures the compiled data are compared with a thermodynamic distribution according (3). Remarkable agreement with data not only for soft but also for hard hadron production is achieved up to the highest ISR energy (Fig.3). It can not be obtained by using QGSM and PYTHIA with mini jet production (Anselmo et al, 1992). At high energies these models predict more hadrons near $x_F = 0$ and harder spectra in the range of large x_F (see Fig.4). As a result k_{in} increases from 0.48 at $\sqrt{s} = 53GeV$ to 0.6 at 10^4GeV (Bellandi et al, 1997), in contradiction with cosmic ray data (Barroso et al, 1997).

5 Discussion on the Effect of the Models

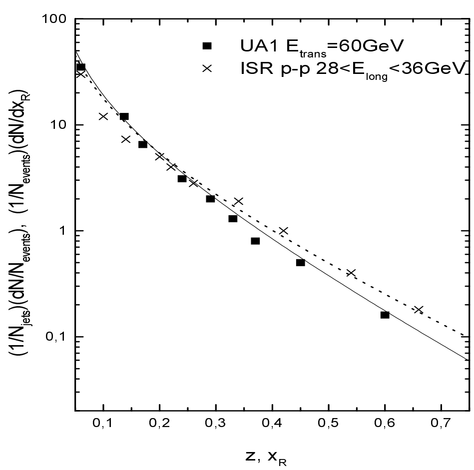
Primary particle mass could be overestimated when experimental data for the gross features of EAS (the depth of shower maximum and the muon to electron ratio, hadron spectra) are compared with simulation results based on models with slow rise of multiplicity (SYBILL) (Popova, 1997). Better fit is



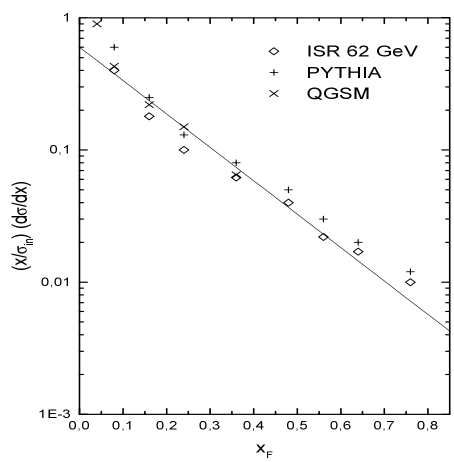
Fugure 1: Comparison of statistical model distribution with inclusive single particle momentum distribution in the interval of hadronizing energy 10 GeV$\leq$ 2 E$^{had}\leq$ 16 GeV



Fugure 2: Comparison of statistical model distribution with inclusive single particle momentum distribution in the interval of hadronizing energy 28 GeV$\leq$ 2 E$^{had}\leq$ 32 GeV



Fugure 3: Comparison of Eq.3 (dot line $\sqrt{s}$=34 GeV full line $\sqrt{s}$=60 GeV) with accelerator data at equivalent $\sqrt{(q_{tot}^{had})^2}$ of the longitudinal momentum distribution in pp(ISR low p_t), pp (UA1 high p_t) and e^+e^- (PETRA)



Fugure 4: Comparison of thermodynamic Eq.3 (full line), PYTHIA(+) and QGSM(x) predictions with ISR data at $\sqrt{s}$=62 GeV

achieved by QGSM with mini jet production. However,an apparent contradiction between the shape of predicted and measured hadron spectra is found due to the overestimated production of hadrons near $x = 0$. As a result, to get agreement with the observed hadron spectra (Kampert et al. 1998), one should assume rather heavy mass composition of primary cosmic rays.

The gross features of EAS can be explained by means of the thermodynamic description of hadron production with $\alpha = 0.26$ if one assumes "iron" enrichment (becoming 65% towards 35%) between $10^5 GeV$ and $10^9 GeV$, in agreement with direct balloon observation, and increasing contribution of protons (about 56% towards 44% irons) in the range of giant showers.

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