Production of fast hadron leader by QCD process

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Abstract

An algorithm of Monte Carlo code for the production of fast hadron
leader in the proton-(anti)proton interaction by QCD process is dis-
cussed.
1 Introduction

At present one of a few most interesting questions is theoretical explanation of the experimental data for hevi-ion collisions. Therefore any alternative explanations of phenomena which could be interpreted as a signature of new physics such as quark-gluon plasma deserve careful elaboration. In the Ref.[1] we place for consideration a new hadronization process based on the cascade decay of rotating strings into hadron states. As it had marked in Ref.[1], long ago it have been already known fact that linearity of Regge trajectory could be explained by supposition that the hadron is a rigid straight rotating string[2]. If the Regge trajectories are unlimited, it gives a chance to consider the rotating strings having large masses too. There is no a complete theory for decay of rotating string, and so we have been constructing a Monte Carlo parametrization for this process[3]. In our cascade string breaking model the process of breaking of mother string into two daughter strings is repeated. The string rotation leads to correlation between the transverse momentum of daughter string and the mass of mother string. Therefore the average transverse momentum of secondary hadrons, produced by decays of rotating strings, grows with the mass of primary string (see Fig.5 in [1] and Fig.10 in [2]), and so the fluctuations of the masses of primary strings (in the model for proton-antiproton collisions) lead to explanation of experimental $P_T$ distribution of secondaries up to $p_T = 4$ Gev at 1800 GeV for proton-antiproton interactions (see Fig.13 in Ref.[3] where there are preliminary results).

For heavy-ion reactions there is widely known theoretical prediction that hard parton-parton interaction and formation of quark-gluon plasma are two sources of secondary particles with high transverse momenta. We hope that our preliminary calculations shown that the string rotation is also the source of high transverse momenta, and so the string rotation can lead to effect which is the very same as vapourization of drops of quark-gluon plasma. Therefore this result can’t be ignored in the realistic calculations of high energy reactions.

The starting point for nucleus-nucleus interactions is nucleon-nucleon interaction, and so we should be constructed proton-(anti)proton Monte Carlo model for high energy interaction where, according to cosmic ray experimental data[4, 5, 6], for interaction at energy $E_{Lab} > 10^{16}$ eV there is a group of very fast hadron leaders, which have not till now the satisfactory theoretical
For the modelling calculations of production of the fast hadron leaders at high-energy proton-(anti)proton interactions we suppose to use a parton model idea that (anti)proton is a collection of quasi-free partons which share its momentum, and that the partons carry negligible transverse momentum. In many models of multiparticle production (see, for example, [7, 8]) in the first approximation the parton structure of proton is a color-triplet quark and an antitriplet diquark, but in the standard parton model it is many (anti)quarks and gluons. Therefore in our calculations we should be taken into account that each incoming hadron is composite object, consisting of constituent (anti)(di)quarks which have possibility to dissociate into quasi-free (anti)(di)quarks and gluons (constituent partons). This process can lead to formation of excited partons by interaction of partons of target and projectile (for example, a gluon of target can be "absorbed" by (anti)(di)quark of projectile). Invariant mass of excited (anti)(di)quark can be chosen as the characteristic of excitation. If this excitation is sufficient to starting of QCD cascade, it should be calculated. If this excitation is under threshold of QCD cascade, we can generate "decay" of excited parton into non-excited parton and hadron leader (see Fig.1a). Therefore for the mass of excited parton there is a threshold which is parameter of modelling and which is a minimal invariant mass sufficient to start of QCD cascade, and simultaneously it may be a maximal invariant mass of excited parton sufficient to start of hadron leader production. However, it should be marked, there is not any restriction to production of the fast hadron leader by excited parton with invariant mass greater of threshold sufficient to start of QCD cascade which has priority at high invariant mass of excited parton. Of course, fast hadron leader can be produced also after QCD cascade when invariant mass of cascading parton becomes less than the value of threshold.

If (constituent) (di)quark and anti(di)quark can’t be decayed, they stretch the primary string which is decayed into secondary hadrons according to the algorithm described in [1].

\[^{1}\] In the frame of our model a qualitative explanation for cosmic ray experimental data about alignment of hadron leaders can be given by additional physics connected with the fast hadron leader production described here and with cascade decay of rotating strings into hadron states. However, it requires detailed description which overstep the limits of the theme of presented paper. Therefore the details will be given elsewhere.

\[^{2}\] Only valence quarks are considered.
2 Formation of excited partons

An algorithm of Monte Carlo (MC) code of formation of excited partons is described in this Section. In our model (as in Ref.[10]) constituent quark of proton can dissociate into quasi-free quark and gluon which has the part \( y \) of four-momentum of constituent quark. The probability of dissociation into interval \( dy \) is formally determined by perturbative formula (see Appendix 1 where the variable \( z = 1 - y \))

\[
\frac{dW}{dy} = \alpha \frac{1 + (1 - y)^2}{y} \quad \text{at} \quad y_{\text{min}} < y < 1 , \quad (1)
\]

and integral probability is determined by the formula

\[
W = \alpha \int_{y_{\text{min}}}^{1} \frac{1 + (1 - y)^2}{y} \quad \text{at} \quad y_{\text{min}} < y < 1 , \quad (2)
\]

where

\[
\alpha = \left[ \int_{y_1}^{1} \frac{1 + (1 - y)^2}{y} \right]^{-1} , \quad (3)
\]

\[
y_{\text{min}} = y_1 \quad \text{at} \quad y_1 > y_0 = \left( \frac{\varepsilon_0}{x E} \right) , \quad (4)
\]

\[
y_{\text{min}} = y_0 \quad \text{at} \quad y_1 < y_0 < 1 , \quad (5)
\]

\[
y_{\text{min}} = 1 \quad \text{at} \quad 1 < y_0 , \quad (6)
\]

\( \varepsilon_0 \) and \( y_1 \) are free parameters of modelling, \( x \) is part of four-momentum which is carried by constituent (anti)(di)quark before dissociation of it, \( E \) is the energy of (anti)proton in c.m.system of collising particles. For example, the values can be chosen as

\[
\varepsilon_0 \sim m_u \quad , \quad y_1 < 0.01 , \quad (7)
\]

where \( m_u = 0.34GeV \) is the mass of constituent \( u \)-quark. As one can see from eqs.(2)-(6), the probability of dissociation grows with energy \( x E \) of constituent quark.

The parts \( x \) and \( x' \) of four-momentum are determined by parton distribution function for the projectile and target. If (according to eq.(2)) there is the process of dissociation of constituent (anti)(di)quark into (anti)(di)quark

\[
\text{and }
\]
gluon, the gluon part \( y \) of four-momentum of constituent quark is generated by the formula

\[
r = \int_{y_{\text{min}}}^{y} \frac{1+(1-y)^2}{y} \, dy / \int_{y_{\text{min}}}^{1} \frac{1+(1-y)^2}{y} \, dy ,
\]

where \( r \) is uniformly distributed random number from the range (0,1). By analogy with eq.(8) the part \( y' \) for gluon from the target can be generated. In this case, in eq.(4) instead \( y_0 \) the value \( y'_0 = (\varepsilon_0 / x'E) \) should be calculated.

Let us now to consider an example for the formation of excited parton \( q'^* \) by interaction

\[
g + q'_c \rightarrow q'^* ,
\]

i.e. a gluon of target is ”absorbed” by antiquark of projectile at proton-antiproton collision\(^ 3\).

Before simulation of the subprocess (9), the probability of this process should be determined. Let \( \rho \) is density of current of protons to antiprotons and \( d^3 \rho \) is given at fixed flowers of constituents \( q_c \) and \( q'_c \) from the intervals \( dx, dx', dy \) provided that constituent antiquark \( \overline{q'}_c \) is not dissociated; and let \( \sigma \) is cross-section of inelastic non-diffractive \( pp \) collisions, \( \sigma^*_q \) is cross-section of the subprocess (9), then the probability of the subprocess (9) is given by the formula

\[
W^*_q = \frac{d^3 \rho \sigma^*_q}{\rho d^3 \sigma} = \frac{\sigma^*_q}{\sigma} .
\]

In the eq.(10) it was taken into account that

\[
\frac{d^3 \rho}{\rho} = \frac{d^3 \sigma}{\sigma} .
\]

According to dimension of cross-section we can choose

\[
\sigma^*_q \propto \frac{1}{M^2_{q'}}
\]

for the invariant mass

\[
M^2_{q'} = (x^2 y^2 + x'^2) M^2 + 2 x y x' (E^2 + P^2)
\]

\(^3\)It should be marked, the subprocess \( q_c + \overline{q'}_c \rightarrow (q + g) + (q' + g') \rightarrow (q + \overline{q}) + (g + g') \rightarrow g'_1 + g'_2 \) can’t be a source to production of hadron leader.
which is under threshold sufficient to start of QCD cascade, or

\[ \sigma_q^* \propto \frac{\alpha_s(M_{q^*}^2)}{M_{q^*}^2} \]  \hspace{1cm} (14)

for the invariant mass sufficient to start of QCD cascade\footnote{In ref.\cite{10} there are examples of cross-sections for the more complicated subprocesses.}. In eqs.(12)-(14) \( M_{q^*} \) is invariant mass of excited antiquark \( q^* \) from (9) and \( P \) is the momentum of (anti)proton in c.m.system of collising particles, \( \alpha_s(M_{q^*}^2) \) is the strong coupling constant. However, the probability value should be at least restricted. Therefore for small invariant mass which is under threshold sufficient to start of QCD cascade, we can choose an approximation of probability for the process (9) as

\[ W_{q^*} \propto \frac{\beta^2}{M_{q^*}^2 + \beta^2} \]  \hspace{1cm} (15)

where \( \beta \) is free parameter of modelling.

The eqs.(2)-(8), (10), (13)-(15) are sufficient for the modelling of starting-point for QCD cascade or production of fast hadron leader.

\section{3 Fast hadron leaders}

Short distance QCD interaction leads to formation of excited (anti)(di)quark state with short life time which is less than time sufficient for the formation of long distance string. Therefore the process of ”decay” of excited (anti)(di)quark with invariant mass under threshold sufficient to start of QCD cascade, i.e. the process of fast hadron leader production (see Fig.1a) is before formation of string.

In Fig.1a it is shown a ”decay” of excited quark \( q^* \). Therefore this diagram is related with QCD diagram in Fig.1b where a quark \( q \) is carried the part of four-momentum \( z \) of excited quark \( q^* \) distributed (see Appendix 1) by the law

\[ f(z) \propto \frac{1 + z^2}{1 - z} \]  \hspace{1cm} (16)

Therefore in Fig.1a we can choose for the ”decay” of excited (anti)(di)quark \( q^* \) the same variable \( z \) and law (16) which has peak in the point \( z=1 \), i.e. hadron
$h$ is carried the part of four-momentum $z$ of excited (anti)(di)quark $q^*$ near by 1 , i.e. this hadron $h$ is fast. In the Fig.1a slow quark $q$ stretches the string which is decayed into secondary hadrons according to the algorithm described in [1]. Therefore in Fig.1a the hadron $h$ is fast leader.

In the frame of our model, each proton-(anti)proton interaction leads to production at least of one fast hadron leader which carries large part of energy of primary particle (see eq.(16)). This process is repeated at second interaction (in the atmosphere), and so, in our model, it can be understood an experimental phenomena that hadron leader has small dissipation of energy at interactions in the atmosphere[2].

Appendix 1

Let us remind of some results of QCD[11] which are important under construction of our model. We take a look at current of virtual photons $\gamma^*$ to quarks $q$ (Fig.2) at fixed c.m.energy $\sqrt{s}$. Let this current of virtual photons have uniform distribution in variable

$$z = \frac{Q^2}{s + Q^2},$$

(17)

where $Q^2$ is squared four-momentum of photon taken with opposite sign. Differential cross-section of the process given by Fig.2 is

$$d^2\sigma = \sigma_1 \gamma_2(p_T^2, z) \, dp_T^2 \, dz \quad \text{at} \quad -t \ll s,$$

(18)

where

$$\gamma_2 = \frac{\alpha_s}{2\pi} \frac{1}{p_T^2} \frac{4}{3} \frac{1 + z^2}{1 - z},$$

(19)

$\sigma_1$ is cross-section of the block 1 in Fig.2, $\alpha_s$ is the strong coupling constant, $p_T$ is gluon transverse momentum given relative to momentum vector of primary quark in c.m.s., $t$ is the squared difference between the momenta of primary quark and gluon (see Fig.2). It is important, at $-t \ll s$ an intermediate quark carries the part $z$ of four-momentum of primary quark in c.m.s.
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**Figure Captions**

**Fig.1**  
(a) The "decay" of excited parton $q^*$ into non-excited parton $q$ and hadron leader $h$.  
(b) QCD diagram for the decay of excited quark $q^*$ into quark $q$ and gluon $g$.

**Fig.2**  
One in a few diagrams of the process $\gamma^* q \rightarrow q g$.  


This figure "FIGURE1.GIF" is available in "GIF" format from:

http://arxiv.org/ps/hep-ph/9910548v1
This figure "FIGURE2.GIF" is available in "GIF" format from:

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