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# Effective Fire-Tube Model for Multiparticle Production in pp Collisions

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**Abstract** A simple phenomenological model for proton-proton collisions is proposed in view of its direct application to nucleus-nucleus high energy reactions. The formalism combines the formation of fire-balls via the space-time development of a non-perturbative fire-tube of excited vacuum, and the subsequent final hadron production through the decay of these fire-balls. Special attention has been paid to the treatment of the diffractive dissociation process in order to properly include leading particle effects. Results of this model are compared with experimental 19.6 GeV p-p data. The leading particle spectra is successfully reproduced in the present treatment.

## 1. INTRODUCTION

Recent developments of high energy heavy ion accelerator technology opened several fascinating perspectives in Nuclear Physics. One of the main objectives in this fiels is to observe the QCD phase transition of hadron matter to a quark-gluon plasma. If realized, it will constitute an almost direct confirmation of the theory of QCD.

In order to be able to perform theoretical studies on this subject, it is essential to clarify the dynamics of multi-particle production during the process of nucleus-nucleus collision.

The study of particle production in hadron-hadron collision processes has already a long history, and many theoretical models have been proposed[1-13]. It is interesting to note that one of the earliest of these models, the hydrodynamical approach, has been recently revived in the light of QCD concepts and the related quark-gluon structure of hadrons[14,15]. This is because the hydrodynamical treatment is

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one of few theoretical schemes which describe explicitly the space-time development of the multiple production mechanism. This constitutes the basic advantage of such an approach in the study of nucleus-nucleus collisions as compared to descriptions which deal only with asymptotic final states, i.e., those that use the S-matrix. The reason for this is that in a nucleus-nucleus collision tha many successive intranuclear collisions that take place are not amenable to a description based on the on-shell S-matrix.

Unfortunately the hydrodynamical model is usually too complex to be applied directly to reconstructing the whole process of a nucleus-nucleus collision on the basis of nucleon-nucleon collisions. One possible way to bypass this complexity is to regard the nucleus, as a whole, as a hydrodynamical object. However, even by doing so, it is still a complicated problem to include the nuclear finite size effects. More importantly, nuclear ground state correlations as well as associated fluctuation effects are lost in this kind of treatment.

Besides the hydrodynamical approach, there exists another type of model which describes the space-time development of hadron-hadron collisions. The phenomenological relativistic string model is such a type. The simplest version of the string model is the Yo-Yo model[1,2]. Although this model has less firm theoretical background, it has some large advantages for practical use.

First, it furnishes the way to simulate the process of multiple particle production, event by event, strictly conserving the energy and momentum. Second, it has a very simple mathematical structure so that its direct application to many-nucleon system is still viable in practice.

The application of the relativistic Yo-Yo model to the quark fragmentation processes in $e^-\bar{e}$ annihilation is found to be successful, and there exist several sophisticated calculations on this type of the analysis of $e^-\bar{e}$ jets[2,16-19].

There already exist some theoretical models which are based on the string mechanism for fragmentation processes in hadron-hadron collisions. However, it seems to us worthwhile to explore further the above mentioned advantages of the relativistic Yo-Yo model in the phenomenological description of the proton-proton collision. It is essential to keep the simplicity and the rigorous conservation of energy and momenta in elementary processes, when we extend the model to the calculation of collision processes between complex nuclei.

When we consider the analysis of nucleus-nucleus collisions, the following basic characteristics of proton-proton processes should correctly be taken into account:

1) Multiplicity distribution
2) Rapidity distribution
3) Transverse momentum distribution
4) Leading particle spectra

In this paper, we extend the relativistic Yo-Yo model to the proton-proton collision process which reproduces the above mentioned observed features of multiple production, without losing the simplicity of the model. In particular, with respect to the leading particle phenomena, it is important to note that there exists a significant contribution from the diffractive process. This last poínt is the most essential one for our future purpose, i.e., the study of nucleus-nucleus processes, since it directly affects the nuclear transparency. One of the main purpose of this work is to extend the model to simulate such a diffractive process which usually is not considered.

## 2. EFFECTIVE FIRE-TUBE MODEL

In this work we take the one dimensional string rnechanisrn as the basic phenomenological picture for the space-time developmentof the hadron fragrnentation process in proton-proton collisions. We suppose that, when two protons collide, they transform themselves into coloured objects due to the exchange of their sea quarks (anti-quarks). Then, such two receding coloured objects 'generate a nonperturbative chromo-electric flux confined in the tube-like volume between them[3]. Namely, after collision, two *excited protons* rush in opposite directions, forming a fire-tube of excited vacuum between them. In our treatment this fire-tube is regarded as a single effective one-dimensional string (see fig. 1).

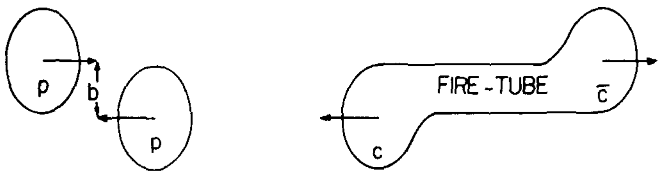


Fig.1 - Fire-tube formation in proton-proton collision for a given impact parameter $b$.

We start with the Hamiltonian for the effective string, for a given impact parameter $b$, given by

$$H(b) = \sqrt{p_1^2 + m_p^2} + \sqrt{p_2^2+m_p^2} + K_{\text{eff}}|x_1-x_2| \qquad (2.1)$$

where $(x_1,p_1)$ and $(x_2,p_2)$ are the coordinate and momenta of the two massive string end points which carry all the proton mass. $K_{\text{eff}}$ is related to the overlapping area $A_b$ of two proton bags as

$$K_{\text{eff}} = \varepsilon_0 A_b \quad , \qquad (2.2)$$

where $\varepsilon_0$ is the mean energy density of the fire-tube, and

$$A_b = \pi R^2 \left|\frac{2}{\pi} (\text{arc sin } (\sqrt{1-Z^2}) - Z\sqrt{1-Z^2})\right| \quad , \qquad (2.3)$$

where $Z = b/2R$ with R the radius of the proton bag.

The motion of the massive end points is described by the hyperbolae[2] in $x$-$t$ plane

$$(x-x_f)^2 - (t-t_f)^2 = \left(\frac{m_p}{K_{\text{eff}}}\right)^2 \qquad (2.4)$$

where the constants of integration $x_f$ and $t_f$ can be chosen as

$$x_f = t_f = \sqrt{s}/2K_{\text{eff}}$$

and $\sqrt{s}$ is the total c.m. energy. The hyperbdae has, asymptotes, the straight trajectories corresponding to massless particle motions[2].

During the string evolution, the fire-tube is expected to snap caused by a spontaneous creation of quark-antiquarks pairs of specific color combination, originating new colorless sub-strings whichcan break up further into smaller sub-strings. We assume that these $q\bar{q}$ pairs are produced with a constant probability density

$$\frac{d^2 p_s}{dx dt} = \text{const.} \tag{2.5}$$

For simplicity, we neglect the masses of quarks (antiquarks) and their possible fermi momenta at the instant of pair production. In this way, the original fire-tube between two excited protons develops into a collection of sub-strings which link a correlated $q$-$q$ pair, or quark (antiquark)-coloured rnassive end point $\bar{c}(c)$. However it is not reasonable to assume that the above decay chain continue indefinitely. After some time, the break-up mechanism ofa sub-string due to $(q\bar{q})$ pair creation will be dominated by another statistical decay mode. Therefore, at the end of its evolution, a sub-string is regarded as a statistical object (fire-ball) rather than a one dimensional string. Here we assume that a fire-ball state is always formed whenever a sub-string does not break before the time of its maximum contraction. Fora fire-ball associated to a particular $q_i\bar{q}_j$ pair, its mass $M_f$ is related to the positions of $i$ and $j$ quarks as

$$(x_i-x_j)^2 - (t_i-t_j)^2 = \left(\frac{M_f}{K_{\text{eff}}}\right)^2 , \tag{2.6}$$

so that $(M_f/K_{\text{eff}})$ corresponds to the maximum distance between $q_i$ and $\bar{q}_j$ in their C.M. system. In eq. (2.6), $(x_i,t_i)$, $(x_j,t_j)$ are, respectively, space-time coordinates of $i$-quark and $j$-quark at the instant of the creation. The same relation holds for the fire-ball forrned by $q(\bar{q})$-$\bar{c}(c)$. Fig. 2a shows a fire-ball formed by a $q\bar{q}$ pair in its own CM and fig. 2b shows a fire-ball after Lorentz boost with veloc ty 1 relative to the original CM. The maximum relative distance $(x_1-x_2)$ is contracted to $(x_1-x_2)/\gamma$ and the time dilated to $T' = T\gamma$.

In our calculations we impose the following mass threshold for fire-balls

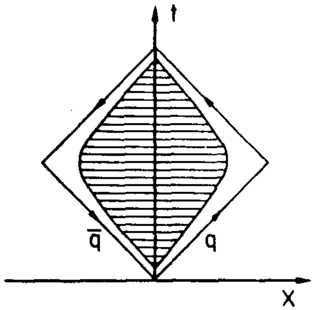


Fig.2a - Fire-ball formed by a $q\bar{q}$ pair in its own CM. The hatched area corresponds to the space-time development of fire-ball when quarks possess a finite mass.

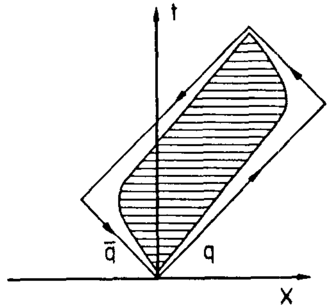


Fig.2b - The same as 2a after Lorentz boost with velocity $\beta$ relative to the original CM.

$$M_f > M_{th} = 2m_\pi \quad \text{for} \quad q\bar{q}$$

and (2.7)

$$M_f > M_{th} = m_p + m_\pi \quad \text{for} \quad q(\bar{q}) - \bar{c}(c)$$

where $m_\pi$ and $m_p$ are the masses of pions and proton, respectively. That is, the probability density for spontaneous $q\bar{q}$ pair creation is null in the area of the $x$-$t$ plane where the above condition is not satisfied.

Fig. 3 shows the space-time evolution of fire-balls in the CM of the proton-proton collision. These fire-balls then decay into final-state hadrons.

In the present treatment, we assume a purely statistical decay mode of these fire-balls into hadrons, mainly for the sake of simplicity. As final product hadrons, we only consider pions, except for protons from the fire-balls at the two end points of the original fire-tube (leading particles). The momentum distribution of state final hadrons is then calculated as a convolution of the isotropic phase-space momentum distribution of each fire-ball decay in their rest frame and the longitudinal momentum distribution of fire-balls acquired through the fire-tube fragmentation mechanism. In this way, the transverse mo-

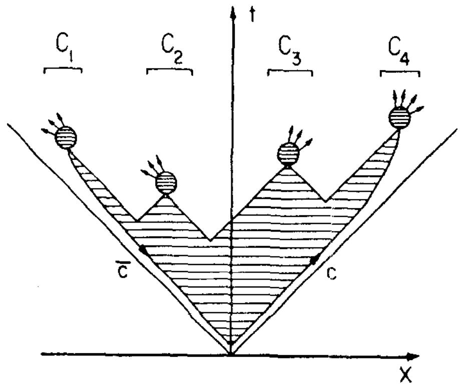


Fig.3 - Space-time evolution of the fire-tube in the CM of proton-proton collision. $C_1$, $C_2$, $C_3$ and $C_4$ are the fire-balls which decay into final hadrons isotropically in their own CM.

menta of final hadrons are due to the isotropic decay of fire-ball in their rest frame and henceforth, the transverse momentum distribution is essentially determined by the mass distribution of fire-balls.

It is a relatively easy rnatter to calculate the rapidity distribution, the transverse momentum distribution and the leading particle spectra using the Monte-Carlo procedure, which is briefly explained in sec. 4. In the next section, we extend the above scheme to include diffractive processes which have important effects on leading particle spectra.

## 3. DIFFRACTIVE INELASTIC PROCESS

One of the trends found in high energy hadronic reactions, in which only a few particles are produced, is the tendency of these particles to gather into two sets, each set moving prodorninantly in the direction of the incident particles. The principal features of this process are the strongly forward-peaked differential cross-sections, their slow variation with energy, the high leading particle longitudinal momenta (>0.8 of initial moment) and the relatively low multiplicity[e] cornpared to the mean multiplicity of all events at the same incident energy. At high energies the experimental inelastic single diffractive cross-section, $a_{DI}$ for proton-proton reactions, is about 20% in the total inelastic cross section $o_I$,[20] Particularly, for our future purpose of studying ultra-relativistic nuclear collisions, fast diffractíve fragments seem to have an important role with respect to the nuclear transparency phenomena[21] arid, consequently, to the amount of the energy density and ternperature of hadron matter accessed by the reaction. Therefore, it is essential to include such a mechanism in our treatment.

We should consider then the possibility for the following single diffractive reactions

$$p + p \rightarrow \begin{cases} p + X \\ X + p \end{cases}$$

where $X$ is an excited hadron with the same intrinsic quantum numbers as those of the proton, i.e., p and $X$ differ only in their mass and spin content. Of course such a diffractive process has a quantum mechanical origin, while the string picture represents rather the classical aspect of time development of the system. However, we still can simulate such a diffractive part by the same mechanism of string break-up if an appropriate criterion is used. As in the diffractive process the momentum transfer is srnall, we associate such a phenomena to a string breaking process at the earlier stage of time development.

In our model, we introduce a diffractive time scale in such a way that those events which occur for time smaller than $\tau_D$ are considered diffractive. In this case, it occurs that one of the protons emerges with the corresponding momentum $P>P_D = K_{\text{eff}}(t_f-\tau_D)$ and the residual excited hadron run in the opposite direction (fig. 4).

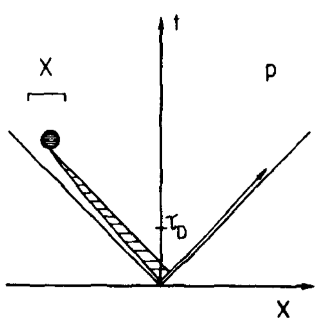


Fig.4 - Diffractive process for the case $p+p \rightarrow p+X$

In practice, we define the diffractive region as the area of the $x$-$t$ plane bounded by c and $\bar{c}$ trajectorie and $t = \tau_D$. We also introduce the diffractive probability density $dP_D/dt$ along the $c(\bar{c})$ trajectory. The probability $P_D$ for a diffractive process to take place is given by

$$P_D = \frac{dP_D}{dt} \cdot \tau_D \tag{3.1}$$

We first assign one particular event as diffractive or non-diffractive according to the probability $P_D$. If the event turns out to be diffractive, we randomly choose one value of $t$ in the interval $t_0<t<\tau_D$, where $t_0$ is the initial time for the c and $\bar{c}$ trajectories, given by

$$x_c(t_0) = x_{\bar{c}}(t_0) = 0 \tag{3.2}$$

Otherwise, the event is considered to develop as a non-diffractive process for $t>\tau_D$.

In this way the two different probabilities $P_D$ and $P_S$ can simulate the competition between diffractive and non-diffractive plenomena. The time $\tau_D$ can be estimated if we consider that the diffractive leading particle momentum $p$ is $p \geq 0.8\ p_0$, where $p_0 - \sqrt{s}/2$ is the incident proton momentum

$$\frac{p}{p_0} = \frac{-K_{eff}(\tau_D - t_f)}{\sqrt{s}/2} - 0.8 \quad . \tag{3.3}$$

We have

$$\tau_D \lesssim t_f - \frac{0.8\ \sqrt{s}/2}{\langle K_{eff}\rangle} \simeq \frac{0.2\ \sqrt{s}/2}{\langle K_{eff}\rangle} \tag{3.4}$$

where $\langle K_{eff}\rangle$ is the mean value of $K_{eff}(b)$, averaged over all values of the impact parameter $b$.

It is interesting to note that the behaviour of the leading particle spectra near $x(=p/p_0)$ equal to unit is given by

$$\left(\frac{1}{\sigma}\frac{d}{dx}\right)_{dif} \propto \int_0^{b_{max}} \exp\left[-\frac{\sqrt{s}}{2}\ \frac{dP_D/dt}{K_{eff}(b)}\ (1-x)\right] bdb \tag{3.5}$$

## 4. MONTE CARLO PROCEDURE

First, the impact parameter b for the proton-proton collision is randomly chosen according to the probability $P(b)\, db \propto b db$ between the values corresponding to the minimum and maximum overllaping area $A_b$, i.e., $0<b<2R$. As explained in sec. 2, we have, for a given impact parameter $b$, a single effective one dimensional string with a constant attractive tension $K_{eff} = \epsilon_0 A_b$ and its space-time evolution is described by the Hamiltonian $H(b)$ eq. (2.1). This space-time evolution is followed numerically by the Monte Carlo method.

After averaging over a number of collisions sufficiently high to obtain statistically stable results covering the whole impact parameter values, we get inclusive quantities to be compared with the experimental data.

### 4.1 - Space-time Evolution - String Fragmentation and Fire-Ball Decay

Once the effective Hamiltonian $H(b)$ is defined for a particular impact parameter $b$, we follow up the string fragmentation mechanism caused by spontaneous creation of quark-antiquark pairs. To do this, we first divide the time interval $T$, corresponding to the time for maximum elongation of the initial $c$-$\bar{c}$ string, into N intervals, $\Delta t = T/N$. We also define the time $\tau_D$ which corresponds to the starting time for the non-diffractive process (fig. 4). Then, in order to procedure quark-antiquark particles at different space-time points we proceed as follows:

For the $i$-th time step $t_i = t_D + \Delta t . i$ we consider a strip $S_i$ of width

$$S_i = |x_{\bar{c}}(t) - x_c(t)|\ \Delta t \tag{4.1}$$

where $x_{\bar{c}}(t)$ and $x_c(t)$ are the trajectories of two coloured end points, c and $\bar{c}$. They are given by

$$\begin{aligned} x_{\bar{c}} &= -(\sqrt{s}/2K_{eff}) + |(t-p_0/K_{eff})^2 + (m_p/K_{eff})^2|^{1/2} \\ x_c &= (\sqrt{s}/2K_{eff}) - |(t-p_0/K_{eff})^2 + (m_p/K_{eff})^2|^{1/2} \end{aligned} \tag{4.2}$$

with

$$P_0 = \sqrt{(s-4m_p^2)}/2 \quad . \tag{4.3}$$

and where the time $t$ is measured from the instant of collision.

Then, we randomly generate inside the strip the coordinates $(x,t)$ of breaking point, according to the probability

$$P_s = (d^2P_s/dxdt)\ \Delta x\ \Delta t \tag{4.4}$$

for $q_i\bar{q}_i$ pair production. These $q_i\bar{q}_i$ particles are created with zero momenta and afterwards run in opposite directions with the speed of light and increasing momenta. The links between $q_i$-$\bar{c}$ and $\bar{q}_i$-$c$ can generate fire-balls with mass $M_f>m_p$, or otherwise stay as sub-strings, which may break at a later time.

The latter case occurs only if the invariant mass of the sub-string is greater than the fire-ball mass threshold $M_{th}$.

When a sub-string is produced another $q_j\bar{q}_j$ pair will be created by the same procedure; the $q_i$-$\bar{q}_j$ and $\bar{q}_i$-$q_j$ links can generate new fire-balls with mass $M_f>M_{th}$ eq. (2.7) or else new sub-strings which will break further.

The above procedure is continued until only fire-balls remain.

## 4.2 - Fire-ball decay

As the last stage to obtain final hadron distributions, we must calculate the final hadron states for each fire-ball decay. These hadron final states are convoluted over the fire-ball mass distribution resulted from the string fragmentation. As mentioned before, we assume a statistical decay mode according to the available phase-space of decay particles. First, we calculate the multiplicity distribution as a function of $M_f$. For that, the probabilities for a fire-ball with $M_f$ to decay into n-particles with equal masses m are calculated by

$$P_n(m_f;m_i) \propto \int \cdots \int \prod_{i=1}^{n} \frac{d^3p_i}{E_i}\, \delta^3\left(\sum_{j=1}^{n} \vec{p}_j\right) \delta\left(\sum_{K=1}^{n} E_K - M_f\right) \tag{4.5}$$

with

$$E_K = (\vec{p}_K + m^2)^{1/2} \tag{4.6}$$

and the average multiplicity will be

$$\langle n\rangle_{M_f} = \frac{\Sigma n P_n}{\Sigma P_n} \tag{4.7}$$

The final momenta of hadrons are generated randomly according to the phase-space[22]. Here, the angular distribution of hadrons due to fire-ball decays is assumed to be isotropic in its rest frame.

### 4.3 - Charge Distribution

In order to attribute the charge distribution to th'e final particles, it is necessary to establish the probability distribution of charged pions for a given fire-ball decay. We take here a very simplified expression[23], assurning that all the fire-balls, except for those containing the original protons, have null isospin. For of fire-ball which contains a proton, we assume that the probability for the proton to lose its charge is equal to 1/2. In the case that charge transfer occurs, we simply add one unit charge to the charged pion distribution determined by the zero isospin case.

## 5. RESULTS AND DISCUSSION

We show in figs. 5-8 the results of our preliminary calculation compared to the experimental results for incident energy $\sqrt{s}$ = 19.6 GeV[24-27]. As seen from these figures, our model provides, at least phenomenologically, a reasonable description of proton-proton process. Particularly the leading particle effect, including its diffractive characteristics is well reproduced.

The parameters taken here are presented in the table below

| $\varepsilon_0$ (GeV/fm$^3$) | $d^2P_s/dxdt$ | $dP_0/dt$ | $\tau_D$ (fm/c) |
|---|---|---|---|
| 0.75 | 1.0 | 0.2 | 1.0 |

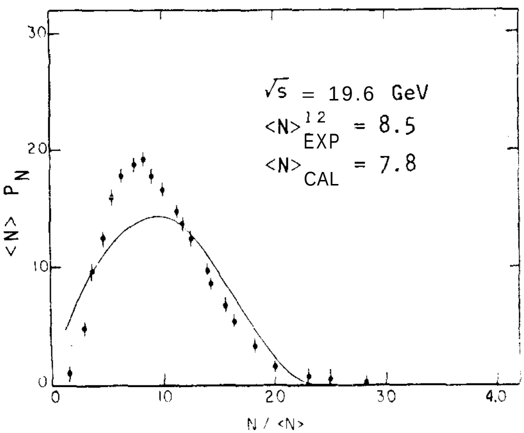


Fig.5 - Normalized multiplicity distribution of charged particles $<n>P_n$ as a function of the KNO scaling variable $Z = n/<n>$. The data (full circles) are from ref. 24. The curve is the present result.

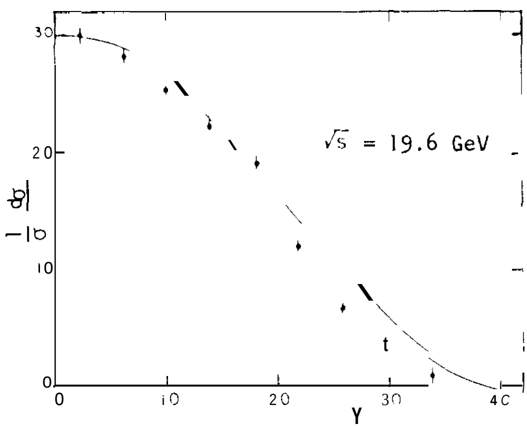


Fig.6 - Charged partcle rapidity ciistribution for pp scattering. The data (full circles) are from ref. 25. The curve is the present results.

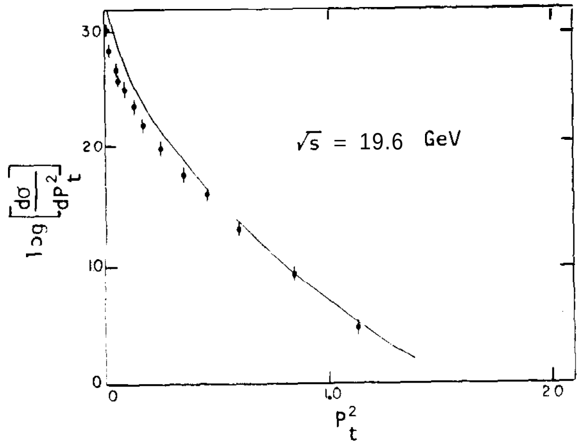


Fig.7 - Charged particle transverse momentum distribution for pp scattering. The data (full circles) are from ref.25. The curve is the present result.

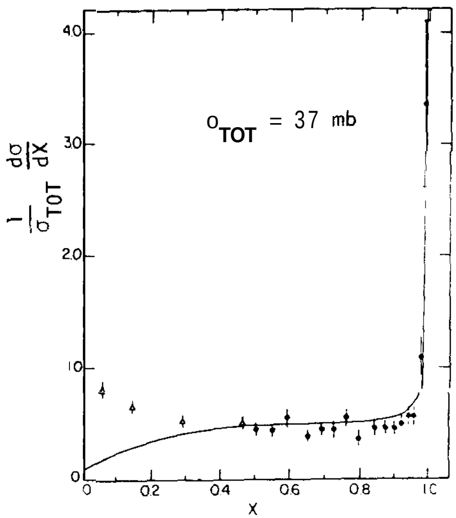


Fig.8 - Leading particle distribution for pp scattering. The data are from ref.26 (triangles) and ref. 27 (full circles). The curve is the present result.

For simplicity the time scale $\tau_D$ for diffractive processes is defined in the original $p$-$p$ CM system. Apparently this definition is not relativistically covariant, although it is a relatively easy matter to introduce the invariant time scale for each proton rest frame. However the result would not be much altered except for a constant factor for $\tau_D$, since the Lorentz factor of protons is almost constant in the time interval $(\tau_D - t_0)$.

The energy density $\varepsilon_0$ has an important role for the fire-ball mass distribution. The larger the value of $\varepsilon_0$ is, the more the heavy fire-balls are formed. This is the expected trend due to the fact that, for larger $\varepsilon_0$ values, the corresponding higher string tension $K_{eff}$ leads to a higher effective energy available for fire-ball mass formation. The formation of heavy fire-balls has the direct consequence in the transverse momentum distribution to raise its tail (large $P_T$).

The non-diffractive probability density $d^2P/dxdt$ acts in the opposite direction to $\varepsilon_0$. In fact, for a given $\varepsilon_0$, the increase of $d^2P_s/dxdt$ leads the string to break at an earlier stage of its time evolution and consequently the high momenta of the massive end points do not leave much energy for heavy fire-ball formation.

It is worthwhile to mention that, instead of its extreme simplicity, our effective fire-tube model gives a reasonable phenomenological description of multiple particle production processes. The calculated resuts are satisfactory with respect to thcse quantities which are most important in the future application of our model to the analysis of nucleus-nucleus collision.

However, in order to apply our model to the relativistic heavy ion processes, some important points should be studied further. They are:

i - Understanding of the incident energy dependence of the model parameters.

ii - Non-isotropic angular distribution for high fire-ball mass.

At sufficiently high incident $E_{CM}$ we have a substantial amount of massive fire-balls with $M_f \gtrsim 4$ GeV. For these fire-balls the isotropic angular distribution must fail[28].

This anisotropy may be taken into our model if we intraduce the hydrodynamical treatment of the heavy fire-ball decay process. In the hydrodynamical model, if the initial volume is contracted, as expected in the present application, the longitudinal expansion of a fire-ball causes a non-isotropic distribution for final hadrons in its rest frame[29].

We have shown that the phenomenological string model can be extended successfully to the proton-proton collisions process without losing its simplicity. Especially, the diffractive behaviour and its effect on the leading particle spectra are well reproduced.

Further studies, including the analysis of themodel parameters with respect to incident energy dependence; hydrodynamical treatment of fire-ball decay, and the extension of the model to nucleus-nucleus collision are now in progress.

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**Resumo**

É proposto um modelo fenomenológico simples para colisões proton-proton visando sua aplicação direta a reações núcleo-núcleo em energias altas. O formalismo combina formação de Solas de fogo durante o desenvolvimento espaço-temporal de um tubo de fogo não perturbativo de vácuo excitado e uma subsequente produção de hadrons finais por decaimento dessas bolas de fogo. Foi dedicada atenção especial ao tratamento do processo de dissociação difrativa de modo a incluir efeitos de partícula dominante. Os resultados deste modelo são comparados com os dados experimentais à energia de 19.6 GeV. O espectro de partícula dominante é bem reproduzido no presente tratamento.