Quark-Matter Droplets in High-Energy Nuclear Collisions

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We explain "intermittency" in recent data, using a simple model in which pions are emitted from quark-gluon-plasma droplets. We find that droplets with a temperature near the QCD phase-transition temperature that emit 10–15 pions, with a droplet volume of 5–10 fm^3, reproduce the observations very well.

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Recently there has been considerable interest in the idea of intermittency, or self-similar behavior, in high-energy nuclear collisions.[1-5] This phenomenon has been predicted to occur as a result of the transition from quark-gluon plasma to normal hadronic matter.[1] In this Letter we reanalyze data which have been suggested to demonstrate intermittency.[2,3] We use a thermal-droplet model in which pions are emitted from plasma droplets at a temperature near the QCD phase-transition temperature. We show that this model can account for existing observations with a mean droplet volume of 5–10 fm^3 and a droplet temperature of about 150 MeV.

Intermittency is most easily seen by studying exclusive scaled factorial moments[4]

$$F_i(M)=\frac{1}{M}\sum_{m=1}^{M} M^i\frac{k_m(k_m-1)\cdots(k_m-i+1)}{N(N-1)\cdots(N-i+1)}, \quad (1)$$

where the data have been split into M bins of equal size, N is the total number of observed particles, and k_m is the number of particles in the mth bin. We also use the inclusive moments

$$\tilde{F}_i(M)=\frac{1}{M}\sum_{m=1}^{M}\frac{M^i}{\langle N\rangle^i}k_m(k_m-1)\cdots(k_m-i+1), \quad (2)$$

where $\langle N\rangle$ is the mean multiplicity. These moments are defined so that they both yield unity when the particle distribution is flat and the multiplicity fluctuations are Poissonian.

We wish to look for intermittency in rapidity, so we divide the system into rapidity bins of equal width in order to calculate the factorial moments. If intermittency is present, the moments will diverge as $M\to\infty$ with a power-law dependence.[4] For general cluster models with no intermittency, the moments are bounded and the asymptotic behavior is[6]

$$F_i(M)=F_i(\infty)-\frac{C_i}{M^2}, \quad (3)$$

where C_i is usually proportional to $\langle N\rangle^{-1}$.

Droplets are likely to form if the QCD phase transition is first order[7] as predicted by lattice calculations.[8] Even if the transition is not first order, the very rapid expansion of the plasma is likely to result in droplet formation. The dynamics of droplet evaporation and decay can be simplified because Monte Carlo cascade simulations have shown that pions produced from droplets interact little after their formation.[9] Droplet models also suggest that two-particle correlations could be a signal for the formation of quark-gluon plasma in high-energy $\bar{p}p$ collisions.[10]

In the simplest thermal-droplet model, the collision produces a large volume of quark-gluon plasma which fragments at a temperature near the QCD phase-transition temperature into N_d small droplets. These droplets are distributed randomly in rapidity; we assume that the probability density to find a droplet at rapidity y_d is flat:

$$p(y_d)=\begin{cases}1/2y_*, & |y_d|<y_*,\\ 0, & y_*\le|y_d|.\end{cases} \quad (4)$$

A droplet then produces n_π pions randomly with a thermal distribution

$$p(y)=\frac{1}{2\cosh^2(y-y_d)}, \quad (5)$$

where y_d is the droplet rapidity and the pions are for now assumed to be massless. Finally we assume that N_d and n_π are given by the Poisson distributions

$$P(N_d)=\frac{\langle N_d\rangle^{N_d}}{N_d!}e^{-\langle N_d\rangle}, \quad (6)$$

$$P(n_\pi)=\frac{\langle n_\pi\rangle^{n_\pi}}{n_\pi!}e^{-\langle n_\pi\rangle}. \quad (7)$$

We begin by calculating the inclusive moment $\tilde{F}_2$. The droplets are distributed independently, so the moment reduces to the form[6]

$$\tilde{F}_2(M)=\tilde{F}_2^{\rm MD}(M)+\tilde{F}_2^{\rm SD}(M), \quad (8)$$

where $\tilde{F}_2^{\rm MD}$ is the contribution from pions produced by multiple droplets and $\tilde{F}_2^{\rm SD}$ is the contribution from pions produced by a single droplet. Higher moments can be broken down in the same manner, but they will contain contributions from most lower moments, so they are more complicated to calculate.

Since the pions are emitted independently, the multiple-droplet contribution is

$$\tilde{F}_2^{\mathrm{MD}}(M)=\left[\frac{\langle N^2-N\rangle}{\langle N\rangle^2}-\frac{\langle n_\pi\rangle}{\langle N\rangle}\right]M\sum_{m=1}^{M}q^2(m)\,, \quad (9)$$

where $q(m)$ is the probability, averaged over all droplets, that a given pion is in bin m. The single-droplet contribution is, similarly,

$$\tilde{F}_2^{\mathrm{SD}}(M)=\frac{\langle n_\pi\rangle}{\langle N\rangle}M\sum_{m=1}^{M}r^2(m)\,, \quad (10)$$

where $r(m)$ is the probability, averaged over a single droplet, that a given pion is in bin m.

We calculate the values of $\tilde{F}_2^{\mathrm{MC}}$ expected from Monte Carlo simulation of the events by dropping the single-droplet contribution from Eq. (8). This procedure gives

$$\tilde{F}_2^{\mathrm{MC}}(M)=\left[\frac{\langle N^2-N\rangle}{\langle N\rangle^2}-\frac{\langle n_\pi\rangle}{\langle N\rangle}\right]M\sum_{m=1}^{M}q^2(m)\,. \quad (11)$$

We use this fit to determine the value of $\langle N^2\rangle$ for these events.

We use Eqs. (4)-(11) to reanalyze the Krakow-Louisiana-Minnesota (KLM) data from O+Ag(Br) collisions;[2] the results are shown in Fig. 1. We leave $\langle n_\pi\rangle$ as a free parameter, and find that the best fit to the data is obtained with $\langle n_\pi\rangle=10$ charged pions per droplet (15 pions per droplet including π^0), corresponding to a droplet volume of 8 fm^3 if the droplet temperature is $T_c=150$ MeV or 3 fm^3 for $T_d=200$ MeV.

It is straightforward to include the effects of massive pions in our model. The only change occurs in Eq. (5), which becomes (assuming Maxwell-Boltzmann statistics for simplicity)

$$p(y)=\frac{c(m_\pi/T_d)}{z^2}\left[1+z+\frac{z^2}{2}\right]e^{-z}\,, \quad (12)$$

where

$$z=\frac{m_\pi}{T_d}\cosh(y-y_d)\,, \quad (13)$$

$c(m_\pi/T_d)$ is included for normalization, and m_π is the pion mass. We repeat our calculation with massive pions with $T_d=m_\pi$; this fit gives us $\langle n_\pi\rangle=8$, corresponding to a droplet volume of 7 fm^3. The theoretical curve is virtually indistinguishable from the curve for massless pions, shown in Fig. 1. The fit is thus insensitive to the droplet temperature, which is good because the droplet temperature is not easily determined.

We also look at preliminary results for O+Ag(Br) and S+Au collisions from the EMU01 Collaboration.[3] They suggest that their S+Au data display intermittency but that their O+Ag(Br) data do not. We cannot compare their data directly to KLM data, since they construct F_2 instead of $\tilde{F}_2$.

We show our fit (for massless pions) to the EMU01 O+Ag(Br) data in Fig. 2. The best fit is achieved with $\langle n_\pi\rangle=2$, which seems to be in conflict with the KLM data. We also use the model to fit the S+Au data; the

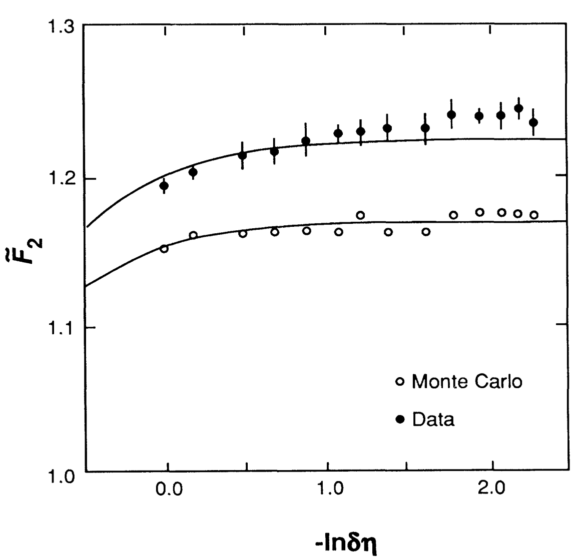

FIG. 1. $\tilde{F}_2$ vs $-\ln\delta\eta$ for O+Ag(Br) at 200A GeV. The upper theoretical curve is from the thermal-droplet model with an average of 15 massless pions per droplet, and the lower curve is our reproduction of the Monte Carlo results. The data points and Monte Carlo results are from Ref. 2.

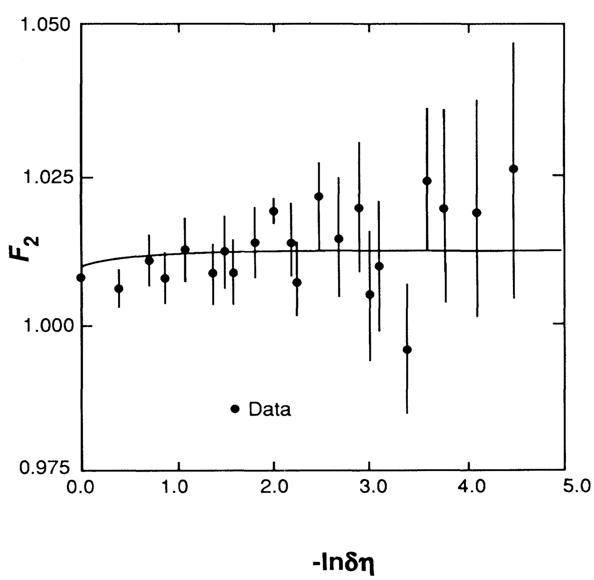

FIG. 2. F_2 vs $-\ln\delta\eta$ for O+Ag(Br) at 200A GeV (events with more than 150 secondaries only). The theoretical curve is from the thermal-droplet model with an average of 3 massless pions per droplet. The data points are from Ref. 3.

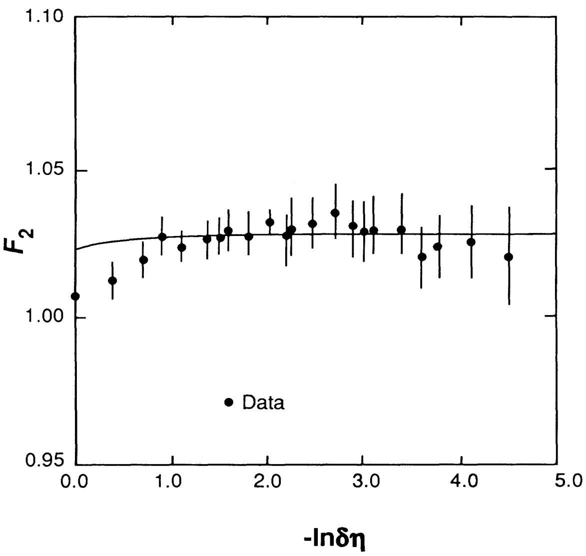

FIG. 3. F_2 vs $-\ln\delta\eta$ for S+Au at 200A GeV (events with more than 300 secondaries only). The theoretical curve is from the thermal-droplet model with an average of 15 massless pions per droplet. The data points are from Ref. 3.

results are shown in Fig. 3. We obtain the best fit with $\langle n_\pi \rangle = 10$, matching the KLM result. Our theoretical prediction deviates somewhat from the data for $\frac{1}{3} < \delta\eta < 1$. However, the fact that our model works well for $\delta n \ll 1$ indicates that intermittency does not occur in these data.

We estimated the errors in our measurements of $\langle n_\pi \rangle$ and $\langle N_d \rangle$ by varying these parameters until the resulting fit missed $\frac{1}{3}$ of the error bars. We found that the KLM data gave $8 \leq \langle n_\pi \rangle \leq 13$ for $m_\pi = 0$ and $7 \leq \langle n_\pi \rangle \leq 9$ for $T_d = m_\pi$. The EMU01 results were $0 \leq \langle n_\pi \rangle \leq 3$ for the O+Ag(Br) events and $5 \leq \langle n_\pi \rangle \leq 15$ for the S+Au events, both for massless pions.

In summary, we have shown that factorial-moment data from the KLM and EMU01 Collaborations can be fitted by a thermal-droplet model which does not exhibit intermittency. The fit is relatively insensitive to the droplet temperature, but is sensitive to the droplet volume. The mean droplet volume is about 7 fm^3 for a droplet temperature of m_π. There is an indication of some residual intermittency in the KLM data, which may arise from Bose-Einstein correlations of the pions produced from the droplets. These correlations will be discussed further in Ref. 6.

The large-droplet formation found in our model is a strong indication that quark-gluon plasma is formed in nuclear collisions at 200A GeV. There are probably many other plausible cluster or droplet models which could fit the data. However, all of them must contain clusters or droplets which emit a fairly large number of pions ($\langle n_\pi \rangle > 10$).[6] The only known explanation for forming such large clusters or droplets in nuclear collisions is a phase transition.

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