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Correlations and intermittency in high-energy nuclear collisions

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We evaluate the strength of rapidity correlations as measured by bin-averaged multiplicity moments for hadron-hadron, hadron-nucleus, and nucleus-nucleus collisions for comparable c.m. energies $\sqrt{s} \sim 20$ GeV. The strength of the correlation decreases rapidly with increasing complexity of the reaction. Although statistically significant cumulant moments, K_2, K_3, and K_4 are found in hadron-hadron (NA22) collisions, higher moments are strongly suppressed (except for K_3 in KLM Collaboration proton-emulsion data) when nuclei are involved. When ordinary factorial moments are decomposed into cumulant moments, the former are seen to be dominated by combinatoric contributions of the (experimentally determined) cumulant moment K_2. Hence rapidity fluctuations and intermittent effects are significantly decreased by the use of nuclei as targets and/or projectiles. This result could possibly be reversed at the onset (at higher energy) of a new phase having strong fluctuations, for example, the long-sought quark-gluon plasma.

The recent observation of unusually large rapidity density fluctuations in leptonic, hadronic, and nuclear collisions has generated considerable interest in trying to understand the underlying dynamics of multiparticle production in high-energy collisions [1]. These fluctuations are detected by measuring the bin-averaged moments F_p defined as

$$F_p(\delta y) = \frac{1}{M} \sum_{m=1}^{M} \frac{\langle n_m(n_m-1)\cdots(n_m-p+1)\rangle}{\langle n_m\rangle^p}$$

$$= \frac{1}{M(\delta y)^p} \sum_{m=1}^{M} \int_{\Omega_m} \prod_i dy_i \frac{\rho_p(y_1\cdots y_p)}{(\bar{\rho}_m)^p} , \qquad (1)$$

where n_m is the number of particles in a bin m, M is the total number of bins, δy is the rapidity bin size ($\delta y = Y/M$), and ρ_p is p-particle density correlation function. In all high-energy collisions, the factorial moments are found to increase with decreasing the bin size. Originally, it was proposed that the power-law behavior of these moments $[F_p \sim (\delta y)^{-\nu_p}]$ is an indication of intermittent behavior in analogy with scaling phenomena in hydrodynamics [2]. We have shown that in hadronic collisions, the observed increase of the moments is a consequence of the short-range correlations and that there is no need to invoke power-law behavior [3].

Here we consider density fluctuations in high-energy proton-nucleus and nucleus-nucleus collisions. We note that moments F_p $(p=3,4,5)$ have large combinatoric contribution from two-particle correlations. Therefore, in order to examine the true higher-order correlations we express F_p in terms of the bin-averaged cumulant moments [4]

$$F_2 = 1+K_2, \quad F_3 = 1+3K_2+K_3 ,$$

$$F_4 = 1+6K_2+3\overline{(K_2)^2}+4K_3+K_4 , \qquad (2)$$

$$F_5 = 1+10K_2+15\overline{(K_2)^2}+10\overline{K_3K_2}+10K_3+5K_4+K_5,$$

where

$$K_p(\delta y) = \frac{1}{M(\delta y)^p} \sum_m \int_{\Omega_m} \prod_i dy_i \frac{C_p(y_1\cdots y_p)}{(\bar{\rho}_m)^p} \qquad (3)$$

and

$$C_2(1,2) = \rho_2(1,2) - \rho_1(1)\rho_1(2) ,$$

$$C_3(1,2,3) = \rho_3(1,2,3) - \rho_2(1,2)\rho_1(3) - \rho_2(2,3)\rho_1(1) - \rho_2(3,1)\rho_1(2) + 2\rho_1(1)\rho_1(2)\rho_1(3) , \qquad (4)$$

$$C_4(1,2,3,4) = \rho_4(1,2,3,4) - \sum_{(4)} \rho_3(1,2,3)\rho_1(4) - \sum_{(3)} \rho_2(1,2)\rho_2(3,4) + \sum_{(12)} \rho_2(1,2)\rho_1(3)\rho_1(4) - 6\rho_1(1)\rho_1(2)\rho_1(3)\rho_1(4) .$$

Clearly, if there are no true, dynamical correlations, cumulants K_p vanish.

The KLM Collaboration has measured the so-called *horizontal* factorial moments defined as

$$F_p^h(\delta y)=\frac{1}{M}\sum_{m=1}^{M}\frac{\langle n_m(n_m-1)\cdots(n_m-p+1)\rangle}{\langle \bar{n}\rangle^p} , \tag{5}$$

where $\bar{n}=\sum_m n_m/M$, for proton and oxygen beams on emulsion target at 60 and 200 GeV/nucleon for oxygen and 200 and 800 GeV/nucleon for protons [5]. Since these moments are sensitive to the shape of the density distribution, they were corrected by the heuristic R factor

$$F_p^c(\delta y)=F_p^h/R(\delta y) , \tag{6}$$

where

$$R(\delta y)=\frac{(1/M)\sum_m\langle n_m\rangle^q}{[(1/M)\sum_m\langle n_m\rangle]^q}$$

$$=\frac{1}{M}\sum_m(\langle n_m\rangle/\bar{n})^q . \tag{7}$$

This correction factor was first introduced by Fialkowski, Wosiek, and Wosiek [6] in order to exclude the contribution coming from the trivial fluctuations due to the nonflat shape of the rapidity distribution. Although the expression (6) is not precisely the same as that connecting Eqs. (1) and (3), it is reasonable to use it to compare the exact equations, Eqs. (2), with the KLM data.

In Fig. 1 we present cumulants K_2 for NA22 [7] (π-p collision at $\sqrt{s}=22$ GeV), KLM [5] (proton, oxygen, and sulfur beam on emulsion at 200 GeV per nucleon), and EMU01 data [8] (sulfur on Gold at 200 GeV per nucleon). All these collisions are approximately at the same c.m. energy per particle. Both NA22 and EMU01 data are vertical moments defined by Eq. (1), while the KLM Collaboration give horizontal (corrected) moments. We note that K_2 decreases in going from light to heavier projectiles, even more in the case of sulfur. Although the two-particle correlation *function* is a poorly translation invariant at these energies, we have found that integrated *moments* are well described using the exponential form for two-particle cumulant correlation [9]:

$$k_2=C_2(y_1,y_2)/\rho_1(y_1)\rho_2(y_2)=\gamma e^{-|y_1-y_2|/\xi} . \tag{8}$$

We have previously derived this expression in our one-dimensional statistical model for multiparticle production based on analogy with Feynman-Wilson "gas" [10]. In this model the parameters γ and ξ are related to the phenomenological coefficients in the Ginzburg-Landau probability functional [10]. The strength of the correlations length ξ, for example, indicates how far the physical system is from the critical point.

From Eq. (8) we get the associated cumulant K_2

$$K_2=2\gamma\xi^2[(\delta y/\xi)-1+e^{-\delta y/\xi}]/\delta y^2 , \tag{9}$$

which can describe both hadronic and nuclear data. We find that for NA22 we need $\gamma=0.331$ and $\xi=2.18$, while for proton emulsion $\gamma=0.29$ and $\xi=1.39$. For KLM and EMU01 heavy-ion data we find a very good fit with $\gamma=0.13$ and $\xi=1.28$ (for oxygen emulsion), $\gamma=0.09$ and $\xi=2.14$ (for sulfur emulsion), and $\gamma=0.08$ and $\xi=2.14$ (for sulfur gold). Our results for K_2 are presented in Fig. 1 (dashed lines). Higher-order cumulants for hadronic and nuclear collisions are shown on Figs. 2–4. The error bars on these figures are calculated for each point separately (i.e., we assume that all the points are independent/uncorrelated). Clearly, if one would want to fit the data points on Figs. 2–4 with a straight line, for example, the correlations between different points would have to be taken into account. For this particular analysis one needs presently unavailable experimental correlation matrix.

While in hadronic collisions K_3 and K_4 are non-negligible (K_3, for example, gives up to 20% contribution to F_3 at small δy), in proton-nucleus and nucleus-nucleus collisions, at the same energy, these cumulants are compatible with zero. (One could argue a very small nonzero K_3 in case of proton-emulsion collision.) This implies that there are no statistically significant correlations of order higher than two for heavy-ion collisions. Thus, in high-energy heavy-ion collisions, the observed increase of the higher-order factorial moments F_p [5] is entirely due to the dynamical two-particle correlations. (In this regard compare the analysis of Ref. [4].) We find that this conclusion holds even in a higher-dimensional analysis. For example, KLM Collaboration has done a two-dimensional analysis (in rapidity y and azimuthal angle ϕ) of the factorial moments [5]. We find that their measured two-dimensional cumulant K_2 is increasing with decreasing bin size ($\delta\phi\,\delta y$) faster than in one-dimensional case, but higher-order cumulants are still consistent with zero [11].

It is intuitively clear that rescattering of initially correlated particles by downstream constituents should decorrelate those initial correlations. Consideration of a multisource scenario [12,13] leads to the same result. However, we have not made quantitative calculations that explain the phenomenological results here. Such calculations are needed to anticipate rapidity fluctuations to be expected at RHIC and LHC energies, in order to see whether suppression of multiplicity cumulants, and the attendant dominance of factorial moments by two-particle cumulants, continues to hold. We note that even if strong space-time fluctuations should occur of the sort associated with transition to a quark-gluon plasma phase, the rapidity moments must obey the identities of Eqs. (2). In this case, however, we expect the higher-cumulant moments to suddenly increase, to reflect the presence of more violent bulk fluctuations preceding hadronization.

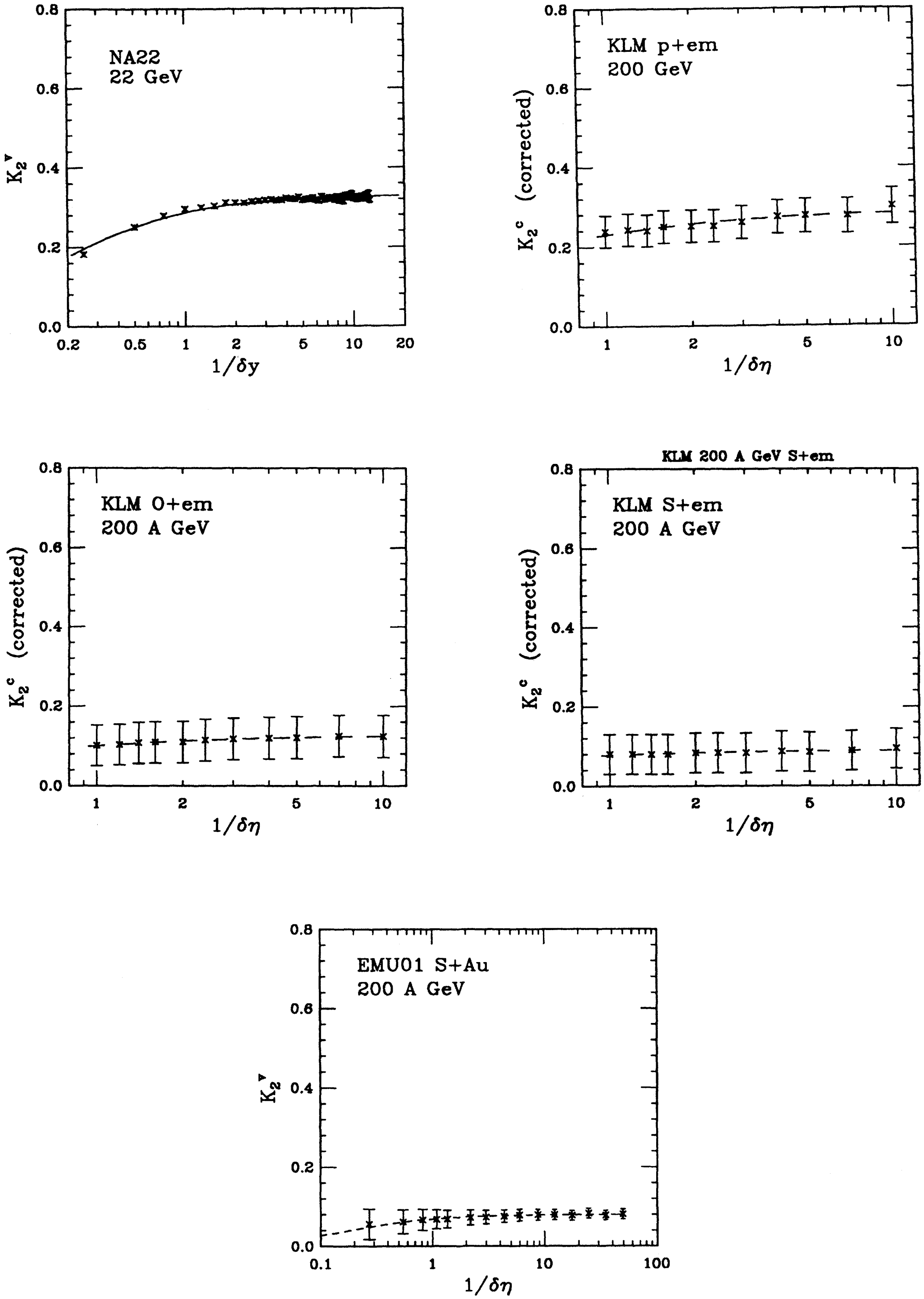

FIG. 1. The cumulant K_2 for NA22 [7], KLM [5], and EMU01 data [8]. Dashed lines represent our results for K_2 using the exponential form for two-particle cumulant correlations given by Eq. (8), with parameters $\gamma=0.331$ and $\xi=2.18$ (NA22), $\gamma=0.29$ and $\xi=1.39$ (p emulsion), $\gamma=0.13$ and $\xi=1.28$ (for oxygen emulsion), $\gamma=0.09$ and $\xi=2.14$ (for sulfur emulsion), and $\gamma=0.08$ and $\xi=2.14$ (for sulfur gold).

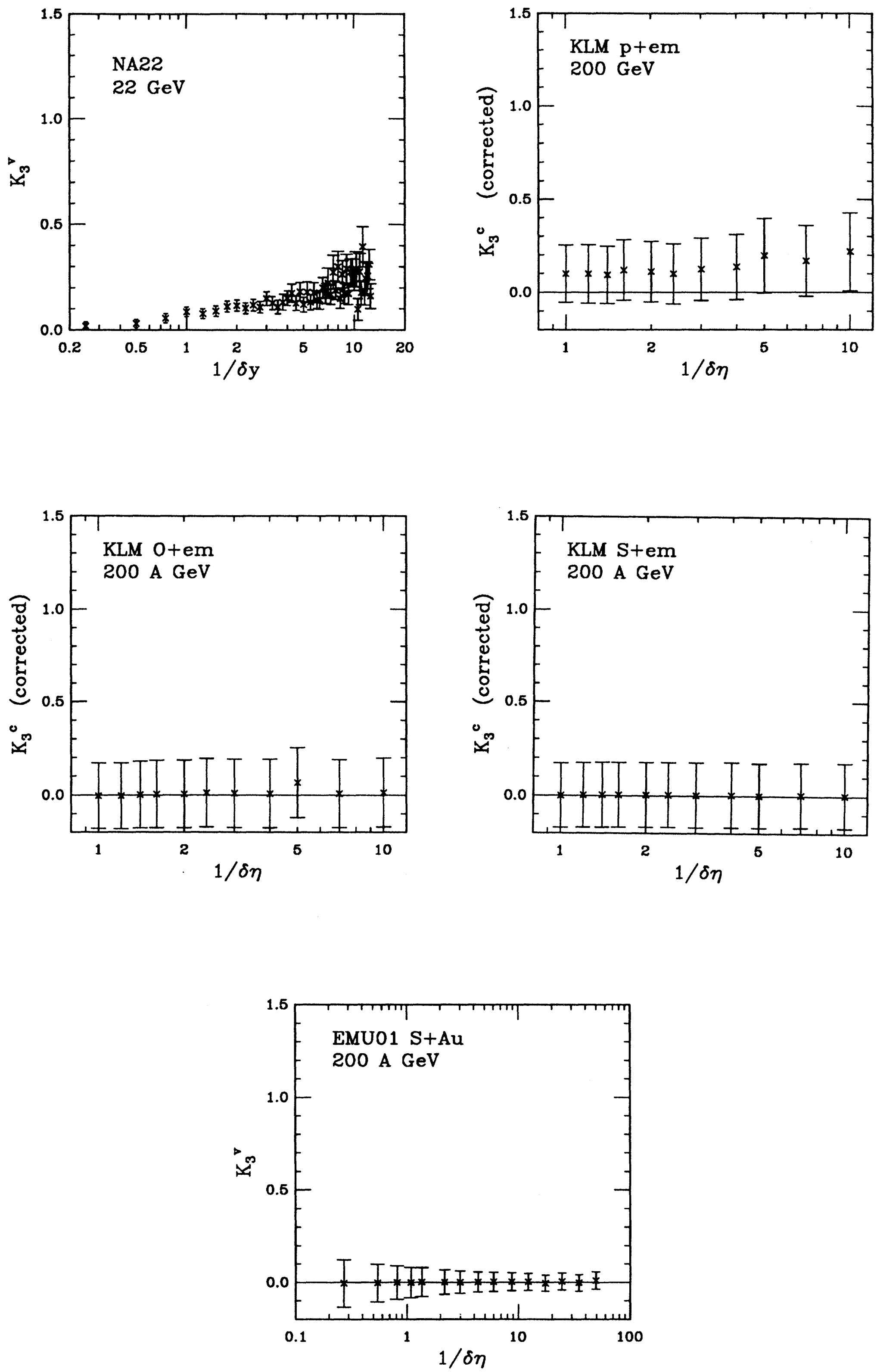

FIG. 2. The cumulant K_3 for NA22 [7], KLM [5] and EMU01 data [8].

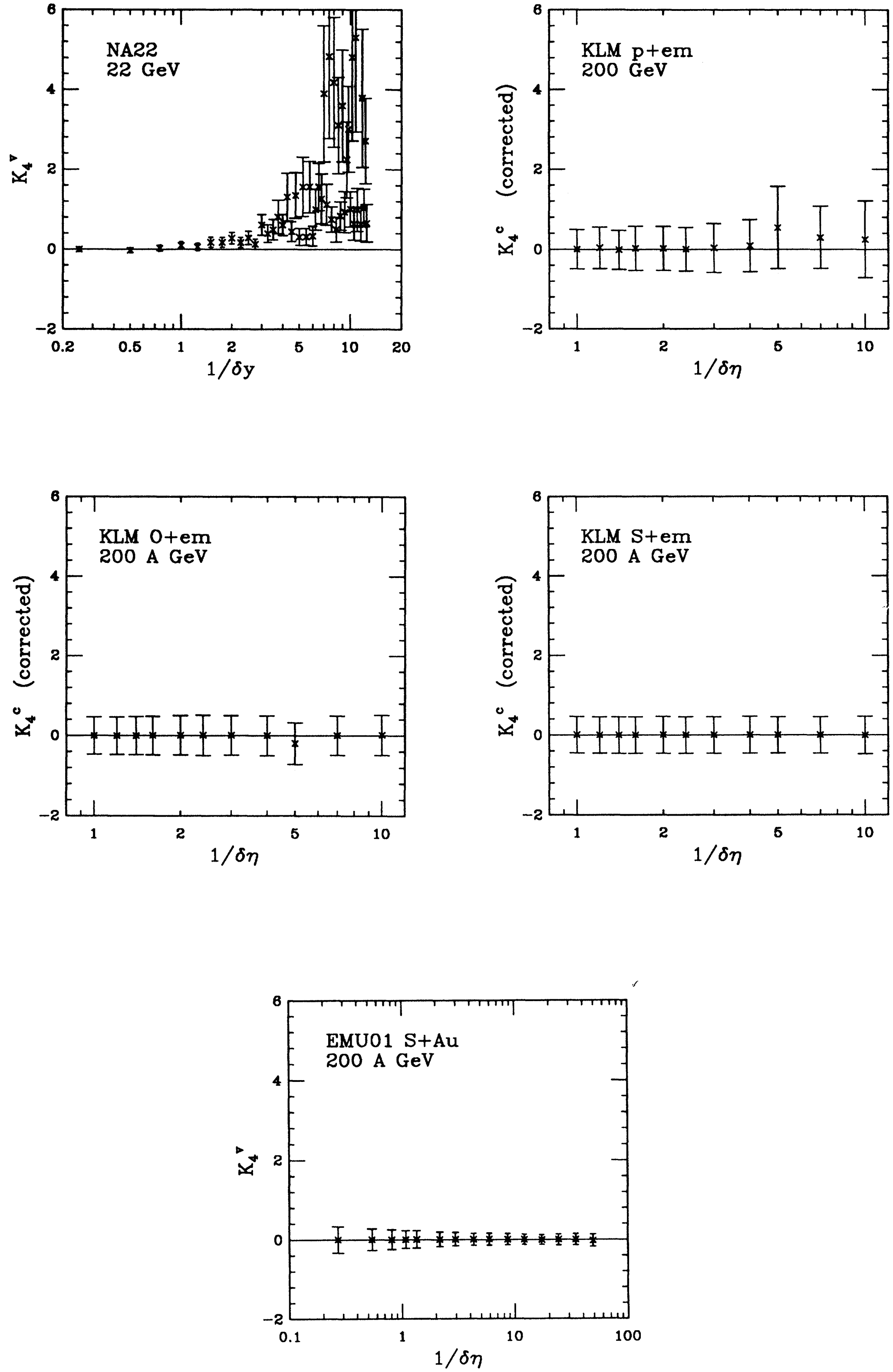

FIG. 3. The cumulant K_4 for NA22 [7], KLM [5] and EMU01 data [8].

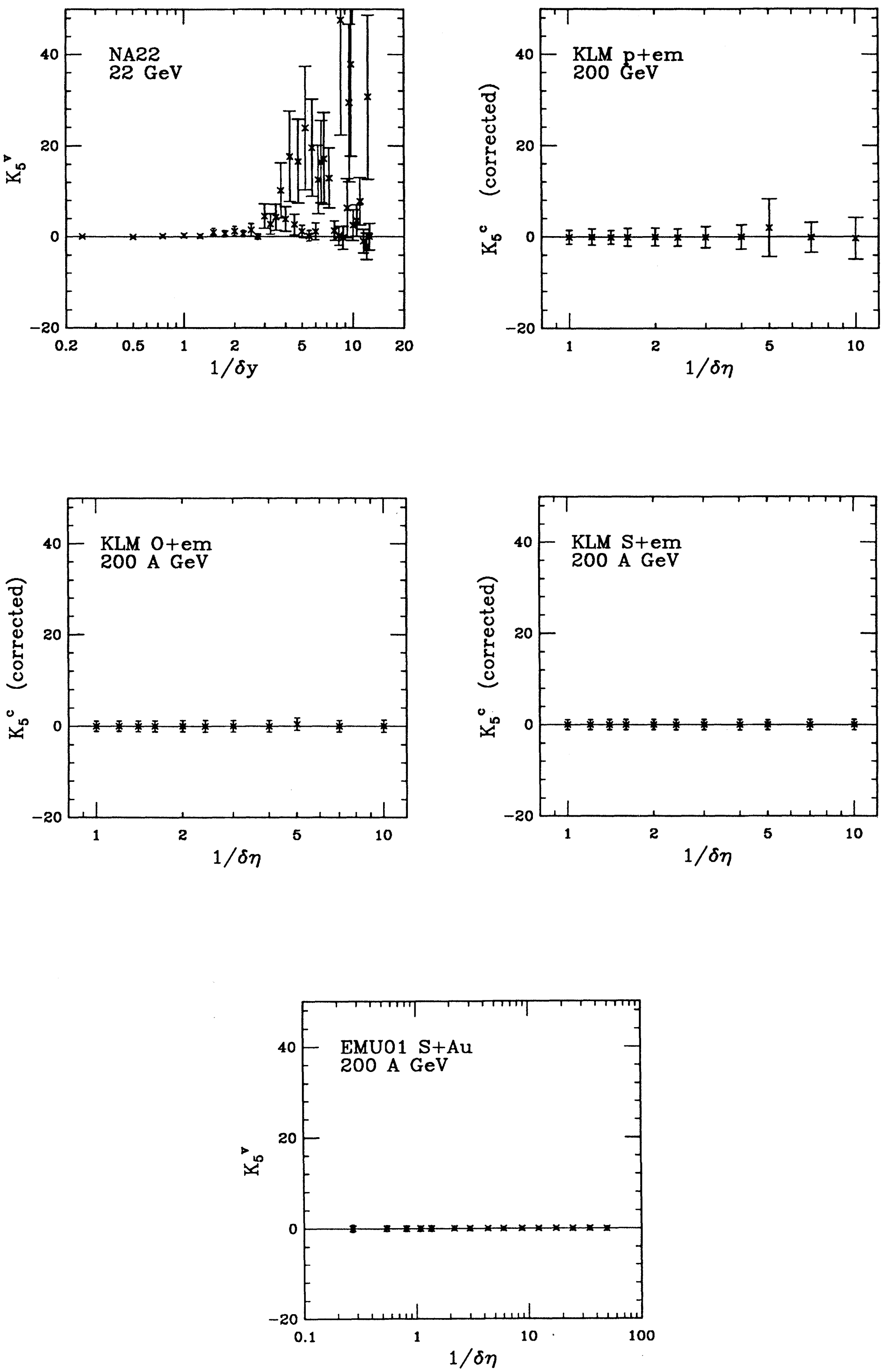

FIG. 4. The cumulant K_5 for NA22 [7], KLM [5] and EMU01 data [8].

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[1] For a review, see *Intermittency in High Energy Collisions*, edited by F. Cooper, R. Hwa, and I. Sarcevic (World Scientific, Singapore, 1991).

[2] A. Białas and R. Peschanski, Nucl. Phys. **B273**, 703 (1986).

[3] P. Carruthers, and I. Sarcevic, Phys. Rev. Lett. **63**, 1562 (1989).

[4] P. Carruthers, H. C. Eggers, and I. Sarcevic, Phys. Lett. B **254**, 258 (1991).

[5] KLM Collaboration, R. Holynski *et al.*, Phys. Rev. Lett. **62**, 733 (1989); Phys. Rev. C **40**, 2449 (1990).

[6] F. Fialkowski, B. Wosiek, and J. Wosiek, Acta Phys. Pol. B **20**, 639 (1989).

[7] NA22 Collaboration, W. Kittel, in *Intermittency in High Energy Collisions* (Ref. 1), p. 83.

[8] EMU01 Collaboration, M. I. Adamovich *et al.*,' Phys. Rev. Lett. **65**, 412 (1990).

[9] H. C. Eggers, P. Carruthers, P. Lipa, and I. Sarcevic, University of Arizona Report No. AZPH-TH/91-15; Phys. Rev. D **44**, 1975 (1991).

[10] P. Carruthers and I. Sarcevic, Phys. Lett. B **189**, 442 (1987).

[11] H. C. Eggers, Ph.D. thesis, University of Arizona (1991).

[12] P. Carruthers and C. C. Shih, Phys. Rev. D **34**, 2710 (1986).

[13] A. Capella, K. Fialkowski, and A. Krzywicki, in *Multiparticle Dynamics, Festschrift for Leon Van Hove,* edited by A. Giovannini and W. Kittel (World Scientific, Singapore, 1990), p. 413; D. Siebert, in *Intermittency in High Energy Collisions* (Ref. 1), p. 259.