MEASUREMENTS OF FLUCTUATIONS IN H.E. SCATTERING USING MID-RAPIDITY E_T AND MULTIPLICITY DISTRIBUTIONS IN NUCLEUS AND NUCLEON COLLISIONS

M. J. TANNENBAUM FOR THE E802 COLLABORATION
Brookhaven National Laboratory, Physics, Bldg. 510c, Upton, NY 11973-5000, USA
E-mail: mjt@bnl.gov

Measurements by the E802 Collaboration of the A-dependence and pseudorapidity-interval ($\delta\eta$) dependence of E_T distributions in a half-azimuth electromagnetic calorimeter are presented for p+Be, p+Au, O+Cu, Si+Au and Au+Au collisions at the BNL-AGS. The issues addressed are whether the shapes of the upper edges of the E_T distributions vary similarly to the the variation in shape with $\delta\eta$ of mid-rapidity charged particle multiplicity distributions and how small a $\delta\eta$ interval would still give a meaningful characterization of the 'nuclear geometry' of a reaction.

1 E_T and Multiplicity distributions at mid-rapidity

Transverse energy measurements in '4π' hadron calorimeters were introduced [1] for the purpose of detecting and studying the hard-scattering of constituents of the proton (discovered at the CERN ISR via high p_T leading particles) by finding localized cores of energy deposition, 'jets', in an unbiased manner. However, the predominant source of transverse energy turned out to be the multiplicity weighted by the $<p_T>$ per particle, $dE_T/d\eta \sim <p_T> \times dn/d\eta$, so that the main utility of E_T distributions in nuclear collisions has been as an analog method of counting the multiplicity of relativistic particles emitted from a reaction to 'characterize' the 'nuclear geometry' (see Fig. 1).

1.1 'Centrality' and percentiles of E_T distributions

At AGS energies, where mid-rapidity is $y_{cm}^{NN} \simeq 1.6 - 1.7$ depending the species, E802/E866 [2] and E814/E877 [3] use E_T in an electromagnetic [2] or hadronic [3] calorimeter to define 'centrality', typically by a certain upper percentile of the distribution (Fig. 1t). The upper tails of the less constrained small aperture mid-rapidity distributions measured by E802/E866 in an EM calorimeter covering $1.3 \leq \eta \leq 2.4$ (and scaled by a factor of 4 in E_T for visual effect) fluctuate more (i.e. have a less steep upper edge) than the more constrained nearly 4π distributions measured by E814/E877 in a hadron calorimeter covering $0.83 \leq \eta \leq 4.7$, *but for the most part the distributions are very similar in shape, and therefore in centrality definition.* Note that for Au+Au, the E_T for

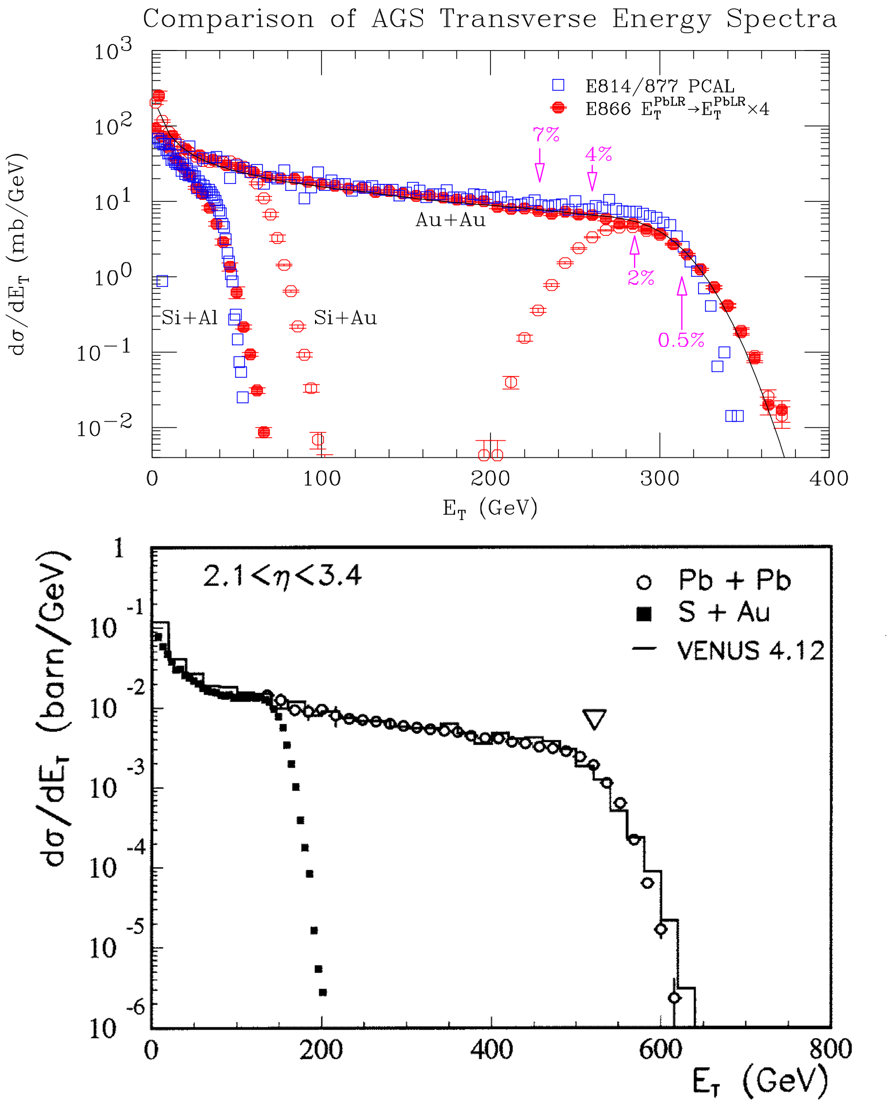

Figure 1: Top(t): AGS measurements—E814/E877 E_T spectra in a full-azimuth hadron calorimeter compared to E802/E866 full azimuth E_T spectra in an EM calorimeter covering a smaller pseudorapidity interval. E802/E866 data include a central Au+Au spectrum defined by the 4 %-ile of the distribution in a Zero Degree Calorimeter (ZCAL). The solid line on the E802/E866 Au+Au data is an empirical calculation (see text). Bottom(b): CERN measurement—NA49 mid-rapidity E_T spectrum in a full-azimuth hadron calorimeter.

a '4%' hard cut is $\sim 20\%$ (!) below the 'knee' of the spectrum, while the E_T spectrum defined by the 4% zero degree calorimeter (ZCAL) cut spans a factor of ~ 2 in E_T. Fig. 1b shows the E_T spectrum measured by NA49 [4] in a hadron calorimeter covering mid-rapidity ($2.1 < \eta < 3.4$) at the higher CERN energy ($y_{cm}^{NN} \simeq 2.9 - 3.0$). These spectra also show the more rounded upper edges, similar to the AGS mid-rapidity distributions. Additionally, the E_T emission in Au+Au (Pb+Pb) relative to Si+Au can be simply read from Fig. 1 and is clearly $\sim 20\%$ larger at AGS energies compared to CERN. This is likely a reflection of the 'stopping' at AGS energies [5] which depresses the energy emission from successive collisions in asymmetric (Si+Au) reactions compared to the symmetric case (Si+Al).

1.2 Simple empirical models are instructive

The solid line shown on the E866 Au+Au spectrum is the result of an empirical 'Wounded projectile nucleon model (WPNM)' in which a B+A spectrum is composed of the sum of 1 to B-fold convolutions of the measured p+Au spectrum weighted according to the 'geometric' probability for 1, 2, ..., B of the projectile nucleons to interact in the target (see Figure 1b). [5] The fact that convolutions of an inclusive p+Au E_T spectrum give an excellent representation of the upper edge of a B+A spectrum—which corresponds to the most central collisions—is another indication of the effect of stopping at AGS beam energies. [5] (The curve on the NA49 data is from a professional cascade model of RHI interactions.)

2 The shapes of multiplicity distributions vs $\delta\eta$—'Intermittency'

It is well known, by now, that the shapes of multiplicity distributions for central collisions of relativistic heavy ions change with the size of the region of phase space in which they are measured—even for relatively 'small' changes of pseudorapidity interval in the range $0.1 \leq \delta\eta \leq 1.0$. This phenomenon, originally developed in terms of the normalized factorial moments of the multiplicity distributions and dubbed 'intermittency', [6] has been explained by the dramatic reduction of the two-particle short-range rapidity correlation length ξ in central RHI collisions to a value, $\xi \sim 0.2$, which is much shorter than the value $\xi \sim 1 - 3$ in nucleon-nucleon collisions, but clearly non-zero. [7]

The shapes of central O+Cu charged multiplicity distributions (see Fig. 2) were well fit by Negative Binomial Distributions (NBD) and simply characterized by the NBD parameter $1/k(\delta\eta)$ which measures the additional fluctuation compared to a Poisson, where $\mu \equiv< n(\delta\eta) >$ is the mean multiplicity on the interval and $\sigma \equiv \sqrt{<n^2> - <n>^2}$ is the standard deviation:

$$\frac{\sigma^2}{\mu^2} = \frac{1}{\mu} + \frac{1}{k(\delta\eta)} \qquad . \tag{1}$$

The shapes of the distributions (Fig. 2) vary from nearly exponential for $\delta\eta = 0.1$ to nearly gaussian for $\delta\eta = 1.0$. One assumes that the same effect, the variation in shape as a function of the pseudorapidity interval, $\delta\eta$, must occur with E_T distributions, but would likely be different in detail.

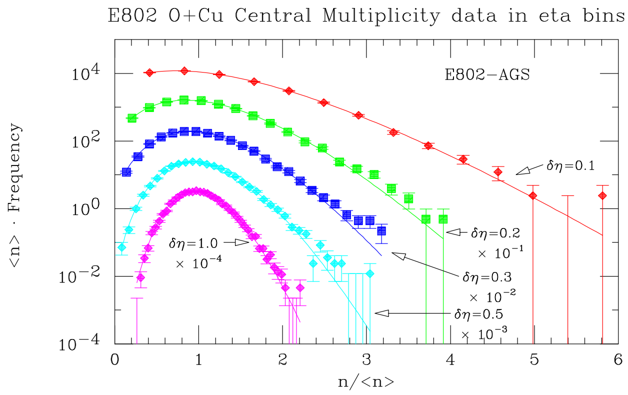

Figure 2: Multiplicity distributions measured in ^{16}O+Cu central collisions as a function of the interval $\delta\eta$ (indicated), scaled by $<n>$ on the interval, for the case when all 16 incident nucleons have interacted as determined by the ZCAL.

For a NBD, the parameter $1/k(\delta\eta)$ (thus the 'shape' of the distribution) is completely determined by the two-particle correlation. The q-fold normalized factorial cumulants from intermittency analyses are nothing other than averages of the q-particle short-range rapidity correlation functions on the interval $\delta\eta$. In detail, the $q = 2$ cumulant measures the weighted average of the normalized two-particle correlation function $R(y_1, y_2)$ on the interval $(0 \leq y_1, y_2 \leq \delta\eta)$:

$$K_2(\delta\eta) = F_2(\delta\eta) - 1 = \frac{\int^{\delta\eta} dy_1 dy_2\, \rho_1(y_1)\rho_1(y_2) R(y_1, y_2)}{\int^{\delta\eta} dy_1 dy_2\, \rho_1(y_1)\rho_1(y_2)} \quad , \tag{2}$$

where K_2 (F_2) is a normalized factorial cumulant (moment), $R(y_1, y_2) = R(0,0)\, e^{-|y_1 - y_2|/\xi}$ is the normalized two-particle short-range rapidity correlation function with exponential correlation length, ξ, and $\rho(y) = dn/dy$ is the inclusive single particle density. [8] The relationship between the intermittency formalism, the NBD parameter and the two-particle correlation becomes clear when $\rho_1(y) = dn/dy$ is constant on the interval, in which case $K_2(\delta\eta)$ is determined by $R(0,0)$ and ξ :

$$K_2(\delta\eta) = F_2(\delta\eta) - 1 = R(0,0) \left\{ 2 \frac{(x - 1 + e^{-x})}{x^2} \right\} \quad , \tag{3}$$

where the quantity in braces is a function, denoted $G(x)$, of the scaled variable $x \equiv \delta\eta/\xi$. For a NBD, $K_q = (q-1)!\, K_2^{q-1}$, so that in a region of constant dn/dy the single parameter $1/k(\delta\eta) = K_2(\delta\eta)$ (Eq. 3) determines <u>all</u> the cumulants.

3 Systematics of Mid-rapidity E_T distributions

Recently, E_T measurements in limited solid angle have become quite popular as a definition 'centrality' in RHI collisions. Hence, it seemed worthwhile to investigate how small a $\delta\eta$ interval would still give a meaningful characterization of the 'nuclear geometry' of a reaction. Also, the simple models noted above have proved useful in understanding the detailed shape of E_T distributions in B+A collisions as a sum of independent collisions weighted according to the 'geometric' probability of the number of total (WNM) or projectile (WPNM) participants in the reaction. If the 'shape' of E_T distributions were controlled by a correlation length and strength which changed with the number of participants *differently* from the effect of random combinations, then these simple models would make no sense, and, in particular, would fail to reproduce the shapes of the upper edges of the spectra.

Systematic measurements of the A dependence of mid-rapidity E_T distributions as a function of the $\delta\eta$ interval were made using the E802 electromagnetic calorimeter (PbGl) which covered half the azimuth with a pseudorapidity acceptance $1.25 \leq \eta \leq 2.50$ (where mid-rapidity for these energies is $y_{cm}^{NN} \simeq 1.6 - 1.7$ depending the species). The E_T distributions (in $\Delta\phi = \pi$) were measured for successively smaller $\delta\eta$ intervals centered (except for the smallest) on $\eta|_0 = 1.86$: $\delta\eta = 1.28$, the full η-acceptance of the calorimeter (actually $1.25 \leq \eta \leq 2.50$); $\delta\eta = 0.96$ $(1.38 \leq \eta \leq 2.34)$; $\delta\eta = 0.64$ $(1.54 \leq \eta \leq 2.18)$; $\delta\eta = 0.32$ $(1.70 \leq \eta \leq 2.02)$; $\delta\eta = 0.16$ $(1.70 \leq \eta \leq 1.86)$. The results for ^{16}O+Cu and for ^{197}Au+Au are shown in in Fig. 3. Evidently, the shapes of the upper edges of E_T distributions change with $\delta\eta$, similarly to Fig. 2.

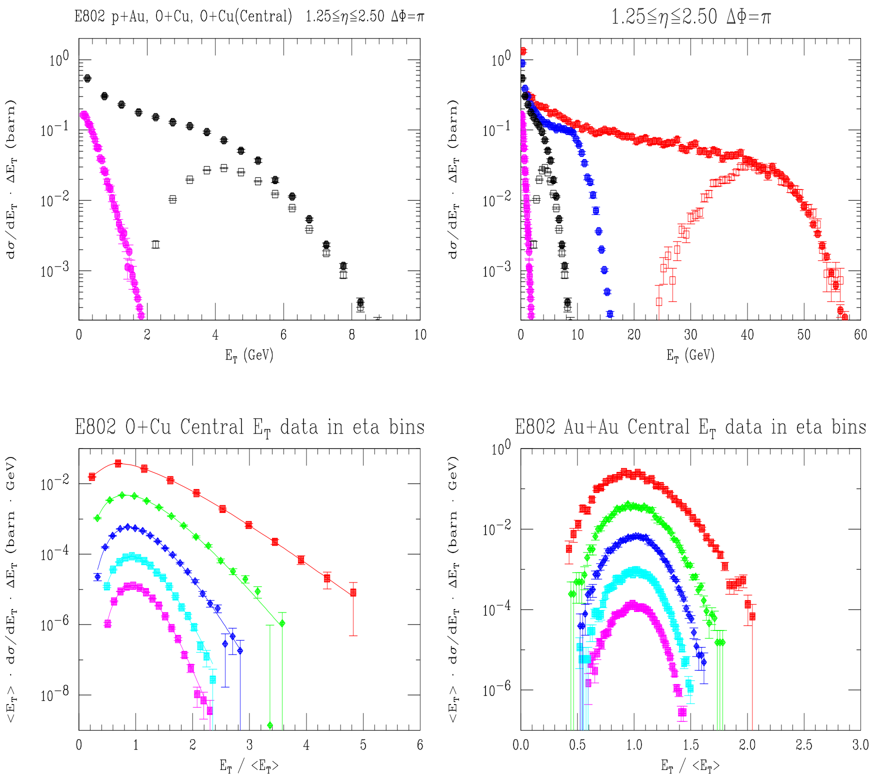

Figure 3: Top: E802 mid-rapidity E_T distributions ($\Delta\phi = \pi$) for the interval $1.25 \leq \eta \leq 2.50$. (Left) p+Au, O+Cu, O+Cu(ZCAL); (Right) previous data, plus Si+Au, Au+Au, Au+Au(ZCAL). Bottom: Central (ZCAL) E_T distributions as a function of $\delta\eta$, normalized by $< E_T >$ on the interval. O+Cu (left), Au+Au (right).

4 Is the WPNM preserved as a function of $\delta\eta$?

A good test of the sensitivity to nuclear geometry as a function of $\delta\eta$ is to see whether the WPNM calculation continues to work. This calculation requires the E_T distributions of p+Au and p+Be as a function of $\delta\eta$, which were obtained. The shapes of the E_T spectra clearly change with $\delta\eta$ for both p+Au and p+Be. However, in each $\delta\eta$ interval, the shapes of the p+Au and p+Be distributions remain essentially *identical* with each other—a further example of mid-rapidity energy stopping at AGS energies. [10] Figure 4 shows that the WPNM calculations for O+Cu, Si+Au, Au+Au continue to work well as $\delta\eta$ is reduced.

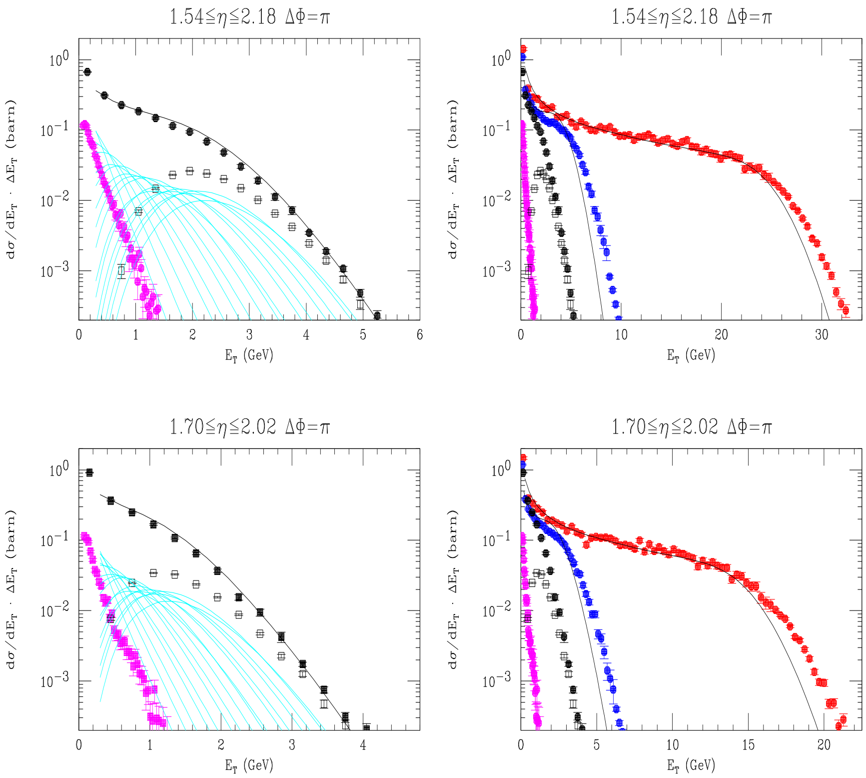

Figure 4: WPNM calculations (lines) for the two smallest $\delta\eta$ intervals for (left) O+Cu, (right) Si+Au, Au+Au. The component E_T spectra corresponding to 1, 2, ...16 independently interacting projectile nucleons are shown for O+Cu. Data shown are (left) p+Au, O+Cu, O+Cu (ZCAL); (right) same data plus Si+Au, Au+Au.

5 CONCLUSIONS

1. The shapes of E_T distributions change with $\delta\eta$ interval.

2. The shape and change of shape with $\delta\eta$ is **Identical** for p+Au and p+Be in E802 for $0.2 \leq \delta\eta \leq 1.25$, around mid-rapidity.

3. The shape (or fluctuation) of multiplicity distributions as parameterized by Normalized Factorial Moments or the NBD parameter $1/k = K_2$ can be related to 2-particle correlations by an elegant theoretical framework; but we could find no such framework for the Gamma distribution param-

eter [2,5] $p(\delta\eta)$ nor for E_T correlations.

4. The Wounded Projectile Nucleon model works remarkably well to relate all the measured spectral shapes of Electromagnetic E_T distributions from p+Au, to O+Cu, to Si+Au to Au+Au at AGS energies for pseudorapidity intervals $\delta\eta$ in the range $0.2 \leq \delta\eta \leq 1.25$.

5. It is clear that E_T distributions in limited regions of $\delta\eta$ provide an excellent characterization of the 'nuclear geometry' of RHI collisions, from which important information about the dynamics can be inferred.

6. At AGS energies, the overall production of particles as observed by mid-rapidity E_T distributions may be interpreted as arising from incoherent nucleon-nucleus collisions, with the further implication that the stopping of the participant nucleons observed in central Au+Au collisions must be related to the identical shapes and evolution of the E_T distributions for p+Au and p+Be. In other words, the 'stopping' should be observable in p+A 'central' collisions.

Acknowledgments

This paper has been authored under contract number DE-AC02-98CH10886 with the U.S. Department of Energy. Accordingly, the U.S. Government retains a non-exclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

References

1. J. D. Bjorken, *Phys. Rev.* D **8**, 4098 (1973)
2. L. Ahle, *et al*, E802 Collaboration, *Phys. Lett.* B **332**, 258 (1994)
3. J. Barrette, *et al*, E814/E877 Collaboration, *Phys. Rev. Lett.* **70**, 2996 (1993)
4. T. Alber, *et al*, NA49 Collaboration, *Phys. Rev. Lett.* **75**, 3814 (1995)
5. T. Abbott, *et al*, E802 Collaboration, *Z. Phys.* C **38**, 35 (1988)
6. For an extensive review of this work, see A. Bialas, *Nucl. Phys.* A **525**, 345c (1991)
7. T. Abbott, *et al*, E802 Collaboration, *Phys. Rev.* C **52**, 2663 (1995)
8. Detailed citations are not reasonable here. See the following reference [9] for more complete citations.
9. M. J. Tannenbaum, *Phys. Lett.* B **347**, 431 (1995)
10. T. Abbott, *et al*, E802 Collaboration, *Phys. Rev.* C **45**, 2933 (1992)