Systematics of Mid-rapidity E_T distributions from p+Be to Au+Au at AGS Energies

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In the period 1986-1992, the E802 Collaboration at the BNL-AGS made systematic measurements of transverse energy (E_T) emission in an electromagnetic calorimeter (PbGl) which covered the pseudo-rapidity interval $1.25 \leq \eta \leq 2.50$ and half the azimuth (where mid-rapidity for these energies is $y_{cm}^{NN} \simeq 1.6 - 1.7$ depending the species). The other half of the azimuth was occupied by a 25 msr magnetic spectrometer with full particle identification. Runs were also taken with two different **full-azimuth** configurations of the PbGl, covering $1.25 \leq \eta \leq 2.44$, and also $1.3 \leq \eta \leq 2.4$. It was noticed that the shapes of the upper edges of the E_T distributions, as represented for example by the p parameter in a gamma distribution fit, seemed to vary with the solid angle of the configuration. To systematically investigate this effect, the A-dependence and pseudorapidity-interval ($\delta\eta$) dependence of E_T distributions in the half-azimuth electromagnetic calorimeter were measured for p+Be, p+Au, O+Cu, Si+Au and Au+Au collisions at AGS energies. These will be presented and discussed.

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E802/E859/E866 Midrapidity E_T Measurements

♡ $E_T \equiv \sum_{\text{photons}} E_\gamma \, \sin\theta \;\; + \sum_{\text{charged, } \beta \geq 0.8} (0.45 \text{ GeV}) \times \sin\theta$

♡ The measure is precise but not accurate.

E_T and Multiplicity Distributions

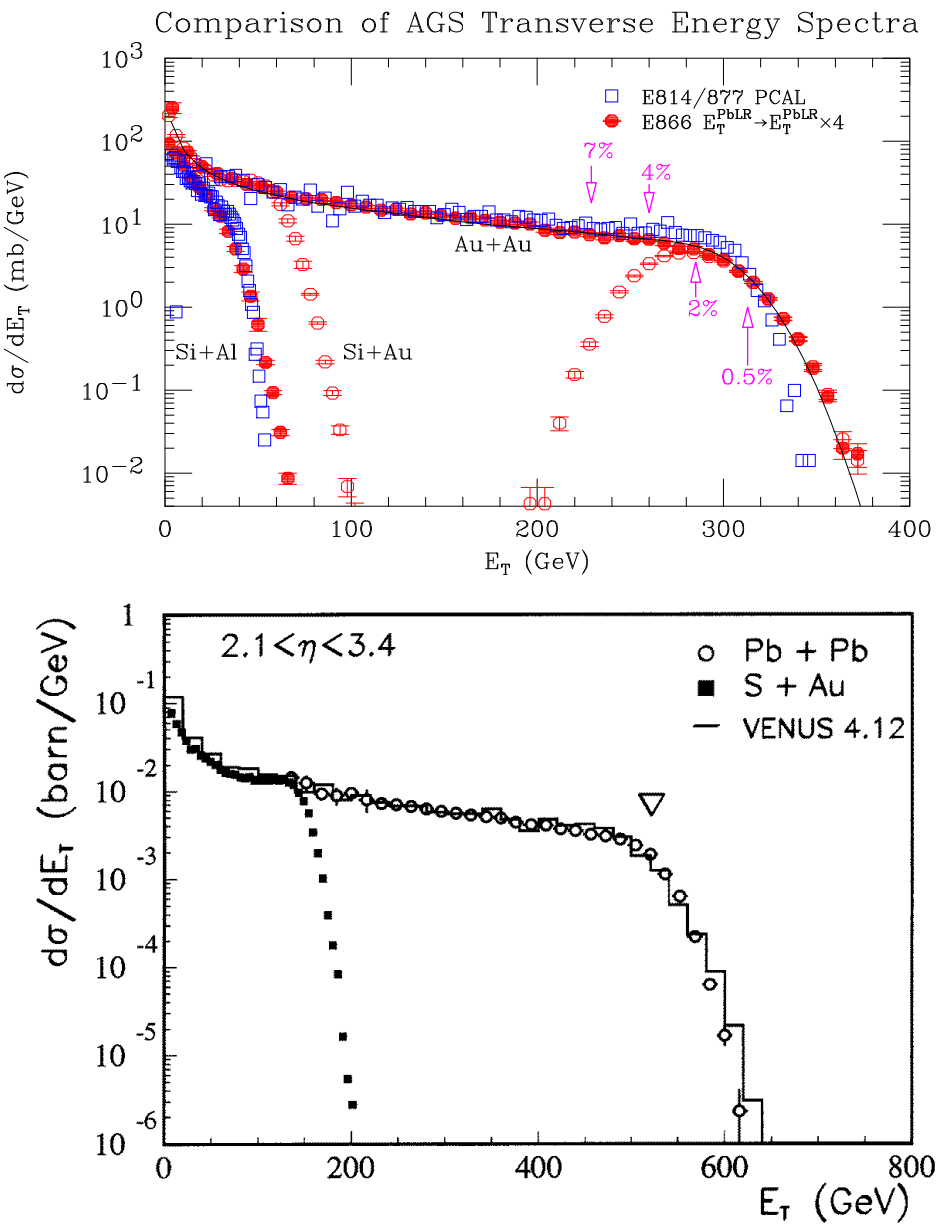


Figure 1: Top(t): AGS measurements—E814/E877 E_T spectra in a full-azimuth hadron calorimeter compared to E802/E866 full azimuth E_T spectra in an EM calorimeter covering a smaller pseudorapidity interval. E802/E866 data include a central Au+Au spectrum defined by the 4 %-ile of the distribution in a 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.

'Centrality' and percentiles of E_T distributions

♡ At the AGS E802/E866 and E814/E877 use E_T in an Electromagnetic or hadronic calorimeter to define 'centrality', typically by a certain upper percentile of the distribution.

♡ The less constrained 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 than the more constrained 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.

♡ The E_T spectra measured by NA49 in a mid-rapidity hadron calorimeter at CERN show the more rounded upper edges, similar to the AGS mid-rapidity distributions.

♡ 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 which depresses the energy emission from successive collisions in asymmetric (Si+Au) reactions compared to the symmetric case (Si+Al).

INTERMITTENCY isn't CHAOS

♡ 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', 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.

♡ The weakened, but finite, short-range rapidity correlations for central RHI collisions had been predicted: The chance of getting two hadrons from the same elementary collision decreases like the number of collisions, so the standard hadron short-range correlations vanish, but the quantum-mechanical Bose-Einstein correlations remain. However, the fact that the rapidity correlation length from B-E interference was so short $\xi_y = 0.19 \pm 0.03$ was not appreciated until demonstrated recently by E802 (PRC56,1544) in agreement with the multiplicity shape analysis.

♡ 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 in calorimeters.

E802 O+Cu Central Multiplicity Distributions vs. $\delta\eta$

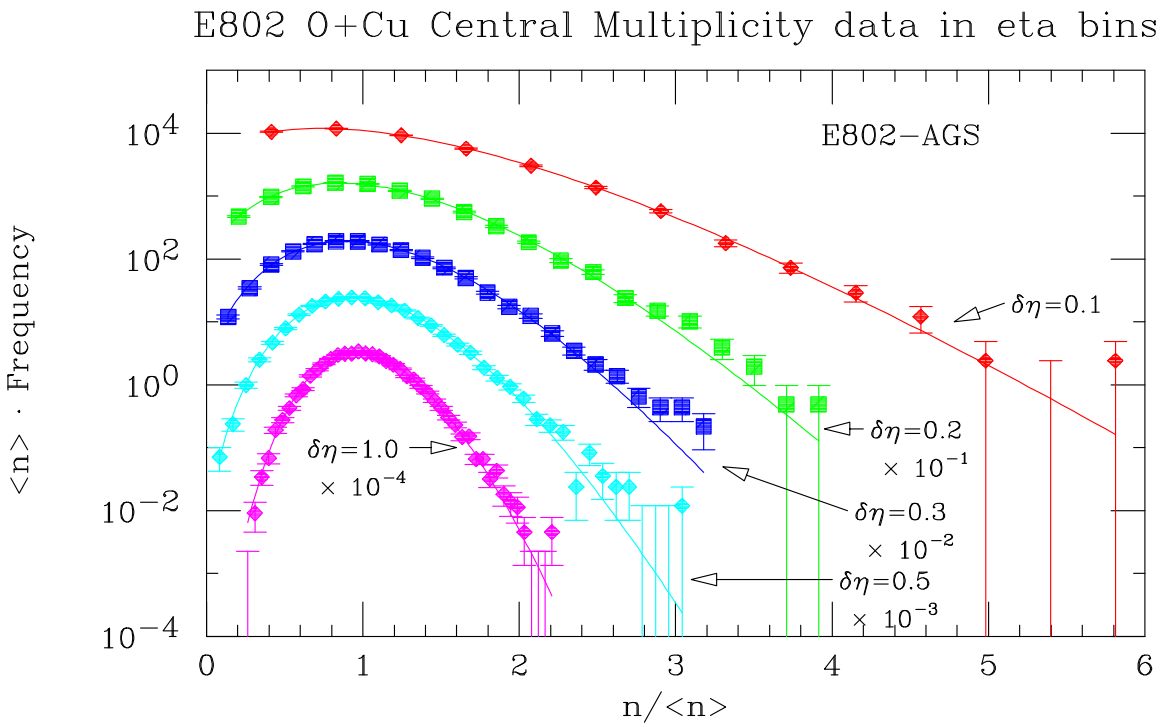


Figure 2: Multiplicity distributions measured in ^{16}O+Cu central collisions as a function of the interval $\delta\eta$ (indicated), scaled by $< n >$ on the interval, for the case when all 16 incident nucleons have interacted as determined by the ZCAL.

♡ The shape of the charged multiplicity distribution varies from nearly exponential for $\delta\eta = 0.1$ to nearly gaussian for $\delta\eta = 1.0$.

♡ The shape of multiplicity distributions as parameterized by Normalized Factorial Cumulants $K_2(\delta\eta)$ or the NBD parameter $1/k = K_2$ is determined by 2-particle correlations in an elegant theoretical framework.

Distributions, Factorial Moments, Cumulants and the Two-Particle Rapidity Correlation

- In short-range rapidity (or pseudo-rapidity) correlation analyses, the normalized two-particle correlation function is usually taken as an exponential:

$$R_2(y_1, y_2) = \frac{\rho_2(y_1, y_2)}{\rho_1(y_1)\rho_1(y_2)} - 1 = R(0,0)\, e^{-|y_1 - y_2|/\xi} \quad , \tag{1}$$

  where $\rho_1(y)$ and $\rho_2(y_1, y_2)$ are the inclusive densities for a single particle (at rapidity y) or 2 particles (at rapidities y_1 and y_2), and ξ is the two-particle short-range rapidity correlation length.

- The two-particle normalized factorial moment (cumulant), F_2 (K_2), is nothing other than the integral of the two-particle correlation function on the interval:

$$K_2(\delta\eta) = F_2(\delta\eta) - 1 = \frac{\int^{\delta\eta} dy_1 dy_2\, \rho_1(y_1)\rho_1(y_2) R_2(y_1, y_2)}{\int^{\delta\eta} dy_1 dy_2\, \rho_1(y_1)\rho_1(y_2)} \quad . \tag{2}$$

- The integrand in the numerator, is the Mueller correlation function, $\mathrm{C}_2(y_1, y_2) = \rho_1(y_1)\rho_1(y_2)R_2(y_1, y_2) = \rho_2(y_1, y_2) - \rho_1(y_1)\rho_1(y_2)$, which is used in the discussion of conventional short-range correlations in multiparticle physics.The denominator of Eq. 2 is simply $<n(\delta\eta)>^2$, the square of the mean multiplicity on the interval.

- For the case of a NBD, $K_2(\delta\eta) = 1/k(\delta\eta)$.

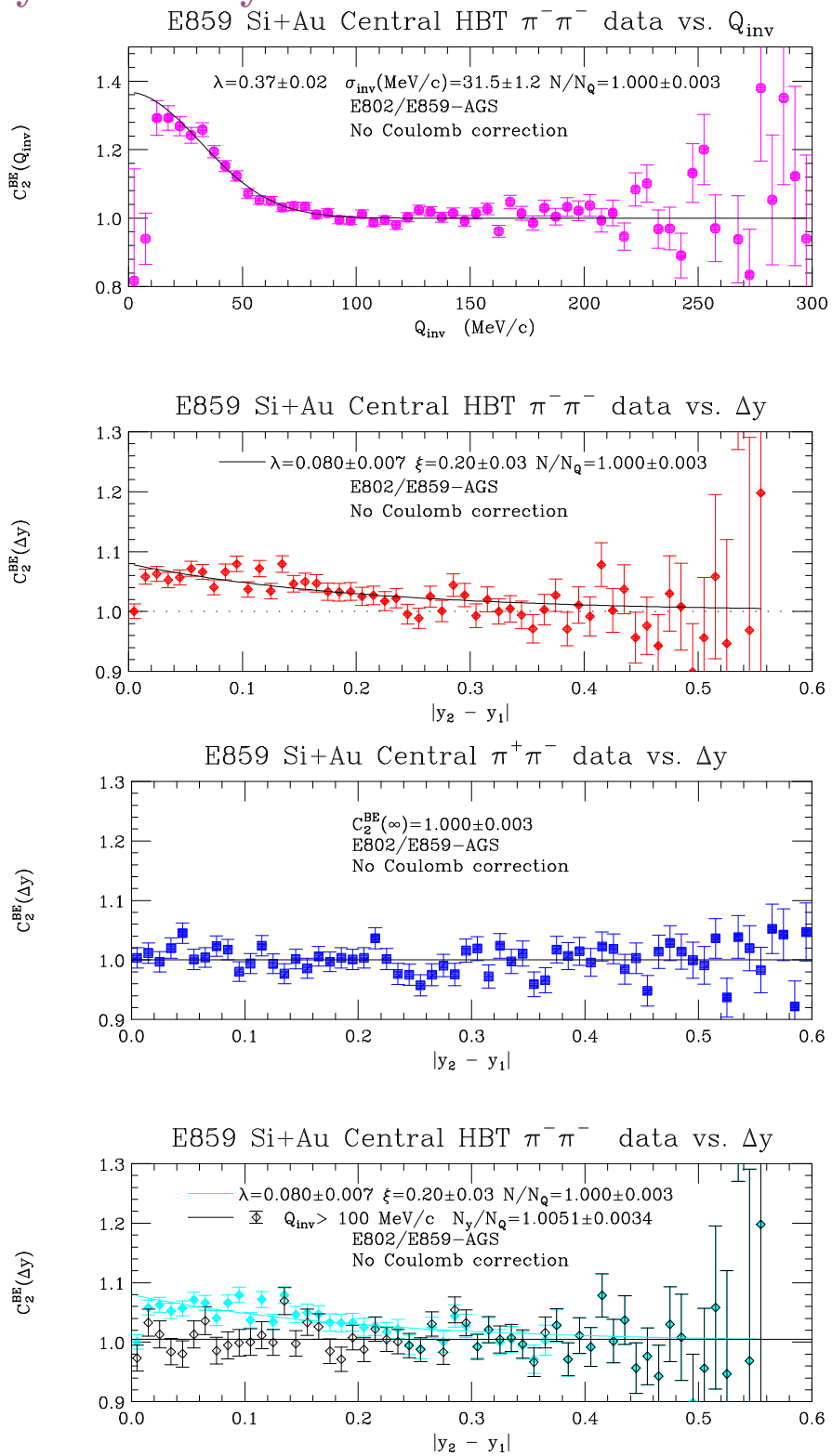
- If the inclusive single particle density, $\rho_1(y) = dn/dy$, is assumed constant on the interval, then the integral can be performed analytically (specifically on the interval $0 \le y_1 \le \delta\eta$, $0 \le y_2 \le \delta\eta$) to obtain the normalized factorial moment $F_2(\delta\eta)$ or normalized factorial cumulant $K_2(\delta\eta)$ in terms of the parameters of Eq. 1:

$$K_2(\delta\eta) = R(0,0)\, G(\delta\eta/\xi) \quad , \tag{3}$$

  where the function $G(x)$ is defined as:

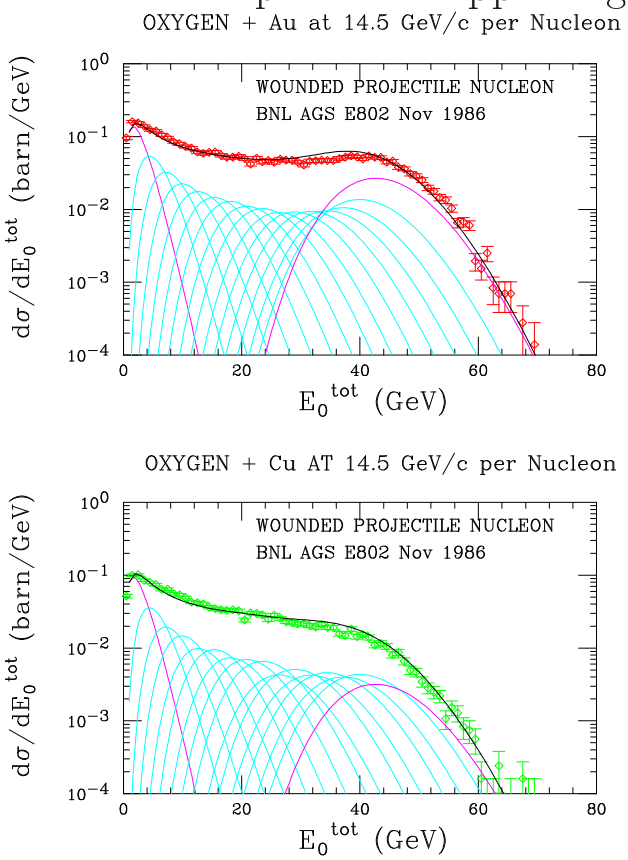
$$G(x) = 2\,\frac{(x - 1 + e^{-x})}{x^2} \quad . \tag{4}$$

Demonstration that the two-pion correlation in rapidity is entirely due to Bose-Einstein correlation



Why study Mid-Rapidity E_T distributions?

♡ As E_T measurements in limited solid angle have recently become quite popular as measurements of 'centrality' of RHI collisions, systematic investigations will be made of the A dependence of such mid-rapidity E_T distributions as a function of the $\delta\eta$ interval. An important issue is that simple models have proved useful in the understanding of the detailed shape of E_T distributions in B+A collisions as a sum of independent p+A collisions weighted according to the 'geometric' probability of the number of total or projectile 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.



Mid-Rapidity E_T distributions vs $\delta\eta$

O+Cu Au+Au

The E_T distributions (in $\Delta\phi = \pi$) were measured for successively smaller $\delta\eta$ intervals centered on $\eta|_0 \sim 1.86$: the full η-acceptance of the calorimeter ($1.25 \leq \eta \leq 2.50$); ($1.38 \leq \eta \leq 2.34$); ($1.54 \leq \eta \leq 2.18$); ($1.70 \leq \eta \leq 2.02$); ($1.70 \leq \eta \leq 1.86$).

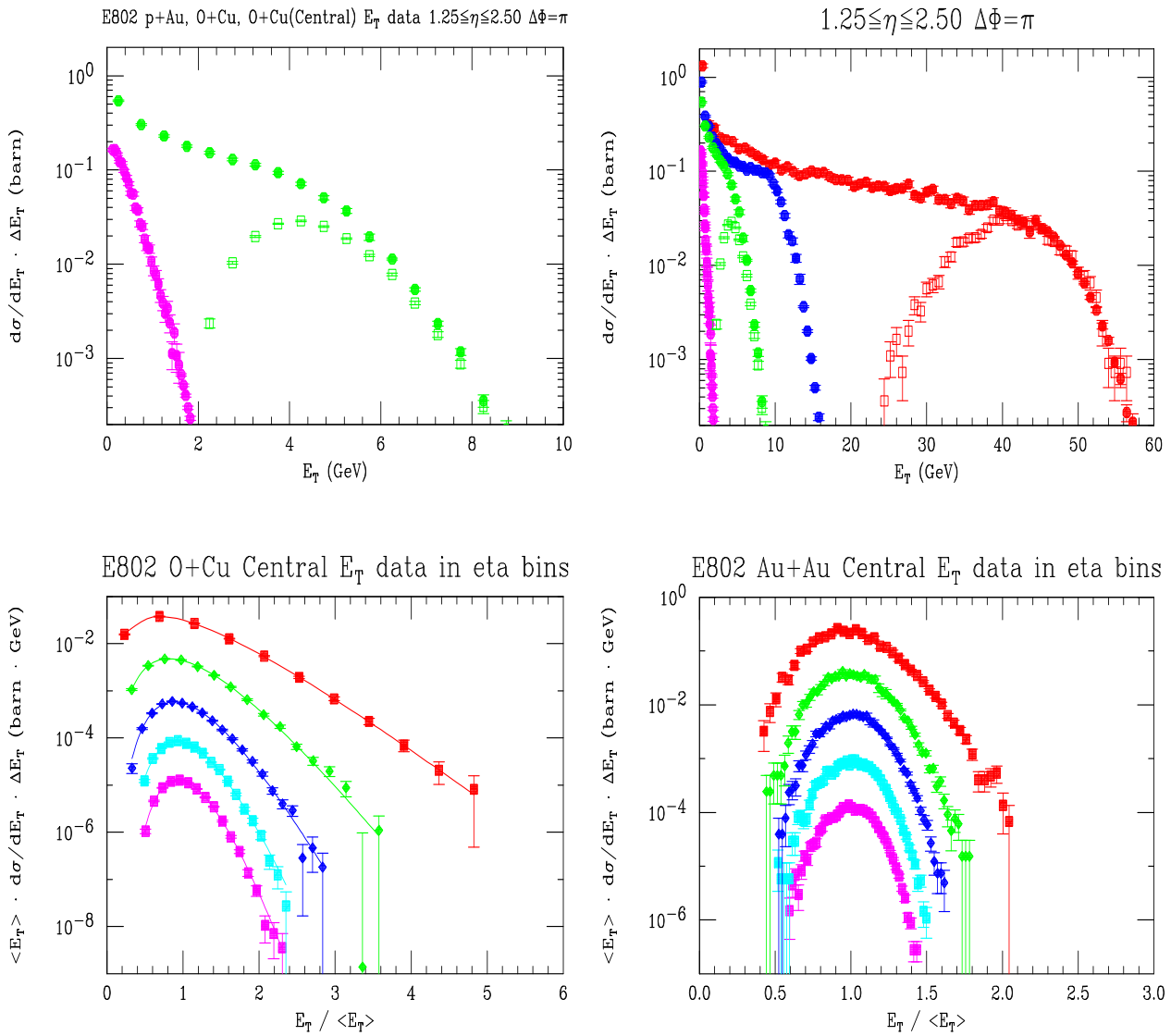


Figure 3: Top: E802 mid-rapidity E_T distributions ($\Delta\phi = \pi$) for the interval $1.25 \leq \eta \leq 2.50$. (Left) p+Au, O+Cu, O+Cu(ZCAL); (Right) previous data, plus Si+Au, Au+Au, Au+Au(ZCAL). Bottom: Central (ZCAL) E_T distributions as a function of $\delta\eta$, normalized by $< E_T >$ on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

Evidently, the shapes of the upper edges of E_T distributions change with $\delta\eta$, similarly to multiplicity.

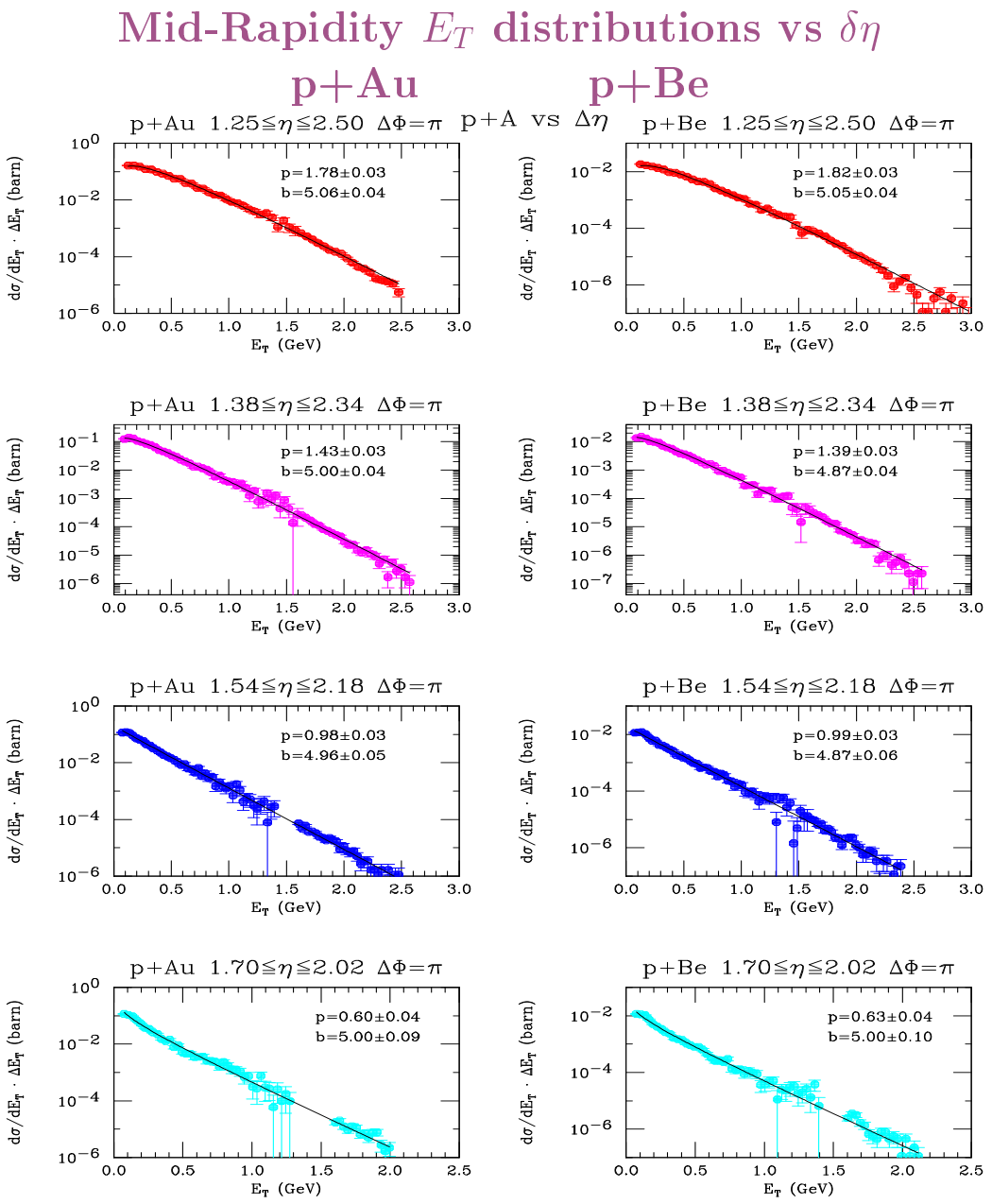


Figure 4: E_T distributions for p+Au (left) and p+Be (right) as a function of decreasing $\delta\eta$ from top to bottom. Adjacent p+Au and p+Be plots have the same $\delta\eta$.

The original E802 measurements showed that the mid-rapidity E_T spectra of p+Au, p+Cu, p+Al and p+Be all exhibit the same shape over roughly 5 decades of cross section—no obvious multiple collisions effects were evident at mid-rapidity for p+A at AGS energies. In the present measurement, as the $\delta\eta$ interval is reduced, the shapes of the E_T spectra clearly change with $\delta\eta$ for both p+Au and p+Be; but in each $\delta\eta$ interval, the shapes of the p+Au and p+Be distributions remain essentially **identical** with each other.

The Wounded Projectile Participant Model Is Preserved as a function of $\delta\eta$

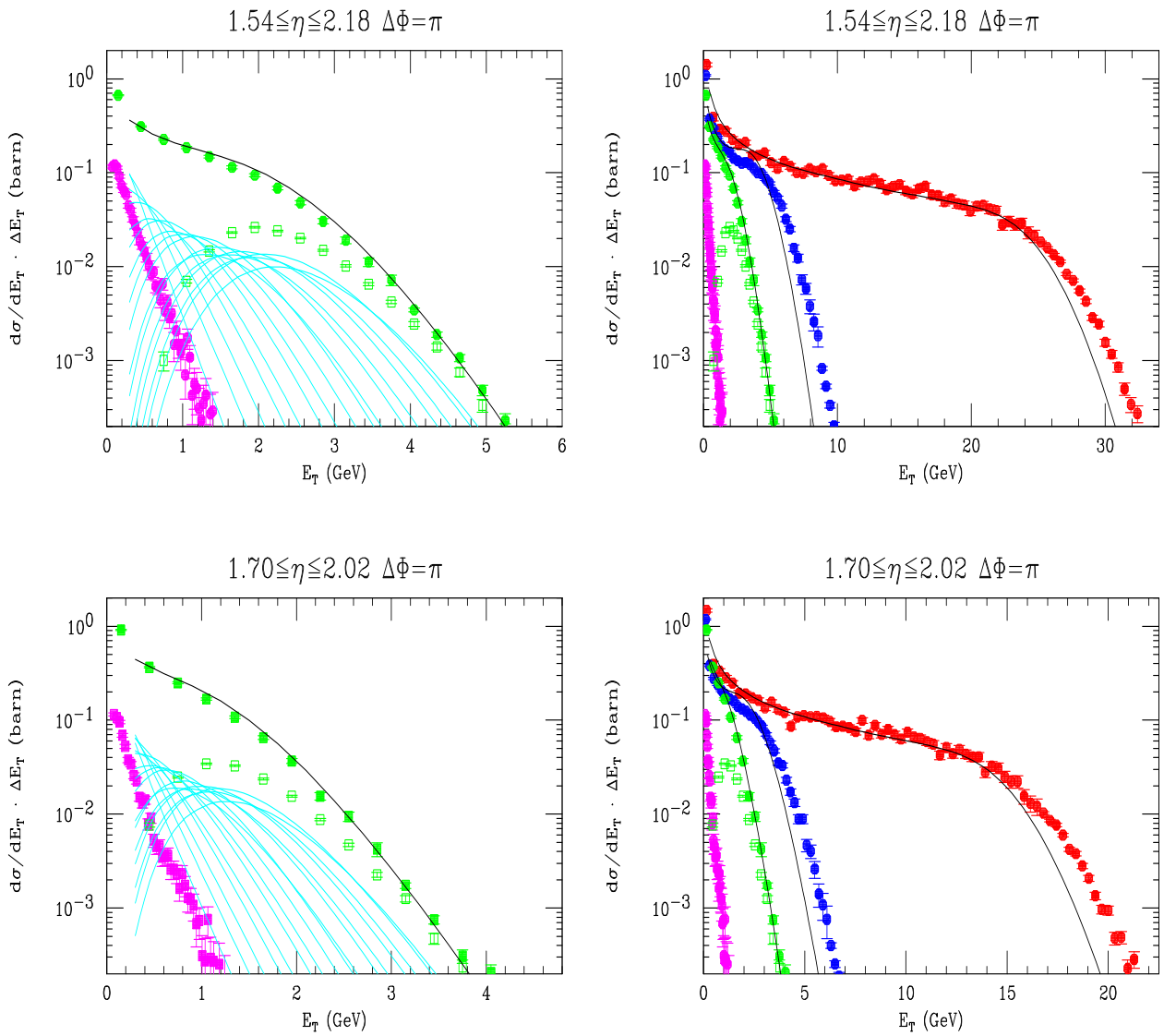
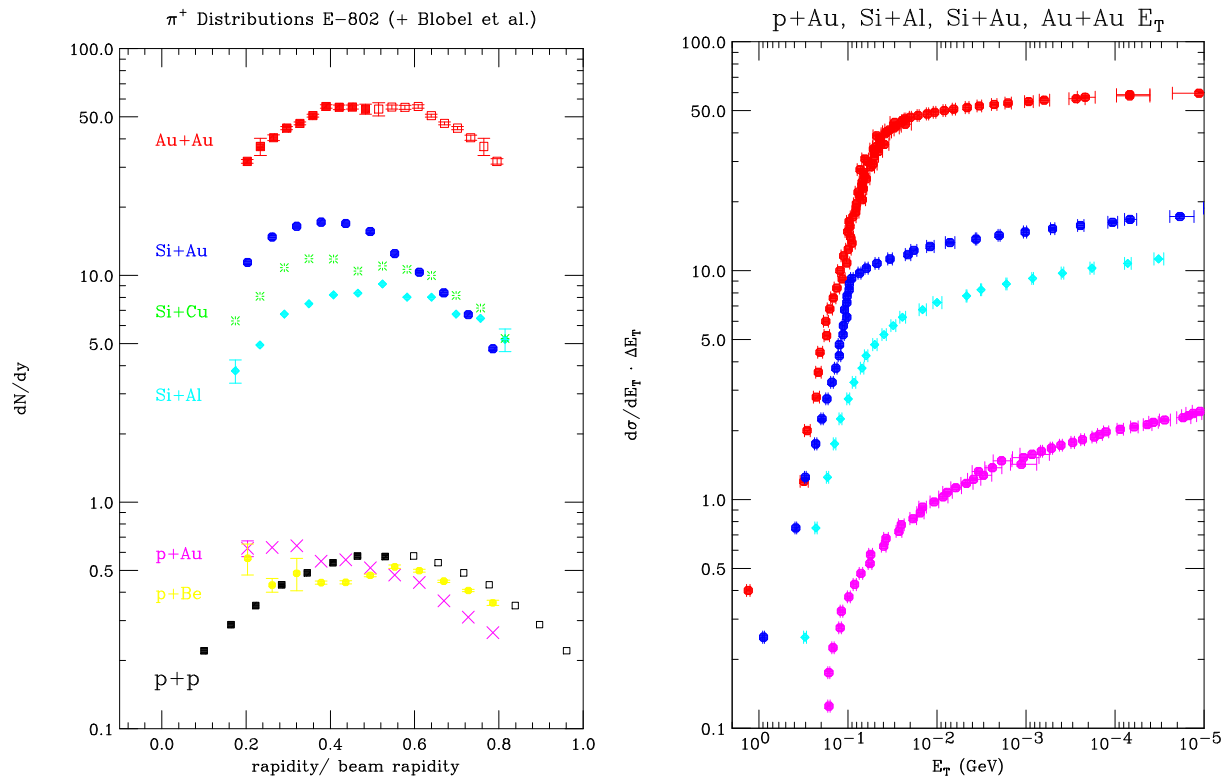


Figure 5: WPNM calculations (lines) for the two smallest $\delta\eta$ intervals for (left) O+Cu, (right) Si+Au, Au+Au. Components are shown for O+Cu. Data shown are (left) p+Au, O+Cu, O+Cu (ZCAL); (right) same data plus Si+Au, Au+Au.

As smaller and smaller $\delta\eta$ intervals are used for the E_T spectra, the probability p_0 for a p+Au reaction to produce zero signal on the interval becomes larger and larger. This effect is easily measured from the ratio of detected cross section in the $\delta\eta$ interval to the inelastic p+Au cross section (1662mb), and must be taken into account when performing the WPNM.

Systematic measurements of dn/dy and E_T in A+A collisions at the AGS (E802...)



On the left, the $dn/dy|_{\pi^+}$ distributions for p+A inclusive and A+A central make it easy to show that Au+Au/p-p∼Au+Au/p+Au=100, much less than 197. Also the p-p or p+Be to p+Au ratios evidently don't follow the wounded nucleon model, since dn/dy doesn't vary at mid rapidity, but it does vary in the beam fragmentation region. The comparison Au+Au/Si+Al is intriguing since the Au+Au/Si+Al data for both dn/dy and E_T (right) are close to the WNM ratio of 7. **However,** from the E_T distributions, it is obvious that the exact value of this ratio depends on the "centrality" cut; since the "shapes" of the distributions vary with A. Thus, a centrality definition using a fixed upper percentile may be too simplistic. The systematics of forward energy distributions may also be subject to complications. The asymmetric Si+Au,Cu collisions show very interesting systematic behavior c.f. Si+Al, but are a problem for a mid-rapidity calorimeter since the maximum in dn/dy moves out of the acceptance region. **What is a reasonable $\delta\eta$ acceptance for an E_T centrality measurement?**

CONCLUSIONS

- Shapes of E_T distributions changes with $\delta\eta$ interval
- The shape $\Gamma(p, b)$ 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.
- 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 parameter $p(\delta\eta)$ nor for E_T correlations.
- 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 $0.2 \leq \delta\eta \leq 1.25$.
- 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.
- 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.