



# Transverse Energy Measurements from the Beam Energy Scan in PHENIX

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## Abstract

Transverse energy distributions at midrapidity have been measured by the PHENIX experiment at the BNL Relativistic Heavy Ion Collider (RHIC) for Au+Au, U+U, Cu+Au, Cu+Cu, <sup>3</sup>He+Au, *d*+Au, and *p*+*p* collisions over a wide energy range from  $\sqrt{s_{NN}} = 7.7$  GeV to  $\sqrt{s_{NN}} = 200$  GeV as a function of centrality. For central Au+Au collisions, it is observed that the midrapidity Bjorken energy density demonstrates a power law behavior from  $\sqrt{s_{NN}} = 7.7$  GeV to  $\sqrt{s_{NN}} = 2.76$  TeV. At a given collision energy, the data presented as a function of  $N_{\text{part}}$  are independent of the size of the collision system. For Au+Au, Cu+Au, and Cu+Cu collisions, the centrality-dependent data are better described by scaling with the number of constituent quark participants than scaling with the number of nucleon participants.

*Keywords:*

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## 1. Introduction

The PHENIX experiment at the BNL Relativistic Heavy Ion Collider (RHIC) has compiled a comprehensive dataset from the years 2000 to 2015 that includes collisions of Au+Au, U+U, Cu+Au, Cu+Cu, <sup>3</sup>He+Au, *d*+Au, and *p*+*p* collisions at a variety of collision energies. This dataset can be exploited to study the dynamics of the colliding system with measurements of transverse energy production at midrapidity,  $dE_T/d\eta$ , as a function of collision energy and centrality. This study is complementary and extends previous studies of dynamics based on charged particle multiplicity production by the PHOBOS experiment [1]. Although PHENIX has also measured charged particle multiplicity [2, 3], only transverse energy measurements will be presented in this article. More details on the PHENIX transverse energy measurements presented here can be found elsewhere [2, 4, 3].

## 2. Energy Dependence of Transverse Energy Production

Figure 1 (left) shows transverse energy production,  $(dE_T/d\eta)/(0.5N_{\text{part}})$ , for central Au+Au and Pb+Pb collisions at midrapidity as a function of  $\sqrt{s_{NN}}$ . Above  $\sqrt{s_{NN}} = 7.7$  GeV, the value of  $(dE_T/d\eta)/(0.5N_{\text{part}})$

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is observed to be well described by a power law,  $(dE_T/d\eta)/(0.5N_{\text{part}}) \propto \sqrt{s_{NN}}^b$ , where the exponent is  $b = 0.428 \pm 0.021$ . These results can also be expressed in terms of the Bjorken energy density [5]

$$\varepsilon_{BJ} = \frac{1}{A_{\perp}\tau} \frac{dE_T}{d\eta} \quad (1)$$

where  $A_{\perp}$  is the transverse overlap area of the nuclei determined from the Glauber model and  $\tau$  is the formation time, typically estimated to be 1 fm/c. Figure 1 (right) shows the Bjorken energy density multiplied by the formation time for central Au+Au and Pb+Pb collisions above  $\sqrt{s_{NN}} = 7.7$  GeV. These data are well described by  $\varepsilon_{BJ}\tau \propto \sqrt{s_{NN}}^b$ , where  $b = 0.422 \pm 0.035$ .

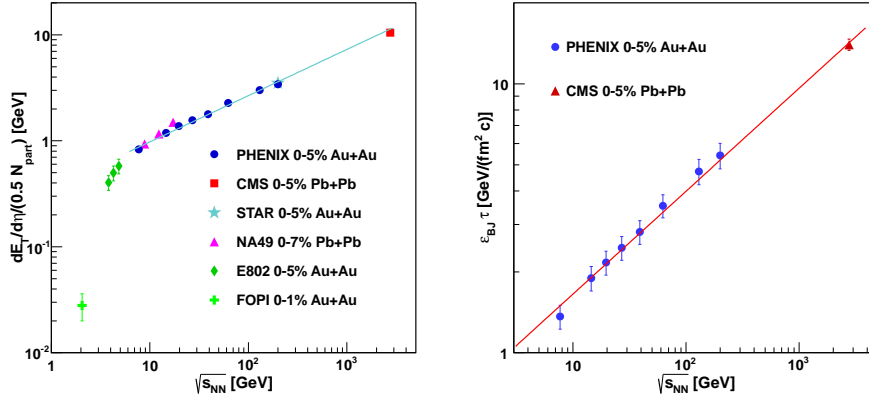


Fig. 1. (Left)  $(dE_T/d\eta)/(0.5N_{\text{part}})$  as a function of  $\sqrt{s_{NN}}$  for central Au+Au and Pb+Pb collisions. In addition to the PHENIX data, data are shown from FOPI [6], E802 [7], NA49 [8], STAR [9], and CMS [10]. The line is a power law fit to the PHENIX data. (Right)  $\varepsilon_{BJ}\tau$  multiplied by  $\tau$  as a function of  $\sqrt{s_{NN}}$  for central Au+Au and Pb+Pb collisions. In addition to the PHENIX data, data are shown from CMS [10]. The line is a power law fit to all of the data points.

### 3. System Size Dependence of Transverse Energy Production

The PHENIX dataset includes Au+Au, Cu+Au, and Cu+Cu collisions at  $\sqrt{s_{NN}} = 200$  GeV along with Au+Au and Cu+Cu collisions at  $\sqrt{s_{NN}} = 62.4$  GeV. This facilitates a study of the system size dependence of transverse energy production. Figure 2 shows the Bjorken energy density multiplied by the formation time as a function of  $N_{\text{part}}$  for these systems. At a given collision energy,  $\varepsilon_{BJ}$  for systems of differing sizes are consistent with each other. This demonstrates that  $\varepsilon_{BJ}$  is independent of the system size at  $\sqrt{s_{NN}} = 200$  and 62.4 GeV.

### 4. Centrality Dependence of Transverse Energy Production

The centrality dependence of  $(dE_T/d\eta)/(0.5N_{\text{part}})$  is typically expressed in terms of the number of nucleon participants,  $N_{\text{part}}$ , as shown in Figure 3 (left) for Au+Au collisions from  $\sqrt{s_{NN}} = 7.7$  to 200 GeV. Note that the midrapidity data increase with increasing  $N_{\text{part}}$  and are not consistent with scaling by the number of nucleon participants in Au+Au collisions from  $\sqrt{s_{NN}} = 200$  GeV all the way down to  $\sqrt{s_{NN}} = 7.7$  GeV. The data can also be examined as a function of centrality expressed as the number of constituent quark participants,  $N_{\text{qp}}$  [11]. This has been estimated using a Glauber model calculation that has been modified to replace nucleons with their constituent quarks [3]. The results are shown in Figure 3 (right), which shows  $(dE_T/d\eta)/(0.5N_{\text{qp}})$  as a function of  $N_{\text{qp}}$  for Au+Au collisions from  $\sqrt{s_{NN}} = 200$  GeV down to 7.7 GeV. For all energies, the data are better described by scaling with  $N_{\text{qp}}$  than scaling with  $N_{\text{part}}$ . This is consistent with

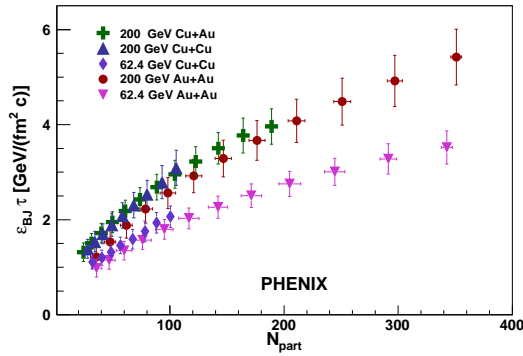


Fig. 2.  $\varepsilon_{BJ}$  as a function of  $\sqrt{s_{NN}}$  for Au+Au, Cu+Au, and Cu+Cu collisions at  $\sqrt{s_{NN}} = 200$  and 62.4 GeV. The error bars represent the statistical and systematic errors.

previous studies of charged particle multiplicity distributions measured by PHOBOS down to  $\sqrt{s_{NN}} = 19.6$  GeV [12]. Figure 4 shows  $(dE_T/d\eta)/(0.5N_{qp})$  as a function of  $N_{qp}$  for Cu+Au and Cu+Cu collisions at  $\sqrt{s_{NN}} = 200$  and 62.4 GeV. The data are also better described by scaling with  $N_{qp}$  for the smaller systems.

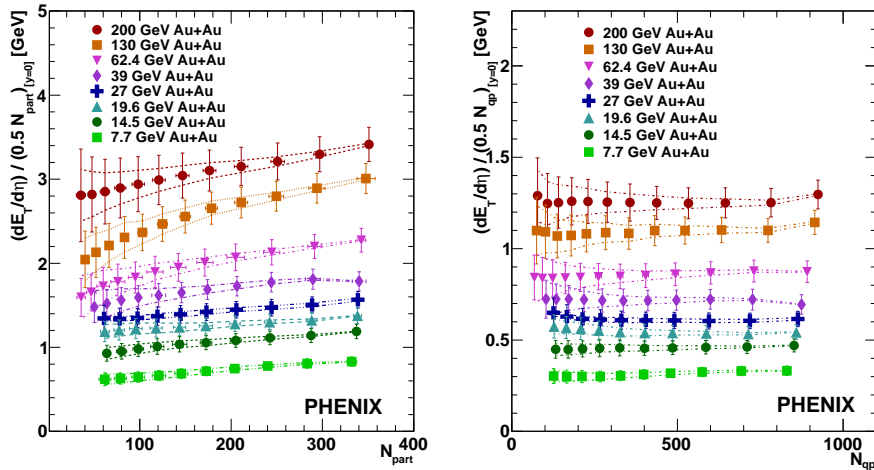


Fig. 3. (Left)  $(dE_T/d\eta)/(0.5N_{part})$  as a function of  $N_{part}$  for Au+Au collisions from  $\sqrt{s_{NN}} = 200$  GeV to 7.7 GeV. (Right)  $(dE_T/d\eta)/(0.5N_{qp})$  as a function of  $N_{qp}$  for Au+Au collisions from  $\sqrt{s_{NN}} = 200$  GeV to 7.7 GeV. For both plots, the lines bounding the points represent the trigger efficiency uncertainty within which the points can be tilted. The error bars represent the remaining statistical and systematic errors.

## 5. Summary

The PHENIX experiment has completed a systematic survey of transverse energy production in a variety of collision systems for  $\sqrt{s_{NN}} = 7.7$  GeV to  $\sqrt{s_{NN}} = 200$  GeV. The Bjorken energy density for central Au+Au collisions at midrapidity is well described by a power law from  $\sqrt{s_{NN}} = 7.7$  GeV up to  $\sqrt{s_{NN}} = 2.76$  TeV. At  $\sqrt{s_{NN}} = 200$  and 62.4 GeV,  $(dE_T/d\eta)/(0.5N_{part})$  presented as a function of  $N_{part}$  is independent of the size of the system. For  $\sqrt{s_{NN}} = 7.7$  to 200 GeV, it is observed that transverse energy production is better

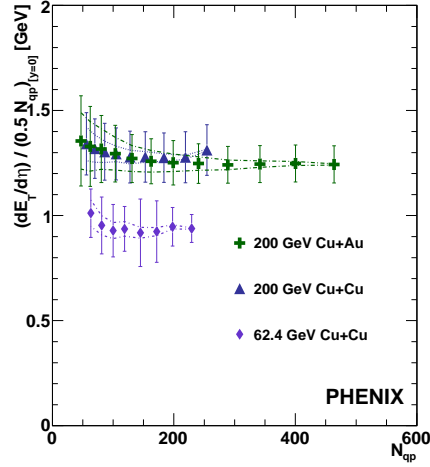


Fig. 4.  $(dE_T/d\eta)/(0.5N_{qp})$  as a function of  $N_{qp}$  for Cu+Au and Cu+Cu collisions for  $\sqrt{s_{NN}} = 200$  GeV and  $\sqrt{s_{NN}} = 62.4$  GeV. The lines bounding the points represent the trigger efficiency uncertainty within which the points can be tilted. The error bars represent the remaining statistical and systematic errors.

described by scaling with respect to the number of constituent quark participants than by the number of nucleon participants.

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