Isolating final state effects in high p_T π^0 production using direct photons in small system collisions with PHENIX

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Abstract. PHENIX observed a 20% suppression in the production of high p_T neutral pions in the most central (0-5%) d+Au collisions at 200 GeV. Through the simultaneous measurement of high p_T direct photons (γ^{dir}) and π^0 production for event samples selected by event activity, the final state effects could be disentangled from cold-nuclear-matter effects and event-selection biases that are inherent in using the standard Glauber model. This isolation of final state effects is achieved by approximating the nuclear modification factor by the double ratio $R_{xA} = (\gamma^{dir}/\pi^0)_{pp}/(\gamma^{dir}/\pi^0)_{xA}$. While the cold-nuclear-matter effects in x+A collisions cancel in the (γ^{dir}/π^0) ratio, the effective number of binary collisions is given by $N_{Coll}^{EXP} = \gamma_{xAu}^{dir}/\gamma_{pp}^{dir}$, which eliminates the dependence on the Glauber model. In addition, many systematic uncertainties cancel in the double ratio.

1 Introduction

In heavy ion collisions, measurements of suppression of hadronic nuclear modification factor in large collision systems, such as Au+Au or Pb+Pb collisions, have been associated with partonic energy loss in the quark-gluon plasma (QGP) [1]. Similarly, the absence of such effects in small system collisions was associated with the lack of final state effects in such systems [2]. However, the observation of hydrodynamic flow in small systems [3], a phenomenon usually associated with the expansion of a hydrodynamical medium when it comes to large collision systems, has raised the possibility of final state effects in small systems, and motivated a systematic study of small systems, by re-investigating the nuclear modification factor in those systems.

The nuclear modification factor (R_{xA}) is obtained as the yield of a given particle in $x + A$ (for this work, x is mainly p, d or ^{3}He) collision ($Y(xA)$), divided by the scaled yield of the same particle in a $p+p$ collision $\left(R_{xA}(p_T) = \frac{Y(xA)}{N_{Coll} \cdot Y(pp)}\right)$. The scaling factor used is the number of binary nucleon-nucleon collisions (N_{Coll}).

The hadronic yields are measured as a function of transverse momenta in a given pseudorapidity range, while the number of binary collisions relates to the multiplicity, and is obtained through the Glauber model [4], with the underlying assumption that an $x + A$ collision is a superposition of N_{Coll} soft binary collisions, which introduces a model dependence to R_{xA}.

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This work details the importance of accounting for this model dependence. It also presents model-independent direct measurements of N_{Coll}^{EXP} and R_{xA} in d+Au collisions, using hard photons.

2 Bias in the centrality determination

In PHENIX, N_{Coll} in $x + A$ is obtained with the charge deposition in the backwards beam-beam-counter (BBC), i.e. in the Au going direction in a d+Au collision, and the use of Glauber model Monte Carlo simulations. This is usually associated also with the impact parameter, as one would naively expect that a central collision (smaller impact parameter) would result in larger event activity. However, as illustrated in Fig. 7 of Ref. [5], the correlation between measurable multiplicity and number of binary collisions (and impact parameter) through the Glauber model is not as strong in small systems as it is in large collision systems.

Furthermore, the assumption that the collisions are all soft in the Glauber model leads to a bias in how centrality is classified. Centrality is classified by the event activity in the BBC, but the presence of a hard scattering event depletes the forwards and backwards event activity while enhancing mid-rapidity activity by the formation of jets or otherwise high p_T particles. This depletion then would lead to some high p_T hadrons coming from central collisions being misidentified as coming from more peripheral collisions, leading to enhancement in peripheral collisions, behavior which was observed in Fig. 10 (a) of Ref. [6]. As described in Ref. [7], with higher p_T particles present at mid-rapidity in the events, the charge deposition on the BBCs is depleted, leading to a bias on the centrality categorization, from central events being classified as peripherals.

This bias due to hard scattering events is not seen in large collision systems, such as Au+Au where the Glauber model has been extensively used. This is due to the fact that the number of interacting nucleons in such collisions is much larger than in the case of small systems. Assuming that the hard scattering occurs on only a single pair of nucleons, the effect is not significant in large systems due to the presence of many other soft events that make up the bulk of the collision. In small systems, however, a single hard scattering makes up a substantial part of the entire event, hence the failure of the Glauber model to describe the event activity from soft collisions.

Further evidence for unaccounted initial state effects on the centrality determination comes from comparing the ratio of the yields of direct photons to neutral pions. Since pions are composed of color charged quarks, it is expected that they would be affected by the formation of a color charged media. Direct photons, however, should not be affected in the same manner. Therefore, the ratio of the yield of those particles should depend on how much media is formed. This can be seen for Au+Au in Fig. 1 (a). In Fig. 1 (b), we can see that for the case of d+Au, the ratio shows no centrality dependence, hence whatever phenomena are affecting the π^0 yield, is equally affecting γ^{dir}, and that cannot be a final state effect, since γ^{dir}s are insensitive to most final state effects, since they do not have any color charge.

3 Direct measure of multiplicity N_{Coll}^{EXP} and $R_{dAu,EXP}^{\pi^0}$

To solve the issue of the centrality bias, and minimize initial state effects, the number of binary collisions is estimated from experimental quantities alone. This is possible under the assumption that the nuclear modification factor for direct photons is unity, which is consistent within uncertainties with previous observations [11]. The number of binary collisions in a x+A system can then be obtained as the ratio of the direct photon yields in the x+A system

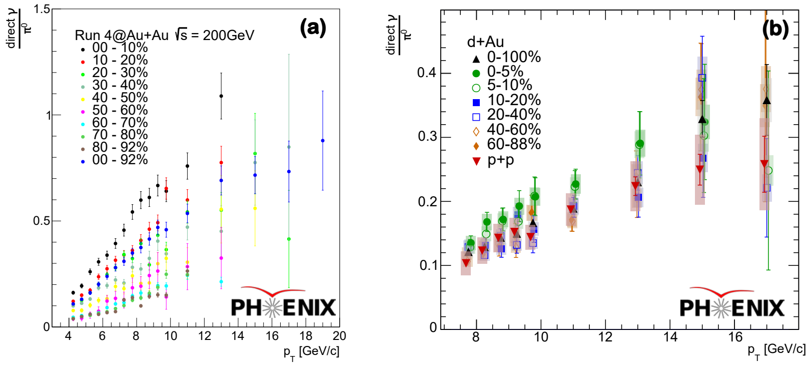

Figure 1. Ratio of the yields of direct photons to neutral pions for Au+Au (a) and d+Au (b). Explanation in text. Data for (a) were taken from Ref. [8] for π^0 and Ref. [9] for γ^{dir}, and can be found in Ref. [10] for (b).

to the yield of direct photons in p+p collisions $\left(N_{Coll}^{EXP} = Y_{xA}^{\gamma^{dir}}(p_T)/Y_{pp}^{\gamma^{dir}}(p_T)\right)$. The nuclear modification factor can then be written as:

$$R_{xA,EXP}^{\pi^0}(p_T) = \frac{Y_{xA}^{\pi^0}(p_T)}{N_{Coll}^{EXP} \cdot Y_{pp}^{\pi^0}(p_T)} = \frac{\left(\gamma^{dir}/\pi^0\right)_{pp}}{\left(\gamma^{dir}/\pi^0\right)_{xA}} \tag{1}$$

This fully experimental measurement of $R_{xA,EXP}^{\pi^0}$ presented in equation 1 has several advantages when it comes to systematic uncertainties: many system dependent uncertainties cancel in the single ratios of γ^{dir}/π^0, such as the uncertainties on the normalization of the spectra, while some that remain, for instance those associated with the π^0 peak extraction, are canceled or reduced by dividing by the same quantity in a different system.

It is then possible to compare the novel N_{Coll}^{EXP} with the one obtained through the Glauber model. We can see in Fig. 2 (a) that the trend presented further confirms the notion of central events being misidentified as peripherals, causing the previously observed enhancement of peripheral R_{xA}, since N_{Coll}^{GL} (the number of binary collisions estimated with the Glauber model) underestimates the number of binary collisions compared to the one obtained through the ratio of direct photons (N_{Coll}^{EXP}). However, one can see that on central events both methods agree, meaning that the previously observed suppression of central events is not due to the bias. The falling trend is still present even after taking into account the systematic uncertainties: even though the values for N_{Coll} seem to agree within uncertainty, the uncertainties are highly correlated between the points, meaning that any shift must apply equally to all points, preserving the deviation.

Using the double ratio from equation 1, the nuclear modification factor no longer exhibits the peripheral enhancement seen in Ref. [6], with the most peripheral events now having $R_{dAu,EXP}^{\pi^0}$ consistent with one at high p_T. The central collisions however, show suppression, with the most central class (0 to 5% centrality) showing up to 20% suppression, with a 4.5σ significance [10], as seen in Fig. 2 (b)

4 Summary and Outlook

By taking advantage of the color blindness of direct photons, we were able to devise a metric for the number of binary collisions and therefore for the nuclear modification purely from ex-

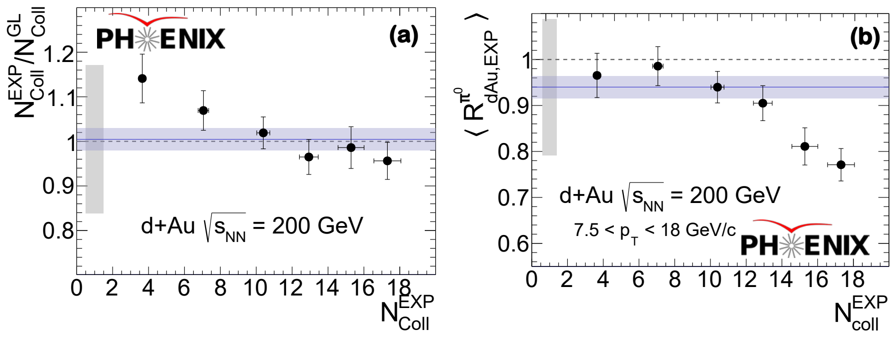

Figure 2. (a) Comparison between N_{Coll} as obtained by the Glauber model (N^{GL}_{Coll}) and by the ratio of direct photons (N^{EXP}_{Coll}). The data used in the figure can be found in Ref. [10]. (b) Average $R^{\pi^0}_{dAu,EXP}$ in the high p_T range (between 7.5 and 18 GeV/c) as a function of event activity. For both figures, the points go from most peripheral (left) to most central (right). In (b) the peripheral points show no enhancement and are consistent with unity within uncertainties. The most central points, however, show significant suppression, hinting at the possibility of final state effects in d+Au collisions at RHIC energies. More information can be found in Ref. [10].

perimentally obtainable quantities. This not only solved the issue of the seemingly nonphysical enhancement of the high p_T peripheral $R^{\pi^0}_{dAu}$, but also demonstrated a strong suppression of the most central events, up to 20% suppression of the most central events, with a 4.5σ significance.

In future work, we shall finish the systematic studies of the small systems, by analyzing the p+Au and ^{3}He+Au datasets (at $\sqrt{s_{NN}}$ = 200 GeV) to verify if this suppression is indeed due to final state effects. If that is the case, one would expect the largest system (^{3}He+Au) to exhibit the strongest suppression, while the smallest (p+Au) the weakest, with the current d+Au system in the middle. The reverse ordering would likely indicate the presence of remaining initial state effects. An analysis of the $p + p$ dataset from the same run as the small systems will also be done, in an effort to reduce the systematic uncertainties on the nuclear modification factor.

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