NUCLEAR MODIFICATION OF HARD SCATTERING PROCESSES IN SMALL SYSTEMS AT PHENIX*

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Collisions of small systems at RHIC exhibit a significant suppression of the nuclear modification factor R_{xA} of jets and high-momentum neutral pions in events with large event activity. This suppression is accompanied by an enhancement of R_{xA} in events with low event activity. Since event activity is commonly interpreted as a measure of the centrality of the collisions, these results call into question any interpretation of the suppression in central collisions that invokes energy loss in a QGP produced small systems. In this contribution, we will compare prompt photon to π^0 production measured by PHENIX in d+Au collision at $\sqrt{s} = 200$ GeV to demonstrate that the apparent centrality dependence is not related to a nuclear modification of hard scattering processes, but likely due to deviations from the proportionality of event activity and centrality in the underlying standard Glauber model calculations. Furthermore, we will use prompt photon production in d+Au relative to $p+p$ collisions to empirically determine the effective number of binary collisions N_{coll} of a given event sample. We find that for all event selections, except for those with the highest event activity, R_{xA} of π^0 is consistent with unity. By comparing p+Au and d+Au collisions, we will investigate the significance of the remaining suppression of high-p_{T} π^0 production in events with high event activity.

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1. Introduction

One of the fundamental questions in relativistic heavy-ion collisions $(A+B)$ is whether particle production is the same as what would be expected from the incoherent superposition of $\mathcal{L}$ nucleon–nucleon $(N+N)$ collisions from the two nuclei, where $\mathcal{L}$ is probabilistic, strongly correlated with the impact parameter b but also depends on the initial state (IS) of

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the relativistic nuclei. The umbrella term "initial state" here encompasses purely geometrical effects, such as fluctuations of the shape of the nucleus and the position of nucleons therein, as well as real physics effects, such as modifications of the parton distribution functions in nuclei (nPDF), gluon saturation, possible changes in $N+N$ cross section, and others. In contrast to IS, fully determined *before* the nuclei collide, the final-state (FS) effects are those processes happening during and because of the collision, and may evolve in time, such as the formation of a Quark–Gluon Plasma (QGP), its transition to a hadron gas (HG), *etc.* Clearly, the experimentally observed particle production is then influenced both by IS and FS. Their joint effect on any type of particle is then characterized by the nuclear modification factor R_{AB} defined as

$$R_{AB}\left(p_{\mathrm{T}}\right) = \frac{\left(\frac{\mathrm{d}^2 N}{\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}\eta}\right)_{AB}}{\langle\mathcal{L}\rangle_{AB} * \left(\frac{\mathrm{d}^2 N}{\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}\eta}\right)_{pp}} = \frac{Y(AB)}{\langle\mathcal{L}\rangle_{AB} * Y(pp)}\,, \tag{1}$$

where p_{T} is the transverse momentum, η is pseudorapidity, $(\frac{\mathrm{d}^2 N}{\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}\eta})_{AB}$ is the double-differential yield of the particle, simplified as $Y(AB)$, with similar notation for $p+p$. Note that R_{AB} does not differentiate between IS and FS effects. Moreover, while $Y(AB)$ is purely an experimental observable, $\mathcal{L}$ is not, it is calculated using some model connecting the impact parameter to some bulk observable such as charged particle multiplicity (N_{ch}) or transverse energy (E_{T}) production. Most often this mapping is based on the Glauber model [1, 2], providing the total number of nucleons interaction at least once (N_{part}) and the total number of binary $N+N$ collisions (N_{coll}). In Eq. (1), the true $\mathcal{L}$ is replaced with the modeled N_{coll}, *i.e.* R_{AB} becomes model-dependent. The model assumes that all $N+N$ collisions are soft (low-momentum exchange). This is true most of the time, but fails in the rare cases when high-p_{T} particles are produced at mid-rapidity. If there are many nucleons on both sides, most $N+N$ collisions will still be average and the Glauber-model-based mapping from event activity (N_{ch}) to centrality (b) will be correct and the calculated N_{coll} is a good approximation of the true $\mathcal{L}$. However, if on the one side, there are only a few nucleons, like in $p/d/^3$He+Au, and one of them participates in a hard scattering, the Glauber mapping might become biased. This might be a possible explanation of earlier results (like [3]), where in $p/d/^3$He+Au at high p_{T} a near-uniform suppression of π^0 is observed in central collisions, and, more significantly, an unexplained enhancement in peripheral collisions is seen when using N_{coll} from the Glauber model. Our goal is to circumvent the model, to find an experimental measure of $\mathcal{L}$ making R_{AB} as defined in Eq. (1) a model-independent quantity, then revisit the nuclear modification in d+Au collisions.

2. Centrality dependence of the direct γ/π^0 ratio at high p_T

Direct photons are all photons that are not coming from the final-state hadron decays. At high $p_{\rm T}$, their primary source is initial hard scattering ($qg \rightarrow q\gamma$) with some small contributions from jet fragmentation [4]. They are color neutral, so virtually immune to FS effects (even in the QGP their mean free path is several hundred fm and increasing with E_γ [5]). In large-on-large ion collisions, their R_{AB} calculated with the Glauber-type $N_{\rm coll}$ is consistent with unity [6, 7], as expected. On the other hand, π^0 in Au+Au collisions is proven to be increasingly suppressed with increasing event activity (centrality) [8, 9]. Therefore, the direct photon over π^0 ratios as a function of $p_{\rm T}$ should line up in distinct, separate bands for different centralities. This can clearly be observed in Fig. 1, left panel. In the right panel, the same ratio is shown for d+Au collisions: within statistical and systematic uncertainties the ratios overlap, they are independent of centrality. Also, they are comparable to the ratios seen in the most peripheral Au+Au collisions. Whatever physics process affects the yield of π^0 at different centralities, affects the direct photons in a similar way — contrary to Au+Au.

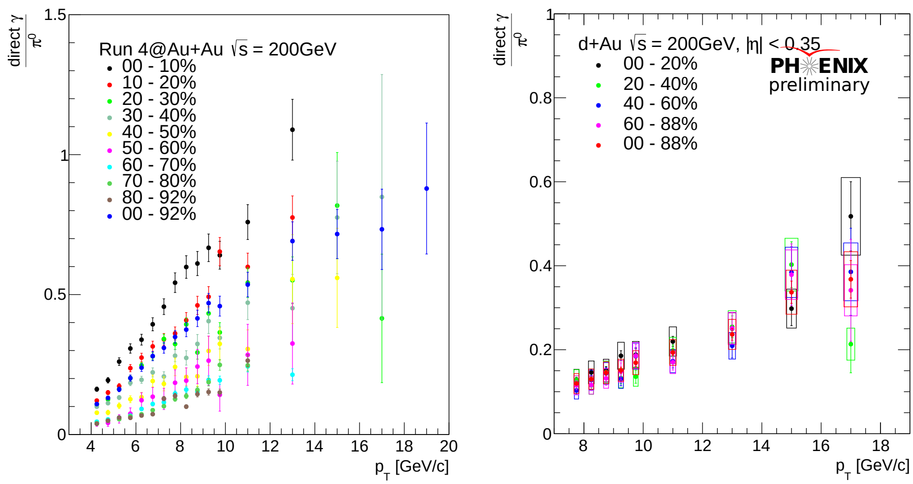

Fig. 1. γ/π^0 ratio for Au+Au (left panel) and d+Au (right panel) collisions for all centrality selections. Au+Au data are from [6, 9]. Note the difference in the $p_{\rm T}$-scale.

3. Redefining the number of collisions with direct photons

As stated above, R_{AB} of direct photons (as in Eq. (1)) is unity in $A+B$ collisions. Turning this around, one can then say that $N_{\rm coll}$ can be *defined experimentally* in the hard-scattering region as the $p_{\rm T}$-dependent ratio of the photon yields in $A+B$ and $p+p$

$$N_{\rm coll}^{\rm EXP}(p_{\rm T}) = \frac{Y_{d{\rm Au}}^{\gamma^{\rm dir}}(p_{\rm T})}{Y_{pp}^{\gamma^{\rm dir}}(p_{\rm T})}\,, \tag{2}$$

and it will be a good approximation of $\mathcal{L}$, devoid of biases due to FS effects. However, if this is true for large-on-large collisions, it is safe to assume that in small-on-large collisions, FS effects cannot be more significant. Therefore, we propose to replace the usual Glauber $N_{\rm coll}$-based $R^{\pi^0}_{d{\rm Au,GL}}$ with the $N_{\rm coll}^{\rm EXP}$-based, purely experimental nuclear modification factor $R^{\pi^0}_{d{\rm Au,EXP}}$ ($p_{\rm T}$-dependence not shown)

$$R^{\pi^0}_{d{\rm Au,EXP}} = \frac{R^{\pi^0}_{d{\rm Au,GL}}}{R^{\gamma^{\rm dir}}_{d{\rm Au,GL}}} = \frac{Y^{\pi^0}_{d{\rm Au}}/Y^{\pi^0}_{pp}}{Y^{\gamma^{\rm dir}}_{d{\rm Au}}/Y^{\gamma^{\rm dir}}_{pp}} = \frac{Y^{\pi^0}_{d{\rm Au}}}{N_{\rm coll}^{\rm EXP}\;Y^{\pi^0}_{pp}}\,. \tag{3}$$

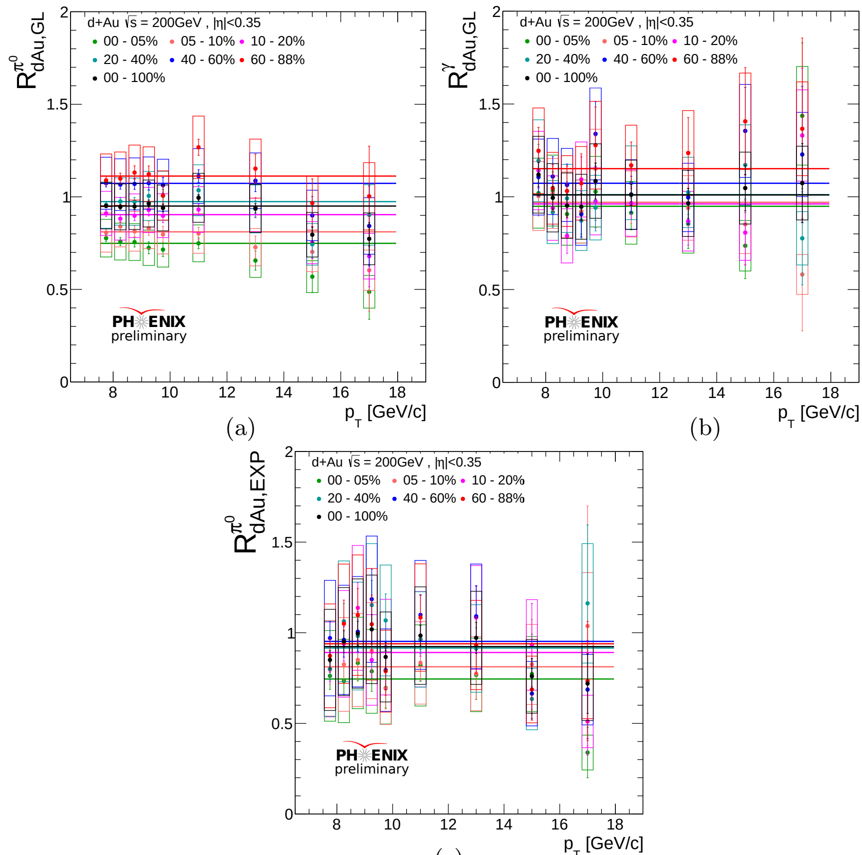

Fig. 2. $R_{d{\rm Au}}$ of π^0 (a) and direct γ (b) obtained from $N_{\rm coll}$ from the Glauber model and $R_{d{\rm Au}}$ of π^0 (c) obtained from $N_{\rm coll}$ derived from experiments.

In Fig. 2, nuclear modification factors are shown using the Glauber $N_{\rm coll}$ (panels (a) and (b)) and with the proposed $N_{\rm coll}^{\rm EXP}$ (panel (c)), all centralities fitted with a constant. With $N_{\rm coll}$, both π^0 (a) and direct photons (b) show a distinct ordering from the most central (smallest R_{AB}) to the most peripheral (largest R_{AB}) collisions. In panel (c), $R^{\pi^0}_{\rm dAu,EXP}$ is shown, where all centralities overlap except for the central (0–5%, 5–10%) bins.

The fitted values, along with their error from panel (c) in Fig. 2 are plotted as a function of $\mathrm{d}N_{\rm ch}/\mathrm{d}\eta$ event activity at mid-rapidity in Fig. 3. The points correspond to the 60–88%, 40–60%, 20–40%, 10–20%, 5–10%, and 0–5% centrality bins.

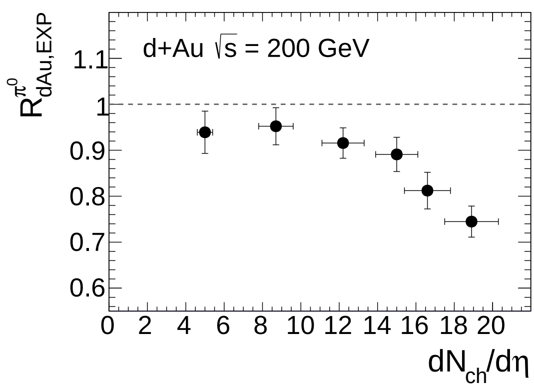

Fig. 3. Average $R^{\pi^0}_{\rm dAu,EXP}$ *versus* event activity $\mathrm{d}N_{\rm ch}/\mathrm{d}\eta$ at mid-rapidity above 8 GeV/c. The points correspond to the 60–88%, 40–60%, 20–40%, 10–20%, 5–10%, and 0–5% centrality bins. A global systematic error of 17.2% is present on all the points plotted.

The systematic uncertainties are small due to cancellations in the double ratio (Eq. (3)). More importantly, there is no identified source of systematic error which has a centrality dependence, that is, the systematic errors are common to all the points, therefore, although the exact position of these points may be shifted up or down by 17.2%, the relative suppression of central value with respect to the peripheral value still remains. For peripheral collisions, $R^{\pi^0}_{\rm dAu,EXP}$ is consistent with unity, but in the most central ones, somewhat surprisingly, a statistically significant suppression is seen. The reasons for that are not clear. Based on these data alone, FS effects — parton energy loss in the small QGP droplets formed — cannot be excluded, nor can be the initial-state effects, or some further, second order bias in the centrality/event activity mapping. PHENIX has collected ^{3}He+Au data in 2014 and a large statistics p+Au dataset in 2015, which are currently analyzed for the same observables. Seeing the evolution of the suppression with projectile size should help to clarify the situation. A larger projectile implies larger QGP droplets, so if the suppression is due to parton energy loss, it should increase from p+Au to ^{3}He+Au. If centrality bias is the reason, it should decrease with projectile size (disappearing in Au+Au), so the suppression should also decrease.

4. Summary

PHENIX has measured simultaneously the yield of high-$p_{\rm T}$ direct photons and π^0 in 200 GeV/c d+Au collisions to clarify the veracity of earlier claims of π^0 suppression in central and enhancement in peripheral collisions. We found that, contrary to the Au+Au case, in d+Au, the direct γ/π^0 ratio is at all $p_{\rm T}$ essentially independent of the centrality selection, albeit with large systematic uncertainties. We introduced a purely experimental measure of the number of binary collisions, $N_{\rm coll}^{\rm EXP}$, and found that with this quantity, the π^0 nuclear modification factors are indeed largely independent of centrality. However, due to the cancellation of many systematic uncertainties, we could show that in the most central collisions, there is still a statistically significant suppression. The reasons for that are unclear, but ongoing analysis of the p+Au and ^{3}He+Au will help understand the underlying physics.

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