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Photon measurements in proton and nucleus collisions at PHENIX

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Abstract

Direct photons provide an excellent probe in studying both the proton and nucleus collisions. The PHENIX measurements of the direct photon-hadron and π^0 -hadron correlations in $p+p$ collisions searches for the breakdown of the QCD factorization. The measurements of the fragmentation functions in $\mathrm{Au}+\mathrm{Au}$ collisions provide an excellent tool to understand the dynamics of the energy loss mechanism in the heavy ion collisions. Furthermore, we summarize the results on the direct photon measurements at low-p_{T} in order to study the thermal radiation in $\mathrm{Au}+\mathrm{Au}$ and $\mathrm{Cu}+\mathrm{Cu}$ collisions at different collision energies.

Keywords
CERN report; direct photon; thermal photon; heavy ion

1 Introduction

The Relativistic Heavy Ion Collider (RHIC) provides a unique capability of colliding polarized protons and light or heavy ion beams. The PHENIX detector records many different particles emerging from RHIC collisions, including photons, electrons, muons, and hadrons. Direct photons are defined as all photons that arise from processes during the collision, rather than from decays of final state hadrons. The biggest challenge in the measurement of direct photons is to distinguish them from the large background of decay photons.

In this paper we summarize the recent PHENIX measurements using direct photons. The first part is focusing on the data collected from $p+p$ collisions at $\sqrt{s}\ = 510$ GeV, which investigates the possible breakdown of the QCD factorization. In the second part we introduce the new results from the highly asymmetric collisions such as $p+\mathrm{Al}$, $p+\mathrm{Au}$ and $d+\mathrm{Au}$ at $\sqrt{s_{NN}}\ = 200$ GeV. In the third part we probe the fragmentation function modification in $\mathrm{Au}+\mathrm{Au}$ collisions and also the thermal photon production from the QGP phase.

2 Proton collisions

There has been much recent activity devoted to the study of parton transverse momentum in high energy hadronic collisions. Observables that are sensitive to parton transverse momentum can potentially provide new insight into the structure of hadrons. The theoretical framework that has been developed [1, 2] to describe parton dynamics in hadrons involves transverse-momentum-dependent (TMD) parton distribution functions (PDFs) and fragmentation functions (FFs). TMD-factorization should be contrasted with the more common collinear factorization theorems, applicable to cases where observables are not sensitive to intrinsic transverse parton momentum.

In $p+p$ collisions the factorization breaking has been predicted at small transverse momentum scale where the non-perturbative objects become correlated [3]. To have sensitivity to possible factorization breaking and modified TMD evolution effects, a particular observable must be sensitive to a small

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scale on the order of Λ_{QCD} and measured over a range of hard scales. The back-to-back dihadron correlation provides a unique probe which is sensitive to the initial and final state transverse momenta [4]. We define the out-of-plane momentum component $p_{out} = p_{\text{T}}{}^{\text{assoc}} \sin\Delta\phi$, where $p_{\text{T}}{}^{\text{assoc}}$ is the transverse momentum of the associated particle and $\Delta\phi$ is the azimuthal angle between the trigger and associated particle. The p_{out} quantifies the acoplanarity of the two-particle pair, and as such it is related to the initial- and final-state k_{T} and j_{T} [4].

In the PHENIX detector we study the both the direct photon-hadron and π^0 -hadron correlation function [4]. For the direct photon correlations, we use the statistical subtraction of the decay photon background and also apply an isolation cut to further remove contributions from the fragmentation photons. Figure 1 shows the p_{out} distribution for direct photon and π^0 triggers. Only the away side hadrons are used in the p_{out} distribution in the $2\pi/3 < \Delta\phi < 4\pi/3$ azimuthal region with respect to the trigger particle. The distributions are fit with a Gaussian function in the small p_{out} region $[-1.1, 1.1]$ and with a Kaplan function ($a(1+p_{out}^2/b)^{-c}$) in the whole range. The power law behavior is generated from hard gluon radiation in the initial state or final state, whereas the Gaussian behavior is generated from the soft k_{T} and j_{T} and is demonstrated in the nearly back-to-back hadrons that are produced around $p_{out} \approx 0$.

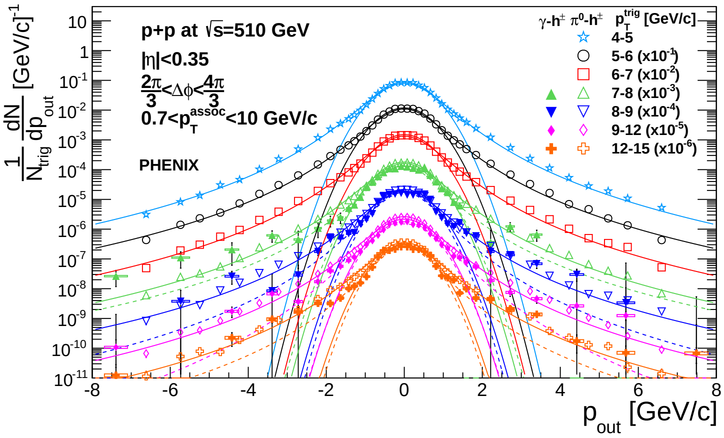

Fig. 1: Per trigger yields of associated charged hadrons as a function of p_{out} [4]. The solid markers correspond to direct $\gamma - h^{\pm}$ and the open markers to the $\pi^0 - h^{\pm}$ correlations. The π^0- and direct photon-triggered distributions are fit with a Gaussian function at small p_{out} and Kaplan function in full range. The 9% total uncertainty on the normalization of the charged hadron yields is not shown.

The left panel in Figure 2 shows the extracted widths from the Gaussian fit for the direct photon- and π^0 -hadron correlations as a function of the $p_{\text{T}}{}^{\text{trig}}$. The systematic uncertainties were calculated by adjusting the Gaussian fit range by +/- 0.15 GeV/c and they are combined with the statistical uncertainties in quadrature. The extracted widths in both the direct photon-hadron and π^0 -hadron correlations are decreasing towards larger $p_{\text{T}}{}^{\text{trig}}$ values. The decreasing trend is opposite from the one expected from TMD factorization [5], which predicts an increasing trend and has been shown in phenomenological analyses of Drell-Yan and SIDIS data [6]. PYTHIA [7] was used to compare the widths, and the decreasing trend was reproduced by the simulations. This is surprising since PYTHIA does not consider explicit factorization breaking. However, it does include the initial and final-state interactions which could be indirectly describing the effects of factorization breaking.

3 Nucleus collisions

The primary focus on the nucleus-nucleus collisions at RHIC collider is to create and study the Quark Gluon Plasma (QGP) [8]. The QGP is a fundamentally new state of matter where the temperature is so high that the quarks and gluons are deconfined. Photons are an excellent probe of this hot and dense, strongly interacting matter as they do not participate in the strong interaction and they leave the matter

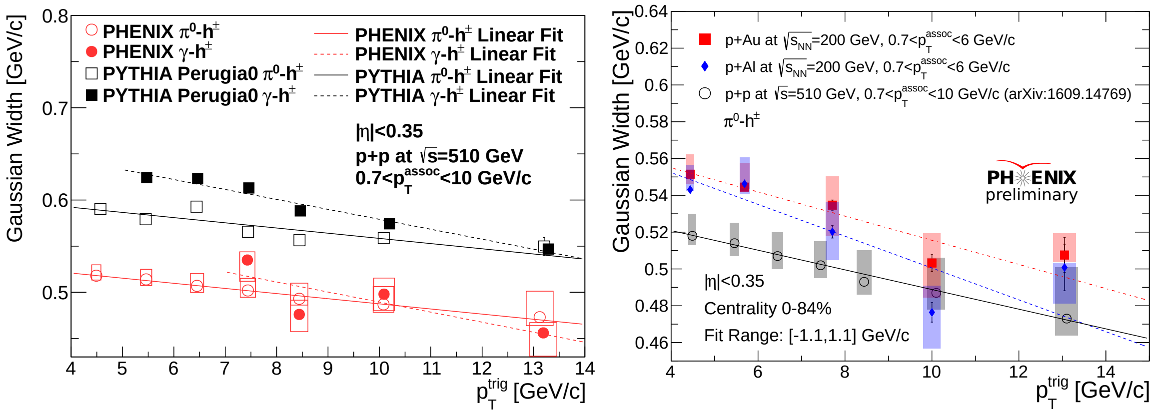

Fig. 2: Left panel: The results of Gaussian widths if $p_{\rm out}$ distributions for π^0 and direct photons from the data and PYTHIA as a function of $p_{\rm T}^{\rm trig}$. PYTHIA produces similar trend as the data, although we obtain a $10-15\%$ higher values for each $p_{\rm T}^{\rm trig}$. Right panel: The results of Gaussian widths of $p_{\rm out}$ distributions for π^0 as a function of $p_{\rm T}^{\rm trig}$ from $p+$ Au and $p+$ Al collisions at $\sqrt{s_{NN}} = 200$ GeV and from $p+p$ collisions at $\sqrt{s} = 510$ GeV.

without further modification. This in fact means that the photons carry the information from the time of their creation. Experimentally, we measure the space-time integrated photon emission.

We recognize several sources which contribute to the overall direct photon production. The prompt photons are created in the initial parton scattering. As they are not affected by the final state effect, they provide an excellent probe to study the initial state effects in nuclear collisions. The other significant source of direct photons are the thermal photons, which come from the thermal radiation of the Quark Gluon Plasma and the Hadron Gas. In addition we expect more sources of direct photons from jet-medium interactions.

3.1 Factorization breaking

The QCD factorization breaking has been also investigated in highly asymmetric proton-nucleus collisions, namely in p+Au and p+Al collisions at $\sqrt{s_{NN}} = 200$ GeV. Similarly, as in $p+p$ collisions we can study the Gaussian width in these collisions. The right panel in Figure 2 shows the comparison of the Gaussian width with the previous $p+p$ result at $\sqrt{s} = 510$ GeV (note that the $p+p$ collision is at different collision energy). At high-${p_{\rm T}}^{\rm trig}$ the widths from the nucleus collisions are consistent with the $p+p$ data. On other hand, at lower $p_{\rm T}$, there seem to be an enhancement of particles observed around pT 5GeV/c, which could be attributed to the 'Cronin'-effect [9]. The slopes in nucleus collisions are also decreasing towards higher $p_{\rm T}$ values. The data suggest a slightly larger slopes than that in the $p+p$ collisions, but it is not conclusive with the current precision of the data.

3.2 Fragmentation Function

It has been established that partons from hard scattering in heavy ion collisions experience energy loss while propagating through the hot and dense medium [10]. The phenomena were observed via the leading hadron and jet suppression also known as "jet-quenching". The parton energy loss can be studied via the jet fragmentation function [11]. The fragmentation function is defined as $D(z) = \frac{1}{N_{\rm jet}} \frac{dN(z)}{dz}$, where $z = p^h/p^{\rm jet}$; $p^{\rm jet}$ is the jet momentum and p^h is the momentum of the hadron jet fragment. As the direct photons are not modified by the medium, they can provide a precise measurement of the momentum of the initial parton or jet, such ${p_{\rm T}}^\gamma \approx {p_{\rm T}}^{\rm jet}$. This is an approximation, as the initial transverse momentum of the parton, $k_{\rm T}$, is not taken into account.

The extraction of a sample triggered purely by direct photons is complicated by the presence of photons from meson decays (dominantly from π^0 decays), which must be removed from the inclusive photon-hadron correlations. In Au+Au, a statistical subtraction determines the direct (i.e. non-decay) photon-hadron correlations from the measured inclusive photon-hadron correlations [11]. The integration in the away side peak is done in the range of $|\Delta\phi - \pi| < \pi/2$, first for the yield per inclusive photon (Y_{inc}), then for the estimated decay photon yield Y_{dec}. The associated yield per direct photon is $Y_{\text{dir}} = (R_\gamma Y_{\text{inc}} - Y_{\text{dec}})/(R_\gamma - 1)$, where R_γ is the ratio of inclusive photons to decay photons. Inclusive photon-hadron correlations are determined from the distribution of photon-hadron pairs as a function of their azimuthal angular separation ($\Delta\phi$).

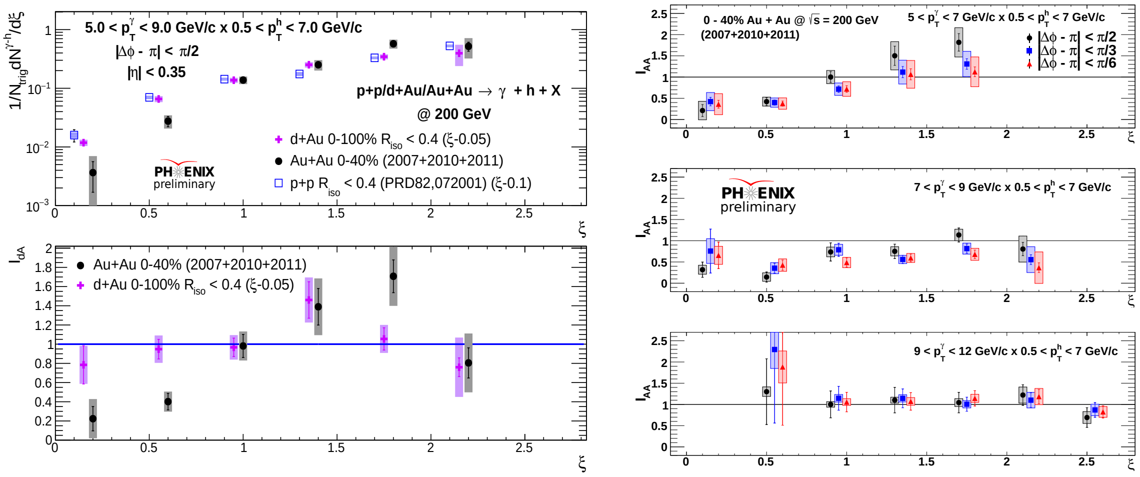

Fig. 3: Left panels: The upper panel shows the per trigger yield of charged hadrons associated with direct photons as a function of $\xi = ln(1/z_T)$ in $p+p$, $d+\text{Au}$ and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The lower panel is showing the ratio of fragmentation function (I_{AA}) between the nucleus-nucleus and $p+p$ collisions. Right panels: The ratios of I_{AA} for the away side charged particles in $0.5 < p_{\text{T}} < 7$ GeV$/c$ with three different $p_{\text{T}}^{\text{trig}}$ ranges. The different colors represent different integration ranges of the away side correlation function.

In order to study the jet fragmentation function, $D(z)$, associated hadron yields are determined as a function of $z_{\text{T}} = {p_{\text{T}}}^h/{p_{\text{T}}}^\gamma$. To focus on the low z_{T} region, one can express the fragmentation function as a function of the variable, $\xi = ln(1/z_{\text{T}})$. Left top panel in Figure 3 shows the the conditional, or per trigger, associated yield, extracted after subtraction of photon-hadron pairs from the bulk underlying event as a function of ξ in $\text{Au}+\text{Au}$, d+Au and $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV. To study the jet fragmentation modification function, we take the ratio between the nucleus-nucleus and $p+p$ collisions ($I_{AA} = Y^{A+A}/Y^{p+p}$) and is shown on the bottom panel in the Figure 3 for d+Au and $\text{Au}+\text{Au}$ collisions. The I_{AA} ratio shows no modification of the fragmentation for the d+Au collisions, while in $\text{Au}+\text{Au}$ collisions there is a large suppression observed at low-ξ and an enhancement at high-ξ.

Furthermore, the new data from the $\text{Au}+\text{Au}$ collisions allow us to study the fragmentation modification in different photon trigger (${p_{\text{T}}}^\gamma$) bins, while using the same associated hadron transverse momenta (${p_{\text{T}}}^h$). The right panels in Figure 3 show the three different I_{AA} ratios, the largest modification is visible in the $5 < {p_{\text{T}}}^\gamma < 7$ GeV$/c$ bin, while it is consistent with unity at all ξ values in the largest selected trigger bin, $9 < {p_{\text{T}}}^\gamma < 12$ GeV$/c$. In addition, we can also study where the missing energy goes by changing the away side integration range between $\pi/2$ and $\pi/6$ shown in different colors in Figure 3. While in the low-ξ region the different integration regions are very consistent, at high-ξ the largest enhancement is in the largest integration range $|\Delta\phi - \pi| < \pi/2$, which suggests that the lost energy of the outgoing parton is scattered in the larger angles.

3.3 Thermal Photons

Analogous to the black body radiation, a formation of the hot and dense matter in the heavy ion collisions would result in emittance of thermal radiation in form of photons and di-electron pairs. The temperature of the medium would directly correlate to the rate of the emission, such that as the temperature cools down, the thermal yield emission rate would slow down. However, while the medium is cooling down it is also rapidly expanding which results in a larger blue shift of the emitted photons in the later stage of the medium evolution [12]. The thermal photon yield was predicted to be dominant in the low-p_{T} region. However, the measurement of direct photons for $1 < p_{\mathrm{T}} < 5$ GeV$/c$ is notoriously difficult due to a large background from hadronic decay photons. In fact, direct photons would contribute only $\approx 10\%$ above the hadronic background.

Figure 4 shows the measured direct photon yield in $\mathrm{Au} + \mathrm{Au}$ and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV [13]. To compare the two different collisions, we fit the $p + p$ data with the modified Hagedorn function and scale it with the number of binary collisions to $\mathrm{Au} + \mathrm{Au}$ data. The scaled fit describes the high-p_{T} region of the $\mathrm{Au} + \mathrm{Au}$ collisions where the pQCD processes are the dominant source of the photons. At low-p_{T} we observed a large excess of the direct photon production in comparison to the scaled $p + p$ collisions.

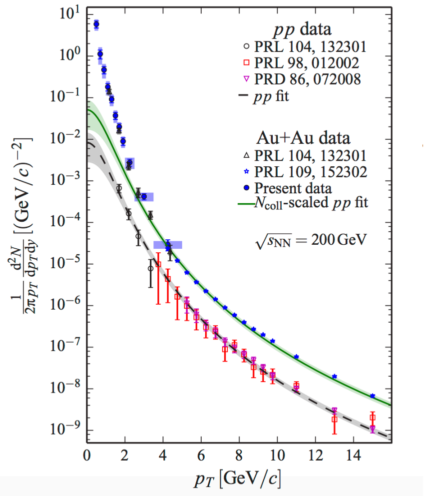

Fig. 4: Invariant yield of direct photons in Au+Au and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV.

The excess of these photons is attributed to thermal photon production from the medium. The excess of the data points can be described with an exponential function with the inverse slope of $T_{\mathrm{eff}} \approx 242 \pm 28(\mathrm{stat}) \pm 7(\mathrm{syst})$ MeV. In case of the static medium the inverse slope would be directly proportional to the average temperature of the medium, yet we now know that it is more the space-time averaged temperature. The temperature in the models should be calculated during the entire cooling down of the medium and in addition also have to include the blue shift from the expansion.

In most theoretical models the thermal photons come from binary processes, therefore their number from a unit volume should be proportional to the square of the number of constituents. The bulk properties on other hand would be proportional to the number of constituents. In Figure 5 shows the integrated yield of direct photons as a function of the number of participant nuclei (N_{part}) in $\mathrm{Au} + \mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 39 - 200$ GeV and $\mathrm{Cu} + \mathrm{Cu}$ collisions at $\sqrt{s_{NN}} = 200$ GeV. We observe that all different collision systems and energies scale on a single curve with the exponent of $\alpha = 1.35 \pm 0.09$. The observed exponent is larger than unity, which suggests that the photons are coming from a thermal source. Although the exponent is smaller than two, that can be attributed to the expanding medium and volume.

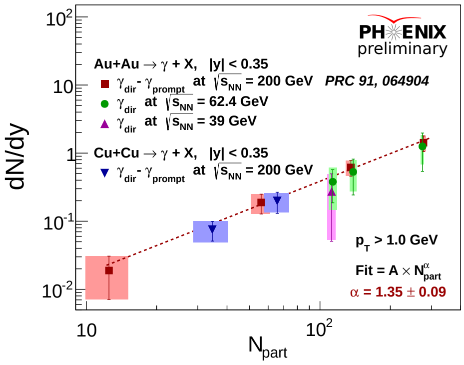

Fig. 5: The integrated yield of direct photons as a function of number of participants in Au+Au collisions at $\sqrt{s_{NN}} = 39 - 200$ GeV and Cu+Cu at $\sqrt{s_{NN}} = 200$ GeV.

4 Summary

We presented the new direct photon-hadron and π^0 -hadron correlation results from $p+p$ collisions at $\sqrt{s} = 510$ GeV and minimum bias p+Au and p+Al collisions at $\sqrt{s_{NN}} = 200$ GeV. The measured Gaussian widths of the p_{out} distributions decrease as the $p_{\mathrm{T}}{}^{\mathrm{trig}}$ increases, which is contradicting the expectation from TMD factorization. We also presented the new measurement on the modification of jet fragmentations in $\mathrm{Au}+\mathrm{Au}$ collisions at $\sqrt{s} = 200$ GeV. These results suggests that the medium enhances production of soft particles preferentially at large angles in comparison in $p+p$ collisions. Lastly, the presented enhancement of the direct photons at low-p_{T} shows a scaling property as a function of the charged hadron multiplicity independent of collision system and energy.

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