HIGH-p_{T} DIRECT-PHOTON RESULTS FROM PHENIX*

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Direct-photon measurements in $p+p$ and Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV from the PHENIX experiment are presented. The $p+p$ results are found to be in good agreement with next-to-leading-order (NLO) perturbative QCD calculations. Direct-photon yields in Au+Au collisions scale with the number of inelastic nucleon–nucleon collisions and do not exhibit the strong suppression observed for charged hadrons and neutral pions. This observation is consistent with models which attribute the suppression of high-p_{T} hadrons to energy loss of quarks and gluons in the hot and dense medium produced in Au+Au collisions at RHIC.

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1. Direct photons in $p+p$ collisions

The virtue of direct photons is that they emerge directly from the interaction of point-like partons in processes like quark–gluon Compton scattering ($q+g \rightarrow q+\gamma$) and quark–anti-quark annihilation ($q+\bar{q} \rightarrow g+\gamma$). Measurements of direct photons in $p+p$ collisions therefore allow to test perturbative QCD (pQCD) without the complication of phenomenological parton-to-hadron fragmentation functions which are needed in the description of high-p_{T} hadron production. Moreover, direct-photon measurements in $p+p$ collisions provide information about the gluon distribution of the proton due to the large contribution from quark–gluon Compton scattering. This is especially interesting for fractional gluon momenta $x_{\mathrm{Bjorken}} \gtrsim 0.1$ because this range is not well constrained by other processes like Deep-Inelastic Scattering and Drell–Yan. However, direct-photon data from $p+p$ and $p+\bar{p}$

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collisions are not generally used in global QCD fits for the determination of parton distribution functions. One reason for this are discrepancies between data and pQCD, especially at low energies (see *e.g.* figure 1(c)). The Relativistic Heavy Ion Collider (RHIC) delivers spin polarized proton beams. A further motivation for direct-photon measurements in PHENIX is to gain insight into the contribution of gluons to the spin of the proton by comparing direct-photon yields in $p+p$ collisions with equal and opposite proton helicities. In this paper, however, the direct-photon cross-section for unpolarized $p+p$ collisions is presented. The experimental challenge in direct-photon measurements is the subtraction of the significant photon background from hadron decays like $\pi^0 \rightarrow \gamma+\gamma$ and $\eta \rightarrow \gamma+\gamma$. The comparison of world data

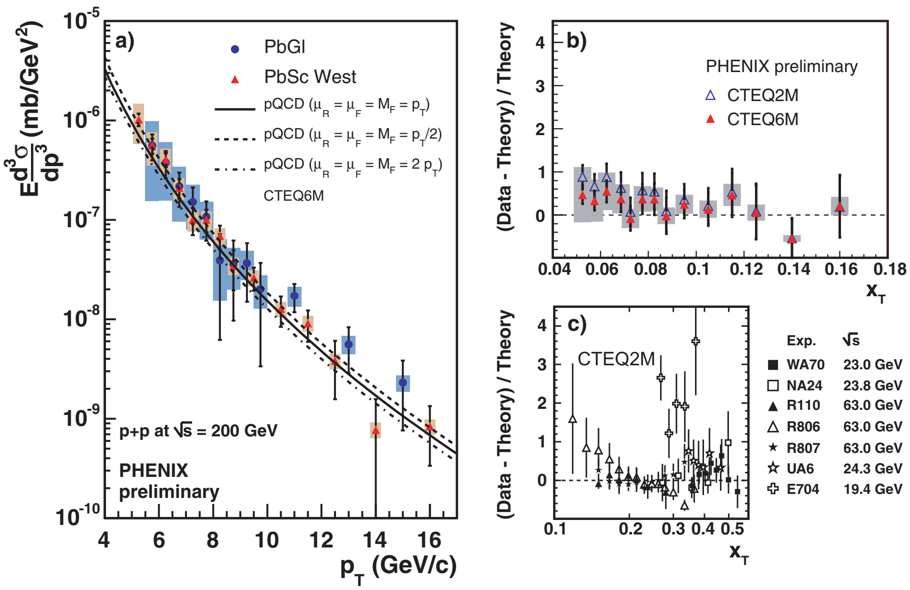

Fig. 1. (a) Invariant direct-photon cross-section in $p+p$ collisions at $\sqrt{s} = 200$ GeV determined with the lead scintillator (PbSc) and the leadglass (PbGl) calorimeter of the PHENIX experiment. (b) Comparison of the PbSc direct-photon spectrum with two pQCD calculations which employ the CTEQ2M and the CTEQ6M parton distribution function, respectively. (c) Comparison of direct-photon world data for $p+p$ collisions at various energies with pQCD calculations which employ the CTEQ2M parton distribution function [4].

on direct-photon production in $p+p$ and $p+\bar{p}$ collisions with pQCD calculations raises the question whether there is a systematic pattern of deviation. It has been argued that measured direct-photon transverse momentum (p_{T}) spectra generally tend to be steeper than pQCD predictions [5]. In this case the agreement between data and pQCD can be improved by introducing a transverse momentum (k_T) of the partons prior to the hard scattering, in addition to the effects expected in the next-to-leading-order description. Recently published results on direct-photon production in $p+p$ and $p+$Be collisions from the fixed-target experiment E706 provide further support for the idea that k_T enhancement needs to be taken into account to describe the data [6].

Direct-photon spectra in $\sqrt{s_{NN}} = 200$ GeV $p+p$ collisions were measured at RHIC with the highly segmented electromagnetic calorimeter (EmCal) of the PHENIX experiment [3]. This detector consists of two subsystems: a lead scintillator sampling calorimeter (PbSc) and a lead glass Cherenkov calorimeter (PbGl). The EmCal covers the pseudorapidity range $|\eta| < 0.35$. The direct-photon cross-section for unpolarized $p+p$ collisions determined with data from RHIC Run-3 is shown in figure 1. The integrated luminosity for this run was 266 nb^{-1}. The independent PbSc and PbGl measurements are consistent and agree with NLO pQCD predictions. There is, in particular, no indication that for the range $p_T \gtrsim 5$ GeV/c covered by the current measurement an additional transverse momentum k_T is needed in the theoretical description.

Experimental and theoretical uncertainties are potentially reduced in the ratio of the direct-photon and neutral-pion cross-sections. Figure 2

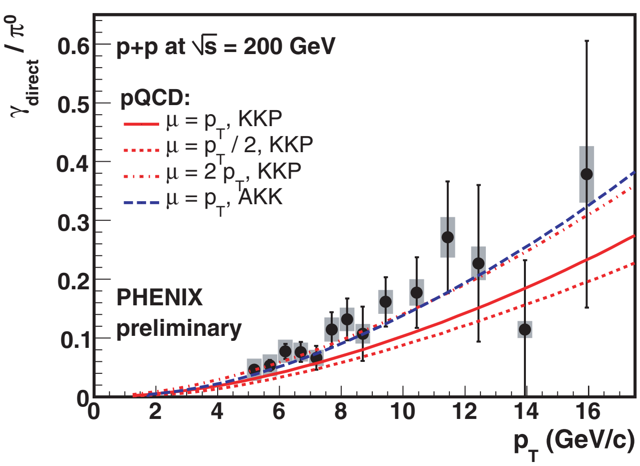

Fig. 2. Comparison of the ratio of the direct-photon and neutral-pion invariant cross-sections for $p+p$ collisions at $\sqrt{s} = 200$ GeV with pQCD predictions. The calculation for the KKP parton-to-pion fragmentation functions [7] is shown for three choices $\mu = \mu_R = \mu_f = M_F$ of the renormalization scale μ_R, the initial-state factorization scale μ_f, and the final-state factorization scale M_f. Moreover, a calculation is shown which employs the AKK fragmentation functions [8].

shows that the measured $\gamma_{\text{direct}}/\pi^0$ ratio agrees with NLO pQCD predictions. The AKK fragmentation functions [8] provide a better description of the PHENIX π^0 spectrum [2] than the KKP fragmentation functions and this in turn leads to a better agreement between the measured and calculated $\gamma_{\text{direct}}/\pi^0$ ratio.

2. Direct photons in Au+Au collisions

Direct-photon measurements in nucleus–nucleus ($A+A$) collisions essentially serve two purposes. At sufficiently high transverse momenta direct photons emerge from initial hard parton–parton scattering, analogous to the production mechanism in $p+p$ collisions. These hard parton–parton scatterings happen prior to the possible formation of a thermalized quark–gluon plasma (QGP). However, due to their electromagnetic nature photons essentially do not interact with the hot and dense plasma. They can thus be used as a measure of the number of initial hard parton–parton scatterings. The second incentive to measure direct photons in $A+A$ collisions is the expected production of thermal direct photons in the QGP. Thermal direct photon are predominantly produced in the early hot phase of the evolution of the plasma and thus provide a means to determine the initial temperature of the QGP. In a window $1 \lesssim p_{\text{T}} \lesssim 3\,\text{GeV}/c$ thermal direct photons from the QGP are expected to be the dominant direct-photon source in Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200\,\text{GeV}$.

One of the most important observations at RHIC is the suppression high-p_{T} hadrons relative to a scaled $p+p$ reference. The suppression is quantified with the nuclear modification factor

$$R_{AA}(p_{\text{T}}) = \frac{\left.\frac{dN}{dp_{\text{T}}}\right|_{A+A}}{\langle T_{AA}\rangle \times \left.\frac{d\sigma}{dp_{\text{T}}}\right|_{p+p}} . \tag{1}$$

The factor $\langle T_{AA}\rangle = \langle N_{\text{coll}}\rangle/\sigma_{\text{inel}}^{p+p}$ reflects the increase of the parton luminosity per $A+A$ collision relative to $p+p$ collisions in the absence of nuclear shadowing. Thus, in the absence of initial-state or final-state nuclear effects R_{AA} will be unity for sufficiently large transverse momenta for which particle production is dominated by hard scattering. The average number $\langle N_{\text{coll}}\rangle$ of inelastic nucleon–nucleon collisions for a given centrality class is determined with a Glauber model calculation.

As can seen in figure 3 neutral pions, η-mesons, and charged hadrons are suppressed by a factor ~ 5 in central Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200\,\text{GeV}$. This can be explained by energy loss of fast quarks and gluons in the QGP. In such models the initial rate of hard parton–parton scatterings scale as

$\langle T_{AA}\rangle$ and the suppression is only due to the final-state interaction with the medium. The measurement of direct photons at high $p_{\rm T}$ provides a unique possibility to test these jet quenching models [1]. Figure 3 shows that the R_{AA} for direct photons in central Au+Au collisions is consistent with unity: unlike hadrons, direct photons are not suppressed. One can conclude that initial hard scattering processes in Au+Au collisions indeed occur at the rate expected from $\langle T_{AA}\rangle$ scaling. The suppression of hadrons at high $p_{\rm T}$ is therefore a final-state effect caused by the hot and dense medium produced in these collisions. This supports models which attribute the hadron suppression to energy loss of partons in the medium and is consistent with the formation of a QGP in Au+Au collisions at RHIC.

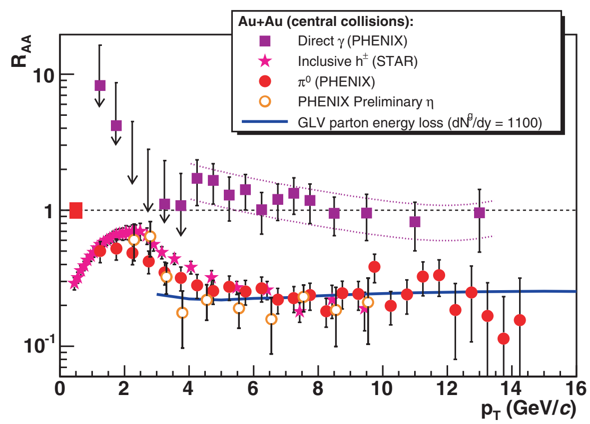

Fig. 3. Nuclear modification factor R_{AA} for direct photons and hadrons in central (0–10% of $\sigma_{\rm inel}^{\rm Au+Au}$) Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV.

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