DIRECT PHOTONS IN p+p, d+Au AND Au+Au COLLISIONS AT $\sqrt{s_{NN}} = 200$ GeV

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The PHENIX experiment has measured direct photons at $\sqrt{s_{NN}} = 200$ GeV in p+p, d+Au and Au+Au collisions. For $p_T < 4$ GeV/c, the internal conversion into $e^+e^-$ pairs has been used to measure the direct photons in Au+Au.

1 Introduction

Direct photons are a unique probe to study the hot and dense matter produced in heavy ion collisions at RHIC. They provide information about the thermalized state of such collisions. Moreover, high-$p_T$ direct photons can be used as a measure of the rate of initial hard parton-parton scatterings.

In p+p collisions, direct photons are produced by hard scattering processes. A direct photon measurement thus is an important baseline for the understanding of the hard scattering contribution in Au+Au collisions as well as - in its own right - a good test of pQCD calculations. Measurements in d+Au collisions allow a quantification of possible initial state effects.

In (central) heavy ion collisions, the temperature of the collision can be obtained via thermal direct photons from the QGP that are expected to be the dominant source of direct photons at 1 GeV/c < $p_T$ < 3 GeV/c while at high transverse momenta hard direct photons can help understanding the observed hadron suppression. There are also theoretical predictions for direct photons produced in the interaction of a jet and the created medium.

2 Measurement of Direct Photons

The measurement is challenging due to a large background from decaying hadrons such as the $\pi^0$ and the $\eta$. Two methods have been applied to measure the direct photon signal: The so-called subtraction or cocktail method has been used for all collision systems. The idea of this method
is to subtract the photons from hadronic decays from all inclusive photons; it has been well established in different analyses.\cite{3,5,6} This method has been applied to the 2003 $p+p$ and $d+Au$ dataset as well as to the large 2004 Au+Au dataset with about 10 times more events than in the 2002 dataset. In the Au+Au case, direct photons have also been measured via their internal conversion into $e^+e^-$ pairs. This measurement has already been described elsewhere\cite{6} and has lead to a significant improvement of the measurement at lower transverse momenta.

The idea of the internal conversion method is to use a process corresponding to the $\pi^0$ (or $\eta$) Dalitz decay where one decay photon is a virtual photon decaying into an $e^+e^-$ pair. The invariant mass distribution of these electron-positron pairs is given by\cite{6}

\begin{equation}
\frac{1}{N_\gamma} \frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi} \sqrt{1 - \frac{4m_e^2}{m_{ee}^2}} \left(1 + \frac{2m_e^2}{m_{ee}^2}\right) \frac{1}{m_{ee}} | F(m_{ee}^2) |^2 \left(1 - \frac{m_{ee}^2}{M^2}\right)^3.
\end{equation}

The same formula applies to any source of real photons as each such source also produces virtual photons at very low masses. In the case of direct photons, there is no phase space limitation when $m_{ee} < \ll p_T^{photon}$.

The great advantage of this method is, that the $e^+e^-$ pairs from the $\pi^0$ Dalitz decay are suppressed at higher invariant masses due to the limited phase space. By measuring the pair yield in such a mass region, e.g. for $90 < m_{ee} < 300$ GeV/$c^2$, the decay photon background can be mostly eliminated. As $\gamma_{direct}^*/\gamma_{incl.}^* = \gamma_{direct}/\gamma_{incl.}$ must be satisfied to derive real photons from the measured virtual photons, one has to relate the obtained yield to the yield in a region with an unrestricted phase space. The term $R_{\gamma_{data}} = N_{data}(90-300\text{ MeV})/N_{data}(0-30\text{ MeV})$ is the ratio of the measured yields in the two intervals, it is used to calculate $\gamma_{direct}^*/\gamma_{incl.}^*$. Therefore, the ratios $R_{\gamma_{direct}}$ and $R_{\gamma_{hadron}}$ are precisely calculated from Equation\cite{1} that de-
Figure 3: a) Direct photon excess for the most central events above the decay photon background for the subtraction and the virtual photon method in Au+Au collisions. b) Direct photon yield for the same centrality from the virtual photon measurement in comparison with different theory calculations: scaled pQCD, thermal model and the sum of both calculations.

scribes the form of the corresponding electron-positron pair spectra. With the knowledge of these ratios, the ratio of the virtual direct photons and the virtual inclusive photons can be calculated as 

\[
\frac{\gamma_{\text{direct}}}{\gamma_{\text{incl.}}} = \frac{N^\text{direct}_{0-30}}{N^\text{incl.}_{0-30}} = \frac{R_{\text{data}} - R_{\text{hadron}}}{R_{\text{direct}} - R_{\text{hadron}}}.
\]

To get the final direct photon yield, the calculated \(\frac{\gamma_{\text{direct}}}{\gamma_{\text{incl.}}}\) is applied to the real inclusive photon yield from the measurement with the subtraction method.

The uncertainty of the internal conversion method is much smaller than the uncertainty of the classical method as most errors cancel in the ratio. Therefore, the systematic error is dominated by the 20% uncertainty of the \(\eta/\pi^0\)-ratio that translates to the same uncertainty in the direct photon yield. Other contributions to the total systematic error of 25% are the error of the inclusive photon yield (10%) and the acceptance for \(e^+e^-\) pairs (5%).

3 Results

The preliminary results for \(p+p\) and minimum bias \(d+Au\) collisions are shown in Figure and compared with a next-to-leading-order perturbative-QCD (NLO pQCD) calculation. The data are consistent with the calculation for the whole shown \(p_T\) range between 5 and 16 GeV/c. Therefore it is justified to use the pQCD calculation as reference for hard direct photons, i.e. direct photons at high transverse momenta, also in Au+Au collisions at the same energy. Preliminary Au+Au results from recent measurements using the large 2004 data sample, are shown for a \(p_T\) region of 4 GeV/c to 13 GeV/c in Figure for eight different centrality classes and
for minimum bias. The data agree with the pQCD expectation for all centralities. Compared to earlier measurements, the errors are smaller and the $p_T$ region has been extended. Further work is done to improve the significance and to further extend the $p_T$ range.

For the lower $p_T$ region, the direct photon spectrum has also been obtained with the internal conversion method. The significance of the preliminary result is compared to the conventional subtraction method in Figure 3 a). The result from the subtraction method is shown as the so-called double ratio $(\gamma/\pi^0_{\text{meas}})/(\gamma/\pi^0_{\text{background}})$ while the virtual photon result is shown as $\gamma_{\text{direct}}/\gamma_{\text{inclusive}} + 1$ which is not exactly equivalent. In contrast to the subtraction method where no significant excess above the hadronic background could be seen for $p_T < 3 \text{ GeV}/c$, a clear signal of direct photons is measured using the new method, being about 10%. Both results are consistent.

The preliminary direct photon invariant yield for the 20% most central events from the internal conversion measurement is shown in Figure 3 b) compared to different theoretical calculations. The direct photon signal has been measured with large significance for the shown $p_T$ range. The $T_{AB}$ scaled pQCD calculation 9 underpredicts the measurement at low transverse momenta $p_T < 3 \text{ GeV}/c$ while a 2+1 hydrodynamical model for the emission of thermal photons with a formation time $\tau_0 = 0.15 \text{ fm}/c$ and an average initial temperature $T_{\text{ave}}. = 378 \text{ MeV}$ ($T_{\text{max}} = 590 \text{ MeV}$) 10 is significantly below the data at $p_T > 3 \text{ GeV}/c$. A combination of both photons sources, however, describes the data, but the temperature obtained for the thermal model has only a meaning if the observed direct photon signal is of thermal origin. Therefore it is necessary to measure the direct photons with the same analysis technique in $p+p$ and $d+Au$ collisions at the same energy for $p_T < 3 \text{ GeV}/c$ as well, where the excess will be much smaller if it is - in Au+Au collisions - from thermal photons. The $d+Au$ measurement will also help understanding the influence of possible initial state effects to the direct photon yield.

4 Summary

The PHENIX experiment has measured direct photons in $p+p$, $d+Au$ and $Au+Au$ collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$. The measured yields in all systems are consistent with a NLO pQCD calculation at high transverse momenta ($p_T > 4.5 \text{ GeV}/c$). Direct photons at $p_T < 4.5 \text{ GeV}/c$ have been measured in Au+Au collisions via their internal conversion into $e^+e^-$ pairs. A significant signal could be extracted for $1 < p_T < 4.5 \text{ GeV}/c$ that is significantly above the expectation from NLO pQCD. However, also taking into account thermal photon emissions, the measurement is in agreement with calculations.

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