

## Direct photon production in heavy-ion reactions at SPS and RHIC

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**Abstract.** A review on experimental results for direct photon production in heavy ion reactions is given. A brief survey of early direct photon limits from SPS experiments is presented. The first measurement of direct photons in heavy ion reactions from the WA98 collaboration is discussed and compared to theoretical calculations. An outlook on the perspective of photon measurements at RHIC is given.

**Keyword.** Direct photons.

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### 1. Introduction

The major motivation to study relativistic heavy-ion collisions is the search for the quark-gluon plasma (QGP), a potential new state of matter where colored quarks and gluons are no longer confined into hadrons and chiral symmetry is restored. To study such a complicated system one wishes for a probe that is not equally complicated in itself. The production of hadrons is of course governed by the strong interaction and therefore adds to the complication. One possible way out might be the study of hard processes where QCD, the theory of strong interaction, enters the perturbative regime and is calculable. The other avenue involves a particle that suffers only electromagnetic interaction: photons – both real and virtual – should be an ideal probe. (For previous reviews on this topic, see [1–3].) While photon production may be less difficult to treat than some other processes in hadronic physics, an adequate treatment in heavy-ion collisions turns out to be far from trivial. Experimentally, high energy direct photon measurement has always been considered a challenge. This is true already in particle physics and even more in the environment of heavy-ion collisions. Nevertheless a lot of progress has been made and a large amount of experimental data is available, though mostly from particle physics. Only one measurement of direct photons exists for heavy-ion collisions and was recently published by the WA98 collaboration [4]. Direct photon measurements in heavy-ion collisions are expected to come into real fruition with the advent of colliders like RHIC and LHC. In this paper I attempt to provide a review of the experimental aspects of the study of direct photon production in heavy-ion collisions. I will first present results from the CERN SPS fixed target program and comparisons to theoretical calculations. In the second part I will discuss the experimental potential of direct photon measurements at RHIC.

## 2. Experimental results at SPS

In heavy-ion collisions the extraction of direct photons is extremely difficult due to the high particle multiplicity. The highest available energy in heavy-ion collisions so far at the CERN SPS has been approximately at the lowest energy where direct photons could be measured in  $pp$ .

Using the relatively light ion beams of  $^{16}\text{O}$  and  $^{32}\text{S}$  at a beam energy of 200 A·GeV, corresponding to a nucleon–nucleon center-of-mass energy of  $\sqrt{s_{NN}} = 19.4\text{ GeV}$ , the experiments WA80 [5,6], HELIOS (NA34) [7] and CERES (NA45) [8] have attempted to measure direct photons. All these measurements have been able to deliver upper limits of direct photon production.

HELIOS has studied  $p$ -,  $^{16}\text{O}$ - and  $^{32}\text{S}$ -induced reactions [7] with a conversion method. The authors estimate the ratio of the integrated yields of inclusive photons and neutral pions:

$$r_\gamma = \frac{N_\gamma}{N_{\pi^0}} \quad (1)$$

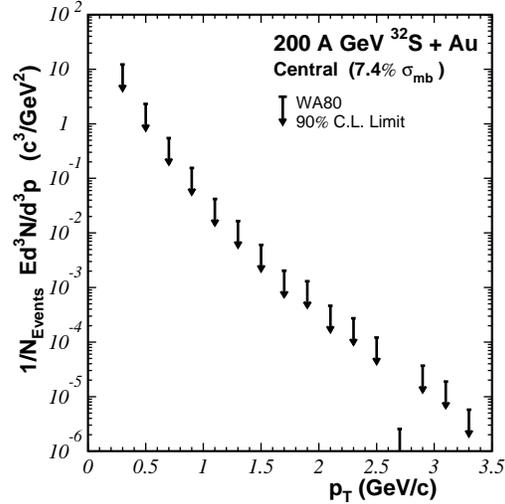
for  $p_T > 100\text{ MeV}/c$ . They calculate the neutral pion yield from the number of negative tracks in their magnetic spectrometer. Their results (with 4–11% statistical and 9% systematic uncertainty) and their estimate of decay photons (with 9% systematic uncertainty) agree within these errors. An analysis of the  $^{32}\text{S}$ -induced data with a higher cutoff of  $p_T = 600\text{ MeV}/c$  yields a comparable result. However, the results are of limited value in the context of both prompt and thermal direct photons, as they are dominated by the lowest  $p_T$ , where the expected direct photon emission would be negligible.

A similar measurement has been performed by the CERES experiment, which has studied  $^{32}\text{S} + \text{Au}$  reactions [8]. Photons are measured when they convert in the target, the  $e^+e^-$ -pairs are reconstructed by tracking in the two RICH detectors. They obtain inclusive photon spectra in central  $^{32}\text{S} + \text{Au}$  reactions in  $0.2\text{ GeV}/c \leq p_T \leq 2.0\text{ GeV}/c$ . The results agree within errors with their hadron decay generator, which is tuned to reproduce charged and neutral pion spectra from different heavy-ion experiments. They estimate a similar ratio of integrated yields:

$$r'_\gamma = \left( \frac{dN_{\text{ch}}}{d\eta} \right)^{-1} \int_{0.4\text{ GeV}/c}^{2.0\text{ GeV}/c} \frac{dN_\gamma}{dp_T} dp_T, \quad (2)$$

which they use – again by comparing to the generator – to establish an upper limit (90% CL) of 14% for the contribution of direct photons to the integrated inclusive photon yield. One of the uncertainties which is difficult to control in this analysis relates to the fact that they use simulated hadron yields in their generator which are tuned to other measurements with different trigger biases and systematic errors, and that especially the neutral pions have not been measured within the same data set.

In addition, the CERES experiment has utilized another method to extract information on a possible direct photon contribution. As in naive pictures of particle production in these reactions the direct photon multiplicity is proportional to the square of the initial multiplicity while the hadron multiplicity should be proportional to the initial multiplicity, i.e. they have studied the multiplicity dependence of the inclusive photon production. Their upper limit on a possible quadratic contribution is slightly lower than the above limit on



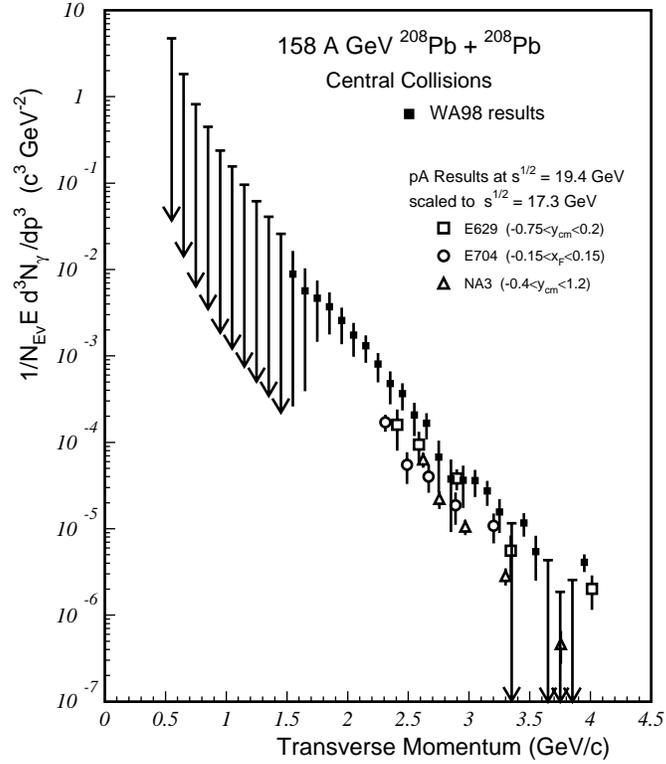
**Figure 1.** Upper limits (90% CL) of the direct photon multiplicity as a function of  $p_T$  in central reactions of  $^{32}\text{S} + \text{Au}$  for  $\sqrt{s} = 19.4$  GeV.

direct photons from  $r'_\gamma$ , its relation to the direct photon contribution is however dependent on the model of particle production. Similar to the HELIOS measurements both these results are dominated by the low  $p_T$  part of the spectra, so the result is consistent with the expectation of a very low direct photon yield at low  $p_T$ .

The WA80 experiment has performed measurements with  $^{16}\text{O}$  [6] and  $^{32}\text{S}$  [5] beams using a lead glass calorimeter for photon detection. The systematic errors are checked by performing the analysis with a number of different choices of experimental cuts. Inclusive photons and  $\pi^0$  and  $\eta$  mesons have been measured in the same data samples, which helps to control the systematic errors. WA80 reports no significant direct photon excess over decay sources in peripheral and central collisions of  $^{16}\text{O} + \text{Au}$  and  $^{32}\text{S} + \text{Au}$ . The average excess in central  $^{32}\text{S} + \text{Au}$  collisions in the range  $0.5 \text{ GeV}/c \leq p_T \leq 2.5 \text{ GeV}/c$  is given as  $5.0\% \pm 0.8\%$  (statistical)  $\pm 5.8\%$  (systematic). A  $p_T$  dependent upper limit (90% CL) of direct photon production as shown in figure 1 has been obtained, which gives more information than the integrated limits, as it can constrain predictions at higher  $p_T$ , where a considerable direct photon multiplicity may be expected.

The upper limits for direct photons from WA80 have been used by a number of different authors to compare their model predictions [9–18]. They can be explained with and without phase transition and, therefore, do not allow a conclusion about the existence of a QGP phase. However, they have triggered investigations of some of the simplifications used in earlier calculations, as e.g. unrealistic equations of state for the hadron gas.

For Pb+Pb collisions at 158 A·GeV, ( $\sqrt{s_{NN}} = 17.3$  GeV) the WA98 experiment has performed photon measurements [4] using similar detectors and analysis techniques as in WA80. In peripheral collisions no significant direct photon excess was found. In central collisions the observed photons cannot entirely be explained by decay photons, implying the first observation of direct photons in high energy heavy-ion collisions. The extracted direct photon spectrum is shown in figure 2. The only other direct photon measurements at a similar energy are from  $p$ -induced reactions. Data from  $pp$  reactions by E704 [19] and



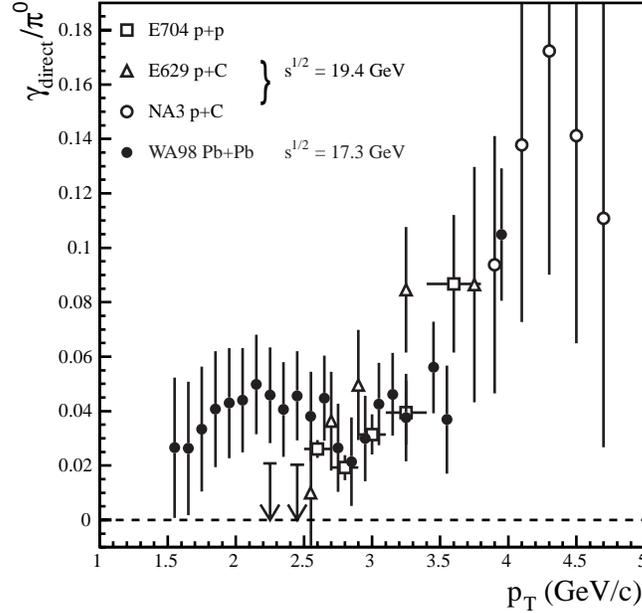
**Figure 2.** Invariant direct photon multiplicity as a function of  $p_T$  in central reactions of Pb+Pb for  $\sqrt{s} = 17.3$  GeV. The error bars correspond to combined statistical and systematic errors, the data points with downward arrows indicate 90% CL upper limits. For comparison scaled direct photon results from  $p$ -induced reaction are included (see text).

from  $p + C$  reactions by E629 [20] and NA3 [21] at  $\sqrt{s} = 19.4$  GeV have been converted to the lower energy  $\sqrt{s} = 17.3$  GeV assuming a scaling according to [22]:

$$E d^3 \sigma_{\gamma} / dp^3 = f(x_T, \theta) / s^2, \tag{3}$$

where  $x_T = 2p_T / \sqrt{s}$  and  $\theta$  is the emission angle of the photon and have been multiplied with the average number of binary nucleon–nucleon collisions in the central Pb+Pb reactions (660). These scaled  $p$ -induced results are included in figure 2 for comparison. They are considerably below the heavy-ion results which indicates that a simple scaling of prompt photons as observed in  $pp$  is not sufficient to explain the direct photons in central Pb+Pb reactions.

It is also instructive to compare the  $\gamma/\pi^0$  ratio extracted from heavy-ion data to those from  $pp$  and  $pC$  in figure 3. The value in heavy-ion data is  $\approx 3\text{--}5\%$  in most of the  $p_T$  range, which is similar to the lowest values extracted in the proton data. This may be taken as a hint that such levels of direct photons approach the feasibility limit of such measurements. Still lower levels will be very hard or impossible to detect. Furthermore, while in this



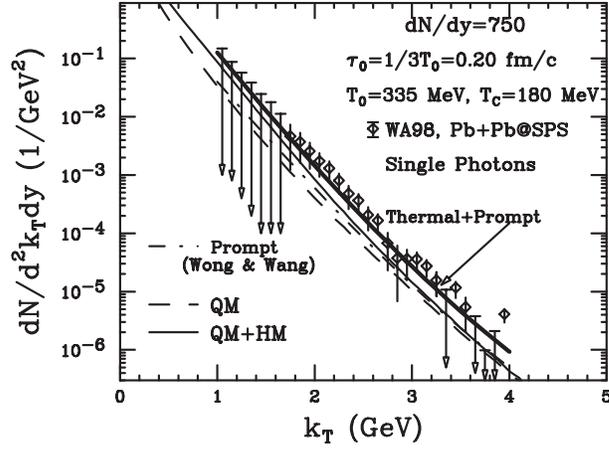
**Figure 3.**  $\gamma_{\text{direct}}/\pi^0$  ratio as a function of  $p_T$  for  $pp$  and  $pC$  reactions  $\sqrt{s} = 19.4$  GeV as in figure 2 (open symbols) and for central Pb+Pb reactions at  $\sqrt{s} = 17.3$  GeV (filled symbols).

ratio the heavy ion data and the proton data agree for high transverse momenta, there is an indication of an additional component at intermediate  $p_T$  in the heavy ion data.

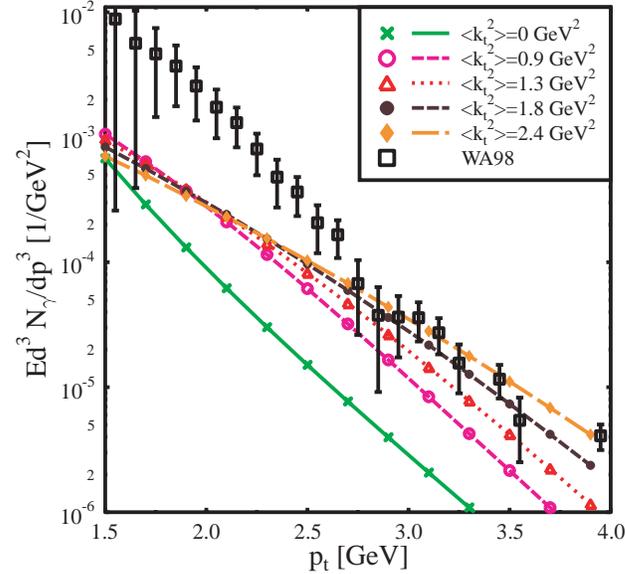
Before attempting to address the thermal production of photons it is mandatory to understand the contribution from hard processes which are expected to dominate at high  $p_T$ . Wong and Wang [23] have calculated this contribution from a next-to-leading order perturbative QCD calculation, where an intrinsic parton momentum of  $\langle k_T^2 \rangle = 0.9$  GeV<sup>2</sup> has been used. This  $\langle k_T^2 \rangle$  is necessary to describe  $p$ -induced reactions at a similar energy. The heavy ion data can, however, not be described by this calculation (see figure 5). Dumitru *et al* [24] have followed up on this question. They showed that the WA98 photon spectrum above  $p_T = 2.5$  GeV can be explained by prompt photons if an additional nuclear broadening of  $\Delta k_T^2 = \langle k_T^2 \rangle_{AA} - \langle k_T^2 \rangle_{pp} \simeq 0.5\text{--}1$  GeV<sup>2</sup> is introduced. For low  $p_T < 2.5$  GeV, however, prompt photons fail to reproduce the WA98 data regardless of the amount of nuclear broadening employed (see figure 5).

A number of groups [25–31] have compared their hydrodynamical calculations with the data of WA98. I will only mention a few examples – for a more detailed discussion see [32].

Srivastava and Sinha [18] argued, using the 2-loop hard thermal loop rate for the QGP contribution and a realistic equation of state for the hadron gas, that QGP is needed to explain the data. Their conclusion is based on the use of a very high initial temperature ( $T_0 = 335$  MeV) and very small initial time ( $\tau_0 = 0.2$  fm/c), which could explain the observed flat photon spectrum for transverse photon momenta  $p_T > 2$  GeV (see figure 4). Srivastava and Sinha [18] have also included prompt photons from the work by Wong and



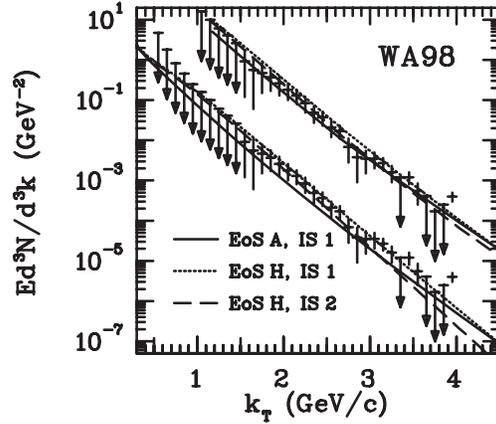
**Figure 4.** Comparison of the WA98 data with a hydrodynamical calculation by Srivastava and Sinha [25]. The  $p$ QCD calculation by Wong and Wang [23] is also shown.



**Figure 5.** The  $p$ QCD photon spectrum calculated for different  $p_T$  broadening in comparison to the WA98 data [24].

Wang [23]. Srivastava and Sinha found that the thermal photons contribute half of the total photon spectrum and that in particular at large  $p_T$  most of the thermal photons are due to the QGP contribution.

Gallmeister *et al* [28] argued that the low momentum part of the WA98 spectrum ( $p_T < 2$  GeV) is consistent with a thermal source, either QGP or hadron gas, which also describes dilepton data. The hard part ( $p_T > 2$  GeV), on the other hand, agrees with the prompt



**Figure 6.** The photon spectrum calculated for different EOS and initial conditions with prompt photons (upper set, scaled by a factor 100) and without (lower set) in comparison to the WA98 data [29]. EoS A, IS 1 contains a phase transition at  $T_c = 165$  MeV, an average initial temperature  $T_0 = 255$  MeV, and a local maximum temperature  $T_{\max} = 325$  MeV. EoS H describes only a HHG with  $T_0 = 234$  MeV,  $T_{\max} = 275$  MeV (IS 1) and  $T_0 = 213$  MeV,  $T_{\max} = 245$  MeV (IS 2).

photon spectrum if its absolute value is normalized to the data, corresponding to a large effective  $K$ -factor of 5.

Huovinen *et al* [29] fixing the initial conditions ( $T_0 = 210$ – $250$  MeV) in their hydrodynamical model partly by a comparison with hadron spectra, were able to describe the data equally well with or without a phase transition (see figure 6). They were able to fit the WA98 data without the need of an extremely high initial temperature, an initial radial velocity, or in-medium hadron masses. This might be caused partly by a strong flow at later stages since they do not assume a boost-invariant longitudinal expansion [32a].

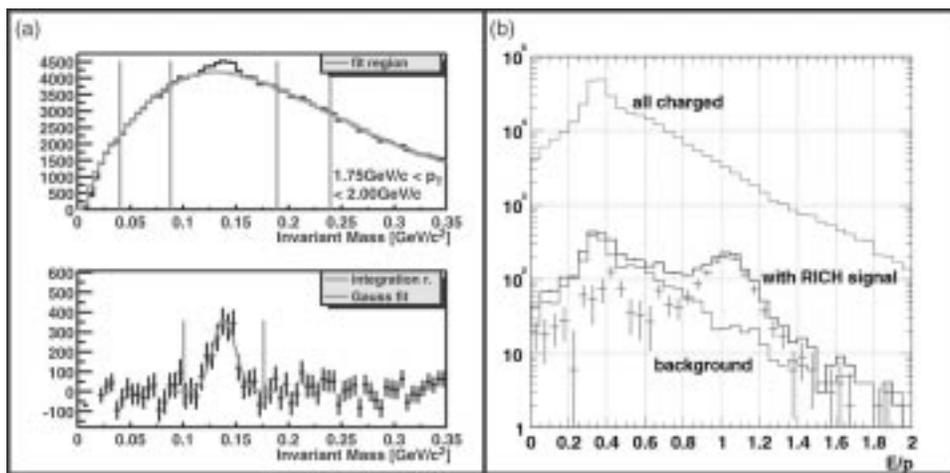
Summarizing, WA98 found a rather flat photon spectrum, which cannot be easily explained by conservative models. It requires either a high initial temperature, a large prompt photon contribution, an initial radial velocity, in-medium modifications of the hadron masses and/or a strong flow at later stages. At the moment, it is fair to say that the uncertainties and ambiguities in the hydrodynamical models and in the rates do not allow to decide from the WA98 photon spectra about the presence of a QCD phase transition in SPS heavy-ion collisions. However, most calculations do require a thermal source with an initial temperature of  $T_i \approx 250$  MeV or higher.

### 3. Outlook for RHIC

In the summer of 2000, experiments at the relativistic heavy ion collider (RHIC) at BNL started to take data in collisions of Au nuclei at  $\sqrt{s_{NN}} = 130$  GeV, continuing with a beam energy of  $\sqrt{s_{NN}} = 200$  GeV from 2001 onwards. First results of the RHIC experiments have already been presented [33]. However results on direct photons are not available at this early stage.

One of the major goals of the PHENIX experiment [34,35] at RHIC is the measurement of direct photons in the central detector arms at mid-rapidity. Photon measurements and neutral meson reconstruction are performed with electromagnetic calorimeters (EMCAL) using two different technologies, a lead glass detector, which consists of the transformed and updated calorimeter used in WA98 and a lead-scintillator sampling calorimeter. In addition, the sophisticated electron detection capabilities should also allow to measure inclusive photons via the  $e^+ - e^-$ -pairs from conversions. The central detectors cover  $90^\circ$  in azimuth and the pseudorapidity range  $|\eta| < 0.35$ . A central magnet provides an axial field, and tracking and momentum measurement is performed in three different sub-systems: pad chambers (PC), drift chambers (DC) and time-expansion chambers (TEC). Electron identification is achieved by simultaneously using a ring imaging Cherenkov counter (RICH) for  $p < 4.7$  GeV/c, electromagnetic energy measurement in the calorimeters for  $p > 0.5$  GeV/c and  $dE/dx$  measurement in the TEC for  $p < 2$  GeV/c. A planned upgrade of the TEC to a transition radiation detector (TRD) will further strengthen the electron identification. Photons converting in the outer shell of the multiplicity and vertex detector (MVD) can be identified as electron pairs with a small, but finite apparent mass [35a]. It is planned to add a converter plate to the experiment for part of the data-taking to minimize uncertainties of the conversion probability and the location of the conversion point. Photons with  $p > 1$  GeV/c will be identified in the calorimeters with hadron suppression from the smaller deposited energy and additional rejection by time-of-flight (for slow hadrons) and shower shape analysis. Furthermore, charged hadrons will be identified by the tracking detectors in front of the calorimeters. The calorimeters will also measure  $\pi^0$  and  $\eta$  production necessary for the estimate of the decay photon background.

Figure 7 illustrates the measurement capabilities of the PHENIX experiment already from the early data of the beam time in 2000. Figure 7a shows an invariant mass spectrum



**Figure 7.** (a) Example of a two-photon invariant mass spectrum as measured by the PHENIX electromagnetic calorimeter (see e.g. [36]). (b) Identification of electrons in the PHENIX experiment from the ratio of electromagnetic energy measured by calorimetry and momentum measured by tracking (see e.g. [37]).

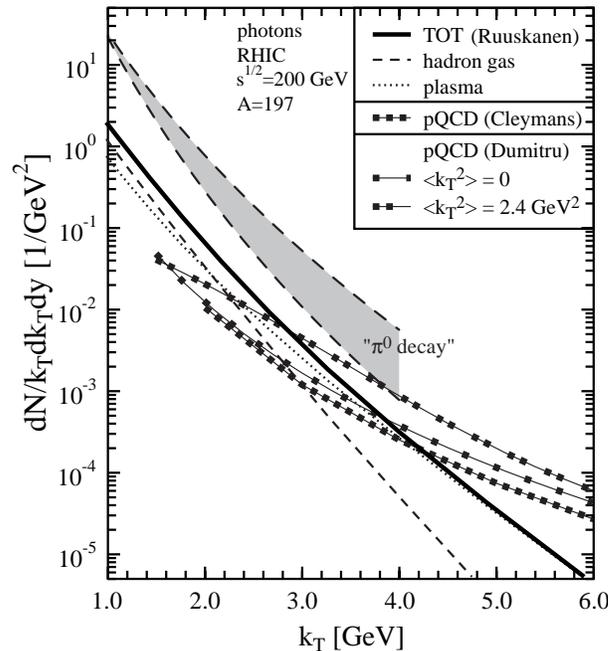
Direct photon production in heavy-ion reactions

of photon pairs measured with the EMCAL. The peak of the neutral pions can easily be observed. In fact, transverse momentum spectra of neutral pions have already been extracted and published [38]. With higher statistics measurements in the year 2001 at the full RHIC energy of  $\sqrt{s_{NN}} = 200$  GeV, a measurement of the  $\eta$  meson will also be performed, providing the basis for an extraction of direct photons from the inclusive photon spectra. The high quality of the electron identification is shown in figure 7b, where distributions of the ratio of the calorimetric energy to the momentum are displayed. While for inclusive charged particles only a smooth distribution is observed, a clear peak at  $E/p = 1$  is observed when a signal of the RICH detector is required.

Different technologies should provide an excellent measurement of direct photons with independent checks of systematic errors. In addition, as RHIC is a dedicated heavy-ion accelerator, a much higher integrated luminosity is expected, which, together with the expected higher photon production rates, will make the RHIC measurements superior to the existing lower energy heavy-ion data.

The dynamic range of the photon measurements at RHIC should extend over the range  $1.0 \text{ GeV}/c \leq p_T \leq 30 \text{ GeV}/c$ , discrimination of high  $p_T$  photons from merging  $\pi^0$  should be possible up to  $p_T = 25 \text{ GeV}/c$ .

In figure 8 predictions for direct photon production at RHIC are shown. Given are the results of hydrodynamic calculations by Ruuskanen and Räsänen [39] assuming a QGP phase transition and an initial time of  $\tau_0 = 0.17 \text{ fm}/c$  and using the complete  $\alpha_S$ -resummed rates from Arnold *et al* [40]. The dashed line shows the contribution from the hadron



**Figure 8.** Predictions for thermal and hard photon production at RHIC as discussed in the text compared to estimates of the background of inclusive photons from neutral pion decays.

gas and the dotted line the contribution from the QGP (respective contributions during the mixed phase are included), while the solid line shows the sum of both contributions. Also included are estimates of hard photon production from  $p$ QCD calculations by Cleymans *et al* [41] and Dumitru *et al* [24]. From this comparison one can see that the hard production should start to dominate the direct photon yield for transverse momenta larger than 3–4 GeV/c.

In addition, figure 8 shows estimates of the background photons from neutral pion decays as a grey band. These are obtained by extrapolating results from the neutral pion measurements at  $\sqrt{s_{NN}} = 130$  GeV. The upper limit is calculated assuming a scaling of the pion yield according to eq. (3). The lower limit has been obtained by assuming that the pion spectrum at all transverse momenta scales as the total multiplicity density – for this scaling a value of 1.14 has been measured by the PHOBOS experiment [42]. It can be seen that the direct photon production within the model used here may easily exceed a value of 10% of the pion decay photons and should thus be reliably measurable at RHIC.

#### 4. Conclusions

The first direct photon measurement in heavy-ion reactions has been successfully performed by the WA98 experiment. The direct photon yield is higher than expected from simple extrapolations of earlier  $p$ -induced reactions. The results may be partially explained by an increased hard photon production in nuclei, i.e.,  $k_T$  broadening. The yield at intermediate  $p_T$  seems to require a thermal source with a high initial temperature.

The future of direct photon measurements in heavy-ion reactions looks bright in view of the advent of the RHIC experiments. The PHENIX experiment is especially geared up to measure photons, the redundancy in this experiment should provide a good control of systematic errors of these difficult measurements.

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