Direct photon calculations in heavy-ion collisions at $\sqrt{s_{NN}} = 62.4 - 200$ AGeV in a
(3+1) dimensional hybrid approach

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Direct photon spectra from central Au+Au- and Cu+Cu-collisions at $\sqrt{s_{NN}} = 62.4, 130$ and 
200 AGeV are calculated within the microscopic transport model UrQMD and a micro+macro
hybrid model. In the latter approach, the high-density part of the transport evolution is replaced
by an ideal 3+1-dimensional hydrodynamic calculation. We study the impact of viscosity and
full local thermalization and compare the calculations to measurements obtained by the PHENIX
collaboration. We find a reasonable agreement with the experimental data for calculations involving
a Quark-Gluon-Plasma phase.

I. INTRODUCTION

Heavy-ion physics is widely used as a tool for the explo-
ration of the phase diagram of strongly interacting
matter. In the collision of heavy nuclei, the nucleons
may be compressed and heated sufficiently to create
a new state of matter that consists of partonic degrees of
freedom, the Quark-Gluon-Plasma (QGP) $^{1,2}$. Indeed,
proposed signatures for the QGP, like strong jet quench-
ing and large elliptic flow have been found by experiments
at the Relativistic Heavy Ion Collider (BNL-RHIC) $^{3-8}$.

Inferring knowledge about the central regions of a
heavy-ion collision is very difficult, since even if a plasma
is created, its lifetime and size are beyond the experi-
mental reach for direct observation, so we are limited to
the study of particles that are emitted from the reaction
zone. Unfortunately, first principle calculations of QCD-
processes are only possible if all involved scales are much
larger than the QCD-scale $\Lambda_{\text{QCD}} \approx 0.2$ GeV. However,
in a heavy-ion collision, most particles have momenta
comparable to $\Lambda_{\text{QCD}}$. Therefore, more phenomenologi-
cal approaches are necessary to explore the bulk of the
matter.

While the abundance of hadronic particles that are
produced in a heavy-ion collision are emitted at the end of
the reaction and carry only indirect information from the
early stages, electromagnetic probes allow for an undis-
turbed view into all stages of the reaction. Photons and
leptons escape the reaction zone without rescattering due
to their very small cross-section, but for the same reason,
their abundancies are rather low, compared to hadronic
species $^3$.

Three different electromagnetic particle species are
currently being measured in heavy-ion experiments:
single- and dielectrons, single- and dimuons and photons.
Direct photons have the advantage that they are created
in scatterings of the partonic or hadronic medium and
are therefore directly coupled to the region of interac-
tion. The leptons, however, are usually created in pairs,
either in the (initial state) Drell Yan process or by the
decay of hadrons. In addition, one of the leptons might be
a neutrino, which escapes observation. Since this process
is governed by the weak interaction, the decay usually
happens outside the fireball. Single leptons are therefore
used to reconstruct weakly decaying heavy quarks, while
the invariant mass distribution of dileptons can be used to
extract spectral functions of vector mesons.

Previous calculations of direct photons from transport
theory include work with UrQMD by Dumitru $^{10}$
and Bäuchle $^{11}$ et al. and with HSD by Bratkovskaya
et al. $^{12}$. Hydrodynamics has been used in many direct
photon calculations, see e.g. $^{13-20}$.

The extraction of the yield of photons from the fireball
(direct photons) is hindered by a huge background of
photons from hadronic decays outside the fireball, which
is dominated by the $\pi^0$- and $\eta$-decays. However, exper-
imental techniques for the extraction of direct photon
yields are well developed and allow to disentangle these
late stage contributions from the scattering contribution.
The experimental methods include a direct estimation of
the background via invariant mass-analysis of the pho-
tons $^{21,22}$, the analysis of interference patterns (using
a Hanburry Brown-Twiss analysis) $^{23}$ and the extrapo-
lation of the spectra of low-mass dileptons to the photon
point $^{24}$.

In this paper, we apply a previously established model
for direct photon emission from hadronic and partonic
sources $^{11}$ and apply it to collision systems measured
by the STAR and PHENIX collaborations at BNL-RHIC.
In Section $^{111}$ we briefly introduce the model and the pa-
rameters used for the present calculations, and in Sec-
tion $^{111}$ we show the direct photon spectra obtained with
our calculations as well as comparisons to the available
data from the PHENIX collaboration $^{25,26}$.

II. THE MODEL

In the present work, direct photon spectra are calcu-
lated in the framework of the microscopic Ultrarelativis-
tic Quantum Molecular Dynamics (UrQMD) transport
model $^{27,29}$, using the hybrid option introduced in ver-
Table 1: The critical energy densities for the mapping from hydrodynamics to transport theory for the various Equations of State. $\epsilon_0 = 146$ MeV/fm$^3$ is the nuclear ground state energy density.

\begin{center}
\begin{tabular}{|c|c|}
\hline
EoS & $\epsilon_{crit}$ \\
\hline
HG-EoS & $5\epsilon_0$ \\
$\chi$-EoS & $7\epsilon_0$ \\
BM-EoS & $5\epsilon_0$ \\
\hline
\end{tabular}
\end{center}

The inclusion of an intermediate phase into the model raises the need for two interfaces, to go from the particle-based description of the transport model to the density-based description of the hydrodynamic model and back again.

The mapping from transport simulation to hydrodynamics is performed at $t_{start} = 0.6$ fm. Here, the energy-density, baryon number-density and momentum densities are calculated from all particles at midrapidity. Particles with a rapidity $|y| > 2$ are propagated in the cascade and do not interact with the bulk medium.

The transition from hydrodynamics back to the cascade proceeds gradually, mapping the temperatures and chemical potentials to particles via the Cooper-Frye formula \cite{22-5} when all cells in the same transverse slice (i.e. at the same position along the beam direction) have diluted below a critical energy density (see Table 1). After the transition to the cascade, rescatterings and decays are calculated in the well-known UrQMD model. For more detailed information on the hybrid model the reader is referred to \cite{22,23}.

### A. Equations of State

Three different Equations of State (EoS) are compared in this work. The effects of thermalization at the transition from the initial stage cascade to hydrodynamics can be explored with the Hadron Gas-EoS (HG-EoS) \cite{30}, which has the same degrees of freedom as the transport phase. To investigate the effects of partonic matter and a phase transition, we use two different models for the EoS: The Chiral Equation of State $\chi$-EoS \cite{31} has a cross-over phase transition to chirally restored and deconfined matter, while the Bag Model Equation of State BM-EoS \cite{31} has a first order phase transition to a Quark Gluon Plasma. In both EoS, the transition happens at around $T_C \approx 170$ MeV.

Table 2: Fit results for the low-$p_\perp$-part ($p_\perp < 2.5$ GeV) of the cascade calculations of Au+Au-collisions at $\sqrt{s_{NN}} = 200$ GeV (see Fig. 1). The fit function is $f(p_\perp) = A \exp \left(-\frac{p_\perp}{T_{slope}}\right)$.

| Centrality | $T_{slope}$ [MeV] | $A$ [GeV$^{-2}$] | $\chi^2$/d.o.f. |
|------------|-------------------|-----------------|-----------------|
| 00%-10%    | 231.9± 9.4        | 2.39±0.67       | 0.038           |
| 00%-92%    | 231.4± 8.5        | 0.41±0.11       | 0.032           |
| 10%-20%    | 234.0±10.0        | 1.26±0.37       | 0.041           |
| 20%-30%    | 239.0±11.4        | 0.56±0.18       | 0.049           |
| 30%-40%    | 239.0±13.1        | 0.27±0.10       | 0.065           |
| 40%-50%    | 243.0±13.4        | 0.12±0.04       | 0.064           |
| 50%-60%    | 235.4± 8.8        | (5.64±1.43)·10^{-2} | 0.032 |
| 60%-92%    | 250.5±11.8        | (6.91±2.08)·10^{-3} | 0.044 |

### B. Photon emission sources

Due to the small creation probability of direct photons, their emission is calculated perturbatively. I.e., the evolution of the underlying event remains unaltered by the emission of direct photons.

The set of channels for direct photon production differ in the transport and hydrodynamic parts of the model. The most important channels, though, are common to both parts, namely $\pi\pi \rightarrow \gamma\rho$ and $\pi\rho \rightarrow \gamma\pi$. Besides photon emission from the Quark-Gluon-Plasma, channels with strangeness are included in the hydrodynamic part. The corresponding rates for photon emission from each hydrodynamic cell are taken from Turbide et al. \cite{24}. In the transport part, additional processes including an $\eta$-meson are included. The corresponding cross-sections have been calculated by Kapusta et al. \cite{34}.

Although Kapusta and Turbide use different Lagrangians to derive their cross-sections and rates, earlier investigations (see \cite{11}) have shown that the thermal rates that can be extracted from Kapusta’s cross-sections using this model agree very well with those parametrized by Turbide et al. The same investigations have shown that the contributions of the hadronic processes that are not common to both models contribute about equally, but not significantly to the final spectra. The numerical implementation for direct photon emission is explained in detail in \cite{11}.

At high transverse momenta, another source becomes important, namely the prompt contribution from hard scatterings of partons in the initial nuclei. The spectra predicted by NLO-pQCD calculations from Gordon and Vogelsang \cite{35} fit the experimental data from the PHENIX-collaboration \cite{25} rather well at high $p_\perp$. Therefore, the pQCD contributions from \cite{35}, scaled by the number of binary collisions ($N_{coll}$) are added to the soft photons calculated here.
The thermal fits (see Table 25) for Au+Au-collisions at low and intermediate transverse momentum $p_{T}$ from cascade calculations and data from the PHENIX collaboration [26] for Au+Au-collisions at $\sqrt{s_{NN}} = 200$ GeV is shown in Fig. 1. One clearly observes that the hadronic transport model (full lines) does not saturate the upper limits of the experimental data. In all centrality bins, the prompt photon yield is significantly larger than predicted by the hadronic cascade. The ratio between pQCD and hadronic contributions is fairly constant among the centrality bins. For comparison, Fig. 1 also shows the spectra obtained with the hybrid model using the Bag Model EoS (BM-EoS) for the two most central bins, 00-10% and 10-20%, which agrees nicely with the data. Thermal fits to the low-$p_{T}$-parts of the cascade spectrum show inverse slope parameters of $T_{slope} \approx 235$ MeV throughout the centrality bins, see Table I.

A more detailed exploration of the low-$p_{T}$-part of the direct photon calculation is shown in Fig. 2. Here, the low-$p_{T}$-data obtained by extrapolating the dilepton yield to zero invariant mass [20] for central (00-20%) and mid-central (20-40%) is shown in comparison to cascade calculations (red solid lines) for central to peripheral collisions. The green dash-dotted lines show the sum of pQCD-calculations [23, 38] and the cascade contribution. For the most central collisions, 00-10% and 10-20%, the spectra from hybrid calculations with the BM-EoS plus pQCD-contribution are shown (violet dotted lines).

III. RESULTS

The comparison between direct photon spectra at low and intermediate transverse momentum $p_{T}$ from cascade calculations and data from the PHENIX collaboration [26] for Au+Au-collisions at $\sqrt{s_{NN}} = 200$ GeV is shown in Fig. 1. One clearly observes that the hadronic transport model (full lines) does not saturate the upper limits of the experimental data. In all centrality bins, the prompt photon yield is significantly larger than predicted by the hadronic cascade. The ratio between pQCD and hadronic contributions is fairly constant among the centrality bins. For comparison, Fig. 1 also shows the spectra obtained with the hybrid model using the Bag Model EoS (BM-EoS) for the two most central bins, 00-10% and 10-20%, which agrees nicely with the data. Thermal fits to the low-$p_{T}$-parts of the cascade spectrum show inverse slope parameters of $T_{slope} \approx 235$ MeV throughout the centrality bins, see Table I.

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In both centrality-bins, the direct photon spectra obtained with the BM-EoS and χ-EoS, which include a phase transition to a deconfined state of matter, are significantly higher than the hadronic HG-EoS-calcualtions and agree with the measured data.

A similar picture presents itself in Au+Au-collisions at lower incident energy $\sqrt{s_{NN}} = 62.4$ GeV and $\sqrt{s_{NN}} = 130$ GeV, shown in the upper panels of Figure 3. The cascade calculations have been omitted from the Figure for clarity.

Thermal fits to the spectra (see Table III) show inverse slope parameters in the range from $\langle N_{coll} \rangle$-scaled prompt photon contribution.

Hybrid model calculations for central (0-20%) and mid-central (20-40%) Cu+Cu-collisions are shown in the lower panels of Figure 3 for all EoS. The thermal fits (see Ta-
FIG. 3: (Color Online). Direct photon spectra calculated with the Hybrid model and HG-EoS (solid blue lines), χ-EoS (dashed orange lines) and BM-EoS (dotted violet lines) without prompt photon contribution. The left panels show calculations for √sNN = 62.4 GeV, the middle panels show calculations for √sNN = 130 GeV and the right panel shows calculations for √sNN = 200 GeV. The upper panels show calculations for Au+Au-collisions, while the lower panel shows calculations for Cu+Cu-collisions. In each panel, the upper curves are central collisions (00-20%) and the lower curves are mid-central collisions (20-40%).

Table III: Fit results for the low-p⊥-part (p⊥ < 2.5 GeV) of the spectra from central (0-20%) and mid-central (20-40%) Au+Au-collisions. The fit function is \( f(p⊥) = A \exp \left( -\frac{p⊥}{T_{slope}} \right) \). The data are shown in Figure 2 (for √sNN = 200 GeV) and Figure 3 (for √sNN = 62.4 GeV, upper left panel and √sNN = 130 GeV, upper central panel).

TABLE III: Fit results for the low-p⊥-part (p⊥ < 2.5 GeV)

| √sNN EoS | centr. | \( T_{slope} \) [MeV] | \( A \) [GeV\(^{-2}\)] | \( χ^2/ν \) |
|----------|--------|------------------------|------------------------|--------------|
| 200      | Transport | 0-20% | 232.5±9.8 | 1.65±0.48 | 0.041 |
| 200      | HG-EoS | 0-20% | 246.7±8.6 | 3.63±0.83 | 0.025 |
| 200      | χ-EoS | 0-20% | 261.9±8.7 | 10.13±2.05 | 0.020 |
| 200      | BM-EoS | 0-20% | 251.4±9.7 | 16.37±4.03 | 0.029 |
| 200      | Transport | 20-40% | 237.3±12.1 | 0.38±0.13 | 0.057 |
| 200      | HG-EoS | 20-40% | 243.4±8.3 | 1.32±0.30 | 0.020 |
| 200      | χ-EoS | 20-40% | 253.0±8.0 | 4.11±0.82 | 0.020 |
| 200      | BM-EoS | 20-40% | 240.6±9.0 | 7.61±1.90 | 0.030 |
| 130      | Transport | 0-20% | 232.5±9.1 | (8.97±2.67) \(*) | 0.035 |
| 130      | HG-EoS | 0-20% | 246.3±8.5 | 3.42±0.66 | 0.024 |
| 130      | χ-EoS | 0-20% | 261.2±8.5 | 9.67±1.93 | 0.019 |
| 130      | BM-EoS | 0-20% | 250.2±9.6 | 15.84±3.88 | 0.039 |
| 130      | Transport | 20-40% | 257.2±11.3 | (5.48±1.50) \(*) | 0.036 |
| 130      | HG-EoS | 20-40% | 242.4±7.4 | 1.26±0.26 | 0.021 |
| 130      | χ-EoS | 20-40% | 252.7±7.9 | 4.01±0.80 | 0.019 |
| 130      | BM-EoS | 20-40% | 240.6±8.8 | 7.46±1.82 | 0.029 |
| 62.4     | Transport | 0-20% | 242.1±13.5 | (5.29±1.95) \(*) | 0.066 |
| 62.4     | HG-EoS | 0-20% | 247.3±8.1 | 3.19±0.67 | 0.022 |
| 62.4     | χ-EoS | 0-20% | 261.8±8.2 | 9.24±1.78 | 0.018 |
| 62.4     | BM-EoS | 0-20% | 250.3±9.5 | 15.13±3.65 | 0.028 |
| 62.4     | Transport | 20-40% | 232.8±9.4 | (4.18±1.16) \(*) | 0.038 |
| 62.4     | HG-EoS | 20-40% | 245.8±8.0 | 1.21±0.26 | 0.022 |
| 62.4     | χ-EoS | 20-40% | 253.9±7.7 | 3.82±0.73 | 0.018 |
| 62.4     | BM-EoS | 20-40% | 240.8±8.6 | 7.33±1.74 | 0.028 |

\(*: \times 10^{-2}, \ #: \times 10^{-3}\)

IV. SUMMARY

We examined the direct photon spectra obtained with a transport and a transport+hydrodynamics hybrid model for collisions of Au+Au and Cu+Cu at energies of √sNN = 62.4, 130 and 200 GeV. We find that the hadronic models (transport model and hybrid model with Hadron Gas EoS) underpredict the data, while calculations with a deconfined state of matter (hybrid model with Chiral or Bag Model EoS) fit the data much better.

Future work with this model will include the extraction of radial and elliptic flow parameters \( v_1 \) and \( v_2 \) for more differential analyses. Also, the influence of chang-

V. OUTLOOK

We found that the inverse slope parameter \( T_{slope} \) or yield \( A \) show no significant energy dependence of inverse slope parameter \( T_{slope} \) or yield \( A \). We observe a clear ordering of the total yield between the Equations of State, with yield from the BM-EoS calculations being higher than that of the χ-EoS, and both yields exceeding that of HG-EoS calculations. However, the inverse slope parameters are similar in HG-EoS and χ-EoS calculations but significantly lower in BM-EoS calculations.
TABLE IV: Fit results for the low-$p_L$-part ($p_L < 2.5$ GeV) of the spectra from central (0-20%) and mid-central (20-40%) Cu+Cu-collisions. The data are shown in Figure 3, lower panels.

| √sNN | EoS   | centr. | $T_{slope}$ [MeV] | $A$ [GeV$^{-2}$] | $\chi^2/\text{dof}$ |
|------|-------|--------|------------------|-----------------|-----------------|
| 200  | HG-EoS| 0-20%  | 252.0± 9.6       | (4.84±1.38)$^a$ | 0.057           |
| 200  | χ-EoS | 0-20%  | 251.5± 7.3       | 1.77±0.39       | 0.033           |
| 200  | BM-EoS| 0-20%  | 237.7± 7.8       | 3.61±0.94       | 0.047           |
| 200  | HG-EoS| 20-40% | 254.6±13.2       | (1.61±0.62)$^a$ | 0.103           |
| 200  | χ-EoS | 20-40% | 242.9± 7.0       | (7.25±1.63)$^a$ | 0.036           |
| 200  | BM-EoS| 20-40% | 292.0± 7.5       | 1.60±0.43       | 0.051           |
| 130  | HG-EoS| 0-20%  | 250.0± 9.3       | (4.78±1.35)$^a$ | 0.056           |
| 130  | χ-EoS | 0-20%  | 250.9± 7.1       | 1.76±0.37       | 0.031           |
| 130  | BM-EoS| 0-20%  | 238.1± 7.9       | 3.56±0.93       | 0.048           |
| 130  | HG-EoS| 20-40% | 240.4± 7.1       | (1.99±0.50)$^a$ | 0.044           |
| 130  | χ-EoS | 20-40% | 242.8± 7.1       | (6.99±1.59)$^a$ | 0.036           |
| 130  | BM-EoS| 20-40% | 228.5± 7.7       | 1.58±0.44       | 0.054           |
| 62.4 | HG-EoS| 0-20%  | 248.2± 7.7       | (4.71±1.11)$^a$ | 0.039           |
| 62.4 | χ-EoS | 0-20%  | 250.2± 6.8       | 1.71±0.35       | 0.029           |
| 62.4 | BM-EoS| 0-20%  | 236.8± 7.4       | 3.52±0.88       | 0.044           |
| 62.4 | HG-EoS| 20-40% | 242.8± 6.9       | (1.87±0.41)$^a$ | 0.034           |
| 62.4 | χ-EoS | 20-40% | 241.7± 6.3       | (6.71±1.37)$^a$ | 0.029           |
| 62.4 | BM-EoS| 20-40% | 227.0± 6.7       | 1.62±0.40       | 0.042           |

$^a$: $\times 10^{-1}$

VI. ACKNOWLEDGEMENTS

This work has been supported by the Frankfurt Center for Scientific Computing (CSC), the GSI and the BMBF. B. Bäuclie gratefully acknowledges support from the Deutsche Telekom Stiftung, the Helmholtz Research School on Quark Matter Studies and the Helmholtz Graduate School for Hadron and Ion Research. This work was supported by the Hessian LOEWE initiative through the Helmholtz International Center for FAIR.

The authors thank Elvira Santini for valuable discussions and Henner Büsching for experimental clarifications.
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