EPJ Web of Conferences **364**, 07002 (2026) https://doi.org/10.1051/epjconf/202636407002
Quark Matter 2025

Direct virtual photon production in Au+Au collisions with STAR BES-II data

Xianwen Bao[1,*] on behalf of the STAR Collaboration

[1]Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao 266237, China

Abstract. In relativistic heavy-ion collisions, electromagnetic probes such as direct photons have the advantage of escaping from the emission sources without suffering strong interactions. Consequently, these photons, which are not from hadron decay, carry the information about the properties and dynamics of the hot and dense medium created in heavy-ion collisions. We report the measurements of the direct virtual photons from STAR experiment, based on the data collected in the Beam Energy Scan Phase II (BES-II) Program at RHIC. The p_T-integrated yields exhibit strong dependence on multiplicity and scale with $(dN_{ch}/d\eta)^{\alpha}$, where $\alpha = 1.43 \pm 0.04$ (stat.) $\pm$ 0.04 (sys.). The p_T-dependent virtual photon mass spectra in $\sqrt{s_{NN}}$ = 54.4 GeV Au+Au collisions are measured for the first time. The results reveal that the observed mass shape of virtual photons varies with p_T, indicating a transition in their production mechanism from an equilibrated system to a non-equilibrated one as p_T increases.

1 Introduction

Direct photons are electromagnetic probes produced during all stages of ultra-relativistic heavy-ion collisions, escaping from the generated hot and dense medium without experiencing strong interactions. They are prompt photons from initial hard parton scattering and thermal photons from the thermal radiation of the medium. Prompt photons are dominate the direct photon yield at high p_T, providing a good way to understand partonic dynamics and testing perturbative QCD theory. At low p_T, where thermal photons dominate, direct photons serve as penetrating probes of quark-gluon plasma (QGP), probing the energy density, temperature, and collective motion of the hot and dense medium generated from the collisions [1].

In this contribution, the measurements of direct virtual photon are presented for the first time at $\sqrt{s_{NN}}$ = 14.6 and 19.6 GeV in different centrality classes from Au+Au collisions from the STAR experiment, together with the previous results at $\sqrt{s_{NN}}$ = 27 and 54.4 GeV. The direct virtual photon mass distributions in different p_T regions in $\sqrt{s_{NN}}$ = 54.4 GeV Au+Au collisions have been studied, aiming a more comprehensive understanding of direct photon production mechanism.

*e-mail: baoxianwen@mail.sdu.edu.cn

2 Experiment and analysis

The presented analyzes use the data from Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 14.6, 19.6, 27, and 54.4 GeV. Charged particle tracks and the average ionization energy loss of particles per unit length ($\langle dE/dx \rangle$) are reconstructed by the Time Projection Chamber (TPC). Good electron identification has been achieved using both the TPC and Time-of-Flight (TOF) detectors. Both TPC and TOF cover the full azimuthal angle ($-\pi < \phi < \pi$) and mid-pseudorapidity ($|\eta| < 1$).

The dielectron invariant mass spectra are obtained by comparing randomly paired opposite-sign ($+-$) and like-sign ($++/--$) electrons/positrons. TPC tracking efficiency, TOF matching efficiency, and electron identification efficiency corrections were applied [3, 4]. Cocktail is the simulated dielectron background that originates from final-state hadron decays, including two-body and Dalitz dacay of π^0, η, η', ω, ϕ, and J/ψ; semi-leptonic decay of charm; and Drell-Yan process. In particular, since η influence the direct photon yield largely and there is no η yield at these collision energies, the η/π^0 ratio is constrained by worldwide data, fixed at 0.470 ± 0.017 for p_{T} = 5 GeV/c.

3 Results

3.1 Dielectron invariant mass spectra

Figure 1 presents the dielectron invariant mass spectra and cocktail within the STAR acceptance in Au+Au collisions from the STAR BES-II program. A clear enhancement caused by direct virtual photons and in-medium ρ^0 can be observed in this presented mass region in 0-20% centrality.

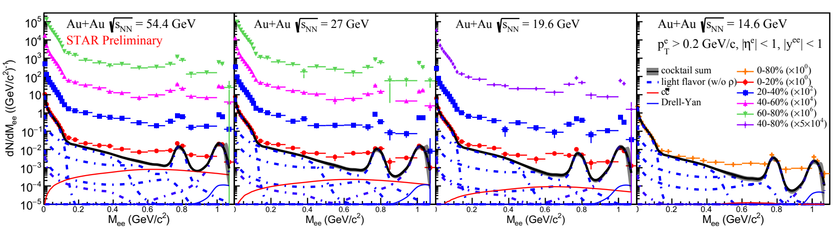

Figure 1. Dielectron invariant mass spectra and cocktail distributions within STAR acceptance from Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 14.6, 19.6, 27, 54.4 GeV.

3.2 Direct photon p_{T} spectra and yields (dN/dy)

The direct virtual photon yield is extracted by internal method via a two-component fitting to the invariant mass distribution in different p_T regions,

$$\frac{dN_{ee}^2}{dM_{ee}dp_T} = r * f_{dir} + (1-r) * f_{ckt}, \tag{1}$$

where r represents the fraction of the direct virtual photons to inclusive photons, f_{dir} and f_{ckt} represent the invariant mass distributions of direct virtual photons and the cocktail in different p_T regions, respectively. The direct virtual photon p_{T} spectra, shown in Fig. 2, are extracted by fitting the dielectron mass spectra in p_{T} intervals. The p_{T}-integrated yields from

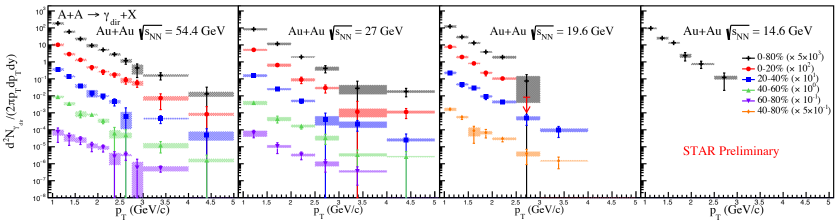

Figure 2. Direct virtual photon p_{T} spectra in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 14.6, 19.6, 27, 54.4 GeV in different centrality classes. Statistical and systematic uncertainties are shown as vertical lines and shaded boxes, respectively. The spectra are scaled for clarity.

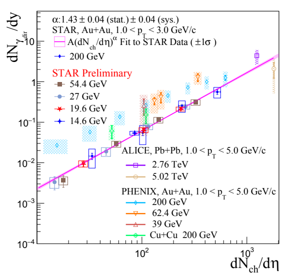

Figure 3. Direct photon yields versus charged particle multiplicity in Au+Au collisions from BES-II program. Solid points represent 14.6, 19.6, 27, 54.4 GeV direct photon yields (1.0 < p_{T} < 3.0 GeV/c) respectively, open points represent 2.76 and 5.02 GeV (1.0 < p_{T} < 5.0 GeV/c) results from ALICE [6, 7] and 39, 62.4, 200 GeV results (1.0 < p_{T} < 5.0 GeV/c) from PHENIX [8, 9], pink line corresponds to the fit to data points from STAR.

1 to 3 GeV/c of direct virtual photons are shown as a function of $dN_{\mathrm{ch}}/d\eta$ in Fig. 3, together with the results from $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV Au+Au collisions measured by STAR previously [5]. A strong multiplicity dependence has been observed for the direct virtual photon yields. An exponential function $(dN_{\mathrm{ch}}/d\eta)^{\alpha}$ is used to fit the direct virtual photon yields from STAR. The scaling power α value is 1.43 ± 0.04(stat.) ± 0.04(sys.).

3.3 Virtual photon mass distribution

To further study the virtual photon mass distribution, a function is shown as Eq. (2),

$$\frac{dN_{ee}}{dM_{ee}} = \gamma^{dir} + C_{ckt} * f_{ckt(w/o\ \omega,\phi)} + C_{\omega} * f_{\omega} + C_{\phi} * f_{\phi} + H_{in-medium}. \tag{2}$$

was used to fit the low mass dielectron continuum at $\sqrt{s_{\mathrm{NN}}}$ = 54.4 GeV, where the direct virtual photon contribution (γ^{dir}) is evaluated by $C * f_{dir} = C * [1 + (q-1)\frac{M_{ee}}{\beta}]^{-\frac{1}{q-1}}$. $f_{ckt(w/o\ \omega,\phi)}$, f_{ω}, f_{ω} represents each component mass shape in the cocktail. C_{ckt}, C_{ω}, C_{ϕ} represents the amplitude. $H_{in-medium}$ represents the dielectron contribution from the QGP medium estimated by TAMU. In this function, the parameter q determines the overall shape of the virtual photon mass distribution. f_{dir} approaches an exponential form when q is close 1, corresponding to a system close to thermal equilibrium. In contrast, when q is closer to 2, f_{dir} exhibits a power-law behavior, indicating a non-equilibrated system. The fitting results are presented in the upper panels of Fig. 4. As the transverse momentum increases, the extracted q increases from 1 to 2. This behavior suggests that the mass distribution of virtual photons changes from exponential to power-law as p_{T} increases, corresponding to the production from the later stage to the earlier stage. Furthermore, comparison between dielectron spectra and the fit in different p_{T} intervals, the contours of different confidence levels obtained from a χ^2-minimization procedure by scanning different q and β are shown in the lower panels. The systematic uncertainty are shown in the lower panels of Fig. 4.

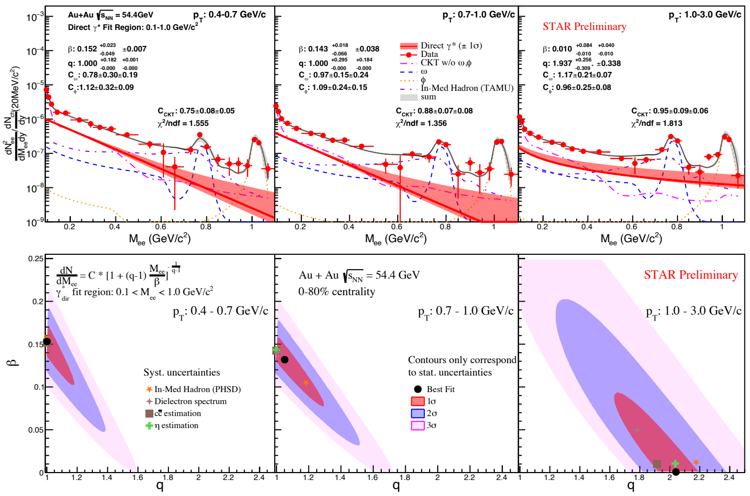

Figure 4. (Upper panels) Direct virtual photon mass distributions in Au+Au collisions at $\sqrt{s_{NN}}$ = 54.4 GeV in different p_T ranges, 0-80%. Red points represent the dielectron mass spectra in different p_T regions, red line is the direct virtual photon fit and red band represent 1σ band. (Lower panels) The constraints on virtual photon distribution extracted by the comparison STAR measurement and fitting in different q and β.

4 Summary

Direct virtual photon p_T spectra have been presented for Au+Au collisions at $\sqrt{s_{NN}}$ = 14.6, 19.6, 27, and 54.4 GeV measured with the STAR experiment. The yields ($1 < p_T < 3$ GeV/c) exhibit a strong dependence on multiplicity and follow a common scaling with $(dN_{ch}/d\eta)^{\alpha}$, where $\alpha = 1.43 \pm 0.04$(stat.) $\pm$ 0.04(sys.). The virtual photon mass spectra have been studied in detail. With p_T increasing from 0.4 to 3 GeV/c, the virtual photon mass distributions change from exponential to power-law, which hints at a production mechanism shifting from an equilibrated to a non-equilibrated system.

Acknowledgments

This work was funded by the project ZR2024QA192 and ZR2022JQ03 supported by Shandong Provincial Natural Science Foundation, and the project 12475142 supported by the National Natural Science Foundation of China.

References

[1] E.V. Shuryak, Phys.Lett.B 78 (1978) 150.
[2] G. David, Rept.Prog.Phys. 83 (2020) 4, 046301.
[3] STAR Collaboration, arXiv:2402.01998 [nucl-ex].
[4] J. Chen *et al.*, Nucl.Sci.Tech. 35 (2024) 12, 214.
[5] L. Adamczyk, (STAR Collaboration), Phys.Lett.B 770 (2017) 451-458
[6] B. Sahlmüller, (ALICE Collaboration), Nucl.Phys.A 956 (2016) 421-424.
[7] D. Peresunko, (ALICE Collaboration), KnE Energ.Phys. 3 (2018) 210-216.
[8] N. J. Abdulameer *et al.* (PHENIX Collaboration), Phys.Rev.C 107 (2023) 2, 024914.
[9] N. J. Abdulameer *et al.* (PHENIX Collaboration), Phys.Rev.C 109 (2024) 4, 044912.