Direct virtual photon production in Au+Au collision at 27 and 54.4 GeV

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Abstract. As electromagnetic probes, photons have the advantage of escaping unimpeded from their emission source, allowing them to carry valuable information about the properties and dynamics of the hot quantum chromodynamics (QCD) medium created in heavy-ion collisions. Particularly, the transverse momentum distribution of direct virtual photons emitted from the hot QCD medium exhibits sensitivity to the system temperature. Direction photons from thermal radiation in the low transverse momentum region are expected to be a quark-gluon plasma (QGP) thermometer. However, the photon from hadronic decays make the extraction of the thermal radiation contribution very challenging.

The STAR experiment has recorded large datasets of Au+Au collisions in the Beam Energy Scan Phase-II (BES-II) program, spanning center-of-mass energies of $\sqrt{s_{\mathrm{NN}}}$ = 3 - 54.4 GeV. In these proceedings, we present the latest direct virtual photon measurement in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 27 and 54.4 GeV, including p_{T} differential invariant yields and total yields in different centrality bin. The total yields increase rapidly with increasing $dN_{\mathrm{ch}}/d\eta$. Notably, it scales with $(dN_{\mathrm{ch}}/d\eta)^{\alpha}$, where $\alpha = 1.46 \pm 0.07$.

1 Introduction

Direct virtual photons play an important role in the study of the QGP. They serve as electromagnetic probes, owing to their ability to escape unimpeded from their emission sources. Direct virtual photon contain prompt photons from initial hard scattering and thermal photons from QGP thermal radiation in heavy ion collision. Because direct virtual photons are produced during all stages of an ultra-relativistic heavy ion collision, they carry information of the properties and dynamics of QGP, such as energy density, temperature and collective motion, integrated over space and time [1] [2].

However, the measurement is challenging due to significant background contributions from hadronic decays. Precise estimation of these backgrounds is essential for accurately determining the thermal radiation originating from QGP.

The PHENIX collaboration reported for the first time the production of direct photons in Au+Au collisions at 200 GeV [3]. Subsequently, STAR collaboration reported for the production of direct virtual photon through internal conversion method in 2017 [4], revealing a

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discrepancy of nearly 4 times lower than direct photon yields of PHENIX, and this difference is still unresolved up to now.

In these proceedings, direct virtual photon measurement results were presented at $\sqrt{s_{\rm NN}}$ = 27 and 54.4 GeV in Au+Au collision at different centralities in STAR experiment and compared to results of the PHENIX and ALICE collaboration, aiming to contribute a more comprehensive understanding of direct photon production in QGP [5].

2 Analysis

The data used in this analysis were collected by STAR detector in 2018 (2017) Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 27 (54.4) GeV respectively. STAR detector provides full azimuthal angle ($-\pi < \phi < \pi$) and mid-pseudorapidity ($|\eta| < 1$) acceptance coverage. The averaged particle ionization energy loss per unit length ($\langle dE/dx \rangle$) and momentum (p) are measured by the time projection chamber (TPC) [6], and the velocity of charged particles is measured by the time of flight (TOF) [7]. The electron identification is achieved by combining the $\langle dE/dx \rangle$ and velocity information.

2.1 Dielectron raw signal extraction

For the reconstruction of the dielectron spectrum, the foreground is constructed by pairing electron and positron candidates after removing background contributions. The background is estimated using like-sign pairs, which includes correlated and combinatorial background. An acceptance correction is applied to the like-sign pairs, which is estimated using unlike-sign and like-sign pairs from an event-mixing technique [8]. Additionally, dielectrons originating from interaction between photon and detector material (photon conversion) are rejected by applying a ϕ_V vs. M_{ee} cut, where ϕ_V represents the opening angle of electron pairs. After subtracting the background from the foreground, the raw signal is obtained.

2.2 Efficiency

Efficiency correction, including electron identification efficiency and electron detection efficiency, is applied to the dielectron raw signal. The particle identification efficiency is calculated by selecting pure electron/positron originating from photon conversion [8]. The TPC reconstruction efficiency is calculated using the embedding technique and TOF matching [9] is determined through a data-driven method. Furthermore, the dielectron pair efficiency as shown in Equation 1, is obtained by multiplying the single track efficiencies of the electron and positron.

$$\begin{aligned} \varepsilon_{e^{+/-}} &= \varepsilon_{TPC} * \varepsilon_{TOF} * \varepsilon_{n\sigma_e} * \varepsilon_{\beta}, \\ \varepsilon_{pair} &= \varepsilon_{e^+} * \varepsilon_{e^-}, \end{aligned} \tag{1}$$

2.3 Direct virtual photon extraction

Direct virtual photons are measured via their internal conversion into dielectron pairs which can be detected by the STAR experiment. However, as mentioned in Sect. 1, there will be backgrounds that need to be subtracted in this analysis. The dominant background originate from dalitz decay of η and π^0, which can be effectively simulated with Monte Carlo, requiring $p_{\rm T}$, mass, ϕ and rapidity distribution as a input for mesons with a di-electron channel. These simulations are normalized using measured hadron yields and $p_{\rm T}$ spectra [10].

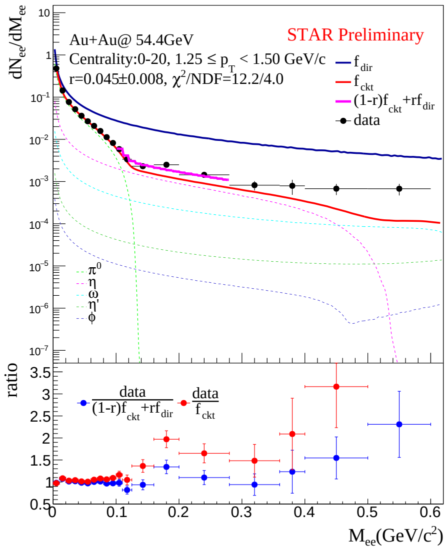

Figure 1. The upper panel show dielectron invariant mass spectrum within STAR acceptance ($p_T^e > 0.2$ GeV, $|\eta^e| < 1$, $|y_{ee}| < 1$) after efficiency correction in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 54.4$ GeV in 0-20% centrality. The dashed and solid red lines show the contributions from hadronic decays. The pink line is obtained by the two component fitting. The lower panel shows the ratio of data to cocktail (red solid circles) and data to two-component fit result (blue solid circles) respectively.

The contribution of direct virtual photons to the inclusive dielectron spectrum is very small. Thus, the estimate of the η contribution needs to be very accurate. The η and π^0 spectra are parametrized using Tsallis blast-wave functions, where the parameters are constrained using existing data [12]. The normalization of η is constrained using worldwide data of η/π^0 [11] ($p_{\mathrm{T}} = 5$ GeV/c). It is fixed to 0.470 ± 0.017 [13].

The form factor of the virtual photon is similar to that of the π^0 dalitz dacay, but significantly different to that of the η dalitz decay. Thus, the mass distribution between the η decay electrons and electron pairs from virtual photons are different, which enables the extraction of direct virtual photon signal via a two-component fit as described by Equation 2.

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

where r is the fraction of direct virtual photons to inclusive virtual photons, f_{dir} and f_{ckt} represent direct virtual photon and cocktail mass distribution respectively. Since the proportion of direct photons is obtained by taking ratio in the method of the direct photons extracting, both of signals and backgrounds in this analysis are eliminated by taking ratio under STAR acceptance.

The result of two component fit (fit range: 0.10-0.28 GeV/c^2) is depicted in Figure 1. Compared with cocktail, data has a slight enhancement contributed by direct virtual photon. We observe that the data over cocktail and the data over the fit is consistent with unity over the mass range in different centrality and p_{T} bins, which indicates reasonable quality of estimation of cocktail and fitting.

3 Results and discussion

3.1 Direct virtual photon p_{T} spectra and yield

The direct virtual photon transverse momentum spectra in different centralities are shown in Figure 2. These spectra include prompt and thermal photons, which provide a chance to measure the thermal radiation characteristics and properties of QGP.

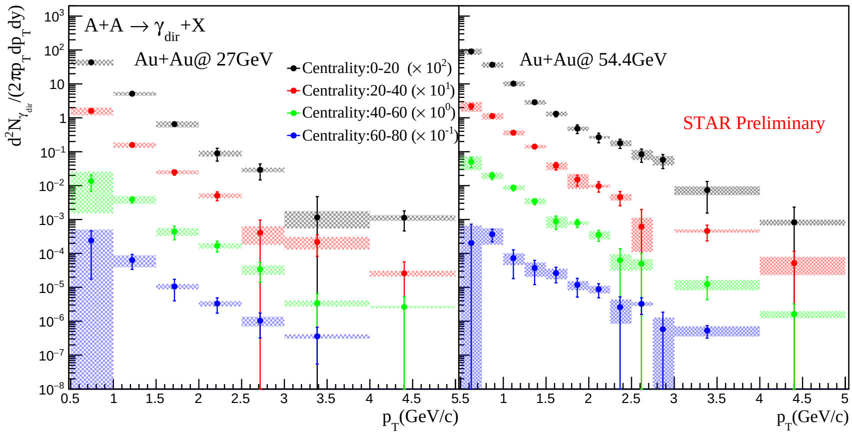

Figure 2. Direct virtual photon transverse momentum spectra in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 27 (left panel) and 54.4 (right panel) GeV. The p_{T} spectra with different color markers present different centralities cases respectively.

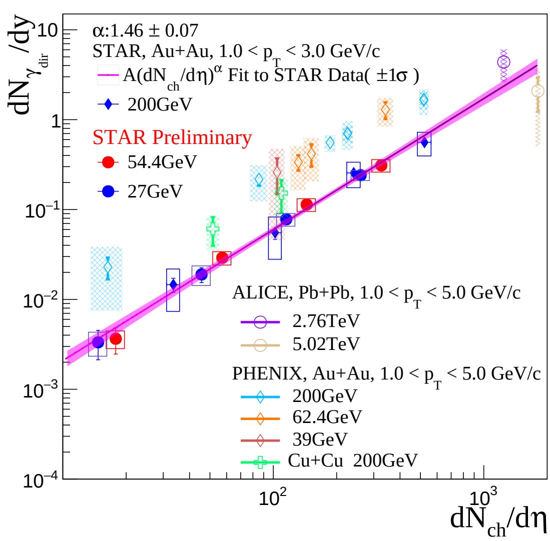

Figure 3. Direct virtual photon yield which integrated in the p_{T} region of 1.0-3.0 GeV/c. The pink line is obtained by fitting 27 (blue solid circles), 54.4 (red solid circles), 200 GeV (blue solid diamonds) direct photon yield from STAR collaboration, pink band indicate the fitting 1σ error. Open circles are the results of ALICE collaboration [16]. Open diamonds and crosses are the results of PHENIX collaboration [17].

STAR presented the 200 GeV direct virtual photon yield in different centralities, which are correlated with $dN_{\mathrm{ch}}/d\eta$ [4]. A comparison with theoretical calculations in proton-proton collisions [18] imply that in Au+Au collisions, the direct photons in the transverse momentum range between 1 and 3 GeV/c is dominated by thermal photons. The integrated-p_T spectrum from 1 to 3 GeV/c of direct virtual photon yields at 27 and 54.4 GeV in Au+Au collision are shown in Figure 3. Comparing the data from STAR collaboration, there is an indication that direct virtual photon yield has strong $dN_{\mathrm{ch}}/d\eta$ dependence [15]. But the results difference between PHENIX and STAR are still unresolved. Equation 3 is used to fit direct photon yield from STAR collaboration. The obtained α value is 1.46 ± 0.07.

$$\frac{dN_{\gamma_{dir}}}{dy} = A * (dN_{\mathrm{ch}}/d\eta)^{\alpha}. \tag{3}$$

4 Summary

We reported the direct virtual photon transverse momentum spectra in Au+Au collision in different centralities at $\sqrt{s_{\mathrm{NN}}}$ = 27 and 54.4 GeV, collected by STAR experiment at RHIC. The direct photon yield reveals a strong dependence on $dN_{\mathrm{ch}}/d\eta$. The direct photon yields measured in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 27, 54.4, and 200 GeV from STAR follow a power-law dependence on the charged particle multiplicity with an exponent alpha = 1.46 ± 0.07. The direct photon yields in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 and 5.02 TeV measured by the ALICE collaboration are also consistent with this power-law dependence despite the large difference in the collision energies. In the future, we will attempt to subtract the prompt photon contribution with the help of theoretical calculations in order to extract the effective temperature of thermal photons. BES-II program will provide an excellent opportunity to extend direct photon measurements to lower collision energies corresponding to higher chemical baryon potential.

5 Acknowledgments

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