Nonprompt direct-photon production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

N. J. Abdullameer, U. Acharya, A. Adare, C. Aidala, N. N. Ajitanand, Y. Akiha, M. Alfred, N. Apadula, H. Asano, B. Azmoun, V. Babintsev, M. Bai, N. S. Bandara, B. Bannier, K. N. Barish, S. Bathe, A. Bazilevsky, M. Beaumier, S. Beckman, R. Belmont, A. Berdnikov, Y. Berdnikov, B. Lichon, B. Blankenship, D. S. Blau, J. S. Bok, V. Borisov, K. Boyle, M. L. Brooks, J. Brzyslawskyj, V. Bunzhovn, M. Campbell, C. Chen, M. Chiu, C. Y. Chi, I. J. Choi, J. B. Choi, T. Chiu, Z. Citron, M. Connors, R. Corlliss, Y. Corrales Morales, M. Csámad, T. Csörgő, T. W. Danley, A. Datta, M. S. Daugherity, G. David, C. T. Dean, D. DeBlasio, K. Dehmelt, D. Denisov, A. Deshpande, E. J. Desmond, A. Dogon, P. Diss, J. H. Do, V. Doornma, A. Drees, K. A. Drees, J. M. Durham, A. Durum, E. Enokizono, R. Esha, B. Fadem, W. Fan, N. Ferce, D. E. Fields, M. Finger, J. R. M. Finger, D. Firk, D. Fitzgerald, S. L. Fokin, J. E. Frantz, A. Franz, A. D. Frawley, P. Gallus, C. Gal, P. Garg, H. Ge, M. Giles, F. Giordano, A. Glenn, Y. Goto, M. Grau, N. Gris, S. Green, M. Grosse Perdekamp, T. Gunji, T. Guo, T. Hachiya, J. S. Haggerty, K. I. Hahn, H. Hamagaki, H. F. Hamilton, J. Hanks, S. Y. Han, M. Harvey, S. Hasegawa, T. O. S. Haseler, K. Hashimoto, K. Hemmick, H. He, J. C. Hill, A. Hodges, R. S. Hollis, K. Homma, B. Hong, T. Hoshino, N. Hotvedt, J. Huang, K. Imai, M. Inaba, I. Iordanova, I. Ishenower, D. Ivanishchev, B. V. Jacak, M. Jezghani, X. Jiang, Z. J, B. M. Johnson, D. J. O. Johnson, D. S. Jumper, S. Kanda, J. H. Kang, D. Kawall, A. V. Kazantzis, J. A. Key, V. Khachatryan, A. Khazandeey, A. Khatiwada, B. Kimelman, C. Kim, D. J. Kim, E. J. Kim, G. W. Kim, M. Kim, T. Kim, D. Kinesis, A. Kinger, E. Kistenev, R. Kitamura, K. Klatsky, D. Kleinjan, P. P. Kline, T. Kolesky, B. Komkov, D. Kotov, L. Kovacs, B. Kurgys, K. Kurita, M. Kurosawa, Y. Kwon, J. G. Lajoie, D. Larionova, A. Lebedev, S. Lee, H. S. Lee, M. Leitch, N. A. Lewis, S. H. Lim, M. X. Liu, X. Li, D. A. Loomis, D. Lynch, S. Lökös, T. Majoros, Y. I. Makdisi, M. Makej, A. Manion, V. I. Manko, E. Mannel, M. McCumber, P. L. McCullough, D. McEwen, C. McKinney, A. Meles, M. Mendoza, A. C. Mignerey, A. Milov, D. K. Mishra, J. T. Mitchell, M. Mitranova, I. Mitranov, S. Miyasaka, S. Mizuno, A. Mohamed, A. K. Mohanty, M. M. Mondal, P. Montuenga, T. Moon, D. D. Morrison, T. V. Moukhanova, B. Mullio, S. Murakami, J. Murata, M. Mwa, K. Nagashima, J. L. Nagle, T. I. Nagy, I. Nakagawa, H. Nakagomi, K. Nakano, C. Nattrass, S. Nelson, K. Netttrakanti, T. Niida, S. Nishimura, R. Nouicer, N. Novitzky, T. Novák, G. Nukazuka, A. S. Nyanin, E. O’Brien, C. A. Ogilvie, J. D. Orjuela Koop, M. Oroz, J. D. Osdorn, A. Oskaarson, K. Ozawa, C. P. Pak, V. Pantuev, V. Papavassiliou, J. S. Park, J. S. Park, M. Patel, S. F. Pate, J. C. Peng, W. Peng, D. V. Perepelitsa, D. G. D. N. Perera, D. Y. Peressounko, C. E. PerezLara, J. Perry, R. Petti, C. Pinkenburg, R. Pinson, R. P. Pisani, M. Potekhin, P. Mun, M. L. Purschke, P. V. Radzevich, J. R. Rak, N. Ramasubramanian, B. J. Ramson, I. Ravinovich, F. K. Reed, D. Reynolds, V. I. Riabov, D. Richford, T. Rinn, S. D. Rohnick, M. Rosati, Z. R. Rowan, J. G. Rubin, J. Runey, B. Sahlinmueller, N. Saito, T. Sakaguchi, H. Sako, V. Samsonov, M. Sarsor, S. Sato, B. Schaefer, B. K. Schmoll, K. Sedgwick, R. Seidl, M. Sexton, D. Sharma, I. Shein, Z. Shi, M. Shibata, T. A. Shibata, K. Shigaki, M. Shimomura, P. Shukla, A. Sickles, C. Silvera, D. Silvermyr, B. Singh, C. Singh, V. Singh, M. Slunecka, K. L. Smith, M. Snowball, R. A. Soltz, W. E. Sondheim, S. Sorensen, I. V. Sourikova, P. W. Stankus, M. Stepianov, S. Stoll, T. Sugitake, A. Sukhanov, T. Sumita, Z. Sun, J. Sun, J. Szklak, R. Takahama, A. Taketani, T. Tanida, M. J. Tannenbaum, S. T. Taranenko, A. Timilsina, T. Todoroki, M. Tomášek, C. L. Towell, R. Towell, I. T. Tseruya, Y. Ueda, B. Ujvari, H. W. van Hecke, J. Velkovska, M. Virtus, V. Vrba, X. Wang, Y. Watanabe, Y. S. Watanabe, F. Wei, A. S. White, C. P. Wong, C. L. Woody, M. Wysocki, B. Xia, L. Xue, S. Yalcin, Y. Yamaguchi, Z. Yin, I. Yoon, J. H. Yoo, I. E. Yushanov, W. A. Zajc, A. Zelenksi, S. Zhou, L. Zou (PHENIX Collaboration)

1 Abilene Christian University, Abilene, Texas 79699, USA
2 Department of Physics, Augustana University, Sioux Falls, South Dakota 57197, USA
3 Department of Physics, Banaras Hindu University, Varanasi 221005, India
4 Bhabha Atomic Research Centre, Bombay 400 085, India
I. INTRODUCTION

Direct photons, defined as those not coming from hadron decays, have long been considered a golden probe towards our understanding of the evolution of relativistic heavy-ion collisions – from the quark-gluon plasma (QGP) phase to the hadron-gas (HG) phase [1]. Unlike strongly interacting probes, such as identified particles and jets, direct photons traverse the medium unmodified due to the small cross section of electromagnetic interaction. These penetrating photons encode information about the environment in which they were created, including the temperature and the collective motion of the medium. While the direct photons at high transverse momentum, $p_T$, are dominated by photons created from hard-scattering processes, such as quark-gluon Compton scattering, in the low-$p_T$ regime, they were initially predicted to be of a thermal origin, being emitted from the QGP and HG phase (see Ref. [2] for a recent review).

The $p_T$ spectrum of low-$p_T$ direct photons from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, first measured by PHENIX [3], shows a clear excess above the hard-scattering contribution estimated from $p+p$ measurements for $p_T$ below 3 GeV/c. Followup measurements by PHENIX have established that low-$p_T$ direct-photon emission also shows a large anisotropy with respect to the reaction plane [4, 5], and that the yield increases faster than $N_{\text{part}}$ or $dN_{\text{ch}}/d\eta$ as a function of the centrality of the collision [6]. Low-$p_T$ direct photons in Au+Au collisions at 200 GeV have also been measured by STAR [7] using the same basic method as [3], but different detection techniques, which leads to different systematic uncertainties between STAR and PHENIX measurements. Quantitatively, STAR results appear to be a factor 3 smaller than those from PHENIX. This tension has not yet been resolved. Furthermore, low $p_T$ photons have been measured in Au+Au at lower $\sqrt{s_{NN}}$ of 39 GeV and 62.9 GeV by PHENIX [8], and in Pb+Pb at $\sqrt{s_{NN}} = 2760$ GeV by ALICE [9].

The excess of direct photons in A+A collisions, in the low-$p_T$ regime, is usually interpreted as the contribution of thermal radiation emitted from the expanding and cooling QGP and HG phase. Due to the rapid anisotropic expansion of the system, the radiation is Doppler shifted. Over the years, several theoretical models have been developed and refined to describe the production rates and space-time evolution of thermal photons in relativistic heavy-ion collisions [10–17]. While most of these state-of-the-art models describe the data qualitatively, they fall short of simultaneously describing all the features of the data quantitatively. To describe the large yield, early emission at high temperatures is favored, while sufficient build up of collective motion is required to explain the large anisotropy, thereby favoring late-stage emission. This tension, often termed as the “direct-photon puzzle”, hints at an incomplete understanding of the different sources and mechanisms of direct-photon production. This has triggered more thoughts on other unconventional photon sources, such as emission from the pre-equilibrium stage, strong magnetic field effects, etc. [10, 18–21]. For that very reason this paper refers to the low-$p_T$-excess direct photons as “nonprompt” instead of “thermal”.

To provide new insights and further understandings, the PHENIX collaboration presents results from the high-statistics 2014 Au+Au data at $\sqrt{s_{NN}} = 200$ GeV. With a 10-fold increase in statistics compared to previously published results, differential direct-photon measurements as functions of $p_T$ and system size over a
broad $p_T$ range from 0.8–10 GeV/c and in 10% centrality classes are discussed. A new algorithm, which utilizes the silicon-vertex detector (VTX) as the conversion material for photons, is developed for this analysis.

The paper is organized as follows: Section II presents the experimental setup relevant to this measurement and the algorithm to reconstruct the conversion photons. Section III describes the double-ratio method to determine the direct-photon excess ratio, $R_\gamma$, and gives details of the experimental measurement. Section IV investigates the systematic uncertainties. Section V discusses the results. Section VI presents the summary and conclusions. Finally, there are two appendices: Appendix A discusses the event mixing procedures and their validity, while Appendix B describes the Monte-Carlo (MC)-sampling method used to derive the final systematic uncertainties.

II. EXPERIMENTAL SETUP AND PHOTON MEASUREMENTS

A. PHENIX 2014 Au+Au $\sqrt{s_{NN}} = 200$ GeV data set

In 2014, a total of 19 billion Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV were recorded by the PHENIX detector at the Relativistic Heavy Ion Collider (RHIC) with a minimum-bias (MB) trigger, based on the response of two beam-beam counters (BBC) [25]. The BBCs are located on either side of the interaction point along the beam axis at $z = \pm 1.44$ m with a pseudorapidity coverage of $0.8 < |\eta| < 3.9$ and full $2\pi$ azimuthal acceptance. The MB trigger requires a coincident signal in both BBCs. Each BBC, comprising 64 Čerenkov counters, measures the total number of charged particles produced during the collision within its acceptance. The charged-particle multiplicity is used to divide the MB events into different centrality classes; 0%–10% corresponds to the most central collisions which produces the largest number of charged particles, while 80%–93% corresponds to peripheral collisions with only a small number of charged particles. The BBCs also utilize the arrival time of the produced particles on each side to determine the collision vertex along the beam direction.

The direct-photon measurement, presented here, is based on the tracking and identification of electrons and positrons from photon conversions in the detector material and the direct calorimetric measurement of photons in the two PHENIX central arm spectrometers shown in Fig. 1 [26]. The VTX [27] comprises four silicon layers at nominal radii of 2.6, 5.1, 11.8, and 16.7 cm. In the beam direction, the active area covers approximately ±11 cm for the innermost layer and ±19 cm for the outer layer. The VTX is not used as an active detector in the measurement. However, it acts as the photon converter, which is critical for this analysis. The total material thickness of the VTX in terms of radiation length, $X_0$, is $\approx 13\%X_0$. Events are selected with a $z$ vertex within ±10 cm of the nominal interaction point. After applying quality assurance criteria, a total of $1.25 \times 10^{10}$ events are analyzed.

The central-arm spectrometers have three major parts: A charged-particle tracking system [28, 29], particle-identification detectors [30], and electromagnetic calorimeters (EMCal) [31]. Each arm covers $90^\circ$ in the azimuthal direction with $|\eta| < 0.35$. The tracking system is located $\approx 2.2$ m from the beam axis outside of an axial magnetic field. The main tracking detectors are drift chambers (DC) and pad chambers (PC1). The DC provides a precise measurement of the transverse momentum for charged particles with $p_T > 0.2$ GeV/c. The PC1 measures the momentum along beam direction, $p_z$. The effective momentum resolution of the central-arm tracking system, for this analysis, is $\sigma_p/p =$

![FIG. 1. (a) The beam view of the PHENIX central-arm spectrometer for the year 2014. (b) A magnified view of the silicon-vertex detector. The solid curves correspond to the electron and positron tracks from photon conversion.](image)
0.8%\(\oplus 2\%\) \(p\) [GeV/c], where \(p\) is the transverse momentum of the track.

Charged tracks are identified as electrons or positrons with a ring-imaging Čerenkov detector (RICH). The RICH has a CO\(_2\) gas radiator with a low radiation threshold for electrons (0.018 GeV/c) and a relatively high threshold for charged pions (> 4.87 GeV/c). Requiring a signal in at least two phototubes in the focal plane of the RICH at the expected ring location effectively separates electrons below 5 GeV/c from charged hadrons. A further matching of the momentum, \(p\), of the charged track to the energy, \(E\), as measured in the EMCal within \(-2\sigma_{E/p} < E/p < 5\sigma_{E/p}\) removes most hadrons remaining in the sample. Here \(\sigma_{E/p}\) is the momentum-dependent resolution of the energy to momentum ratio, \(E/p\).

For the calorimetric identification of photons, two types of calorimeters are used, lead-scintillator (PbSc) and lead-glass (PbGl). The PbSc EMCal, which covers 3/4 of the acceptance, is a sandwich sampling detector, also referred to as a Shashlik type calorimeter. Based on the widths of reconstructed \(\pi^0\) mass through the \(\pi^0 \rightarrow \gamma \gamma\) decay, the effective photon-energy resolution in this analysis is \(\sigma_{E}/E = 8.1\%/\sqrt{E\ [\text{GeV}]}\oplus 5.0\%\). The remaining 1/4 of the acceptance is covered by the PbGl EMCal, which is a homogeneous Čerenkov-type detector with an effective resolution of \(\sigma_{E}/E = 8.7\%/\sqrt{E\ [\text{GeV}]}\oplus 5.8\%\). Nominal cuts on the energy threshold (\(E > 500\) MeV) and shower shape (\(\chi^2 < 3\)) are applied to identify photons.

**B. External photon conversions in the VTX**

Earlier measurements of direct photons from PHENIX are based on three different strategies to measure photons in A+A collisions. The calorimeter method is used to measure photons with \(p_T\) of several GeV/c via their energy deposited in the EMCal \[3\]. To access lower \(p_T\), \(e^+e^-\) pairs from photon conversions are reconstructed with the tracking system. These \(e^+e^-\) pairs are either from “internal” conversions of virtual photons emitted from the collision \[3\] or “external” conversions of photons in the detector material \[5\].

Here, external photon conversions at the VTX detector are reconstructed from \(e^+e^-\) pairs. The VTX material is distributed between 2 and 25 cm along the radial direction. Depending on the conversion point, a different amount of magnetic field is traversed by the \(e^+e^-\) pair. In the standard PHENIX track-reconstruction algorithm, the tracking system measures a part of the trajectory outside of the magnetic field at a radial position of \(\approx 2.2\) m. The momentum vector is determined by assuming that the particle originates at the event vertex. This assumption is incorrect for the \(e^+e^-\) pairs from conversions in the VTX material. Both \(e^+\) and \(e^-\) traverse a smaller \(\int BdI\) than tracks from the vertex and thus the azimuthal component of the momentum vector is mismeasured in opposing directions, leading to an artificial opening angle and mismeasured mass of the \(e^+e^-\) pair. Because the magnetic field in the region of the VTX detector is approximately constant at 0.9 Tesla, the artificial mass acquired is proportional to the radial location of the conversion point. Fig. 2 shows the mass of \(e^+e^-\) pairs simulated with the GEANT3 PHENIX-detector simulation \[32\], different curves represent photon conversions in different VTX layers. The \(m_{e^+e^-}\) is larger for conversions at larger radii with most conversions occurring in the third and fourth layers of the VTX, where the material budget is the largest.

To correctly reconstruct and identify photon conversions at different VTX layers, a new track-reconstruction algorithm is developed. The new algorithm relies on the fact that the \(e^+\) and \(e^-\) from a conversion have the same origin and that their momenta were initially parallel in radial direction. This additional constraint eliminates the need to assume the origin of the track.

The algorithm is illustrated in Fig. 3. For all radii between 0 and 30 cm, all possible momenta of the \(e^+\) and \(e^-\) are scanned to identify the azimuthal location \(\phi_{\text{conv}}\) at which the track is perpendicular to the circle of the given radius, or in other words points back radially to the event vertex. The conversion point is determined by finding the radius for which the difference of the azimuthal angles of the \(e^+e^-\) pair, \(\delta\phi = \phi_+ - \phi_-\), becomes zero. If such radius exists, the pair is identified as a conversion candidate at the location \((\phi_{\text{conv}}, r_{\text{conv}})\), where \(\phi_{\text{conv}}\) is the azimuthal angle of the conversion point, reconstructed with a resolution of \(\approx 1\) mrad, and \(r_{\text{conv}}\) is the radial position reconstructed with a resolution of \(\approx 2\) cm.
as $e^+ e^-$ pair from a photon conversion. The probability is averaged over all parent $\pi^0$ $p_T$ that can contribute to the given conversion photon $p_T$.

(ii) The conditional acceptance and efficiency $\langle \epsilon_{\gamma} f \rangle$ is the conditional probability to detect and reconstruct the second $\pi^0$ decay photon with the EMCal, given that the first decay photon was reconstructed as $e^+ e^-$ pair from a photon conversion. The probability is averaged over all parent $\pi^0$ $p_T$ that can contribute to the given conversion photon $p_T$.

(iii) The cocktail ratio $\gamma_{\text{hadr}} / \gamma^0$ is the ratio of all photons from hadron decays over only those photons from $\pi^0$ decays.

The following sections discuss how each term is determined.

B. Ratio of the measured photon yields $N_{\gamma}^\text{incl} / N_{\gamma}^\text{tag}$

Electrons and positrons in a given event are combined to $e^+ e^-$ pairs and conversion candidates are selected with appropriate cuts, which results in a foreground sample of $e^+ e^-$ pair $F_{\gamma e e}$. All conversion candidates in a conversion photon $p_T$ bin, are combined with all photon showers in the EMCal above an energy threshold, $E_{\text{cut}}$. The invariant mass $m_{e^+ e^-}$ is calculated and all combinations that lie in a mass window around the $\pi^0$ mass are considered as candidates for tagged photons $F_{\gamma e e}$. Due to the large particle multiplicity in Au+Au collisions, there are many false combinations where the electron, positron or photon are not from the same source. These background pairs must be subtracted statistically to obtain the signals of interest $S_{\gamma e e}$ and $S_{\gamma e e}$.

For $e^+ e^-$ pairs, there are two possible combinations, signal pairs of interest $S_{\gamma e e}$ and uncorrelated background $B_{\gamma e e}$ pairs where the electron and positron are from different sources. Their sum constitutes the foreground $F_{\gamma e e}$:

$$F_{\gamma e e} = S_{\gamma e e} + B_{\gamma e e}.$$  \hfill (2)

When the $e^+ e^-$ pairs are combined with photons to $e^+ e^- \gamma$ combinations, both types of $e^+ e^-$ pairs are combined with photons that are either correlated or uncorrelated with the pair:

$$F_{\gamma e e} = S_{\gamma e e} + B_{\gamma e e} + B_{\gamma e e} + B_{\gamma e e}.$$ \hfill (3)

Introducing $i, j, k$ as the source of the positron, electron, and photon, respectively, the terms in Eq. 3 are:

(1) The first term is the signal of interest with positron, electron, and photon from the same source ($i = j = k$).

(2) The second term represents the cases where the $e^+ e^-$ pair is combined with uncorrelated photons. This includes the case ($i = j \neq k$), where the $e^+ e^-$ pair is correlated and randomly combined with a $\gamma$ as well as the case ($i \neq j \neq k$) where all three are from different sources.
(3) The third term represents cases \((i \neq j = k) \vee (j \neq i = k)\), where the \(e^+e^-\) pair is not from the same source but the \(\gamma\) is correlated with either the \(e^+\) or the \(e^-\).

Each of the background terms is determined with different event-mixing procedures, which were developed using the MC method. The event-mixing procedures and their validity are discussed in detail in Appendix A.

1. Determination of the inclusive photon yield \(N_{\gamma}^{\text{incl}}\)

Photons that convert at the VTX detector are selected by pairing electron and positron tracks to \(e^+e^-\) pairs. All pairs are required to have a valid conversion point at a radial location within the VTX detector, between 1 and 29 cm. In addition, both tracks need to match in the beam direction within \(|\Delta z| < 4\) cm. The invariant mass distribution of the selected \(e^+e^-\) conversion pairs is shown in Fig. 4 for the \(p_T\) range 1.0 < \(p_T\) < 1.2 GeV/c. The four panels correspond to four different centrality selections. Each panel shows the same peak structure, which is characteristic of the multilayer structure of the VTX detector.

![Figure 4](image_url)

**FIG. 4.** Mass distribution, \(m_{e^+e^-}\), of the \(e^+e^-\) pairs after conversion selection cuts are applied. All four panels are for the same \(p_T\) range 1.0 < \(p_T\) < 1.2 GeV/c for four different centrality selections (a) 0%–20%, (b) 20%–40%, (c) 40%–60% and (d) 60%–93%. Shown are the foreground FG\(^{ee}\), background BG\(^{ee}\) and signal SG\(^{ee}\).

The \(e^+e^-\) pairs passing the conversion selection criteria contain uncorrelated \(e^+e^-\) pairs, where the \(e^+\) and \(e^-\) are from different sources. These backgrounds are also shown in Fig. 4. Because of its combinatorial nature, the background to foreground ratio increases towards more central-event selections. An event-mixing technique is used to estimate and subtract this background (see Appendix A for details). In this technique, an \(e^+\) from event A is paired with an \(e^-\) from another event B to produce the random \(e^+e^-\) pair sample. To assure the events A and B have similar topological characteristics, it is required that both events:

(a) are from the same 10% centrality selection,
(b) have their interaction vertex within \(\Delta z = 2.5\) cm,
(c) have their reaction planes aligned within \(\Delta \phi = \pi/6\).

After the subtraction of the uncorrelated background, more than 99% of the pairs are from photon conversion in the VTX materials. The remaining pairs are from internal virtual photon conversions that passed the conversion selection criteria. The sources of these pairs are similar to those of the photon conversion pairs, with the majority resulting from \(\pi^0\) Dalitz decays. An additional lower mass cut at 0.04 GeV/\(c^2\) removes about 90% of these internal conversions, rendering the remainder negligible. Finally, \(N_{\gamma}^{\text{incl}}\) is calculated by integrating the counts in the mass range from 0.04 to 0.12 GeV/\(c^2\), corresponding to layers 3 and 4 of the VTX. The analysis is repeated for bins in \(p_T\) and in centrality.

2. Tagged photon raw yield \(N_{\gamma}^{\pi^0,\text{tag}}\)

Next, the subset of \(e^+e^-\) pairs in the \(N_{\gamma}^{\text{incl}}\) sample that can be tagged as photons from a \(\pi^0\) decay, \(N_{\gamma}^{\pi^0,\text{tag}}\), is determined. For a given event, each \(e^+e^-\) conversion candidate, in the mass window in which \(N_{\gamma}^{\text{incl}}\) is counted, is paired with all reconstructed showers in the EMCal with shower shape \(\chi^2 < 3\) and energy larger than \(E_{\text{cut}} = 0.5\) GeV, excluding those matched to the \(e^+e^-\) pair itself. The energy cut, together with the \(p_T\) cut of 0.2 GeV/c on the \(e^+\) and \(e^-\), constitutes an implicit asymmetry cut on the \(\pi^0\) decay photons that depends on the \(p_T\) of the \(\pi^0\). For all \(e^+e^-\gamma\) combinations, the invariant mass \(m_{ee\gamma}\) is calculated. This constitutes the foreground FG\({^{ee\gamma}}\), for which an example is given in Fig. 4 for the \(e^+e^-\) pair in the \(p_T\) range 1.0 < \(p_T\) < 1.2 GeV/c. The four panels (a) to (d) correspond to four centrality selections 0%–20%, 20%–40%, 40%–60%, and 60%–93%, respectively.

Despite the large background, the signal, SG\({^{ee\gamma}}\), is clearly visible as a peak around the \(\pi^0\) mass, even in panel (a), which is the most central event selection. As discussed above, the background BG\({^{ee\gamma}}\) has two components:

\[
\text{BG}^{ee\gamma} = \text{BG}_{\text{uncorr}}^{ee\gamma} + \text{BG}_{\text{corr}}^{ee\gamma}
\]

for which the shape and normalization are obtained from the event-mixing procedures described in Appendix A.
The results are also shown in Fig. 5. The uncorrelated background, $B_{\text{corr}}^0$, is given in panels (a) to (d). The much smaller correlated background, $B_{\text{corr}}^\gamma$, is only revealed after $B_{\text{uncorr}}^\gamma$ is subtracted from the foreground, $F_{\gamma}^{ee\gamma}$. The differences are given in panels (e) to (h) for central to peripheral events, respectively. Figure 5 indicates that the correlated background decreases with centrality from $B_{\text{corr}}^\gamma/(F_{\gamma}^{ee\gamma} - B_{\text{uncorr}}^\gamma) = 8.6\%$ in central collisions to $0.5\%$ in the most-peripheral collisions.

For the $0\%$–$20\%$ centrality selection, Fig. 6 shows the mass distributions $m_{ee\gamma}$ for four different $e^+e^-$ pair $p_T$ ranges. The representation is the same as for Fig. 5. Panels (a) through (d) all show a clear peak around the $\pi^0$ mass. The backgrounds are the largest for low $p_T$ and the most central events. As $p_T$ increases and the event multiplicity decreases, the backgrounds are significantly reduced.

Because of the complexity of the particle correlations present in the real Au+Au collision events, including effects of collective expansion, jet production, hadron decays, etc., there is a small residual background that is not captured by the event-mixing procedure. To remove this background, a low-order polynomial, $f_{ee\gamma}$, is fitted to the ratio $(F_{\gamma}^{ee\gamma} - B_{\text{corr}}^\gamma)/B_{\text{uncorr}}^\gamma$ in the mass range $0.05$–$0.08$ and $0.23$–$0.45$ GeV/$c^2$. This function is used to correct $B_{\text{uncorr}}^\gamma$ before it is finally subtracted. Thus, the final distribution for $N_{\gamma}^0,\text{tag}$ is:

$$ N_{\gamma}^0,\text{tag} = F_{\gamma}^{ee\gamma} - B_{\text{corr}}^\gamma - (1 + f_{ee\gamma}) \times B_{\text{uncorr}}^\gamma. \quad (5) $$

An example of the residual background is given in Fig. 7 for the $e^+e^-$ pair $p_T$ range of $1$ to $1.2$ GeV/$c$ and $0\%$–$20\%$ centrality selection. In panel (a), $F_{\gamma}^{ee\gamma}$ with all the background components are shown. Panel (b) gives a second-order polynomial fit to the ratio $(F_{\gamma}^{ee\gamma} - B_{\text{corr}}^\gamma)/B_{\text{uncorr}}^\gamma$, $f_{ee\gamma}$, which is used to determine the residual background. Due to the unfavorably small signal-to-background ratio in this case, the residual background in the $\pi^0$ mass region is $\approx 9.4\%$. The residual background quickly drops with $p_T$ and centrality bins, for example as $p_T$ increases to $3$ GeV/$c$, the residual background reduces to $2.7\%$. For each $p_T$-centrality bin combination, $N_{\gamma}^0,\text{tag}$ is extracted by integrating the number of entries in a window around the $\pi^0$ peak ($0.09 < m_{ee\gamma} < 0.19$) GeV/$c^2$ after all background subtractions are applied.

Note that the extracted $N_{\gamma}^0,\text{tag}$ described in this section can also be used to measure the $\pi^0$ invariant yield once corrected with detector acceptance and efficiency, which can potentially extend the previous PHENIX $\pi^0$ measurements to lower $p_T$ regions. However, to establish such a measurement, in particular the evaluation of systematic uncertainties requires significant additional work that is beyond the scope of this manuscript.

### C. Conditional probability $(\epsilon, f)$

The probability, $(\epsilon, f)$, that the second photon is in the acceptance and is reconstructed, given a conversion $e^+e^-$ pair from a $\pi^0$ decay, is extracted from the single $\pi^0$ simulation. In this simulation, individual $\pi^0$ are tracked through the PHENIX MC-simulation framework. The $\pi^0$ are generated with $d^2N/dp_Tdy$ spectra that were fitted to $\pi^+\pi^-$ data measured by PHENIX (see Sec. III D), uniform in the rapidity range $|y| < 0.5$, and uniform over $2\pi$ in azimuthal angle, $\phi$.

The energy scale and resolution of the EMCal in the MC simulation is tuned as closely as possible to resemble the one observed in data by comparing the mean and width of the measured and simulated $\pi^0$ mass distribution. The $\pi^0$ are reconstructed through the $\pi^0 \rightarrow \gamma\gamma$ decay channel. For this purpose an asymmetry of less than $20\%$ between the energies of the two decay photons was applied to keep the two-photon energies similar.

In the single $\pi^0$ MC simulation, $e^+e^-$ pairs in the mass window $0.04 < m_{ee\gamma} < 0.12$ GeV/$c^2$ are counted to determine $N_{ee}^\gamma$, the number of reconstructed $e^+e^-$ pairs in a given $e^+e^-$ pair $p_T$ bin. The sub-sample for which the second photon of the $\pi^0$ decay is reconstructed as a shower in the EMCal is counted as $N_{ee}^{\gamma,\text{tag}}$. The value of $(\epsilon, f)$ is then determined as:

$$ \langle \epsilon, f \rangle = \frac{N_{ee}^{\gamma,\text{tag}}}{N_{ee}}. \quad (6) $$

For the extraction of $N_{ee}^{\gamma,\text{tag}}$, the presence of other showers in the EMCal needs to be taken into account. This is done by embedding the showers from the simulated single $\pi^0$ into the EMCal response from Au+Au collisions at the tower level. The combined EMCal information is then reclustered to form new showers. All of the showers that contain energy deposited by the embedded single $\pi^0$ (identified by the MC ancestry information) are combined with the $e^+e^-$ pair.

Similar to the $N_{ee}^{\gamma,\text{tag}}$ extraction from data, a residual background subtraction is applied. This eliminates any remaining background inside the $\pi^0$ counting window. The residual background is estimated by a second order polynomial function fit in the mass range $0.05$–$0.08$ and $0.23$–$0.45$ GeV/$c^2$. This residual background mainly comes from events where both decay photon convert to $e^+e^-$ pairs, and the reconstructed conversion photon gets paired with the EMCal cluster of the $e^+$ or $e^-$ from the other conversion. The extracted $(\epsilon, f)$ is shown in Fig. 8 as a function of the $e^+e^-$ pair $p_T$ for the four centrality selections.

The increasing trend of $(\epsilon, f)$ with increasing conversion photon $p_T$ is partly due to the decrease in the opening angle between the conversion photon and the second photon so that the second photon is more likely to fall into the acceptance of the EMCal. Another important factor is that the average energy of the second photon increases with increasing conversion photon $p_T$, and hence,
the efficiency of the energy threshold cut increases towards higher \( p_T \). The difference in \((\epsilon, f)\) between different centrality classes is mainly related to the shower shape (\(\chi^2\)) selection, because the showers are more distorted in central Au+Au collisions due to the larger detector occupancy, resulting in more accidental overlaps from the underlying event, and the centrality dependent parent \( \pi^0 \) \( p_T \) distributions.
FIG. 7. (a) An example for FG(\text{ee\gamma}) and the various background components after normalization in the indicated regions. (b) The ratio (FG(\text{ee\gamma}) – BG(\text{ee\gamma}))/BG_{\text{uncorr}} and the polynomial fit to determine the residual-background correction \(f_{\text{ee\gamma}}\).

D. Cocktail ratio \(\gamma_{\text{hadr}}/\gamma^{0}\)

The last ingredient to calculate \(R_{\gamma}\) is the cocktail ratio \(\gamma_{\text{hadr}}/\gamma^{0}\) of photons from \(\pi^{0}\), \(\eta\), \(\omega\), and \(\eta'\) decays over those from \(\pi^{0}\) decays. The cocktail ratio is obtained using the PHENIX meson decay generator EXODUS, which simulates mesons according to given input \(p_{T}\) spectra, decays them based on the known decay kinematics and branching ratios, and aggregates the decay photons in the PHENIX detector acceptance.

The photons from \(\pi^{0}\) decays are generated from distributions obtained by fitting a modified Hagedorn function (Eq. 7) to charged pion [33] and neutral pion [33, 35] data measured by PHENIX for the rapidity range \(|y| < 0.5\).

\[
E \frac{d^{3}N_{\gamma}}{dp^{3}} = A \left( e^{-\frac{p_{T}^{2}+m^{2}}{2T}} + \frac{p_{T}}{p_{0}} \right)^{-n}.
\]  

(7)

The fit parameters are summarized in Table IV for MB collisions, as well as for nine centrality bins. The \(\eta\) meson \(p_{T}\) spectra are obtained by multiplying the \(\pi^{0}\) spectrum with the \(\eta/\pi^{0}\) ratio, following the procedure suggested in [36].

\[
E \frac{d^{3}N_{\eta}}{dp^{3}} = E \frac{d^{3}N_{\pi^{0}}}{dp^{3}} \times \frac{\eta/\pi^{0}}{R_{\text{flow}}}.
\]  

(8)

where \(R_{\text{flow}}\) is the ratio of \(K^{\pm}/\pi^{\pm}\) for a given centrality over \(K^{\pm}/\pi^{\pm}\) in \(p+p\) collisions. This procedure makes use of the world data for \(\eta/\pi^{0}\) from \(p+p\) and small system collisions (see [36] for references), and it avoids the assumption of \(m_{T}\) scaling used in earlier work [10], which has been shown to overestimate the number of \(\eta\) mesons produced below 2 GeV/c in \(p_{T}\) in \(p+p\) and small system collisions.

FIG. 8. Conditional probability \(\langle c_{y}, f \rangle\) as a function of \(p_{T}\) in 0%–20%, 20%–40%, 40%–60% and 60%–93% centrality classes.

| centrality       | \(A\)   | \(a\)   | \(b\)   | \(p_{0}\) | \(n\) |
|------------------|--------|--------|--------|--------|-----|
| c(GeV/c)^{-2}     |        |        |        |        |     |
| min.bias         | 504.5  | 0.5169 | 0.1626 | 0.7366 | 8.274 |
| 0%–10%           | 1331.0 | 0.5654 | 0.1945 | 0.7429 | 8.361 |
| 10%–20%          | 1001.0 | 0.5260 | 0.1628 | 0.7511 | 8.348 |
| 20%–30%          | 750.7  | 0.4900 | 0.1506 | 0.7478 | 8.299 |
| 30%–40%          | 555.3  | 0.4534 | 0.1325 | 0.7525 | 8.333 |
| 40%–50%          | 364.5  | 0.4333 | 0.1221 | 0.7385 | 8.261 |
| 50%–60%          | 231.2  | 0.4220 | 0.1027 | 0.7258 | 8.220 |
| 60%–70%          | 118.1  | 0.4416 | 0.0959 | 0.7230 | 8.163 |
| 70%–80%          | 69.2   | 0.2850 | 0.0347 | 0.7787 | 8.532 |
| 80%–93%          | 51.1   | 0.2470 | 0.0169 | 0.7101 | 8.453 |

TABLE I. Parameters for the modified Hagedorn function Eq. 8 to PHENIX data [33,35] from Au+Au collisions at \(\sqrt{s_{NN}} = 200\) GeV.
collisions. It also includes the centrality dependent modification, \( R_{\text{flow}} \), of the \( \eta_{\text{pt}} \) spectra in Au+Au collision due to radial flow, which was not taken into account in earlier work \( \text{(5)} \). The modification \( R_{\text{flow}} \) is estimated using measured kaon spectra \( \text{(27)} \). For peripheral Au+Au collisions, the new approach to determine the \( \eta \) yield results in a few percent reduction of the number of predicted decay photons in the range 1-2 GeV/c, compared to the \( m_T \) scaling approach based on Eq. \( \text{(7)} \) that was taken in earlier work \( \text{(6)} \). The difference is within the systematic uncertainties quoted in that work. For central and semicentral collisions the new and old approach agree better in the sense that they predict very similar decay photon yields above 1 GeV/c, with any differences being much smaller than the quoted systematic uncertainties. This agreement arises when accounting for the modification of the \( \eta \) meson spectrum due to radial flow, which shifts \( \eta \) mesons from low to mid \( p_T \). This shift results in more decay photons above 1 GeV/c in the presence of radial flow, and moving the predicted yield closer to the one derived from \( m_T \) scaling. At high \( p_T \), the \( \eta/\pi^0 \) ratio demonstrates a universal value at high \( p_T \), consistent with 0.487±0.024, independent of collision energy, system size, or centrality. The values for \( dN/dy \) for \( \eta/\pi^0 \), \( K^\pm/\pi^\pm \) and \( R_{\text{flow}} \) are summarized in Table \( \text{II} \) for \( 1 < p_T < 2 \) GeV/c, where the effects of flow are expected to be the largest for different centralities for Au+Au collisions at 200 GeV.

The contribution from \( \omega \) and \( \eta' \) decays are based on \( p_T \) distributions using the \( \pi^0 \) spectrum and replacing by \( f(\sqrt{p_T^2 + m_{\text{meson}}^2 - m_{\pi^0}^2}) \). The normalization of \( \omega \) and \( \eta' \) are fixed at \( p_T = 5 \) GeV/c to 0.9±0.06 and 0.25±0.075, respectively \( \text{(6)} \). The cocktail ratio \( \gamma_{\text{hadr}}/\gamma_{\pi^0} \) is shown in Fig. \( \text{II} \).

![FIG. 9. Cocktail ratio as a function of \( p_T \) in the most central (0%–20%) and the most peripheral (60%–93%) centrality classes.](image)

Table II. \( dN/dy \) for \( \eta/\pi^0 \), \( K^\pm/\pi^\pm \) and \( R_{\text{flow}} \) for \( 1 < p_T < 2 \) GeV/c for Au+Au collisions at \( \sqrt{s_{\text{NN}}} = 200 \) GeV. There is an overall scale uncertainty of 0.03 on \( R_{\text{flow}} \) and \( \gamma_{\text{hadr}}/\gamma_{\pi^0} \) at 0%–20%.

| Centrality     | \( K^\pm/\pi^\pm \) | \( R_{\text{flow}} \) | \( R_{\text{flow}} \times (\eta/\pi^0)_{\text{universal}} \) |
|---------------|----------------------|------------------------|-------------------------------------------------|
| 0%–20%        | 0.411 ± 0.003        | 1.20 ± 0.02            | 0.250 ± 0.004                                   |
| 20%–40%       | 0.396 ± 0.002        | 1.15 ± 0.02            | 0.237 ± 0.004                                   |
| 40%–60%       | 0.371 ± 0.002        | 1.08 ± 0.02            | 0.220 ± 0.004                                   |
| 60%–93%       | 0.337 ± 0.002        | 0.98 ± 0.02            | 0.199 ± 0.004                                   |

IV. SYSTEMATIC UNCERTAINTIES

This section describes the sources of systematic uncertainties for each of the three components for the calculation of \( R_{\gamma} \). The systematic uncertainties are categorized into three types according to the correlation between the measured data points:

- Type A: No (or unknown) correlation between data points – uncertainties on the individual data points can fluctuate independently, in the same way as the statistical uncertainties.

- Type B: The uncertainties are correlated between data points – the fluctuation of each data point can be determined by the fluctuation of the neighboring points.

- Type C: A special form of type B uncertainty – every data point fluctuates with the exact same fraction.

In the final results, type A systematic uncertainties are combined with the statistical uncertainties and type B and C are combined to obtain the total systematic uncertainty.

The following subsections discuss the major individual sources contributing to the systematic uncertainties on \( R_{\gamma} \) and on the direct-photon yield. All contributions are summarized in Table \( \text{III} \) and depicted in Fig. \( \text{II} \) and Fig. \( \text{I} \) as functions of \( p_T \) for \( R_{\gamma} \) and \( \gamma_{\text{dir}} \). The final systematic uncertainties on \( \gamma_{\text{dir}} \) and on all quantities derived from \( \gamma_{\text{dir}} \) are determined using the error-sampling method discussed in Appendix \( \text{II} \).

A. Systematic uncertainties on \( N_{\gamma}^{\text{incl}}/N_{\gamma}^{\text{0,tag}} \)

1. Purity of the conversion photon sample

Due to the high multiplicity of photons produced in Au+Au collisions, the background in the conversion sample from uncorrelated \( e^+e^- \) pairs can be as large as 10%
TABLE III. Summary of systematic uncertainties for $R_\gamma$ and $\gamma^{\text{dis}}$. Uncertainties for which ranges are given vary with $p_T$. For details see Figs. [10] and [11].

| Observable | Factor | Source | correlation in $p_T$ | correlation in centrality | 0%-20% | 20%-40% | 40%-60% | 60%-93% |
|------------|--------|--------|----------------------|----------------------------|--------|--------|--------|--------|
| $R_\gamma$ | $N^{\text{incl}}_\gamma/N^{\text{incl}}_{\gamma,\text{tag}}$ | purity | Type B | Type B | $<1\%$ | $<1\%$ | $<1\%$ | $<1\%$ |
| $N^{\text{pi}}_{\gamma,\text{tag}}$ | residual background | Type A | Type A | 1.5%-4.5% | 0.5%-4% | 0.5%-4% | 0.5%-4% |
| $N^{\text{e}^0,\text{tag}}_{\gamma}$ | event mixing | Type B | Type B | 1.5% | 1.5% | 1.5% | 1.5% |
| $\langle \epsilon, f \rangle$ | energy scale | Type B | Type B | 3% | 3% | 3% | 3% |
| | conversion loss | Type C | Type C | 3% | 3% | 3% | 3% |
| | $\gamma$ efficiency | Type B | Type A | $<1.4\%$ | $<1\%$ | $<1\%$ | $<1\%$ |
| active area & acceptance | input $\pi^0$ $p_T$ spectra | Type B | Type A | 1% | 1% | 1% | 1% |
| $\gamma^{\text{had}}/\gamma^{\text{e}^0}$ | $\eta/\pi^0$ | Type B | Type C | 1–1.5% | 1–1.5% | 1–1.5% | 1–1.5% |
| | $\omega, \eta'$ | Type B | Type C | $<1\%$ | $<1\%$ | $<1\%$ | $<1\%$ |
| $\gamma^{\text{had}}$ | input $\pi^0$ $p_T$ spectrum | Type B | Type A | 10%-24% | 10%-24% | 10%-25% | 10%-24% |

for the most central collisions and the lowest $p_T$ from 0.8 to 1.0 GeV/$c$. This background is subtracted statistically with a certain accuracy. To estimate the effect on the final results, significantly more and less stringent conversion selection cuts were applied, hence, increasing or reducing the purity. The value of $\langle \epsilon, f \rangle$ $N^{\text{incl}}_\gamma/N^{\text{incl}}_{\gamma,\text{tag}}$, obtained from the different cuts, varies by less than 1%. This range is quoted as systematic uncertainty due to the limited purity of the conversion sample.

2. $\pi^0$ yield extraction

One of the main sources of systematic uncertainty on the $R_\gamma$ measurement is the tagged photon or $\pi^0$ yield extraction. The uncertainty of $\pi^0$ yield extraction arises from two sources: (i) from the residual background subtraction, which is highly correlated with the statistical accuracy of the mixed event background normalization, and (ii) imperfect description of the large backgrounds using event-mixing techniques.

To evaluate the size of the uncertainty from the residual background subtraction, different estimates are compared. These include using different functional forms for the fit and different fit ranges to anchor the residual background fit. In addition, the counting window for $\pi^0$ signal extraction is varied. This gives a spread of $\langle \epsilon, f \rangle$ $N^{\text{incl}}_\gamma/N^{\text{incl}}_{\gamma,\text{tag}}$ values in each $p_T$ and centrality bin. The standard deviation of the spread is quoted as the uncertainty. Due to the correlation with the statistical accuracy of the foreground in the background region, this uncertainty depends on $p_T$ and centrality.

To test the validity of the event-mixing techniques, an MC simulation with high multiplicity $\pi^0$ events is performed. Details are discussed in Appendix [A]. The simulation shows that $N^{\text{e}^0,\text{tag}}_{\gamma}/\langle \epsilon, f \rangle$ can be determined with the event-mixing technique to better than 1.5%.

B. Systematic uncertainty on $\langle \epsilon, f \rangle$

1. Energy scale

The accuracy of the energy scale of the EMCal is the main source of systematic uncertainties in the $\langle \epsilon, f \rangle$ evaluation. Because of the energy threshold cut, the second photon is reconstructed only for $\approx25\%$ of the $e^+e^-$ pairs with the lowest $p_T$, even though the photon was in the EMCal acceptance. Any potential mismatch of the energy scale between the simulation and real data will cause $\langle \epsilon, f \rangle$ to be off; a higher (lower) energy scale in simulation can be determined with $\langle \epsilon, f \rangle$ $N^{\text{incl}}_\gamma/N^{\text{incl}}_{\gamma,\text{tag}}$, obtained from the different cuts, varies by less than 1%. This range is quoted as systematic uncertainty due to the limited purity of the conversion sample.

2. Conversion photon loss

Another important source of systematic uncertainty on $\langle \epsilon, f \rangle$ is related to the probability that the second photon converts to an $e^+e^-$ pair before reaching the EMCal. Depending on the location of the conversion point, the second photon may not be properly reconstructed, thereby reducing $\langle \epsilon, f \rangle$. To account for the conversion...
and, hence, \( \langle \epsilon, f \rangle \) will by systematically off. As there is essentially no magnetic field after the DC exit window, the \( e^+ e^- \) pair from conversions between the DC and the EMCal will likely merge into one shower in the EMCal. Therefore, the value of \( \langle \epsilon, f \rangle \) is most sensitive to differences in the material budget of the VTX. Comparison of the available information about the materials and their thickness for all detector subsystems, reveals that the conversion probability in material within the magnetic field is known to better than 3%, which directly translates into and uncertainty of 3% on \( R_{\gamma} \).

3. Photon efficiency

An EMCal shower shape, \( \chi^2 \), cut is used to identify photon candidates among the EMCal energy clusters and to reduce the number of hadrons in the sample. Similar to the energy scale uncertainty, a difference between the shower shape in simulation and the data will translate directly into a systematic shift of \( \langle \epsilon, f \rangle \). To evaluate this uncertainty, the \( \chi^2 \) is varied simultaneously in both data and simulation and \( \langle \epsilon, f \rangle \) \( \sigma_{\text{MC}}/N_{\text{data}} \) is recalculated. It changes by 1.4% for 0.8–2 GeV/c in the 0%–20% centrality bin and by less than 1% for all the other cases.

4. Active area and geometric acceptance

Due to the limited geometrical acceptance of EMCal and some inactive areas, the second photon is registered only for \( \approx 35\% \) of the \( e^+ e^- \) pairs at the lowest \( p_T \). Therefore, the accuracy with which the acceptance and dead areas are known will contribute to the systematic uncertainties on \( \langle \epsilon, f \rangle \). The uncertainty of the acceptance is the result of the accuracy with which the radial location of the EMCal sectors can be determined. The possible remaining offset leads to \(< 0.3\% \) difference in acceptance along \( \phi \) direction and \(< 0.9\% \) in \( z \) direction. The dead areas in the real EMCal are carefully matched to the MC simulation and the accuracy of the dead area determination is found to be better than 0.6%. It is due to the cases when a tower malfunctioned only in a very small number of events, and not masked out in the simulation. Combining all these effects, the systematic uncertainty on \( R_{\gamma} \) from the acceptance is set to 1%.

5. Input \( \pi^0 \) distribution

Because \( \langle \epsilon, f \rangle \) is averaged over all parent \( \pi^0 \) \( p_T \) that contribute to a given \( e^+ e^- \) pair \( p_T \) bin, the \( p_T \) dependence of \( \langle \epsilon, f \rangle \) is sensitive to the shape of the \( \pi^0 \) distribution. The \( \pi^0 \) parent distribution was determined for each centrality selection by a fit to the best available data from Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) measured by the same experiment [33, 35]. The remaining uncertainty on \( \langle \epsilon, f \rangle \) is smaller than 1%.
6. Weak decays and secondary interactions

The tagged photon samples include decay photons from $\pi^0$ from weak decays and $\pi^0$ produced in secondary interactions. Because these $\pi^0$ do not originate from the event vertex, $\langle \epsilon_f \rangle$ may be modified. Secondary interactions contribute less than 0.1% of the $\pi^0$ yield above $p_T$ of 1 GeV/c and thus any distortions of $\langle \epsilon_f \rangle$ are negligible. Decays of $K^0$ are the predominate source of $\pi^0$ from weak decays. They contribute between 5.8% to 3% of the inclusive $\pi^0$ yield above 1 GeV/c. With $c\tau = 2.68\text{cm}$, a fraction of 20% to 25% of those decays occur after the 3rd but before the 4th layer of the VTX, which corresponds to the conversion photon sample used in this measurement. Therefore, in the data there are 1-2% more conversions in the 4th relative to the 3rd layer compared to the MC simulation of primary $\pi^0$. The potential difference of $\langle \epsilon_f \rangle$ was estimated to be smaller than 1%.

C. Systematic uncertainty on $\gamma_{\text{hadr}}/\gamma_{\pi^0}$

The ratio $\gamma_{\text{hadr}}/\gamma_{\pi^0}$ accounts for photons from hadron decays that occur after the kinematic freeze, other than those from $\pi^0$. The three largest contributors are decays of $\eta$, $\omega$, and $\eta'$ mesons, which contribute $\approx 23\%$ of the decay photons at high $p_T$. All other contributions to $\gamma_{\text{hadr}}$ are negligible. Of the additional decay photons more than $80\%$ are from the $\eta \rightarrow \gamma \gamma$ decay, hence the accuracy with which $\eta/\pi^0$ is known will determine the systematic uncertainties on $R_\gamma$ from this source. The $p_T$ and centrality dependent upper and lower bounds on $\eta/\pi^0$ for Au+Au collisions at $\sqrt{s_{NN}} = 200\text{ GeV}$ are taken from [36]. Together with the much smaller uncertainty on the contribution from $\omega$ and $\eta'$ decays, the systematic uncertainty on $R_\gamma$ is below $2\%$ for the entire $p_T$ range.

D. Systematic Uncertainties on $\gamma_{\text{dir}}$

Once $R_\gamma$ is determined, the direct-photon yield $\gamma_{\text{dir}}$ is calculated as:

$$\gamma_{\text{dir}} = (R_\gamma - 1) \gamma_{\text{hadr}}.$$  

In addition to the uncertainties on $R_\gamma$, the uncertainty on $\gamma_{\text{hadr}}$ needs to be determined. These systematic uncertainties have been studied in detail in [6]. The main sources of uncertainty come from the accuracy with which the $\pi^0$ $p_T$ spectrum can be determined. These largely cancel in $R_\gamma$, but propagate directly to $\gamma_{\text{hadr}}$. The input $\pi^0$ spectrum is based on measurements of charged pions, and $\pi^0$ from different data taking periods (see Sec. [3]). Each data set comes with its own systematic uncertainties, and in addition, the differences between different measurements are of the order of $10\%$ [38]. The latter is the dominant uncertainty. The uncertainty on the spectra of other mesons ($\eta$, $\eta'$, $\omega$) also contributes to the uncertainty on $\gamma_{\text{hadr}}$, but to a much smaller extent.

V. RESULTS

A. Direct photon $R_\gamma$

Figure [2] shows $R_\gamma$ as function of photon $p_T$ for every $20\%$ centrality class. The vertical error bar on each point corresponds to the statistical uncertainty, while the box gives the systematic uncertainty. The new results are compared with all other published PHENIX results for Au+Au at $\sqrt{s_{NN}} = 200\text{ GeV}$; these were obtained with different methods and have largely independent systematic uncertainties. The open circles were determined using the external conversion method deploying the HBD detector as converter [6], the full squares are from a virtual photon internal conversion measurement [1], and the open squares were measured with the EMCal alone [39]. All measurements agree well within their independent systematic uncertainties.

The 2014 data presented here have smaller statistical uncertainties than in previous publications at RHIC due to the increased luminosity and significantly larger amount of conversion material. The new results provide a continuous measurement across a wide range of $p_T$ from 0.8 to 10 GeV/c. This range has previously been covered by measurements done with different techniques with different systematics. Up to 3 to 4 GeV/c internal or external photon conversions to $e^+e^-$ pairs have been used, while above 4 GeV/c photons were measured in the EMCal. For all centrality selections, $R_\gamma$ shows a significant excess that is rather constant below $\approx 3\text{ GeV/c}$. Beyond that, $R_\gamma$ increases with $p_T$, the increase being most pronounced for central collisions, and $R_\gamma$ continuously decreases towards more peripheral collisions. This is expected as phenomena such as jet quenching reduce the number of decay photons from hadron decays in more central collisions, which in turn increases $R_\gamma$ [33, 35].

The high statistics of the 2014 data set allows to divide the data sample into nine centrality bins, from 0%–10% to 80%–93%, 10% bins each, except for the last one which is slightly larger. The resulting $R_\gamma$ are shown in Fig. [13] Up to 50%–60% centrality, data from the earlier calorimeter measurement [39] are also shown.

For most bins the overall shape of $R_\gamma$ as a function of $p_T$ is similar to what is observed in Fig. [12] with a notable difference for panel (i), which is the most-peripheral centrality 80%–93%. Below 5 GeV/c, the most-peripheral Au+Au data show no significant excess above unity and are very consistent with the direct-photon result from $p+p$ collisions, which is also shown in panel (i). The MC sampling method is used to calculate both the statistical and systematic uncertainties on $\gamma_{\text{dir}}$ and all quantities derived from the direct photon $p_T$ spectra. This method propagates the error correctly in the presence of unphysical values of $R_\gamma < 1$ and $p_T$ and centrality dependent correlations of uncertainties; it is discussed in detail in Appendix [3].
FIG. 12. The ratio, $R_\gamma = \gamma^{incl}/\gamma^{had}$, as a function of conversion photon $p_T$ in 0%–20%, 20%–40%, 40%–60% and 60%–93% centrality bins. The 2014 Au+Au data at $\sqrt{s_{NN}} = 200$ GeV are compared to results from previous PHENIX publications (see Refs. 3, 6, 39).

B. Direct-photon invariant yield

The direct-photon spectra are calculated from $R_\gamma$ and $\gamma^{had}$ using Eq. 9. The results for all 10% centrality selections are given in Fig. 14. Figure 15 compares the direct-photon spectra with previous measurements, as shown in broader centrality bins (a) 0%–20%, (b) 20%–40%, (c) 40%–60%, and (d) 60%–93%. Each panel also presents the $N_{coll}$-scaled perturbative quantum chromodynamics (pQCD) calculation [12] and a fit to direct-photon data from $p+p$ collisions at $\sqrt{s} = 200$ GeV [40, 42]. The $p+p$ fit is performed with a pQCD-inspired functional form [43]:

$$\frac{d^3N}{dp_T^2dy} = \frac{A_{pp}}{(1 + \left(\frac{p_T}{p_0}\right)^2)^n},$$

(10)

where the parameters are $A_{pp} = 1.60 \times 10^{-4}$ (GeV/c)$^{-2}$, $p_0 = 1.45$ GeV/c and $n = 3.3$. The error band around the central fit function represents the uncertainty propagated from both the data and the unknown true functional form of the spectrum down to very low $p_T$. The $p+p$ fit and the pQCD calculation agree well above 2 GeV/c, and can be used as an estimate for the prompt-photon contribution.

Figure 15 also shows that the direct-photon yield for $p_T$ larger than 2.5 GeV/c is well described by the $N_{coll}$-scaled $p+p$ result and pQCD calculations, which confirms that the high-$p_T$ direct photons are predominately from initial hard-scattering processes. Below 4–5 GeV/c a clear direct-photon excess develops above the prompt component, gradually becoming larger towards lower $p_T$.

C. Nonprompt direct-photon excess

To extract the direct-photon excess above the prompt-photon contribution, the $N_{coll}$ scaled $p+p$ fit is subtracted from the Au+Au data. This excess is thought to be mostly the radiation that is emitted during the collision from the hot-expanding fireball, and will be referred to here as nonprompt direct-photon spectra. Figure 16 compares the nonprompt direct-photon spectra to previously published results from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [6], which had significantly lower statistics. The new 2014 data extend the coverage, both in $p_T$ and centrality.

The data are very consistent in the region of overlap. In the range 0.8 to 1.9 GeV/c, the data are fitted with an exponential function and the results are also shown
TABLE IV. Inverse slopes fitted to the direct-photon spectra in different $p_T$ ranges, and for different centrality selections. For each centrality range, $N_{\text{coll}}$ and $dN_{\text{ch}}/d\eta$ values are quoted, which are taken from previous work [44, 45], except for the $dN_{\text{ch}}/d\eta$ values for the two most peripheral bins. Those were extrapolated using a fit of the form $dN_{\text{ch}}/d\eta = B(N_{\text{coll}})^\beta$.

| Centrality | $dN_{\text{ch}}/d\eta$ | $N_{\text{coll}}$ | $T_{\text{eff}}$ (GeV/c) | $T_{\text{eff}}$ (GeV/c) |
|------------|------------------------|-------------------|---------------------------|---------------------------|
|            |                        |                   | $0.8 < p_T < 1.9$ GeV/c   | $2 < p_T < 4$ GeV/c       |
| 0%–20%     | 519.2 ± 26.3           | 770.6 ± 79.9      | 0.277 ± 0.017             | 0.428 ± 0.031             |
| 20%–40%    | 225.4 ± 13.2           | 282.4 ± 28.4      | 0.264 ± 0.010             | 0.354 ± 0.019             |
| 40%–60%    | 85.5 ± 8.0             | 82.6 ± 9.3        | 0.247 ± 0.007             | 0.392 ± 0.028             |
| 60%–93%    | 16.4 ± 2.8             | 12.1 ± 3.1        | 0.253 ± 0.011             | 0.331 ± 0.036             |
| 0%–10%     | 623.9 ± 32.2           | 951 ± 98.5        | 0.268 ± 0.024             | 0.514 ± 0.061             |
| 10%–20%    | 414.2 ± 20.2           | 590.1 ± 61.1      | 0.303 ± 0.024             | 0.358 ± 0.033             |
| 20%–30%    | 274 ± 14.8             | 357.2 ± 35.5      | 0.263 ± 0.011             | 0.352 ± 0.024             |
| 30%–40%    | 176.8 ± 11.6           | 207.5 ± 21.2      | 0.256 ± 0.011             | 0.339 ± 0.020             |
| 40%–50%    | 109.4 ± 9.1            | 111.1 ± 10.8      | 0.244 ± 0.009             | 0.347 ± 0.024             |
| 50%–60%    | 61.6 ± 7.1             | 54.1 ± 7.9        | 0.246 ± 0.017             | 0.345 ± 0.031             |
| 60%–70%    | 32 ± 5                 | 24 ± 6            | 0.261 ± 0.015             | 0.319 ± 0.049             |
| 70%–80%    | 16 ± 4                 | 10 ± 3            | 0.263 ± 0.016             | 0.335 ± 0.044             |
| 80%–93%    | 7 ± 2                  | 4 ± 1             | –                         | –                         |

FIG. 14. Invariant yield of direct photons as a function of conversion photon $p_T$ in 0%–10% to 80%–93% centrality bins.

FIG. 16. The slope values are given in Table IV. All centrality selections are consistent with an average inverse slope, $T_{\text{eff}}$, of $\approx 0.260 \pm 0.011$ GeV/c. However, it is evident from Fig. 16 that the nonprompt direct-photon spectra are not described by a single exponential but rather have a continually increasing with $p_T$ inverse slope, $T_{\text{eff}}$. Figure 17 brings this out more clearly where each nonprompt direct-photon spectrum is divided by a fit with a fixed slope, $T_{\text{eff}} = 0.260$ GeV/c. All centrality selections follow the same trend. Over the $p_T$ range of up to 2 GeV/c the ratios are consistent with unity, but above 2 GeV/c, they start to rise monotonically.

To quantify this changing slope, the nonprompt direct-photon spectra are fitted with a second exponential function in the $p_T$ range from 2 to 4 GeV/c; the results are also included in Fig. 16. All data are consistent with an average inverse slope of 0.376 ± 0.037 GeV/c, which is significantly larger than the slope observed below $p_T = 2$ GeV/c. Above 4 GeV/c, the statistical and systematic uncertainties from the prompt-photon subtraction become too large for a detailed analysis.

To establish any dependence on the system size, the nonprompt direct photon spectra are determined for each 10% centrality bin, and subsequently fitted by two exponential functions in the $p_T$ ranges $0.8 < p_T < 1.9$ GeV/c and $2 < p_T < 4$ GeV/c. The resulting $T_{\text{eff}}$ values are tabulated in Table IV and depicted in Fig. 16 as a function of $dN_{\text{ch}}/d\eta$. The figure also shows the average of the inverse slope values from fitting Fig. 16. The $T_{\text{eff}}$ values are consistent with a constant value, independent of $dN_{\text{ch}}/d\eta$. However, given the uncertainties on the data, a possible increase of $T_{\text{eff}}$ with $dN_{\text{ch}}/d\eta$ can not be excluded.
The direct-photon spectra shown in Fig. 14 are integrated where all rapidity densities are densities at midrapidity. In more detail, the direct-photon yield and the nonprompt component, are tabulated in (a) 0%–20%, (b) 20%–40%, (c) 40%–60% and (d) 60%–93% centrality bins. The 2014 Au+Au data at $\sqrt{s_{NN}} = 200$ GeV are compared to results from previous PHENIX publications (see Refs. 3, 5, 39).

In addition to investigating the $p_T$ and system-size dependence of the shape of the nonprompt direct-photon spectra, one can also look at the dependence of the yield on system size and $p_T$. As reported previously, the integrated direct-photon yield scales with $dN_{ch}/d\eta$ to a power $\alpha$ [8]:

$$\frac{dN}{d\eta} = \int_{p_T,\text{max}}^{p_T,\text{min}} \frac{dN_{\gamma}}{dp_T} \frac{dp_T}{d\eta} dp_T = A \left( \frac{dN_{ch}}{d\eta} \right)^{\alpha}, \quad (11)$$

where all rapidity densities are densities at midrapidity. The direct-photon spectra shown in Fig. 14 are integrated from $p_T,\text{min} = 1$ GeV/$c$ to $p_T,\text{max} = 5$ GeV/$c$ and plotted as a function of $dN_{ch}/d\eta$ in Fig. 15. They are in reasonable agreement with a compilation of other direct-photon results [3, 40], also shown in the figure. All data follow a trend similar to the $N_{\text{coll}}$ scaled $p+p$ fit, shown as band, but at a roughly 10 times larger yield. Scaling with $N_{\text{coll}}$ corresponds to $\alpha = 1.25 \pm 0.02$ [3]. The current high statistics data allow for finer centrality binning and changes this picture somewhat at the lowest and highest $dN_{ch}/d\eta$. Fitting only the new results in Fig. 15 gives a value of $\alpha = 1.11 \pm 0.02(\text{stat}) \pm 0.03(\text{sys})$. This value is lower, but consistent within systematic uncertainties, with $\alpha = 1.23 \pm 0.06 \pm 0.18$, found by fitting all previously published PHENIX A+A data [40].

Note that the previous PHENIX measurements obtained the $\eta$ spectrum by $m_T$-scaling the $\pi^0$ spectrum, while in the current measurement the $\eta$ spectrum is obtained from the $\eta/\pi^0$ ratio using the world data. There are significant differences between the two approaches in the low-$p_T$ region [59]. Because the integration range starts at low $p_T$ and is wide (1–5 GeV/$c$), the power $\alpha$ is smaller than previously published values, but is consistent within stated systematic uncertainties. However, it is also consistent with unity within uncertainties.

To better understand the behavior of the scaling power, $\alpha$, in more detail, the direct-photon yield and its nonprompt component are integrated for six different nonoverlapping finer $p_T$ regions and for 10% centrality classes. The integrated nonprompt yields are shown in Fig. 16. The $\alpha$ values are determined for each $p_T$ selection by fitting the data with Eq. (11). The fits are also shown in the figure. All $\alpha$ values, both for the direct photon yield and the nonprompt component, are tabulated in Table VI and shown in Fig. 17. It is evident that the
values for the direct component, for higher \( p_T \) ranges, are consistent with the prompt component, \( \alpha = 1.25 \pm 0.02 \), corresponding to \( N_{\text{coll}} \) scaling. However, they tend to be smaller, but still consistent within systematic uncertainties, with previous measurements [8] for the lower \( p_T \) ranges.

With increasing \( p_T \), the \( \alpha \) values for the nonprompt component are slightly lower than those from direct photons. The systematic uncertainties are larger due to the subtraction. The values of \( \alpha \) for the nonprompt component, as shown in Fig. 21, are remarkably constant with no evident \( p_T \) dependence.

### VI. Concluding Discussion of the Results

The PHENIX collaboration has measured direct-photon production in \( \text{Au+Au} \) collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) using photon conversions to \( e^+e^- \) pairs. A large yield of direct photons below a \( p_T \) of 3 GeV/c is observed for all centrality bins except for the most peripheral bin of 80\%-93\% with \( dN_{\text{ch}}/d\eta = 7.4 \), where it seems to be consistent with the prompt-photon production. The next centrality bin from 70\%-80\% with \( dN_{\text{ch}}/d\eta = 15.5 \) already shows a significant yield with properties very similar to that of the radiation from the more central bins.

The nonprompt direct-photon spectra are isolated by subtracting the prompt-photon contribution, which is es-
estimated through a fit to the direct-photon data from $p+p$ collisions at $\sqrt{s} = 200$ GeV, measured by PHENIX, and scaled by $N_{\text{coll}}$. Results are obtained for the $p_T$ range from 0.8 to 5 GeV/$c$ and for 0%–93% central collisions, covering a system size spanning two orders of magnitude in $dN_{\text{ch}}/d\eta$ from $\approx 7$ to 620. The wealth of data enabled PHENIX to carry out double-differential analyses of the shape of the momentum spectra and the rapidity density $dN_{\gamma}/d\eta$ in $p_T$ and $dN_{\text{ch}}/d\eta$.

For the centrality selections from 0%–10% to 70%–80%, all nonprompt direct-photon spectra are very similar in shape, exhibiting increasing $T_{\text{eff}}$ from 0.2 to 0.4 GeV/$c$ over the $p_T$ range from 0.8 to 4 GeV/$c$. The changing $T_{\text{eff}}$ is not surprising, because the spectra are time integrated over the full evolution of the expanding fireball, from its earliest pre-equilibrium state, through the QGP phase, crossing over to a HG, and further expanding and cooling until hadrons eventually stop interacting. Throughout the evolution the system cools, and thus earlier phases are characterized by higher temperatures. In turn, the contributions from the earliest times of the evolution are likely to dominate the emission at higher $p_T$, consistent with the observation of an increasing $T_{\text{eff}}$ with $p_T$.

In the lower $p_T$ range from 0.8 to 1.9 GeV/$c$, the spectra are well described by a $T_{\text{eff}} = 0.26$ GeV/$c$. This is consistent with what is expected for radiation from the late QGP stage until freeze-out [14]. During this period of the evolution, the temperature drops from $\approx 170$ MeV near the transition to $\approx 110$ MeV when the system freezes out. At the same time the system is rapidly expanding and thus, the radiation is blue shifted. This compensates the temperature drop and results in an average $T_{\text{eff}} \approx 0.26$ GeV/$c$, with only minor variations with centrality of the collision. In Ref. [14], a moderate increase of $T_{\text{eff}}$ with centrality was predicted. While the data favors a $T_{\text{eff}}$ independent of centrality, they are not precise enough to exclude a moderate change.

Above a $p_T$ of 2 GeV/$c$, the inverse slope of the spectra continues to increase with $p_T$. Between $p_T = 2$ and 4 GeV/$c$ the average inverse slope is $T_{\text{eff}} \approx 0.376$ GeV/$c$. This $T_{\text{eff}}$ is larger than what model calculations for a rapidly expanding HG can accommodate, thus suggesting that emissions from the QGP phase and earlier times in the evolution starts to dominate the spectra. Expected initial temperatures at RHIC are $\approx 375$ MeV with maximum $T_{\text{eff}}$ in the range of 0.35 to 0.4 GeV/$c$, depending on viscosity [14]. Thus, it is likely that in addition to photons from the QGP phase, photons from the pre-equilibrium phase are also needed to account for the measured $T_{\text{eff}}$.

In Fig. 22, the measured nonprompt direct-photon spectra are compared to a recent calculation including contributions from the pre-equilibrium phase [10] [47]. These calculations predicted that the pre-equilibrium radiation becomes the dominant source above a $p_T$ of 3 GeV/$c$. In the range $2 < p_T < 4$ GeV/$c$, a fit of the thermal contribution with an exponential function
Because the QGP phase has a larger relative contribution under-}

tanding. From the pre-equilibrium phase needs further theo-

rical increases with \( \alpha \) in [14] predict that the radiation from the HG phase scale no apparent dependence on \( \alpha \). The 2014 Au+Au data at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) are compared to results from a previous PHENIX publications (see Ref. [6]).

results in an inverse slope of \( \approx 0.36 \text{ GeV}/c \), while for the pre-equilibrium contribution a larger inverse slope of \( \approx 0.52 \text{ GeV}/c \) is found, for the more central collisions. Fitting the same \( p_T \) range for the combined thermal and pre-equilibrium spectra from the model gives an inverse slope of \( \approx 0.425 \text{ GeV}/c \). While the shape is reproduced well, the overall yield predicted by the calculations falls short compared to the data, in particular, below 2 GeV/c where the nonprompt-photon yield appears to be a factor of two to three larger.

The integrated nonprompt direct-photon yield exhibits a power-law relation with \((dN_{ch}/d\eta)^{\alpha}[8]\). Fitting the power \( \alpha \) for multiple nonoverlapping \( p_T \) ranges results in values consistent with \( \alpha = 1.12 \pm 0.06\text{stat} \pm 0.14\text{syst} \) with no apparent dependence on \( p_T \). The model calculations in [14] predict that the radiation from the HG phase scale with \( \alpha \) close to 1.2, while those from the hot and dense QGP phase exhibit closer to a \((dN_{ch}/d\eta)^2\) dependence. Because the QGP phase has a larger relative contribution to the \( p_T \) spectrum with increasing \( p_T \), it is expected that \( \alpha \) increases with \( p_T \). However, the \( p_T \) dependence of \( \alpha \) from the pre-equilibrium phase needs further theoretical understanding.

In conclusion, the 10-fold increase in statistics compared to previous samples of Au+Au collisions recorded by PHENIX enabled detailed measurements of the radiation from the hot and expanding fireball. The experimentally observed inverse slopes of the \( p_T \) spectra are qualitatively consistent with predictions for thermal and pre-equilibrium radiation. However, there seems to be more photons emitted from Au+Au collisions than can be accounted for in model calculations. Furthermore, although this work presents no new data on the azimuthal anisotropy, maximum anisotropy is observed for photons \( \approx 2–3 \text{ GeV}/c \). In this \( p_T \) range, the yield is larger than what would be expected from a rapidly but anisotropically expanding hadronic fireball. Finally, the centrality dependence of the nonprompt direct-photon yield, expressed in terms of the scaling power \( \alpha(p_T) \), shows no indication of changing with \( p_T \).

ACKNOWLEDGMENTS

We thank the staff of the Collider-Accelerator and Physics Departments at Brookhaven National Laboratory and the staff of the other PHENIX participating institutions for their vital contributions. We also thank J.F. Paquet for many fruitful discussions and sharing additional information. We acknowledge support from the Office of Nuclear Physics in the Office of Science of the Department of Energy, the National Science Foundation, Abilene Christian University Research Council, Research Foundation of SUNY, and Dean of the College of Arts and Sciences, Vanderbilt University (USA), Ministry of Education, Culture, Sports, Science, and Technology and the Japan Society for the Promotion of Science (Japan), Natural Science Foundation of China (People’s Republic of China), Croatian Science Foundation and Ministry of Science and Education (Croatia), Ministry of Education, Youth and Sports (Czech Republic), Centre National de la Recherche Scientifique, Commissariat à l’Énergie Atomique, and Institut National de Physique Nucléaire et de Physique des Particules (France), J. Bolyai Research Scholarship, EFOP, the New National Excellence Program (ÚNKP), NKFIH, and OTKA (Hungary), Department of Atomic Energy and Department of Science and Technology (India), Israel Science Foundation (Israel), Basic Science Research and SRC(CENUm) Programs through NRF funded by the Ministry of Education and the Ministry of Science and ICT (Korea), Ministry of Education and Science, Russian Academy of Sciences, Federal Agency of Atomic Energy (Russia), VR and Wallenberg Foundation (Sweden), University of Zambia, the Government of the Republic of Zambia (Zambia), the U.S. Civilian Research and Development Foundation for the Independent States of the Former Soviet Union, the Hungarian American Enterprise Scholarship Fund, the US-Hungarian Fulbright Foundation, and the US-Israel Binational Science Foundation.
Appendix A: Event-mixing procedures and validation

In this analysis, $e^+e^-$ pairs and $e^+e^−\gamma$ combinations result from combining positrons, electrons, and photons measured in the same event. Given the large multiplicity of produced particles in Au+Au collisions, the combinations include a significant background from particles of different physical origin, for example different $\pi^0$ decays. For $e^+e^-$ pairs there are two possible combinations: signal pairs, $SG^{ee}$, that have the same source and background pairs, $BG^{ee}$, that have different sources. Both types will be combined with photons to get $e^+e^−\gamma$ combinations. There are three possibilities: A correlated $e^+e^-$ pair is combined with a photon from the same source ($SG^{e\gamma}$); the $e^+e^-$ pair is not correlated, but the photon is correlated to the $e^+$ or $e^−$ ($BG^{e\gamma}_{corr}$); or the photon is uncorrelated to the $e^+e^-$ pair, irrespective whether it is $SG^{ee}$ or $BG^{ee}$ ($BG^{e\gamma}_{uncorr}$).

All backgrounds are determined using event-mixing techniques that were developed and validated with MC studies of high-multiplicity events, for which a large sample of simulated $\pi^0$ events was generated. These events serve as pseudodata. The $\pi^0$ are generated according to the experimentally observed $p_T$ spectrum, uniform in azimuthal angle, and with a constant rapidity density of 280 $\pi^0$, which corresponds to the typical $\pi^0$ multiplicity in the most central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

From these pseudodata, $N^{incl}_\gamma$ and $N^{e\gamma,tag}_\gamma$ are extracted using the cuts and event-mixing schemes developed for the analysis of real data. They are corrected by $\langle \epsilon, f \rangle$, resulting in $R_\gamma$. Because in the pseudodata there are no other hadronic decay channels contributing to $\gamma^{hadr}$ other than $\pi^0$, the $R_\gamma$ from this pseudodata is given by:

$$R^{\text{pseudo}}_\gamma = \frac{N^{incl}_\gamma}{N^{e\gamma,tag}_\gamma} \times \langle \epsilon, f \rangle$$  \hspace{1cm} (A1)

As there are no direct photons in the pseudodata, the expected result would be $R_\gamma = 1$, within the statistical uncertainties of the simulation. The rest of this sections details each step of the $R_\gamma$ determination from the pseudodata. The exact same procedure is also applied to the real data.
1. Determination of the inclusive photon yield $N_{\gamma_{\text{incl}}}$

Photon conversion candidates are created by combining $e^+$ and $e^-$ from the same pseudodata event by requiring a valid conversion point within $1 < R < 29$ cm. This results in a foreground, $\text{FG}^{ee}$, containing a signal, $\text{SG}^{ee}$, that is, conversions of $\pi^0$ decay photons, and a background, $\text{BG}^{ee}$, where the $e^+$ and $e^-$ come from conversion of two different $\pi^0$ decay photons. The background is determined by combining electrons and positrons from different pseudodata events, which are paired and subjected to the same cuts and conversion selection criteria. The mixed event background thus obtained, $\text{MBG}^{ee}$, is normalized to the foreground, $\text{FG}^{ee}$, in the mass region $0.16 < m_{e^+e^-} < 0.3$ GeV/$c^2$, which does not contain $e^+e^-$ pairs from conversions (see Fig. 2 for reference).

Figure 23(a) shows the background, $\text{MBG}^{ee}$, obtained from the mixed event technique together with the true background, $\text{BG}^{ee}$, which was obtained from the MC ancestry information. Figure 23(b) shows the results (solid curve) after subtracting the mixed-event background from the foreground and (open symbols) subtracting the true background. Note that the two are practically indistinguishable, which means that $\text{BG}^{ee}$ is equal to $\text{MBG}^{ee}$.

Even though the background can be subtracted accurately with the mixed-event technique to obtain $N_{\gamma_{\text{incl}}}$, the subtraction can only be done statistically. Thus in the next step, where conversion photons from $\pi^0$ decays are tagged, the background pairs also need to be matched with EMCal showers. This substantially increases the background in the $m_{e^+e^-}$ distribution. To reduce this background, additional cuts are applied in the conversion-photon selection.

The magnetic field deflects electrons and positrons in a plane perpendicular to the beam direction ($z$). Thus, $e^+e^-$ pairs from a conversion can be constrained by requiring a match in the beam direction using the PC1 information. A cut of $|\Delta z| < 4$ cm is applied. Because the conversion reconstruction algorithm uses the projection of the tracks in the plane perpendicular to the beam axis, the additional match reduces the number of possible random-track combinations significantly. The $z$ cut effec-
tively truncates the mass distribution as the $e^+e^-$ pairs are required to have the possible conversion point at radii below 29 cm and only the pairs with an opening angle in the beam direction will create larger masses. The background rejection is clearly visible in Fig. [24]. The background normalization for the mixed events is given by the less-restrictive cuts shown in Fig. [23] and applied here. For the lowest $p_T$ and the highest-multiplicity bin, the background rejection is approximately a factor of eight with a signal efficiency of more than 85%. The background has two components: (i) combinations $e^+e^-$, where the shower in the EMCal and the electron or positron are from the same event (FG) and different event-mixing setups. The uncorrelated background can be determined with $\pi^0$ simulation, for which an example is given in panel (a) of Fig. [26]. Despite the large background the signal $N_{e^+e^-}$ is clearly visible as peak around the $\pi^0$ mass. The background has two components: (i) combinations $e^+e^-$ with an EMCal shower from another unrelated $\pi^0$ decay denoted as $BG_{\text{uncorr}}$ and (ii) a correlated background, $BG_{\text{corr}}$, where the shower in the EMCal and the electron or positron are from the same $\pi^0$ decay, but the $e^+e^-$ pair itself is a combination of an $e^+$ and $e^-$ from different $\pi^0$ decay photons. The uncorrelated background can be determined with a similar event mixing technique as used for the extraction of the mixed-event technique, MBG to 0.12 GeV/c, and the highest-multiplicity bin, the $p_T$ range and $N_{\text{incl}}$ is calculated in the mass range from 0.04 to 0.12 GeV/c$^2$ by subtracting the background obtained from the mixed-event technique, MBG$^{\text{incl}}$, from the foreground, FG$^{\text{incl}}$. The result is compared to the true number of photon conversions determined from the MC-ancestry information in Fig. [25]. Panel (b) shows that the difference is less than 1% for all $p_T$.

2. The tagged photon yield $N_{e^+e^-}^{\text{tag}}$

Next, the subset $N_{e^+e^-}^{\text{tag}}$ of $e^+e^-$ pairs in the $N_{\text{incl}}$ sample that can be tagged as photons from a $\pi^0$ decay is determined. For a given pseudodata event, each $e^+e^-$ conversion candidate is paired with all reconstructed showers in the EMCal, excluding the showers matched to the $e^+e^-$ pair itself. For each combination the invariant mass $m_{e^+e^-}$ is calculated. This constitutes the foreground, FG$^\gamma$, for which an example is given in panel (a) of Fig. [26]. The analysis is repeated for the entire accessible $p_T$ range and $N_{\text{incl}}$ is calculated in the mass range from 0.04 to 0.12 GeV/c$^2$ by subtracting the background obtained from the mixed-event technique, MBG$^{\text{incl}}$, from the foreground, FG$^{\text{incl}}$. The result is compared to the true number of photon conversions determined from the MC-ancestry information in Fig. [25]. Panel (b) shows that the difference is less than 1% for all $p_T$. The background rejection is clearly visible in Fig. [24]. The background normalization for the mixed events is given by the less-restrictive cuts shown in Fig. [23] and applied here. For the lowest $p_T$ and the highest-multiplicity bin, the background rejection is approximately a factor of eight with a signal efficiency of more than 85%. The background to foreground ratio, $BG^{\text{corr}}/FG^{\text{incl}}$, is 12.1%. As $p_T$ increases the multiplicity decreases and the $BG^{\text{corr}}/FG^{\text{incl}}$ ratio decreases to 0.3% at the $p_T$ above 7 GeV/c.

The analysis is repeated for the entire accessible $p_T$ range and $N_{\text{incl}}$ is calculated in the mass range from 0.04 to 0.12 GeV/c$^2$ by subtracting the background obtained from the mixed-event technique, MBG$^{\text{incl}}$, from the foreground, FG$^{\text{incl}}$. The result is compared to the true number of photon conversions determined from the MC-ancestry information in Fig. [25]. Panel (b) shows that the difference is less than 1% for all $p_T$.
The random background, $\text{MBG}_{\text{corr}}^{ee\gamma}$, can easily be determined in a third event-mixing step, where $e^+$, $e^-$, and $\gamma$ are from three different events. The $\text{MBG}_{\text{comb}}^{ee\gamma}$ is normalized to $(\text{MBG}_{\text{corr}}^{ee\gamma} + \text{MBG}_{\text{uncorr}}^{ee\gamma})$ in the mass range from 0.65 to 1.0 GeV/$c^2$ and subtracted. Figure 27(a) shows the result, $\text{MBG}_{\text{corr}}^{ee\gamma}$, together with the foreground and the other background components.

Last but not least, to account for any possible mismatch between the true background and the one obtained from our multistep event-mixing procedure, the ratio $(\text{FG}^{ee\gamma} - \text{MBG}_{\text{corr}}^{ee\gamma} - \text{MBG}_{\text{uncorr}}^{ee\gamma})/\text{MBG}_{\text{uncorr}}^{ee\gamma}$ is fit with a second-order polynomial, $f_{ee\gamma}$, excluding the $\pi^0$ peak regions. The fit result is shown as a line on Fig. 27(b). This fit is used to correct $\text{MBG}_{\text{uncorr}}^{ee\gamma}$ before subtraction.

The final distribution for $N_{\gamma}^{0\text{-tag}}$ is thus:

$$N_{\gamma}^{0\text{-tag}} = \text{FG}^{ee\gamma} - \text{MBG}_{\text{corr}}^{ee\gamma} - (1 + f_{ee\gamma}) \text{MBG}_{\text{uncorr}}^{ee\gamma} \quad (A2)$$

For each $p_T$ bin $N_{\gamma}^{0\text{-tag}}$ is extracted by counting the number of entries in a window around the $\pi^0$ peak ($0.09 < m_{ee\gamma} < 0.19$) GeV/$c^2$. Figure 28 shows $N_{\gamma}^{0\text{-tag}}$ as function of $p_T$ using the true MC-ancestry information and the event-mixing technique. Overall the agreement is very good, however, the result from the event-mixing technique is on average lower. This mismatch is accounted for in the systematic uncertainties on $R_\gamma$, which is discussed in more detail in the next section.

3. Completing the validation by determining $R_\gamma$

With $N_{\gamma}^{\text{incl}}$ and $N_{\gamma}^{0\text{-tag}}$ established from the pseudodata, the conditional probability $\langle e_\gamma f \rangle$ remains to be determined to calculate $R_\gamma$ and fully validate the background-subtraction procedure. In the same way as for the data, a single $\pi^0$ simulation is embedded into pseudodata events. The $e^+e^-\gamma$ pairs and $e^+e^-\gamma$ combinations are reconstructed and counted as discussed in Sec. 3.1. The extracted $\langle e_\gamma f \rangle$ is shown in Fig. 29 as a function of the conversion photon $p_T$.

With $N_{\gamma}^{\text{incl}}/N_{\gamma}^{0\text{-tag}}$ from the pseudodata and $\langle e_\gamma f \rangle$ from the embedded single $\pi^0$ simulation in hand, $R_\gamma$
Appendix B: Uncertainty propagation with a MC sampling method

The uncertainties on $\gamma_{\text{dir}}$ and any other quantity derived from $\gamma_{\text{dir}}$, such as $T_{\text{eff}}$ or $\alpha$, are determined using a MC-sampling method, which allows taking into account the $p_T$ and centrality dependent correlations of individual sources of systematic uncertainties, as well as the fact that the region $R_\gamma < 1$ is unphysical.

1. Systematic uncertainties

In the MC-sampling method, for each source of uncertainty, $i$, a variation $\delta_i$ of $R_\gamma$ or $\gamma_{\text{hadr}}$ is sampled from a Gaussian distribution centered at zero with a width corresponding to the associated uncertainty, $\sigma_i$. The size of $\delta_i$ depends not only on $\sigma_i$, but also on whether the adjacent bins in $p_T$ and centrality have uncorrelated (Type A) or correlated (Type B/C) uncertainties due to the source $i$. The values of $\sigma_i$ and classification of each source is summarized in Table I.

If source $i$ is classified as uncorrelated, $\delta_i$ is calculated independently for neighboring bins from Gaussian distributions of width $\sigma_i$. For correlated uncertainties of Type C in $p_T$ or centrality, $\delta_i$ is calculated with one common fraction $w$ so that $\delta_i = w \sigma_i$ for all points. The fraction $w$ is determined randomly from a Gaussian distribution of width 1. And finally, for Type B uncertainties, $\delta_i$ is determined separately for the minimum and maximum of the $p_T$ or centrality range using the same procedure as Type C. All intermediate points are varied proportionally to create a smooth transition from the minimum to the maximum of the range. Uncertainties on the input $p_T$ distribution are a special case of Type B uncertainties, as it is known that the systematic uncertainties move simultaneously either up or down. In this case, $\delta_i$ at the minimum and maximum of the range are chosen to have the same sign.

After applying all variations $\delta_i$ to recalculate $R_\gamma$ and $\gamma_{\text{hadr}}$, new values of $\gamma_{\text{dir}}$, $T_{\text{eff}}$, and $\alpha$ are determined. This process is repeated multiple times, taking into account the different sources of uncertainties, to obtain a distributions of $\gamma_{\text{dir}}$, $T_{\text{eff}}$, and $\alpha$. The width of these distribution is quoted as the systematic uncertainty. For individual $\gamma_{\text{dir}}$ points, it is possible that $(\gamma_{\text{dir}} - \sigma)$ is less than 0, that is, unphysical. In such cases, an upper limit of 90% confidence level (CL) is quoted based on the part of the probability distribution in the physical region $f_0^{\text{upper}} / f_0^{+\infty} = 90%$.

2. Statistical uncertainties

The statistical uncertainties on $R_\gamma$ are assumed to have a Gaussian probability distribution and for most cases the statistical uncertainty on $\gamma_{\text{dir}}$ can be calculated with the usual error propagation. However, there are two cases that need to be treated separately:

- $R_\gamma < 1$: In this case $\gamma_{\text{dir}}$ is unphysical, and hence an upper limit at 90% CL is quoted, based on the physical part of the probability distribution $f_0^{\text{upper}} / f_0^{+\infty} = 90%$.

- $R_\gamma - \sigma_{\text{stat}} < 1$: In this case $\gamma_{\text{dir}}$ is in the physical region, but consistent with zero within less than one standard deviation. For these situations the central value is shown, but the uncertainty is given as 90% CL, calculated as above.

[1] E. V. Shuryak, Quark-gluon plasma and hadronic production of leptons, photons and psions, Phys. Lett. B 78, 150 (1978).
[2] G. David, Direct real photons in relativistic heavy ion collisions, Rept. Prog. Phys. 83, 046301 (2020).
[3] A. Adare et al. (PHENIX Collaboration), Enhanced production of direct photons in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV and implications for the initial temperature, Phys. Rev. Lett. 104, 132301 (2010).
[4] A. Adare et al. (PHENIX Collaboration), Observation of direct-photon collective flow in $\sqrt{s_{NN}}=200$ GeV Au+Au collisions, Phys. Rev. Lett. 109, 122302 (2012).
[5] A. Adare et al. (PHENIX Collaboration), Azimuthally anisotropic emission of low-momentum direct photons in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV, Phys. Rev. C 94, 064901 (2016).
[6] A. Adare et al. (PHENIX Collaboration), Centrality dependence of low-momentum direct-photon production in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV, Phys. Rev. C 91, 064904 (2015).
[7] L. Adamczyk et al. (STAR Collaboration), Direct virtual photon production in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV, Phys. Lett. B 770, 451 (2017).
[8] A. Adare et al. (PHENIX Collaboration), Beam Energy and Centrality Dependence of Direct-Photon Emission from Ultrarelativistic Heavy-Ion Collisions, Phys. Rev. Lett. 123, 022301 (2019).
[9] J. Adam et al. (ALICE Collaboration), Direct photon production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Phys. Lett. B 754, 235 (2016).
[10] C. Gale, J.-F. Paquet, B. Schenke, and C. Shen, Multimessenger heavy-ion collision physics, Phys. Rev. C 105, 014909 (2022)

[11] O. Linnyk, E. L. Bratkovskaya, and W. Cassing, Effective QCD and transport description of dilepton and photon production in heavy-ion collisions and elementary processes, Prog. Part. Nucl. Phys. 87, 50 (2016)

[12] J.-F. Paquet, C. Shen, G. S. Denicol, M. Luzum, B. Schenke, S. Jeon, and C. Gale, Production of photons in relativistic heavy-ion collisions, Phys. Rev. C 93, 044906 (2016)

[13] L. McLerran and B. Schenke, The Glasma, Photons and the Implications of Anisotropy, Nucl. Phys. A 929, 71 (2014)

[14] C. Shen, U. W. Heinz, J.-F. Paquet, and C. Gale, Thermal photons as a quark-gluon plasma thermometer reexamined, Phys. Rev. C 89, 044910 (2014)

[15] H. van Hees, C. Gale, and R. Rapp, Thermal Photons and Collective Flow at the Relativistic Heavy-Ion Collider, Phys. Rev. C 84, 054906 (2011)

[16] K. Dusling and I. Zahed, Thermal photons from heavy ion collisions: A spectral function approach, Phys. Rev. C 82, 054909 (2010)

[17] M. Dion, J.-F. Paquet, B. Schenke, C. Young, S. Jeon, and C. Gale, Viscous photons in relativistic heavy ion collisions, Phys. Rev. C 84, 064901 (2011)

[18] H. van Hees, M. He, and R. Rapp, Pseudo-critical enhancement of thermal photons in relativistic heavy-ion collisions, Nucl. Phys. A 933, 256 (2015)

[19] J. Berges, K. Reygers, N. Tanji, and R. Venugopalan, Parametric estimate of the relative photon yields from the glasma and the quark-gluon plasma in heavy-ion collisions, Phys. Rev. C 95, 054904 (2017)

[20] M. Heffernan, P. Holber, and R. Rapp, Universal parametrization of thermal photon rates in hadronic matter, Phys. Rev. C 91, 027902 (2015)

[21] O. Linnyk, V. Konchakovski, T. Steinert, W. Cassing, and E. L. Bratkovskaya, Hadronic and partonic sources of direct photons in relativistic heavy-ion collisions, Phys. Rev. C 92, 054914 (2015)

[22] G. Basar, D. E. Kharzeev, and V. Skokov, Conformal anomaly as a source of soft photons in heavy ion collisions, Phys. Rev. Lett. 109, 202303 (2012)

[23] G. Basar, D. E. Kharzeev, and E. V. Shuryak, Magnetosolitoniumsce and its signatures in photon and dilepton production in relativistic heavy ion collisions, Phys. Rev. C 90, 014905 (2014)

[24] B. Muller, S.-Y. Wu, and D.-L. Yang, Elliptic flow from thermal photons with magnetic field in holography, Phys. Rev. D 89, 026013 (2014)

[25] M. Allen et al. (PHENIX Collaboration), PHENIX inner detectors, Nucl. Instrum. Methods Phys. Res., Sec. A 499, 549 (2003)

[26] K. Adcox et al. (PHENIX Collaboration), PHENIX detector overview, Nucl. Instrum. Methods Phys. Res., Sec. A 499, 469 (2003)

[27] A. Taketani (PHENIX Collaboration), A silicon vertex tracker for PHENIX, Nucl. Phys. A 774, 911 (2006)

[28] K. Adcox et al. (PHENIX Collaboration), PHENIX central arm tracking detectors, Nucl. Instrum. Methods Phys. Res., Sec. A 499, 489 (2003)

[29] J. T. Mitchell et al. (PHENIX Collaboration), Event reconstruction in the PHENIX central arm spectrometers, Nucl. Instrum. Methods Phys. Res., Sec. A 482, 491 (2002)

[30] M. Aizawa et al. (PHENIX Collaboration), PHENIX central arm particle ID detectors, Nucl. Instrum. Methods Phys. Res., Sec. A 499, 508 (2003)

[31] L. Apehacette et al. (PHENIX Collaboration), PHENIX calorimeter, Nucl. Instrum. Methods Phys. Res., Sec. A 499, 521 (2003)

[32] R. Brun, F. Bruyant, M. Maire, A. C. McMpherson, and P. Zanarini, GEANT3 (1987).

[33] S. S. Adler et al. (PHENIX Collaboration), Suppressed π^0 production at large transverse momentum in central Au+Au collisions at √sNN = 200 GeV, Phys. Rev. Lett. 91, 072301 (2003)

[34] S. S. Adler et al. (PHENIX Collaboration), Identified charged particle spectra and yields in Au+Au collisions at √sNN = 200 GeV, Phys. Rev. C 69, 034909 (2004)

[35] A. Adare et al. (PHENIX Collaboration), Suppression pattern of neutral pions at high transverse momentum in Au+Au collisions at √sNN = 200 GeV and constraints on medium transport coefficients, Phys. Rev. Lett. 101, 232301 (2008)

[36] Y. Ren and A. Drees, Examination of the universal behavior of the g-to-π0 ratio in heavy-ion collisions, Phys. Rev. C 104, 054902 (2021)

[37] A. Adare et al. (PHENIX Collaboration), Spectra and ratios of identified particles in Au+Au and d+Au collisions at √sNN = 200 GeV, Phys. Rev. C 88, 024906 (2013)

[38] A. Adare et al. (PHENIX Collaboration), Heavy Quark Production in p+p and Energy Loss and Flow of Heavy Quarks in Au+Au Collisions at √sNN = 200 GeV, Phys. Rev. C 84, 044905 (2011)

[39] S. Afanasiev et al. (PHENIX Collaboration), Measurement of Direct Photons in Au+Au Collisions at √sNN=200 GeV, Phys. Rev. Lett. 109, 152302 (2012)

[40] S. S. Adler et al. (PHENIX Collaboration), Measurement of direct photon production in p+p collisions at √s = 200 GeV, Phys. Rev. Lett. 98, 012002 (2007)

[41] A. Adare et al. (PHENIX Collaboration), Direct-Photon Production in p+p Collisions at √s = 200 GeV at Midrapidity, Phys. Rev. D 86, 072008 (2012)

[42] A. Adare et al. (PHENIX Collaboration), Direct photon production in d+Au collisions at √sNN=200 GeV, Phys. Rev. C 87, 054907 (2013)

[43] A. Adare et al. (PHENIX Collaboration), Low-momentum direct-photon measurement in Cu+Cu collisions at √sNN=200 GeV, Phys. Rev. C 98, 054902 (2018)

[44] S. S. Adler et al. (PHENIX Collaboration), Systematic studies of the centrality and √sNN dependence of the dE_γ/dη and dN_γ/dη in heavy ion collisions at rapidity, Phys. Rev. C 71, 034908 (2005) [Phys. Rev. C 71, 049901(E) (2005)].

[45] A. Adare et al. (PHENIX Collaboration), Transverse energy production and charged-particle multiplicity at midrapidity in various systems from √sNN = 7.7 to 200 GeV, Phys. Rev. C 93, 024901 (2016)

[46] N. J. Abdulameer et al. (PHENIX), Low-pT direct-photon production in Au+Au collisions at √sNN = 39 and 62.4 GeV, Phys. Rev. C 107, 024914 (2023).

[47] J. F. Paquet, (2022), private communication.