



Measurement of isolated-prompt photon–hadron correlations in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

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Abstract The ALICE Collaboration has measured the azimuthal correlation between trigger isolated-prompt photons and associated charged hadrons in Pb–Pb collisions at the CERN LHC, at a centre-of-mass energy per nucleon pair of $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The trigger isolated-prompt photons are measured in the transverse-momentum range $18 < p_T^\gamma < 40$ GeV/c and pseudorapidity range $|\eta^\gamma| < 0.67$. The isolation selection is based on a charged particle isolation momentum threshold $p_T^{\text{iso, ch}} = 1.5$ GeV/c within a cone of radius $R = 0.2$. The associated charged particles are measured in the transverse-momentum ranges $p_T^h > 1.8$ GeV/c and pseudorapidity $|\eta^h| < 0.9$. The yield $D(z_T)$ of associated hadrons per trigger, with $z_T = p_T^h/p_T^\gamma$, is measured in three Pb–Pb collision centrality classes: central (0–30%), semicentral (30–50%), and peripheral (50–90%). The $D(z_T)$ measurement in pp collisions with the same p_T^γ interval was too limited statistically, but at a lower p_T^γ interval, showing agreement with theoretical predictions. Therefore, an approximation to the standard I_{AA} is computed from the $D(z_T)$ conditional yields, using NLO pQCD predictions as pp reference, the I_{pQCD} . A strong suppression of this ratio is observed in central collisions compared to peripheral collisions. The result extends to a lower p_T^γ relative to those reported in previously published Pb–Pb collisions measurements at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The I_{pQCD} measurement is compared to I_{AA} calculations with an NLO pQCD model that includes energy loss, and to the CoLBT-hydro model. The I_{pQCD} results from central collisions are also compared with I_{AA} measurements of jets correlated with isolated-prompt photons and of hadrons correlated with Z^0 bosons, both reported by the CMS Collaboration at the LHC, as well as with direct photon–hadron correlation I_{AA} measurements reported by the PHENIX and STAR Collaborations at RHIC.

1 Introduction

Heavy-ion collisions (AA) at ultrarelativistic energies produce a quark–gluon plasma (QGP) [1–9], a state of deconfined quarks and gluons. The high-energy quarks and gluons produced by partonic hard scatterings, which occur at the early stages of the collision, lose energy via collisional and radiative processes in the presence of a QGP [10, 11]. As a consequence, the high transverse-momentum (p_T) jet and hadron production, as well as the jet-fragmentation pattern, are modified with respect to their characteristics in proton–proton (pp) collisions: this effect is known as “jet quenching” [12–14]. The RHIC and LHC experiments have indeed reported a strong suppression of the production of jets and hadrons for $p_T \gtrsim 5$ GeV/c in central Pb–Pb and Au–Au collisions, which has been attributed to jet quenching [15–24].

The jet-radiation pattern can be explored via measurements of the fragmentation functions, which are the distributions of the number of constituents within a jet according to their relative contribution to the overall jet transverse momentum. The ratio of the fragmentation functions in AA over pp collisions, I_{AA} , is used to study the jet modifications induced by the QGP, for example, in jet or di-hadron azimuthal correlation measurements [25–29].

Electroweak bosons – direct-prompt photons (γ), Z^0 , and $W^\pm$ – are produced in the first instants of the collision, do not interact strongly with the QGP, therefore, their production, aside from cold nuclear effects, is unmodified [30–33], as reported at RHIC [34, 35] and the LHC [35–46]. At leading order (LO) in perturbative quantum chromodynamics (pQCD), they are produced in association with a parton emitted back-to-back in azimuthal angle and with similar p_T , which, in contrast to the boson, interacts with the QGP. Therefore, electroweak bosons can be used as a reference for the energy scale of the hard scattering process – as such, they are called “triggers”. The distribution of hadrons from the hadronisation of the parton recoiling from the trigger can be expressed with the following proxy for the parton fragmentation function: $D(z_T) = \frac{1}{N^{\text{trig}}} \frac{dN^h}{dz_T}$,

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with $z_T = p_T^h/p_T^{\text{trig}}$, where N^{trig} is the number of trigger particles, p_T^h and p_T^{trig} are the charged particle and trigger transverse momenta, respectively, and N^h is the number of charged particles with momentum fraction z_T associated to the trigger. Azimuthal-correlation measurements between electroweak bosons and hadrons provide an effective way to probe the nuclear modification of the parton fragmentation function, avoiding biases in jet-energy reconstruction present in reduced-jet areas, which can be modified by jet quenching. Direct γ -hadron correlations were measured at RHIC by the STAR [47] and PHENIX [48] Collaborations in Au–Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV, and direct γ -jet [49,50] and Z^0 -hadron [51,52] correlations were measured at the LHC by the CMS and ATLAS Collaborations in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. In those measurements, a strong modification of the jet pattern with respect to pp collisions has been observed. The ALICE Collaboration also measured isolated-prompt γ -hadron correlations in pp and p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [53], where no modification of the fragmentation pattern was observed, a result expected since QGP formation, and therefore, jet quenching is not likely in such collisions.

The kinematic range probed for Pb–Pb collisions in the measurement presented in this article, using direct-prompt photons as triggers, measured via the isolation technique described below, offers access to lower Q^2 relative to other LHC experiments, where the largest nuclear effects can be expected, and to a similar p_T^γ range as RHIC measurements. The relative energy loss and the steepness of the partonic spectra can enhance the observable suppression, and the interplay between parton virtuality and medium scales may become more relevant.

At LO in pQCD, direct-prompt photons are produced via $2 \rightarrow 2$ processes: (i) quark–gluon Compton scattering $qg \rightarrow q\gamma$, and (ii) quark–antiquark annihilation $q\bar{q} \rightarrow g\gamma$, with a small contribution from $q\bar{q} \rightarrow \gamma\gamma$. In addition, non-direct prompt photons are produced by higher-order processes, like parton fragmentation or Bremsstrahlung. Requiring the photons to be “isolated” allows suppression of the contributions not only from fragmentation and Bremsstrahlung photons [54] but also from photons originating from hadron decays, as these photon sources are commonly accompanied by other parton fragments. The isolation criterion requires that the sum of the transverse momenta of the produced particles (p_T^{iso}) in a cone with angular radius R around the photon direction is smaller than a given threshold value. The advantage of this selection is that it can be applied in both experimental measurements and theoretical calculations.

This paper presents the isolated-prompt γ -hadron correlations measured in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by the ALICE Collaboration, using data samples collected in the years 2015 and 2018. The trigger particles are isolated-

photon candidates in a pseudorapidity (η) range $|\eta^\gamma| < 0.67$ and a p_T range of $18 < p_T^\gamma < 40$ GeV/c, that were selected with an isolation cone radius $R = 0.2$ and isolation momentum threshold $p_T^{\text{iso, ch}} = 1.5$ GeV/c using only charged particles in the cone. The associated charged particles are measured with $p_T^h > 1.8$ GeV/c and $|\eta^h| < 0.9$. The isolated-photon identification and event selections are the same as in the isolated-prompt photon p_T -differential spectra measurement presented in Ref. [45].

The correlation procedure followed is close to the one presented for the measurement in pp and p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV in Ref. [53]. In this article, the $D(z_T)$ distribution obtained for hadrons emitted opposite to the photon, at azimuthal angle with respect to the photon of $3/5\pi < |\Delta\phi| = \phi^\gamma - \phi^h < \pi$ rad, is presented. To observe the modification of hadron fragmentation due to jet quenching, a baseline free of nuclear effects is needed. In this measurement, theoretical next-to-leading-order (NLO) pQCD calculations without jet quenching are used. Additionally, the data are confronted with theoretical models that include energy loss. The ratios of the $D(z_T)$ distribution to the NLO pQCD calculation without energy loss are compared to the ratios of the $D(z_T)$ in AA over pp collisions, both calculated with theory models including energy loss or measured in different RHIC and LHC experiments.

This paper is divided into the following sections: Sect. 2 briefly presents the detector setup and the data sample used for the analysis; Sect. 3 describes the photon selection procedure; Sect. 4 presents the azimuthal correlation and $D(z_T)$ measurements and corrections. The systematic uncertainties are presented in Sect. 5, and the final results and conclusions are presented in Sects. 6 and 7, respectively. Additional figures giving more details on this analysis are available in Ref. [55].

2 Detector and event selection

The ALICE experiment and its performance during the LHC Run 2 (2015–2018) are described in Refs. [56,57]. Photon reconstruction was performed using the Electromagnetic Calorimeter (EMCal) [58], which covers $\Delta\phi < 173^\circ$ and $|\eta| < 0.7$, while charged particles used in the photon isolation and azimuthal correlation were reconstructed with the combination of the Inner Tracking System (ITS) [59] and the Time Projection Chamber (TPC) [60], with a combined coverage of $|\eta| < 0.9$ and full azimuthal angle. The forward scintillator arrays (V0) [61] and zero degree calorimeters (ZDC) [57] were used for online triggering, and for event selection and characterisation. For a brief description of the detector’s setup, see Ref. [45].

The data were taken with a minimum bias (MB) interaction trigger and EMCal Level-1 photon-dedicated triggers

(L1- γ). The MB trigger is defined as a coincidence between the V0A and the V0C (forward and backwards V0 detectors) trigger signals. In the 2015 Pb–Pb sample, the MB triggered data were taken so that the centrality distribution was uniform, but for the 2018 data sample, the 0–10% and 30–50% centrality classes were enhanced with dedicated V0 triggers. Events above 90% centrality are excluded, since there are substantial contributions from electromagnetic processes, and their low multiplicity results in an inefficient trigger. The L1- γ triggers are based on energy depositions in 4×4 calorimeter cells larger than 10 GeV in Pb–Pb for the year 2015. For the 2018 Pb–Pb collisions, the threshold has been set at 10 GeV for the 50% more central collisions, and at 5 GeV for the other centrality classes. A detailed description of the L1- γ triggers can be found in Ref. [58].

An offline event selection based on the V0 timing information is applied to remove beam-induced background events [62]. In addition, further beam-background reduction is obtained in Pb–Pb collisions using the information from two ZDCs positioned at 112.5 m on either side of the nominal interaction point. In particular, a selection is applied to the correlation between the sum and the difference of times measured in each of the ZDCs [57]. Finally, only events with a primary vertex along the beam direction within ± 10 cm from the centre of the apparatus are considered in this analysis, to grant a uniform acceptance in η .

The measurement presented here is performed in three Pb–Pb collision centrality classes: 0–30%, 30–50%, and 50–90%. The integrated luminosity used for each centrality class are $7767 \pm 75 \text{ nb}^{-1}$, $1325 \pm 21 \text{ nb}^{-1}$ and $378 \pm 8 \text{ nb}^{-1}$, respectively, the same as in Refs. [45,46].

3 Isolated-photon reconstruction and selection

Isolated-prompt photons are reconstructed via the following steps: (a) reconstruction of clusters of cells in the calorimeter and of tracks with the ITS and the TPC; (b) photon identification via charged-particle vetoing using track–cluster matching and via the cell-energy spread (shower shape); and (c) selection of isolated-photon candidates. This section briefly describes the selection procedure, however, all details can be found in Refs. [45,46], where the same data samples are used, and the same selections are applied.

In the EMCal, made of independent readout channels called “cells”, particles deposit their energy in several adjacent cells. Each such fragmented energy deposit is grouped into a cluster by a clusterisation algorithm. Various versions of these algorithms, together with the detector calibration procedure and corrections, are described in detail in Ref. [58]. While single photons create almost round clusters, other clusters can have a wider, elongated shape; for example, when several particles deposit their energy nearby

in the detector, or when electrons hit the EMCal at a pronounced angle. The most frequent cases are neutral-meson decays into two photons, which are reconstructed as a single cluster when the angular distance between both photons is such that their electromagnetic showers overlap partially. Merged and single-photon clusters can be discriminated by the “shower shape” variable $\sigma_{\text{long}, 5 \times 5}^2$, which is derived from the largest eigenvalue of the cluster cell spatial distribution in the $\eta - \varphi$ plane [58] restricted to 5×5 cells centred in the cluster highest-energy cell [45,46]. In this article, “photon candidates” refer to clusters with a “narrow” circular shape, i.e., a small shower shape value ($0.1 < \sigma_{\text{long}, 5 \times 5}^2 < 0.3$), while “ π^0 candidates”, which are used to estimate the background in the signal region, refer to clusters with a “wide” elliptic shape ($0.4 < \sigma_{\text{long}, 5 \times 5}^2 < 1$). For more details and discussion, see Refs. [45,46].

An isolation criterion is applied to the photon candidate to suppress the contribution by fragmentation and neutral-meson decay photon production. In this measurement, this is based on the so-called “isolation momentum”, $p_{\text{T}}^{\text{iso, ch}} = \sum p_{\text{T}}^{\text{h}} - \pi \times R^2 \times \rho_{\text{UE}}$, i.e. the sum of the transverse momenta of all charged particles (p_{T}^{h}), inside a cone of radius $R < \sqrt{(\eta^{\text{h}} - \eta^{\gamma})^2 + (\varphi^{\text{h}} - \varphi^{\gamma})^2}$ around the photon candidate, located at coordinates η^{γ} and φ^{γ} in the angular space, and where η^{h} and φ^{h} are the coordinates of the measured charged particles. The isolation momentum is corrected by the contribution of the underlying-event (UE) momentum density (ρ_{UE}), estimated in a rectangular band around and excluding the isolation cone covering $|\Delta\eta^{\text{h}}| < 0.9$ and $\Delta\varphi^{\text{h}} = 2(R+0.1)$ rad (details can be found in Refs. [45,46]). Typically, a value of $R < 0.4$ is used in pp and p–Pb collisions [53,63–65], but the smaller value $R = 0.2$ was chosen for this measurement to reach purity and efficiency values as large as possible in central Pb–Pb collisions, given the large underlying-event contribution in the cone [45,46]. The purity is indeed higher in central collisions for $R = 0.2$ than for $R = 0.4$ since the underlying-event fluctuations are significantly smaller and thus less background is accepted as isolated. Accepted tracks in the cone are required to satisfy $|\eta^{\text{h}}| < 0.9$ and $p_{\text{T}}^{\text{h}} > 0.15 \text{ GeV}/c$. The track definition is given in Refs. [46,64], and is the same as that used for the hadron correlation in the next section. The candidate photon is declared isolated if $p_{\text{T}}^{\text{iso, ch}} < 1.5 \text{ GeV}/c$.

Although selections were applied, the isolated-photon candidate sample still contains a sizeable contribution from background clusters, mainly from neutral-meson decay photons. The sample purity is estimated by a procedure known as the “ABCD method” [45,63–70], which uses double ratios between four different classes of measured clusters (wide and narrow, isolated and non-isolated) and a Monte Carlo-based factor to correct the correlation between the four classes. The obtained purity ranges from 0.5 in the least central class to 0.65 in the most central class [45,55].

4 Azimuthal correlation

The azimuthal correlation distribution is constructed using isolated-photon candidate triggers with a momentum in the range $18 < p_T^{\text{trig}} < 40$ GeV/c, and a pseudorapidity $|\eta^{\text{trig}}| < 0.67$. They are associated with charged particles, i.e. tracks measured by the TPC and ITS, that are selected with a transverse momentum $p_T^h > 1.8$ GeV/c and $|\eta^h| < 0.9$. The choice of the lower p_T^{trig} and p_T^h limits are driven by the large collision underlying event, preventing a clear signal observation in the lowest z_T intervals.

The raw conditional yield of hadrons with respect to the trigger is written as $S(\Delta\eta, |\Delta\phi|) = \frac{1}{N^{\text{trig}}} \frac{d^2 N^h(\Delta\eta, |\Delta\phi|)}{d\Delta\eta d|\Delta\phi|}$, where $\Delta\eta = \eta^{\text{trig}} - \eta^h$, $|\Delta\phi| = \phi^{\text{trig}} - \phi^h$ (the absolute value indicates that the distribution is mirrored for $\Delta\phi > \pi$ rad and $\Delta\phi < 0$ rad to reduce the statistical uncertainties), N^{trig} is the number of trigger particles, and N^h is the number of associated hadrons.

The analysis strategy consists of four main steps to obtain the isolated-prompt photon $D(z_T)$ distribution using azimuthal correlations to associated tracks triggered by high- p_T isolated-narrow (prompt- γ signal + π^0 background) and isolated-wide (π^0) clusters:

1. estimation and subtraction of the underlying-event contribution from $S(\Delta\eta, |\Delta\phi|)$ in the collision;
2. estimation and subtraction of the background contribution in the trigger sample, primarily due to π^0 decays;
3. for each z_T interval, integration of the resulting azimuthal distribution in the $|\Delta\phi|$ range opposite to the trigger-particle direction;
4. correction for the track-reconstruction efficiency.

The particles originating from the collision's underlying event are uncorrelated to the hard process which produces the trigger particles considered in this measurement. The underlying-event contribution to the azimuthal correlation conditional yield is therefore estimated by correlating trigger clusters with tracks from other collisions with similar characteristics. A pool of such collisions, called the “mixed-event sample”, is filled for different intervals of: centrality, in steps of 10% between 0 and 90%; reaction plane angle [71], in steps of $\pi/4$ between 0 and π rad; and z -vertex position, within intervals of 2 cm between +10 cm and −10 cm. The resulting distributions, $M(\Delta\eta, |\Delta\phi|)$, which are obtained similarly to $S(\Delta\eta, |\Delta\phi|)$ but normalised by the total number of mixed events per candidate trigger used, are then subtracted from the same-event distributions, $C(\Delta\eta, |\Delta\phi|) = S(\Delta\eta, |\Delta\phi|) - M(\Delta\eta, |\Delta\phi|)$.

Figure 1 shows the raw azimuthal yield of hadrons associated with isolated-narrow cluster triggers, for semicentral Pb–Pb collisions in a given p_T^γ and z_T interval. Distributions

for the same p_T^{trig} interval but for different centrality and z_T intervals, can be found in Ref. [55]. The mixed- and same-event distributions are similar to each other in the angular region perpendicular to the trigger direction ($|\Delta\phi| \sim \pi/2$), which indeed is expected to be dominated by the underlying event. The hard-process contribution is visible as a peak due to the recoiling jet, located on the side opposite to the trigger ($|\Delta\phi| = \pi$ rad), but the background contamination in the photon candidate sample also generates a peak on the trigger side ($|\Delta\phi| = 0$ rad).

Photons from π^0 decays represent the largest fraction of the contamination in the C_{narrow} distribution, the rest comes mainly from η meson decays. η and π^0 triggers at the p_T range covered by this measurement, significantly larger than their masses, present C distributions that agree in PYTHIA 8 simulations. The C_{wide} is almost entirely triggered by π^0 decays. Therefore, assuming that photon clusters from neutral meson decays with narrow or wide shapes have the same azimuthal correlation distribution, the isolated-prompt γ –hadron azimuthal correlation is calculated by $C_{\gamma\text{iso}}(\Delta\eta, |\Delta\phi|) = \frac{1}{P} \times C_{\text{narrow}}(\Delta\eta, |\Delta\phi|) - \frac{1-P}{P} \times C_{\text{wide}}(\Delta\eta, |\Delta\phi|)$, where P is the purity presented in the previous section that ranges from 0.5 to 0.65 from the least to the most central class [55]. At the p_T^{trig} interval of this measurement, background clusters, narrow and wide, are mostly those containing two photons from the meson decay. The results of this procedure are shown in Fig. 2 for semicentral Pb–Pb collisions. Figures for the same p_T^{trig} interval but for different centrality and z_T intervals can be found in Ref. [55]. The values of the correlation functions for narrow and wide trigger clusters are very close, resulting in a significant statistical uncertainty in the measurement.

The $D(z_T)$ distribution is obtained by integrating the points above $3\pi/5$, and correcting for geometrical acceptance, detector inefficiencies and resolution, inactive detector areas, and underlying-event subtraction effects. In order to obtain the correction factor, the detector response is modelled by Monte Carlo simulations reproducing the detector conditions during the data-taking periods. The corrections are obtained using PYTHIA 8 (version 8.210 [72] with the Monash 2013 tune [73]) as a particle generator, creating pp collisions in intervals of transverse momentum of the hard scattering with a prompt photon and a jet (γ –jet) calculated at LO in the final state. The transport of the generated particles in the detector material is performed using GEANT3 [74]. Each simulated pp collision is embedded into a real Pb–Pb minimum-bias triggered event selected within the different centrality classes considered, so that the effect of the low-energy particles from the underlying event is properly taken into account. For the calorimeter clusters, the embedding is performed at the cell level by summing the cell energy of the data and of the simulation. For the charged particles,

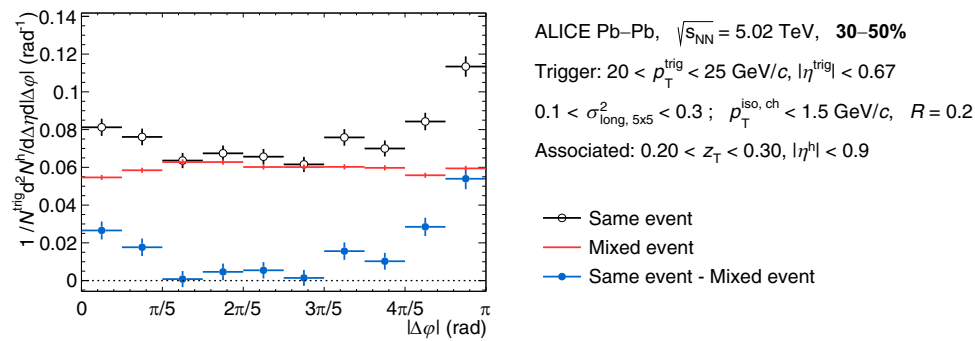


Fig. 1 Azimuthal correlation distributions in the 30–50% centrality class of Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and for the interval $0.20 < z_T < 0.30$, for isolated-narrow clusters triggered in the range $20 < p_T^{\text{trig}} < 25$ GeV/c, with charged-particle tracks in the

same collision (“Same event”, black-open circles) or in a different collision (“Mixed event”, red without marker). The result of subtracting the mixed-event distribution is shown in blue-full circles. The vertical bars indicate the statistical uncertainties

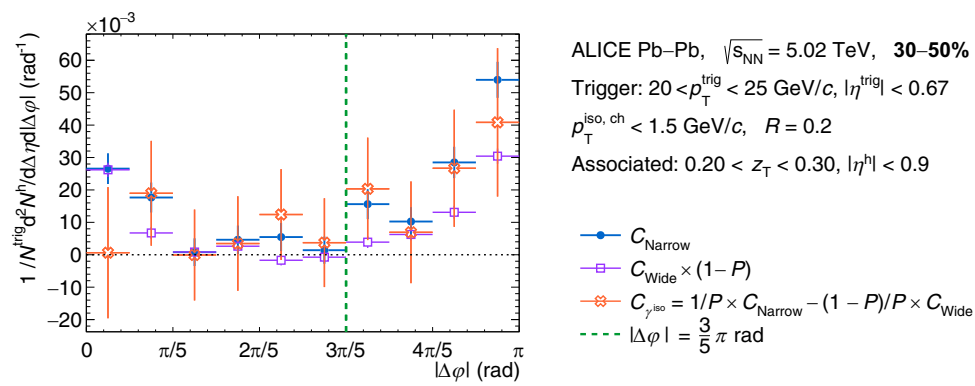


Fig. 2 Azimuthal correlation distributions in the 30–50% centrality class of Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the intervals $0.20 < z_T < 0.30$ and $20 < p_T^{\text{trig}} < 25$ GeV/c. Each marker corresponds to a different trigger: isolated-narrow clusters (blue-full circles), also shown in Fig. 1; isolated-wide clusters (violet-open squares), scaled

by $1 - P$, where P is the purity; isolated-photon triggers (orange-empty crosses), calculated using the equation in the text. The vertical bars indicate the statistical uncertainties. The dashed-green line at $|\Delta\phi| = 3/5\pi$ indicates the lower limit of the integration used in the $D(z_T)$ calculation

the embedding is done at the track level, adding the tracks coming from the data to the list of available tracks from the simulation. The $D(z_T)$ function from the γ -jet simulation is obtained in the same way as in data. The correction factor is calculated as the ratio of the $D(z_T)$ values for generated tracks and reconstructed tracks, which is almost constant for all centralities for $z_T > 0.2$ and is approximately 1.2. For smaller z_T , the correction factor decreases below unity for semicentral and peripheral collisions, but increases for the most central collisions up to a value of almost three (more details in Ref. [55]). This article reports in Sect. 6 the correlation for central collisions in the centrality class 0–30%, which was obtained by adding the corrected conditional yields of the centrality classes 0–10% and 10–30%, weighted by the number of triggers in each class.

5 Systematic uncertainties

The considered sources of systematic uncertainty are the isolated-photon purity, the shower-shape selection for wide clusters, the tracking efficiency, the centrality intervals chosen to fill the mixed-event pool, and the mixed-event underlying-event estimation. The values of the systematic uncertainties for the different sources and the total systematic uncertainty are summarised in Table 1 for two z_T intervals.

The total uncertainty assigned to the purity correction, σ_P , reported in Ref. [45, 46] is used to vary the purity value $\pm\sigma_P$, resulting in an uncertainty with a z_T dependence, from low to high z_T : from 6 to 20% in central collisions, from 3 to 11% in semicentral collisions, and from 5 to 16% in peripheral collisions. Semicentral collisions have a lower uncertainty than peripheral collisions due to the higher purity and lower systematic uncertainty.

Table 1 Summary of uncorrelated relative systematic uncertainties in per cent for two selected high- and low- z_T intervals: $0.10 < z_T < 0.15$ and $0.40 < z_T < 0.60$

	0–30%		30–50%		50–90%	
	Low z_T	High z_T	Low z_T	High z_T	Low z_T	High z_T
Photon purity	6.4%	20.3%	2.7%	11.6%	5.5%	16.6%
$\sigma_{\text{long}, 5 \times 5}^2$	7.9%	7.9%	5.8%	5.8%	5.6%	5.6%
Underlying event	8.8%	5.9%	7.2%	4.5%	8%	5.9%
Mixed-event pool	6.1%	6.1%	4.7%	4.7%	3.9%	3.9%
Tracking efficiency	5.3%	1.7%	4.1%	1.8%	4.4%	1.6%
Total	15.7%	23.5%	11.5%	14.6%	12.7%	18.9%

The uncertainty due to the choice of the background wide-cluster $\sigma_{\text{long}, 5 \times 5}^2$ range is investigated by comparing the results obtained for various $\sigma_{\text{long}, 5 \times 5}^2$ selections: $0.35 < \sigma_{\text{long}, 5 \times 5}^2 < 1.0$, $0.5 < \sigma_{\text{long}, 5 \times 5}^2 < 1.0$, and $0.4 < \sigma_{\text{long}, 5 \times 5}^2 < 0.8$. The resulting uncertainty is z_T -independent and changes from 6% in central collisions to 4% in peripheral collisions.

To estimate the effect of the tracking efficiency on the measurement, a fraction of randomly chosen tracks is removed. This fraction is defined by the tracking efficiency uncertainty due to the matching of the ITS-TPC tracks, which varies with track p_T : for central collisions, it is about 3.6% at low p_T (below 1 GeV/c), decreasing to about 2% for larger momenta; for semicentral and peripheral collisions, it has a similar magnitude and track- p_T dependence, but is lower by less than 0.5%.

The effect of the centrality ranges used in the mixed-event pool is checked by selecting intervals two times smaller for the centrality (5% instead of 10%): the uncertainty, z_T -independent, is 6% in central and 4% in peripheral collisions. For the z -vertex and reaction-plane angle, the effect of using finer intervals was found to be negligible.

Finally, an uncertainty is assigned to the hypothesis that the mixed-event method could not fully capture the underlying event. Assuming that the $C_{\gamma^{\text{iso}}}$ and C_{wide} distributions must be flat and sit at zero in the region $1 < \Delta\varphi < \pi/2$, the relative systematic uncertainty is calculated as $\frac{B/2}{I-B/2}$, where $I = \int N^h(\Delta\varphi)d\Delta\varphi$ is the integral of the $3\pi/5 < \Delta\varphi < \pi$ signal region, and $B = \int C_{\text{fit}}d\Delta\varphi$ is the integral of the constant fit value C_{fit} in $1 < \Delta\varphi < \pi/2$ of the C_{wide} distribution ($C_{\gamma^{\text{iso}}}$ has large statistical fluctuations and it is not expected to be different). This uncertainty decreases from lowest- to highest- z_T interval from 8.8 to 6% in central collisions, from 7.3 to 4.5% in semicentral collisions, and from 8 to 6% in peripheral collisions.

The total systematic uncertainty is obtained by adding in quadrature the contributions from all the sources. It ranges from 15.7 to 23.5% (from low to high z_T) for central collisions, 9.6 to 14.6% (minimum at mid z_T and maximum at

high z_T) for semicentral collisions, and 12.7 to 18.9% (from low to high z_T) for peripheral collisions. Among the systematic uncertainty sources, the mixed-event subtraction source dominates in the first z_T intervals, where the other sources contribute at the level of 3 to 6%; only starting from z_T larger than 0.35, the purity uncertainty source dominates. The statistical uncertainty dominates the systematic one over the whole z_T range in all the Pb–Pb collision centrality classes. It ranges between 20 and 40% for most of the points.

For the ratio of the measurement in central or semicentral to peripheral collisions, the uncertainty due to the tracking efficiency and the effect of the centrality ranges in the mixed-event pool fully cancels out, and the others partially, except the uncertainty on the mixed-event underlying-event removal, which is fully propagated and dominates. The total systematic uncertainty ranges from 14 to 16% in central over peripheral collisions, and from 13 to 14% in semicentral over peripheral collisions.

6 Results

This section presents the main results of the isolated-prompt photon–hadron correlation measurement. The isolated-photon trigger is measured in a transverse-momentum range of $18 < p_T^\gamma < 40$ GeV/c at midrapidity ($|\eta^\gamma| < 0.67$), with a charged-particle isolation-momentum threshold of $p_T^{\text{iso, ch}} = 1.5$ GeV/c in a cone of radius $R = 0.2$ around the photon candidate. The associated charged particles are measured with $p_T^h > 1.8$ GeV/c and $|\eta^h| < 0.9$. The $D(z_T)$ distribution is extracted after subtracting the underlying-event and decay-photon contribution, by integrating the azimuthal angle region $|\Delta\varphi| > 3\pi/5$. Figure 3 shows the measured $D(z_T)$ distributions in three Pb–Pb collision centrality classes: 0–30%, 30–50%, and 50–90%.

The results are compared with NLO pQCD calculations including energy loss in the QGP [75, 76] (“NLO pQCD+ ΔE_{loss} ”). They include jet energy loss controlled by the in-medium energy-loss density $\hat{q}$ and medium temperature T , and calculated by the Higher-Twist formalism

[77] with energy loss given by $\hat{q}/T^3$, extracted from single hadron p_T spectrum, di-hadron, and direct γ -hadron correlation data at different $\sqrt{s_{NN}}$ energies (0.2, 2.76, and 5.02 TeV) by the IF-Bayesian analysis [78–80]. The model obtains the parton-parton hard scattering cross sections by perturbation calculation and convolves them with the CT18A parton density functions [81] and Kniehl–Kramer–Potter fragmentation functions [82]. The NLO pQCD calculations include fragmentation photons, which are reduced by applying the same isolation method. The calculated uncertainty is based on the extrapolated $\hat{q}/T^3$ energy loss at the 95% confidence level.

The results in central and semicentral collisions are also compared with the “Coupled Linear Boltzmann Transport and hydrodynamics” model [83] (“CoLBT-hydro”). The CoLBT-hydro model is developed for event-by-event simulations of jet transport and jet-induced medium excitation in high-energy heavy-ion collisions by a (3+1)D hydrodynamics that has a source term from energy-momentum deposition by propagating jet shower partons [83]. In the CoLBT-hydro model, the interactions are again driven by $\hat{q}$, but its value is extracted mainly from a single jet and isolated γ -jet correlation measurements in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The calculation uncertainty is derived from the $\hat{q}$ estimation uncertainty.

Both models use the same centrality classes and kinematical selection criteria for the trigger and associated charged particles as those used in the data. An agreement is observed between the data and both theoretical predictions. The discrimination between the two models is not yet possible due to current uncertainties. Figure 3 also displays the $D(z_T)$ distribution obtained from NLO pQCD simulations of pp collisions, without energy loss. The uncertainty in the calculations is estimated by varying the factorisation scale μ of the fragmentation functions: $0.7p_T^\gamma$, $1.2p_T^\gamma$ (centre value), and $2p_T^\gamma$. The measured $D(z_T)$ distributions are suppressed compared to the NLO pQCD calculations for pp collisions for central and semicentral Pb–Pb collisions, reflecting the high- p_T hadron suppression in the presence of the QGP.

To better illustrate the modification, the ratio of the $D(z_T)$ distributions in AA to pp collisions, the $I_{AA} = \frac{D(z_T)_{AA}}{D(z_T)_{pp}}$, is calculated in per-trigger yield measurements. The $D(z_T)$ distribution for isolated γ -hadron correlations has been measured by the ALICE Collaboration in pp collisions at $\sqrt{s} = 5.02$ TeV [53], but with a different p_T^γ range ($12 < p_T^\gamma < 40$ GeV/c). Due to the large amount of underlying events present in the Pb–Pb collisions, it is not possible to go as low in p_T^γ as in the pp collisions measurement. On the other hand, a reanalysis of the pp collisions data using a higher p_T^γ threshold is not accessible due to the statistical limitations on that sample. For these reasons, the NLO pQCD calculations (no energy loss, no cold nuclear matter effects) are used as a pp collisions reference, which have been shown to

describe the pp collisions data well. In Ref. [55], a comparison between the published pp results and this pQCD calculation, performed over a different p_T^γ interval, is presented. The results are found to be consistent with the calculation, taking into account the expected 5–10% deviation in PYTHIA 8 arising from the difference in the p_T^γ interval. Therefore, the NLO pQCD calculations are used in this measurement as a proxy of the I_{AA} denominator, by using the ratio $I_{pQCD} = \frac{D(z_T)_{AA}}{D(z_T)_{pQCD pp}}$, which is shown in Fig. 4.

Excluding the first z_T interval, a clear difference can be seen in central collision data with respect to the NLO pQCD calculation for pp collisions: the ratio is around 0.5, and moves closer to unity when more peripheral collisions are analysed, as expected for a quenching in the QGP. The I_{AA} calculations from the presented theoretical models, which include energy loss, agree with the measurements in all three centrality classes. In the lowest- z_T interval, the I_{pQCD} ratio tends to be higher than at larger z_T , for all three centrality classes, which is expected for central collisions. The I_{pQCD} is also compared to an NLO pQCD I_{AA} prediction that only includes cold nuclear matter effects (CNM) and no energy loss by using EPPS21 nuclear parton distribution functions (nPDFs) [84]. Uncertainties related to the nPDFs are given at 90% confidence level and were obtained by performing the calculations for each of the 107 eigenvector sets of EPPS21, resulting in uncertainties of the order of 20%. The uncertainty relative to the factorisation scale μ is also shown, and it largely cancels out in the ratio with values around 1.5%. This I_{AA} prediction is provided without centrality dependence. The calculation is close to unity and cannot reproduce the observed magnitude of the suppression observed in central Pb–Pb collisions, unlike the other models that include energy loss.

Another interesting ratio is the I_{CP} defined as the ratio between the $D(z_T)$ distributions in central or semicentral collisions over the peripheral ones, $I_{CP} = \frac{D(z_T)_{0-30\%, 30-50\%}}{D(z_T)_{50-90\%}}$. Figure 5 shows the measured I_{CP} as a function of z_T for central and semicentral centralities. Statistical uncertainties also dominate the results, but the expected dependence of the suppression on centrality is well visible. The distributions are rather flat and, on average, of the order of 0.5 and 0.75, respectively. The results are compared to the equivalent theory ratio calculated using the NLO pQCD+ ΔE_{loss} model, showing agreement.

In Figs. 6 and 7, these I_{pQCD} results are compared with other equivalent I_{AA} measurements: respectively isolated γ -jet [49] and Z^0 -hadron [52] correlations in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at the LHC by the CMS Collaboration; and direct γ -hadron correlations obtained by the STAR [47] and PHENIX [48] Collaborations in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC.

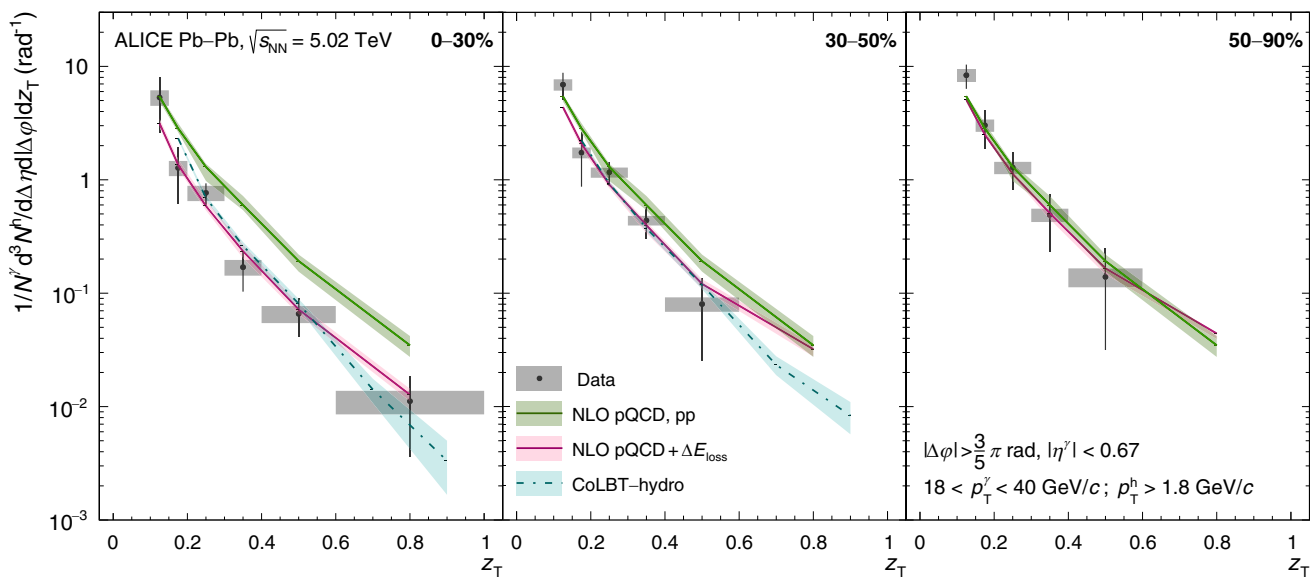


Fig. 3 $D(z_T)$ distributions for isolated-prompt photon-hadron correlations measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for three centrality classes: 0–30% (left), 30–50% (middle), and 50–90% (right). The boxes and vertical lines represent the systematic and statistical uncertainties, respectively. Different theory predictions are shown: an

NLO pQCD calculation including energy loss [75,76] (pink line and uncertainty band), and from CoLBT-hydro [83] (cyan-dashed line and uncertainty band). Also, an NLO pQCD prediction for pp collisions at $\sqrt{s} = 5.02$ TeV is shown (green line and uncertainty band)

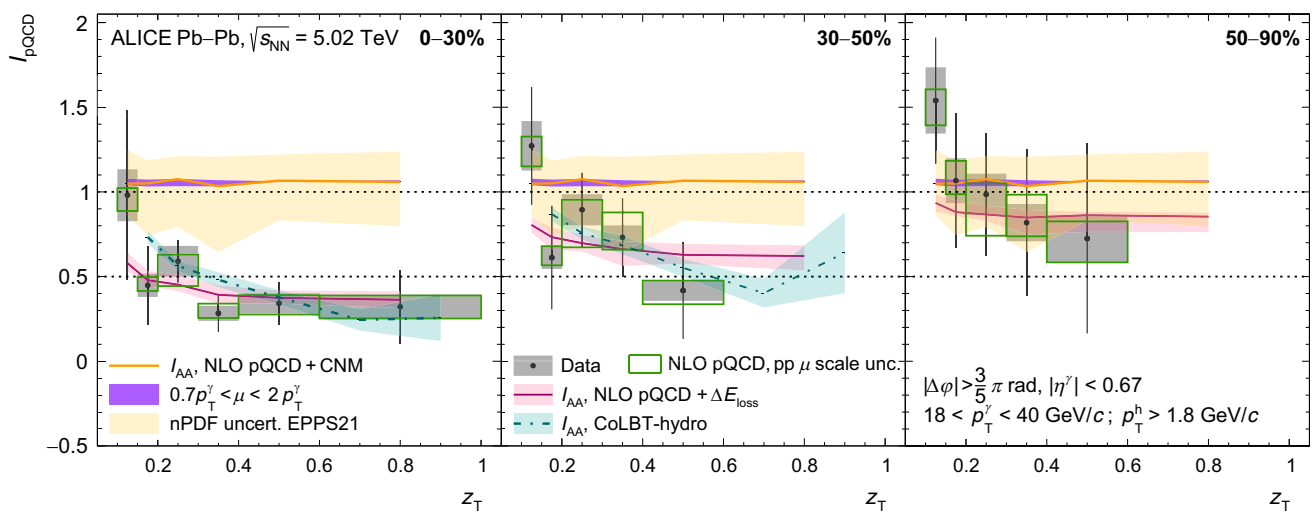


Fig. 4 Ratio of the measured $D(z_T)$ distributions in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV to the NLO pQCD predictions for pp collisions at $\sqrt{s} = 5.02$ TeV, I_{pQCD} , all distributions in the denominator and numerator are shown in Fig. 3. Each panel shows a different centrality class: 0–30% (left), 30–50% (middle), and 50–90% (right). The grey-filled boxes and vertical-black lines represent the data systematic and statistical uncertainties, respectively. The green-open boxes represent the μ scale uncertainty for the denominator NLO pQCD calculation for

pp collisions. Different theory predictions for the I_{AA} , which include energy loss, are shown: an NLO pQCD calculation [75,76] (pink line and uncertainty band), and from a CoLBT-hydro calculation [83] (cyan-dashed line and uncertainty band, not for peripheral collisions). Also, an NLO pQCD prediction, which includes CNM effects only (no energy loss, no centrality dependence), is reported (light orange line and uncertainty bands)

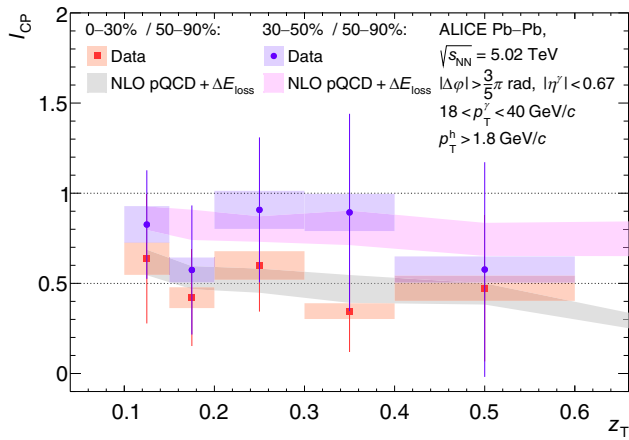


Fig. 5 I_{CP} ratio of the $D(z_T)$ distributions for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in Fig. 3 for data: 0–30% over 50–90% (red squares), and 30–50% over 50–90% (violet bullets). The boxes represent the systematic uncertainties, while the vertical bars indicate the statistical uncertainties. Also, the equivalent ratios from the NLO pQCD calculation for Pb–Pb collisions, including energy loss, are shown as a band indicating the theory uncertainty

Since the p_T and rapidity ranges of the trigger and associated hadrons, and the centrality ranges used by ALICE and the other experiments are not the same (see Figs. 6 and 7 for details), and ALICE uses a theoretical pp reference, they can only be compared qualitatively. The ALICE Collaboration has lower p_T^γ than the CMS Collaboration measurements (18 to 40 GeV/c compared to p_T^γ above 60 GeV/c or p_T^Z above 30 GeV/c). The three distributions are compatible in the common z_T ranges. At low z_T (below 0.15), the CMS isolated γ –jet and Z^0 –hadron correlations can probe the enhancement of the low- p_T hadrons. Overall, the comparison hints at a better agreement between the ALICE and CMS Z^0 –hadron correlation since they have the same centrality range and closer trigger p_T .

The STAR experiment also reports a similar I_{AA} measurement, although in a lower p_T^γ region (12 to 20 GeV/c) and in more central collisions than ALICE. Their results are compatible and overlap in the common z_T range, but the PHENIX I_{AA} differs significantly below $z_T = 0.45$. The higher z_T yield reported by the PHENIX Collaboration can be explained by the lower p_T^γ : the lower energy-associated partons lose more energy relatively. Also, the measurement could be more sensitive to the enhancement of soft hadrons: the lowest p_T^h at $z_T = 0.1$ is 0.5 GeV/c for PHENIX, while it is 1.2 and 1.8 GeV/c for STAR and ALICE, respectively. Also, the higher z_T yield reported by the PHENIX Collaboration can reflect the higher relative energy loss of the lower energy of the associated partons. Despite the differences in the various measurements, the trends and magnitudes of the I_{AA} and the I_{pQCD} ratios in the common z_T ranges measured

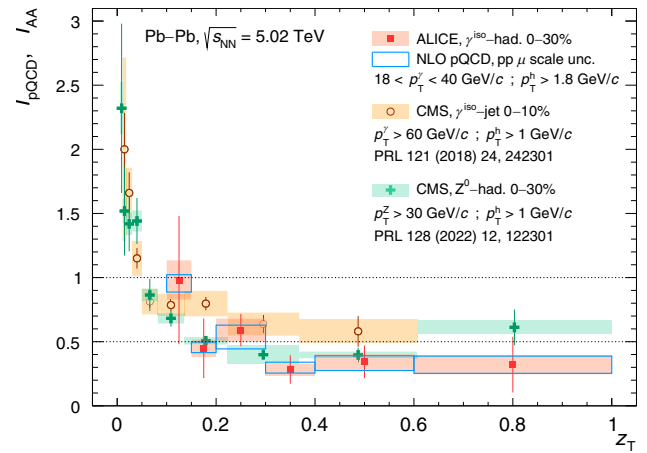


Fig. 6 I_{pQCD} for central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured in ALICE for isolated-prompt γ –hadron correlations, and I_{AA} measured in CMS for isolated-prompt γ –jet correlations [49] and Z^0 –hadron correlations [52] also in central collisions. The boxes and vertical lines represent the systematic and statistical uncertainties, respectively. For ALICE, the blue-open boxes represent the μ scale uncertainty for the denominator NLO pQCD calculation for pp collisions

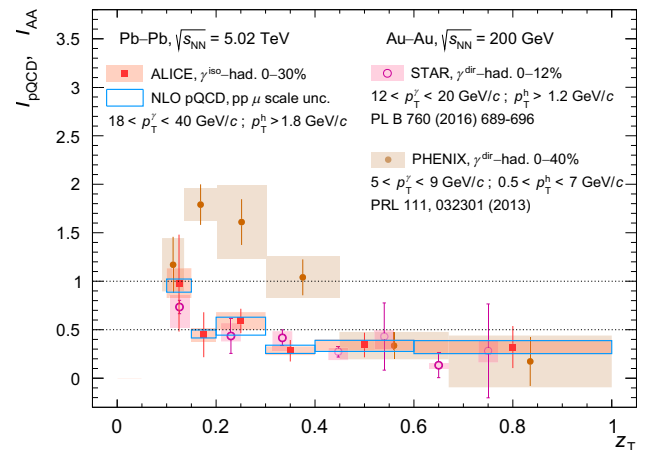


Fig. 7 Isolated-prompt γ –hadron correlations I_{pQCD} for central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured by the ALICE Collaboration, and I_{AA} for central Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured by the PHENIX [48] and STAR [47] Collaborations at RHIC, also in central collisions. The boxes represent the systematic uncertainties, while the vertical bars indicate the statistical uncertainties. For ALICE, the blue-open boxes represent the μ scale uncertainty for the denominator NLO pQCD calculation for pp collisions

at LHC and RHIC are similar, except for PHENIX due to the low trigger momentum.

7 Conclusions

The isolated-prompt photon–hadron correlation in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV was measured by the ALICE experiment for different centrality classes, in the transverse-momentum and pseudorapidity ranges $18 < p_T^\gamma < 40$ GeV/c

and $|\eta^\gamma| < 0.67$ for the photon triggers, and $p_T^h > 1.8$ GeV/c and $|\eta^h| < 0.9$ for the associated charged particles. The measured $D(z_T)$ conditional yields show an agreement with NLO pQCD+ ΔE_{loss} and ColBT-hydro calculations that both include energy-loss mechanisms. The I_{pQCD} ratio, approximately equivalent to the I_{AA} , replacing the reference measured in pp collisions data with an NLO pQCD calculation without energy loss (in agreement with $D(z_T)$ measurements in pp collisions at lower p_T^γ), shows a strong suppression in central collisions and less suppression in semicentral collisions. The uncertainties do not allow declaring that a suppression is also visible in peripheral collisions. In all three centrality intervals, the models including jet quenching agree with the data. At the same time, NLO pQCD calculations, which include only cold-nuclear-matter effects, fail to reproduce the measured I_{pQCD} ratio for central Pb–Pb collisions. The I_{CP} ratio shows a decrease in $D(z_T)$ when going from peripheral to more central collisions, and also agrees with NLO pQCD+ ΔE_{loss} calculations.

The I_{pQCD} results for central Pb–Pb collisions have been compared with I_{AA} measurements from CMS and STAR Collaborations. Although they use different selection criteria, $\sqrt{s_{\text{NN}}}$, and different pp collisions reference, the trends in the same z_T intervals agree and are consistent with a large suppression of high- p_T hadrons at high z_T in the most central Pb–Pb collisions. The current measurement extends the lower limit of p_T^γ to a lower value compared to previous measurements by other LHC experiments. The results have also been compared with PHENIX Collaboration results, which use a lower trigger and hadron p_T than STAR and ALICE, finding a significantly enhanced soft hadron distribution at low z_T , likely due to the larger relative energy loss of the back-to-back lower-energy partons.

This measurement serves as a benchmark for Run 3 and upcoming Run 4 isolated-prompt photon–hadron correlation analyses in ALICE. With new datasets offering increasingly robust statistical samples, particularly the pp collisions sample at the same centre-of-mass energy, more accurate correlation measurements will be possible, allowing for a more precise investigation of different centrality classes and access to lower and higher p_T^γ values and smaller z_T intervals. The increased statistics will enable differential studies, such as examining correlations in different event-plane angle regions in the Pb–Pb collisions 30–50% centrality class.

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Code Availability Statement This code/software will be made available on reasonable request. [Authors’ comment: This manuscript has associated code/software in a data repository. The code/software used for the analysis is publicly available on the github repository, at the links <https://github.com/alisw/AlRoot> and <https://github.com/alisw/AlPhysics/>].

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References

- ALICE Collaboration, S. Acharya, The ALICE experiment – a journey through QCD. *Eur. Phys. J. C* **84**, 813 (2024). <https://doi.org/10.1140/epjc/s10052-024-12935-y>. [arXiv:2211.04384](https://arxiv.org/abs/2211.04384) [nucl-ex]
- B.V. Jacak, B. Muller, The exploration of hot nuclear matter. *Science* **337**, 310–314 (2012). <https://doi.org/10.1126/science.1215901>
- B. Müller, J. Schukraft, B. Wyslouch, First results from Pb+Pb collisions at the LHC. *Annu. Rev. Nucl. Part. S.* **62**, 361–386 (2012). <https://doi.org/10.1146/annurev-nucl-102711-094910>
- P. Braun-Munzinger, V. Koch, T. Schäfer, J. Stachel, Properties of hot and dense matter from relativistic heavy ion collisions. *Phys. Rep.* **621**, 76–126 (2016). <https://doi.org/10.1016/j.physrep.2015.12.003>. [arXiv:1510.00442](https://arxiv.org/abs/1510.00442)
- W. Busza, K. Rajagopal, W. van der Schee, Heavy ion collisions: the big picture, and the big questions. *Annu. Rev. Nucl. Part. Sci.* **68**, 339–376 (2018). <https://doi.org/10.1146/annurev-nucl-101917-020852>. [arXiv:1802.04801](https://arxiv.org/abs/1802.04801) [hep-ph]
- PHENIX Collaboration, K. Adcox et al., Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: experimental evaluation by the PHENIX Collaboration. *Nucl. Phys. A* **757**, 184–283 (2005). <https://doi.org/10.1016/j.nuclphysa.2005.03.086>. [arXiv:nucl-ex/0410003](https://arxiv.org/abs/nucl-ex/0410003) [nucl-ex]
- STAR Collaboration, J. Adams et al., Experimental and theoretical challenges in the search for the quark-gluon plasma: The STAR Collaboration’s critical assessment of the evidence from RHIC collisions. *Nucl. Phys. A* **757**, 102–183 (2005). <https://doi.org/10.1016/j.nuclphysa.2005.03.085>. [arXiv:nucl-ex/0501009](https://arxiv.org/abs/nucl-ex/0501009) [nucl-ex]
- PHOBOS Collaboration, B. Back et al., The PHOBOS perspective on discoveries at RHIC. *Nucl. Phys. A* **757**, 28–101 (2005). <https://doi.org/10.1016/j.nuclphysa.2005.03.084>. [arXiv:nucl-ex/0410022](https://arxiv.org/abs/nucl-ex/0410022) [nucl-ex]
- BRAHMS Collaboration, I. Arsene et al., Quark–gluon plasma and color glass condensate at RHIC? The perspective from the BRAHMS experiment. *Nucl. Phys. A* **757**, 1–27 (2005). <https://doi.org/10.1016/j.nuclphysa.2005.02.130>. [arXiv:nucl-ex/0410020](https://arxiv.org/abs/nucl-ex/0410020) [nucl-ex]
- M. Djordjevic, Collisional energy loss in a finite size QCD matter. *Phys. Rev. C* **74**, 064907 (2006). <https://doi.org/10.1103/PhysRevC.74.064907>. [arXiv:nucl-th/0603066](https://arxiv.org/abs/nucl-th/0603066)
- B. Ilic, M. Djordjevic, Understanding mass hierarchy in collisional energy loss through heavy flavor data. *Phys. Rev. C* **106**, 014902 (2022). <https://doi.org/10.1103/PhysRevC.106.014902>. [arXiv:2203.06646](https://arxiv.org/abs/2203.06646) [hep-ph]
- J.D. Bjorken, Energy loss of energetic partons in quark-gluon plasma: possible extinction of high p_T jets in hadron-hadron collisions. Fermilab report FERMILAB-PUB-82-059-T, Fermilab report (1982). <https://ss.fnal.gov/archive/1982/pub/Pub-82-059-T.pdf>
- M. Gyulassy, P. Levai, I. Vitev, Jet quenching in thin plasmas. *Nucl. Phys. A* **661**, 637–640 (1999). [https://doi.org/10.1016/S0375-9474\(99\)85106-9](https://doi.org/10.1016/S0375-9474(99)85106-9). [arXiv:hep-ph/9907343](https://arxiv.org/abs/hep-ph/9907343)
- D. d’Enterria, Jet quenching. *Landolt-Bornstein* **23**, 471 (2010). https://doi.org/10.1007/978-3-642-01539-7_16. [arXiv:0902.2011](https://arxiv.org/abs/0902.2011) [nucl-ex]
- S.T.A.R. Collaboration, J. Adams et al., Transverse-momentum and collision-energy dependence of high- p_T hadron suppression in Au+Au collisions at ultrarelativistic energies. *Phys. Rev. Lett.* **91**, 172302 (2003). <https://doi.org/10.1103/physrevlett.91.172302>. [arXiv:nucl-ex/0305015](https://arxiv.org/abs/nucl-ex/0305015) [nucl-ex]
- PHENIX Collaboration, A. Adare et al., Suppression pattern of neutral pions at high transverse momentum in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and constraints on medium transport coefficients. *Phys. Rev. Lett.* **101**, 232301 (2008). <https://doi.org/10.1103/PhysRevLett.101.232301>. [arXiv:0801.4020](https://arxiv.org/abs/0801.4020) [nucl-ex]
- PHENIX Collaboration, A. Adare et al., Neutral pion production with respect to centrality and reaction plane in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. *Phys. Rev. C* **87**, 034911 (2013). <https://doi.org/10.1103/PhysRevC.87.034911>. [arXiv:1208.2254](https://arxiv.org/abs/1208.2254) [nucl-ex]
- ALICE Collaboration, S. Acharya et al., Transverse momentum spectra and nuclear modification factors of charged particles in pp, p–Pb and Pb–Pb collisions at the LHC. *JHEP* **11**, 013 (2018). [https://doi.org/10.1007/JHEP11\(2018\)013](https://doi.org/10.1007/JHEP11(2018)013). [arXiv:1802.09145](https://arxiv.org/abs/1802.09145) [nucl-ex]
- CMS Collaboration, V. Khachatryan et al., Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *JHEP* **04**, 039 (2017). [https://doi.org/10.1007/jhep04\(2017\)039](https://doi.org/10.1007/jhep04(2017)039). [arXiv:1611.01664](https://arxiv.org/abs/1611.01664) [nucl-ex]
- ALICE Collaboration, S. Acharya et al., Production of charged pions, kaons, and (anti-)protons in Pb–Pb and inelastic pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *Phys. Rev. C* **101**, 044907 (2020). <https://doi.org/10.1103/PhysRevC.101.044907>. [arXiv:1910.07678](https://arxiv.org/abs/1910.07678) [nucl-ex]
- ALICE Collaboration, J. Adam et al., Measurement of jet suppression in central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *Phys. Lett. B* **746**, 1–14 (2015). <https://doi.org/10.1016/j.physletb.2015.04.039>. [arXiv:1502.01689](https://arxiv.org/abs/1502.01689) [nucl-ex]
- ALICE Collaboration, S. Acharya et al., Measurements of inclusive jet spectra in pp and central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *Phys. Rev. C* **101**, 034911 (2020). <https://doi.org/10.1103/PhysRevC.101.034911>. [arXiv:1909.09718](https://arxiv.org/abs/1909.09718) [nucl-ex]
- ATLAS Collaboration, M. Aaboud et al., Measurement of the nuclear modification factor for inclusive jets in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector. *Phys. Lett. B* **790**, 108–128 (2019). <https://doi.org/10.1016/j.physletb.2018.10.076>. [arXiv:1805.05635](https://arxiv.org/abs/1805.05635) [nucl-ex]
- CMS Collaboration, V. Khachatryan et al., Measurement of inclusive jet cross sections in pp and PbPb collisions at $\sqrt{s_{NN}} = 2.76$

- TeV. Phys. Rev. C. **96**, 015202 (2017). <https://doi.org/10.1103/PhysRevC.96.015202>. arXiv:1609.05383 [nucl-ex]
25. ATLAS Collaboration, M. Aaboud et al., Measurement of jet fragmentation in Pb+Pb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector. Phys. Rev. C. **98**, 024908 (2018). <https://doi.org/10.1103/PhysRevC.98.024908>. arXiv:1805.05424 [nucl-ex]
 26. CMS Collaboration, S. Chatrchyan et al., Measurement of Jet Fragmentation in PbPb and pp Collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Phys. Rev. C. **90**, 024908 (2014). <https://doi.org/10.1103/PhysRevC.90.024908>. arXiv:1406.0932 [nucl-ex]
 27. S.T.A.R. Collaboration, J. Adams et al., Evidence from d + Au measurements for final state suppression of high p(T) hadrons in Au+Au collisions at RHIC. Phys. Rev. Lett. **91**, 072304 (2003). <https://doi.org/10.1103/PhysRevLett.91.072304>. arXiv:nucl-ex/0306024
 28. ALICE Collaboration, K. Aamodt et al., Particle-yield modification in jet-like azimuthal di-hadron correlations in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Phys. Rev. Lett. **108**, 092301 (2012). <https://doi.org/10.1103/PhysRevLett.108.092301>. arXiv:1110.0121 [nucl-ex]
 29. ALICE Collaboration, J. Adam et al., Jet-like correlations with neutral pion triggers in pp and central Pb–Pb collisions at 2.76 TeV. Phys. Lett. B, **763**, 238–250 (2016). <https://doi.org/10.1016/j.physletb.2016.10.048>. arXiv:1608.07201 [nucl-ex]
 30. F. Arleo, Quenching of photon and pion spectra at intermediate RHIC energy. JHEP **07**, 032 (2007). <https://doi.org/10.1088/1126-6708/2007/07/032>. arXiv:0706.1848 [hep-ph]
 31. ATLAS Collaboration, G. Aad et al., Centrality, rapidity and transverse momentum dependence of isolated prompt photon production in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV measured with the ATLAS detector. Phys. Rev. C. **93**, 034914 (2016). <https://doi.org/10.1103/PhysRevC.93.034914>. arXiv:1506.08552 [hep-ex]
 32. F. Arleo, K.J. Eskola, H. Paukkunen, C.A. Salgado, Inclusive prompt photon production in nuclear collisions at RHIC and LHC. JHEP **04**, 055 (2011). [https://doi.org/10.1007/JHEP04\(2011\)055](https://doi.org/10.1007/JHEP04(2011)055). arXiv:1103.1471 [hep-ph]
 33. B.-W. Zhang, I. Vitev, Direct photon production in d+A and A+A collisions at RHIC. Mod. Phys. Lett. A **24**, 2649–2658 (2009). <https://doi.org/10.1142/s0217732309031971>. arXiv:0810.3194 [nucl-th]
 34. PHENIX Collaboration, S.S. Adler et al., Centrality dependence of direct photon production in $\sqrt{s_{NN}} = 200$ GeV Au + Au collisions. Phys. Rev. Lett. **94**, 232301 (2005). <https://doi.org/10.1103/PhysRevLett.94.232301>. arXiv:nucl-ex/0503003 [nucl-ex]
 35. PHENIX Collaboration, S. Afanasiev et al., Measurement of direct photons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Phys. Rev. Lett. **109**, 152302 (2012). <https://doi.org/10.1103/PhysRevLett.109.152302>. arXiv:1205.5759 [nucl-ex]
 36. ATLAS Collaboration, G. Aad et al., Measurement of $W^\pm$ boson production in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector. Eur. Phys. J. C **79**, 935 (2019). <https://doi.org/10.1140/epjc/s10052-019-7439-3>. arXiv:1907.10414 [nucl-ex]
 37. CMS Collaboration, S. Chatrchyan et al., Study of W boson production in PbPb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Phys. Lett. B **715**, 66 (2012). <https://doi.org/10.1016/j.physletb.2012.07.025>. arXiv:1205.6334 [nucl-ex]
 38. ALICE Collaboration, S. Acharya et al., $W^\pm$ -boson production in p–Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. JHEP **05**, 036 (2023). [https://doi.org/10.1007/JHEP05\(2023\)036](https://doi.org/10.1007/JHEP05(2023)036). arXiv:2204.10640 [nucl-ex]
 39. ATLAS Collaboration, G. Aad et al., Measurement of Z boson production in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector. Phys. Rev. Lett. **110**, 022301 (2013). <https://doi.org/10.1103/PhysRevLett.110.022301>. arXiv:1210.6486 [hep-ex]
 40. CMS Collaboration, A.M. Sirunyan et al., Study of Z production in PbPb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV in the dimuon and dielectron decay channels. JHEP **03**, 022 (2015). [https://doi.org/10.1007/JHEP03\(2015\)022](https://doi.org/10.1007/JHEP03(2015)022). arXiv:1410.4825 [nucl-ex]
 41. ATLAS Collaboration, G. Aad et al., Z boson production in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured by the ATLAS experiment. Phys. Lett. B **802**, 135262 (2020). <https://doi.org/10.1016/j.physletb.2020.135262>. arXiv:1910.13396 [nucl-ex]
 42. CMS Collaboration, A.M. Sirunyan et al., Constraints on the initial state of Pb–Pb collisions via measurements of Z-boson yields and azimuthal anisotropy at $\sqrt{s_{NN}} = 5.02$ TeV. Phys. Rev. Lett. **127**, 102002 (2021). <https://doi.org/10.1103/PhysRevLett.127.102002>. arXiv:2103.14089 [hep-ex]
 43. CMS Collaboration, S. Chatrchyan et al., Measurement of isolated photon production in pp and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Phys. Lett. B **710**, 256–277 (2012). <https://doi.org/10.1016/j.physletb.2012.02.077>. arXiv:1201.3093 [nucl-ex]
 44. CMS Collaboration, A.M. Sirunyan et al., The production of isolated photons in PbPb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV. JHEP **07**, 116 (2020). [https://doi.org/10.1007/jhep07\(2020\)116](https://doi.org/10.1007/jhep07(2020)116). arXiv:2003.12797 [hep-ex]
 45. ALICE Collaboration, S. Acharya et al., Measurement of the inclusive isolated-photon production cross section in pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Eur. Phys. J. C **85**, 553 (2025). <https://doi.org/10.1140/epjc/s10052-025-13971-y>. arXiv:2409.12641 [nucl-ex]
 46. ALICE Collaboration, S. Acharya et al., Supplemental figures: measurement of the inclusive isolated-photon production cross section in pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. ALICE-PUBLIC-2024-003 (2024). <https://cds.cern.ch/record/2910556>
 47. S.T.A.R. Collaboration, L. Adamczyk et al., Jet-like correlations with direct-photon and neutral-pion triggers at $\sqrt{s_{NN}} = 200$ GeV. Phys. Lett. B **760**, 689–696 (2016). <https://doi.org/10.1016/j.physletb.2016.07.046>. arXiv:1604.01117 [nucl-ex]
 48. PHENIX Collaboration, A. Adare et al., Medium modification of jet fragmentation in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured in direct photon-hadron correlations. Phys. Rev. Lett. **111**, 032301 (2013). <https://doi.org/10.1103/PhysRevLett.111.032301>. arXiv:1212.3323 [nucl-ex]
 49. CMS Collaboration, A.M. Sirunyan et al., Observation of medium-induced modifications of jet fragmentation in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using isolated photon-tagged jets. Phys. Rev. Lett. **121**, 242301 (2018). <https://doi.org/10.1103/PhysRevLett.121.242301>. arXiv:1801.04895 [hep-ex]
 50. ATLAS Collaboration, M. Aaboud et al., Comparison of fragmentation functions for jets dominated by light quarks and gluons from pp and Pb+Pb collisions in ATLAS. Phys. Rev. Lett. **123**, 042001 (2019). <https://doi.org/10.1103/PhysRevLett.123.042001>. arXiv:1902.10007 [nucl-ex]
 51. ATLAS Collaboration, G. Aad et al., Medium-induced modification of Z-tagged charged particle yields in Pb + Pb collisions at 5.02 TeV with the ATLAS detector. Phys. Rev. Lett. **126**, 072301 (2021). <https://doi.org/10.1103/PhysRevLett.126.072301>. arXiv:2008.09811 [nucl-ex]
 52. C.M.S. Collaboration, A.M. Sirunyan et al., Using Z boson events to study Parton-medium interactions in Pb–Pb collisions. Phys. Rev. Lett. **128**, 122301 (2022). <https://doi.org/10.1103/PhysRevLett.128.122301>. arXiv:2103.04377 [hep-ex]
 53. ALICE Collaboration, S. Acharya et al., Measurement of isolated photon-hadron correlations in $\sqrt{s_{NN}} = 5.02$ TeV pp and p–Pb collisions. Phys. Rev. C **102**, 044908 (2020). <https://doi.org/10.1103/PhysRevC.102.044908>. arXiv:2005.14637 [nucl-ex]
 54. R. Ichou, D. d’Enterria, Sensitivity of isolated photon production at TeV hadron colliders to the gluon distribution in the proton. Phys. Rev. D **82**, 014015 (2010). <https://doi.org/10.1103/PhysRevD.82.014015>. arXiv:1005.4529 [hep-ph]
 55. ALICE Collaboration, D.A.H. Abdallah et al., Supplemental figures: measurement of the isolated photon–hadron correlations in

- Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. ALICE-PUBLIC-2026-001 (2026). <https://cds.cern.ch/record/2959357>
56. ALICE Collaboration, K. Aamodt et al., The ALICE experiment at the CERN LHC. JINST **3**, S08002 (2008). <https://doi.org/10.1088/1748-0221/3/08/S08002>
 57. ALICE Collaboration, B.B. Abelev et al., Performance of the ALICE Experiment at the CERN LHC. Int. J. Mod. Phys. A **29**, 1430044 (2014). <https://doi.org/10.1142/S0217751X14300440>. arXiv:1402.4476 [nucl-ex]
 58. ALICE Collaboration, S. Acharya et al., Performance of the ALICE electromagnetic calorimeter. JINST **18**, P08007 (2023). <https://doi.org/10.1088/1748-0221/18/08/P08007>. arXiv:2209.04216 [physics.ins-det]
 59. ALICE Collaboration, K. Aamodt et al., Alignment of the ALICE inner tracking system with cosmic-ray tracks. JINST **5**, P03003 (2010). <https://doi.org/10.1088/1748-0221/5/03/P03003>. arXiv:1001.0502 [physics.ins-det]
 60. J. Alme et al., The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events. Nucl. Instrum. Methods A **622**, 316–367 (2010). <https://doi.org/10.1016/j.nima.2010.04.042>. arXiv:1001.1950 [physics.ins-det]
 61. ALICE Collaboration, E. Abbas et al., Performance of the ALICE VZERO system. JINST **8**, P10016 (2013). <https://doi.org/10.1088/1748-0221/8/10/P10016>. arXiv:1306.3130 [nucl-ex]
 62. ALICE Collaboration, B. Abelev et al., Centrality determination of Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ALICE. Phys. Rev. C **88**, 044909 (2013). <https://doi.org/10.1103/PhysRevC.88.044909>. arXiv:1301.4361 [nucl-ex]
 63. ALICE Collaboration, S. Acharya et al., Measurement of the inclusive isolated photon production cross section in pp collisions at $\sqrt{s} = 7$ TeV. Eur. Phys. J. C **79**, 896 (2019). <https://doi.org/10.1140/epjc/s10052-019-7389-9>. arXiv:1906.01371 [nucl-ex]
 64. ALICE Collaboration, S. Acharya et al., Measurement of the inclusive isolated-photon production cross section in pp collisions at $\sqrt{s} = 13$ TeV. Eur. Phys. J. C **85**, 98 (2025). <https://doi.org/10.1140/epjc/s10052-024-13506-x>. arXiv:2407.01165 [hep-ex]
 65. ALICE Collaboration, S. Acharya et al., Measurement of isolated prompt photon production in pp and p–Pb collisions at the LHC. Eur. Phys. J. C **85**, 1407 (2025). <https://doi.org/10.1140/epjc/s10052-025-14802-w>. arXiv:2502.18054 [nucl-ex]
 66. ATLAS Collaboration, G. Aad et al., Measurement of the inclusive isolated prompt photon cross section in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. Phys. Rev. D **83**, 052005 (2011). <https://doi.org/10.1103/PhysRevD.83.052005>. arXiv:1012.4389 [hep-ex]
 67. ATLAS Collaboration, G. Aad et al., Measurement of the inclusive isolated prompt photon cross-section in pp collisions at $\sqrt{s} = 7$ TeV using 35 pb⁻¹ of ATLAS data. Phys. Lett. B **706**, 150–167 (2011). <https://doi.org/10.1016/j.physletb.2011.11.010>. arXiv:1108.0253 [hep-ex]
 68. ATLAS Collaboration, G. Aad et al., Measurement of the inclusive isolated prompt photon cross section in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector using 4.6 fb⁻¹. Phys. Rev. D **89**, 052004 (2014). <https://doi.org/10.1103/PhysRevD.89.052004>. arXiv:1311.1440 [hep-ex]
 69. ATLAS Collaboration, G. Aad et al., Measurement of the inclusive isolated prompt photon cross section in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector. JHEP **08**, 005 (2016). [https://doi.org/10.1007/JHEP08\(2016\)005](https://doi.org/10.1007/JHEP08(2016)005). arXiv:1605.03495 [hep-ex]
 70. ATLAS Collaboration, M. Aaboud et al., Measurement of the cross section for inclusive isolated-photon production in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector. Phys. Lett. B **770**, 473–493 (2017). <https://doi.org/10.1016/j.physletb.2017.04.072>. arXiv:1701.06882 [hep-ex]
 71. A.M. Poskanzer, S.A. Voloshin, Methods for analyzing anisotropic flow in relativistic nuclear collisions. Phys. Rev. C **58**, 1671–1678 (1998). <https://doi.org/10.1103/PhysRevC.58.1671>. arXiv:nucl-ex/9805001
 72. T. Sjöstrand et al., An introduction to PYTHIA 8.2. Comput. Phys. Commun. **191**, 159–177 (2015). <https://doi.org/10.1016/j.cpc.2015.01.024>. arXiv:1410.3012 [hep-ph]
 73. P. Skands, S. Carrazza, J. Rojo, Tuning PYTHIA 8.1: the Monash, tune. Eur. Phys. J. C **74**(2014), 3024 (2013). <https://doi.org/10.1140/epjc/s10052-014-3024-y>. arXiv:1404.5630 [hep-ph]
 74. R. Brun, F. Carminati, S. Giani, GEANT detector description and simulation tool. (1994). <https://cds.cern.ch/record/1082634>. W5013, W-5013, CERN-W5013, CERN-W-5013
 75. M. Xie, X.-N. Wang, H.-Z. Zhang, γ -hadron spectra in p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Phys. Rev. C **103**, 034911 (2021). <https://doi.org/10.1103/PhysRevC.103.034911>. arXiv:2003.02441 [hep-ph]
 76. H. Zhang, J.F. Owens, E. Wang, X.-N. Wang, Tomography of high-energy nuclear collisions with photon-hadron correlations. Phys. Rev. Lett. **103**, 032302 (2009). <https://doi.org/10.1103/PhysRevLett.103.032302>. arXiv:0902.4000 [nucl-th]
 77. W.-T. Deng, X.-N. Wang, Multiple Parton scattering in nuclei: modified DGLAP evolution for fragmentation functions. Phys. Rev. C **81**, 024902 (2010). <https://doi.org/10.1103/PhysRevC.81.024902>. arXiv:0910.3403 [hep-ph]
 78. M. Xie, W. Ke, H. Zhang, X.-N. Wang, Global constraint on the jet transport coefficient from single-hadron, dihadron, and γ -hadron spectra in high-energy heavy-ion collisions. Phys. Rev. C **109**, 064917 (2024). <https://doi.org/10.1103/PhysRevC.109.064917>. arXiv:2208.14419 [hep-ph]
 79. M. Xie, W. Ke, H. Zhang, X.-N. Wang, Information-field-based global Bayesian inference of the jet transport coefficient. Phys. Rev. C **108**, L011901 (2023). <https://doi.org/10.1103/PhysRevC.108.L011901>. arXiv:2206.01340 [hep-ph]
 80. X.-N. Wang, Why the observed jet quenching at RHIC is due to Parton energy loss. Phys. Lett. B **579**, 299–308 (2004). <https://doi.org/10.1016/j.physletb.2003.11.011>. arXiv:nucl-th/0307036
 81. T.-J. Hou et al., New CTEQ global analysis of quantum chromodynamics with high-precision data from the LHC. Phys. Rev. D **103**, 014013 (2021). <https://doi.org/10.1103/PhysRevD.103.014013>. arXiv:1912.10053 [hep-ph]
 82. B.A. Kniehl, G. Kramer, B. Potter, Fragmentation functions for pions, kaons, and protons at next-to-leading order. Nucl. Phys. B **582**, 514–536 (2000). [https://doi.org/10.1016/S0550-3213\(00\)00303-5](https://doi.org/10.1016/S0550-3213(00)00303-5). arXiv:hep-ph/0010289
 83. W. Chen, S. Cao, T. Luo, L.-G. Pang, X.-N. Wang, Effects of jet-induced medium excitation in γ -hadron correlation in A+A collisions. Phys. Lett. B **777**, 86–90 (2018). <https://doi.org/10.1016/j.physletb.2017.12.015>. arXiv:1704.03648 [nucl-th]
 84. K.J. Eskola, P. Paakkinen, H. Paukkunen, C.A. Salgado, EPPS21: a global QCD analysis of nuclear PDFs. Eur. Phys. J. C **82**, 413 (2022). <https://doi.org/10.1140/epjc/s10052-022-10359-0>. arXiv:2112.12462 [hep-ph]

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Batigne⁹⁹, D. Battistini^{34,92}, B. Batyunya¹³⁹, L. Baudino^{24,b}, D. Bauri⁴⁶, J. L. Bazo Alba⁹⁸, I. G. Bearden⁸⁰, D. Behera^{47,77}, S. Behera⁴⁶, M. A. C. Behling⁶³, I. Belikov¹²⁶, V. D. Bella¹²⁶, F. Bellini²⁵, R. Bellwied¹¹², L. G. E. Beltran¹⁰⁵, Y. A. V. Beltran⁴³, G. Bencedi⁴⁵, O. Benchikhi⁷³, A. Bensaoula¹¹², S. Beole²⁴, A. Berdnikova⁹¹, L. Bergmann⁷¹, L. Bernardinis²³, L. Betev³², P. P. Bhaduri¹³², T. Bhalla⁸⁷, A. Bhasin⁸⁸, B. Bhattacharjee⁴⁰, L. Bianchi²⁴, J. Bielčik³⁴, J. Bielčíková⁸³, A. Bilandzic⁹², A. Binoy¹¹⁴, G. Biro⁴⁵, S. Biswas⁴, M. B. Blidaru⁹⁴, N. Bluhme³⁸, C. Blume⁶³, F. Bock⁸⁴, T. Bodova²⁰, L. Boldizsár⁴⁵, M. Bombara³⁶, P. M. Bond³², G. Bonomi^{54,131}, H. Borel¹²⁷, A. Borissov¹³⁹, A. G. Borquez Carcamo⁹¹, E. Botta²⁴, N. Bouchhar¹⁷, Y. E. M. Bouziani⁶³, D. C. Brandibur⁶², L. Bratrud⁶³, P. Braun-Munzinger⁹⁴, M. Bregant¹⁰⁶, M. Broz³⁴, G. E. Bruno^{31,93}, V. D. Buchakchiev³⁵, M. D. Buckland⁸², G. F. Budiski¹⁰⁶, H. Buesching⁶³, S. Bufalino²⁹, P. Buhler⁷³, N. 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