Photon and neutral meson measurements with the ALICE experiment at the LHC

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Abstract. The measurements of photons and neutral mesons, such as $\pi^0$ and $\eta$, allow to explore the QCD matter created in heavy-ions collisions. In pp collisions, observables such as differential particle production cross sections can be used to test perturbative QCD calculations and constrain PDFs. In Pb-Pb collisions, neutral meson spectra address the medium induced suppression, whereas low transverse momentum direct photons allow to obtain information on the QCD medium temperature or anisotropic flow.

We present an overview of photon and neutral meson measurements, employing three different methods which use both ALICE calorimeters, as well as the central tracking system via the photon conversion method. These experimental results are compared with theoretical predictions.

1. Introduction
Quantum chromodynamics (QCD), which describes the strong interaction, predicts a phase transition above a given critical energy density from ordinary nuclear matter - composed of hadrons - to a hot and dense plasma of deconfined partons: the Quark-Gluon Plasma (QGP). The measurement of photons and neutral mesons allows to test perturbative QCD (pQCD) with pp collisions, but also to study the properties of the QGP, which is created in ultra-relativistic heavy-ion collisions.

Measured neutral mesons and photons give different information depending on the $p_T$ range of the measurements. At low $p_T$, neutral mesons can give insight about collective effects via the modification of their $p_T$ spectra and thermal photons, which are radiated by the fireball, allow to access bulk properties. On the other hand, at high $p_T$, neutral mesons coming from the fragmentation of partons created in hard processes during the early stages of the collision allow us to study medium induced parton energy loss. On the contrary, photons produced in hard scattering processes, do not interact strongly with the QGP and provide unmodified information on the early stage of the collisions.

2. Photon and neutral meson detection in the ALICE experiment
The ALICE experiment is dedicated to the study of the QGP at the LHC [1].

Photons are detected using three complementary methods: electromagnetic shower detection with both ALICE electromagnetic calorimeters (EMCal and PHOS) and the photon conversion method (PCM) within the ALICE tracking system, using the Inner Tracking System (ITS) and the Time Projection Chamber (TPC).
The EMCal calorimeter is composed of sampling layers of Pb (1.4 mm thickness) and scintillator (1.7 mm thickness). The detector energy resolution is: 
\[
\sigma_E = 0.05 + 0.11 \sqrt{E} + 0.017. 
\]
The EMCal is located at 4.4 m from the ALICE interaction point and covers 1.4 pseudo-rapidity units and 100° in azimuth angle during Run I [2].

The PHOS calorimeter is composed of PbWO₄ crystals. The granularity of the detector is higher than for the EMCal and its energy resolution is:
\[
\sigma_E = 0.018 + 0.033 \sqrt{E} + 0.011. 
\]
The PHOS is located at 4.6 m from the ALICE interaction point and its acceptance covers 0.26 units in pseudo-rapidity and 60° in azimuth angle during Run I [3].

The PCM method allows to measure photons by reconstructing the \(e^+e^-\) pairs coming from the conversion of photons in material. The low conversion probability, of about 8 % [4], is compensated by the large acceptance of the tracking system: 1.8 units in pseudo-rapidity and full coverage in azimuth (\(\phi\)).

The \(\pi^0\) and \(\eta\) neutral mesons are identified by reconstructing the invariant mass \((M_{\gamma\gamma})\) of all photon pairs in an event. The PCM method allows to reach very low \(p_T\) \((p_T > 0.3 \text{ GeV}/c)\) for the \(\pi^0\) reconstruction with an excellent resolution, while EMCal and PHOS allow to reach higher \(p_T\) \((up to 20 \text{ GeV}/c)\).

All three methods provide independent measurements with different sources of systematic uncertainties. Combining their measurements therefore allows to minimize those.

3. Neutral meson measurement in pp collisions

Measurements in pp collisions are necessary as a reference for Pb-Pb collisions and will test the pQCD predictions.

Figure 1 shows the \(\pi^0\) \(p_T\)-differential invariant cross section obtained from PCM and PHOS combined measurements. The invariant cross section is presented for several center of mass energies \(\sqrt{s} = 0.9, 2.76, 7\) and 8 TeV (the last one is a preliminary PHOS only measurement) [5]. The invariant cross sections are compared with PYTHIA and next-to-leading order pQCD (NLO pQCD) calculations with MSTW parton distribution functions (PDF) and DSS14 fragmentation functions (FF) [6]. A good overall agreement is found between data points and calculations, although some tension appears at high \(p_T\) and center of mass energy.

Figure 2 presents the \(\eta\) \(p_T\)-differential invariant cross sections also obtained with PCM and PHOS combined measurements. The invariant cross sections are shown for three center of mass energies \(\sqrt{s} = 0.9, 2.76\) and 7 TeV. The measurements are compared to NLO pQCD calculations with CTEQ6M5 PDF and the AES fragmentation function [7]. The observed stronger discrepancy between data and calculations compared to \(\pi^0\) is due to the PDF and fragmentation function chosen as shown by Fig. 2.

The \(p_T\) dependence of the \(\eta/\pi^0\) ratio, presented in Fig. 3, for center of mass energies \(\sqrt{s} = 2.76\) and 7 TeV [5], allows us to compare strange and light quark production. This ratio flattens, above 4 GeV/c, for both center of mass energies around the value compatible with the NLO pQCD calculations using CTEQ6M5 as PDF and DSS \((\pi^0)\) and AES \((\eta)\) for the fragmentation functions. Although this set of PDF and fragmentation function doesn’t reproduce the individual spectra, their bias seems to mainly cancel out in the ratio.

4. Neutral meson measurement in Pb-Pb collisions

The nuclear effects present in Pb-Pb collisions can be quantified with the nuclear modification factor:

\[
R_{AA} = \frac{d^2N_{AA}}{dp_Td\eta} \frac{T_{AA}}{d^2\sigma_{pp}} \frac{d\sigma_{pp}}{dp_Td\eta} \quad (1)
\]
Figure 1. \( \pi^0 \) invariant cross section in pp collisions at \( \sqrt{s} = 0.9, 2.76, 7 \) and 8 TeV, obtained from PCM and PHOS combined measurements. The results are compared to NLO pQCD (MSTW + DSS) and PYTHIA calculations.

Figure 2. Left: \( \eta \) invariant cross section in pp collisions at \( \sqrt{s} = 0.9, 2.76 \) and 7 TeV, obtained from PCM and PHOS combined measurements. The results are compared to NLO pQCD (CTEQ6M5 + AES) and PYTHIA calculations. Right: Comparison of \( \pi^0 \) invariant cross section with NLO pQCD (CTEQ6M5 + AES). The same discrepancy is observed for \( \eta \) and \( \pi^0 \).

Figure 3. \( p_T \) dependence of the \( \eta/\pi^0 \) ratio for pp collisions at \( \sqrt{s} = 2.76 \) (left) and 7 TeV (right) together with results from NLO pQCD calculations.
where $< T_{AA} > = N_{coll} / \sigma_{pp}^{inel}$, $< N_{coll} >$ is the number of binary collisions in Pb-Pb collisions and $\sigma_{pp}^{inel}$ is the inelastic cross section for pp collisions.

Figure 4, left panel, presents the PCM and PHOS combined measurement of the invariant yield of $\pi^0$ from the 2010 data [8]. The invariant yield is shown for six centrality classes. The right panel presents the nuclear modification factor obtained for three centrality classes: central (0-5%), semi-central (20-40%) and peripheral (60-80%). A suppression at high $p_T$ is observed and is attributed to an increasing energy loss in the medium with centrality. Those results are in agreement, at high $p_T$, with the $R_{AA}$ of other particle species [9].

The energy dependence of the $\pi^0$ nuclear modification factor as a function of $p_T$ is presented in Fig. 5 [8]. The ALICE result for central collisions is compared to the SPS result [10] at $\sqrt{s} = 17.3$ GeV and to the PHENIX results at $\sqrt{s} = 39, 62.4$ and 200 GeV [11][12]. With the growth of the center of mass energy, two competitive effects appear: a higher energy density which enhances the suppression of the high-$p_T$ particle yields, and a harder parton spectrum which drives the nuclear modification factor closer to unity. The net effect observed is a decrease of the nuclear modification factor with an increasing center of mass energy.

Figure 6 presents the first $\eta$ (right panel) measurement in Pb-Pb collisions at the LHC together with $\pi^0$ (left panel) invariant yields from EMCal and PCM combined measurements with 2011 data for central (0-10%) and semi-central (20-50%) collisions. The 2011 dataset allows to extend the $p_T$ reach up to 20 GeV/$c$, with respect to the 2010 dataset. NLO pQCD calculations with MSTW for the PDF and DSS14 ($\pi^0$) and DSS07 ($\eta$), scaled by $< N_{coll} >$ are used as a the pp reference up to 20 GeV/$c$ and appear as the grey lines on both figures to highlight the known suppression in Pb-Pb collisions compared to pp collisions.
Figure 5. $\sqrt{s_{NN}}$ evolution of the $\pi^0$ $R_{AA}$ $p_T$ dependence.

Figure 6. Left: $\pi^0$ invariant yield from EMCal and PCM combined measurements in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the 2011 data. Right: $\eta$ invariant yield from EMCal and PCM combined measurements in Pb-Pb collisions with 2011 data. The grey lines correspond to NLO pQCD calculations.

The $p_T$ dependence of the $\eta/\pi^0$ ratio obtained from 2011 data is shown in Fig. 7. This ratio is compared to the $\eta/\pi^0$ ratio measured in 7 TeV pp collisions [5] (left), to the $K^+/\pi^+$ ratio measured in Pb-Pb collisions [13] (middle) and to NLO pQCD with added energy loss [14] (right). The $\eta/\pi^0$ ratio seems compatible, within the large uncertainties, with $\eta/\pi^0$ ratio in pp collisions and $K^+/\pi^+$ ratio in Pb-Pb collisions. The pQCD calculation reproduces qualitatively the data.

5. $\pi^0$-hadron correlations
Partons that are produced in hard processes at the early stage of the collisions will hadronize in the QCD vacuum in pp collisions. In Pb-Pb collisions, the parton will pass through the QGP
and will interact with the medium and therefore lose energy and then will hadronize.

The measurement of \( \pi^0 \)-hadron correlations is performed by associating high \( p_T \) \( \pi^0 \) which comes from a parton emitted in a hard process with all the hadrons of the same event. On the away side (opposite side of the \( \pi^0 \)), correlated hadrons mainly come from the recoiling parton that went through the medium in Pb-Pb collisions, leading to an energy loss of this parton. Hence the comparison of \( \pi^0 \)-hadron correlations in pp and Pb-Pb collisions allows to highlight the parton energy loss mechanism.

The angular correlations \( \Delta \varphi = \varphi^{\pi^0} - \varphi^{\text{hadron}} \) for pp and Pb-Pb collisions are presented in Fig. 8. The underlying event is not subtracted in the figures presented. The two peaks observed at \( \Delta \varphi = 0 \) and \( \Delta \varphi = \pi \) come from the two jets emitted back-to-back in the hard process. The medium induced per-trigger yield modification factor, \( I_{AA} \), is built from the yield \( Y \) of one of the peaks (i.e. its integral after subtraction of the underlying event):

\[
I_{AA}(p_T^{\pi^0}, p_T^{\text{assoc}}) = \frac{Y_{AA}(p_T^{\pi^0}, p_T^{\text{assoc}})}{Y_{pp}(p_T^{\pi^0}, p_T^{\text{assoc}})}
\]

The variation of the yield, \( Y \), with \( p_T^{\text{assoc}} \) (transverse momentum of the associated hadrons) is presented in Fig. 9 for the near and away side peaks, for a given \( p_T^{\text{trig}} \) bin (transverse momentum of the \( \pi^0 \)). An enhancement of the yield is observed in Pb-Pb collisions compared to pp collisions on the near side (where the \( \pi^0 \) is). On the away side, where the hadrons from the fragmentation of the recoiling parton are found, a suppression is observed, which is attributed to parton energy loss in the QCD medium.

6. Direct photon measurement in Pb-Pb collisions

The measurement of direct photons in Pb-Pb collisions is crucial to better estimate bulk properties, as the temperature or energy density. Direct low \( p_T \) photons can be extracted by subtracting the decay photons from the inclusive photon spectrum. This is achieved by the calculation of the double ratio \( R_\gamma = \frac{\gamma^{\text{inc}}}{\gamma^{\text{decay}}} \) where \( \gamma^{\text{inc}} \) stands for the inclusive photon spectrum, \( \gamma^{\text{decay}} \) for the simulated decay photon cocktail spectrum and \( \gamma^{\text{param}} \) for the parametrization of the measured \( \pi^0 \) spectrum. Figure 10 (left panel), shows that \( R_\gamma \) is above unity, in particular in central collisions over the full measured \( p_T \) range, which reflects the contribution from direct photons [4]. At high \( p_T \) (\( p_T > 4 \text{ GeV}/c \)) and all centralities an excess compatible with pQCD and JETPHOX predictions [15] is observed. At low \( p_T \) and central

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**Figure 7.** The \( \eta/\pi^0 \) ratio obtained for Pb-Pb collisions with 2011 data, shown in all three panels, is compared to the \( \eta/\pi^0 \) ratio in pp collisions (left), to the \( K^\pm/\pi^\pm \) ratio in Pb-Pb collisions (middle) and to NLO pQCD calculations with added energy loss (right).
Figure 8. Relative azimuthal angle distribution of correlated $\pi^0$-hadron pairs for pp collisions (left) and Pb-Pb collisions (right). The angular distributions are presented for several $p_{T}^{assoc}$ bins. The away side peak is hardly visible in Pb-Pb collisions due to a large contribution from the underlying event.

Figure 9. $I_{AA}$ on the near side (left) and on the away side (right) peaks for a given $p_{T}^{trig}$ bin (for explanation see text).

collisions a 2.6σ excess relative to pQCD is observed (Fig. 10 right panel), which is attributed to the presence of direct thermal photons radiated by the QGP. Figure 10, right panel, presents the $p_{T}$ spectrum extracted for direct photons where an excess of about 2.6σ of direct photons attributed to thermal photons radiated by the QGP can be seen at low $p_{T}$ for central collisions.

7. Conclusions
Neutral mesons and photons are measured by ALICE in a wide $p_{T}$ range with complementary methods.

The neutral meson cross sections have been presented for pp collisions. They are fairly well
Figure 10. Left: $R_\gamma$ as a function of $p_T$ (see text). Right: direct photon $p_T$ spectrum for three centrality classes in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

described by NLO pQCD calculations and PYTHIA in the intermediate $p_T$ region ($< 10$ GeV/$c$). The $\eta/\pi^0$ ratio is also well described by NLO pQCD calculations.

In Pb-Pb collisions, the $\pi^0$ invariant yield measurement and the corresponding $R_{AA}$ show an increasing $\pi^0$ suppression with increasing centrality and center of mass energy. The $\eta$ measurement in Pb-Pb collisions, which is the first $\eta$ measurement at the LHC, allows to access the $\eta/\pi^0$ ratio in Pb-Pb collisions. Within the large uncertainties this ratio is compatible with $\eta/\pi^0$ ratio in pp collisions and also the $K^\pm/\pi^\pm$ ratio in Pb-Pb collisions.

$\pi^0$,hadron correlations have been presented for pp and Pb-Pb collisions. The medium induced per-trigger yield modification factor, $I_{AA}$, shows a suppression in Pb-Pb collisions on the away side, which is attributed to parton medium-induced energy loss.

Finally, an excess of low $p_T$ photons has been observed in Pb-Pb collisions, and it can be attributed to thermal photons radiated by the QGP.

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