Neutral meson and direct photon analysis with ALICE

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Abstract. The measurement of neutral mesons, particularly $\pi^0$’s and $\eta$’s, plays an important role in the study of the Quark-Gluon Plasma (QGP), the hot and dense medium created in high-energy heavy-ion collisions. Parton energy loss in the QGP, often called jet quenching, can be assessed via measuring the suppression of high-$p_T$ $\pi^0$’s in heavy-ion collisions, when compared to pp collisions using the nuclear modification factor ($R_{AA}$). Furthermore, neutral mesons are the dominant source of photons in pp and Pb-Pb collisions, and their precise measurement is required to measure direct photons that are produced thermally within the QGP or in hard initial scatterings in the earliest phases of the collision. In both cases, high-quality measurements in pp collisions are required as a reference for Pb-Pb collisions. ALICE measurements of neutral meson spectra cover a large $p_T$ range, with the Photon Conversion Method - which requires measurements from the ITS and TPC - covering low to intermediate $p_T$ and the PHOS and EMCal electromagnetic calorimeters covering an intermediate to high $p_T$ range. In this presentation, measurements of $\pi^0$’s and $\eta$’s obtained from the ALICE experiment, for pp collisions at several collisional center of mass energies ($\sqrt{s_{NN}}$), from 0.9 TeV to 8 TeV and in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, will be presented. The reconstruction of neutral mesons using the Photon Conversion Method (PCM) will also be discussed.

1. Introduction

High energy heavy-ion collision experiments are believed to produce an extremely hot, dense phase of matter comprised of deconfined partons, known as the Quark-Gluon Plasma (QGP) [1, 2]. The ALICE Experiment [3] at CERN’s Large Hadron Collider (LHC) [4] is mainly concerned with the study of heavy-ion collisions, particularly, the study of the QGP.

The verification of the QGP and characterisation of its properties is a complex procedure requiring the analysis of several complementary measurements. Among the observables used to probe this evolving state of matter is the measurement of direct photons. These are photons that are emitted from the evolving system as opposed to those photons from hadronic decays. Since photons only interact electromagnetically with the strongly coupled medium, and considering the size of said medium, the information they bear pertaining to the properties of the system at the time of their production remains relatively undistorted [5]. There are numerous mechanisms responsible for the production of direct photons. Direct photons of particular interest are prompt photons from initial hard scattering processes [6] and those from thermal scatterings [7] in both the QGP and hot hadron gas phases of the medium. In A-A collisions these different processes are expected to have varying contributions to direct photon production.
depending on the analysed $p_T$ regions. Prompt photon production - from quark-gluon scattering and quark-anti-quark annihilation - calculable via next-to-leading order (NLO) perturbative Quantum Chromodynamics (pQCD)\[8\], is expected to dominate at high $p_T$. On the other hand, thermal photons are expected to dominate direct photon production in A-A collisions at low $p_T$ ($p_T \lesssim 4$ GeV/c). The inclusive photon signal is dominated by a large background attributable to hadron decays, of which $\sim 80\%$ and $\sim 18\%$ is due to neutral pion and $\eta$ mesons, respectively \[9\].

Hadron production in pp and A-A collisions at $p_T \gtrsim 3$ GeV/c, is attributable to initial hard scatterings which subsequently undergo jet fragmentation \[10\]. High energy partons traversing a QGP will experience energy loss due to parton-medium interactions. These energy losses are manifested as suppressed hadron production in the high $p_T$ region. A measure of this suppression is given by the particle nuclear modification factor,

$$R_{AA} = \frac{d^2N/dp_t dy|_{AA}}{(T_{AA}) \times d^2\sigma/dp_t dy|_{pp}},$$

where the nuclear overlap function, $\langle T_{AA} \rangle = \langle N_{coll} \rangle / \sigma_{inel}^{pp}$ is related to the average number of inelastic nucleon-nucleon collisions \[11\] with $\langle N_{coll} \rangle$ being the number of nucleon-nucleon binary collisions and $\sigma_{inel}^{pp}$ being the pp inelastic cross-section. Measurement of the $R_{AA}$ can give insight into the mechanisms of parton energy loss and hence allow for an improved characterisation of the QGP.

2. Measurements

The ALICE detector is well equipped for the measurement of photons. The ALICE Photon Spectrometer (PHOS) \[13\] is a highly segmented electromagnetic calorimeter comprised of PbWO$_4$ crystals, with a coverage in pseudorapidity and azimuth of $|\eta| < 0.13$ $\Delta \phi = 60^\circ$, respectively. PHOS measures electromagnetic showers created by photons interacting with the scintillator material. The purity of photon samples measured by PHOS is ensured by performing cuts on the energy, size and dispersion of the particle electromagnetic shower. Another means of measuring photons is by using the Photon Conversion Method (PCM); this reconstructs converted photons within the detector via tracking the $e^+e^-$ conversion products. $e^+e^-$ pairs from conversion photons originate from secondary vertices some distance from the primary vertex and are said to have a $V^0$ topology - due to the charge neutrality of the conversion photon and V-shaped topology of the secondary track pairs. The low conversion probability of photons ($\sim 8.5\%$) in the detector is compensated by the large acceptance ($|\eta| < 0.9$ and $\Delta \phi = 2\pi$ coverage) of the Inner Tracking System (ITS) \[3\] and the Time Projection Chamber (TPC) \[14\] which together track the $e^+e^-$ pairs. High purity photon samples are achieved by performing cuts on the decay topology and on charged track properties. Details of these measurements for pp and Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV are presented in \[15\].
The measurement of neutral mesons, particularly $\pi^0$s, is an important measurement in its own right [12]. Extracting the direct photon signal requires the subtraction of the decay photon spectrum from the inclusive photon spectrum. $\pi^0$ and $\eta$ decays, which constitute the bulk of the decay photon spectrum, are reconstructed by calculating the invariant mass of photon pairs using,

$$M_{\gamma\gamma} = \sqrt{2E_{\gamma 1}E_{\gamma 2}(1-\cos\theta_{1,2})},$$

where $E_{\gamma 1}$ and $E_{\gamma 2}$ represent the two photon energies, and $\theta_{1,2}$ describes the opening angle between them.

As indicated in Fig. 1, PHOS is particularly adept at reconstructing the $\pi^0$ in the mid to high $p_T$ range. PCM, on the other hand, exhibits an exceptional energy resolution from low to mid $p_T$ with a $\pi^0$ peak width of $\sigma_{\pi^0} \approx 3$ MeV/c at low $p_T$. The combination of PCM and PHOS enables the reconstruction of $\pi^0$ and $\eta$ mesons over a large $p_T$ range.

Much of the difficulty in measuring the direct photon signal is in obtaining a good estimate of the decay photon signal. The decay photon spectrum is calculated using a Monte Carlo based approach, to which the parametrised $\pi^0$ - and if available the $\eta$ - spectrum is used as input. The remaining hadron contribution to the decay spectrum is estimated using $m_T$ scaling [17]. Merely subtracting the decay photon spectrum from the inclusive photon spectrum results in large uncertainties in the direct photon spectrum. These uncertainties are primarily attributable to certain systematic uncertainties in the measurement procedure. In [15] the main sources of systematic uncertainties for PCM are attributable to the material budget of the detector ($\sim 4.5\%$) and the photon selection criteria which is as high as $\sim 4\%$ at low $p_T$. The main systematic uncertainties in the case of PHOS are the uncertainties in the energy scale of the detector ($\sim 9.5\%$) and on the efficiency of the reconstruction calculation, which is as high as $\sim 3\%$ in the $0-20\%$ centrality class. To minimise these uncertainties, one calculates the direct photon spectrum in the following manner:

$$\gamma_{\text{dir}} = \gamma_{\text{inc}} - \gamma_{\text{decay}} = \gamma_{\text{inc}}\left(1 - \frac{\gamma_{\text{decay}}}{\gamma_{\text{inc}}}\right),$$

where the reciprocal of the above fraction is redefined as a double ratio, given by:

$$R_\gamma \equiv \frac{\gamma_{\text{inc}}}{\pi_0^{\text{param}}} / \frac{\gamma_{\text{decay}}}{\pi_0^{\text{param}}},$$

Figure 2. $\pi^0 R_{AA}$ for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for centrality classes 0-5%, 20-40% and 60-80%. Vertical bars and boxes represent statistical and systematic uncertainties respectively. Horizontal bars describe the bin width. The boxes around unity describe the uncertainty of the average nuclear overlap function ($T_{AA}$) and the normalization uncertainty of the $pp$ spectrum added in quadrature [16].
where \( \pi^0_{\text{param}} \) is the parametrised \( \pi^0 \) spectrum. The systematic uncertainties characteristic of each fraction in Eq. (2) partially cancel [15]. A \( R_\gamma \) value greater than unity indicates a direct photon signal. The double ratio in Eq. (2) is used in Eq. (1) to calculate the direct photon spectrum.

3. Results

Fig. 2 shows the combined \( \pi^0 \) \( R_{AA} \) for PHOS and PCM for three different centrality classes. In all centrality classes the \( R_{AA} \) exhibits a peak in the region \( 1 \lesssim p_T \lesssim 2 \text{ GeV}/c \), and decreases in the \( 2 \lesssim p_T \lesssim 3 - 6 \text{ GeV}/c \) region followed by a flattening out of the \( R_{AA} \) at larger \( p_T \). In the high \( p_T \) region, where \( \pi^0 \) production is expected to be dominated by fragmentation of hard scattered partons, an increase in suppression with increasing centrality is observed. In the high \( p_T \) region, an \( R_{AA} \) of \( \sim 0.5 - 0.7 \) is observed in the 60-80% centrality class, and as low as \( \sim 0.1 \) in the 0-5% centrality class. Given the expectation that more central collisions create a larger medium, one would expect that at high \( p_T \) where parton energy loss due to hard parton-medium interactions should be dominant, a larger medium being traversed would result in an increase in parton energy loss and hence an increase in suppression at high \( p_T \). These measurements are in agreement with these expectations.

In Fig. 3, a measurement of an excess above the decay photon signal, represented by the double ratio, \( R_\gamma \), for pp collisions at \( \sqrt{s} = 7 \text{ TeV} \) along with NLO pQCD calculations of the double ratio are shown. This measurement provides a baseline for the double ratio measurement performed in Fig. 4 [9]. Although measurements and NLO pQCD calculations are in agreement, the large systematic uncertainties, do not allow for a decisive conclusion on the existence of direct photon production in pp collisions at \( \sqrt{s} = 7 \text{ TeV} \).

The left side of Fig. 4 shows the double ratio for three centrality classes for Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \). All centrality classes exhibit a direct photon excess in the \( p_T \gtrsim 4 \text{ GeV}/c \) range. The 0-10% centrality class also exhibits an excess in the \( 2 \lesssim p_T \lesssim 4 \text{ GeV}/c \) range. The double ratio in all centralities is compared to three NLO pQCD calculations [15] - which predict the prompt photon contribution to the direct photon yield - scaled up according to the number of expected binary collisions in each class [18]. In all centrality classes, pQCD calculations are in agreement with the measurements in the \( p_T \gtrsim 5 \text{ GeV}/c \) region. The excess of \( \sim 10-15\% \) for 0-20% centralities - not predicted by the scaled pQCD calculations - in the \( 0.9 \lesssim p_T \lesssim 2.1 \text{ GeV}/c \) region suggests the presence of another source of direct photons in central collisions. The excess for each data point in this \( p_T \) region is \( \sim 2\sigma \) above unity. The combined significance of the excess in the \( 0.9 \lesssim p_T \lesssim 2.1 \text{ GeV}/c \) region is found to be 2.6\( \sigma \) [15]. The right hand side of Fig. 4 shows the direct photon spectra for the three centralities, calculated from the double ratios on the left. The direct photon spectra are compared to four state of the art direct photon calculations, over and beyond the entire \( p_T \) range of the data. All models assume the formation of a QGP and include the contribution of pQCD photons. The primary difference between the models is their treatment of the space-time evolution of the system. The van Hees et al [19] calculation is
Figure 4. (left) The measured double ratio in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for 0-20%, 20-40% and 40-80% centrality classes. The measured double ratio spectra are compared to scaled NLO pQCD predictions as well as JETPHOX event generator predictions. (right) Comparison of several models with direct photon spectra in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for the 0-20% (scaled by a factor 100), the 20-40% (scaled by a factor 10) and 40-80% centrality classes. Contribution of pQCD photons is included in all models. In addition, the more central 0-20% and 20-40% classes are fitted with an exponential function [15].

Based on ideal hydrodynamics. The Chatterjee et al [20] model is based on a (2+1D) event-by-event ideal hydrodynamics calculation with fluctuating initial conditions under the assumption of longitudinal boost invariance. The Paquet et al [21] calculation is similar to the Chatterjee calculation; however, instead of ideal hydrodynamics, viscous hydrodynamics is used. The Linnyk et al. [22] calculation is based on an off-shell transport approach in which the full evolution of the collision is described microscopically. The models also adopt different initial conditions of the system; namely, the time at which the space-time evolution of the system begins and the initial temperature at the centre of the fireball. Unfortunately, a comparison of the effectiveness of the models cannot be determined as all models fall within the systematic uncertainties of the measurements. Consequently, a reduction of systematic errors is required. Although they agree within the uncertainties, at low $p_T$ for the most central class, the models appear to slightly underestimate the data.

For a static medium in thermal equilibrium the distribution of the thermal radiation is described by Planck’s law, which in the case of sufficiently high energy photons can be approximated by Wien’s approximation described by an exponential. Consequently, models in which thermal photon production is the dominant source of direct photons at low $p_T$, make the argument that an exponential function $\propto \exp\left(-p_T/T_{\text{eff}}\right)$ fitted to this region of the direct photon spectrum is a valid procedure [7], where the inverse slope parameter $T_{\text{eff}}$ can be interpreted as a characterisation of the effective temperature of the medium averaged over its entire space-time evolution [23]. However, because the medium is cooling and expanding rapidly at speeds of up to $2/3c$, one would have to integrate over the states of the system during its space-time evolution and take into
account the the red- and blue-shifting of the emitted photons. This in general should not result in an exponential distribution. As such, the relationship between $T_{\text{eff}}$ and the mean temperature of the system is less direct. This complicates the interpretation of $T_{\text{eff}}$, but a correlation between the slope and the initial temperature still exists [24]. In the two most central classes, over the region $0.9 < p_T < 2.1 \text{ GeV}/c$, the pQCD calculation by Paquet et al. was subtracted from the direct photon measurement, and to this region an exponential of the form $A \exp(-p_T/T_{\text{eff}})$ was fitted. The extracted inverse slope parameter in the most central class, $T_{\text{eff}} = 297 \pm 12^{\text{stat}} \pm 41^{\text{syst}} \text{ MeV}$ significantly exceeds the requisite critical temperature $T_c = 155 - 170 \text{ MeV}$ for creating a QGP [25, 26].

4. Conclusion
Neutral pion and direct photon measurement with ALICE using PHOS in conjunction with PCM, allows for a large coverage in $p_T$. In addition, at high $p_T \gtrsim 6 \text{ GeV}/c$, a large suppression in $\pi^0$ production in most central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ is consistent with parton energy loss. For $p_T \gtrsim 5 \text{ GeV}/c$, measurements of the direct photon yield, for all centralities, are in agreement with NLO pQCD calculation, scaled by the number of binary nucleon-nucleon collisions. Although only achieving a 2.6$\sigma$ significance, an excess in direct photon production at $p_T \lesssim 4 \text{ GeV}/c$, for the most central classes was observed. In 0-10% centralities, an exponential fit to the $0.9 < p_T < 2.1 \text{ GeV}/c$ region was found to have an inverse slope parameter $T_{\text{eff}} = 297 \pm 12^{\text{stat}} \pm 41^{\text{syst}} \text{ MeV}$. Consequently, the measurement of thermal photons in heavy-ion collisions at larger collision energies will be performed with ALICE Pb-Pb data at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$. Greater statistics should reduce statistical uncertainties, however; a better handle on systematic uncertainties is necessary to achieve more precise measurements.

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