# Study of neutral meson production with photon conversions in the MPD experiment at NICA

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**Abstract.** The MPD experiment is aimed to study strongly interacting matter in nucleus-nucleus collisions at the future NICA collider in the energy range 4-11 GeV per nucleon pair. Neutral pion and η measurements via two-photon decays will allow the MPD experiment to extend the variety of registered particle species and will provide important information on dynamics and properties of the medium created in heavy ion collisions at NICA energies. The measurement of neutral pion and η meson spectra is also important as a first step towards the analysis of thermal photons sensitive to the temperature of the produced medium. In this contribution, the feasibility of neutral meson production measurements in the two-photon channel via photon conversions will be presented, and implications for the study of thermal photons will be discussed.

## 1. Introduction

The main purpose of the MPD experiment [1] at the NICA collider [2] is to study the behaviour of nuclear matter in heavy ion collisions under extreme conditions. The energy range of the NICA collider $4 < \sqrt{s_{NN}} < 11$ GeV allows one to study fundamental QCD properties at high baryon densities and search for chiral symmetry restoration and deconfinement phenomena. One of the goals of the MPD experiment physics program is the study of the neutral mesons production.

Neutral meson spectra carry important information on the dynamics and properties of the medium produced in heavy ion collisions. Neutral pion and η spectra and their nuclear modification factors were measured in a wide range of energies starting from $\sqrt{s_{NN}} = 17.3$ GeV at SPS [3] up to $\sqrt{s_{NN}} = 200$ GeV at RHIC [4-7] and $\sqrt{s_{NN}} = 5020$ GeV at the LHC [8-13]. At RHIC and LHC energies, light mesons appear to be strongly suppressed in the transverse momentum range $2 < p_T < 5$ GeV/$c$ with significantly smaller suppression observed for light baryon species. This suppression pattern is usually attributed to the interplay of several effects: rescattering of hard partons in the initial state, strong radial flow and recombination effects. In nucleus-nucleus collisions at SPS energies ($\sqrt{s_{NN}} = 17.3$ GeV), the dominant role in the modification of hadron spectra is played by the rescattering of hard partons in the initial state. Comparison of measured hadron yields in Pb-Pb and p-Pb collisions revealed a factor of two suppression of hadron spectra in most central Pb-Pb collisions. Assuming that initial rescattering effects are cancelled in the ratio of yields in Pb-Pb and p-Pb collisions, it was argued that significant parton energy loss is observed at SPS energies. Nevertheless, the hadron suppression effects are expected to be less pronounced at lower energies due to transition from partonic to hadronic degrees of freedom. The range

of collision energies at the NICA collider is perfect for the studies of these transition effects and the study of neutral meson production at NICA will provide important supplementary information.

Measurements of neutral pion and η mesons provide valuable input for the studies of thermal photons, one of the hot topics in heavy ion physics. The yields of thermal photons in central nucleus-nucleus collisions at RHIC and LHC appear to exceed the yields in pp collisions scaled by the number of binary collisions by order of magnitude [14]. Effective temperature of soft photons at RHIC and LHC energies far exceeds the temperature predicted for the phase space transition into the deconfined state [15-17]. This observation was used as one of the main arguments in favour of the quark-gluon plasma formation in heavy ion collisions at RHIC and LHC. Measurements of effective temperature and yields of thermal photons at lower energies would be extremely useful to track down the transition from hadronic to partonic degrees of freedom at NICA energies. Measurements of azimuthal distributions of emitted thermal photons relative to the reaction plane at NICA energies would also be very important for the resolution of the so-called "photon puzzle": elliptic flow coefficient (second coefficient in the Fourier decomposition of azimuthal distributions) measured in nucleus-nucleus collisions at RHIC and LHC appears to be much larger than predicted in modern theoretical calculations [18-20]. Precision measurements of elliptic flow and yields of $\pi^0$ and η mesons would be very important for the extraction of thermal photon yields and azimuthal distributions since $\pi^0$ and η decays are dominant sources of background photons at low transverse momenta.

There are two complimentary experimental methods used to measure photons and neutral meson decays: calorimetry and photon conversions. Electromagnetic calorimeters usually become efficient at relatively high transverse momenta, $p_T > 2$ GeV/c. At low transverse momenta, $p_T < 4$ GeV/c, the optimal method is to measure photon conversions $\gamma \rightarrow e^+e^-$ in the detector material with $e^+$ and $e^-$ daughters measured in the tracking system. The conversion method allows one to perform photon measurements starting from $p_T$ about 0.5 GeV/c, characteristic for the thermal emission of photons from the hadron gas and deconfined partonic medium. Moreover, the conversion method provides much better resolution at low transverse momenta compared to the calorimetric method, e. g. the width of the $\pi^0$ peak at $p_T \sim 1$ GeV/c measured via conversions in the ALICE experiment is about 1.9 MeV/$c^2$, much smaller compared to PHOS and EMCAL measurements providing the width of about 6.1 and 13.4 MeV/$c^2$, respectively [21].

In this contribution, we present feasibility studies on the measurement of neutral mesons and soft photons reconstructed via photon conversions in Au+Au collisions at $\sqrt{s_{NN}}$ = 4 and 11 GeV with the MPD detector.
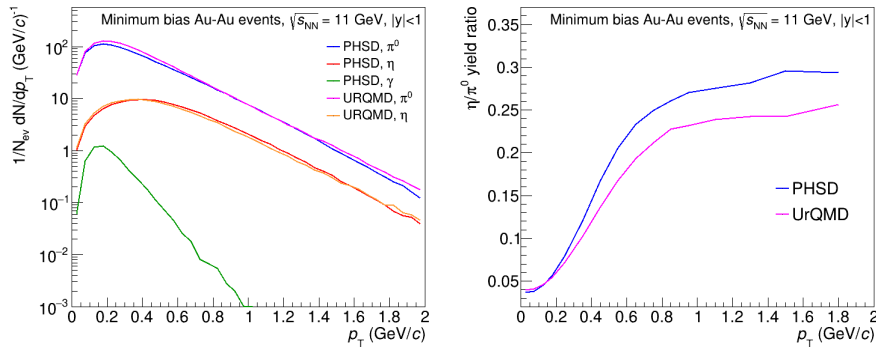
## 2. Differential yields of neutral mesons and direct photons

To evaluate rapidity and $p_T$ differential per-event yields of neutral mesons and direct photons in minimum bias Au-Au collisions at two extreme NICA energies, $\sqrt{s_{NN}}$ = 4 GeV and $\sqrt{s_{NN}}$ = 11 GeV, the PHSD generator was used [22]. The yields of neutral mesons from PHSD were compared to the yields evaluated with the UrQMD generator at $\sqrt{s_{NN}}$ = 11 GeV [23]. The resulting rapidity distributions are provided in Figure 1 showing nice agreement between UrQMD and PHSD generator predictions. $p_T$-integrated η meson yields are a factor 9-10 lower compared to $\pi^0$ yields. Direct photon yields are smaller than $\pi^0$ yields by two orders of magnitude meaning that $\pi^0 \rightarrow \gamma\gamma$ and $\eta \rightarrow \gamma\gamma$ decays will constitute a considerable background in the direct photon studies.

The $p_T$ differential per-event yields at mid-rapidity are shown in Figure 2 (left). One can clearly see that the $p_T$ distribution of direct photons is much softer compared to $\pi^0$ and η $p_T$-shapes due to thermal nature of the direct photon production at NICA energies. Relative contribution of photons from neutral meson decays is expected to decrease towards lower transverse momenta resulting in increasing signal-to-background ratio for the direct photon measurements.
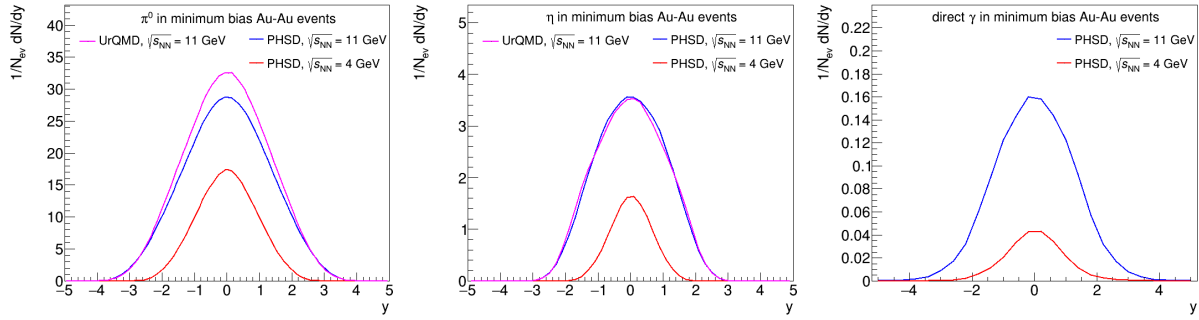
**Figure 1.** Rapidity-differential yields of neutral mesons and direct photons in minimum bias Au-Au collisions at $\sqrt{s_{NN}} = 4$ GeV and $\sqrt{s_{NN}} = 11$ GeV evaluated with PHSD and UrQMD generators.



**Figure 2.** $p_T$ differential yields of neutral mesons and direct photons (left) and $\eta/\pi^0$ yield ratio (right) in minimum bias Au-Au collisions at $\sqrt{s_{NN}} = 11$ GeV evaluated with PHSD and UrQMD generators.

The $p_T$ differential yields of $\pi^0$ and $\eta$ mesons also reveal different trends. Corresponding $\eta/\pi^0$ yield ratios evaluated with the PHSD and UrQMD generators are compared in Figure 2 (right). The $\eta/\pi^0$ yield ratios rapidly grow at low transverse momenta and flatten out at $p_T$ above 1 GeV/$c$. UrQMD and PHSD generators predict significantly different $\eta/\pi^0$ ratios at high $p_T$. Future measurements of this ratio in the MPD experiment will serve as an important constraint on the particle production mechanisms implemented in various theoretical models.

## 3. Methodology. Photon conversion probability and reconstruction efficiency

One of the important steps in the reconstruction of neutral mesons using the photon conversion method is the estimation of the photon conversion probability. The efficiency of the photon conversion method strongly depends on the material budget in front of the tracking system since the photon conversion probability is directly related to the effective radiation length $x/X_0$ of various detector layers as $P = 1 - \exp(-7/9\, x/X_0)$. For example, the effective radiation length of $11.4 \pm 0.5\%$ $X_0$ results in the conversion probability of about 8.5% in the ALICE detector [24].

The following estimates were obtained for the MPD Stage I detector including the beam pipe and the TPC but without the ITS. Typical distributions of photon conversion vertices in $rz$ and $xy$ planes are shown in Figure 3. The effective radiation length of the 1mm-thick beryllium beam pipe located at R = 4 cm does not contribute much to the photon conversion ($x$ is about 0.3% $X_0$), so the majority of photon conversions originates from various inner TPC structures (azimuth-averaged effective radiation length is about 2.4% $X_0$). Photon trajectories are usually inclined with respect to the detector layers resulting in effective increase of the photon conversion probability. The resulting dependence of the photon conversion probability on the photon momentum in the MPD detector is shown in Figure 4 (left). The conversion probability rapidly grows in the range from 0 to 0.2 GeV/$c$ and flattens out at the level of about 4.5%. The conversion probability can be increased with the installation of the inner tracking system or a dedicated photon convertor (e.g. cylindrical metal pipe).

Electron and positron tracks from the photon conversion have to be reconstructed in the TPC, therefore a minimum requirement of at least 10 points measured in the TPC was applied on the track selection. Photon candidates were reconstructed by considering pairs of tracks with opposite charge and a small distance of closest approach. In order to suppress contributions from uncorrelated pairs and weak decays of strange hadrons, additional requirements were applied on the angle between the plane perpendicular to the magnetic field and the plane which is spanned by the momentum vectors of the $e^+e^-$ pair ($\psi_{pair} < 0.2$ rad). Finally, we applied cuts on the invariant mass of the reconstructed pair ($m_{pair} < 0.25$ GeV/$c^2$) and on the angle between pair momentum and the direction to the vertex ($\cos(\theta) < 0.2$).
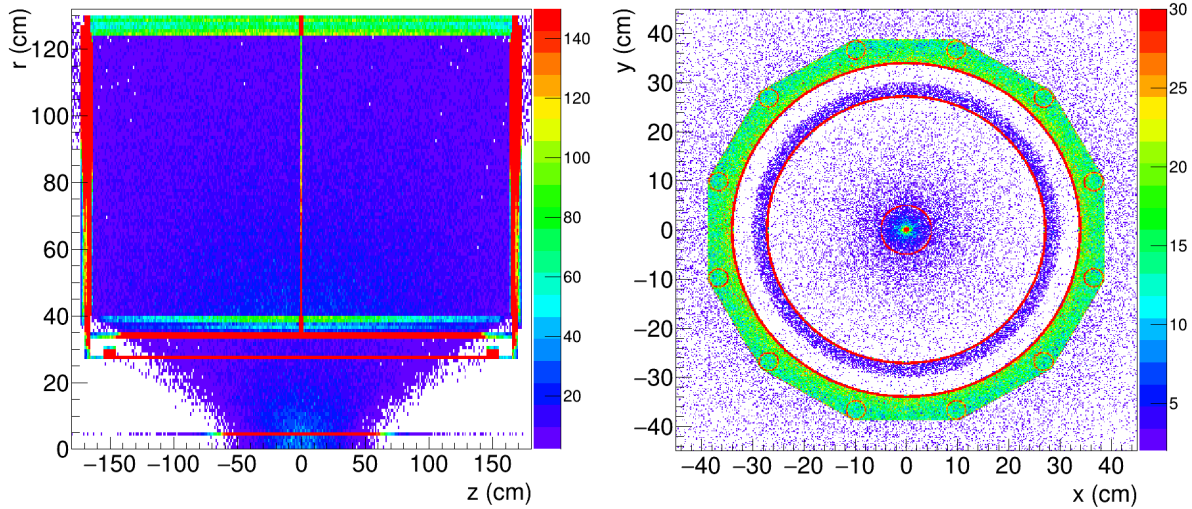


**Figure 3.** Simulated distribution of photon conversion centers in $rz$ plane (left) and in $xy$ plane (right) in the future MPD experiment.
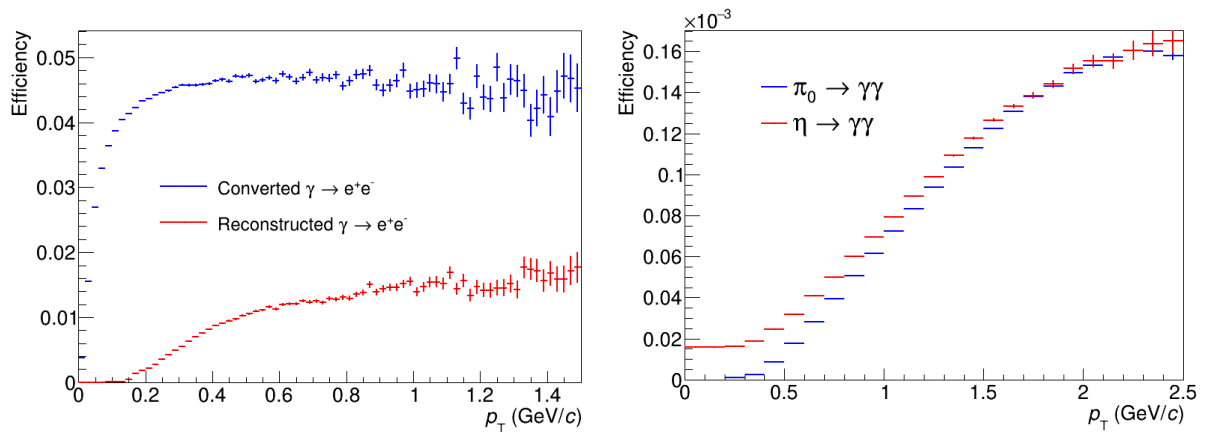


**Figure 4.** Probability of photon conversion in the beam pipe and in the inner TPC structures and corresponding photon reconstruction efficiency as a function of the photon transverse momentum (left) and $\pi^0$ and $\eta$ reconstruction efficiency as a function of the meson transverse momentum measured with the photon conversion method (right) in the future MPD experiment.

The selected dielectron sample can be further refined using particle identification capabilities of the MPD detector. Typical distributions of particle mass in TOF (left) and d$E$/d$x$ measurements in TPC (right) as function of particle momentum are shown in Figure 5. One can conclude that TPC measurements provide reasonably good electron separation in the range of momenta from 0.2 to 0.5 GeV/$c$ while TOF starts to be efficient at momenta below 0.3 GeV/$c$. TOF and TPC particle identification measurements were combined and a Bayesian probability of at least 90% for both tracks to be consistent with the electron hypothesis was required.

The resulting photon reconstruction efficiency is shown in Figure 4 (left). The selections described above result in the photon reconstruction efficiency a factor 3 lower than the photon conversion probability. The optimisation of selection criteria is a subject of future studies.
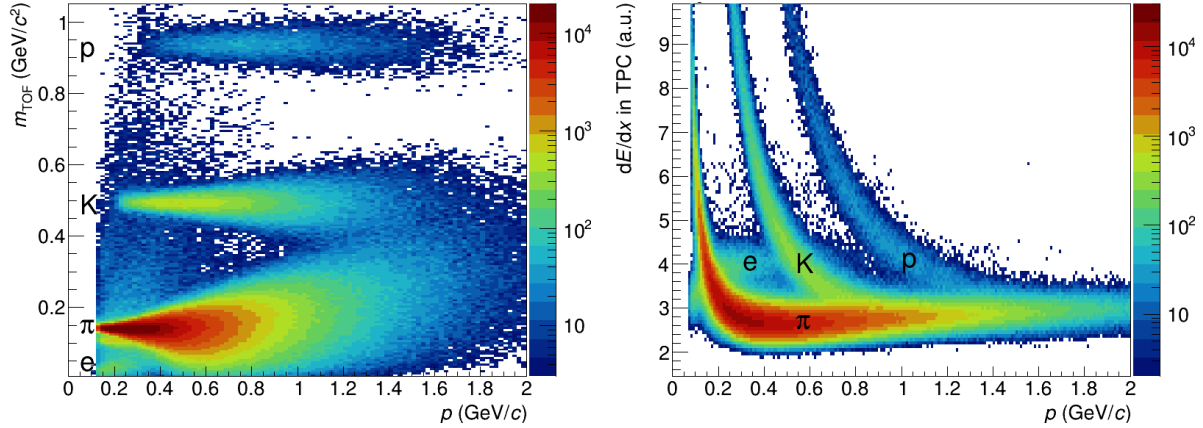


**Figure 5.** Particle mass measurements in TOF (left) and d$E$/d$x$ measurements in TPC (right) as a function of particle momentum.

## 4. Reconstruction of neutral mesons using photon conversion method

Reconstruction of $\pi^0$ and $\eta$ mesons requires both photons to be reconstructed in the MPD detector thus their efficiency scales as a square of the photon reconstruction efficiency. The resulting efficiencies as a function of meson transverse momentum are shown in Figure 4 (right). Efficiencies for both neutral mesons reach a maximum efficiency of about 0.016%. at $p_T$ about 2.5 GeV/c.

The invariant mass distribution of diphoton pairs with $p_T > 1$ GeV/c reconstructed with the photon conversion method in 1.5M minimum bias events at $\sqrt{s_{NN}} = 11$ GeV simulated with the URQMD generator [23] is shown in Figure 6. A clear $\pi^0$ peak is seen on top of combinatorial background with a signal/background ratio of the order of 1. The invariant mass distribution was parametrized using a Gaussian function for the signal and a second order polynomial for the background. The obtained width of the $\pi^0$ peak is about 4.0±0.8 MeV/c$^2$, a factor 2 larger compared to ALICE $\pi^0$ measurements based on the photon conversion method. Nevertheless, the measured width is still much better compared to the $\pi^0$ width obtained with calorimetric measurements. The available statistics of URQMD events is not enough to get a visible $\eta$ signal. The expected background for $\eta$ meson is factor two higher compared to the $\pi^0$ case while the signal yield is expected to be factor 10 lower therefore the signal-to-background ratio for $\eta$ mesons can be roughly estimated to be on the level of about 1/20.

The obtained efficiencies and signal-to-background ratios allow one to estimate the expected yields and statistical uncertainties for $\pi^0$ and $\eta$ mesons at $p_T$ above 1 GeV/c in minimum bias events. The expected luminosities in the first three years of running will hardly exceed $5\times10^{26}$ cm$^{-2}$s$^{-1}$. Assuming 10 weeks of running per year with 50% duty factor, one can expect about 100M minimum bias events collected in the first year of running resulting in about 7K $\pi^0$ and 1K $\eta$ decays reconstructed via photon conversions with about 1.6% and 15% statistical uncertainty, respectively. Starting from 2024, the NICA luminosities in Au-Au collisions are expected to reach $10^{27}$ cm$^{-2}$s$^{-1}$ allowing MPD to collect factor 200 higher statistics per year and opening a possibility for multi-differential studies of $\pi^0$ and $\eta$ production. Moreover, installation of the inner tracking system will result in a significant increase of the photon conversion probability and neutral meson yields.

## 5. Conclusions

The obtained results show that properties of $\pi^0$ and $\eta$ mesons can be experimentally studied in Au-Au collisions at $\sqrt{s_{NN}} = 11$ GeV with the MPD detector at NICA. The integrated yields can be obtained already during the first year of running. Centrality and $p_T$ differential measurements will become possible when the NICA collider reaches its nominal luminosity of $10^{27}$ cm$^{-2}$s$^{-1}$.
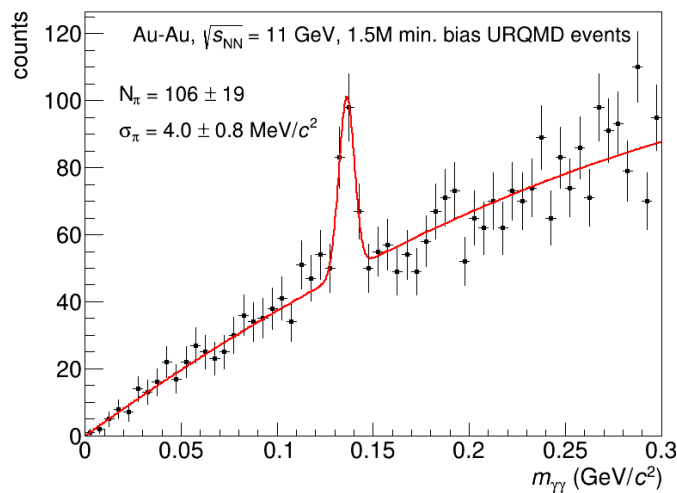
**Figure 6**: Invariant mass distribution of diphoton pairs with $p_{\mathrm{T}} > 1$ GeV/$c$ reconstructed using photon conversion method in minimum bias events at $\sqrt{s_{NN}} = 11$ GeV simulated with the URQMD generator in the Monte-Carlo model of the future MPD experiment.

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