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Requirements on Timing Resolution of the ALICE PHOS Detector.

Authors:

Yu.Kharlov,
Institute for High Energy Physics, Russia, Protvino
M.Ippolitov, D.Peressounko
Russian Research Center "Kurchatov Institute"

Abstract:

The main physics goal of the ALICE experiment is to search for the quark gluon plasma (QGP). The properties of the QGP can be explored, in particular, via detection of direct photons. Direct photon measurement in ALICE experiment will be performed with the electromagnetic calorimeter PHOS. It is expected that the main limiting factor in thermal photon measurement will be systematic errors. The detailed analysis of the sources of the systematic errors of direct photon extraction with PHOS one can find in [1]. Hadron contamination of photon spectrum is the most uncertain value of systematic error. The most important hadron contamination comes from misidentification of antineutrons and neutrons in PHOS. This contamination can be considerably reduced by applying a time-of-flight cut. In this paper we summarize available at the moment information about neutron and antineutron contamination of photon spectrum in central Pb+Pb collisions at LHC, compare different methods of decreasing of this contamination, including time-of-flight analysis, and formulate requirements on the timing resolution of the PHOS spectrometer.

Requirements on Timing Resolution

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Introduction

The main physics goal of the ALICE experiment is to search for the quark gluon plasma (QGP). The properties of the QGP can be explored, in particular, via detection of direct photons. Direct photon measurement in ALICE experiment will be performed with the electromagnetic calorimeter PHOS. It is expected that the main limiting factor in thermal photon measurement will be systematic errors. The detailed analysis of the sources of the systematic errors of direct photon extraction with PHOS one can find in [1]. Hadron contamination of photon spectrum is the most uncertain value of systematic error. The most important hadron contamination comes from misidentification of antineutrons and neutrons in PHOS. This contamination can be considerably reduced by applying a time-of-flight cut. In this paper we summarize available at the moment information about neutron and antineutron contamination of photon spectrum in central Pb+Pb collisions at LHC, compare different methods of decreasing of this contamination, including time-of-flight analysis, and formulate requirements on the timing resolution of the PHOS spectrometer.

Physics background

There are several sources of direct photons in heavy ion collisions [3] which can be classified as follows:

1. In the initial stage of collision, during the penetration of colliding nuclei through each other, “prompt” photons are produced via basic quantum chromodynamics (QCD) processes – Compton scattering, annihilation and bremsstrahlung. Spectrum of these photons is not thermal (exponential), but rather power-low. As a result, prompt photons dominate at high transverse momenta (P_t >10 GeV/c). Recently a new process of direct photon production was proposed [4], related to the interaction of hard jets with a hot matter, created in the central zone of the collision. Photons, emitted in these interactions will have a bit softer spectrum, but still considerably contribute at high P_t. We will classify them as prompt photons below.
2. In the next stage of the collision the hot matter comes to an approximate thermal equilibrium and QGP formation may occur with temperatures between several hundreds MeV and 1 GeV. Being created, QGP matter rapidly expands, cools and the back transition from QGP to an ordinary hadronic matter takes place. Hadronic matter in turn expands and finally decuples into final state hadrons. As any hot matter, QGP and hadronic matter irradiates photons, called “thermal” photons. These thermal photons dominate in the transverse momentum range 1-10 GeV/c.

Sum of the thermal and prompt photons is referred to as “direct” photons. Some of final state hadrons, created in decoupling of hadronic matter, decay onto photons. Mainly these are π^o, η, ω, ρ mesons. Photons, originated in decays of final state hadrons are called as “decay” photons. These photons contribute up to 95% of the total photon yield and most strongly dominate at low momentum part of the P_t spectrum.

Inclusive photon spectrum in ultrarelativistic heavy ion collision is a sum of direct and decay photons. In Fig.1 one can find predictions of the ratio of N_{incl}/N_{dec} for Pb+Pb collisions at LHC [8] together with PHENIX RHIC experimental data [7]. For RHIC energies the ratio of direct photons over decay photons is expected to be larger than 10% for P_t >3 GeV/c. At the lowest energies main input to direct photons comes from thermal production, while for P_t>5 GeV/c direct photons originates mostly from primary hard QCD collisions. The overall behavior experimental data from RHIC and predictions for LHC are similar: direct photons contribute up to 10% at small P_t and prompt photons dominate at P_t>10 GeV/c. There are several predictions for direct photon spectra for LHC. The review of different predictions one can find in [8]. Most of available estimates agree that proportion of the direct photons do not exceed 10-15 % of the total photon yield.

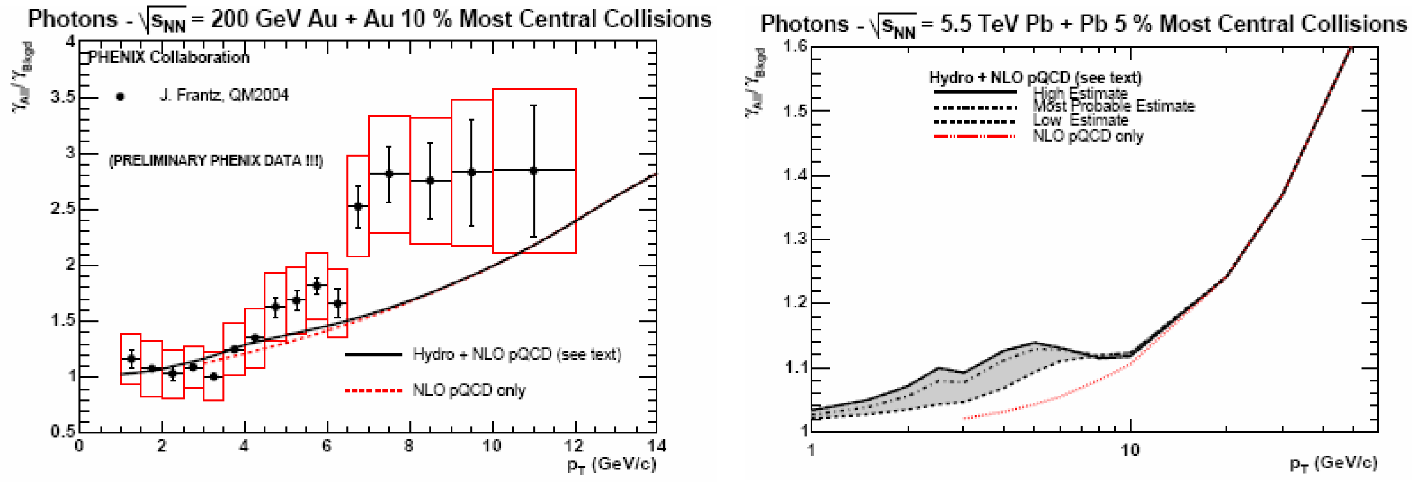

Fig.1.Ratio of inclusive photons to decay photons. Left plot - theoretical predictions for RHIC energies compared with PHENIX data [6]. Red boxes are systematic errors. Right plot - predictions for LHC [8].

Direct photons measurements in relativistic heavy ion collisions were started at CERN SPS accelerator – experiments WA80 [2], WA98 [5] and RHIC collider experiment PHENIX [6]. WA80 experiment presented only upper limits on direct photons production in 200 AGeV S+Au reaction. WA98 experiment was the first to publish significant excess of direct photons in 158 AGeV Pb+Pb reaction. RHIC experiment PHENIX [6] also reported high excess of direct photons in Au+Au collisions at 200 AGeV.

Experimentally, to extract direct photon yield one measures inclusive photon spectrum and spectra of final hadrons, calculates yield of decay photons and subtracts decay photon spectrum from the inclusive one. One can go even further and calculate yield of prompt photons (either from pQCD predictions or from pp and pA collisions at the same energy scaled with number of binary collisions) and subtracting it from direct photons spectrum calculate thermal part of the direct photon signal. Presently a large amount of data on prompt photon yield in pp and pA collisions exists from fixed target experiments up to Tevatron energies [4].

As it was described above, direct photon yield N_{dir} appears as a difference between the measured inclusive photon yield and the decay photon yield expected from decays of final state hadrons:

$$Ndir = Ninc - Ndec = Ninc \cdot (1 - \frac{Ndec}{Ninc})\,, \tag{1}$$

where N_{incl} and N_{dec} are amounts of measured inclusive and calculated background decay photons. Yield of background photons is calculated by Monte Carlo simulations of radiative decays of hadrons. The largest input to the background comes from two-photon decay of π^0 and η mesons, which are extracted from the same data used to obtain the inclusive photons yield. Together both mesons constitute up to 97% of decay photons. The rest 3% of background comes from ω, ρ and other resonances.

Since, as it was shown, direct photons make only 10 percent of the inclusive photon yield, the latter should be measured with accuracy, better than 1% and therefore, all contaminations, including neutron and antineutron should be estimated with corresponding precision.

Photon spectrometer

The photon spectrometer PHOS (PHOton Spectrometer) in the ALICE experiment [1] is designed to detect, identify and measure with high resolution the 4-momenta of inclusive photons in wide energy range from 200 MeV up to 100 GeV. In addition it is able to detect neutral mesons through their 2 photon decay channels. PHOS is an electromagnetic spectrometer consisting of Electro Magnetic Calorimeter (EMC) and Charge Particle Veto (CPV) [1,3,8] detectors. It will be situated on the bottom of the ALICE setup at distance 460 cm from interaction point and will cover $-0.12 < \eta < 0.12$ in pseudorapidity and 100^o in azimuthal angle. Its total area is approximately 8 m^2. PHOS is subdivided into 5 independent modules.

The EMC is an electromagnetic calorimeter of high granularity consisting of 17920 detection channels of lead-tungstate crystals, $PbWO_4$(or PWO), of 22x22x180 mm^3 in dimensions (20 radiation length in depth, one Moliere radius in the cross section), coupled to avalanche photodiodes with a low-noise preamplifiers. To increase the light yield of the PWO crystals the EMC will be operated at a low temperature. PHOS is subdivided into 5 modules. Each EMC module is segmented on 3584 detection channels (56x64).

The main requirements on the FEE electronics, ensuring measurement of direct photon spectrum with necessary levels of statistical and systematic errors, are:

- least count single channel 2-5 MeV;
- dynamic range from 5-10 MeV to 80 GeV;
- timing resolution 1 ns at 2 GeV (see below);
- production of trigger signals for L0 and L1 triggers.

Particle identification in PHOS

PHOS is able to measure three main parameters of particle which develop showers in it: deposited energy, position and time-of-flight. For photons and electrons deposited energy is equal to the total energy of the particle. Together with position it allows to reconstruct 4-momenta of incident particles. The energy and spatial resolutions as well as timing resolution measured using dedicated electronics with PHOS prototypes. Results are presented in Table.1.

Table 1. Experimentally measured parameters of PHOS.

Energy, GeV	1	2	15
Energy resolution, %	3.7	2	1.1
Position resolution, mm	4.5	2.5	1
ToF resolution, ns	0.5	0.5	-

Particle identification in the PHOS is based on three independent characteristics of the shower [9]:

- Shower shape (shower width, shower dispersion) cut. This cut is based on the fact that hadrons produce much wider shower in EMC than photons or electrons and thus it helps distinguish between photons and hadrons. This cut is most efficient when a shower is developed in several crystals, that is for clusters with relatively large energies E>1-1.5 GeV.
- Cut on time-of flight (ToF) of particles from the interaction point to EMC. This cut separates photons from massive hadrons. A particle is identified as a photon if its time of flight is consistent with ToF of photons which is in case of PHOS equal 15.3 ns. This cut is most efficient at small energies of the particles E < 2 GeV (see Fig.2), where we have good resolution between photons and hadrons. ToF cut is most important for discrimination between photons and soft antineutrons which might deposit a large energy due to annihilation.
- CPV cut, based on matching of the position reconstructed in EMC and CPV. This cut will reject charged particles and efficient at all energies.

One of the most considerable contaminations of the photon spectrum is contamination by antineutrons. Due to annihilation in the detector an additional 2 GeV are added to the kinetic energy and therefore such antineutrons contaminate photon spectrum at much higher transverse momenta and this contamination is significant.

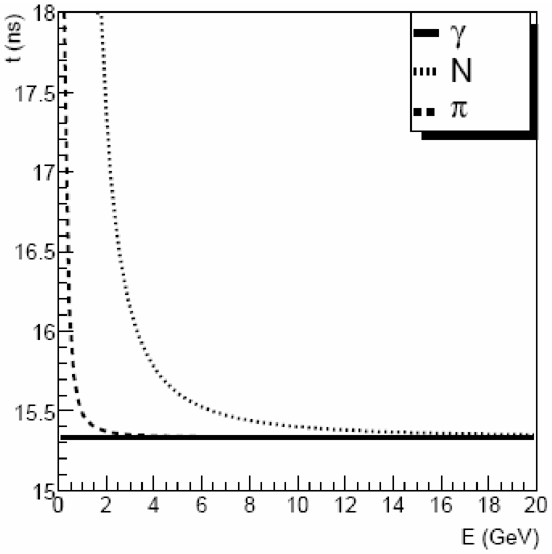

Fig.2 ToF of different particles from interaction point to the PHOS surface [9].

The efficiency of the ToF cut depends mainly on the time resolution of EMC. The measurements with fast PMTs and fast electronics show that crystals themselves can provide ToF measurements with resolution of 0.2 ns [12]. Our measurements with APD readout and specially constructed for ToF measurements and relatively fast electronics shows ToF resolution value ~0.5 ns for deposit energies more than 1 GeV [13]. Thus, the final ToF resolution also depends on light readout and properties of FEE.

The simulated dependence of the ToF from energy for different types of particle one can see on Fig.2. Using this figure one can estimate ToF resolution necessary to distinguish between photons and particles with a non-zero mass. For example, it is impossible to distinguish photons and nucleons with kinetic energies more than 3-4 GeV if a ToF resolution is 1 ns or larger.

Hadron contamination for different TOF resolutions

1.Simulation results.

In this section we present estimates of the photon spectrum contamination obtained within the ALIROOT framework. As we have already mentioned, the most important contaminations come from neutrons and antineutrons, therefore we first consider these contributions separately. In figs. 4-6 we present results of simulations [9] in which we use as input pion, neutron and antineutron spectra extracted from central HIJING events and transported through the ALICE setup using ALIROOT. Here only PHOS is included with constant ToF resolution. One can find relative yield of photons, *n* and *n̈* as a function of deposited energy without implementing of ToF cut (Fig.4) and with ToF cut corresponding to 1 ns (Fig.4) and 2 ns (Fig.6) resolutions. Dispersion cut was not included in all cases. Crucial input of *n* and *n̈* is around photon energies 1.5-2 GeV/C. If no ToF cut is implemented, one can expect *n̈* contamination on the level of 5-10 %. Implementation of ToF cut with 2 ns and 1 ns ToF resolution will decrease contamination to accepted level of 1-2% and 0.5% accordingly.

Simulation of the total hadron contamination to photon spectra taking in account energy dependence of TOF reported in [10] for central Pb-Pb collisions. In these simulations, hadron contamination arose from misidentification of all reconstructed particles as photons. From another hand, the efficiency of true photon identification becomes lower in the high-multiplicity environment caused by central Pb-Pb collisions and secondary interactions with the detectors situated in front of PHOS (ITS and TPC). Two cases of PHOS time-of-flight resolution σ_t were considered, σ_t=2 ns/E(GeV) and σ_t=4 ns/E(GeV). Results of simulation are presented in figs.7-9. To illustrate possibilities of background suppression data with a shower shape cut also presented. Implementation of the shower shape and ToF cuts lead to contamination of neutron and antineutron at 2 GeV on the level ~1% for 2 ns/E and ~2-3% for 4 ns/E ToF resolution. Without ToF cut contamination at 2 GeV is ~5%.

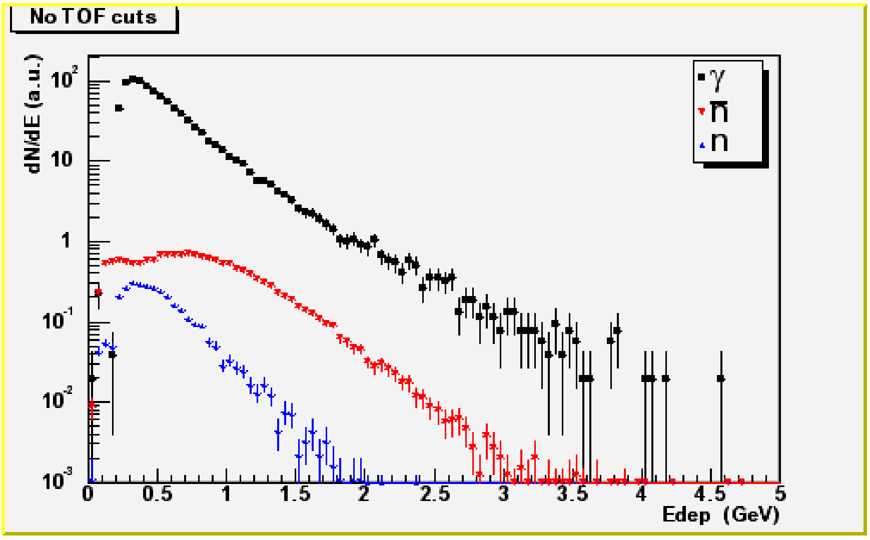

Fig.4 Photons, neutron and antineutrons identified as photons. No ToF cut[9].

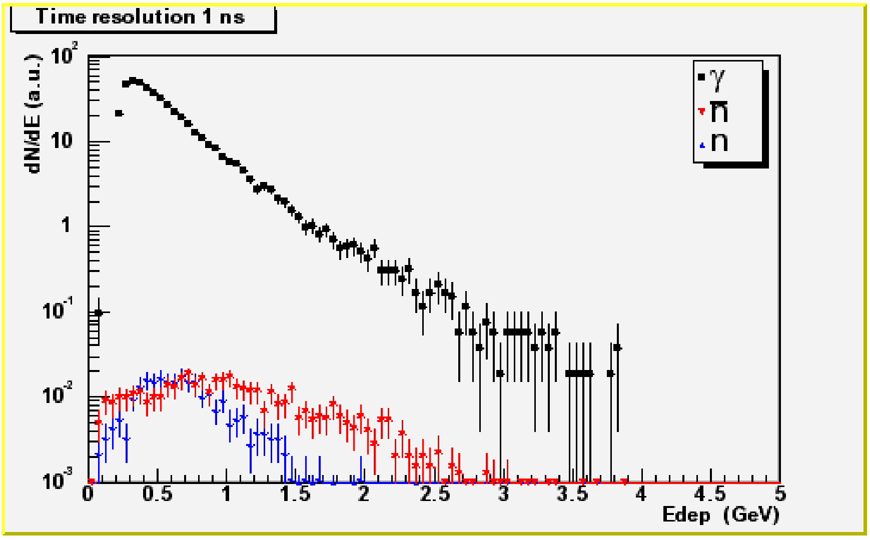

Fig.5 Photons, neutron and antineutrons identified as photons for time resolution 1 ns [9].

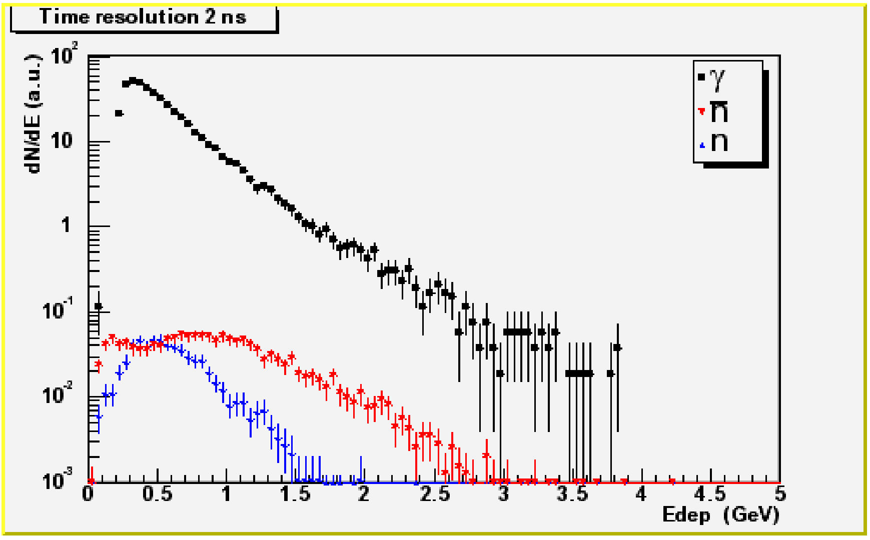

Fig.6 Photons, neutron and antineutrons identified as photons for time resolution 2 ns [9].

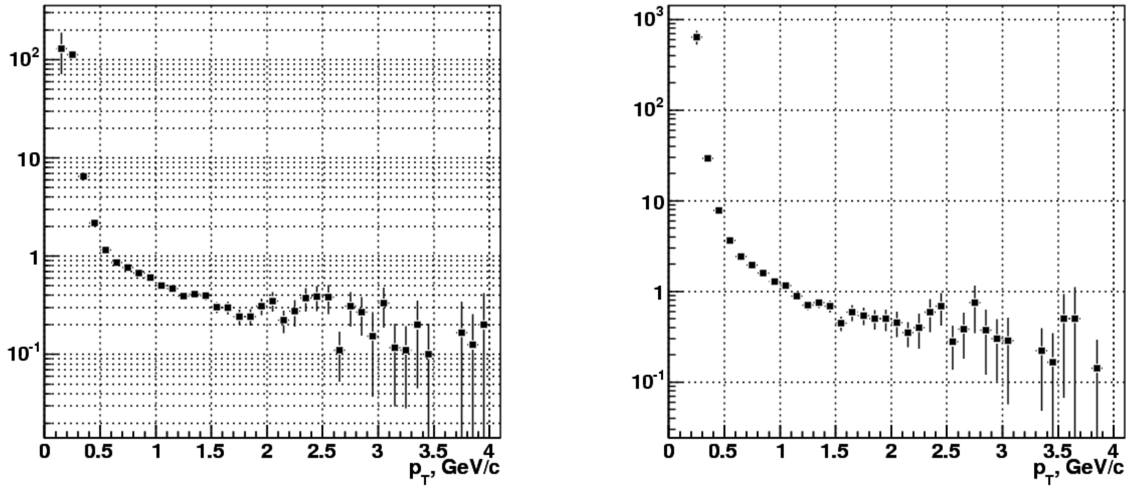

Fig.7. Contamination by neutral hadrons vs. P_t. *Only ToF* cut implemented. Left plot σ_t=2 ns/E, right plot σ_t=4ns/E, where E in GeV.

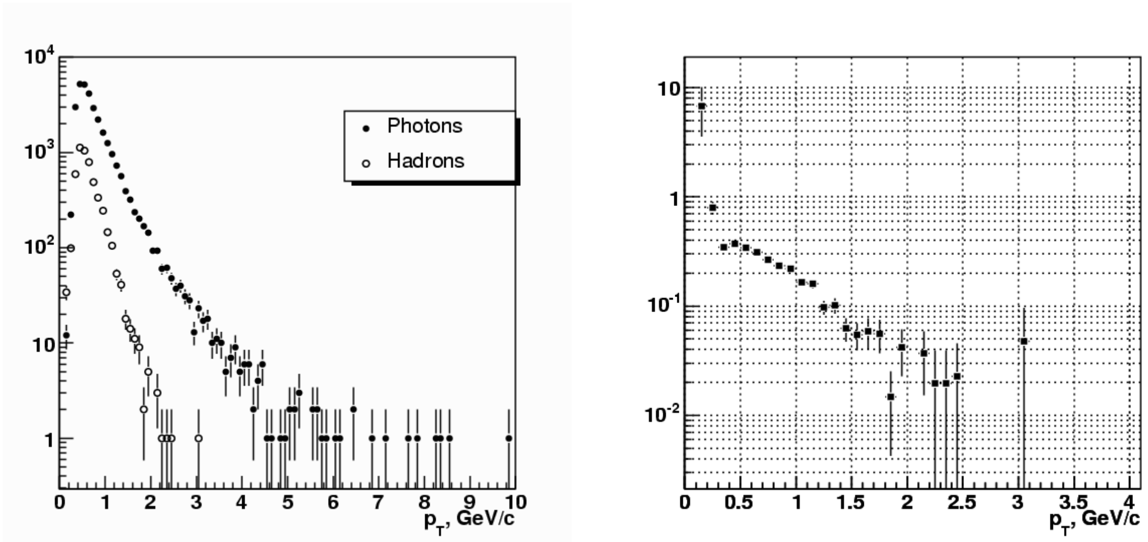

Fig.8. Contamination by neutral hadrons vs. P_t. *Shower shape and CPV* cuts are implemented. Left plot - spectra of photons and photon-like hadrons (hadrons identified as photons). Right plot - contamination of photon-like hadrons.

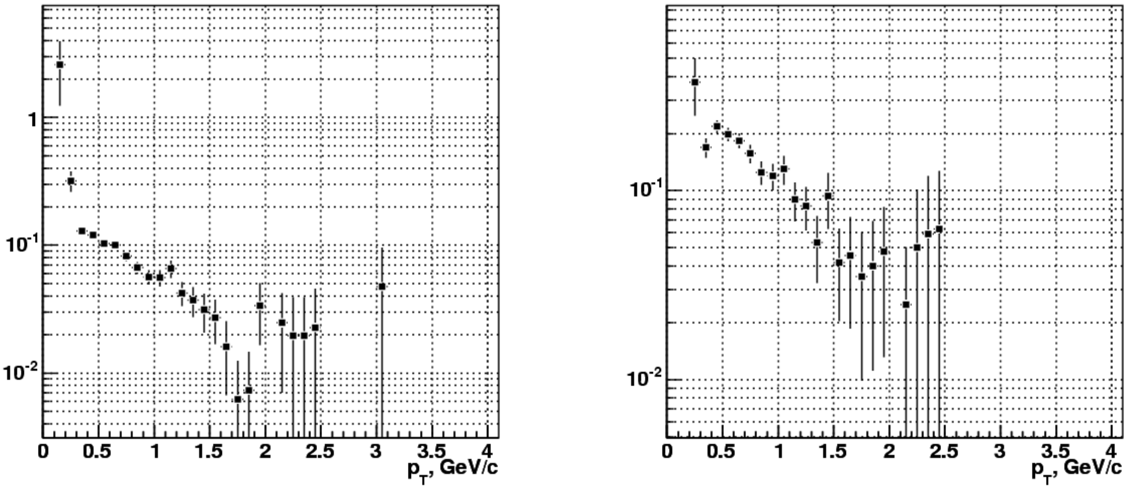

Fig.9. Contamination by neutral hadrons vs. P_t. *ToF, shower shape and CPV* cuts are implemented. Left plot - σ_t=2 ns/E, right plot - σ_t=4ns/E, where E in GeV.

To summarize the most critical contaminations to photon spectrum are antineutrons since they annihilate in crystals and deposit additional 2 GeV energy to their kinetic energy. This leads to contamination on the level more than 10% for energy of photons between 2-4 GeV. In contrast, neutron contamination is negligible 0.1% in all relevant P_t.

2. Experimental data.

Contamination level of neutral hadrons (mainly neutrons) for fixed target experiment WA98 [2] was on the level 1.9% at 2.5 GeV and 1% at 1 GeV for central 158AGeV Pb+Pb collisions.

Contaminations of antineutrons for d+Au collisions at RHIC energies [10] can be estimated from antiproton spectra, measured with PbSc PHENIX electromagnetic calorimeter with ToF resolution ~0.6 ns. The results are shown in table 2 for different types of cuts. Most critical contaminations are 22% measured at P_t around ~2 GeV/C. By implementing combination of shower dispersion and ToF cut one can reduce level of antineutron contamination up to level of <2%.

Table.2 Neutral hadron (neutron and antineutron) contamination for different cuts [11]

Pt, GeV/c	No cuts	ToF cut only	Shower shape cut only	ToF+shower shape cut
1	7%	<1%	3%	<1%
2	22%	3%	3%	2%
3	13%	10%	2%	2%

Conclusions

Direct photons are important powerful tool for investigation of the properties of the hot nuclear matter, and thermal photons is a clear signal about QGP formation. Theoretically predicted excess of direct photon production above decay photon spectrum at LHC might be higher than 10% at P_t>1-2 GeV/c.

Neutral hadrons – neutrons and antineutrons, can be misidentified as photons in segmented electromagnetic calorimeters, is one of the important source of systematic errors for the measurements of direct photons in ultra-relativistic heavy-ion reactions.

In fixed target experiments [2] antineutron contamination is negligible, but neutron can contribute up to 1.9 % in the total systematic error. For collider experiments (PHENIX at RHIC and ALICE at LHC) neutron contamination is negligible, but a antineutron one is more important since higher yield of antineutrons compared to fixed target experiments and annihilation in a crystal and deposition of the additional 2 GeV energy to their kinetic energy. This may result in contamination more than 10% for P_t between 2-4 GeV therefore suppression of antineutron contamination becomes very important.

Antineutron contamination can be decreased by 2 independent cuts, namely shower shape cut and ToF cut. Simulations demonstrate that combinations of 2 cuts may result to significant decrease (to the level 1-2%) of systematic error due-to antineutron misidentification only if ToF resolution of PHOS will on the level 1 ns at energy 2 GeV. Further suppression of antineutron contamination could be achieved by introducing corrections using antiproton spectra.

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