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Dzelepov Laboratory of Nuclear Problems

FINAL REPORT ON THE SUMMER STUDENT PROGRAM

Optimization of electromagnetic calorimeter for study of prompt photon productions at NICA SPD

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1 Abstract

NICA (Nuclotron-based Ion Collider fAcility) is a new accelerator complex designed at the Joint Institute for Nuclear Research (Dubna, Russia). One of the main goals of NICA is studying properties of strong interactions via measurements with prompt photons. Such measurements will be carried out on Spin Physics Detector (SPD). For the registration of photons on SPD a electromagnetic calorimeter (EMCAL) will be used. This report discusses the influence of the EMCAL parameters on the determination of the prompt photons signal of with their subsequent optimization.

2 Introduction

NICA (Nuclotron-based Ion Collider fAcility) [1] is a new accelerator complex designed at the Joint Institute for Nuclear Research (Dubna, Russia) to study properties of dense baryonic matter and the nature and properties of strong interactions between elementary constituents of the Standard Model of particle physics – quarks and gluons. For studying properties of strong interactions longitudinally and transversally polarized protons and deuterons will be used.

NICA will provide variety of beam species ranged from protons and polarized deuterons to very massive gold ions. Heavy ions will be accelerated up to kinetic energy of 4.5 GeV per nucleon, the protons – up to 12.6 GeV. The heart of the NICA complex is the upgraded accelerator "Nuclotron" (have being working at JINR since 1993). The two interaction points are foreseen at the NICA collider rings: one for heavy-ion studies with the MPD detector and another for polarized proton and neutron beams for the SPD experiment.

SPD is a Spin Physics Detector, which is specialized on measurements of spin effects in collisions of non-polarized, longitudinally and transversely polarized proton and deuteron beams. These measurements can provide an access to all leading twist collinear and Transverse-Momentum Dependent parton distribution functions of quarks and anti-quarks in nucleons.

According to the naive quark-parton model (QPM) of nucleons, the proton (neutron) consist of three spin-1/2 valence quarks. Quarks interact between themselves by exchange of gluons, which are also the nuclear constituents. Gluons can produce a sea of any type (flavor) quark–anti-quark pairs. Parton Distribution Functions (PDFs) are universal characteristics of the internal nucleon structure.

Physicists expected that the quarks carry all the proton spin. However, the value of the quark contributions, determined in EMC experiment, is only about 33% of total proton spin. This surprising and puzzling result was termed the "proton spin crisis".

Now the quark-parton structure of nucleons and respectively the quark-parton model of nucleons are becoming more and more complicated. In Quantum Chromodynamics (QCD), PDFs depend not only on quark and gluon momentum fractions, but also on Q^2 , four-momentum transfer. Partons can have an internal momentum, k, with possible transverse component, k_T. A number of PDFs depends on the order of the QCD approximations. Measurement of collinear (integrated over k_T) and Transverse Momentum Dependent (TMD) PDFs, which are not well measured or not discovered yet, is the main goal of SPD.

Measurement with prompt photons is direct access to gluon distributions in nucleons [2]. Prompt photon is produced via gluon Compton scattering ($qg \rightarrow q\gamma$) sub-process, and quark anti-quark annihilation ($q\bar{q} \rightarrow g\gamma$) subprocess.

The total cross section of the direct photon production in the pp-collision at $\sqrt{s}$=24 GeV via the Compton scattering (according to PYTHIA 6.4) is equal to 1100 nb, while the cross section of the $q\bar{q}$ annihilation is about 200 nb. So, the gluon Compton scattering is the main mechanism of the direct photon production.

From the global QCD analysis of all DIS data one can find the non-polarized nucleon PDFs (the superscript a is usually omitted) for each parton.

The spin-dependent part of the cross section can be studied measuring of the transverse single spin asymmetry A_N defined as follows:

$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

Here $\sigma^{\uparrow}$ and $\sigma^{\downarrow}$ are the cross sections of the direct photon production for the opposite transverse polarizations of one of the colliding protons.

Total pp cross section is 40 mb and planed luminosity of NICA is about $L = 10^{32}\ cm^{-2}\ s^{-2}$. Average multiplicity of decay photons is about 9 photons per event [3]. It is expected 34800000 background photons and 122 prompt photons per 1 second. The main source of photons (almost 99%) in proton-proton collisions is production and decay of π^0 and η mesons. Number of photons from π^0 decays exceeds by more than 20 times the number of photons from η decays. Therefore, in this report, the contribution of photons from the η decays will not be considered.

The π^0 decay photons can be categorized into two groups. One is the group of two tag photons, which means that both of two photons from π^0 decay are detected. Another group is one tag photon, which means that one photon from π^0 decay escapes from a detector or it cannot be detected due to the bed registration efficiency, bad energy resolution of the detector, bad channel of the detector and so on. Such photons could be considered as the prompt photons because it has no pair to reconstruct π^0. One tag photons is the main background in prompt photons measurements.

Almost the only one way to measure number of prompt photons at the experiment is to reconstruct all possible photons of π^0 decays and to take in account inefficiency of reconstruction, obtained with the help of Monte-Carlo simulation. The simulation calculates R which is the ratio of one tag photons to two tag photons. Then, the one tag photon is evaluated by multiplying the R by the number of two tag photons. The prompt photon yields can be evaluated with the following equation:

$$N_{prompt} = N_1 - 2N_0k$$

where $k = \frac{1}{R} - 1$, N_{prompt}, N_0, N - numbers of prompt photons, all detected photons and π^0 mesons. Effective reconstruction of π^0 decays is the main way to suppress the background in prompt photons measurements.

For the registration of photons on SPD a electromagnetic calorimeter will be used.

3 Electromagnetic calorimeter (EMCal)

At present, various variants of construction of an electromagnetic calorimeter are considered. The most likely an electromagnetic calorimeter of shashlyk type will be used.

Sampling calorimeter essential property:

1. fine Scintillator – Lead structure with sampling fraction (SF) 20-30;
2. moliere Radius is about 3.3 cm – 3.4 cm;
3. number of Radiation lengths 15-17 – depended from number of layers;
4. granularity – rectangular cell size 4 cm – 5.5 cm – depended from particles occupancy;
5. scintillator quality: composition, attenuation length;
6. photo Sensor Photodetector Efficiency (PDE);
7. long time stability (especially thermostability);
8. WLS fibers quality: diameter, attenuation length.

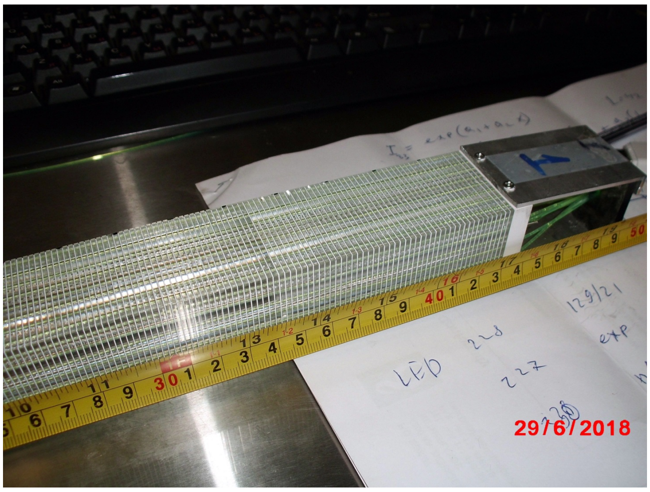

Figure 1: EMCal first module assembling to test wrapping and mirror conditions.

This report discusses several tasks that were solved during JINR Summer Students Program. They are all connected with the optimization of electromagnetic calorimeter for study of prompt photon productions at NICA SPD.

4 Methods

4.1 Goals

The main goal of this practice was study of the influence of the EMCAL parameters on the determination of the prompt photons signal of with their subsequent optimization.

The following tasks were solved: study of the EMCAL parameters influence on the width of the two photons invariant mass distribution; study of the EMCAL energy threshold on the π^0 reconstruction efficiency; study of the dependence of the π^0 reconstruction efficiency on the size of the calorimeter cells.

4.2 Software

Monte Carlo simulation, event reconstruction for simulated data, data analysis and visualization are performed by an object oriented C++ toolkit SPDroot [4]. It is based on the FairRoot framework initially developed for the FAIR experiments at GSI Darmstadt and partially compatible with MPDroot and BM@Nroot software used at MPD and BM@N, respectively.

The SPD detector description for Monte Carlo simulation is based on the ROOT geometry while transportation of secondary particles through material of the setup and simulation of detector response is provided by GEANT4 code. The standard multipurpose generators like Pythia6 and Pythia8 as well as specialised generators can be used for simulation of primary nucleon-nucleon collision.

4.3 Two photons invariant mass distributions

π^0 can be reconstructed via photons invariant mass distribution. Invariant mass was calculated as $M = (P_1 + P_2)^2 = P_1 P_2$, where P_1 and P_2 are four-vectors of photons.

The resolution of energy can be estimated as $\frac{\sigma}{E} = \sqrt{A^2 + \frac{B^2}{E}}$, where E- is the energy of detected particle, A represents detector inhomogeneity, B represents statistical broadening. For SPD these parameters are: $A = 0.01$ and $B = 0.038$ GeV$^{0.5}$.

To take into account resolution of the detector, the energy of the detected particle was randomly generated according to the Gaussian distribution with the $\sigma = E\sqrt{A^2 + \frac{B^2}{E}}$. As the result peak corresponding to pions in the invariant masses distribution takes the Gaussian shape with the σ.

Figure 2 shows the invariant mass spectrum of two photons for the EMCAL threshold of 100 MeV and 500 MeV.

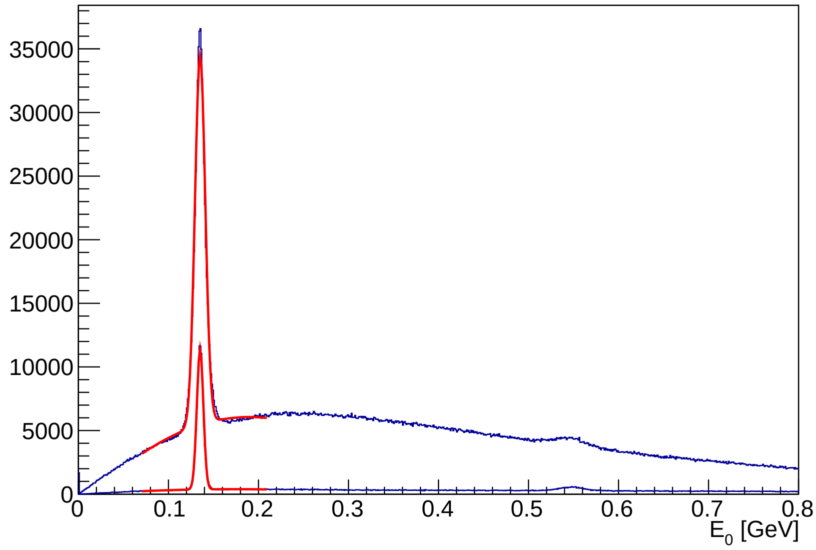

Figure 2: Invariant mass spectrum of two photons for the EMCAL threshold of 100 MeV and 500 MeV.

4.4 Dependence of the π^0 reconstruction efficiency on the energy threshold for photons in the detector

Dependences of π^0 reconstruction efficiency on the energy threshold for photons in the detector were obtained.

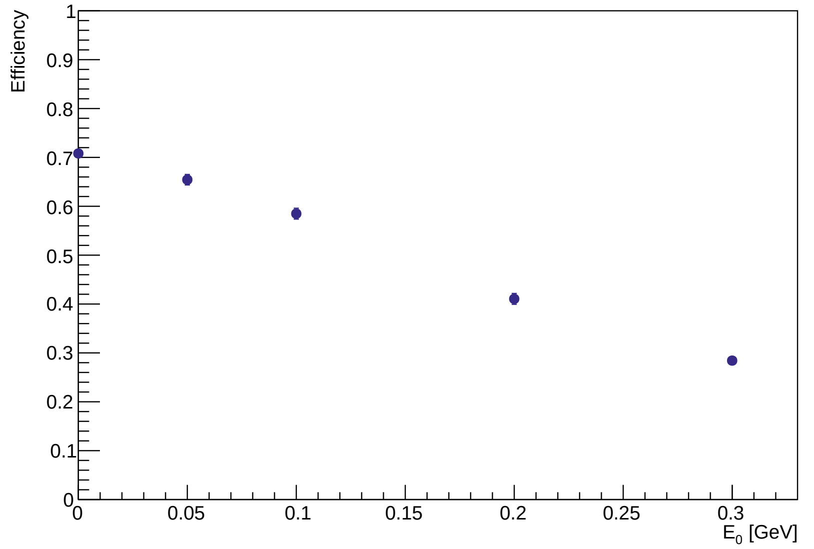

Figure 3: Dependences of π^0 reconstruction efficiency on the ECAL energy threshold.

4.5 Dependence of the π^0 reconstruction efficiency on the size of the calorimeter cells

EMCal consist of rectangular cells. In the case when in one event two or more photons enter the same cell, only first photon will be detected. This happens because of nonzero EMCal time resilution. Thus, the size of the cells will directly affect the photons detecting efficiency, and hence π^0 reconstruction efficiency.The smaller the cell size, the higher reconstruction efficiency. However, the minimum cell size is determined by the Molière radius. The Molière radius is a characteristic constant of a material giving the scale of the transverse dimension of the fully contained electromagnetic showers initiated by an incident high energy electron or photon. At present, it is assumed that a calorimeter with Moliere Radius is about 3.3 cm – 3.4 cm will be used. Based on this fact, cells with size 4 cm - 5.5 cm are planned to use.

It is also possible that the photon hits the cell boundary. In this case, none of the cells that have a given boundary can no longer register photons in this event.

In this work dependence of reconstruction efficiency on cell size was studied in the following way. In the case when the distance between the coordinates of the photons registration points is smaller than the specified size R, it was considered that only the first photon was detected.

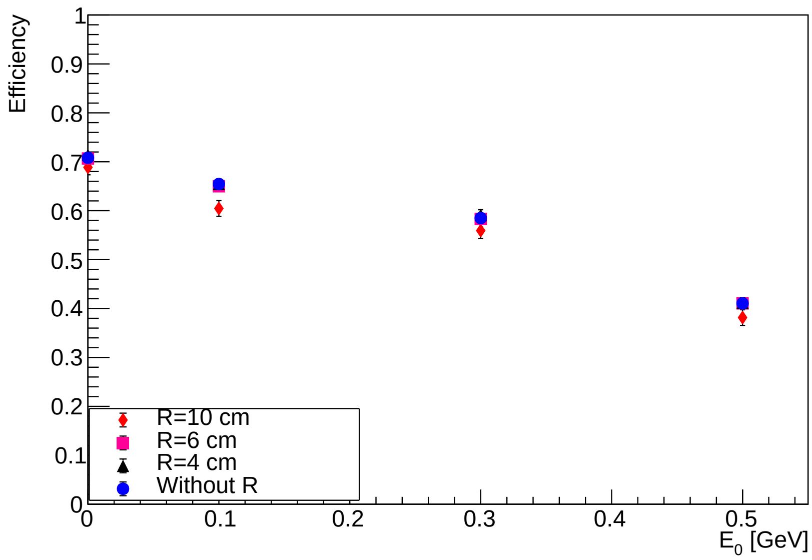

Figure 4: The efficiency of the $\pi^0 \to \gamma\gamma$ decay reconstruction as a function of cluster energy threshold for different granularities of the ECAL.

5 Conclusion

The assigned tasks were solved. It was obtained, that:

1. Width of the π^0 peak in the invariant mass distribution is $(5.74 \cdot 10^{-3} \pm 10^{-5})$ GeV for 0.1 GeV EMCAL energy threshold and $(3.62 \cdot 10^{-3} \pm 10^{-5})$ GeV for 0.5 GeV EMCAL energy threshold.

2. π^0 reconstruction efficiency grows with decreasing EMCAL energy threshold.

3. π^0 reconstruction efficiency weakly depends on the EMCAL cell size, until this size exceeds 10 cm.

This results will be used in conceptual design project of the SPD set-up.

References

[1] http://nica.jinr.ru/

[2] Letter of Intent presented at the meeting of the JINR Program Advisory Committee (PAC) for Particle Physics on 25–26 June 2014.

[3] http://nuclphys.sinp.msu.ru/ihem/ihem03.htm

[4] https://git.jinr.ru/nica/spdroot