JOINT INSTITUTE FOR NUCLEAR RESEARCH
Dzhelepov Laboratory of Nuclear Problems
Scientific-Experimental Division of Colliding Beams

FINAL REPORT ON THE SUMMER STUDENT PROGRAM

“Simulation of charmonium events in different configurations of the SPD detector at NICA collider”

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Abstract

Project NICA (Nuclotron based Ion Collider fAcility) is formed by a new accelerator complex designed at the Joint Institute for Nuclear Research (Dubna, Russia) to study the properties of dense baryonic matter. After putting the NICA collider into operation, scientists will try to create in laboratory a state of matter which is a mixed phase of quark and hadronic matter. It will provide several beam species with energies up to 13 GeV. Two interaction points will be located at the NICA collider rings, one for heavy ion studies with the MPD (Multiple Purpose Detector) and another for polarized beams in the SPD (Spin Physics Detector). The main goal of SPD is to provide information about spin structure of nucleon. In this work the SPDRoot tool was used for simulation and analysis of results. J/ψ events were simulated in solenoid and toroid configurations of SPD magnetic field in order to obtain efficiency distributions. The obtained very low statistics for solenoid did not reflect well muon absorption, but for toroid the inefficiencies are caused by two effect: electromagnet's material and low momentum of muons. SPDRoot was upgraded to include Hybrid configuration, then J/ψ events were simulated. For this configuration the efficiency for J/ψ detection was obtained $\eta = (93.1 \pm 0.1)\%$. The loss of efficiency is caused by the absorption of muons in the rings of the magnet and the trapping of low moment muons by the applied magnetic field. Also, were simulated the J/ψ distributions of momentum components, parallel and transversal to z axis, and the X_{cj} events using the channels $\mathrm{g} + \mathrm{g} \rightarrow \mathrm{X}_{\mathrm{c}0,1,2} + \mathrm{g}$. The detection efficiency is almost the same for $\mathrm{X}_{\mathrm{c}0,1,2}$, about 80 %.

Introduction

Project NICA (Nuclotron based Ion Collider fAcility) is formed by a new accelerator complex designed at the Joint Institute for Nuclear Research (Dubna, Russia) to study the properties of dense baryonic matter. After putting the NICA collider into operation, scientists will try to create in laboratory a state of matter which is a mixed phase of quark and hadronic matter. It will provide several beam species with energies up to 13 GeV. The two interaction points will be located at the NICA collider rings, one for heavy ion studies with the MPD (Multiple Purpose Detector) and another for polarized beams in the SPD (Spin Physics Detector).

One of the main goals of SPD is to measure the asymmetries in the lepton pair production in the collision of non-polarized, longitudinally and transversally polarized proton and deuteron beams looking for knowledge about. Possible layout of this detector is under discussion. It will provide information about spin distributions in nucleon structure.

In this work it is given a brief description about NICA project and SPD as well as Charmonium and its formation. It is used SPDRoot as a tool for simulation and analysis of results. J/ψ events are simulated in solenoid and toroid configurations of SPD magnetic field in order to obtain efficiency distributions.

A hybrid configuration is also considered, charmonium distributions are computed and it is analyzed the contributions of decay channels in efficiency.

NICA

NICA is under implementation at the Joint Institute for Nuclear Research in Dubna as a flagship project in High Energy Physics [1]. It consists of a Nuclotron based Ion Collider, Baryonic Matter at Nuclotron (BM@N) experiment, Multiple Purpose Detector (MPD) and the Spin Physics Detector (SPD).

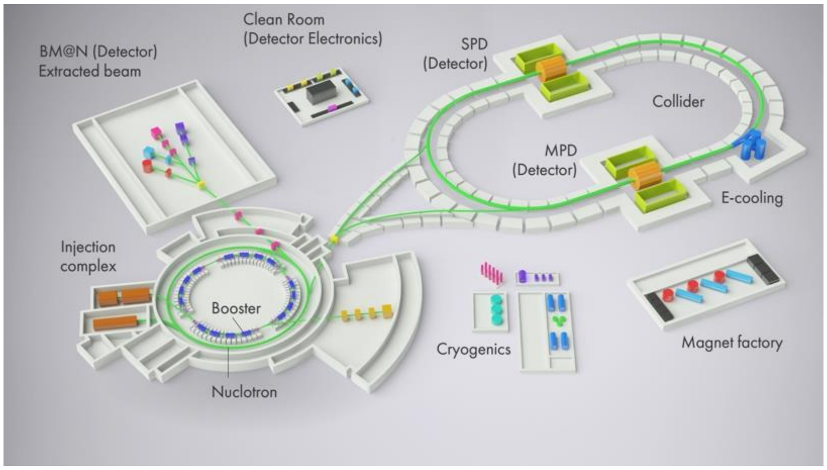


Fig. 1. Scheme of the NICA Complex.

The main goal of these facilities is the search for the mixed phase of quark and hadronic matter as a consequence of a first order transition in analogy with a liquid-gas phase. For that reason, it will have an energy range of $\sqrt{s_{\mathrm{NN}}} = 4 - 11\ \mathrm{GeV}$ for gold and lighter nuclei which will provide a great opportunity to explore the properties of strongly interacting matter in a region of temperatures and baryons densities where is suspected to be the critical point in the QCD phase diagram (see Fig. 2).

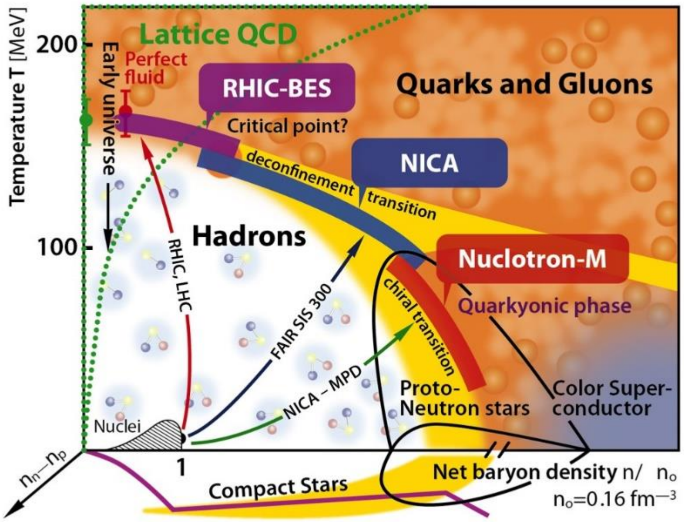


Fig. 2. QCD Phase Transition.

Spin Physics Detector

The SPD is still under design, the final version will be defined after detailed Monte-Carlo simulations focusing in the main processes it should study.

SPD must be capable of obtaining data about significant effects concerning spin and polarization, such as:

- Drell-Yan (DY) process with longitudinally and transversely polarized proton and deuteron beams from which it could be extracted Parton Distribution Functions (PDFs).
- PDFs from J/Ψ production.
- Spin effects in baryon, meson and photon production.
- Diffractive processes.
- Cross sections, helicity amplitudes and double spin asymmetries in elastic reactions.
- Spectroscopy of quarkonium.

Starting from that base SPD has some minimal requirements:

- Close to 4π geometrical acceptance.
- High precision ($\sim 50 \mu m$) and fast vertex detector.
- High precision ($\sim 100 \mu m$) and fast overall tracker.
- Good particle ID capabilities.
- Efficient muon range system.
- Good electromagnetic calorimeter.
- Low material budget over the track paths.
- Trigger and DAQ system able to cope with event rates at luminosity of $10^{32} (cm\ s)^{-1}$.
- Modularity and easy access to detector elements, making possible further configuration and upgrade.

Taking this into account the most likely configuration for the detector is reported in [2]:

Proposed scheme of the SPD (Fig. 3):

- Toroid/Solenoid magnet system.
- Silicon Vertex Detector.
- Drift chambers.
- Electromagnetic calorimeter.
- Muon System.
- Trigger System.
- End-cup detector with Range System, tracking system and electromagnetic calorimeter.

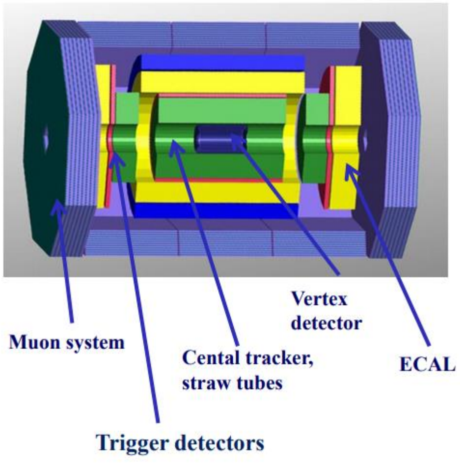
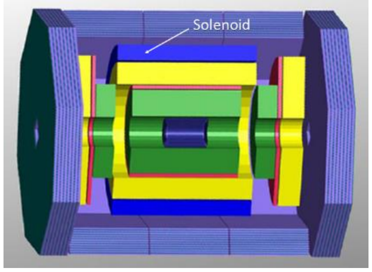


Fig 3. Main SPD components.

Concerning the magnet system there are three main configurations that has been taken into account:

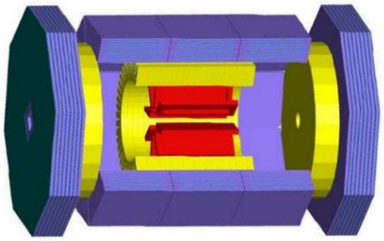
- Solenoid:



It consists of a solenoid (Fig. 4) that produces a magnetic field with a homogeneity that is foreseen to be better than 1% over the central zone. The main disadvantage is that it needs a special magnetic shield for transverse polarized beams and it has influence on beam polarization. In relation to the advantages are the acceptance and uniformity of the field of this configuration.

Fig. 4. Solenoid configuration.

- Toroid:



It consists of 8 superconducting coils (Fig. 5, red color) symmetrically placed around the beam axis. The key drawbacks are the loss of acceptance and the complexity of the field, but, as benefit it obtains no magnetic field in the beam pipe and the spectrometer can be compact.

Fig. 5. Toroid configuration.

- Hybrid:

It is a hybrid version that contains both toroid and solenoid, as a result it would have better acceptance and the spectrometer would remain compact. It is under study yet.

SPDRoot

It is a simulation and analysis framework based in object-oriented C++ designed for NICA/SPD Detectors. It contains experiment-specific libraries and scripts artifacts which permits to gather information about the interactions occurring in the detector environment during the experiment. The SPD detector description for Monte Carlo simulation is based on ROOT geometry, transportation of secondary particles through material is provided by Geant4 code and Pythia6 is used as specialized generator in primary proton-proton collision.

Charmonium

It can be established a close analogy with the hydrogen atom or positronium. In both cases the main interaction is the electromagnetic. In charmonium the leading is the strong interaction, quantum numbers and basic properties can be described with a pair charm and anti-charm. Using the spectral notation, then different levels of energy can be defined to be several particles already discovered (Fig. 6). A wider analysis about charmonium is done in [3]. Charmonium production is of great interest, the description of the process is a challenge and an important test for our understanding of QCD. Comprehensive understanding would make us to be able to separate quark-antiquark annihilation from gluon-gluon fusion contributions and thus, to benefit from statistics of inclusive J/ψ events to measure and interpret transverse spin asymmetries. Also, production is sensitive to gluon content of colliding hadron, while experimentally J/ψ can be easily reconstructed from the very clear di-lepton decay modes, so it is a wonderful tool to probe gluon parton distribution functions.

Charmonium production

There are two contemporary models describing charmonium production: Color Evaporation Model (CEM) and Non-Relativistic Quantum Chromo-dynamics. Both take into account color-singlet and color-octet configurations.

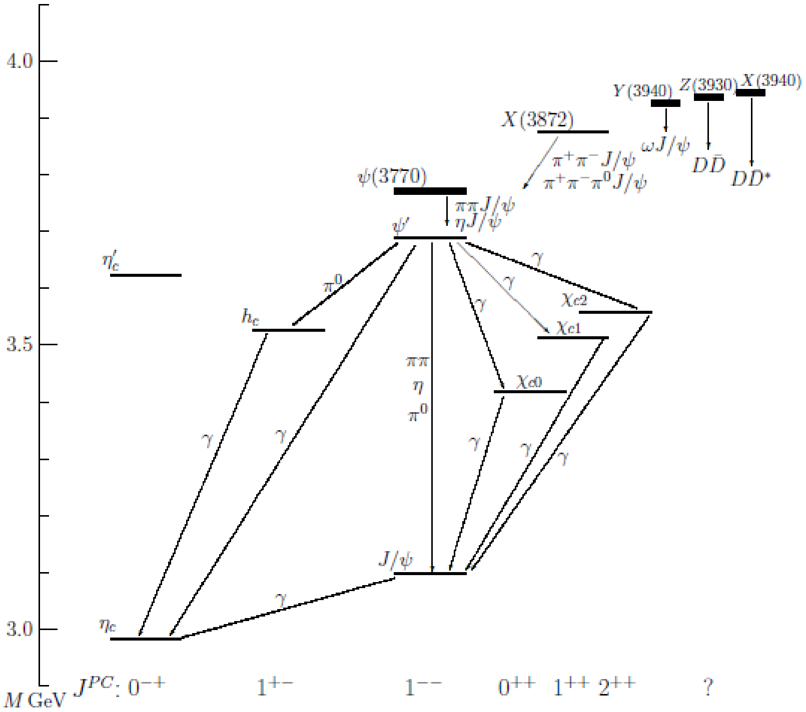


Fig. 6. Main states of charmonium.

In CEM charmonium production is proportional to the cross section of $c\bar{c}$ pair production between $2m_c$, where m_c is the mass of charm quark, and open charm threshold. The sum over colors and spins of charm and anti-charm is implied. The proportionality coefficients are assumed to be process independent. This model is deeper explained in [4]. Despite simplicity, it describes very well the $\sqrt{s}$-dependence and differential cross-section.

The NRQCD is the most rigorous model (details can be seen in [5, 6]). It is based in the factorization conjecture where the parton cross-section factorizes to hard perturbative part that describes the production of $c\bar{c}$ pair on the scale $\frac{1}{m_c}$ and non perturbative soft part that describes formation of charmonium state.

Results and discussion

Loss of efficiency in solenoid

Simulations of production of J/ψ were made using SPDRoot, a J/ψ meson is said to be reconstructed (taken into account in the results) if it decays into a pair muon-antimuon and then they are detected in the range system. So J/ψ detection efficiency depends on muon's. The most significant result in the solenoid configuration is the efficiency of muon detection (Fig. 7, taken from [7] for purposes of illustration, results were at very low statistics and did not reflect well this effect) as a function of theta (shown in Fig. 8).

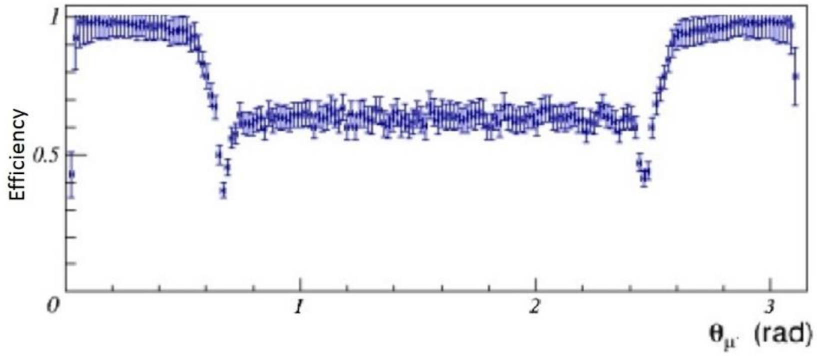


Fig. 7. Efficiency vs. theta in range system solenoid configuration.

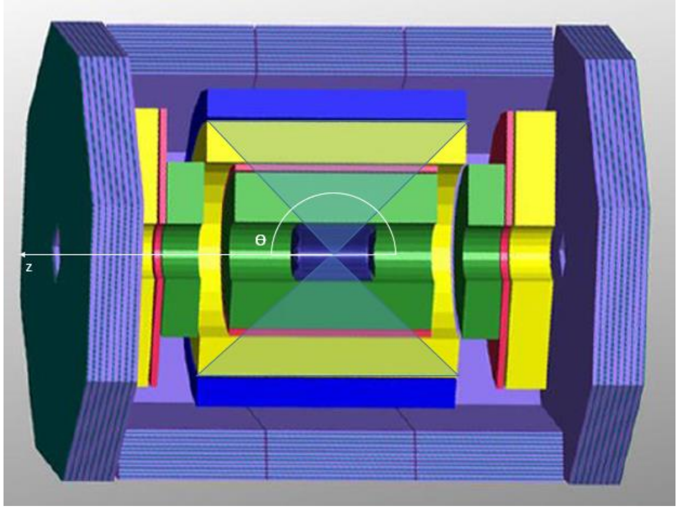


Fig. 8. Theta and Z axis in solenoid configuration.

The collision point is in the middle of Fig. 8. As it can be seen, blue shade corresponds to the angle that includes the solenoid (represented in intense blue) whose material produces the loss of efficiency reflected in Fig. 7 between 0.6 rad and 2.6 rad. For other distributions look at [7].

Loss of efficiency in toroid configuration

As in solenoid configuration J/ψ detection depends on muon's. In this case inefficiencies are caused by two effect: electromagnets material and low momentum of muons.

Electromagnets contribution can be seen in Fig. 9, angle theta is represented in Fig. 10 as well as the rings of the toroid in red.

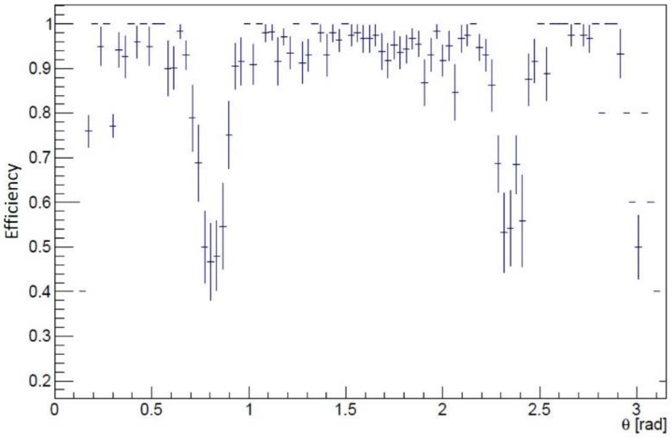


Fig. 9. Efficiency vs. theta in toroid configuration.

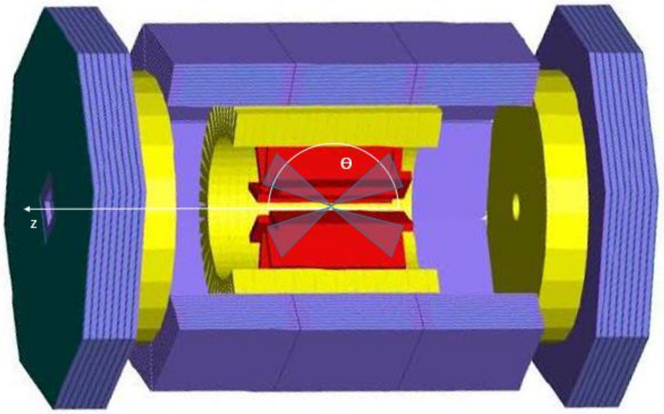


Fig. 10. Z and theta in toroid configuration.

Collision point is in the middle of Fig. 10, blue shade indicates the angle where muons are more absorbed by rings material.

Low momentum muons are harder to detect because of the magnetic field applied, they are trapped inside the rings and decay before they reach the range system, simulation results are shown in Fig. 11.

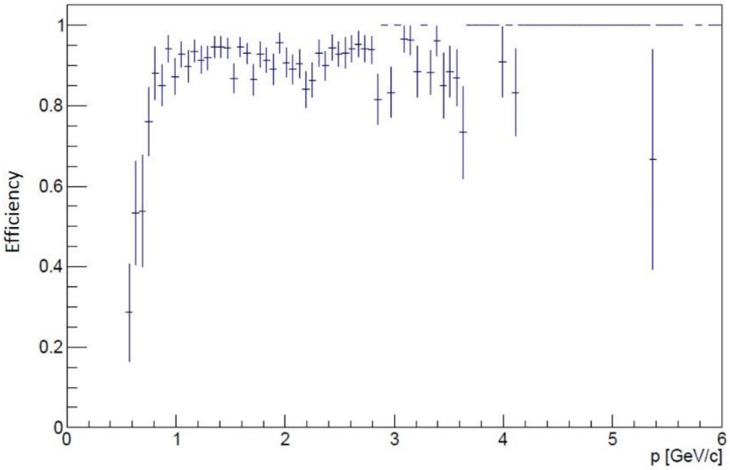


Fig. 11. Efficiency vs. momentum of muons.

J/ψ Distributions in Hybrid configuration

SPDRoot was upgraded to include Hybrid configuration, then J/ψ events were simulated. In Fig. 12 it is shown the distributions of J/ψ which decay into muon pairs, it was taken the same system of reference that in toroid configuration.

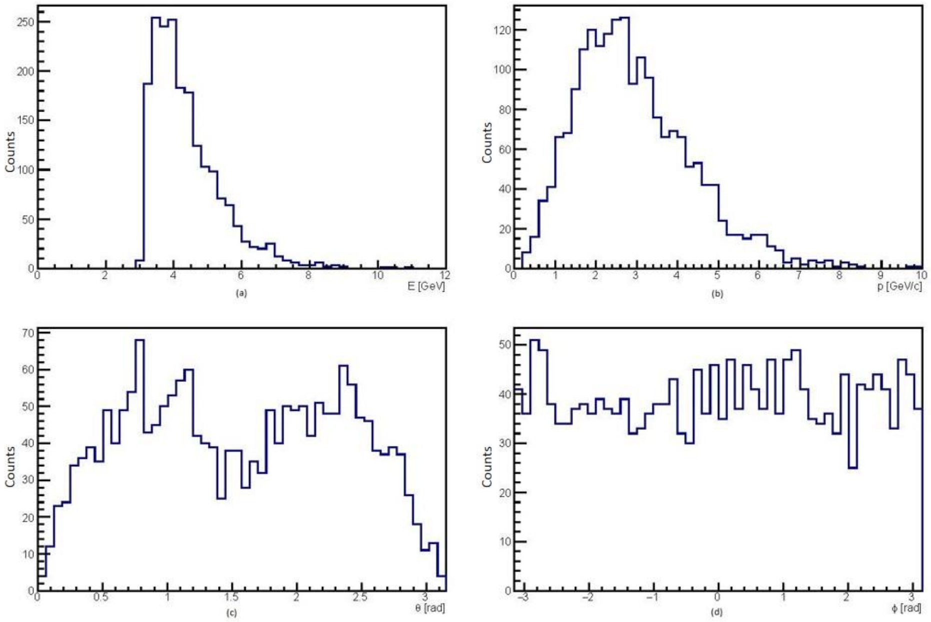


Fig. 3. J/ψ distributions in hybrid configuration, (a) counts vs. energy, (b) counts vs. momentum, (c) counts vs. theta and (d) counts vs. phi.

If both muons are detected in the range system, J/ψ is said to be reconstructed. According to that, efficiencies were calculated (Fig. 13). The efficiency for J/ψ detection obtained is $\eta = (0.931 \pm 0.001)$.

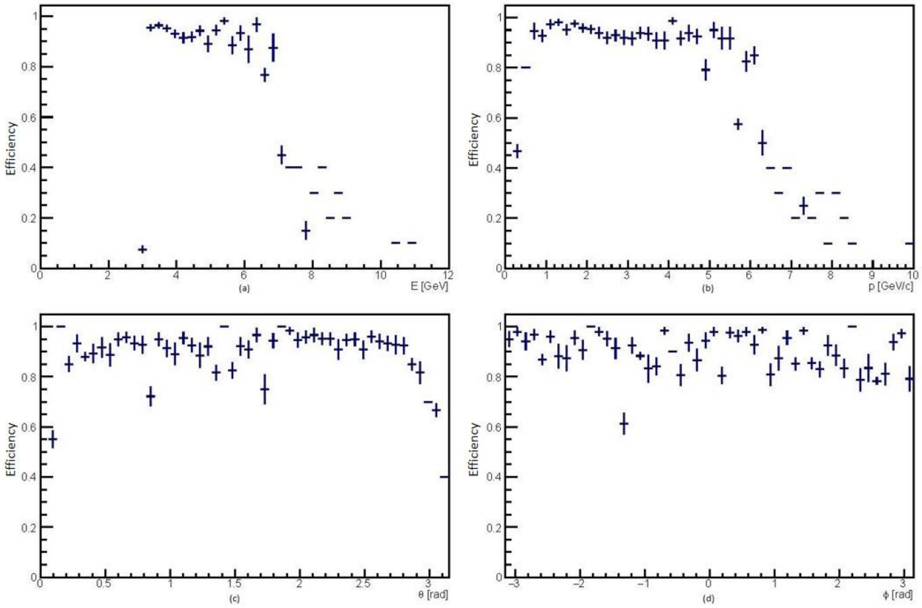


Fig. 4. J/ψ efficiencies in hybrid configuration, (a) efficiency vs. energy, (b) efficiency vs. momentum, (c) efficiency vs. theta and (d) efficiency vs. phi.

The loss of efficiency is caused by the absorption of muons in the rings of the magnet (Fig. 14 (a)), made evident in Fig. 14 (d), and by the magnetic field applied which makes muons with low momentum to be trapped and decay before they reach the range system, evidenced in Fig. 14 (b).

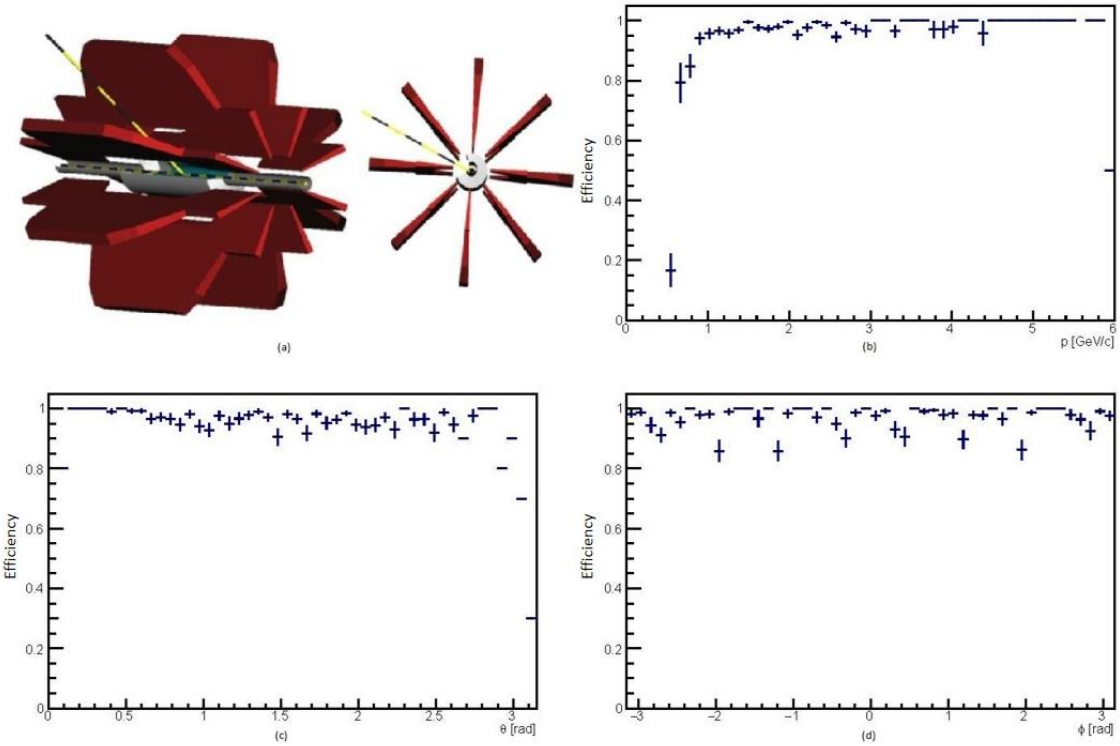


Fig. 14. Muon efficiencies in hybrid configuration, (a) magnet rings, (b) efficiency vs. momentum, (c) efficiency vs. theta and (d) efficiency vs. phi.

It was also simulated J/ψ distributions of momentum components, parallel and transversal to z axis (Fig. 15). Most probable value of $p_{||}$ oscillates around 0 while p_T around $1.5\ \mathrm{GeV}/c$.

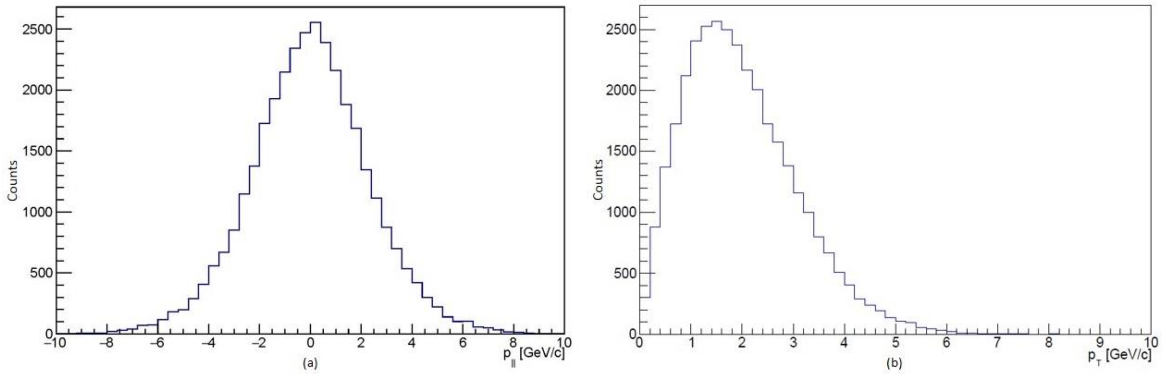


Fig. 55. J/ψ distributions for components of momentum, (a) parallel component and (b) transversal component.

$\mathrm{X_{cj}}$ Distributions in Hybrid configuration

$\mathrm{X_{cj}}$ events were simulated using the channels $\mathrm{g} + \mathrm{g} \rightarrow \mathrm{X_{c0,1,2}} + \mathrm{g}$. X_{cj} is said to be reconstructed if it decays into J/ψ and a photon, J/ψ decays into a muon pair, both muons are detected in the range system and the photon is detected in the electromagnetic calorimeter. Efficiencies of detection are shown in Fig. 16, 17 and 18.

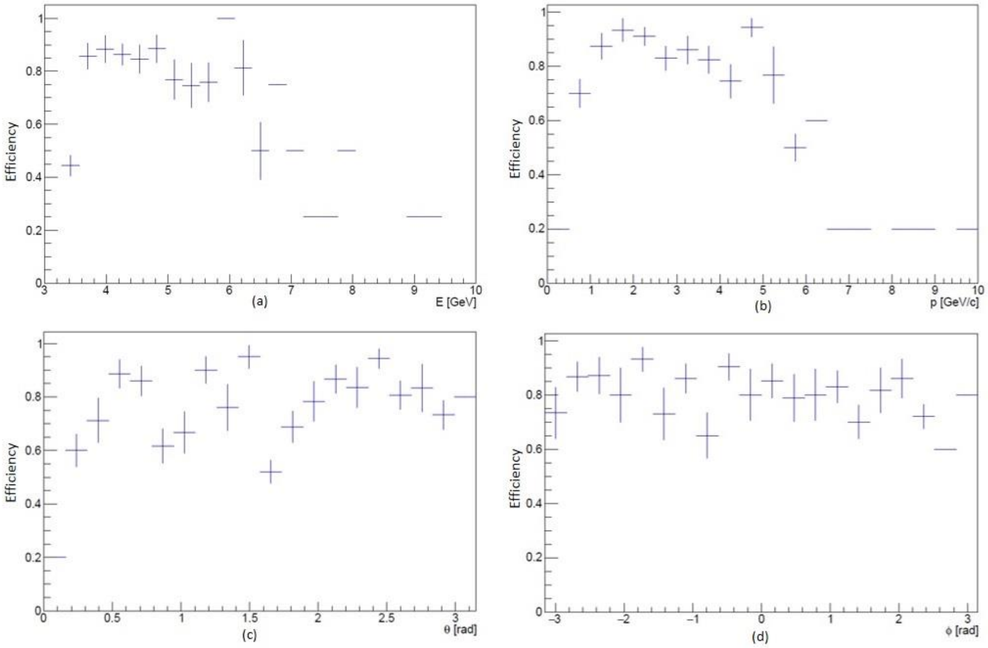


Fig. 6. X_{c0} Efficiency distributions in hybrid configuration, (a) efficiency vs. energy, (b) efficiency vs. momentum, (c) efficiency vs. theta and (d) efficiency vs. phi.

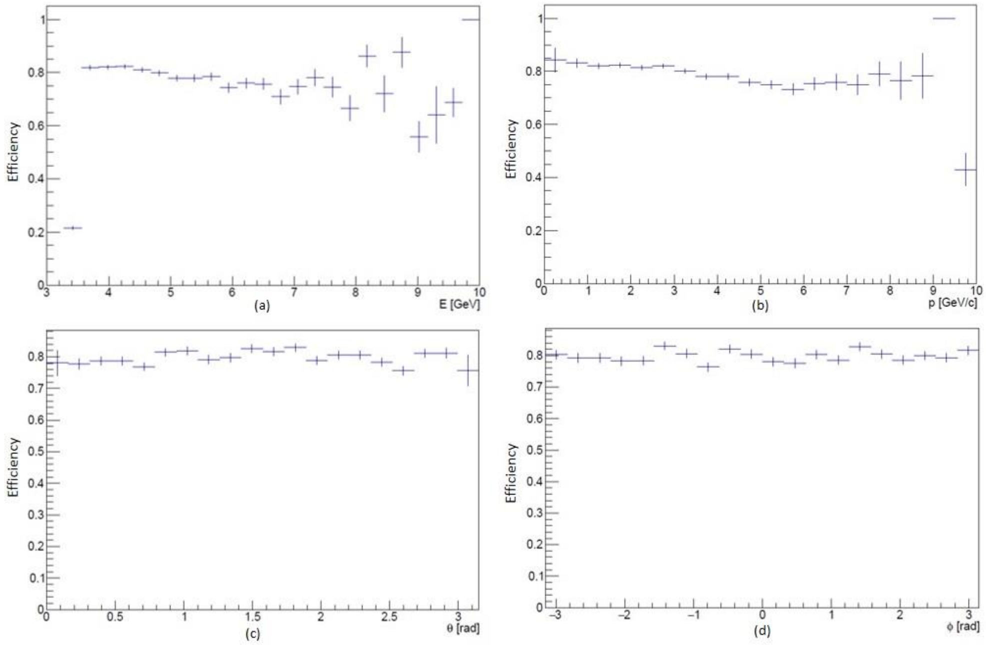


Fig. 7. X_{c1} Efficiency distributions in hybrid configuration, (a) efficiency vs. energy, (b) efficiency vs. momentum, (c) efficiency vs. theta and (d) efficiency vs. phi.

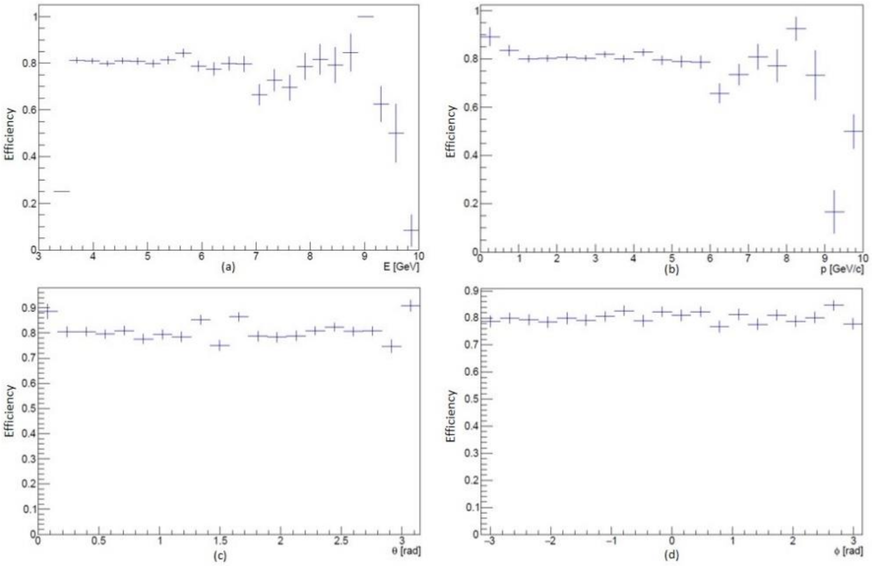


Fig. 8. X_{c2} Efficiency distributions in hybrid configuration, (a) efficiency vs. energy, (b) efficiency vs. momentum, (c) efficiency vs. theta and (d) efficiency vs. phi.

As it can be seen, X_{c0} has a higher uncertainty with respect to X_{c1} and X_{c2}, it occurs because X_{c0} decays into J/ψ and photon only $(1.40 \pm 0.05)\%$ of the time, while X_{c1} and X_{c2} decay $(34.3 \pm 1.0)\%$ and $(19.0 \pm 0.5)\%$ respectively [8].
Detection efficiency is almost the same for $\mathrm{X}_{\mathrm{c0,1,2}}$:
$\eta_{\mathrm{X}_{\mathrm{c0}}} = (82.9 \pm 1.9)\%$
$\eta_{\mathrm{X}_{\mathrm{c1}}} = (80.8 \pm 0.3)\%$
$\eta_{\mathrm{X}_{\mathrm{c2}}} = (80.1 \pm 0.4)\%$
This result is consistent with the fact that X_{cj} efficiency compiles both J/ψ ,mentioned above, and Photon detection, shown in Fig. 19, efficiencies. Photons are absorbed by the magnet rings (Fig. 14 (a), 19 (d)) and the solenoid (Fig. 19 (c)).

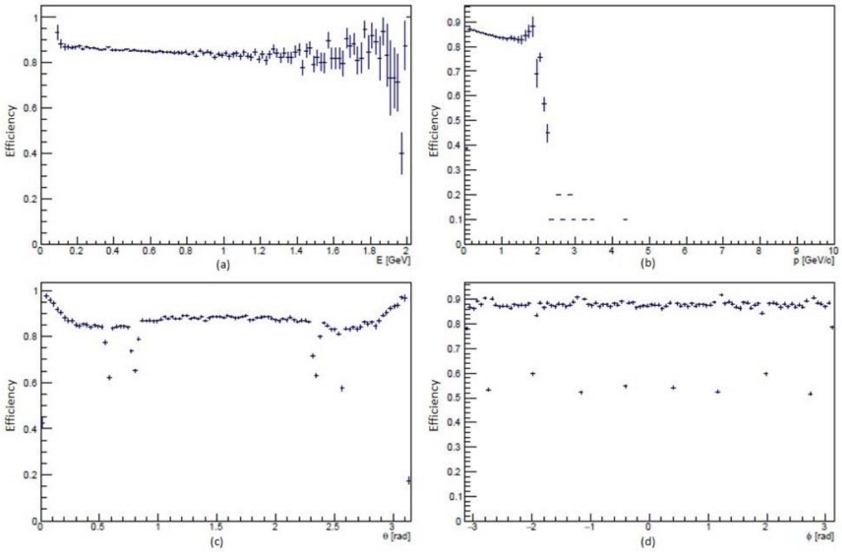


Fig. 19. Photon from X_{c1} efficiency distributions in hybrid configuration, (a) efficiency vs. energy, (b) efficiency vs. momentum, (c) efficiency vs. theta and (d) efficiency vs. phi.

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