NA61/SHINE experiment upgrade with vertex detector for open charm measurements

Yasir Ali and Paweł Staszel for the NA61/SHINE collaboration

M. Smoluchowski Institute of Physics, Jagiellonian University, Reymonta 4, 30-059 Krakow Poland

E-mail: yasir.ali@uj.edu.pl

Abstract.
The feasibility study of direct open charm measurements by its decay into two daughter particles, pion and kaon, in central Pb-Pb collision at SPS energies of 158 AGeV and 40 AGeV, shows that such measurements are viable at NA61/SHINE experiment if it is supplemented with a dedicated Vertex Detector (VD). We use AMPT (A Multi-Phase Transport model) event generator to generate the physical input for simulation and employed GEANT4 application to describe particle transport through the experimental setup. The VD will allow for precise track reconstruction at the target proximity. The direct open charm measurements will be a challenging due to the low production yield and short life time of D^0 mesons. The obtained results are based on the predicted yields of D^0 meson by Hadron String Dynamic (HSD) model. This study also addresses the issue of VD optimization and the emphasis is put on the prospect of the development of a VD based on CMOS technology.

1. Introduction

Open heavy flavor is an important probe of the dense matter formed in heavy ion collision. The measurement of D^0 mesons provide a unique opportunity to test the validity of perturbative QCD-based and statistical models of nucleus-nucleus collisions at high energies. So far there are no direct open charm measurements at SPS energies while extensive studies have been done in the past and new experimental initiatives are proposed to measure charmonia states at SPS energies [1]. Recently, it was pointed out by Satz [2] that only precise measurement of both open and hidden charm will allow to construct observables that can provide information on the in-medium behaviour of quarkonia in a model independent way. Thus we developed a feasibility study dedicated to the measurement of the D^0 mesons (open charm) in Pb+Pb collision at SPS energies. This study is done for top SPS energy of 158 AGeV and for lower energy of 40 AGeV. This measurement is challenging due to the short life time and low production yield of D^0 mesons. D^0 meson can be reconstructed by its decay into hadronic and semi-leptonic decay channels. We have considered only the bench mark channel of two body hadronic decay in which D^0 meson decays into pion and kaon with the branching ratio of 3.9% [3]. The other channels will be addressed in the future consideration. For the physical input we generated 200k 0-10% central events with AMPT (A Multi-Phase Transport Model) event generator. It provides good background description which in case of this study are distributions of charged hadrons, mostly pions and kaons [4]. The AMPT model predicts the average production yield of 0.01 for $D^0 + \overline{D}^0$ per central Pb+Pb event. This value seems to be underpredicted with respect

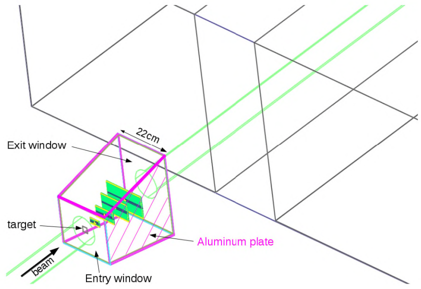

Figure 1. The helium vessel containing four vertex detector stations, carbon fiber support and water cooling tubes.

to PYTHIA results scaled to the number of binary nucleon-nucleon collisions in central Pb+Pb equal to 0.21 [5] as well as with respect to the prediction of the HSD model. Because HSD model was tuned to properly describe available p+A and π+A charm production data at SPS energies, we scaled the AMPT production yield to the prediction of the HSD model. The average yield of D^0 mesons predicted by HSD model is 0.1 [6].

GEANT4 is employed to describe the particle transport through experimental setup. In order to reconstruct D^0 mesons a dedicated vertex detector providing high position resolution was conceived.

2. Vertex Detector for open charm measurements

The NA61/SHINE (SHINE = SPS Heavy Ion and Neutrino Experiment) [7] at the CERN SPS is a fixed target experiment whose description is given by [8]. This experiment will be upgraded by a dedicated VD which allows for precise tracking at the target proximity. The VD modelled in GEANT4 consists of four detection stations VDS1, VDS2, VDS3 and VDS4 located respectively at distances of 5 cm, 10 cm, 15 cm, and 20 cm downstream of the target. The external transverse dimensions of the stations are 2×4 cm^2 (VDS1), 4×8 cm^2 (VDS2), 6×12 cm^2 (VDS3), 8×16 cm^2 (VDS4). These dimensions allow to cover more than 99% of the acceptance of pions and kaons originating from the decay of D^0 mesons. The range of kinematical acceptance is described by [9].

Each station has also a square hole (3×3 mm^2) in the central part which allows the beam ions to go through without an interaction. The stations and the target are closed in the aluminium vessel as shown in Figure 1. The vessel is equipped with thin front and back kapton windows and filled with helium gas at atmospheric pressure to minimize multiple scattering of the produced particles. The advantage of helium is that it reduces the primary beam, and spectator interactions.

The track reconstruction is based on the hits generated during particle transport through vertex detector stations, Vertex Time Projection Chamber (VTPC1 and VTPC2). Only the tracks accepted in VTPC detectors are considered in the subsequent analysis. The acceptance is defined in the similar way as it is done in the standard NA61/SHINE simulation which is described in detail in [10]. In the invariant mass distribution for kaon-pion pairs at the collision energy of 158A GeV we found that the combinatorial background is few orders of magnitude higher than the $D^0 + \overline{D^0}$ signal shown in red colour. In order to suppress the large combinatorial background, four cuts were developed namely, cut on the track transverse momentum p_T, cut on the track impact parameter d cut on the longitudinal position V_z of the track pair vertex relative to primary interaction point and cut on the parent particle impact parameter D. The first two are single-particle cuts, while the two other are two-particle cuts. It should be stressed

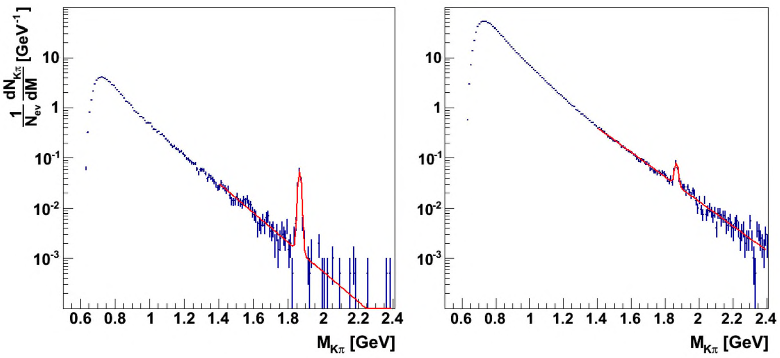

Figure 2. The invariant mass of pion-kaon pairs after full background reduction. The red curve represents fit with sum of exponential (background) and Gaussian function (D^0 signal). Left: analysis done using PID information, right: analysis that does not utilize the PID information

that last three cuts require the precise tracking information at the target proximity from the proposed VD.

The analysis assumes perfect particle identification (PID), i.e. for each track the related specie type was known. The invariant mass distribution with all the cuts applied, assuming perfect PID, at the collision energy of 158A GeV, is shown in the left panel of Figure 2. This plot is to be compared to the one in the right panel of Figure 2, which presents results of analysis that does not utilize the PID information. As can be seen from the comparison of the plots, analysis without PID suffers from a much higher background. Nevertheless, it is feasible to extract the signal yield even in such analysis. For the analysis assuming perfect PID we obtain signal to background (S/B) = 17 and with the case of no PID we obtain S/B = 1.0. When we extrapolate the results to 50 M events (anticipated event number collected during 1-2 months of the NA61/SHINE data taking) the total number of collected open charm mesons is $\sim 64000/(64000)$ with Signif $= 246/(197)$ for perfect PID/(no PID) case. The reason to compare analysis with and without PID, is that in the NA61/SHINE experiment, exact identification on track by track basis is not possible in the whole phase space. Therefore, the real situation is between the two quoted analysis types.

We also developed simulation to determine the requirements for the detector. In the first vertex detector station for 0-10% central interactions, we observed the high hit occupancy in the inner region which is 5 hits/mm^2/event. The probability of empty frame is 95%, for single event is 4.7% and for pile-up is 2.5%. This high occupancy suggest to use pixel detector technology for the VD stations. The NA61/SHINE requirements in terms of resolution, material budget, radiation tolerance and time resolution are fullfilled by MIMOSA-26 device [11]. This chip is basically a sensor chip based on the Monolithic Active Pixel sensors with fast binary readout and is suitable for charge particles detection with the flux of 10^4 hits/mm^2/s and provides the resolution of 3.5 μm in both directions. The sensor is 50 μm thick and total thickness of detector is of the order of 0.3% X_0 [11].

To cover the active areas of the VD stations requires 126 MIMOSA-26 sensors. It was, however, realised that the protoype version of the VD has to build first to allow for testing the general concept of data reconstruction, the service systems responsible for mechanical support, sensor cooling, data readout and data synchronization. VDS1 and VDS2 will be equipped with 2 sensors each, and VDS3-VDS4 with 4 sensors. The VD prototype version will consist of 12 sensors. We developed simulations to find the most optimal locations of the sensors in order

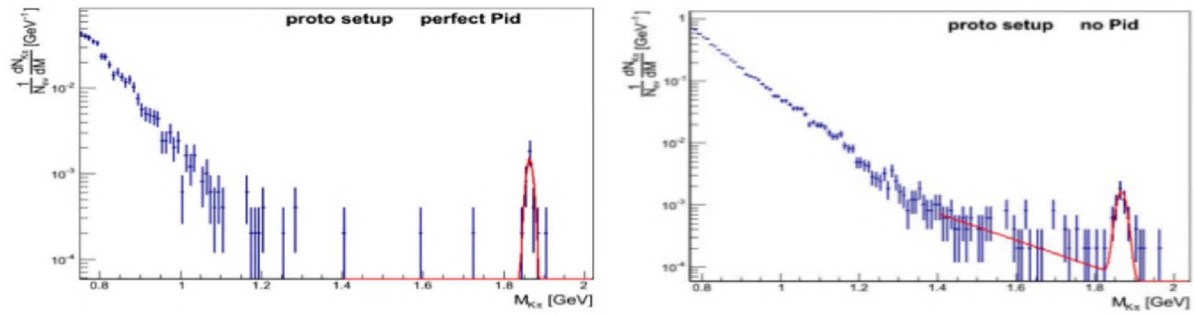

Figure 3. The combinatorial invariant mass spectrum for 0-10% central Ar+Ca collisions at 158 AGeV after background reduction for the prototype of VD.

to maximize the acceptance of the D^0 signal. We performed simulation of such measurement generating physical input by the AMPT event generator. We generated 500k 0-10% central Ar+Ca collisions at 158 AGeV. The results of the simulation with PID and no PID are shown in Figure 3 where we plotted invariant mass spectrum after all suppression cuts have been applied. From the plot one can see a well pronounced D^0 signal with the S/B = 11 and the Signif = 4.5. According to the schedule of the current NA61/SHINE scientific program we will be able to test the performance of prototype detector integrated with the rest of the experimental setup in February 2015 with the Ar beam colliding on Ca target at the top SPS energy of 158 AGeV. The results might be relevant not only for the test but also for physics output providing first measurement of open charm at the SPS energy.

3. Conclusion

Measurements of heavy flavor mesons gives better understanding of nucleus-nucleus reactions at relativistic energies. Open charm measurements are feasible with NA61/SHINE experiment at CERN-SPS energies if it is upgraded with high resolution VD. The MIMOSA-26 sensors fulfil all requirements imposed by NA61/SHINE application and will be used as a basic detection element in the VD stations. We will build prototype version of the VD which will be tested on the beam to prove the general concept of data reconstruction.

This contribution reports on the technical work motivated by the future experimental programme of the NA61/SHINE Collaboration at the CERN SPS. Authors gratefully acknowledge the contribution of NA61/SHINE to the results presented. This work is supported by the Foundation for Polish Science — MPD program, co-financed by the European Union within the European Regional Development Fund and the National Science Centre of Poland, grant UMO-2012/04/M/ST2/00816.

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