First $D^0 + \overline{D}^0$ measurement in nucleus-nucleus collisions at SPS energies with NA61/SHINE

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Abstract. The measurement of open charm meson production provides a tool for the investigation of the properties of the hot and dense matter created in nucleus-nucleus collisions at relativistic energies. In particular, charm mesons are of vivid interest in the context of the study of the nature of the phase-transition between confined hadronic matter and the quark-gluon plasma. Recently, the NA61/SHINE experimental setup was upgraded with a high spatial resolution Vertex Detector which enables the reconstruction of secondary vertices from open charm meson decays.

The first direct neutral D meson yields at the SPS energy regime will be shown. The analysis used the 20% most central Xe+La collisions at 150A GeV/c from the data set collected in 2017. It allowed the estimation of the mid-rapidity yields ($\mathrm{d}N/\mathrm{d}y$) of $D^0 + \overline{D}^0$ using their $\pi^{\pm} + K^{\mp}$ decay channels and phase space corrections derived from the three models AMPT, PHSD, and PYTHIA/Angantyr. The results will be compared and discussed in the context of several model calculations including statistical and dynamical approaches.

1 Introduction

The study of open charm production is a sensitive tool for detailed investigations of the properties of hot and dense matter formed in nucleus-nucleus collisions. Since heavy quarks are produced in hard scattering processes in the early stage of the collision, by studying them one can get insight to the properties of the created medium. In particular, such measurements are of vivid interest at the SPS energies, which are close to the quark-gluon plasma creation threshold.

Also such study gives a unique opportunity to test the validity of theoretical models based on perturbative Quantum Chromodynamics and Statistical model approaches for nucleus-nucleus collisions at SPS energies, which provide very different predictions for charm yields [1]. However, up to now there were no open charm measurements in this energy regime.

2 Open charm measurements by NA61/SHINE

The SPS Heavy Ion and Neutrino Experiment (NA61/SHINE) [2] at CERN was designed for studies of the properties of the onset of deconfinement and search for the critical point of strongly interacting matter by investigating p+p, p+A and A+A collisions at different

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beam momenta from 13A to 150/158A GeV/c for ions and up to 400 GeV/c for protons. The main tracking detectors are four Time Projection Chambers (TPC) which provide momentum, charge and particle identification (PID) for the particles produced in the collision.

The heavy-ion programme of the NA61/SHINE experiment at CERN SPS has been expanded to allow precise measurements of particles with short lifetime. To meet the challenges of open charm measurements, NA61/SHINE was upgraded with the Small Acceptance Vertex Detector (SAVD). SAVD was composed of four detector planes located 5, 10, 15 and 20 cm downstream of the target. The planes were constructed using position-sensitive MIMOSA-26AHR pixel sensors [3]. SAVD provided precise vertex reconstruction with excellent spatial resolution. The obtained transverse and longitudinal primary vertex resolution was $\sigma_{x,y} \approx 1$ μm and $\sigma_z = 15$ μm, respectively. The SAVD acceptance for D^0, $\overline{D}^0$ was $-0.5 < y < 1.0$, $0.2 < p_T < 2.0$ GeV/c, and the analysis presented here was performed in this kinematic range. More details about SAVD, track and vertex reconstruction can be found in Refs. [4, 5].

The $D^0+\overline{D}^0$ reconstruction is done via $\pi^{\pm}+K^{\mp}$ decay channel. The SAVD tracks matched to TPC tracks are used to search for the $D^0+\overline{D}^0$ signal. In the analysis presented here, the PID information was not used. Each track is paired with all the opposite-sign tracks from the same event and is assumed to be either a kaon or a pion, thus each pair contributes twice in the combinatorial invariant mass distribution. In order to suppress the combinatorial background of the invariant mass distribution, the following cuts are applied:

- cut on the daughter track impact parameter, $d > 36$ μm;
- cut on the distance of closest approach between the daughter tracks, $DCA < 42$ μm;
- cut on the longitudinal distance between the D^0 decay vertex candidate and the primary vertex scaled with the gamma factor, $V_z/\gamma > 0.15$ μm;
- cut on the impact parameter of the back-extrapolated D^0 candidate momentum vector, $D < 20$ μm;
- cut on the D^0 candidate momentum in laboratory frame, $13 < p < 38$ GeV/c.

Figure 1 shows the $K^{\pm}\pi^{\mp}$ invariant mass distribution after the applied cuts. The peak corresponding to $D^0+\overline{D}^0$ has a statistical significance, $S/\sqrt{S+B}$, of approximately 6.

3 Analysis results

In order to determine the necessary corrections and calculate the absolute value of $D^0+\overline{D}^0$ yield, simulations with GEANT4 were performed. The input to GEANT4 consists of events generated by the EPOS model [6], while the embedded D^0, $\overline{D}^0$ mesons were generated with phase space distributions obtained from the three models: AMPT [7], PHSD [8] and PYTHIA/Angantyr [9], which predict quite different (y, p_T) distribution of open charm.

After applying corrections from Monte Carlo, the corrected yield for each phase space assumption was calculated. The results are presented in Table 1. The visible yield $N(D^0+\overline{D}^0)_{visible}$ corresponds to the yield in the $-0.5 < y < 1.0$, $0.2 < p_T < 2.0$ GeV/c rapidity-transverse momentum range covered by the SAVD acceptance. In order to obtain the rapidity density, $\mathrm{d}N(D^0+\overline{D}^0)/\mathrm{d}y\ _{-0.5<y<1.0}$, and the 4π integrated yield, $\langle D^0+\overline{D}^0\rangle$, the extrapolation factors for each of the models were determined. The AMPT model predicts that about 84% of $D^0+\overline{D}^0$ are produced in the SAVD acceptance, while PHSD and PYTHIA/Angantyr predict this fraction to be approximately 67%. Thus, $\langle D^0+\overline{D}^0\rangle$ differ significantly between the model assumptions.

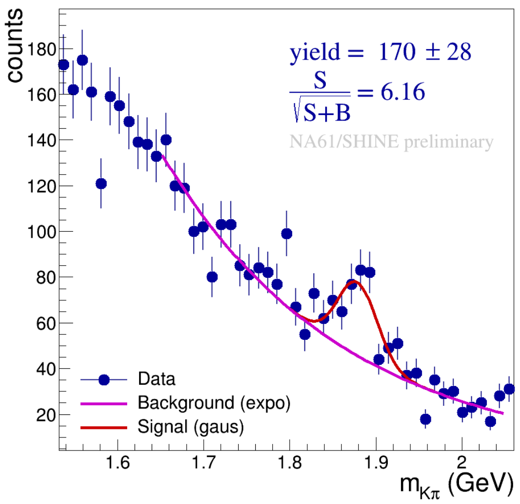

Figure 1. The $K^{\pm}\pi^{\mp}$ invariant mass distribution after the applied cuts for Xe+La collisions at 150A GeV/c taken in 2017. The invariant mass distribution was fitted (red line) using an exponential function to describe the background and a Gaussian to describe the $D^0 + \overline{D}^0$ signal contribution. The indicated uncertainties are statistical only.

Table 1. Results for the visible yield, dN/dy at mid-rapidity and yield in 4π of $D^0 + \overline{D}^0$ obtained assuming the phase space distribution for AMPT, PHSD and PYTHIA/Angantyr models. The first indicated uncertainty corresponds to the statistical uncertainty and the second – to the systematic uncertainty. The systematic uncertainty does not include the model-dependent phase space correction.

correction with:	$N(D^0 + \overline{D}^0)_{visible}$	$\frac{dN(D^0+\overline{D}^0)}{dy}\big\vert_{-0.5<y<1.0}$	$\langle D^0 + \overline{D}^0 \rangle$
AMPT	0.184 ± 0.032	0.129 ± 0.023 ± 0.035	0.218 ± 0.039 ± 0.060
PHSD	0.204 ± 0.036	0.148 ± 0.026 ± 0.036	0.303 ± 0.054 ± 0.074
PYTHIA/Angantyr	0.201 ± 0.035	0.147 ± 0.026 ± 0.037	0.300 ± 0.052 ± 0.075

Figure 2 shows the comparison of the obtained 4π yield $\langle D^0 + \overline{D}^0 \rangle$ with the results of various model predictions. The precision of the data is sufficient to discriminate between the current model predictions. While microscopic models (AMPT, PYTHIA/Angantyr, PHSD, HSD [10]) tend to significantly underestimate $D^0 + \overline{D}^0$ yield, ALCOR [11] and SMES [12] models are overestimating it.

An estimation based on measurements of the $D^0 + \overline{D}^0$ cross-section in different p+A collision systems and in a range of collision energies, $\sqrt{s_{NN}}$, spanning between 20 and 40 GeV [13], scaled by the number of binary collisions in order to correspond to central Xe+La reactions, yields a value that is below the NA61/SHINE measurement with a statistical significance of 2-3σ.

4 Summary and outlook

The presented analysis shows the first-ever direct measurement of open charm in nucleus-nucleus collisions at SPS energies. The precision of this result is sufficient to disentangle between the different theoretical predictions.

During CERN's long-shutdown 2 the TPC readout and DAQ of NA61/SHINE were upgraded increasing the data taking rate from 80 Hz to 1.2 kHz [14]. Within the upgrade also a new Vertex Detector based on ALPIDE sensors was installed. In 2022–2023 NA61/SHINE collected at the level of 180 M events of Pb+Pb collisions at 150A GeV/c. These data will

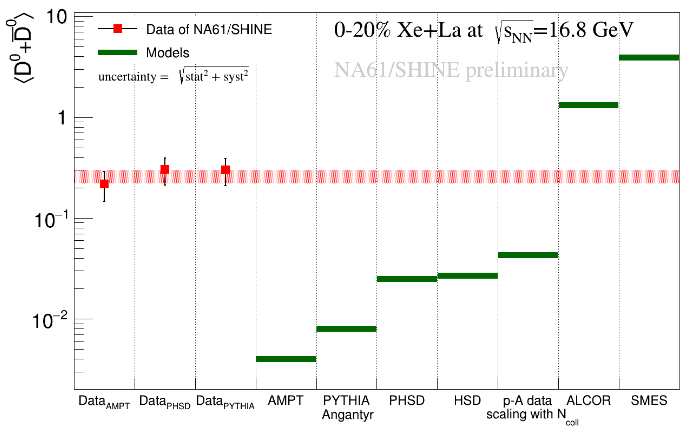

Figure 2. Comparison of the obtained result to theoretical model predictions. The red band indicates the theoretical uncertainty of the result due to the unknown phase space distribution of D^0, $\overline{D}^0$.

allow double differential measurements of D^0 and $\overline{D}^0$ in rapidity and transverse momentum, as well as measurements of other charmed hadrons. This study will provide a further, better insight into charm production mechanisms at energies close to the QGP creation threshold.

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