First $D^0 + \overline{D}^0$ measurement in heavy-ion 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 experimental setup of the NA61/SHINE experiment was upgraded with the high spatial resolution Vertex Detector which enables the reconstruction of secondary vertices from open charm meson decays.
In this presentation the first D^0 meson yields at the SPS energy regime will be shown. The analysis used the most central 20% of Xe+La collisions at 150A GeV/c from the data set collected in 2017. This allowed the estimation of the corrected yields (dN/dy) for $D^0 + \overline{D}^0$ via its $\pi^{+/-} + K^{-/+}$ decay channel at mid-rapidity in the center-of-mass system. 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 heav 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 collisions at SPS energies, which provide very different predictions for charm yields [1].

However, up to now there were no open charm measurements at this energy regime.

2 Open charm measurements at 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 beam momenta from 13*A* to 158*A* GeV/c for ions and upto 400 GeV/c for protons. The

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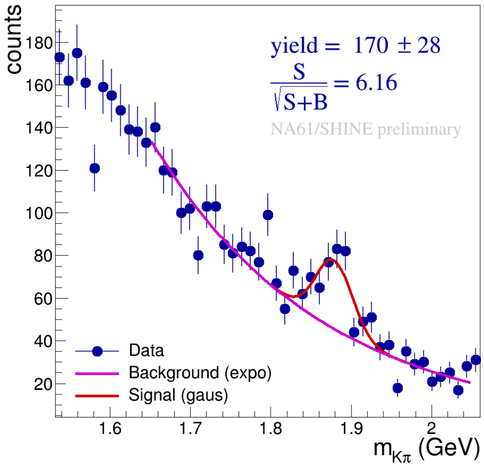

Figure 1. Invariant mass distribution of unlike charge sign π, K decay track candidates for Xe+La collisions at 150*A* GeV/*c* taken in 2017. The invariant mass distribution was fitted (red line) using of an exponential function to describe the background and a Gaussian to describe the $D^0 + \overline{D}^0$ signal contribution. The indicated errors are statistical only.

main tracking detectors are four Time Projection Chambers (TPC) which provide momentum, charge and particle identification (PID) of the produced in the collision particles.

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 challenges of open charm measurements NA61/SHINE was upgraded with the Small Acceptance Vertex Detector (SAVD). SAVD is composed of four detector planes located 5, 10, 15 and 20 cm downstream the target. The planes are constructed from position-sensitive MIMOSA-26AHR pixel sensors [3]. SAVD provides precise spatial resolution of vertex reconstruction. The obtained primary vertex resolution is $\sigma_{x,y} \approx 1\ \mu$m, $\sigma_z = 15\ \mu$m. The SAVD acceptance for D^0, $\overline{D^0}$ is $-0.5 < y < 1.0,\ 0.2 < p < 2.0\ GeV$, and the analysis presented here performed in this bin. More details about SAVD, track and vertex reconstruction can be found [4, 5]

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 another track 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 following cuts are applied:

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

Figure 1 shows the invariant mass distribution of unlike charge daughter candidates with the applied cuts. The peak corresponding to $D^0 + \overline{D}^0$ has the significance $\frac{S}{\sqrt{S+B}}$ on the level of 6σ.

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 error corresponds to statistical uncertainty and the second - to systematically. Systematical uncertainty doesn't include the correction to model-dependent phase space.

correction with:	$N(D^0 + \overline{D}^0)_{visible}$	$\frac{dN(D^0+\overline{D}^0)}{dy}_{-0.5<y<1.0}$	$\langle D^0 + \overline{D}^0 \rangle$
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

3 Analysis results

In order to obtain the corrections and calculate the absolute value of $D^0 + \overline{D}^0$ yield, the GEANT4 simulations were performed. The background in the Monte Carlo (MC) event was described using the EPOS model [6], while the signal phase space was parametrized using 3 models: AMPT [7], PHSD [8] and PYTHIA/Angantyr [9], which predict quite different phase space distribution of open charm.

After applying corrections from MC, the corrected yield for each phase space assumption was calculated. The results are presented in the table 1. The visible yield $N(D^0 + \overline{D}^0)_{visible}$ corresponds to the yield in the $-0.5 < y < 1.0$, $0.2 < p < 2.0$ GeV rapidity-transverse momentum bin covering SAVD acceptance. In order to obtain $dN(D^0 + \overline{D}^0)/dy\ _{-0.5<y<1.0}$ and the 4π yield $\langle D^0 + \overline{D}^0 \rangle$ the extrapolation factors for each of the models were obtained. The AMPT model predicts that about 84% of $D^0 + \overline{D}^0$ produced in the SAVD acceptance, while PHSD and PYTHIA/Angantyr predict on the level 67%. Thus, $\langle D^0 + \overline{D}^0 \rangle$ differ significantly between the model assumptions.

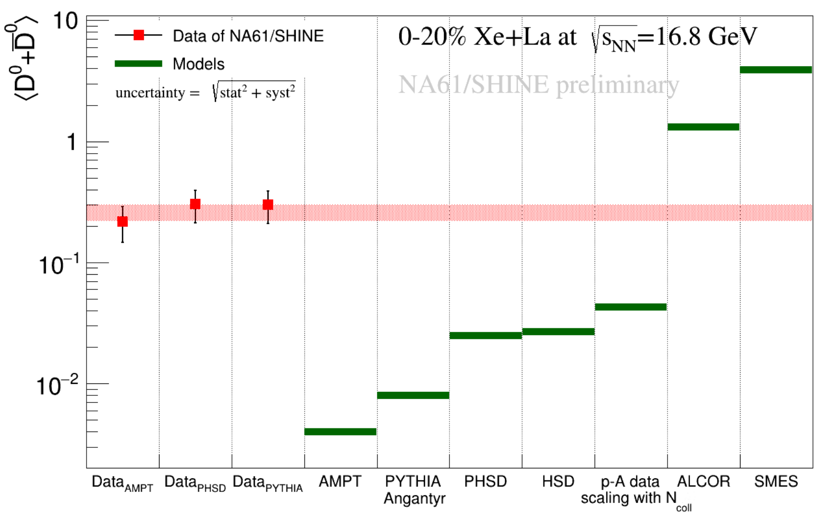

Figure 2. Comparison of the obtained result to theoretical model predictions. The red band indicated the theoretical uncertainty of the result due to unknown phase space distribution.

Fig.2 shows the comparison of the obtained 4π yield $\langle D^0 + \overline{D}^0 \rangle$ to the theoretical model predictions. The precision of the data is sufficient enough to discriminate between 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.

Extrapolation of the p+A data using PYTHIA energy dependence assumption [13] which was scaled with the number of collisions $N_c oll$ predict the value on the level of $2 - 3\sigma$ lower than the obtained result. However, the extrapolation is done for the energy at which p+A data was not measured and the energy extrapolation is model-dependent.

4 Summary and outlook

The analysis of showed the first direct observation of open charm at SPS energies in heavy-ion collisions with the precision of the result sufficient to disentangle between theoretical models.

Looking forward, NA61/SHINE was upgraded during CERN long-shutdown 2 to increase the data taking rate from 80Hz to 1kHz [1]. Within the upgrade the new Vertex Detector based on ALPIDE sensors developed was installed, as well as the TPC readout and DAQ were being upgraded. In 2022-2023 NA61/SHINE collected on the lever of 180M events of Pb+Pb collisions at $150A$GeV/c. These data should allow rapidity and transverse momentum differential measurements of D^0 and $\overline{D}^0$, as well as measurements of other charm hadrons. This study will provide a better insight into charm production mechanisms at energies close to the production threshold.

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References

[1] A. Aduszkiewicz *et al.* (NA61 Collaboration), CERN-SPSC-2018-008 / SPSC-P-330-ADD-10 (2018)

[2] N. Abgrall *et al.* (NA61 Collaboration), JINST **9**, P06005 (2014)

[3] M. Deveaux *et al.*, J. Instrum. **6**, C02004 (2011)

[4] A. Merzlaya, PhD thesis, https://cds.cern.ch/record/2771816 (2021)

[5] A. Aduszkiewicz *et al.*, Eur. Phys. J. C **83** no.6, 471 (2023)

[6] T. Pierog *et al.*, Phys. Rev. C **92** no.3, 034906 (2015)

[7] Z. W. Lin *et al.*, Phys. Rev. C **72**, 064901 (2005)

[8] W. Cassing and E. L. Bratkovskaya, Nucl. Phys. A **831**, 215-242 (2009)

[9] C. Bierlich *et al.*, JHEP **10**, 134 (2018)

[10] O. Linnyk *et al.*, Int. J. Mod. Phys. E **17**, 1367-1439 (2008)

[11] P. Levai *et al.*, J. Phys. G **27**, 703-706 (2001)

[12] M. Gazdzicki and C. Markert, Acta Phys. Polon. B **31** no.4, 965-983 (2000)

[13] P. Braun-Munzinger *et al.*, Eur. Phys. J. C **1**, 123-130 (1998)