PHYSICS BEYOND COLLIDER — FUTURE NA61*

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The NA61/SHINE experiment studies hadron production in hadron–hadron, hadron–nucleus and nucleus–nucleus collisions. The physics program includes strong interaction studies, measurements for neutrino physics experiments and measurements for cosmic ray experiments. Future plans are to extend the program by new measurements needed to understand the onset of deconfiment like open charm production in nucleus+nucleus collisions as well as by studies of fragmentation cross sections required to interpret new AMS-II data. This new program can be realized only by 2020 and requires upgrades to the present NA61/SHINE detector setup.

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1. Measurement of open charm (D^0 and $\bar{D}^0$ meson) production as extension of the strong interaction program

NA61/SHINE proposes to measure open charm (D^0 and $\bar{D}^0$ meson) production in central Pb+Pb collisions with an upgraded detector system at the CERN SPS. This will be the first precision measurements of open charm production in heavy-ion collision in the CERN SPS energy domain. The measurements will provide the long-awaited data crucial for the following topics:

— J/ψ production as probe of deconfinement,

— open charm yield as probe of deconfinement,

— open charm production mechanism: pQCD *versus* statistical models.

Charmonium production has proven to be one of the crucial probes for studying the formation of the quark–gluon plasma in high-energy nuclear collisions [1]. It was noted that colour screening in the plasma would reduce and eventually prevent the binding of charm quarks and antiquarks

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to produce charmonia, thus suppressing charmonium production in nuclear collisions and providing evidence for deconfinement. The c–$\bar{c}$ pairs produced in energetic p+p interactions are converted into open charm mesons and charmonia. One finds about 90% of them in open charm mesons, and the remaining 10% in charmonia (J/ψ and excited charmonium states). Due to shadowing, parton energy loss *etc.*, the overall scaled number of c–$\bar{c}$ pairs produced in nuclear collisions may well be smaller than in proton–proton interactions. This, of course, will reduce the relative charmonium production rate in A+A collisions relative to p+p interactions, even if there are no medium effects on c–$\bar{c}$ binding. Hence, the effect of the medium on the c–$\bar{c}$ binding can only be determined by studying the charmonium yield relative to the yield of open charm hadron production. Such a comparison has not been possible at the SPS, since measurements of open charm hadrons require strong suppression of background that was not possible up to now. Measurements of open charm were performed at RHIC where it was indeed found that in Au+Au and U+U collisions, the relative J/ψ yield at low transverse momenta drops by up to 80% with increasing collision centrality [2]. At the LHC, such a comparison is not yet conclusive due to difficulties in measuring low transverse momentum D mesons. Moreover, predictions of models on open charm yield at the top SPS energy differ significantly. The statistical model estimate of the open charm yield is by more than an order of magnitude higher than that based on pQCD. Both estimates suffer from large systematic uncertainties. The predicted system size dependence in these two approaches is also very different. Furthermore, both approaches predict a rapid change of collision energy dependence when crossing the energy of the onset of deconfinement. So far, only an indirect measurement of the open charm yield in nucleus–nucleus collisions at the top SPS energy exists. It is not reliable enough to distinguish between the pQCD and the statistical model predictions. Therefore, these different models are still viable.

The proposed direct and precise measurements of open charm production in Pb+Pb collisions at the SPS will help to clarify this situation. It is necessary to stress that the upgraded ALICE experiment at the LHC will perform precise measurements of open charm production after 2020. This together with the proposed project of NA61/SHINE gives the opportunity to obtain a detailed picture of charm production at the SPS and LHC energies.

Moreover, the results from CERN are being complemented by the corresponding measurements from RHIC. All these measurements give a unique opportunity to get detailed data on charm production across the currently available energy range. The proposed measurements of D^0 and $\bar{D}^0$ production in central Pb+Pb collisions at the SPS will be possible after upgrading the NA61/SHINE experimental set-up by:

— Construction of a Large Acceptance Vertex Detector (LAVD), which will provide precise tracking downstream of the target and thus reduce by many orders of magnitude the background below the D^0 and $\bar{D}^0$ peaks.

— Replacement of the TPC electronics which will increase the read-out rate by a factor of about 10 (up to 1 kHz).

— Upgrade of the trigger and data acquisition systems as required by the LAVD and TPC upgrades.

The proposed LAVD detector is already designed and is planned to be produced based on the hardware of ALPIDE sensors developed for the ITS/MFT ALICE projects [3, 4]. One of the considered geometries of the LAVD is presented in Fig. 1.

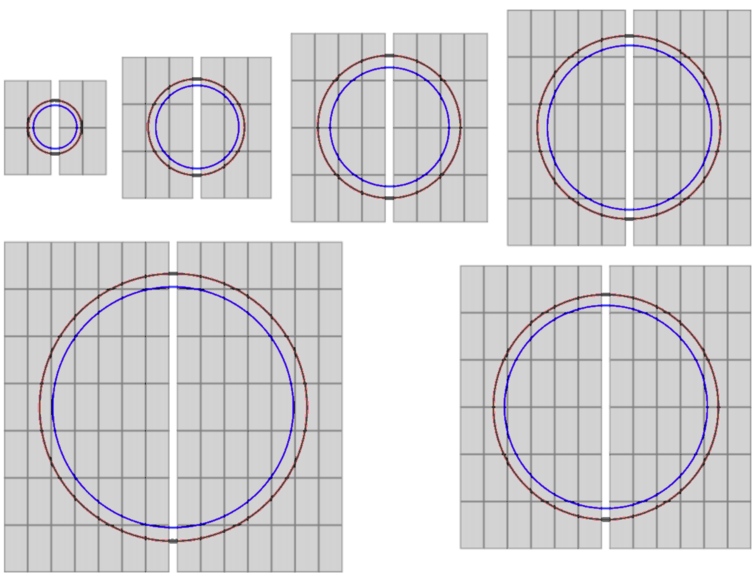

Fig. 1. One of the considered Large Acceptance Vertex Detector geometries based on ALPIDE sensors. 6 layers are to be spaced in beam direction by 5 cm. The geometry is optimized to register decay products of D^0 and $\bar{D}^0$ mesons and avoid beam particles in the acceptance of the LAVD.

Concerning the TPC electronics upgrade, the present ALICE TPC read-out electronics, which will be replaced during the long shutdown LS2, will be transferred and adapted to NA61/SHINE. Simulation results indicate that with the upgrades, NA61/SHINE will observe about 40 k D^0 and $\bar{D}^0$ meson decays during 10 days of data taking on central Pb+Pb collisions at 150 A GeV/c. Figure 2 presents transverse momentum and rapidity distributions of D^0 and $\bar{D}^0$ generated by the AMPT model (black dots), in acceptance of the LAVD (orange triangles) and in the acceptance of the LAVD after geometrical cuts (blue squares) for one day of data taking. The expected statistics is similar to that recorded up to now by ALICE in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [5]. Measurements of open charm yield at $75\,A\,\mathrm{GeV}/c$ and $40\,A\,\mathrm{GeV}/c$ should also be possible. The measurements will be performed down to $p_{\mathrm{T}} = 0$ and give information over a large fraction of all produced D^0 and $\bar{D}^0$ mesons.

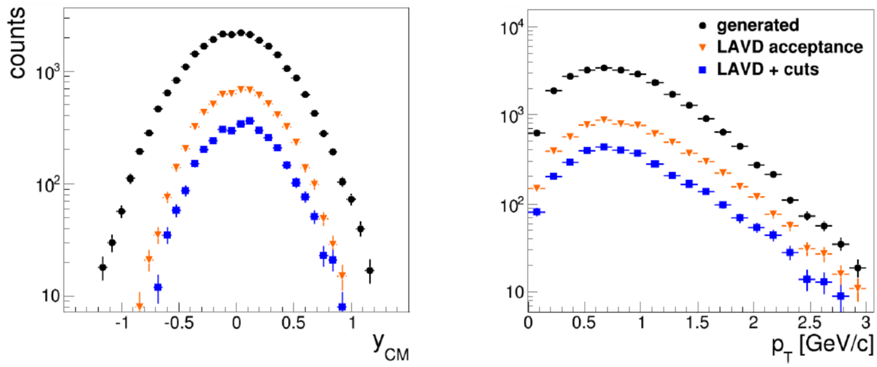

Fig. 2. (Colour on-line) Transverse momentum and rapidity distributions of D^0 and $\bar{D}^0$ mesons. Black points are D^0 and $\bar{D}^0$ generated by the AMPT model, orange triangles show predicted signal in the acceptance of the LAVD, and blue squares present the predicted signal in the acceptance of the LAVD after geometrical cuts optimized to increase the signal-to-background ratio in the D^0 signal region by a factor of 2×10^5 while only reducing the number of signal pairs by a factor 2.

2. Fragmentation cross section as extension of measurements for cosmic ray experiments

A wealth of new data on Galactic Cosmic Rays has recently been collected by the AMS and PAMELA space experiments. The fluxes of leptons, nuclei and antiprotons from GeV to TeV are now known to an unprecedented percent-level precision [6–12], and provide a unique diagnostic of cosmic-ray propagation in the Galaxy [13] and an opportunity to find signatures of dark matter annihilation in the Galaxy [14, 15].

Galactic cosmic rays can be classified as being of primary and secondary origin. Primary cosmic-ray nuclei are assumed to be accelerated in supernova remnants (*e.g.*, ^{1}H, ^{4}He, C, O, Fe), whereas secondary nuclei are created in nuclear interactions of primary cosmic rays with protons and helium nuclei of the interstellar medium (*e.g.* ^{2}H, ^{3}He, Li, Be, B, sub-Fe). The flux ratios of secondary to primary cosmic rays are key observables to determine the characteristics of propagation of cosmic rays in the Galaxy, such as the effective diffusion coefficient and its energy dependence, the column depth of material traversed by cosmic rays and the time they spend in the Galaxy before escaping. The most studied flux ratio is the B/C ratio because it is the easiest to measure.

The interpretation of measurements of Galactic cosmic rays usually proceeds in two steps. First, the parameters of cosmic-ray diffusion in the Galaxy are estimated by analysing the measured flux ratios of secondary and primary nuclei for an assumed propagation model. Using these parameters, the quantity of interest (*e.g.* the flux of secondary antimatter as a background to dark matter searches) can then be predicted. Unfortunately, this approach is severely hampered by uncertainties of the modelling of the propagation of cosmic rays in the Galaxy [17–19] due to the 10–20% uncertainty on the cross sections for nuclear fragmentation [20, 21]. These uncertainties propagate directly to the flux predictions, *i.e.* if the integrated mass density is derived from the measured B/C ratio with 20% too low cross section for boron production, then the predicted secondary antimatter fluxes will be 20% too low as well.

The most important reactions relevant for the B/C ratio are occurring in interactions of C and O nuclei with hydrogen. The available data on carbon interactions are displayed in Fig. 3 and a similar situation is found for oxygen primaries [16]. It can be seen that a precise measurement of the cross sections at around 13 $A\,\mathrm{GeV}/c$ (about the lowest energy available in the SPS beam line), could improve the experimental situation dramatically. The NA61/SHINE facility is perfectly suited to perform the needed cross-

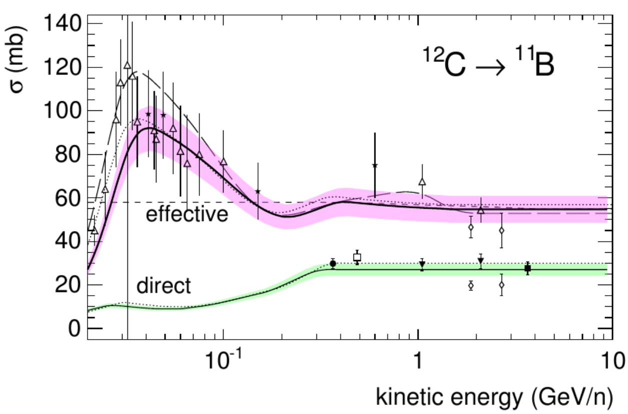

Fig. 3. (Colour on-line) ^{11}B production in $^{12}\mathrm{C}+p$ interactions. The lower grey (green) band denotes the direct production, $^{12}\mathrm{C}+p \to ^{11}\mathrm{B}$, the upper grey (purple) band includes the production via the decay of ^{11}C, *i.e.* $^{12}\mathrm{C}+p \to ^{11}\mathrm{C} \to ^{11}\mathrm{B}$ [16].

section measurements for specific isotopes. The collaboration has already successfully taken data with secondary light ion beams (*e.g.* B, C, Si) [22, 23].

In 2018, a test run is planned, primarily to study the feasibility of fragmentation measurements with NA61/SHINE. The gained experience will allow to formulate an experimental programme for the measurement of fragmentation cross sections with NA61/SHINE in 2020 after the Long Shutdown 2.

3. Summary

The NA61/SHINE experiment plans to extend the physics program beyond 2020 after the Long Shutdown 2 by measurements of open charm production in Pb+Pb collisions at 40, 75 and 150 A GeV/c and measurements of fragmentation cross sections needed for the interpretation of cosmic ray experiments. Additionally, the importance of hadron production measurements for on-going and future neutrino experiments is strongly emphasized by the neutrino physics communities. Many accelerator and atmospheric neutrino experiments expressed interest in new additional thin-target measurements beyond 2020 in the momentum range from a few GeV/c up to 120 GeV/c.

REFERENCES

[1] T. Matsui, H. Satz, *Phys. Lett. B* **178**, 416 (1986).

[2] A. Adare *et al.*, *Phys. Rev. C* **93**, 034903 (2016).

[3] M. Šuljic *et al.*, *JINST* **11**, C11025 (2016).

[4] G. Aglieri Rinella *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **845**, 583 (2017).

[5] J. Adam *et al.*, *J. High Energy Phys.* **1603**, 081 (2016).

[6] M. Aguilar *et al.*, *Phys. Rev. Lett.* **117**, 231102 (2016).

[7] M. Aguilar *et al.*, *Phys. Rev. Lett.* **117**, 091103 (2016).

[8] M. Aguilar *et al.*, *Phys. Rev. Lett.* **115**, 211101 (2015).

[9] M. Aguilar *et al.*, *Phys. Rev. Lett.* **114**, 171103 (2015).

[10] M. Aguilar *et al.*, *Phys. Rev. Lett.* **113**, 221102 (2014).

[11] M. Aguilar *et al.*, *Phys. Rev. Lett.* **113**, 121102 (2014).

[12] L. Accardo *et al.*, *Phys. Rev. Lett.* **113**, 121101 (2014).

[13] A.W. Strong, I.V. Moskalenko, V.S. Ptuskin, *Annu. Rev. Nucl. Part. Sci.* **57**, 285 (2007).

[14] T.A. Porter, R.P. Johnson, P.W. Graham, *Annu. Rev. Astron. Astrophys.* **49**, 155 (2011).

[15] J. Lavalle, P. Salati, *Comptes Rendus Phys.* **13**, 740 (2012).

[16] N. Tomassetti, *Phys. Rev. D* **96**, 103005 (2017) [arXiv:1707.06917 [astro-ph.HE]].

[17] D. Maurin, A. Putze, L. Derome, *Astron. Astrophys.* **516**, A67 (2010).

[18] Y. Genolini, A. Putze, P. Salati, P.D. Serpico, *Astron. Astrophys.* **580**, A9 (2015).

[19] N. Tomassetti, *PoS* **ICRC2015**, 553 (2016).

[20] I.V. Moskalenko, S.G. Mashnik, Proceedings, 28^{th} International Cosmic Ray Conference, Tsukuba, Japan, July 31–August 7, 2003, p. 1969.

[21] W.R. Webber, A. Soutoul, J.C. Kish, J.M. Rockstroh, *Astrophys. J. Suppl.* **144**, 153 (2003).

[22] H. Strobele, I. Efthymiopoulos, *CERN Cour.* **52N4**, 33 (2012).

[23] N. Abgrall *et al.*, *JINST* **9**, P06005 (2014).