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Constraining production models with light (anti-)nuclei measurements in small systems with ALICE at the LHC

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Abstract

The production of deuterons and anti-deuterons in pp collisions at $\sqrt{s} = 7$ and 13 TeV has been studied as a function of charged-particle multiplicity using the ALICE detector at the LHC. The preliminary results are shown here, together with those obtained in heavy-ion collisions. They are presented by focusing the discussion on the comparison with expectations from hadron-coalescence models.

Keywords: Anti-nuclei, Coalescence

1. Introduction

The production of nuclei and anti-nuclei in light particle collisions is thought to be the result of a coalescence process of protons and neutrons which are nearby in space and have similar velocities at the last stage of the collision. Coalescence models [1, 2, 3], implementing such a picture, have been able to successfully describe observations in pp collisions at the CERN ISR [4] and Tevatron [5], in DIS scattering at HERA [6, 7], electron-positron collisions at CLEO [8] and at LEP [9]. At LHC the ALICE Collaboration reported the production of (anti-)deuterons, (anti-)triton and (anti-) ^3He in pp collisions at $\sqrt{s} = 0.9, 2.76$ and 7 TeV [10, 11], confirming the validity of hadron-coalescence models also at very high collision energy. The deuteron production in pp collisions at $\sqrt{s} = 7$ and 13 TeV has been also studied as a function of the charged-particle multiplicity at mid-rapidity ($dN_{\text{ch}}/d\eta$), and the corresponding preliminary results are presented in this paper for the first time. A multiplicity dependent analysis of nuclei yields allows one to investigate their production at various sizes of the hadronic emission region, described only in more advanced coalescence models [3].

2. Analysis strategy

A detailed description of the ALICE detector and its performance can be found in [12]. The key features of ALICE are the high quality tracking and particle identification capabilities, which allow for the measurement of the light (anti-)nuclei production at the LHC. The measurement presented here is based on two data

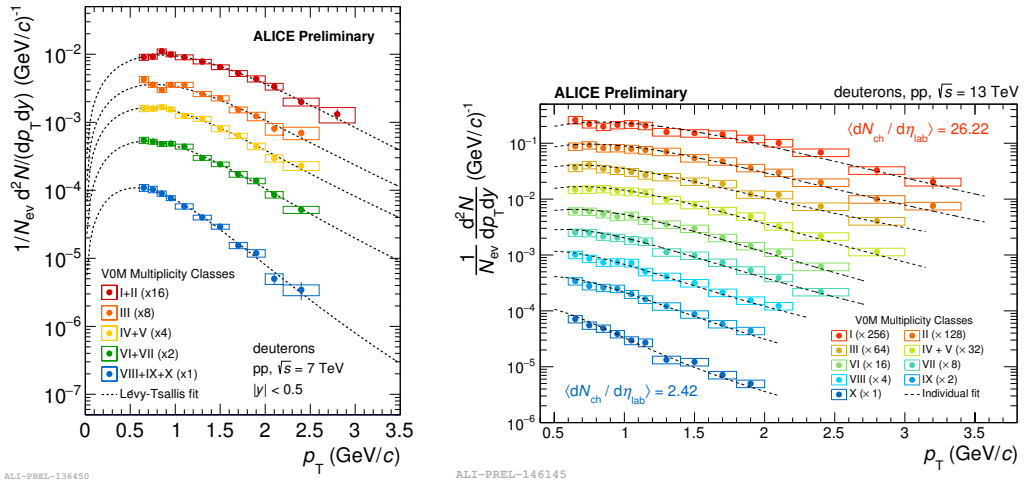


Fig. 1. Transverse-momentum spectra of deuterons measured at mid-rapidity in pp collisions at $\sqrt{s} = 7$ TeV (left) and at $\sqrt{s} = 13$ TeV (right) in various multiplicity classes. The vertical bars are the statistical uncertainties, the hollow boxes represent the systematic ones. The dashed lines correspond to individual fits to the data performed with the Lévy-Tsallis function.

samples of minimum-bias pp collisions at $\sqrt{s} = 7$ and 13 TeV, collected in 2010 and 2016, respectively. The identification of (anti-)deuterons at low transverse momenta ($p_T < 1$ GeV/c) is performed via the measurement of their specific energy loss provided by the Time Projection Chamber (TPC). At higher p_T the deuteron signal suffers from an increasing contamination from pions, kaons and protons. To extend the deuteron identification at higher transverse momenta, the measurement of the particle velocity provided by the Time Of Flight (TOF) detector is used. A certain amount of deuterons detected in this way at low p_T (up to about 1.4 GeV/c) is produced in secondary interactions (spallation) and not in the primary collision. The corresponding correction is estimated as in [11] and is based on the measurement of the Distance of Closest Approach (DCA) of the tracks to the primary vertex provided by the Inner Tracking System (ITS).

3. Results

The transverse momentum spectra of deuterons at $\sqrt{s} = 7$ and 13 TeV in the considered multiplicity classes are shown in Fig. 1. Since the $\sqrt{s} = 7$ TeV data sample contains about half of the number of events of the $\sqrt{s} = 13$ TeV data sample, larger multiplicity classes are defined in the first case. At both energies, in order to extrapolate the spectra to low and high p_T , the distributions are individually fitted with the Lévy-Tsallis function [13]. A hardening of the spectra from low to high multiplicity is visible, which was already observed for lighter particles such as pions, kaons and protons [14]. The ratios between deuteron and anti-deuteron spectra are compatible with unity within the uncertainties independent of p_T and multiplicity. Since coalescence models predict that the yield ratio \bar{d}/d is equal to $(\bar{p}/p)^2$ and the production of protons and anti-protons is the same at LHC energies, the results are in agreement with expectations. Most of the coalescence model predictions are given for the so called coalescence parameter B_A , where A is the mass number of the nucleus under study. In our case it corresponds to B_2 , which relates the formation of composite deuterons to the one of primordial protons and neutrons through a simple power law [1, 3]:

$$\frac{1}{2\pi p_T^d} \frac{d^2 N^d}{dp_T^d dy} = B_2 \left(\frac{1}{2\pi p_T^p} \frac{d^2 N^p}{dp_T^p dy} \right)^2, \quad (1)$$

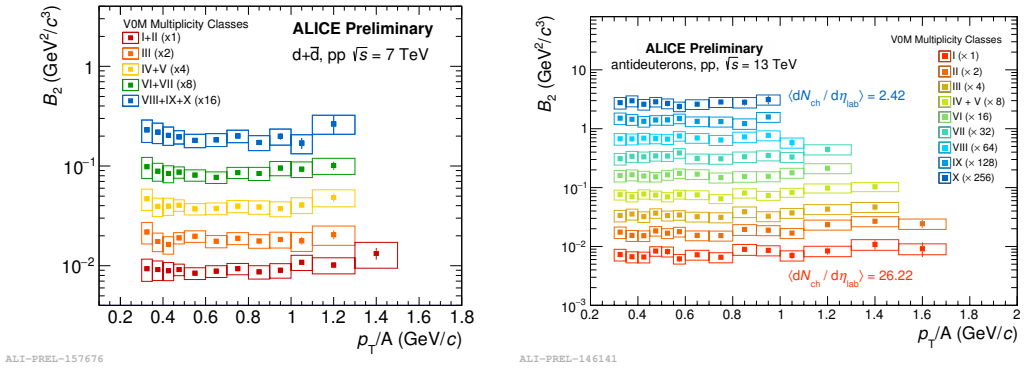


Fig. 2. Coalescence parameter B_2 as a function of the transverse momentum per nucleon at $\sqrt{s} = 7$ TeV (left) and $\sqrt{s} = 13$ TeV (right) in various multiplicity classes at the LHC.

where the proton yield is measured at the half of the transverse momentum of deuterons i.e. $p_T^p = p_T^d/2$ and where neutrons are assumed to have the same invariant production spectra as protons. Figure 2 reports the measured B_2 at $\sqrt{s} = 7$ and 13 TeV, as a function of the transverse momentum per nucleon (p_T/A). At both energies B_2 does not show a significant p_T dependence, as also observed in p–Pb collisions [15]. This is in agreement with a simple coalescence model [1, 2], where a point-like nucleon emitting source with no correlations between proton and neutron momenta is assumed. On the contrary, in central Pb–Pb collisions B_2 is found to increase with p_T [10], which is expected to occur in the presence of a radially expanding source [16]. For a fixed value of the transverse momentum per nucleon ($p_T/A = 0.75$ GeV/c), B_2 is shown as a function of charged-particle multiplicity in Fig. 3 (left), together with the one measured in p–Pb [15] and Pb–Pb collisions [10, 17] at the LHC. The observed multiplicity dependence, not predicted by simple coalescence models, is related to the increasing source volume, going from low to high multiplicities, which suppresses the coalescence probability (the larger is the distance between the two nucleons, the less likely they combine). This effect, precisely quantified in more elaborate coalescence models [3], is less pronounced in pp because in such collisions the typical size of the hadronic emission region is not larger than the size of the deuteron.

The ratio of the p_T integrated yields of deuterons and protons as a function of multiplicity is reported in Fig. 3 (right). The d/p yield ratio is found to increase with multiplicity in pp and p–Pb collisions. Note that the systematic uncertainties are strongly correlated across multiplicity, therefore the enhancement is significant. In a first approximation, neglecting the spatial extension of the source, since $d/p \propto p$ in a simple coalescence picture, this enhancement can be directly related to the fact that the number of protons and neutrons produced in the collision rises with multiplicity. In a second order approximation, releasing the assumption that the source volume can be neglected, the observed trend in pp and p–Pb collisions are better explained by means of more advanced coalescence models [3] as due to an enhanced nucleon density with multiplicity, and not simply related to the proton and neutron increasing abundances. No dependence of the d/p ratio on the multiplicity is observed in Pb–Pb collisions and the roughly constant value is in agreement with expectations from thermal-statistical models [10].

4. Conclusions

Preliminary results of deuteron and anti-deuteron production as a function of charged-particle multiplicity in pp and p–Pb collisions at the LHC confirm the validity of nucleon-coalescence models in small systems at the LHC. A simple coalescence approach is able to predict the constant behaviour of B_2 as a function of the particle momentum but fails to describe the multiplicity dependence. More elaborate models, accounting

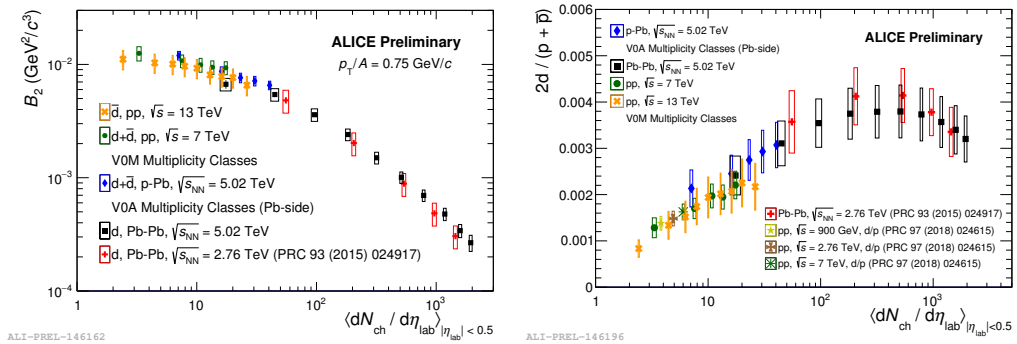


Fig. 3. Coalescence parameter B_2 of (anti-)deuteron at $p_T/A = 0.75$ GeV/c (left) and deuteron-to-proton ratio (right) as a function of multiplicity at mid-rapidity at the LHC.

for the size of the source, are needed to qualitatively explain the suppression of B_2 with multiplicity. The same models relate the enhancement of the d/p ratio observed in small systems to the increasing nucleon density in space coordinates. A precise estimate of the source radii depending on multiplicity is necessary for a quantitative comparison of experimental data with model predictions.

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