Observation of light nuclei at ALICE and the $X(3872)$ conundrum

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The new data reported by ALICE on the production of light nuclei with $p_\perp \lesssim 10$ GeV in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV are used to compute an order-of-magnitude estimate of the expected production cross sections of light nuclei in proton-proton collisions at high transverse momenta. We compare the hypertriton, helium-3, and deuteron production cross sections to that of $X(3872)$, measured in prompt pp collisions by CMS. The results we find suggest a different production mechanism for the $X(3872)$, making questionable any loosely bound molecule interpretation.

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As first discussed in [1], one expects a suppression of loosely bound hadron molecules in high energy $pp(\bar{p})$ collisions. Small relative momenta in the center of mass of such molecular hadrons, needed to preserve a state with few keVs' binding energies, are in fact hard to obtain in hadron collisions at high energy and $p_\perp$.

Despite this, the $X(3872)$, one of the most studied loosely bound hadron molecule candidates [2], is strongly produced at the LHC—see e.g. Ref. [3]. This might simply be the indication that the X hadron molecule interpretation is not correct (for the alternative tetraquark model, see Refs. [4–6]).

Assuming that final state interaction mechanisms are at work—the description of which requires several model-dependent assumptions [7,8]—it has been proposed that the relative kinetic energy might be reduced in the center of mass of the hadron pair constituting the X, in such a way to match a shallow discrete level of some interhadron potential. A hadron molecule would then be formed, with a precise relation between binding energy and strong coupling to its constituent hadrons [9]. Since the mass and branching ratios of the X have not been measured with the required precision yet, it is still unclear if this relation is fulfilled.

Final state interactions should also favor the prompt formation of *bona fide* light nuclei in high energy hadronic collisions. It would therefore be of great interest to measure the pp (anti)deuteron production cross section in the same $p_\perp$ region where the X has been observed [10].

Unfortunately, (anti)deuteron production in pp collisions at $p_\perp$ values as high as ≈15 GeV (where the X is clearly seen at CMS [3]) has not been measured yet.

However, very recently the ALICE Collaboration reported results on the production of deuteron, helium-3 (^{3}He) and hypertriton ($^3_\Lambda$H) light nuclei in relatively high $p_\perp$ bins in Pb-Pb collisions, at $\sqrt{s_{\rm NN}} = 2.76$ TeV [11,12]. This is potentially a very exciting result for the reasons described above.

We would like to draw attention to these data and propose a way to exploit them to provide an order-of-magnitude estimate of light nuclei production in pp collisions, to compare with the X data.

As a first approximation, one can assume that there are no medium effects enhancing or suppressing the production of light nuclei in Pb-Pb collisions. This is equivalent to state that each nucleus-nucleus collision is just an independent product of $N_{\rm coll}$ proton-proton collisions, with $N_{\rm coll}$ computed in a Glauber Monte Carlo calculation as a function of the centrality class. We use the results from Ref. [13], which are compatible at 1σ level with the ALICE ones [14], and never more different than 3%. To compare with $\sqrt{s} = 7$ TeV data, we rescale our estimated cross sections by a factor $\sigma_{pp}^{\rm inel}(7\ {\rm TeV})/\sigma_{pp}^{\rm inel}(2.76\ {\rm TeV}) = 1.1$.

Consider for example the production of the hypertriton observed by ALICE in Pb-Pb collisions.[1] Neglecting medium effects, the pp cross section can be estimated with

$$\begin{aligned}\left(\frac{d\sigma(^3_\Lambda{\rm H})}{dp_\perp}\right)_{pp} &= \frac{\Delta y}{\mathcal{B}(^3{\rm He}\,\pi)} \times \frac{1}{\mathcal{L}_{pp}} \left(\frac{d^2N(^3{\rm He}\,\pi)}{dp_\perp dy}\right)_{pp} \\ &= \frac{\Delta y}{\mathcal{B}(^3{\rm He}\,\pi)} \times \frac{\sigma_{pp}^{\rm inel}}{N_{\rm evt}} \left(\frac{d^2N(^3{\rm He}\,\pi)}{dp_\perp dy}\right)_{pp} \\ &= \frac{\Delta y}{\mathcal{B}(^3{\rm He}\,\pi)} \times \frac{\sigma_{pp}^{\rm inel}}{N_{\rm coll}} \left(\frac{1}{N_{\rm evt}}\frac{d^2N(^3{\rm He}\,\pi)}{dp_\perp dy}\right)_{\rm Pb\text{-}Pb}. \end{aligned} \tag{1}$$

ALICE analyzes ^{3}He$\,\pi$ pairs, and thus we need to divide by the branching ratio for the $^3_\Lambda{\rm H} \to {}^3{\rm He}\,\pi$

[1]In the following, the average of hypertriton and antihypertriton data is understood.

decay—$\mathcal{B}(^3\text{He}\,\pi) \approx 25\%$ [15]—in order to deduce the number of parent hypertritons. We stress that the experimental data in Ref. [11] are indeed normalized to $N_{\text{evt}} = N_{\text{Pb-Pb}}^{0\text{–}10\%}$, i.e. the total number of inelastic Pb-Pb collisions analyzed (about 20×10^6 events in the 0–10% centrality bin). We use $\sigma_{pp}^{\text{inel}} = 73$ mb, as measured in $\sqrt{s} = 7$ TeV collisions [16], and $\Delta y = 2.4$ to compare with the CMS analysis [3]. In this centrality class, we use $N_{\text{coll}}^{0\text{–}10\%} = 1518$ [13].

Similarly, we can estimate the ^{3}He distribution in pp collisions from the ALICE Pb-Pb data in the 0–20% centrality class [12], using $N_{\text{coll}}^{0\text{–}20\%} = 1226$ [13]. We remark that the selection of these events rejects any ^{3}He not produced in the primary vertex, i.e. the hypertriton decay products. Since the ^{3}He data points with $p_\perp < 4.4$ GeV show a deviation from the exponential behavior, likely due to the expansion of the medium, we perform an exponential fit to the points in the region $p_\perp \in [4.45, 6.95]$ GeV only. Alternatively, we fit hypertriton and ^{3}He data with the blast-wave model,[2] which describes particle production properties by assuming thermal emission from an expanding source [17]. This model is expected to reproduce correctly the low and medium $p_\perp$ regions in Pb-Pb collisions. Since we are rescaling Pb-Pb data to pp by a constant factor, the same shape holds in our estimated pp data and gives a guess on the asymptotic exponential behavior. The results are shown in Fig. 1.

Our rescaling to pp collisions does not take into account either medium effects nor the fact that the coalescence/recombination mechanism can be enhanced in Pb-Pb collisions [18]. In fact, such phenomena are known to favor the production of many-body hadrons with respect to what is expected in vacuum. Medium effects are discussed later.

For the deuteron we use ALICE pp data [12] to estimate

$$\left(\frac{d\sigma(d)}{dp_\perp}\right)_{pp} = \Delta y \times \sigma_{pp}^{\text{inel}} \left(\frac{1}{N_{pp}^{\text{inel}}}\frac{d^2N(d)}{dp_\perp dy}\right)_{pp}, \qquad (2)$$

N_{pp}^{inel} being the number of pp inelastic collisions collected. We perform the fit to the points in the region $p_\perp \in [1.7, 3.0]$ GeV, which shows a good exponential behavior.

The CMS analysis of X production provides the differential cross section times the branching fraction $\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$. The latter has not been measured yet, and the lower limit reported in the PDG is $\mathcal{B} > 2.6\%$ [19]. An estimate for the upper limit has been reported, $\mathcal{B} < 6.6\%$ at 90% C.L. [20]; we use instead the more conservative value $\mathcal{B} = 8.1^{+1.9}_{-3.1}\%$ [6]. The comparison in Fig. 1 shows that, according to the most conservative exponential fit in the left panel, the extrapolated hypertriton production cross section in pp collisions would fall short by about 2–3 orders of magnitude with respect to the X production, and much more according to the blast-wave fit in the right panel. The drop of the deuteron cross section, which is directly measured in pp collisions, appears definitely faster.

As we mentioned already, the main problem for the production of loosely bound molecular states in proton-proton collisions is the difficulty in producing the constituents close enough in phase space. However, it is well known that the interaction of elementary partons with the collective hot dense medium causes relevant energy loss of the partons themselves. This effect is usually quantified by the nuclear modification factor [21–25]

$$R_{AA} = \frac{\left(\frac{1}{N_{\text{evt}}}\frac{d^2N}{dp_\perp dy}\right)_{\text{Pb-Pb}}}{N_{\text{coll}}\left(\frac{1}{N_{\text{evt}}}\frac{d^2N}{dp_\perp dy}\right)_{pp}}, \qquad (3)$$

which compares the particle yield in Pb-Pb collisions with that in pp. It then follows that the method used to obtain Eq. (1) corresponds to assume $R_{AA} = 1$.

While for ordinary hadrons medium effects generally lead to a suppression of the particle yield—i.e. $R_{AA} < 1$—conversely they can favor the production of hadronic molecules. The role of the medium would be, in fact, that of decreasing the relative momenta of the components with respect to the zero temperature case due to the well-known jet quenching effect [26,27]. This would favor their coalescence into the final bound state by reducing their relative momenta directly at parton level.

The coalescence model is based on the sudden approximation[3] and is implemented by calculating the overlap of the density matrix of the constituents with the Wigner function of the final composite particle. In particular, it has the important property of taking into account the inner structure of the considered hadron. If one only requires the vicinity in momentum space, the $p_\perp$ distribution of a composite state with N constituents coming out of a hot QCD medium is roughly given by

$$\frac{dN_{\text{b}}}{dp_\perp}(\boldsymbol{p}_\perp) \sim \prod_{i=1}^{N}\frac{dN_i}{dp_\perp}(\boldsymbol{p}_\perp/N), \qquad (4)$$

where N_{b} is the number of final bound states and N_i is the number of produced constituents. This would also explain why in Fig. 1 the cross sections for the ^{3}He and hypertriton

[2]The blast-wave function is

$$\frac{dN}{dp_\perp} \propto p_\perp \int_0^R r dr m_\perp I_0\left(\frac{p_\perp \sinh\rho}{T_{\text{kin}}}\right) K_1\left(\frac{m_\perp \cosh\rho}{T_{\text{kin}}}\right),$$

where $m_\perp$ is the transverse mass, R is the radius of the fireball, I_0 and K_1 are the Bessel functions, $\rho = \tanh^{-1}\left(\frac{(n+2)\langle\beta\rangle}{2}(r/R)^n\right)$, and $\langle\beta\rangle$ is the averaged speed of the particles in the medium.

[3]i.e. the assumption that the binding of the constituents happens on small time scales and therefore their wave function remains unchanged during the transition to the bound state.

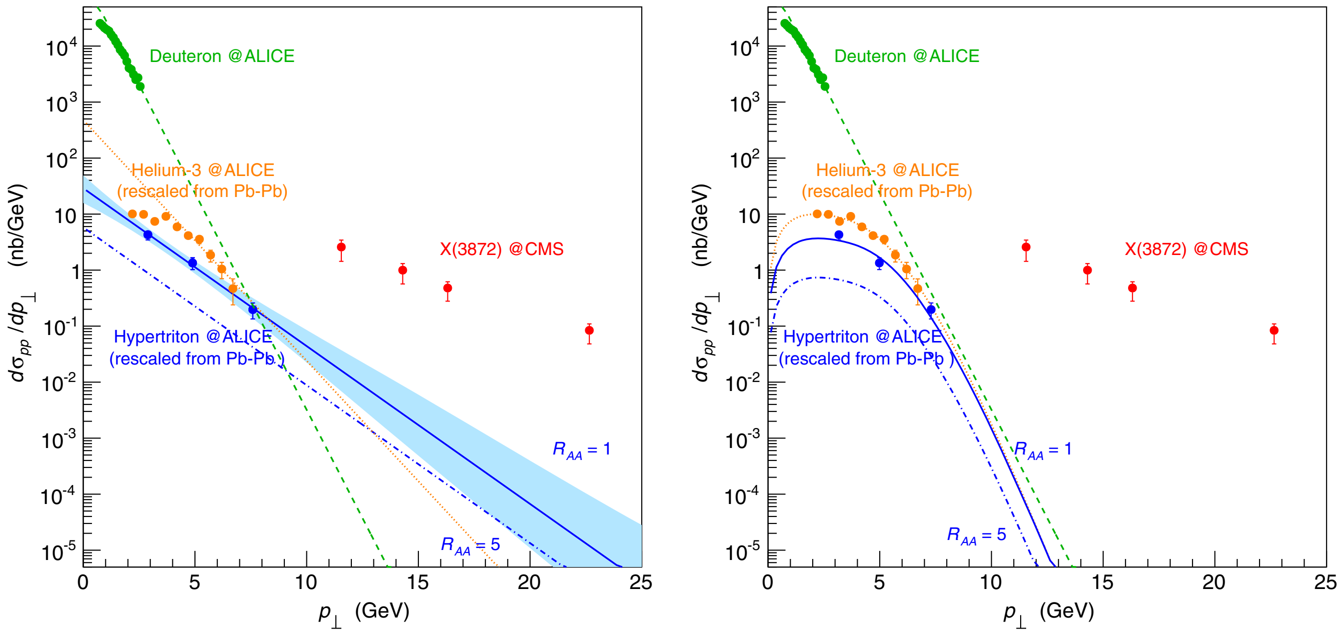

FIG. 1 (color online). Comparison between the prompt production cross section in pp collisions of $X(3872)$ (red), the deuteron (green), ^{3}He (orange), and the hypertriton (blue). The X data from CMS [3] are rescaled by the branching ratio $\mathcal{B}(X \to J/\psi\pi\pi)$. Deuteron data in pp collisions are taken from ALICE [12]. The ^{3}He and hypertriton data measured by ALICE in Pb-Pb collisions [11,12] have been rescaled to pp using a Glauber model, as explained in the text. The dashed green line is the exponential fit to the deuteron data points in the $p_\perp \in [1.7, 3.0]$ GeV region, whereas the dotted orange one is the fit to the ^{3}He data points. The solid and dot-dashed blue lines represent the fits to hypertriton data with $R_{AA} = 1$ (no medium effects) and a hypothetical constant value of $R_{AA} = 5$. The hypertriton data points are horizontally shifted at the bin centers of gravity—being defined as the point at which the value of the fitted function equals the mean value of the function in the bin. (*Left panel*) The hypertriton data are fitted with an exponential curve, and the light blue band is the 68% C.L. for the extrapolated $R_{AA} = 1$ curve. ^{3}He data in the $p_\perp \in [4.45, 6.95]$ GeV region are also fitted with an exponential curve. (*Right panel*) The hypertriton and ^{3}He data are fitted with blast-wave functions [17], the parameters of which are locked to the ^{3}He ones obtained in Ref. [12].

are several orders of magnitude smaller than the deuteron one: one additional p or Λ, close enough in phase space, must be produced.

It has already been shown that coalescence effects in Pb-Pb collisions can have relevant consequences on the production of multiquark states. In particular, molecular states with small binding energy are expected to be *enhanced*, i.e. $R_{AA} > 1$ [28].

Unfortunately there is no measurement of R_{AA} for the deuteron as a function of $p_\perp$. However, there is another nuclear modification factor which is often used,

$$R_{CP} = \frac{\left(\frac{1}{N_{\rm evt}}\frac{d^2N}{dp_\perp dy}\right)^{0\text{–}10\%}_{\text{Pb-Pb}} / N^{0\text{–}10\%}_{\rm coll}}{\left(\frac{1}{N_{\rm evt}}\frac{d^2N}{dp_\perp dy}\right)^{60\text{–}80\%}_{\text{Pb-Pb}} / N^{60\text{–}80\%}_{\rm coll}}. \tag{5}$$

This quantity is a comparison between the most central and the most peripheral Pb-Pb collisions and therefore provides another valid indicator of the strength of medium effects (which should be absent in the less dense, most peripheral events). The fact that R_{AA} and R_{CP} measurements for hadron species are strongly correlated to each other is shown experimentally by a thorough data analysis reported by ATLAS [23], up to very high $p_\perp \sim 100$ GeV.

Using the ALICE data presented in Ref. [11], we can compute R_{CP} for the deuteron as a function of $p_\perp$ and compare it with that for generic charged tracks, as reported in Ref. [23]—see Fig. 2. We use $N^{60\text{–}80\%}_{\rm coll} = 27.5$ [13]. As one immediately notices, the difference from ordinary hadrons is striking. The presence of the QCD medium is extremely effective at enhancing the production of the deuteron for the reasons explained before. In fact, R_{CP} for this hadronic molecule becomes larger than unity for $p_\perp \gtrsim 2.5$ GeV, and in particular we have $R_{CP} = 1.7$ at the last point with $p_\perp = 3.1$ GeV. Using the blast-wave fitting function for the peripheral data taken from Ref. [11], we also extrapolate up to the end point of the central data, confirming the growth of R_{CP} with $p_\perp$.

We expect a similar behavior in R_{AA}, in particular a value larger than 1 for $p_\perp$ large enough.

To get an independent rough estimate for R_{AA}, we assume the deuteron production cross section in pp collisions to scale with $\sqrt{s}$ like the inelastic cross section and compare the ALICE data in central Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV with the ones in pp collisions at $\sqrt{s} = 7$ TeV [12]. Indeed, we find that R_{AA} exceeds 1 at $p_\perp = 2.1$ GeV and reaches 5 at $p_\perp = 4.3$ GeV. This gives strength to our expectation for $R_{AA} > 1$. To display the

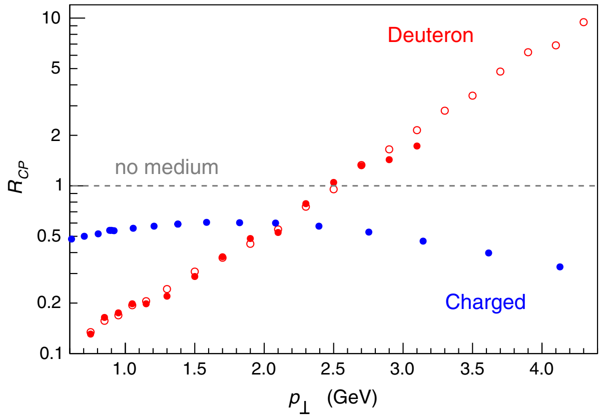

FIG. 2 (color online). Comparison between the nuclear modification factor R_{CP} for the deuteron (red) and for generic charged tracks (blue) [23] in central (respectively, 0–10% and 0–5%) vs peripheral (60–80%) Pb-Pb collisions. We evaluate R_{CP} either taking the bin-by-bin ratio of ALICE data [12] (full disks) or using the values given by the blast-wave fit for the peripheral Pb-Pb data and extrapolating up to $p_\perp \sim 4.8$ GeV (open disks). The dashed line corresponds to no medium effects, $R_{CP} = 1$. It is worth noticing that $R_{CP}(d)$ gets enhanced at $p_\perp \gtrsim 2.5$ GeV.

size of this effect, we plot also the hypertriton curves for $R_{AA} = 5$ in Fig. 1.

One naturally expects for a similar enhancement to be even more relevant for three-body nuclei like ^{3}He and the hypertriton. Its role would be to further *decrease* the extrapolated cross section in prompt pp collisions. As we already said, indeed, a value of $R_{AA} > 1$ applied to Pb-Pb data implies a pp cross section even smaller than predicted by the Glauber model. Even though qualitative conclusions can already be drawn, a quantitative analysis substantiated by data at higher $p_\perp$ is necessary for a definitive comparison with the X case.

Even assuming that only a hot pion gas is excited in Pb-Pb collisions, there would likely be a large number of final state interactions with pions catalyzing the formation of a loosely bound hypertriton along the lines discussed in Refs. [6,10,29]. In any case, such an environment is present in the Hadron Resonance Gas corona formed when the outer shell of the QCD medium cools down [30].

In summary, the extrapolation of the deuteron and ^{3}He data in pp collisions shown in Fig. 1 suggests that loosely bound molecules are hardly produced at high $p_\perp$. The extrapolated curve of hypertriton data from Pb-Pb collisions might lead to milder conclusions, although we expect it should be significantly suppressed when medium effects are properly subtracted. Such effects are indeed already sizeable for the deuteron as shown in Fig. 2, and probably even more relevant for three-body nuclei.

We are aware that for an unbiased and definitive comparison with X production at $p_\perp$ as high as 15 GeV the deuteron (or hypertriton) should be searched in pp collisions rather than in Pb-Pb to avoid the complications of subtracting medium effects. These analyses can be performed by ALICE and LHCb during Run II. One of the purposes of this paper is to further motivate the required experimental work.

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