Neutron skin effect in $W^+$ and $W^-$ production in high-energy proton-lead collisions

M. Alvioli$^{a,1}$, M. Strikman$^b$

$^a$Consiglio Nazionale delle Ricerche, Istituto di Ricerca per la Protezione Idrogeologica, via Madonna Alta 126, I-06128 Perugia, Italy
$^b$104 Davey Lab, The Pennsylvania State University, University Park, PA 16803, USA

Abstract

We extend our Monte Carlo generator of global configurations in nuclei to include different spatial distributions of protons and neutrons in heavy nuclei taking into account the difference of spatial correlations between two protons, two neutrons and proton-neutron pairs. These configurations are used for building an event generator for proton-heavy nucleus collisions at the LHC for final states with a hard interaction in the channels where cross section for p-p and p-n scattering differ. Soft interactions are taken into account in the color fluctuation extension of the Glauber algorithm taking into account the inherently different transverse geometry of soft and hard p-N collisions. We use the new event generator to test an interesting observation of Ref. [1] that the ratio of $W^\pm$ production rates in p-Pb collisions should significantly deviate from the inclusive value for peripheral collisions due to the presence of a neutron skin. We qualitatively confirm expectation of Ref. [1], though for a realistic centrality trigger, we find the effect to be a factor of two smaller than the original estimate.

1. Introduction

Increased accuracy of neutron skin measurements [2, 3] allowed comparison of measurements with state-of-the-art nuclear structure calculations [4].

Recently it was pointed out that the presence of the neutron skin in heavy nuclei leads to observable effects in proton-ion collisions at LHC energies due to the difference of the cross sections of a number of hard collision processes involving quarks for pp and pn scattering [1, 5]. The most practical case presented by the authors is the asymmetry of $W^\pm$ production cross sections. The deviations of the asymmetry from its inclusive value are larger for peripheral collisions. Thus, a study of this ratio should provide a sensitive test of the procedures used to determine centrality of the proton-nucleus and nucleus-nucleus high-energy collisions.

$^1$Correspondence to: massimiliano.alvioli@irpi.cnr.it
In this paper we perform a Monte Carlo (MC) study of the $W^+ / W^-$ asymmetry taking into account two effects neglected in Ref. [1]: fluctuations of the number of collisions at a given impact parameter, and fluctuations of centrality determinators used in the experimental studies. Overall we find that these effects reduce the deviation of the asymmetry from its inclusive value by a factor of two, as compared to the results of Ref. [1].

The paper is organized as follows. Section 2 describes our results for nucleon configurations in $^{208}$Pb for models with uncorrelated, central-correlated and fully-correlated configurations with built-in skin effect. Section 3 describes the algorithm for generating different hard interactions with protons and neutrons in combination with universal soft interactions. Definitions of centrality are presented in Section 4. Our numerical results for asymmetry are presented in Section 5, followed by conclusions in Section 6.

2. Nuclear configurations

In this section we describe our results for $^{208}$Pb configurations calculated using the MC code described in [6]. The original code was modified to account for neutron skin effect, the experimental and theoretical observation the neutron density extends further from the center of the nucleus than the proton density. The code also automatically accounts for short range nucleon-nucleon (NN) correlations effects. Such effects were explicitly investigated using correlated configurations in high-energy heavy-ion collisions in Refs. [7, 8, 9].

The inclusion of nucleon-nucleon correlations is based on the notion of a nuclear wave function $\psi$, which contains nucleonic degrees of freedom and which is used in our algorithm to modify iteratively the positions of randomly distributed nucleons using the Metropolis method so that the final positions correspond to the probability density given by $|\psi|^2$. The method reproduces single particle nucleon densities [6, 10] given by the nucleus profile provided as an input, by construction, as well as the basic features of the two-nucleon density [11, 12, 13, 14, 15, 16, 17, 18, 19, 20], calculated accounting for NN correlations, within a number of high-precision approaches. The model wave function is taken in the following form:

$$\psi(x_1, \ldots, x_A) = \prod_{i<j} \hat{f}_{ij} \phi(x_1, \ldots, x_A), \quad (1)$$

where $\phi$ is the uncorrelated wave function and $\hat{f}_{ij}$ are nucleon-nucleon correlation operators [10]; here, $x_i$ denotes the position ($r_i$), spin and isospin projections ($\sigma_{zi}$ and $\tau_{zi}$, respectively) of the $i$-th nucleon. The correlation operator contains a detailed spin-isospin dependence, which is the same as the one contained in NN potentials of the Argonne family and others, which is defined as follows:

$$\hat{f}_{ij} = \sum_{n=1}^{6} \hat{O}_{ij}^{(n)} f^{(n)}(r_{ij}). \quad (2)$$


Here $\hat{O}_{ij}^{(n)}$ are the standard operators [21] used in the above mentioned NN potentials:

$$\hat{O}_{ij}^{(n)} = (1, \sigma_i \cdot \sigma_j, S_{ij}) \otimes (1, \tau_i \cdot \tau_j).$$  \hspace{1cm} (3)$$

The spatial dependence of the correlation functions $f^{(n)}$ in Eq. (2) is shown in Fig. 1.

One-body density [6, 10, 16, 17] is defined as:

$$\rho^{(1)}(r) = \rho^{(1)}(r_1)|_{r_1=r} = A \int \prod_{i=2}^{A} dr_i^2 |\Psi(r_1, \ldots, r_A)|^2$$  \hspace{1cm} (4)$$

and two-body density is:

$$\rho^{(2)}(r_1, r_2) = A(A-1) \int \prod_{i=3}^{A} dr_i^2 |\Psi(r_1, \ldots, r_A)|^2.$$  \hspace{1cm} (5)$$

The densities in Eqs. (4) and (5) are spin-isospin summed quantities. If the summations (not shown in Eqs. (4) and (5)) over the individual isospin variables of particle “1”, in Eq. (4), and of particles “1” and “2”, in Eq. (5), are not carried out, partial quantities can be obtained. In particular, we can investigate the proton and neutron contributions to the one-body density, and the different proton-proton, proton-neutron and neutron-neutron contributions to the two-body density. In particular we consider the radial two-body density:

$$\rho^{(2)}(r_{12}) = A \int dR \rho \left( r_1 = R + \frac{1}{2} r, r_2 = R - \frac{1}{2} r \right).$$  \hspace{1cm} (6)$$

The quantities presented in Eqs. (4) and (6) can be calculated straightforwardly using the nuclear configurations.

We produced configurations using three different approximations, namely i) the no-correlation approximation, ii) a repulsive, central correlation function, iii) a realistic set of spin- and isospin-dependent correlation functions, obtained using variational calculations of medium-heavy nuclei [12]. The approximation i) is provided as a baseline, and it can be achieved simply by imposing that the one-body density calculated from the MC configurations reproduces a Woods-Saxon parametrization of the nucleus profile. The approximation of ii) was already introduced in Ref. [6], and it can be achieved by introducing the additional constraint that the produced configurations maximize the objective function, the square of Eq. (1), where the only central correlation, $f^{(n=1)}(r_{ij}) = f^{(c)}(r_{ij})$, is retained in Eq. (2). The approximation iii) was not implemented in the original version of our MC code [6] and it was partially implemented in a previous study of initial-state anisotropies in heavy-ion collisions from the Monte Carlo Glauber (MCG) model. In this paper we present results for the fully correlated nuclear configurations, obtained by introducing NN correlations generated by including up to the tensor, spin-isospin-dependent operator in Eq. (2). This way we effectively take into account the three-body-induced correlations, arising from
the non-commutative nature of the tensor operator which only survives in the
operator chains including three particles. A nice discussion of this effect and
a graphical representation of the tensor operator acting on three nucleons was
presented in Ref. [14].

Inclusion of neutron skin effects in the nuclear configurations was done fol-
lowing the parametrization of [3]. Each configuration is generated with a finite
number of nucleons distributed with a density $\rho(r)$ described by Woods-Saxon
distributions with different parameters for protons and neutrons:

$$
\rho^{(p,n)}(r) = \frac{\rho_0}{1 + e^{(r-R_0^{p,n})/a_{p,n}}}; \quad (7)
$$

$\rho_0$ is the density at the center of the nucleus. The neutron radius $R_0$ and skin
depth $a_n$ Woods-Saxon parameters ($R_0^n = 6.7 \text{ fm}, a_n = 0.55 \text{ fm}$) were obtained
in Ref. [3] using coherent pion photoproduction data while the proton ones ($R_0^p
= 6.68 \text{ fm}, a_n = 0.447 \text{ fm}$) are commonly taken from high-energy elastic electron
scattering measurements [22].

Results for the one-body density are shown in Fig. 2. The figure shows a
comparison of the ratio of the proton one-body density, $\rho^{(p)}(r)$, to the neutron
one-body density, $\rho^{(n)}(r)$. The densities were calculated using our MC code,
with uncorrelated, central-correlated and fully-correlated configurations, and
compared to the experimental measurements of [3]. All of the calculated den-
sities compare well with the measured ratio, as they should, since the inclusion
of NN correlations does not affect the nucleus profile.

Figure 3 shows the radial two-body densities (cf. Eq. (6)). The different
contributions from proton-proton, proton-neutron and neutron-neutron pairs in
Fig. 3 are shown separately. The figure shows two-body distributions obtained
with the configurations of $^{208}$Pb, highlighting the striking differences between
correlated and uncorrelated configurations, including skin effect for all the three
approximations described above. In particular, the inclusion of NN correlations
results in vanishing two-body densities at zero pair separation. Moreover, the
fully-correlated density overshoots the central-correlated one at NN separations
between 1.0 and 2.0 fm. This feature is entirely due to pn pairs, as it is evident
from Figure 3(b).

Configurations including full two-body and three-body induced correlations,
and including also nuclear deformations where applicable, were produced for
other nuclei: $^{12}$C, $^{40}$Ca, $^{48}$Ca, $^{63}$Cu, $^{197}$Au, $^{238}$U. These configurations will be
presented elsewhere. All configurations will be posted on our project webpage2.

3. Hard trigger geometry

The basic quantity calculated in the MCG approach, using the nuclear con-
figurations described in Section 2, is the probability of the projectile proton to
experience $\nu$ inelastic (soft) interactions with the nucleons of the target nucleus.

2http://sites.psu.edu/color/
In particular, for the purpose of this work, we are interested in calculating the separate contributions from protons and neutron in the target, which we denote as \( P_{\text{soft},(p,n)}(b, \nu) \).

We can calculate the most general form of the probability of interaction with \( N \) nucleons, with \( N_p \) protons and with \( N_n \) neutrons, as a function of both \( \nu \) and of the impact parameter, and subsequently we can single out only the \( b \) dependence, as follows:

\[
P_{\text{soft},(p,n)}(b) = 2\pi b \sum_{\nu} P_{\nu}^{\text{soft},(p,n)}(b),
\]

or the only \( \nu \) dependence, integrating over \( b \), as follows:

\[
P_{\text{soft},(p,n)}(\nu) = \int db \, P_{\text{soft},(p,n)}(b, \nu),
\]

where \( \text{soft} \) indicates that inelastic interactions were restricted to soft ones.

In a previous work [23], we introduced a method to further require that an event contained a hard interaction. Correspondingly, we calculated the probability \( P_{\text{hard},(p,n)}(b, \nu) \) of having an event in which \( \nu \) inelastic interactions occurred, one of which was a hard interaction, for the scattering of a proton on a nucleus at the impact parameter \( b \).

Since the location of the hard interaction on the transverse plane is unknown, we can calculate the cross section differential in impact parameter by taking the convolution of the generalized parton distributions \( F_g \) of the projectile and target nucleons, and then integrate over all the possible transverse positions for each hard interaction and for each simulated p-Pb event. In each event, we select one particular nucleon as the one experiencing the hard interaction, based on the probability of hard interaction, which for each nucleon \( j \) is obtained as:

\[
p_j = \frac{F_g(b + \rho - b_j)}{\sum_k F_g(b + \rho - b_k)},
\]

where the \( b \) is the incoming proton’s impact parameter, \( \rho \) is its transverse distance from the hard interaction point and \( b_j \) is the \( j \)-th target nucleon transverse position. Figure 4 is an illustration of the transverse geometry.

Once one target nucleon is selected as the hard-interacting one, we calculate the number of soft-interacting nucleons among the remaining \( A-1 \) nucleons in the target, and obtain the probability of events with a hard trigger as follows:

\[
P_{\text{ev}}^{\text{hard},(p,n)}(\nu) = \frac{1}{A} \int db d\rho \prod_{j=1}^{A} d\rho_j F_g(\rho) \sum_{i=1}^{A} F_g(\rho_i) p(\nu; \text{event}),
\]

where \( p(\nu; \text{event}) \) is the probability that in, a specific event, \( \nu \) inelastic collisions occurred, including the hard one. We keep the dependence on the particular event here, because that is the stage at which we integrate the position of the hard interaction over the whole transverse plane in each simulated event.
Figure 5 presents the quantities $P_{\text{soft;hard}}(b,\nu)$ calculated using the method outlined above both in the Glauber approximation. A second method includes the effects of fluctuations of NN cross section were first introduced by [24, 25, 26], and implemented in the MCG model in [27]. The implementation is straightforward as it requires simply introducing probability distribution over the strength of the p-N interaction [27]. Various aspects of fluctuations in p-A and A-A collisions using our configurations at LHC and RHIC energies were investigated in [23, 27, 28, 29, 30, 31].

The various quantities in Fig. 5 depend only on $\nu$, as they were integrated over the impact parameter as in Eq. (9), and both averaged over a significant number of events. The figure illustrates the effect of CF on the probability distributions as a function of the number of collisions $\nu$. Both the distributions in Fig. 5(a) were obtained with the standard MCG model, with fixed p-N cross section, while the distributions in Fig. 5(b) were obtained including an event-by-event fluctuating p-N cross section $\sigma_{\text{pN}}^\nu$, i.e. with account of CF effects. It is evident that the the distributions including CF extend to much larger $\nu$, as a consequence of the smearing of centrality due to the event-by-event fluctuation of the p-N cross section [27].

We calculate the probability that the projectile experiences one hard interaction in an event containing a total of $\nu$ interactions. By construction, $\nu-1$ of them are soft interactions. We can distinguish these quantities for proton and neutrons, that is, distinguish when the hard interaction occurred with a proton or with a neutron in the target. Figure 6 shows the proton-to-neutron ratio $P_{\text{hard}}(\nu) = \frac{\langle \int db P_{\text{hard}}(b,\nu) \rangle}{\nu}$ distributions. In the figure, we show quantities calculated with: i) the Glauber approximation and un-correlated configurations, ii) Glauber and fully correlated configuration, and iii) Glauber and CF, with un-correlated configurations. We can see that CF effects are about 10% in the most peripheral events, while correlations effects are rather small and go in the opposite direction. In the following, we will investigate these features in individual centrality bins, first for the proton-to-neutron ratio, and eventually for the $W^+/W^-$ cross sections ratio.

The probabilities defined in Eq. (9) can be integrated in the intervals of centrality calculated as in Eq. (17), for events with a hard trigger, i.e.: 

$$P_{\text{ev;i}}^{\text{hard}}(\nu) = \int_{b_i}^{b_{i+1}} db \int P_{\text{ev;i}}^{\text{hard}}(b,\nu),$$

and then calculate the average number of collisions, in each centrality bin, as follows:

$$<\nu_{p,n}>_i = \frac{\sum_{\nu} \nu P_{\text{ev;i}}^{\text{hard}(p)}(\nu)}{\sum_{\nu} P_{\text{ev;i}}^{\text{hard}(n)}(\nu)}.$$  

Note that in Eq. (13) we have distinguished the cases when the hard interaction occurred with a proton or with a neutron, so that we can calculate the ratio

$$<\nu^p>_i / <\nu^n>_i.$$  

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To estimate the ratio of the $W^+$ to $W^-$ production we need to take into account that the corresponding cross sections depend on the quark content of the nucleons. Namely, $W^+$ production on neutrons occurs with a probability $a$, relative to $W^+$ production on protons, and vice-versa for $W^-$ production. We introduced this dependence in our MCG code calculating new probabilities which incorporate different weights for $W$ production on protons and neutrons, i.e. with different values of $a$ in the definition of the relative probability.

4. Definition of centrality

As a first approximation, we define centrality bins with respect to impact parameter $b$ as follows. Based on the definition of the total inelastic cross section:

$$\sigma_{\text{in}}^A = \int db \sum_{n=1}^{A} \sigma_n(b),$$  \hspace{1cm} (15)

the $k$-th term in the above equation being:

$$\sigma_n(b) = 2\pi b \left( \frac{n}{A} \right) \left( \sigma_{\text{in}}^{pN} T(b) \right)^n \left( 1 - \sigma_{\text{in}}^{pN} T(b) \right)^{A-n},$$  \hspace{1cm} (16)

with $\sigma_{\text{in}}^{pN} = \sigma_{\text{tot}}^{pN} - \frac{\sigma_{\text{in}}^{pN^2}}{4\pi B^2}$, we define bins in $b$, $[b_i, b_{i+1}]$, such as:

$$f_i = \frac{1}{\sigma_{\text{in}}^A} \int_{b_i}^{b_{i+1}} db \sigma_n(b)$$  \hspace{1cm} (17)

where $f_i = \{0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1\}$ as required to compare with the results of Ref. [1].

The definition of centrality was refined following the method used in experimental analyses, using the ATLAS experiment studies of centrality as follows. The correlation between hadron production at central rapidities and at $-4.9 < \eta < -3.2$ in the nucleus outgoing direction in p-A collisions at $\sqrt{s} = 5$ TeV can be interpreted in the framework of CF [32] phenomena. Due to the approximate Feynman scaling near the nuclear fragmentation region, energy conservation effects are not expected to affect the total transverse energy, $\Sigma E_T$, or to be strongly correlated with the activity in the rapidity-separated central and forward rapidities regions. This expectation is validated by a measurement of $\Sigma E_T$ as a function of hard scattering kinematics in p-p collisions [33]. Distributions of $\Sigma E_T$ were constructed as a function of the number of participating nucleons, $\nu + 1$. Simple Glauber estimates of $\nu$ resulted in $\Sigma E_T$ distributions narrower than those observed in the data. Using the CF approach, instead, leads to a broader $\nu$ distribution due to the $\sigma_{\text{in}}^{pN} > \langle \sigma_{\text{in}}^{pN} \rangle$ tail of the distribution for p-N inelastic cross section $P_p(\sigma_{\text{in}}^{pN})$ [25], and produces overly broad $\Sigma E_T$ distributions. Based on these observations, parametrization of $\Sigma E_T$ was built and used to calculate the relative contributions from collisions with different $\nu$ values to the p-A centrality classes (bins in $\Sigma E_T$) used by the ATLAS.
collaboration. Application of the $\Sigma E_T$ parametrization to our case leads to the centrality classes shown in Fig. 7. The figure shows that a broad range of values for $\nu$ contribute to each centrality class, as expected from the CF approach with a fluctuating p-N cross section.

5. Results

The ratio defined in Eq. (14) is shown in Fig. 8. The figure shows results for centrality classes defined by both the total inelastic cross section method and using the $\Sigma E_T$ parametrization. Using the total inelastic cross section method, we find a result which is essentially consistent with the analysis of Ref. [1], in each centrality class. With this definition of centrality, the Glauber and CF results practically coincide.

At the same time using the experimental procedure for determining centrality classes we find a significant reduction of sensitivity to neutron skin effect. Account of CF effects leads to a further reduction of the sensitivity. Qualitatively the reason is that the number of wounded nucleons at a given impact parameter fluctuates quite significantly already in the Glauber model and even more so in the CF model.

We checked the effect of NN correlations on the quantity defined by Eq. (14). We have previously done so for the proton-to-neutron ratio of inclusive $P^{hard,(p,n)}(\nu)$ probabilities, which are shown in Fig. 6. Results for the same quantity, but integrated within different centrality bins, are shown in Fig. 9. In this case we actually compared only the ratios obtained with the Glauber approach (no CF effects) and with centrality determined by the $T(b)$ method. We repeated the calculation with un-correlated and with fully-correlated configurations. The comparison in Fig. 9 reveals little effect from the inclusion of NN correlations.

The final result of our work is illustrated in Fig. 10. Experimentally the asymmetry of $W^+$ and $W^-$ production, described as follows:

$$A = (d\sigma^+ - d\sigma^-)/(d\sigma^+ + d\sigma^-),$$

was measured at the LHC in pp scattering (for review and references see [34]) with a maximal value of $A \approx 0.26$.

We show results for pretty large values of $a = d_{pn}\sigma^+ / d_{pn}\sigma^- \approx d_{pp}\sigma^- / d_{pp}\sigma^-$, namely $a = 0.2$ and $a = 0.4$, corresponding to production of $W$ in the backward kinematics where a valence quark of a nucleon annihilates with a sea antiquark of the projectile proton. In this kinematics $d_{pn}\sigma^+ = d_{pp}\sigma^- \text{ and } d_{pn}\sigma^- = d_{pp}\sigma^+$. We find a reduction of the ratio of $W^+$ to $W^-$ production cross sections, when centrality is accounted for in an accurate way as well as color fluctuations. Typically, the deviation of the asymmetry from the inclusive value $(Z+aN)/(aZ+N)$ is reduced by a factor of two.

Eventually, we explicitly investigated the effect of using completely un-correlated or fully-correlated nuclear configurations; results are shown in Fig. 11. In both cases the inclusion of correlations provide little to no difference.
The effect is smaller or equal than that on the effective proton-to-neutron ratio, both in the un-binned ratio, in Fig. 6, and in the ratio classified in centrality bins, in Fig. 9.

6. Conclusions

We confirmed the observation of Ref. [1] that the ratio of the rates of production of W^+ and W^- in p-Pb collisions should depend on centrality of the collision due to the presence of the neutron skin. We found that expected centrality dependence of the ratio is sensitive to the model used to determine centrality, making this process a good testing ground for checking the centrality models especially for peripheral contributions.

To ensure a realistic treatment of the nucleus wave function we also extended our event generator to produce configurations including effects of NN correlations in different spin-isospin states, the skin effect, etc. The fully-correlated 208Pb configurations including neutron skin are available for download, for other possible applications, along with configurations for other nuclei. The configurations are distributed as plain text tables, and are readily usable by any p-A and A-A numerical model which takes nucleon positions as an input [28, 35, 36, 37], and for more accurate modeling of peripheral heavy ion collisions at collider energies. In particular it would be possible to extend the calculation Ref. [1] of the W^+/W^- ratio in peripheral Pb-Pb collisions by including the effects of fluctuations. Moreover, the configurations can be used in combination with models for p-p studies which can be implemented within processes involving nuclei [38, 39].

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References

[1] H. Paukkunen, Neutron skin and centrality classification in high-energy heavy-ion collisions at the LHC, Phys. Lett. B745 (2015) 73–78. doi:10.1016/j.physletb.2015.04.037.

[2] C. J. Horowitz, K. S. Kumar, K. S. Michaels, Electroweak measurements of neutron densities in CREX and PREX at JLab, USA, The European Physical Journal A 50 (2014) 48. doi:10.1140/epja/i2014-14048-3.

[3] C. M. Tarbert, et al., Neutron skin of 208Pb from coherent pion photoproduction, Phys. Rev. Lett. 112 (2014) 242502. doi:10.1103/PhysRevLett.112.242502.
[4] G. Hagen, A. Ekström, C. Forssén, G. Jansen, R., W. Nazarewicz, T. Pappenbrock, K. Wendt, A., S. Bacca, N. Barnea, B. Carlsson, C. Drischler, K. Hebeler, M. Hjorth-Jensen, M. Miorelli, G. Orlandini, A. Schwenk, J. Simonis, Neutron and weak-charge distributions of the $^{48}$Ca nucleus, Nature Physics 12 (2016) 186 – 190. doi:10.1038/nphys3529.

[5] I. Helenius, H. Paukkunen, K. J. Eskola, Neutron-skin effect in direct-photon and charged hadron-production in Pb+Pb collisions at the LHC, Eur. Phys. J. C77 (3) (2017) 148. doi:10.1140/epjc/s10052-017-4709-9.

[6] M. Alvioli, H. Drescher, M. Strikman, A Monte Carlo generator of nucleon configurations in complex nuclei including nucleon–nucleon correlations, Physics Letters B 680 (3) (2009) 225 – 230. doi:https://doi.org/10.1016/j.physletb.2009.08.067.

[7] M. Alvioli, H. Holopainen, K. J. Eskola, M. Strikman, Initial-state anisotropies and their uncertainties in ultrarelativistic heavy-ion collisions from the Monte Carlo Glauber model, Phys. Rev. C 85 (2012) 034902. doi:10.1103/PhysRevC.85.034902.

[8] J.-P. Blaizot, W. Broniowski, J.-Y. Ollitrault, Correlations in the Monte Carlo Glauber model, Phys. Rev. C 90 (2014) 034906. doi:10.1103/PhysRevC.90.034906.

[9] M. Alvioli, M. Strikman, Beam fragmentation in heavy ion collisions with realistically correlated nuclear configurations, Phys. Rev. C 83 (2011) 044905. doi:10.1103/PhysRevC.83.044905.

[10] M. Alvioli, C. C. d. Atti, H. Morita, Ground-state energies, densities and momentum distributions in closed-shell nuclei calculated within a cluster expansion approach and realistic interactions, Phys. Rev. C 72 (2005) 054310. doi:10.1103/PhysRevC.72.054310.

[11] J. L. Forest, V. R. Pandharipande, S. C. Pieper, R. B. Wiringa, R. Schiavilla, A. Arriga, Femtometer toroidal structures in nuclei, Phys. Rev. C 54 (1996) 646–667. doi:10.1103/PhysRevC.54.646.

[12] M. Alvioli, C. Ciofi degli Atti, H. Morita, Proton-neutron and proton-proton correlations in medium-weight nuclei and the role of the tensor force, Phys. Rev. Lett. 100 (2008) 162503. doi:10.1103/PhysRevLett.100.162503.

[13] R. Schiavilla, R. B. Wiringa, S. C. Pieper, J. Carlson, Tensor Forces and the Ground-State Structure of Nuclei, Phys. Rev. Lett. 98 (2007) 132501. doi:10.1103/PhysRevLett.98.132501.

[14] H. Feldmeier, W. Horiiuchi, T. Neff, Y. Suzuki, Universality of short-range nucleon-nucleon correlations, Phys. Rev. C 84 (2011) 054003. doi:10.1103/PhysRevC.84.054003.
[15] M. Alvioli, C. Ciofi degli Atti, L. P. Kaptari, C. B. Mezzetti, H. Morita, S. Scopetta, Universality of nucleon-nucleon short-range correlations: two-nucleon momentum distributions in few-body systems, Phys. Rev. C 85 (2012) 021001. doi:10.1103/PhysRevC.85.021001.

[16] M. Alvioli, C. Ciofi degli Atti, L. P. Kaptari, C. B. Mezzetti, H. Morita, Universality of nucleon–nucleon short-range correlations and nucleon momentum distributions, International Journal of Modern Physics E 22 (08) (2013) 1330021. doi:10.1142/S021830131330021X.

[17] M. Alvioli, C. Ciofi degli Atti, H. Morita, Universality of nucleon-nucleon short-range correlations: The factorization property of the nuclear wave function, the relative and center-of-mass momentum distributions, and the nuclear contacts, Phys. Rev. C 94 (2016) 044309. doi:10.1103/PhysRevC.94.044309.

[18] D. Lonardoni, A. Lovato, S. C. Pieper, R. B. Wiringa, Variational calculation of the ground state of closed-shell nuclei up to \( A = 40 \), Phys. Rev. C 96 (2) (2017) 024326. doi:10.1103/PhysRevC.96.024326.

[19] D. Lonardoni, S. Gandolfi, X. B. Wang, J. Carlson, Single- and two-nucleon momentum distributions for local chiral interactions, Phys. Rev. C 98 (1) (2018) 014322. doi:10.1103/PhysRevC.98.014322.

[20] R. Cruz-Torres, A. Schmidt, G. Miller, L. Weinstein, N. Barnea, R. Weiss, E. Piasetzky, O. Hen, Short range correlations and the isospin dependence of nuclear correlation functions, Physics Letters B 785 (2018) 304 – 308. doi:https://doi.org/10.1016/j.physletb.2018.07.069.

[21] V. R. Pandharipande, R. B. Wiringa, Variations on a theme of nuclear matter, Rev. Mod. Phys. 51 (1979) 821–859. doi:10.1103/RevModPhys.51.821.

[22] M. Warda, X. Viñas, X. Roca-Maza, M. Centelles, Analysis of bulk and surface contributions in the neutron skin of nuclei, Phys. Rev. C 81 (2010) 054309. doi:10.1103/PhysRevC.81.054309.

[23] M. Alvioli, L. Frankfurt, V. Guzev, M. Strikman, Revealing “flickering” of the interaction strength in pA collisions at the CERN LHC, Phys. Rev. C 90 (2014) 034914. doi:10.1103/PhysRevC.90.034914.

[24] G. Baym, L. Frankfurt, M. Strikman, Color fluctuations in hadrons and nucleus-nucleus collisions, Nuclear Physics A 566 (1994) 149 – 156. doi: https://doi.org/10.1016/0375-9474(94)90619-X.

[25] G. Baym, B. Blattel, L. L. Frankfurt, H. Heiselberg, M. Strikman, Correlations and fluctuations in high-energy nuclear collisions, Phys. Rev. C 52 (1995) 1604–1617. doi:10.1103/PhysRevC.52.1604.
[26] B. Blaettel, G. Baym, L. L. Frankfurt, H. Heiselberg, M. Strikman, Hadronic cross-section fluctuations, Phys. Rev. D47 (1993) 2761–2772. doi:10.1103/PhysRevD.47.2761.

[27] M. Alvioli, M. Strikman, Color fluctuation effects in proton–nucleus collisions, Physics Letters B 722 (4) (2013) 347 – 354. doi:https://doi.org/10.1016/j.physletb.2013.04.042.

[28] M. Rybczyński, G. Stefanek, W. Broniowski, P. Bożek, Glissando 2: Glauber initial-state simulation and more..., ver. 2, Computer Physics Communications 185 (6) (2014) 1759 – 1772. doi:https://doi.org/10.1016/j.cpc.2014.02.016.

[29] M. Alvioli, B. A. Cole, L. Frankfurt, D. V. Perepelitsa, M. Strikman, Evidence for $x$-dependent proton color fluctuations in $pA$ collisions at the CERN Large Hadron Collider, Phys. Rev. C 93 (2016) 011902. doi:10.1103/PhysRevC.93.011902.

[30] M. Alvioli, L. Frankfurt, D. Perepelitsa, M. Strikman, Global analysis of color fluctuation effects in proton– and deuteron–nucleus collisions at RHIC and the LHC, Phys. Rev. D98 (7) (2018) 071502. doi:10.1103/PhysRevD.98.071502.

[31] M. Alvioli, L. Frankfurt, V. Guzey, M. Strikman, M. Zhalov, Mapping color fluctuations in the photon in ultraperipheral heavy ion collisions at the Large Hadron Collider, Phys. Lett. B767 (2017) 450–457. doi:10.1016/j.physletb.2017.02.034.

[32] G. Aad, et al., Measurement of the centrality dependence of the charged-particle pseudorapidity distribution in proton–lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector, Eur. Phys. J. C76 (4) (2016) 199. doi:10.1140/epjc/s10052-016-4002-3.

[33] G. Aad, et al., Measurement of the dependence of transverse energy production at large pseudorapidity on the hard-scattering kinematics of proton-proton collisions at $\sqrt{s} = 2.76$ TeV with ATLAS, Phys. Lett. B756 (2016) 10–28. doi:10.1016/j.physletb.2016.02.056.

[34] W. Barter, Inclusive single gauge boson production in $\sqrt{s} = 7, 8$ and 13 TeV proton-proton collisions, in: Proceedings, 51st Rencontres de Moriond on Electroweak Interactions and Unified Theories: La Thuile, Italy, March 12-19, 2016, 2016, pp. 217–224. arXiv:1605.02487.

[35] J. S. Moreland, J. E. Bernhard, S. A. Bass, Alternative ansatz to wounded nucleon and binary collision scaling in high-energy nuclear collisions, Phys. Rev. C92 (1) (2015) 011901. doi:10.1103/PhysRevC.92.011901.
[36] J. Weil, J. Steinberg, J. Staudenmaier, L. G. Pang, D. Oliynichenko, J. Mohs, K. Kretz, T. Kehrenberg, A. Goldschmidt, B. Bäuchle, J. Auvinen, M. Attems, H. Petersen, Particle production and equilibrium properties within a new hadron transport approach for heavy-ion collisions, Phys. Rev. C94 (5) (2016) 054905. doi:10.1103/PhysRevC.94.054905.

[37] S. McDonald, C. Shen, F. Fillion-Gourdeau, S. Jeon, C. Gale, Hydrodynamic predictions for Pb+Pb collisions at 5.02 TeV, Phys. Rev. C95 (6) (2017) 064913. doi:10.1103/PhysRevC.95.064913.

[38] C. Bierlich, G. Gustafson, L. Lönnblad, H. Shah, The Angantyr model for Heavy-Ion Collisions in PYTHIA8, JHEP 10 (2018) 134. doi:10.1007/JHEP10(2018)134.

[39] K. Welsh, J. Singer, U. W. Heinz, Initial state fluctuations in collisions between light and heavy ions, Phys. Rev. C94 (2) (2016) 024919. doi:10.1103/PhysRevC.94.024919.
Figure 1: The spatial dependence of the correlation functions $f^{(n)}(r_{ij} = r_{12})$ appearing in Eq. (2). Each of the functions shown in the figure couples with the corresponding spin-isospin-dependent operator in Eq. (2). From Ref. [10].
Figure 2: The proton-to-neutron ratio of one-body densities as defined in Eq. (4), compared with the experimental data from Ref. [3].
Figure 3: The two-body density of $^{208}\text{Pb}$, as defined in Eq. (6), obtained with our configurations. (a): curves corresponding to different nucleon pairs, proton-proton (pp), proton-neutron (pn) and neutron-neutron (nn), whose sum is the total two-nucleon density (Total). (b): the effect of correlations in the case of proton-neutron pairs. All the curves are normalized according to the corresponding number of pairs in the nucleus.
Figure 4: Sketch of the transverse geometry of a hard collision, occurring at the location pointed by the vector $x$. The vector $b$ points to the position of the incoming proton, and $b_i$ to the $i$–th target nucleon. From Ref. [23].
Figure 5: Analysis of the soft and hard probabilities of interaction as a function of the number of collisions $\nu$. In both panels, we compare the quantity $P_{\text{hard}}(\nu)/\nu$ with $P_{\text{soft}}(\nu)/\langle \nu \rangle$. All calculations are independent of neutron skin effects, and the protons and neutrons were not distinguished, for the sake of illustration of the color fluctuations effect, which are absent in (a), and included in (b).
Figure 6: The proton-to-neutron ratio of the probability $P_{\text{hard}}(\nu)$, calculated selecting only proton or neutrons in the target; we show separately the effects of NN correlations and of color fluctuations, for illustration purposes. The horizontal dashed line correspond to $Z/N$. 
Figure 7: The probability of interaction $P_{\text{soft}}(\nu)$, calculated within the color fluctuations approximation, and the different contributions to each centrality bin, according to the most accurate definition of centrality, based on $\Sigma E_T$. The thick black line shows the total probability; we did not distinguish between protons or neutron, here.
Figure 8: The effective proton-to-neutron ratio. Green curve: the most basic approximation (comparable with the results of [1]), where we used the definition of centrality based on the thickness function integral, $(T(b))$ and Glauber model. Blue curve: Glauber model with definition of centrality based on experimental model ($\Sigma E_T$). Gold curve: the most refined approximation, where we used the experimental definition of centrality and included color fluctuations (CF) effects. The horizontal dashed line correspond to $Z/N$. 
Figure 9: The effect of using correlated configurations on the effective proton-to-neutron ratio, in the simplest Glauber approximation and centrality defined using $T(b)$ (also shown in Fig. 8). The horizontal dashed line correspond to $Z/N$. 
Figure 10: The ratio of the $W^+$ production cross section to the $W^-$ one, calculated assuming $\sigma_+^i \propto P_{\text{hard}}^\text{hard}(p) + aP_{\text{hard}}^\text{hard}(n)$, and $\sigma_-^i \propto aP_{\text{hard}}^\text{hard}(p) + P_{\text{hard}}^\text{hard}(n)$, to account for the different $d$ and $u$ quark content of protons and neutrons. The dashed and dot-dashed horizontal lines correspond to the quantity $(Z+aN)/(aZ+N)$, for $a = 0.4$ and $a = 0.2$, respectively.
Figure 11: Effects of nucleon-nucleon correlations on the ratio of the $W^+$ production cross section to the $W^-$ one, defined as in Fig. 10. We compare the results in the case $a = 0.2$ (blue curves, also shown in Fig. 10), with the corresponding calculations including correlations (yellow curves). Dashed lines correspond to the most basic approximation, where not CF nor accurate centrality definitions were accounted for; both effects are present in the calculation of solid lines. In both cases the inclusion of correlations provide little to no difference. The dashed and dot-dashed horizontal line correspond to the quantity $(Z + aN)/(aZ + N)$. 