Double parton scattering in $pA$ collisions at the LHC revisited

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We consider the production of $W$-boson plus dijet, $W$-boson plus b-jets and same sign $WW$ via double parton scattering in $pA$ collisions at the LHC and evaluate the corresponding cross sections. The impact of a novel DPS contribution pertinent to $pA$ collisions is quantified. Exploiting the experimental capability of performing measurements differential in the impact parameter in $pA$ collisions, we discuss a method to single out such a contribution. The method allows the subtraction of the single parton scattering background and it gives access in a very clean way to double parton distribution functions in the proton. We show that in the $Wjj$ and $Wbb$ channels the observation of DPS is possible with data already accumulated in $pA$ runs and that the situation will improve for the next high luminosity runs. Finally for DPS observation in the $ssWW$ channel one needs either significant increase of integrated luminosity beyond that foreseen in next runs or improved methods for $W$ reconstruction, along with its charge, in hadronic decay channels.

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I. INTRODUCTION

The flux of incoming partons in hadron-induced reactions increases with the collision energy so that multiple parton interactions (MPI) take place, both in $pp$ and $pA$ collisions. The study of MPIs started in eighties in Tevatron era [1, 2], both experimentally and theoretically. Recently a significant progress was achieved in the study of MPI, in particular of double parton scattering (DPS). From the theoretical point of view a new self consistent pQCD based formalism was developed both for $pp$ [3–10] and $pA$ DPS collisions [11] (see [12] for recent reviews). From the experimental point of view, among many DPS measurements performed recently, the one in the $W$+dijet final state is of particular relevance for the present analysis. The corresponding cross section was measured in $pp$ both by ATLAS and CMS [13, 14] and the DPS fraction was found to be 5-8% of the total number of $W$+dijet events. Moreover recent observations of double open charm [15–18] and same sign $WW$ (ssWW) production [19] clearly show the existence of DPS interactions in $pp$ collisions.

The MPI interactions play major role in the Underlying event (UE) and thus are taken into account in all MC generators developed for the LHC [20, 21]. On the other hand the study of DPS will lead to understanding of two parton correlations in the nucleon. In particular the DPS cross sections involves new non-perturbative two-body quantities, the so called two particle Generalised Parton Distribution Functions ($g$GPDs), which encode novel features of the non-perturbative nucleon structure. Such distributions have the potential to unveil two-parton correlations in the nucleon structure [22, 23] and to give access to information complementary to the one obtained from nucleon one-body distributions.

The study of MPI and in particular of the DPS reactions in $pA$ collisions is important for our
understanding of MPI in \( pp \) collisions and it constitutes a benchmark of the theoretical formalism available for these processes. On the other hand the MPI in \( pA \) collisions may play an important role in underlying event (UE) and high multiplicity events in \( pA \) collisions. Moreover it was argued in [11] that they are directly related to longitudinal parton correlations in the nucleon.

The theory of MPI and in particular DPS in \( pA \) collisions was first developed in [24], where it was shown that there are two DPS contributions at work in such a case. First, there is the so-called DPS1 contribution, depicted in the left panel of Fig. (1), in which the incoming nucleon emits two partons that interact with two partons in the target nucleon in the nucleus, making such a process formally identical to DPS in the \( pp \) collisions. Next there is a new type of contribution, depicted in the right panel of Fig. (1) and often called DPS2, in which the two partons emitted by the infalling nucleon interact with two partons each of them belonging to the distinct nucleons in the target nucleus located at the same impact parameter. Such a contribution is parametrically enhanced by a factor \( A^{1/3} \) over DPS1 contribution, \( A \) being the atomic number of the nucleus.

The basic challenge in observing and making precision studies of DPS both in \( pp \) and \( pA \) collisions is the tackling the large leading twist (LT), single parton scattering (SPS), background. This problem is especially acute in \( pA \) collisions where, due to several orders of magnitude lower luminosity relative to \( pp \) collisions, rare DPS cross sections will suffer serious deficit in statistics [25, 26].

Recently a new method was suggested [27] which could allow the observation of DPS2 in \( pA \) collisions. It was pointed out that the DPS2 has a different dependence on impact parameter than LT and DPS1 contributions. Namely while the LT and DPS1 contribution are proportional to the nuclear thickness function \( T(B) \), \( B \) being the \( pA \) impact parameter, the DPS2 contribution is proportional to the square of \( T(B) \). Therefore the cross section producing a given final state can be schematically written as:

\[
\frac{d^2\sigma_{pA}}{d^2B} = \left( c^{LT}_{pA} + c^{DPS1}_{pA} \right) \frac{T(B)}{A} + c^{DPS2}_{pA} \frac{T^2(B)}{\int d^2B T^2(B)},
\]

where \( T(B) \) is normalized to the atomic number \( A \) of the nucleus. This observation gives the possibility to distinguish the DPS2 contribution in \( pA \) collisions from both the LT and DPS1 contributions that are instead linear in \( T(B) \). This approach was used in [27] to study two-dijets processes in \( pA \) collisions.

The purpose of the present paper is to investigate whether the latter approach can be used to observe the DPS2 process in \( pA \) collisions for the following final states, ordered by decreasing cross
sections:

\[ pA \rightarrow W^\pm + \text{dijets} + X, \]
\[ pA \rightarrow W^\pm + b\bar{b} - \text{jets} + X, \]
\[ pA \rightarrow W^\pm + W^\pm + X. \]

In all considered channels one electroweak boson \((W^\pm)\) is produced in one of the scatterings, which then leptonically decays into muon and a neutrino. A second scattering in the same \(pA\) collision produces the remaining part of the final state \((jj, b\bar{b}, W^\pm)\). The first process, as it emerges from our simulations, has the advantage of higher statistics which could allow the characterization of the DPS cross section. The second one has been discussed in detail in [28] in \(pp\) collisions and, despite the lower rate, its study is relevant since DPS contribution is an important background to new physics searches with the same final state. The third one is a gold channel DPS reaction but suffer of very low cross sections [29–31].

We show in the following that in the \(Wjj\) and \(Wb\bar{b}\) cases there is rather large number of events that allows to determine \(DPS_2\) already from data already recorded in \(pA\) runs in 2016 at the LHC. The situation will improve even more for the next runs for \(pA\) runs at LHC scheduled for 2024. On the other hand the \(ssWW\) process suffers from a rather low statistics, even for the next runs. Nevertheless we expect we shall be able to observe it in the future runs if \(W\) reconstruction techniques will allow to establish the \(W\) charge from its hadronic decays.

The paper is organised as follows. In Section II we briefly review the theoretical framework which are based on our calculations. In the following three Sections we present our results for each considered final state and the corresponding discussion. Our findings are summarised in the conclusion.

II. THEORETICAL FRAMEWORK

The cross section for the production of final states \(C\) and \(D\) in \(pA\) collisions via double parton scattering can be written as the convolution of double \(2\)GPD \(G_p, G_A\) of the proton and the nuclei [11]:

\[
\frac{d\sigma_{DPS}^{CD}}{d\Omega_C d\Omega_D} = \int \frac{d^2 \Delta}{(2\pi)^2} \frac{d\sigma_{Ik}^C(x_1, x_3)}{d\Omega_C} \frac{d\sigma_{jl}^D(x_2, x_4)}{d\Omega_D} G_{ij}^p(x_1, x_2, \Delta) G_{kl}^A(x_3, x_4, -\Delta). \tag{2}
\]

Notably, two parton GPDs depend on the transverse momentum imbalance momentum \(\Delta\). Eq.\(2\) can be suitably extended to describe DPS in \(pA\) collisions [11, 24]. Since our analysis will especially deal with impact parameter \(B\) dependence of the cross section, we find natural to rewrite Eq.\(2\) in coordinate space, introducing the double distributions \(D_{p,A}\) which are the Fourier conjugated of \(G_{p,A}\) with respect to the \(\Delta\). In such a representation the latter represent the number density of parton pairs with longitudinal fractional momenta \(x_1, x_2\), at a relative transverse distance \(\vec{b}_\perp\) and do admit a probabilistic interpretation. In the impulse approximation for the nuclei, neglecting possible corrections due to the shadowing for large nuclei, and taking into account the fact that \(R_A \gg R_p\) for heavy nuclei, we can rewrite the latter expression in \(\vec{b}_\perp\) space as [11, 24]

\[
\frac{d\sigma_{DPS}^{CD}}{d\Omega_1 d\Omega_2} = \frac{m}{2} \sum_{i,j,k,l} \sum_{N=p,n} \int d\vec{b}_\perp \int d^2 B D_{ij}^p(x_1, x_2; \vec{b}_\perp) D_{kl}^N(x_3, x_4; \vec{b}_\perp) T_N(B) \frac{d\sigma_{Ik}^C}{d\Omega_C} \frac{d\sigma_{jl}^D}{d\Omega_D},
\]

\[
+ \frac{m}{2} \sum_{i,j,k,l} \sum_{N_3=N_4=p,n} \int d\vec{b}_\perp D_{ij}^p(x_1, x_2; \vec{b}_\perp) \int d^2 B f_{N_3}^k(x_3) f_{N_4}^l(x_4) T_{N_3}(B) T_{N_4}(B) \frac{d\sigma_{Ik}^C}{d\Omega_C} \frac{d\sigma_{jl}^D}{d\Omega_D}. \tag{3}
\]
Here $m = 1$ if $C$ and $D$ are identical final states and $m = 2$ otherwise, $i, j, k, l = \{q, \bar{q}, g\}$ are the parton species contributing to the final states $C(D)$. In Eq. (3) and in the following, $d\sigma$ indicates the partonic cross section for producing the final state $C(D)$, differential in the relevant set of variables, $\Omega_C$ and $\Omega_D$, respectively. The functions $f^i$ appearing in Eq. (3) are single parton densities and the subscript $N$ indicates nuclear parton distributions. All these densities do additionally depend on the factorization scales $\mu_{C(D)}$ whose values are set to the largest scale produced in a given final state.

The nuclear thickness function $T_{p,n}(B)$, mentioned in the Introduction and appearing in Eq. (3), is obtained integrating the proton and neutron densities $\rho_{0_{p,n}}^{(p,n)}$ in the nucleus over the longitudinal component $z$

$$T_{p,n}(B) = \int dz \rho_{0_{p,n}}^{(p,n)}(B, z),$$

where we have defined $r$, the distance of a given nucleon from nucleus center, in terms of the impact parameter $B$ between the colliding proton and nucleus, $r = \sqrt{B^2 + z^2}$. Following Ref. 32, for the $^{208}Pb$ nucleus, the density of proton and neutron is described by a Wood-Saxon distribution

$$\rho_{0_{p,n}}^{(p,n)}(r) = \frac{\rho_{0_{p,n}}^{(p,n)}}{1 + e^{(r-R_0^{(p,n)})/a_{p,n}}},$$

For the neutron density we use $R_0^p = 6.7$ fm and $a_n = 0.55$ fm 33. For the proton density we use $R_0^p = 6.68$ fm and $a_p = 0.447$ fm 33. The $\rho_{0_{p,n}}^{(p,n)}$ parameters are fixed by requiring that the proton and neutron density, integrated over all distance $r$, are normalized the number of proton and neutron in the lead nucleus, respectively.

As already anticipated, the DPS1 contribution, the first term in Eq. (3), stands for the 2 to 2 contribution at work in $pp$ collisions. It does depend linearly on the nuclear thickness function $T$ and therefore scales as the number of nucleon in the nucleus, $A$.

The second term, the DPS2 contribution, contains in principle two-body nuclear distributions. We work here in the impulse approximation, neglecting short range correlations in the nuclei since their contribution may change the results by several percent only 27. The latter term is therefore proportional to the product of one-body nucleonic densities in the nucleus, i.e. it does depend quadratically on $T$ and, notably, it scales as $A^{4/3}$.

We shall work here for simplicity in the mean field approximation for the nucleon. In such approximation double GPD has a factorized form:

$$D_{ij}^{p,n}(x_1, x_2, \mu_A, \mu_B, \vec{r}_\perp) \simeq f_i^{p,n}(x_1, \mu_A)f_j^{p,n}(x_2, \mu_B)\mathcal{T}(\vec{r}_\perp),$$

where the function $\mathcal{T}(\vec{r}_\perp)$ describes the probability to find two partons at a relative transverse distance $\vec{r}_\perp$ in the nucleon and it is normalized to unity. In such a simple approximation, this function does not depend on parton flavour and fractional momenta. Then one may define the so called effective cross section as

$$\sigma_{eff}^{-1} = \int d\vec{r}_\perp [\mathcal{T}(\vec{r}_\perp)]^2,$$

which controls the double parton interaction rate. Under all these approximations the DPS cross section in $pA$ collision can be rewritten as

$$\frac{d\sigma^{CD}_{DP}}{d\Omega_C d\Omega_D} = \frac{m}{2} \sum_{i,j,k,l \in N=p,n} \sigma_{eff}^{-1} f_p^{(i)}(x_1)f_p^{(j)}(x_2)f_N^{(k)}(x_3)f_N^{(l)}(x_4) \frac{d\sigma^C_{ik}}{d\Omega_C} \frac{d\sigma^D_{jl}}{d\Omega_D} \int d^2 B T_N(B),$$

$$+ \frac{m}{2} \sum_{i,j,k,l \in N_3,N_4=p,n} f_p^{(i)}(x_1)f_p^{(j)}(x_2)f_N^{(k)}(x_3)f_N^{(l)}(x_4) \frac{d\sigma^C_{ik}}{d\Omega_C} \frac{d\sigma^D_{jl}}{d\Omega_D} \int d^2 B T_{N_3}(B)T_{N_4}(B).$$
We find important to remark the key observation that leads to the second term of Eq. (3): namely that the $b$ and $B$ integrals practically decouple since the nuclear density does not vary on subnuclear scale $[11, 24, 35]$. As a result this term does depend on double GPD integrated over transverse distance $b_\perp$, i.e. at $\Delta = 0$, for which we assume again mean field approximation:

$$\int d\vec{b}_\perp D_{ij}^{ij}(x_1, x_2; \vec{b}_\perp) \simeq f_p^i(x_1) f_p^j(x_2).$$ (9)

In the DPS1 term, deviations from the mean field approximation for 2GPDs are taken into account at least partially by using in our calculations the experimental value of $\sigma_{eff}$ measured in $pp$ collisions. Additional corrections of order $10\%-20\%$ to eq. (8) due to longitudinal correlations in the nucleon $[11]$ and beyond mean field approximation will be neglected in the following. Note that after integration in $b_\perp$, this will be the only nonperturbative parameter characterising the DPS cross section. We shall neglect small possible dependence of $\sigma_{eff}$ on energy. Indeed while there is some dependence on energy in pQCD and mean field approach, it is at least partly compensated by nonperturbative contributions to $\sigma_{eff}$ $[36]$.

In this last part of the Section we specify the kinematics and additional settings with which we evaluate Eq.(8). We consider proton lead collisions at a centre-of-mass energy $\sqrt{s_{pN}} = 8.12$ TeV. Due to the different energies of the proton and lead beams ($E_p = 6.5$ TeV and $E_{Pb} = 2.56$ TeV per nucleon), the resulting proton-nucleon centre-of-mass is boosted with respect to the laboratory frame by $\Delta y = 1/2 \ln E_p/E_N = 0.465$ in the proton direction, assumed to be at positive rapidity. Therefore the muon and jets rapidities, in this frame, are given by $y_{CM} = y_{lab} - \Delta y$ which, given the rapidity coverage in the laboratory system $|y_{lab}| < 2.4$, translates into the range $-2.865 < y_{CM} < 1.935$. In all calculations, we have always considered proton-nucleon centre-of-mass rapidities. The relevant partonic cross sections have been evaluated at leading order $[37]$ in the respective coupling differential in muon and/or jets transverse momenta and rapidities in order to be able to implement realistic kinematical cuts used in experimental analyses. For the jet cross sections, final state partons are identified as jets, as appropriate for a leading order calculation. We use CTEQ6L1 free proton parton distributions $[38]$ and EPS09 nuclear parton distribution $[39]$. Consistently with the cross section calculations, both distributions have been evaluated at leading order with factorisation scales fixed to $M_W$ and/or the transverse momentum of the jets, depending on the considered final state.

III. RESULTS : $W^{\pm}jj$

In this Section we present results for the associated production of one electroweak boson in one of the scatterings, which then decays leptonically into a muon and a neutrino, and of a dijet system produced in the other. This process has been already analyzed in pp collisions at $\sqrt{s}=7$ TeV by ATLAS $[13]$ and CMS $[14]$ whose results constitute therefore a solid baseline for this analysis. For this channel we define the fiducial phase space for muon in terms of its transverse momentum and rapidity by requiring that $p_{T}\mu > 25$ GeV and $|y_{\mu_{lab}}| < 2.4$, which are mutuated from the analysis of Ref. $[40]$. The fiducial phase space for jets is given by $p_{T}^{jets} > 20$ GeV and $|y_{jets}| < 2.4$. As already discussed, set aside the factorization hypothesis on double PDFs, the DPS2 term is largely free of unknowns. On the contrary, the DPS1 contribution needs, as input, a value for $\sigma_{eff}$. As already mentioned, both ATLAS $[13]$ and CMS $[14]$ have measured the DPS contribution to the $Wjj$ final state in $pp$ collisions at $\sqrt{s} = 7$ TeV and found $\sigma_{eff}$ to be:

$$\sigma_{eff}^W = 15 \pm 3 \text{ (stat.)} \pm 5 \text{ (syst.)} \text{ mb},$$

$$\sigma_{eff}^{Wjj} = 20.7 \pm 0.8 \text{ (stat.)} \pm 6.6 \text{ (syst.)} \text{ mb}.$$
TABLE I: Predictions for $Wjj$ (left) and $Wbb$ (right) DPS cross sections in $pA$ collisions in fiducial phase space. These numbers refer to charged summed $W$ cross sections accounting for the $W$ boson decaying into muons as well as electrons. The quoted error is entirely due to $\sigma_{\text{eff}}$ uncertainty.

|         | $\sigma^{Wjj}$ [nb] | $\sigma^{Wbb}$ [pb] |
|---------|---------------------|---------------------|
| DPS1    | $18 \pm 6$         | $102 \pm 34$       |
| DPS2    | 47                  | 269                |
| DPS     | $66 \pm 6$         | $372 \pm 34$       |

We combine these numbers into $\bar{\sigma}_{\text{eff}} = 18\pm6$ mb. Since we simulate $pA$ collisions at $\sqrt{s_{pN}}=8.12$ TeV, a centre-of-mass energy close to the energies at which those values of $\sigma_{\text{eff}}$ have been extracted, we use such an average in our numerical simulations for the $Wjj$ and $Wbb$ final states, neglecting any possible dependence of $\sigma_{\text{eff}}$ on energy.

The only source of theoretical systematic error that we associate to the predictions is the one relative to the $\sigma_{\text{eff}}$ uncertainty. Theoretical errors due to missing higher orders can be kept under control by using higher order calculations, which are known and available in the literature. Uncertainties related to PDFs and nuclear effects are by far subleading in the present context.

We are now in position to discuss our results. First we are interested to quantify at the integrated level the DPS2 contribution to DPS in $pA$ collisions, which, despite having been predicted theoretically $[24]$, has not been yet observed experimentally.

For this purpose we first report in left column of Tab. I the values of the fiducial cross section for producing $Wjj$ final state via DPS mechanisms. These number accounts for $W$ charged summed cross sections considered in both the muon and electron decay channels. From the table it appears that the DPS2 contribution is more than two times larger with respect to DPS1 one. With these numbers at our disposal we may use the strategy put forward in Ref. $[27]$ to separate the DPS2 contribution. The latter exploits the experimental capabilities to accurately relate centrality with the impact parameter $B$ of the $pA$ collision.

We start discussing the method by presenting in the left panel of Fig. 2 the $Wjj$ DPS cross section differential in impact parameter $B$. In the right panel of the same plot the same differential distribution is normalized to the nuclear thickness functions. With such a normalization, the DPS1 contribution will contribute a constant value to the cross section, as well as the LT background (not
shown in the plot), while DPS2 will show a $B$ dependence driven by $T(B)$. The DPS2 observation will essentially rely on the experimental ability to distinguish a non-constant behaviour of such a normalized distribution.

The efficiency of this discrimination method will depend on the accumulated integrated luminosity. Here we choose a value in line with data recorded in 2016 $pA$ runs of $\mathcal{L}dt = 0.1\text{pb}^{-1}$. For this purpose we present in the central panel of Fig. (3) the number of DPS signal events for the $Wjj$ channel integrated in bins of $B$. The distribution presents a kinematic zero at $B = 0$ due to the jacobian arising from Eq. (3) when the cross section is kept differential in $B$. On the same plot is also superimposed the uncertainty on the predictions coming from the propagation of the error on $\sigma_{eff}$.

Assuming that statistical errors follow a Poissonian distribution, we present in the right panel of Fig. (3) the expected number of signal events integrated in bins of $B$ and normalized to the integral of the nuclear thickness function in that bin, $n_i^1 = \int d^2B T_A(B)$, where the integration is over the $i$-bin edges. It appears that the expected uncertainties will allow a discrimination of the non-constant DPS2 contribution. Quite interestingly the method can be applied to subtract the overwhelming LT contribution, or, at the least to complement the subtraction techniques already developed. For this purpose we may define the following quantity

$$R(i, i_0) = \frac{N_{ev}^i}{n_1^i} - \frac{N_{ev}^0}{n_1^0},$$

(10)

It is then easy to verify by integrating over two distinct $B$ bins Eq. (1) that $R$ is independent of the LT and DPS1 contributions. In Eq. (10) $N_{ev}^i$ is the number of events in the $i$-$B$-bin for the assumed integrated luminosity. The index $i = 0$ corresponds to the subtraction bin, chosen in the peripheral, yet not the most peripheral one. The choice of subtraction point was discussed in [27].

In our simulation we choose the subtraction bin to be the one for which $6 < B < 7 \text{fm}$ and indicate with $N_{ev}^0$ the number of events in that bin. The resulting contribution is presented in the left panel of Fig. (3).

Such quantity will be completely independent from LT SPS background and DPS1 contribution since both contribute a constant to the $B$ distribution. The method will be as much efficient as experimental errors will allow to discriminate a non-constant behavior in the data. The number of

FIG. 3: The subtracted quantity defined in Eq. (10) (left). Number of DPS signal events in $Wjj$ final state expected with $\mathcal{L}dt = 0.1\text{pb}^{-1}$ integrated in nine bins of $B$ (center). Number of events normalized, in each $B$ bin, to the integral of the nuclear thickness function (right).
DPS2 events in a given bin $i$ can be restored from this quantity as

$$N_{i,DPS2}^{\text{ev}} = R(i, i_0) \frac{n_2^i}{n_2^i/n_1^i - n_0^i/n_1^0},$$

where we have defined $n^i_B = \int d^2 B T^2_A(B)$ and, again, the integration is over the $i$-bin edges.

Given the large number of signal DPS events in the $Wjj$, the characterization of the DPS cross section can be attempted by inspecting the charged lepton rapidity distributions. The latter are presented in the left panel of Fig. (4) for all different charge contribution and DPS mechanism and are obtained integrating over impact parameter $B$ and over dijet phase space. As can be observed from the plot, the DPS1 and DPS2 mechanisms produce quite similar distributions in lepton rapidity and therefore such an observable is not expected to be able to discriminate among them. This conclusion, however, may change if correlations beyond the mean field approximation are sizeable and might eventually generate a distortion of the spectra. Correlations beyond mean field approximation could also be appreciated by considering the lepton charge asymmetry, an extension of the familiar observable defined in SPS:

$$A(y_{\mu}^{CM}) = \frac{d\sigma_{DPS}(W^+jj) - d\sigma_{DPS}(W^-jj)}{d\sigma_{DPS}(W^+jj) + d\sigma_{DPS}(W^-jj)}.$$

The corresponding distribution is presented in the right panel of Fig. (4). Given the factorized ansatz for double PDFs and that the dijet system is completely integrated over, its lineshape is the same as the lepton charge asymmetry measured in SPS production of $W^\pm$ in $pA$ collisions, see for example Fig. (4) of Ref. [40]. Therefore, after proper subtraction of LT and DPS1 contribution, the observation in data of any departure from the predicted line shape might be an indication of parton correlations not accounted for in the mean field approximation.

IV. RESULTS : $Wbb$

We consider in this Section a special case of the former in which the second scattering produces a $b\bar{b}$ heavy-quark pair. This particular final state has been analyzed in detail in $pp$ collisions in [28] where a number of kinematic variables have been proposed to disentangle the signal DPS process from the SPS background. It is worth noticing that this final state is particularly important for
new physics searches so that the DPS component needs to be properly modelled. For this final state we use $\bar{\sigma}_{\text{eff}} = 18 \pm 6 \text{ mb}$ as for the $Wjj$ case.

We define the fiducial phase space for muon in terms of its transverse momentum and rapidity by requiring that $p_T^\mu > 25 \text{ GeV}$ and $|y_{\text{lab}}^\mu| < 2.4$. The fiducial phase space for $b$-jets is given by $p_T^{b-jets} > 20 \text{ GeV}$ and $|y_{\text{lab}}^{b-jets}| < 2.4$. In this particular case, the factorisation scale for $bb$-jet system is fixed to the transverse mass of the jet. The $Wbb$ cross sections results are reported in the right column of Tab. II. As expected, they are reduced by two order of magnitude with respect to the $Wjj$ case. Assuming again a rather conservative scenario in which the integrated luminosity is $L dt = 0.1 \text{ pb}^{-1}$, we present the expected number of DPS signal events in the central panel of Fig. 5 integrated in bins of $B$. Adopting the same strategy as in the $Wjj$ case, we present in the right panel of Fig. 5 the expected number of signal events normalized to the integral of the nuclear thickness function in bin of $B$. In the left panel of Fig. 5 we present, for this particular final state, the subtracted quantity defined in Eq. (10). From these plots it is clear that for this final state, given the lower number of events, the identification of a non-constant behaviour in data will be more difficult. Nevertheless, since at the $B$-integrated level, the DPS2 contribution is more than twice the DPS1 one, this channel has anyway the potential to allow the observation of the DPS2 mechanism.

V. RESULTS : $ssWW$

Double Drell-Yan like processes have been recognized as an ideal laboratory to investigate DPS [2, 41] and its factorization property [42]. Among this class of process, the production of a same sign $W$ boson pair ($ssWW$), where each $W$-boson is produced in a distinct hard scattering, has received special attention [29, 31, 43–46], since single parton scattering (SPS) at tree-level starts contributing to higher order in the strong coupling and can be suppressed by additional jet veto requirements. This process has been investigated in $pA$ collisions in Ref. [47].

A measurement of the $ssWW$ DPS cross section in $pp$ collisions at $\sqrt{s} = 13$ TeV has been recently reported by the CMS collaboration [19]. In that analysis a value of $\sigma_{\text{eff}} = 12.7^{+5.0}_{-2.9} \text{ mb}$ has been extracted and which will be used in our predictions, assuming that such a value is valid also at $\sqrt{s_{pN}} = 8.16 \text{ TeV}$, the nominal energy at which we simulate $pA$ collisions in this analysis. Again we assumed that its value is the same in both charged channels and the same across the fiducial phase space. Both $W$’s are required to decay into same sign muons being the fiducial phase space mutuated from the analysis of [40]: it is given by $p_T^\mu > 25 \text{ GeV}$ for the leading muon, $p_T^\mu > 20$.
TABLE II: Fiducial cross sections for $ssWW$ DPS cross sections for the positive (left), negative (central) and charged summed (right) dimuon final state for all DPS contributions. The quoted errors follow form the propagation of $\sigma_{\text{eff}}$ uncertainty.

|       | $\sigma^{\mu^+\mu^+}$ [fb] | $\sigma^{\mu^+\mu^-}$ [fb] | $\sigma^{\mu^+\mu^+} + \sigma^{\mu^+\mu^-}$ [fb] |
|-------|-----------------------------|-----------------------------|--------------------------------------------------|
| DPS1  | $48_{-11}^{+19}$           | $31_{-7}^{+12}$             | $79_{-18}^{+31}$                                 |
| DPS2  | 88                          | 58                          | 146                                              |
| DPS   | $136_{-11}^{+19}$           | $89_{-7}^{+12}$             | $225_{-18}^{+31}$                                |

FIG. 6: DPS cross sections as a function of the $B$ (left) and expected number of events $\mathcal{L}dt=1\text{ pb}^{-1}$ in the charged summed dimuon channel.

GeV for the subleading one and $|y_{\mu^\pm}| < 2.4$ for muons rapidities.

We report the cross sections results in Tab. II for various DPS mechanisms and for separate dimuon charges configurations. In Fig. 6 we present the differential cross sections and the number of expected events for $\mathcal{L}dt=1\text{ pb}^{-1}$, a value within reach at future $pA$ runs at LHC.

Considering all leptonic channels ($\mu^\pm\mu^\pm$, $e^\pm\mu^\pm$, $e^\pm e^\pm$), the resulting fiducial cross section is four times larger than that reported in Tab. II and it is of order 1 pb. These results are consistent with the ones reported in Ref. [47] after noting that those have been obtained at higher $\sqrt{s_{pN}} = 8.8$ TeV with respect to the one used here and that cross sections have been calculated there at next to leading order. Given these numbers we conclude that the observation of DPS in this channel will not only depend on the integrated luminosity accumulated in future $pA$ runs but also on the experimental ability to reconstruct $W$’s and its charge via its hadronic decays.

VI. CONCLUSIONS

In this paper we have calculated DPS cross sections for a variety of final states produced in $pA$ collisions at the LHC. We have discussed a strategy to separate the so called DPS2 contributions, pertinent to $pA$ collisions, which relies on the experimental capabilities to correlate centrality with impact parameter $B$ of the proton-nucleus collision. With this respect the $Wjj$ final state has large enough cross sections to allow the method to be used already with 2016 recorded data. Moreover the distribution in lepton charge asymmetry has the potential to uncover correlations in double GPD beyond the mean field approximation. The $Wbb$ finale state, having lower rate, can still be
used at the inclusive level to search for the DPS2 contribution. The observation of the $ssWW$ final state, being a clean but a rare process, will depend crucially on the running conditions of the future $pA$ runs and $W$-reconstruction experimental capabilities.

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