Same-sign WW production in proton-nucleus collisions at the LHC as a signal for double parton scattering

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Abstract

The production of same-sign W-boson pairs from double parton scatterings (DPS) in proton-lead (p-Pb) collisions at the CERN Large Hadron Collider is studied. The signal and background cross sections are estimated with next-to-leading-order perturbative QCD calculations using nuclear parton distribution functions for the Pb ion. At $\sqrt{s_{\text{NN}}} = 8.8$ TeV the cross section for the DPS process is about 150 pb, i.e. 600 times larger than that in proton-proton collisions at the same centre-of-mass energy and 1.5 times higher than the p-Pb $\rightarrow W^+W^-+2$-jets single-parton background. The measurement of such a process, where 10 events with fully leptonic W’s decays are expected after cuts in 2 pb$^{-1}$, would constitute an unambiguous DPS signal and would help determine the effective $\sigma_{\text{eff}}$ parameter characterising the transverse distribution of partons in the proton.

1 Introduction

The existence of multi-parton interactions (MPI) in high-energy hadronic collisions \cite{1} is a natural consequence of the fast increase of the parton flux at small parton fractional momenta $x = p_{\text{parton}}/p_{\text{hadron}}$ and the requirement of unitarization of the cross sections in perturbative quantum chromodynamics (pQCD) \cite{2,3,4,5}. Without MPI, the pQCD cross sections show a dramatic growth with increasing centre-of-mass energies leading to a violation of unitarity ($\sigma_{\text{parton-parton}} > \sigma_{\text{pp}}$) at momentum transfers as large as $\mathcal{O}(7 \text{ GeV})$ in proton-proton (p-p) collisions at the Large Hadron Collider (LHC) \cite{7}. Basic experimental observations in proton-(anti)proton collisions – such as the distributions of hadron multiplicities in minimum bias collisions \cite{8} and the underlying event activity in hard scattering interactions \cite{9} – can only be reproduced by Monte Carlo (MC) event generators such as \textsc{pythia} \cite{10} and \textsc{herwig} \cite{11}, by including MPI contributions which are modeled perturbatively using an impact-parameter description of the transverse parton profile of the colliding protons. Although MPI at semi-hard scales of a few GeV are an unambiguous (experimental and theoretical) source of particle production in high-energy hadronic collisions, the evidence for double parton scattering (DPS) processes producing two independently-identified hard particles in the same collision is currently based on relatively indirect measurements (see below).

The study of DPS processes provides not only valuable information on the spatial structure of the hadrons \cite{12} and on multi-parton correlations in the hadronic wave-function \cite{13}, but also a good experimental and theoretical control of the DPS final-states is needed in searches of new physics at the LHC (such as e.g. Higgs \cite{14,15}, supersymmetry \cite{17}, and $W_1W_L$ scattering \cite{18}). Various measurements exist in p-p and p-Pb collisions which are consistent with DPS contributions in multi-jet final-states at $\sqrt{s} = 63 \text{ GeV}$ \cite{19}, 630 GeV \cite{20}, and 1.8 TeV \cite{21,22}; in $\gamma+3$-jets events at $\sqrt{s} = 1.8 \text{ TeV}$ \cite{23} and 1.96 TeV \cite{24}; and in (preliminary) $W+2$-jets results at $\sqrt{s} = 7 \text{ TeV}$ \cite{25}. Such measurements show an excess of events in some differential distributions with respect to the expectations from contributions from single-parton scatterings (SPS) alone, although with uncertainties related to higher-order SPS corrections. The production of same-sign WW production – with a theoretical cross section with small uncertainties and a characteristic final-state with like-sign leptons plus (large) missing transverse energy ($E_T$) from the undetected neutrinos – has no SPS backgrounds at the same order in the strong coupling $\alpha_s$, and has been proposed since various years as a “smoking gun” process to univocally signal the occurrence of DPS in p-p collisions \cite{26,27}.
In this paper we investigate DPS production of like-sign WW in proton-nucleus collisions (p-A, where A indicates the number of nucleons) at the CERN LHC. The larger transverse parton density in nuclei compared to protons results in enhanced DPS cross sections coming from interactions where the two partons of the nucleus belong to (i) the same nucleon and (ii) two different nucleons \[\sigma_{PA}^{DPS} = \sigma_{PA}^{DPS,1} + \sigma_{PA}^{DPS,2} \].

In Section 2 we provide the generic form of both contributions in (1) as a function of the corresponding single-parton proton-proton cross sections. In Section 3 we outline the theoretical setup used and in Section 4 we quantify the cross sections for the production of same-sign W pairs and associated backgrounds in proton-lead (p-Pb) collisions in the range of LHC centre-of-mass (c.m.) energies \[36\] and beyond \[37\], using next-to-leading-order (NLO) calculations complemented with recent proton and nucleus parton distribution functions (PDF). Accounting for the leptonic decay branching ratios and applying standard kinematical requirements on the final-state particles, we find about 10 DPS same-sign WW events expected in 2 pb\(^{-1}\) integrated luminosity for p-Pb at \(\sqrt{s_{NN}} = 8.8\) TeV. The main conclusions of the work are summarised in Section 5.

2 Cross sections for double parton scattering in p-p and p-A collisions

2.1 Generic hadron-hadron collisions

In a generic hadron-hadron collision, the inclusive DPS cross section from two independent hard parton subprocesses \((hh' \rightarrow ab)\) has been derived in the momentum representation, taking into account the transverse (impact parameter) vector connecting the centres of the colliding hadrons in the transverse plane. The factor \(\Gamma_{ab}^{h} = \gamma_{ab}^{h} / m\) typically assumed that they can be decomposed in terms of longitudinal and transverse components

\[
\gamma_{ab}^{h} = \gamma_{ab}^{l} \times \gamma_{ab}^{t} = \frac{m}{2} \sum_{i,j,k,l} \int \Gamma_{i,j}^{l}(x_1, x_2; b_1, b_2; Q_1^2, Q_2^2) \times \sigma_{i,j}^{h}(x_1, Q_1^2) \sigma_{i,j}^{h}(x_2, Q_2^2) \times \Gamma_{i,j}^{t}(x_1', b_1 - b, b_2 - b; Q_1^2, Q_2^2) d x_1 d x_2 d x_1' d x_2' d b_1 d b_2 d^2 b.
\]

In this expression, \(\Gamma_{i,j}^{l}(x_1, x_2; b_1, b_2; Q_1^2, Q_2^2)\) and \(\sigma_{i,j}^{h}(x, Q^2)\) are double parton distribution functions which depend on the longitudinal parton momentum fractions \(x_1\) and \(x_2\), and on the transverse vector \(b_1\) and \(b_2\) of the two parton undergoing the hard processes at the scales \(Q_1\) and \(Q_2\). \(\sigma_{i,j}^{h}\) and \(\gamma_{ab}^{h}\) are the parton-level subprocess cross sections, and \(b\) is the impact parameter vector connecting the centres of the colliding hadrons in the transverse plane. The factor \(m/2\) appears due to the symmetry of the expression for the interchange of \(i\) and \(j\) parton species: \(m = 1, 2\) for indistinguishable and distinguishable parton subprocesses respectively. The double parton distribution functions \(\Gamma_{i,j}^{l}(x_1, x_2; b_1, b_2; Q_1^2, Q_2^2)\) encode all the information of interest with regard to multiple parton interactions, and it is typically assumed that they can be decomposed in terms of longitudinal and transverse components

\[
\Gamma_{i,j}^{l}(x_1, x_2; b_1, b_2; Q_1^2, Q_2^2) = D_{i,j}^{l}(x_1, x_2; Q_1^2, Q_2^2) f(b_1) f(b_2),
\]

where \(f(b_1)\) describes the transverse parton density and is supposed to be an universal function for all types of partons with the fixed normalization

\[
\int f(b_1) f(b_1 - b) d^2 b_1 d^2 b = \int r(b) d^2 b = 1, \quad \text{with the overlap function} \quad r(b) = \int f(b_1) f(b_1 - b) d^2 b_1.
\]

Making the further assumption that the longitudinal components \(D_{i,j}^{l}(x_1, x_2; Q_1^2, Q_2^2)\) reduce to the “diagonal” product of two independent single-parton distribution functions,

\[
D_{i,j}^{l}(x_1, x_2; Q_1^2, Q_2^2) = D_{i}^{l}(x_1; Q_1^2) D_{j}^{l}(x_2; Q_2^2),
\]

2
the cross section of double parton scattering can be finally expressed in the simple generic form

\[ \sigma_{DPS}^{pp} = \frac{m}{2} \frac{\sigma_{SPS}^{pp \to a} \cdot \sigma_{SPS}^{pp \to b}}{\sigma_{eff}} \]

where \( \sigma_{SPS} \) is the standard inclusive single-hard scattering cross section, computable perturbatively to a given order in \( \alpha_s \),

\[ \sigma_{SPS}^{pp \to a} = \sum_{i,k} \int D_i^b(x_1; Q_1^b) f(b_1) \hat{\sigma}_a^{bh}(x_1, x'_1) \times D_i^b(x'_1; Q_1^b) f(b_1 - b) dx_1 dx'_1 d^2 b_1 d^2 b \]

\[ = \sum_{i,k} \int D_i^b(x_1; Q_1^b) \hat{\sigma}_a^{bh}(x_1, x'_1) D_i^b(x'_1; Q_1^b) dx_1 dx'_1 , \]

and \( \sigma_{eff} \) is a normalization cross section associated with the effective transverse overlap area \( \rho \) of the partonic correlations that produce the DPS process:

\[ \sigma_{eff} = \left[ \int d^2 b \, \hat{\rho}(b) \right]^{-1} . \]

In p-p collisions, the approximate range of numerical values of this effective cross section has been obtained empirically from fits to data \([12, 25]\):

\[ \sigma_{eff} \approx 13 \pm 2 \text{ mb} . \]

The validity of the simplifying assumptions leading to Eq. (6) in combination with the interpretation of \( \sigma_{eff} \) as a measure of the effective transverse parton interaction area given by Eq. (8) – which are quite customary and economic expressions from a computational point of view – is the object of current revision \([12, 38–46]\). In particular, the presence of a correlation term in the two-parton distributions, now neglected in Eq. (5), results in a decrease of the effective cross section \( \sigma_{eff} \) (i.e. an increase of the final DPS cross section) with the growth of the hard scale \([41, 47, 48]\), while the dependence of \( \sigma_{eff} \) on the total energy at fixed scales is rather weak \([48]\). Thus, Eq. (6), which will be employed hereafter in this work, should actually provide a conservative estimate of the DPS cross section for the process under consideration.

### 2.2 Proton-nucleus collisions

In proton-nucleus collisions, the parton flux is enhanced by the number \( A \) of nucleons in the nucleus and – modulo small (anti)shadowing effects in the nuclear PDF \([49]\), see below – the single-parton cross section is simply expected to be that of proton-proton collisions (or, more exactly, that of proton-nucleon collisions p-N with \( N = p, n \) including protons and neutrons with their appropriate relative fraction) scaled by the factor \( A \) \([50]\), i.e.

\[ \sigma_{SPS}^{pA \to ab} = \sigma_{SPS}^{pN \to ab} \int T_{pA}(r) \, d^2 r = A \cdot \sigma_{SPS}^{pN \to ab} . \]

Here, \( T_{pA}(r) \) is the standard nuclear thickness function, analogous to \( f(b) \) in Eqs. (3) and (4), as a function of the impact parameter \( r \) between the colliding proton and nucleus, given by an integral of the density function over the longitudinal direction \( T_{pA}(r) = \int p_A(r) \, dz \), normalised to \( \int T_{pA}(r) \, d^2 r = A \).

The corresponding DPS p-A cross section is the sum of the two terms of Eq. (11):

- The first term is just the DPS cross section in p-N collisions similarly multiplied by \( A \):

\[ \sigma_{DPS,1}^{pA \to ab} = A \cdot \sigma_{DPS}^{pN \to ab} , \]
• the second contribution, for which interactions with partons from two different nucleons are involved in the scattering, involves the square of $T_{pp}^2$. \(28\)

\[
\sigma_{DPS^{2}}^{pA \rightarrow ab} = \sigma_{DPS}^{pN \rightarrow ab} \cdot \sigma_{pp} \cdot F_{pA},
\]

\[\text{with } F_{pA} = \frac{A - 1}{A} \int T_{pA}^2(r) d^2r,\]

which assumes again that the double PDF of the nucleons are factorised in both longitudinal and transverse components as in Eqs. (3) and (5). The factor \((A - 1)/A\) is introduced to take into account the difference between the number of nucleon pairs and the number of different nucleon pairs. The effect of extra “non-diagonal” interference terms (which cannot be expressed in terms of parton densities alone) computed in the case of light nuclei in [34] would lead, together with other correlations discussed above, to an increase of the value of $\sigma_{DPS^{2}}^{pA \rightarrow ab}$, but we believe that these are effectively covered by the current uncertainty $\sigma_{pp}$, Eq. (9).

Thus, adding (11) and (12) the inclusive cross section of a DPS process with two hard parton subprocesses $a$ and $b$ in a p-A collision can be written as

\[
\sigma_{DPS}^{pA \rightarrow ab} = A \sigma_{DPS}^{pN \rightarrow ab} \left[ 1 \pm \frac{1}{A} \sigma_{pp} \cdot F_{pA} \right],
\]

which is enhanced by the factor in parentheses compared to the corresponding DPS cross section in proton-proton (or, more exactly, p-N) collisions. Let us evaluate this factor in the case of proton-lead collisions. In the simplest approximation that the nucleus has a spherical form with uniform nucleon density of radius $R_A = r_0A^{1/3}$ with $r_0 = 1.25$ fm, the integral of the nuclear thickness factor (13) is $F_{pA} = 9A(A - 1)/(8\pi R_A^2) = 31.5$ mb\(^{-1}\) for a Pb nucleus ($A = 208$). If, instead of the hard-sphere approximation, one directly evaluates the integral using the standard Fermi-Dirac spatial density for the lead nucleus ($R_A = 6.36$ fm and surface thickness $a = 0.54$ fm) [51] one obtains $F_{pA} = 30.4$ mb\(^{-1}\). Thus, for the value of $\sigma_{pp}$ determined experimentally, Eq. (9), the DPS enhancement factor (14) in p-Pb compared to A-scaled p-N collisions is of order $[1 + \sigma_{pp}F_{pA}/A] \approx 3$.

The final formula for DPS in proton-nucleus collisions can be written as a function of the elementary proton-nucleon single-parton cross sections, combining Eqs. (6) and (14), as

\[
\sigma_{DPS}^{pA \rightarrow ab} = \left( \frac{m}{2} \right) \frac{\sigma_{SPS}^{pN \rightarrow a}}{\sigma_{pp}^{pN \rightarrow b}} \cdot \frac{\sigma_{DPS}^{pN \rightarrow ab}}{\sigma_{pp}^{pA}},
\]

with the normalization effective cross section amounting to

\[
\sigma_{pp} = \frac{\sigma_{pp}}{A + \sigma_{pp}F_{pA}} = 21.5 \pm 1.1 \text{ mb} \]

\[\text{(16)}\]

where the last equality holds for p-Pb using $A = 208$, $\sigma_{pp} = 13 \pm 2$ mb and $F_{pA} = 30.4$ mb\(^{-1}\). In summary, the DPS cross sections are enhanced by a factor of $\sigma_{pp}/\sigma_{pp} \approx 3A \approx 600$ in proton-lead compared to proton-proton (or, in general, nucleon-nucleon) collisions, i.e. they are a factor of 3 higher than the naive expectation based on the $A$-scaling of the single-parton cross sections, Eq. (10). Thus, in general the significance for any DPS measurement in p-A collisions, $S = N_{SPS}^{pA}/N_{SPS}^{pN}$, will be enhanced by a factor of $3 \sqrt{A}$ compared to p-p collisions, i.e. by a factor of ~40 for p-Pb. One can thus exploit such a large expected DPS signal over the SPS background in proton-nucleus collisions to study double-parton scattering in detail and in particular to determine the value of $\sigma_{pp}$, independently of other DPS measurements in p-p collisions – given that the parameter $F_{pA}$ in Eq. (16) depends on the comparatively better known transverse density profile of nuclei.

Although in this paper we will be computing the proton-nucleon single-parton cross sections using NLO calculations that take directly into account the proper combination of p-p and p-n collisions – i.e. we will be using directly Eq. (15) with $\sigma_{SPS}^{pN \rightarrow a} = \sigma_{SPS}^{pA \rightarrow ab}/A$ calculated using nuclear PDFs for the Pb ion to obtain the corresponding DPS cross sections – we close this Section by writing explicitly the generic p-A DPS expression including the
individual p-p and p-n collisions for a generic nucleus of proton number Z and neutron number N = A – Z:

\[
\sigma_{\text{DPS}}^{pA\rightarrow ab} = \left( \frac{m}{2} \right) \sigma_{\text{SPS}}^{\text{pp} \rightarrow a} \cdot \sigma_{\text{SPS}}^{\text{pp} \rightarrow b} + N \cdot \sigma_{\text{SPS}}^{\text{pp} \rightarrow a} \cdot \sigma_{\text{SPS}}^{\text{pp} \rightarrow b}
\]

\[
+ \left( \frac{m}{2} \right) F_{\text{pa}} \left[ Z(A - 1) / (A(A - 1)) \cdot \sigma_{\text{SPS}}^{\text{pp} \rightarrow a} \cdot \sigma_{\text{SPS}}^{\text{pp} \rightarrow b} + Z \cdot N / (A(A - 1)) \cdot \sigma_{\text{SPS}}^{\text{pp} \rightarrow a} \cdot \sigma_{\text{SPS}}^{\text{pp} \rightarrow b} \right]
\]

\[
+ Z \cdot N / (A(A - 1)) \cdot \sigma_{\text{SPS}}^{\text{pp} \rightarrow a} \cdot \sigma_{\text{SPS}}^{\text{pp} \rightarrow b} + N(N - 1) / (A(A - 1)) \cdot \sigma_{\text{SPS}}^{\text{pp} \rightarrow a} \cdot \sigma_{\text{SPS}}^{\text{pp} \rightarrow b}
\]

3 Theoretical setup

The interest of like-sign W-boson pair production as a signature of DPS in high-energy hadronic collisions is three-fold. First, all the relevant production cross sections can be computed perturbatively at NLO accuracy and have small theoretical uncertainties. Second, the W\(^\pm\) production cross sections at the LHC are the highest for any electroweak particle (Z and Drell-Yan production are comparatively smaller), resulting in a potentially observable DPS WW cross section. Third, in single-parton scatterings, the same-sign SS processes are suppressed since the lowest order at which two same-sign W bosons can be produced is with two jets (WWjj) [26], three-fold. First, all the relevant production cross sections can be computed perturbatively at NLO accuracy and have small theoretical uncertainties. Second, the W\(^\pm\) production cross sections at the LHC are the highest for any electroweak (vector-boson fusion) processes, where \(\alpha_w\) is the electroweak coupling.

We compute the same-sign DPS signal, \(\sigma_{\text{DPS}}^{\text{pp} \rightarrow ab}\), with \(m = 1\). The single-parton W cross section \(\sigma_{\text{SPS}}^{\text{pp} \rightarrow W}\) entering in the DPS expression, as well as the SPS same-sign WWjj background, are computed at NLO accuracy (using the central NLO sets of the CT10 PDF [54] for the proton and the EPS09 nuclear PDF [55] for the Pb ion). The NLO calculation[4] used here reproduce well the experimental single-W [56,58] and W\(^+\)W\(^-\) [59,62] production cross sections measured in p-p collisions at \(\sqrt{s_{\text{NN}}} = 7\) TeV, as well as the single-W cross sections in p-p and Pb-Pb at \(\sqrt{s_{\text{NN}}} = 2.76\) TeV [58].

The use of nuclear PDF (EPS09) for the lead ion not only takes into account nuclear “shadowing” modifications of the bound relative to free nucleons, but it also properly accounts for the different isospin (u- and d-quark) content of the lead ion given by its different proton (Z = 81) and neutron (N = 127) numbers. Such an effect is important in the case of isospin-sensitive particles like the W boson, and explains the relatively enhanced W\(^-\) production cross sections measured in Pb-Pb with respect to p-p collisions at \(\sqrt{s_{\text{NN}}} = 2.76\) TeV [58]. At 8.8 TeV, the use of the EPS09 nuclear PDF results in a modification of the total W\(^+\) (W\(^-\)) production cross section by about -7% (+15%) compared to those obtained for p-p collisions using the proton CT10 PDF. The largest impact in the final cross sections is due to the proton-versus-lead isospin differences since nuclear (anti)shadowing effects alone decrease the integral W\(^+\) and W\(^-\) yields respectively by 4.5% and 3% only [63].

All numerical results are evaluated using the latest standard model input parameters for particle masses, widths and couplings [64]. The single-W\(^\pm\) production is formally computed fixing the renormalization and factorization scales at \(\mu = \mu_F = \mu_R = m_W\), whereas we use \(\mu = 2m_W\) for the W\(^+\)W\(^-\) cross section (shown here only as a reference). The background WWjj cross sections in mcfm are formally computed at LO, but detailed studies [65,66] have shown that the extra NLO corrections can be accounted for by setting the renormalization and factorization scales at \(\mu = 150\) GeV. Indeed, for such a scale choice the W\(^+\)W\(^-\)+2-jet inclusive LO and NLO cross sections are found to nearly coincide in p-p at \(\sqrt{s} = 14\) TeV (\(\sigma_{\text{LO}} = 2.4\) fb and \(\sigma_{\text{NLO}} = 2.5\) fb) [65]. Same-sign W-pairs can also be produced via vector-boson-fusion (VBF) processes [68,69], which are not included in the mcfm package. We have determined the VBF WWjj contribution at NLO using vbfnlo [70,71] (version 2.6) with the same set of parameters used for mcfm, except that the theoretical scales are set to the momentum transfer of the exchanged W, Z boson \((\mu^2 = t_{W,Z})\). Since vbfnlo is not interfaced to nuclear PDFs, we use CT10 for both the proton and the Pb ion. This choice introduces a small difference (below 5%) in the VBF cross sections according to the results obtained running a similar weak-boson fusion process in mcfm (VBF Higgs\(\rightarrow\)W\(^+\)W\(^-\) production) with CT10 and EPS09. The pure

\[^1\]Next-to-NLO calculations, available for the single-W production, increase by a few percent the pQCD cross sections and further improve the data-theory agreement.
The uncertainties of the SPS NLO single-W cross sections amount to about ±10% as obtained by taking into account the EPS09 nPDF eigenvector set (the proton PDF uncertainties are much lower in the relevant regions of parton fractional momentum and virtuality), and by independently varying the \(\mu_F\) and \(\mu_R\) scales within a factor of two. The quoted uncertainties for the QCD WWjj cross sections are those from the full-NLO calculations [63]. The uncertainties for the VBF cross sections are much smaller as they do not involve any gluons in the initial state. In the case of the DPS cross section, the SPS uncertainties are added in quadrature with the ±15% uncertainty of \(\sigma_{\text{VBF}}\), Eq. (9), and result in a total uncertainty of about ±18% in the final cross section.

### 4 Results

Table 1 collects the cross sections and associated uncertainties for the relevant individually computed processes for p-Pb collisions at two c.m. energies \(\sqrt{s_{\text{NN}}} = 5.0\) TeV (corresponding to the first p-Pb run in 2013) and 8.8 TeV (nominal energy). We note that, in general, the SPS cross sections presented here are larger than those obtained for p-p collisions (scaled by \(A\)) in previous calculations [17], since the latter have been computed only at LO accuracy.

| p-Pb final-state: \(\sqrt{s_{\text{NN}}} = 5.0\) TeV | \(W^+\) | \(W^-\) | \(W^+W^-(DPS)\) | \(W^+W^-jj\) (QCD) | \(W^+W^-jj\) (VBF) |
|---|---|---|---|---|---|
| Code (process #): | MCFM (1) | MCFM (6) | MCFM (251) | MCFM (259) | \(\text{Eq. (15)}\) |
| Order (\(\sigma_{\text{units}}\)): | NLO (\(\mu_b\)) | NLO (\(\mu_b\)) | 'NLO' (pb) | NLO (pb) | (pb) |
| \(\sqrt{s_{\text{NN}}} = 5.0\) TeV | 6.85 ± 0.68 | 5.88 ± 0.59 | 12.1 ± 1.2 | 12.4 ± 0.6 | 44 ± 8 |
| \(\sqrt{s_{\text{NN}}} = 8.8\) TeV | 12.6 ± 1.3 | 11.1 ± 1.1 | 40.4 ± 4.0 | 51.8 ± 2.0 | 152 ± 27 |

Figure 1 shows the resulting total cross sections for all relevant processes in p-Pb in the range of c.m. energies in the nucleon-nucleon system of \(\sqrt{s_{\text{NN}}} \approx 2–20\) TeV. The nominal p-Pb LHC energy is 8.8 TeV (dashed vertical line in the plot) but we have extended the calculations up to 2.5 times this value into the range reachable in a proposed future high-energy upgrade of the collider [37]. The upper curve in the plot corresponds to the SPS cross sections for \(W^+\) and \(W^-\) production (at 8.8 TeV the former is about 12% higher than the latter). The second curve corresponds to the unlike-sign \(W^+W^-\) SPS cross sections, which is added to the plot for comparison purposes. The third curve corresponds to the same-sign WW signal DPS cross section which rises from \(\sigma_{\text{DPS}}^{\text{pPb-ww}} = 5\) pb up to about 1 nb in the considered range of c.m. energies. The last curve corresponds to the SPS background \(\sigma_{\text{SPS}}^{\text{pPb-wwjj}}\), obtained adding the QCD (MCFM) and weak-boson-fusion (\(\text{VBF}^{\text{lo}}\)) cross sections for negative and positive W pairs, which is found to be about a factor of 1.5 lower than the DPS signal.

The cross sections plotted in Figure 1 are total inclusive ones and do not include W decays, nor cuts on any of the final-state particles. The W leptonic fraction ratios, \(W \rightarrow \ell^+\nu\ell^+\nu\) (\(\ell = e, \mu, \tau\)), amount to 1/9 for each lepton flavour, the other 2/3 being due to hadronic quark-antiquark decays. Taking into account the standard electron and muon decay modes measured for both W-bosons (ee, \(\mu\mu, e\mu, e\mu\)) would therefore reduce the WW yields by a factor of \(B_{\ell^+\ell^-} = (4/9)^2 \approx 1/20\), although including \(e^+\) and \(\mu^+\) from leptonic tau-decays in the WW \(\rightarrow e\tau, \mu\tau, \tau\tau\) final-states would decrease the corresponding branching ratio only to \(B_{\ell^+\ell^-} \approx 1/16\). A more aggressive scenario combining the \(W \rightarrow \mu\ell\) and \(W \rightarrow j\ell\) decays, as done at Tevatron [72, 73] and also at the LHC [62], would result in a reduction of the visible cross section by a branching factor of \(B_{\ell^+\ell^-} = (2/9 \cdot 4/3) \approx 1/3.3\), though this would require the determination of the sign of the charge of the jets which is not obvious a priori (although see e.g. [74] for recent developments). In order to conservatively estimate the expected yields measured at the LHC, we consider the purely

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\(^2\)For single-W, the K-factor \(K = \sigma_{\text{NLO}}/\sigma_{\text{LO}} = 1.15\) results in a 30% increase of the DPS WW cross section compared to the LO DPS estimate.
Figure 1: Total production cross sections for single-W and W-pair boson(s) in p-Pb collisions as a function of c.m. energy, for single-parton and double-parton (DPS) scatterings. The $W^+W^-$ labels indicate that $W^+W^-$ and $W^-W^-$ cross sections have been added. The width of the DPS curve indicates its associated uncertainty (dominated by $\sigma_{\text{eff}}$). The dashed vertical line indicates the nominal $\sqrt{s_{\text{NN}}} = 8.8$ TeV nucleon-nucleon c.m. energy in p-Pb collisions at the LHC.

leptonic decay branching ratios and we include in the generator-level mcfm calculations typical ATLAS and CMS fiducial requirements for the decay leptons: $|\eta| < 2.4$, $p_T^\ell > 20$ GeV/c and $E_T^\ell > 20$ GeV [56,57]. Such a kinematical selection reduces the visible WW cross section by about a factor of two which, combined with small reconstruction inefficiencies of the final-state particles, would result in a factor of $\varepsilon \approx 1/30$ reduction of the WW yields at the LHC. We do not consider here other possible backgrounds ($t\bar{t}$, W,Z+jets, WZ,ZZ production ...) which are commonly removed applying a jet-veto requirement and/or extra criteria on the invariant masses of the two leptons.

In conclusion, for a DPS cross section of $\sigma^{\text{DPS}}_{\text{pPb} \to \text{WW}} \approx 150$ pb at $\sqrt{s_{\text{NN}}} = 8.8$ TeV the total number of events expected in one p-Pb run is $N = \sigma^{\text{DPS}}_{\text{pPb} \to \text{WW}} \cdot L_{\text{int}} \cdot \varepsilon \approx 1–10$ for an integrated-luminosity of $L_{\text{int}} = 0.2–2$ pb\(^{-1}\), where the first value is the nominal (but conservative) luminosity [36] and the second one assumes that one can use the same proton beam intensity and/or emittance as in the current p-p running. We note also that the p-Pb instantaneous luminosities at the LHC, at variance with the p-p operation mode, result in a very small event pileup [76] and make the measurement accessible without complications from overlapping p-Pb collisions occurring simultaneously in the same bunch crossing.

5 Conclusions

The formalism of double parton scattering (DPS) in high-energy proton-nucleus collisions has been reviewed and a simple generic formula has been derived for the computation of the corresponding DPS cross sections as a function of (i) the single-parton cross sections in proton-proton collisions, and (ii) the $\sigma_{\text{eff}}$ parameter describing the transverse density of partons in the proton. The DPS cross sections in p-Pb are found to be enhanced by a factor of $3A \approx 600$ compared to those in p-p collisions at the same energy. The significance of the DPS measurements over the expected backgrounds in p-Pb is a factor of $3 \sqrt{A} \approx 40$ higher than that in p-p collisions. As a particular case, we have studied same-sign W-boson pair production in proton-lead collisions at LHC centre-of-mass energies, using NLO predictions – mcfm with nuclear PDFs for the QCD processes, and vbfhlo for the electroweak backgrounds – for the production of single inclusive W and for the same-sign WWjj backgrounds. At the nominal $\sqrt{s_{\text{NN}}} = 8.8$ TeV
energy, the DPS cross section for like-sign WW production is about 150 pb, i.e. 600 times larger than that in proton-proton collisions at the same centre-of-mass energy and 1.5 times higher than the single-parton same-sign WW+2-jets background. The measurement of such a process, where 10 events with fully leptonic W’s decays are expected after cuts in 2 pb$^{-1}$, would constitute an unambiguous DPS signal at the LHC, and would help determine the $\sigma_{\text{eff}}$ parameter characterising the effective transverse parton area of hard interactions in hadronic collisions.

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