Parton correlations in same-sign $W$ pair production via double parton scattering at the LHC

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Same-sign $W$ boson pairs production is a promising channel to look for signatures of double parton interactions at the LHC. The corresponding cross section has been calculated by using double parton distribution functions, encoding two parton correlations, evaluated in a Light-Front quark model. The obtained result is in line with previous estimates which make use of an external parameter, the so called effective cross section, not necessary in our approach. The possibility to observe for the first time two-parton correlations, in the next LHC runs, has been established.

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It is known since a long time that a proper description of final states in hadronic collisions requires the inclusion of processes where more than one pair of partons participate in a single hadronic collision, the so-called multiple partonic interactions (MPI) [1, 2]. Due to LHC operation, the wide subject of MPI is having in these years a renewed interest [3]. At low transverse momenta, MPI effects and energy flows. The effect of MPI is present also in hard scattering processes. In this letter, we are interested in double parton scattering (DPS), in which parton pairs from two hadrons interact between each other, and both collisions are hard enough to apply perturbative techniques. While these processes need to be well controlled since they could represent a background to New Physics searches, the main focus of this work is the sensitivity of DPS to relevant features of the non-perturbative nucleon structure, not accessible otherwise. In particular, DPS cross section depends on non-perturbative quantities, the structure, not accessible otherwise. In particular, DPS to relevant features of the non-perturbative nucleon structure.

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The physical meaning of Eq. 2 is that, once the process $A$ has occurred with cross section $\sigma^A_{SPS}$, the ratio $\sigma^R_{SPS}/\sigma_{eff}$ represents the probability of process $B$ to occur. A constant value of $\sigma_{eff}$ has been assumed in all the experimental analyses performed so far, so that the technical implementation of Eq. 2 is rather easy. In this way, different collaborations have extracted values of $\sigma_{eff}$ which are consistent within errors, irrespective of center-of-mass energy of the hadronic collisions and of the final state considered. A comprehensive compilation of experimental results on $\sigma_{eff}$ is reported in Ref. [13], where the latest DPS measurement in the four jet final state is presented.

To understand the approximation leading to Eq. 2 from Eq. 1, let us write dPDFs in the latter in a fully factorized form:

$$D_{ij}(x_1, x_2, \mu_A, \mu_B, \vec{b}_\perp) = f_i(x_1, \mu_A)f_j(x_2, \mu_B)T(\vec{b}_\perp),$$

where the function $T(\vec{b}_\perp)$ describes the probability to have two partons at a transverse distance $\vec{b}_\perp$. Then, inserting Eq. 4 into Eq. 11, one obtains Eq. $\sigma_{eff}$, 2, as follows

$$\sigma_{eff}^{-1} = \int d\vec{b}_\perp |T(\vec{b}_\perp)|^2,$$

with $T(\vec{b}_\perp)$ controlling the double parton interaction rate. It is clear that, as a consequence of the approximation [4], $\sigma_{eff}$ does not show any dependence on parton fractional momenta, hard scales or parton species.

Actually, if factorized expressions are not used, $\sigma_{eff}$ depends on longitudinal momenta. Since dPDFs are basically unknown, and only sum rules relating them to PDFs are available [15, 16], model calculations, developed at low energy, but able to reproduce relevant features of nucleon parton structure, can be used and have been proposed. In such model calculations, factorized structures, Eq. 4, do not arise, and $\sigma_{eff}$ depends non-trivially on longitudinal momenta. In particular, this was found in a Light-Front (LF) Poincaré covariant constituent quark model (CQM), reproducing the sum rules of dPDFs [17, 18], as well as in a holographic approach [19]. In this letter we will evaluate DPS cross sections, using different models of dPDFs, to establish wether forthcoming LHC data will exhibit (for the considered final state) such features, not yet seen in the present uncertain experimental scenario.

Let us now summarise our calculation. We first consider the SPS $W^{\pm}$ production and subsequent decay into muon at center-of-mass energy $\sqrt{s}$:

$$pp \rightarrow W^{\pm} \rightarrow \mu^{\pm}(p_\mu),$$

indicating with $\mu^{\pm}$ the corresponding cross sections. Defining quarks according to their charge, i.e. $D = d, s, b$ and $U = u, c, t$, we consider the following partonic sub-processes

$$U(p_a)D(p_b) \rightarrow \mu^{+}(p_\mu)\bar{\nu}_\mu(p_\nu),$$

$$D(p_a)\bar{U}(p_b) \rightarrow \mu^{-}(p_\mu)\nu_\mu(p_\nu),$$

where particle four-momenta are indicated in parenthesis. Differential cross sections are calculated in terms of the muon transverse momentum $p_T = |\vec{p}_T|$ and pseudo-rapidity $\eta_\mu$, defined in the hadronic center-of-mass frame. The partonic Lorentz invariants $\hat{u}$ and $\hat{t}$, in terms of these variables, read

$$\hat{t} = (p_a - p_b)^2 = -x_a\sqrt{s}p_Te^{-\eta_\mu},$$

$$\hat{u} = (p_b - p_\mu)^2 = -x_b\sqrt{s}p_Te^{\eta_\mu},$$

from which parton fractional momenta can be calculated as

$$x_a = e^{\eta_\mu}\frac{M_W}{\sqrt{s}}(A \pm B),$$

$$x_b = e^{-\eta_\mu}\frac{M_W}{\sqrt{s}}(A \mp B),$$

with $A = M_W/(2p_T)$, $B = \sqrt{A^2 - 1}$ and $M_W$ the $W$-boson mass. The unobserved neutrino causes an under-determination of the $W$-rapidity and, in turns, the twofold ambiguity in Eq. 10. Cross sections are evaluated in the narrow width approximation, i.e. at fixed $\hat{s} = (p_a + p_b)^2 = M_W^2$, and read

$$\frac{d^2\sigma^{pp \rightarrow W^{\pm}(-\mu^+\nu)}}{d\eta dp_T} = \frac{G_F^2}{6\sqrt{s}W} \frac{V_{u\hat{t}}}{A^2 - 1} \times \left[ f_U(x_a, \mu_F)f_D(x_b, \mu_F)p_T^2 + f_D(x_a, \mu_F)f_U(x_b, \mu_F)p_T\right]^2,$$

where $G_F$ is the Fermi constant, $\Gamma_W$ the $W$ boson decay width and $V_{ij}$ the CKM matrix elements whose values are taken from Ref. [21]. The $\sigma^-$ cross section is obtained exchanging $U \leftrightarrow D$ and $\hat{t} \leftrightarrow \hat{u}$ in Eq. 11. The PDFs appearing in Eq. 11 are evaluated at a factorization scale $\mu_F = M_W$ and therefore PDFs from CQM calculations, related to low momentum scales, need to be properly evolved. The evolution is performed at LO by using DGLAP equations. We adopt a variable flavour number scheme and parameters as in LO version of MSTW08 distribution [21]. In particular heavy quark masses are set to $m_c = 1.4$ GeV and $m_b = 4.75$ GeV and the one-loop running coupling is fixed at $Z$-boson mass scale to be $\alpha_s(m_Z) = 0.13939$ [21]. For PDFs provided by the LF CQM one has

$$f_d(x, Q_0^2) = 1/2f_u(x, Q_0^2),$$

at the hadronic scale $Q_0^2$, where three valence quarks carry all proton momentum. Since this scale is generally located in the infrared regime, PDFs evolution and corresponding cross sections are very sensitive to its choice. Defined, therefore, in the present paper, $Q_0^2$ is fixed requiring that $\sigma^+$ and $\sigma^-$, calculated by using evolved LF PDFs, match the corresponding predictions obtained with the DYNNLC code [22] at LO by using MSTW08 PDFs [21]. For both simulations we set $\sqrt{s} = 13$ TeV and define the muon fiducial phase space in SPS to be $p_T^{\mu} > 20$ GeV and $|\eta_\mu| < 2.4$. As shown in Fig. 1 considering the cross section summed over the $W$ boson charge, this procedure localizes the central value of the
We note that, for a given value of $Q^2$, a simultaneous description of $\sigma^+$ and $\sigma^-$ cannot be achieved, a fact which is ascribed to the model assumption for PDFs in Eq. (12) and it is an example of typical drawback of PDFs CQMs calculations. In order to take into account this deficiency, we assign a theoretical error to $Q^2$ allowing it to vary in the range $0.24 < Q^2 < 0.28$ GeV$^2$, where the limits are fixed requiring that cross sections obtained via LF model reproduce $\sigma^+$ and $\sigma^-$ predicted by DYNLO (straight lines in Fig. 1). Having fixed $Q^2$ in SPS processes and being dPDFs obtained within the same LF model adopted for PDFs, we can use the same $Q^2$ range for dPDFs. In this way the estimate of DPS cross sections does not require additional parameters. Double PDFs in the LF model are defined at $Q^2$ as $f_{u\bar{d}} = f_{d\bar{u}} = f_{u\bar{u}}(x_1, x_2, Q^2, \vec{b}_\perp)$.

\begin{equation}
\sigma^+ + \sigma^- \quad \sigma^-
\end{equation}

At this scale, when integrated over $\vec{b}_\perp$, dPDFs satisfy number and momentum sum rules [12]. Their perturbative QCD evolution is presently known only at leading logarithmic accuracy [23, 24], however the presence of the so-called inhomogeneous term in the evolution equations is still under investigation [3, 16, 25]. In the present paper dPDFs are evolved with the same scheme and parameters used for PDFs but using homogeneous evolution equations valid at fixed values of $\vec{b}_\perp$ [3, 26].

The partial phase space for this model is ascribed to the model assumption for PDFs in Eq. (12).

\begin{equation}
\frac{d^4\sigma_{pp\to \mu^+\mu^-X}}{d\eta_1dp_{T,1}d\eta_2dp_{T,2}} = \sum_{i,k,j,l} \frac{1}{2} \int d^2\vec{b}_\perp
\end{equation}

\begin{equation}
\times D_{ij}(x_1, x_2, \vec{b}_\perp, M_D)D_{kl}(x_3, x_4, \vec{b}_\perp, M_W)
\end{equation}

\begin{equation}
\times \frac{d^2\sigma_{pp\to \mu^+\mu^-X}}{d\eta_1dp_{T,1}}d\eta_2dp_{T,2} I(\eta_i, p_{T,i}) .
\end{equation}

The function $I(\eta_i, p_{T,i})$ in Eq. (13) implements the kinematical cuts reported in Tab. 1 which we mutuate from the 8 TeV analysis of Ref. [27]. In Eq. (13) we are neglecting the supposed small contributions coming from longitudinally polarized dPDFs [12]. Eq. (13) will be evaluated with three different models of dPDFs described in the following in order of increasing complexity. In the simplest one, called MSTW, dPDFs are parameterized as products of MSWT08 PDFs according to Eq. (4). In the second one, the so-called GS09 model [13], the factorized form Eq. (11), properly corrected to fulfill dPDFs sum rules, is assumed only at a momentum scale $Q^2$. Such initial conditions are evolved with dPDFs evolution equations with the inhomogenous term included [23, 24]. Therefore, with respect to model MSTW, GS09 takes into account additional perturbative correlations [4, 15, 23, 28]. The DPS cross section based on MSTW and GS09 models can be evaluated only assuming a constant $\sigma_{eff}$ in Eq. (12). In the present work, we will use, as a reference value, $\sigma_{eff} = 17.8 \pm 4.2$ mb, which is the average of two recent extractions [29, 30] in the $W$-boson plus dijet final state, the latter being the closest to the one considered here. The only available information in this channel is a lower limit, $\sigma_{eff} > 5.91$ mb at $95\%$ confidence level, recently obtained with an integrated luminosity $L=19.7$ fb$^{-1}$ at $\sqrt{s} = 8$ TeV [27].

In the last model [17], called QM, dPDFs have been evaluated within the LF framework, generalizing the approach of Ref. [31] for the calculation of PDFs. As a result, fully correlated dPDFs are obtained [17]. In such a model, longitudinal and transverse correlations are generated among valence quarks and gluons dPDFs, the use of this model in the present analysis is particularly relevant. First of all, within this model, the DPS cross section can be calculated using Eq. (11), without any assumption on $\sigma_{eff}$, at variance with MSTW and

**TABLE I: Fiducial DPS phase space used in the analysis.**

| $pp$, $\sqrt{s}$ = 13 TeV | $p_{T,\mu}^{leading}$ > 20 GeV, $p_{T,\mu}^{subleading}$ > 10 GeV | $|p_{T,\mu}^{leading}| + |p_{T,\mu}^{subleading}|$ > 45 GeV | $|\eta_\mu|$ < 2.4 | $|\Delta R_{\mu\mu}|$ > 3.0 |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| $|p_{T,\mu}|$ < 20 GeV, $|\eta_\mu|$ < 1.8 | $|p_{T,\mu}|$ > 20 GeV, $|\eta_\mu|$ > 1.8 | $|p_{T,\mu}|$ > 50 GeV, $|\eta_\mu|$ > 1.8 |

| $20$ GeV < $M_{inv}$ < $75$ GeV | $M_{inv}$ < $105$ GeV |

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[1]...

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GS09. Moreover, the simultaneous use of single and double PDFs obtained from the same LF dynamics, allows one to investigate the role of parton correlations on potentially sensitive observables. Theoretical systematic errors are associated to our predictions as follows. Uncertainties related to missing higher order corrections, denoted by δμF, are estimated for all models, varying μF in the range 0.5 M_W < μF < 2.0 M_W; the ones due Q0-fixing, denoted by δQ0, are given by varying this parameter in the range 0.24 < Q0 < 0.28 GeV^2. A further error, δσ_{eff}, is assigned to MSTW and GS09 predictions, due to δσ_{eff} uncertainty. In Tab. II we report DPS cross sections, integrated in the fiducial volume, evaluated using the above models. Predictions based on MSTW and GS09 are close, while QM one is smaller by around 15%, although they are all consistent within errors.

For all the considered models, cross sections rise as μF increases, an effect induced by the sea quark growth at ⟨x⟩ ≈ 10^{-2} (typical of this process). We have estimated that, if the integrated luminosity L is greater than 300 fb^{-1}, the central values of the QM and GS09 predictions can be discriminated. It is worth noting that, if the measurement were performed also in the eμ (eμ+eμ) channel, the number of signal events would increase by a factor three (four).

In Tab. III predictions of models GS09 and QM for default values of parameters of charged ssWV cross sections (indicated by σ^{−−} and σ^{++}) integrated in the fiducial volume, are compared. While agreement between model predictions is found for σ^{++}, a rather smaller σ^{−−} is obtained in model QM, due to the assumption in Eq. (10). The ratio σ^{−−} and σ^{++} is therefore a suitable observable to investigate the flavor structure of dPDFs.

In order to analyze correlations encoded in dPDFs, we consider the differential cross section in the variable η_{1} · η_{2} which, neglecting the boost generated by W-decay into leptons, can be approximated via Eqs. (10) as

\[ η_{1} · η_{2} \simeq \frac{1}{4} \ln \frac{x_{1}}{x_{3}} \ln \frac{x_{2}}{x_{4}}, \]  

(15)

where fractional momenta are subject to the invariant mass constraint x_{1}x_{3} = x_{2}x_{4} = M_W^2/s. The result, converted into per-bin number of events assuming an integrated luminosity L = 300 fb^{-1}, is presented in Fig. 2. The maximum is located at η_{1} · η_{2} ≈ 0, where annihilating partons equally share the momentum fractions, x ∼ M_W/√s, in at least one scattering. At large and positive (negative) values of η_{1} · η_{2}, muons are produced in the same (opposite) emisphere and the fast drop of the cross section is associated to the fall off of dPDFs as one of the partons in the same proton approach the large x limit. We note that predictions based on GS09 and QM models show a rather similar shape and are compatible within their sizeable errors. To deal with such large uncertainties, differential cross sections, normalized to the total ones (Tab. III), may be considered. In this way, the predictions of MSTW and GS09 models do not depend any more on the choice of μ_{eff} and the related error cancels. Moreover, for model QM, we verified that the scale variations δμF and δQ0, acting basically on normalizations, almost cancel in the ratio. A shape comparison can then be used to discriminate among models and their factorized structure. In the present analysis, however, we prefer to discuss the effects of correlations on a more familiar quantity, σ_{eff}.

To this aim we use the LF approach for both PDFs and dPDFs to evaluate SPS and DPS differential cross sections, Eqs. (11) and (14), respectively, integrated in bins of η_{1} · η_{2}. With these ingredients we obtain, through Eq. (2), a prediction for σ_{eff} intrinsic to the LF model, called hereafter δσ_{eff}. If a corresponding procedure is performed on cross sections integrated in the fiducial volume, one

| dPDFs | σ^{++} + σ^{−−} [fb] |
|-------|------------------------|
| MSTW  | 0.77^{+0.23}_{−0.21} (δμF) +0.18^{−0.18}_{−0.18} (δσ_{eff}) |
| GS09  | 0.82^{+0.24}_{−0.26} (δμF) +0.19^{−0.19}_{−0.19} (δσ_{eff}) |
| QM    | 0.69^{+0.18}_{−0.18} (δμF) +0.12^{−0.12}_{−0.12} (δQ0) |

**TABLE II:** Model predictions for W-charge summed cross sections in fiducial region in Tab. II.

| dPDFs | σ^{−−} [fb] | σ^{++} [fb] | σ^{++}/σ^{−−} |
|-------|-------------|-------------|----------------|
| GS09  | 0.54        | 0.28        | 1.9            |
| QM    | 0.53        | 0.16        | 3.4            |
| GS09/QM | 1.01      | 1.78        | -              |

**TABLE III:** Ratio of cross sections for same sign muons production in fiducial region.
obtains the constant value
\[
\langle \tilde{\sigma}_{\text{eff}} \rangle = 21.04 \pm 0.07 \, (\delta Q_0) \pm 0.06 \, (\delta \mu_F) \, \text{mb}.
\] (16)
This value is compatible, within errors, with \( \tilde{\sigma}_{\text{eff}} \) experimentally determined. Both \( \tilde{\sigma}_{\text{eff}} \) and \( \langle \tilde{\sigma}_{\text{eff}} \rangle \) are shown in Fig. 3 and, being ratios, are both stable against \( \mu_F \) and \( Q_0 \) variations. The departure of \( \tilde{\sigma}_{\text{eff}} \) from a constant value is a measure of two parton correlations in the proton. These are primarily correlations in longitudinal momenta but, as shown using the fully correlated model QM, they are related to the ones in transverse space in an irreducible way \( ^{32} \). We have estimated that this departure could be appreciated with an integrated luminosity \( \mathcal{L} \) of around 1000 fb\(^{-1} \), at 68% confidence level, reachable in the planned LHC runs. Our conclusion is that the extraction of this observable in bins of \( \eta_1 \cdot \eta_2 \) is a convenient strategy to look for parton correlations.

Summarising, we have calculated \( s s W W \) cross sections in a LF model for dPDFs, carefully estimating the corresponding uncertainties. Our predictions, completely intrinsic to the approach, are in line with those obtained by other approaches which make use of the external parameter \( \sigma_{\text{eff}} \). This indicates that the model is able to catch the transverse structure of the DPS process. Furthermore, we have established that, in this specific final state, transverse and longitudinal correlations, embodied in dPDFs, could be observed in the next LHC runs.

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