Double parton scattering and 3D proton structure: A Light-Front analysis

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Abstract Double parton scattering, occurring in high energy hadron-hadron collisions, e.g. at the LHC, is usually investigated through model dependent analyses of the so called effective cross section $\sigma_{\text{eff}}$. We present a dynamic approach to this fundamental quantity making use of a Light-Front model treatment. Within such a framework $\sigma_{\text{eff}}$ is initially evaluated at low energy scale using the model and then, through QCD evolution, at high energy scale to reach the experimental conditions. Our numerical outcomes are consistent with the present experimental analyses of data in kinematical region we investigate. An important result of the present work is the $x_i$ dependence of $\sigma_{\text{eff}}$, a feature directly connected to double parton correlations and which could unveil new information on the three dimensional structure of the proton.

Keywords Partons · Multi parton interactions · Parton correlations

1 Introduction

In hadron-hadron collisions, possible signals of Multi Parton Interactions (MPI), due to the interactions of at least two partons of each hadron, have been investigated for a long time [1]. Recently, thanks to the possibilities offered by the Large Hadron Collider (LHC), RUN 2, a lot of attention on this subject has been paid [2, 3, 4]. In the present talk, we focus our scrutiny on the simplest MPI process, double parton scattering (DPS). The cross section for this process, assuming factorization, depends on non-perturbative quantities, the so called double parton distribution functions (dPDFs), which describe the joint probability of finding two partons at a given transverse distance with given longitudinal momentum fractions. dPDFs are therefore related to the three-dimensional (3D) nucleon structure [5] and are non-perturbative quantities. Tractable model calculations of the dPDFs have been proposed in the last few years (e.g. Refs. [6, 7, 8]). In particular, in Refs. [8, 9], dPDFs have been evaluated by means of a Light-Front (LF) approach, which allows one to achieve a Poincaré covariant treatment and then to reproduce the essential dPDFs sum rules. Let
us stress that even if there are no clear data from which dPDFs can be extracted, a signature of DPS has been observed and measured in several experiments [10; 11; 12; 13; 14; 15]. In particular the DPS cross section is estimated through the so called “effective cross section”, \( \sigma_{eff} \) and evaluated in model dependent ways. Despite large error bars \( \sigma_{eff} \) is found to be constant w.r.t. the center-of-mass energy of the collision and the longitudinal momentum fractions carried by the interacting partons. In order to calculate \( \sigma_{eff} \) in our dynamical model, a useful expression has been derived in Ref. [14]. Thanks to that study, \( \sigma_{eff} \) can be be directly evaluated from the calculations of dPDFs. In particular, in [10] and here, use has been made of the results discussed in Ref. [8], in which d PDFs have been estimated by means of a LF model. In the next sections the main results of the calculations of \( \sigma_{eff} \) will be properly shown and described.

2 The effective cross section

In this section, starting from the phenomenological definition of \( \sigma_{eff} \), a direct relation between this quantity and standard parton distribution functions (PDFs) and dPDFs will be shown. \( \sigma_{eff} \), is usually defined through a “pocket formula” when a DPS process produces two final states \( A \) and \( B \) [3]:

\[
\sigma_{eff} = \frac{m \sigma_{pp}^p \sigma_{pp}^{'p}}{2 \sigma_{pp}^{double}} .
\]  

Here, \( m = 1 \) if \( A \) and \( B \) are identical and \( m = 2 \) if they are different. In the numerator, \( \sigma_{pp}^{ij'} \) is the differential cross section for the inclusive process \( pp' \to A(B) + X \) and reads as follows:

\[
\sigma_{pp}^{ij'}(x_{1(2)}, x_{1(2)}', \mu_{1(2)}) = \sum_{i,k} F_i^p (x_{1(2)}, \mu_{1(2)}) F_k^{p'} (x_{1(2)}', \mu_{1(2)}) \tilde{\sigma}_{ik}^{A(B)} (x_{1(2)}, x_{1(2)}', \mu_{1(2)}) ,
\]

where here \( F_i^p \) is the standard single PDF, the indices read \( i, k = \{ q, \bar{q}, g \} \) and \( \mu_{1(2)} \) is the factorization scale for the process \( A(B) \). On the other hand side, the denominator of Eq. (1) is the differential double parton scattering cross section:

\[
\sigma_{pp}^{ij}(x_1, x_1', x_2, x_2', \mu_1, \mu_2) = \frac{m}{2} \sum_{i,j,k,l} \int D_{ij}(x_1, x_2; k_\perp, \mu_1, \mu_2) \tilde{\sigma}_{ik}^{A}(x_1, x_1', \mu_1) \\
\times D_{kl}(x_1', x_2', -k_\perp, \mu_1, \mu_2) \tilde{\sigma}_{jl}^{B}(x_2, x_2', \mu_2) \frac{d k_\perp}{(2\pi)^2} .
\]

In Eq. (2), \( D_{ij}(x_1, x_2; k_\perp) \), often called “double generalized parton distributions” (2GPDs) [17; 18], depends on \( k_\perp \), the transverse momentum imbalance of the partons 1 and 2; 2GPDs are the Fourier transform of the dPDFs \( D_{ij}(x_1, x_2; r_\perp) \), which depend on \( r_\perp \), the transverse separation, in coordinate space, between two partons. \( D_{ij}(x_1, x_2; r_\perp) \) represents the probability of finding parton pairs \( i, j \) with longitudinal momentum fractions \( x_1, x_2 \) and transverse distance \( r_\perp \). This is the non-perturbative input describing soft-physics. Let us point out the physical content of \( \sigma_{eff} \). In Eq. (1), if the occurrence of the \( B \) were not biased by that of the \( A \), instead of the ratio \( \sigma_B/\sigma_{eff} \) one would read \( \sigma_B/\sigma_{inel} \), representing the probability to have \( B \) once \( A \) has taken place assuming rare hard multiple collisions. The difference between \( \sigma_{eff} \) and \( \sigma_{inel} \) measures therefore correlations between the interacting partons in the colliding proton.

Now a suitable expression of \( \sigma_{eff} \) for microscopic calculations, in particular highlighting the \( x_i \)-dependence of \( \sigma_{eff} \), will be derived. First of all, let us assume that heavy quark flavors do not contribute in the process and that elementary cross section, appearing in Eqs. (2) and (3), is basically (see Ref. [14] for details) \( \sigma_{ij}(x, x') = C_{ij} \bar{\sigma}(x, x') \), where \( \bar{\sigma}(x, x') \) is a universal function, and \( C_{ij} \) are color factors, with \( i, j = q, \bar{q}, g \), which stay in the ratio \( C_{qq} : C_{qg} : C_{gq} = 1 : (4/9) : (4/9)^2 \).
At this point, inserting Eqs. (2)-(3) in Eq. (1) together with these assumptions, one finds the following formal expression of $\sigma_{\text{eff}}$:

$$\sigma_{\text{eff}}(x_1, x'_1, x_2, x'_2) = \frac{\sum_{i,k,j,l} i_F(x_1) j_F(x'_1) k_F(x_2) l_F(x'_2) C_{ik} C_{jl} \sum_{i,j,k,l} C_{ik} C_{jl}}{\Delta_{x_1, x_2, k_\perp}} \int D_{ij}(x_1, x_2; k_\perp) D_{kl}(x'_1, x'_2; -k_\perp) \frac{dk_\perp}{(2\pi)^2}. \quad (4)$$

As one can see, in the above equation, assuming a complete factorized ansatz for dPDFs in terms of standard PDFs, e.g., $D_{ij}(x_1, x_2; k_\perp) \propto F_i(x_1) F_j(x_2) T(k_\perp)$, one obtains a constant value of $\sigma_{\text{eff}}$ w.r.t. to $x_i$. This scenario is realized neglecting double parton correlations. This is the kind of condition often guessed for the extraction of $\sigma_{\text{eff}}$ from data since there is no experimental information on dPDFs. The problems related to the uncorrelated ansatz are discussed in a number of papers (see, e.g., Refs. [2; 3; 19]). In particular, in the valence region we are interested here, this assumption is not supported by model calculations [6; 7; 8], due to the presence of double parton correlations. Before describing our results, the present experimental scenario is shown in Fig. 1 where $\sigma_{\text{eff}}$, measured by different experiments [10; 11; 12; 13; 14; 15; 16; 17; 18], which analyzed the latter quantity with different final states at different values of the center-of-mass energy, $\sqrt{s}$, has been plotted. As one can see, a constant value of $\sigma_{\text{eff}}$ could be consistent with the data within the large experimental errorbars, which could hide the fundamental information on the possible $x_i$-dependence. Let us stress that such important dependence could open new ways to access the 3D nucleon structure [3].

Nowadays, fundamental information on the 3D structure of the nucleon, related to the transverse position of partons, is usually investigated thorough the study and the measurements of hard-exclusive processes such as deeply virtual Compton scattering (DVCS), which allows to access the Generalized Parton Distributions (GPDs) (see Ref. [20] for recent developments). Further information could be obtained via the investigation of dPDFs in its full $x_i$ dependence which can be extracted from $\sigma_{\text{eff}}$ in DPS. Let us remark that the information encoded in dPDFs are anyhow complementary to those provided by GPDs in impact parameter space. In fact, the latter quantities are one-body densities describing the probability of finding a parton with longitudinal momentum fraction $x$ at a given transverse distance from the center of the target, while, dPDFs are two-body distributions related to the relative distance between two partons with given $x_1$ and $x_2$. In other words, the measurements of DPS could access information on the average transverse distance of two fast or slow partons: a very interesting dynamical feature, not included in GPDs.

3 Calculation of the effective cross section within a LF approach

dPDFs can not be easily evaluated within QCD while they can be estimated at a low energy scale, $\Lambda_{QCD}$, using models, as extensively done for the PDFs (e.g., Ref. [21]). The results of these analyses should then be evolved using perturbative QCD (pQCD) in order to match data taken at an energy scale $Q > \Lambda_{QCD}$. The pPDF evolution is discussed e.g. in Refs. [2; 3; 22; 23; 24; 25]. The analysis we are presenting makes use of the Poincaré covariant Light-Front model approach, allowing for a correct starting point for a precise pQCD evolution. Thanks to this feature, our model calculations can be relevant for the analysis of high-energy data.

The model, chosen in order to grasp the most relevant features of dPDFs, is the one presented and described in Ref. [24], being already used for the studies of other different distributions (see, e.g., Refs. [25; 26] and references therein). The explicit calculation of $D_{ij}(x_1, x_2; k_\perp, \mu)$ has been described in details in Refs. [2; 3; 8; 9]. In particular, let us point out that strong correlation effects are present at the scale of the model and still sizable, in the valence region, at the experimental scale, i.e. after pQCD evolution. At low values of $x$, presently studied at the LHC, correlations become less relevant, although their effects are still important for the spin-dependent contributions to unpolarized proton scattering. In order to evaluate
Fig. 2 $\sigma_{\text{eff}}(x_1, x_2, Q^2)$ for the values of $x_1, x_2$ measured in Ref. [10]. Left panel: hadronic scale; right panel: $Q^2 = 250 \text{ GeV}^2$.

$\sigma_{\text{eff}}$, the single and the double PDFs, appearing in Eq. (4) have been calculated imposing a unique factorization scale $\mu_1 = \mu_2 = \mu_0$ (as in, e.g., Refs. [2; 4; 27]), where $\mu_0$ is the hadronic scale, where only valence quarks are present. Here and in Ref. [16] we focus our analysis on the kinematics of the old AFS data [10], i.e. $x_1 \approx x'_1, x_2 \approx x'_2$ and $0.2 \leq x_{1,2} \leq 0.3$ and the average energy scale turns out to be $Q^2 \approx 250 \text{ GeV}^2$. The results of the calculations are shown in Fig. 2, at the scale of the model, $\mu_0^2 \approx 0.1 \text{ GeV}^2$, and after non-singlet evolution to $Q^2$ (details on the fixing of the hadronic scale and on the calculation of the QCD evolution can be found in Ref. [8]). As one can see, a strong $x_1, x_2$ dependence has been found in this narrow kinematical range at both the experimental and the model scales. One should notice that the three old experimental extractions of $\sigma_{\text{eff}}$ [10; 11; 12], which include the valence region (cf. Fig. 1), lie in the obtained range of values of $\sigma_{\text{eff}}$ shown in Fig. 2. Let us remark two important issues on the pQCD evolution of dPDFs. In our approach, there is only evolution on $x_1, x_2$, being the one on $k_\perp$ still an open challenge and, furthermore, since we are interested, for the moment being, on the valence region, only the homogenous part of the evolution equations has been taken into account in our calculation. Moreover, in Ref. [16], the average value of $\sigma_{\text{eff}}, \bar{\sigma}_{\text{eff}} \sim 10.9 \text{ mb}$, is in good agreement with the experimental data reported in Fig. 1.

4 Conclusions

In the present work, a suitable expression of $\sigma_{\text{eff}}$ for microscopic calculations, in terms of dPDFs and standard PDFs, has been derived. In order to perform the calculation of $\sigma_{\text{eff}}$, use has been made of a relativistic Poincaré covariant quark model. In particular, our investigation predicts an $x_i$ dependence of $\sigma_{\text{eff}}$, whose values are consistent with data including the valence region. Moreover, such dependence, found when a non singlet evolution of the valence distributions is performed, as well as when perturbatively generated gluons are included into the scheme, is a feature not easily read in the available data. The measurement of $\sigma_{\text{eff}}$ in restricted $x_i$ ranges would lead, therefore, to a first signature of double parton correlations in the proton, a novel and interesting aspect of the 3D structure of the nucleon.

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