Double parton scattering: 
a study of the effective cross section 
within a Light-Front quark model

Matteo Rinaldi, Sergio Scopetta
Dipartimento di Fisica e Geologia, Università degli Studi di Perugia,
and Istituto Nazionale di Fisica Nucleare, Sezione di Perugia,
via A. Pascoli, I - 06123 Perugia, Italy

Marco Traini
Dipartimento di Fisica, Università degli studi di Trento, and INFN - TIFPA,
Via Sommarive 14, I - 38123 Povo (Trento), Italy

Vicente Vento
Departament de Fisica Teòrica, Universitat de València
and Institut de Fisica Corpuscular, Consejo Superior de Investigaciones
Científicas, 46100 Burjassot (València), Spain

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Abstract

We present a calculation of the effective cross section $\sigma_{\text{eff}}$, an important ingredient in the description of double parton scattering in proton-proton collisions. Our theoretical approach makes use of a Light-Front quark model as framework to calculate the double parton distribution functions at low-resolution scale. QCD evolution is implemented to reach the experimental scale. The obtained $\sigma_{\text{eff}}$, when averaged over the longitudinal momentum fractions of the interacting partons, $x_i$, is consistent with the present experimental scenario. However the result of the complete calculation shows a dependence of $\sigma_{\text{eff}}$ on $x_i$, a feature not easily seen in the available data, probably because of their low accuracy. Measurements of $\sigma_{\text{eff}}$ in restricted $x_i$ regions are addressed to obtain indications on double parton correlations, a novel and interesting aspect of the three dimensional structure of the nucleon.
1 Introduction

Multi Parton Interactions (MPI), occurring when more than one parton scattering takes place in the same hadron-hadron collision, have been discussed in the literature since long time ago [1] and are presently attracting considerable attention, thanks to the possibilities offered by the Large Hadron Collider (LHC) (see Refs. [2] [4] [5] [6] for recent reports). In particular, the cross section for double parton scattering (DPS), the simplest MPI process, depends on peculiar non-perturbative quantities, the double parton distribution functions (dPDFs), describing the number density of two partons with given longitudinal momentum fractions and located at a given transverse separation in coordinate space. dPDFs are naturally related to parton correlations and to the three-dimensional (3D) nucleon structure, as discussed also in the past [7].

No data are available for dPDFs and their calculation using non perturbative methods is cumbersome. A few model calculations have been performed, to grasp the most relevant features of dPDFs [8] [9] [10]. In particular, in Ref. [10] a Light-Front (LF) Poincaré covariant approach, able to reproduce the essential sum rules of dPDFs, has been described. Although it has not yet been possible to extract dPDFs from data, a signature of DPS has been observed and measured in several experiments [11] [12] [13] [14] [15] [16]: the so called “effective cross section”, $\sigma_{eff}$. Despite of large errorbars, the present experimental scenario is consistent with the idea that $\sigma_{eff}$ is constant w.r.t. the center-of-mass energy of the collision.

In this letter we present a predictive study of $\sigma_{eff}$ which makes use of the LF quark model approach to dPDFs developed in Ref. [10].

The definition of $\sigma_{eff}$ is reviewed in the next section where the present experimental situation is also summarized. Then the results of our approach are presented critically discussing the dynamical dependence of $\sigma_{eff}$ in view of future experiments. Conclusions are drawn in the last section.

2 The effective cross section

The effective cross section, $\sigma_{eff}$, is defined through the so called “pocket formula”, which reads, if final states $A$ and $B$ are produced in a DPS process (see, e.g., [5]):

$$\sigma_{eff} = \frac{m}{2} \frac{\sigma_{A}^{pp'} \sigma_{B}^{pp'}}{\sigma_{pp}^{double}} .$$

$m$ is a process-dependent combinatorial factor: $m = 1$ if $A$ and $B$ are identical and $m = 2$ if they are different. $\sigma_{A(B)}^{pp'}$ is the differential cross section for the inclusive process $pp' \rightarrow A(B) + X$, naturally defined as:
\[ \sigma_{pp}^{ij}(x_1, x_1', \mu_1) = \sum_{i,k} F_i^p(x_1, \mu_1) F_k^p(x_1', \mu_1) \hat{\sigma}_{ik}^A(x_1, x_1', \mu_1), \] (2)

\[ \sigma_{pp}^{ij}(x_2, x_2', \mu_2) = \sum_{j,l} F_j^p(x_2, \mu_2) F_l^p(x_2', \mu_2) \hat{\sigma}_{jl}^B(x_2, x_2', \mu_2), \] (3)

where \( F^p_{i(j)} \) is a one-body parton distribution function (PDF) with \( i, j, k, l = \{ q, \bar{q}, g \} \), \( \mu_1(2) \) is the renormalization scale for the process \( A(B) \), \( \sigma_{pp}^{\text{double}} \), the remaining ingredient in Eq. (1), appears in the natural definition of the cross section for double parton scattering:

\[ \sigma_d = \int \sigma_{pp}^{\text{double}}(x_1, x_1', x_2, x_2', \mu_1, \mu_2) \, dx_1 \, dx_1' \, dx_2 \, dx_2', \] (4)

and reads:

\[ \sigma_{pp}^{\text{double}}(x_1, x_1', x_2, x_2', \mu_1, \mu_2) = \frac{m}{2} \sum_{i,j,k,l} \int D_{ij}(x_1, x_2; k_\perp, \mu_1, \mu_2) \, \hat{\sigma}_{ik}^A(x_1, x_1') \, \hat{\sigma}_{jl}^B(x_2, x_2') \]

\[ \times D_{kl}(x_1', x_2'; -k_\perp, \mu_1, \mu_2) \frac{d k_\perp}{(2 \pi)^2}. \] (5)

In the above equation, \( k_\perp (-k_\perp) \) is the transverse momentum unbalance of the parton 1 (2), conjugated to the relative distance \( r_\perp \) (the reader should not confuse \( k_\perp \) with the intrinsic momentum of the parton, argument of transverse momentum dependent parton distributions). The quantity \( D_{ij}(x_1, x_2; k_\perp) \), called sometimes 2\textit{GPDS} [17, 18], is therefore the Fourier transform of the so called double distribution function, \( D_{ij}(x_1, x_2; r_\perp) \), which represents the number density of partons pairs \( i, j \) with longitudinal momentum fractions \( x_1, x_2 \), respectively, at a transverse separation \( r_\perp \) in coordinate space. dPDFs, describing soft Physics, are nonperturbative quantities.

Two main assumptions are usually made for the evaluation of dPDFs:

a) factorization of the transverse separation and the momentum fraction dependence:

\[ D_{ij}(x_1, x_2; k_\perp, \mu) = D_{ij}(x_1, x_2, \mu) \, T(k_\perp, \mu); \] (6)

b) factorized form also for the \( x_1, x_2 \) dependence:

\[ D_{ij}(x_1, x_2, \mu) = F_i(x_1, \mu) F_j(x_2, \mu) \, \theta(1 - x_1 - x_2)(1 - x_1 - x_2)^n. \] (7)

The expression \( \theta(1 - x_1 - x_2)(1 - x_1 - x_2)^n \), where \( n > 0 \) is a parameter to be fixed phenomenologically, introduces the natural kinematical constraint \( x_1 + x_2 \leq 1 \) (in Eqs. (6) and (7) the same scale \( \mu = \mu_1, \mu_2 \) is assumed, for brevity).
Figure 1: Centre-of-mass energy dependence of $\sigma_{eff}$ measured by different experiments using different processes [11, 12, 13, 14, 15, 16]. The figure is taken from [16].

One comment about the physical meaning of $\sigma_{eff}$ is in order. In Eq. (1), if the occurrence of the process $B$ were not biased somehow by that of the process $A$, instead of the ratio $\sigma_B/\sigma_{eff}$ one would read $\sigma_B/\sigma_{inel}$, representing the probability to have the process $B$ 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.

Let us discuss now the dynamical dependence of $\sigma_{eff}$ on the fractional momenta $x_1, x_1', x_2, x_2'$. By inserting Eqs. (2-5) in Eq. (1), and omitting the dependence on the renormalization scales for simplicity, one gets the following expression for $\sigma_{eff}$:

$$\sigma_{eff}(x_1, x_1', x_2, x_2') = \frac{\sum_{i,k} F^p_i(x_1) F^{p'}_k(x_1') \hat{\sigma}_{ik}^A(x_1, x_1') \{ \sum_{j,l} F^p_j(x_2) F^{p'}_l(x_2') \hat{\sigma}_{jl}^B(x_2, x_2') \}}{\sum_{i,j,k,l} \hat{\sigma}_{ik}^A(x_1, x_1') \hat{\sigma}_{jl}^B(x_2, x_2') \int D_{ij}(x_1, x_2; k_\perp) D_{kl}(x_1', x_2'; -k_\perp) \frac{dk_\perp}{(2\pi)^2}}.$$  \hspace{1cm} (8)

Eq. (8) clearly shows the dynamical origin of the dependence of $\sigma_{eff}$ on the fractional momenta $x_1, x_1', x_2, x_2'$. Even within the “zero rapidity region”, ($y = 0$), where $x_1 = x_1', x_2 = x_2'$, such a dependence, although simplified, is still effective.

Assuming that heavy flavors are not relevant in the process, the dependence on the “parton type”, $i = q, \bar{q}, g$, of the elementary cross section is basically [19]:

$$\hat{\sigma}_{ij}(x, x') = C_{ij} \hat{\sigma}(x, x'),$$ \hspace{1cm} (9)
where $\sigma(x, x')$ is a universal function, and $C_{ij}$ are color factors which stay in the ratio:

$$C_{gg} : C_{qg} : C_{qq} = 1 : (4/9) : (4/9)^2.$$  

(10)

Using Eq. (9), Eq. (8) simplifies considerably:

$$\sigma_{\text{eff}}(x_1, x'_1, x_2, x'_2) = \sum_{i,k,j,l} F_i(x_1) F_k(x'_1) F_j(x_2) F_l(x'_2) C_{ik} C_{jl} \int D_{ij}(x_1, x_2; k_\perp) D_{kl}(x'_1, x'_2; -k_\perp) \frac{dk_\perp}{(2\pi)^2}.$$  

(11)

The present experimental scenario is illustrated in Fig.1. The experiments [11, 12, 13, 14, 15, 16], at different values of the center-of-mass energy, $\sqrt{s}$, and with different final states, explore different regions of $x_i$. Experiments at high $\sqrt{s}$ access low $x_i$ regions, in general. The old AFS data [11] are in the valence region ($0.2 \leq x_i \leq 0.3$), the Tevatron data [13, 14] are in the range $0.01 \leq x_i \leq 0.4$ while the recent LHC data [15, 16] cover a lower average $x_i$ range and are dominated by the glue distribution.

Remarkably the experimental evidences are compatible with a constant value of $\sigma_{\text{eff}}$ in Eq. (11), the $x_i$-dependence being probably hidden within the experimental uncertainties. In fact one should stress that the knowledge of the $x_i$-dependence of $\sigma_{\text{eff}}$ would open the access to information on the $x_i$-dependence of the dPDFs $D_{ij}(x_1, x_2; r_\perp)$, entering the definition of $\sigma_{\text{eff}}$: a direct way to access the 3D nucleon structure [7]. Nowadays, the aspects of the 3D nucleon structure related to the transverse position of partons are investigated through hard-exclusive electromagnetic processes, such as deeply virtual Compton scattering (DVCS), extracting the Generalized Parton Distributions (GPDs) (see Ref. [20] for recent results). The information encoded in DPS, dPDFs and in $\sigma_{\text{eff}}$, in its full $x_i$ dependence, are anyway different and complementary to those provided by GPDs in impact parameter space. While the latter quantities are one-body densities, depending on the distance, of the interacting parton with given $x$, from the transverse center of the target, in DPS one is sensitive to the relative distance between two partons with given longitudinal momentum fractions. In other words, the investigation of dPDFs from DPS, is relevant to know, for example, the average transverse distance of two fast partons or two slow partons: a very interesting dynamical feature, not accessible through GPDs.

### 3 Light-Front quark model calculation of the effective cross section

dPDFs have a non-perturbative nature, and, at present, cannot be calculated in QCD. However they can be explicitly calculated, at a low resolution scale, $Q_0 \sim \Lambda_{\text{QCD}}$, using quark models, as extensively done for the usual PDFs. The results of these calculations should be then evolved using perturbative QCD (pQCD) in order to match data taken at a momentum scale $Q > Q_0$. 

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The procedure is nowadays well established (see, e.g., Ref. [21] and references therein). The QCD evolution procedure of dPDFs (from $Q_0$ to $Q > Q_0$) is well known [22, 23], and currently implemented in a systematic way (see Ref. [3, 24] and references therein).

The first model calculations of dPDFs in the valence region, at the hadronic scale $Q_0$, have been presented in a bag model framework [8], and in a constituent quark model (CQM) [9]. Of course CQM have the peculiar advantage of including correlations in a way consistent with the quark dynamics, from the very beginning, a property that the bag model cannot fulfill.

In particular the fully Poincaré covariant Light-Front model approach we developed in Ref. [10] respects relevant symmetries, broken in the descriptions of Refs. [8, 9], allowing for a correct evaluation of the Mellin moments of the distributions and, consequently, for a precise pQCD evolution to high momentum transfer. In this way our model calculations can be relevant for the analysis of high-energy data.

The model, extensively applied to the evaluation of different parton distributions, (see, e.g., Refs. [25, 26, 27] and references therein), is a good candidate to grasp the most relevant features of dPDFs (see Ref. [25] for details). For the present study it is enough to recall that the proton state is given by a spatial wave function and an SU(6) symmetric spin-isospin part. The spatial part is numerical solution of a relativistic Mass equation, dynamically responsible for the presence of correlations between the two quarks in the CQM wave function (a non-relativistic version of the model was introduced in Ref. [28]). The Light-Front calculations of $D_{ij}(x_1, x_2, k_\perp, \mu)$, in Ref. [10], shows that the factorization of Eq. (6) is basically valid, but the common assumption of Eq. (7) is strongly violated. Besides, the strong correlation effects present at the scale of the model are still sizable, in the valence region, at the experimental scale, i.e. after QCD evolution. At the low values of $x$, presently studied at the LHC, the correlations become less relevant, although their effects are still important for the spin-dependent contributions to unpolarized proton scattering.

We have explicitly calculated single and double parton distributions entering Eq. (11), and then $\sigma_{\text{eff}}$ relying on the natural assumption Eq. (11) only. We adhere, in addition, to the common choice of a single renormalization scale $\mu_1 = \mu_2 = \mu_0$, where $\mu_0$ has to be interpreted, in the present approach, as the hadronic scale where only valence quarks $u$ and $d$ are present. Considering the symmetries of our model, one has $u(x, \mu_0) = 2d(x, \mu_0)$, $D_{u,u}(x_1, x_2, k_\perp, \mu_0) = 2D_{u,d}(x_1, x_2, k_\perp, \mu_0)$ and Eq. (11) simplifies to

$$\sigma_{\text{eff}}(x_1, x'_1, x_2, x'_2, \mu_0) = \frac{81u(x_1, \mu_0) u(x'_1, \mu_0) u(x_2, \mu_0) u(x'_2, \mu_0)}{64 \int D_{uu}(x_1, x_2; k_\perp, \mu_0) D_{uu}(x'_1, x'_2; -k_\perp, \mu_0) \frac{dk_\perp}{(2\pi)^2}}. \quad (12)$$

Since the experimental data in the valence region are mainly restricted at zero rapidity ($y = 0$), where $x_i = x'_i$, one remains with

$$\sigma_{\text{eff}}(x_1, x_2, \mu_0) = \frac{81u(x_1, \mu_0)^2 u(x_2, \mu_0)^2}{64 \int D_{uu}(x_1, x_2; k_\perp, \mu_0)^2 \frac{dk_\perp}{(2\pi)^2}}. \quad (13)$$
Figure 2: $\sigma_{eff}(x_1, x_2, Q^2)$ for the values of $x_1, x_2$ measured in Ref. [11]. Left panel: hadronic scale; right panel: $Q^2 = 250$ GeV$^2$.

In order to illustrate our results we will concentrate on the valence region where the present model is more predictive. In particular we concentrate on the kinematics of the old AFS data [11], which means $y = 0$ ($x_1 = x'_1, x_2 = x'_2$) and $0.2 \leq x_{1,2} \leq 0.3$. The average momentum scale, again assumed to be the same for the processes initiated by the two different collisions, turns out to be $Q^2 \approx 250$ GeV$^2$. The results of the calculations are shown in Fig. 2, at the scale of the model, $\mu_0^2 \approx 0.1$ 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. [10]).

What is immediately seen is an $x_{1,2}$ dependence of the results, which change up to 100% even in this narrow kinematical range. Such a dependence is found at both the experimental and the model scale. The slope of the surface in the right panel of Fig. 2 is inverted w.r.t. that in the left panel. It is not a surprising feature, due to the different evolution properties of the numerator and denominator in Eq. (12) and consistent with the evolution calculated in Ref. [10]. This $x$ dependence, found at the hadronic scale as well as at high $Q^2$, can be attributed to different dynamical and kinematical properties:

1. both the numerator and the denominator vanish quickly with $x_i$ through the valence region, but the latter vanishes faster, mainly due to the kinematic constraint $x_1 + x_2 \leq 1$ of the dPDF, a quantity appearing only in the denominator. The LF model correctly reproduce such a kinematical constrain;

2. the correlations introduced by the LF dynamics and effective both in the $x_i$ and $k_\perp$ dependence;
3. the correlations induced by the pQCD evolution in the valence region.

In order to be more intuitive let us restrict to two different extreme scenarios:

i) At very low-$x_i$ gluons are strongly dominating (this is the hypothesis in [17], partially corrected in [18]), so that it is enough to consider $i, j, k, l = g$. Assuming, in addition, a fully factorized approach: $D_{gg}(x, x', k_\perp) = F_g(x) F_g(x') g(k_\perp)$, $\sigma_{eff}$ becomes:

$$\sigma_{eff}(x_1, x'_1, x_2, x'_2) \rightarrow \sigma_{eff} = \frac{1}{\int g^2(k_\perp) \frac{dk_\perp}{(2\pi)^2}}.$$  \hspace{1cm} (14)

A similar assumption is used in Ref. [17] to obtain an estimate of $\sigma_{eff}$ which turns out to be about twice the experimental value. Obviously, the validity of Eq.(14) is spoiled by correlation effects and restricted to very low-$x_i$. The problems related to the uncorrelated ansatz are discussed in a number of papers (see, e.g., Ref. [2, 29, 30, 31]). In particular, in the valence region this assumption is not supported by model calculations [8, 9, 10] and it is certainly untrue in pQCD, being also spoiled by QCD evolution. In other words, several arguments lead to the conclusion that, in general, $\sigma_{eff}$ should be $x_i$ dependent, namely: breaking of the factorization ansatz; the QCD evolution; contribution of more than one parton type (not only gluons as at very low $x_i$) to the DPS cross section.

ii) Let us now consider a simple way to reduce the results of our calculation to a fully factorized approach to dPDFs, following the hypothesis often assumed (cfr. Eqs. (6), (7)):

$$D_{uu}(x_1, x_2; k_\perp, \mu_0) = u(x_1, \mu_0) u(x_2, \mu_0) f_{uu}(k_\perp),$$  \hspace{1cm} (15)

where a natural definition for the "effective form factor", $f_{uu}(k_\perp)$, in our approach, is

$$f_{uu}(k_\perp) = \frac{1}{4} \int dx_1 dx_2 D_{uu}(x_1, x_2; k_\perp, \mu_0),$$  \hspace{1cm} (16)

a quantity which turns out to be scale independent. Within this approximation, Eq. (12) yields:

$$\sigma_{eff}(x_1, x'_1, x_2, x'_2, \mu_0) \rightarrow \sigma_{eff} = \frac{81}{64 \int f_{uu}^2(k_\perp) \frac{dk_\perp}{(2\pi)^2}} \simeq 10.9 \, mb,$$  \hspace{1cm} (17)
a value which turns out to be independent on the momentum scale \( Q \) and on the longitudinal momentum fractions \( x_i, x'_i \). It is remarkable that it compares reasonably well with the sets of data shown in Fig.1. Of course the validity of our simplified result is restricted to the valence region where the model is predictive and the numerical estimate is connected to the ability of the model to capture (in its wave function) the correct average distribution of the valence quarks in transverse space.

The \( x \)-dependence we are discussing does not emerge from the present data, probably not accurate enough. Our study points out therefore to an experimental scenario where more precise measurements in narrow \( x_i \) regions could shed new light on the structure of the proton and on the nature of hard proton-proton collisions. If the \( x \)-dependence is seen, one will gain, through \( \sigma_{eff} \), a first indication of double parton correlations and a fresh look at the 3D proton structure.

4 Conclusions

We have calculated the effective cross section \( \sigma_{eff} \) within a relativistic Poincaré covariant quark model. Extracted from proton-proton scattering data by several experimental collaborations in the last 30 years, \( \sigma_{eff} \) represents a tool to understand double parton scattering in a p-p collision. Our investigation predicts a behavior of \( \sigma_{eff} \) which, when averaged over the longitudinal momentum fractions \( x_i, x'_i \), is consistent with the present experimental scenario, in particular with the sets of data which include the valence region. However, at the same time, an \( x_i \) dependence of \( \sigma_{eff} \) is found, a feature not easily read in the available data. We conclude that the measurement of \( \sigma_{eff} \) in restricted \( x_i \) ranges would lead to a first indication of double parton correlations in the proton, addressing a novel and interesting aspect of the 3D structure of the nucleon. The analysis of peculiar processes where these effects could be most easily seen, as well as the extension of the model to obtain a better description of the low-\( x \) region, presently studied at LHC, are in progress.

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