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

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ABSTRACT

We present a calculation of the effective cross section σ_{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 a framework to calculate the double parton distribution functions at low-resolution scale. QCD evolution is implemented to reach the experimental scale. The obtained values of σ_{eff} in the valence region are consistent with the present experimental scenario, in particular with the sets of data which include the same kinematical range. However the result of the complete calculation shows a dependence of σ_{eff} on x_i, a feature not easily seen in the available data, probably because of their low accuracy. Measurements of σ_{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. [2–6] for recent reports). In particular, the cross section for double parton scattering (DPS), the simplest MPI process, depends on specific 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 [8–10]. In particular, in Ref. [10] a Light-Front (LF) Poincaré covariant approach, naturally reproducing 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 [11–16]: the so called "effective cross section", σ_{eff}. Despite of large errorbars, the present experimental scenario is consistent with the idea that σ_{eff} is constant w.r.t. the center-of-mass energy of the collision.

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

The definition of σ_{eff} is reviewed in the next section, where an operative expression, suitable for microscopic studies and model calculations, is derived and the present experimental situation is summarized. Then the results of our approach are presented critically, discussing the dynamical dependence of σ_{eff} in view of future experiments. Conclusions are drawn in the last section.

2. The effective cross section

The effective cross section, σ_{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]):

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$$\sigma_{eff} = \frac{m}{2} \frac{\sigma_A^{pp'} \sigma_B^{pp'}}{\sigma_{double}^{pp}}. \quad (1)$$

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 $pp' \to A(B) + X$, naturally defined as:

$$\sigma_A^{pp'}(x_1, x_1', \mu_1) = \sum_{i,k} F_i^p(x_1, \mu_1) F_k^{p'}(x_1', \mu_1)\, \hat{\sigma}_{ik}^A(x_1, x_1', \mu_1), \quad (2)$$

$$\sigma_B^{pp'}(x_2, x_2', \mu_2) = \sum_{j,l} F_j^p(x_2, \mu_2) F_l^{p'}(x_2', \mu_2)\, \hat{\sigma}_{jl}^B(x_2, x_2', \mu_2), \quad (3)$$

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

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

and reads:

$$\sigma_{double}^{pp}(x_1, x_1', x_2, x_2', \mu_1, \mu_2) = \frac{m}{2} \sum_{i,j,k,l} \int D_{ij}(x_1, x_2; \mathbf{k}_\perp, \mu_1, \mu_2)\, \hat{\sigma}_{ik}^A(x_1, x_1', \mu_1) \times D_{kl}(x_1', x_2'; -\mathbf{k}_\perp, \mu_1, \mu_2) \hat{\sigma}_{jl}^B(x_2, x_2', \mu_2)\, \frac{d\mathbf{k}_\perp}{(2\pi)^2}. \quad (5)$$

In the above equation, $\mathbf{k}_\perp$ ($-\mathbf{k}_\perp$) is the transverse momentum unbalance of the parton 1 (2), conjugated to the relative distance $\mathbf{r}_\perp$ (the reader should not confuse $\mathbf{k}_\perp$ with the intrinsic momentum of the parton, argument of transverse momentum dependent parton distributions). The quantity $D_{ij}(x_1, x_2; \mathbf{k}_\perp)$, called sometimes "double generalized parton distributions" ($_2GPDS$) [17,18], is therefore the Fourier transform of the so called double distribution function, $D_{ij}(x_1, x_2; \mathbf{r}_\perp)$, which represents the number density of partons pairs i, j with longitudinal momentum fractions x_1, x_2, respectively, at a transverse separation $\mathbf{r}_\perp$ 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:

$$D_{ij}(x_1, x_2; \mathbf{k}_\perp, \mu) = D_{ij}(x_1, x_2, \mu)\, T(\mathbf{k}_\perp, \mu); \quad (6)$$

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

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

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).

One comment about the physical meaning of σ_{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 σ_B/σ_{eff} one would read σ_B/σ_{inel}, representing the probability to have the process B once A has taken place assuming rare hard multiple collisions. The difference between σ_{eff} and σ_{inel} measures therefore correlations between the interacting partons in the colliding proton.

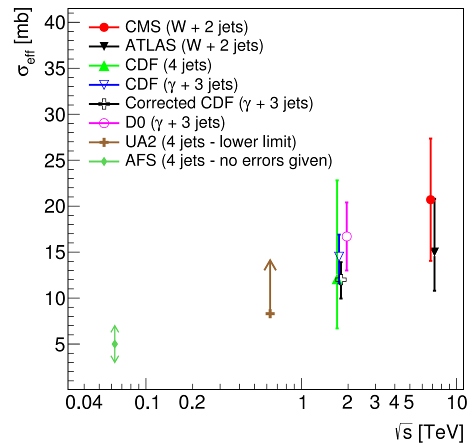

Fig. 1. Center-of-mass energy dependence of σ_{eff} measured by different experiments using different processes [11–16]. The figure is taken from [16].

Let us discuss now the dynamical dependence of σ_{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 factorization scales for simplicity, one gets the following expression for σ_{eff}:

$$\sigma_{eff}(x_1, x_1', x_2, x_2') = \frac{\left\{\sum_{i,k} F_i^p(x_1) F_k^{p'}(x_{1'})\, \hat{\sigma}_{ik}^A(x_1, x_{1'})\right\} \left\{\sum_{j,l} F_j^p(x_2) F_l^{p'}(x_{2'})\, \hat{\sigma}_{jl}^B(x_2, x_{2'})\right\}}{\sum_{i,j,k,l} \hat{\sigma}_{ik}^A(x_1, x_1')\, \hat{\sigma}_{jl}^B(x_2, x_2') \int D_{ij}(x_1, x_2; \mathbf{k}_\perp)\, D_{kl}(x_1', x_2'; -\mathbf{k}_\perp) \frac{d\mathbf{k}_\perp}{(2\pi)^2}}. \quad (8)$$

Eq. (8) clearly shows the dynamical origin of the dependence of σ_{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]:

$$\hat{\sigma}_{ij}(x, x') = C_{ij} \bar{\sigma}(x, x'), \quad (9)$$

where $\bar{\sigma}(x, x')$ is a universal function, and C_{ij} are color factors which stay in the ratio:

$$C_{gg} : C_{qg} : C_{qq} = 1 : (4/9) : (4/9)^2. \quad (10)$$

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

$$\sigma_{eff}(x_1, x_1', x_2, x_2') = \frac{\sum_{i,k,j,l} F_i(x_1) F_k(x_1') F_j(x_2) F_l(x_2') C_{ik} C_{jl}}{\sum_{i,j,k,l} C_{ik} C_{jl} \int D_{ij}(x_1, x_2; \mathbf{k}_\perp) D_{kl}(x_1', x_2'; -\mathbf{k}_\perp) \frac{d\mathbf{k}_\perp}{(2\pi)^2}}. \quad (11)$$

The present experimental scenario is illustrated in Fig. 1. The experiments [11–16], 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 σ_{eff} in Eq. (1), 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 σ_{eff} would open the access to information on the x_i-dependence of the dPDFs