Multiparton scatterings at the LHC

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Abstract

The large parton flux at high energy gives rise to events where different pairs of partons interact contemporarily with large momentum exchange. A main effect of multiple parton interactions is to generate events with many jets at relatively large transverse momenta. The large value of the heavy quarks production cross section may however give also rise a sizable rate of events with several b-quarks produced. We summarize the main features of multiparton interactions and make some estimate of the inclusive cross section to produce two $b\bar{b}$ pairs within the acceptance of the ALICE detector.

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1 Multiparton scatterings and Jets in proton-proton collisions

The description of jet production in hadronic collisions with a momentum transfer of the order of the c.m. energy, where the process is characterized by a single large energy scale factor, represents one of the most successful applications of the conventional, fixed$-x$, perturbative QCD. In this regime higher orders in the perturbative expansion of the elementary interaction are related directly to processes where an increasing number of large p_t jets are produced and virtual corrections are a rapidly converging expansion in powers of the strong coupling constant. The simplest perturbative scheme is however no more adequate when two or more different scales become relevant. An interesting case where two scales play an important role is when the c.m. energy of the partonic process, although much larger than the hadronic scale, is nevertheless very small as compared with the c.m. energy of the hadronic interaction, namely $\hat{s} \ll s$, where $\hat{s} \equiv xx's$, with x, x' the momentum fractions of the interacting partons and s the Mandelstam invariant of the hadronic collision. In this kinematical regime the typical final state is characterized by the presence of many jets and, while the partonic collision is still well described by the conventional perturbative approach, the overall semi-hard component of the hadronic interaction acquires a much richer structure. A recent analysis performed by CDF[1] of the jet evolution and underlying event in $p\bar{p}$ collisions shows that, while the leading jet is fairly well described by QCD Monte Carlo models in a wide kinematical range, the models fail do describe correctly the underlying event, which is populated by several further jets at a relatively low p_t. From the theoretical point of view one may get in touch with the problem looking at the cross section to produce large p_t jets, integrated on the exchanged momentum with the cutoff p_{cut}. When p_{cut} is moved towards relatively small values, the integrated cross section, being divergent for $p_{cut} \to 0$, becomes very large already well inside the kinematical regime where perturbation theory is meaningful, so that one faces a unitarity problem. Indeed the cross section for production of jets with $p_t > 5$GeV measured by UA1[2] is about $15 - 20mb$, in $p\bar{p}$ collisions at a c.m. energy of 900 GeV. In fig.2 the total, the inelastic non-diffractive and the cross section to produce jets with $p_t > 5$GeV (minijets) are plotted as a function of energy[3], showing that one foresees a high energy regime where the integrated inclusive cross section of jet production (long-dashed curve in the figure) exceeds the value of the total inelastic cross section. If considering hadron-nucleus and nucleus-nucleus collisions, the unitarity problem in jet production appears at larger transverse momenta and with smaller nucleon-nucleon c.m. energies.

The origin of the unitarity problem is in the large flux of partons, active for producing large p_t processes at high energies. When the incoming partons flux is very large there is a finite probability of producing events where different pairs of partons interact independently in a given hadronic interaction, with momentum exchange above p_{cut}, generating states with many jets at a relatively large p_t. In the integrated inclusive cross section of jet production, those events count with the multiplicity factor of the partonic collisions and, as a consequence, the inclusive cross section is not bounded by the value of the total inelastic cross section. In the kinematical region where the inclusive cross sections of jet production is comparable to the total inelastic cross section, the average number of par-

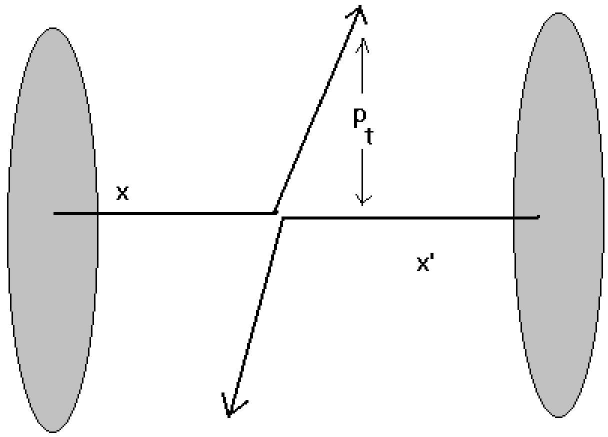

Figure 1: Single parton scattering

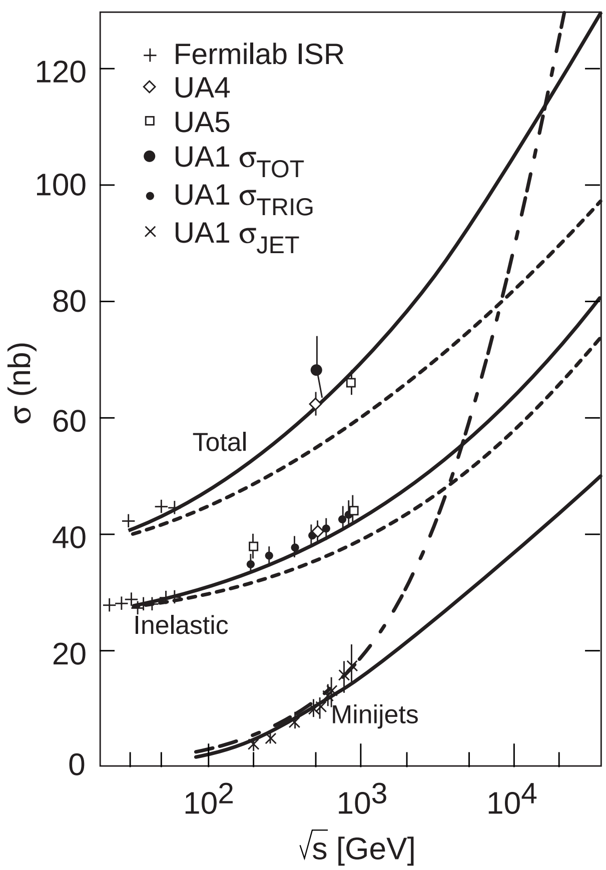

Figure 2: Total, inelastic nondiffractive and minijet cross sections as a function of the c.m. energy[3]

tonic interactions in a typical inelastic event is close to one and the probability of multiple parton collisions is large. Interestingly in this regime the single scattering expression of perturbative QCD is still meaningful, and represents correctly the integrated inclusive cross section, which, as required by the cancellation property discussed by Abramovsky, Gribov and Kancheli[4] for interactions where multiple exchanges take place, is given by the single scattering term expression. Notice that, since in the inclusive each partonic collision contributes with its multiplicity, the inclusive cross section is proportional to the average number of multiple interactions, which ultimately is also the reason of the simple theoretical result of the AGK cancellation. On the other hand, precisely for the same motivation, the inclusive cross section gives only a rather limited information on the production dynamics.

To gain a deeper insight one needs to look at different and less inclusive physical observables. From the experimental point of view the simplest quantity of this kind is the semi-hard cross section, namely the cross section which counts all events with at least one jet produced, which is related to the probability of not having any hard interactions at all in a inelastic event. The semi-hard cross section is hence bounded by the value of the total inelastic cross section and therefore characterized by an intrinsic dimensional scale factor. A consequence is that the semi-hard cross section, contrarily to the inclusive cross section, cannot be obtained by evaluating the single scattering expression of perturbative QCD (where the only relevant dimensional factors are the kinematical variables). In fact the semi-hard cross section needs an infinite number of perturbative terms to be evaluated, corresponding to all possible processes with any number of multiple parton collisions. To obtain a complete information on the semi-hard interaction dynamics one needs to measure systematically all the moments of the distribution of multiple parton collisions, which implies measuring all inclusive cross sections with any number of produced jets and isolating the corresponding multiple parton scattering contributions. A given configuration with many jets may be in fact originated in various ways with different elementary partonic processes. Each multiple scattering term is nevertheless characterized by a different dimensional scale factor so each multiparton scattering process has a peculiar dependence on the c.m. energy and on the lower cutoff in p_t, while the typical pattern of the final state produced is obtained by superposing single scattering events. The different contributions to the semi-hard cross section, with a given number of elementary partonic collisions, may be therefore disentangled by looking at the energy and cutoff dependence of the cross section and by studying the pattern of the final states produced. A possible way to obtain the dimensional scale factors characterizing the different multiparton scatterings, is to measure the relative rates of production of 1, 2, 3 etc. jets as a function of the lower cutoff in p_t. By moving from the large to a relatively low p_t region the ratios in fact change, as compared to the expectations bases on the conventional single scattering production mechanism, because of the increasingly large contribution of multiple scatterings at relatively low p_t. The measurement of the azimuthal correlations between charged tracks at relatively large p_t is a further tool to identify production processes characterized by independent hard collisions at the parton level.

The non-perturbative input to a multiparton interaction is a multiparton distribution, which contains independent informations on the hadron structure, as compared to the one-body parton distributions usually considered in large-p_t processes. Multiparton distributions depend in fact linearly on the multiparton correlations of the hadron structure. Notice that multi-parton scatterings have been already implemented in some QCD Monte Carlo program, to the purpose of describing the minimum bias event in high energy hadronic collisions[5]. A basic hypothesis there is however that all input multi-parton distributions are trivial (namely poissonians at a fixed impact parameter), which amounts neglecting all multiparton correlations. The difficulties of the QCD Monte Carlo programs to describe the underlying event in hard collisions at 1.8TeV[1], even after switching on multi-parton scatterings, and the results of the analysis of the simplest case of multi-parton scattering, the double parton collision[6][7], point on the contrary in the direction of the existence of non trivial correlations effects in the hadron structure. An exhaustive description of the hard component of the interaction, in high energy hadronic collisions, requires therefore an explicit investigation of each different multiparton scattering process and the measurement of all various correlation parameters.

2 Double parton scattering

The simplest case of multiparton interaction is the double collision. Correspondingly the simplest state produced is represented by four jets with transverse momenta above the cutoff p_{cut} and balanced in pairs. The same state may also be produced by the leading QCD $2 \rightarrow 4$ process. While the latter process can be estimated at the three level without much effort[8][9], the evaluation of the double parton scattering contribution is in principle much more uncertain. The main reason of uncertainty is represented by the non-perturbative input needed to the double parton collision, the two-body parton distributions, which contains the information on the two-body parton correlations. All discussions on the double parton collision process rely on assumptions on the two-body parton correlations. Since multiple parton interactions are a sizable effect at low x, where the parton flux is large, correlations in momentum fraction should not be a major effect, so that a reasonable hypothesis is to neglect correlations in fractional momenta in the multi-parton distributions. Not all possible correlations can however be neglected, since the interacting partons must be correlated in transverse space, belonging to the same hadron. It seems therefore reasonable, at least in the low x region, to make the hypothesis that the only relevant correlations are those in the transverse parton coordinates. With this assumption, on rather general grounds, the inclusive double parton scattering cross section is given by the product of two single parton scattering cross sections with a scale factor, which depends smoothly on the c.m. energy and on the cut-off and which, in general, depends on the parton process considered. One might in fact expect different kinds of partons to have a different distribution in transverse space inside the hadron. The double scattering cross section $\sigma_D(A,B)$ for the two parton processes A and B is then written as

$$\sigma_D(A,B) = \frac{m}{2}\sum_{ijkl}\Theta^{ij}_{kl}\sigma_{ij}(A)\sigma_{kl}(B) \tag{1}$$

where $\sigma_{ij}(A)$ is the hadronic inclusive cross section for two partons of kind i and j to undergo the hard interaction A, while the partons k and l undergo the hard interaction B with cross section $\sigma_{kl}(B)$. The factor m equals 1 when the two parton processes A and B are identical, while its value is 2 if they are distinguishable. The factors

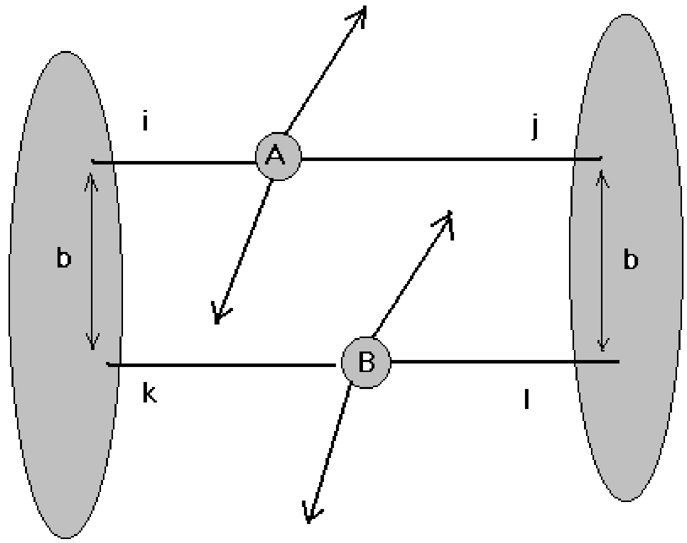

Figure 3: Double parton scattering

$$\Theta^{ij}_{kl} = \int d^2 b F^i_k(b) F^j_l(b) \tag{2}$$

are geometrical coefficients, with dimensions of inverse cross section. The function $F^i_k(b)$ represents the density of the pair of partons k, i in a hadron as a function of the relative transverse distance b, normalized to one. Since the partonic interactions A and B, being characterized by a scale of momentum transfer much larger than the hadronic dimension ($p_t \gg 1/R$) are well localized in transverse space inside the hadron, the relative transverse distance between the pair k, i and between the pair l, j of the two colliding hadrons must be equal, in order to have the alignment necessary for the double interaction to take place. The cross section is then obtained by summing over all possible configurations, with the interacting parton pairs at the same relative transverse distance b in the two hadrons[10].

Double parton collisions have been measured by CDF[6][7] looking at final states with three minijets and one photon. The cross section has been expressed as

$$\sigma_D = \frac{1}{\sigma_{eff}} \quad \sigma_S(\gamma j)\sigma_S(jj) \tag{3}$$

which may be obtained from Eq.1 making the assumption that the geometrical coefficients Θ^{ij}_{kl} do not depend on the different kinds of interacting partons $ijkl$. The experiment gives as a output the value of the scale factor:

$$\sigma_{eff} = 14.5 \pm 1.7^{+1.7}_{-2.3} \quad \text{mb} \tag{4}$$

Given the kinematical range available to the CDF experiment, the sum on the different kinds of partons is dominated by the contribution where three of the indices in Eq.1 refer to gluons and one to quarks, so that basically $\sigma_{eff} \simeq 1/\Theta^{qg}_{gg}$.

While, at least in the limited kinematical range available, the scale factor does not show evidence of dependence on the fractional momenta of the interacting partons, consistently with the hypothesis of no correlation in the x-variables, the actual measured value of σ_{eff} points, on the contrary, towards the existence of non-trivial correlations of the proton structure in transverse space[11][12]. In the case of no correlations, one would in fact expect $\sigma_{eff} = h\sigma_{NSD}$, where h is a geometrical enhancement factor and σ_{NSD} the nucleon non-single-diffractive cross section (namely the inelastic cross section minus the single diffractive cross section) whose value, measured by CDF, is 50.9$\pm$1.5 mb. The geometrical enhancement factor keeps into account that multiple parton collisions are more likely to take place at small impact parameters, where the overlap of the matter distributions of the two interacting hadrons is larger. The indication obtained, considering different possibilities for the density of partons in space, is that the value of h should be close to 1/2, which would give a σ_{eff} roughly twice as big as the measured value. One may then argue that the experimental indication points towards the existence of non trivial correlation effects in transverse space.

A natural implication of the existence of correlations in transverse space is that different pairs of partons are characterized by different typical transverse distances, which amounts to a non negligible dependence of the scale factors Θ^{ij}_{kl} on the different indices. Even if this is the case, the double parton scattering cross section may still be expressed by the factorized form in Eq.3 used by the CDF experimental analysis. When Θ^{ij}_{kl} has a sizable depence on the indices, σ_{eff} however not only changes with the kind of double parton process considered, but also depends on the c.m. energy of the hadronic collision and on the phase space cuts applied, since, given a definite final state, the luminosity of the different kinds of initial state partons contributing to the process changes both with energy and with the cuts applied to the final state[13]. On the other hand the indication of non-trivial correlations in transverse space implies a structure of the proton much richer than obtainable through deep inelastic scattering experiments with electron beams, where the information accessible is limited by the pointlike structure of the projectile.

To access the transverse space structure one needs therefore to measure the different scale factors which characterize the multiple parton collision processes. By selecting final states as $jjjj$, $b\bar{b}b\bar{b}$, $c\bar{c}c\bar{c}$ one would measure Θ^{gg}_{gg}, while final states with a prompt photon as, γjjj, $\gamma jb\bar{b}$ or $\gamma jc\bar{c}$ will allow one to obtain Θ^{qg}_{gg} and to test, by comparing with the CDF result, its energy dependence. The scale factor Θ^{qg}_{qg} may be measured by looking at double parton collisions with a Drell-Yan pair accompanied by two minijets or by a pair of heavy quarks. Another interesting case is that of the production of two equal sign W bosons, which, at relatively low transverse momenta, is dominated by double parton collisions[14] and which allows one to have information on the correlation in transverse space of valence quarks.

All final states produced by double parton collisions can be produced also by the more conventional leading QCD mechanism, where the hard process is initiated by two partons. The contribution of multiparton scatterings is however enhanced with energy, in such a way that, while the probability of a double parton collision generating two equal sign b-quarks is rather small at Tevatron energy, one may estimate a cross section of the order of 1 μb to observe two equal sign b quarks with $|\eta| \leq .9$ at LHC. To compare the two sources of two equal sign b quark production, in the ALICE detector, the rates of the two processes are plotted in the fig. 4. The c.m. energies are 14 TeV and 5.5 TeV. In the upper figures the curves are plotted against p_t^{min}, which is the smallest among all the transverse

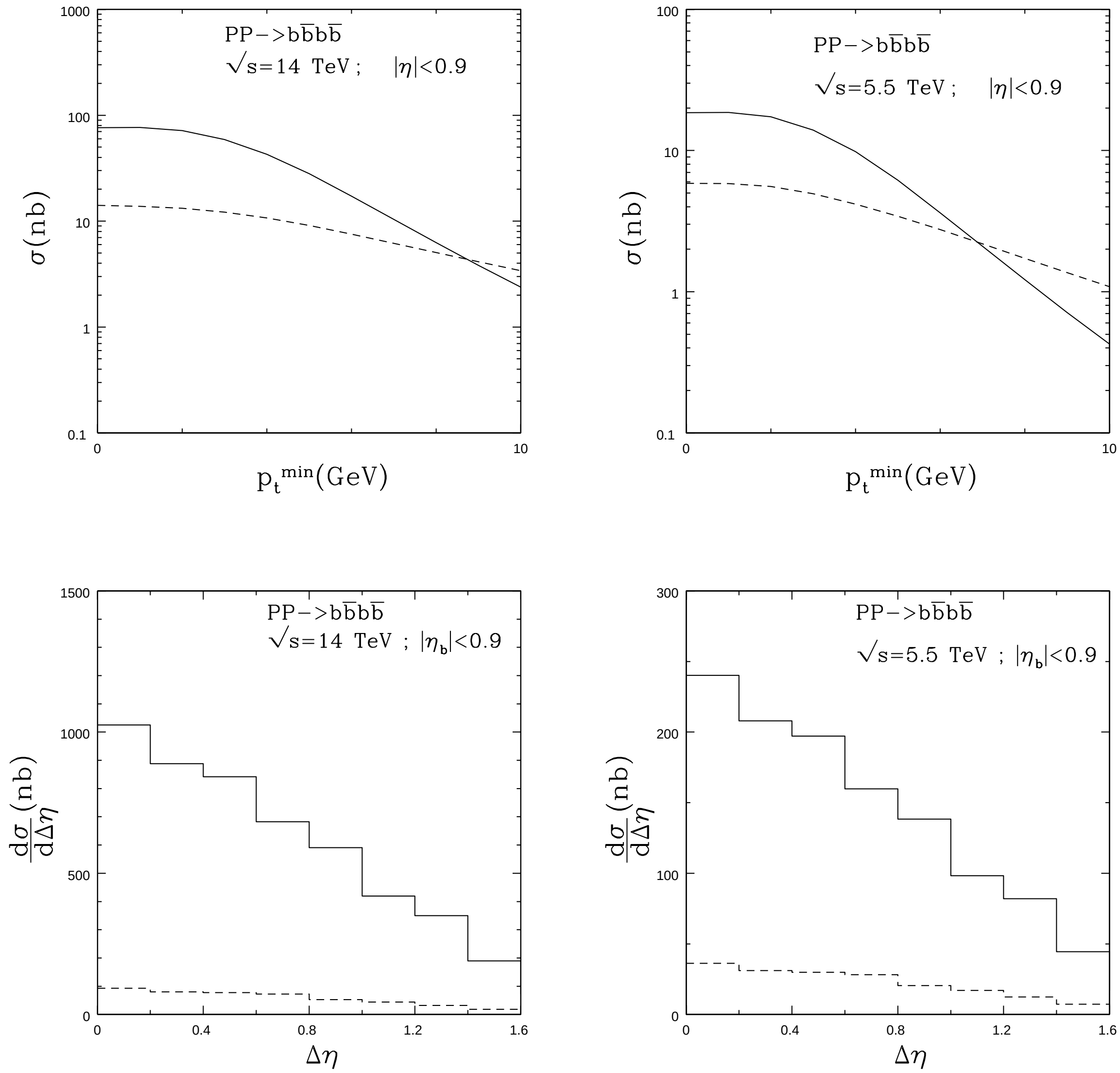

Figure 4: Upper figures: cross sections, for producing two pairs $b\bar{b}$ with $|\eta| \leq .9$ and with c.m. energies of 14 TeV and 5.5 TeV, as a function of p_t^{min}, the smallest among all the transverse momenta of the produced quarks. Lower figures: pseudorapidity difference distributions for two b-quarks with $|\eta| \leq .9$ and with c.m. energies of 14 TeV and 5.5 TeV. The continuous lines are the double parton scattering $(2 \to 2)^2$, the dashed lines are the leading QCD $2 \to 4$.

momenta of the produced quarks. All the quarks are inside the pseudorapidity interval $|\eta| \leq .9$. The lower figures represent the distributions of the pseudorapidity difference between two b-quarks. In this last case the two b-quarks only are within $|\eta| \leq .9$. All processes have been evaluated at the lowest order in α_s; a factor $k = 5.5$ has been however introduced to account for higher order corrections, which have been assumed to be the same in the $2 \rightarrow 2$ and in the $2 \rightarrow 4$ processes. The value of the k-factor has been obtained using the results on heavy quark production in the k_t-factorization approach[15]. As a scale factor for the double collision term the value of σ_{eff} measured by CDF has been used. The leading QCD $2 \rightarrow 4$ contribution is represented by the dashed lines and the double parton scattering term by the continuous lines. In the low p_t^{min} region double parton scatterings dominate over the leading QCD $2 \rightarrow 4$ process by a large factor. Preliminary estimates indicate that the effect of multiple parton interactions is even more pronounced when considering $c\bar{c}$ pairs production. The large values obtained for the double parton scattering cross sections are an indication that on one hand one should be able to isolate easily the double parton scattering contributions while, on the other, there should be a sizable probability of observing also triple, quadruple etc. parton collision processes.

As the single scattering term is proportional to the average number of partonic collisions, the double is proportional to the dispersion in the distribution of multiple collisions. The relatively small value measured for σ_{eff}, whose inverse is proportional to the double scattering term, is therefore an indication of large fluctuations in the number of produced jets. One therefore expects a relatively large number of events without much activity and a relatively small number of events with many more large p_t fragments than average. Given the large cross section expected at the LHC a similar effect should be observed also in charm production. At the LHC the inclusive cross section of $c\bar{c}$ production, integrated over all phase space, might in fact be of the order of 20 mb, while the corresponding double parton scattering cross section might reach values as high as 12 mb. One would then observe a relatively small number of events with charm, with the unusual feature of being however characterized by a considerably large number of $c\bar{c}$ pairs. In such a scenario triple and even quadruple parton collisions leading to several $c\bar{c}$ pairs would be easily measurable.

The simplest estimate of the triple scattering cross section may be obtained by neglecting all correlations in x and assuming that the scale factors do not depend on the different species of interacting partons. In that case all unknowns of the triple scattering process are reduced to a single quantity, so that, for three identical interactions, one may write

$$\sigma_T = \frac{1}{3!} \frac{\sigma_S^3}{\tau \sigma_{eff}^2} \tag{5}$$

where τ is the unknown, dimensionless quantity (of order unity) to be measured by the triple scattering experiment, while σ_{eff} is the scale factor already measured in a double parton scattering experiment. More general expressions of the triple, quadruple etc. cross sections may be easily written introducing different scale factors, depending on the different species of interacting partons and expressed through integrals of the n-parton densities in transverse space, in a way analogous to the double scattering cross section in Eq.s (1)(2).

3 Summary

All multiple parton scattering effects increase considerably at the LHC, enhancing features of the typical inelastic event as the increase of $\langle p_t \rangle$ with multiplicity, already observed by UA1, and changing the distribution in multiplicity of the jets produced with a relatively low p_t. A characteristic feature of multiparton interactions is the dependence of the cross section on dimensional scale factors, whose origin is geometrical and which are introduced into dynamics by the non-perturbative input to the process. Differently with respect to the usual non-perturbative input to a large p_t - fixed x interaction, the non-perturbative input to a multiparton process is in fact a multiparton distribution, which is a dimensional quantity and contains information on the non perturbative structure independent on the knowledge of the one-body structure functions usually investigated in large p_t processes. In the simplest case of a double collision the information is represented by the factors Θ^{ij}_{kl} discussed above. It should be stressed that one cannot obtain the factors Θ^{ij}_{kl} by testing the hadron with an elementary probe. Multiparton scatterings are hence a unique tool for a deeper investigation on the hadron structure, which have the potential of providing a rather interesting new physical output. The scale factors are in fact a measure of the typical transverse distance between different pairs of partons inside the hadron, so their determination gives one access to the three-dimensional structure of the hadron.

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