Multiple interactions: summarizing remarks (theory)

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1 Introduction

In recent years it has been more and more realized that multiple interactions play an important role for the analysis of hadron-hadron collisions. This applies to the structure of the underlying event and, most important, to the calculation of inclusive cross sections: corrections due to multiple interactions may represent an important background in the search for new physics. The analysis of multiple jet events at the Tevatron (also confirmed by HERA data) has clearly shown that double chains are at work. It is expected that, at the LHC, the number of participating chains may become quite sizable.

For inclusive cross sections it may be useful to recapitulate the simplest master formulae: the usual collinear factorization scheme leads to

$$d\sigma = \sum_{i_1 i_2} \int dx_1 dx_2 f_{i_1}(x_1,\mu) d\hat{\sigma}_{i_1 i_2 \to 2\,jet}(x_1, x_2, \mu; \boldsymbol{p}_1, Y_1, \boldsymbol{p}_2, Y_2) f_{i_2}(x_2, \mu). \tag{1}$$

But in certain kinematic regions it also receives corrections from the two chain configuration:

$$d\sigma^{DP} = \frac{m}{\sigma_{eff}} \sum_{i_1,j_1,i_2,j_2} \int dx_1 dy_1 dx_2 dy_2 H_{i_1 j_1}(x_1, y_1; \mu_a, \mu_b; \vec{\Delta})$$

$$d\hat{\sigma}_{i_1 i_2 \to\, jet}(x_1, y_1, \mu_a; \boldsymbol{p}_1, Y_1) d\hat{\sigma}_{j_1 j_2 \to jet}(y_2, y_2, \mu_b; \boldsymbol{p}_2, Y_2) H_{i_2 j_2}(x_2, y_2; \mu_a, \mu_b; \vec{\Delta}). \tag{2}$$

(further explanations are given below, see Fig.1). For the double parton densities H_{ij} often a simple factorizing ansatz is used:

$$H_{ij}(x_1, x_2; \mu_a, \mu_b; \vec{\Delta}) = f_i(x_1, \mu_a) f_j(x_2, \mu_b). \tag{3}$$

During this meeting important contributions have been presented which lead to much deeper insight into the theory behind (2) and, more general, into the theory of multiple interactions and their importance in high energy hadron collisions. There following comments will summarize a few of them, without any claim of completeness. The first section lists a few recent studies of the magnitude of corrections due to multiple interactions. The second part summarizes results of a few recent studies devoted mainly to the hard scattering matrix elements inside the double parton cross section. In a third section a few comments will made about the evolution of double parton densities. Finally, a few comments on open questions of the theory of multiple interactions, in particular related to rapidity gap final states,

2 Evidence for the presence of multiple interactions

For the analysis of experimental data it is important to address individual processes and investigate the size of corrections due to double parton scattering. A candidate for exhibiting the presence of double parton scattering is the production of same-sign W pairs [1, 2]. The paper [2] concludes that a small excess of events due to double parton scattering could be observed at the LHC. Particular attention is also given to the evolution of double parton densities: using evolution equations [3] which contain additional parton splitting processes and thus go beyond the simple 'double DGLAP' factorization ansatz (3), the authors observe novel and nontrivial kinematic correlations between the produced W bosons. Double Drell Yan production with two opposite side lepton pairs has been investigated in [4, 5].

A very promising class of processes is the double heavy meson production, in particular, double J/Ψ production [6],[7]. Ref. [6] makes a simple factorizing ansatz for the double parton cross section and shows, in a histogram of the mass distribution of the J/Ψ-pair, the need to include the double parton cross section. Ref. [7] estimates the integrated cross section and concludes that the double parton contribution is almost of the same order (2.0nb) as the single parton cross section (4.15nb). Both groups of authors argue that the observed LHCb cross section strongly supports the presence of double parton scattering.

Other processes for which double parton cross sections have been calculated include $b\bar{b}jet\,jet$ [8], and $Wb\bar{b}$ production [9, 10]. In particular, when plotting event rates as functions of variables which discriminate between single and double parton scattering, e.g.

$$S_{p_T} = \frac{1}{\sqrt{2}} \sqrt{ \left(\frac{|p_T(b_1, b_2)|}{|p_T(b_1)| + |p_T(b_2)|} \right)^2 + \left(\frac{|p_T(l, \nu)|}{|p_T(l)| + |p_T(\nu)|} \right)^2 } \tag{4}$$

one observes a fairly clear separation between single and double parton density contribution: double parton scattering prefers small values of this variable (pair-wise balancing). Also, 2-dimensional plots are useful for illustrating the separation of double and single parton scattering. The $Wb\bar{b}$ final states attracts interest, since it is a background for Higgs production in the $HW^{\pm}$ mode.

With the experience obtained by these studies of individual processes it will be important to now perform dedicated studies of the final states relevant for new physics, e.g. the Higgs channels $\gamma\gamma$, WW, or ZZ.

3 Theory of multiple interactions

After the pioneering investigations of Treleani et al.[11, 12, 13, 14] recently several new efforts have been made to develop a QCD-based theory of multiple interactions [15, 16, 17] , [18, 19, 20, 21, 22].

An important point stressed by several of these papers is the structure of double parton interactions in transverse coordinates or transverse momenta (Fig.1). A particular aspect can be read off from Fig.1a: the double parton densities above and below the production vertices depend upon the additional momentum transfer $\vec{\Delta}$ (cf.eq.(1)): the neglect of this dependence, as it is done in the factorization approximation (3), looses this information. In transverse coordinates (Fig.1b) this means that part of the transverse dependence is washed out.

Apart from the momentum (coordinate) dependence, the general analysis of multiple interactions shows nontrivial structures in color and spin. For example, in Fig.1a the partons

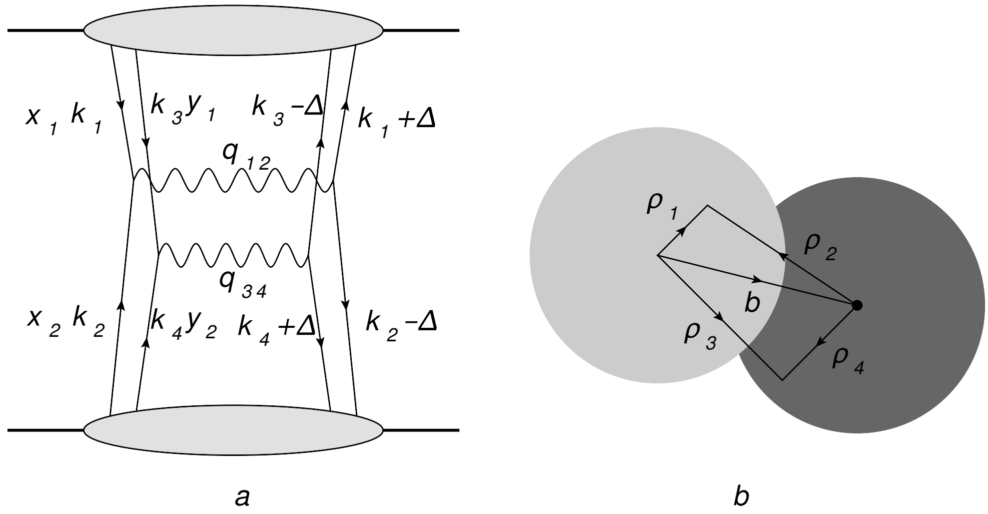

Figure 1: the transverse structure of double parton scattering: (a) transverse momenta (b) in the transverse coordinate plane

with momenta k_1 and $k_1 + \Delta$ do not have to be in a t-channel color singlet state (as it is assumed in the factorization ansatz). The detailed account of correlations in color and spin may lead to interesting observable effects. As an example, in double Drell Yan production, it has been pointed out that there are interesting transverse correlations in the azimuthal angular distributions of the final states.

An important issue is the momentum suppression of multiple interactions relative to single parton scattering. In Fig.1 the large momentum scales are given by the momenta $q_{12}^2 \sim q_{34}^2 \sim Q^2$. The overall scaling behavior of the differential double scattering cross section is $\sim 1/Q^4\Lambda^2$, similar to the production in a single hard scattering. Therefore, in the fully differential cross section, multiple hard interactions are not power supposed. The situation changes if one integrates over the transverse momenta $\vec{q}_{12}$ and $\vec{q}_{34}$: in double scattering processes both produced momenta result from transverse parton momenta and are limited to size Λ, whereas in single hard scattering processes the individual transverse momenta can be large while their sum is of order Λ. Therefore, after integration over the transverse momenta one has the scaling results $\sim \Lambda^2/Q^4$ and $\sim 1/Q^2$ for double and single parton scattering, resp. , i.e. double parton scattering becomes higher twist. In more detail one finds that, in multijet final states, there exist special kinematic regions ('back to back kinematics') where multiple scattering has little or no suppression relative to single parton scattering.

A theoretical issue that has come up with the derivation of multiple parton cross sections is the role of the splitting of one parton into two partons (Fig.2). Whereas some authors have viewed this splitting as an additional contribution inside the double parton evolution (see below), it has also been argued that the contribution shown in Fig.2 should be viewed as a loop correction to the subprocess: 2 partons $\rightarrow$ 2 gauge bosons in single parton scattering.

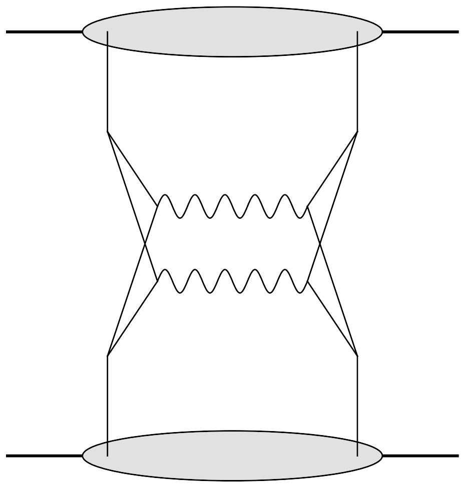

Figure 2: parton splittings

4 Theory of the evolution of multiparton correlators

As it has been said before, in phenomenological applications double parton densities are often assumed to factorize (cf.(3)), and consequently their evolution follows the 'double DGLAP' scheme. But as we already said, this approximation neglects correlations which may have also numerical significance. As to the general theory of multiparton evolution, we first remind that there exist two different approaches: one is based upon the evolution of quasipartonic higher twist operators in deep inelastic scattering [23] and can be viewed as an extension of the DGLAP leading twist framework. There exist no factorization theorems for multiparton correlators. The other one uses the BKP equations [24] and applies to small-x values; it is the extension of the BFKL equation to more than two t-channel gluons. This small-x framework allows the application of the AGK counting rules [25] which, among other predictions, also proves the absence of soft rescattering corrections in single or double inclusive cross section formulae. In the so-called double logarithmic approximation the two schemes overlap. Both schemes contain transitions from two to four partons (gluons) and, within four-partons t-channel states, the sum over pairwise interactions (Fig.3). The factorization ansatz corresponds to Fig.3b: it contains two noninteracting color singlet ladders with zero momentum transfer. In configuration space the production subprocesses from these two chains are completely uncorrelated.

In [3] a modified evolution scheme has been investivated in more detail: the evolution equations contain an additional term which accounts for the splitting of a single partons into two partons (Fig.2) (see also [26]). In more recent papers [28, 27] the splitting kernel illustrated in Fig.3e has been taken into account. The numerical study contained in [2] reports that this additional term in the evolution equations leads to observable correlation effects.

A slightly different step beyond the double DGLAP approximation is taken in [29]: in addition to the evolution of the two noninteracting ladders (14) and (23) in Fig.3b one can have a 'recombination' to two other ladders, e.g. the pairs (13) and (24) (Fig.3c). The numerical investigation in [30] which includes such 'switches' finds large correlation effects which again

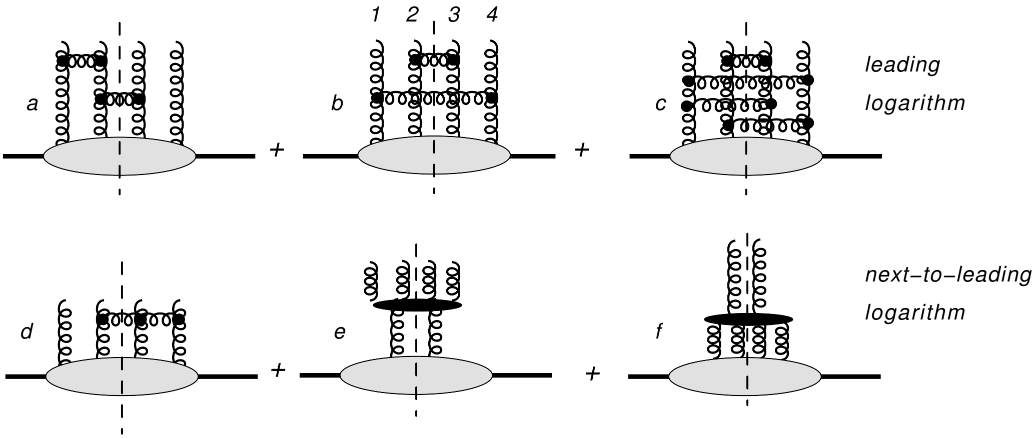

Figure 3: schematic view of evolution kernels in multiparton states

emphasizes the need to go beyond the factorizing approximation.

So far the discussion has been about small numbers of different parton chains. Large numbers of chains are expected to appear in the context of saturation, where the evolution of gluon densities is determined by number-changing kernels (Fig.3f). As an example, the recently observed ridge effect in *pp* collisions [31] has stimulated the idea [32, 33] that the observed characteristics (high multiplicity, long range rapidity correlation and azimthal correlations, momentum scale in the region of the saturation scale) can be attributed to saturation. Interestingly, within the interpretation given in [32, 33] the two gluon correlators enter in a combination which resembles the 'recombination' mentioned before.

5 Diffraction

One of the aspects of multiple interactions which needs more attention is the account for final states with large rapidity gaps inside the underlying event. On the partonic level, large rapidity gaps occur if color singlet exchanges are included; radiation of partons from single parton chain tends to lead to small rapidity intervals. It is instructive to review the situation at HERA. Fig.4a illustrates the 'normal' event structure, where radiation from the single gluon or quark line produces final states without large rapidity separations. The momentum scale Q_0^2 separates the perturbative (hard) part from the nonperturbative (soft) part. Large rapidity gaps, however, may occur inside the proton remnants, mediated either by soft Pomeron exchange (Fig.4b) or by two gluon exchange (Fig.4c). The first case belongs to soft diffraction (characterized by momentum scales up to Q_0^2), the latter one to semihard diffraction (up to momenta of the order $Q_1^2 > Q_0^2$). It is clear that Fig.4b is part of Fig.4a (and must not be added separately), whereas Fig.4c has to be counted as an additional contribution (potentially of higher twist, e.g. diffractive vector meson production). For the evolution above the initial scale Q_0^2 (Fig.4b) or Q_1^2 (Fig.4c) one has the usual DGLAP evolution equations.

Turning to hadron hadron scattering the situation changes drastically. For single chains (Fig.5a) soft diffraction is contained inside the initial conditions (Figs.5b) whereas semihard

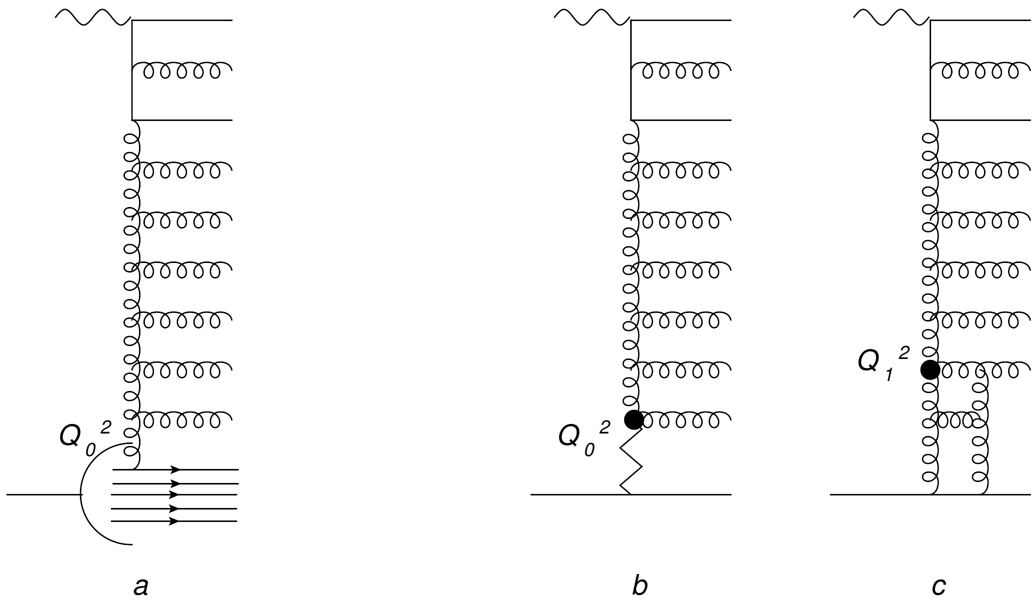

Figure 4: diffractive final states at HERA

diffraction needs to be included separately (Fig.5c). But it is known that these contributions are suppressed by radiation from additional chains (Fig.5d). As a result, in *pp* scattering the number of events with rapidity gaps is suppressed in comparison with deep inelastic scattering. This suppression is commonly encoded in the 'suppression factor' (Fig.5e). The consistent implementation of diffractive final states into event generators represents an important challenge for the near future.

Turning to diffractive cross sections, there is no consistent theory. But empirically cross section formulae can often, to a good approximation, be factorized into a hard and a soft part (Fig.5e); physically this corresponds to taking into account only low mass states between the rescattering and the hard process and thus neglecting so-called enhanced contributions. For the very interesting case of double diffractive Higgs production the question has been raised whether the factorization into a hard subprocess (gluon-gluon fusion into a Higgs particle) and a soft survival factor is a represents an adequate approximation, but no conclusive answer has been found.

6 Conclusions

This conference has shown that multiparton interactions represent a challenge, both for improving our theoretical understanding and for consistently implementing multiple interactions into event generators.

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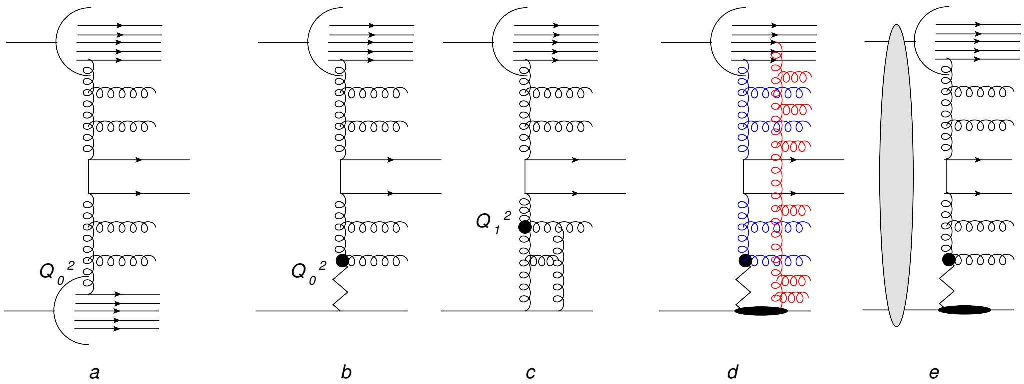

Figure 5: diffractive final states in pp collisions

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