1. Introduction

The contribution of multiple parton interactions (MPI) to high-energy hadronic collisions has been considered since the early days of the QCD parton model [1–7]. In the absence of a first-principle systematic approach to go beyond single parton interaction in the framework of QCD factorization formulas, progress on MPI has since been driven mainly by Monte Carlo modeling [8–11] – see the recent comprehensive overview [12] of MPI developments from the standpoint of the PYTHIA Monte Carlo event generator. Within this context, experimental signals of MPI have emerged from comparison of Monte Carlo simulations with collider measurements at the SppS, HERA, Tevatron, LHC for production of multi-jets, multi-leptons, photons, heavy flavors [13–20].

The relevance of MPI for LHC phenomenology [21–24] has spurred efforts in the last few years to investigate the theoretical basis of multiple parton scattering from the point of view of perturbative QCD and factor-
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The role of small-\(x\) processes in the physics of multiparton interactions is multifaceted. Besides, methods have been suggested for estimating the ratio of MPI to single parton scattering contributions from data \[38\text{-}59\].

The region of small longitudinal momentum fractions \(x\) plays a particularly important role in the context of MPI \[60\] because with decreasing \(x\) parton densities grow, and with high parton densities the probability for significant contributions beyond single parton interaction increases. MPI may be expected to affect the detailed structure of the exclusive components of final states even when inclusive cross sections are not influenced. Indeed, MPI signals are sought for experimentally in multi-differential cross sections and final-state correlations. Therefore, the exclusive structure of multi-particle final states associated with small-\(x\) processes is particularly crucial to the discussion of MPI.

MPI are also naturally connected with aspects of small-\(x\) physics such as diffraction and saturation. It is instructive to think of this from the viewpoint of the AGK cutting rules \[61\text{-}64\] in the Regge picture of hadronic interactions. Fig. 1 provides a schematic illustration of the relationship between diffraction, saturation and multiparton interaction in terms of Regge theory cut diagrams. The graph in fig. 1\(a\) depicts a diffractive cut, while the graphs in fig. 1\(b\) and 1\(c\), corresponding to different cuts, depict respectively single-multiplicity interactions with saturation corrections and double-multiplicity interactions. The AGK rules \[61\] connect the different processes in Fig. 1 \[62\]. This connection also has an analogue in the partonic Monte Carlo models for MPI \[8, 9\].

In this article we give a concise account of the role of small-\(x\) processes in the physics of multiparton interactions. We concentrate on general concepts rather than describing specific results, with a view to pointing the reader to broad areas of interplay of small-\(x\) dynamics and MPI. Sec. 2 discusses...
theoretical approaches to the evolution of small-\(x\) final states and their potential impact on MPI. Secs. 3, 4 and 5 address different aspects of small-\(x\) physics relevant to MPI: diffraction, saturation and multi-jet production. We summarize in Sec. 6.

2. MPI and the evolution of small-\(x\) final states

In general, experimental measurements do not allow one to observe multiple interactions explicitly. What can be observed in the experiment are particles and jets, distributed in phase space, and what can be measured are correlations among them as well as multiplicities. Such correlations and multiplicities of particles and jets can then be interpreted within different theoretical frameworks.

MPI become increasingly important with energy as parton densities grow with decreasing \(x\). Even though they may not influence the inclusive rates for hard processes with a large \(p_T\) momentum transfer, MPI can contribute significantly to highly differential cross sections, sensitive to the detailed distribution of multi-particle final states produced by parton evolution.

The evolution of parton cascades based on collinear factorization and DGLAP evolution \cite{65,68}, implemented in Monte Carlo event generators such as \textsc{Pythia} \cite{69}, \textsc{Herwig} \cite{70}, \textsc{Sherpa} \cite{71} (called DGLAP shower in the following), is known to describe measurements well over a large range of observables. However, when longitudinal momentum fractions \(x\) become small and parton densities increase new effects are expected.

In fact, new QCD dynamics is known to arise when trying to push the parton evolution picture to higher and higher energies \(\sqrt{s}\). On one hand, soft-gluon emission currents \cite{73,74} are modified by terms that depend on the total transverse momentum transmitted down the initial-state parton decay chain \cite{75}. Correspondingly, high-energy factorization formulas apply which are valid at fixed transverse momentum \cite{76,79}. On the other hand, the structure of virtual corrections at high energy implies, besides Sudakov form factors, transverse-momentum dependent (TMD) – but universal – splitting functions and new “non-Sudakov” form factors \cite{75,80,81}, which are necessary to take into account soft-gluon coherence not only for collinear-ordered emissions but also in the non-ordered region that opens up at high \(\sqrt{s}/p_T\). These finite TMD corrections to parton branching are

\footnote{This terminology is used for brevity. It is a misnomer though, as DGLAP is an inclusive equation. See also note at the end of this section, and \cite{72} for a related discussion.}
implemented in the CCFM evolution equations \([75, 80, 82, 83]\), and, in the high-energy factorization framework, are found to have important implications for multiplicity distributions and the structure of angular correlations in final states with high multiplicity \([84, 87]\). The CCFM evolution equations may be thought of as forming a bridge between the small-angle DGLAP \([65–68]\) and high-energy BFKL \([88–90]\) regimes.

In phenomenological analyses which perform comparisons of experimental measurements for multi-particle final states and correlations with Monte Carlo calculations based on DGLAP shower event generators such as Pythia, Herwig, Sherpa, it is found that MPI are needed to describe measurements such as soft particle spectra in minimum bias events, the underlying events in jet production as well as (de-)correlations in multi-jet events, including 4-jet, \(b\bar{b} + jj\), \(W + j\) events.

However, in calculations based on high-energy factorization \([76, 77]\) and CCFM \([75, 80, 82, 83]\) (or BFKL \([88–90]\)) transverse momentum dependent parton densities (unintegrated parton density functions uPDFs), the correlation between partons and particles in the final state is different from those predicted by the DGLAP shower, since finite transverse momenta in the initial state are included from the beginning. The small-\(x\) behavior of the (unintegrated) parton densities obtained from CCFM evolution (e.g. Ref. \([91]\)) is different compared to the one from DGLAP distributions, and therefore the amount of multiple partonic interactions might also be different. Multi-parton radiation in CCFM evolution is allowed in an angular-ordered region of phase space, which is determined by small-\(x\) gluon coherence \([85]\). This makes a new scenario possible, in which the higher transverse momenta in the parton cascade, compared to a Monte Carlo simulation based on DGLAP shower, can produce final states similar to what is obtained from MPI.

The Monte Carlo event generator CASCADE \([92, 93]\), based on CCFM uPDFs and high-energy factorization, includes initial state parton showering according to the CCFM evolution equation (called CCFM shower in the following) as well as final state parton shower and hadronization. Studies \([94–96]\) of jet production at high rapidity based on simulations with CASCADE (without MPI) show that the energy flow outside the jets is significantly larger than what is obtained from Pythia without MPI. In Ref. \([97]\) the relation between Monte Carlo simulations using MPI and high-energy factorization has been studied using mini-jets. It was found that jet

\(^{b}\)Unlike DGLAP, CCFM is an exclusive equation. The terminology of DGLAP shower and CCFM shower is somewhat misleading. Strictly speaking, only the latter is defined.
distributions are similar in both approaches, suggesting that at least part of the effects that are attributed to MPI when comparing Monte Carlo calculations based on DGLAP shower with data are already contained in the single scattering when using uPDFs and high-energy factorization.

3. Diffractive dissociation and MPI

In the scattering matrix formalism \cite{98} hadronic diffraction is thought of as arising from fluctuations in the scattering amplitude. Regge theory incorporates high-mass diffraction through pomeron exchange with triple (and multiple) pomeron couplings \cite{99,101}. Both these ideas were given partonic interpretations, respectively in \cite{102} and \cite{103}. The partonic interpretation of hard diffraction leads to the notion of diffractive parton densities.

Diffractive processes in deep inelastic scattering (DIS) have been measured in great detail at HERA. Based on the factorization theorem for diffractive DIS \cite{104,108}, diffractive parton densities \cite{109} have been obtained. However, using these diffractive parton densities diffractive jet production in hadron-hadron collisions is predicted to be of the order of 10 times larger than the measurements \cite{110,113}. Therefore, whilst deep inelastic diffraction can be understood in terms of color transparency (see \cite{114,118} for structure functions and \cite{119,120} for jet and charm production), new (absorptive) effects occur in hadron-hadron diffraction. In most of the current phenomenological models, these are embodied in gap suppression factors, or gap survival probabilities.

Multiparton interactions in addition to the diffractive process can destroy the experimental signature of diffractive interactions, i.e. a region in rapidity which is devoid of energy deposition (rapidity gap, see fig. 2b). Estimates on the probability of multiple interactions lead to a suppression factor which is in the correct order of magnitude. Recently a relation between multiple parton scattering and hard diffractive processes has been implemented in Pythia \cite{121}. This model, based on diffractive parton densities (as obtained from HERA) together with MPI, allows one to predict hard diffractive processes in hadron-hadron collisions without introducing artificially gap suppression factors. It is very encouraging that predictions coming from this new model \cite{121} follow the trend of the measurements of hard diffractive dijet production at the LHC.

In a process as shown in fig. 2a, the density of partons in the forward or backward regions (indicated by the yellow box) is different from those of processes shown in fig. 2b, because one interaction chain allows no particle
Fig. 2. Left: Non-diffractive multiparton interactions. Middle: Sketch of a diffractive process together with a non-diffractive process, destroying the rapidity gap. Right: multiparton interactions inside the dissociative system.

radiation, while the other does. Experimentally it is difficult to identify such processes, but they play a role when adjusting parameters to describe the underlying event and multiparton interactions. It will be important that in forthcoming Monte Carlo tuning diffractive processes are included, since this might lead to different parameters describing particle multiplicity.

While multiparton interactions can destroy a rapidity gap, multiparton interactions can also occur within the diffractive dissociation system (fig. 2c), if the diffractive system has a large enough mass $M_X$. At MPI@LHC 2017 the effect of MPI inside the diffractive system $M_X$ was shown for the first time [122] in a measurement of $dn/d\eta$ for event samples enhanced with single diffractive dissociation. Investigating such processes (with hard diffractive events), MPI can be studied in a very new environment and one can investigate in detail the energy dependence of MPI (and its energy dependent parameters) as a function of the center of mass energy of the pomeron-proton system $M_X$ (indicated in fig. 2c).

A further mechanism relating inelastic diffraction and MPI is discussed in Refs. [58, 59, 123], based on two-pomeron contributions to the generalized double parton distribution function [27].

4. Saturation effects and MPI

In the context of total hadron-hadron cross sections [124] and their rise with energy [125], unitarity constraints are given, at fixed impact parameter, by the “black disc” limit of the scattering matrix [126, 127]. In this limit, the elastic cross section equals half the total cross section. Such saturation effects are important, for instance, for the observed behavior of the diffrac-
tive cross section \[128\]. In the Regge theory picture, saturation implies the breakdown of the simple Regge pole behavior and the onset of multiple pomeron exchange \[129\].

Unitarity arguments are also used to treat saturation of parton densities in the case of hard processes in the limit of high energies (or large nuclei) \[130, 134\], with corresponding nonlinear evolution equations \[135, 139\]. This saturation formalism is given in terms of color-dipole degrees of freedom rather than parton degrees of freedom. (See also \[140, 141\] for an alternative, dipole-based perspective on saturation.) It has limited applicability in the region of high transferred momenta well above the saturation scale. See e.g. discussion in \[142, 143\]. Therefore, even though the saturation formalism is constructed in the case of hard processes, it is generally not relevant to jet physics at high \(p_T\).

On the other hand, for energies high enough the scale at which saturation effects become important can rise into the region of transverse momenta \(p_T\) large compared to \(\Lambda_{\text{QCD}}\), say, \(p_T \sim \mathcal{O}(5 \text{ GeV})\) – potentially, a region of weak-coupling but nonperturbative dynamics, sitting just above the saturation scale. This was the scenario proposed in Ref. \[144\]. It was emphasized in \[144\] that in this scenario a connection arises between saturation and MPI. The connection could be seen in terms of two aspects of the Monte Carlo model \[8, 9, 11\]: the contribution of multiple interactions, and the screening of the jet production cross section.

One of the arguments leading to the introduction of MPI in Monte Carlo event generators \[8–10\] was the observation that the \(2 \rightarrow 2\) partonic cross section integrated above \(p_{T\min}\) over the transverse momentum of the final partons can become larger than the inelastic \(pp\) cross section for values of \(p_{T\min} \gg \Lambda_{\text{QCD}}\). Since the \(2 \rightarrow 2\) cross section is a jet – and not an event – cross section, the ratio \(\sigma(\sigma > p_{T\min})/\sigma_{\text{inel}}\) was interpreted as the average number of interactions per event.

The \(2 \rightarrow 2\) partonic cross section for small transverse momenta is \(d\sigma/dp_T \sim \alpha_s^2/p_T^4\), and diverges for \(p_T \rightarrow 0\). This behavior is related to the non-perturbative nature of the process for small \(p_T\) and is regulated in models based on collinear factorization by introducing an additional cut-off parameter, such that \(d\sigma/dp_T \sim \alpha_s^2/p_T^4 \rightarrow \alpha_s^2(p_T^2 + p_{T0}^2)/(p_T^2 + p_{T0}^2)^2\), with an arbitrary but finite parameter \(p_{T0}\). This parameter \(p_{T0}\) separates the perturbative from the non-perturbative regions and has to be determined from fits to experimental data. At LHC energies, this parameter was determined to be of the order of 2-3 GeV, far above \(\Lambda_{\text{QCD}}\). In general, \(p_{T0}\) depends on the center-of-mass energy \(\sqrt{s}\).
In Ref. [144] it was proposed to measure the leading mini-jet or leading track cross section for a direct investigation of the behavior of the cross section from the perturbative to the nonperturbative region at small $p_T$. In Ref. [145] a measurement of leading track and leading mini-jet cross sections was reported which shows directly how the cross section is saturated at small $p_T$. The observation of the turnover of the cross section from a $\sim 1/p_T^4$ behavior to a constant value, independent of Monte Carlo modeling, is an important result.

For interpretation of this result, see discussions in Refs. [146, 147], which examine impact-parameter unitarity constraints for minijets, and in Refs. [148–153], which use nonlinear evolution equations for parton distributions at fixed transverse momentum.

5. MPI in multi-jet production

Mueller-Navelet jets [154], having comparable transverse momenta and large rapidity separation (fig. 3a), have long been investigated as a probe of BFKL [88–90] dynamics. While experimental measurements of forward-backward jets at the LHC [155–158] do not point to any striking BFKL signature, and PYTHIA Monte Carlo simulations compare well with data, interest has grown in examining MPI contributions (included in the PYTHIA
simulations) to such processes (fig. 3). Studies of the simplest term from double parton scattering in a collinear framework \cite{159} and a transverse momentum dependent framework \cite{160} suggest that the latter leads to smaller double-scattering contribution.

A simulation, including a full treatment of the final state, based on the \textit{CCFM shower} will be of great importance. The \textsc{Cascade} Monte Carlo event generator (based on CCFM parton showers) is not designed at present to treat this process, since this process involves flavor channels not yet included in the Monte Carlo. Very recently a first step towards a determination of \(k_T\)-dependent parton densities for all flavors has been reported in Refs. \cite{72, 161}, which could be used to obtain a more complete simulation of the final state in \textsc{Cascade}.

![Fig. 4. Sketch for recoil treatment in high-energy factorization](image)

At present, experimental signals for hard double parton scattering come from studies of correlations in 4-jet, \(b\bar{b}+2\)-jet and \(W/Z+jet\) events. In the case of double parton scattering, the jets or \(b\bar{b}\) pair or \(W/Z\) bosons which come from one interaction will be decorrelated from those coming from the second interaction. However, such a decorrelation could also originate from significant transverse momenta of the initial-state partons within a single interaction. This can be studied by using multi-leg matrix element calculations (for example at least 2 → 6 for the 4-jet case in order to allow initial transverse momenta of the 2 → 3 subprocess) or by using, in the high-energy factorization framework \cite{76, 77}, off-shell matrix elements for 2 → 4 together with uPDFs. One such study has been performed in Ref. \cite{162} and an interesting observation was made: the prediction from a
single chain interaction for the azimuthal angular correlation $\Delta S$ between two jet pairs is already very close to the experimental measurements of Ref. [19].

An important point in interpreting this result, however, concerns the role of parton showers. In fig. 4 a schematic picture is given for a generic hard process described by high-energy factorization. Since the transverse momenta of the incoming partons can have any kinematically allowed value, and especially the $k_T$ can be larger than the $p_T$ of the partons of the matrix element process (indicated by ME in fig. 4), the simulation of the recoils (in form of an explicit parton shower) cannot be neglected as they might significantly contribute. This is different from the case of simulations based on a DGLAP shower, where the ME-partons constitute the partons with the highest $p_T$. Predictions for jets based on approaches including the initial-state transverse momentum should take into account the recoils besides the uPDFs. Thus, before a conclusion on the size of MPI in the high-energy factorized calculation can be drawn, a full simulation including parton showers is needed.

6. Summary

At high energies, when the density of partons is large, multiple partonic interactions can occur with non-negligible rates. The relation of the rise of the parton density at small longitudinal momentum fractions $x$ and the occurrence of saturation, diffraction and multi-parton interaction is being studied both experimentally and theoretically.

MPI affect primarily highly differential cross sections and the detailed distribution of multi-particle final states produced by parton evolution. Theoretical predictions for MPI observables are thus sensitive to the theory of final states associated with small $x$. We have discussed the role of different approaches to small-$x$ QCD evolution in the interpretation of measurements in terms of multi-parton interaction.

Small-$x$ aspects of MPI influence both soft-interaction and hard-interaction processes. We have illustrated this by discussing their effects in diffraction, saturation, multi-jet production.

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