PROCEEDINGS OF SCIENCE

Small x, Diffraction and Vector Mesons Working Group Summary

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We summarize the results discussed in the working group on Small x, Diffraction and Vector Mesons at the DIS 2013 workshop.

XXI International Workshop on Deep-Inelastic Scattering and Related Subject - DIS2013,
22-26 April 2013
Marseille, France

PoS(DIS 2013)015

1. Experimental overview

A wide variety of experimental results addressing open questions in the areas of low-x dynamics, multi-parton interactions and underlying event/minimum bias studies, and exclusive and diffractive processes were presented. Results from HERA, the Tevatron, and five (ATLAS, ALICE, CMS, LHCb, TOTEM) LHC experiments were presented, including several new results for DIS 2013. An incomplete overview is given here, with an emphasis on recent results.

1.1 Low-x dynamics and searches for BFKL effects

New results on the azimuthal decorrelation of dijets widely separated in rapidity were discussed by CMS, using data collected at $\sqrt{s} = 7$ TeV with dijet rapidity separations up to $\Delta y < 9.4$ [1]. In measurements of the azimuthal decorrelation and cosines of the Fourier coefficients, Herwig was able to provide a good description of the data. In the ratios of the Fourier coefficients, expected to be the most sensitive observable to BFKL effects, the data was in good agreement with recent NLL+ BFKL calculations. However, it was also shown that the addition of angular ordering and MPI effects to DGLAP-based generators such as Pythia can result in significant decorrelations in the cosine ratios (Fig. 1).

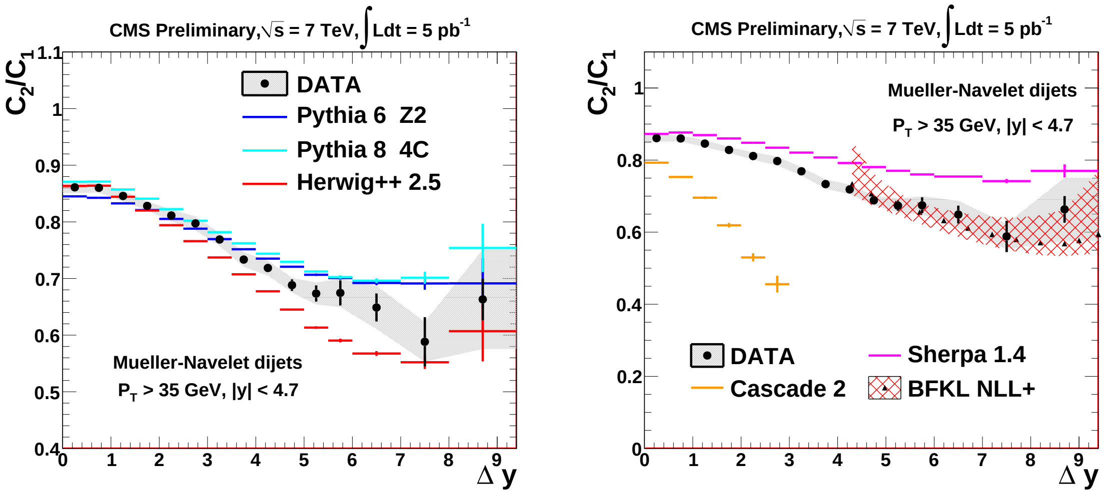

Figure 1: Ratio of cosines of Fourier coefficients in Mueller-Navelet dijet events (points with error bars), compared to the predictions of DGLAP-based Monte Carlo generators and BFKL predictions (shaded band).

1.2 Diffraction

Measurements of tagged hard diffractive dijet photoproduction from H1 were reviewed, with a selection designed to enhance the sensitivity to survival probability effects [4]. Hints of factorization breaking were seen when comparing to NLO predictions, with a gap survival probability of $0.67 \pm 0.10(\text{exp.}) \pm 0.24(\text{theor.})$, consistent with previous untagged H1 measurements (Fig. 2). However, no effect was observed in the corresponding untagged analysis from ZEUS.

In the area of soft diffraction, new measurements were presented by TOTEM and CMS. TOTEM measured the single diffractive cross section using tagged protons, and double diffractive cross section using the T1 and T2 telescopes. CMS measured single and double diffractive cross

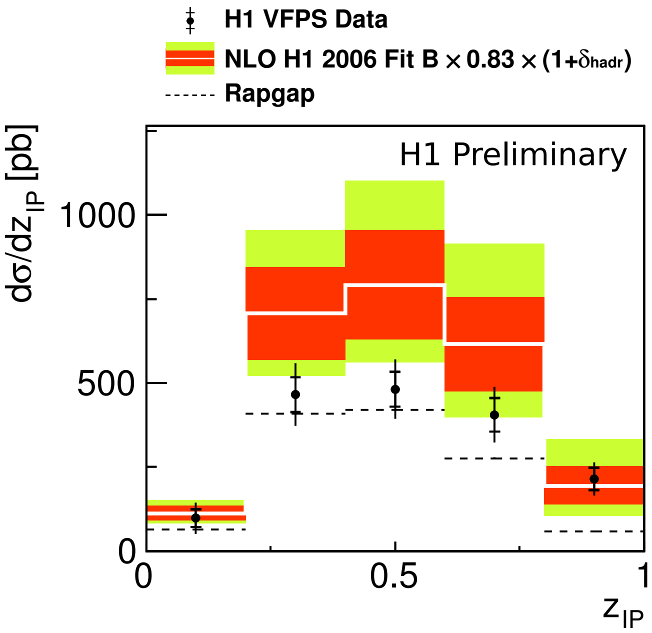

Figure 2: Distribution of z_{IP} measured in proton-tagged diffractive dijet photoproduction at H1 (points with error bars), compared to NLO predictions (solid histograms).

sections using rapidity gaps, with the CASTOR calorimeter used to extend the coverage in the forward region. The measured single and double diffractive cross sections from TOTEM were [3]:

$$\sigma_{SD}(3.4 < M_{SD} < 1100\text{GeV}) = 6.5 \pm 1.3 \text{ mb},$$
$$\sigma_{DD}(4.7 < |\eta_{min}| < 6.5) = 120 \pm 25\ \mu\text{b}.$$

The measured cross sections from CMS were [4]:

$$\sigma_{SD}(-5.5 < \log_{10}\xi < -2.5) = 4.27 \pm 0.04(\text{stat.})^{+0.65}_{-0.58}(\text{syst.})\text{ mb},$$

$$\sigma_{DD}(\Delta\eta > 3, M_X > 10\text{ GeV}, M_Y > 10\text{ GeV}) = 0.93 \pm 0.01(\text{stat.})^{+0.26}_{-0.22}(\text{syst.})\text{ mb}.$$

The TOTEM and CMS measurements were compared to the predictions of MC models within the measured phase space, with Pythia8-MBR, Pythia8-4C, and QGSJetIII performing well. Differential cross sections as a function of the gap size were measured to $\Delta\eta^F < 8.4$ and shown to be consistent between CMS and ATLAS [5], within uncertainties.

1.3 Exclusive processes

Preliminary results on exclusive $\pi\pi$ production at CDF were shown, with a focus on understanding the low-mass scalar resonances [6]. The high-statistics data had been collected during special low-pileup runs at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 1960$ GeV shortly before the end of Tevatron operations. A complicated resonance structure in the region $m(\pi\pi) < 2.0$ GeV was observed, with further studies ongoing.

New results on J/ψ photoproduction in ep collisions were presented by H1, with a simultaneous measurement of the elastic and proton-dissociative contributions to low $|t|$ for the first time [7].

The measurements were found to be consistent with pQCD-inspired predictions. In pp collisions, LHCb measured exclusive J/ψ photoproduction at 7 TeV [8]. The results were found to be in agreement with the energy dependence of the H1 and ZEUS results, and extended the range of $W_{\gamma p}$ probed to ~ 1 TeV.

In exclusive $\gamma\gamma$ interactions, CMS presented a search for $\gamma\gamma \to WW$ scattering at 7 TeV [9]. Two candidate events were found, consistent with the Standard Model expectation. The result was interpreted in terms of Anomalous Quartic Gauge Couplings, with the obtained limits exceeding those of LEP by a factor of $\sim$100 with a form factor of $\Lambda_{\rm cutoff} = 500$ GeV.

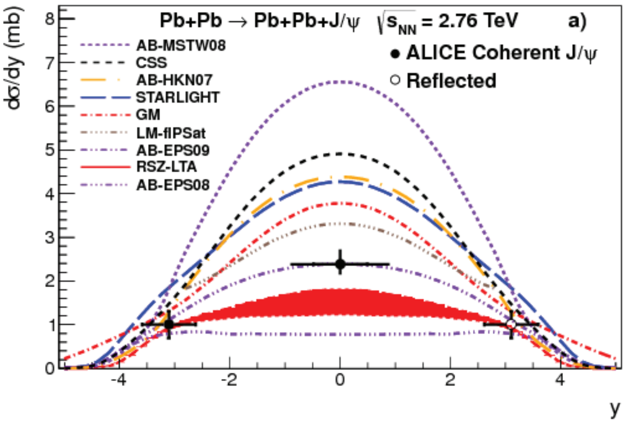

Figure 3: Differential cross section dσ/dy measured in ultraperipheral heavy ion collisions with the ALICE detector. The data (points with error bars) are shown in comparison to various theoretical predictions (as described in the legend).

Finally, J/ψ photoproduction in ultraperipheral heavy ion collisions (UPC) was studied by ALICE [10]. Large signals were observed in the $J/\psi \to \mu\mu$ and $J/\psi \to ee$ channels, allowing a differential measurement of cross sections vs. rapidity $d\sigma/dy$ (Fig. 3). These were found to be consistent with models including nuclear gluon shadowing. First signals for UPC J/ψ events extracted from pPb collisions were also shown.

1.4 Minimum bias, underlying event, and multi-parton interactions

A number of results on minimum bias and underlying event studies at the LHC were presented, with an emphasis on the connection to the physics of multiparton interactions and the importance for Monte Carlo tuning.

In ATLAS, a new measurement of the underlying event activity in events with calorimeter jets was presented. The use of calorimeter cluster variables in combination with charged tracks allowed the measurement to be extended to $|\eta| < 4.8$ for the first time. The measurements were further performed for an inclusive selection, and an exclusive selection with exactly two jets above threshold, in order to remove contributions from extra jets in the event. It was observed that the evolution of the underlying event activity vs. the p_T of the leading jet was not well described by any of the MC models tested [11].

A new measurement of the charged dN/dη and leading track p_T at 8 TeV was presented, using special runs in which the CMS and TOTEM experiments participated in data taking with a common trigger. The combination of the TOTEM T2 telescopes with CMS central tracking allowed for a measurement of dN/dη covering $|\eta| < 2.4$ and $5.3 < |\eta| < 6.5$ [3, 12]. New measurements of the leading track p_T [12] and of jet and underlying event properties as a function of multiplicity were also discussed [13].

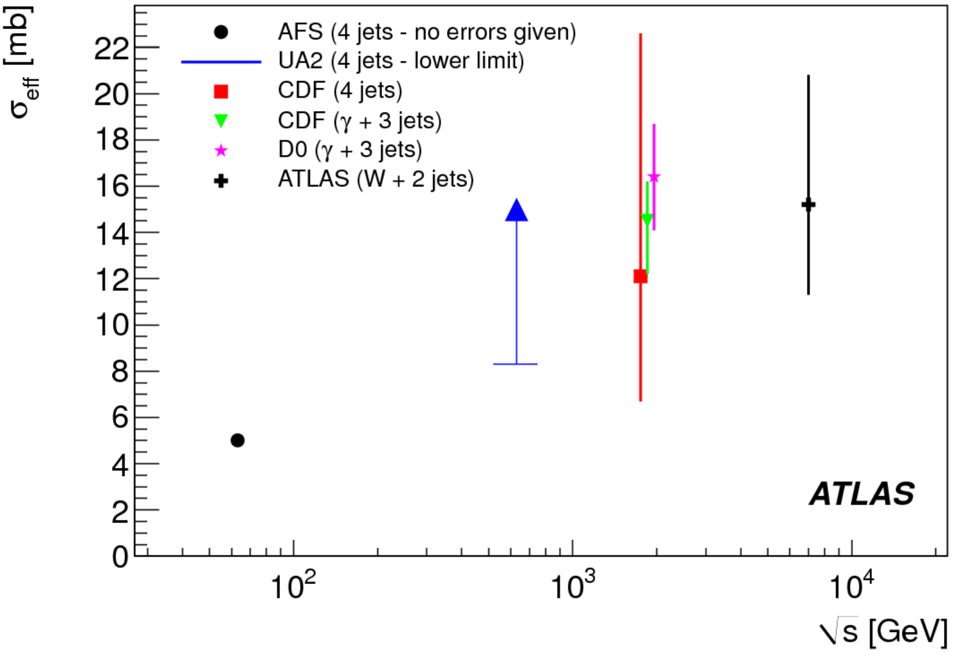

Figure 4: Summary of $\sigma_{\text{eff.}}$ measurements in double parton scattering.

In addition to minimum bias and underlying event measurements, multiparton interactions were investigated through hard double parton scattering at $\sqrt{s} = 7$ TeV. Both ATLAS and CMS studied differential distributions in W+jets events that were expected to be sensitive to DPS [14,15]. In addition, ATLAS performed a fit to the normalized jet p_T imbalance to extract an effective cross section value of:

$$\sigma_{eff} = 15 \pm 3(\text{stat.})^{+5}_{-3}(\text{syst.}),$$

which was compatible with measurements at lower energies in the γ+jets and 4-jet final states within uncertainties (Fig. 4).

2. Theory overview

2.1 Recent theoretical developments on high-energy effective theories

The high-energy effective action, constructed in 1995-1997 [16–18] and then investigated in order to fix the corresponding Feynman rules [19], had no application until very recently. In a nutshell, the Lipatov vertex is the building block of the real part of the BFKL kernel. It appears when evaluating the amplitude of the $2 \to 3$ high-energy process at Born order, where the $t-$channel particles and the emitted ones are gluons. This amplitude is computed in the multi-regge kinematics (MRK) in which the configuration with a large gap in rapidity between the sources and the emitted particle dominates the phase space. It involves the QCD triple-vertex and the four possible Bremsstrahlung emissions from the sources, these five contributions being combined in a single $2 \to 1$ vertex. The $t-$channel gluons which are dressed by the interaction are named gluonic reggeon (R). The key point is that the emitted gluon (P) is soft with respect to the emitters, which manifest themselves as eikonal lines. Based on this, one defines two Reggeon fields A_+ and A_- which incorporate this eikonal nature, either from upper or lower side, on top of usual QCD gluons. The effective action incorporates the various RP transitions as as well as the RPP vertex. Now, one may iterate them in order to compute building blocks, the first one being the Lipatov vertex. The high energy effective action is local in rapidity. In the leading order (LO) BFKL picture, this corresponds to the MRK, while in the next-to-leading-order (NLO) approximation, a more involved situation occurs, named quasi-multiregge kinematics (QMRK), since emitted particles may be grouped together in clusters which are separated by rapidity gaps, while the rapidity of particles inside a given cluster is fixed. Thus, the effective action should be supplemented with additional rules... which makes life hard [20].

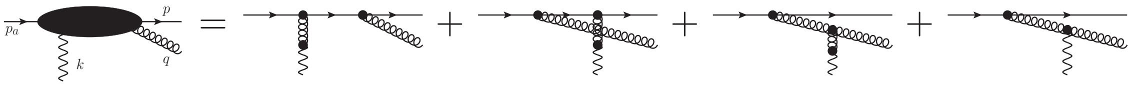

Figure 5: The quasi-elastic quark vertex at NLO using the effective action. The wavy lines denote the gluonic reggeon while the coil springs are gluons.

Recently, this action has been used for practical purpose [21, 22]. First, several non trivial analytical results have been reobtained [23], like the quasi-elastic quark vertex at NLO (see Fig. 5), which is the jet vertex for Mueller-Navelet jets (one R in $t-$channel) [24,25], as well as the two-loop gluon Regge trajectory (thus including the evaluation of non-trival loops) [26, 27]. Furthermore, a new result have been obtained using the Lipatov action, which is a building block for forward-backward jets with rapidity gap: this is the jet vertex at NLO (the Mueller-Tang jet impact factor, i.e. with two R in $t-$channel, now forming a color singlet).

Second, another approach [28], which has been proven to be equivalent to the Lipatov action at Born order, relies on the use of on-shell amplitudes in which the kinematics is treated exactly. The price to pay is to introduce complex momenta. Interestingly, this trick does not spoil the gauge symmetry. Within this kinematics, the high energy approximation in the form of usual eikonal couplings can than be performed. From the practical point of view, these manipulations can be implemented numerically [29, 30]. This led to an evaluation of ratio of observable distributions for $p-p$ versus $p-Pb$ collisions.

In the BFKL framework, the (global) (quasi) conformal symmetry is central at LO and NLO [31]. In the singlet channel, the full momentum space NLO BFKL kernel (i.e. also the non-forward part of the NLO BFKL kernel) was computed directly [32], in the so-called standard form. However, it is not quasi-conformal invariant (i.e. conformal up to the running coupling effect). It turns out that its Möbius form [33] (i.e. the dipole representation, which is obtained by passing to the coordinate space, and restricting the space of functions to the ones vanishing for identical positions), can be made quasi-conformal invariant after using the color neutrality of the impact factor [34]. In momentum space, it was then possible to obtain the difference between the standard and the quasi-conformal kernel [35, 36]. Recently, the same study has been performed in the adjoint representation [37]. Besides its interest for QCD, due to the above-mentioned crucial property of quasi conformal invariance, the LO and NLO BFKL equation has also been studied in the $\mathcal{N} = 4$ SUSY theory, which is conformal invariant. Recently, the corresponding gluon Green's function has been numerically studied [38], using an iterative method [39–41].

2.2 High density, saturation

The dipole model is an inspiring and powerful paradigm, for many processes. At an electron-hadron or electron-nucleus collider, deep-inelastic scattering can be understood as a dipole of “tunable“ size r interacting with the target (p or A), that gets denser at higher energies. Processes involving exclusive final states can be included with an appropriate wave function to describe the produced state. A lot of understanding of the dipole scattering amplitude was gained at HERA, at the border of the dense/saturation regime of QCD. It is ”easy” to formulate the QCD evolution of the dipole amplitude with the energy as radiative corrections to the dipole wave function. This includes the BFKL [42–45] (at low density), BK [46, 47] and B-JIMWLK [48–56] equations (accounting for high-density effects). In particular, the impact-parameter dependent saturation model [57], based on the Mueller-Glauber model (thus, it does not include any small-x dynamics à la BK), provides a unified description [58, 59] for the x, Q^2 , W and t dependencies of HERA data.

The description of power corrections (or twist corrections) in exclusive processes is a long-standing problem. Due to the recent measurements performed at HERMES, HERA and JLab in diffractive electroproduction of vector mesons, the interest for this question has been renewed [60]. The light cone collinear factorization (LCCF) [61, 62] provides a framework to deal with contributions beyond the leading twist [63]. Considering the infinite tower of Fock states of the ρ meson, at twist 3 there are two sources of transverse polarization: a little off-collinearity of the $q\bar{q}$ pair inside the $q\bar{q}$ Fock state (kinematical twist 3), or a contribution from the $q\bar{q}g$ Fock state (genuine twist 3). The LCCF then provides a good description of ratios of amplitude for ρ_T versus ρ_L electroproduction [64]. Recently, a consistent framework has been constructed [65, 66], which combines the LCCF to produce a meson beyond leading twist and the dipole QCD model at high density, allowing for an inclusion of saturation effects. For that purpose, the key point is to reformulate the LCCF in coordinate space and to use QCD equations of motions. This leads to an exact factorization of the whole amplitude as the universal dipole-proton scattering amplitude convoluted with the overlap of the γ^* and ρ_T wave functions (there are no multipole contribution apart from the dipole one), proving that the dipole model is still valid at twist 3, as illustrated in Fig. 6.

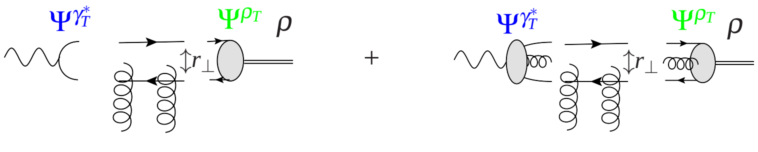

Figure 6: The dipole factorized form of the $\gamma_T^* \to \rho_T$ transition at twist 3. Left: kinematical twist 3. Right: genuine twist 3.

Based on models for the distribution amplitudes of the ρ, the obtained amplitudes are in good agreement with HERA data. The above factorization provides a way to relate the wave function of the produced exclusive state with their distribution amplitudes. Still, these wave functions are non-perturbative objects which cannot be calculated in perturbative QCD. The promising AdS/QCD correspondence provides a way to compute them in an analytic way [67]. In the case of the ρ, the obtained light-front wavefunction gives predictions for the cross-sections of diffractive ρ production that are in agreement with HERA data [68, 69].

There are several ways to test QCD at high density, where saturation effects for transverse momenta below the saturation scale Q_s are expected. At a hadron collider, one needs to find appropriate production processes. Two processes are under theoretical and experimental investigation, namely the p_T-broadening and the forward dijet azimuthal correlations, as shown is Fig. 7.

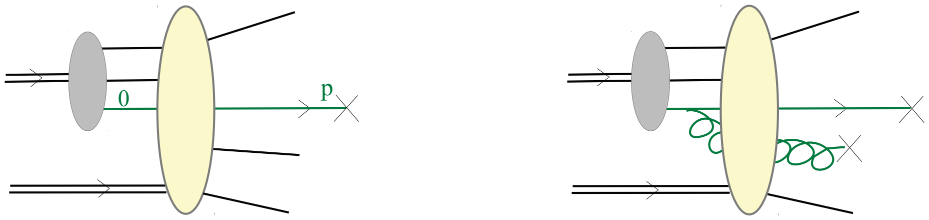

Figure 7: Left: p_T-broadening: one observes a jet of transverse momentum $p_T \sim Q_s$. Right: one observes two forward jets, which are back-to-back if the target is dilute.

At NLO, the evolution of p_T-broadening amplitudes with the energy can be shown [70, 71] to be identical with the evolution of forward scattering amplitudes of color dipoles off nuclei, as illustrated in Fig. 8. The study of di-hadron azimuthal correlations $\Delta\phi$ between two hadrons is considered to be one of the best signal for saturation. Indeed at RHIC, among the two near side ($\Delta\phi = 0$) and away side ($\Delta\phi = \pi$) peaks observed in $p\,p \to h_1\,h_2\,X$ collision, the second one almost disappears in $d\,Au \to h_1\,h_2\,X$ collision, due to saturation effects inside the heavy ion mainly affecting the back-to-back configurations at parton level [72, 73]. It has been proven that this observable only involves dipole and quadrupole contributions in the large N_c limit. This conclusion remains valid for multiparticle production [74].

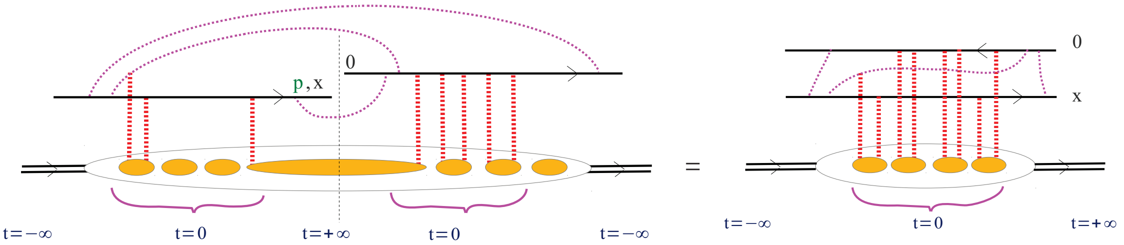

Figure 8: The p_T-broadening is equivalent to the dipole amplitude.

It is still an open question to include Sudakov logarithms at small x consistently with saturation effects from first principles. Recently, a new equation [75] has been proposed in order to combine the CCFM equation [76–79], which has angular ordering, and has the nice feature of including BFKL equation and Sudakov logarithms, and the BK equation, in order to include saturation effects in exclusive final states [80, 81]. The trick there is to rewrite the BK equation in a resummed form which is more suitable in view of including exclusive final states effects. The inclusion of angular ordering is then performed based on an educated guess. When compared with the CCFM equation, this new KGBJS equation has the expected feature of introducing a saturation mechanism for low transverse momenta at small x [82].

2.3 Testing QCD in the perturbative Regge limit at LHC

The phenomenology of QCD in the perturbative Regge limit is a very active subject, which has been renewed by the LHC experiments. In order to obtain reliable results, one should identify processes in which a hard scale allows for the use of perturbative methods. In this spirit, several studies have been presented in the workshop, including $\gamma\gamma \to J/\psi J/\psi$ in ultraperipheral $AA \to AAJ/\psi J/\psi$ collisions, for which the hard scale is provided by $M_{J/\psi}$ [83]. A detailled comparison of the box-diagram contribution w.r.t. the two gluon exchange is performed, showing the expected dominance of the later one for large invariant mass [84]. Another interesting process, in which the hard scale is given by the heavy quark mass, is the diffractive open charm production [85], for which two competitive mechanisms exist, the Ingelman-Schlein model, which dominates, and the gluon dissociation model [86]. Still, precision studies require to take into account NLL corrections. Besides, the single and double diffractive prompt photon production at the LHC could provide an interesting access to the quark content of the pomeron [87].

In view of precision studies in the BFKL framework, the evaluation of the amplitude of a high energy process requires the knowledge of both the NLL pomeron and the NLL impact factors. Indeed, the effect of passing from LL to NLL impact factors is now known to be very significant, as it has been shown for Mueller-Navelet jets [88, 89], one of the main process under investigation at LHC to reveal the high energy dynamics of QCD - the only one at a complete NLL precision level [90]. The comparison with the recent CMS data is discussed in section 1. Although the NLL prediction still suffer from theoretical uncertainties, like the renormalisation scale fixing problem, the later has been investigated very recently, suggesting that the CMS data for the azimuthal correlation between jets provide a very convincing signal for high energy resummation effects [91]. This process will surely be one of the most debated in the near future, in view of the coming data from LHC at higher energies. Besides the above discussed NLL impact factors with initial gluons or massless quarks [92, 93], the initial heavy quark case is also known [94] but its numerical implementation requires further studies [95].

2.4 Multiparton interactions

There are now several experimental indications that multiparton interactions (MPIs) have sizable effects in collider experiment, has shown in the experimental section. However, the theory for these processes is under development [96]. In the case of double parton scattering (DPS), several kinds of correlations are particularly relevant, involving longitudinal momentum fractions, impact parameters, spins and colors. Due to these correlations [97], the use of simplistic models, which predict the effective cross section σ_{eff} to be sizably much larger than the one experimentaly extracted (see Fig. 4), is doubtful [98]. From a practical point of view, it is very important phenomenologically to construct models for the double parton distribution functions (DPDFs) involved in DPS. Several ansatz can be constructed for the initial distributions [99, 100], inspired by a factorised form made of two single PDFs which cannot be a pure product due to the above mentioned correlations. Any model should at least satisfy momentum and valence quark number sum rules, which make the construction of these initial condition not an easy task [101]. These initial conditions are then evolved to an arbitrary scale according to QCD evolution equations [102–104] which are extensions of the usual DGLAP equations [105–108] for DPDFs.

Besides the above treatment in the spirit of collinear factorization, one should note that the low x limit is of particular interest based on the fact that the gluonic PDF growths very fast, increasing the probability of multipartonic events. Such a mechanism may thus have a sizable effect in processes governed by perturbative Regge dynamics, like the Mueller-Navelet jets discussed above. One should note that MPIs are contributions which are involved, in the context of saturation, in the description of the color glass condensate. This is of particular interest in the understanding of the azimuthal distribution of a hadron pair at RHIC and LHC [109–111].

2.5 The Regge limit at LHC

Besides the above mentioned hard high energy processes, traditional Regge approach allows one to investigate high energy processes at the LHC. One of the traditionally investigated channel is the elastic $pp \to pp$ differential cross. Relying on the Barger-Phillips model, it has been possible to construct an ansatz fitted on ISR and LHC7 data [112], providing predictions for this elastic process at future high energy experiments, including LHC at higher energies [113]. A comparison of predictions of diffractive, elastic, total, and total-inelastic pp cross sections based on the RENORM Regge model for diffraction [114, 115] with recent measurements at the LHC has been presented [116]. The more exclusive diffractive photon bremsstrahlung [117] has been also discussed based on the Regge analysis [118].

3. Conclusions

Approximately 20 experimental talks and 20 theoretical talks were presented in the Small x, Diffraction, and Vector Mesons session, with far too many interesting results to cover in a short summary.

From the experimental side, the high-statistics data from HERA and the Tevatron continued to provide new precision measurements, using the full datasets collected by both colliders. Meanwhile new data from pp and $PbPb$ collisions at the LHC were used to confront theoretical predictions for BFKL effects, multiparton interactions, and $I\!P$- and γ-induced processes at high energy, with more results expected to come.

From the theoretical side, efforts have been pursued in order to provide observables in order to test the high energy dynamics of QCD. Still, only a few observables have been studied at a precision level, i.e. at BFKL NLL, in view of the high statistics LHC data to come. Based on several noticeable forward steps which have been made recently in order to compute the needed building blocks, there is a hope to gain further insights into this high energy dynamics, with a precision level competitive with the fixed order calculations. The dipole model is clearly one of the key model which can incorporate many high-energy effects including the saturation involving both nucleons and nuclei. The potential experimental signals of multiparton interactions require to begin building a strong foundation from the theory side. Many very interesting questions have been raised, based on the expected non-trivial correlations between the involved partons. Thus, it is at the moment still very difficult to interpret these data from first principles, although there exist several very interesting models. At high energy and high densities, the investigation of the effect of multiparton interactions is even more difficult to investigate, due to the difficulty of performing a systematic twist counting.

We would like to thank all speakers in this session for excellent talks, and the organizers of DIS 2013 for their support and organization of this workshop.

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