Introduction to Diffraction

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Abstract
We summarize the main activities of the Working Group on Diffraction in this workshop, which cover a wide range of experimental, phenomenological and theoretical studies. Central themes are exclusive and inclusive diffraction at HERA and the LHC, multiple interactions and rapidity gap survival, and parton saturation.

1 Forward proton tagging at the LHC as a means to discover new physics

The use of forward proton tagging detectors at CMS and ATLAS as a means to search for and identify the nature of new physics at the LHC was one of the major topics of discussion at the workshop. The process of interest is the so-called 'central exclusive' production process $pp \to p \oplus \phi \oplus p$, where $\oplus$ denotes the absence of hadronic activity (a 'gap') between the outgoing intact protons and the decay products of the central system ϕ. The final state therefore consists of *only* the decay products of the system ϕ, which can be seen in the central detectors, and the two outgoing protons, which must be detected at some point downstream of the interaction point where they emerge far enough from the LHC beams. To this end, the feasibility of installing proton tagging detectors at 420 m from the interaction points of ATLAS and/or CMS, at a suitable time after the initial start-up of the LHC, is currently being assessed [1]. These would complement and increase the acceptance of the detectors already planned in the 220 m/240 m region by CMS / TOTEM and ATLAS. The choice of the 420 m region is set by the central system masses of interest; protons which lose approximately 60 GeV of their longitudinal momentum — the interesting range from the point of view of Higgs boson searches — emerge from the beam in this region.

The motivation for these studies stems from the unique properties of central exclusive production. Firstly, the mass of the central system ϕ can be measured to high accuracy by measuring the four-momenta of the outgoing protons alone, without reference to the central system (the so-called 'missing mass method' [2]). The achievable mass resolution and the acceptance as a function of mass of the 420 m detectors (in combination with the already planned 220 m proton detectors) are discussed in detail in these proceedings [3,4]. The resolution can be as good as 1 GeV for a Higgs boson of mass 140 GeV. As an example, in the case of a 140 GeV Standard Model Higgs decaying to two W bosons, and the subsequent leptonic decays of one or both of the W's to leptons plus neutrinos, six events are expected with no modification of the level-1 trigger thresholds of ATLAS and CMS for 30 fb^{-1} of delivered luminosity. We discuss the trigger issues in more detail below. This number is expected to double if realistic changes are made to the leptonic trigger thresholds [5].

A second crucial advantage is that, to a good approximation, the central system ϕ is produced in the $J_z = 0$, C and P even state, and an absolute determination of the quantum numbers of any resonance is possible by measuring correlations between the outgoing proton momenta. Observation of any resonance production with associated proton tags, therefore, allows a determination of its quantum numbers, something that is difficult to do in any other process at the LHC. Such a determination could be made with only a few 'gold-plated' events.

Thirdly, states which would otherwise be very difficult to detect in conventional channels can be detected in the central exclusive channel. Perhaps the best-studied example is the high $\tan\beta$ region of the MSSM, where over 100 signal events can be detected with backgrounds lower by an order of magnitude or more, within 30 fb^{-1} of delivered luminosity at the LHC [6]. There are extensions to the MSSM in which central exclusive production becomes in all likelihood the only method at the LHC of isolating the underlying physics. One example [7] is the case where there are non-vanishing CP phases in the gaugino masses and squark couplings. In such scenarios, the neutral Higgs bosons are naturally nearly degenerate for large values of $\tan\beta$ and charged Higgs masses around 150 GeV. In such scenarios, observing the mass spectrum using forward proton tagging may well be the only way to explore such a Higgs sector at the LHC. Explicit CP-violation in the Higgs sector can be observed as an asymmetry in the azimuthal distributions of the tagged protons [8].

From an experimental perspective, the key issue along with the mass resolution and acceptance is the level-1 (L1) trigger efficiency. The problem is that detectors at 420 m from the interaction points of ATLAS or CMS are too far away to participate in a L1 trigger decision without an increase in the trigger latency. This means that the central detectors, or forward detectors up to 220 m, must be relied upon to keep candidate events until the signals from 420 m can be used in higher level trigger decisions. A full description of the work done at the workshop is presented in Refs. [9, 10] in these proceedings. The most difficult case is that of a low-mass (120 GeV) Higgs boson decaying in the b-quark channel (a decay mode that will not be observed in any other measurement at the LHC). The relatively low transverse momenta of the b-jets necessitate L1 jet E_T thresholds as low as 40 GeV. Thresholds that low would result in a L1 trigger rate of more than 50 kHz, because of the QCD background, and thus would essentially saturate the available output bandwidth. The output rate of a 2-jet L1 trigger condition with thresholds of 40 GeV per jet can be kept at an acceptable level of order 1 kHz in the absence of pile-up (i.e. for a single proton–proton interaction per bunch crossing) by either using the TOTEM T1 and T2 detectors (or the ATLAS forward detectors) as vetoes — central exclusive events have no energy in these regions — or by requiring that a proton be seen in the TOTEM (or ATLAS) detectors at 220 m on one side of the interaction point. This gives a sufficient reduction of the QCD background event rate. At higher luminosities, up to $2 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$, where pile-up is present, it is necessary to combine a 220 m tag with additional conditions based on event topology and on H_T, the scalar sum of all L1 jet E_T values. These L1 trigger conditions result in signal efficiencies between 15% and 20%. A further 10% of the Higgs events can be retained by exploiting the muon-rich final state in the $H \to b\bar{b}$ mode, with no requirements on the forward detectors. Other interesting decay channels, such as WW and $\tau\tau$, should be possible at the highest luminosities ($1 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$) since both ATLAS and CMS will trigger on such events routinely using only the central detectors.

As well as upgrading the proton tagging capabilities of ATLAS and CMS, there was also discussion of upgrading the very forward region of CMS to extend the pseudo-rapidity coverage up to $|\eta| \sim 11$. This would allow proton x values down to 10^{-8} to be probed, opening up an unexplored region of small-x parton dynamics [11].

In summary, central exclusive production provides an excellent means of measuring the masses of new particles with a precision at the 1 GeV level, irrespective of the decay mode of the particles. It also provides a clean way of unambiguously determining the quantum numbers of any resonances produced in the central exclusive process (including Standard Model and MSSM Higgs bosons) at the LHC.

In certain regions of the MSSM, and indeed for any scenarios in which the new particles couple strongly to gluons, central exclusive production may be the discovery channel[1]. The challenge is to design and build proton tagging detectors with the capability to measure the momentum loss of the outgoing protons at the 1 GeV level.

2 Theory of diffractive Higgs production

It is a fact that the theoretical predictions for central exclusive production suffer from several sources of uncertainty. The theoretical framework is presented and critically assessed in the contribution by Forshaw [13]. The emphasis is on the calculations of the Durham group, which are performed within perturbative QCD. The use of perturbative QCD is shown to be justified, with around 90% of the contribution to the Standard Model Higgs production cross-section ($m_H = 120$ GeV) coming from the region where the gluon virtualities are all above 1 GeV.

One of the main sources of uncertainty in the perturbative calculation arises from a lack of knowledge of the proton's generalized, unintegrated gluon distribution function, and so far estimates are based upon theoretically motivated corrections to the more familiar gluon distribution function. It is hard to make an accurate assessment of the uncertainty arising from this source, but currently a factor of 2 uncertainty on the Higgs production cross-section is probably not unrealistic. Measurements of exclusive diffraction at HERA can help constrain the generalized gluon distribution in kinematics similar to the one relevant for exclusive Higgs production at the LHC [14]. High-quality data are now available for $ep \to e\, J/\Psi\, p$. Exclusive production of Υ mesons and deeply virtual Compton scattering $ep \to e\gamma p$ involve smaller theoretical uncertainties, but are experimentally more demanding and should be explored in more detail with HERA II data.

Since the focus is on exclusive final states such as $p \oplus H \oplus p$, it is necessary to sum the Sudakov logarithms which arise in perturbation theory. One must go beyond summing the leading double logarithms and sum also the single logarithms. Without the single logs, one vastly underestimates the production rate. Unfortunately, perturbative emissions are not the only way to spoil the exclusive nature of the final state: extra particles can also be produced as a result of soft interactions between the colliding protons. To account for such soft interactions is clearly outside of the scope of perturbation theory and one is forced to resort to non-perturbative models. It is universally assumed that one can estimate the effect of forbidding additional particle production by simply multiplying the perturbative cross-section by an overall 'gap survival' factor [15]. The two most sophisticated models of this factor are discussed in some detail and compared with each other in the contribution of Gotsman et al. [16]. It turns out that, although the approaches are different in many respects, they tend to predict very similar values for the gap survival factor. Nevertheless, both models are essentially multi-channel eikonal models and one would like to test them against data. Fortunately that is possible: data from HERA and the Tevatron already tend to support the theoretical models and future measurements at the LHC will allow one to further constrain them.

Uncertainties in the gluon densities and in our knowledge of gap survival can be reduced as we test our ideas against data, both at present colliders and at the LHC itself. Fortunately, these uncertainties essentially factorize (from the hard subprocess which produces the central system) into a universal 'effective gluon luminosity' function. Thus one can hope to extract the important physics associated with the production of the central system by first measuring the luminosity function in a 'standard candle' process. The ideal candidate is $pp \to p + \gamma\gamma + p$ [17] since the hard subprocess is well known ($gg \to \gamma\gamma$) and the effective gluon luminosity can be extracted over a wide kinematic range. In this way one might hope to extract the effective coupling of any centrally produced new physics to two gluons.

[1]For a recent review of the physics case for FP420, see [12] and references therein.

During the period of the workshop, Monte Carlo codes have been developed which simulate the theoretical predictions for both interesting signal processes and also the associated backgrounds. These codes are now routinely used, for example, to help develop the case for the installation of low-angle proton detectors at the LHC, and new processes are being added with time. A review and comparison of the various Monte Carlos is to be found in the contribution of Boonekamp et al. [18].

3 Diffractive structure functions and diffractive parton distributions

The cross-section for the reaction $ep \to eXp$ can be expressed in terms of the diffractive structure functions F_2^D and F_L^D, in analogy to the way in which $d\sigma/dx\,dQ^2$ is related to the structure functions F_2 and F_L for inclusive DIS, $ep \to eX$. The function F_2^D describes the proton structure in processes in which a fast proton is present in the final state; F_L^D corresponds to longitudinal polarization of the virtual photon. Since in diffractive events the proton typically loses a fraction of less than 0.02–0.03 of its initial momentum, the parton participating in a diffractive interaction has a fractional momentum which is also less than 0.02–0.03. Diffractive DIS thus probes the low-x structure of the proton, in a way complementary to that provided by non-diffractive DIS.

Diffractive structure functions, like the usual ones, can be expressed as the convolution of universal partonic cross-sections and a specific type of parton distribution functions, the diffractive PDFs. This is the so-called diffractive factorization theorem. Diffractive PDFs can be determined by means of QCD fits similar to those used for extracting the standard PDFs from the F_2 data.

Several measurements of F_2^D are available from the H1 and ZEUS collaborations. Three alternative approaches have been used to select diffractive events:

1. a fast proton is required in the final state; this can be done only be means of a proton spectrometer able to detect scattered protons which do not leave the beam pipe (see e.g. [19]);
2. a rapidity gap in the forward direction is required;
3. the different shape of the M_X distribution for diffractive and non-diffractive events is exploited.

Method 1 selects the reaction $ep \to eXp$ with a high degree of purity; the acceptance of proton spectrometers is, however, small, yielding comparatively small samples. Methods 2 and 3 select the reaction $ep \to eXY$, as opposed to $ep \to eXp$, with Y a proton or a low-mass system. Samples selected with these two methods may include some contamination from non-diffractive processes. Method 3 suppresses the contribution of subleading exchanges (i.e. Reggeon and pion exchanges, as opposed to Pomeron exchange), which is instead present in the samples selected with methods 1 and 2.

Results obtained with the three methods are presented and compared in these proceedings [20]. Methods 2 and 3 yield results for F_2^D which are higher than those obtained with the LPS by factors as large as 1.4, depending on the degree of forward coverage. This normalization difference is due to the proton-dissociative background (from $ep \to eXY$) and is relatively well understood. Having corrected for this effect, the results of the three methods exhibit, at present, a fair degree of agreement. However, differences in the shapes of the Q^2, β and $x_{I\!P}$ dependences become apparent especially when comparing the results obtained with method 3 and those obtained with methods 1 and 2. The origin of these differences is at present not clear. An urgent task for the HERA community is to understand these discrepancies and provide a consistent set of measurements of F_2^D.

Several NLO fits of the F_2^D data were discussed at the workshop [20–22]. The corresponding parametrizations are available in Ref. [23]. The diffractive PDFs are dominated by gluons, as expected given the low-x region probed, with the density of gluons larger than that of quarks by a factor 5–10. There are significant discrepancies between the results of the fits, reflecting, at least in part, the differences in the fitted data. In addition, Martin, Ryskin and Watt [22] argue that the leading-twist formula used in Refs. [20,21] is inadequate in large parts of the measured kinematics, and use a modified expression which includes an estimate of power-suppressed effects.

The discrepancies between the various diffractive PDFs, while not fully understood, are at the moment the best estimate of their uncertainties. Here as well, it is imperative that the HERA community provide a consistent set of diffractive PDFs. Not only are they important for our understanding of the proton structure, but they are also an essential input for any calculation of the cross-sections for *inclusive* diffractive reactions at the LHC — which are interesting in themselves in addition to being a potentially dangerous background to the central *exclusive* production processes discussed in Sections 1 and 2.

No direct measurement exists of F_L^D. The dominant role played by gluons in the diffractive parton densities implies that the leading-twist F_L^D must also be relatively large. A measurement of F_L^D to even modest precision would provide an independent and theoretically very clean tool to verify our understanding of the underlying dynamics and to test the gluon density extracted indirectly in QCD fits from the scaling violations of F_2^D. This is discussed in Ref. [24].

4 Diffractive charm and dijet production at HERA

As mentioned in Section 2, the possibility to observe central exclusive processes depends critically on the survival probability of large rapidity gaps. This probability is not unity as a consequence of the rescattering between the spectator partons in the colliding hadrons: these interactions generate final-state particles which fill the would-be rapidity gap and slow down the outgoing proton or antiproton [16]. This is why the diffractive factorization theorem [25] is expected to fail for hadron–hadron scattering — and therefore also for resolved photoproduction, where the photon acts as a hadron.

In $p\bar{p}$ collisions at the Tevatron, breaking of diffractive factorization was indeed observed. The fraction of diffractive dijet events at CDF is a factor 3 to 10 smaller than that predicted on the basis of the diffractive parton densities obtained at HERA. Similar suppression factors were observed in all hard diffractive processes in proton–antiproton collisions.

In photoproduction processes, however, the situation is far from clear at the moment. A recent ZEUS result [26] indicates that the cross-section for diffractive photoproduction of D^* mesons, a process dominated by the *direct* photon component, is well described by NLO QCD predictions based on the diffractive PDFs. This lends support to the idea that in direct processes the photon is pointlike and that the diffractive factorization theorem holds in this case. Conversely, diffractive dijet data from H1 and ZEUS are better described by a global suppression of *both* the direct and resolved contribution. A discussion of how this might be understood is given in Refs. [27, 28], where a critical study of the factorization scheme and scale dependence of resolved and direct contributions is presented.

5 Multiple scattering at HERA and the LHC

A thorough analysis of the event structure at the LHC will have to take into account contributions from multiple-parton interactions, i.e. from interactions involving more than one parton in each of the colliding protons. Such multiple interactions are expected to be particularly important in the region of small longitudinal momentum fractions and not too high momentum scales. At HERA there are several pieces of evidence that multiple interactions are present; the strongest one comes from the observation of diffractive final states in deep-inelastic electron–proton scattering. A useful tool for analysing these multiple interactions are the so-called AGK cutting rules. During this workshop several groups have studied their application to HERA and to future LHC scattering processes.

The theoretical basis of the AGK rules in perturbative QCD has been outlined in Ref. [29], and a few first applications to HERA and to LHC scattering processes have been addressed. The contribution by Watt et al. [30] uses the AGK rules for deriving, from the measured *diffractive* structure function, absorptive corrections to the *inclusive* structure function F_2. An iterative scheme is then set up which leads to corrected parton densities: at low Q^2 and small x, they tend to be higher than those without absorptive corrections. In particular, they seem to weaken the trend of the gluon density becoming negative, which has been seen in the global parton analyses of both MRST2004 and CTEQ6.

The study presented in Ref. [31] is based upon a specific saturation model that has been successfully applied both to the total $\gamma^* p$ cross-section and to the diffractive process $\gamma^* p \to J/\Psi\, p$. An analysis of this model, based upon the AGK rules, leads to the conclusion that contributions of multiple interactions to F_2 are quite sizeable, even for Q^2 as large as 40 GeV^2.

6 Parton saturation: from HERA to the LHC

A key experimental finding of HERA is the strong rise of structure functions at small x, which implies a high density of small-x gluons in the proton. From theoretical considerations, it is clear that for sufficiently large parton densities, dynamics beyond what can be described by leading-twist factorization and linear DGLAP evolution must become important. If the associated momentum scale is high enough, the strong coupling is still small enough to serve as an expansion parameter, but at very high gluon densities the gluon potential can be so strong that the non-linear term $g_s f^{abc} A^b_\mu A^c_\nu$ in the gluon field strength is as large as the linear term $\partial_\mu A^a_\nu - \partial_\nu A^a_\mu$. High parton densities thus offer the possibility to study QCD in a strongly non-linear regime, and the effective theory of such a 'colour glass condensate' is reviewed in Ref. [32]. A possible link between the strong gluon fields in this description and QCD instantons is discussed in Ref. [33].

The theory and phenomenology of parton saturation are in rapid development, of which the workshop could only provide a snapshot. Data on both inclusive and diffractive deeply inclusive scattering, in particular their very similar energy dependence at given Q^2, suggest that saturation effects are relevant in HERA kinematics, see Ref. [34] and references therein. When saturation is important, the usual parton densities cease to be the key input quantities for describing physical processes. For many reactions a suitable quantity is instead the colour-dipole cross-section — a concept that has been successfully applied in HERA phenomenology. An important theoretical laboratory to study saturation effects is provided by the non-linear Balitsky–Kovchegov equation. In a contribution to the workshop, this equation has been applied to the colour-dipole cross-section for the proton [35]. To describe saturation in pp collisions in general requires non-perturbative functions that can be written as matrix elements of Wilson line operators; *one* of these functions is the colour-dipole cross-section just mentioned [32]. The formulation of suitable evolution equations for pp scattering is an active area of research [36].

7 Rapidity gaps in electroweak processes

Diffractive processes are characterized by rapidity gaps. Such gaps can also originate from the exchange of a photon, a W or a Z boson (see for example Ref. [15]). Selecting events with large rapidity gaps filters out specific final states and, at the same time, leads to better-constrained event kinematics. However, the event rate is lowered by the gap survival probability, as discussed in the previous sections.

The contribution by Amapane et al. [37] discusses the possibility to study the scattering of longitudinally polarized vector bosons (V_L) in pp collisions with the CMS detector at the LHC. $V_L V_L$ fusion may lead to Higgs production; should the Higgs boson not exist, the cross-section for $V_L V_L$ scattering will deviate from the Standard Model prediction at high invariant masses of the $V_L V_L$ system. In all cases, $V_L V_L$ scattering should shed light on the mechanism behind the electroweak symmetry breaking. Preliminary studies based on Pythia and a fast simulation of the CMS detector are encouraging. It will be interesting to investigate in more detail the potential of the rapidity-gap signature for improved signal extraction and background control.

Large rapidity gaps at hadron colliders can also be due to photon exchange. In this case, a direct tagging of high-energy photon interactions can be achieved by using forward proton detectors [38]. Both photon–photon and photon–proton interactions at the LHC have been studied [39]. Some of these events can be used to scan the gap survival probability in impact parameter space, which would help to constrain models for gap survival. A reference point is given by single W boson photoproduction, which has been studied theoretically in this context [40] and is being investigated at HERA.

Finally, diffractive photoproduction of Υ mesons, currently being studied at HERA, can be accessed at the LHC in an extended range of small x. This will provide a very clean channel to study the generalized gluon distribution (see Section 2) and can be seen as a complement to measurements of the usual gluon distribution at very small x, for instance in forward jet production at the LHC.

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