Diffraction from HERA to the LHC

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Abstract. Following a 15 year programme of intensive research into diffractive electron-proton scattering at HERA, it is important to transfer the knowledge and experience gained into the LHC programme. This contribution raises some current issues in diffraction at the LHC and suggests ways in which they might be addressed using HERA results.

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INTRODUCTION

Our understanding of rapidity gaps and colour singlet exchange in the strong interaction has developed substantially over the past 15 years through the study of soft and hard diffractive processes at HERA. Approximately 50 papers have been published on the topic in refereed journals by each of the H1 and ZEUS collaborations. Diffraction will also be a topic of considerable interest at the LHC, firstly in its own right, but also for the understanding of pile-up, for luminosity monitoring and as a selection tool for rare or exotic processes. This contribution [1] discusses some of the areas in which information from HERA can usefully be fed into the LHC programme. Much more information is available on the topic elsewhere, notably in the proceedings of the 2004-8 HERA-LHC workshop [2].

DEFINING DIFFRACTION

It is usual to break down the total cross section in hadronic scattering experiments into elastic, single-diffractive (SD, $pp \to Xp$ in the LHC context), double-diffractive (DD, $pp \to XY$) and non-diffractive (ND) contributions. Taking the SD process as an example, diffractive kinematics are described in terms of the invariant mass M_X of the diffractively produced system X and the Mandelstam t variable corresponding to the squared four-momentum transfer. A further variable, $\xi = M_X^2/s$, is commonly introduced, where Mandelstam s is the square of the centre of mass energy. In SD events at LHC energies, M_X can vary from $m_p + m_\pi$ to more than 1 TeV.

The cross section is vastly dominated by modest values of t, such that the intact proton is scattered through only a small angle. The scattered proton and the undecayed system X are separated by a pseudorapidity difference $\Delta\eta = -\ln\xi$. Following hadronisation, there should be a gap in the rapidity distribution of final state particles which is slightly smaller than this.

At moderate values of ξ, the observables of large rapidity gaps and intact protons with leading longitudinal momentum make definitions of the SD process relatively straight-forward. Similarly, DD processes in which neither the X nor the Y systems have large masses lead to pseudorapidity gaps which are large enough to unambiguously characterise the process. However, at very small ξ values, the diffractively produced particles typically escape detection, leading to the dominating systematics in total cross section measurements at HERA [3] and possibly also at the LHC.

In terms of physical observables, it is only possible to distinguish unambiguously between a diffractive event and an ND process with a gap occurring due to hadronisation fluctuations when $\Delta\eta$ is large [4] and ξ is correspondingly small (typically $\lesssim 10^{-2}$). The commonly used Monte Carlo generators PYTHIA [5, 6] and PHOJET [7, 8] attempt to decompose the entire cross section into diffractive and non-diffractive contributions. Whilst this is certainly a useful categorisation, there are ambiguities particularly at the interface between the DD and ND processes, where the decomposition is rather ad hoc and differs between the different generators. There is no means of universally defining diffraction. In contrast, measurements defined by upper ξ cuts are well defined in terms of physical observables, though they don't permit a unique categorisation of all events.

HERA kinematics are particularly favourable for measurements of the single photon dissociation process $\gamma p \to Xp$. The approach first taken by the H1 collaboration in [9] satisfies the requirement of being well defined in terms of hadron level observables. A completely general algorithm is applied to decompose all final states into two systems X and Y. All final state particles are ordered in rapidity and the systems X and Y are, by definition, separated by the largest gap in rapidity between neighbouring particles. Similar approaches are now being adopted by LHC experiments.

THE POMERON FLUX FACTOR

Motivated by Regge phenomenology, most models of diffraction are based on a flux factor of pomerons from the proton, which is usually parametrised as

$$f_{\mathbb{P}/p}(x_{\mathbb{P}},t) \propto \frac{e^{B_{\mathbb{P}}t}}{x_{\mathbb{P}}^{2\alpha_{\mathbb{P}}(t)-1}} , \tag{1}$$

where the pomeron trajectory $\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}}t$ is assumed to be linear, and the parameter $B_{\mathbb{P}}$ expresses the spatial extent of the interaction region. The values of these parameters have been extracted in various fits to H1 and ZEUS data. Independently of the overall hardness of the interaction, pomeron intercepts very close to 1.10 have been extracted a number of times [9, 10, 11, 12, 13]. Given that it coincides closely with results from fits to pp data [14, 15], such a value seems likely to be appropriate at the LHC.

A pomeron slope of $\alpha' \sim 0.25$ GeV^{-2} has previously been extracted from soft hadron-hadron elastic and diffractive scattering data [16]. Results from both diffractive DIS [11, 12] and exclusive J/ψ photoproduction [17] at HERA have been incompatible with this and much closer to zero. The dynamics driving the difference between ep and pp results for $\alpha' \sim 0.25$ GeV^{-2} are not yet fully understood.

The slope of the exponential t dependence $B_{I\!P}$ varies with the hardness of the interaction. It is in the region of 6 GeV^{-2} in diffractive DIS [11, 12], but reaches 4 GeV^{-2} for exclusive J/ψ production [17], very close to the minimum possible value for SD processes, set by the size of the proton.

MODELLING SOFT DIFFRACTIVE CROSS SECTIONS

In many soft diffractive models, a pomeron flux is combined with a total pomeron-proton cross section, which is often converted to an elastic amplitude via Mueller's generalised optical theorem [18], such that triple Regge diagrams are the relevant contributions to the SD and DD cross sections.

One lesson from HERA [9] and before [19, 20] is that several triple Regge terms may contribute, not only the best known triple pomeron diagram. Since non-diffractive contributions are suppressed with increasing s, the only candidate that is likely to be an issue at the LHC is the '$I\!PI\!PI\!R$' contribution, in which the basic exchange is a pomeron ($I\!P$), but the total pomeron-proton cross section is generated by sub-leading meson ($I\!R$) exchange. This contributes at the smallest M_X, and has the same s dependence as the $I\!PI\!PI\!P$ contribution. A further complication is that the triple pomeron coupling used in soft models [8] is derived from low energy data which are almost certainly influenced by non-diffractive contributions.

MODELLING HARD DIFFRACTIVE CROSS SECTIONS

The parton level structure of diffractive exchange is usually expressed in terms of Diffractive Parton Distribution Functions (DPDFs), which can be extracted from the cross section for the diffractive DIS process $ep \rightarrow eXp$ at HERA. There is now rather good agreement on the diffractive DIS cross section between H1 and ZEUS and between measurements using selection methods with very different systematics [21]. The DPDFs have been extracted recently by several groups [10, 13, 22, 23] in the framework of next-to-leading order (NLO) DGLAP evolution. They lead to a good description of numerous observables in diffractive DIS, including charged current cross sections, heavy flavour and jet yields. They are also an essential ingredient in calculating a wide range of hard diffractive LHC processes [24].

The diffractive quark density and the gluon density at moderate momentum fractions z are well constrained from the fits to the diffractive DIS cross section data. However, the sensitivity to the gluon density is lost at the largest z, which is among the most important regions for LHC studies, being the main background to central exclusive production [25]. Diffractive dijet data from HERA considerably improve the constraints on the high z gluon [23], though interpreting this region remains problematic theoretically [22].

RAPIDITY GAP DESTRUCTION & FACTORISATION BREAKING

QCD factorisation in diffraction is expected to break down due to rescattering (or 'absorptive') effects wherever hadronic remnants are present, a phenomenon which is now well established in comparisons between HERA and Tevatron data [26]. A 'gap survival probability' factor must therefore be included in diffractive hadron-hadron scattering cross section calculations based on DPDFs. All diffractive processes at the LHC are affected, with survival probabilities estimated to be no more than a few percent [27]. Understanding the detailed physics of gap destruction is thus the main challenge for the first studies of hard diffraction at the LHC.

Although gap survival is not an issue in DIS, nor in 'direct' photoproduction, in 'resolved' photoproduction, where the photon interacts via its hadronic structure, the resulting 'photon remnant' may lead to rescattering. Photoproduction thus provides a control experiment in which the onset and nature of absorptive gap destruction may be investigated. The effect has now been established in leading neutron studies [28] but the most quantitative and intriguing results have emerged from diffractive dijet photoproduction measurements. When comparing data with NLO predictions which do not account for gap destruction effects, neither H1 [29, 30] nor ZEUS [31] observe any significant difference between the quality of the description of resolved and direct photoproduction. The overall survival probability is significantly larger than that expected in models of resolved photoproduction based on ideas which successfully describe gap survival at the Tevatron [32]. A recent modified treatment in which resolved photoproduction is broken down into point-like and hadron-like components is more promising [33].

MONTE CARLO IMPLEMENTATIONS

To date, only a limited amount of the information from HERA has been implemented in the commonly used Monte Carlo generators for minimum bias physics at the LHC. Both PYTHIA and PHOJET factorise diffractive cross sections into a pomeron flux factor convoluted with a total pomeron-proton cross section. Whilst the flux factor in PHOJET is relatively standard, the 'critical pomeron' value of $\alpha_{I\!P}(0) = 1$ used in the default PYTHIA flux [34] in lower than would be expected based on HERA and other data.

The interface between hard and soft diffraction is treated differently in the Monte Carlo generators. PYTHIA6 made no attempt to model hard diffractive scattering, producing final state particles using a string model, resulting in insufficient contributions at large p_T [35]. The model of diffraction in PYTHIA8 [6] is identical to that in PYTHIA6 at the level of cross sections and their ξ and t dependences. However, at large M_X, the details of the pomeron-proton interaction are obtained from DPDFs [10], rather than from triple Regge phenomenology. PHOJET contains both hard and soft diffractive contributions. The hard contribution uses a very old set of CKMT DPDFs [36]. As has been shown at HERA [37], this is likely to lead to a poor description of final state observables.

For detailed predictions of final states produced in hard diffraction, specialised models based on DPDFs from HERA are available (e.g. RAPGAP [38] and POMWIG [39]). None of the generators considered here contains any model of rapidity gap destruction due to absorptive or multiple scattering effects. By measuring hard diffractive cross sections at the LHC and comparing the results with predictions based on modern DPDFs from HERA, it will be possible to constrain gap survival factors empirically.

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