Multigap Diffraction at LHC

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Abstract. The large rapidity interval available at the Large Hadron Collider (LHC) offers an arena in which the QCD aspects of diffraction may be explored in an environment free of gap survival complications using events with multiple rapidity gaps.

SOFT DIFFRACTION

Diffractive processes are characterized by large rapidity gaps, defined as regions of (pseudo)rapidity [1] in which there is no particle production. Diffractive gaps are presumed to be produced by the exchange of a color singlet quark/gluon object with vacuum quantum numbers referred to as the *Pomeron* [2, 3] (the present paper contains excerpts from these two references).

Traditionally diffraction had been treated in Regge theory using an amplitude based on a simple Pomeron pole and factorization. This approach was successful at $\sqrt{s}$ energies below $\sim$ 50 GeV [4], but as collision energies increased to reach $\sqrt{s}$ =1800 GeV at the Fermilab Tevatron the SD cross section was found to be suppressed by a factor of $\sim \mathscr{O}(10)$ relative to the Regge-based prediction [5]. This blatant breakdown of factorization was traced back to the energy dependence of the Regge theory $\sigma_{sd}^{tot}(s)$,

$$d\sigma_{sd}(s,M^2)/dM^2 \sim s^{2\varepsilon}/(M^2)^{1+\varepsilon}, \tag{1}$$

which is faster than that of $\sigma^{tot}(s) \sim s^{\varepsilon}$, so that at high $\sqrt{s}$ unitarity would have to be violated if factorization held.

In contrast to the Regge theory prediction of Eq. (1), the measured SD M^2-distribution shows no explicit s-dependence (M^2-scaling) over a region of s spanning six orders of magnitude [6]. Thus, factorization appears to *yield* to M^2-scaling. This is a property built into the *Renormalization Model* of hadronic diffraction, in which the Regge theory Pomeron flux is renormalized to unity [7].

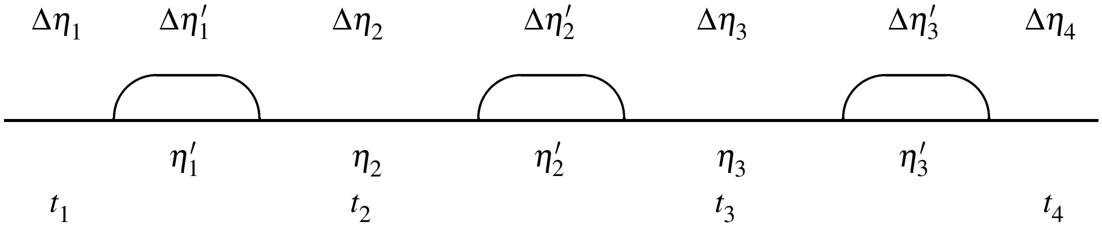

FIGURE 1. Average multiplicity $dN/d\eta$ versus η for a process with four rapidity gaps $\Delta\eta_{i=1-4}$.

In a QCD inspired approach, the renormalization model was extended to central and multigap diffractive processes [8], an example of which is the four-gap process shown schematically in Fig 1. In this approach cross sections depend on the number of wee partons [9] and therefore the pp total cross section is given by

$$\sigma_{pp}^{tot} = \sigma_0 \cdot e^{\varepsilon \Delta\eta'}, \tag{2}$$

where $\Delta\eta'$ is the rapidity region in which there is particle production. Since, from the optical theorem, $\sigma^{tot} \sim \mathrm{Im}\,\mathrm{f}^{\mathrm{el}}(t=0)$, the full parton model amplitude may be written as

$$\mathrm{Im}\,\mathrm{f}^{\mathrm{el}}(t,\Delta\eta) \sim e^{(\varepsilon+\alpha' t)\Delta\eta}, \tag{3}$$

where $\alpha' t$ is a simple parameterization of the t-dependence of the amplitude. On the basis of this amplitude, the cross section of the four-gap process of Fig. 1 takes the form

$$\frac{d^{10}\sigma^D}{\Pi_{i=1}^{10} dV_i} = N_{gap}^{-1} \underbrace{F_p^2(t_1)F_p^2(t_4)\Pi_{i=1}^4 \left\{e^{[\varepsilon+\alpha' t_i]\Delta\eta_i}\right\}^2}_{\text{gap probability}} \times \kappa^4 \left[\sigma_0\, e^{\varepsilon \sum_{i=1}^3 \Delta\eta_i'}\right], \tag{4}$$

where the term in square brackets is the pp total cross section at the reduced s-value, defined through $\ln(s'/s_0) = \sum_i \Delta\eta_i'$, κ (one for each gap) is the QCD color factor for gap formation, the gap probability is the amplitude squared for elastic scattering between two diffractive clusters or between a diffractive cluster and a surviving proton with form factor $F_p^2(t)$, and N_{gap} is the (re)normalization factor defined as the gap probability integrated over all 10 independent variables t_i, η_i, η_i', and $\Delta\eta \equiv \sum_{i=1}^4 \Delta\eta_i$.

The renormalization factor N_{gap} is a function of s only. The color factors are $c_g = (N_c^2-1)^{-1}$ and $c_q = 1/N_c$ for gluon and quark color-singlet exchange, respectively. Since the reduced energy cross section is properly normalized, the gap probability is (re) normalized to unity. The quark to gluon fraction, and thereby the Pomeron intercept parameter ε may be obtained from the inclusive parton distribution functions (PDFs) [2]. Thus, normalized differential multigap cross sections at $t=0$ may be fully derived from inclusive PDFs and QCD color factors without any free parameters.

The exponential dependence of the cross section on $\Delta\eta_i$ leads to a renormalization factor $\sim s^{2\varepsilon}$ independent of the number of gaps in the process. This remarkable property of the renormalization model, which was confirmed in two-gap to one-gap cross section ratios measured by the CDF Collaboration (see [2]), suggests that multigap diffraction can be used as a tool for exploring the QCD aspects of diffraction in an environment free of rapidity gap suppression effects. The LHC with its large rapidity coverage provides the ideal arena for such studies.

HARD DIFFRACTION

Hard diffraction processes are those in which there is a hard partonic scattering in addition to the diffractive rapidity gap. SD/ND ratios for W, dijet, b-quark, and J/ψ production at $\sqrt{s}$ =1800 GeV measured by the CDF Collaboration are approximately equal ($\sim 1\%$), indicating that the rapidity gap formation probability is largely *flavor independent*. However, the SD structure function measured from dijet production is suppressed by $\sim \mathcal{O}(10)$ relative to expectations based on diffractive PDFs measured from diffractive DIS at HERA.

A modified version of our QCD approach to soft diffraction can be used to describe hard diffractive processes and has been applied to diffractive DIS at HERA, $\gamma^* + p \to p + Jet + X$, and diffractive dijet production at the Tevatron, $\bar{p} + p \to \bar{p} + \text{dijet} + X$ in [3]. The hard process generally involves several color "emissions" from the surviving proton, the sum of which comprises a color singlet exchange with vacuum quantum numbers. Two of these emissions are of special interest, one at $x = x_{Bj}$ from the proton's hard PDF at scale Q^2, which causes the hard scattering, and another at $x = \xi$ (fractional momentum loss of the diffracted nucleon) from the soft PDF at $Q^2 \approx 1$ GeV^2, which neutralizes the exchanged color and forms the rapidity gap. Neglecting the t-dependence, the diffractive structure function could then be expressed as the product of the inclusive hard structure function and the soft parton density at $x = \xi$,

$$F^D(\xi, x, Q^2) = \frac{A_{\text{norm}}}{\xi^{1+\varepsilon}} \cdot c_{g,q} \cdot F(x, Q^2) \Rightarrow \frac{A_{\text{norm}}}{\xi^{1+\varepsilon+\lambda(Q^2)}} \cdot c_{g,q} \cdot \frac{C(Q^2)}{\beta^{\lambda(Q^2)}}, \tag{5}$$

where $c_{g,q}$ are QCD color factors, λ is the parameter of a power law fit to the hard structure function in the region $x < 0.1$, A_{norm} is a normalization factor, and $\beta \equiv x/\xi$.

At high Q^2 at HERA, where factorization is expected to hold [7, 12], A_{norm} is the nominal normalization factor of the soft PDF. This factor is constant, leading to two important predictions, which are confirmed by the data:

i) The Pomeron intercept in diffractive DIS (DDIS) is Q^2-dependent and equals the average value of the soft and hard intercepts:

$$\alpha_{I\!P}^{DIS} = 1 + \lambda(Q^2), \quad \alpha_{I\!P}^{DDIS} = 1 + \frac{1}{2}\left[\varepsilon + \lambda(Q^2)\right] \tag{6}$$

ii) The ratio of DDIS to DIS structure functions at fixed ξ is independent of x and Q^2:

$$R\left[\frac{F^D(\xi, x, Q^2)}{F^{ND}(x, Q^2)}\right]_{\text{HERA}} = \frac{A_{\text{norm}} \cdot c_q}{\xi^{1+\varepsilon}} = \frac{\text{const}}{\xi^{1+\varepsilon}} \tag{7}$$

At the Tevatron, where high soft parton densities lead to saturation, A_{norm} must be renormalized to

$$A_{\text{renorm}}^{\text{Tevatron}} = 1/\int_{\xi_{min}}^{\xi=0.1} \frac{d\xi}{\xi^{1+\varepsilon+\lambda}} \propto \left(\frac{1}{\beta \cdot s}\right)^{\varepsilon+\lambda}, \tag{8}$$

where $\xi_{min} = x_{min}/\beta$ and $x_{min} \propto 1/s$. Thus, the diffractive structure function acquires a term $\sim (1/\beta)^{\varepsilon+\lambda}$, and the ratio of the diffractive to inclusive structure functions a term $\sim (1/x)^{\varepsilon+\lambda}$. This prediction is confirmed by CDF data, where the x-dependence of the diffractive to inclusive ratio was measured to be $\sim 1/x^{0.45}$ (see [2]).

A comparison [1] between the diffractive structure function measured on the proton side in events with a leading antiproton to expectations from diffractive DIS at HERA showed approximate agreement, indicating that factorization is largely restored for events that already have a rapidity gap. Thus, as already mentioned for soft diffraction, events triggered on a leading proton at LHC provide an environment in which the QCD aspects of diffraction may be explored without complications arising from rapidity gap survival.

PROPOSED PROGRAM OF MULTIGAP DIFFRACTION AT LHC

The rapidity span at LHC running at $\sqrt{s} = 14$ TeV is $\Delta\eta = 19$ as compared to $\Delta\eta = 15$ at the Tevatron. This suggests the following program for studies of non-suppressed diffraction:

- Trigger on two forward rapidity gaps of $\Delta\eta_F \geq 2$ (one on each side of the interaction point), or equivalently on forward protons of fractional longitudinal momentum loss $\xi = \Delta p_L/p_L \leq 0.1$, and explore the central rapidity region of $|\Delta\eta| \leq 7.5$, which has the same width as the entire rapidity region of the Tevatron. In such an environment, the ratio of the rate of dijet events with a gap between jets to that without a gap, *gap*+[jet-gap-jet]+*gap* to *gap*+[jet-jet]+*gap*, should rise from its value of $\sim 1\%$ at the Tevatron to $\sim 5\%$.
- Trigger on one forward gap of $\Delta\eta_F \geq 2$ or on a proton of $\xi < 0.1$, in which case the rapidity gap available for non-suppressed diffractive studies rises to 17 units.

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[1] Performed by the author and K. Hatakeyama (see [2]) using CDF published data and preliminary H1 diffractive parton densities [11].