IMAGING THE PROTON VIA HARD EXCLUSIVE PRODUCTION IN DIFFRACTIVE pp SCATTERING*

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We discuss the prospects for probing Generalized Parton Distributions (GPDs) via exclusive production of a high-mass system (H = heavy quarkonium, di-photon, di-jet, Higgs boson) in diffractive pp scattering, $pp \rightarrow p + H + p$. In such processes the interplay of hard and soft interactions gives rise to a diffraction pattern in the final-state proton transverse momenta, which is sensitive to the transverse spatial distribution of partons in the colliding protons. We comment on the plans for diffractive pp measurements at RHIC and LHC. Such studies could complement future measurements of GPDs in hard exclusive ep scattering (JLab, COMPASS, EIC).

It is well-known that the parton densities measured in inclusive deep-inelastic ep scattering describe also the partonic initial state in pp collisions with hard processes (Drell-Yan pair production, high-mass jets). This remarkable universality is a consequence of the QCD factorization of both processes. Recently, the study of the partonic structure of the nucleon has been extended to the Generalized Parton Distributions (GPDs), which describe the transverse spatial distribution of partons and are measured in hard exclusive processes in ep scattering. An interesting question is whether the GPDs, too, can be probed in pp collisions with hard processes. In Ref. 1 we have demonstrated that certain information about the GPDs can be gained from processes in which a high-mass system (H = heavy quarko-

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Fig. 1. Interplay of hard and soft interactions in exclusive hard diffraction $pp \rightarrow p + H + p$, Eq. (1). (a) Hard scattering process. (b) Modification by soft spectator interactions in the independent interaction approximation (see Ref. 1 for details).

nium, di-photon, di-jet, Higgs boson) is produced in exclusive diffractive pp scattering,

$$pp \rightarrow p + (\text{gap}) + H + (\text{gap}) + p. \quad (1)$$

In such processes the interplay of hard and soft interactions gives rise to a diffraction pattern in the final-state proton transverse momenta, which is sensitive to the transverse spatial distribution of partons in the colliding protons. The realization of this program presents a major challenge to theory and experiment. In these proceedings we summarize the role of GPDs in hard exclusive diffraction and comment on the plans for diffractive measurements at RHIC and LHC.

In hard diffractive processes, Eq. (1), the high-mass system H is produced in a hard scattering process involving exchange of two gluons between the protons (see Fig. 1a). The requirement of absence of QCD radiation (imposed experimentally by the selection of exclusive events) forces this process to be highly localized in space-time and ensures that the gluons have virtuality of the order of a scale Q^2 in the range $\Lambda_{\text{QCD}}^2 \ll Q^2 \ll M_H^2 \ll s$. In analogy with deeply-virtual electromagnetic Compton scattering, the gluon-proton amplitudes in this process can be computed in terms of the gluon GPDs of the protons. Following Ref. 1, the amplitude of the hard scattering process can be represented as

$$T_{\text{hard}}(\mathbf{p}_{1\perp}', \mathbf{p}_{2\perp}'; \mathbf{p}_{1\perp}, \mathbf{p}_{2\perp}; \xi_1, \xi_2) = \kappa H_g(x_1, \xi_1, t_1) H_g(x_2, \xi_2, t_2), \quad (2)$$

where H_g is the gluon GPD at the scale Q^2 , $\xi_{1,2} = (M_H/\sqrt{s})e^{\pm y_H}$ the longitudinal momentum losses of the protons (y_H is the rapidity of H), $x_{1,2} \approx \xi_{1,2}$, and $t_1 \approx -(\mathbf{p}_{1\perp}' - \mathbf{p}_{1\perp})^2$ etc. the invariant momentum transfers

to the protons. The function $\kappa(s, \xi_1, \xi_2)$ contains the $gg \rightarrow H$ coupling, which for production of a system with quantum numbers other than 0^+ depends also on the transverse momenta.

The amplitude of the hard scattering process Eq. (2) is modified by soft spectator interactions, which are likewise constrained by the requirement that no additional particles be produced. This effect is the essence of the idea of “rapidity gap survival” in diffraction. It was shown in Ref. 1 that in the approximation where hard and soft interactions are independent the modification can be computed in a model-independent way in terms of the pp elastic scattering amplitude. The amplitude for the diffractive process Eq. (1) is then given by (see Fig. 1b; we suppress all arguments except the proton transverse momenta)

$$T_{\text{diff}}(\mathbf{p}'_{1\perp}, \mathbf{p}'_{2\perp}) = \int \frac{d^2 \Delta_{\perp}}{(2\pi)^2} T_{\text{hard}}(\mathbf{p}'_{1\perp}, \mathbf{p}'_{2\perp}; \mathbf{\Delta}_{\perp}, -\mathbf{\Delta}_{\perp}) S_{\text{el}}(s, \mathbf{\Delta}_{\perp}), \quad (3)$$

where S_{el} is the S -matrix of pp elastic scattering, which can be expressed in terms of the elastic scattering amplitude, $T_{\text{el}}(s, t)$, *viz.* its profile function in impact parameter representation, $\Gamma(s, \mathbf{b})$, as

$$S_{\text{el}}(s, \mathbf{\Delta}_{\perp}) = (2\pi)^2 \delta^{(2)}(\mathbf{\Delta}_{\perp}) + (4\pi i/s) T_{\text{el}}(s, t = -\mathbf{\Delta}_{\perp}^2) \quad (4)$$

$$= \int d^2 b e^{-i\mathbf{\Delta}_{\perp} \cdot \mathbf{b}} [1 - \Gamma(s, \mathbf{b})]. \quad (5)$$

The diffractive cross section obtained from Eq. (3) leads to a simple “geometric” expression for the rapidity gap survival probability, which was studied in detail in Ref. 1.

The transverse momentum dependence of the diffractive cross section described by Eq. (3) is essentially an interference phenomenon. The diffractive amplitude is the sum of the original hard amplitude [“1” in Eq. (5)] and the amplitude modified by elastic scattering [“ Γ ” in Eq. (5)]. To illustrate the resulting diffraction pattern in the $\mathbf{p}'_{1\perp}$ and $\mathbf{p}'_{2\perp}$ dependence, we evaluate Eq. (3) with simple analytic parametrizations of the ingredients (see Ref. 1 for details). The profile function of the pp elastic amplitude has been determined from fits to the pp elastic and total cross section data. We parametrize it as $\Gamma(s, \mathbf{b}) = \exp\{-\mathbf{b}^2/[2B(s)]\}$, where $B = 21.8 \text{ GeV}^{-2}$ at $\sqrt{s} = 14 \text{ TeV}$ from extrapolation of fits to the present data. Note that this function approaches the black-disk limit, $\Gamma \rightarrow 1$, at $b = 0$; for a detailed discussion of the role of this effect in diffraction see Ref. 1. The t -slope of the gluon GPD has been extracted from measurements of exclusive J/ψ photo/electroproduction;^{2,3} see Ref. 4 for an overview. We parametrize the t -dependence as $H_g(x, \xi, t) \propto \exp(B_g t/2)$, with $B_g = 3.24 \text{ GeV}^{-2}$ in the x -

Fig. 2. Transverse momentum dependence of the cross section for exclusive double-gap diffraction, Eq. (1). The plots show $|T_{\text{diff}}|^2$ (with $\kappa = 1$) as a function of $\mathbf{p}'_{2\perp}$, for three values of $\mathbf{p}'_{1\perp} = (p'_{1x}, 0)$. The top plots are 2-dimensional log-scale contour plots in $\mathbf{p}'_{2\perp}$; the bottom plots show the distributions for $\mathbf{p}'_{2\perp} = (p'_{2x}, 0)$.

and Q^2 range relevant to production of a system with $M_H \approx 100 \text{ GeV}$ at the LHC. Figure 2 shows $|T_{\text{diff}}|^2$ as a function of $\mathbf{p}'_{1\perp}$, for fixed values of $\mathbf{p}'_{2\perp}$. The pattern can be understood as the wave generated by T_{hard} diffracting off the “hole” formed by the soft interaction profile, $1 - \Gamma(s, \mathbf{b})$. By measuring this dependence one can perform detailed tests of the diffractive reaction mechanism.

The diffraction pattern of Fig. 2 is sensitive to the t -dependence of the gluon GPD. While the slope of the latter is to some degree known from measurements of exclusive J/ψ photo/electroproduction at Fermilab² and HERA,³ more precise data on the shape of the t -dependence would be useful in order to make more accurate predictions. For the valence quark GPDs, such information will come from measurements of hard exclusive processes in ep scattering (deeply-virtual Compton scattering, meson production) with JLab 12 GeV ($0.1 < x < 0.7$) and COMPASS ($0.01 \leq x < 0.1$), extending previous exploratory measurements at JLab 6 GeV and HERMES.⁵ The proposed Electron Ion Collider (EIC) would open a new frontier for the study of hard exclusive processes in the range $0.001 < x < 0.1$, with the capability of fully differential measurements in x , Q^2 , and t .⁵ Depend-

Fig. 3. Summary of high energy pp total cross section data, including Tevatron $p\bar{p}$ data (PDG compilation⁶). The curve is a phenomenological fit based on the parametrization of Ref. 7. The kinematics of the planned LHC and RHIC measurements are also shown.

ing upon the x -range, different exclusive reaction channels ($ep \rightarrow ep\gamma$, $ep \rightarrow epp$, $\gamma^*p \rightarrow pJ/\psi$ and others) have different relative sensitivity to the gluon and quark GPDs, allowing one to disentangle the different GPDs. An interesting question is whether measurements of diffractive pp scattering could themselves contribute to our knowledge of the t -dependence of the GPDs, and thus to the program of “quark/gluon imaging” of the proton.

The formalism described here also requires precision knowledge of the pp elastic scattering amplitude. Figure 3 summarizes the present status of pp total cross section data.⁶ Note that there are no precise pp data above the ISR energy range. The planned measurements at the LHC will greatly enlarge the database. Measurements of polarized pp elastic scattering at RHIC⁸ would be very useful for understanding the onset of the black-disk regime at small impact parameters and the role of spin-flip amplitudes.

The derivation of Eq. (3) for the diffractive amplitude is based on the approximation of independence of hard and soft interactions. As we point out in Ref. 1, the fact that at the LHC energy even hard interactions approach the black-disk regime requires qualitative changes of this picture. Preliminary studies show that this effect increases the effective impact parameters in diffraction compared to the independent interaction approximation, thus narrowing the t_1, t_2 -distribution. Measurements of the $\mathbf{p}'_{1\perp}, \mathbf{p}'_{2\perp}$ -dependence would in fact be very useful to study this new effect.

Measuring rapidity gap events in a collider requires detectors integrated into the accelerator lattice. The BNL-RHIC pp2pp experiment⁸ is currently installing Si tracking stations at 60 m from the STAR Interaction Point (IP). With a dedicated beam tune of $\beta^*(\text{IP}) = 20$ m, the experiment will measure elastic scattering at $\sqrt{s} = 200$ GeV for $0.003 < -t < 0.03$ GeV². Future

runs will reach $\sqrt{s} = 500 \text{ GeV}$. The same beam tune will detect central production in STAR, in coincidence with double diffractive (rapidity gap) tagging in the range $0.005 < \xi_{1,2} < 0.05$. A future tracking installation is planned between the DX and D0 magnets. For the full STAR luminosity, this will allow rapidity gap tagging for $0.01 < \xi \leq 0.15$, correlated with $0.5 \geq |\mathbf{p}'_{\perp}| \geq 0 \text{ GeV}/c$. The TOTEM experiment at the LHC⁹ has installed forward trackers 200 m on either side of the CMS IP. In a series of special tunes with $\beta^* \leq 1540 \text{ m}$, TOTEM will measure pp elastic scattering for $0.001 \leq -t < 8 \text{ GeV}^2$, as well as σ_{tot} and the Re/Im ratio of the forward scattering amplitude. At full CMS luminosity, TOTEM will tag single and double diffractive events with central production for $0.01 \leq \xi < 0.15$. The FP420 collaboration¹⁰ proposes to install proton trackers at 420 m from the interaction points of CMS and ATLAS. This would extend the tagging range for rapidity gap events down to $\xi \geq 0.001$.

In summary, LHC and RHIC are expected to produce extensive data on double diffractive production over a very wide range of s and ξ , as well as precise pp elastic and total cross section results. To further elaborate how the diffractive data could be interpreted in terms of GPDs, and perhaps be used to gain information about the GPDs, is an outstanding challenge for theory. More generally, the concept of GPDs is emerging as a potentially unifying framework for high-energy ep and pp scattering with hard processes.

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