DIP AND BUMP IN PROTON SINGLE-DIFFRACTIVE DISSOCIATION*

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A dip–bump structure in the squared four-momentum transfer (t) distribution of proton's single- and double-diffractive dissociation is predicted around $t \approx -4$ GeV^2 for single-diffractive distribution at LHC energies.

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1. Introduction

Measurements of single (SD), double (DD), and central (CD) diffraction dissociation is among the priorities of the LHC research program. As for now, a lot of studies of high-energy diffraction dissociation physics were performed at different research programs, *e.g.* at the Fermilab (Tevatron) or the LHC (ALICE, SPS, ...). Back in the 2000s, Goulianos, in a series of papers [1] introduced the theoretical approach to calculate cross sections of single, double, and central diffraction.

The basic configurations of reactions with diffractive dissociation are listed below and shown in Fig. 1. Each one is characterized by large rapidity gaps corresponding to the exchange of a trajectory with vacuum quantum numbers (Pomeron). Multi-gap reactions with multi-Pomeron exchanges are also possible when the incoming energy is large enough.

Starting from the 70s, diffractive dissociation was intensively studied both theoretically and experimentally. At the Fermilab, a rich spectrum of resonances in missing masses was revived, still waiting for a better physical interpretation.

An approach based on the Regge-pole factorization was developed in a series of papers [2], see [3] and references therein where single- and double-diffractive dissociation was studied with emphasis on resonances in missing masses treated on the basis of an original duality-based model.

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In the present paper, we continue our program focused on resonance production in missing masses including also the model of Goulianos–Ciesielski [5], modified to include resonances in missing masses. A novel development is the study of a possible dip–bump structure in SD and DD.

We consider diffraction dissociation with configurations shown in Fig. 1 and listed below:

$$\begin{aligned}
\text{Elastic (1):}\quad & pp \to pp\,,\\
\text{SD (2):}\quad & pp \to pX(pY)\,,\\
\text{DD (3):}\quad & pp \to XY\,,\\
\text{CD (DPE) (4):}\quad & pp \to pZp\,,\\
\text{CD}_\text{S}\text{ (5):}\quad & pp \to XZp\,,\\
\text{CD}_\text{D}\text{ (6):}\quad & pp \to XZY\,,
\end{aligned}$$

where X and Y represent diffraction dissociated protons (nucleon resonances), and Z are diffraction produced mesons in the central system. Note that SD (2) implies two symmetric reactions, *i.e.* $p + p' \to X + p'$ and $p + p' \to p + X$. Schematically, those processes are shown in Fig. 1. Many more diffraction dissociation configurations (*e.g.* those with multi-Pomeron exchanges) are possible.

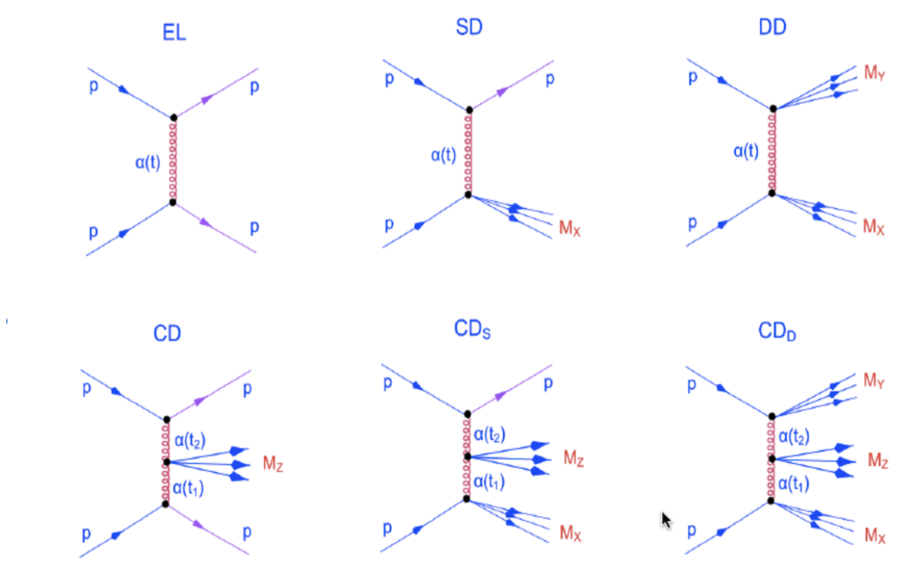

Fig. 1. Diagrams of elastic scattering (EL) and diffraction dissociation (single, double, and central).

1.1. Kinematic variables

The fraction of the momentum of the proton carried by the Pomeron (ξ) is related to the rapidity gap width (Δy) by $\xi = \mathrm{e}^{-\Delta y}$. The variable ξ, in turn, is defined as $\xi_{\mathrm{SD}} = M^2/s$ (for SD), $\xi_{\mathrm{DD}} = M_1^2 M_2^2/(s \cdot s_0)$ (for DD), and $\xi_{\mathrm{CD}} = \xi_1 \cdot \xi_2 = M^2/s$ (for CD). Furthermore, ξ is related to the Feynman scaling variable x_{F}: $\xi = 1 - x_{\mathrm{F}}$.

2. Dip and bump in elastic scattering

The dipole Pomeron scattering amplitude is defined as [4]

$$\begin{aligned} A_P(s,t) &= \frac{\mathrm{d}}{\mathrm{d}\alpha}\left[\mathrm{e}^{-i\pi\alpha/2} G(\alpha)\Big(s/s_0\Big)^{\alpha}\right] \\ &= \mathrm{e}^{-i\pi\alpha/2}\Big(s/s_0\Big)^{\alpha}\Big[G'(\alpha) + \Big(L - i\pi/2\Big)G(\alpha)\Big], \end{aligned} \qquad (1)$$

where $L \equiv L(s) = \ln(s/s_0)$ and $\alpha \equiv \alpha(t)$ is the Regge (here, the Pomeron) trajectory. Since the first term in squared brackets determines the shape of the cone (the derivative becomes the leading term), one fixes

$$G'(\alpha_P) = a_P \,\mathrm{e}^{b_P[\alpha_P - \alpha_{0P}]}\,, \qquad (2)$$

where α_{0P} is the intercept of α_P. $G(\alpha_P)$ is recovered by integration

$$G(\alpha_P) = \int \mathrm{d}\alpha_P G'(\alpha_P) = a_P\left(\mathrm{e}^{b_P[\alpha_P - \alpha_{0P}]}/b_P - \gamma_P\right). \qquad (3)$$

The integration constant γ_P alone has no physical meaning but its numerical value affects strongly the fits.

From the LHC energies on, the contribution from secondary Reggeons can be neglected and one can rely on the Pomeron contribution only, eventually supplied by the odderon,

$$A^{pp}_{p\bar{p}}(s,t) = A_P(s,t) \mp A_O(s,t)\,, \qquad (4)$$

$$A_O(s,t) = -iA_{P\to O}(s,t)\,. \qquad (5)$$

By introducing the parameter $\epsilon_P = \gamma_P b_P$, the Pomeron amplitude can be rewritten in a geometrical form

$$\begin{aligned} A_{(s,t)} &= i\frac{a_P}{b_P}\left(\frac{s}{s_{0P}}\right)^{\alpha_{0P}} \mathrm{e}^{-\frac{i\pi}{2}(\alpha_{0P}-1)}\Big[r_{1P}^2\,\mathrm{e}^{r_{1P}^2[\alpha_P(t)-\alpha_{0P}]} \\ &\quad -\varepsilon_P r_{2P}^2\,\mathrm{e}^{r_{2P}^2[\alpha_P(t)-\alpha_{0P}]}\Big], \end{aligned} \qquad (6)$$

where $r_{1P}^2(s) = b_P + L - i\pi/2$ and $r_{2P}^2(s) = L - i\pi/2$.

We use the norm where

$$\sigma_{\rm tot}(s) = \frac{4\pi}{s}\,{\rm Im}\,A(s,t=0)\,, \tag{7}$$

$$\frac{{\rm d}\sigma_{\rm el}}{{\rm d}t}(s,t) = \frac{\pi}{s^2}\left|A\left(s,t\right)\right|^2 . \tag{8}$$

Fits to the data by the Regge dipole Pomeron and odderon can be found *e.g.* in papers [3, 6].

A dipole amplitude generates a dip–bump structure in the differential cross section. The positions of the dip and bump depend on poorly known slope b of the connected with the differential cross section. The smaller the value of b, the higher the $|t|$ value where the dip–bump structure appears. Thus, in the picture provided by the dipole Regge framework, one expects that in single-diffractive dissociation, a possible dip–bump structure appears at higher $|t|$ values than it does in elastic scattering.

It is known that in pp elastic scattering, the slope of the diffraction cone is energy dependent and rises with increasing energy. At the same time, as the energy rises, the position of the dip–bump structure moves to smaller $-t$ values. The energy-dependent slope is given by the derivative of the logarithm of the differential cross section at $t=0$. In the case of a single-diffractive dissociation, the slope of the differential cross section depends not only on the energy but also on the mass squared of the produced hadronic system as discussed above. Thus parallel to elastic scattering, it is not surprising that the dip–bump structure of the differential cross section of single diffraction through the mass dependence moves in $-t$.

3. From elastic scattering to single-diffractive dissociation (SD)

To generate a dip–bump structure in single-diffractive dissociation, we introduce a dipole Pomeron and odderon exchange to the differential cross section.

By using the proton relative momentum loss variable $\xi = M^2/s$, we get

$$\frac{{\rm d}^2\sigma_{\rm SD}^{PPP}}{{\rm d}t\,{\rm d}\xi} = \left(G'^2(\alpha)+2L_{\rm SD}G(\alpha)G'(\alpha)+G^2(\alpha)\left(L_{\rm SD}^2+\frac{\pi^2}{4}\right)\right) \times\xi^{1-2\alpha(t)}\sigma^{Pp}(s\xi)\,, \tag{9}$$

where

$$L_{\rm SD}\equiv -\ln\xi\,. \tag{10}$$

One finds the position of the dip and the bump in the t dependence of the SD differential cross section

$$t_{\rm dip}^{\rm SD} = \frac{1}{\alpha' b}\ln\frac{\gamma b L_{\rm SD}}{b+L}\,, \tag{11}$$

$$t_{\rm bump}^{\rm SD} \;=\; \frac{1}{\alpha' b}\ln\frac{\gamma b\left(4L_{\rm SD}^2+\pi^2\right)}{4(b+L_{\rm SD})^2+\pi^2}\,. \tag{12}$$

4. Resonances in missing masses

The above model [5] is valid for large, Regge behaved missing masses. Our innovation is in the extension of the model valid also in the region of moderate M_i^2, dominated by resonances (Fig. 2). The idea [2] is based on duality, by which resonances in the direct channel are produced by the pole decomposition of the dual amplitude, dominated by "Reggeized" Breit–Wigner poles with non-linear, complex direct-channel Regge trajectories, providing for finite widths of resonances.

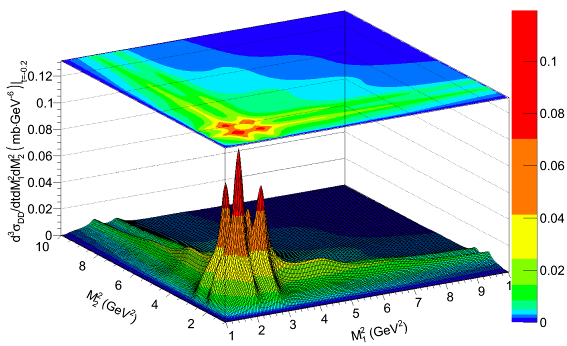

Fig. 2. Resonances in missing masses.

The $\gamma^* p$ total cross section is related to the structure function by

$$\sigma_t^{\gamma^* p}\left(x,Q^2\right) = \frac{8\pi}{P_{\rm CM}\sqrt{s}}\,{\rm Im}\;A^{\gamma^* p}\left(s\left(x,Q^2\right),t=0,Q^2\right)\;, \tag{13}$$

where $P_{\rm CM}$ is the absolute value of center-of-mass momentum of the reaction.

A Reggeon (here, the Pomeron) is similar to the photon, hence Pomeron–proton interaction is similar to photon–proton DIS, where $-Q^2=q^2\to t$ and $s=W^2\to M^2$. Thus, replacing the virtual photon with a Pomeron and substituting $Q^2=-t$, $s=M^2$, we obtain [3, 6]

$$F_2\left(M^2,t\right) = \frac{-t4(1-x)^2}{\alpha\left(M^2-m_p^2\right)\left(1+4m_p^2x^2/-t\right)^{3/2}}\,{\rm Im}\;A^{Pp}\left(M^2,t\right)\;, \tag{14}$$

where $x\equiv x(M^2,t)$ and, instead of x, we use M^2 as variable.

5. Summary

We predict a dip followed by a dump in proton single-diffractive dissociation around $t \approx -4$ GeV^{-2} (see Fig. 3). The prediction is sensitive to the poorly known slope of SD. Further studies, both theoretical and experimental are needed.

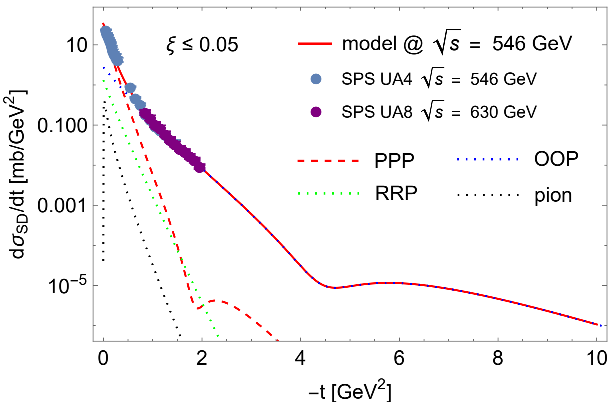

Fig. 3. Predicted dip–bump structure in the t distribution of the ξ integrated differential cross section of single-diffractive dissociation at $\sqrt{s} = 546$ GeV.

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