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INVESTIGATION OF SINGLE PROTON DISSOCIATION [1]

We consider the single proton diffraction dissociation at low missing masses focusing on the interplay between diffractive processes and resonance production. The model incorporates the concept of duality, where the observed cross sections are explained by both smooth background processes and discrete resonance contributions. At low missing masses M_X, this approach leverages the Regge proton trajectory to account for the role of resonances in the cross section. Recent experimental data are used to refine model parameters, enhancing the accuracy of predictions for the differential cross section behavior in the resonance region.

Keywords: single diffraction dissociation, structure function of proton, resonance region, low missing masses, differential cross section.

1. Introduction

Experimental data consistently show that, in high-energy hadron scattering, most events are localized within the small momentum transfer region [1]. Within the framework of Regge theory the interaction between hadrons is carried out through the exchange of Reggeons between their structural components (see Fig. 1, *a*), which ensures the small momentum transfer.

This means that the size of the interaction region between a particle within the hadron and the Reggeon will be large. As a result, the wavelength of the particle interacting with the Reggeon becomes comparable to the size of the interaction region (see Fig. 1, *b*). This creates conditions for the diffraction [2, 3] of the structural particle in the interaction region (see Fig. 1, *c*). The described process can lead to the creation of new particles.

To explain this, we consider an optical analogy. Let us consider the passage of white light through two prisms (see Fig. 2, *a*). One prism disperses the beam into a spectrum, while the other recombines this spectrum into the same beam that it was at the beginning. However, if a small particle is placed between the prisms (see Fig. 2, *b*), some of the waves will scatter off it. Then these scattered waves will not recombine with the remaining waves into a white beam. Therefore, after the light passes through the system of two prisms, in addition to the white beam, we will also have beams that formed due to diffraction on the particle. Just as the field of a light wave can be decomposed into a Fourier integral, the state of a hadron can also be decomposed into a basis of states corresponding to different models of its structure [3,4]. The decomposition of this kind is schematically shown in Fig. 2, *c*. If hadrons do not interact, then, at any given moment, we can both decompose the hadronic state into a series and "recombine" the series into a hadronic state, similar to how prisms disperse and recombine a white beam. But if one of the structural particles scatters off a Reggeon, it will transition to a state that will not "recombine" with the other components of the decomposition into the original hadronic state (see Fig. 2, *d*). Thus, the particle that is "knocked out" of the hadron in this

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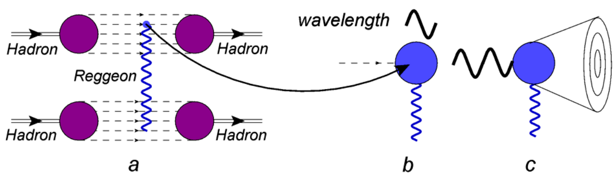


Fig. 1. Reggeon exchange between the structural components of hadrons (a). Relationship between the wavelength of the structural component and the size of the interaction region (b). Diffraction of the structural component on the interaction region (c)

way causes the creation of observed secondary particles, i.e., diffraction dissociation of the hadron. In this work we will consider the single diffraction dissociation. In the next section, we will discuss the model used to calculate the differential cross section and total cross section.

2. The Construction of the Proton Structure Function

The dominant theoretical framework for explaining a single diffraction dissociation (see Fig. 3) is based on Regge theory and the Pomeron exchange hypothesis. In this model, the Pomeron is treated as a colorless object that allows the exchange of momentum without breaking up the proton completely, leading to a diffractive final state. Diffraction dissociation plays a role in probing the structure function of the proton, especially in the context of deep inelastic scattering (DIS) experiments where diffractive processes contribute to understanding the internal quark and gluon distribution within the proton. The diffractive process $p + p \to p + X$ can be viewed as an elastic process. Instead of the elastic scattering amplitude, we consider the scattering amplitude with Pomeron-hadron vertex. We obtain double differential cross section:

$$\frac{d^2\sigma}{dtdM_x^2} \approx \frac{9\beta^4}{4\pi}\left[F^p(t)\right]^2 \left(\frac{s}{M_x^2}\right)^{2\alpha_p(t)-2} \frac{W_2(t, M_x^2)}{2m}, \quad (1)$$

where t is the momentum transfer between colliding particles, s is the square of the center-of-mass energy of the collision, β is the quark-Pomeron coupling, m is proton mass, $W_2\left(t, M_x^2\right)$ is a structure function of proton, $\alpha_P\left(t\right) = 1.08 + 0.25t$ is the Pomeron trajectory, $F^p\left(t\right) = \left(1.0 - t/0.71\right)^{-2}$ is the proton elastic form factor.

The main question is how to obtain the proton structure function $W_2\left(t, M_x^2\right)$. This structure function

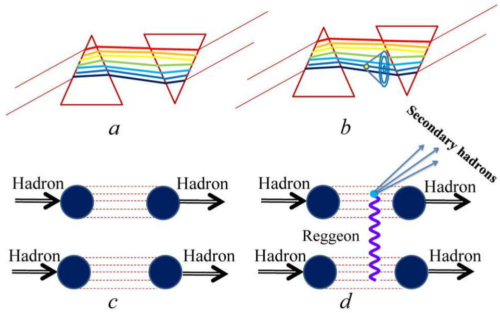
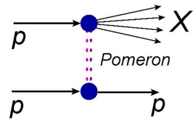


Fig. 2. Decomposition and recombination of white light: passing through two prisms (a). Diffraction effects of a particle between two prisms: formation of secondary beams alongside the white beam (b). Decomposition of hadronic states into component states: analogy with white light and prisms (c). Effect of Reggeon scattering on hadronic states: formation of secondary particles (d)

Fig. 3. Single diffraction dissociation, where p is proton, X is the dissociated system



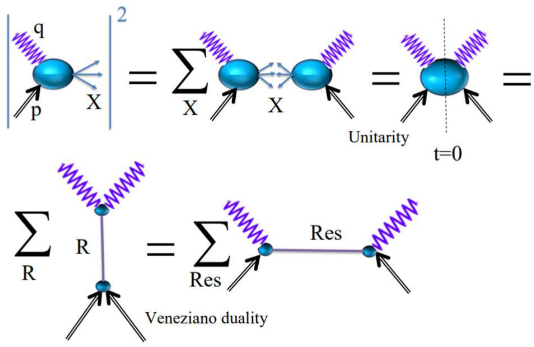


Fig. 4. Connection, through unitarity and Veneziano-duality, between the inelastic form factor and the sum of direct-channel resonances

can be obtained through the deep inelastic process [5]. Using unitarity condition and duality [5], the amplitude $A\left(M_X^2, t\right)$ can be calculated as a sum of resonance contributions (see Fig. 4).

Inserting the proton structure function $W_2\left(t, M_x^2\right)$ into equation (1), we obtain

$$\frac{d^2\sigma}{dtdM_x^2}\left(M_x^2, t\right) = A_0 \left(\frac{s}{M_x^2}\right)^{2\alpha_p(t)-2} \times$$
$$\times \frac{x(1-x)^2\left[F^p(t)\right]^2}{\left(M_x^2 - m^2\right)\left(1 - \frac{4m^2x^2}{t}\right)^{3/2}} \sum_{n=1}^{3} \left[f\left(t\right)\right]^{2n+2} \times$$
$$\times \frac{\operatorname{Im}\alpha(M_x^2)}{\left[2n + 0.5 - \operatorname{Re}\alpha(M_x^2)\right]^2 + \left[\operatorname{Im}\alpha\left(M_x^2\right)\right]^2}, \quad (2)$$

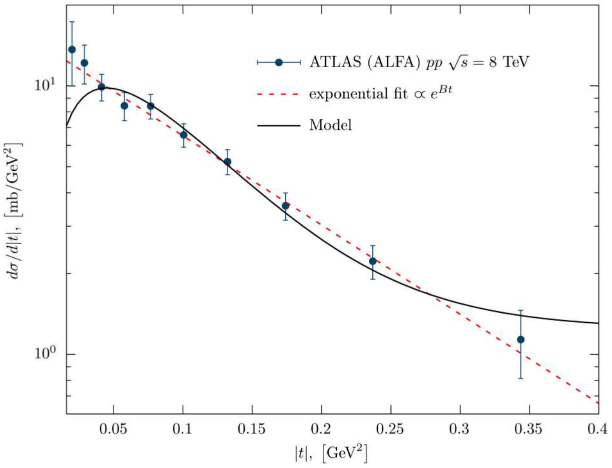


Fig. 5. The differential cross section $d\sigma/dt$ of single diffraction dissociation as a function of $|t|$ compared with the experimental data [8]. The dashed line is the exponential fit. The solid line is the model fit with the constant background contribution b_0

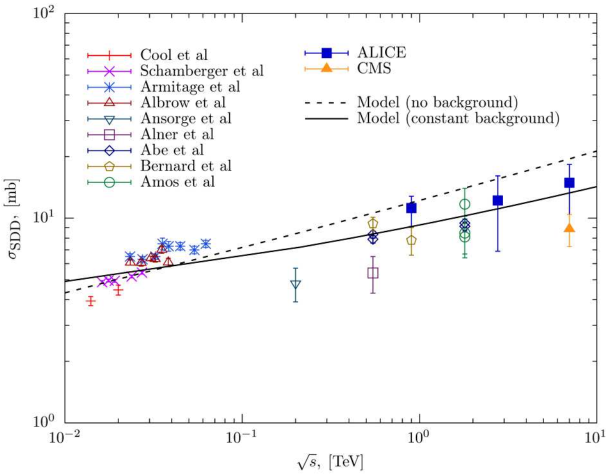


Fig. 6. The total single diffraction dissociation cross section as a function of $\sqrt{s}$. The dashed line is the model fit to the experimental data [9–20] without background contribution. The solid line is the fit with the constant background contribution b

where $A_0 = 9a\beta^4/\pi\alpha_{fs}$ is the normalization factor, α_{fs} is fine structure constant, $x = -t/(M_X^2 - m^2 - t)$ is Bjorken variable, $f(t) = (1 - t/t_0)^{-2}$ is the form factor, t_0 is the model parameter, $\alpha\left(M_X^2\right)$ is the baryonic resonance trajectory.

In *pp* scattering experiments, the interaction between incoming protons can excite the baryons into higher resonant states. The study of angular distributions and energy dependence of the scattering cross sections reveals the contributions from various resonant states. The production of resonances provides evidence of baryon Regge trajectories. In this model, we have four baryons resonances data N(939), N(1680), N(2220), N(2700) [6] which included in the Regge trajectory. The results of the fit of the trajectory to these resonances data are shown in [7].

The study of the single diffraction dissociation with small missing mass offers insights into soft QCD interactions and the nature of the Pomeron. The behavior of the differential cross section (2) in the resonance region at small missing masses M_X are shown in [5]. When M_X refers to cases where the dissociated system has a low invariant mass, close to the mass of the proton, then these processes are often associated with elastic-like scattering. In this work, we have included the contributions from the resonance region $2\ \text{GeV}^2 \leqslant M_X^2 \leqslant 8\ \text{GeV}^2$. The elastic contributions do not fall within the resonance region, therefore, we consider these contributions as background.

3. Results

As a result, we calculate the differential cross section of single diffraction dissociation and the total single diffraction dissociation cross section. We integrate the expression (2) over M_X^2 in resonance region, and we fit it to the experimental data [8]. The fit parameters are $A_0 = 35.58\ \text{mb/GeV}^2$, $t_0 = 1.486\ \text{GeV}^2$, and $b_0 = 8.2\ \text{mb/GeV}^2$, with $\chi^2/\text{d.o.f.} \approx 1.07$. The result of the fit is shown in Fig. 5.

We also calculate the total single diffraction dissociation cross section (see Fig. 6). The values of parameters are $A_0 = 378.43 \pm 16.68\ \text{mb/GeV}^2$ and $b = 1.85 \pm 0.16\ \text{mb/GeV}^2$, with $\chi^2/\text{d.o.f.} = 10.72$.

4. Conclusions

In this work, we have examined the process of single diffractive dissociation with Pomeron exchange at low missing masses M_X. The Pomeron arises naturally from Regge theory, which was developed to explain the behavior of the scattering amplitudes at high energies and low momentum transfer. In [21] to predict a dip-bump structure in single diffractive dissociation, an Odderon exchange and dipole Pomeron are incorporated into the differential cross section. The model presented in this paper shows a good fit to the experimental data, but on the plot Fig. 5, you can see an increase in the differential cross section near zero, which is a drawback of this model. In our opinion, this drawback is related to the fact that the contributions to the cross section are considered only in the resonance region, while the contributions from elastic processes are treated as background. Perhaps, a separate model is needed to accurately account for the contributions from elastic processes.

In this paper, the differential cross section $d\sigma/dt$ of single diffraction dissociation and the total single diffraction dissociation cross section are calculated using C++ program with ROOT framework which is primarily used for the data analysis in high-energy physics.

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1. Konstantin A. Goulianos. Diffractive interactions of hadrons at high-energies. *Phys. Rept.* **101**, 169 (1983).
2. E. Feinberg, I. Pomeranchuk. High energy inelastic diffraction. Phenomena. *Nuovo Cimento Suppl.* **3**, 652 (1965).
3. M.L. Good, W.D. Walker. Diffraction disssociation of beam particles. *Phys. Rev.* **120**, 1857 (1960).
4. A.B. Kaidalov. Diffractive production mechanisms. *Phys. Rept.* **50**, 157 (1979).
5. L.L. Jenkovszky, O.E. Kuprash, J.W. Lämsä, V.K. Magas, R. Orava. Dual-Regge approach to high-energy, low-mass diffraction dissociation. *Phys. Rev. D* **83**, 056014 (2011).
6. C. Amsler *et al.* (Particle Data Group). Review of particle physics. *Phys. Lett. B* **667**, 1-1340 (2008).
7. R. Fiore, L.L. Jenkovszky, F. Paccanoni, A. Prokudin. Baryonic Regge trajectories with analyticity constraints. *Phys. Rev. D* **70**, 054003 (2004).
8. The ATLAS collaboration, G. Aad *et al.* Measurement of differential cross sections for single diffractive dissociation in $\sqrt{s} = 8$ TeV pp collisions using the ATLAS ALFA spectrometer. *J. High Energy Phys.* **2020**, 42 (2020).
9. R.L. Cool, K. Goulianos, S.L. Segler, H. Sticker, S.N. White. Diffraction Dissociation of $\pi^{\pm}$, $K^{\pm}$, and $p^{\pm}$ at 100 and 200 GeV/c. *Phys. Rev. Lett.* **47**, 701 (1981).
10. R.D. Schamberger, J. Lee-Franzini, R. McCarthy, S. Childress, P. Franzini. Mass spectrum of proton-proton inelastic interactions from 55 to 400 GeV/c at small momentum transfer. *Phys. Rev. D* **17**, 1268 (1978).
11. J.C.M. Armitage *et al.* Diffraction dissociation in proton-proton collisions at ISR energies. *Nucl. Phys. B* **194**, 365 (1982).
12. M.G. Albrow *et al.* Inelastic diffractive scattering at the CERN ISR. *Nucl. Phys. B* **108**, 1 (1976).
13. R.E. Ansorge *et al.* Diffraction dissociation at the CERN pulsed collider at CM energies of 900-GeV and 200-GeV. *Z. Phys. C* **33**, 175 (1986).
14. G.J. Alner *et al.* UA5: A general study of proton-antiproton physics at $\sqrt{s} = 546$ GeV. *Phys. Rep.* **154**, 247 (1987).
15. F. Abe *et al.* Measurement of $p\bar{p}$ single diffraction dissociation at $\sqrt{s} = 546$ and 1800 GeV. *Phys. Rev. D* **50**, 5535 (1994).
16. D. Bernard *et al.* The cross section of diffraction dissociation at the cern SPS collider. *Phys. Lett. B* **186**, 227 (1987).
17. N.A. Amos *et al.* A luminosity-independent measurement of the pp total cross section at $\sqrt{s} = 1.8$ TeV. *Phys. Lett. B* **243**, 158 (1990).
18. N.A. Amos *et al.* Diffraction dissociation in pp collisions at $\sqrt{s} = 1.8$ TeV. *Phys. Lett. B* **301**, 313 (1993).
19. V. Khachatryan *et al.* Measurement of diffractive dissociation cross sections in pp collisions at $\sqrt{s} = 7$ TeV. *Phys. Rev. D* **92**, 012003 (2015).
20. B. Abelev *et al.* Measurement of inelastic, single- and double-diffraction cross sections in proton–proton collisions at the LHC with ALICE. *Europ. Phys. J. C* **73**, 2456 (2013).
21. L. Jenkovszky, R. Schicker, I. Szanyi. Dip-bump structure in proton's single diffractive dissociation at the large hadron collider. *Universe* **10**, 208 (2024).

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ДОСЛІДЖЕННЯ ОДИНАРНОЇ
ДИФРАКЦІЙНОЇ ДИСОЦІАЦІЇ ПРОТОНА

Розглядається одинарна дифракційна дисоціація протона при малих втратах маси. Увага зосереджена на взаємодії між дифракційними процесами та утворенні резонансів. Модель включає концепцію дуальності, де спостережувані перерізи пояснюються як фоном, так і дискретними внесками резонансів. При втратах маси M_X цей підхід використовує траєкторію протонів Редже для врахування внеску резонансів у переріз. Останні експериментальні дані використовуються для уточнення параметрів моделі, що підвищує точність прогнозів щодо поведінки диференціального перерізу в області резонансів.

Ключові слова: одинарна дифракційна дисоціація, структурна функція протона, область резонансів, малі маси, диференціальний переріз.