ISSN 1063-7796, Physics of Particles and Nuclei, 2017, Vol. 48, No. 5, pp. 827–828. © Pleiades Publishing, Ltd., 2017.
Original Russian Text © A.V. Karpishkov, M.A. Nefedov, V.A. Saleev, A.V. Shipilova, 2017, published in Fizika Elementarnykh Chastits i Atomnogo Yadra, 2017, Vol. 48, No. 5.

Hard Processes at High Energies in the Reggeized-Parton Approach[1]

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Abstract—Dominant contributions to the cross sections of hard processes at high energies come from the processes with multi-Regge kinematics which reflect the Reggeization of partonic amplitudes as a fundamental property of quantum-field gauge theories. The report briefly describes the Reggeized-parton approach based on the k_T factorization at high energies and on the Lipatov's effective field theory for Reggeized gluons and quarks.

DOI: 10.1134/S1063779617050227

1. REGGEIZED-PARTON APPROACH

In the collinear parton model (CPM), partonic amplitudes are expanded in the powers of the strong-coupling constant $\alpha_S(Q^2)$ using the perturbation theory, and higher-order corrections are consistently taken into account. This model adequately describes the processes with a single hard scale in Q such as the lepton deep-inelastic scattering on protons and nuclei and hadronic production of heavy quarks and gauge bosons [1]. When applied to processes with several hard scales in Q, the CPM encounters problems arising from the presence of large logarithmic terms proportional to $[\alpha_S \log(Q_1/Q_2)]^n$ in higher orders of the perturbation series. In the Regge limit in which the Q scale of the high-energy is much less than the total collision energy, $Q \ll \sqrt{S}$, one has to take into account large logarithmic terms $[\alpha_S \log(1/x)]^n$ where $x \sim Q/\sqrt{S}$.

This can be done using the approach of high-energy factorization, *i.e.,* the k_T factorization depending on the transverse momenta and virtualities of initial partons [2]. In this approach, the cross section of a hard process in a hard-energy hadron collision factorizes as

$$d\sigma(pp \to \mathcal{H} + X) = \sum_{i,j} \Phi_i(x_1, t_1, Q^2) \otimes \Phi_j(x_2, t_2, Q^2) \otimes d\hat{\sigma}_{ij}(\mathcal{H}, t_1, t_2), \quad (1)$$

where $d\hat{\sigma}_{ij}(\mathcal{H}, t_1, t_2)$ is the hard-scattering coefficient (equal to the cross section of the partonic subprocess $ij \to \mathcal{H}$ in the leading approximation), and $\Phi(x_{1,2}, t_{1,2}, Q^2)$ are the unintegrated parton distribution functions (UPDFs). In a specific case, when $t_{1,2} \ll Q^2$ and parton virtualities in a hard process can be neglected, the calculus may rely on the so-called "transverse-momentum-dependent" scheme in which the large logarithmic corrections proportional to $[\alpha_S \log^2(Q^2/t_{1,2})]^n$ and $[\alpha_S \log(Q^2/t_{1,2})]^n$ are consistently estimated. This applies, in particular, to the production of massive leptonic pairs with small transverse momenta when $\Lambda_{QCD} \ll p_T \sim \sqrt{t_{1,2}} \ll Q \ll \sqrt{S}$. However, initial-parton virtualities cannot longer be neglected in the region of large transverse momenta, $p_T \sim \sqrt{t_{1,2}} \sim x_{1,2}\sqrt{S}$. In this case, one must use the Reggeized-parton approach (RPA) which is based on the properties of BFKL factorization in the Regge limit [2]. In this approach, the amplitude of a hard process of particle production factorizes to gauge-invariant blocks describing the particle clusters strongly separated in rapidity. These clusters interact among themselves through t-channel exchanges of Reggeized gluons or quarks viewed as new gauge-invariant degrees of freedom in quantum chromodynamics (QCD) at high energies. The multi-Regge asymptotics of partonic amplitudes are conveniently deduced using the effective gauge-invariant field theory for the QCD high-energy limit developed by Lipatov [3]. In the Reggeized-parton approach, UPDFs are obtained using the Kimber–Martin–Ryskin scheme [4], which allows one to derive them from the known collinear PDFs satisfying the DGLAP evolution equations [1]. This is done by folding in the parton's transverse momentum and virtuality at the final stage of the QCD evolution, thereby guaranteeing that the particles emitted in the hard collision and those of the parton cascade be separated in rapidity.

[1] Talk at the International Session–Conference on the Physics of Fundamental Interactions (JINR Section, Physics Department, Russian Academy of Sciences), Dubna, April 12–15, 2016.

2. HARD PROCESSES IN THE REGGEIZED-PARTON APPROACH

At collider energies of $\sqrt{S_{ep}} = 314$ GeV for HERA, $\sqrt{S_{p\bar{p}}} = 1.8, 1.96$ TeV for the Tevatron, and $\sqrt{S_{pp}} = 7$ and 13 TeV for the LHC, the conditions of the Regge and multi-Regge kinematics are satisfied in the processes of c- and b-quark production at $p_T \ll \sqrt{S}$, e.g., with transverse momenta up to 20–30 GeV. The p_T spectra of the D and B mesons were derived in [5] using RPA within the fragmentation model adequately describe the experimental data of the CDF, D0, CMS, and LHCb collaborations. Likewise, the spectra of the charmonium and bottomonium states produced at the Tevatron and LHC colliders are adequately reproduced by the scheme based on the RPA and the nonrelativistic QCD model that takes into account the singlet and octet mechanisms for the production of heavy quarkonia [6]. The spectra of single jets and direct photons measured at the LHC also agree with the RPA-based predictions for transverse momenta up to 100–200 GeV [7]. In [8], the data on various two-particle correlations in the pair production of light-quark jets, photons, and b-quark jets and in the photon–jet associated production were shown to agree with the RPA-based predictions.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research under grant No. 14-02-00021 and by the Ministry of Education and Science of Russia under the Samara University Competitiveness Program for 2013–2020, project 3.5093.2017/8.9.

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Translated by A. Asratyan