Forward Physics Hard Processes and Saturation: Theory and Phenomenology Review

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Selected aspects of the theory and phenomenology of production of forward jets at the LHC and RHIC are overviewed. In the theory part we discuss basics of frameworks originating from the BFKL dynamics while in the phenomenology part we present results for forward-central jet correlations at the LHC and forward di-jet production at RHIC.

§1. Introduction

Physics in the forward region at hadron colliders is traditionally dominated by soft particle production. However, with the LHC and recent results from RHIC on d-Au scattering\textsuperscript{1)–4)} forward physics phenomenology turns into a largely new field\textsuperscript{5)–7)} involving both soft and hard production processes, because of the phase space opening up at high center-of-mass energies. At the LHC owing to the unprecedented reach in rapidity of the experimental instrumentation, it becomes possible to carry out a program of high-p\textsubscript{T} physics in the forward region. Apart from the purely QCD relevance forward jet production enters the LHC physics program in an essential way for new particle searches, e.g. in vector boson fusion search channels or for the Higgs boson.\textsuperscript{8)} Another area of potential interest in forward physics employs near-beam proton taggers: this will enable studies to be made in the central high-p\textsubscript{T} production mode with forward protons, which can be used for both standard-candle and discovery physics.\textsuperscript{9)} In addition to collider physics applications, measurements of forward particle production at the LHC will serve as input to the modeling of high-energy air showers in cosmic ray experiments.\textsuperscript{10)} The forward production of high-p\textsubscript{T} particles brings jet physics into a region characterized by multiple energy scales and asymmetric parton kinematics. In order to account for multi jet rates in this multi-scale region, it is necessary to use formalisms which go beyond fixed order and include perturbative QCD resummations. The approaches which we are going to overview here are High Energy Factorization (HEF)\textsuperscript{11)} and the HEJ\textsuperscript{12)–14)} framework, for other approaches we refer the reader to \textsuperscript{15)} and \textsuperscript{16)}. Another aspect of forward jet physics is that it probes at least one of the parton density at values of $x$ low enough to study saturation effects, a phenomenon for which there is growing evidence, more extensively.

§2. Hard processes in p-p scattering

In this section we review selected frameworks for calculations of observables characterizing the production of jets in proton-proton collisions with the condition
that the rapidity gap between the produced jets is large. In particular we focus on
the production of a forward jet associated with a central jet. In a proton collision
process in which a forward jet is associated with a central jet, one collimated group
of high $p_T$ hadrons continues along the direction of one of colliding protons – for-
ward detector region, while another group heads toward central region. The high $p_T$
production at microscopic level can be understood as originating from collision of
two partons where one of them which is almost on-shell carries a large longitudinal
momentum fraction $x_2$ of mother proton ($p_2$) while the other one carries a small
longitudinal momentum fraction $x_1$ of the other proton ($p_1$) and is off-shell.

2.1. High Energy Factorization (HEF)

One of the frameworks to describe forward jets is provided by High Energy
Factorization which was derived after the observation of gluon exchange dominance
at high energies. Similarly to collinear factorization it decomposes the cross-section
into parton density functions characterizing incoming hadrons at fixed transverse
momentum, and perturbatively calculable matrix elements. However, apart from
large logarithms of hard scale it also resums large logarithms coming from energy
ordering. The formula for high energy factorization takes the form:

$$
\frac{d\sigma}{dy_1 dy_2 d^2 p_{1t} d^2 p_{2t}} = \sum_{a,b,c,d} \int \frac{d^2 k_1}{\pi} \frac{1}{16 \pi^2 (x_1 x_2 S)^2} |M_{ab \rightarrow cd}|^2 \\
\times \delta^2(\vec{k}_1 - \vec{p}_{3t} - \vec{p}_{4t}) A^*_{a/A}(x_1, k_1^2, \mu^2) f_{b/B}(x_2, \mu^2) \\
\times \frac{1}{1 + \delta_{cd}},
$$

where $k_1 \equiv |k_1|$ and $p_{3t}$ and $p_{4t}$ are transversal momenta of final state partons.
The function $A^*_{a/A}(x_1, k_1^2, \mu^2)$ is the unintegrated gluon distribution which is a solution
to high energy factorisable evolution equations like BFKL, CCFM or BK, and
$f_{b/B}(x_2, k_2^2, \mu^2)$ is the integrated parton density which is a solution of the DGLAP
equation. They describe distributions of transversal and longitudinal momenta of
partons in the incoming protons $A$ and $B$ respectively. The sum is made over all fla-
vors of initial and final state partons. The matrix elements relevant for high energy
factorization describe a hard subprocess where at least one of the incoming partons
is off mass shell. They are calculated by applying the high-energy eikonal projectors
to scattering amplitudes $M$. In Ref. 17) matrix elements relevant for forward jets
phenomenology have been calculated, in fully exclusive form. The framework of high
energy factorization has been implemented in the multi-process Monte Carlo event
generator CASCADE. 18)

2.2. High Energy Jets (HEJ)

Another framework with its origin in high energy resummation is High Energy
Jets (HEJ). 12)–14) It addresses the description of multiple hard perturbative cor-
rections in both the (low) fixed-order and in the parton shower formulation. The
perturbative description obtained with HEJ reproduces, to all orders in QCD, the
high energy limit for both real and virtual corrections to the hard perturbative matrix element. The basic idea of this approach relies on similar observation as in HEF that the dominant contribution at highest energies is due to the exchange of a gluon in the $t$ channel. In this approach the limit of pure $N$-jet amplitudes for large invariant mass between each jet of similar transverse momentum is described by the FKL-amplitudes\(^{(19),(20)}\), which are the foundation of the BFKL framework\(^{(21)}\). The physical picture arising from the FKL amplitudes is one of effective vertices connected by $t$-channel propagators. In this respect this framework needs less approximation than the BFKL equation. The virtual corrections are approximated with the Regge gluon trajectory for the $t$-channel gluon propagators. The final result is a formalism which provides a good approximation order-by-order to the full QCD results, and is fast enough to evaluate all-order results for the amplitudes which can be explicitly constructed and integrated over the $n$-body phase spaces. The cross section in the HEJ framework takes the form:

$$\sigma_{qQ \rightarrow 2j} = \sum_{n=2}^{\infty} \prod_{i=1}^{n} \left( \int_{p_{i\perp}=0}^{p_{i\perp}=\infty} \frac{d^{2}p_{i\perp}}{(2\pi)^{3}} \int \frac{dy_{i}}{2} \right) \frac{|M_{\text{HEJ}}^{\text{reg}}(\{p_{i}\})|^{2}}{s^{2}} x_{a} f_{A,q}(x_{a}, Q_{a}) x_{2} f_{B,Q}(x_{b}, Q_{b}) (2\pi)^{4} \delta^{2}\left(\sum_{k=1}^{n} P_{k\perp}\right) O_{2j}(\{p_{i}\}),$$  \hfill (2.2)

where $|M_{\text{HEJ}}^{\text{reg}}(\{p_{i}\})|$ is the regularized matrix element in which real contributions are built from effective vertices and the virtual contributions originate from the gluon trajectory. The collinear parton densities are $x_{a} f_{A,q}(x_{a}, Q_{a})$, $x_{2} f_{B,Q}(x_{b}, Q_{b})$, and the
function \( O_{2j}(\{p_i\}) \) is equal to one if all final state particles represent jets, otherwise it gives zero.

An interesting observable of the forward central jet production process to which both of the presented frameworks have been applied and have been compared to data, is the \( p_T \) spectrum of produced forward and central jets see Fig. 1. This observable is useful for example in testing and pushing further the development of hard scale dependent unintegrated gluon densities. This is necessary first of all because so far the unintegrated gluon densities were applied mainly to processes at low scales and secondly because the hard scale is not introduced in a unique manner.

§3. Saturation and hard processes in hadron-nuclei scattering

3.1. Saturation at RHIC

Perturbative Quantum Chromodynamics (pQCD) at high energies generates a scale called the saturation scale \( Q_s \). The need for the existence of such a scale originates back to investigations of unitarity violation\(^{23}\) by linear equations of pQCD.\(^{21,24}\) To resolve this problem, higher order perturbative corrections of nonlinear type within the Balitsky-Kovchegov, CGC/JIMWLK framework (i.e. nonlinear modifications to summation of logarithms of the type \( \alpha_s^n(\ln s)^n \)) were considered.\(^{26–30,32–36}\) These unitarity corrections have a clear physical meaning for they require gluons to recombine. The saturation scale depends on energy and its existence prevents gluon densities from rapid growth. Existing data suggest that the phenomenon of saturation occurs in nature. The seminal example is provided by a discovery of the geometrical scaling in HERA data\(^{37}\) and more recently by successful description of the observed de-correlation of forward di-hadrons in \( d+Au \) collisions as compared to \( p-p \) collisions in the RHIC data.\(^{1–4}\)

Here we will focus on the second of process mentioned above. The kinematic range for forward particle detection at RHIC is \( x_p \sim 0.4 \) and \( x_A \sim 10^{-3} \) at the \( \sqrt{s} = 200 \) GeV. Therefore the dominant partonic subprocess is initiated by valence quarks in deuteron, and the \( dAu \rightarrow h_1h_2X \) cross-section is obtained from the \( qA \rightarrow qgX \) cross-section.\(^{38}\) The de-correlation is measured as the coincidence probability to, given a trigger particle in a certain momentum range, produce an associated particle in another momentum range. It is given by:

\[
CP(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig}}
\]

with

\[
N_{pair}(\Delta\phi) = \int y_i, |p_{i\perp}| \frac{dN_{pA \rightarrow h_1h_2X}}{d^2p_1 d^3p_2}, \quad N_{trig} = \int y,p_{\perp} \frac{dN_{pA \rightarrow hX}}{d^3p}.
\]

In Fig. 2 the comparison of data to CGC predictions is shown. The agreement with data is very good and provides support for alternative explanations of the phenomenon of suppression of the forward hadron in \( d+Au \) which might also be explained by partonic energy loss during propagation through nuclear matter and which is not considered in the CGC framework.
Fig. 2. (color online) The coincidence probability at a function of $\Delta \phi$. Left: CGC calculations\textsuperscript{38}) for p+p and central d+Au collisions, the disappearance of the away-side peak is quantitatively consistent with the STAR data. Right: CGC predictions for different centralities of the d+Au collisions, the near-side peak is independent of the centrality, while the away-side peak reappears as collisions are more and more peripheral.

3.2. Towards p-Pb in LHC

One of the prospects for the LHC is to study collisions of protons with Pb nuclei. For a detailed prospect for this we refer the reader to 40). One of the opportunities is to reduce the uncertainty of nuclear pdfs and use this knowledge to interpret $A + A$ data. From our perspective the most interesting opportunity is to make use of the asymmetry of this initial configuration to access the forward region and to study the saturation effects with nuclear targets extending the kinematically access by several orders of magnitude in $x$. To be prepared for this experiment and fully profit from it, one needs however further theoretical developments in the field of unintegrated parton densities. One of the open questions is how to account both for exclusive final states at large $p_T$ like for example discussed above di-jets and saturation. The problem is that the frameworks used at present either accounts for hardness like DGLAP, CCFM or for saturation like CGC/BK and an approach when one accounts for both is missing. Practically it means that the CCFM gluon density is not proper at small $k_T$ while the BK gives unphysical gluon densities at large $k_T$, see Fig. 3). It is however possible to introduce nonlinear effects into the CCFM framework and therefore to allow both for hard processes and nonlinear effects within one framework. One of the methods is to introduce proper boundary conditions which suppress the gluon density for certain combinations of $k_T$ and $x$.\textsuperscript{41–43}) Another approach is to allow for coherent emission of gluons accompanied by the dynamical fusion of gluons.\textsuperscript{44})

§4. Conclusions

We gave an overview of forward physics at LHC and RHIC focusing on jet final states. The goal was to show frameworks which follow from the same perturbative principle at high energy asymptotics i.e. the BFKL like summation of large logarithms of the type $\alpha_s^n \ln(s/s_0)^n$. We also pointed at the possible prospects for p+Pb collisions which would provide an excellent opportunity to constrain parton densi-
Fig. 3. (color online) Comparison of unintegrated gluon densities obtained from rc-BK from 40) and CCFM evolution. The blue dotted line corresponds to the rc-BK gluon density while the red and green lines correspond to the CCFM unintegrated gluon densities evaluate at different factorization scales.

ties and to study both hard processes and dense systems. This requires development of a unified framework which will allow for studies of parton saturation and hard processes.

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