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Nuclear and Particle Physics Proceedings 289–290 (2017) 71–76

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Aspects of hard QCD processes in proton–nucleus collisions

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Abstract

Hard processes in high-energy proton–nucleus collisions are a powerful tool in order to investigate several importants aspects of QCD in a nuclear medium, such as nuclear shadowing, parton multiple scattering or medium-induced gluon radiation. I review in these proceedings recent progress in that field.

Keywords: Hard processes, QCD, proton–nucleus collisions

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1. Introduction

Given the title of this conference, the utility of hard processes to probe QCD media – whether nuclear matter or the quark-gluon plasma – in nuclear collisions needs little introduction. First of all, their variety is appealing: measurements in heavy-ion collisions at RHIC and at LHC include electroweak processes (prompt photons, weak bosons), inclusive and heavy-flavour jets, as well as light and heavy hadrons. Moreover, most of these processes are well understood in QCD, meaning that perturbative calculations exist – either fixed order, typically next-to-leading order (NLO) in the strong coupling constant α_s, or including resummation – and accurately describe pp collision data; this is, however, less true when it comes to the production of hadrons, and in particular quarkonium production which remains far from being understood. Very much discussed at this conference, jet quenching and quarkonium suppression are among the most spectacular manifestations of quark-gluon plasma formation in heavy-ion collisions. Extracting the physical properties of the QCD plasma from these experimental observations remains however a delicate, albeit exciting, challenge.

Proton–nucleus collisions are (slightly) less complex than heavy-ion collisions, but no less interesting. In these reactions, the QCD medium under consideration, ‘cold’ nuclear matter, is simpler than the quark-gluon plasma: it is static, with a known nuclear density profile (despite the fluctuating positions of the nucleons inside the nucleus). At the LHC, bulk observables in pPb collisions may point to the formation of a hot medium; its influence on hard processes, however, often appears limited (a possible exception being the production of excited quarkonia). Moreover, on the experimental side measurements are more easily performed due to the lower multiplicity underlying event. In short, the field of hard processes in pA collisions aims at the precision of the QCD studies performed in pp collisions while allowing for a quantitative study of nuclear medium effects in a controlled environment.

In these proceedings I will discuss several QCD phenomena expected to affect the rate of hard processes in pA collisions, either within QCD collinear factorization (Section 2) or clearly beyond this framework (Section 3). Section 4 is devoted to the event activity dependence and the correlations between soft underlying event and hard process.

2. Collinear factorization

Let us first consider a generic hard process in pp collisions, characterized by a hard scale Q much larger than a typical hadronic scale, $Q \gg \Lambda = \mathcal{O}(1\ \text{GeV})$. (Think of the production of a large transverse momentum parton or a massive weak boson.) According to QCD collinear factorization, the production cross sec-

https://doi.org/10.1016/j.nuclphysbps.2017.05.014

tion can be written symbolically as

$$\sigma^{\mathrm{pp}} = f_i^p(\mu) \otimes f_j^p(\mu) \otimes \hat{\sigma}_{\mathrm{ij}}(\mu, \mu') + O\left(\alpha_s^k\right) + O\left(\frac{\Lambda^n}{Q^n}\right), \tag{1}$$

in which long distance physics is encoded into parton distribution functions (PDF) of the incoming protons, f^p, while the partonic cross section, $\hat{\sigma}$, represents short distance physics[1]. Collinear factorization exhibits strong predictive power: (i) PDF are non-perturbative but universal quantities, which can be probed either in deep inelastic scattering or in hadronic collisions, and (ii) the short distance scattering is computable (at least in principle, if not in practice) at any order in perturbation theory. One should also keep in mind that collinear factorization is an approximation. On top of neglecting higher-order terms in the perturbative expansion, process-dependent power corrections (so-called 'higher-twist') of order[2] $O(\Lambda^n/Q^n)$ might contribute significantly to the cross section when the scale Q is not too large.

What about collinear factorization in pA collisions? Regarding the nucleus as any other hadron, the cross section Eq. (1) could be written as

$$\sigma^{\mathrm{pA}} = f_i^p(\mu) \otimes f_j^A(\mu) \otimes \hat{\sigma}_{\mathrm{ij}}(\mu, \mu') + O\left(\alpha_s^k\right) + O\left(\frac{\Lambda_{\mathrm{A}}^n}{Q^n}\right),$$

with f^A now being the PDF of the nucleus. Note the new scale Λ_{A} controlling the power corrections which could, in principle, increase with the target size. Consequently higher-twist processes are likely to be enhanced in pA collisions with respect to pp collisions.

An important question is what to expect for f^{A}. Imagine a super dilute nucleus, in which nucleons are separated over macroscopic distances: the PDF of such a nucleus would simply be given by the incoherent sum over the proton and neutron PDF. The leading twist cross section (neglecting power suppressed corrections for the time being) would thus simply be expressed as $\sigma^{\mathrm{pA}} = Z\ \sigma^{\mathrm{pp}} + (A - Z)\ \sigma^{\mathrm{pn}} \simeq A\ \sigma_{\mathrm{pp}}$ (assuming $\sigma^{\mathrm{pp}} \simeq \sigma^{\mathrm{pn}}$ for QCD processes at high energy) making the nuclear production ratio, $R_{p\mathrm{A}} \equiv 1/A\ \sigma^{\mathrm{pA}}/\sigma^{\mathrm{pp}}$, normalized to unity. In practice, however, the typical distance between nucleons, say 1 fm, is much smaller than the (Ioffe) length over which the hard process develops, $\ell_c = 1/(2mx_2)$, x_2 being the target parton momentum fraction of the nucleon and m the nucleon mass. When $\ell_c \gtrsim 1$ fm, equivalently at small $x_2 \lesssim 10^{-1}$, several nucleons in the target contribute coherently to the hard process, leading to the depletion of nuclear PDF (nPDF) ratios, $R_i \equiv f_i^A/Af_i^p < 1$, known as shadowing. The precise determination of shadowing, and more generally nPDF at any value of x, is thus an important requirement in order to predict accurately the yields of hard processes in pPb collisions at the LHC.

As is the case for their proton counterparts, the nPDF cannot be computed from first principles (although their evolution, in either x or Q^2, is perturbative) and need to be extracted from global fits to data. Over the last years various nPDF sets based on DGLAP evolution have been extracted at NLO accuracy and a first attempt (KA15) has been made recently at NNLO [1]. Due to the lack of data on nuclear targets the present nPDF sets still suffer from large uncertainties, especially at small x and in the gluon sector; for the same reason it was shown that the present nPDF global fits suffer from a strong sensitivity on their parametrization at the input scale [2]. Using reweighting techniques [3], the present and future LHC pPb data can be used to significantly narrow the uncertainties of the nPDF sets currently available [4]. What are the best processes to constrain nuclear parton densities at the LHC? Some 'ideal' requirements (not strictly necessary but which I consider preferable) are listed:

(i) The scale Q should be 'large enough' compared to the saturation scale of the nucleus, $Q \gg Q_s$ (typically $Q_s \simeq$ 1–3 GeV at the LHC), in order to avoid the appearance of non-linear evolution effects not taken into account in the nPDF global fits; this would also suppress large power corrections entering pA cross sections. Note however that nPDF effects are expected to vanish at very large scales ($R_i^A(x, Q^2 \to \infty) \to 1$) because of QCD evolution; to illustrate this, the gluon nPDF ratio given by EPS09 at $x = 10^{-3}$, $R_g^{\mathrm{Pb}} = 0.84$ at $Q^2 = 10\ \mathrm{GeV}^2$ while $R_g^{\mathrm{Pb}} = 0.96$ at $Q^2 = 10^4\ \mathrm{GeV}^2$. Therefore Q should not be chosen too large in order to keep some sensitivity in the data;

(ii) Due to multiple scattering, the well-known modification of the $p_\perp$ spectrum of particles produced in pA collisions (the so-called 'Cronin effect') is likely to spoil a clean extraction of nPDF. Such an effect nevertheless disappears for $p_\perp$-integrated cross sections or at $p_\perp \gg Q_s$. In other words, it may be safer *not* to use $p_\perp$-differential cross sections at moderate $p_\perp$ values, say $p_\perp \lesssim 10$ GeV;

(iii) The production of color neutral hard probes should

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[1] Factorization and renormalization scales are of order $\mu \sim \mu' \sim Q$ to avoid the appearance of large logarithms $\ln(Q/\mu)$.

[2] Typically $n = 1$ or $n = 2$ depending on the specific process.