EFFECTS OF DENSE MATTER ON HADRON PRODUCTION IN HEAVY-ION COLLISIONS ‡

G. PAPP[1,2], G. BARNAFÖLDI[3], G. FAI[1], P. LÉVAI[3], Y. ZHANG[1]

[1] *CNR, Kent State University, Kent, OH, USA*
[2] *HAS Research Group, ELTE, Budapest, Hungary*
[3] *KFKI RMKI, P.O. Box 49, Budapest, Hungary*

Abstract

The intrinsic transverse momentum distribution of partons in the nucleon can be used to explain a large amount of high-p_T hadron and photon production data in high-energy nucleon-nucleon collisions at energies $\sqrt{s} \approx 20$ to 1800 GeV. However, proton-nucleus experiments at energies ≈ 30 GeV show an extra enhancement (Cronin effect) in the yield of photons and mesons compared to a simple extrapolation of the proton-proton data. This enhancement is due to the effect of the dense hadronic matter encountered by the projectile proton in the nuclear environment. We discuss the origin and the properties of the nuclear enhancement.

1 Introduction

In hard particle production in proton-nucleus (pA) collisions, the effect of the nuclear medium manifests itself in a cross section enhancement at high transverse momentum relative to a simple superposition of the proton-proton (pp) production cross section[1]. The purpose of this contribution is to study the Cronin effect, and to look for an explanation in terms of the dense nuclear medium that the projectile proton has to traverse in pA collisions. The presence of the medium leads to an increase of the width of the transverse momentum distribution of partons. The transverse momentum distribution of partons is recently also utilized in the description of dilepton data at SPS[2].

2 Transverse momentum distribution in pp collisions

The E609 collaboration extracted a width of $\langle k_T \rangle = (0.9 \pm 0.2)$ GeV/c for the transverse momentum distribution of partons in the proton from dijet events

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at 400 GeV/c[3]. We use $\langle k_T \rangle$ as an energy dependent parameter to obtain a satisfactory description of hard-particle production cross sections in the center-of-mass energy range 18 GeV $\leq \sqrt{s} \leq$ 65 GeV in pp collisions. The transverse momentum distribution enters in the perturbative QCD (pQCD) calculation of the hard-particle production cross section via the factorization-theorem based convolution

$$\begin{aligned} E\frac{d\sigma^{pp}}{d^3p} &= \sum_{abcd}\int dx_1 dx_2\ d^2k_{T1}\ d^2k_{T2}\ f_{a/p}(x_1,Q^2) g_1(\vec{k}_{T1})\ f_{b/p}(x_2,Q^2) g_2(\vec{k}_{T2}) \\ & \qquad \frac{d\sigma}{d\hat{t}}(ab \to cd)\,\frac{D_c(z_c,\widehat{Q}^2)}{\pi z_c} \quad , \end{aligned} \tag{1}$$

where the connection to the observed incoming and outgoing particles is established through the parton distribution functions (PDFs) $f(x,Q^2)$ and fragmentation functions (FFs) $D(z,\widehat{Q}^2)$[4]. The value of z_c is fixed by energy-momentum conservation. The transverse momentum distribution is denoted by $g(\vec{k}_T)$, and as an approximation, is taken to be a Gaussian: $g(\vec{k}_T) = \exp(-k_T^2/\langle k_T^2 \rangle)/\pi\langle k_T^2 \rangle$. Here, $\langle k_T^2 \rangle$ is the 2-dimensional width of the k_T distribution and it is related to the average transverse momentum of one parton as $\langle k_T^2 \rangle = 4\langle k_T \rangle^2/\pi$.

The cross section of the hard subprocesses in Eq. (1) is to be calculated in pQCD. In principle, the order in the strong coupling constant, to which this is done, is a matter of decision based on the convergence of the series. At next-to-leading order (NLO), the cross section can be viewed as

$$\frac{d\sigma^{NLO}}{d\hat{t}} = \frac{d\sigma^{NLO}_{Born}}{d\hat{t}} + \frac{d\sigma^{NLO}_{corr}}{d\hat{t}} = K\frac{d\sigma^{NLO}_{Born}}{d\hat{t}} \quad , \tag{2}$$

where the factor K may depend on both, the center-of-mass energy and the transverse momentum, and represents an approximate way to take into account corrections beyond the Born term. For sufficiently high energies and transverse momenta $K = const.$ is a good approximation[5]. We adapted $K = 2$ in the present calculation. For the PDFs we used the MRST98 set[6], which is a NLO parameterization and incorporates an intrinsic k_T. The scales are fixed, $\Lambda_{\overline{MS}}(n_f = 4) = 300$ MeV and $Q = \widehat{Q} = p_T/2$. An NLO parameterization was used for the FFs, too[7], thus assuring the consistency of Eq. (1). The energy dependence of $\langle k_T^2 \rangle$ and the quality of the agreement with hard π^0 and γ production data in pp collisions is displayed in Ref. [8]. Note that a satisfactory description of the pion spectra does not appear possible in NLO without transverse-momentum smearing[9].

3 Enhanced transverse momentum in pA collisions

The Cronin effect in pA collisions can be understood phenomenologically[10] in terms of an increased $\langle k_T^2 \rangle$ according to

$$\langle k_T^2 \rangle_{pA} = \langle k_T^2 \rangle_{pp} + C \cdot h_{pA}(b) \ . \tag{3}$$

Here, $h_{pA}(b)$ describes the number of nucleon-nucleon collisions at impact parameter b, which contribute to the transverse momentum broadening of the partons in the projectile. The particle-producing hard collision is clearly not counted, but it is also not obvious that all other possible collisions contribute. We therefore use the term *effective* to distinguish the transverse-momentum broadening collisions. Each effective collision imparts a transverse momentum squared C on average.

If it is assumed that the projectile proton suffers soft collisions, which do not change the projectiles identity as a proton, but enhance the width of the transverse momentum distribution of its partons via random interactions, each imparting some transverse momentum, then all collisions of the projectile at impact parameter b are effective. This can be expressed by using $h_{pA}^{all}(b) = \nu_A(b) - 1$, where $\nu_A(b) = \sigma_{NN}\, t_A(b)$ is the collision number at impact parameter b, with σ_{NN} being the total nucleon-nucleon cross section. However, using this prescription, the coefficient C turns out to be target dependent[8].

Furthermore, it is necessary to use values as high as $C \approx 1$ GeV^2 with this prescription, no longer characteristic of soft physics. Thus it is natural to assume that the projectile proton suffers a more drastic change while traveling through the dense matter of the target nucleus. In particular, we assume that the projectile proton will break up in a hard or semi-hard collision. As a consequence of this violent event, partonic degrees of freedom become appropriate. The enhanced width of the transverse momentum distribution reflects this change of the physically relevant degrees of freedom, and gets "measured" in the collision that breaks the proton apart.

We studied scenarios where only a fraction of the possible $\nu_A(b) - 1$ collisions is effective in the sense of nucleon-nucleon collisions. In the limiting case, referred to as the *saturating* prescription, we allow at most one effective collision using a smoothed step function $h_{pA}^{sat}(b)$, defined as

$$h_{pA}^{sat}(b) = \begin{cases} 0 & \text{if } \ \nu_A(b) < 1 \\ \nu_A(b) - 1 & \text{if } \ 1 \le \nu_A(b) < 2 \\ 1 & \text{if } \ 2 \le \nu_A(b) \end{cases} \ . \tag{4}$$

The saturated Cronin factor is denoted by C^{sat}. By the saturating prescription we limit our consideration to at most one *effective* transverse momentum

Figure 1: **Left panel**: Data to theory ratio on a linear scale for the $pW \to \pi^0 X$ reaction at $\sqrt{s} = 27.4$ GeV, data from [1]. We show $C^{sat} = 1.2$ GeV^2 (full line) and $C^{sat} = 0$ (dashed line). **Right panel**: Data to theory ratio for the $pBe \to \gamma X$ reaction at $\sqrt{s} = 31.6$ GeV, data from [11]. Solid line indicates $C^{sat} = 1.2$ GeV^2, dashed line means $C^{sat} = 0$.

broadening collision in the above sense.

The left panel of Fig 1. shows the data/theory ratio on a linear scale for the $pW \to \pi^0 X$ reaction with (full line) and without (dashed line) the saturated Cronin enhancement, using the value $C^{sat} = 1.2$ GeV^2, with the data from Ref. [1]. In the left panel we illustrate that the same value of C_{sat} provides a satisfactory description of recent photon production data in p + Be collisions in the same energy region[11]. Since the effect of the nuclear medium on the projectile proton should not depend on the outgoing particle, we consider the common value of C_{sat} a strength of our model.

Our C^{sat} is determined at $\sqrt{s} \approx 30$ GeV. Its value may of course depend on the center-of-mass energy. This dependence needs to be mapped out in a wide energy range up to $\sqrt{s} = 200$ GeV in order to make the model useful for RHIC predictions. On the other hand, we expect C^{sat} to be independent of the target and of the produced hard particle. Systematic experimental studies to test these predictions would be welcome.

4 Summary

We reported on a phenomenological model to understand the Cronin effect. The enhancement of hard particle production cross sections in pA collisions relative to scaled pp results was connected to an increase in the width of the transverse momentum distribution of the projectile as it traverses the dense nuclear medium of the target. Physically rather different pictures for the enhancement of the transverse momentum width were studied. The extreme saturating prescription gives reasonable agreement with available data at the present level of the calculation.

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