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"Naked" Cronin effect in $A + A$ collisions from SPS to RHIC

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Abstract. Baseline computations of the Cronin effect in nuclear collisions at energies spanning the SPS and the RHIC accelerators are performed in the Glauber-Eikonal model, which ascribes the effect to initial-state incoherent multiple parton scatterings. The model accounts very well for the mid-rapidity Cronin effect in hadron–nucleus collisions in the $\sqrt{s} = 27$–$200\,\text{GeV}$ center of mass energy range, and will be extended to nucleus–nucleus collisions. The computations are performed under the assumption that the partons do not interact with the medium produced in the collision. Therefore, medium effects such as energy loss in a quark–gluon plasma may be detected and measured as deviations from the presented baseline computation of the "naked" Cronin effect.

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1 Introduction

The Cronin effect [1] is the deformation of hadron transverse momentum spectrum in hadron–nucleus ($p+A$) and nucleus–nucleus ($A+A$) collisions relative to linear extrapolation from proton–proton ($p+p$) reactions. The Cronin effect may be quantified by taking the hadron transverse momentum (p_T) spectrum in $p+A$ collisions in a given centrality class (c.cl.), normalizing it to binary scaled $p+p$ collisions by the inverse thickness function T_A, and finally dividing it by the $p+p$ spectrum:

$$R_{hA} = \frac{1}{T_A(\text{c.cl.})} \frac{\mathrm{d}N}{\mathrm{d}p_\text{T}^2 \mathrm{d}y}^{pA\to hX}(\text{c.cl.}) \Bigg/ \frac{\mathrm{d}\sigma}{\mathrm{d}p_\text{T}^2 \mathrm{d}y}^{pp\to hX} . \quad (1)$$

For $A + A$ collisions, an analogous definition of R_{AA} is used. To cancel systematic errors as much as possible, it is also customary to take the ratio of a given centrality class to the most peripheral one.

In $p + A$ collisions, the ratio R_{hA} is smaller than 1 at low momentum $p_\text{T} \lesssim 2\,\text{GeV}$ (the spectrum is suppressed). At intermediate $p_\text{T} \sim 2$–$6\,\text{GeV}$ is larger than 1 (the spectrum is enhanced) and finally tends to 1 at higher p_T's (the spectrum follows a $p+p$ scaling). The described bell shape of the "Cronin ratio" R_{hA} has been observed on a wide energy range, $\sqrt{s} \approx 20$–200, and for different hadron species [1,2].

In $A+A$ at low energy, $\sqrt{s} = 17.4\,\text{GeV}$, at SPS [3], one observes a similar behavior of the Cronin ratio as in $p+A$ collisions. However, at RHIC energy $\sqrt{s} = 63$–$200\,\text{GeV}$, the above described bell shape appears on top of a largely suppressed spectrum [4]. This suppression is often interpreted as due to energy loss of a parton traveling a medium of density up to 15 times the normal nuclear density [5], largely sufficient for the creation of a quark–gluon plasma (QGP).

An intriguing fact in both the $p + A$ and $A + A$ cases is the much larger magnitude of the effect on baryons compared to mesons, with the difference between the two seeming to decrease with energy [1,6]. This aspect of the famed "baryon/meson" anomaly in high energy nuclear collision has not yet found an accepted explanation in theory, and will later come back into our discussion.

In this note, I discuss the Glauber-Eikonal (GE) model computation [7] of the Cronin effect in $A + A$ collisions. The model describes multiple parton scatterings in pQCD and extrapolates the physics of proton–proton ($p+p$) collisions to $p + A$ and $A + A$ collisions without ad hoc parameters for the nuclear case. This allows a baseline computation of the Cronin effect in $A+A$ without the further complications of medium-induced modifications of the p_T spectrum. This is what I call the bare, or "naked", Cronin effect. Comparison with experimental data allows one to measure the medium-induced effects, and in particular to detect when the medium begins to suppress hadron spectra as a function of the energy and centrality of the collisions.

2 The Glauber-Eikonal model

The Glauber-Eikonal (GE) approach [7] to the Cronin effect treats multiple $2 \to 2$ partonic collisions in collinearly factorized pQCD. The low-p_T spectra in nuclear collisions

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are suppressed by unitarity. At moderate p_{T}, the accumulation of transverse momentum leads to an enhancement of transverse spectra. At high p_{T} the binary scaled $p+p$ spectrum is recovered.

The cross-section for the production of a hadron h with transverse momentum p_{T} and rapidity y in $p+A$ collisions at fixed impact parameter b is written as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2p_{\mathrm{T}}\mathrm{d}y\mathrm{d}^2b}^{pA\to hX} = \langle xf_{i/p}\rangle \otimes \frac{\mathrm{d}\sigma^{iA}}{\mathrm{d}^2p_{\mathrm{T}}\mathrm{d}y_i\mathrm{d}^2b} \otimes D_{i\to h}\Big|_{y_h=y} + T_A(b)\langle xf_{j/A}\rangle \otimes \frac{\mathrm{d}\sigma^{jp}}{\mathrm{d}^2p_{\mathrm{T}}\mathrm{d}y_j} \otimes D_{j\to h}\Big|_{y_h=-y}, \quad (2)$$

where the crossed-circle symbols denote appropriate integrations and summations over parton flavors i and j; see [7] for details. The first term in (2) accounts for multiple semihard scatterings of the parton i on the target nucleus; in the second term the nucleus partons are assumed to undergo a single scattering on the proton. $T_A(b)$ is the target nucleus thickness function, and $D_{i\to h}$ is the fragmentation function of the i parton. The average parton flux from the proton, $\langle xf_{i/p}\rangle$, and the parton–nucleon cross-section, $\mathrm{d}\sigma^{iN}$, are defined as

$$\frac{\mathrm{d}\sigma^{iN}}{\mathrm{d}^2p_{\mathrm{T}}\mathrm{d}y_i} = K\,\frac{\mathrm{d}\hat\sigma^{ij}}{\mathrm{d}\hat t}(p_0) \otimes x_j f_{j/N}(\langle k_T^2\rangle), \quad (3)$$

$$\langle xf_{i/p}\rangle = K\,x_i f_{i/p}(\langle k_T^2\rangle) \otimes \frac{\mathrm{d}\hat\sigma^{ij}}{\mathrm{d}\hat t}(p_0) \otimes x_j f_{j/N}(\langle k_T^2\rangle) \times \left(\frac{\mathrm{d}\sigma^{iN}}{\mathrm{d}^2p_{\mathrm{T}}\mathrm{d}y_i}\right)^{-1}, \quad (4)$$

where only the sum over j is understood. $\hat t$ is the Mandelstam variable and $\mathrm{d}\hat\sigma/\mathrm{d}\hat t$ are leading order parton–parton cross-sections in collinearly factorized pQCD. K is a constant factor which takes into account next-to-leading order corrections. To regularize the IR divergences of the single-scattering pQCD parton–nucleon cross-sections, a small mass regulator p_0 is introduced in the propagators, and $Q=\sqrt{p_{\mathrm{T}}^2+p_0^2}/2$ is the scale of the hard process. Finally, a small intrinsic transverse momentum, $\langle k_T^2\rangle = 0.52\,\mathrm{GeV}^2$, is introduced to better describe the hadron spectra in $p+p$ collisions at the intermediate $p_{\mathrm{T}}\approx 2$–$5\,\mathrm{GeV}$. Since all parameters have been fixed in $p+p$ collisions, we are able to compute the spectra in $p+A$ and $A+A$ collision with no extra freedom.

The free parameters p_0 and K in (3)–(4) are fitted to, viz., low- and high-p_{T} hadron production data in $p+p$ collisions at the energy and rapidity of interest. For this study, I took from [7] the values of p_0 extracted at $\sqrt{s}=27.4$ and $200\,\mathrm{GeV}$, viz., $p_0=0.7$ and $1.0\,\mathrm{GeV}$, and assumed a logarithmic dependence on the energy:

$$p_0 = 0.151 + 0.100\log\left(\frac{s}{1\,\mathrm{GeV}}\right) \pm 10\%\,\mathrm{GeV}\,. \quad (5)$$

As regards the K factor, it turns out to be $K\approx 1$, quite insensitive to the energy of the collision in the 27–200 GeV energy range, and I will use this value throughout this note. Clearly, one would need more systematic studies of spectra in $p+p$ collisions, especially when extrapolating the parameters at the SPS energy of 17 GeV. These will be presented elsewhere.

Nuclear effects are included in $\mathrm{d}\sigma^{iA}$, the average transverse momentum distribution of a parton who suffered at least one semihard scattering on the target nucleus A:

$$\frac{\mathrm{d}\sigma^{iA}}{\mathrm{d}^2p_{\mathrm{T}}\mathrm{d}y\mathrm{d}^2b} = \sum_{n=1}^{\infty}\frac{1}{n!}\int \mathrm{d}^2b\,\mathrm{d}^2k_1\cdots\mathrm{d}^2k_n\,\delta\left(\sum_{i=1,n}\boldsymbol{k}_i - \boldsymbol{p}_{\mathrm{T}}\right) \times\frac{\mathrm{d}\sigma^{iN}}{\mathrm{d}^2k_1}T_A(b)\times\cdots\times\frac{\mathrm{d}\sigma^{iN}}{\mathrm{d}^2k_n}T_A(b) \times \mathrm{e}^{-\sigma^{iN}(p_0)T_A(b)}\,. \quad (6)$$

This equation sums all processes with n multiple $2\to 2$ parton scatterings. The exponential factor in (6) represents the probability that the parton suffered no semihard scatterings after the nth one, and explicitly unitarizes the cross-section at the nuclear level.

The above presented GE model describes quite well the energy and centrality dependence of the Cronin effect on pion production in $p+A$ collisions at Fermilab, $\sqrt{s}=27.4\,\mathrm{GeV}$, and in $d+\mathrm{Au}$ collisions at RHIC, $\sqrt{s}=200\,\mathrm{GeV}$; see [7] and Fig. 1. As all other models based on multiple initial-state parton scatterings, the model fails in describing the effect on baryon production. The main reason is that baryon production is not understood in this framework even at the $p+p$ level, which is the starting point of the GE approach; see (3) and (4). An alternative explanation of the baryon/meson anomaly based on final-state parton recombination [10] is more successful in this respect than the independent fragmentation approach used in the GE model.

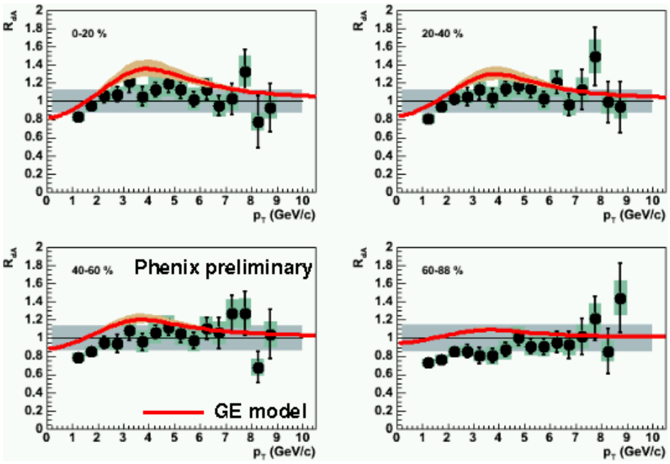

Fig. 1. Cronin effect on neutral pion production as a function of centrality in $d+\mathrm{Au}$ collisions at RHIC. Curved lines and the band are the GE model computation with its theoretical uncertainty. The horizontal gray band is the experimental uncertainty in the normalization of the ratio. Figure adapted from [9]

3 The "naked" Cronin effect in $A + A$ collisions

The natural generalization of (2) to the case of nucleus–nucleus collisions is to allow the partons from the target nucleus to rescatter on the projectile nucleus, as well:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2p_\mathrm{T}\mathrm{d}y\mathrm{d}^2b}^{AB\to hX} = \int \mathrm{d}^2s \times \left\{ T_A(b-s)\langle xf_{i/A}\rangle \otimes \frac{\mathrm{d}\sigma^{iB}}{\mathrm{d}^2p_\mathrm{T}\mathrm{d}y_i\mathrm{d}^2s} \otimes D_{i\to h}\Big|_{y_h=y} + T_B(s)\langle xf_{j/B}\rangle \otimes \frac{\mathrm{d}\sigma^{iA}}{\mathrm{d}^2p_\mathrm{T}\mathrm{d}y_i\mathrm{d}^2(b-s)} \otimes D_{j\to h}\Big|_{y_h=-y} \right\} . \quad (7)$$

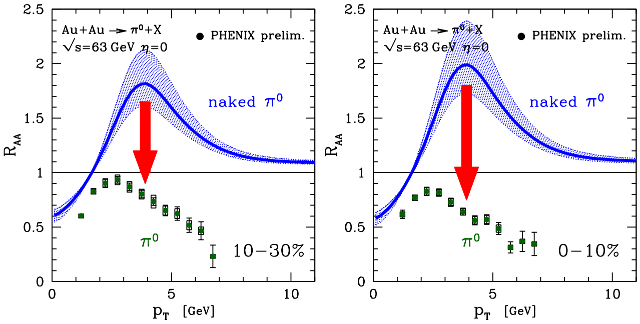

Fig. 2. Naked Cronin effect on π^0 production in Au + Au collisions at $\sqrt{s} = 62\,\mathrm{GeV}$ compared to preliminary PHENIX experimental data from [9]

As no medium effects are included in this formula, what we are computing is the "naked" Cronin effect, i.e., the effect stripped of medium-induced modifications such as, e.g., jet quenching. Hence, the resulting Cronin ratio may be used as a baseline to detect and measure jet quenching.

Consider, e.g., the preliminary PHENIX data on π^0 production in Au+Au collisions at $\sqrt{s} = 63\,\mathrm{GeV}$ in Fig. 2. The characteristic bell shape of the Cronin effect at moderate p_T is clearly suppressed. However, the magnitude of the suppression is not self-evident from experimental data alone: a computation is needed of the unsuppressed spectrum. The comparison of experimental data and the GE model computation shows a quite large jet quenching. Going from central to peripheral collisions, the suppressed experimental Cronin peak and the unsuppressed theoretical curve approach each other. As we can expect this trend to continue in more and more peripheral events, a natural question arises: at what centrality does the quenching starts? This is clearly a very important question, whose answer will help to pinpoint the conditions for QGP formation.

As PHENIX data on π^0 in more peripheral bins are not yet available, we may turn to PHOBOS data on charged hadron ($h^\pm$) production. Here we come across the baryon/meson anomaly previously discussed: the GE model underestimates the Cronin effect on protons and antiprotons, which give a sizable contribution to the $h^\pm$ sample. To attempt nonetheless an answer to the question of when does the medium start to quench hadrons, we may compare $h^\pm$ data to the computation for π^0's; see Fig. 3. The required modification of the shape and magnitude of theoretical curves can be estimated by comparing the PHOBOS $h^\pm$ data points with PHENIX π^0 data point in similar centrality bins. With the above caveats in mind, we can estimate that hadron quenching starts at a centrality of around 40%.

I would like to stress the importance of the availability of a theoretical computation of the naked Cronin effect on the example of the 4 most peripheral bins in Fig. 3 (up to 15–25% centrality). The data points do not show a medium effect by themselves: they arise above 1 at $p_\mathrm{T} \approx 1.5$–$2\,\mathrm{GeV}$, display a nice Cronin peak and seem to converge to 1 again at higher p_T inside the systematic errors. This behavior would point to an unsuppressed Cronin effect, but the comparison to the naked Cronin curve (modulo the baryon/meson anomaly) shows a sizable medium effect starting at around 40%, which otherwise might have passed unnoticed.

Finally, we can address the WA98 data on π^0 production in Au + Au collisions at $\sqrt{s} = 17\,\mathrm{GeV}$ [4]. Here we have two complications. On the experimental side, there

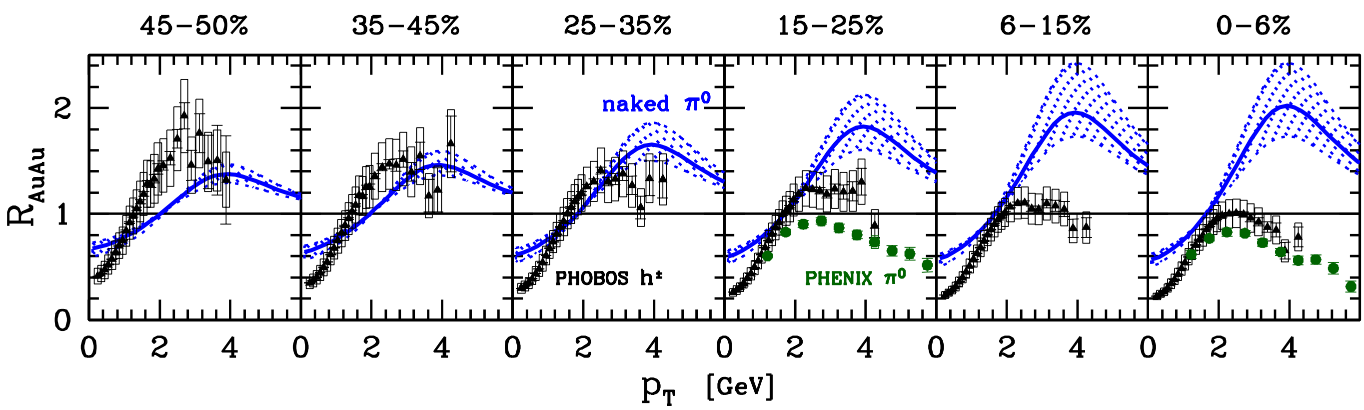

Fig. 3. Naked Cronin effect on π^0 production in Au + Au collisions at $\sqrt{s} = 62\,\mathrm{GeV}$ compared to experimental data for $h^\pm$ from PHOBOS (black triangles) [8] and π^0 from PHENIX (green disks) [9]

is a large uncertainty on the $p+p$ spectrum to be used as a normalization in (1), due to different extrapolations of higher energy data; see [11] for more details and references. On the theory side, we have an uncertainty on the $p_0(\sqrt{s})$ and $K(\sqrt{s})$ parameters due to the extrapolation at this low energy of values extracted [7] from data at $\sqrt{s}=27$ and 200 GeV. Preliminary computations show a moderate quenching in central collisions.

4 Perspectives

A cross check of WA98 results may be obtained using the minimum bias data sample of NA60 [12] for In + In collisions at $\sqrt{s}=17$ GeV. The dimuon trigger data, which has a bias toward central collisions, may also be used.

NA60 can also perform a nice experimental study of the system size dependence of the Cronin effect on $h^{\pm}$ production in $p+A$ collisions at low $\sqrt{s}=17$–27 GeV. Indeed, the experimental setup has 7 nuclei (ranging from beryllium to uranium) mounted in the target region and sharing the same beam [12]. This allows one to measure the ratio R^{σ} of differential cross-sections on two different nuclei because the beam luminosity cancels in the ratio

$$R^{\sigma}_{pA/pB} = \frac{1}{A}\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2\mathrm{d}y}^{pA\to hX} \Bigg/ \frac{1}{B}\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2\mathrm{d}y}^{pB\to hX} , \quad (8)$$

where B is the lightest available nucleus, in this case beryllium. The A dependence of the ratio is analogous to the centrality dependence, but eliminates the large experimental uncertainties due to the determination of the centrality and to the normalization of the Cronin ratio. Moreover, without need of centrality cuts the statistics may be sufficient to probe the high-p_T region and test the multi parton scattering mechanism, which predicts a divergence of the Cronin ratio at $p_T=4$ GeV and 8 GeV in collision of, viz., $\sqrt{s}=17$ GeV and 27 GeV. Theoretical computations will need to take into account the bias toward central collisions induced by the dimuon trigger, which is the only trigger used in $p+A$ collisions.

The baryon/meson anomaly is a pervasive phenomenon in QCD: it is not limited to hadronic and nuclear collisions, but present also in the HERMES measurements of hadron production in deep inelastic scattering on nuclei (nDIS) [13]. In this case, the ratio of hadron multiplicities on a nuclear target and on deuterium is measured as a function of $z=E_h/\nu$, where E_h is the hadron momentum and ν is the virtual photon energy. Experimentally, meson quenching is observed on the whole $z=0.2$–1 range, while protons are enhanced at $z\lesssim 0.4$ and suppressed above; both the quenching and enhancement increase with A. At HERMES the typical hadron momentum $E_h\approx 2$–12 GeV is comparable to mid-rapidity hadron momenta measured at RHIC: there is a lot to be learned from nDIS about hadronization, both experimentally and theoretically, which can be applied to RHIC physics!

5 Conclusions

The Glauber-Eikonal model is successful in explaining the Cronin effect on mid-rapidity meson production in $p+A$ collisions on a wide range of energy, $\sqrt{s}=27$–200 GeV. When extended to $A+A$ collisions, it gives a reliable baseline computation of what the Cronin effect should look like in the absence of the medium-induced hadron quenching.

By comparing the GE computation with experimental data it is possible to study the onset and magnitude of hadron quenching. As an example, I studied recent PHENIX and PHOBOS data in Au + Au collisions at $\sqrt{s}=63$ GeV, and found that the produced medium begins to quench hadron spectra in collisions of around 40% centrality, with a strength quickly increasing with centrality. Preliminary analysis of WA98 data at $\sqrt{s}=17$ GeV suggests a moderate hadron quenching in central collisions. A systematic analysis of all the available experimental data is under preparation.

More can be learned about the Cronin effect in low-energy $p+A$ collisions from the unique multiple target setup of the NA60 experiment by studying, as proposed in this note, the A dependence of the ratio (8) of differential cross-sections on a target nucleus A and on beryllium, the lightest available target.

The HERMES data on nuclear DIS can shed light on the baryon/meson anomaly and the space-time evolution of the hadronization process in a cleaner and more controllable setting than nuclear collisions. I would like to invite heavy ion theorists and experimentalists to carefully read HERMES papers: there is a lot to be learned which is directly relevant to RHIC physics.

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