Multiple scattering and $p_t$-broadening at RHIC energies

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In ultrarelativistic heavy-ion collisions, in the $2 \text{ GeV} < p_\perp < 6 \text{ GeV}$ transverse momentum region, the soft and semi-hard multiple scattering of the incoming nucleons in the nuclear medium results in the broadening of the expected hadronic (e.g. pion) $p_\perp$ spectra relative to proton-proton ($pp$) collisions. Thus, higher transverse-momentum regions are populated than in $pp$ collisions. In a perturbative QCD based calculation we include the intrinsic transverse momentum ($k_\perp$) of the partons in the nucleon (determined from $pp$ collisions), augmented by the extra broadening obtained via a systematic analysis of proton-nucleus ($pA$) collisions in the energy range $17 < \sqrt{s} < 39$ AGeV. The original polynomial spectra are modified, and a nearly exponential spectrum appears in the region $2 \lesssim p_\perp \lesssim 3.5 \text{ GeV}$. At present RHIC energies ($\sqrt{s} = 130$ AGeV), the slope of the calculated spectra is reminiscent of that of fluid-dynamical descriptions, but lacks any thermal origin. We determine and discuss the size of the modifications originating in multiple scattering, which lead to this state of affairs.

1. Introduction

With the start of RHIC operation new data are now available for high energy heavy ion collisions. This makes it possible to contrast the models to the experimental data and to learn about new effects in this so far unreachable domain.

In this talk we discuss the features of some hadronic spectra in Au+Au collisions at 130 GeV. First we give an introduction to the pQCD-improved parton model and fix our parameters in $pp$ collisions. Next, we study the available $pA$ experiments in order to understand the nuclear (Cronin) effect, the enhancement of particle production in a certain $p_\perp$ range compared to $pp$ collisions. Finally, we present our calculation for nucleus-nucleus ($AA$) collisions at present RHIC energy.

2. Perturbative QCD

The classical pQCD parton model assumes factorization of the hadron (meson $M$) production cross section, namely, the particle production is interpreted as a superposition
of elementary, partonic collisions [2],

\[ E_M \frac{d\sigma_{pp}}{d^3p} = \sum_{abcd} \int dx_a dx_b dz_c f_{a/p}(x_a, Q^2) f_{b/p}(x_b, Q^2) \frac{d\sigma_{ab\to cd}}{dt} \frac{D_{M/c}(z_c, \hat{Q}^2)}{\pi z_c^2} \delta(s+\hat{t}+\hat{u}), \quad (1) \]

where \( f_{a/p}(x_a, Q^2) \) is the parton distribution function (PDF), i.e. the probability of finding parton \( a \) in the proton with momentum fraction \( x_a \) at transverse momentum scale \( Q \), \( d\sigma/d\hat{t} \) is the pQCD calculable cross section of quarks and gluons, while \( D_{M/c}(z_c, \hat{Q}^2) \) is the fragmentation function (FF) of parton \( c \) into a meson \( M \) with the meson carrying a momentum fraction \( z_c \) of the parton at transverse momentum scale \( \hat{Q} \). The PDF and FF, contain all the non-perturbative information and are fixed by experimental data. In our calculation we use the leading order GRV [3] PDF and the leading order KKP [4] FF. (We also carried out approximate NLO calculations [5]).

Evaluating integral (1) numerically and comparing it to existing experimental data of charged and neutral pion and kaon production in \( pp \) and \( p\bar{p} \) reactions in the range of \( \sqrt{s} = 17 - 1800 \) GeV we found a factor of two discrepancy with the theory underestimating the yield. Even more sophisticated NLO calculations failed to reproduce the pion spectra [6]. This motivates us to introduce another non-perturbative parameter, the intrinsic transverse momentum of partons. Such a quantity is not fictitious: it has been measured experimentally [7]. We consider the distribution of this intrinsic transverse momentum to be Gaussian for simplicity, and fix its width from experiments. The integral for both incoming partons in Eq. (1) is modified to

\[ dx_a f_{a/p}(x_a, Q^2) \longrightarrow dx_a d^2k_{\perp,a} \frac{e^{-k_{\perp,a}^2/\langle k_{\perp}^2 \rangle}}{\pi \langle k_{\perp}^2 \rangle} f_{a/p}(x_a, Q^2). \quad (2) \]

The fit of the intrinsic transverse momentum width is shown in Fig. 1 for pions. A similar plot may be obtained for kaons (with much less experimental data available). Using the intrinsic transverse momentum distribution with a width given by the figure we were able to fit \( pp \) experimental data within 30% for \( p_\perp > 2 \) GeV.

Having fitted the \( pp \) data using Eqs. (1-2) parameterized by the \( \langle k_{1,\perp}^2 \rangle_{pp} \) values, we now turn to the \( pA \) collisions. It was found in experiments that there is an extra nuclear enhancement in \( pA \) collisions compared to the simple scaling of \( pp \) data in a certain \( p_\perp \) range (Cronin effect) [8]. One needs to extend integral (1-2) as

\[ E_M \frac{d\sigma_{pA}}{d^3p} = \int d^2b \ t_A(b) E_M \frac{d\sigma_{nn}^{mn}(\langle k_{1,\perp}^2 \rangle_{pA}, \langle k_{1,\perp}^2 \rangle_{pp})}{d^3p}. \quad (3) \]

Here \( t_A(b) \) is the nuclear thickness function at impact parameter \( b \), \( t_A(b) = \int dz g(b, z) \) and the nucleon-nucleon cross section has a dependence on the width of intrinsic transverse momentum of the proton and nucleons in nuclei \( A \), respectively. Furthermore, due to the nuclear environment the partonic distribution functions are modified with a shadowing and antishadowing region [9].

The theoretical interpretation of the Cronin effect is related to the nuclear environment, the average intrinsic transverse momentum of a parton increases due to multiscattering,

\[ \langle k_{1,\perp}^2 \rangle_{pA} = \langle k_{1,\perp}^2 \rangle_{pp} + C \ h(\nu_A(b) - 1), \quad (4) \]
where $\nu_A(b)$ is the number of target nucleons in the channel swept by the incoming proton at impact parameter $b$, $h$ is an “effectivity” function, selecting the number of target nucleons contributing to the $\langle k_{\perp}^2 \rangle$ enhancement of the projectile and $C$ is the average momentum square imparted in one nucleon-nucleon collision. For the effectivity function we tried a function linearly rising with the number of particles inside the channel and saturating after $n$ collisions. Requiring approximate target and energy independence of $h$ we found that the best fit is achieved using $n = 3 - 4$ with average momentum square impart $C_{n=4} \approx 0.4$ GeV$^2$. In the following we use this value for central nucleus-nucleus collisions.

Next, we performed a simulation of the ongoing RHIC experiments on meson production at $\sqrt{s} = 130$ GeV in Au+Au collisions. This requires a modification of Eq. (3) extending it to the case of two colliding nuclei,

$$E_M \frac{d\sigma^{AB}}{d^3p} = \int d^2b d^2r \ t_A(b) t_B(\vec{r}) \ E_M \frac{d\sigma^{nn}_{M}(\langle k_{\perp}^2 \rangle_{pA}, \langle k_{\perp}^2 \rangle_{pB})}{d^3p}. \quad (5)$$

Based on Fig. 1 we used $\langle k_{\perp}^2 \rangle_{pp} = 1.6$ GeV$^2$. A simple calculation without the nuclear enhancement and shadowing agrees well with the peripheral PHENIX results on $\pi^0$ production [10]. However, for central collisions there is a disagreement between this pQCD model and the experimental data, indicating a strong suppression in the particle production. A possible candidate explaining this phenomenon is jet quenching [11].

An interesting quantity to study is the slope of the meson production cross section. For peripheral collisions (no shadowing and nuclear enhancement) a pQCD calculation yields
a non-exponential spectrum with a slope parameter rising with the transverse momenta (Fig. 2 dotted line). However, in case of central collisions in a $p_{\perp}$ window 2–3.5 GeV the slope parameter is almost constant resembling an exponential (thermal) spectrum. Predictions for lower transverse momentum are uncontrollable within pQCD. Our studies show that at SPS energies this plateau is more pronounced and extends to the highest transverse momenta measured.

3. Conclusion

In this talk we showed that at high transverse momenta ($p_{\perp} > 2$ GeV) pQCD augmented with an intrinsic transverse momentum distribution of the partons gives a good description of $pp$, $pA$ and $AA$ collisions. A “thermal” slope is observed in central $AA$ collisions in a transverse momentum window 2–3.5 GeV despite the non-thermal character of the model. At RHIC energies, however, a strong suppression is observed in hadron production in central collisions compared to pQCD calculations. A possible explanation is presented in [11].

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