DIFFERENCES IN HIGH p_T MESON PRODUCTION BETWEEN CERN SPS AND RHIC HEAVY ION COLLISIONS*

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In this talk we present a perturbative QCD improved parton model calculation for light meson production in high energy heavy ion collisions. In order to describe the experimental data properly, one needs to augment the standard pQCD model by the transverse momentum distribution of partons ("intrinsic k_T"). Proton–nucleus data indicate the presence of nuclear shadowing and multi-scattering effects. Further corrections are needed in nucleus–nucleus collisions to explain the observed reduction of the cross section. We introduce the idea of proton dissociation and compare our calculations with the SPS and RHIC experimental data.

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1. Introduction

During the last decade, as the bombarding energy increased, nuclear collision data have become available for high transverse momentum particle production. Perturbative Quantum Chromodynamics (pQCD) is believed to

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be applicable in this regime. In this talk we present a pQCD based parton model and test it in proton–proton (pp), proton–nucleus (pA), and nucleus–nucleus (AA) collisions from CERN to Tevatron energies. Our main goal is to understand first the elementary processes, like particle production in pp reactions, then learn about the mechanism of the nuclear enhancement and finally, based on these studies, make "predictions" for AA collisions. Confronting our result to the available experimental data, we may look for any new phenomena, which cannot be described within the original pQCD based parton model.

Expectations about what may happen at high energies or large colliding systems include the formation of a Quark Gluon Plasma (QGP). In case QGP was formed in the reaction, the outgoing jets would suffer an energy loss due to collisions in the opaque plasma and a suppression in particle production would result. This jet quenching [1] is expected to be prominent in high bombarding energy central heavy ion collisions. Another effect is due to the fragility of the proton, indicated by the fact that after a momentum transfer of ~1–1.2 GeV it is blown to pieces [2]. This proton dissociation is also expected to happen at higher bombarding energies and be most visible in central heavy ion collisions, where transverse momentum may accumulate.

The talk is organized as follows: in the first section we discuss the basic assumptions and formulae of a pQCD improved parton model, presenting it at work in light meson production in pp collisions. Next, we present an analysis of the pA collisions and deduce some information on the nuclear enhancement (Cronin effect) [3]. Parameters fixed in this section will be used to study AA collision at CERN SPS and RHIC energies. Results deviate from experimental data for heavy ions. We present possible explanations for this discrepancy and conclude that further experiments are necessary to clarify the underlying physical picture.

2. Light meson production in *pp* collisions

The invariant cross section for the production of hadron h in a pp collision is described in the pQCD-improved parton model on the basis of the factorization theorem as a convolution [4]:

$$E_h \frac{d\sigma_h^{pp}}{d^3p} = \sum_{abcd} \int dx_a dx_b dz_c \; f_{a/p}\left(x_a, Q^2\right) \; f_{b/p}\left(x_b, Q^2\right) \; \frac{d\sigma}{d\hat{t}}(ab \to cd) \times \frac{D_{h/c}\left(z_c, Q'^2\right)}{\pi z_c^2} \, \hat{s}\, \delta(\hat{s} + \hat{t} + \hat{u}) \,, \tag{1}$$

where $f_{a/p}(x,Q^2)$ and $f_{b/p}(x,Q^2)$ are the parton distribution functions (PDFs) for the colliding partons a and b in the interacting protons as functions of momentum fraction x, at scale Q, $d\sigma/d\hat{t}$ is the hard scattering cross section of the partonic subprocess $ab \to cd$, and the Fragmentation Function (FF), $D_{h/c}(z_c, Q'^2)$ gives the probability for parton c to fragment into hadron h with momentum fraction z_c at scale Q'. We use the convention that the parton-level Mandelstam variables are written with a 'hat' (like $\hat{t}$ above). We fix the scales as $Q = p_{\rm T}/2$ and $Q' = p_{\rm T}/(2z_c)$.

Such a model represents the "hard" physics and should not be pushed below a scale $p_{\rm T} \lesssim 1$–2 GeV. In the following we restrict ourselves to Leading Order (LO) pQCD, using the LO form of the partonic cross sections, PDF's and FF's [5].

It was noted as soon as pQCD calculations were applied to reproduce high-$p_{\rm T}$ hadron production [6], that this naive picture fails, especially at the lower end of the $p_{\rm T}$ range, $2 \le p_{\rm T} \le 6$ GeV. The partons participating in meson production are bound inside nucleons and cannot be considered to be in an infinite momentum frame. The concept of intrinsic transverse momentum was introduced [6] to take into account the correction to the infinite momentum frame. A value of $\langle k_{\rm T}\rangle \sim$0.3–0.4 GeV could be easily understood in terms of the Heisenberg uncertainty relation for partons inside the proton. However, a larger average transverse momentum of $\langle k_{\rm T}\rangle \sim 1$ GeV was extracted from jet–jet angular distributions (see *e.g.* [7]) and explained theoretically as the effect of gluon rescattering inside the nucleus [8].

Phenomenologically, the transverse momentum may be introduced by using a product assumption and extending each integral over the parton distribution functions to $k_{\rm T}$-space [8]

$$dx\ f_{a/p}(x,Q^2) \to dx\ d^2k_{\rm T}\ g(\vec{k}_{\rm T})\ f_{a/p}(x,Q^2)\,, \tag{2}$$

where $g(\vec{k}_{\rm T})$ is the intrinsic transverse momentum distribution of the relevant parton in the proton, and in this talk it is chosen to be a Gaussian

$$g(\vec{k}_{\rm T}) \ = \frac{1}{\pi\langle k_{\rm T}^2\rangle}\, {\rm e}^{-k_{\rm T}^2/\langle k_{\rm T}^2\rangle}\,. \tag{3}$$

We made a systematic study of available *pp* experiments producing high $p_{\rm T}$ pions and fitted the 2-dimensional width parameter $\langle k_{\rm T}^2\rangle$ [3]. The best fit values are presented in Fig. 1. A similar plot can be obtained for kaon production [3].

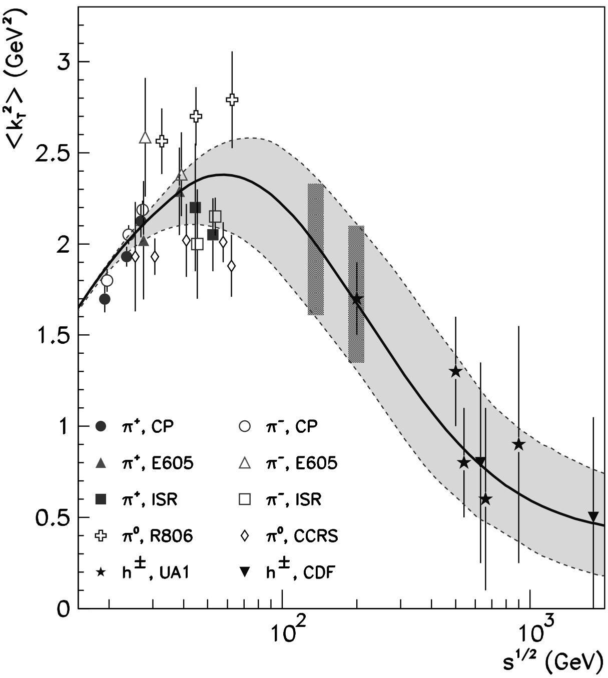

Fig. 1. The best fit values of $\langle k_{\mathrm{T}}^2 \rangle$ in $pp \to \pi X$ [9,10] and $p\bar{p} \to h^{\pm} X$ [11,12] reactions. Where large error bars would overlap at the same energy, one of the points has been shifted slightly for better visibility. The band is drawn to guide the eye.

3. Proton–nucleus collisions

Having fixed the intrinsic transverse momentum distribution in pp collisions we turn now to pA collisions and investigate the nuclear enhancement (Cronin effect) [13]. It was found experimentally that in the $2\,\mathrm{GeV} < p_{\mathrm{T}} < 5\,\mathrm{GeV}$ transverse momentum region there are more particles produced than it was expected from a simple scaling of pp data. Within the present model this can be explained by an additional term in the width of the intrinsic transverse momentum distribution, which takes into account a broadening due to associated semi-hard inelastic collisions

$$\langle k_{\mathrm{T}}^2 \rangle_{pA} = \langle k_{\mathrm{T}}^2 \rangle_{pp} + C \; h_{pA}(b) \,, \tag{4}$$

where $\langle k_{\mathrm{T}}^2 \rangle_{pp}$ is the width of the transverse momentum distribution of partons in pp collisions from the previous section, $h_{pA}(b)$ describes the number of *effective* nucleon–nucleon (NN) collisions at impact parameter b which impart an average transverse momentum squared C. The coefficient C is expected to be approximately independent of p_{T}, of the target used, and probably of beam energy (at least in the energy range studied in Refs. [9,13]).

In pA reactions, where one of the partons participating in the hard collision originates in a nucleon with additional NN collisions, we will use the pp width from Fig. 1 for one of the colliding partons and the enhanced width (4) for the other. The effectivity function $h_{pA}(b)$ can be written in terms of the number of collisions suffered by the incoming proton in the target nucleus, $\nu_A(b) = \sigma_{NN}\, t_A(b)$, where σ_{NN} is the inelastic nucleon–nucleon cross section and $t_A(b) = \int dz\, \rho(b,z)$ is the nuclear thickness function. Assuming that only the first $m-1$ semi-hard collisions preceeding the hard collision contribute to the broadening of the width, we define the effectivity function as

$$h_{pA}(b) = \begin{cases} \nu_A(b) - 1 & \nu_A(b) < m \\ m - 1 & \text{otherwise}\,. \end{cases} \qquad (5)$$

The value $m = \infty$ corresponds to the scenario where all semi-hard collisions contribute to the broadening. For realistic nuclei $\nu_A(b)$ do not exceed the value of 6, so we restrict ourselves to the region $1 < m < 6$ and examine the dependence of the results on the possible choices between these limits.

According to the Glauber picture, the hard pion production cross section from pA reactions can be written as an integral over impact parameter b

$$E_\pi \frac{d\sigma_\pi^{pA}}{d^3p} = \int d^2b\; t_A(b)\; E_\pi \frac{d\sigma_\pi^{pp}\left(\langle k_{\rm T}^2\rangle_{pA}, \langle k_{\rm T}^2\rangle_{pp}\right)}{d^3p}\,, \qquad (6)$$

with a further modification of the PDFs: in the nuclear environment "shadowing" effects [14, 15] modify the distribution functions. Here we use an average, scale independent parameterization [14],

$$f_{a/A}\left(x,Q^2\right) = S_{a/A}(x)\left[\frac{Z}{A} f_{a/p}\left(x,Q^2\right) + \left(1 - \frac{Z}{A}\right) f_{a/n}\left(x,Q^2\right)\right]\,, \qquad (7)$$

where $f_{a/n}\left(x,Q^2\right)$ is the PDF for the neutron.

Confronting the calculations with experimental data [9] for Be, Ti and W targets at three different energies, we obtain the best fit with $m = 4$ and $C \approx 0.4\,\mathrm{GeV}^2$ [3] and will use these values for AA reactions in the next section.

4. Nucleus–nucleus collisions

Nucleus–nucleus collisions do not involve additional parameters in the pQCD parton model with intrinsic $k_\perp$, both partons entering the hard collision gain extra broadening of the width according to (4), *i.e.* depending on the number of nucleons within the other nucleus in the channel swept by the particle. Thus,

$$E_\pi \frac{d\sigma_\pi^{AB}}{d^3p} = \int d^2b\, d^2r\; t_A(r)\; t_B(|\vec{b} - \vec{r}|)\, E_\pi \frac{d\sigma_\pi^{pp}\left(\langle k_{\rm T}^2\rangle_{pA}, \langle k_{\rm T}^2\rangle_{pB}\right)}{d^3p}\,. \qquad (8)$$

In the following we calculate and compare to experimental data the pionic cross sections for CERN SPS reactions with $\langle k_{\rm T}^2\rangle_{pp}$ =1.6 and 1.7 GeV^2 for 200 and 158 AGeV collisions, respectively (see Fig. 1), and with $m = 4$, $C = 0.4$ GeV^2. Next, we investigate the recent RHIC heavy ion collision at 130 GeV with $\langle k_{\rm T}^2\rangle_{pp}$ =2.0 GeV.

4.1. CERN SPS energy

Let us now confront the theoretical model (8) with the CERN SPS experiments WA80 [16] and WA98 [17] for central collisions, calculating the invariant cross section of pion production in the 25% most central S+S, 7.7% most central S+Au, and 12.7% most central Pb+Pb collisions within the experimental rapidity windows.

The data over theory ratio (D/T) is presented in Fig. 2 (left). For the lighter systems this ratio approaches 1 above $p_{\rm T} \gtrsim 2.5$ GeV, while for the lead collisions we see that such a model over-predicts the experimental values by 40%. In the following we speculate on the origin of this discrepancy.

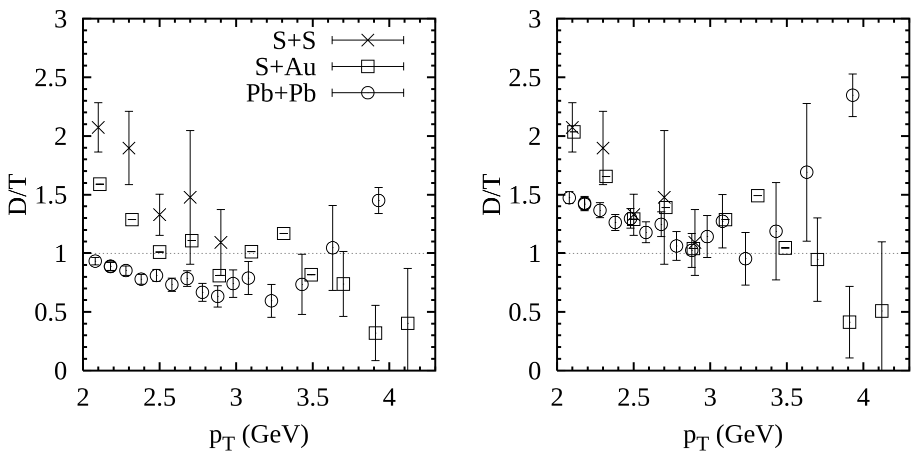

Fig. 2. Data/theory ratio at CERN SPS S+S (crosses), S+Au (boxes) and Pb+Pb (circles) for high $p_{\rm T}$ pion production reactions. Left: ratio without proton dissociation, right: ratio with proton dissociation after 4 collisions.

A possible candidate for the reduction of the cross section in large systems is the proton dissociation mentioned in the introduction. Our pA collision study showed that each pp inelastic collision adds $\sim$ 400 MeV transverse momentum to the partons inside the proton (on the average). After a few such collisions the partons gain high enough transverse momenta to become free of the proton and during this transition process they do not interact (dead time). We assume that such a proton is "lost" for the reaction and does not participate in particle production anymore. We note that such a picture corresponds to a modification of the original Glauber model. It reduces the cross section for heavy nuclei in central collisions and has no effect for light nuclei or peripheral collisions. Furthermore, since central collisions have a small weight in the total cross section, the value of the latter changes insignificantly due to the proposed modification.

In technical terms the above picture corresponds to changing the thickness expression

$$t_A(r)\ t_B(|\vec{b}-\vec{r}|) \tag{9}$$

in Eq. (8) in the following way: assuming that the nucleon dissociates after N_c collisions, we divide the incoming "rows" into packets of N_c nucleons. The first packet from the projectile collides with the first packet of the target and dissociates. This is followed by colliding the next pair of packets and so on till the last (incomplete) packets collide. Note that unpaired packets will not produce any collisions in this framework.

Now we ask: how many collisions may the proton suffer before it disintegrates (*i.e.* what is the value of N_c)? We vary this parameter to have the same D/T ratio for all the three experiments studied. The best fit is achieved with $N_c = 4$ (Fig. 2 right-hand side), which, by random walk arguments, corresponds to a $\sqrt{N_c C} \approx 1.25\,\mathrm{GeV}$ transverse momentum scale.

In the next subsection we study the plausibility of this idea in recent RHIC experiments.

4.2. RHIC energy

Since recent RHIC experiments [18] suggest a drastic reduction of the pion production cross section in central collisions, we now investigate what effects may lead to such a suppression. One possibility is jet quenching [1], which takes into account the energy loss of partons traveling through a diffractive medium. As a result, jets, normally producing high $p_\perp$ mesons, are shifted to smaller transverse momenta resulting in a large decrease of produced mesons at higher tranverse momenta. The shift, or loss, may be dialed through the properties of the surrounding matter (*e.g.* QGP). In order to be able to assess those properties one has to know the uncertainties related to other effects. Fig. 3 (left) shows the influence of nuclear shadowing and of the Cronin effect in heavy ion collisions. Both of them have a substantial impact modifying the pion production cross section by up to 50%, working in opposite directions. The uncertainty related to them may render an assessment of jet quenching unreliable. The Cronin effect was never studied systematically at higher energies; our estimate is completely based on a lower energy study ($\sqrt{s} \sim 30$–$40\,\mathrm{GeV}$).

Proton dissociation (studied in the previous subsection) is another possible effect modifying theoretical predictions. We show suppressions produced by different values of parameter N_c, indicating the number of collisions after which the proton dissociates and does not participate in particle production. Using the value deduced from the CERN SPS ($N_c = 4$) reduces the cross section by 45% in Au+Au at 130 AGeV collisions (indicated by the thick line in the right panel of Fig. 3). If we assume that at the higher energies of RHIC the proton dissociation is more effective, than an assumption of $N_c = 3$ may be reasonable, resulting in a 60% reduction. The proper value should be extracted from a systematic pA study planned at RHIC and from the different centrality cuts. However, this value of suppression is still too low to explain the experimental pion production data in central collisions, leaving some room for jet quenching.

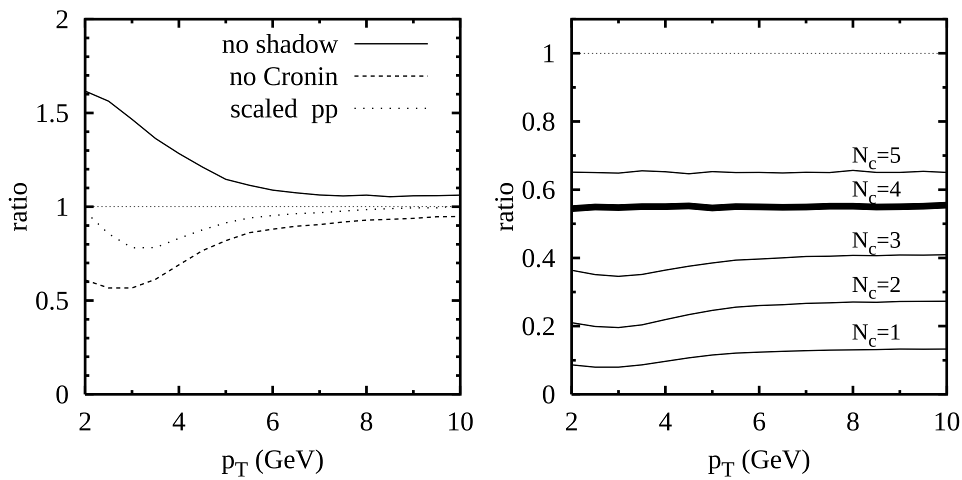

Fig. 3. Left: ratio of invariant cross section neglecting different terms as compared to the full pQCD calculation: neglecting shadowing (solid line), neglecting Cronin effect (dashed line), and neglecting both (dotted line). Right: ratio of invariant cross section with proton dissociation compared to the full pQCD calculation.

5. Conclusions

In this talk we presented a pQCD based parton model augmented by the transverse momentum distribution of the partons. The width of this distribution is controlled by two terms, the pp value, fixed by the experiments, and a nuclear part, which gives extra enhancement due to semi-hard collisions. We introduced the idea of proton dissociation, and concluded on the basis of CERN SPS experiments that such an extension of the Glauber model does not contradict the experiments. The best value corresponds to 4 collisions before the proton disintegrates, which is consistent with the picture of nuclear enhancement of the transverse momentum distribution width obtained from pA collisions.

In high energy heavy ion collisions particle production at high transverse momenta is a delicate interplay between intrinsic transverse momentum enhancement, nuclear shadowing, the Cronin effect, proton dissociation, and jet quenching. In order to be able to separate all these effects one needs a systematic study of pp, pA and AA reactions at different energies with the same facility. RHIC with the planned pA program provides a unique opportunity to study the onset of the proton dissociation by increasing the target size and the onset of jet quenching in AA collisions with centrality cuts or by the change of the projectile size.

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