Physics motivation

Increase of the rapidity coverage will allow to investigate several new phenomena.

I. NUCLEAR SHADOWING

A. Quark shadowing

The phenomenon of nuclear shadowing - reduction of the interaction cross section of lepton - nucleus scattering as compared to the incoherent sum of the individual cross sections at high energies / small x has a long history. For a recent review and references see [1]. It is due to large coherence length in the small x interactions. The phenomenon was observed by several experimental groups in deep inelastic muon-nucleus scattering. There is an evidence of small nuclear shadowing for the lowest $x = 0.03$ data point of the FNAL Drell-Yan data[2].

The major obstacle that hinders our deeper knowledge of nuclear parton distribution functions (nPDFs) at small x is that, up to the present day, all experiments aiming to study nPDFs are performed with fixed (stationary) nuclear targets. In these data, the values of x and Q^2 are strongly correlated and one measures nPDFs essentially along a curve in the $x - Q^2$ plane rather than exploring the entire plane. Moreover, for $Q^2 > 1$ GeV^2, the data cover the region $x > 5 \times 10^{-3}$, where the effect of nuclear shadowing is just setting in. As a result, when one attempts to globally fit the available data by modeling nPDFs at some initial scale Q_0^2 *assuming dominance of the leading twist* and then performing QCD evolution, various groups [3–6] produce significantly different results [8]. Moreover due to a strong correlation of x and Q^2 it is hardly possible to separate the higher twist effects which could be large and even dominate[7] in this Q-range.

A dynamical calculation of the nuclear shadowing is possible based on the Gribov theory[9] which allows to relate it to the cross section of the diffractive scattering off a nucleon. Several calculations along these lines were reported [10–14] which reasonably reproduce the DIS data. To separate the higher twist and leading twist effects one needs to combine the Gribov theory and the Collins factorization theorem [15] for hard diffraction in DIS. The resulting leading twist theory of nuclear shadowing was developed and elaborated in Refs. [16, 17] The analysis of the current data within this framework has concluded [18] that *the low-x NMC data [19] are likely to contain significant higher twist effects, which contribute approximately 50% to the nuclear shadowing correction to* F_2^A.

The generic feature of all dynamical calculations of F_{2A}/F_{2N} are that it is a weak function of Q^2 for $Q^2 \geq 10GeV^2$ and that the transition from color transparency (no shadowing) region to the kinematics where shadowing becomes a weak function of x takes place between $x \sim 10^{-2}$, and $x \sim 10^{-3}$.

Measurements of antiquark distributions in this kinematics are feasible via production of dileptons using proposed extension of the PHENIX detector. It would be possible to combine measurements with several nuclei as well as data with a different centrality trigger to investigate this physics as a function of nuclear thickness reaching thicknesses 1.5 times larger than the average thickness of the heavy nuclei.

It is worth emphasizing that measurements in the kinematics will be hardly possible at other facilities under construction, or at various stages of planning: at LHC the backgrounds from the charm will be too high, while at EIC minimal x for $Q^2 = 10GeV^2$ corresponds to $\approx 310^{-3}$. In fact the EIC measurements at $x \sim 10^{-}3$ will nicely complement the RHIC measurements exploring the region of smaller Q^2. The important advantage of the Drell-Yan process is a very advanced perturbative QCD theory of the process. In particular the recent NNLO calculations demonstrated a good convergence of the perturbative series [20].

Another important aspect of the Drell-Yan process is that distribution of dileptons over the transverse momentum carries information about perturbative dynamics of soft gluon radiation, see [23] and references therein. It is therefore sensitive to the presence of the saturation/black disk regime (the limit in which the strength of interaction reaches the maximal possible value corresponding to $\sigma_{tot} = 2\pi R_A^2$) at small transverse momenta, say $\leq 1GeV/c$. The presence of the large gluon densities at low resolution scale would lead to much stronger increase of $\left\langle p_\perp^2 \right\rangle$ with A than at fixed target energies. Another signature of proximity to the saturation would be a significantly weaker dependence of the cross section on the mass of the produced dilepton pair - $d\sigma/dx_1 dx_2$ becomes a weak function of M^2 instead of been $\propto 1/M^2$ [24]:

$$\frac{d\sigma(p + A \to \mu^+\mu^- + X)}{dx_A dx_p} = \frac{4\pi\alpha^2}{9}\frac{K(x_A, x_p, M^2)}{M^2} F_{2p}(x_p, Q^2) \cdot \frac{1}{6\pi^2} M^2 \cdot 2\pi R_A^2 \ln(x_0/x_A), \tag{1}$$

Note here, that in the forward kinematics the Drell-Yan mechanism of the dilepton production may dominate already for $M \geq 2GeV$ since the production of the charm particle is strongly suppressed in the forward direction. These measurements will contribute also significantly to the understanding of the dynamics of the heavy onium production in the forward region. In particular it would be possible to check whether absorption of J/ψ at large x_F is the same as at fixed target energies, or stronger , for example due to onset of the gluon shadowing.

B. Gluon shadowing

So far there is no experimental information directly relevant for the gluon nuclear shadowing. So the current fits to the DIS data accentually do not constrain the gluon shadowing (even if one assumes that the higher twist effects are small) - see compilation of [8].

The leading twist theory of nuclear shadowing predicts large gluon shadowing at $x \leq 10^{-3}$ based on the information about strength of the diffraction in the gluon channel measured at HERA where this strength was found to be larger than in the quark channel in a wide range of Q^2. In the RHIC kinematics detection of the hard processes dominated by scattering off smallx gluons requires measurement of two jets (photon and a jet). In the case of single inclusive measurements like production off the forward π^0 -mesons [21] moderately small x ($x_g \sim 0.02$) give a larger contribution [22].

The upgraded PHENIX detector will be able to probe the gluon densities via observation of the reaction $g + q \rightarrow \gamma + jet$ at $x \sim 10^{-3}$, $p_\perp \geq 5GeV/c$. In this kinematics gluon shadowing for heavy nuclei is expected to be of the order of a factor of 0.6 and hence can be easily detected. One would also be able to study production of the leading pion and balancing forward jet. Also, by changing x of the parton in the incoming proton (deuteron) while keeping x_g fixed it will be possible to separate effects of leading twist shadowing and effects of energy losses for the propagation of the incoming/final parton through the nuclear media.

It is worth emphasizing here that measurements of the gluon shadowing in this kinematics will provide an important ingredient for modeling/interpretation of the central AA collisions at LHC where typical x's for the minijet production at central rapidities are $\sim 10^{-3}$ and where gluon shadowing enters quadratically into the calculation of the cross section. The question of the leading twist gluon shadowing is also important in the framework of the color glass condensate models. The original model [25] did not contain the leading twist shadowing, while the recent extensions of the model do find the leading twist gluon shadowing (though they did not come yet with predictions for the quark shadowing), for review and references see [26].

II. MAPPING OF THE THREE DIMENSIONAL NUCLEON PARTON STRUCTURE

The systematic studies of hard inclusive processes during the last two decades have led to a pretty good understanding of the single parton densities in nucleons. However very little is known about multiparton correlations in nucleons which can provide critical new insights into the dynamics of the strong interactions, and allow to discriminate between different models of nucleons. Such correlations may be generated, for example, by the fluctuations of the transverse size of the color field in the nucleon leading, via color screening, to correlated fluctuations of the densities of gluons and quarks.

A related source of correlations is QCD evolution, since a selection of a parton with a given x, Q^2 may lead to a local (in transverse plane) enhancement of the parton density at different x values. Also, practically nothing is known about possible correlations between the transverse size of a particular configuration in the nucleon and the longitudinal distribution of partons in this configuration. Extention of the PHENIX forward acceptance will allow to study these phenomena in double parton scattering and via correlation of hard and soft components of the produced hadronic system.

A. Double parton scattering

Extension of the the acceptance range of the PHENIX will make it possible to study multiple parton collisions both in pp and pA collisions. Such processes allow to probe parton correlations in colliding hadrons. Experiment at FNAL collider by CDF [27] have established a significant cross section of this process (see this paper also for extensive list of reference to earlier experimental and theoretical papers). The double parton scattering cross section, being proportional to the square of the elementary parton-parton cross section, is therefore characterized by a scale factor with dimension of the inverse of a length squared. The dimensional quantity is provided by the nonperturbative input to the process, namely by the multiparton distributions. In fact, because of the localization of the interactions in transverse space, the two pairs of colliding partons are aligned, in such a way that the transverse distance between the interacting partons of the target hadron is practically the same as the transverse distance between the partons of the projectile. The double parton distribution is therefore a function of two momentum fractions and of their transverse distance. Analysis of the CDF data indicates presence of the significant correlations between partons in the nucleon [28, 29]. These correlations can arise due to the correlation of quarks and gluons in constituent quarks at low resolution scale, due to the correlation between partons produced in the course of the perturbative (the so–called "hot spots" of Ref. [30]). Hence it is very important to measure the double parton scattering at different $p_\perp$, for different channels - correlations maybe different for quark-quark, quark-gluon, and gluon-gluon cases. Presence of the nucleon polarization may add an interesting new dimension to such studies.

The proton (deuteron) nucleus collisions will provide an important additional information on the multiparton densities. This is because in this case in addition to the impulse approximation contribution (scattering of two partons of the incoming nucleon off two partons of the target nucleon), a contribution to the scattering off two different nucleons of the nucleus is present. The second contribution does not depend on transverse correlation of partons in the nucleons. It increases faster with A: $\sigma_D^2/\sigma_D^1 \approx .68(A/12)^{.39}$ [31] and hence it is expected to dominated in the case of proton-heavy nucleus scattering. Hence the combined measurements of double parton scattering in pp and pA scattering will allow to measure separately longitudinal and transverse correlations of partons in the nucleon. (Situation will be less favorable in the case of the deuteron-nucleus scattering due to the contribution of the scattering of proton and neutron off two different nucleons of the nucleus)

B. Proton-ion collisions probe transverse nucleon structure

It is quite possible that in some subclass of events the distribution of constituents in the initial proton may be unusually local in the transverse (impact parameter) plane when the proton collides with the ion. If this is so, its effective cross-section per nucleon will be greatly reduced, perhaps all the way to the perturbative-QCD level. If the effective cross-section of such a point-like configuration goes below 20mb, there will be an appreciable probability that it can penetrate through the center of a heavy ion and survive. This would lead to a highly enhanced yield of diffractive production of the products of the point-like configuration in collisions with heavy ions as compared to the case of proton-proton scattering.

Not only might the properties of the final-state collision products depend upon the nature of the transverse structure of the proton primary at arrival at the collision point, but even the conventional parton distributions may also be affected. In particular, the smallness of the configuration is likely to be correlated with the joint x-distribution of its constituents. This kind of non factorization may be determined by the study of the perturbative-QCD processes of dilepton, direct-photon, or dijet production as a function of the centrality of the collision, multiplicity of soft hadrons, as well as a function of the atomic number. [**?**] Naturally such studies would require also experimental investigation of the production of the soft hadrons as a function of impact parameter at RHIC energies where it may differ quite strongly from the one observed at fixed target energies.

One possible kinematics where a strong correlation is expected is when a parton with large $x(x \geq 0.6)$ is selected in the proton. The presence of such a parton requires three quarks to exchange rather large momenta. Hence one may expect that these configurations have a smaller transverse size and therefore interact with the target with a smaller effective cross-section $\sigma_{eff}(x)$. Suggestions for such a dependence of the size on x are widely discussed in the literature. Using as a guide a geometric (eikonal type) picture of pA interactions and neglecting (for simplicity) shadowing effects for nuclear parton densities one can estimate the number of wounded nucleons $\nu(x, A)$ in events with a hard trigger (Drell-Yan pair, γ-jet, dijet,...) as a function of σ_{eff} [33]:

$$\nu(x, A) = 1 + \sigma_{eff}(x)\frac{A-1}{A^2}\int T^2(b)\ d^2b, \tag{2}$$

where the nuclear density per unit area $T(b)\int_{-\infty}^{\infty} dz\rho_A(r), \int T(B)d^2B = A.$ and $\rho_A(b, z)$ is the nuclear density. At RHIC for average inelastic pPb collisions and $\sigma_{eff} \sim \sigma_{inel}(pp)$ Eq.2 leads to $\nu \approx 5$. This is somewhat larger than the average number of wounded nucleons in pA collisions, due to the selection of more central impact parameters in events with a hard trigger.

A decrease of the effective cross-section for large x, say, by a factor of 2, would result in a comparable drop of the number of particles produced at central rapidities as well as in a smaller number of nucleons produced in the fragmentation of the nucleus. in the nucleus fragmentation region.

III. PARTICLE PRODUCTION IN THE PROTON FRAGMENTATION REGION

The A-dependence of hadron production in the proton fragmentation region remains one of the least understood aspects of hadron-nucleus interactions. Practically all available data are inclusive and correspond to the energies where the cross section of inelastic NN scattering is about three times smaller than at LHC. They indicate that the cross-section is dominated by the production of leading particles at large impact parameters, where the projectile interacts with only one or two nucleons of the nucleus. As a result very little information is available about hadron production at the central impact parameters which are most crucial for the study, for example of AA collisions. Theoretical predictions for this region are also rather uncertain.

In eikonal type models, where the energy is split between several soft interactions, one may expect a very strong decrease of the yield of the leading particles. The dependence is expected to be exponential with path length in the nucleus; their mean energy is attenuated exponentially. On the other hand, if the valence partons of the projectile do not lose a significant amount of their initial momentum, as suggested by the models motivated by perturbative QCD, see review in [34], the spectrum of leading particles may approach a finite limit for large A and central impact parameters [35]. Indeed in this case the leading partons will acquire significant transverse momenta and will not be able to coalescence back into leading baryons and mesons as it seemingly happens in the nucleon-nucleon collisions. As a result they will fragment practically independently leading to much softer distributions in the longitudinal momentum for mesons and especially for baryons [35].

Current estimates indicate that the strength of the interaction of fast partons in the nucleon ($x_p \geq 10^{-1}$ for RHIC) with heavy nuclei at the central impact parameters may approach the black disk limit for transverse momenta $p_t^{b.d.l.} \leq 1GeV/c$. Under this scenario all these partons will acquire large transverse momenta $\sim p_t^{b.d.l.}(x_A)$. Hence in the black disk limit p_t broadening of the partons should be much larger than at low energies where p_t broadening is consistent with the QCD multiple rescattering model [34]. This would lead to a very significant p_t broadening of the spectrum of leading hadrons [37]. Probably the most feasible way to study this effect will be to measure the p_t distribution of the leading hadrons (neutrons, K_L, π^0) for the collisions at the central impact parameters, which will closely follow the p_t distribution of leading quarks [38] It is worth emphasizing that a strong p_t broadening which should increase with increase of x_F clearly distinguishes this mechanism of the suppression of the leading hadron spectrum from the soft physics effect of the increase of the total pp cross-section which is rather mild between the fixed target energies at RHIC. At the same time at very large p_t effect of the leading twist shadowing will tame the increase of the transverse momenta with A.

IV. INELASTIC COHERENT DIFFRACTION

The process of inelastic diffraction provides a unique way to measure the fluctuations of the strength of hadron interactions. In particular the ratio of the inelastic and elastic diffractive cross sections at $t = 0$ is equal to the variance of the distribution over the strength of the interaction, ω_σ [39]. The the variance first increases with energy reaching maximum, $\omega_\sigma \sim 0.35$ at $\sqrt{s} \sim 60GeV$. It is expected to be still large at RHIC: $\omega_\sigma \sim 0.25 \div 0.3$. At LHC it is expected to drop to $\omega_\sigma \sim 0.06$. The inelastic small t coherent diffraction off nuclei provides one of the most stringent tests of the presence of the fluctuations of the strength of the interaction in NN interactions. The answer is expressed through $P(\sigma)$ - probability distribution for interaction with the strength σ[40].

$$\sigma_{diff}^{hA} = \int d^2b \Bigg(\int d\sigma P_h(\sigma) |\langle h|F^2(\sigma,b)|h\rangle| - \Big(\int d\sigma P(\sigma) |\langle h|F(\sigma,b)|h\rangle| \Big)^2 \Bigg) . \tag{3}$$

Here $F(\sigma, b) = 1 - e^{-\sigma T(b)/2}$, and $T(b)$ was defined above. Eq.3 provides a good description of (very limited) fixed target diffractive date at $E_p \sim 400GeV$. It predicts the A-dependence of the total cross section of coherent inelastic diffraction at RHIC $\sim A^{0.4}$ for $A \geq 40$, and the cross section of inelastic coherent diffraction off heavy nuclei $\sim 65mb$[41]. Note also that with increase of A contribution of the configurations of smaller size increases, so by selecting special final states (most likely with sufficiently large $p_\perp$ it would be possible to enhance the A-dependence to $\propto A^{1 \div 1.2}$ corresponding to the color transparency regime.

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[] The impact-parameter dependence is accessible in the proton - nucleus collisions via a study of nuclear fragmentation into a number of channels, for an extensive discussion see [32].