QCD and pA physics at RHIC

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Outline

1. Nuclear shadowing and taming of parton densities - the case for forward physics at pA RHIC
2. Color fluctuations in nucleons I - diffractive phenomena

   ◇ *Exclusive hard diffraction:* from mapping $q\bar{q}$ pion wave function to mapping qqq proton wave function.

   ◇ *Color fluctuations in soft processes:* (i) inelastic diffraction, (ii) elastic and quasielastic pA scattering
3. Color fluctuations in nucleons II - study of 3D nucleon wave function via correlation of hard and soft observables
4. Multiparton correlations in nucleons and nuclei
5. Leading hadron spectra for central pA collisions

Main focus

- Use of pA collisions to study correlations of hard partons, correlations between soft and hard partons and multipartons correlations in nucleons and nuclei

- Measurement of nuclear parton densities at very small $x \sim 2 - 4 \cdot 10^{-4}$ - search for shadowing and non linear effects

- Proton propagation through nuclei - pA-AA interface

Small x forward physics

Alvero, Collins, Strikman Whitmore, 97

x, Q range

$$x_1 \geq \frac{4p_T^2}{x_2 s}, \quad Q^2 \sim p_T^2.$$

$$x_1 = \frac{p_T}{\sqrt{s}}\left(e^{y_1} + e^{y_2}\right) \qquad x_2 = \frac{p_T}{\sqrt{s}}\left(e^{-y_1} + e^{-y_2}\right)$$

Cross sections are large $\rightarrow$ *can use* $x_1 \equiv x_p$ *up to* $x_p \sim 0.5$

$\Longrightarrow$ For Drell-Yan $M_{\mu\mu} \geq 4GeV$ for $E_p = 250GeV, E_A = 100GeV$ corresponds to x_A down to $3 \cdot 10^{-4}$!!!

Observables for measurements of $G_A(x, Q^2), \bar{q}_A(x, Q^2)$

QUARKS

- Drell-Yan at$p_t \ll M_{\bar{l}l}$
- Charm production at $x_A \sim x_{min}$

GLUONS

- Drell-Yan at $p_t \sim M_{\bar{l}l}$

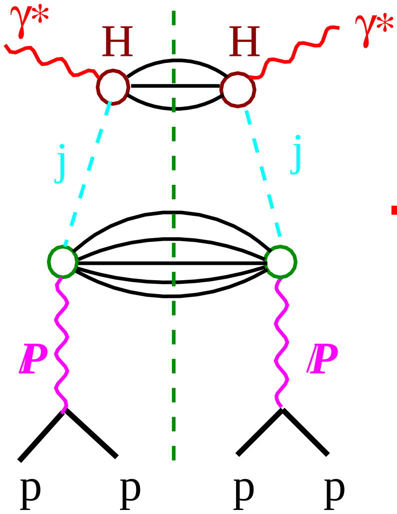
Study of final states in these events is also very efficient for the study of parton propagation through nuclei.

p_t dependence as a function of x_A is a signal for saturation. • jet + photon

- Charm production at $x_A > x_{min}$
- jet + jet

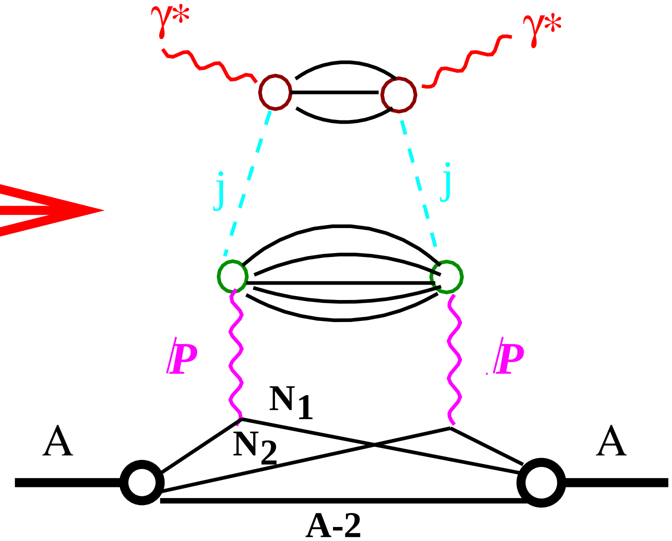
Important advantage of forward pA kinematics: soft hadron spectrum is strongly suppressed - better conditions for observing jets with moderate p_t.

Theorem: In the low thickness limit the leading twist nuclear shadowing is unambiguously expressed through the diffractive parton densities $f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$ of ep scattering. FS 98



Hard diffraction

off parton "j"



Leading twist contribution

to the nuclear shadowing for

structure function $f_j(x,Q^2)$

$$f_{j/A}(x,Q^2)/A = f_{j/N}(x,Q^2) - \frac{1}{2}\int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \int_x^{x_0} dx_{I\!P} \cdot$$

$$\cdot f_{j/N}^D\left(\beta, Q^2, x_{I\!P}, t\right)_{|k_t^2=0} \rho_A(b,z_1)\rho_A(b,z_2)\cos(x_{I\!P} m_N(z_1-z_2)),$$

where $f_{j/A}(x,Q^2), f_{j/N}(x,Q^2),$ are inclusive parton densities; $\rho_A(r)$ is the nucleon density in the nucleus.

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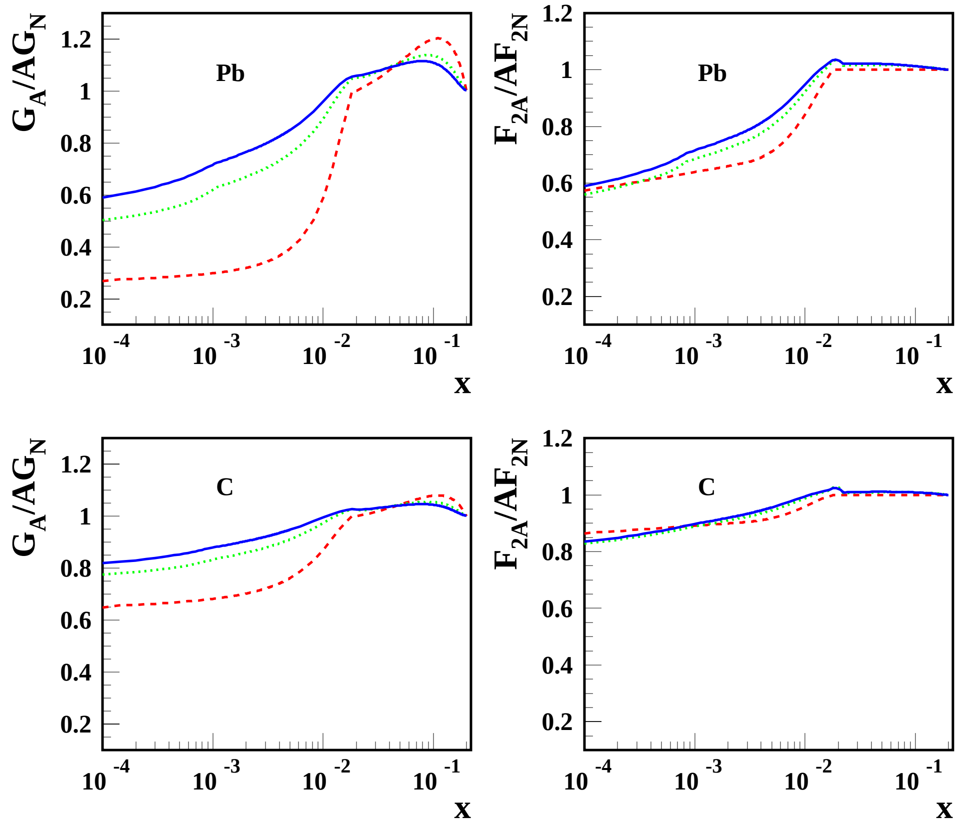
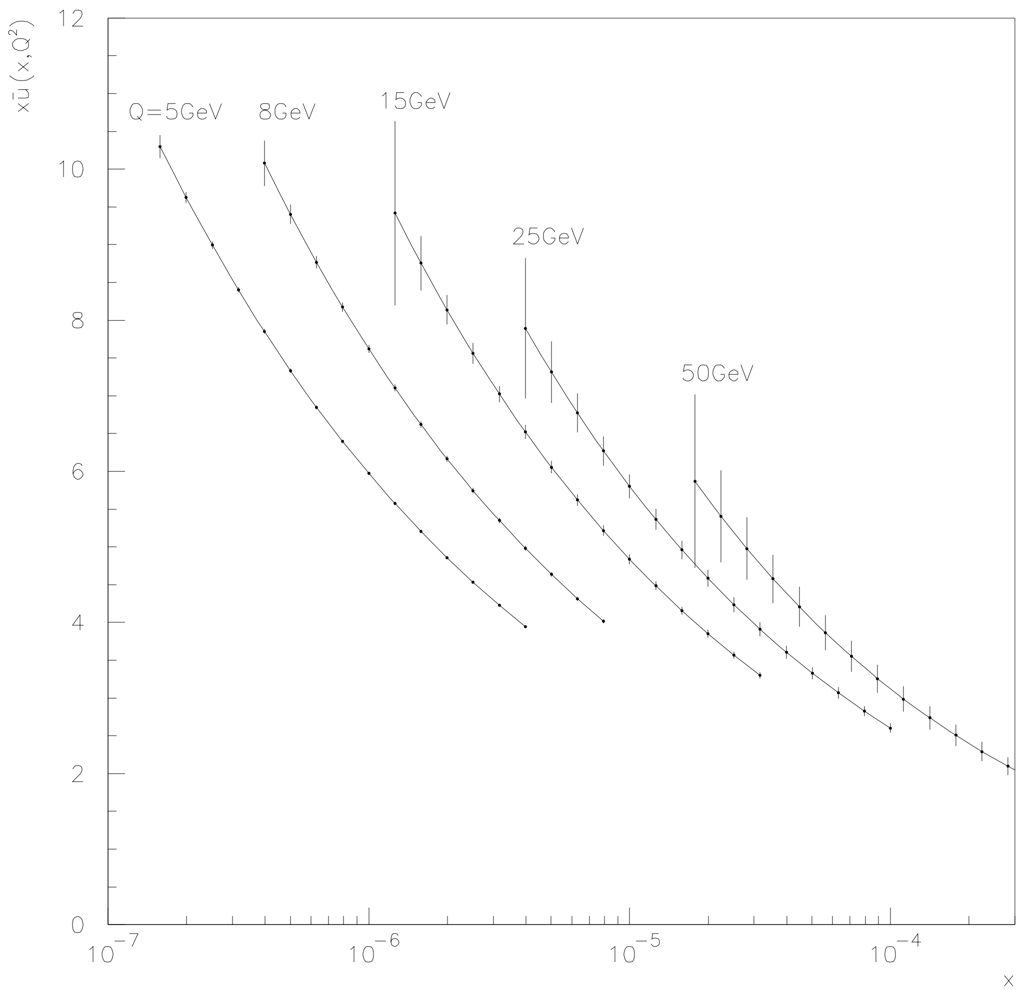


Dependence of G_A/AG_N and F_{2A}/AF_{2N} on x for Q=2 (dashed), 5 (dotted), 10 GeV (solid) curves calculated using diffractive parton densities extracted from the HERA data, the quasieikonal model for $N \geq 3$, and assuming validity of the DGLAP evolution.

Note that for the central impact parameters there is a further suppression of G_A/G_N



The $\bar{u}$ antiquark distribution with error bars calculated from the Drell-yan cross section and dta sample corresponding to an integrated luminosity of $100pb^{-1}$ for LHC pp collisions. For pA RHIC at 250x100 GeV one has to rescale x by a factor of 2000 and consider luminosity of about $2pb^{-1}$ for p-gold collisions.

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The growth of parton densities at small x cannot continue without taming. The simplest argument is based on unitarity for the scattering of small dipoles. FS & Koepf 96

In the leading twist:

$$\sigma^{inel} \gg \sigma^{el}$$

Absolute upper limit $\sigma^{inel} = \sigma^{el}$

For the interaction with nucleon

$$\sigma^{inel} \le \frac{\pi r_N^2}{(1+\beta^2)} = 22 \text{ mb} \ ,$$

For the nucleus

$$\sigma_A^{inel} \le \frac{1}{2}\sigma_A^T = \pi R_A^2$$

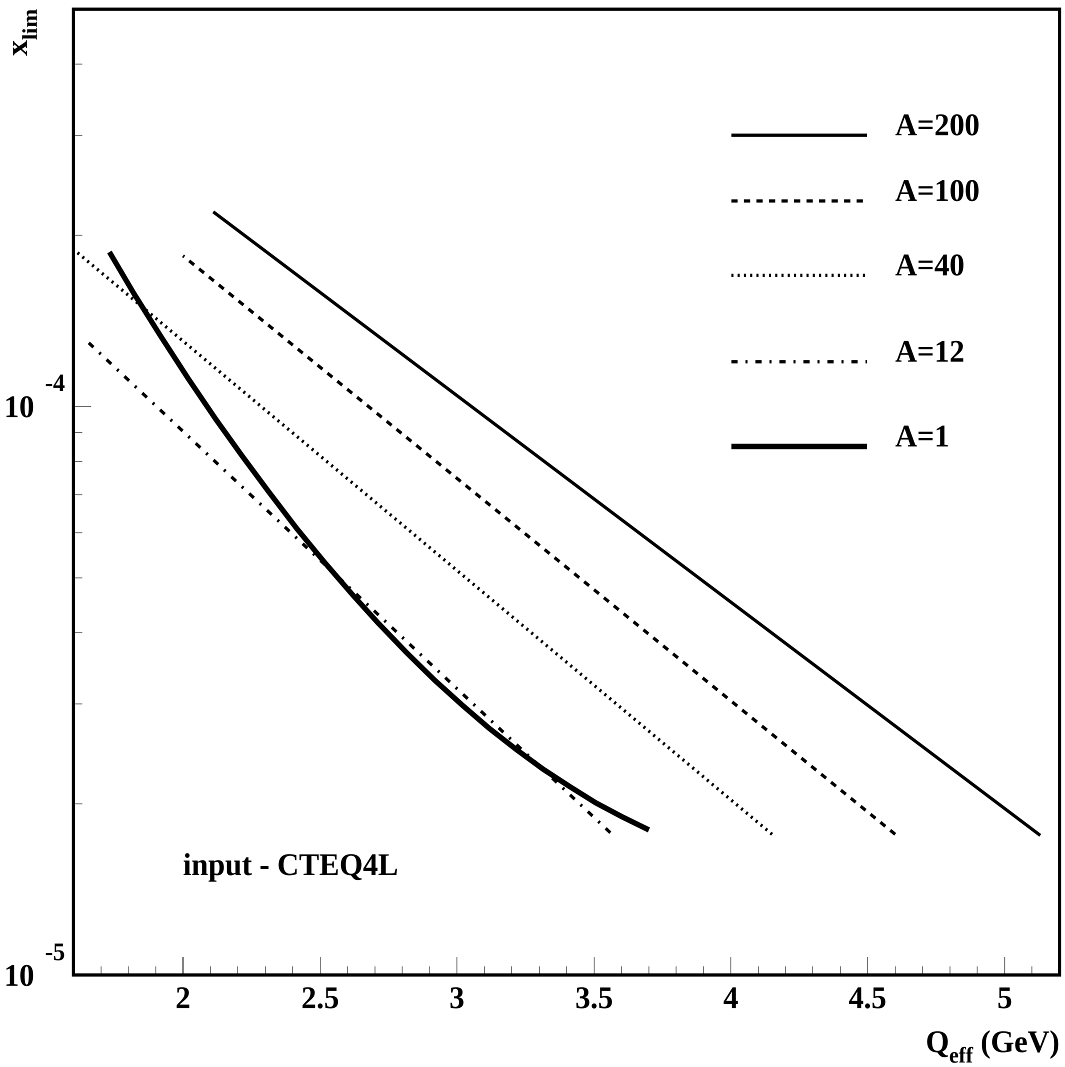
Using

$$\sigma_A^{q\bar{q}}(b^2, x') = \frac{\pi^2}{3} b^2 \left[x' G_A(x', \lambda/b^2) \right] \alpha_s(\lambda/b^2)$$

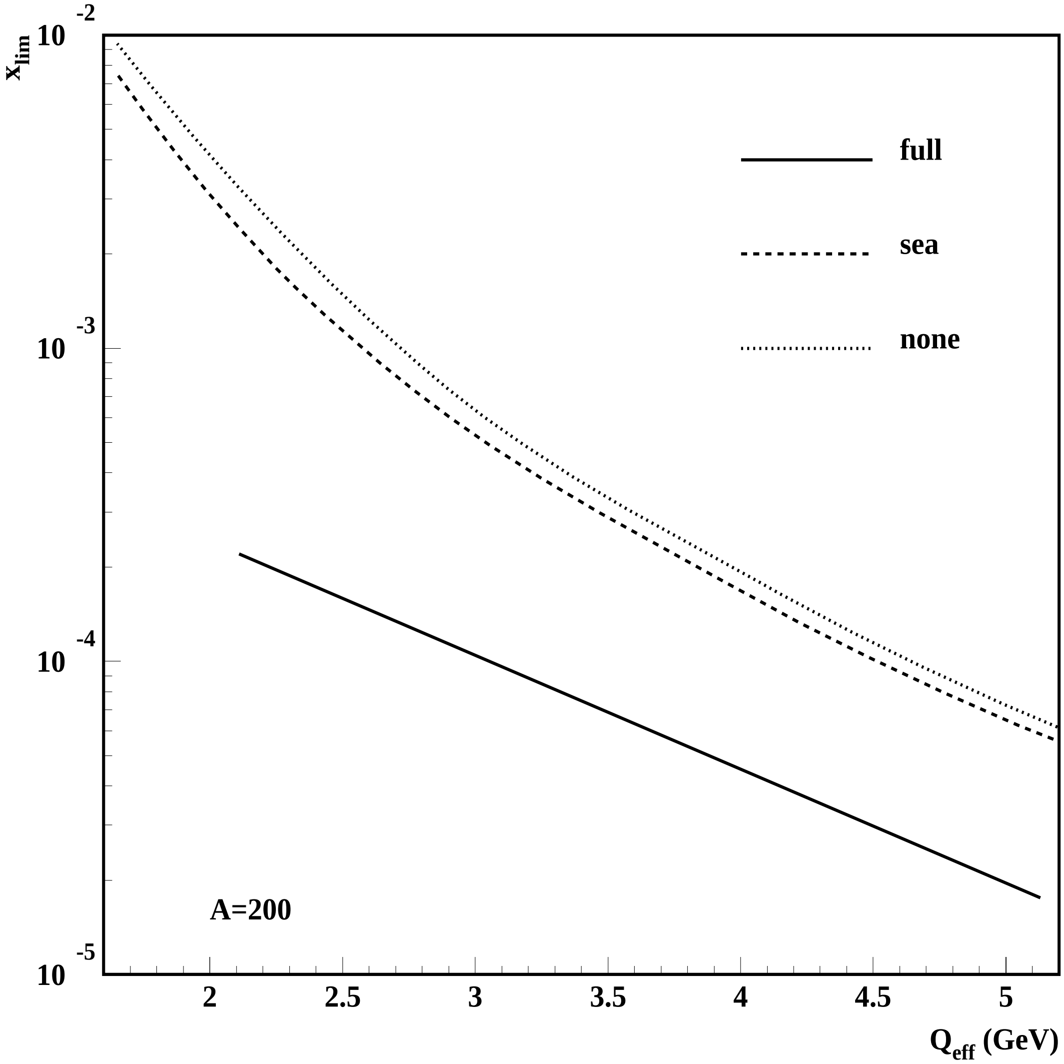
$$\sigma_A^{q\bar{q}g}(b^2, x') = \frac{3\pi^2}{4} b^2 \left[x' G_A(x', \lambda/b^2) \right] \alpha_s(\lambda/b^2)$$

we find that unitarity would be relevant already at the edge of pA RHIC kinematics for gluons in heavy nuclei even if the gluon shadowing is as large as suggested by our analysis of G_A

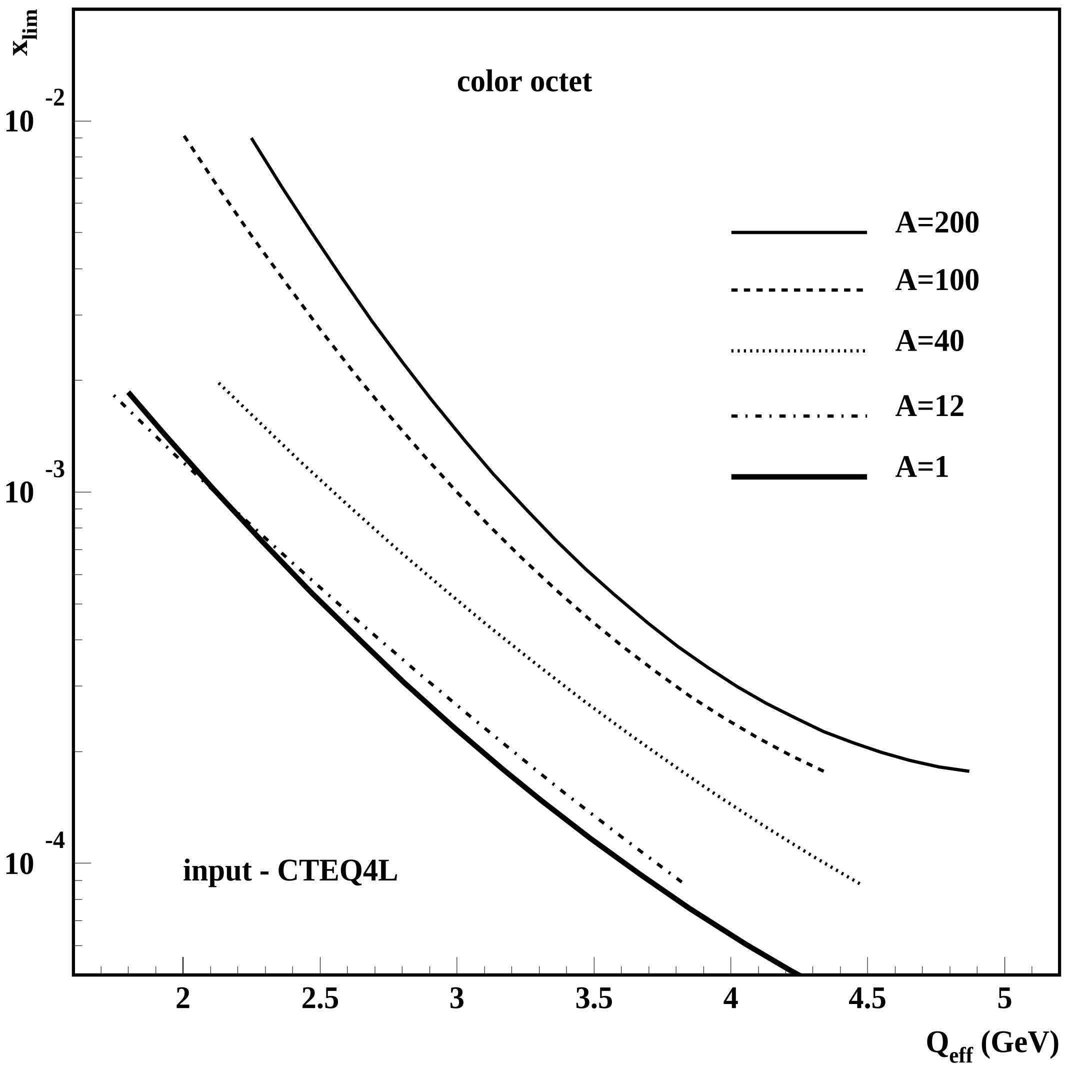
Note that for central collisions limits correspond effectively to $1.5^3 \sim 3.5$ times lighter nuclei.



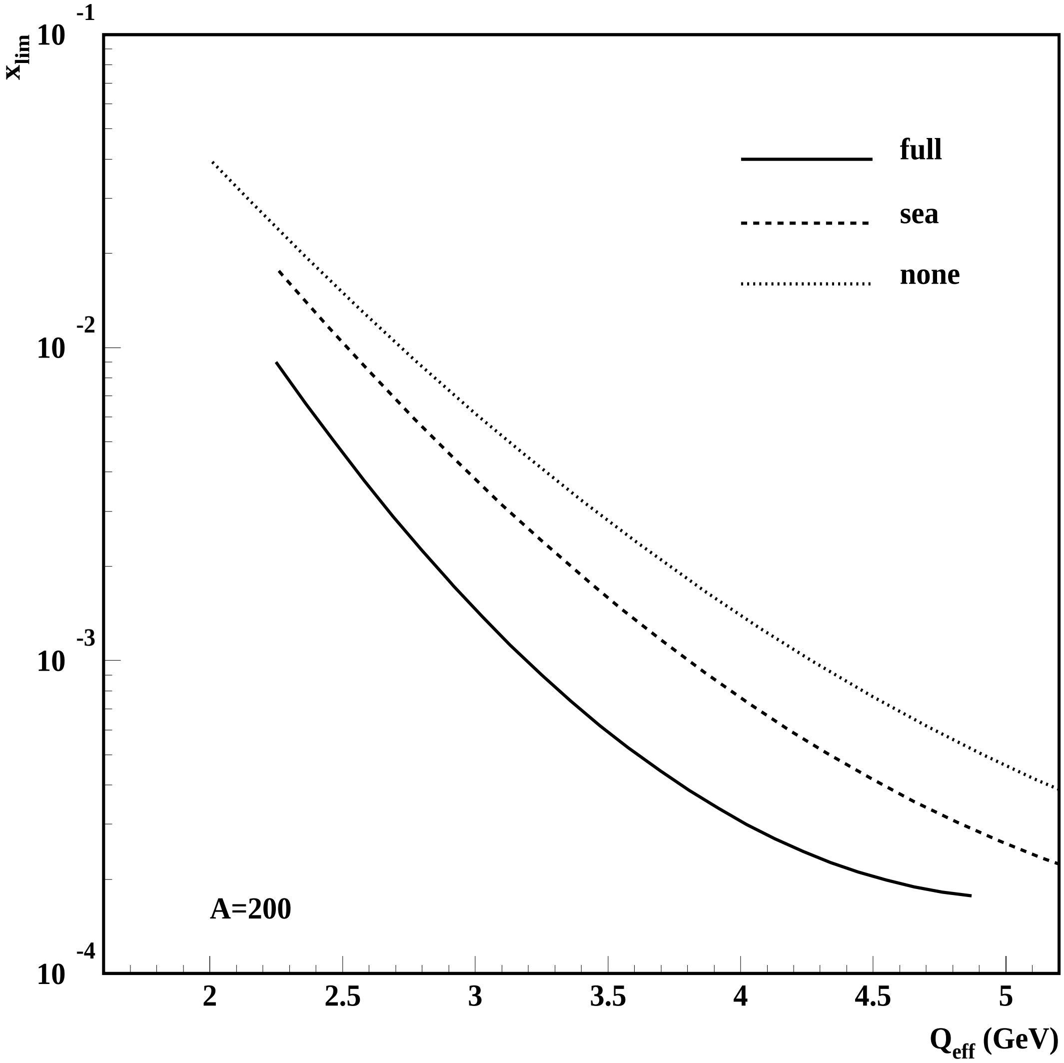
The unitarity boundary for the inelastic $q\bar{q}$-nucleus cross sections for nuclei with A=12, 40, 100, and 200. The unitarity boundary for the inelastic $q\bar{q}$-nucleon cross section is presented as a thick solid line. Guzey & FS 2000



The unitarity boundary for the inelastic $q\bar{q}$-nucleus cross sections for nuclei with A=200. The amount of nuclear shadowing for gluons is varied: the solid line corresponds to the full amount of shadowing, the dashed line corresponds to the gluons shadowed as the sea quarks, and the dotted line is for gluons without shadowing.



The unitarity boundary for the inelastic $q\bar{q}g(gg)$ (color octet)-nucleus cross sections for nuclei with A=12, 40, 100, and 200. The unitarity boundary for the inelastic $q\bar{q}g$-nucleon cross section is presented as a thick solid line.



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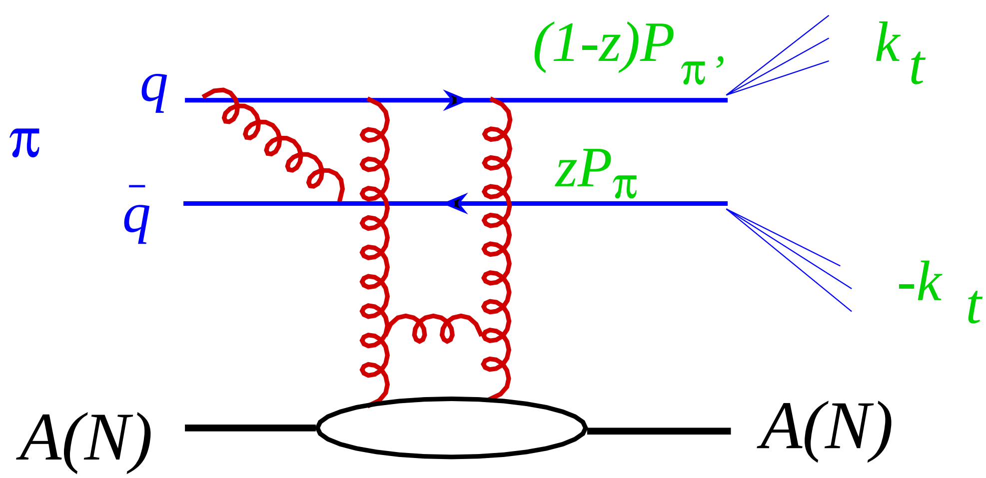
Recently theoretical methods were developed to calculate hard exclusive processes with longitudinal photons and hard exclusive hadron induced processes directly from QCD. The simplest hadronic process probing this physics:

$$\pi + N(A) \rightarrow \text{``}2high\ p_t\ jets'' + N(A)$$

Mechanism:

Pion approaches the target in a frozen small size $q\bar{q}$ configuration and scatters elastically via interaction with $G_{target}(x, Q^2)$.

(pQCD treatment: Frankfurt, Miller, S, 93)



$$Amplitude(p_t, t = 0) \propto \int d^2b\psi_\pi(b)\sigma_{\text{``}q\bar{q}\text{''}-N(A)}(b, s)\exp(ik_tb)$$

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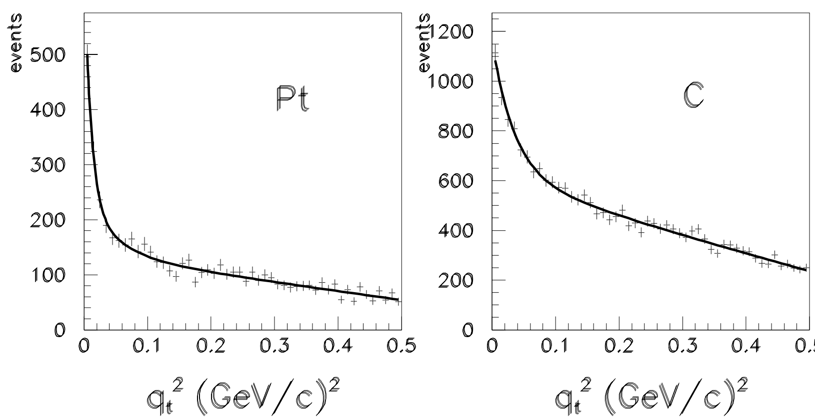
$\Longrightarrow$ A-dependence: $A^{4/3}\left[\frac{G_A(x,k_t^2)}{AG_N(x,k_t^2)}\right]^2$, where $x = M^2_{dijet}/s$.

$\Longrightarrow$ $\frac{d\sigma(z)}{dz} \propto \phi_\pi^2(z) \approx z^2(1-z)^2$ where $z = E_{jet_1}/E_\pi$.

$\Longrightarrow$ k_t dependence $\frac{d\sigma}{d^2k_t} \propto \frac{1}{k_t^n}, n \approx 8$

First E-791 (FNAL) data (D.Ashery 1998-2000) for $E^\pi_{inc} = 500 GeV$

♡ Coherent peak is well resolved:



Number of events as a function of q_t^2, where $q_t = \Sigma_i p_t^i$

♡♡ Observed A-dependence $A^{1.61\pm0.08}$ $[C \to Pt]$

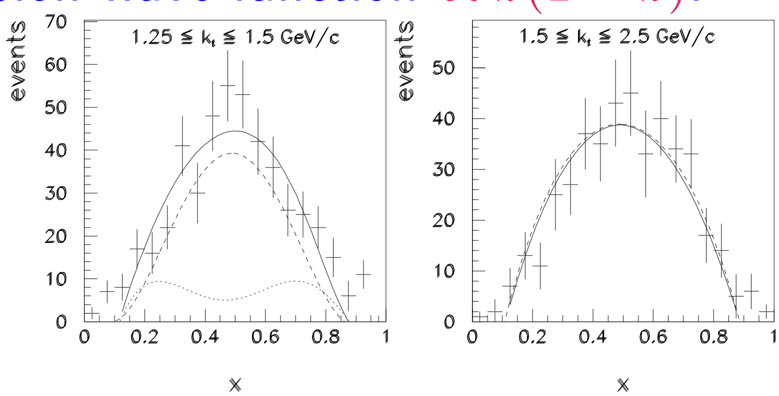
FMS prediction $A^{1.54}$ $[C \to Pt]$ for large k_t
& extra small enhancement for intermediate k_t.

For soft diffraction the Pt/C ratio is ~ 7 times smaller!!

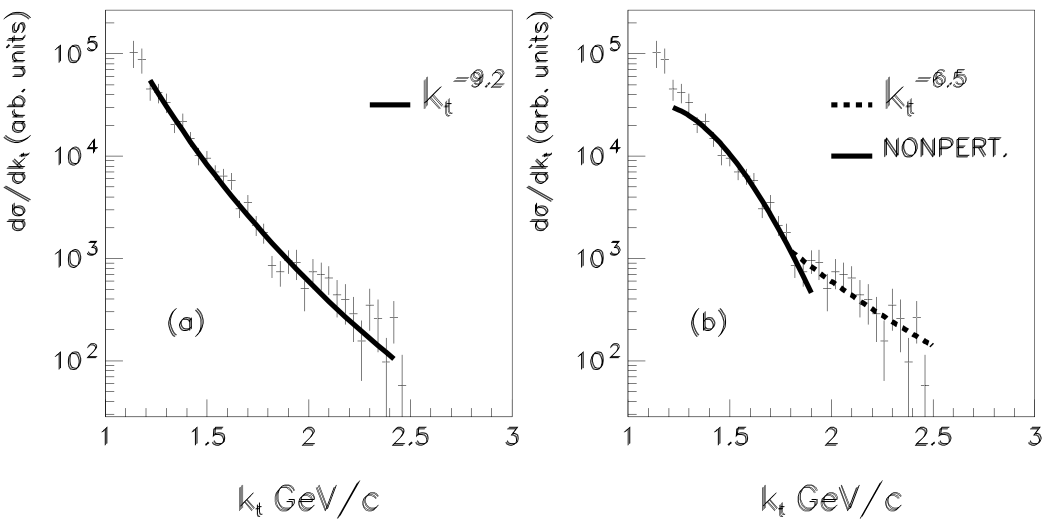
(An early prediction Bertch, Brodsky, Goldhaber, Gunion 81

$\sigma(A) \propto A^{1/3}$)

♡♡♡ The z dependence is consistent with dominance of the asymptotic pion wave function $\propto z(1-z)$.



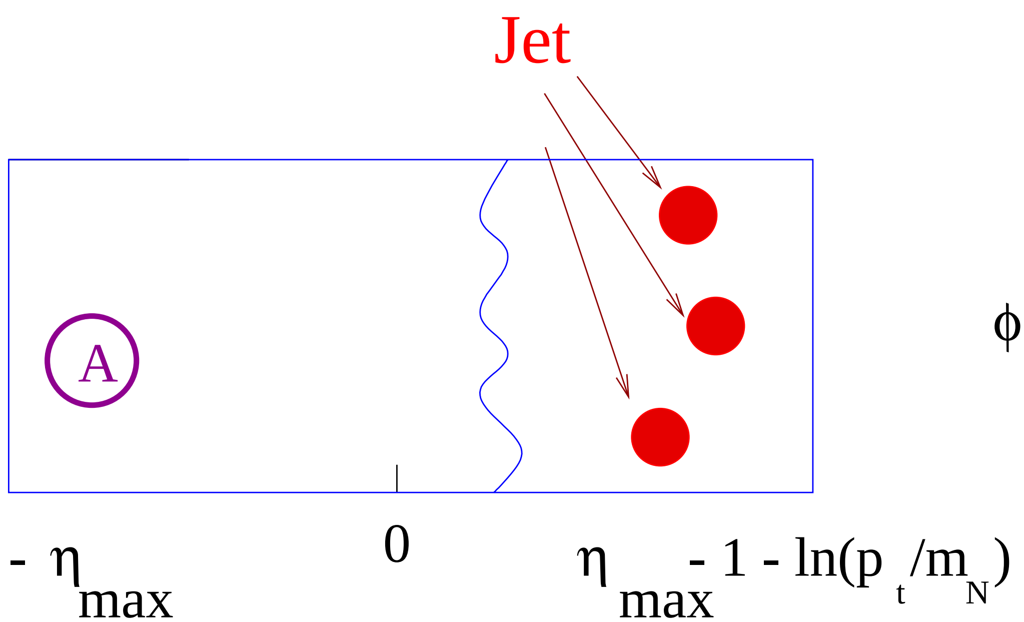
♡♡♡♡ k_t^{-n} dependence of the cross section is close to the QCD prediction - $n \sim 8.5$ for the kinematics of E971



$\Longrightarrow$

- High-energy color transparency is **directly** observed.
- The pion $q\bar{q}$ wave function is **directly** measured.

Next step: Measuring three quark component of the proton wave function in the process
$p + A \to 3\ jets + A$



Lego plot for coherent 3 jet production in proton -nucleus scattering

The process is analogous to the 2jet fragmentation of pion studied by E971.

$$\frac{d\sigma(pA \to (jet_1 + jet_2 + jet_3) + A)}{dt \prod_{i=1}^{3} dx_i d^2 p_{ti}} \propto \left[\alpha_s x_A G_A(x_A, p_t^2)\right]^2 \cdot$$

$$\cdot \frac{\phi_N^2(x_1, x_2, x_3)}{\prod_{i=1}^{3} p_i^4} \delta^2(\sum_{i=1}^{3} \vec{p_{ti}} - q_t) \delta(\sum_{i=1}^{3} x_i - 1) G_N^2(t) F_A^2(t),$$

where $t = -q_t^2, x_A = M_{3jet}^2/2s$. Coefficient is also calculable in pQCD. $\phi_N^(x_1, x_2, x_3)$ is relevant for calculation of proton decay probability.

RHIC advantages - at a collider it is easy to select coherent processes using zero angle neutron calorimeter.

At RHIC one can vary energy proton energy. If no taming of gluon densities $xG(x, Q^2 \sim 40GeV^2) \propto x^{-1/2}$

$\Longrightarrow \quad \sigma_{3jet} \propto s!!!$

For $p_t^{jet} \geq 3GeV/c$ effective Q^2 is large enough so that A-dependence of gluon shadowing is rather weak.

$\Longrightarrow \quad \sigma_{3jet}(A) \propto A^{1.1}$ vs $\sigma_{soft\ diffr.} \propto A^{0.5-0.6}$.

Comments:

- If diquark-quark correlations are present in nucleons one can look for 2 jet fragmentation.

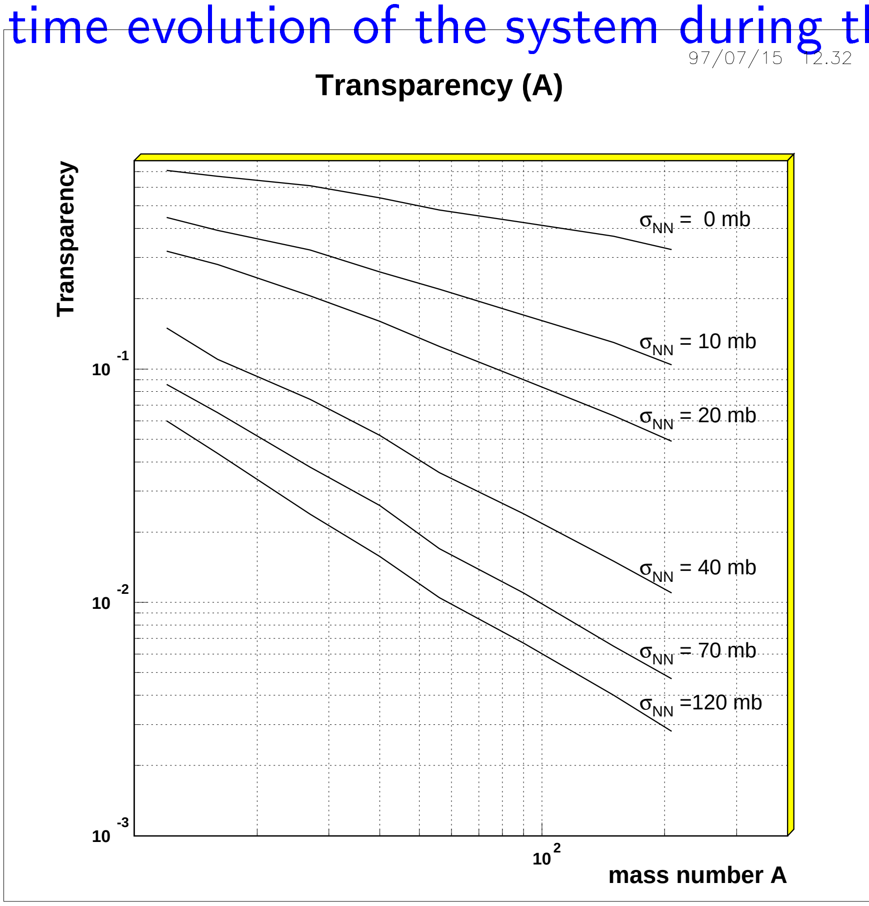
- For polarized proton beams spin dependence of the three - jet emission is likely.

- Interesting to search for exclusive channels at smaller p_t like $p \to p\pi^+\pi^-, \Lambda K^+$ to find an effective trigger for interaction in point like configuration. If this would work can use double diffraction in pp scattering as a trigger for the scattering of two small dipoles.

Color transparency at large energies - are small size configurations important for large ~few GeV^2 elastic pp scattering?

Simple to check using $pA \to pp(A-1)$ scattering. Since the projectile proton and one of outgoing protons are very fast (relative to the nucleus) these nucleons can be considered as frozen during the collision.

$\Longrightarrow$ Effect of CT is much larger and much more sensitive to the size of the interacting system than for low energies where space time evolution of the system during the collision is important.



Soft elastic and inelastic diffraction - probing color fluctuations in nucleons.

Starting point - nucleon is a composite system which size, number of partons fluctuates. At high energies fluctuations are Lorentz delated.

$\Longrightarrow$ Can characterize the strength of fluctuations by the **probability for a hadron to interact with a given cross section - $P_h(\sigma)$**

$P(\sigma)$ satisfies a number constraints which can be derived based on information about soft diffraction off proton and deuteron. Baym, Blattel, Heiselberg, FS 93

$$\int P(\sigma)d\sigma = 1, \int P(\sigma)\sigma d\sigma = \langle\sigma\rangle \equiv \sigma_{tot}$$

$$\int P(\sigma)\sigma^2 d\sigma = \langle\sigma^2\rangle = (1+\omega_\sigma)\langle\sigma\rangle^2 \, , \int P(\sigma)(\sigma - \langle\sigma\rangle)^3 d\sigma \approx 0 \, .$$

In particular one can extract ω_σ from:

$$\omega_\sigma = \frac{\left(\frac{d\sigma(pp\to p+X)}{dt}\right)^{inel}_{t=0}}{\left(\frac{d\sigma(pp\to pp)}{dt}\right)^{el}_{t=0}} = \frac{\langle\sigma^2\rangle - \langle\sigma\rangle^2}{\langle\sigma\rangle^2} \, ,$$

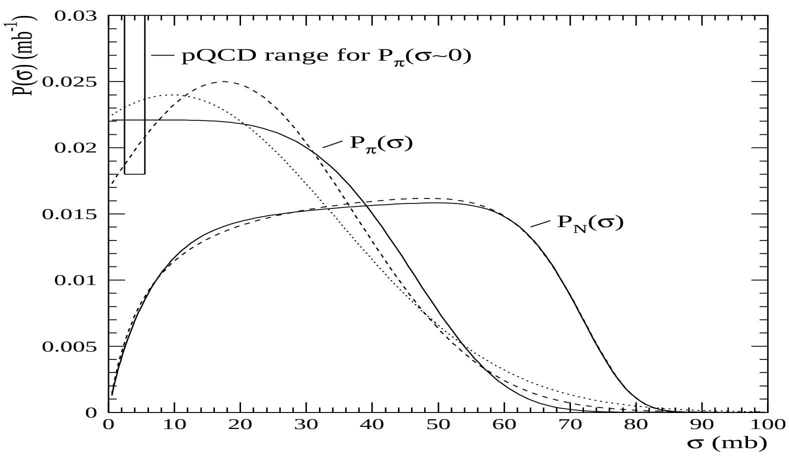
Experimentally ω_σ increases at fixed target and ISR energies:

$$\omega_\sigma(\sqrt{s} = 30GeV) \approx 0.25 \qquad \omega_\sigma(\sqrt{s} = 60GeV) \approx 0.35$$

and drops above $\sqrt{s} = 600GeV$: $\omega_\sigma(\sqrt{s} = 600GeV) \approx 0.2$

GUESS: $\omega_\sigma(\sqrt{s} = 200GeV) \approx 0.25 - 0.3$

Using in addition pQCD constrain on behaviour of $P(\sigma)$ at small σ we found that fluctuations of strength of interaction are amazingly large (diquark-quark dipole can lead to such fluctuations !?)

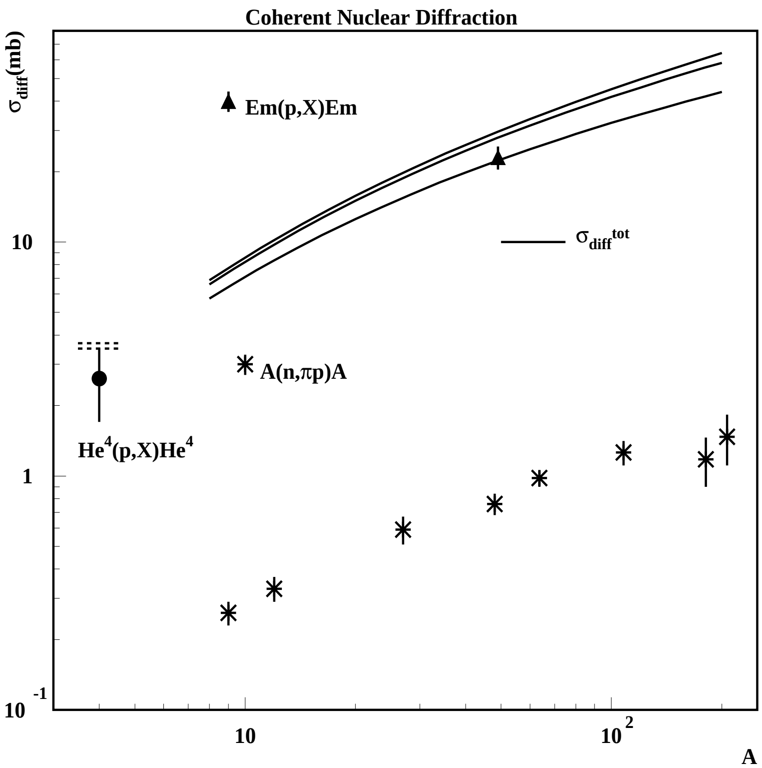


The distribution over cross sections $P(\sigma)$ for protons and pions.

Note: Large ω_σ leads to large fluctuations in pA and AA collisions Baym, Blattel, Heiselberg, FS 93 tions. The most efficient is the incoherent diffraction off nuclei at small t. One finds (Miller &FS 93)

$$\sigma^{hA}_{diff} = \int d^2b \left(\int d\sigma P_h(\sigma) |\langle h|F^2(\sigma,b)|h\rangle| - \left(\int d\sigma P(\sigma) |\langle h|F(\sigma,b)|h\rangle| \right)^2 \right.$$

Here $F(\sigma, b) = 1 - e^{-\sigma T(b)/2}$, $T(b) = \int_{-\infty}^{\infty} \rho_A(b, z) dz$, and $\rho_A(b, z)$ is the nuclear density.

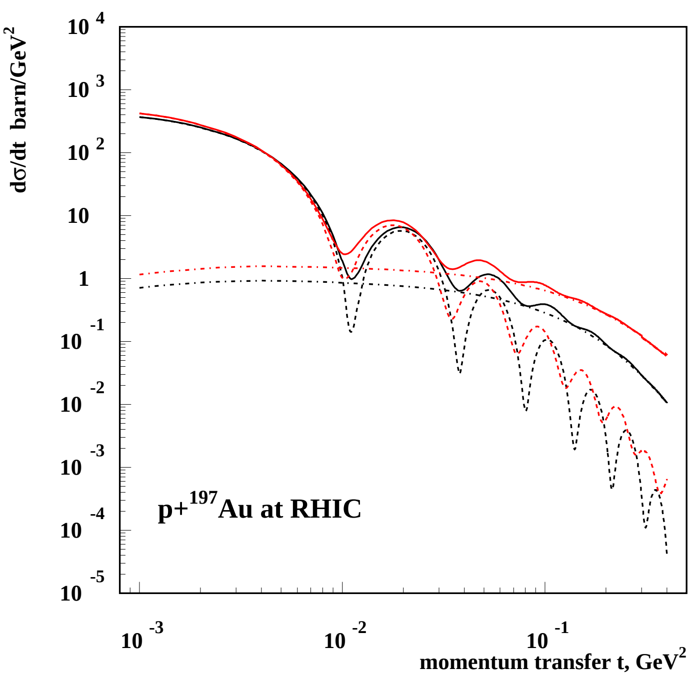


The cross section of coherent diffraction dissociation of protons and neutrons on nuclei as a function of the atomic number A. The solid lines are the theoretical prediction based on the above eqn. The data on the reaction $n + A \to p\pi^- + A$ from FNAL is presented as stars and the data for the emulsion targets is presented as triangles. The data point, presented by the dot, corresponds to $A = 4$. Data are extracted from FNAL ^4He jet target experiment. The theoretical prediction for coherent diffraction on ^{4}He is given by the dashed lines

$\Longrightarrow$ Studies of inelastic diffraction in pA scattering at RHIC would allow to determine color fluctuations in protons at very high energies in the region of turnover to a much more black regime of TeV energies. The FMS prediction for RHIC $\sigma^{inel.dif.} \propto A^{0.5-0.6}$ - significantly weaker A-dependence than for fixed target energies as a consequence of increase of $\sigma_{tot}(pp)$.

$\rightarrow$ Note that a veto on production of forward neutrons is a very effective indicator of nucleus remaining intact.

Elastic and quasielastic scattering are also rather sensitive to color fluctuations. Red curves include fluctuations. Solid curves are sum of elastic and quasielastic cross sections. Dashed curves are quasielastic cross sections.



Multi-jet production - study of parton correlations

At high energies two (three ...) pairs of partons can collide to produce multijet events which have distinctive kinematics from the process *two partons* $\to$ *four partons*. In pp scattering one measures a product of $f(x_1, x_2)$ - longitudinal light-cone double parton density and "transverse correlation area" - σ_{eff}. CDF observed the effect in a restricted kinematics and found $\sigma_{eff} \sim 14mb$ rather small, indicating *high degree of correlations in transverse plane.*

Need to check and measure $f(x_1, x_2)$ independent of σ_{eff}.

$\Longrightarrow$ Study A-dependence MS & Treliani 95

Nuclear enhancements: $\sigma = \sigma_1 \cdot A + \sigma_2$

The first term is due to interactions where two partons of the nucleus belong to the same nucleon and the second term is due to interactions with partons of two different nucleons.

$$\frac{\sigma_2}{\sigma_1 \cdot A} \approx \frac{(A-1)}{A^2 \cdot \sigma_{eff}} \int T^2(b)\ d^2b \approx 0.45 \cdot \left(\frac{A}{10}\right)^{0.5}_{|A \geq 10, \sigma_{eff} \sim 14mb}.$$

For $\sigma_{eff} \sim 14mb$ the second term is two times larger than the first term for $A \sim 200$!!!

3-dimensional mapping of the nucleon

Fluctuations of interaction strength are likely to be correlated with longitudinal parton momenta.

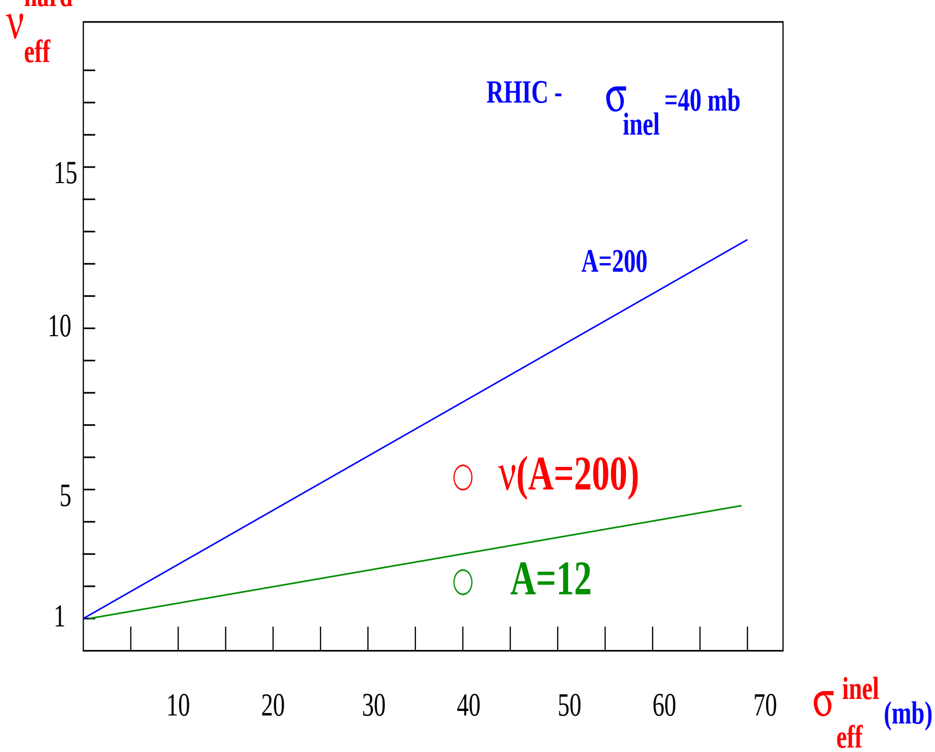
EXAMLE: The presence of a parton with large $x \geq 0.6$ requires three quarks to exchange rather large momenta, one may expect that these configurations have a smaller transverse size and hence interact with the target with a smaller effective cross-section $\sigma_{eff}(x)$.

Idea: Use the hard trigger to determine x_p and accompaning characteristics of the event to measure $\sigma_{eff}(x)$.

F&S85

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} F&S 85

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



Dependence of the number of inelastic interactions with the target on the transverse size of the probed configuration for a hard trigger like $p + A \rightarrow \mu^+\mu^- + X$ reaction

Observables:

◇ Multiplicity of "soft" neutrons in the nuclear fragmentation region

◇ "Multiplicity of fast protons at $x_F \geq 1.2$" $\propto \nu_{eff}$

◇ "Multiplicity of hadrons at $y_{c.m.} \sim 0''$ $\propto \nu_{eff}$

◇ A-dependence of the leading hadrons along proton direction. How big is absorption - naively for a hard trigger very strong suppression. However there is interesting possibility of limiting absorption curve A.Berera, MS, W.S. Toothacker W.D.Walker J.J. Whitmore

Conclusions:

- Proving parton densities
  - Forward detector would allow to measure gluon and quark shadowing down to the region where taming effects as well as absolute magnitude of shadowing are large.
  - x-range will nicely complement & overlap with eRHIC allowing tests of violation of pQCD factorization.

- Mapping of the proton wave function
  - Measurement of three quark component of the nucleon wave function.
  - Color fluctuations in nucleons: global effects & x-dependent effects
  - Multiparton correlations in nucleons.

- Nucleon/Parton propagation through nuclei
  - Test of AGK relation for central multiplicity

$$\frac{d\sigma^{p+A\to h+X}}{dy}(y_{c.m.}\sim 0) = A\frac{d\sigma^{p+p\to h+X}}{dy}(y_{c.m.}\sim 0)$$

  - Dynamics of Leading hadron particle production $x_p \geq 0.3$ through study of long range correlations with $y_{c.m.} \sim 0$ production and hard triggers of centrality.
  - Cosmic ray connection.