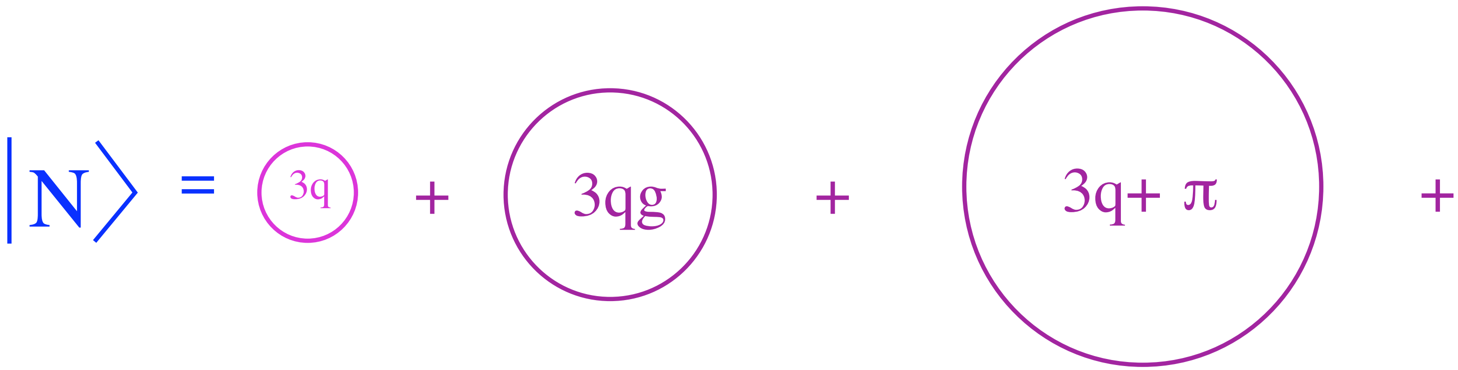
Diffractive phenomena in pA and eA scattering.

Mark Strikman, PSU

BNL eA/pA workshop ,
May 6, 05

Color fluctuations in the nucleon wave function & 3-dimensional mapping of the nucleon



Fluctuations of interaction strength are likely to be correlated with quark content of the hadron. Smallest configurations are most likely the minimal Fock state ones.

Important feature of QCD: QCD sum rules, form factors at large Q, chiral dynamics.

Experimental evidence: Pion diffraction into two jets, inelastic coherent diffraction off nuclei.

At RHIC energies the variance of the interaction strength is still large

$\omega_\sigma \sim 0.25 \div 0.3$ At LHC it is expected to drop to $\omega_\sigma \sim 0.06$

Three methods of experimental study in coherent pA scattering

- Hard exclusive diffraction of proton into three jets
- Soft coherent diffraction: $p + A \rightarrow X + A$
- Hard diffraction pA: $p + A \rightarrow \text{"}two\ jets\text{"} + X + A$
  as a function of x of the parton in the proton.

Another option is study of the associated hadron production in hard scattering processes involving a leading quark or gluon in the proton like DY production at large x_p

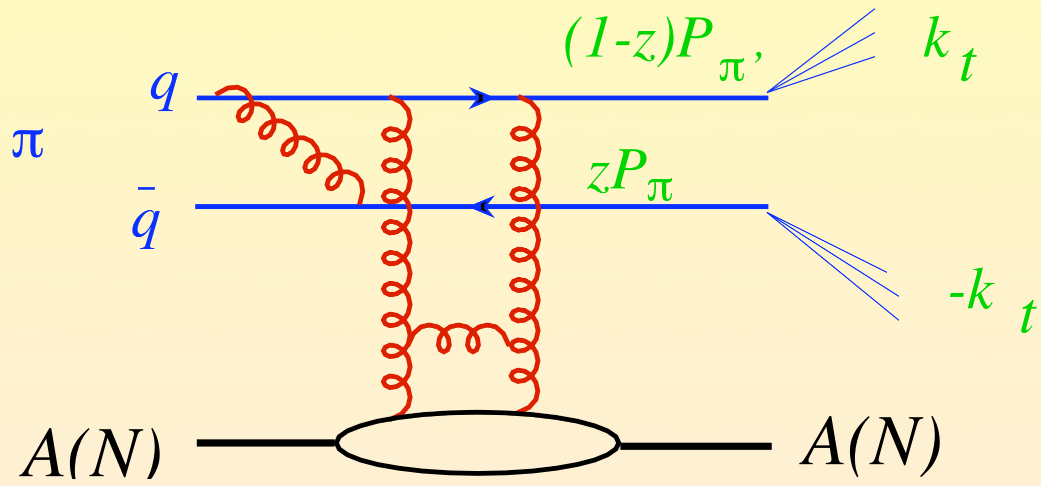
Very forward physics: $p + A \to 3\ jets + A$

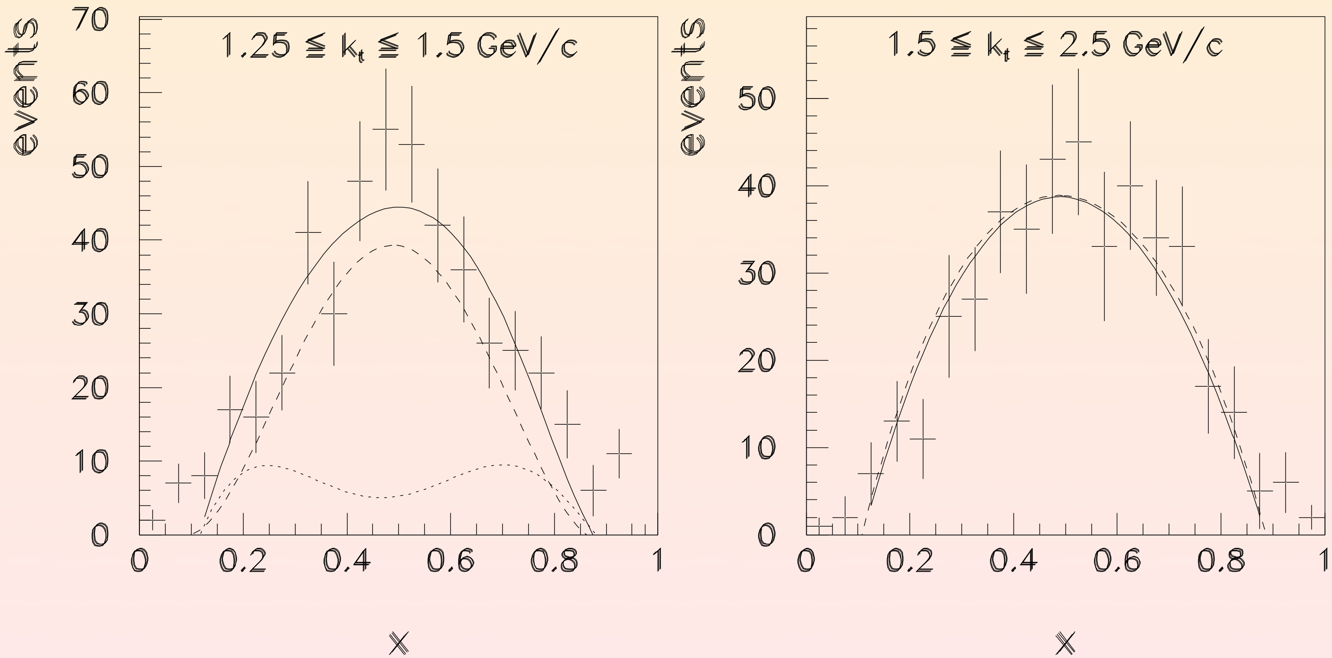
- Measurement of the proton wave function in $|3q>$ configuration with small transverse distance separation.

- Color transparency & Color opacity

Extension of the study of $\pi + N(A) \to ``2\ high\ p_t\ jets'' + N(A)$

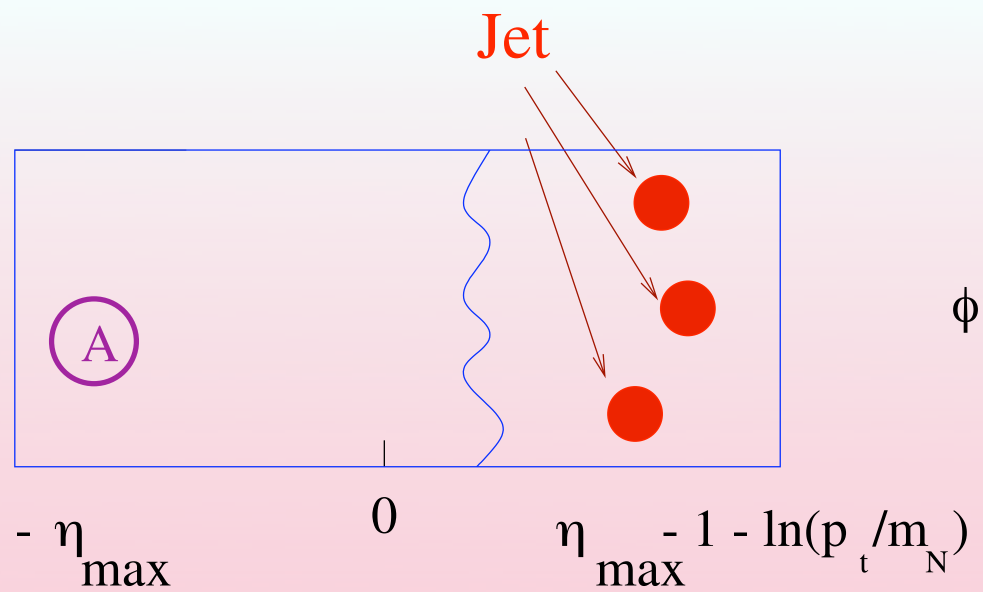
by FNAL 791 (2001), which confirmed Miller &F&S 93 prediction for the A-dependence, z-, p_t-dependence of the dijet coherent cross section.





Solid lines are the asymptotic (large p_t) prediction:

$$\sigma(z) \propto \phi_\pi^2(z) \propto (1-z)^2 z^2$$



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

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

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

where $t = -q_t^2, x_A = M_{3\,jet}^2/2s, \phi_N$ nucleon 3 q wave function.

Advantages of the collider kinematics: it is easy to select coherent processes using zero angle neutron calorimeter. Energy dependence is very strong if there is no taming of gluon densities since

$$xG_A(x, Q^2 \sim 40\ GeV^2) \propto \frac{1}{\sqrt{x}} \quad \Longrightarrow \quad \sigma_{3\ jet} \propto s\ !!!$$

At RHIC one can hope to distinguish three jet configurations with

$p_t \geq 3\ GeV/c$ corresponding to $x = \frac{M^2_{3\ jet}}{s} = \frac{9p_t^2}{s} \sim 10^{-3}$

For such transverse momenta shadowing is rather weak function of A

$xG_A \propto A^{-0.1}$ $\Longrightarrow \sigma_{3\ jet}(A) \propto A^{1.1}$ *as compared to* $\sigma_{soft\ diffr.} \propto A^{0.6}$

The magnitude of the cross section is 10^{-5} mb per nucleon.

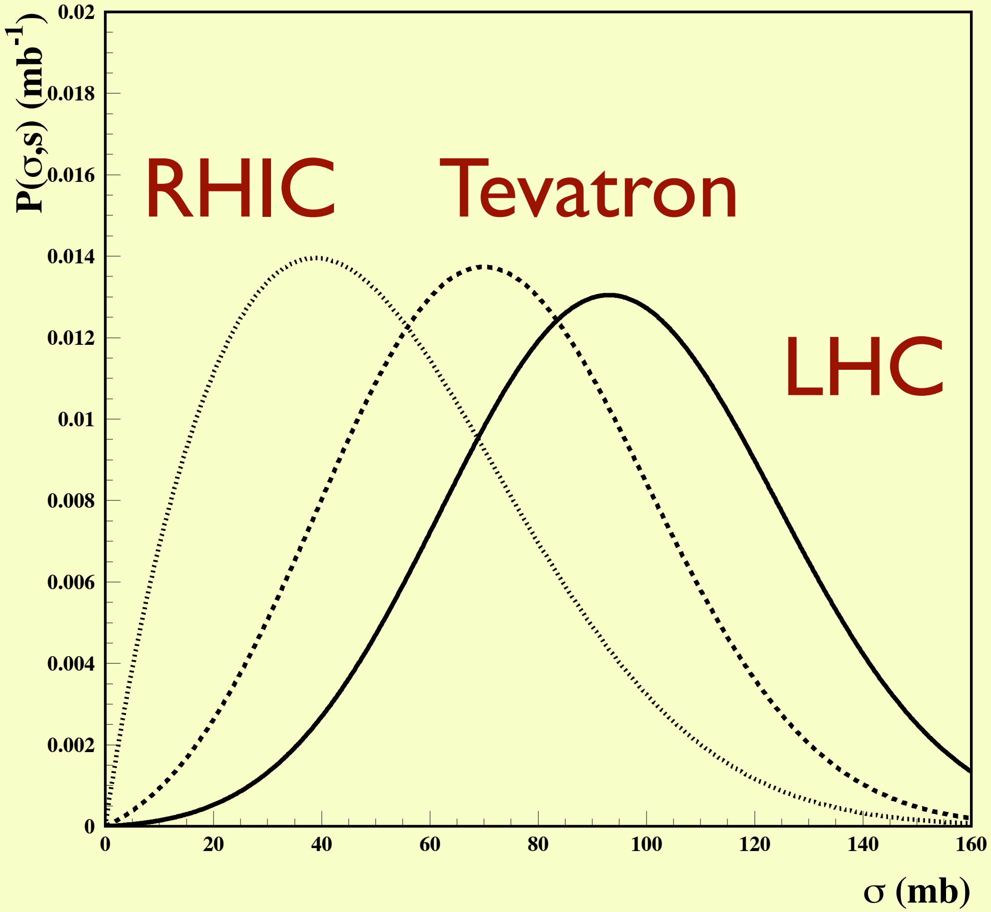
Comments:

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

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. (Miller &FS 93)

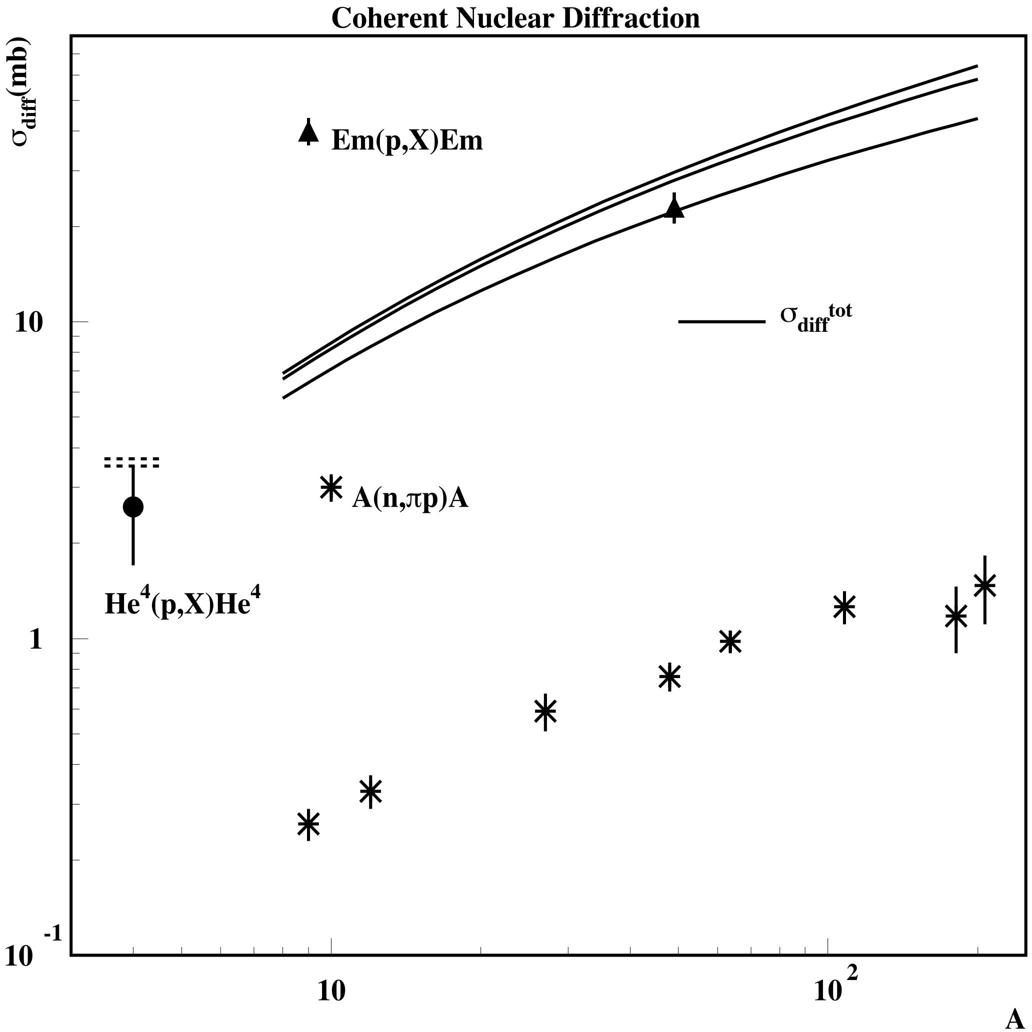
$$\sigma^{hA}_{diff} = \int d^2b \left(\int d\sigma P_h(\sigma) |\langle h|F^2(\sigma,b)|h\rangle| - \left(\int d\sigma P(\sigma) |\langle h|F(\sigma,b)|h\rangle| \right)^2 \right) .$$

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.



Comment: Fluctuations of strength of nucleon interaction lead to strong modifications of the distribution over the number of wounded nucleons (Baym, LF, MS 93)

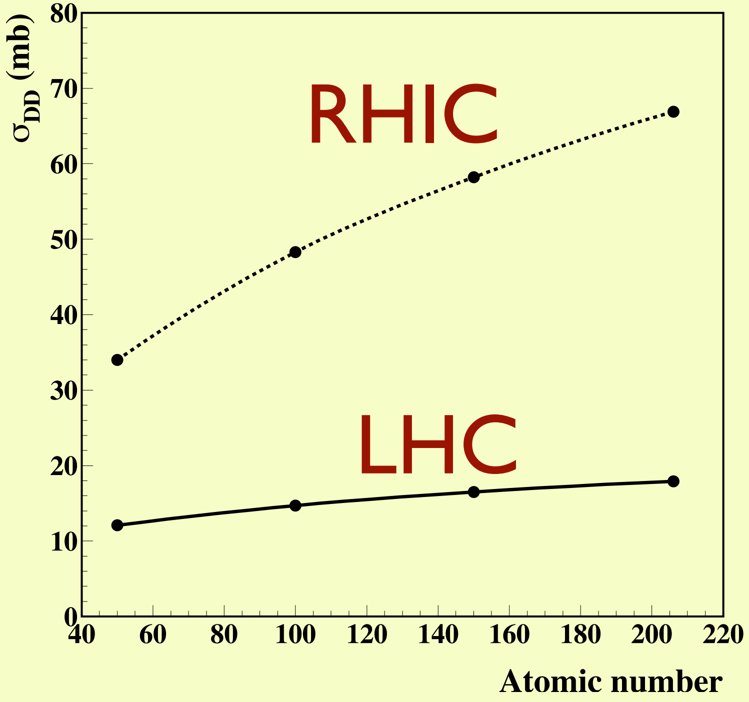
Guzey and MS 05



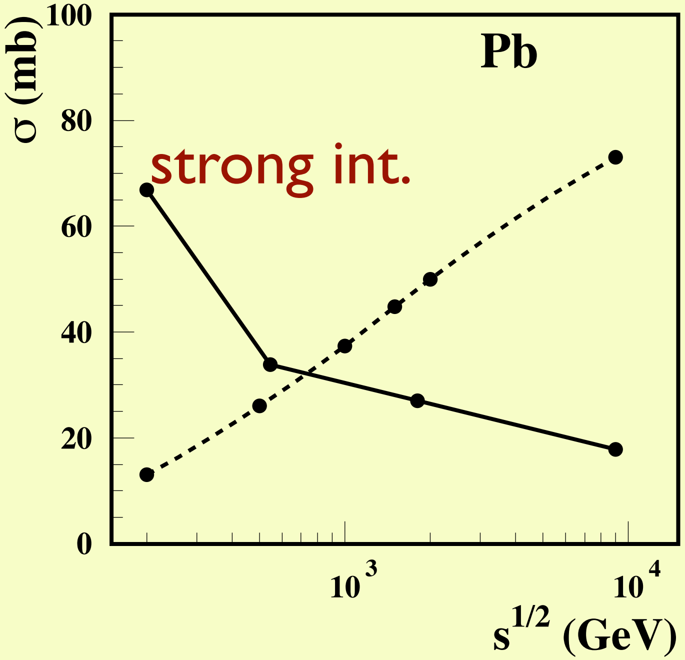
The cross section of coherent diffraction dissociation of protons and neutrons on nuclei as a function of the atomic number A. The solid lines are the theoretical prediction based on the above eqn. Total cross section data are from the FNAL emulsion and ^{4}He jet target experiments. The FNAL data on the reaction $n + A \to p\pi^- + A$ a small fraction of the total diffractive cross section is presented as stars have similar A-dependence for all masses and provide a good indication of the overall trend of the A-dependence. The theoretical prediction for coherent diffraction on ^{4}He is given by the dashed lines.

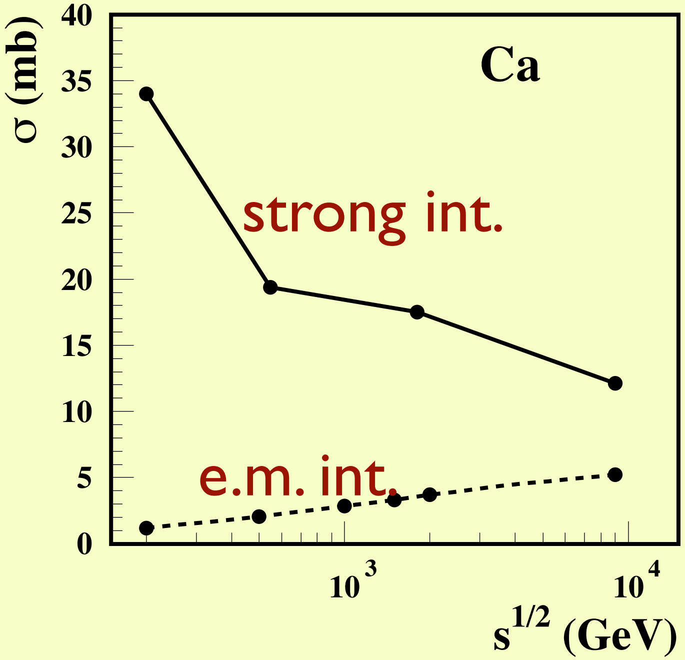
$\Longrightarrow$ Studies of inelastic diffraction in pA scattering at RHIC would allow to determine color fluctuations in protons at very high energies in the region of turnover to a much more black regime of TeV energies. The FMS prediction for RHIC $\sigma^{inel.dif.} \propto A^{0.5-0.6}$ - significantly 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.



Guzey and MS 05





e.m. int. = inelastic interaction of protons with the Coulomb field of the nucleus

E.m. mechanism is small at RHIC, however one will need to investigate whether there maybe a bigger relative contribution if one would investigate rare channels like those mentioned above.

For exclusive diffraction into three jets MS & LF found correction to be small even at LHC. So situation is likely to be the same for RHIC for wide range of channels. Still further studies are necessary. Clearly not a problem for lighter ions like Ca.

Conclusions: Diffraction is one more reason *for expanding the acceptance of the RHIC detectors (new detector?) in the very forward region.*

Diffraction in eA scattering

Total cross section is closer to elastic case in pA than to inelastic simply because due to small e.m. coupling the process $\gamma^* \rightarrow h \rightarrow \gamma^*$ is very small.

Virtual photon converts to configurations of very different size / strength of interaction. In inclusive DIS - bulk sum. In diffraction they enter separately.

Coherent diffraction: several limits probing different physics

In the limit of strong absorption - black body limit (which is not the same as saturation) - diffractive would reach 1/2 of the total cross section.

$$\frac{d\sigma^{eA}_{diff}}{dx\,dQ^2\,dM^2\,d\cos\theta} \propto \frac{\pi R_A^2}{12\pi^3}\frac{Q^4\rho(M^2)}{(M^2+Q^2)^2}\left(\frac{3}{8}\frac{M^2}{Q^2}(1+\cos^2\theta)+\frac{3}{4}\varepsilon\sin^2\theta\right)$$

Consequences:

Dominant final state - two jets with distribution over cos θ like in e^+e^- annihilation (three-jets events are also like in e^+e^-)

Production of jets with large transverse momenta is enhanced relative to DGLAP

BBL for coherent exclusive vector meson (VM) electroproduction: *restoration of the vector dominance answer due to diagonality of transitions in the BBL !!!*

$$\frac{d\sigma^{\gamma_T^*+A\to V+A}}{dt} = \frac{M_V^2}{Q^2}\frac{d\sigma^{\gamma_L^*+A\to V+A}}{dt} = \frac{(2\pi R_A^2)^2}{16\pi}\frac{3\Gamma_V M_V^3}{\alpha(M_V^2+Q^2)^2}\frac{4\left|J_1(\sqrt{-t}R_A)\right|^2}{-tR_A^2}$$

Q -dependence e.g. for σ_L: $1/Q^2$ for BBL vs $1/Q^6$ in the leading twist !!!

Hard Exclusive Diffraction

Motivation:

- ♥ Establishing the Q^2 range where QCD factorization is valid for exclusive processes. At what Q^2 nucleon GPD's can be measured (C.Weiss talk)

- ♥ Comparison of nuclear GPDs and nuclear pdfs.

Semiinclusive hard diffraction

Motivation:

- ♥ Much deeper understanding of small x nuclear dynamics via measurement of Pomeron- Pomeron interactions, nuclear diffractive pdfs.

☛Exclusive diffraction - photon & vector meson production. $x \geq 0.02$ Parton densities practically A-independent. Leading twist expectation for the amplitudes:

$$M(\gamma^* + A \to \gamma(V) + A) = A F_A(t)\, M(\gamma^* + A \to \gamma(V) + A)$$

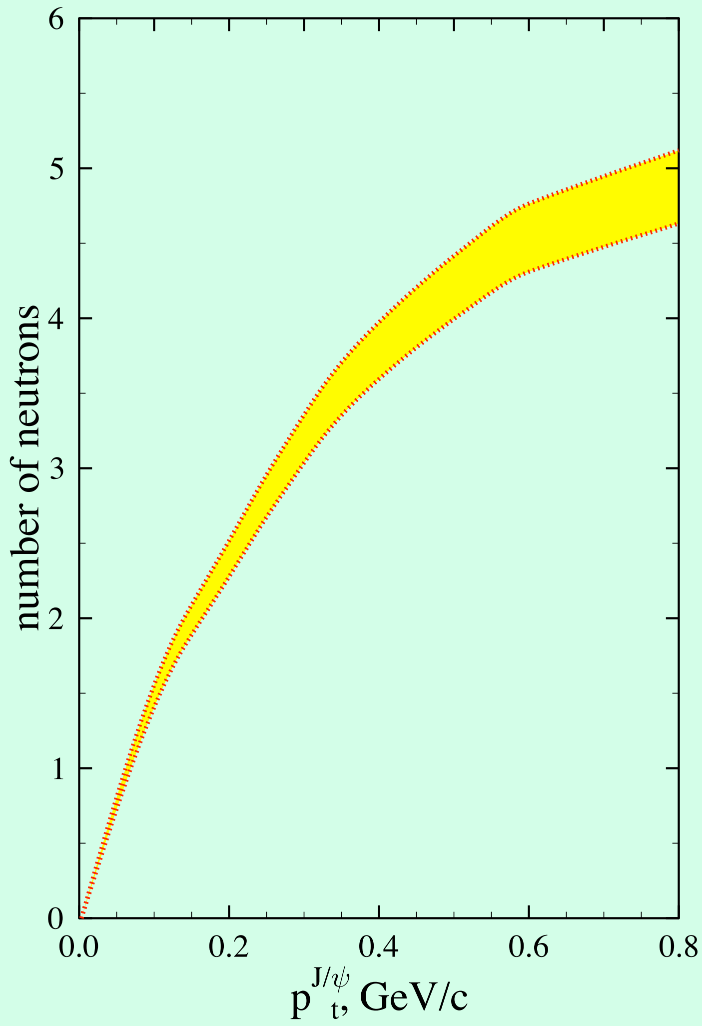
Observed for the J/ψ photoproduction at FNAL.

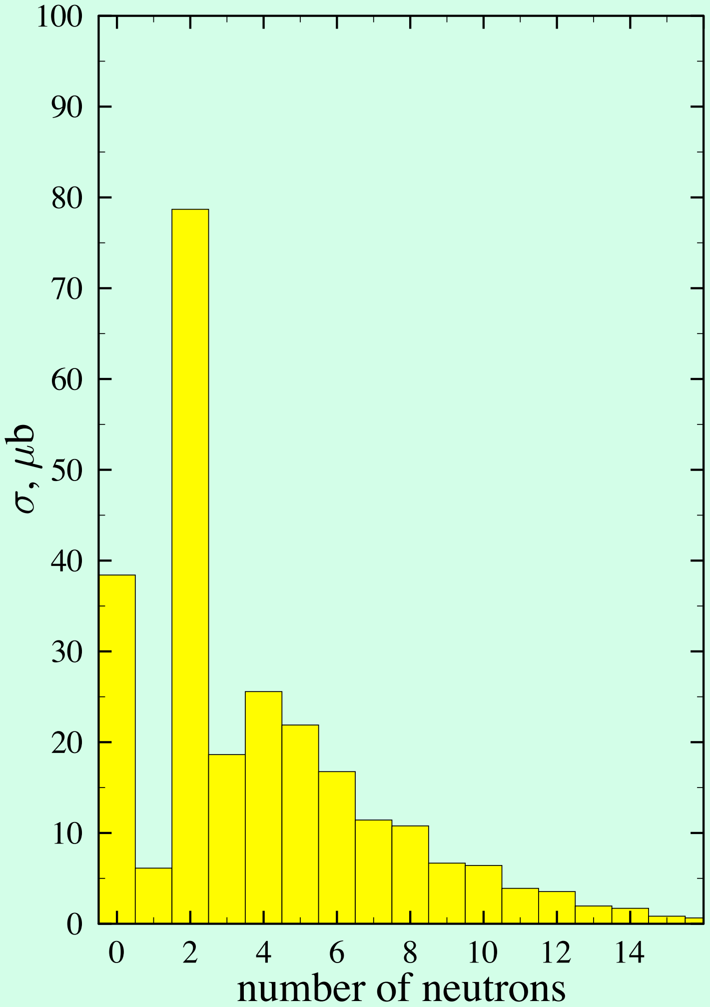
At what Q^2 LT works for vector mesons? Leading twist dominates in the elementary reaction for $Q^2 \geq 10 - 15\ GeV^2$ only. However, squeezing may work already for $Q^2 \geq 5\ GeV^2$ (FKS95) leading to the color transparency phenomenon for much larger range of Q and hence to a possibility to measure the ratios of nucleon GPDs for a broad range of reactions.

Alternative probe: incoherent exclusive processes for $|t| \geq 0.1\ GeV^2$:

$$d\sigma(\gamma^* + A \to \gamma(V,\pi,K..) + A')/dt =$$
$$= Z\, d\sigma(\gamma^* + p \to \gamma(V,\pi,K..) + N)/dt + (A-Z)\, d\sigma(\gamma^* + n \to \gamma(V,\pi,K..) + N)/dt$$

Important advantage of collider kinematics - possibility to use ZDC to select the processes without nucleon excitation





Number of neutrons produced in the process $\gamma + A \rightarrow J/\psi + A'$

Tverskoi, Zhalov, MS 05

☛Exclusive diffraction - γ & VM production for $x \le 0.02$.

☀ DVCS on nuclei is doable - possible to measure both imaginary and real part. Large nuclear effects extend to x~0.1 for the real part. (Freund and MS 03)

☀ Onset of perturbative color opacity:

$$M(\gamma^*+A\rightarrow V+A)=AF_A(t)\,M(\gamma^*+A\rightarrow V+A)G_A(x,Q^2)/G_N(x,Q^2)$$

First checks via ultraperipheral ion-ion collisions at LHC -

J/ψ photoproduction off nuclei – at $x \geq 10^{-3}$

EIC will be able to measure nuclear GPDs via DVCS and next to measure VM to see whether suppression is similar, and study it as a function of Q^2 - interplay of HT and LT shadowing.

Nuclear Diffractive parton densities

Collins factorization theorem: consider hard processes like

$$\gamma^* + T \to X + T(T'), \ \gamma + T \to \ jet_1 \ + \ jet_2 + X + T$$

one can define conditional (fractional) parton distributions

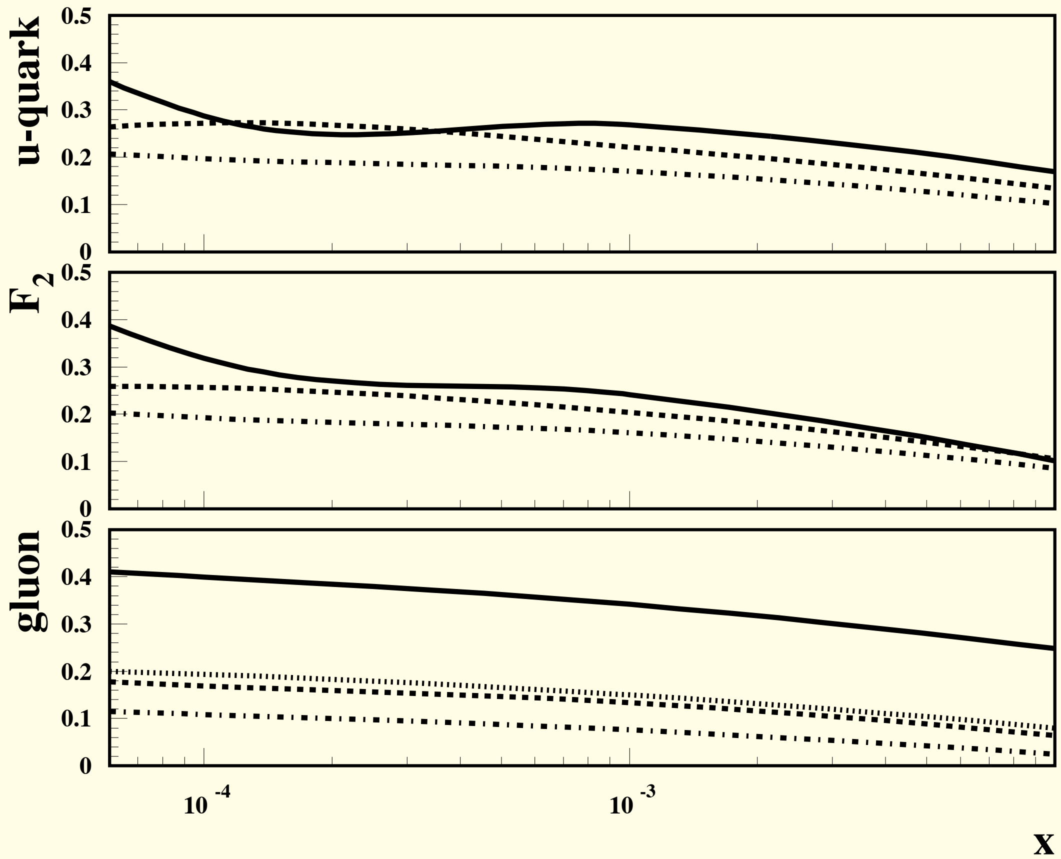
$f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$ where $x_{I\!P} \equiv 1 - x_{T_f}$

Theorem: for fixed $x_{I\!P}, \ t$

the same Q evolution as for normal pdf's.

Nuclear diffractive pdfs were calculated by Guzey et al 03 in the same approximations as LT nuclear pdf's (no model necessary for double rescattering)

Measurement of the leading twist inclusive diffraction off nuclei - expected to be a significant fraction of the cross section for x<0.01



The ratios of diffractive and inclusive pdfs for the u-quarks and gluons and NLO F_{2A}'s for Pb. The solid curves correspond to Q=2 GeV; the dashed curves correspond to Q=10 GeV; the dot-dashed curves correspond to Q=100 GeV. In addition, for the gluons the dotted curve correspond to Q=5 GeV (Guzey, FS -03)

Note that maximal value of the ratio is 1/2 - black body limit. Both quark and gluon interactions with heavy nuclei are close to this limit for Q=2 GeV !!!

EIC kinematics: To ensure coherence one needs

$x/\beta < 0.01$

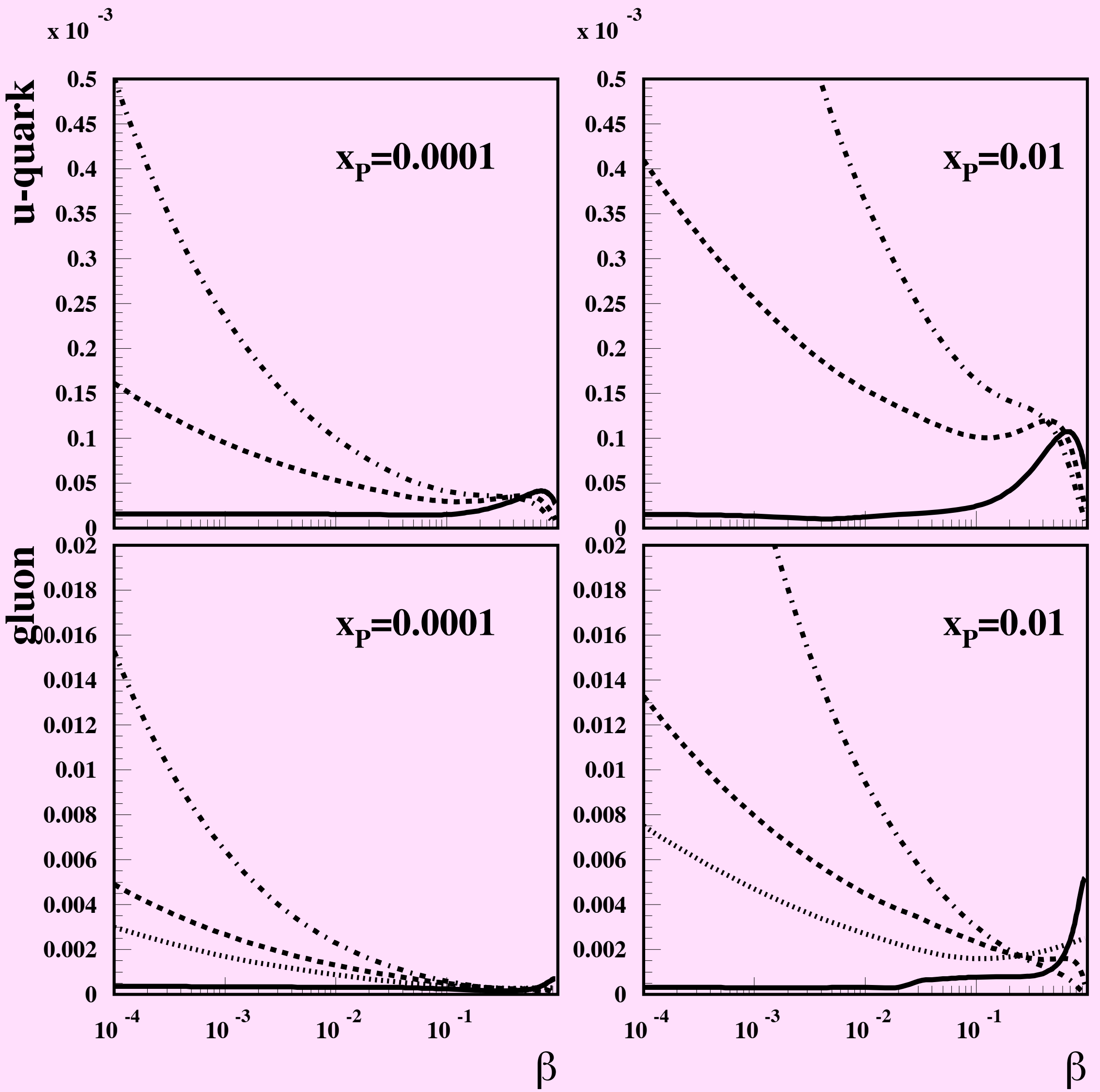
Scaling - reasonably large produced mass > 2GeV

take x=0.005, which allows Q^2 up to 15 GeV^2

$\beta=0.5, \quad M^2 = Q^2$

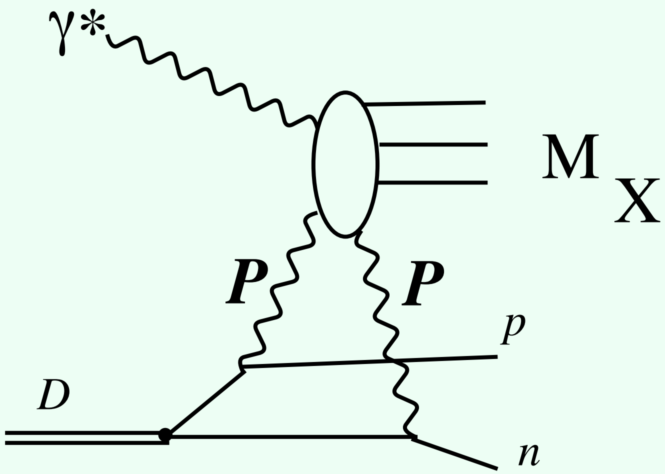
There is a phase space to study LT nuclear diffractive pdfs !!!
Though it is rather limited would complement measurements at LHC using ultraperipheral collisions.

One also predicts a complicated dependence of the distribution on the diffractive mass as a function of flavor, Q, and $\beta = Q^2/(M^2+Q^2)$.



☛ SemiInclusive diffraction at $x \leq 0.02$ off deuteron

- *Double tagging for the deuteron in special kinematics - measure of "Pomeron-Pomeron" interactions.*



Similar for the proton beams

- *Coherent diffraction of the deuteron at large $-t > 0.5$ GeV^2*

Conclusions

- ☺ EIC would allow to study diffraction in several kinematics relevant to the issues of color transparency, onset of color opacity ; leading twist diffraction in the kinematics which could not be probed at LHC; look for onset of black body limit regime.

- ☺ Various experimental tests of conjectured connection between diffraction in the scattering off nucleon/nuclei and nuclear shadowing

- ☺ Color transparency/opacity phenomena, first determinations of nuclear GPDs, establishing the Q^2 range for studies of GPDs of nucleon in hard exclusive processes.

- ☺ pA diffractive processes: color fluctuations in nucleons should be studied - relevant for inelastic pA; looking for effective methods of triggering on small configurations in nucleons.

Many of the discussed measurements though doable from the angle of luminosity and kinematics are a challenge for detector design, systematics, etc.