THERA: eA Observables for new QCD phenomena

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THERA: eA Highlights

Prime Objective - study QCD in the limit of high parton densities deep into the region where large screening effects and presence of nonlinear dynamics is expected and regime of interaction with a nearly black target is possible.

Observables:

• *Scaling violation for the ratio*

$R_{2A}(x,Q^2) = \frac{2}{A} F_{2A}(x,Q^2)/F_{2D}(x,Q^2)$,

study of gluon shadowing via dijet production in $\gamma + A$ scattering.

Qualitative Expectation in the nonlinear regime: $F_{2A} \propto 2\pi R_A^2 Q^2 \ln(1/x)$ up to $Q^2(x)$ which grows with A.

$\Longrightarrow$ amplified version of the Caldwell plot for heavy nuclei, and decrease of $R_{2A}(x,Q^2)$ with increase of Q^2.

- *Measurement of the A-dependence of* σ_L.

More sensitive to the gluon channel and hence larger non-linear effects are expected.

- *Exclusive Diffraction*

Two simplest (theoretically) observables are ρ and J/ψ elastic production off nuclei. This does not require detection of in the nucleus direction since the peak is very narrow and one can use also information about lack of neutrons.

Expectation is that when $x \leq 10^{-3}$ one will reach regime of color opacity: The cross section will be strongly suppressed as compared with a naive color transparency expectation:

$$\sigma_A(t) \propto A^2 F_A^2(t) \sigma_N(t),$$

where $F_A(t)$ is the nucleus form factor.

Other way to address this question is to study the energy dependence of say J/ψ production for a given nucleus. The expectation is that in the screening regime the fast growth will turn to a nearly energy independent behavior. Study of this pattern as a function of Q^2 would provide a sensitive test of interplay of opacity and transparency.

Main practical questions are counting rate and acceptance. Our estimates indicated that at HERA one would need 10 pb^{-1} per nucleus.

- *Inclusive Diffraction*

This is direct test of the degree of blackness of interaction.

Expectation: probability of coherent diffraction for heavy nuclei is close to 50% and somewhat different for the gluon and quark channels. The THERA kinematics allows to study dynamics of nearly black interactions as a function of x, Q^2 and for different triggers and look for early signals of the black body regime.

- *Fluctuations of the central multiplicity*

Another useful observable is study of the fluctuations of multiplicity for central rapidities - expectation is that the fluctuations of multiplicity should increase with A and be of long range in rapidity. It appears that the current detectors will have good acceptance in this region.

Outline

◇ Longitudinal distance scales in DIS - what experimental facilities do we need?

◇ Small x parton densities in nuclei - brief summary of the current data and challenges for the future

◇ Nuclear shadowing in DIS and hard diffraction in ep DIS

◇ Color transparency and color opacity in eA diffraction

◇ Final states in nondiffractive small x DIS

A sample of fundamental questions of QCD to be addressed at HERA/THERA

- Phase transitions in QCD - many degrees of freedom, strong interactions - could be many phases/transitions

- How large is cross section of interaction of small hadrons (oniums) with nucleons/nuclei at high energies? Would nuclei be transparent to a high-energy $J/\psi, \Upsilon$?

- How far down in x it is necessary to go to observe a break down of the linear DGLAP evolution equations?

- Can DIS interactions reach nearly black limit at least for large targets

- Can gluon fields of nucleons in nuclei strongly screen each other at small x leading to a large gluons shadowing, suppression of minijet production in the heavy ion collisions at LHC?

Longitudinal distances in DIS

The cross section of DIS can be expressed through the commutator of two e.m. currents in coordinate space: $J_\mu(y)$

$$\langle N \,| [J_\mu(y_1), J_\lambda(y_2)] |\, N \rangle$$

where y_1 and y_2 are the points where γ^* has been absorbed and emitted.

Analysis of the structure of the DIS processes leads to

$$(y_1 - y_2)_{transverse} \sim \frac{1}{Q}$$

,

$$l_{coh} \equiv (y_1 - y_2)_{longitudinal} \sim \frac{1}{2m_N x}$$

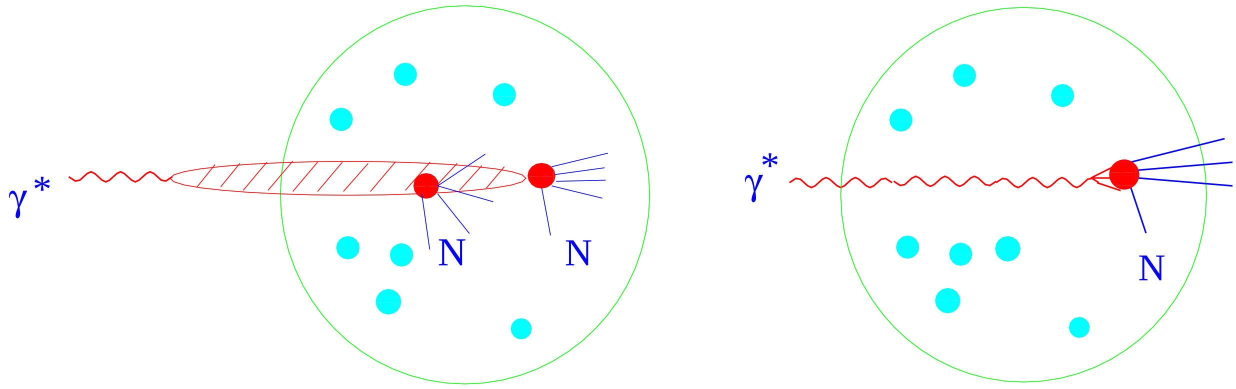
Here $-Q^2$ is four momentum squared of the photon, $x = Q^2/2(qp_N)$ is the Bjorken scaling variable.

At THERA one can reach $l_{coh} \sim 10^5 fm \gg 2R_A$.

The reason: Virtual photon transforms to a hadronic (quark-gluon) configuration $|h\rangle$ which propagates distances

$$l_{coh} = \frac{2q_0}{Q^2 + M_h^2} \approx \frac{1}{2m_N x} \quad \textit{in the DIS limit},$$

which by far exceed the nucleus size of $2R_A$ (large Ioffe distances). (This key feature of space time development of the high-energy DIS is a backbone of many analyses of small x DIS at HERA)



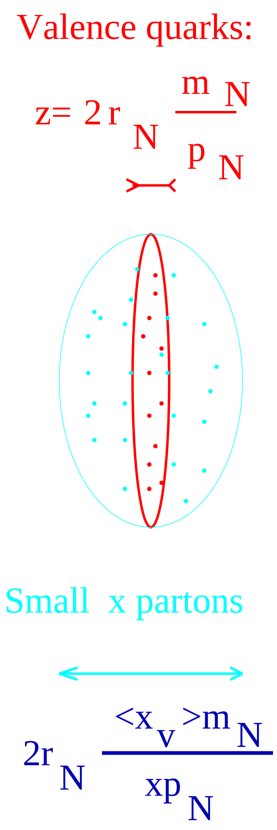
Small $x, l_{coh} \gg R_A$ **Large** $x \geq 0.2, l_{coh} \leq 2fm$

Direct test of this feature of QCD is a paradoxical phenomenon of nuclear shadowing in $\gamma(\gamma^*) - A$ scattering: $\frac{\sigma_{\gamma A}}{A\sigma_{\gamma N}} < 1$ in spite of the small value of $\sigma_{\gamma N}$.

Historically, this phenomenon was first suggested as a direct way to observe hadron properties of light.
Stodolsky(1967), Gribov(1969), Brodsky & Pumplin(1969)

Complementary language for small x - infinite momentum frame

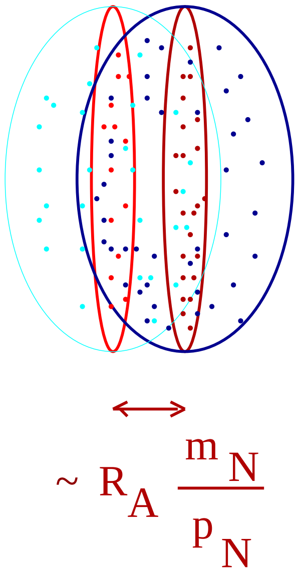
In the fast frame nucleon looks as a *"MATRESHKA"* ("Russian doll set"): fast partons in nucleons are contracted to a pancake of radius R_N and a small longitudinal size $z = 2r_N \frac{m_N}{p_N}$ while the small x partons form pancakes of $\frac{\langle x_v \rangle}{x}$ times larger size ($\langle x_v \rangle \sim 0.2$ is average x of the valence quarks)



A nucleus looks as a collection of $MATRESHKA$'s with valence quarks not overlapping and clouds of partons of different nucleons with

$$x \ll \langle x_v \rangle \frac{r_N}{R_A}$$

completely overlapping:



⇒ Small x partons in nucleus and in nucleon occupy the same small longitudinal volume.

$\Rightarrow$One can consider small x parton density per unit transverse area:

$$\frac{4}{3}\rho_0 R_A x G_N(x,Q^2),$$

where $\rho_0 \sim 0.16 fm^{-3}$ is the average nuclear density.

At central impact parameters (probed by measuring e.g. $\sigma(eAu)-\sigma(eCa)$)
parton density/unit area is 1.5 times larger:

$$2\rho_0 R_A x G_N(x,Q^2)$$

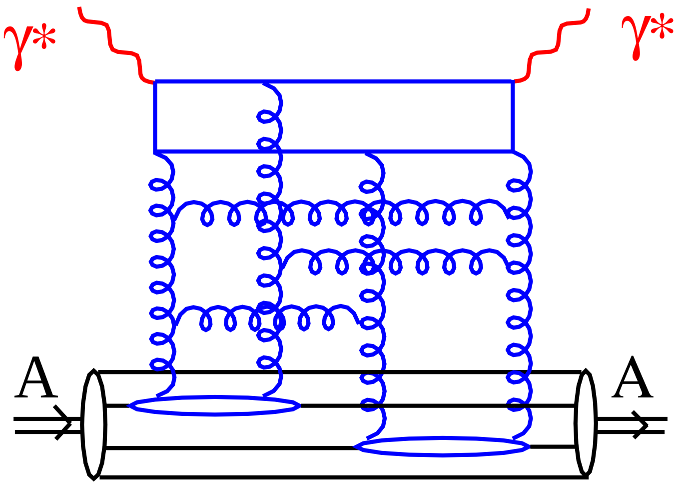
.

$\Longrightarrow$ Large enhancement of the parton densities/area in nuclei as compared to nucleons. For the central impact parameters:

$$\frac{G_A/\pi R_A^2}{G_N/\pi r_N^2} \approx A^{\frac{1}{3}} \frac{G_A}{AG_N} \quad \Longrightarrow \quad \approx 6\Big|_{A=200} \quad IF \quad \frac{G_A}{AG_N} \approx 1$$

$\Longrightarrow$ HERA (THERA) it would be possible to probe QCD at a factor of $\sim 6(10)$ higher gluon densities than at ep HERA

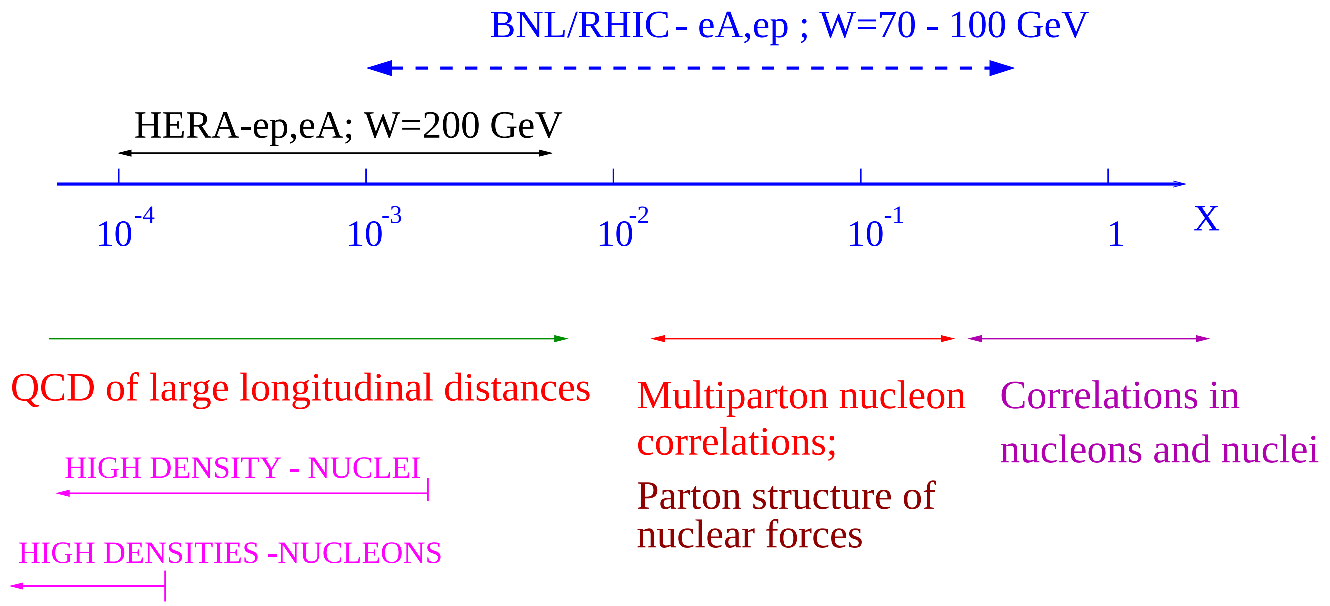
Small x: interaction of overlapping tubes of partons in the perturbative strongly interacting phase over large distances



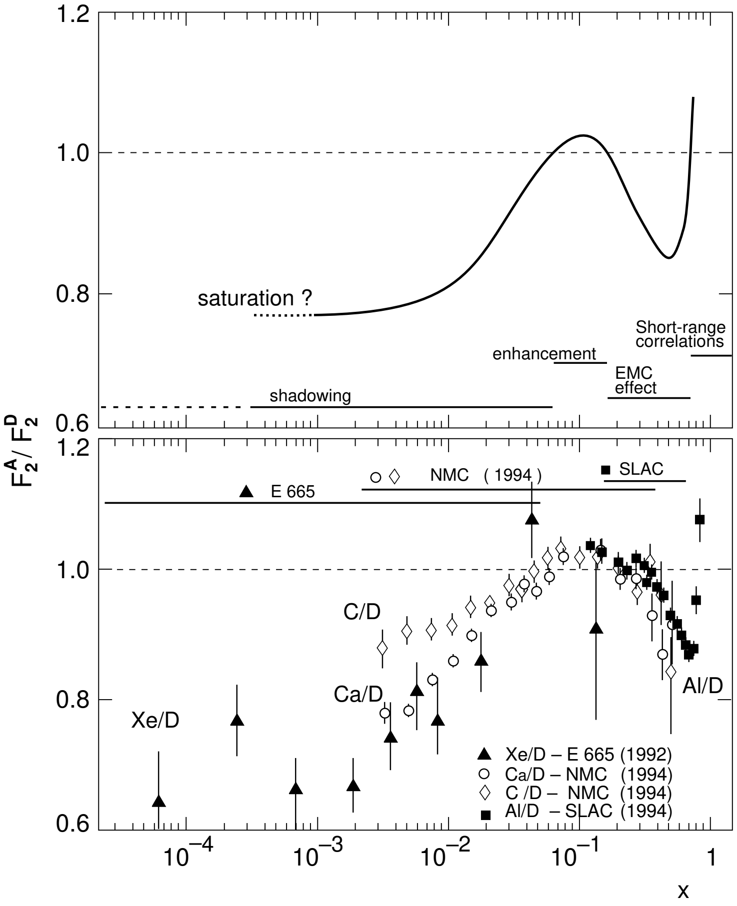
$\Longrightarrow$ Studies of DIS at different x-ranges study different (complementary) aspects of QCD

Due to kinematics of DIS the optimal range of studies shifts to smaller x with increase of the collider energy.

$\Longrightarrow$ A set of electron machines is necessary to cover the $10^{-4} \leq x \leq 1$ range



Summary of the current information on A-dependence of parton densities at $x \leq 0.2$



Results for $R_A(x, Q^2) = \frac{2}{A} \frac{F_{2A}(x,Q^2)}{F_{2D}(x,Q^2)}$:

- $x \sim 0.1$ enhancement: $R_{A=40}(x \sim 0.1) \sim 1.05$
- Shadowing for $x \leq 0.04$
- Q^2 scaling of $R_A(x, Q^2)$

Summary of information on A-dependences of parton densities

Nuclear shadowing is directly observed for $\bar{q}$, indirectly for G_A, V_A.

Nuclear enhancement (antishadowing) for $x \sim 0.1$ is directly observed for q_V. Indications of a large enhancement for gluons. Enhancement is absent for antiquarks

Reminder The $x \sim 0.1$ region corresponds to distances $\sim 1-2fm$ relevant for the quark-gluon nature of internuclear forces. *The observed A dependence of $R_g, R_{\bar{q}}$ is hardly consistent with the meson picture of the short-range nuclear forces which predicted a 10-20% enhancement of $\bar{q}_A/\bar{q}_N$.*

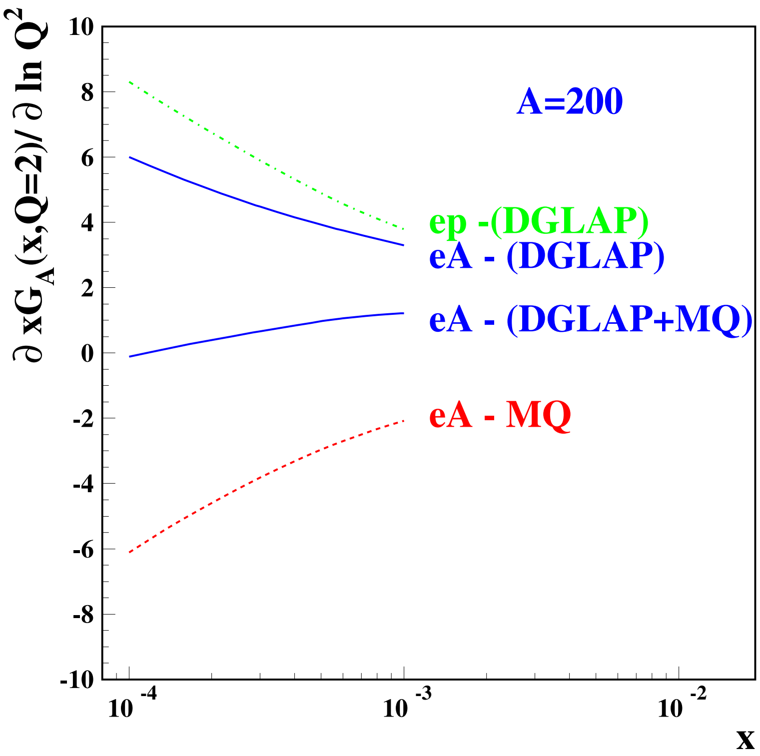
AA connection Significant modifications of parton densities (largest for the central impact parameters) have to be accounted for in interpreting nucleus-nucleus collisions at RHIC.

Scaling violation of $\frac{\partial R_A(x,Q^2)}{\partial \ln Q^2}$ predicted by QCD calculations in DGLAP was observed by NMC at $x \geq 0.02$ The leading twist QCD evolution leads to further increase of $\frac{\partial R_A(x,Q^2)}{\partial \ln Q^2}$ at smaller x, Nonlinear effects would be manifested in a slower increase of $R_A(x,Q^2)$ with increase of x.

HERA observed a drop of $\frac{\partial F_{2p}(x,Q^2)}{\partial \ln Q^2}$ at $x \sim 10^{-4}, Q^2 = 2GeV^2$ which may indicate a break down of DGLAP

A factor of 6 increase in densities $\Longrightarrow$ nonlinear effects up to $Q^2 \sim 10GeV^2$??

For the gluon channel this effect can be seen for example using the simplest model of nonlinear effects of Mueller and Qiu (86):



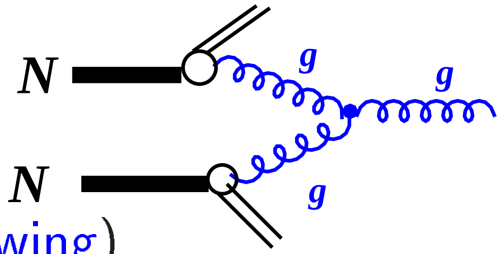
THERA kinematics allows to study behaviour of parton densities deep into the region high parton densities and produce decisive checks of various ideas about QCD state in this limit based on the A-dependence of various quantities with a number of crosschecks:

- Gluons
  - Scaling violation for F_{2A} ratio;
  - A-dependence of σ_L. Doable for suffiently high lumi due to ability to change E_e; Amplification of nonlinear effects.
  - Charm and J/ψ production
  - Leading dijet production (hints from the E665 FNAL experiment).
- Sea quarks
  - A-dependence of F_{2A}.

Why eA at small x is interesting - *Preview*

Fast nucleus (parton) frame: parton localization $\propto \frac{1}{x}$.

At small x partons from different nucleons overlap and can fuse, like:



$\Longrightarrow$ Deplete small x region ($\equiv$ shadowing).

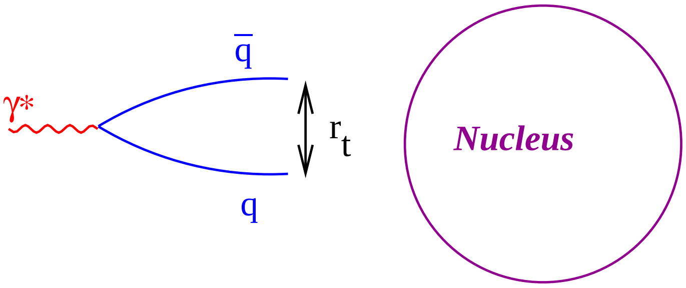
Similar densities are reached in a nucleon at much smaller x

$$\Downarrow$$

***Nucleus - an amplifier** of non-linear effects at small x*

Nucleus rest frame:

At small x, $q\bar{q}$ coherence length $l_c = 1/2m_N x \gg 2R_A$: $|q\bar{q}\rangle$ (not γ^*) interacts with nucleus:



(a) If $q\bar{q}$ size is large

$\Longrightarrow$Interactions like for *hadron-nucleus scattering*

$\Longrightarrow \sigma_{tot} \propto A^{2/3} \rightarrow$ shadowing

(b) If $q\bar{q}$ size is small $\Longrightarrow$ Color transparency $\rightarrow \sigma_{tot} \propto A$

(c) If $q\bar{q}$ size is small BUT $x \leq 3 \cdot 10^{-3} \Longrightarrow$ increase of $q\bar{q} - N$interaction due to larger gluon densities $\Longrightarrow$ Perturbative color opacity $\rightarrow \sigma_{tot} \propto A^{2/3}$

Nucleus as - a test bench of color transparency and color opacity

Diffraction in DIS and Shadowing

One of the most important discoveries of HERA is large magnitude of diffraction ($\gamma^* + p \to X + p$ with $|x_F(p)| \geq 0.99$) in DIS: $\sigma_{diff}/\sigma_{tot} \sim 0.1 - 0.15$.

Diffraction is a measure of the strength of the interaction. From optic theorem the average cross section for interaction of diffracting hadronic component of γ^*, σ_{eff}, is

$$\sigma_{eff} = \frac{16\pi \frac{d\sigma_{diff}(\gamma^*+p\to X+p)}{dt}\Big|_{t=0}}{\sigma_{tot}(\gamma^* + p)}$$

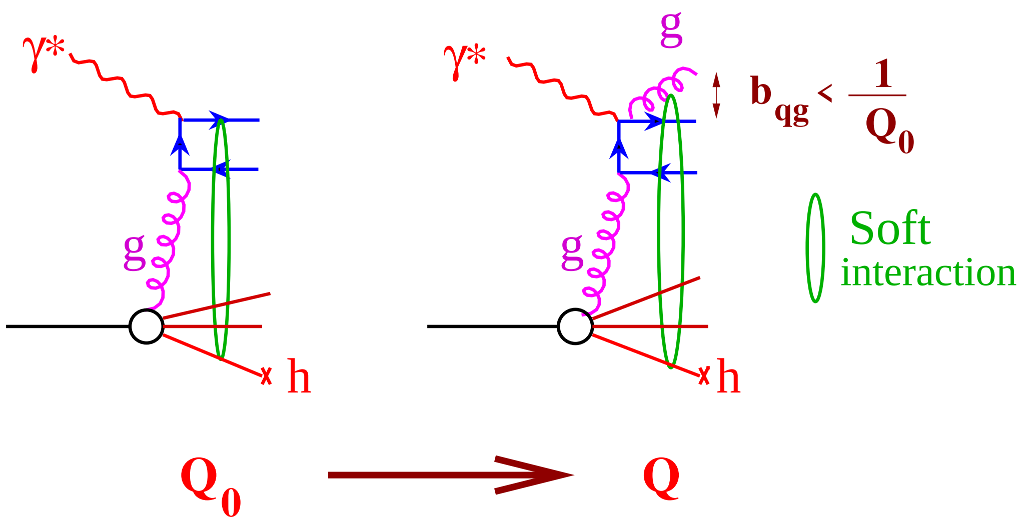
In the language of the fast (parton) frame, diffraction is a measure of the interaction of partons in the nucleon wave function at corresponding small x.

QCD factorization theorem for inclusive diffraction:

Collins 97

Differential cross section of the target fragmentation process $\gamma^* + N \to X + h$ for fixed $x_F^h < 0, p_t$ evolves with Q^2 according to the DGLAP evolution equations.

Physics of factorization theorem: Soft interactions between "h" and the partons emitted in the $\gamma^* - parton$ interaction does not resolve changes of color distribution between the scale $Q_0 \gg soft\ scale$ and $Q^2 > Q_0$



$\rightarrow$ Production of "h" when a parton at x, Q^2 is hit is the same as when an "ancestor" parton is hit at x, Q_0^2.

One defines $f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$, the leading twist diffractive structure functions for the processes where parton j with $x = x_{bj}$ is removed from the nucleon and a proton with $x_{I\!P} = 1 - x_F^p$ is produced.

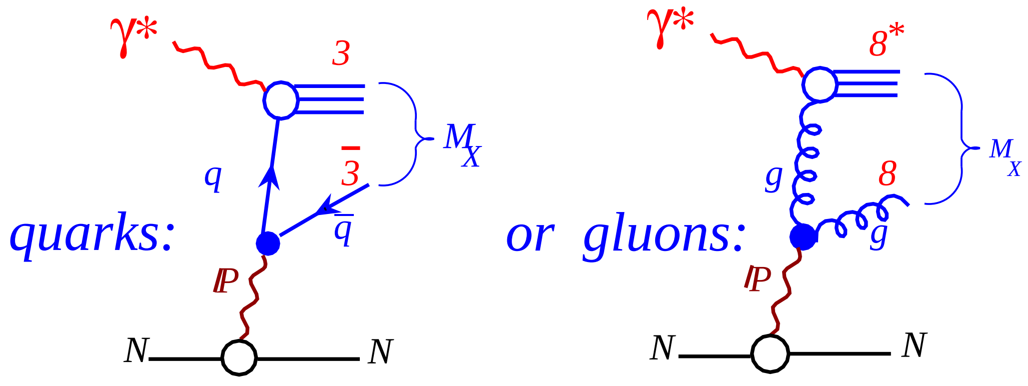
HERA data

(a) Approximate scaling for the diffractive structure functions $f_j(\beta, Q^2, x_{I\!P}, t)$ for $Q^2 \geq 4\ GeV^2$ and large probability of the rapidity gap:

$$P_q = \frac{\sigma(\gamma^* + p \to X + p)_{x_{I\!P} \leq 0.01, x \leq 10^{-3}}}{\sigma_{tot}(\gamma^* + p)} \approx 0.1$$

(b) Factorization theorem allows to define a probability

$P_j(x, Q^2) = \int f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t) dt dx_{I\!P} / f_j(x, Q^2)$ of diffractive gaps for the hard processes induced by hard scattering off

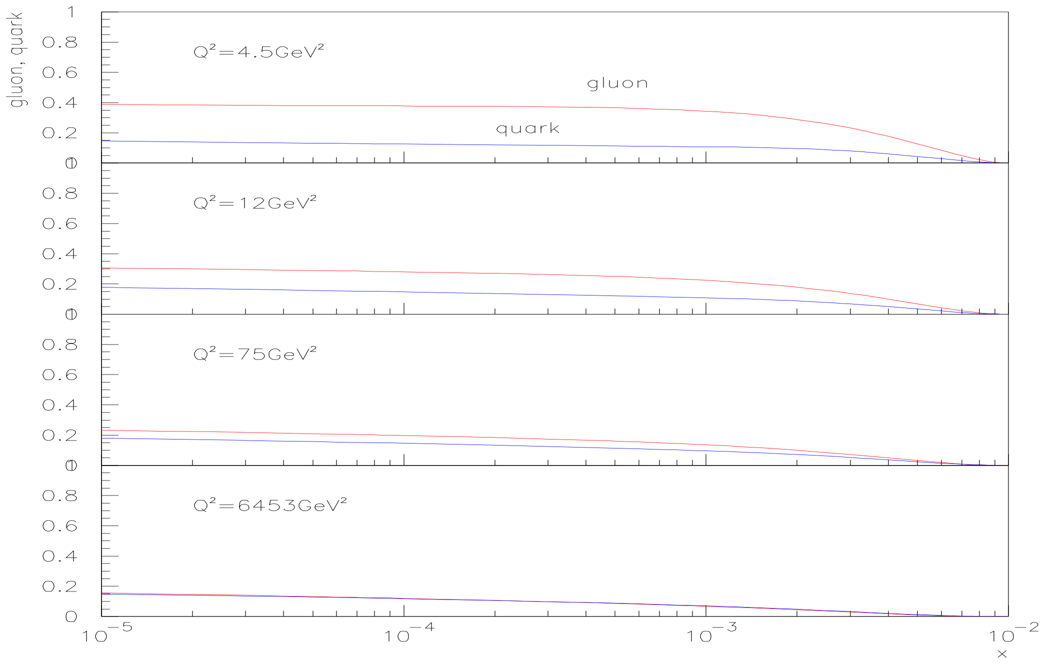


If the interaction in the gluon sector at small x reaches strengths close to the unitarity limit we should expect that P_g is rather close to 1/2 and much larger than P_q.

Using pQCD expression for $\sigma^{inel}_{color\ octet\ dipole-N}$ (to be discussed later):

$$P_g(x = 10^{-4}, Q^2 = 10GeV^2) \approx 1/3$$

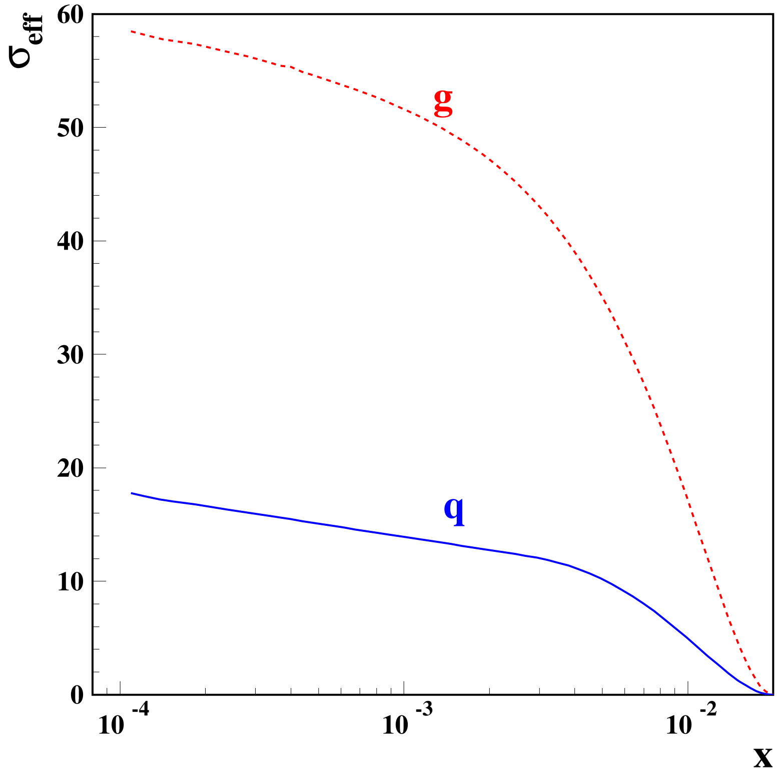
Indeed, using the global fit of Alvero, Collins and Whitmore we find: $P_g \gg P_q, P_g(x \leq 10^{-3}, Q = 2) \approx 0.4$!!



The ACW fit and the optic theorem $\sigma_{eff}(x,Q^2) \equiv \frac{16\pi d\sigma^{dif}/dt_{|t=0}}{\sigma} \Longrightarrow$ average cross sections for the configurations which contribute to quark ($3 \times \bar{3}$ dipole) and gluon ($8 \times 8^*$-dipole) induced diffraction.

$\sigma_{eff}^{q(g)}(x,Q)$ for

$Q = Q_0 = 2GeV$:

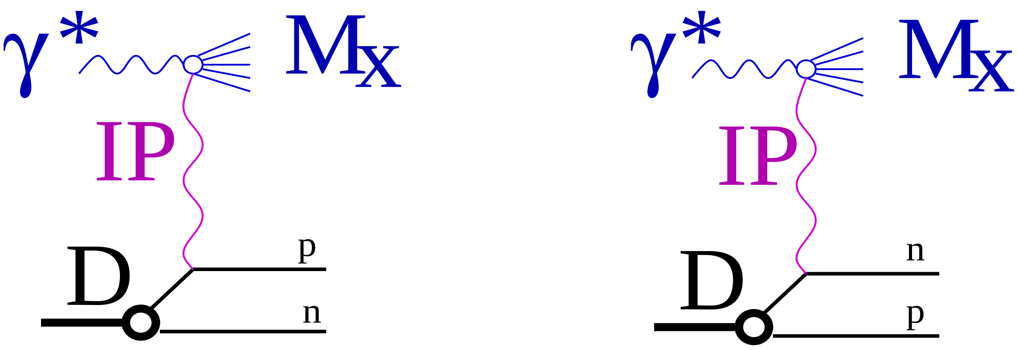


$\sigma_{eff}^{gluons}(x=10^{-4}, Q=4) \sim 30mb$ and even larger value of $\sigma_{eff}^{gluons}(x=10^{-4}, Q=2) \sim 50mb$ indicate presence of very (super) strong interactions in the gluon sector. These strong interactions should be due to some perturbative dynamics of strong gluon fields since the $\gamma + p \to J/\psi + p$ data indicate that pQCD for these Q occupies most of the phase volume.

This argument for super strong gluon interactions at small x is complementary to the unitarity argument based on perturbative calculation of "small color octet dipole"- nucleon interaction.

Deep connection between high-energy diffraction and phenomenon of nuclear shadowing. Gribov 68

Qualitatively this is due to a possibility of small momentum transfer $-t = x_{I\!P}^2 m_N^2$ where $x_{I\!P} = x_{\mathrm{Bj}}(1 + M_{dif}^2/Q^2)$. If $\sqrt{-t} \leq$ "average nucleon momentum in D(A)" amplitudes of diffractive scattering off proton and off neutron interfere:



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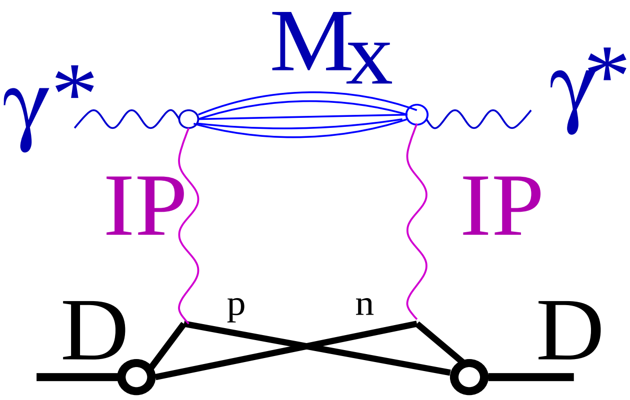
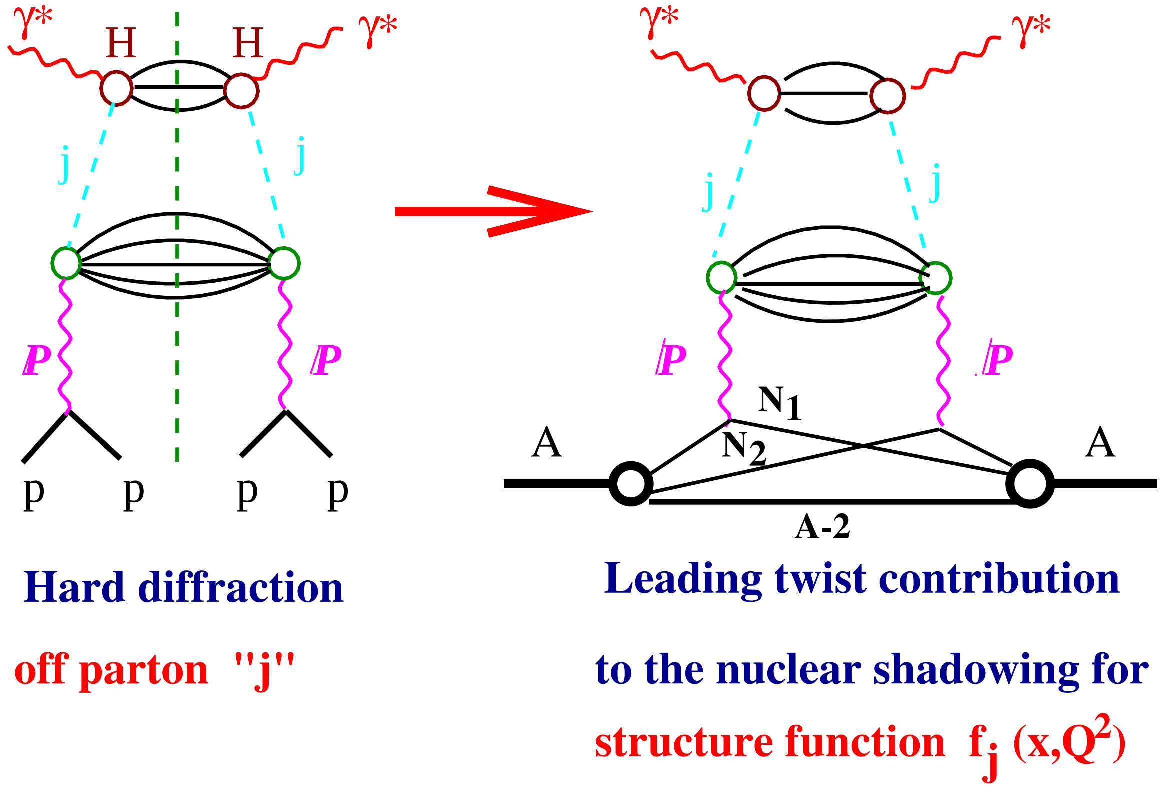


Double scattering diagram for the $\gamma^* D$ scattering

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



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

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

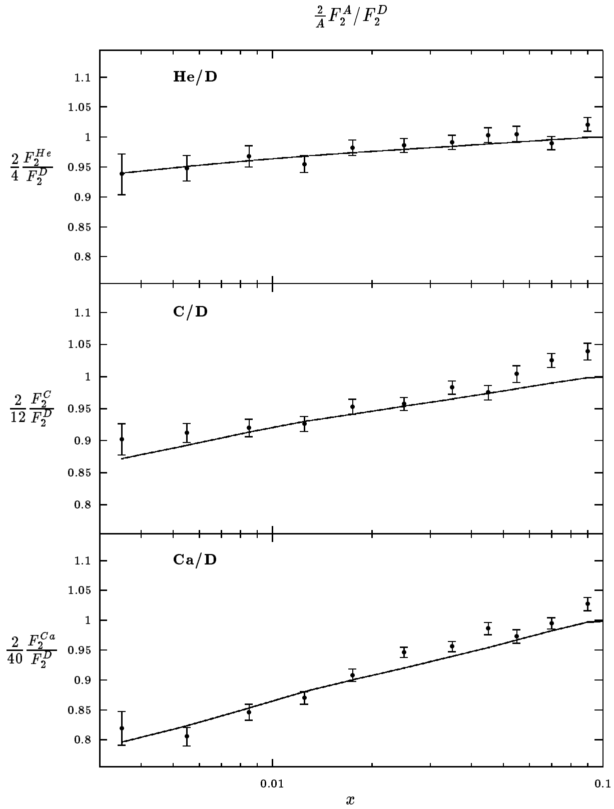
where $f_{j/A}(x, Q^2), f_{j/N}(x, Q^2)$, are inclusive parton densities; $\rho_A(r)$ is the nucleon density in the nucleus.

A factor ~ 3 larger probability of gluon induced diffraction	$\Leftrightarrow$	Gluon nuclear shadowing is much larger than quark nuclear shadowing

Warning: Practically all perturbative models of diffraction in DIS lead to a larger diffraction in the gluon sector. So HERA results are welcomed, but the uncertainties in the extraction of the gluon diffractive densities are still rather large even if the leading twist dominance is assumed. Further uncertainties are due to nonlinear, higher twist effects. $\sigma^g_{eff} \geq 40mb$ indicates that nonlinear regime is reached in the gluon sector already at $x \sim 10^{-3}$.

Note than in a number of models of nuclear shadowing which do not incorporate information about the gluon induced diffraction it is assumed that shadowing in the gluon channel would be smaller than in the quark channel

The Gribov theory for $\sigma_{tot}(\gamma^* A)$ agrees well with the F_{2A}/F_{2D} shadowing data. In early days calculations involved modeling diffraction FS88-89, Kwiecinski89, Brodsky & Liu 90, Nikolaev & Zakharov 91. Now one can use the HERA diffractive data (this involves a certain extrapolation of the HERA data to smaller W) to explain the high precision NMC data essentially without free parameters:



Comparison of the NMC data with the calculation within the Gribov theory by Capella, Kaidalov, Merino, Pertermann, Tran Thanh Van (97)

For calculations of the gluon shadowing due to large value of σ_{eff} interactions with $N = 3, 4..$ nucleons become very important. One needs extra dynamic input to model fluctuations of strength of interaction which enter differently in the interactions with $N \geq 3$ nucleons. Hence current estimates are rather crude. Obviously, study of gluon densities in heavy nuclei in the shadowing region will provide unique information about dynamics of diffraction, and is likely to lead to observation of nonlinear effects.

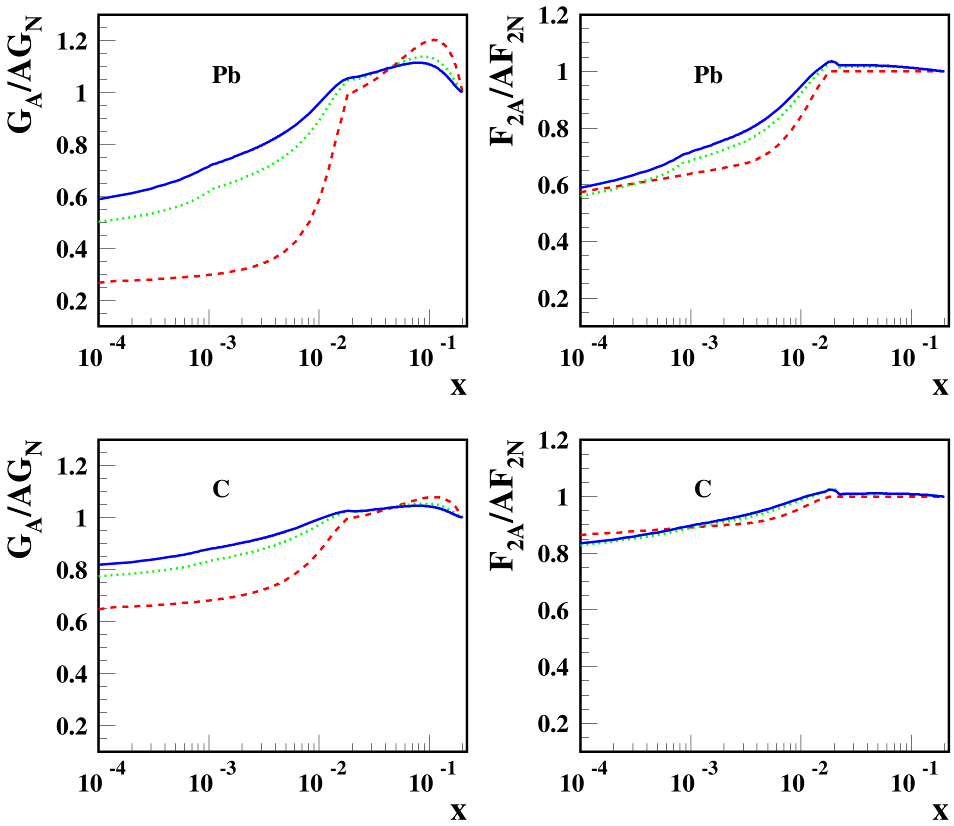
We find that that the nuclear gluon densities for $A \geq 200$ and $Q^2 \leq 10GeV^2, x \leq 10^{-3}$ are rather close to the unitarity (black body) limit (which can be derived from analysis of the generalization of the Gribov representation to the gluon sector FS98)

$$xG_A(10^{-4}, Q^2 = 10) \sim \frac{40}{A^{1/3}} \quad \rightarrow 6 \ (for \quad A = 200)$$

as compared to $xG_N(10^{-3}, Q^2 = 10) \sim 10, xG_N(10^{-4}, Q^2 = 10) \sim 20,$

Already based on the black body upper limit for xG_A large shadowing for $x \leq 10^{-3}$.

$\Longrightarrow$ Violation of DGLAP is likely for gluon parton densities in heavy nuclei at $x \leq 10^{-3}$.



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.

Diffractive small x phenomena off nuclei

The gold plated observables of new QCD phenomena which allow *unambiguous interpretation without a complicated theoretical analysis*:

- *Fraction of diffractive events:* If the interactions in DIS at small x become strong, the fraction of diffractive events should approach the black body limit of 1/2. This should hold both for the total cross section of inclusive diffraction and for semi-inclusive processes dominated by gluons such as charm production.

- *A-dependence of vector meson production:*

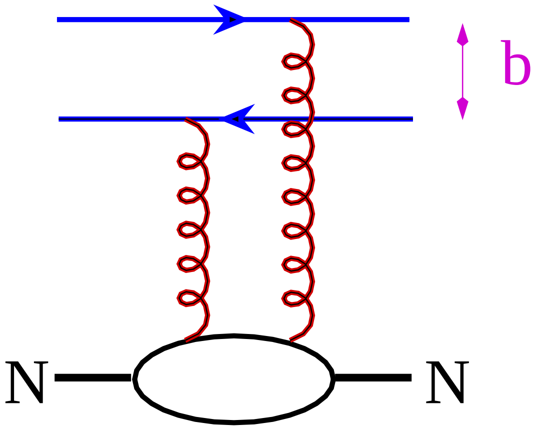
  The regime $x \geq 5 \cdot 10^{-3}$ of color transparency: practically no absorption of small color dipoles.

  $\Longrightarrow$ Definite prediction of the cross section of coherent processes $\propto A^{4/3}$.

  The regime $x \leq 3 \cdot 10^{-3}$ of color opacity: a dramatic slowdown of the A-dependence of coherent J/Ψ photo/electro production by a factor $\sim A^{0.4}$. A similar trend is expected for other hard exclusive diffractive processes.

Is nuclear medium transparent to ultra-high energy small color singlets, like J/ψ ?

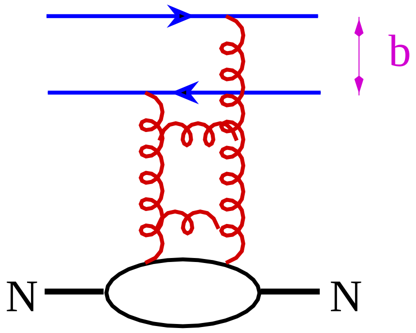
Naive expectation - small objects interact weakly. Gauge invariance for a small dipole-hadron interaction $\rightarrow$



Two gluon exchange model

$$\sigma = C\, b^2$$ **(F.Low 75)**

C does not depent on E_{inc}



pQCD in the leading log b approximation (Baym, Blattel,FS, 93)

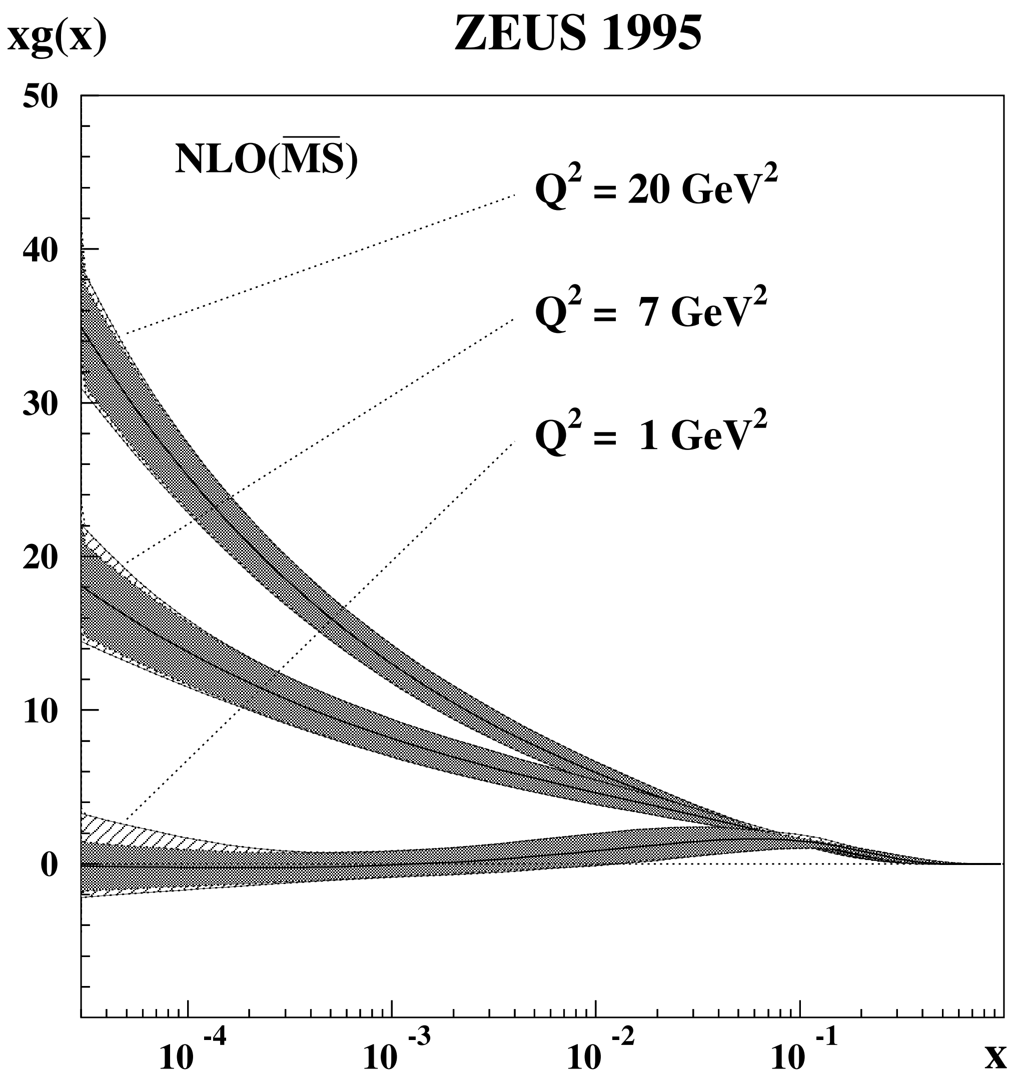
$$\sigma^{inel}(b,E_{inc}) = \frac{\pi^2}{3} b^2 \alpha_s \; x \, G_N\left(x, \frac{\lambda}{b^2}\right)$$

Qualitative difference from QED: cross section rapidly increases with W - a fingerprint of small size dipole interaction in DGLAP kinematics. ($\lambda(x = 10^{-3}, Q^2 = 10\ GeV^2 \approx 9$)

For color octet dipole cross section is $9/4$ times larger.

$$\Longrightarrow \quad \sigma(s, Q^2_{eff} = 4\ GeV^2) \propto \left(\frac{s}{s_0}\right)^{0.2};$$

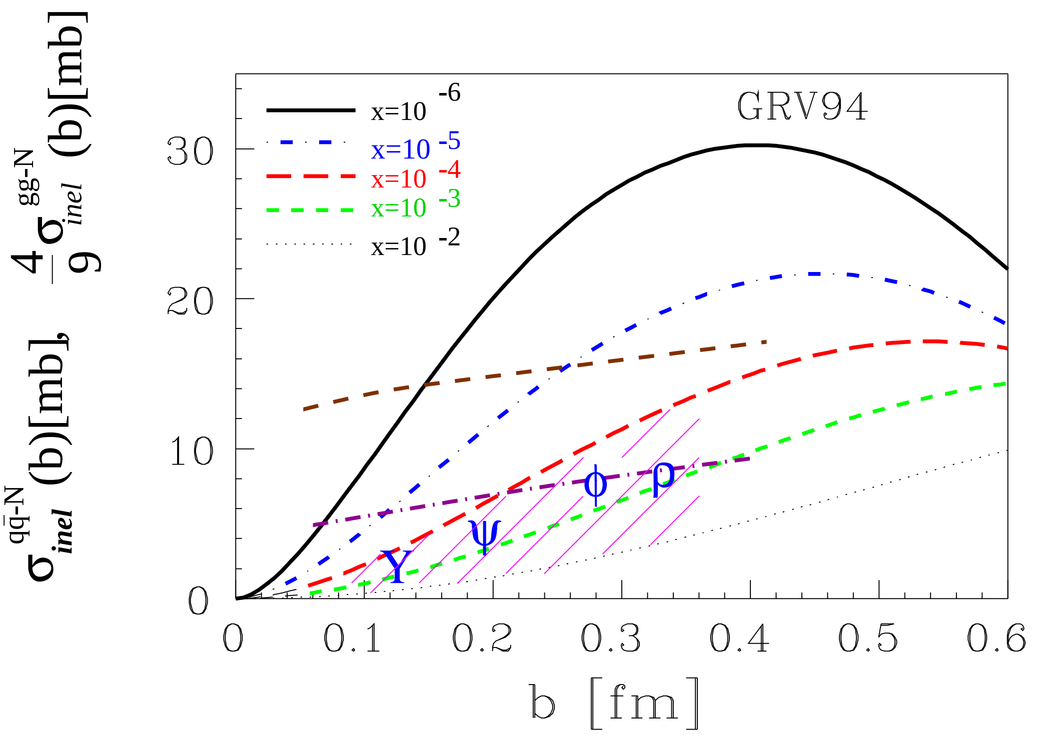
$$\sigma(s, Q^2_{eff} = 40\ GeV^2) \propto \left(\frac{s}{s_0}\right)^{0.4}$$



From S-channel unitarity (analog of Froissart bound) - $\sigma_{inel} \geq \sigma_{el}$ the growth should stop - breakdown of DGLAP

$\sigma^{inel}_{small\ dipole-nucleon} \leq \frac{4\pi B_{2g}}{1+(Re/Im)^2} \sim 18mb$ (FS & Koepf 96)

$B_{2g} \sim 4GeV^{-2}$ is the slope of two-gluon form factor of the nucleon.



Unitarity limit for $q\bar{q}$-N scattering

Unitarity limit for gg-N scattering

Exclusive $\rho, \phi, J/\psi, \Upsilon$ vector meson production probes $10^{-4} \leq x \leq 10^{-2}, .1 \leq b \leq .35fm$

Relevant for HERA where $\sigma_{inel}^{color\ oct.-N}(10^{-4}, 10\ GeV^2) \sim$ 16 mb

Even more important at THERA where it would reach 25 mb.

Breakdown of the twist decomposition occurs in the discussed kinematics occurs when only few perturbative gluons are emitted (2-4), (couple of logs in $\ln Q^2$, one -two logs in $\ln(1/x)$) well before one could use the BFKL approximation.

For THERA regime BFKL maybe more relevant.

For $A \sim 200$ $\sigma_{inel}^{color\ oct.-A} \leq \pi R_A^2$ implies for A=200: $\sigma_{inel}^{gg-A}/A\sigma_{inel}^{gg-N} \leq 0.6$ for $x = 10^{-3}, Q^2 = 5GeV^2$

$\Longrightarrow$ Large nuclear gluon shadowing effects at THERA/HERA follow already from unitarity for $x \sim 10^{-4}$ up to $Q^2 \sim 20 - 40GeV^2$

Note that the unitarity argument does not tell whether in this limit dynamics is nonlinear, though this seems natural.

$\Longrightarrow$ *Prime objectives of the exclusive eA diffraction studies*

♣Color transparency:

$\frac{\frac{d\sigma}{dt}(\gamma^* A \to MA)\Big|_{t=0}}{\frac{d\sigma}{dt}(\gamma^* N \to MN)\Big|_{t=0}} = A^2$ - Lack of the absorption of produced diffractive states in nuclei in the coherent diffraction.

The QCD factorization theorem for exclusive processes:

$$\frac{\frac{d\sigma}{dt}(\gamma^* A \to VA)\Big|_{t=0}}{\frac{d\sigma}{dt}(\gamma^* N \to VN)\Big|_{t=0}} = \left[\frac{F_A^L(x,Q)}{F_N^L(x,Q)}\right]^2 = \frac{G_A^2(x,Q)}{G_N^2(x,Q)}$$

$\Rightarrow$ Color transparency for $x \geq 0.01$

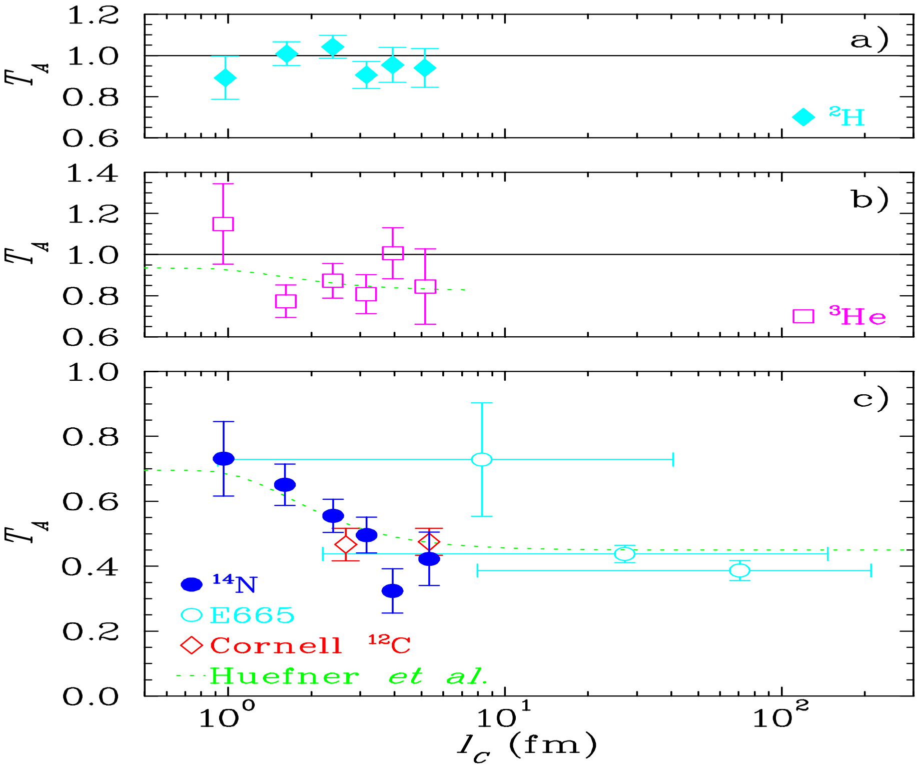
In the Q^2 range of color transparency: $Q^2 \geq 5GeV^2$ for ρ-mesons?, all Q^2 for J/ψ ? vector meson production could be used as a low Q^2 "gluonometer".

Note that prediction of CT Miller & FS 93 in a related $\pi + A \to$ $2\ high\ p_t\ jets + A$ was recently confirmed in the FNAL E791 experiment Ashery et al 99 at $x \sim 0.02$

Experimental evidence for CT in exclusive DIS

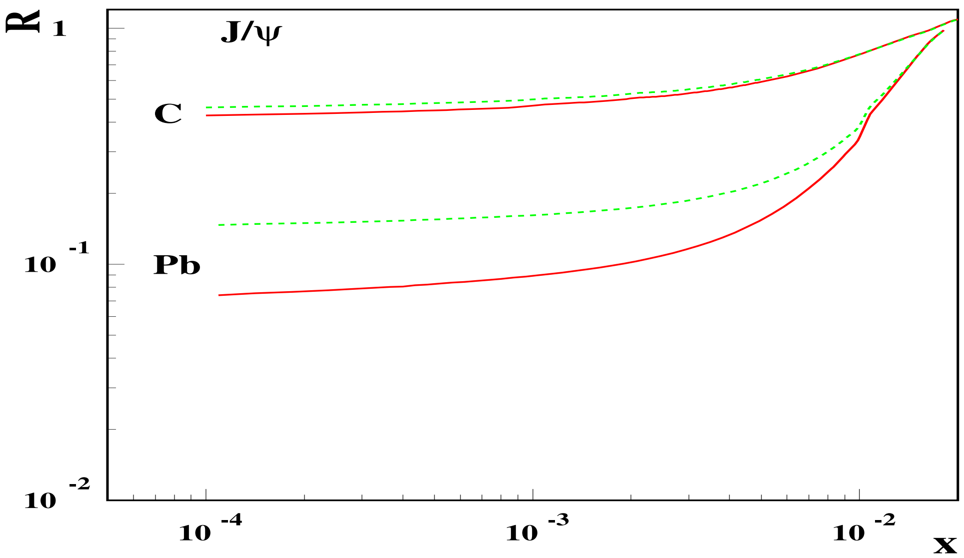
◇ Observed at FNAL in coherent J/ψ production off nuclei

◇ Marginal evidence in production of ρ-mesons in the process $\gamma^* + A \to \rho + A'$. Practically all the data are either at small $l_{coh} = \frac{1}{m_N x} \leq 2R_A$ or at small Q^2.



Compilation of quasielastic ρ-production data: blue points and data for $^3He,^2H$ are from HERMES.

♣ **Color opacity:** Gluon shadowing would lead to a dramatic decrease of the yield of VM production at small x (yields are still large to measure the cross section accurately). Predicted A-dependence for coherent J/ψ production at very small x is about the same as for photoproduction of ρ-mesons!?



Color opacity effect for coherent J/ψ photoproduction.

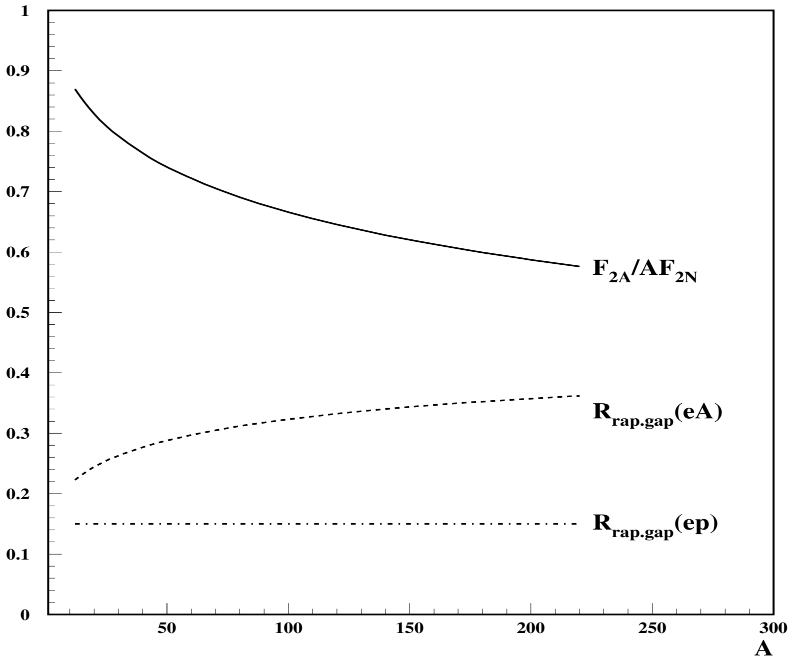
The x dependence of the ratio $R = \frac{\frac{\sigma_A(x)}{\sigma_N(x)}}{\frac{\sigma_A(x=0.02)}{\sigma_N(x=0.02)}}$

The leading twist predictions are with (**dashed**) and without (**solid**) account of the fluctuations of the interaction strength.

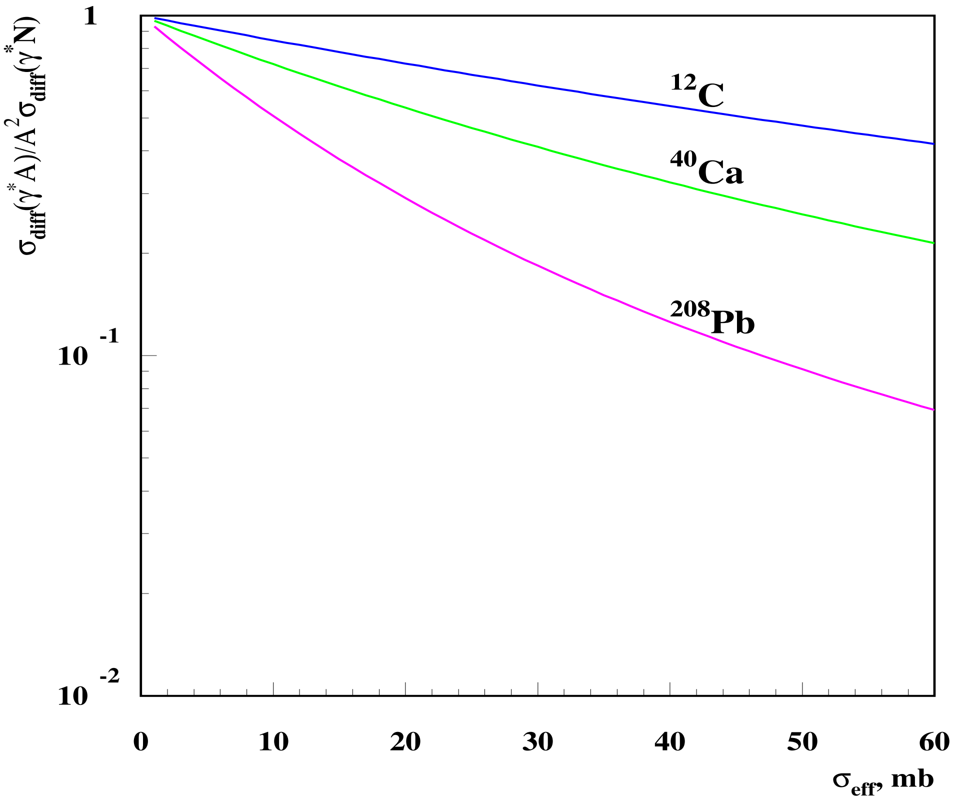
Inclusive and semiinclusive channels: diffractive structure functions, charm production, dijets...

Prime objective:
Determine directly how "black" are DIS interactions with nuclei?

Key signature of breakdown of PQCD expansion to look for: Probability of the rapidity gap, $P_{gap} \geq .3$ for large A ($P_{gap} \to 1/2$ for $A \to \infty$) :



A-dependence of nuclear shadowing and probability of rapidity gap events in the eikonal approximation for $N \geq 3$ nucleon interactions for $Q^2 \sim 4GeV^2, x \leq 3 \cdot 10^{-3}$ The dot-dashed curve assumes A-independent probability of the rapidity gap events.



Sensitivity of the ratio

$$\frac{\frac{d\sigma(\gamma^*+A)}{dt}}{A^2\frac{d\sigma(\gamma^*+N)}{dt}}_{|t=0}$$

to the average strength of the interaction, σ_{eff} for $A = 200$.

For gluon induced diffraction even a larger values of the diffraction fraction due to $\sigma_{eff} \sim 50$ mb

Larger fraction of diffraction for charm ($\sim 50\%$ for $A \sim 200$) than for light quarks??!!

Transition from quark induced diffraction to gluon induced diffraction may lead to increase of the rapidity gap probability with p_t of the jets?

More general predictions are possible in the QCD extention of the Gribov limit McDermott, F, Guzey, S,99

Gribov black body limit of DIS

In 1969 Gribov deduced the following formulae for the Unitarity Limit for structure functions of DIS:

$$F_T = \frac{2\pi r_{target}^2}{12\pi^3} \int_0^{\delta s} \frac{dM^2 \rho(M^2) M^2 Q^2}{(M^2 + Q^2)^2}$$

$$F_L = \frac{2\pi r^2_{target}}{12\pi^3}\int_0^{\delta s}\frac{dM^2 Q^4 \rho(M^2)}{(M^2+Q^2)^2}.$$

where $\delta \sim 1/2m_N x$ (refereed by Bj as Gribov paradox).

Main assumption (natural for soft strong interactions) is that all hadronic configurations at high energies interact with a heavy nucleus with $\sigma_{tot} = 2\pi R_A^2$.

In QCD color transparency leads to violation of this assumption, $\sigma \propto b^2$, and to the Bjorken scaling. However an increase of gluon densities may resurrect the Gribov limit. Answer is the same up to coefficient before $\ln(1/x)$ which is reduced by a factor $\sim 1/3$.

Using Gribov arguments we observe that diffraction for configurations for which Gribov regime is fulfilled should grossly violate scaling

$$\frac{dF_T^{D(2)}(x,Q^2)}{dM^2} = \frac{\pi r^2_{target}}{12\pi^3}\frac{Q^2 M^2 \rho(M^2)}{(M^2+Q^2)^2}$$

$\Longrightarrow$ *Such a behavior would occur even though the total cross section as a whole could be rather far from the black limit.*

$\Rightarrow$ **Study of inelastic diffraction would:**

- Provide a direct test of the strengths of interaction in the quark and gluon sector - identify the channels for which interaction is close to black for heavy nuclei. This information will be complementary to the study of the A dependence of G_A/G_N.

- Allow to find out the origin of gluon component of the "Pomeron"

Requirements to detector for measurement of diffraction

- Exclusive processes.

  For coherent processes - very steep peak in p_t distribution of the produced vector meson (pair of mesons,...) $\sim \exp(-R_A^2 p_t^2/3)$. If p_t resolution is not sufficient one can use anti-coincidence with production of nuclear fragments in particular zero angle neutrons.

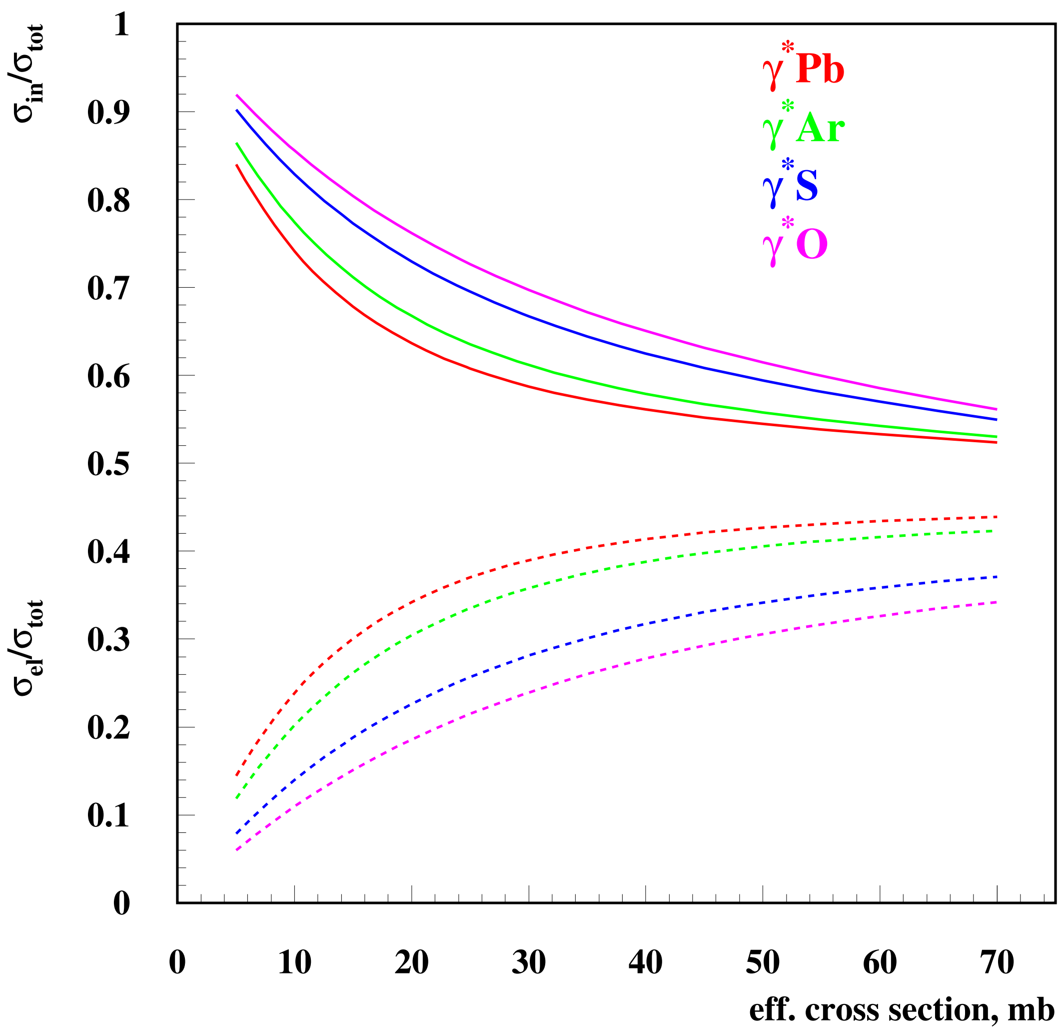
- Inclusive diffraction.

  Expectation: most of diffractive events lead to a nucleus in a ground state. For heavy nuclei inelastic interactions with nuclei lead to ≥ 4 neutrons and can be easily rejected. For A=16 breakup/elastic is $\sim 20\%$ and can be reduced further by using neutrons, etc.

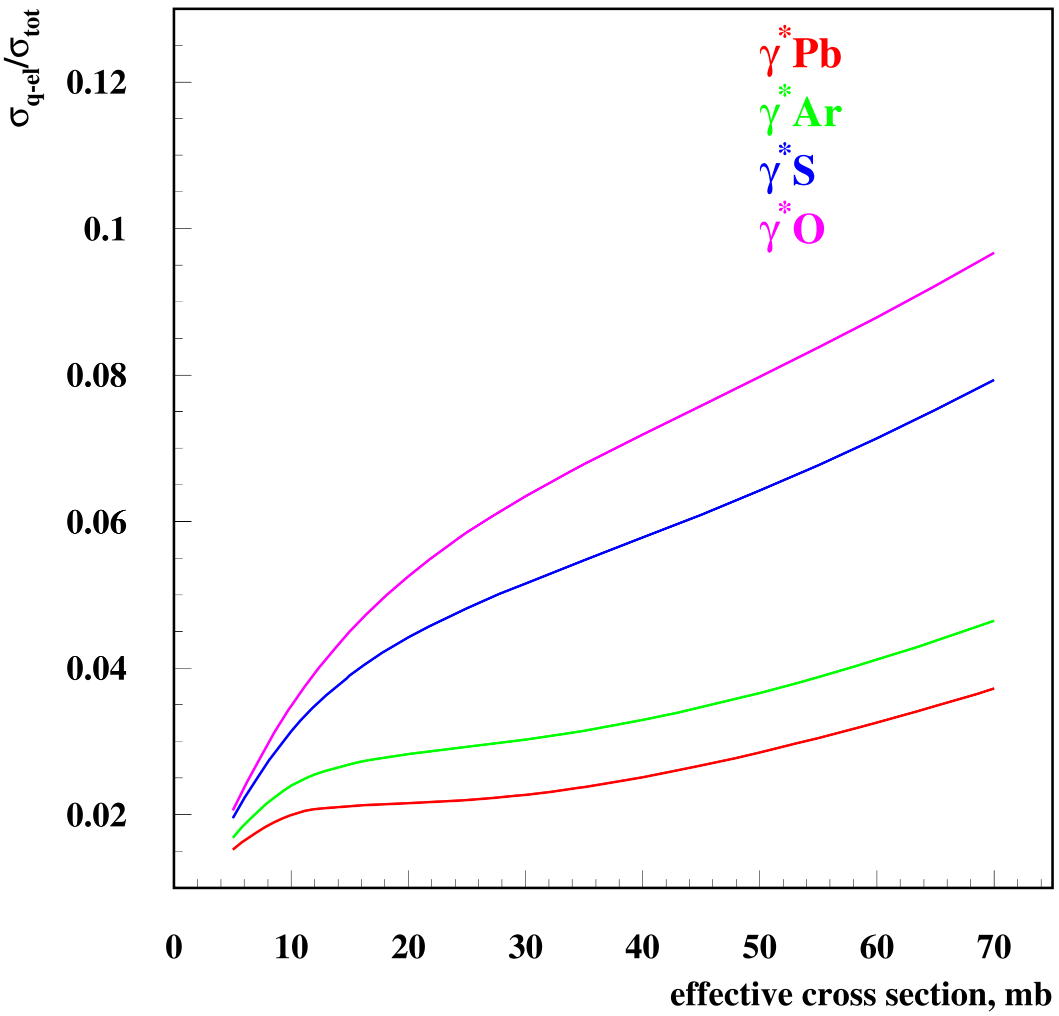
Paradoxically, measurement of diffraction in eA scattering is probably easier than in ep and the relative contribution is expected to be much larger for small x.

Optimal nuclei

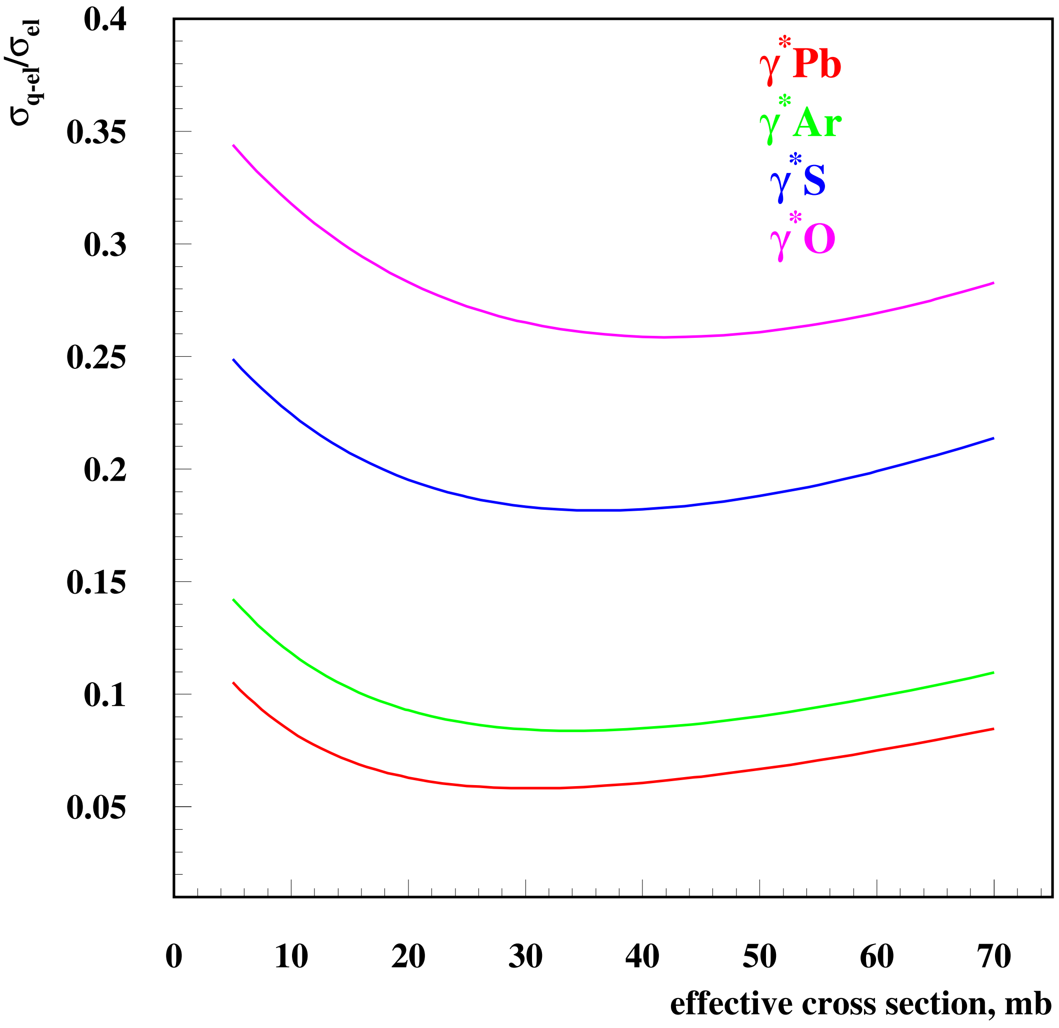
If interactions in the gluon channel is indeed strong it would be advantageous to relatively light nuclei like ^{16} where dependence of $\frac{\sigma_{el}}{\sigma_{tot}}$ on the average strength of interaction is much stronger.

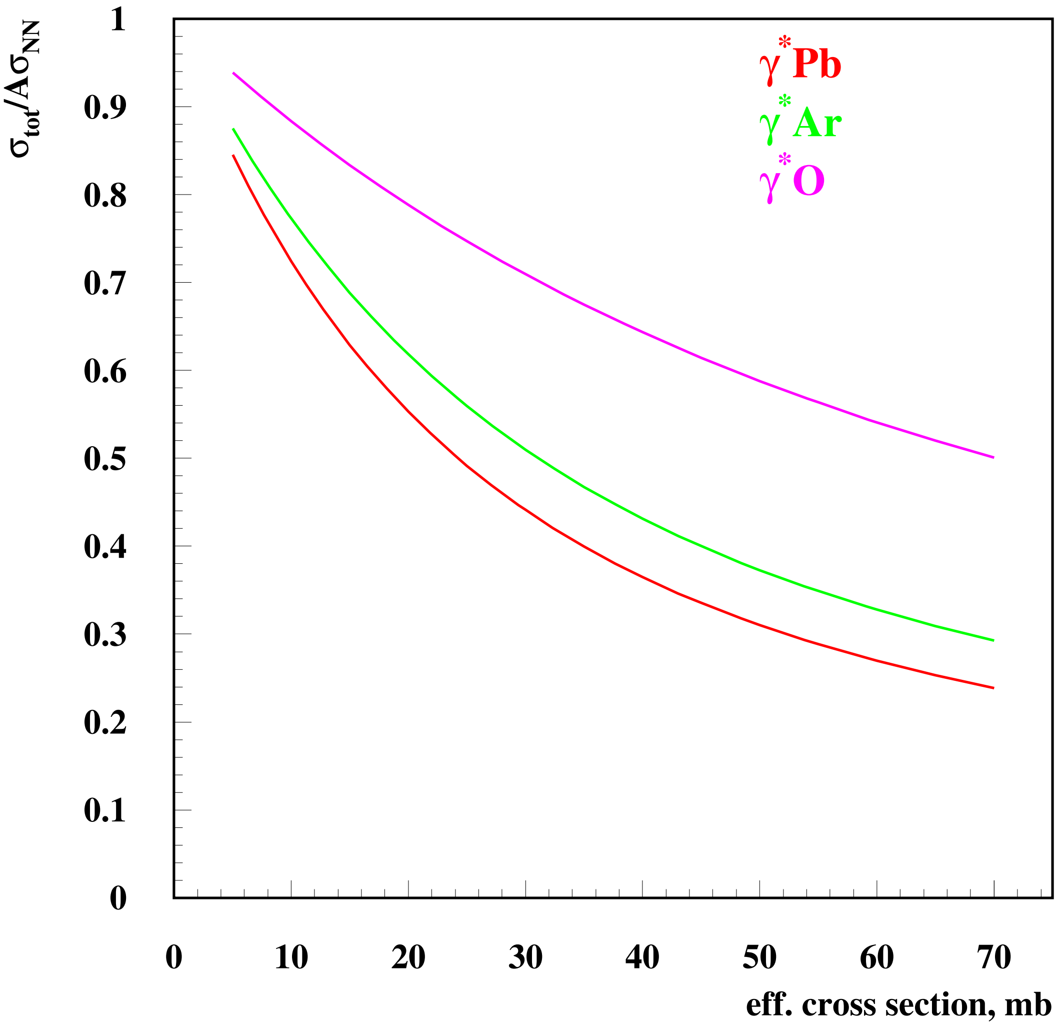


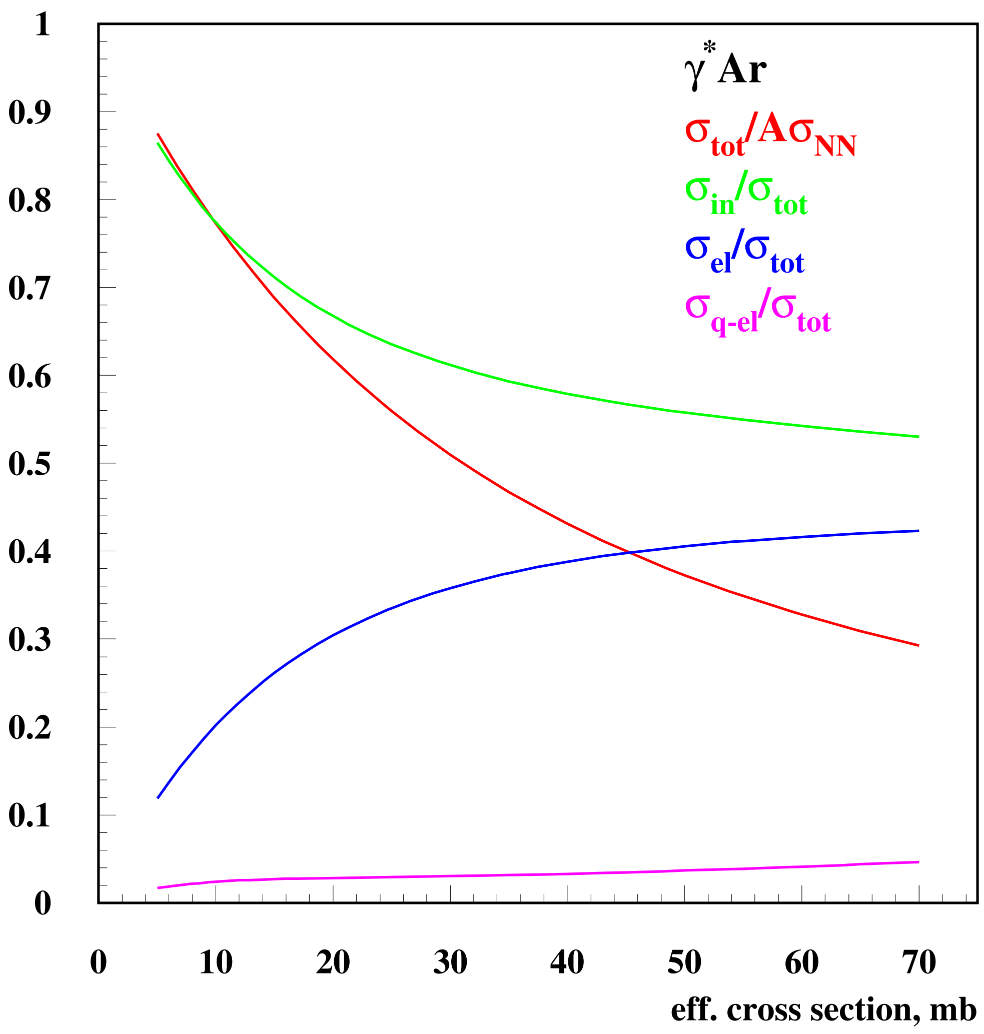
14-15.4.00, THERA, M.Strikman



$\sigma_{q\text{-}el}/\sigma_{tot}$
0.12
0.1
0.08
0.06
0.04
0.02
0
10
20
30
40
50
60
70
effective cross section, mb
γ^*Pb
γ^*Ar
γ^*S
γ^*O


$\sigma_{q\text{-}el}/\sigma_{el}$
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
10
20
30
40
50
60
70
effective cross section, mb
γ^*Pb
γ^*Ar
γ^*S
γ^*O


$\sigma_{tot}/A\sigma_{NN}$
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
γ^*Pb
γ^*Ar
γ^*O
0
10
20
30
40
50
60
70
eff. cross section, mb


γ*Ar
σtot/AσNN
σin/σtot
σel/σtot
σq-el/σtot
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
60
70
eff. cross section, mb

Non-diffractive hadron production

Hadron production in *high-energy hadron, photon - nucleus* scattering - one of the least understood phenomena Possibility to tune the γ^* and similar energy range of RHIC for pA collisions - **potential for illuminating comparisons**

A sample of new phenomena to investigate:

- Transition from low Q soft physics to pQCD physics for leading ($z \equiv x_F \geq 0.3$) hadron multiplicity $N(z)$:

Low Q $\rightarrow$ absorption $\frac{dN^{\gamma+A\rightarrow h+X}}{dz} \ll \frac{dN^{\gamma+A\rightarrow h+X}}{dz}$ for large A (Generally believed but not checked experimentally.)

$$\updownarrow$$

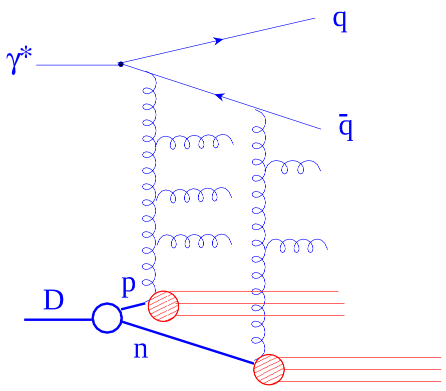
Large Q - QCD factorization: $\rightarrow \frac{dN}{dz}$ is A-independent

- QCD Landau-Migdal- Pomeranchuk effect - p_t broadening of the leading hadron spectra - Qualitative difference between QCD and QED

- Changes in the structure of the final states related to the small x phenomenon of shadowing and diffraction.

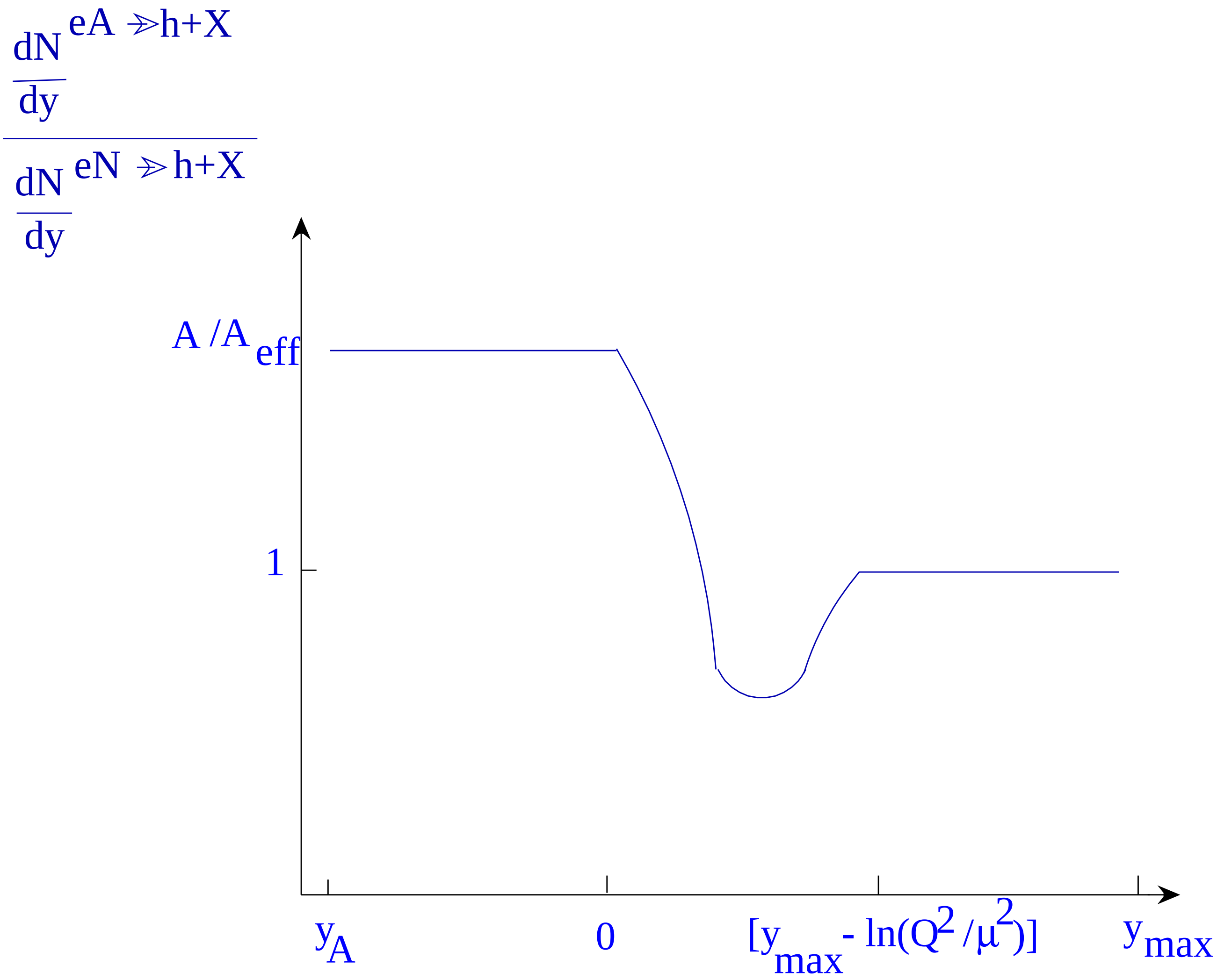
Diffraction originates from the presence of partons with small virtualities which screen the leading parton(partons) with large virtuality and can rescatter elastically from a target (several target nucleons in the case of nuclear target).

⇒Inelastic interactions of these soft partons with several nucleons:



⇒ Plenty of new revealing phenomena in small x DIS eA scattering, resembling hadron-nucleus scattering but with a shift in rapidity from $y_{max}(current)$:

♠ A dip at the rapidities $y \sim y_{max} - \ln(\left\langle M^2_{dif} \right\rangle / \mu^2)$ - a test of the rapidities of soft partons involved in the diffraction.



♠♠ Increase of the average multiplicities of the produced hadrons at $y_{c.m.} \leq 0$ by a factor $A\sigma_{eN}/\sigma_{eA}$. Further increase of N(z) is possible in the nuclear fragmentation region due to secondary cascade effects.

♠♠♠ Local fluctuations of multiplicity in the central rapidity region, e.g. the observation of a broader distribution of the number of particles per unit rapidity, $n(\Delta\eta)$, due to fluctuations of the number of wounded nucleons.

♠♠♠♠ Correlation of the central multiplicity with the multiplicity of neutrons in the forward neutron detector if its azimuth acceptance is large enough (most effective for heavy nuclei).

Summary

Small x eA physics -
Green pastures of QCD

$\rightarrow$ Plenty of new QCD phenomena to be discovered: gluon nuclear shadowing, color transparency, color opacity, pQCD in nonlinear domain,...
[*these are just expected discoveries - what about unexpected ones?*]
$\rightarrow$ Unique feature of the THERA kinematics is that it includes a wide range of Q^2 at $x \sim 10^{-4}$ where interaction with heavy nuclei may be close to the Gribov black limit. Several correlated observables would allow to build a detailed picture of the QCD bound states in the regime of high densities.