Requirements for eA detector.

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Natural road map.

1. Put in deuterons
2. Try polarized deuterons
3. Relatively low lumi ^{16}O, ^{40}Ca (?) [~10 pb^{-1}/A]
4. If nuclear effects are indeed strong and reveal new QCD dynamics push for cooling, high lumi, heavy nuclei.

Deuteron: weakly bound system

⇒ sourse of quasifree neutrons

caveats: EMC effect & nuclear shadowing

Cannot measure $F_{2n} = F_{2d} - F_{2p}$ at small x

⇓

Need tagging to measure

$F_{2p} - F_{2n}$ & $g_{1p} - g_{1n}$ at $x \lesssim 0.05$

$x > 0.5$

) Can study nuclear coherent effects where both nucleons are involved.

te: isospin zero: g_{1d} is OK ($\lesssim 4\%$ nuclear effects)

better for study of ΔG_N from $\frac{\partial}{\partial \ln Q^2} g_{1N}$ than g_{1p}

Deuteron: tagging of p,n

Safe kinematics $|k_N| \le 150$ MeV

deuteron rest frame

Collider frame:

$$\left|\frac{p_N}{p_D} - 0.5\right| \equiv |z_N - 0.5| \le 0.07 \ , \ k_t \le 100-150 \text{ MeV/c}$$

physical background: diffraction $\Rightarrow$ changes $z_N \to z_N - \frac{x_{IP}}{2}$

for $x \le 0.01$

& transverse kick $p_t \simeq \sqrt{\frac{1}{B_{diff}}} \simeq 350$ MeV $\gg k_{Deut}$.

divergence of the beam $p_{d_t} \ne 0 \Rightarrow p_{N_t} = p_{dt}$

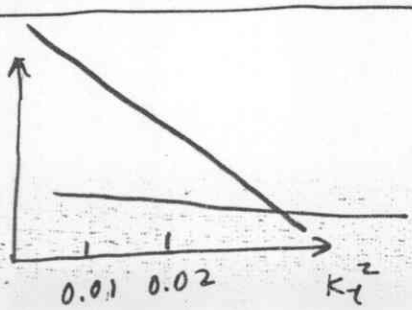
take $\langle p_{d\,divergence}^2 \rangle = (150 \text{ MeV})^2$

$\Rightarrow$ spectator p_t distribution including smearing $\}$: $\exp - B_s p_t^2$, $B_s \gtrsim \frac{1}{\langle 150^2 \text{MeV}^2 \rangle}$

take $\sigma_{diff} / \sigma_{tot} = 0.1$

$$\frac{\text{background}}{\text{spectators}} = 0.1 \frac{B_{diff}}{B_{diff} + B_s} \exp\left[\frac{B_s^2 k_t^2}{B_{diff} + B_s}\right] \simeq 0.013 \exp(42 k_t^2)$$

$\lesssim 4\%$ for $k_t < 150$ MeV/c



Problem: for $x \lesssim 0.01$

$$\frac{F_{2p} - F_{2n}}{(F_{2p} + F_{2n})/2} \ll 1$$

$$\Downarrow$$

need to know efficiencies for p & n detections with high accuracy !??

Way out: use constraint

$$\sigma_{\gamma^* p} - \sigma_{\gamma^* n} \to 0 \text{ for } x \to 0 \quad \text{at fixed } Q^2.$$

Need weak x dependence of tagging efficiencies for $x < 0.01$.

i) Polarized deuteron: easy to measure helicity due to D wave using spectators

$$\left.\begin{matrix} + \\ 0 \end{matrix}\right] \quad \frac{\sigma_+ - \sigma_0}{\left(\frac{\sigma_+ + \sigma_- + \sigma_0}{3}\right)} \propto \frac{w(u - w/\sqrt{2})}{u^2 + w^2} \qquad \begin{bmatrix} u - \text{S wave} \\ w - \text{D wave} \end{bmatrix}$$

~10% analysing power for the tagging range.

Nuclear coherent effects

Total cross sections – nuclear shadowing:

$$\frac{F_{2D}(x,Q^2)}{F_{2N}(x,Q^2)} - 1 \sim -2\% \quad x \sim 10^{-2}$$

$$-4\% \quad x \sim 10^{-4}$$

] probably hopeless

polarized deuteron:

D – wave correlated with spin ⇒

probability of double interactions depends on helicity

$$T_{20} = \frac{\sigma_{\pm} - \sigma_0}{\frac{2\sigma_{+} + \sigma_0}{3}} \sim 1\% \quad x \sim 10^{-2}$$

? is it doable ?

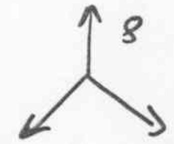
$$2\% \quad x \sim 10^{-4}$$

Coherent interactions are enhanced if special kinematics is selected [strongly enhanced for $\vec{d}$]

Examples

$\gamma^* + {}^2\overset{(\rightarrow)}{H} \rightarrow \rho + {}^2H$ $t \gtrsim 0.5\,GeV^2$

$\gamma^* \rightarrow {}^2\overset{(\rightarrow)}{H} \rightarrow \rho + p + n$ in "Mersedi" configuratio[n]



p_t plane

~400 MeV/c   400 MeV/c

Q^2 - dependence :   eikonal —

$\overline{\sigma(e+p \rightarrow V+p)} \sim \frac{1}{Q^4}$

leading twist
gluon shadowing

$\overline{\sigma(e+p \rightarrow V+p)} \sim const$

Need good acceptance for p & n at z~0.5

and for deuterons at z~1.

Nuclei : Interesting physics

$\propto$ nuclear thickness

Comparing nuclei for the same p_A/A allows to select central impact parameters:

$Ca - {}^{16}O \simeq Ca$ at small impact parameters

$\simeq$ gain of 1.5 in thickness

$$A \to (1.5)^3 A \simeq 4A\Big|_{Ca} \simeq 150$$

To reduce systematics:

(a) two nuclei in a ring

(b) Frequent switching from ${}^{16}O$ to ${}^{40}Ca$.

$[\,{}^{4}He \leftrightarrow {}^{16}O \simeq {}^{40}Ca\,]$

Impotant for normalization

$F_2({}^{40}O)/F_2({}^{16}O)\ (x \in 0.1-0.3) = 1.0$ within few %.

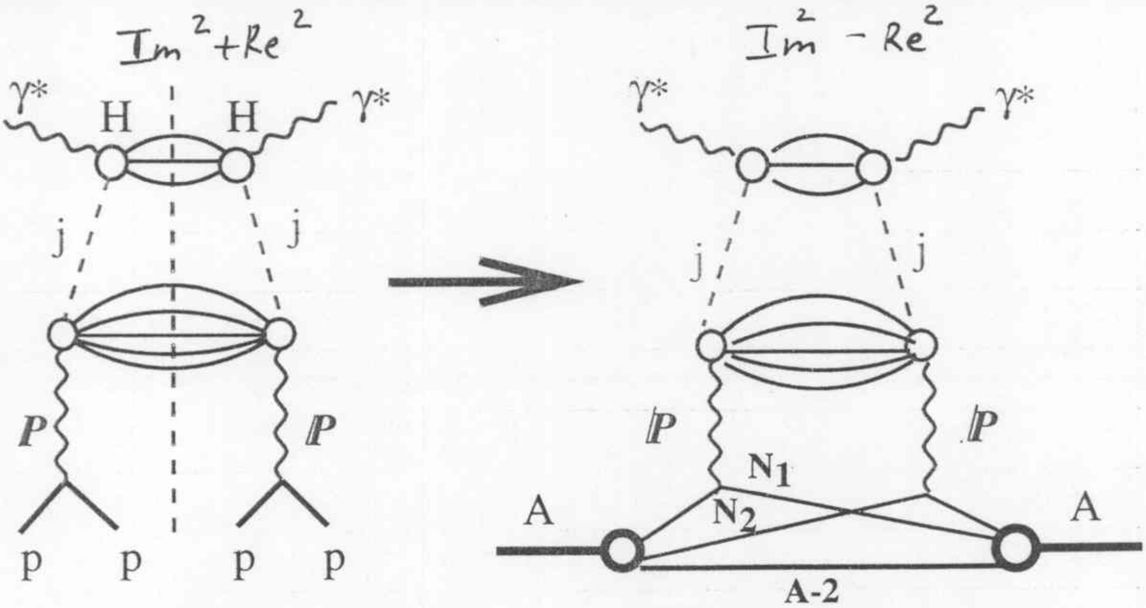
General expectation:

for $x \lesssim 0.005$ when coherence length $\sim \frac{1}{2 m_N x} \gg 2R_A$

strong differences between eA & ep phenomena.

Quite a lot can be predicted based on information from hard ep diffraction.

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 $f_j(x,Q^2)$

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

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

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, $\eta = \frac{1-(Re/Im)^2}{1+(Re/Im)^2}$

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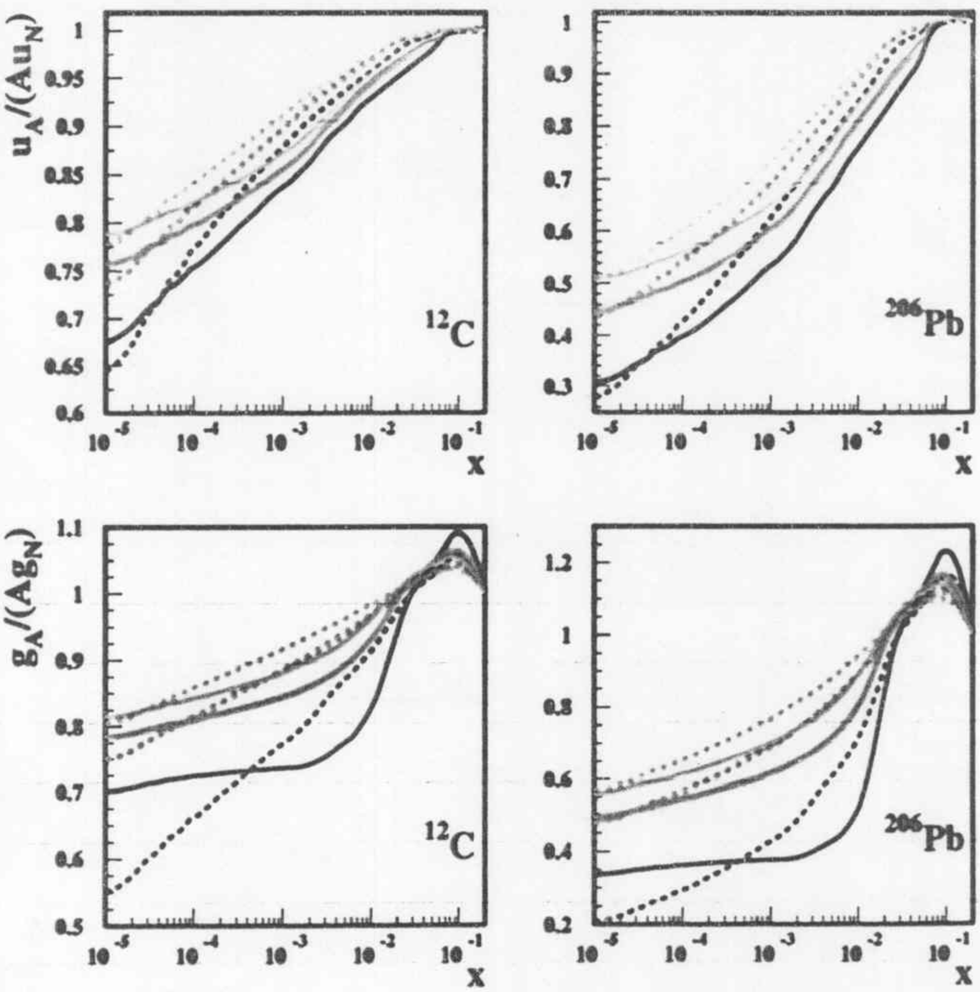


'he ratio of nuclear to nucleon up-quark and gluon parton istributions as a function of x, scaled by nucleon number, l. Two representative sets of diffractive parton densities, ACWT+" and "H1" are used to calculate nuclear shadowing or each nucleon and taken together they give an indication of he spread of theoretical predictions. The black, red, and green urves are for Q = 2, 5, 10 GeV, respectively. L. Frankfurt, '. Guzey, M. McDermott and M. Strikman, "Electron nucleus ollisions at THERA," hep-ph/0104252.

Diffractive small x phenomena off nuclei

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

[Can a small dipole have a shadow?]

- *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.

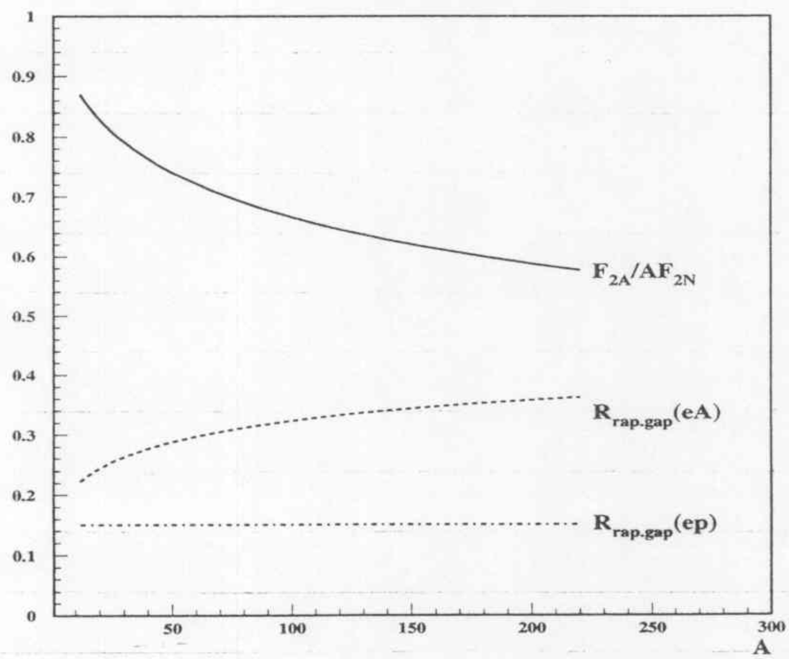
$\Longrightarrow$ Definite prediction of the cross section of coherent processes $\propto A^{4/3}$. [Observed in $\pi + A \to 2\,jets + A$]

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.

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

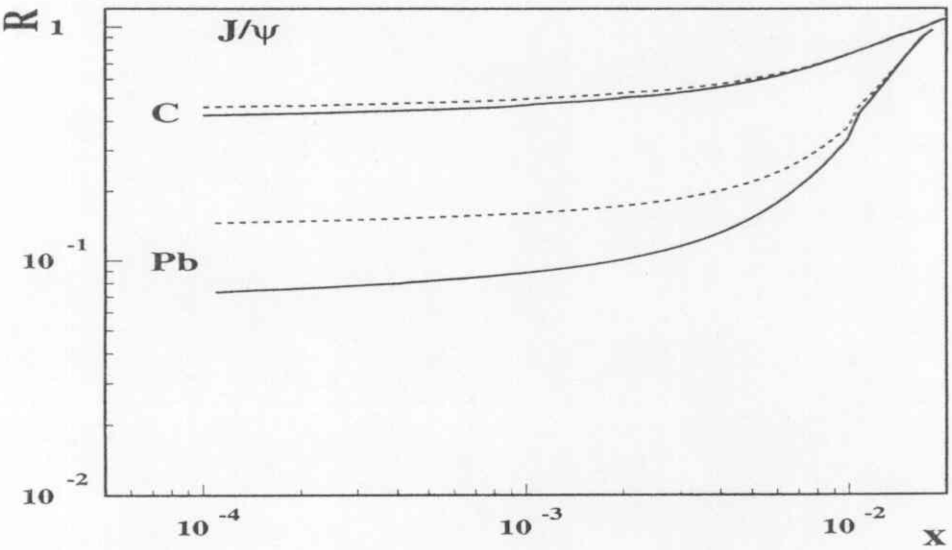
Prime objective:
Determine directly how "black" are DIS interactions with nuclei?

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



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.

♣ **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.

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. To observe diffractive minima p_t resolution better than ~100MeV/c (tough)

- 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. (spectator proton "z" ~ 0.5)

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 use nuclei with A~16 since in this case dependence of $\sigma_{diff}/\sigma_{tot}$ on the strength of interaction is much stronger.

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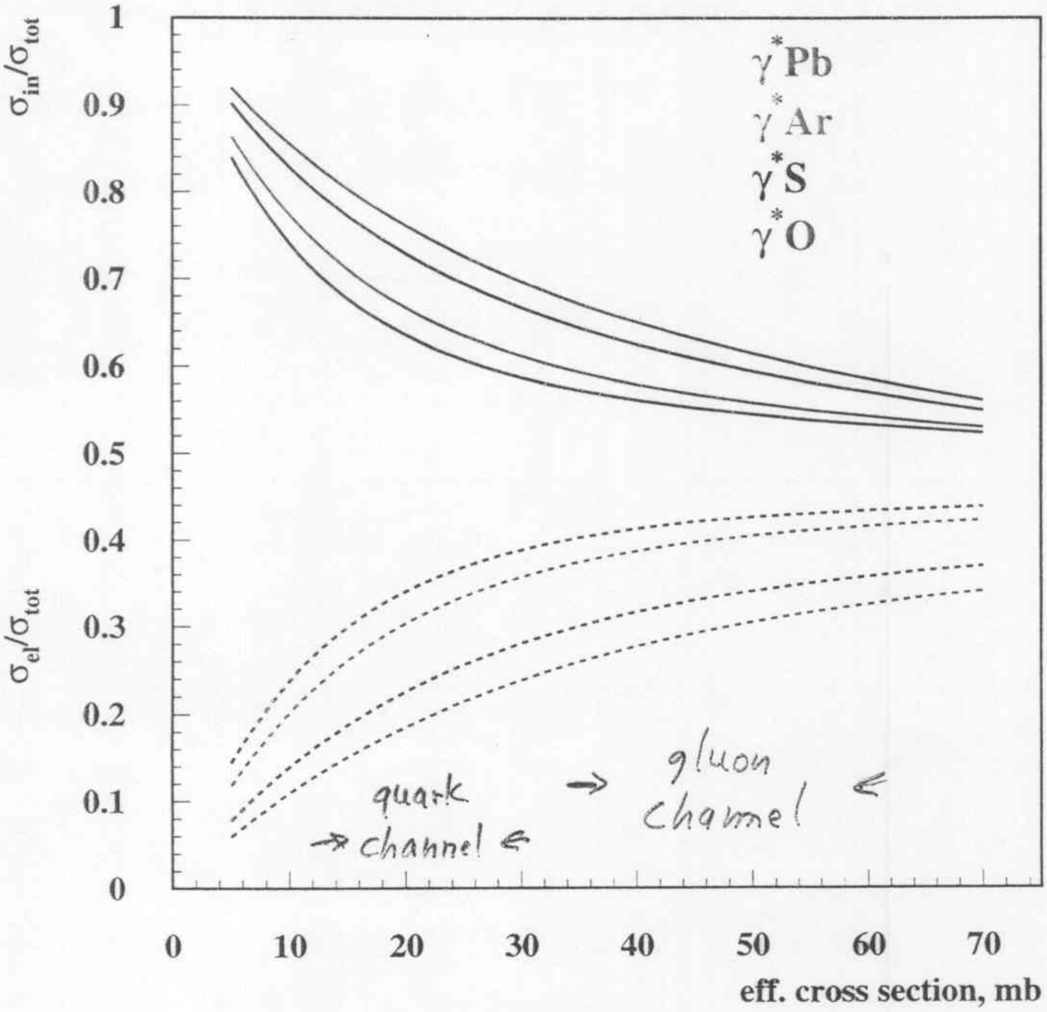

$\sigma_{el} \equiv \sigma_{coherent\ diffraction}$

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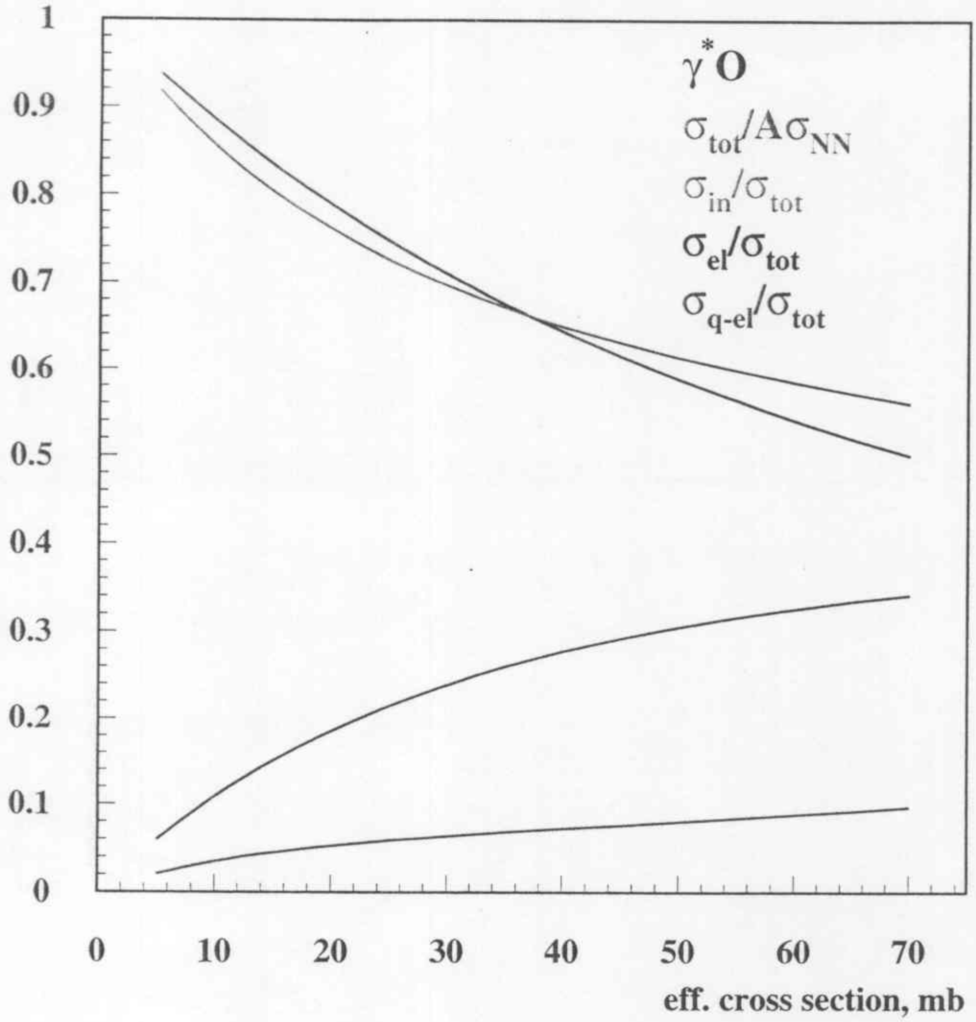


γ*O
σtot/AσNN
σin/σtot
σel/σtot
σq-el/σtot
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
60
70
eff. cross section, mb

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.)

$$\updownarrow$$

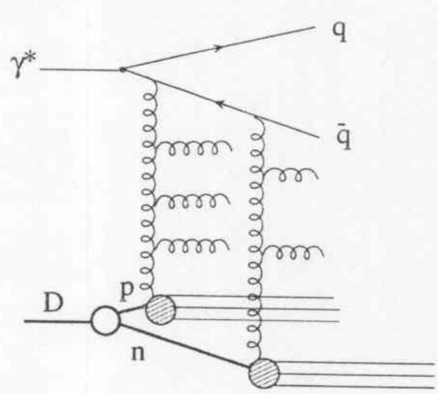
Large Q - QCD factorization: $\rightarrow \frac{dN}{dz}$ is A-independent

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

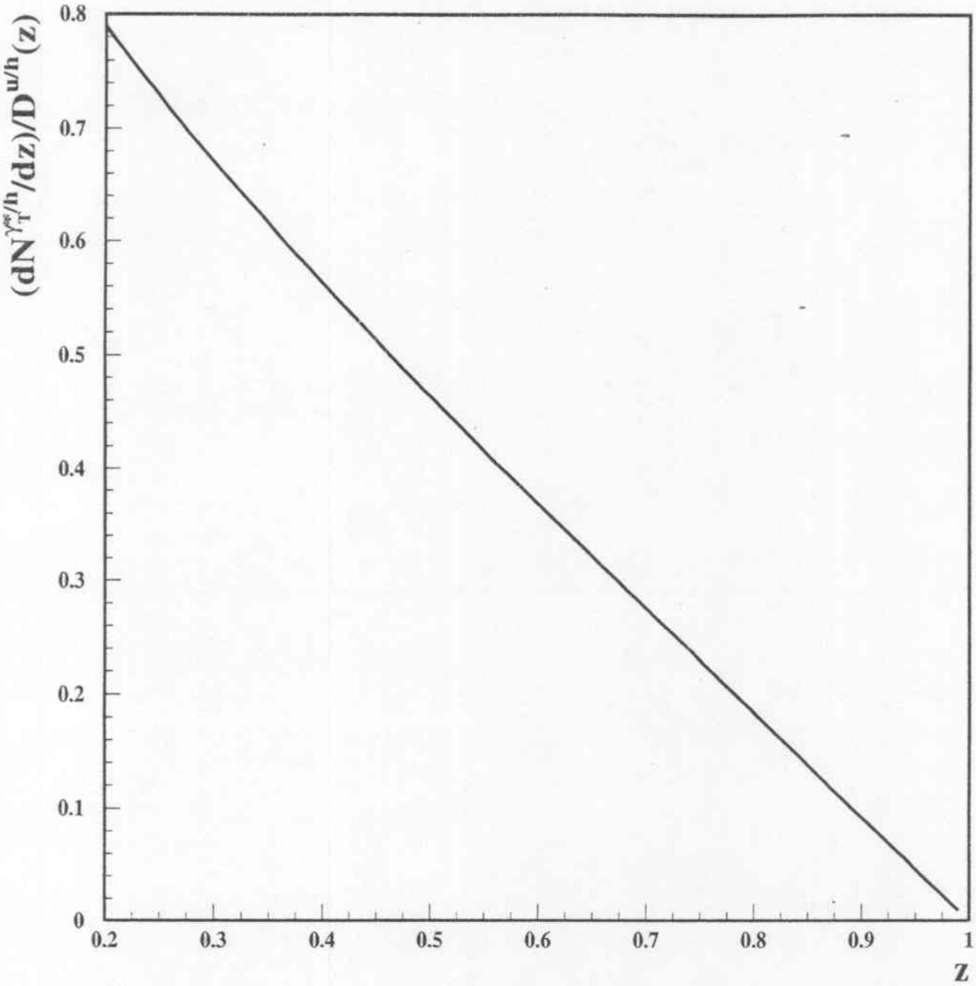
- Changes in the structure of the final states related to the small x phenomenon of shadowing and diffraction.

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:

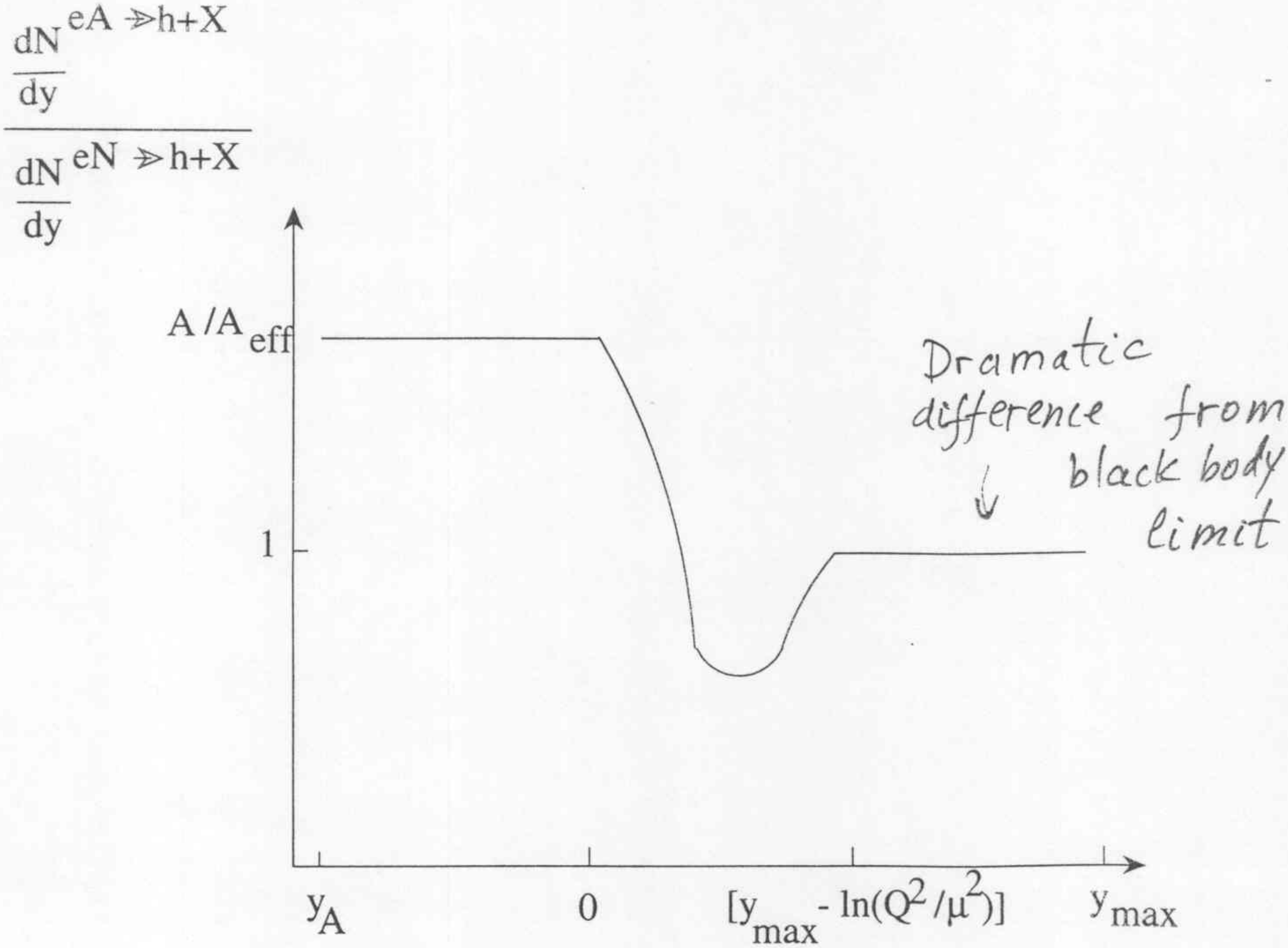


⇒ Plenty of new revealing phenomena in small x DIS eA scattering, resembling hadron-nucleus scattering but with a shift in rapidity from $y_{max}(current)$:



The total differential multiplicity normalized to the up quark fragmentation function, $(dN^{\gamma_T^*/h}/dz)/D^{u/h}(z,Q^2)$, as a function of z at Q^2=2 GeV^2 calculated in the BBL.

♠ 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. ⇒ Important to extend detectors in proton direction and to be able to detect up to 5 times larger multiplicities/ rapidity.

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♠♠♠ 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).

Conclusions

Current detectors will be able to observe major gold plated phenomena with $A > 2$ nuclei.

For deuteron physics and some aspects of eA physics

- improve detector acceptance for $z \sim 0.5$

- broader coverage of rapidities between 0 and y_A, ability to measure high hadron densities.