Nuclear shadowing in DIS, diffraction and high energy color transparency

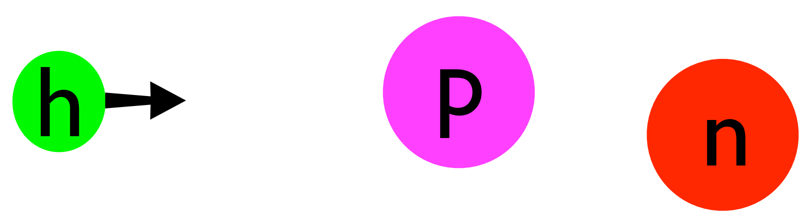
+ peek at "HERA III" at LHC

Mark Strikman, PSU

EINN05, Milos, September 23, 2005

Outline

- Nuclear shadowing in DIS - is this obvious?



$\Rightarrow \quad \sigma_{h\,^2H} < \sigma_{hp} + \sigma_{hn}$

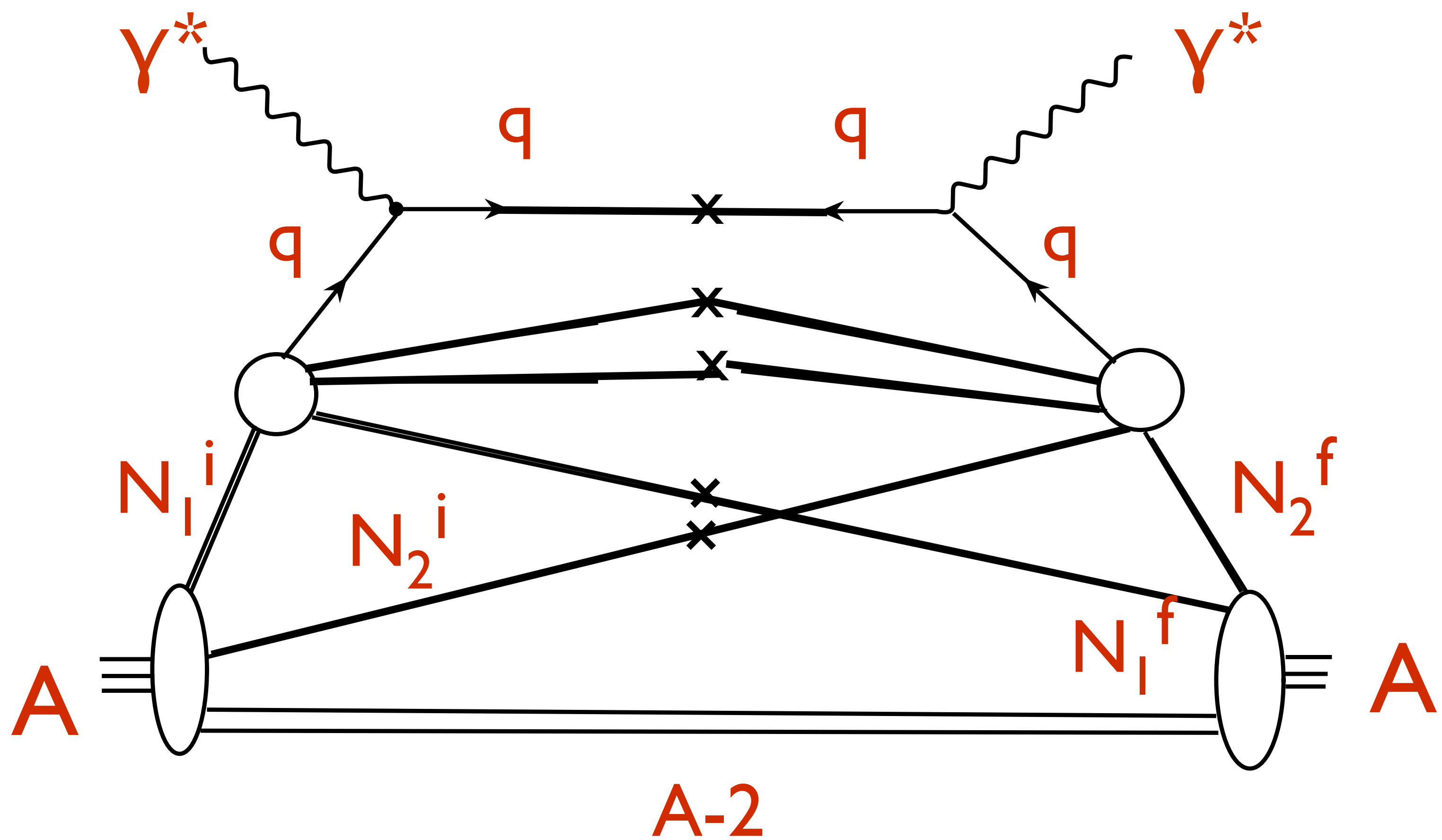
$\sigma_{e\,^2H}(x,Q^2) < \sigma_{ep}(x,Q^2) + \sigma_{en}(x,Q^2)$ in DIS???

- Nuclear shadowing and DIS diffraction
- Observations of high energy color transparency
- Ultraperipheral collisions - new tool for nuclear shadowing and CT studies

Nuclear shadowing and diffraction

Usually one starts from an impulse approximation form for the scattering of a hard probe (γ^*,W) off a nucleus. In the parton language - QCD factorization. Can we trust impulse approximation form in the hadronic basis for the nucleus wave function?

Consider interference between scattering off two different nucleons



Introduce nucleon light-cone fractions, α.   Free nucleon $\alpha=1$, $\alpha_f \leq 1-x$

For nucleus to have significant overlap of |in> and <out| states

$$\alpha_{N_1^f} \leq \alpha_{N_1^i} - x \sim 1,\ \alpha_{N_2^i} \leq \alpha_{N_2^f} - x \sim 1$$

Interference is very strongly suppressed for $x > 0.2$ - would require very large momenta in the nucleus WF

Additional suppression because of the suppression of large

$$z \equiv x_F = \frac{\alpha}{1-x}$$ for $x \geq 0.1$

$$\frac{d\sigma(z)}{dz/z}_{|z\to 1} \propto (1-z)^{n(x)}, \; n(x \geq 0.2) \sim 1, \; n(0.02 < x < 0.1) \sim 0, \; n(x < 0.01) \sim -1.$$

FS77

$\Longrightarrow$ Interference is very small for $x > 0.1$ and impossible for $x > 0.3$.

situation is more subtle for pion fields.

$\Longrightarrow$ Large interference for $x < 0.01$ due to the final states where small light cone fraction is transfered to the nucleon $\equiv$ diffraction. It results in the leading twist shadowing as well as higher twist shadowing.

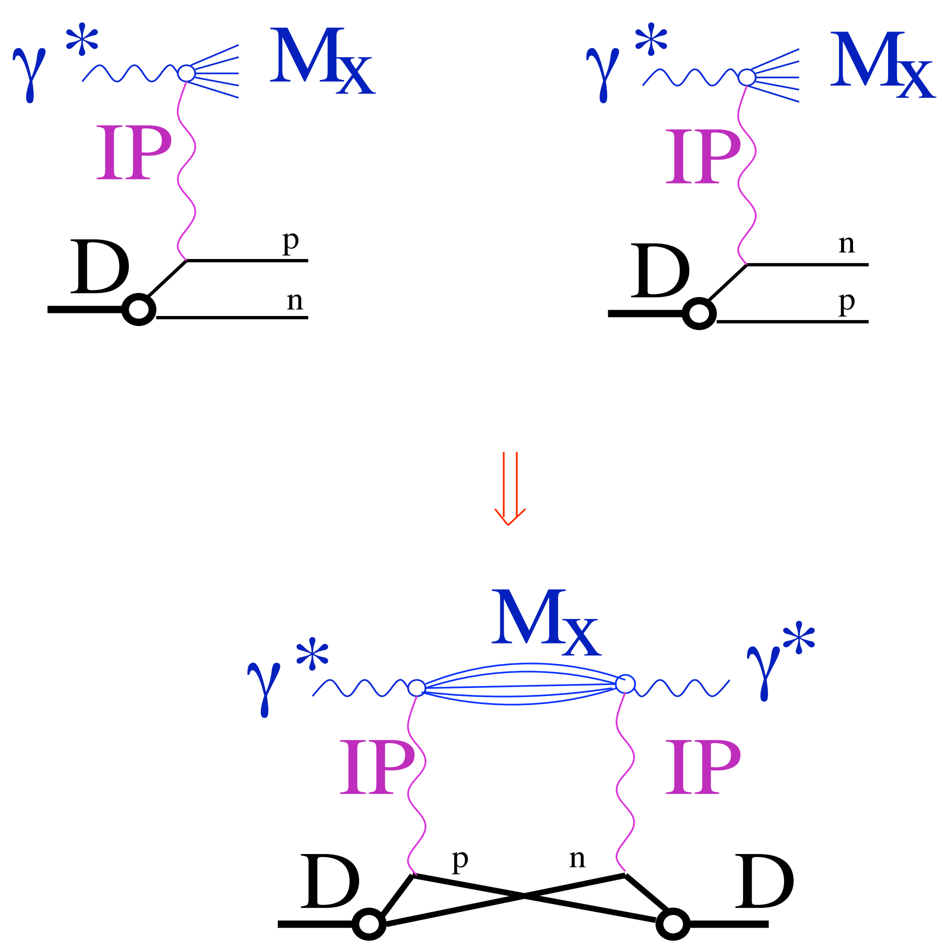
How big is HT shadowing is an open question. Issue of duality.

Deep connection between phenomenon of diffraction and nuclear shadowing - Gribov 1968 - relates cross section of diffraction in elementary reaction $\gamma^* + N \to X + N$ and deviation of cross section of scattering off nuclei from additivity.

Qualitatively, the connection is due to a possibility of small momentum transfer to the nucleon at small x, where

$$If\ \sqrt{-t} \leq \text{"}average\ momentum\ in\ nucleon(nucleus)$$

amplitudes of diffractive scattering off proton and off neutron interfere



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

$$\frac{d\sigma^{\gamma^*+D\to M_X+(pn)}}{dt\, dM_X^2} = \frac{d\sigma^{\gamma^*+N\to M_X+(pn)}}{dt\, dM_X^2}(2+2F_D(4t))$$

Here $F_D(t)$ is the deuteron form factor. For $t=0$ - 100% constructive interference - (pn) system is D. Coherence dies out at large t.

Integrate over t, M_X ➡ positive correction to the impulse approximation. Coincides with the Gribov shadowing correction to the total cross section (up to small corrections due to the real part of the amplitude).

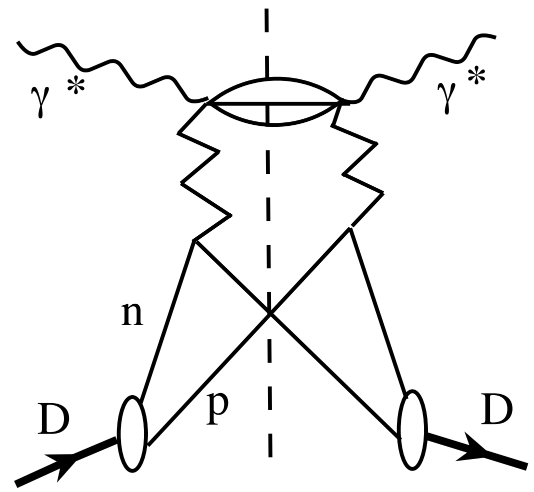
However the sign is opposite !!!

Explanation is unitarity - Abramovskii, Gribov, Kancheli cutting rules (AGK).

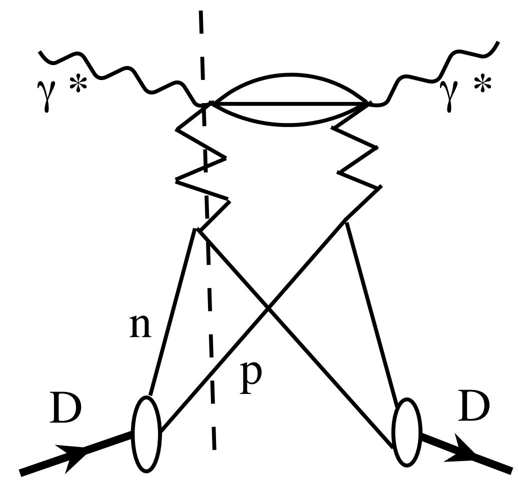
$$\sigma_{tot} = \sigma_{impulse} + \sigma_{shad}$$

$$\sigma_{shad} = \sigma_{dif} + \sigma_{single} + \sigma_{double} = -\sigma_2$$

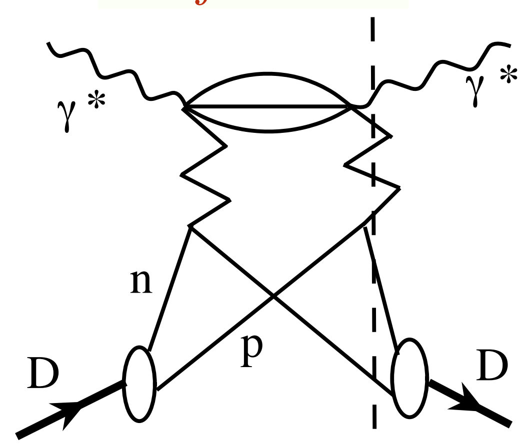
AGK relation between cross sections of different channels:



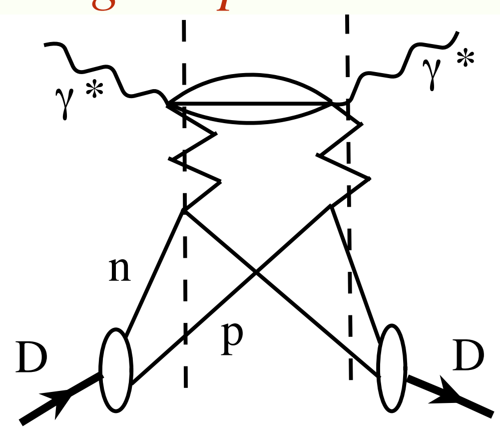
$$\sigma_{dif} = \sigma_2$$



$$\sigma_{single\ "p"} = -2\sigma_2$$



$$\sigma_{single\ "n"} = -2\sigma_2$$



$$\sigma_{double} = 2\sigma_2$$

Using AGK we rederived original Gribov result extending it to include the real part effects. This approach does not require separation of diffraction into leading twist and higher twist parts.

Detour: Diffractive phenomena - inclusive diffraction and measurement of diffractive pdf's

Collins factorization theorem: consider hard processes like

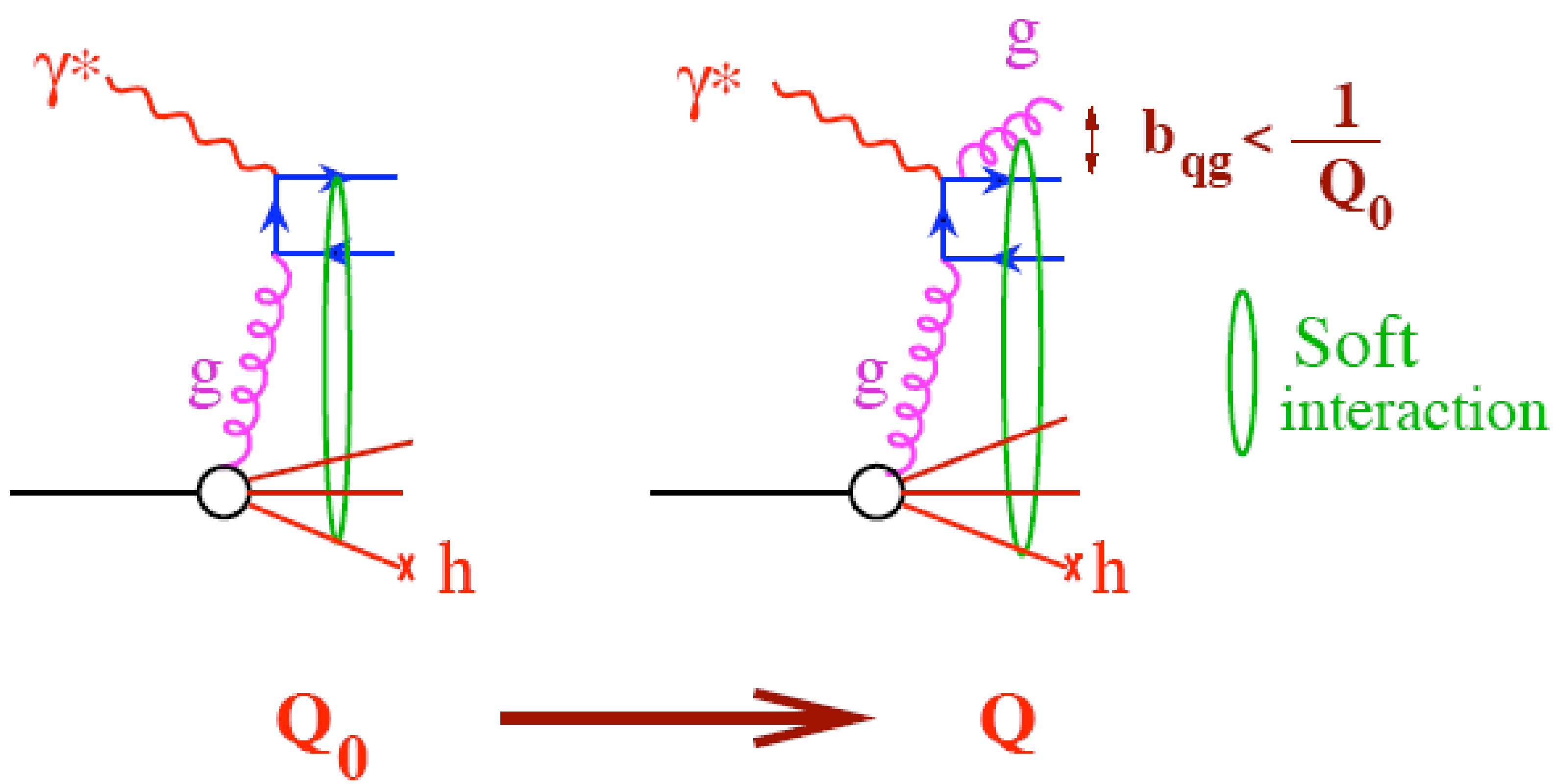
$$\gamma^* + T \to X + T(T'), \;\; \gamma + T \to \; jet_1 \; + \; jet_2 + X + T$$

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 for diffractive pdf's as for normal pdf's.

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 $Q^2 > Q_0$



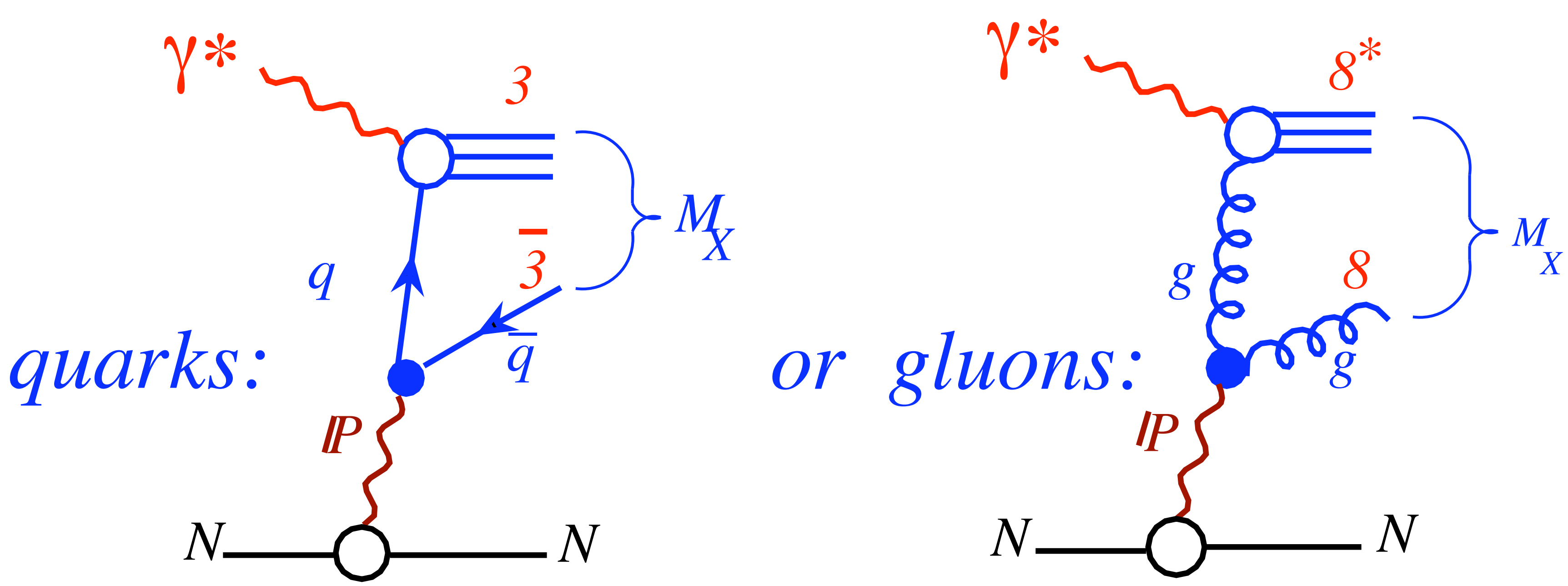
$\rightarrow$ Production of *"h"* when a parton at x, Q^2 is hit is the same as when an "ancestor" parton is hit at x, Q_0^2.

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:

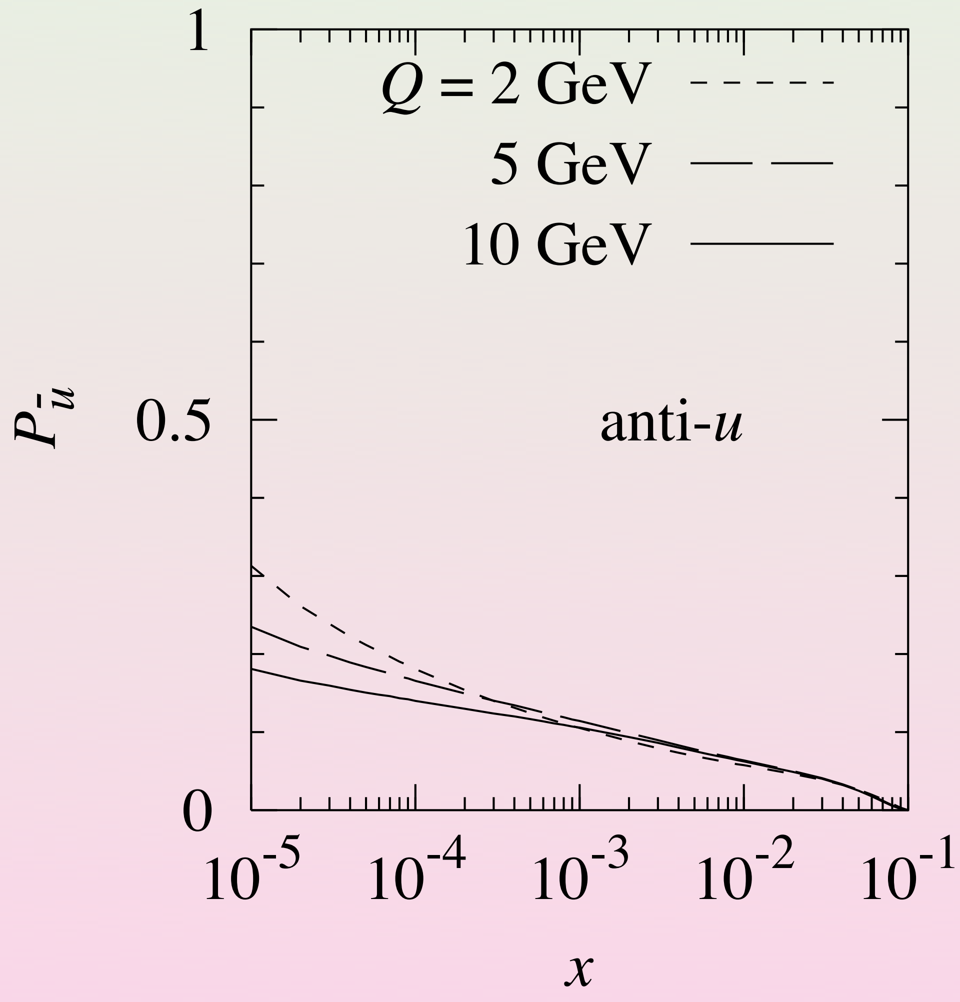
$$P_q = \frac{\sigma(\gamma^* + p \to X + p)_{x_{I\!P} \leq 0.01, x \leq 10^{-3}}}{\sigma_{tot}(\gamma^* + p)} \approx 0.1$$

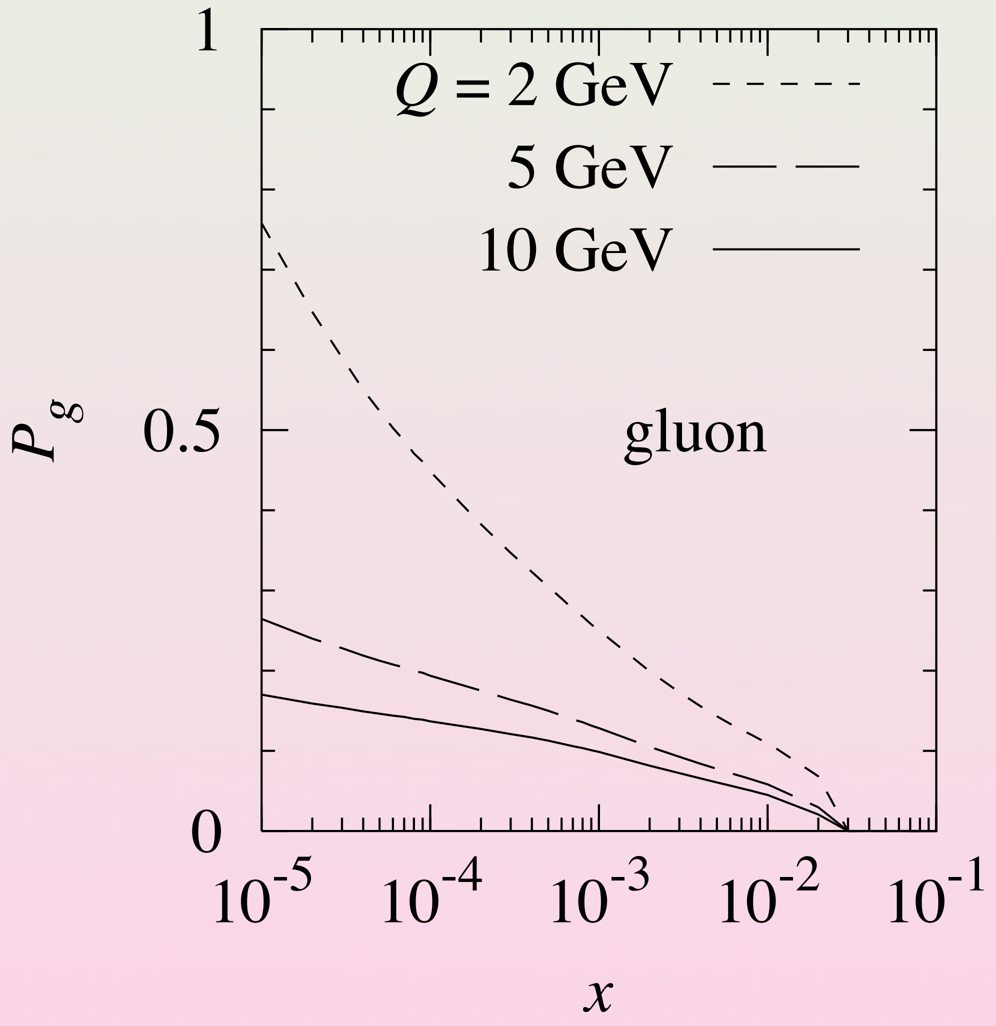
(b) Factorization theorem allows to define a probability $P_j(x, Q^2) = \int f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t) dt dx_{I\!P} / f_j(x, Q^2)$ of diffractive gaps for the hard processes induced by hard scattering off



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

Consistent with the analysis of the HERA data:



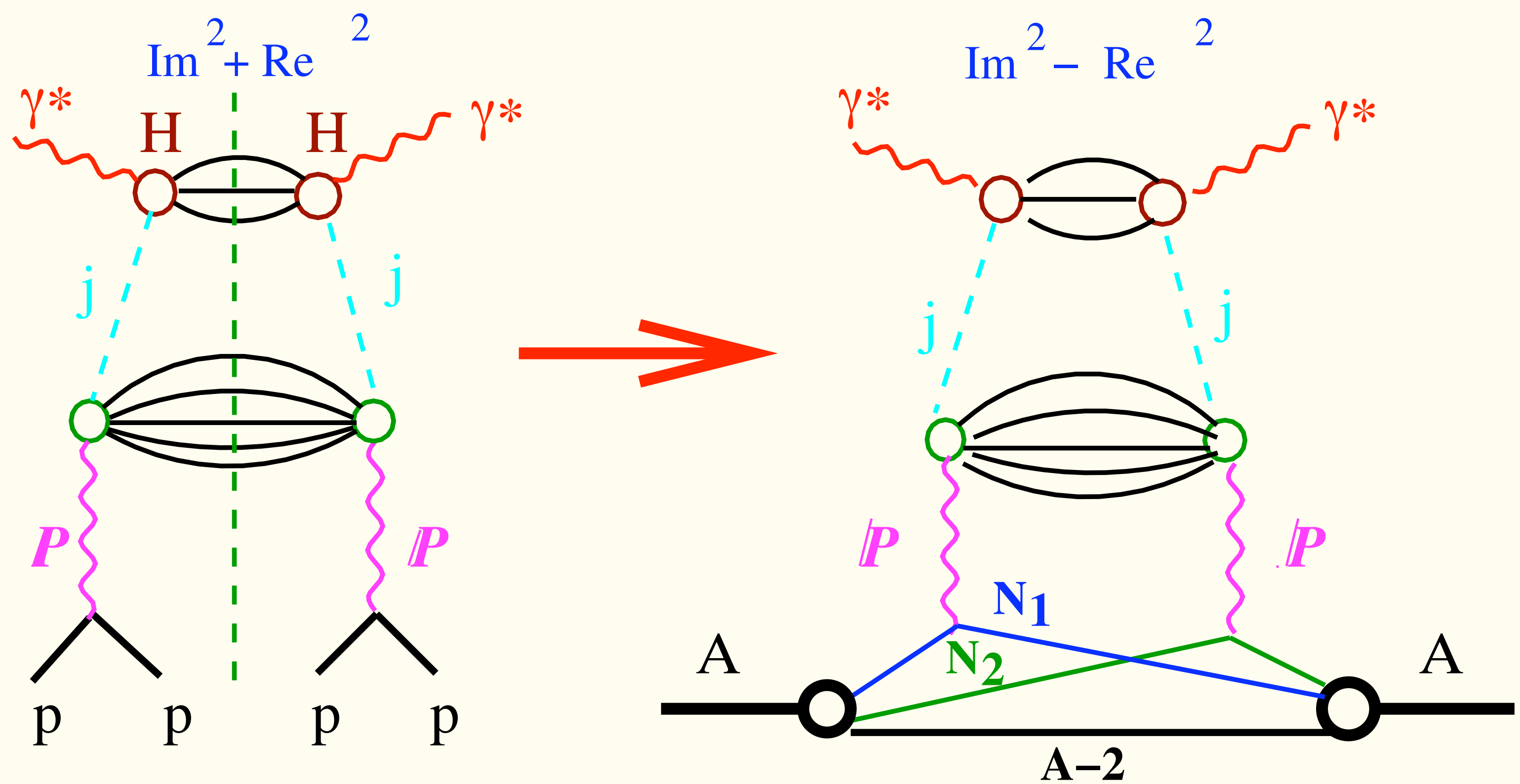


Probability of diffractive scattering from anti– quarks(left)and gluons(right), extracted from a fit to the H1 data.

Theoretical expectations for shadowing in the LT limit

Combining Gribov theory of shadowing and pQCD factorization theorem for diffraction in DIS allows to calculate LT shadowing for all parton densities (FS98) (instead of calculating F_{2A} only)

Theorem: In the low thickness limit the leading twist nuclear shadowing is unambiguously expressed through the nucleon diffractive pdf's: $f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$



Hard diffraction

off parton "j"

Leading twist contribution

to the nuclear shadowing for

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

Theorem: in the low thickness limit (or for x>0.005)

$$f_{j/A}(x,Q^2)/A = f_{j/N}(x,Q^2) - \frac{1}{2+2\eta^2}\int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \int_x^{x_0} dx_{I\!P} \cdot$$
$$\cdot f^D_{j/N}(\beta, Q^2, x_{I\!P}, t)\rho_A(b,z_1)\ \rho_A(b,z_2)\, \mathrm{Re}\left[(1-i\eta)^2 \exp(i x_{I\!P} m_N (z_1 - z_2))\right],$$

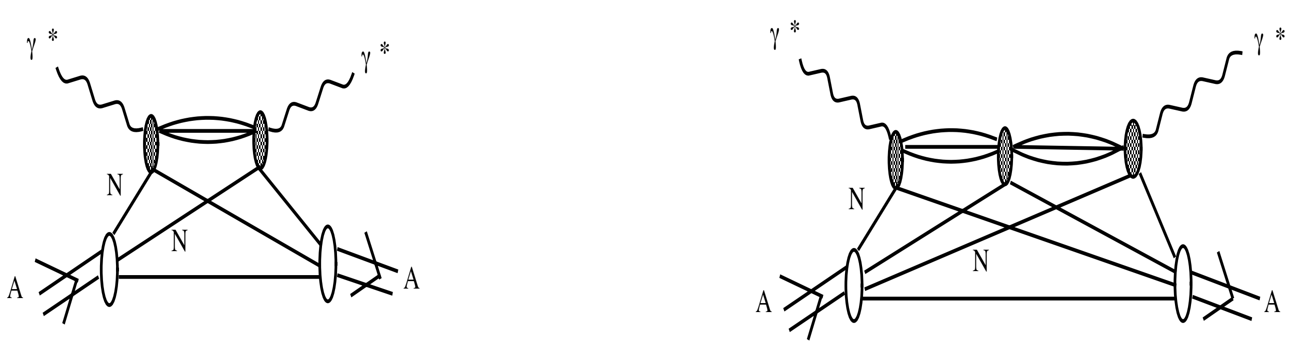
where $f_{j/A}(x,Q^2), f_{j/N}(x,Q^2)$ are nucleus(nucleon) pdf's,

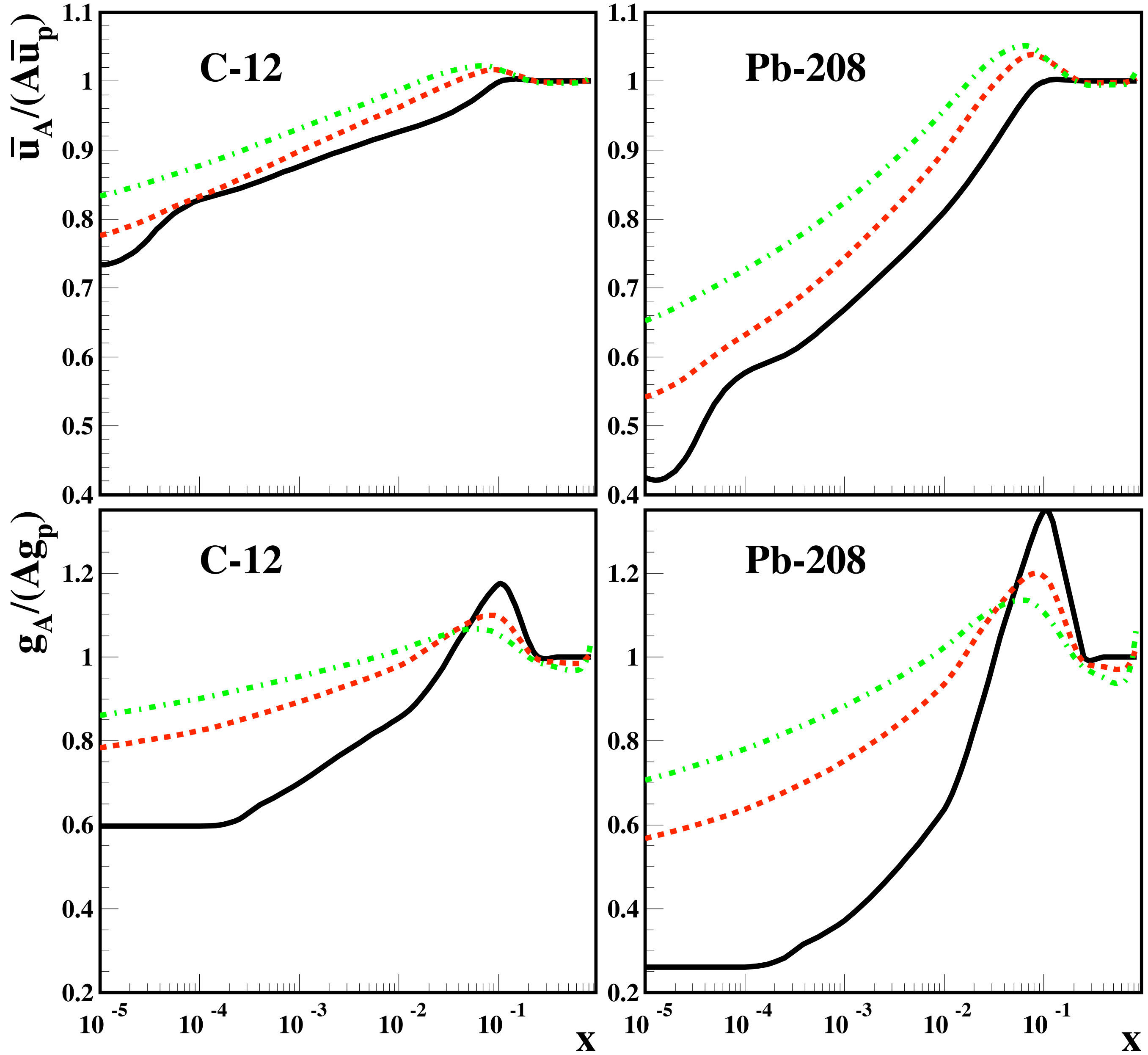
$\eta = ReA^{diff}/ImA^{diff} \approx 0.3,\ \rho_A(r)$ nuclear matter density.

$x_0(quarks) \sim 0.1,\ x_0(gluons) \sim 0.03$

Next step: use the HERA measurements of diffractive quark and gluon PDFs which indicate dominance of the gluon induced diffraction to calculate gluon and quark shadowing.

Detailed analysis in Guzey, FS & McDermott + further studies in Guzey et al 04. Numerical studies include higher order rescattering terms and HERA measurements of diffractive quark and gluon PDFs which indicate dominance of the gluon-induced diffraction to calculate gluon and quark shadowing.





Dependence of G_A/AG_N and $\bar{q}_A/A\bar{q}_N$ on x for Q=2 (solid), 10 (dashed), 100 GeV (dot-dashed) 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.

Large gluon shadowing at x~ 0.003 agrees semi quantitatively with dA RHIC data: PHENIX data on J/ψ production.

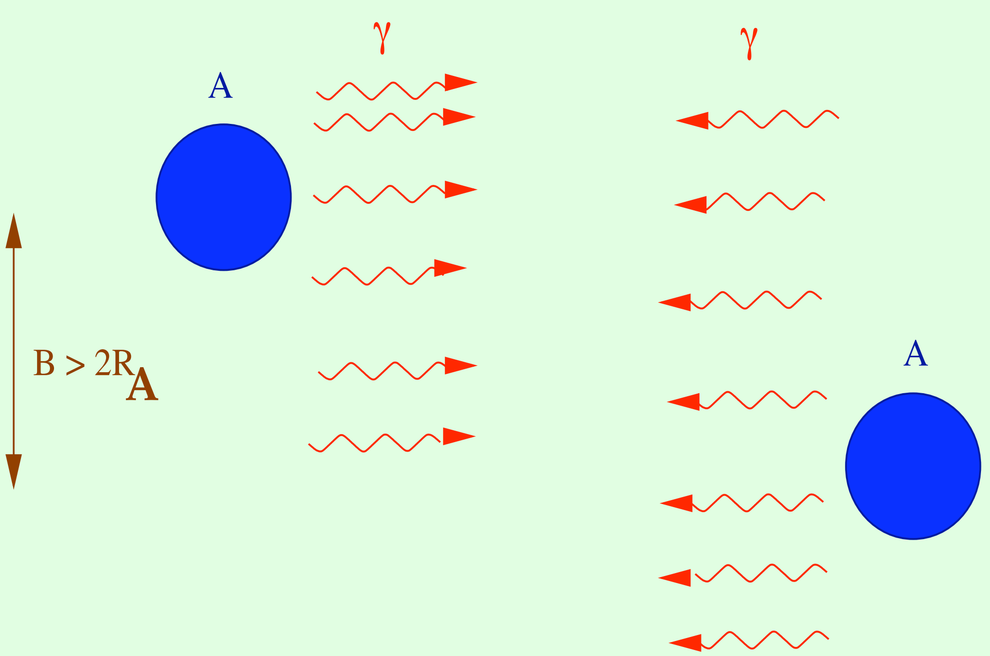
Inclusive small x dynamics

Decade from now: LHC ≥ five years of running including ion-ion, and nucleon - nucleus runs, further data from RHIC.

Main tool:

- Ultraperipheral ion-ion collisions : γ - A scattering up to W= 1 TeV

What is UPC? Collisions of nuclei (pA) at impact parameters $b \geq 2R_A$ where strong interaction between colliding particles is negligible

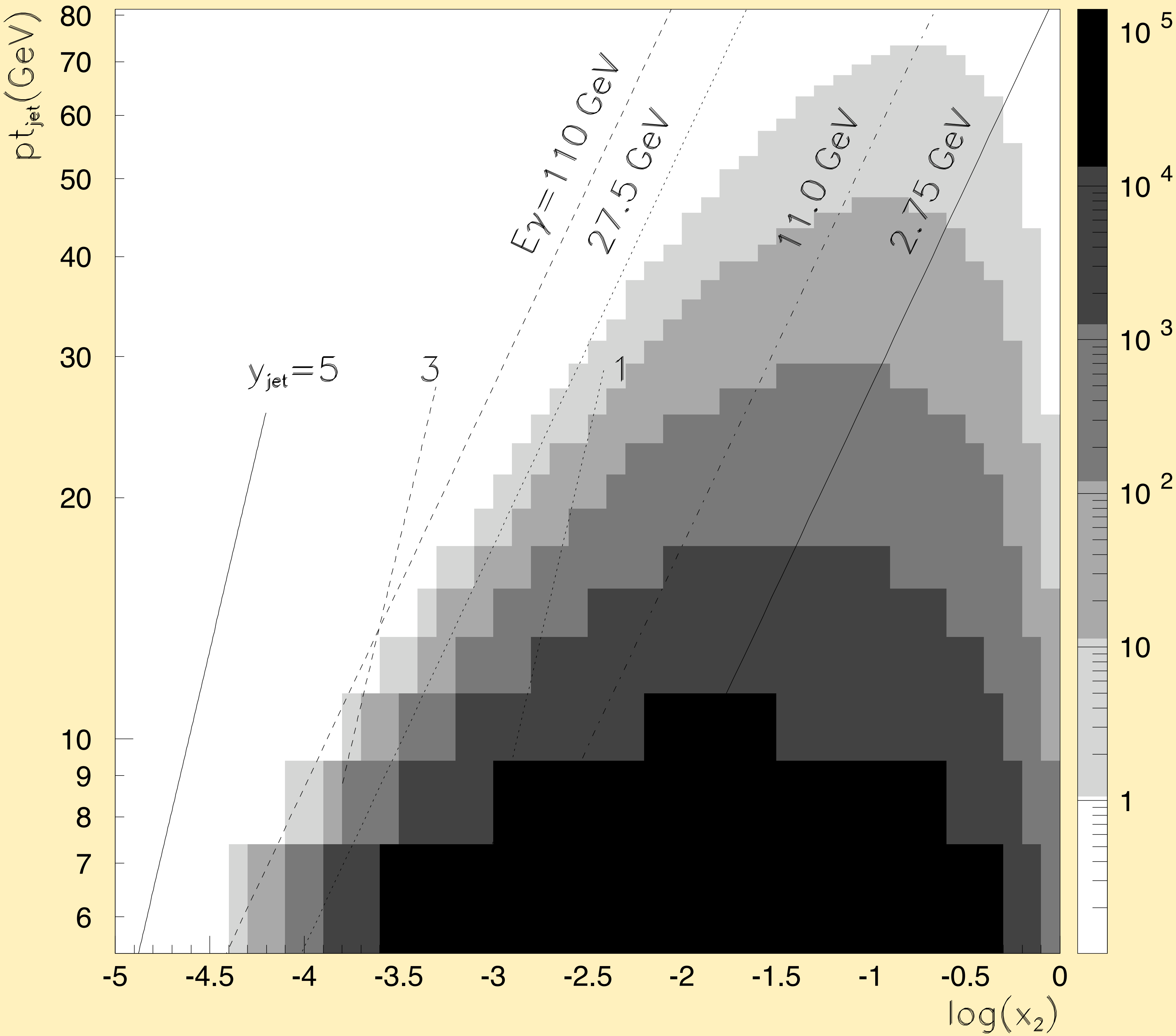


Ultraperipheral Nucleus–Nucleus Collision

- *Supplementary studies - using pA scattering.*

Will measure A-dependence of gluons in several reactions and quarks in a couple of processes for $10^{-2} \geq x \geq$ few 10^{-5}, Q≥ 5 GeV

HERA III at LHC



Expected rate of dijet photoproduction for a 1 month LHC Pb+Pb run at 0.4×10^{27} $cm^{-2}s^{-1}$. Rates are counts per bin of ± 0.25 x_2 and 2 GeV/c in p_T.

R.Vogt, S.White, MS

Can one make predictions for LHC without theory - just on the basis of the analysis of the current nuclear DIS data?

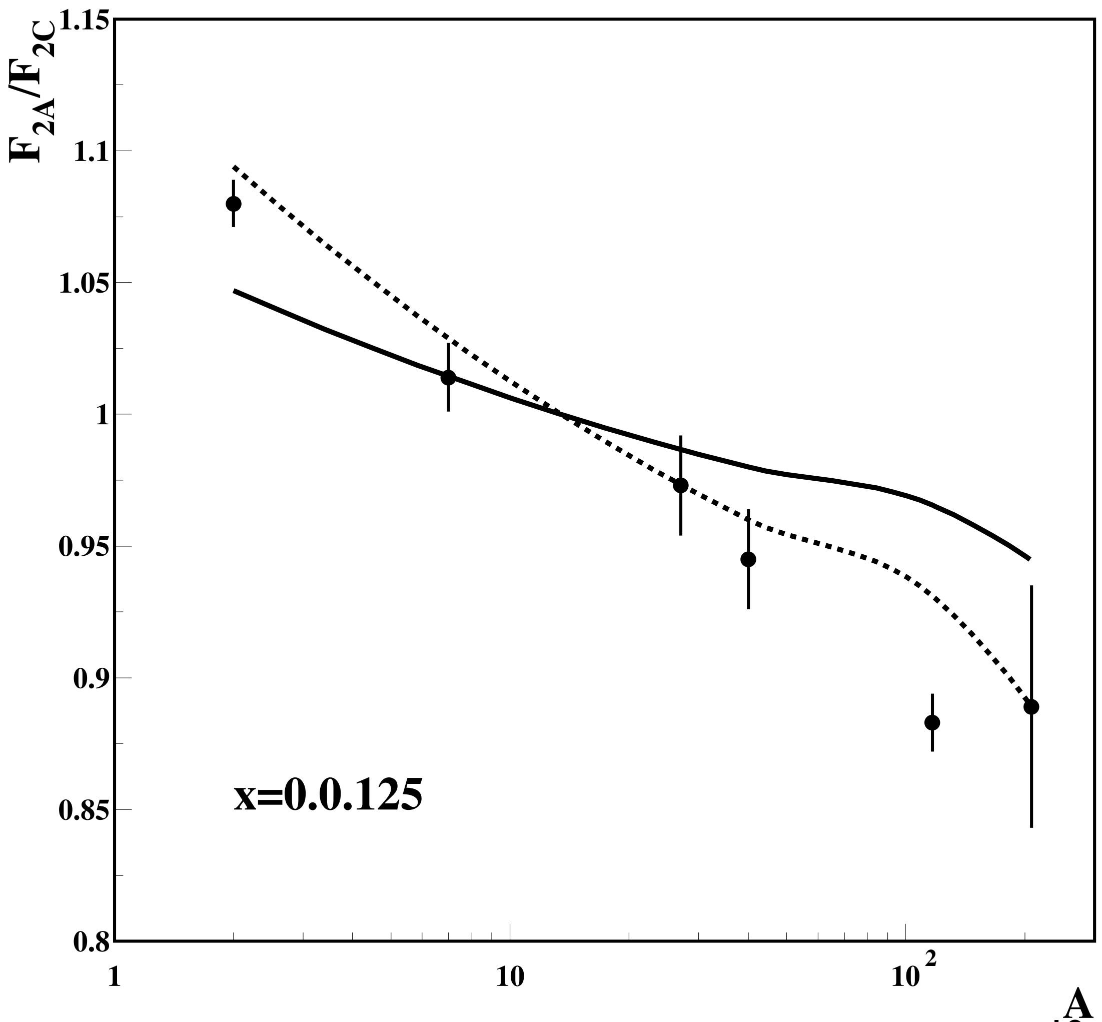
_NO !!!_

At small x where shadowing for γ^*A scattering data is significant higher twist (HT) effect appear to be important as Q^2 of the data are small (correlated with decrease of x).

Frankfurt, Guzey, MS: HT~50% ; Qiu, Vitev -HT up to 100%

in particular very large contribution of $\rho-$meson production which is definitely a higher twist (this contribution was first emphasized in context of the DIS data by Bodalek & Kwiczinski, Piller & Weise, Thomas & Melnitchouk.

The Gribov theory appears to work for low Q eA scattering where diffraction to the lightest mesons is important. In particular the A-dependence is reproduced without free parameters as only double scattering is important



A-dependence of nuclear shadowing. ***Test of the double scattering dominance.*** The NMC data on F_2^A/F_2^C are compared to our LT+VDM predictions (solid curve). The dashed curve is obtained by scaling up the shadowing correction of the solid curve by the factor two.

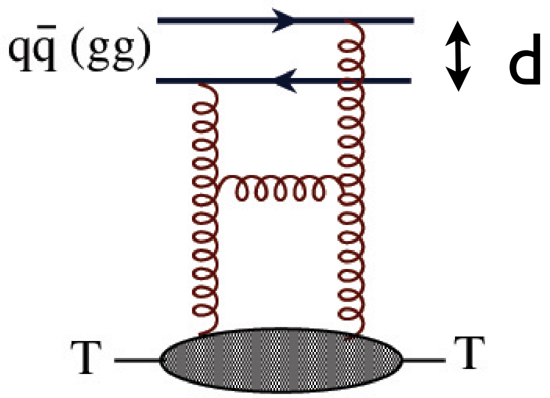
LT vs HT contributions in the NMC kinematics.

Recently we analyzed relative contributions of LT and HT for the kinematics of NMC. For x ~ 0.005 and $Q^2 = 2\ GeV^2$ about 40-50% of shadowing is due to the HT contribution, mostly due to enhancement of diffraction to low masses - the lightest vector mesons. (No local duality in this case if we trust the HERA LT fits to diffraction !!!). Thus HT is significant though it does not dominate like in the Qiu and Vitev fit, while EKS98, Kumano et al,... fits which assume dominance of the LT at such Q^2 appear to be an oversimplification.

One needs detailed measurements of the diffraction for x,Q range of NMC - COMPASS, HERMES?

High energy color transparency

One of the key features of QCD - interaction of small objects with hadrons is weak though rapidly increases with energy (color transparency)



$$\sigma_{inel} = \frac{\pi^2}{3} F^2 d^2 \alpha_s(\lambda/d^2) x G_T(x.\lambda/d^2)$$

F^2 Casimir operator of color SU(3) F^2 (quark) =4/3 F^2(gluon)=3

$\Longrightarrow$ Need to trigger on small size configurations at high energies.

Two ideas:

$\diamond$ Select special final states: diffraction of pion into two high transverse momentum jets - an analog of the positronium inelastic diffraction. Qualitatively - from the uncertainty relation $d \sim 1/p_t(jet)$

$\diamond$ $\diamond$ Select a small initial state - diffraction of longitudinally polarized virtual photon into mesons. Employs the decrease of the transverse separation between q and $\bar{q}$ in the wave function of γ^*_L, $d \propto 1/Q$.

Recently a number of two-body processes off nucleon, nucleus, γ... was discovered which can be **legitimately** *calculated in pQCD due to color screening/transparency for interaction of small color singlets:*

(new QCD factorization theorems)

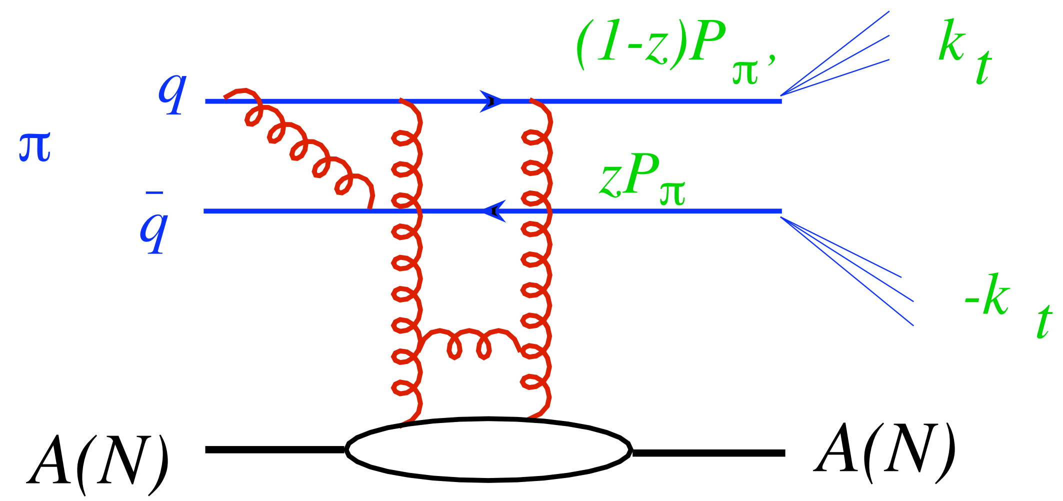
- π + T $\rightarrow$ 2 jets +T   Frankfurt, Miller, S. 93
- $\gamma_L^* N \rightarrow V(\rho, J/\Psi, \rho'..) + N$ Brodsky, Frankfurt, Gunion, Mueller, S., 94
- $\gamma_L^* N \rightarrow Meson(\pi, K, \eta,)\,[Few\ meson\ system] + Baryon$ Collins, FS 96
- $\gamma_L^* p \rightarrow forward\ \ N + \pi, \gamma_L^* p \rightarrow forward\ \ \Lambda + K^+$
  $\gamma_L^* p \rightarrow forward\ \ \bar{p} + NN$,   FS & Polyakov 98
- $\gamma^* + N \rightarrow \gamma + N$ Bartels &Loewe 82; Dittes, Muller, Robaschik, Geyer,Horejse 88; Ji 96-97, Radyushkin 96-98, Freund & FS 97, Freund & Collins 98
- $\gamma^* + \gamma \rightarrow \pi\pi$ M. Diehl, T. Gousset, B. Pire 98

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

Mechanism:

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

the first analysis for πp scattering Randa(80), nuclear effects - Bertsch, Brodsky, Goldhaber, Gunion (81), pQCD treatment: Frankfurt, Miller, MS (93)



$$A(\pi + N \rightarrow 2\ jets + N)(z, p_t, t = 0) \propto \int d^2 d\psi_\pi^{q\bar{q}}(z, d)\sigma_{\text{“}q\bar{q}\text{”}-N(A)}(d, s)\exp(ik_t \cdot d),$$

$d = r_t^q - r_t^{\bar{q}}$, $\psi_\pi^{q\bar{q}}(z, d) \propto z(1-z)_{d\rightarrow 0}$ is the light-cone $q\bar{q}$ pion wave function.

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

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

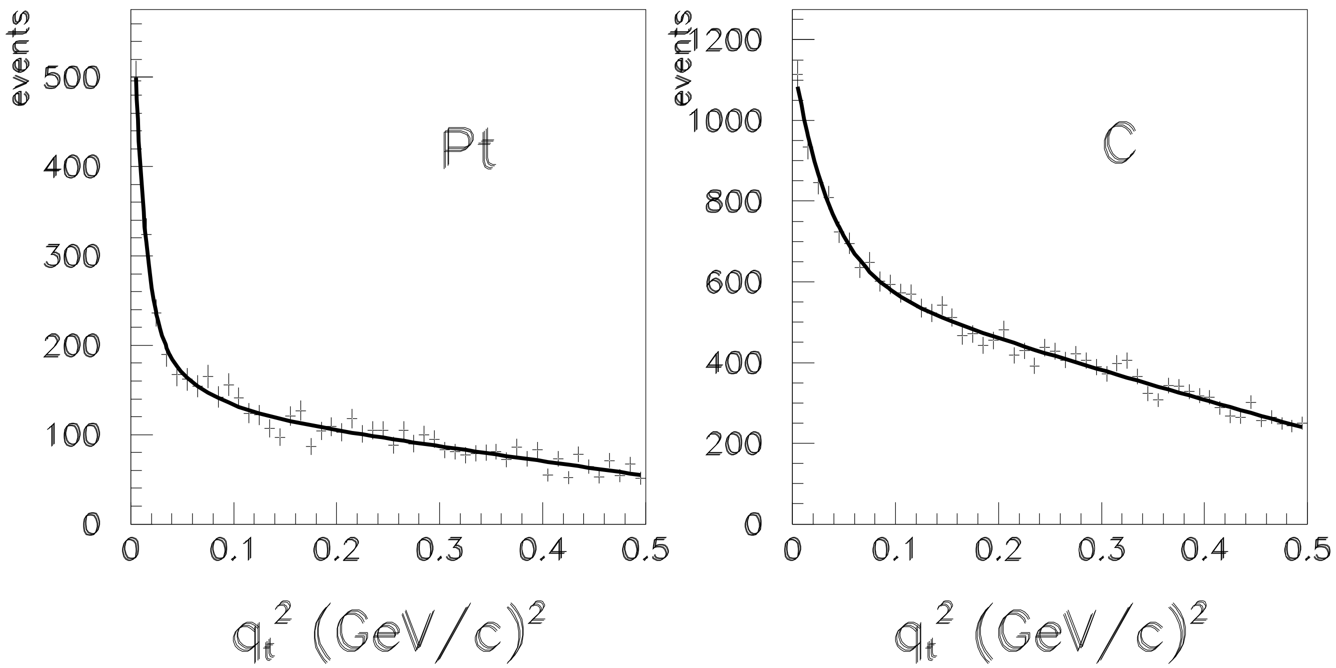
$\Longrightarrow$ k_t dependence: $\frac{d\sigma}{d^2k_t} \propto \frac{1}{k_t^n}, n \approx 8$ for $x \sim 0.02$

$\Longrightarrow$ Absolute cross section is also predicted

What is the naive expectation for the A-dependence of pion dissociation for heavy nuclei? Pion scatters off a black absorptive target. So at impact parameters $b < R_A$ interaction is purely inelastic, while at $b > R_A$ no interaction. Hence $\sigma_{inel} = \pi R_A^2$. How large is σ_{el}? Remember the Babinet's principle from electrodynamics: scattering off a screen and the complementary hole are equivalent. Hence $\sigma_{el} = \pi R_A^2$, while inelastic diffraction occurs only due to the scattering off the edge and hence $\propto A^{1/3}$

The E-791 (FNAL) data $E^{\pi}_{inc} = 500 GeV$ (D.Ashery et al, PRL 2000)

♡ Coherent peak is well resolved:



Number of events as a function of q_t^2, where $q_t = \Sigma_i p_t^i$ for the cut $\Sigma p_z \geq 0.9 p_\pi$.

♡♡ 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 Bertsch, Brodsky, Goldhaber, Gunion 81

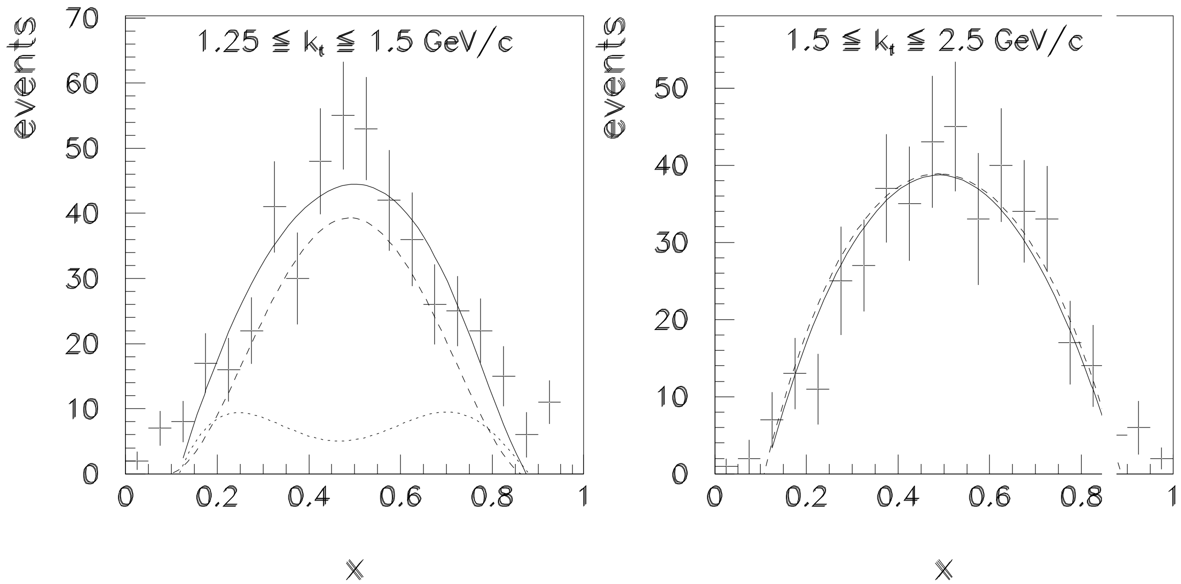
$\sigma(A) \propto A^{1/3}$)

In soft diffraction color fluctuations are also important leading to

$$\sigma_{soft\ diffr}(\pi + A \to X + A) \propto A^{.7}$$

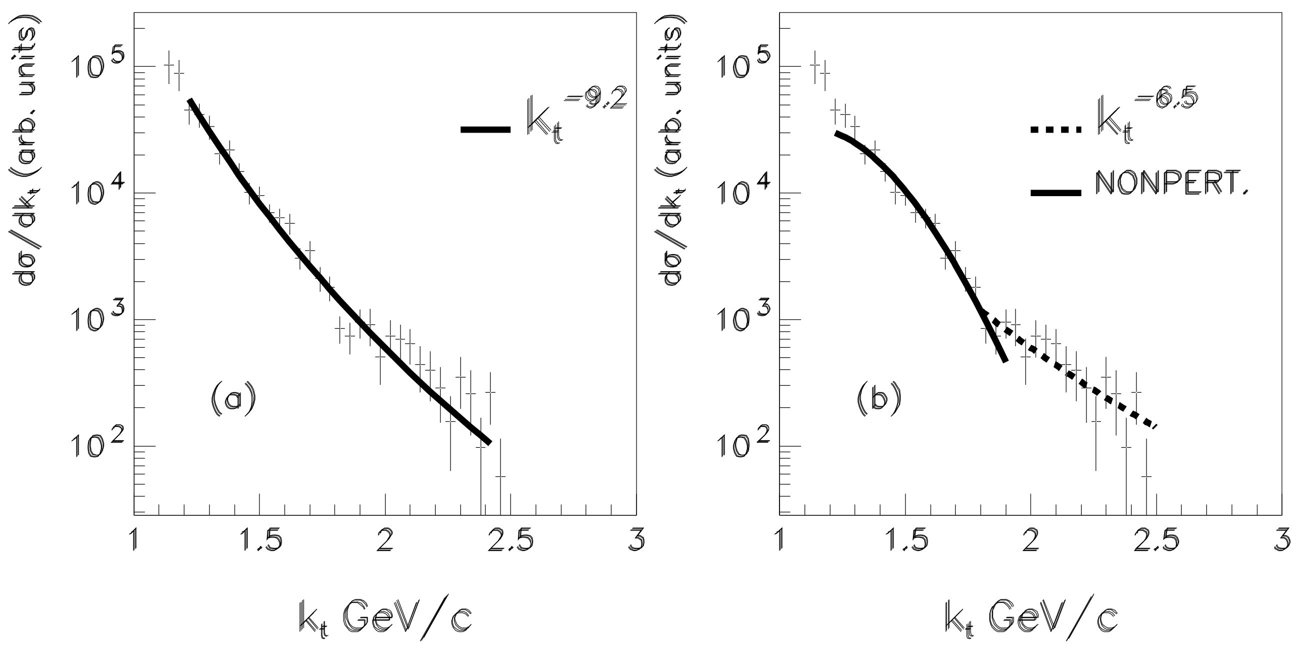
Miller Frankfurt &S, 93

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



Solid lines - fit: $\sigma(z) \propto \phi_\pi^2(z) \propto (1-z)^2 z^2$

♡♡♡♡ k_t^{-n} *dependence of* $d\sigma/dk_t^2 \propto 1/k_t^{7.5}$ *for* $k_t \geq 1.7 GeV/c$ *close to the QCD prediction -* $n \sim 8.0$ *for the kinematics of E971*

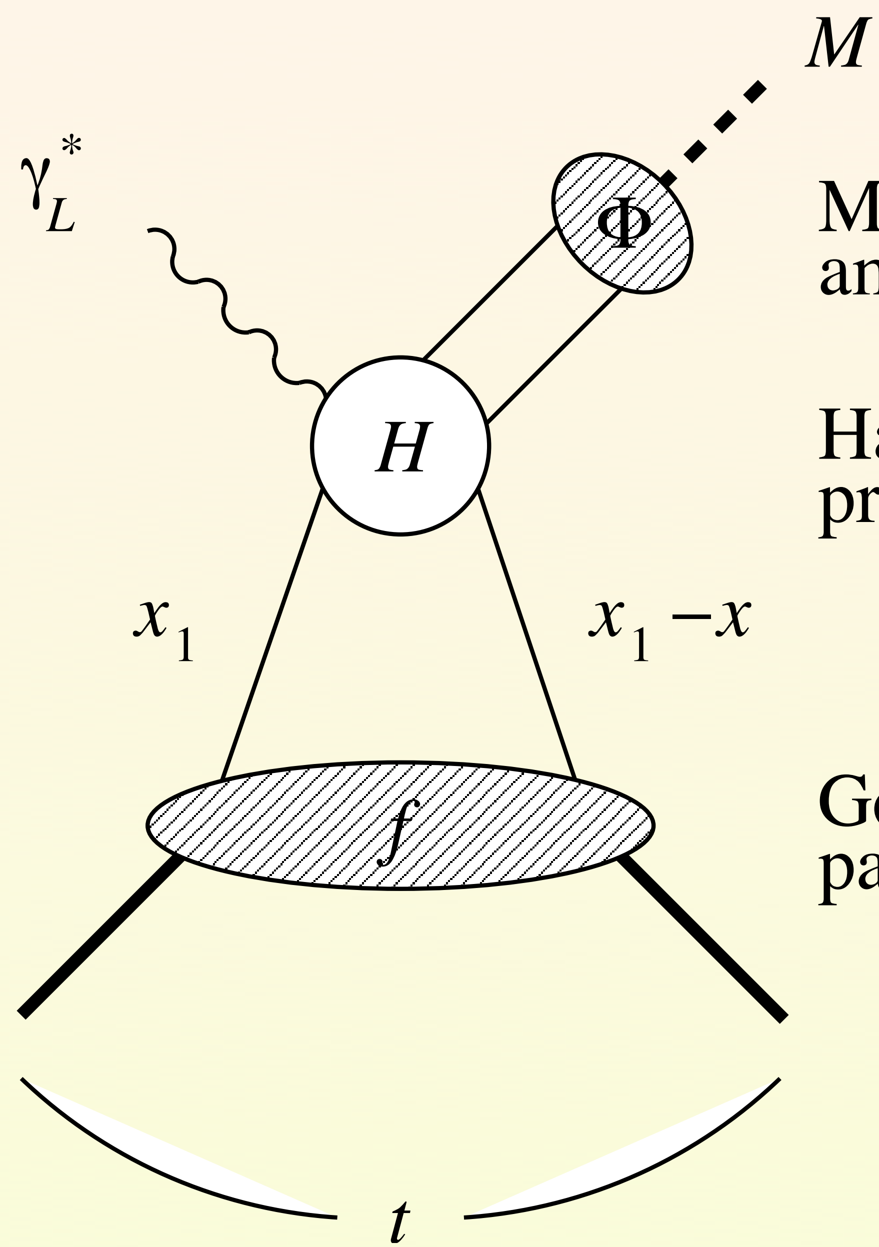


$\Longrightarrow$ • *High-energy color transparency is* **directly** *observed.*

• *The pion* $q\bar{q}$ *wave function is* **directly** *measured.*

QCD factorization theorem for DIS exclusive meson production

(Brodsky, Frankfurt, Gunion, Mueller, MS 94 - vector mesons, small x; general case Collins, Frankfurt, MS 97)



Meson distribution amplitude

Hard scattering process

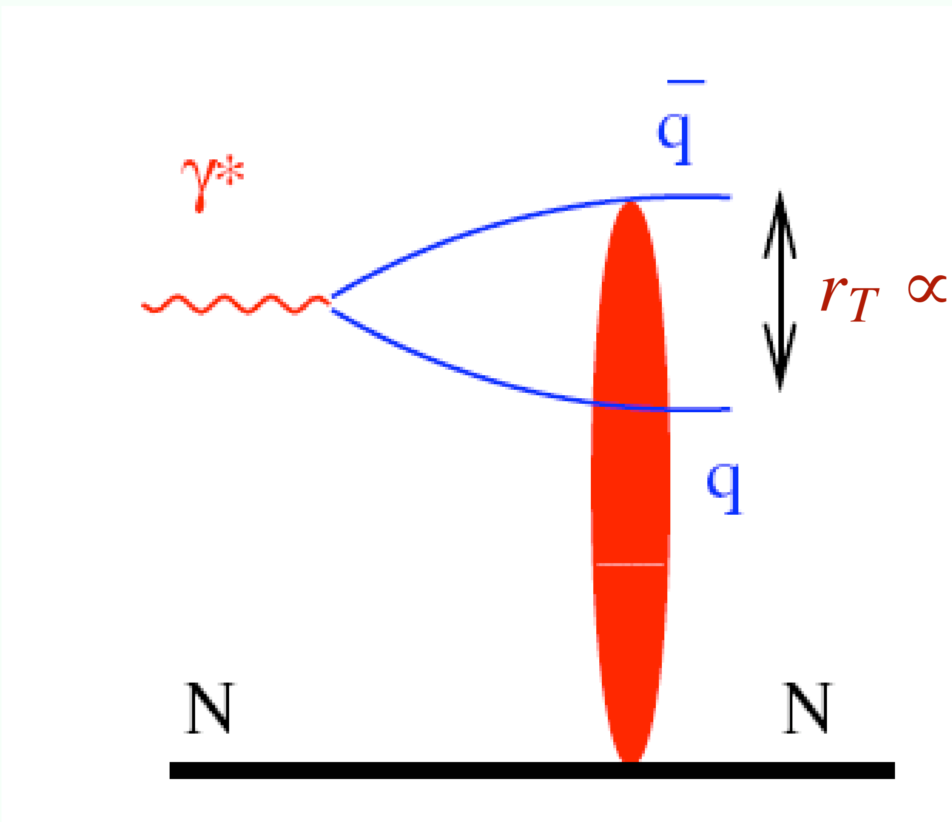
Generalized parton distribution

Extensive data on VM production from HERA support dominance of the pQCD dynamics. Numerical calculations including finite transverse size effects explain key elements of high Q^2 data. The most important ones are:

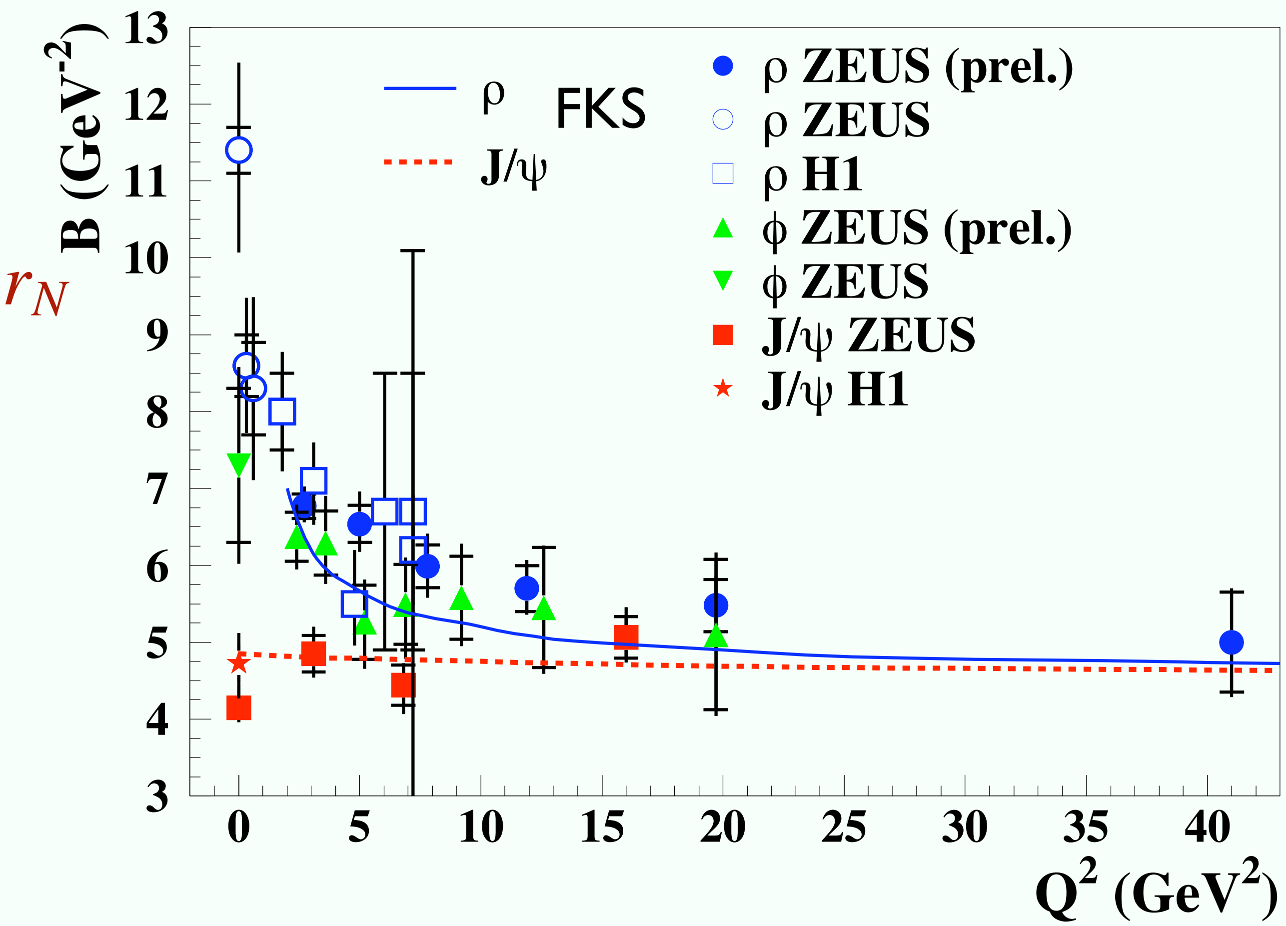
- Energy dependence of J/ψ production; absolute cross section of production $J/\psi, \Upsilon$

- Absolute cross section and energy dependence of $\rho-$meson production at $Q^2 \geq 20\ GeV^2$. Explanation of the data at lower Q^2 is more sensitive to the higher twist effects, and uncertainties of the low Q^2 gluon densities.

- Universal t-slope: process is dominated by the scattering of quark-antiquark pair in a small size configuration - t-dependence is predominantly due to the transverse spread of the gluons in the nucleon. Data agree with the predicted pattern of the onset of universal regime [Frankfurt,Koepf, MS] 97



$$r_T \propto \frac{1}{Q}(\frac{1}{m_c}) \ll r_N$$



Convergence of the t-slopes, B ($\frac{d\sigma}{dt} = A\exp(Bt)$, of ρ-meson electroproduction to the slope of J/ψ photo(electro)production.

⇒ Transverse distribution of gluons can be extracted from $\gamma + p \to J/\psi + N$

Factorization theorem for production of vector mesons in DIS limit (or photoproduction of heavy oniums):

$$\frac{\frac{d\sigma}{dt}(\gamma^* A \to MA)\big|_{t=0}}{\frac{d\sigma}{dt}(\gamma^* N \to MN)\big|_{t=0}} = \frac{G_A^2(x,Q)}{G_N^2(x,Q)}$$

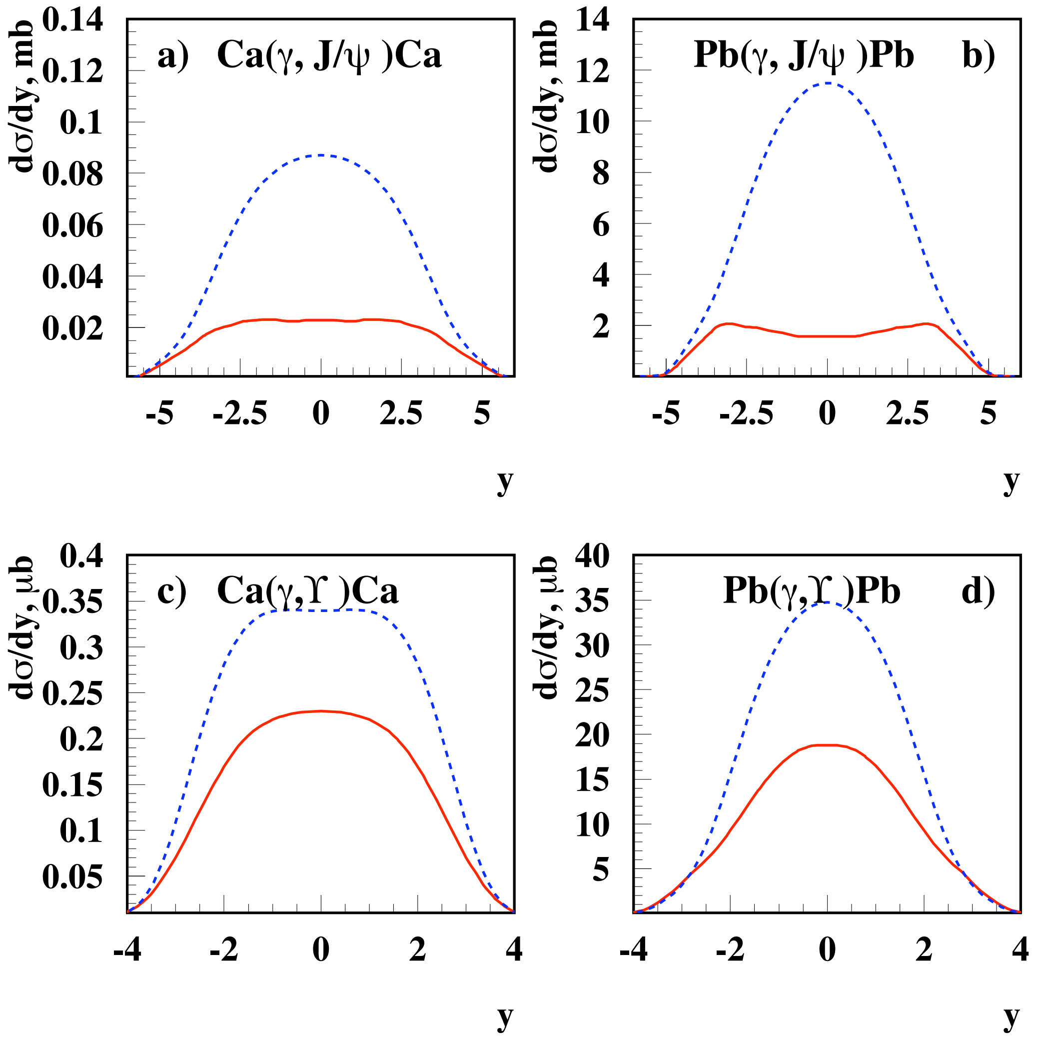
$\Longrightarrow$ ♣ **Color transparency** *for* $x \geq 0.02$

For J/ψ *at all* Q^2*; For* $\rho, \phi, \pi\pi, ...$ *at* $Q^2 \geq 5\ GeV^2$ *?.*

$\Longrightarrow$ ♣ **Perturbative color opacity for** $x < 0.01$ **due to leading twist gluon shadowing (to be studied at EIC and ultraperipheral collisions at LHC)**

At very small x - complete opacity - black disk limit: amplitude at t=0, $\propto A^{2/3}$

☛ *Onset of perturbative color opacity at small x and onium coherent photoproduction.*



The rapidity distributions for the J/ψ and Υ coherent production off Ca and Pb in UPC at LHC calculated with the leading twist shadowing based on H1 parameterization of gluon density(solid line) and in the Impulse Approximation(dashed line).

Conclusions

- Deep connection between leading twist nuclear shadowing and hard inclusive diffraction at HERA allow reliable predictions for LHC for $x \leq 10^{-3}$, without using rather ambiguous information from the data analysis at much higher x and low Q.

- Prediction of high energy color transparency is directly confirmed in $\pi \to 2$ jets process and it forms the basis of the theory of exclusive hard DIS processes. Challenge - to observe CT at intermediate energies - need a better treatment of expansion effects and a number of nuclear phenomena like quenching, generalized eikonal approximation with isobars.

Studies of UPC at LHC will address many (though not all) of the benchmark issues of HERA III proposal including

★ *Small x physics with protons and nuclei in* a factor of ten *larger energy range though at higher virtualities both in inclusive and diffractive channels*

★ Interaction of small dipoles at ultrahigh energies - J/ψ, γ production at W up to 1 TeV - approach to regime of black body limit, color opacity

★ Low Q will be missed - will require studies at eRHIC