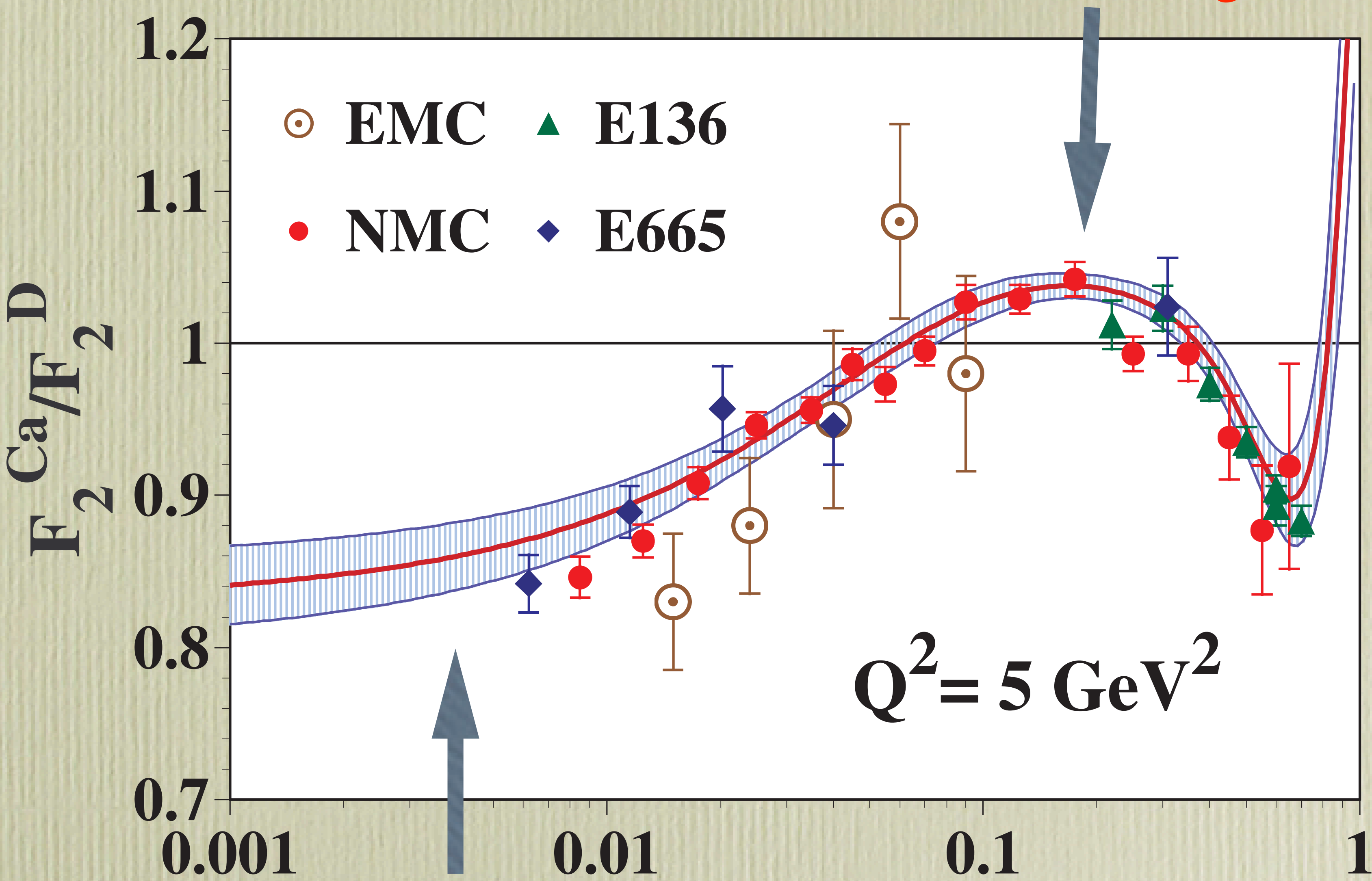
Nuclear Shadowing and Anti-Shadowing in QCD

- Relation to Diffractive DIS and Final-State Interactions
- Novel Color Effects
- Non-Universality of Antishadowing
- Implications for NuTeV

I. Schmidt, J. J. Yang, and SJB "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D **70**, 116003 (2004) [arXiv:hep-ph/0409279].

H. J. Lu and SJB "Shadowing And Antishadowing Of Nuclear Structure Functions," Phys. Rev. Lett. **64**, 1342 (1990).

Anti-Shadowing



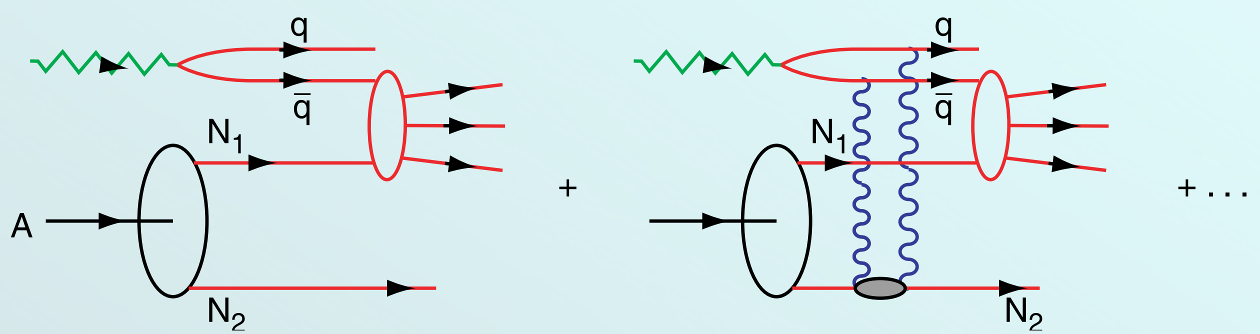
Shadowing

x

M. Hirai, S. Kumano and T. H. Nagai,
"Nuclear parton distribution functions
and their uncertainties,"
Phys. Rev. C **70**, 044905 (2004)
[arXiv:hep-ph/0404093].

Anti-Shadowing

Origin of Nuclear Shadowing in Glauber - Gribov Theory



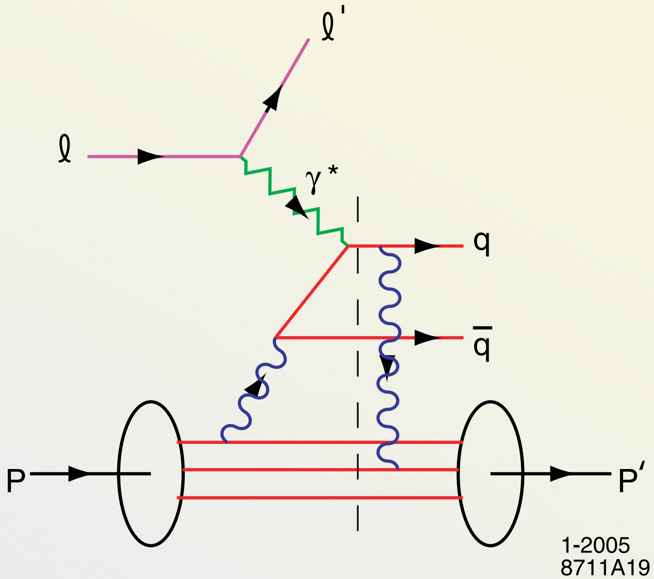
Interference of one-step and two-step processes

Interaction on upstream nucleon diffractive

Phase i X i = - 1 produces destructive interference

No Flux reaches down stream nucleon

Anti-Shadowing



Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate
Pomeron

Need Imaginary Phase to Generate
T-Odd Single-Spin Asymmetry

Physics of FSI not in Wavefunction of Target

Shadowing and Antishadowing in Lepton-Nucleus Scattering

- Shadowing and Antishadowing in DIS arise from interference of multi-nucleon processes in nucleus

Phases!

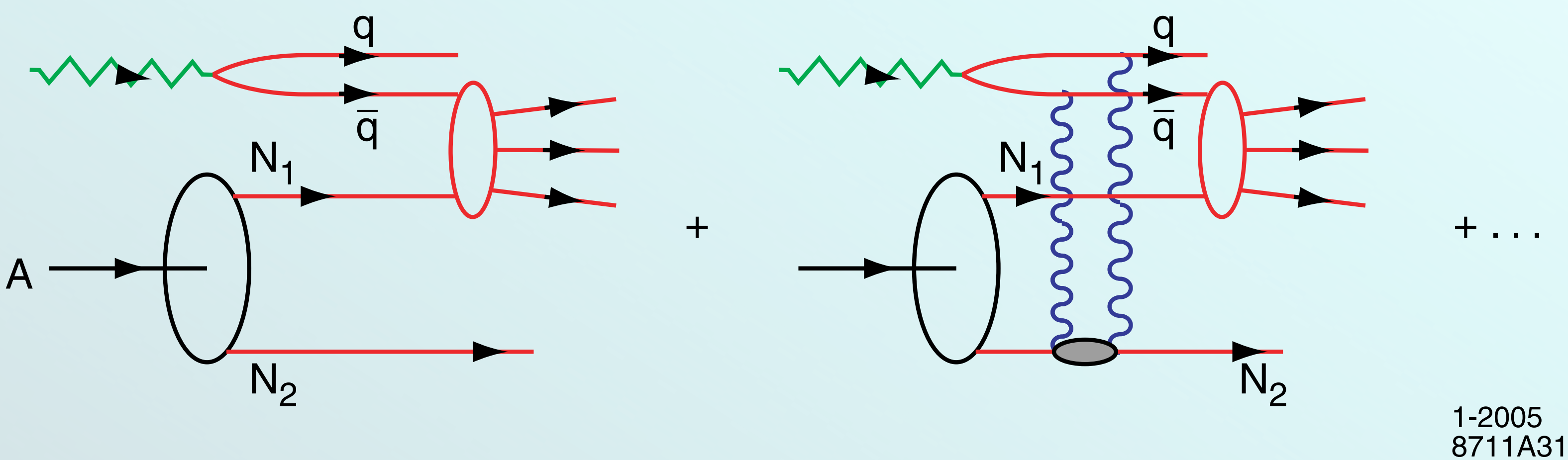
- Not due to nuclear wavefunction

Wavefunction of stable nucleus is real.
Effect of multi-scattering of $q\overline{q}$ in nucleus.

- Bjorken Scaling :

Interference requires leading-twist diffractive DIS processes

Nuclear Shadowing in QCD



Nuclear Shadowing not included in nuclear LFWF !

Anti-Shadowing

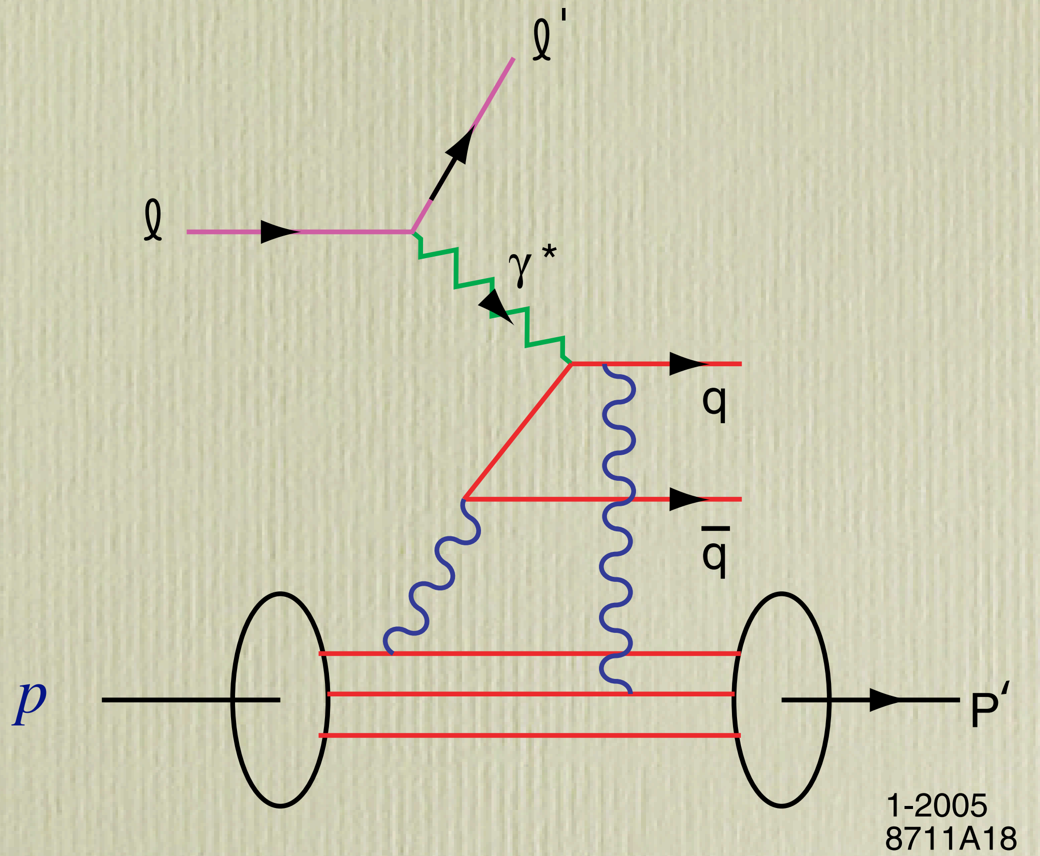
Shadowing and Antishadowing in Lepton-Nucleus Scattering

- Shadowing: Destructive Interference
of Two-Step and One-Step Processes
Pomeron Exchange

- Antishadowing: Constructive Interference
of Two-Step and One-Step Processes!
Reggeon and Odderon Exchange

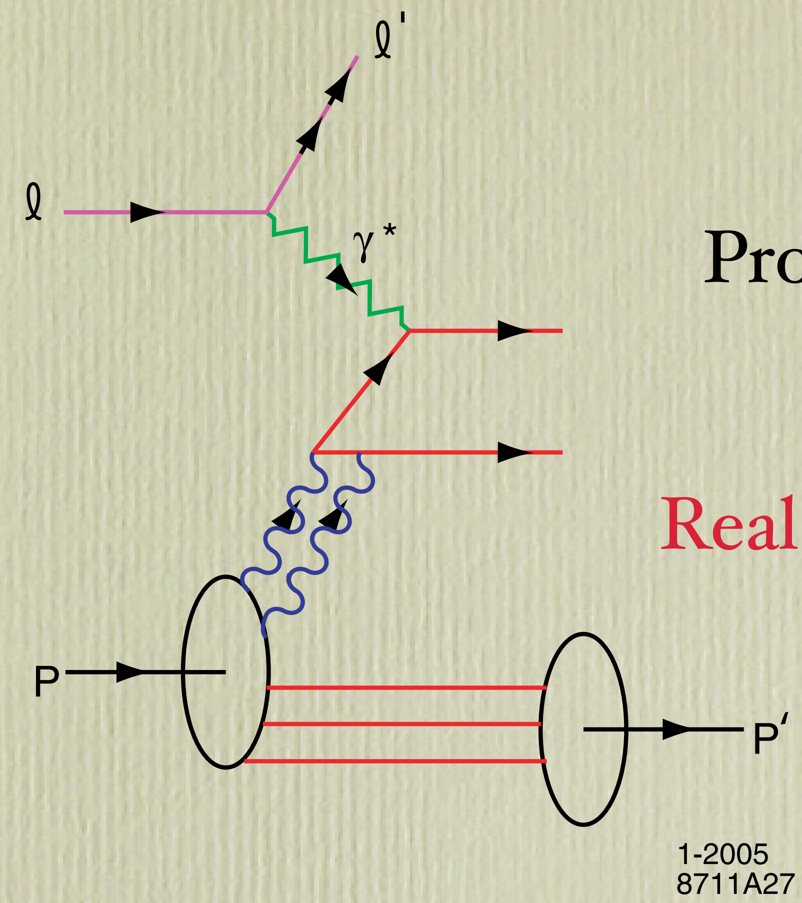
- Antishadowing is Not Universal!
Electromagnetic and weak currents:
different nuclear effects !
Potentially significant for NuTeV Anomaly}

Final State Interaction Produces Diffractive DIS



Anti-Shadowing

Problem: Wrong Phase



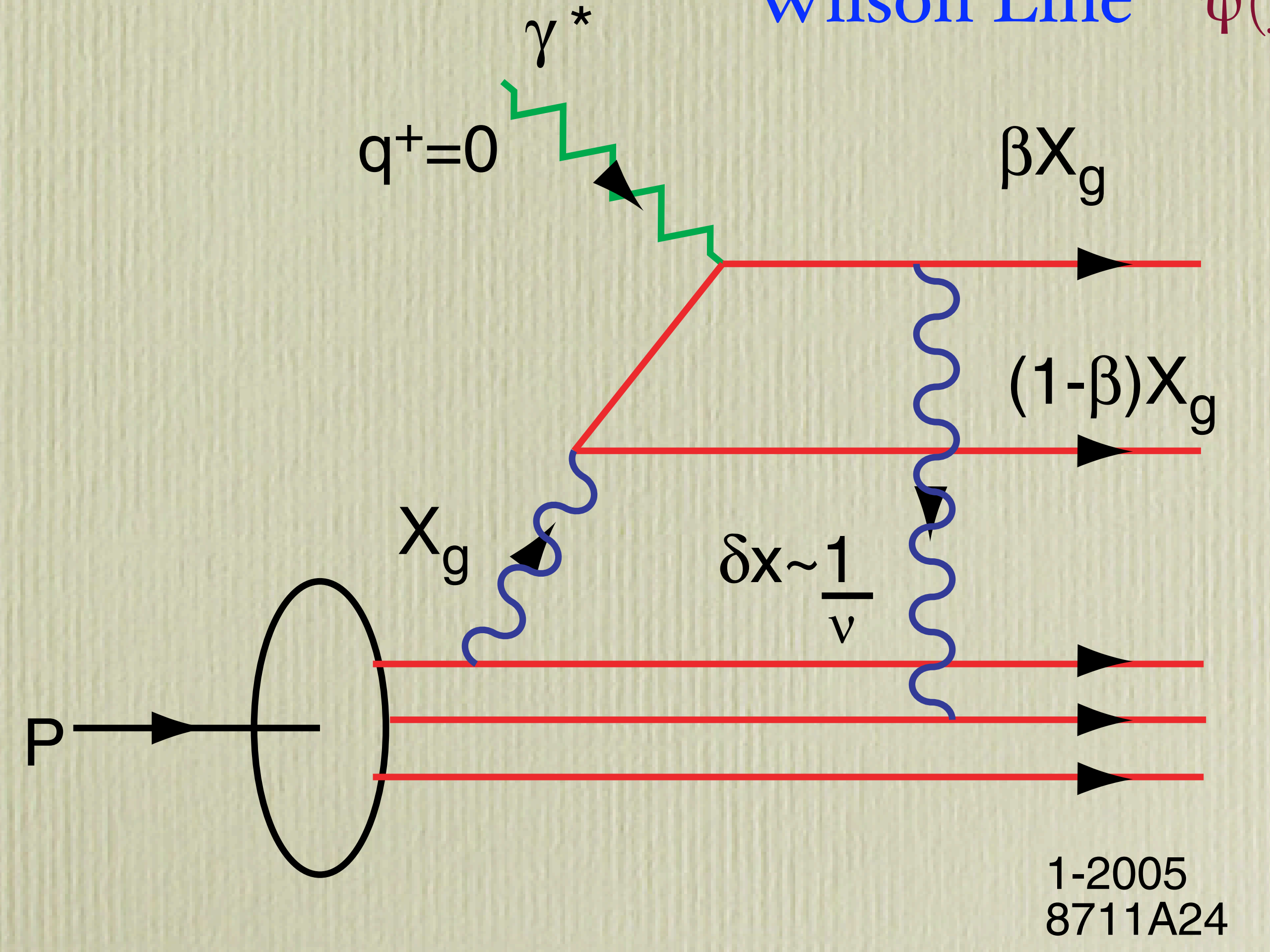
Pomeron acts as constituent of proton

Real; should be imaginary

Need Final State Interactions !

QCD Mechanism for Rapidity Gaps

Wilson Line $\overline{\psi}(y)\int_0^y dx\, e^{iA(x)\cdot dx}\,\psi(0)$



Anti-Shadowing

QCD factorization

- QCD factorization theorem: Separation of hard and soft

  The quark PDF is given by

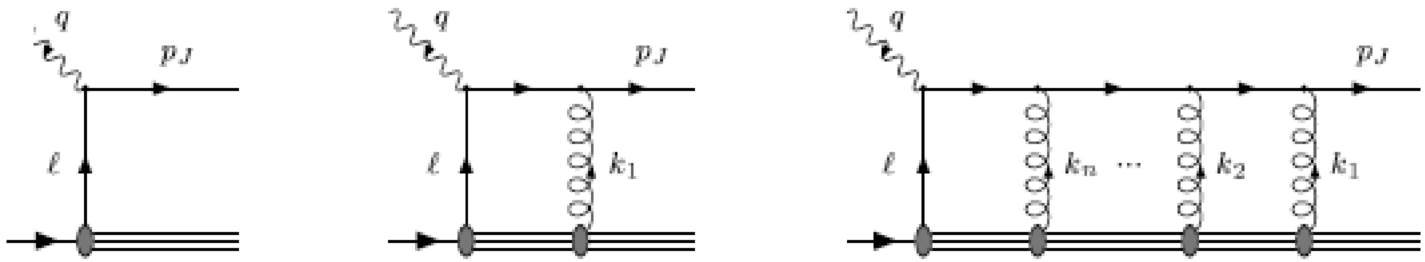
$$f_{q/N} \sim \int dx^- e^{-ix_B p^+ x^-/2} \langle N(p) \,|\, \bar{\psi}(x^-)\gamma^+ W[x^-;0]\,\psi(0)\,|\, N(p)\,\rangle_{x^+=0}$$

Wilson line: $W[x^-;0] = \mathrm{P}\exp\left[ig\int_0^{x^-} dw^- A_a^+(0,w^-,0_\perp)t_a\right]$

- DIS: $W[x^-;0] \to$ *rescattering of struck quark* on target
- $A^+ \to$ longitudinal *instantaneous* (in x^+) gluon exch.
- No $A^\perp$ within Ioffe coherence length $x^- \sim 1/m_p x_B$

$$\overline{\psi}(y) \int_0^y dx\, e^{iA(x)\cdot dx}\, \psi(0)$$

Wilson line means that DIS looks something like this:



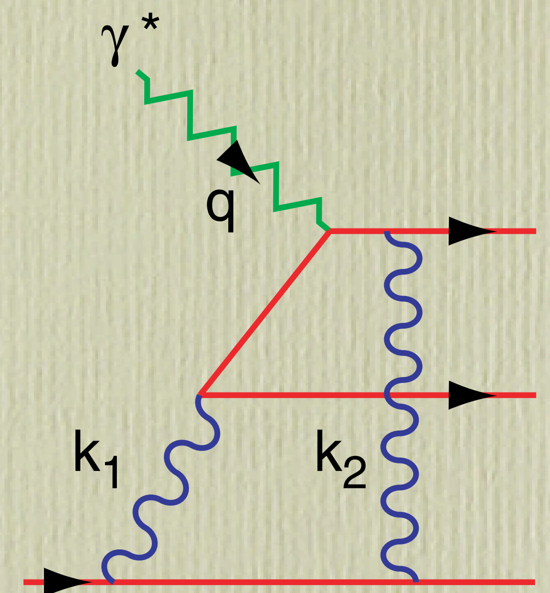
Brodsky, Hoyer, Marchal, Peigné and Sannino (BHMPS) showed that [Phys. Rev. D65 (2002) 114025]

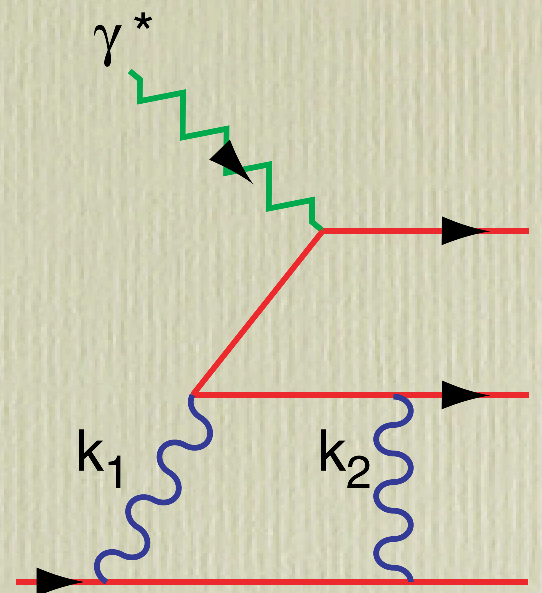
- rescattering can lead to on-shell intermediate states and *imaginary amplitudes* and cannot be ignored in any gauge
- not even in $A^+ = 0$ gauge!

It has also been shown to yield nuclear shadowing and single spin asymmetries.

Enberg

Final State Interactions in QCD



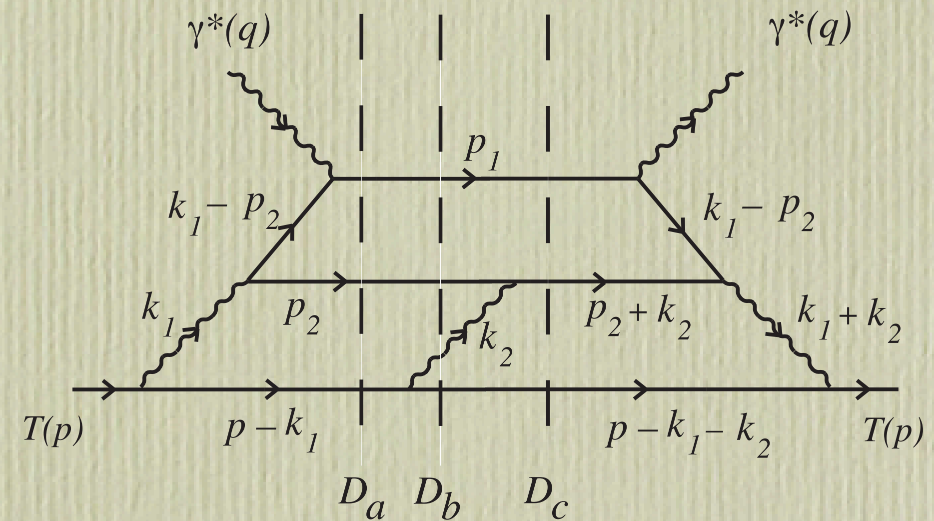


Feynman Gauge   Light-Cone Gauge

Result is Gauge Independent

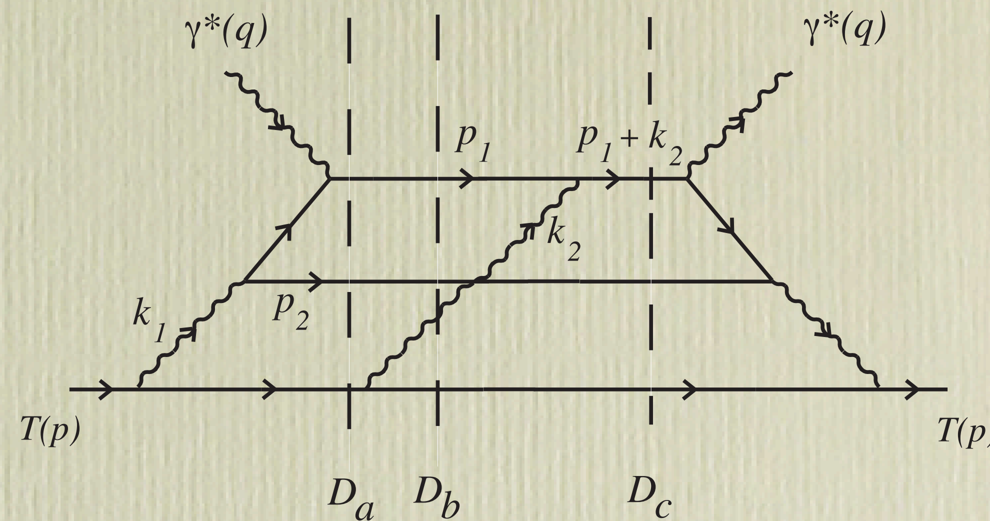
Anti-Shadowing

Final State Interactions Non-Zero in QCD



(a)

Light-Cone Gauge

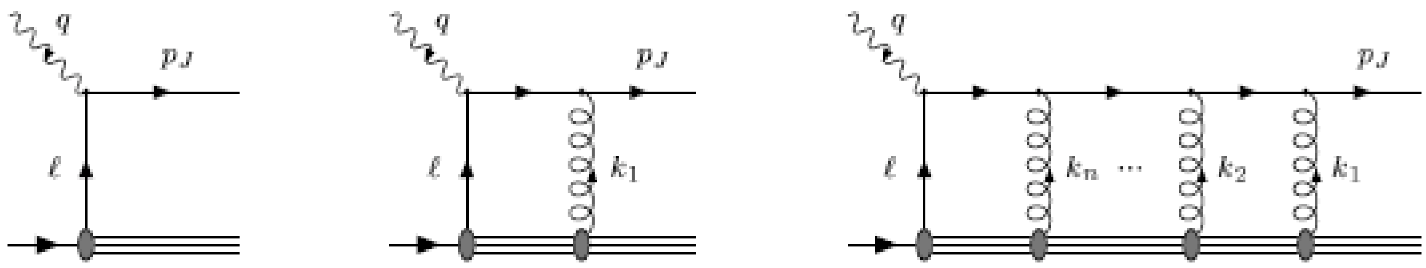


(b)

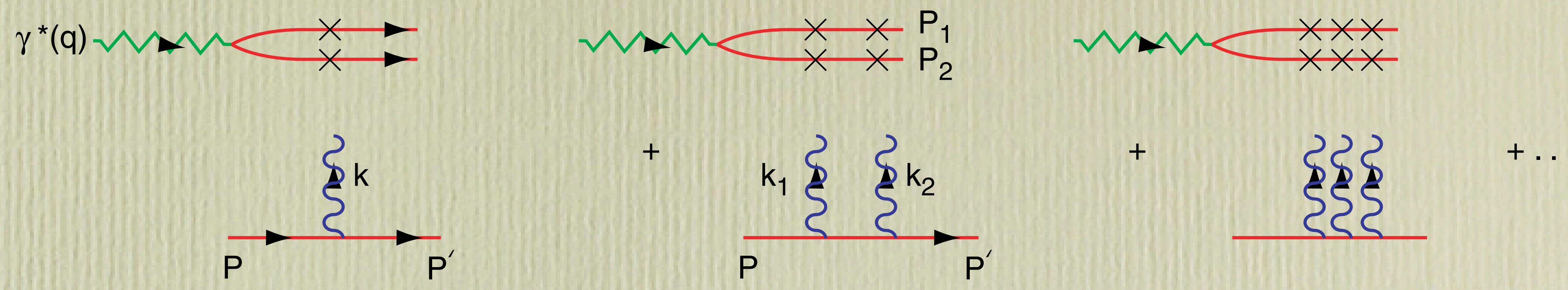
Feynman Gauge

Anti-Shadowing

Rescattering and factorization

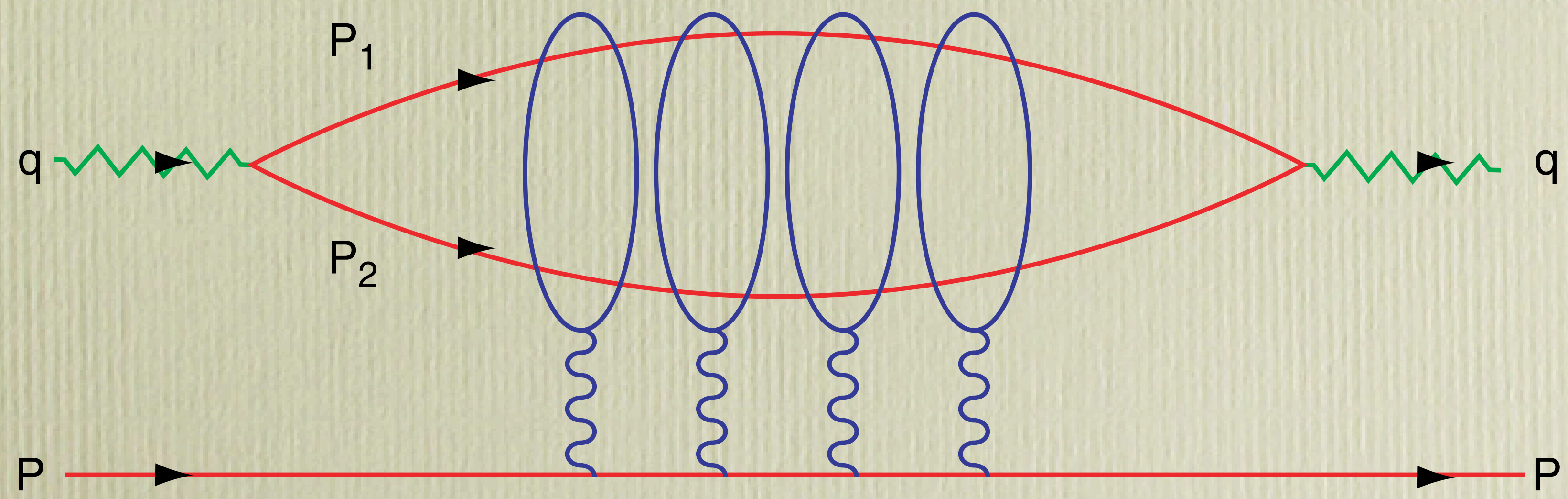


- Important to realize that the rescattering is compatible with factorization theorems *by construction*
  - the Wilson line is a part of the definition of the PDF, so the rescattering is also a part of the PDF
- When one measures the PDF in experiments, one measures the PDF *including* rescattering
- In a similar way, the diffractive PDFs are included in the inclusive PDFs



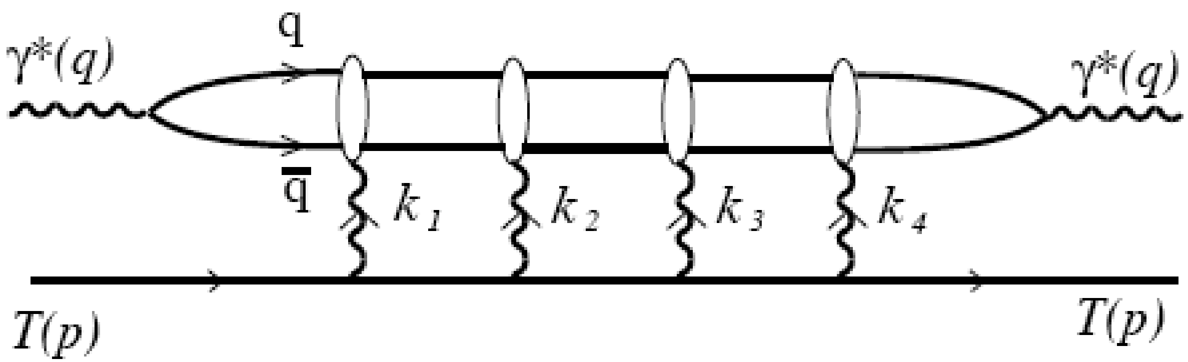
Sum Eikonal Interactions

Similar to Color Dipole Model



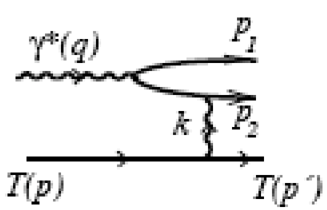
Rescattering toy model

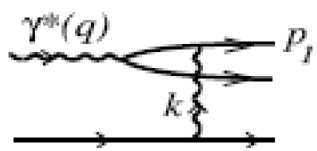
BHMPS: Toy model — scalar abelian gauge theory:



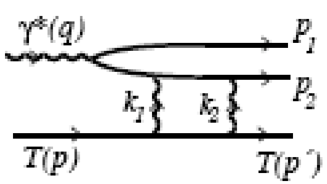
$x_B \to 0$: on-shell intermediate states $\to$ imag. 2-gluon ampl.

as required for pomeron from crossing symmetry





$$\propto g^2 K_0(m r_\perp) \log\left(\frac{|\boldsymbol{R}_\perp + \boldsymbol{r}_\perp|}{|\boldsymbol{R}_\perp|}\right)$$



$$\propto i g^4 K_0(m r_\perp) \left[\log\left(\frac{|\boldsymbol{R}_\perp + \boldsymbol{r}_\perp|}{|\boldsymbol{R}_\perp|}\right)\right]^2$$

Rescattering factorizes in coordinate space!

$$Q^4 \frac{d\sigma}{dQ^2\, dx_B} = \frac{\alpha_{\rm em}}{16\pi^2} \frac{1-y}{y^2} \frac{1}{2M\nu} \int \frac{dp_2^-}{p_2^-} d^2\vec{r}_T\, d^2\vec{R}_T\, |\tilde{M}|^2$$

where

$$|\tilde{M}(p_2^-, \vec{r}_T, \vec{R}_T)| = \left| \frac{\sin\left[g^2\, W(\vec{r}_T, \vec{R}_T)/2\right]}{g^2\, W(\vec{r}_T, \vec{R}_T)/2} \tilde{A}(p_2^-, \vec{r}_T, \vec{R}_T) \right|$$

is the resummed result. The Born amplitude is

$$\tilde{A}(p_2^-, \vec{r}_T, \vec{R}_T) = 2eg^2 MQp_2^-\, V(m_{||} r_T) W(\vec{r}_T, \vec{R}_T)$$

where $m_{||}^2 = p_2^- M x_B + m^2$ and

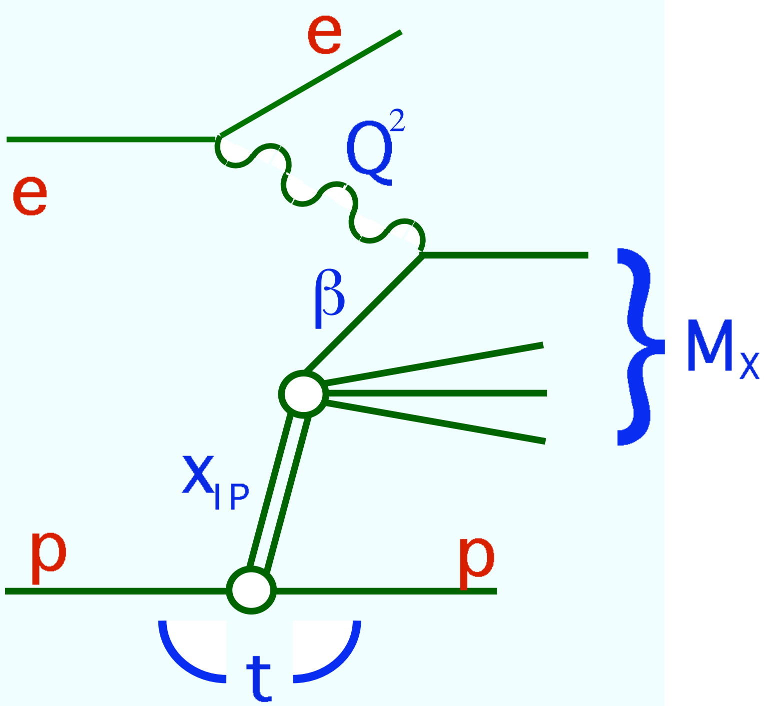
$$V(m\, r_T) \equiv \int \frac{d^2\vec{p}_T}{(2\pi)^2} \frac{e^{i\vec{r}_T\cdot\vec{p}_T}}{p_T^2 + m^2} = \frac{1}{2\pi} K_0(m\, r_T).$$

The rescattering effect of the dipole of the $q\bar{q}$ is controlled by

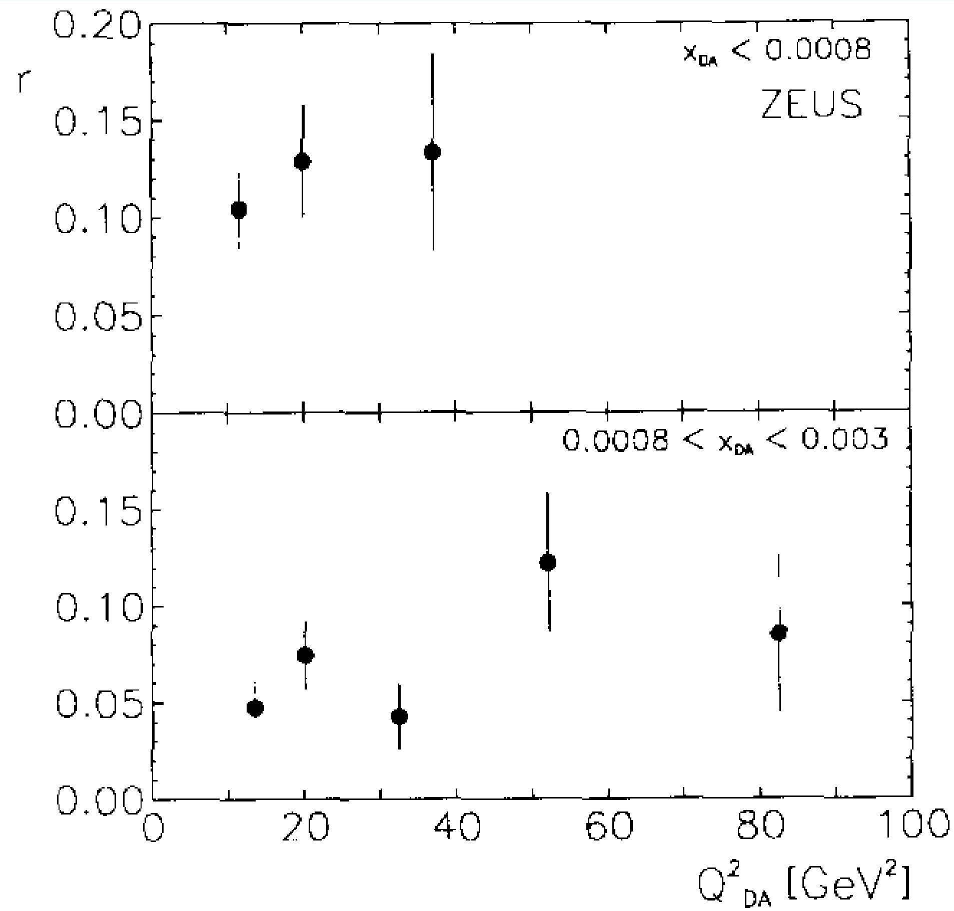
$$W(\vec{r}_T, \vec{R}_T) \equiv \int \frac{d^2\vec{k}_T}{(2\pi)^2} \frac{1 - e^{i\vec{r}_T\cdot\vec{k}_T}}{k_T^2} e^{i\vec{R}_T\cdot\vec{k}_T} = \frac{1}{2\pi} \log\left(\frac{|\vec{R}_T + \vec{r}_T|}{R_T}\right).$$

Precursor of Nuclear Shadowing

Anti-Shadowing



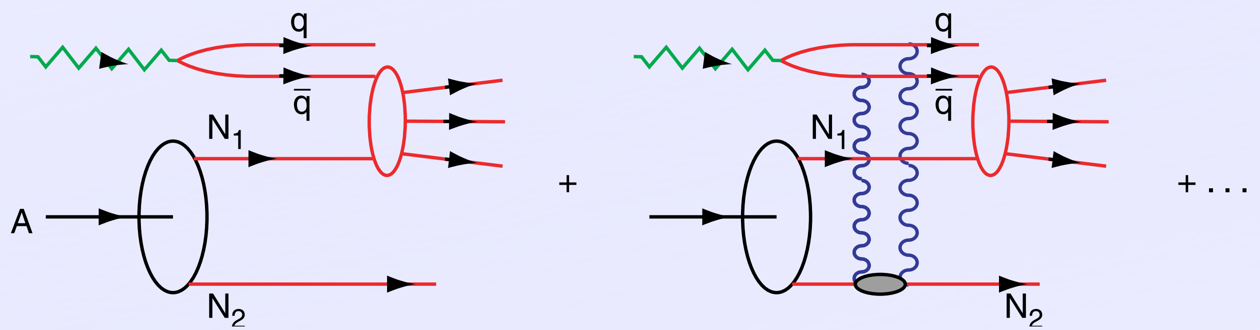
10% of DIS events are diffractive !



Fraction r of events with a large rapidity gap, $\eta_{\max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

M. Derrick et al. [ZEUS Collaboration], Phys. Lett. B 315, 481 (1993).

Origin of Nuclear Shadowing in Glauber - Gribov Theory



Interference of one-step and two-step processes

Interaction on upstream nucleon diffractive

Phase i X i = - 1 produces destructive interference

No Flux reaches down stream nucleon

Anti-Shadowing

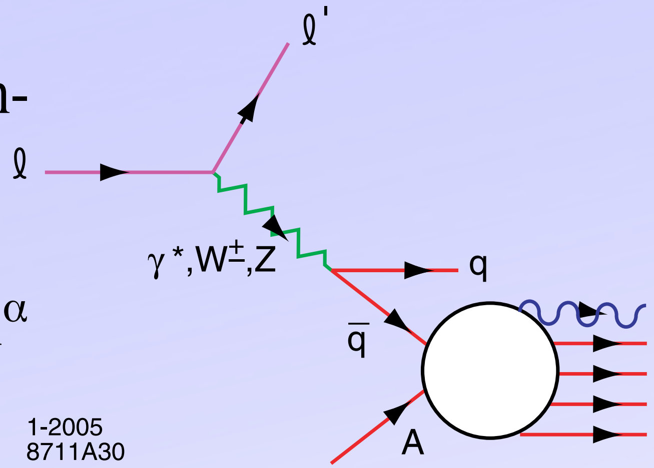
Origin of Nuclear Shadowing and Regge Behavior of Deep Inelastic Structure Functions

in light-cone gauge

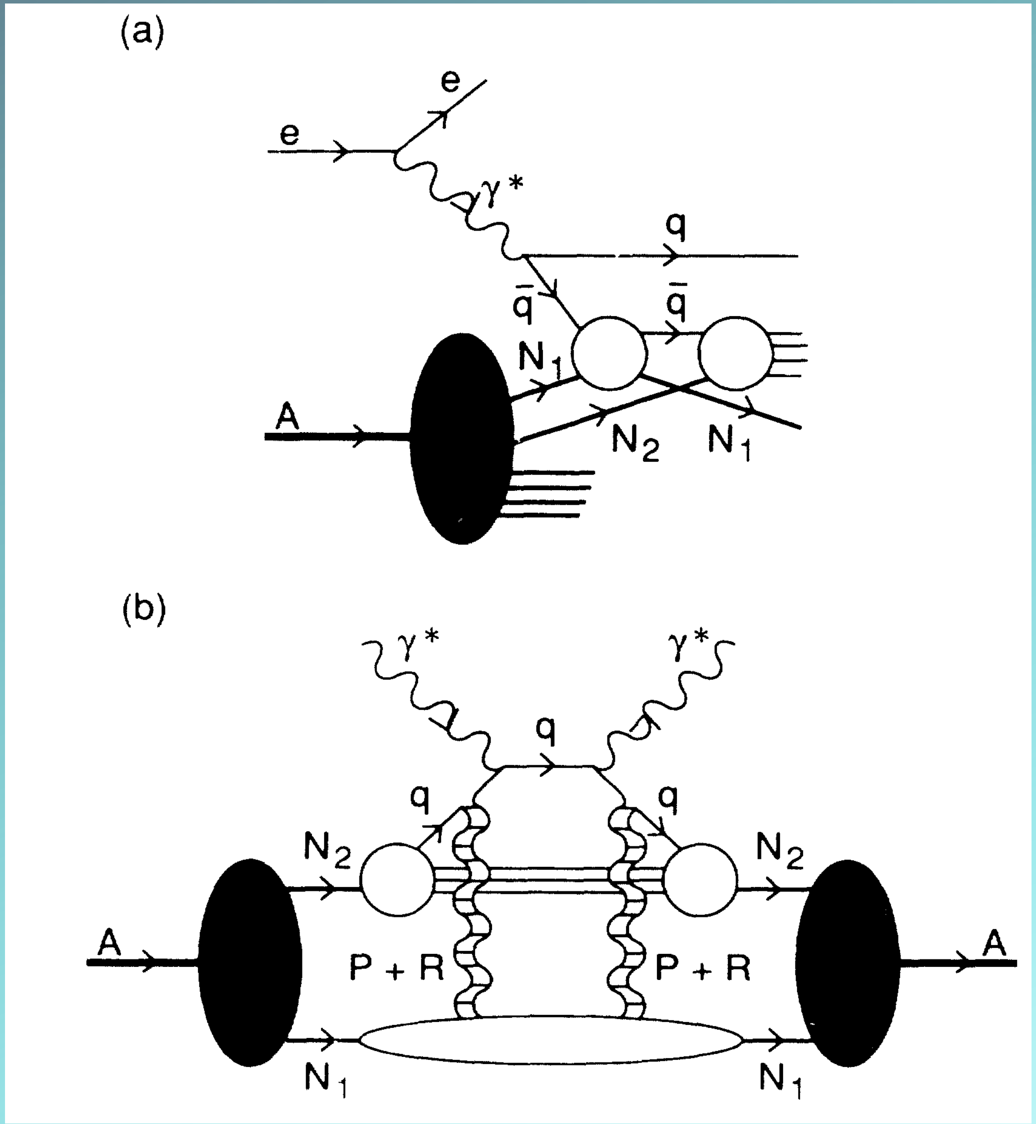
Antiquark Interacts with Target Nucleus at Effective Energy $\hat{s} \propto 1/x_{Bj}$

$\sigma_{\bar{q}N} \sim \hat{s}^{\alpha_R - 1} \rightarrow F_{2N}(x_{bj}) \sim x^{1-\alpha_R}$ at small x_{bj}

Shadowing of antiquark-nucleus cross section $\sigma_{\bar{q}A} \sim A^{\alpha}$ produces same A depenence of nuclear structure function

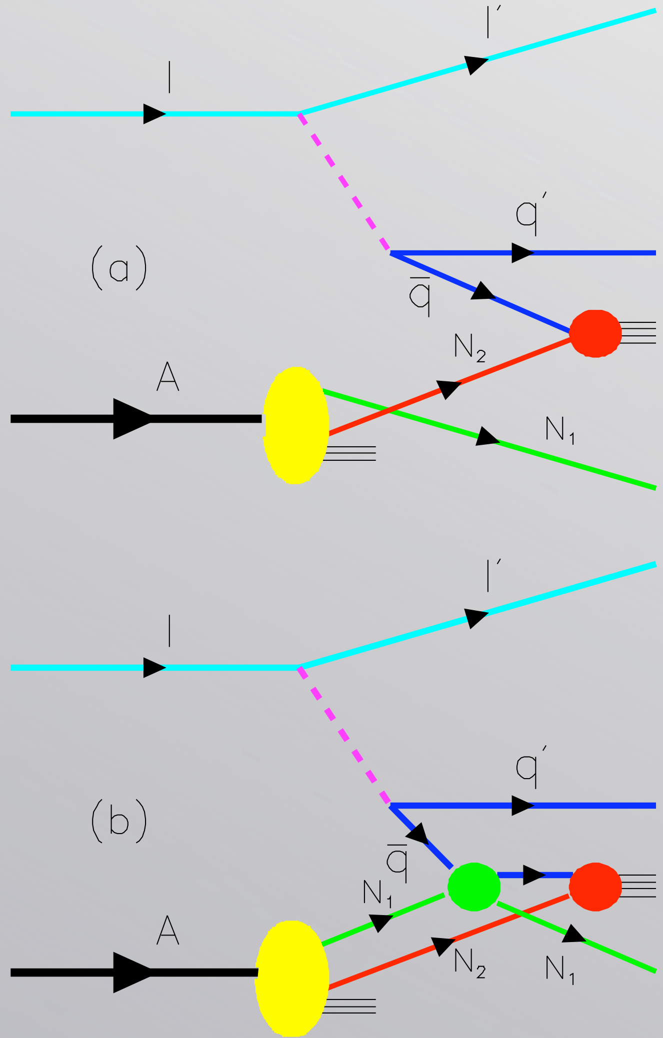


Anti-Shadowing



Pomeron and Reggeon Exchange

Anti-Shadowing

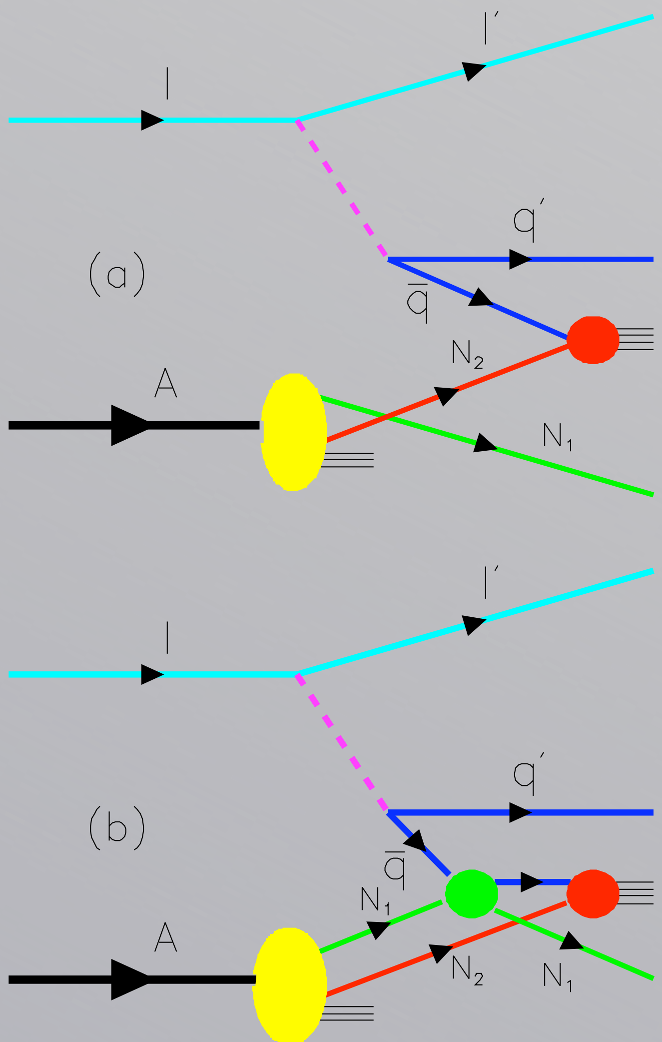


The one-step and two-step processes in DIS on a nucleus.

Coherence at small Bjorken x_B :
$1/Mx_B = 2\nu/Q^2 \geq L_A$.

If the scattering on nucleon N_1 is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\overline{q}$ flux reaching N_2.

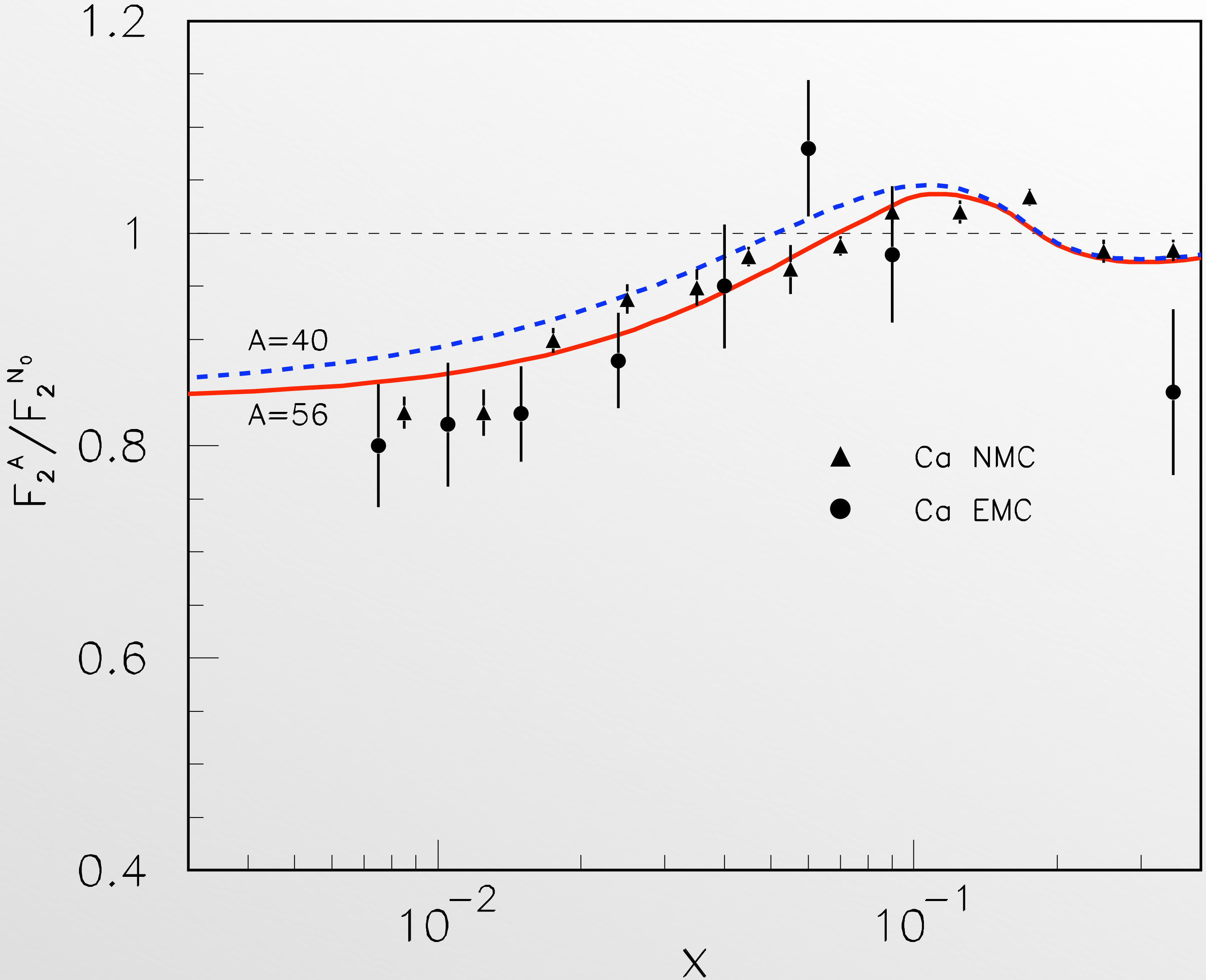
$\rightarrow$ Shadowing of the DIS nuclear structure functions.



The one-step and two-step processes in DIS on a nucleus.

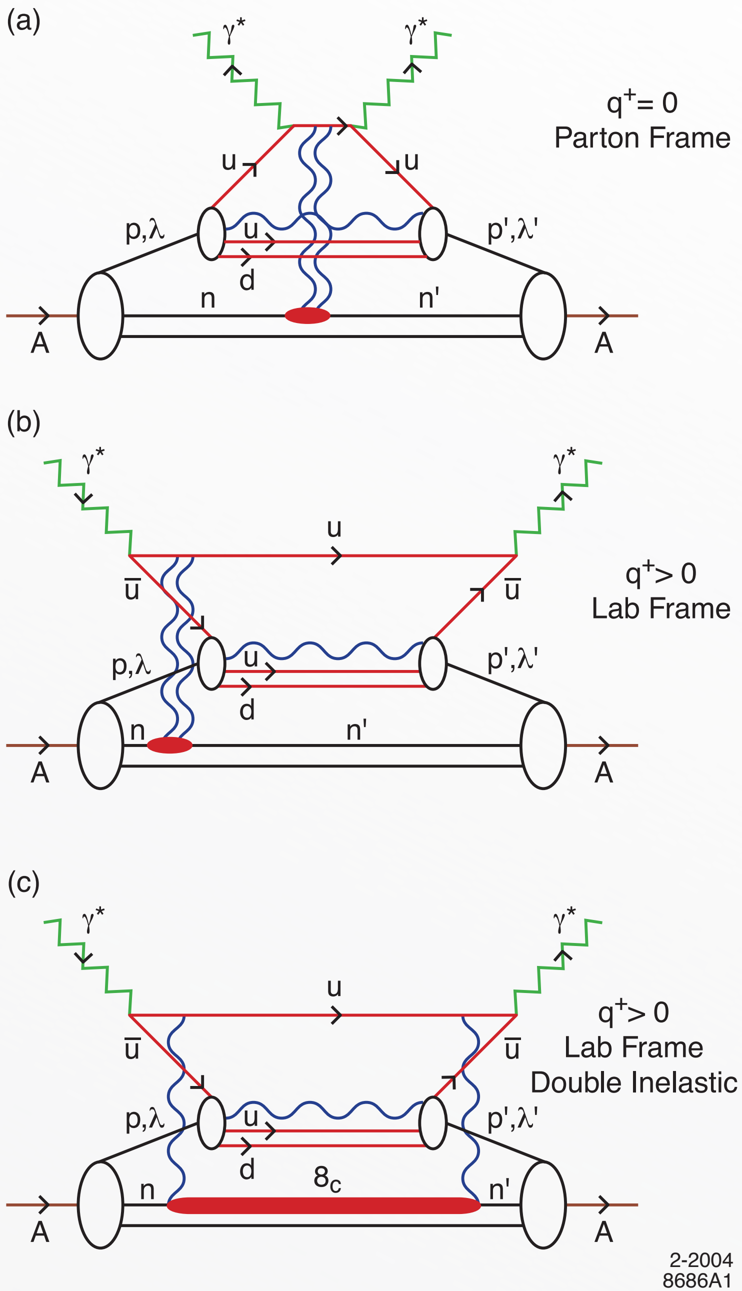
If the scattering on nucleon N_1 is via $C = -$ Reggeon or Odderon exchange, the one-step and two-step amplitudes are opposite in phase, enhancing the $\bar{q}$ flux reaching N_2

$\rightarrow$ Antishadowing of the DIS nuclear structure functions



I. Schmidt, J. J. Yang, and SJB
[arXiv:hep-ph/0409279]

Anti-Shadowing



Parton model frame ($q^+ \leq 0$) :
Two-gluon exchange

Color-dipole model frame ($q^+ > 0$)
Two-gluon exchange

Color-dipole model frame ($q^+ > 0$)
Double-inelastic contribution

Anti-Shadowing

Phases of Reggeon exchange amplitudes determined from analyticity and crossing behavior: $C = +$ signature factor

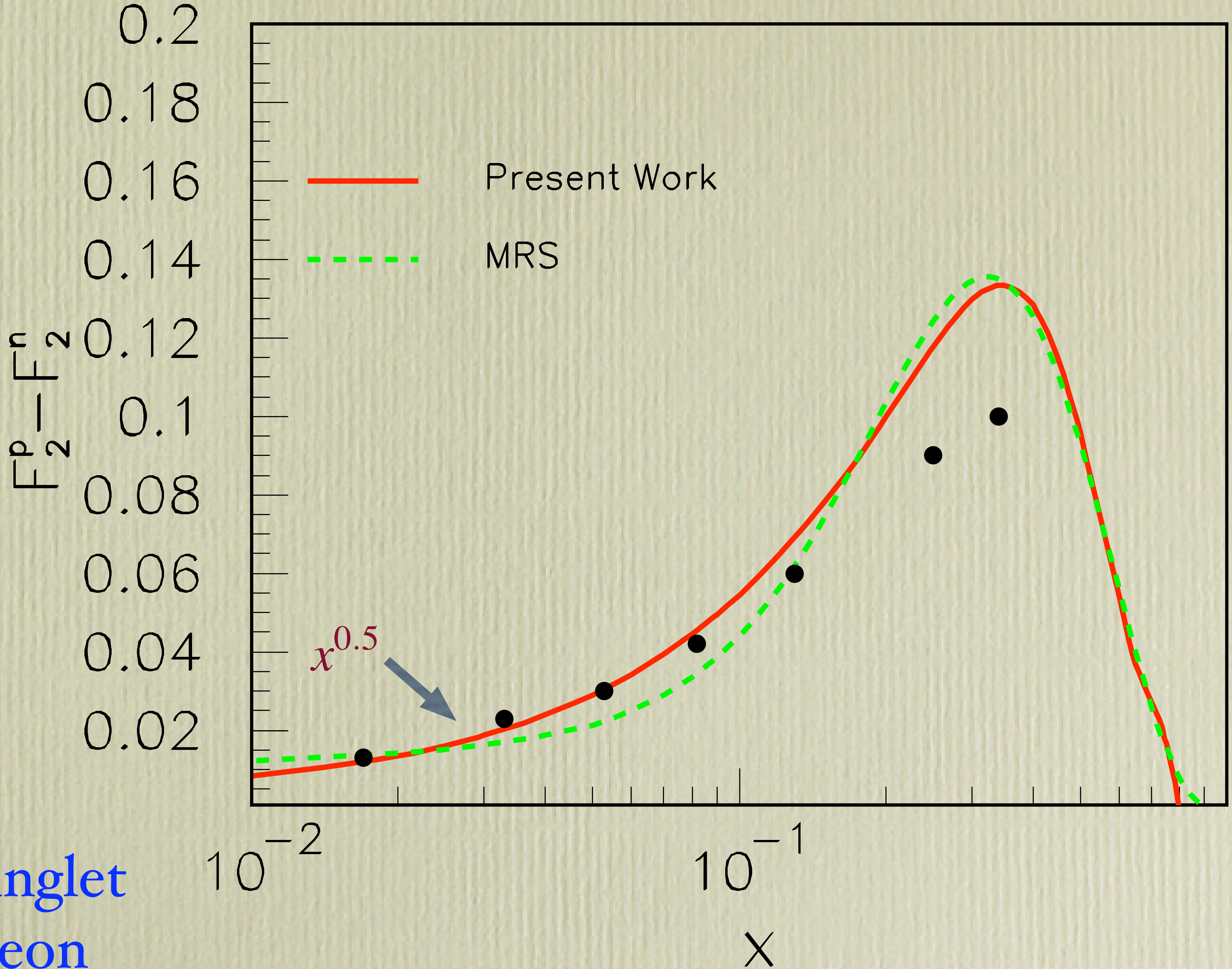
Magnitude of Reggeon exchange and Regge intercept determined from Kuti-Weiskopf behavior of non-singlet structure functions

$F_{2p}(x, Q^2) - F_{2n}(x, Q^2) = C_R x^{1-\alpha_R(0)}$
at small x.

$\alpha_R \sim 0.5$

$$
\begin{aligned}
T_{\overline{u}-p} \quad = \quad & \sigma\Big[s\left(i + \tan\frac{\pi\delta}{2}\right)\beta_1(\tau^2) - s\beta_{\mathcal{O}}(\tau^2) - (1-i)s^{1/2}\beta^{0^+}_{1/2}(\tau^2) \\
& +(1+i)s^{1/2}\beta^{0^-}_{1/2}(\tau^2) - (1-i)s^{1/2}\beta^{1^+}_{1/2}(\tau^2) + W(1-i)s^{1/2}\beta^{\text{pseudo}}_{1/2}(\tau^2) \\
& +(1+i)s^{1/2}\beta^{1^-}_{1/2}(\tau^2) + is^{-1}\beta^{u}_{-1}(\tau^2)\Big],
\end{aligned}
$$

Anti-Shadowing



Non-singlet Reggeon Exchange

Anti-Shadowing

Reggeon Exchange

Phase of two-step amplitude relative to one step:

$$\frac{1}{\sqrt{2}}(1-i) \times i = \frac{1}{\sqrt{2}}(i+1)$$

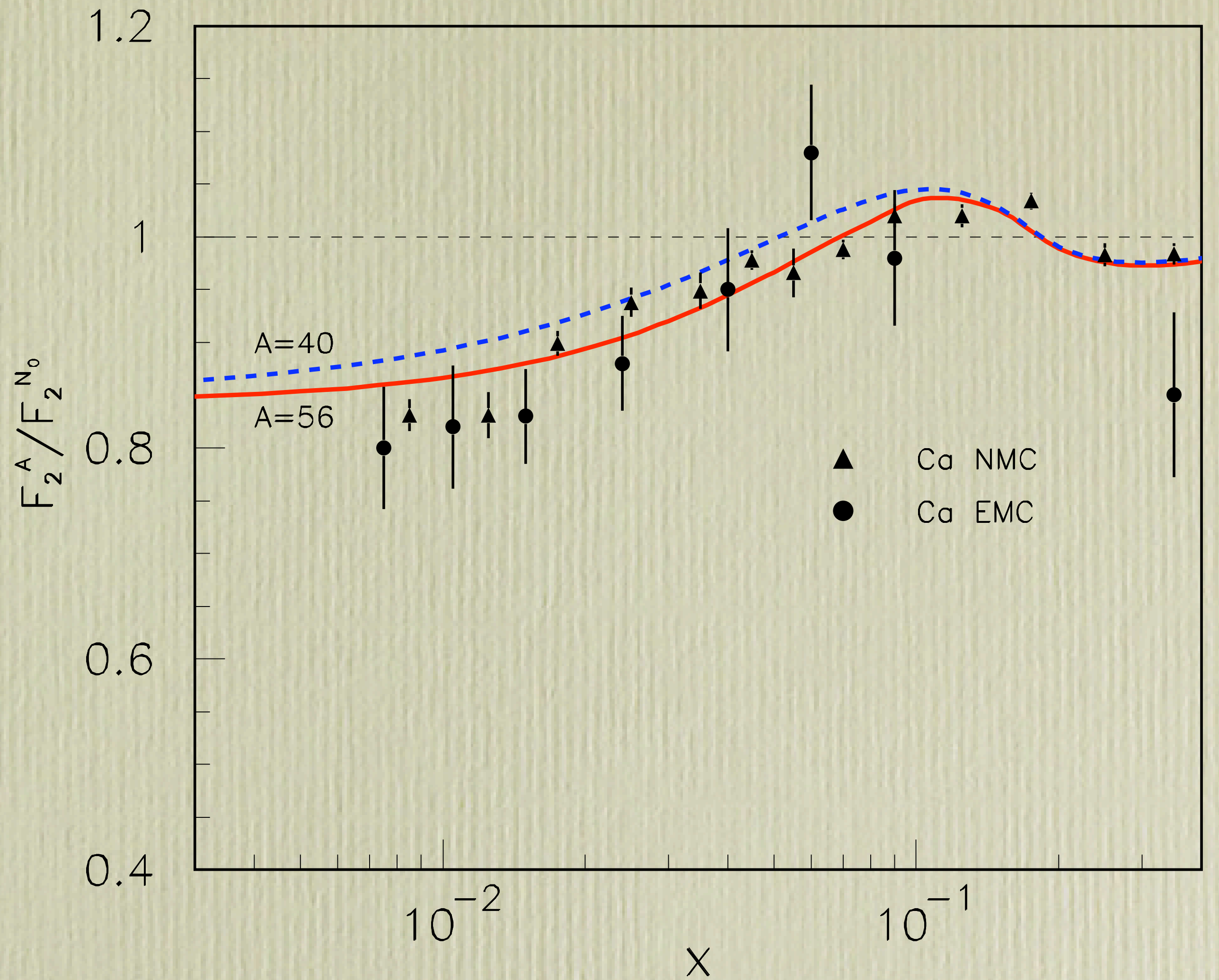
Constructive Interference

Depends on quark flavor!

Thus antishadowing is not universal

Different for couplings of $\gamma^*, Z^0, W^{\pm}$

Anti-Shadowing

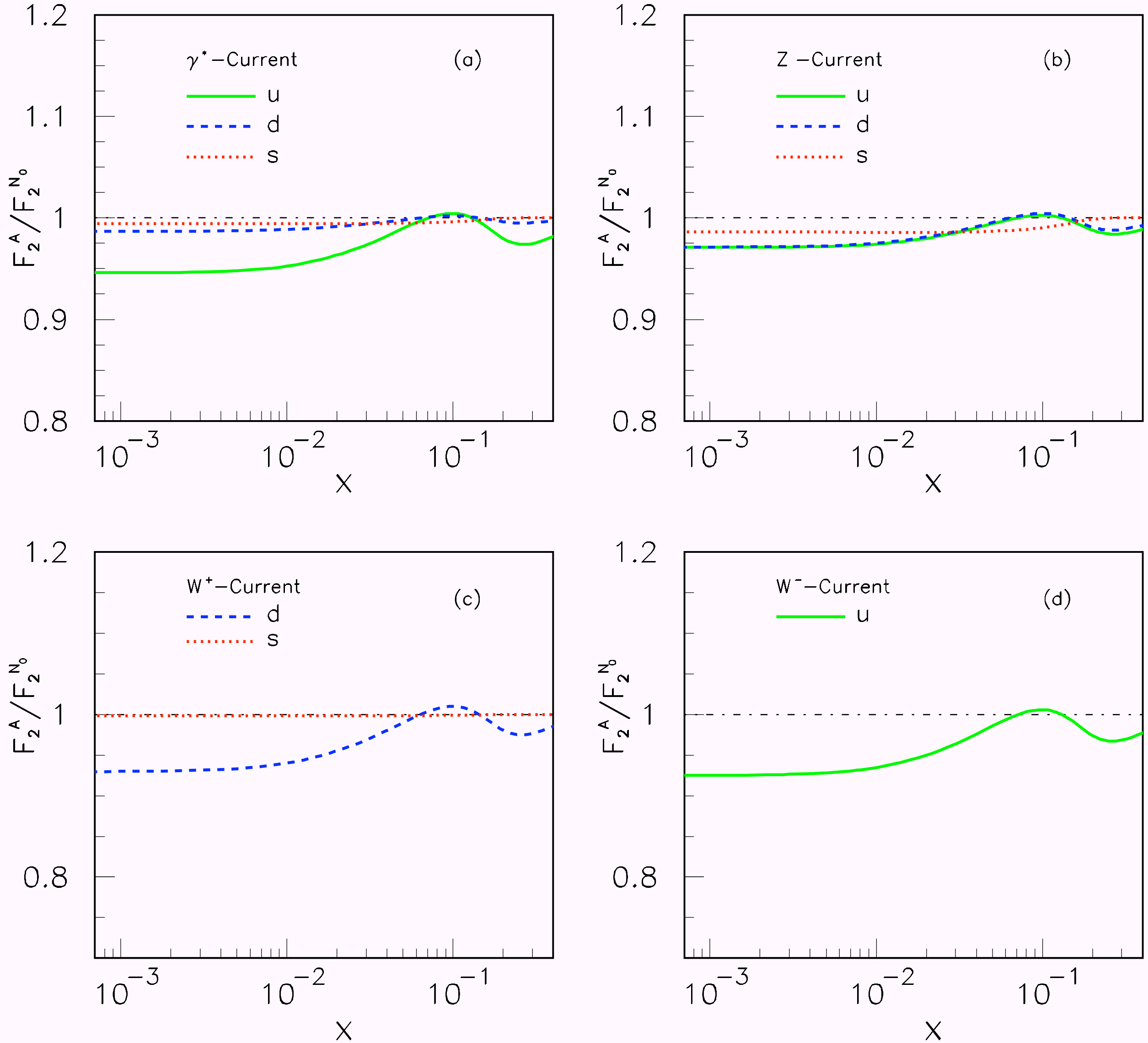


The nuclear shadowing and antishadowing effects at $\langle Q^2 \rangle = 1\ \mathrm{GeV}^2$

S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].

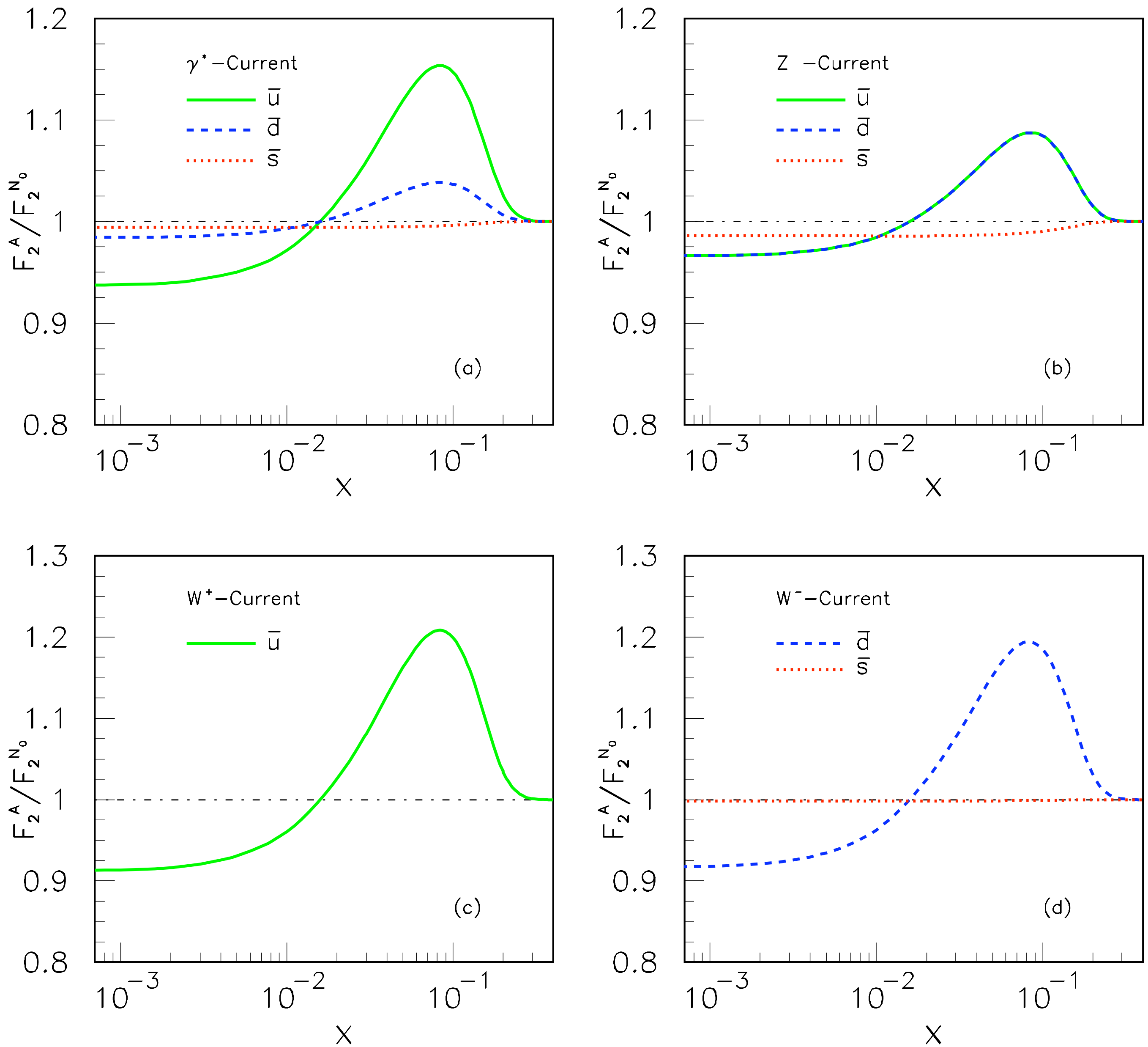
Anti-Shadowing

Shadowing and Antishadowing of DIS Structure Functions



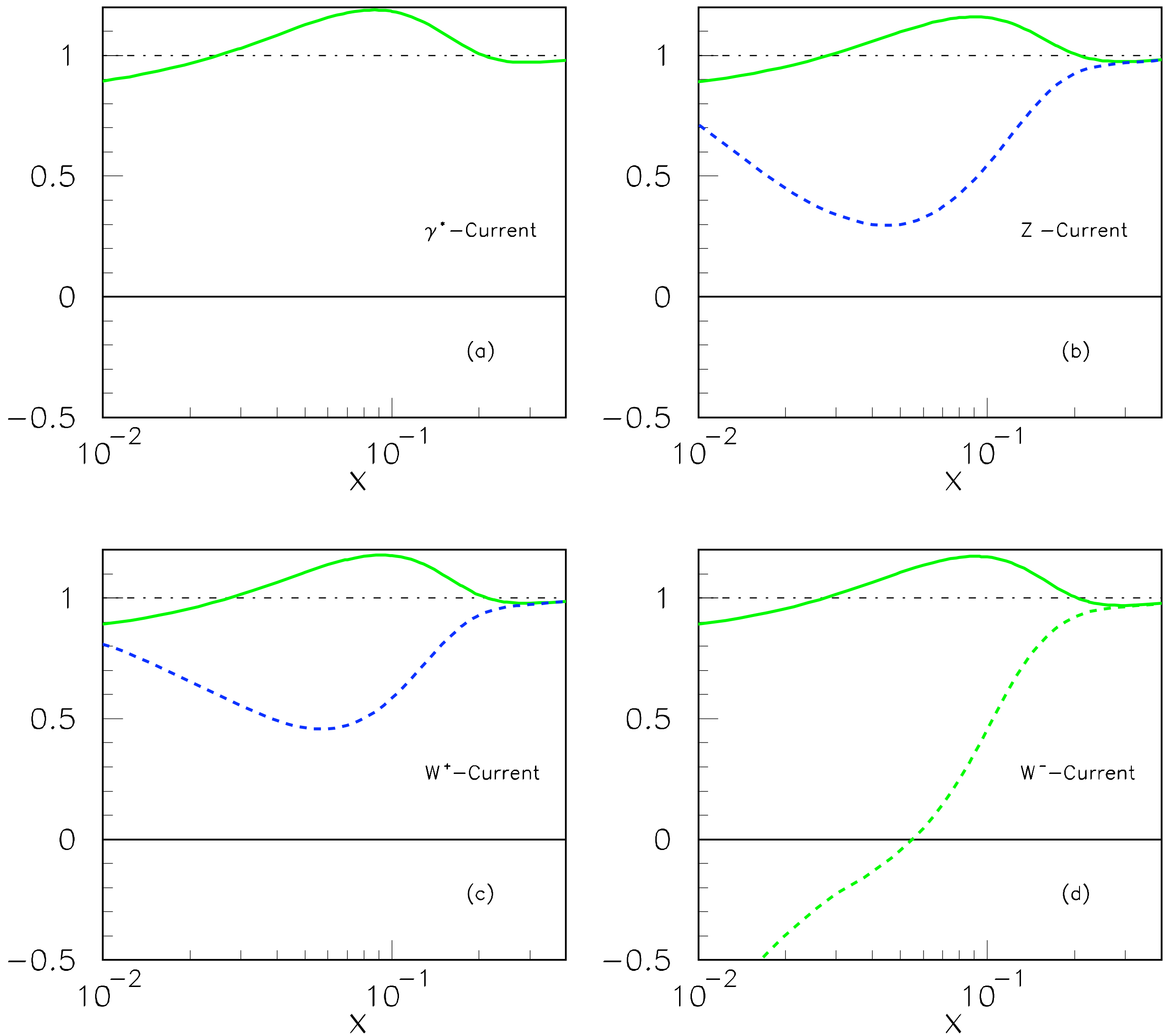
S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].

Anti-Shadowing



Nuclear Effect not Universal !

Anti-Shadowing



Ratios $F_2^A/F_2^{N^0}$ (solid curves) and $F_3^A/F_3^{N^0}$ (dashed curves)

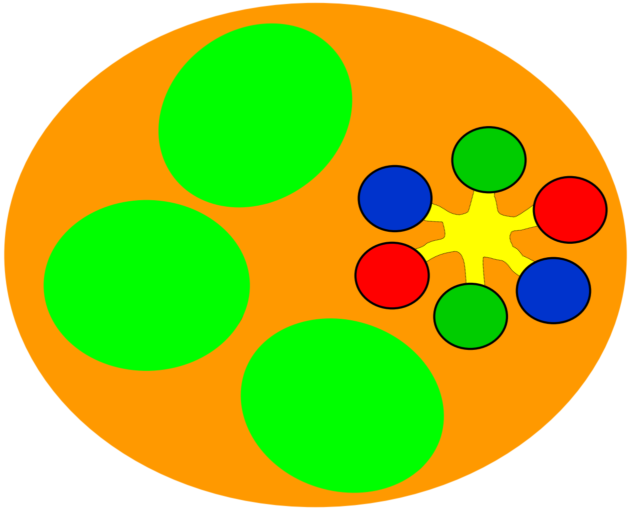
Anti-Shadowing

Estimate 20% effect on extraction of $\sin^2\theta_W$ for NuTeV

Need new experimental studies of antishadowing in

- Parity-violating DIS
- Spin Dependent DIS
- Charged and Neutral Current DIS

Do multi-quark clusters exist in the nuclear wavefunction?
Do they contribute significantly to the EMC effect?

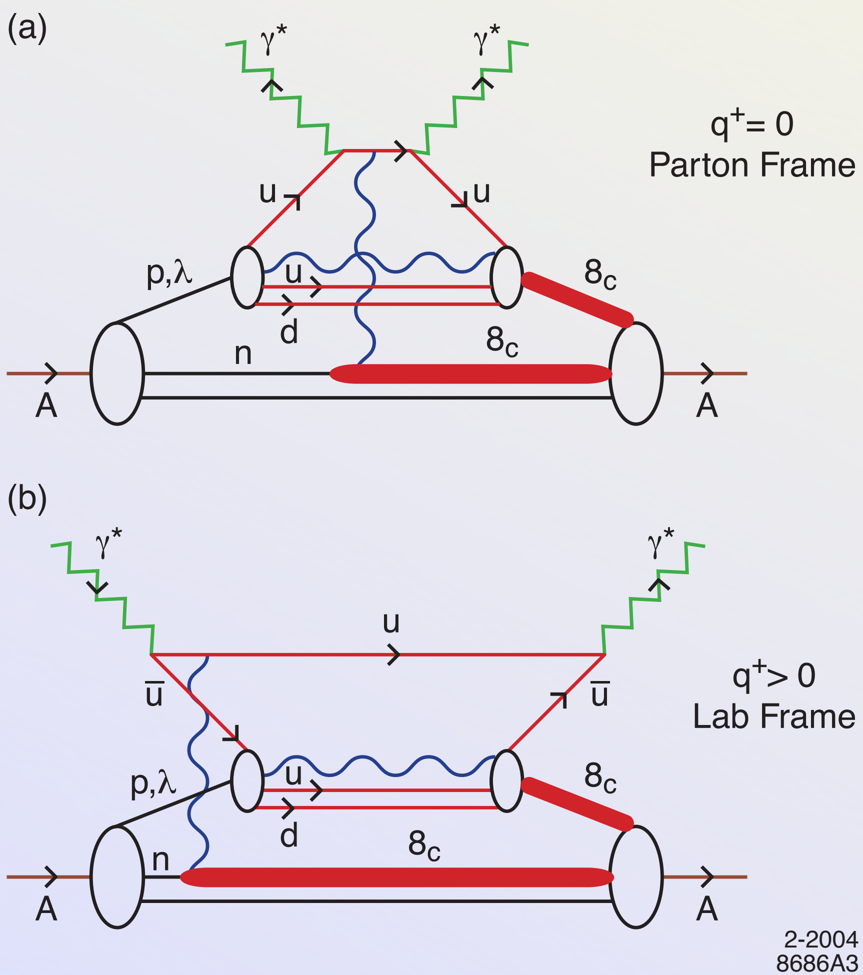


Hidden Color!

Anti-Shadowing

Novel Color Effects in Nuclei

“Hidden-Color” Contribution to Nuclear Structure Functions



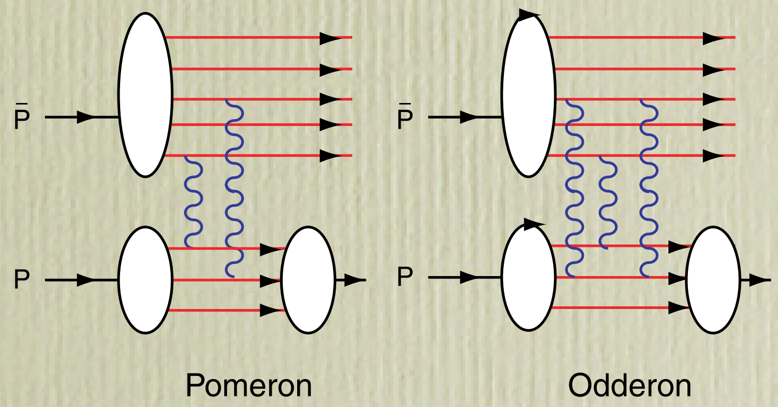
Parton model frame ($q^+ \leq 0$) :

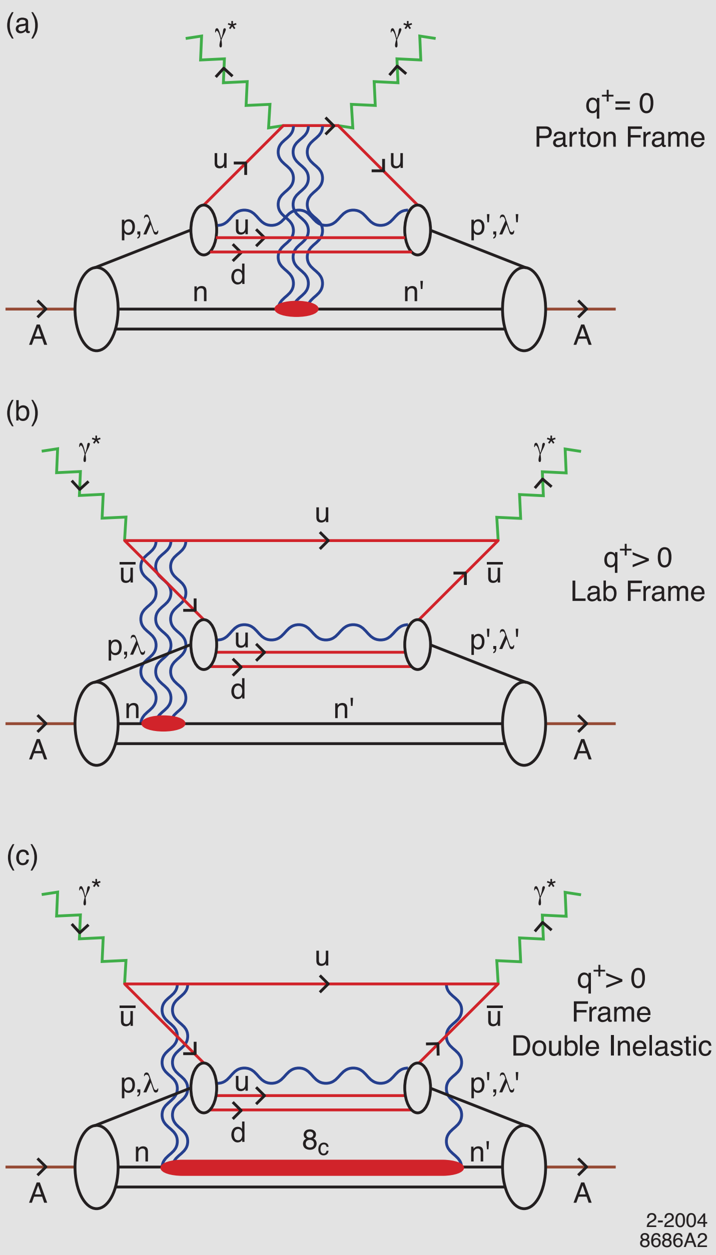
Color-dipole model frame ($q^+ > 0$)

Anti-Shadowing

The Odderon

- Three Gluon Exchange
- Interference of 2-gluon and 3-gluon exchange leads to matter/antimatter asymmetries
- Asymmetry in jet asymmetry in $\gamma p \to c\bar{c}p$
- Analogous to lepton energy and angle asymmetry $\gamma Z \to e^+e^-Z$
- Pion Asymmetry in $\gamma p \to \pi^+\pi^- p$





Odderon Contribution to Nuclear Anti-Shadowing

Parton model frame ($q^+ \leq 0$)
Three-gluon exchange

Color-dipole model frame ($q^+ > 0$)
Three-gluon exchange

Color-dipole model frame ($q^+ > 0$)
Double-inelastic contribution

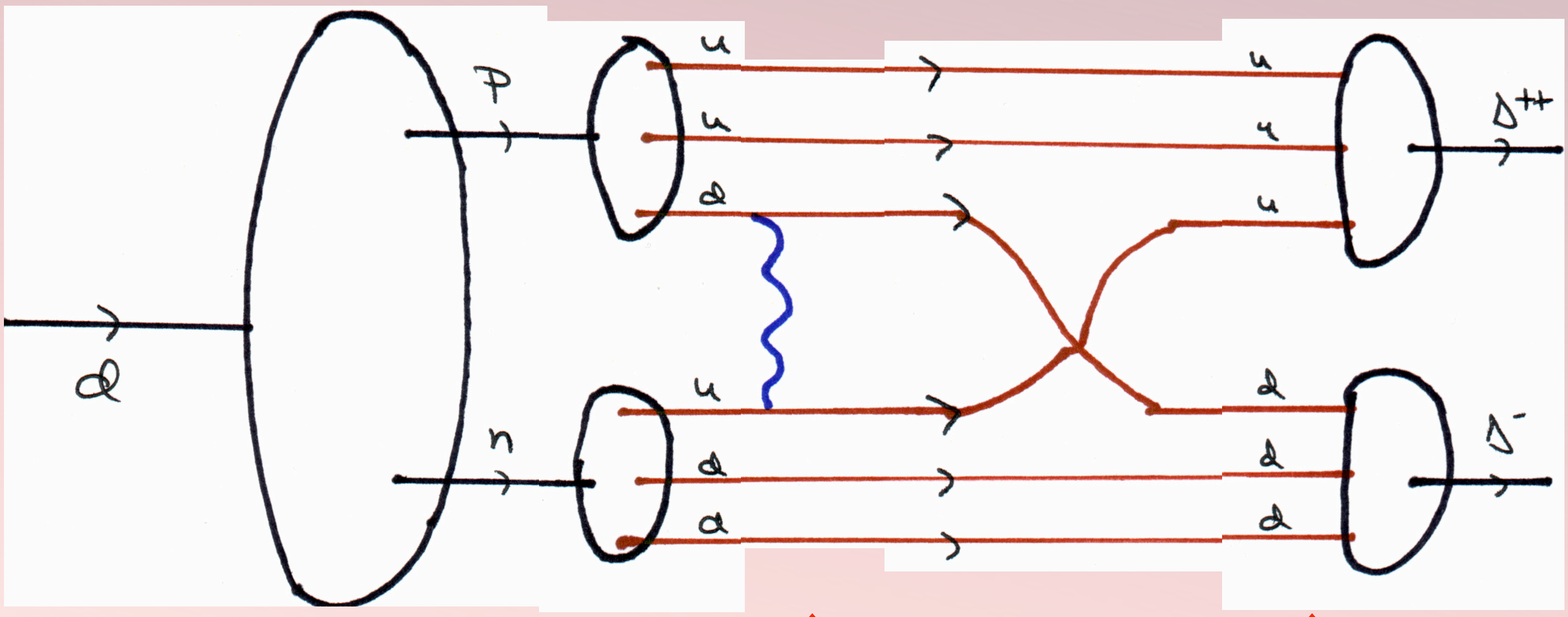
Anti-Shadowing

Lepage, Ji, sjb

Hidden Color in QCD

- Deuteron six quark wavefunction:
- 5 color-singlet combinations of 6 color-triplets -- one state is |n p>
- Components evolve towards equality at short distances
- Hidden color states dominate deuteron form factor and photodisintegration at high momentum transfer
- Predict $\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn)$ at high Q^2

Structure of Deuteron in QCD



Hidden Color Fock State

Delta-Delta Fock State

The evolution equation for six-quark systems in which the constituents have the light-cone longitudinal momentum fractions x_i ($i=1,2,\ldots,6$) can be obtained from a generalization of the proton (three-quark) case.[2] A nontrivial extension is the calculation of the color factor, C_d, of six-quark systems[5] (see below). Since in leading order only pairwise interactions, with transverse momentum Q, occur between quarks, the evolution equation for the six-quark system becomes $\{[dy]=\delta(1-\sum_{i=1}^{6} y_i)\prod_{i=1}^{6} dy_i$, $C_F=(n_c^2-1)/2n_c=\frac{4}{3}$, $\beta=11-\frac{2}{3}n_f$, and n_f is the effective number of flavors$\}$

$$\prod_{k=1}^{6} x_k\left[\frac{\partial}{\partial\xi}+\frac{3C_F}{\beta}\right]\tilde{\Phi}(x_i,Q)=-\frac{C_d}{\beta}\int_0^1 [dy]\,V(x_i,y_i)\,\tilde{\Phi}(y_i,Q),$$

$$\xi(Q^2)=\frac{\beta}{4\pi}\int_{Q_0^2}^{Q^2}\frac{dk^2}{k^2}\alpha_s(k^2)\sim\ln\left(\frac{\ln(Q^2/\Lambda^2)}{\ln(Q_0^2/\Lambda^2)}\right).$$

$$V(x_i,y_i)=2\prod_{k=1}^{6} x_k\sum_{i\neq j}^{6}\theta(y_i-x_i)\prod_{l\neq i,j}^{6}\delta(x_l-y_l)\frac{y_j}{x_j}\left(\frac{\delta_{h_i\bar{h}_j}}{x_i+x_j}+\frac{\Delta}{y_i-x_i}\right)$$

where $\delta_{h_i\bar{h}_j}=1$ (0) when the helicities of the constituents $\{i,j\}$ are antiparallel (parallel). The infrared singularity at $x_i=y_i$ is cancelled by the factor $\Delta\tilde{\Phi}(y_i,Q)=\tilde{\Phi}(y_i,Q)-\tilde{\Phi}(x_i,Q)$ since the deuteron is a color singlet.

Quantum Chromodynamic Predictions for the Deuteron Form Factor

$$F_d(Q^2) = \int_0^1 [dx][dy]\varphi_d^\dagger(y,Q) \times T_H^{6q+\gamma^*\to 6q}(x,y,Q)\varphi_d(x,Q), \qquad (1)$$

where the hard-scattering amplitude

$$T_H^{6q+\gamma^*\to 6q} = [\alpha_s(Q^2)/Q^2]^5 t(x,y) \times [1+O(\alpha_s(Q^2))] \qquad (2)$$

gives the probability amplitude for scattering six quarks collinear with the initial to the final deuteron momentum and

$$\varphi_d(x_i,Q) \propto \int^{k_{\perp i}<Q} [d^2k_\perp]\psi_{qqq\,qqq}(x_i,\vec{k}_{\perp i}) \qquad (3)$$

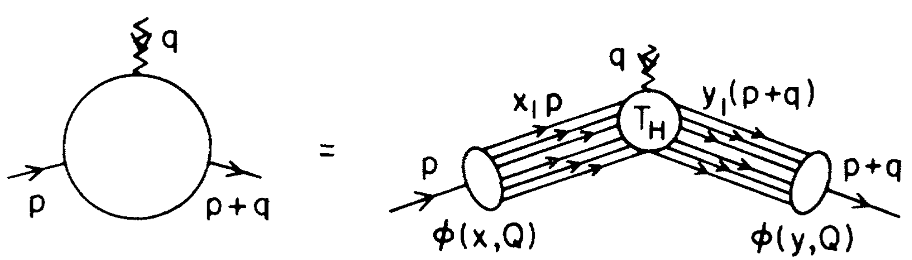


FIG. 1. The general structure of the deuteron form factor at large Q^2.

ref: Lepage, Ji, sjb

QCD Prediction for Deuteron Form Factor

$$F_d(Q^2) = \left[\frac{\alpha_s(Q^2)}{Q^2}\right]^5 \sum_{m,n} d_{mn} \left(\ln \frac{Q^2}{\Lambda^2}\right)^{-\gamma_n{}^d - \gamma_m{}^d} \left[1 + O\left(\alpha_s(Q^2), \frac{m}{Q}\right)\right]$$

Define “Reduced” Form Factor

$$f_d(Q^2) \equiv \frac{F_d(Q^2)}{F_N{}^2(Q^2/4)} .$$

Same large momentum transfer behavior as pion form factor

$$f_d(Q^2) \sim \frac{\alpha_s(Q^2)}{Q^2} \left(\ln \frac{Q^2}{\Lambda^2}\right)^{-(2/5)\, C_F/\beta}$$

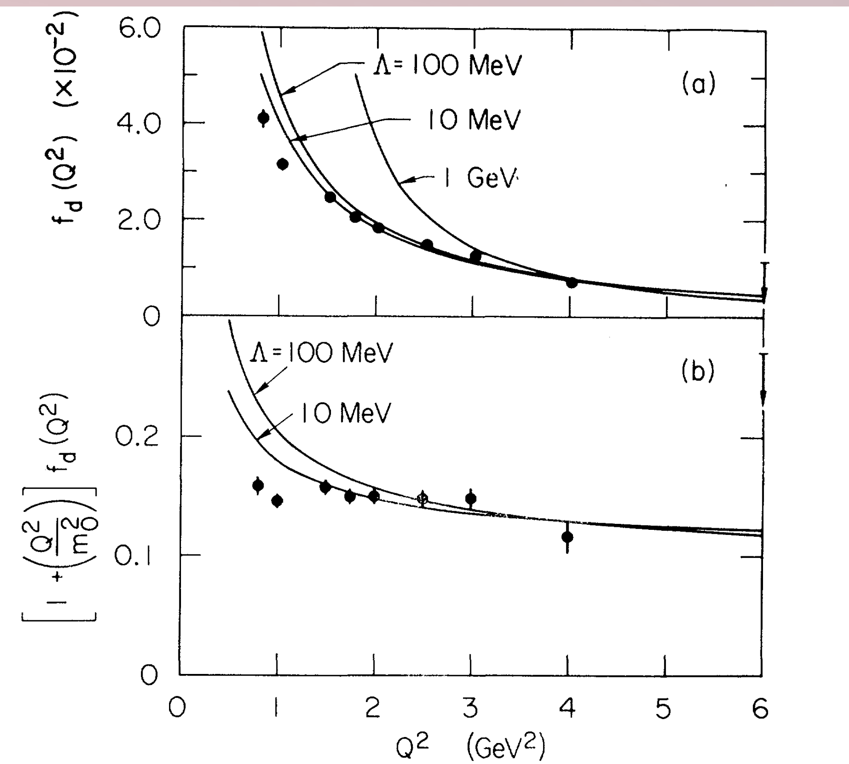
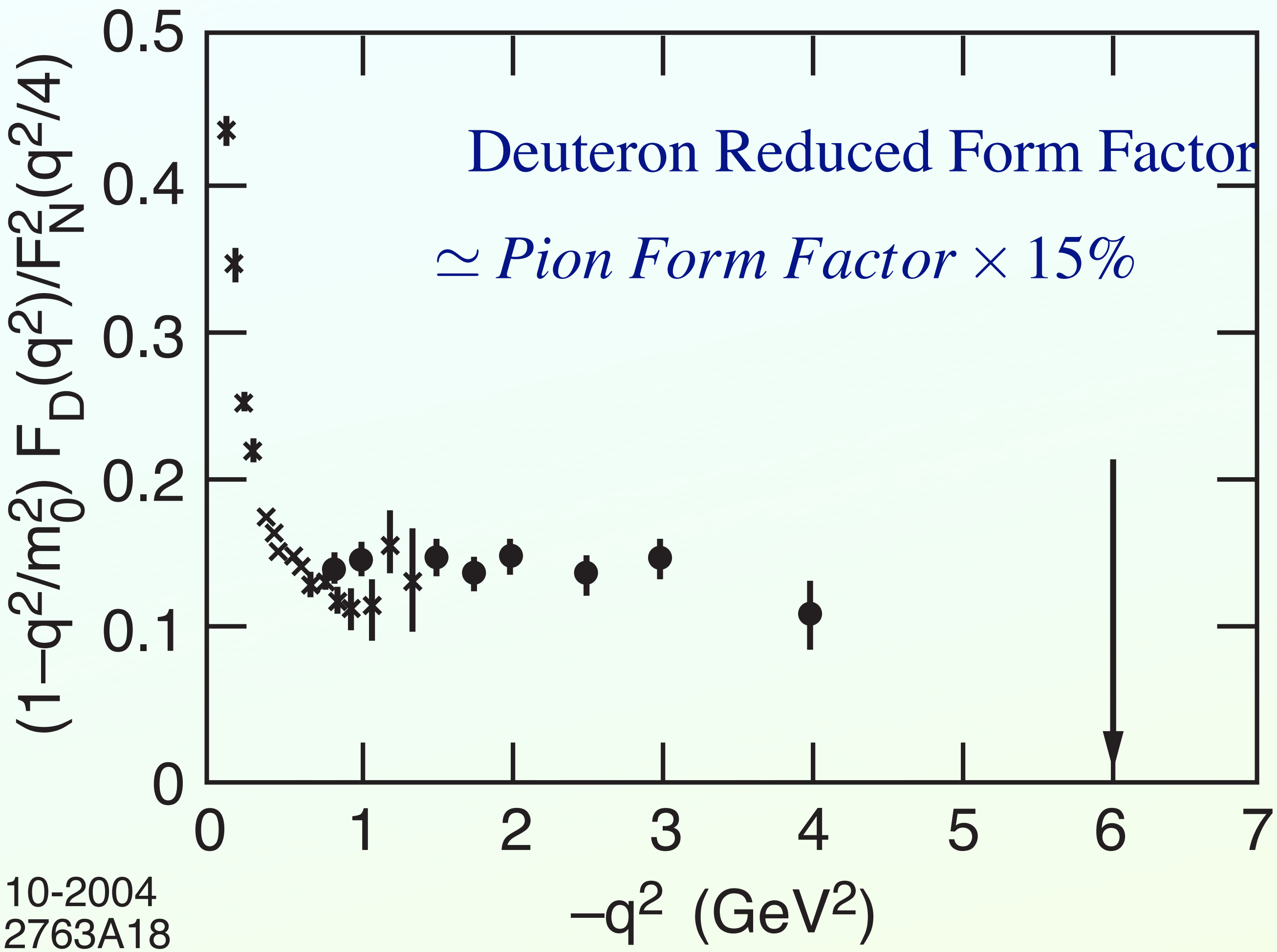


FIG. 2. (a) Comparison of the asymptotic QCD prediction $f_d(Q^2) \propto (1/Q^2)[\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with final data of Ref. 10 for the reduced deuteron form factor, where $F_N(Q^2) = [1 + Q^2/(0.71\ \mathrm{GeV}^2)]^{-2}$. The normalization is fixed at the $Q^2 = 4\ \mathrm{GeV}^2$ data point. (b) Comparison of the prediction $[1 + (Q^2/m_0{}^2)] f_d(Q^2) \propto [\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with the above data. The value $m_0{}^2 = 0.28\ \mathrm{GeV}^2$ is used (Ref. 8).



- 15% Hidden Color in the Deuteron

Anti-Shadowing

Hidden Color of Deuteron

Deuteron six-quark state has five color - singlet configurations, only one of which is n-p.

Asymptotic Solution has Expansion

$$\psi_{[6]\{33\}} = \left(\frac{1}{9}\right)^{1/2} \psi_{NN} + \left(\frac{4}{45}\right)^{1/2} \psi_{\Delta\Delta} + \left(\frac{4}{5}\right)^{1/2} \psi_{CC}$$

Look for strong transition to Delta-Delta

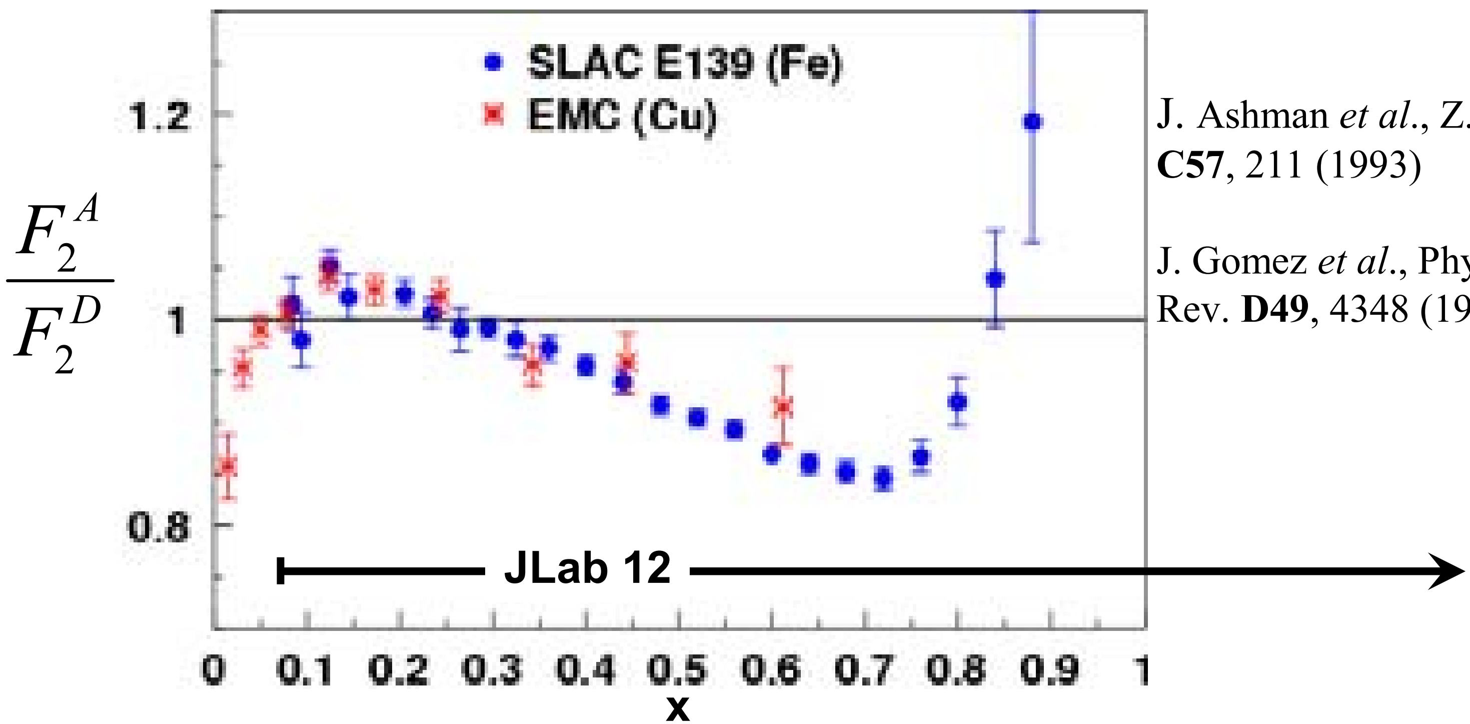
Anti-Shadowing

Quark Structure of Nuclei: Origin of the EMC Effect

W. Brooks

- Observation that structure functions are altered in nuclei stunned much of the HEP community 23 years ago
- ~1000 papers on the topic; the best models explain the curve by change of nucleon structure, BUT more data are needed to *uniquely* identify the origin

What is it that alters the quark momentum in the nucleus?



J. Ashman *et al*., Z. Phys. **C57**, 211 (1993)

J. Gomez *et al*., Phys. Rev. **D49**, 4348 (1994)

Shadowing and Antishadowing in Lepton-Nucleus Scattering

- Shadowing and Antishadowing in DIS arise from interference of multi-nucleon processes in nucleus

Phases!

- Not due to nuclear wavefunction

Wavefunction of stable nucleus is real.
Effect of multi-scattering of $q\bar{q}$ in nucleus.

- Bjorken Scaling :

Interference requires leading-twist diffractive DIS processes

Anti-Shadowing