# Nuclear Chromodynamics

## Signals of QCD in Nuclear Processes

- JLAB 12 GeV $e^-$
- GSI 15 GeV $\bar{p}$

DIS: By scaling, DGLAP
quark prop. in nuclei
shadowing, antishadowing, Fermi, Etc

Hard Exclusive Processes

Color Transparency
Hidden Color
Anomalous Charm Production
Conformal Scaling
Reduced Amplitudes

J=0, DHG for Nuclei

Off-shell, medium Effects

Nuclear LFWFs

$$\boxed{\text{QCD : Fundamental Theory of Hadrons \underline{and} Nuclei}}$$

$$\mathcal{L}_{QCD} = -\frac{1}{4} G_{\mu\nu}^2 + \sum_q \bar{\Psi}_q (i \not{D} - m_q) \Psi_q$$

$$iD_\mu = i\partial_\mu - g A_\mu$$

* invariant under $SU(3)_c$ gauge transformations

$$\Psi(x) \to e^{i\chi(x)} \Psi(x) \qquad \Psi = \begin{pmatrix} \Psi_R \\ \Psi_B \\ \Psi_G \end{pmatrix}$$

$\Psi$, $\bar{\Psi}$ : spin $\frac{1}{2}$ quarks, antiquarks
$3_c$ $\qquad \bar{3}_c$

$$G_{\mu\nu} = \frac{1}{ig}[D_\mu, D_\nu]$$
$$= \partial_\mu A_\nu - \partial_\nu A_\mu + g[A_\mu, A_\nu] : \text{ spin 1 gluons } \quad 8_c$$


For Nuclear Physics : Scientific Revolution

at long wavelength : chiral theory
of mesons and nucleons

at short wavelengths . q and g
$\lambda \lesssim 1\,\text{fm}$ degrees of freedom
become manifest!

QCD: scale $\Lambda_{QCD} \sim 200$ MeV

$q, g$ : $d < 1$ fm

$Q^2 > \Lambda^2_{QCD}$

Bj scaling

DGLAP evolution

Same interactions control

exclusive reactions

nuclear dynamics

Conformal Correspondence Principle

$\beta \to 0$, $m_q \to 0$

conformal invariance

at short distance

QCD : one scale $\Lambda_{QCD} \sim 200$ MeV

expect QCD to be applicable

at $Q^2 \gg \Lambda_{QCD}$

# Analytic Limits of QCD

## "Abelian Correspondence Principle"

Huet + S&B

$$\lim_{N_c \to 0} \mathrm{QCD}\left(\text{fixed } \hat{\alpha} = C_F \alpha_s,\ \hat{n} = \frac{n_F}{T C_F}\right)$$

$$= \text{Abelian Theory}\ (\hat{\alpha}, \hat{n})$$

$$C_F = \frac{N_c^2 - 1}{2N_c},\ T = 1/2$$

* hadron, nuclei ⇒ atoms, molecules

## "Conformal Correspondence Principle"

$$\lim_{\substack{\beta \to 0 \\ m_q \to 0}} \mathrm{QCD} = \text{Conformal QCD} \quad (\text{fixed } \bar{\alpha}_s)$$

Parisi

Frishman Lepage S&B Sachrajda

* Remarkable constraints on QCD predictions

* Conformal expansion of distribution amplitude and OPE

V. Braun et al

* Commensurate Scale Relations

No renormalon ambiguities

Lu, Rathsman, Gardi, Grunberg, Kataev, S&B

# Near-Conformal QCD

At short distances, high momentum transfer

QCD is nearly scale-invariant

$$x^\mu \to \lambda x^\mu$$

"Conformal" invariance

Parisi
Frishman, Lepage, SJB
Sachrajda, Dangaard

* Consequences


$$x = \frac{k^+}{p^+} = \frac{Q^2}{2p\cdot q}$$

$$\frac{d\sigma}{d^3p/E}(ep \to e'X) \Rightarrow \frac{d\sigma}{dt}(eq \to eq) * F(x)$$

"Bjorken Scaling"

Scale invariant: $$\frac{d\sigma}{dt}(eq \to eq) = \frac{1}{s^2} F(\theta_{cm})$$

point-like lepton, quark interactions

$$s = E_{cm}^2$$

$$t = (P_\ell - P_{\ell'})^2 = q^2 = -Q^2$$

# Theories with Conformal Symmetry

invariant under Poincare transformations $M^{\mu\nu}, P^{\nu}$
+ Conformal transformations $D, K^{\nu}$

generators form group

$$\boxed{SO(4,2)} \qquad (d=4)$$

SO(4,2) has representations on both

and $\left\{ \begin{array}{l} \text{Minkowski space} \quad R^{(3,1)} \\ AdS_5 \end{array} \right.$

Minkowski metric

$$ds^2 = dt^2 - d\vec{x}^2$$

$AdS_5$ metric

fifth dim.

$$ds^2 = \frac{r^2}{R^2}\left(dt^2 - d\vec{x}^2\right) - \frac{R^2}{r^2}dr^2$$

Dilatations

$$x^{\mu} \to \lambda x^{\mu} \quad ; \quad (x^{\mu}, r) \to \left(\lambda x^{\mu}, \frac{r}{\lambda}\right)$$

Predictions from conformal QCD:
+ $AdS_5 \times S^5$ + large $N_c$

large $Q^2$
Form Factors

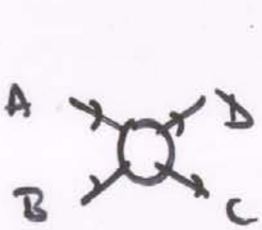
$$F(Q^2) \sim \left(g_{YM}^2 N_c\right)^{\frac{(n-1)}{2}} \left(\frac{\Lambda_0}{Q}\right)^{2n+|\ell_z|-2}$$

$$F_2(Q^2)/F_1(Q^2) \sim \left(\frac{M\Lambda_0}{Q^2}\right)$$

mod logs, anom. dim.

$$\mathcal{M}(Q^2)_{AB\to CD}$$

Polchinski - Strassler
de Teramond, SJB




$$\sim \frac{\left(g_{YM}^2 N_c\right)^{\frac{1}{4}(n_T-2)}}{N_c} \left[\frac{\Lambda_0}{Q}\right]^{n+|\ell_z|-4}$$

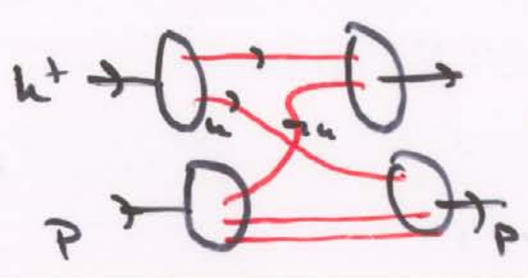
← QIM

BF, MMT

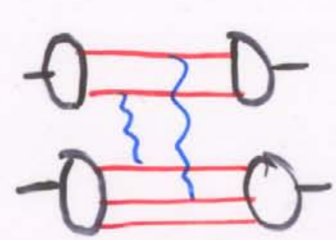
$$n_T = n_A + n_B + n_C + n_D$$

✗ Non-perturbative derivation

✗ large $N_c$: QIM dominant



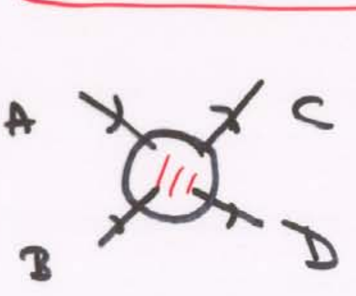

$\gg$



suppressed at large $N_c$

# Conformal Invariance and QCD

BF, MNT



$$\frac{d\sigma}{dt}(AB \to CD) \Rightarrow \frac{1}{s^{n_{TOT}-2}} F(t/s)$$

$$-t/s = \frac{1}{2}(1-\cos\theta_{cm})$$

high momentum transfer

| Examples | $n_{TOT}$ | $d\sigma/dt$ |
|---|---|---|
| $eq \to eq,\ qq \to qq,\ \gamma q \to qq$ | $2+2+2+2$ | $\frac{1}{s^2}$ |
| $\gamma p \to \pi^+ n$ | $1+3+2+3$ | $\frac{1}{s^7}$ |
| $pp \to pp$ | $3+3+3+3$ | $\frac{1}{s^{10}}$ |
| $ep \to ep,\ \gamma p \to \gamma p$ | $1+3 \to 1+3$ | $\frac{1}{s^6}$ |

Form Factors

$$F_H^2(t) = \frac{\frac{d\sigma}{dt}(eH \to eH)}{\frac{d\sigma}{dt}(eq \to eq)} \Rightarrow F_H(t) \neq \frac{1}{t^{n-1}}$$

New derivation (without perturbation theory)

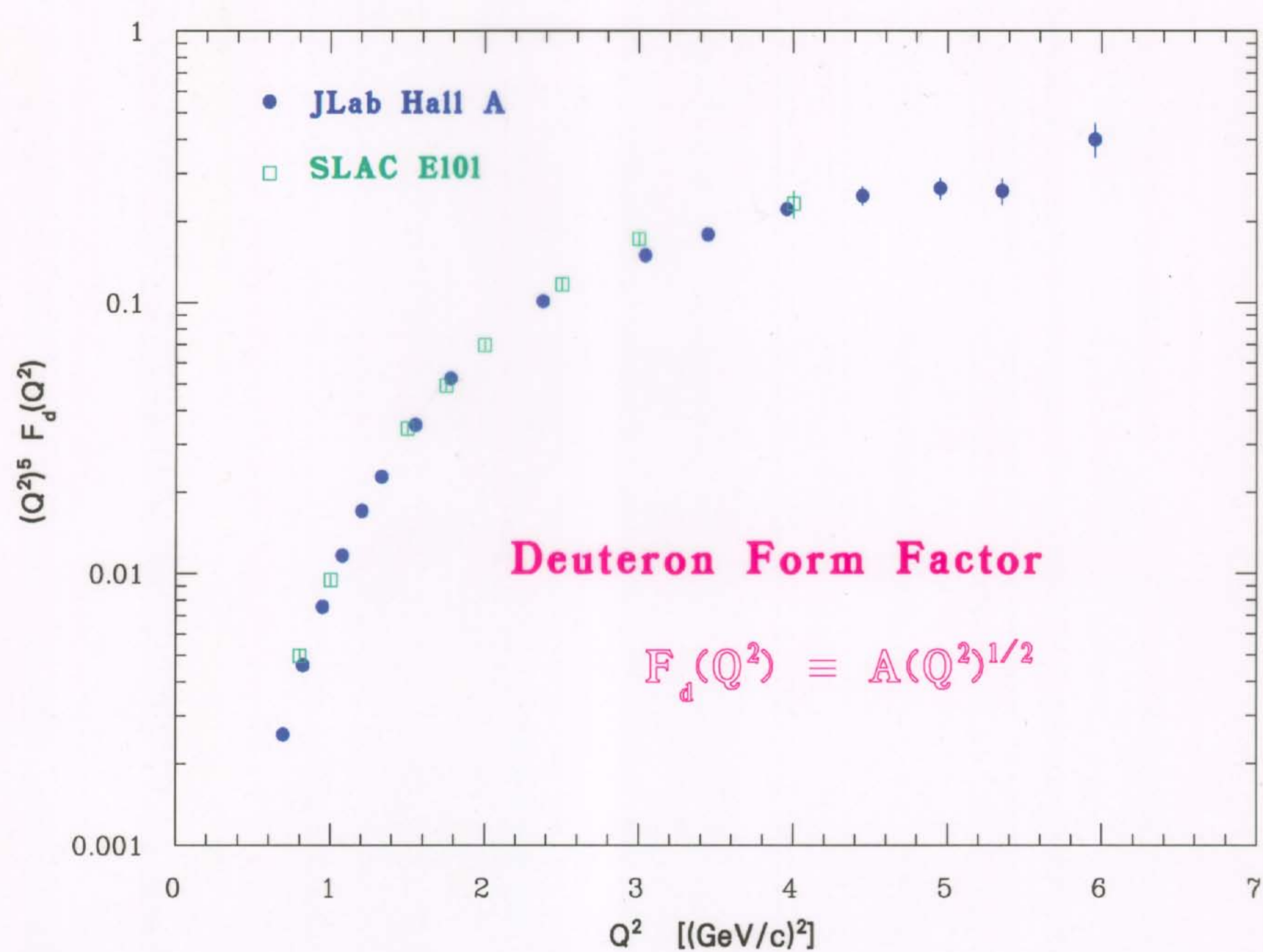
AdS/CFT

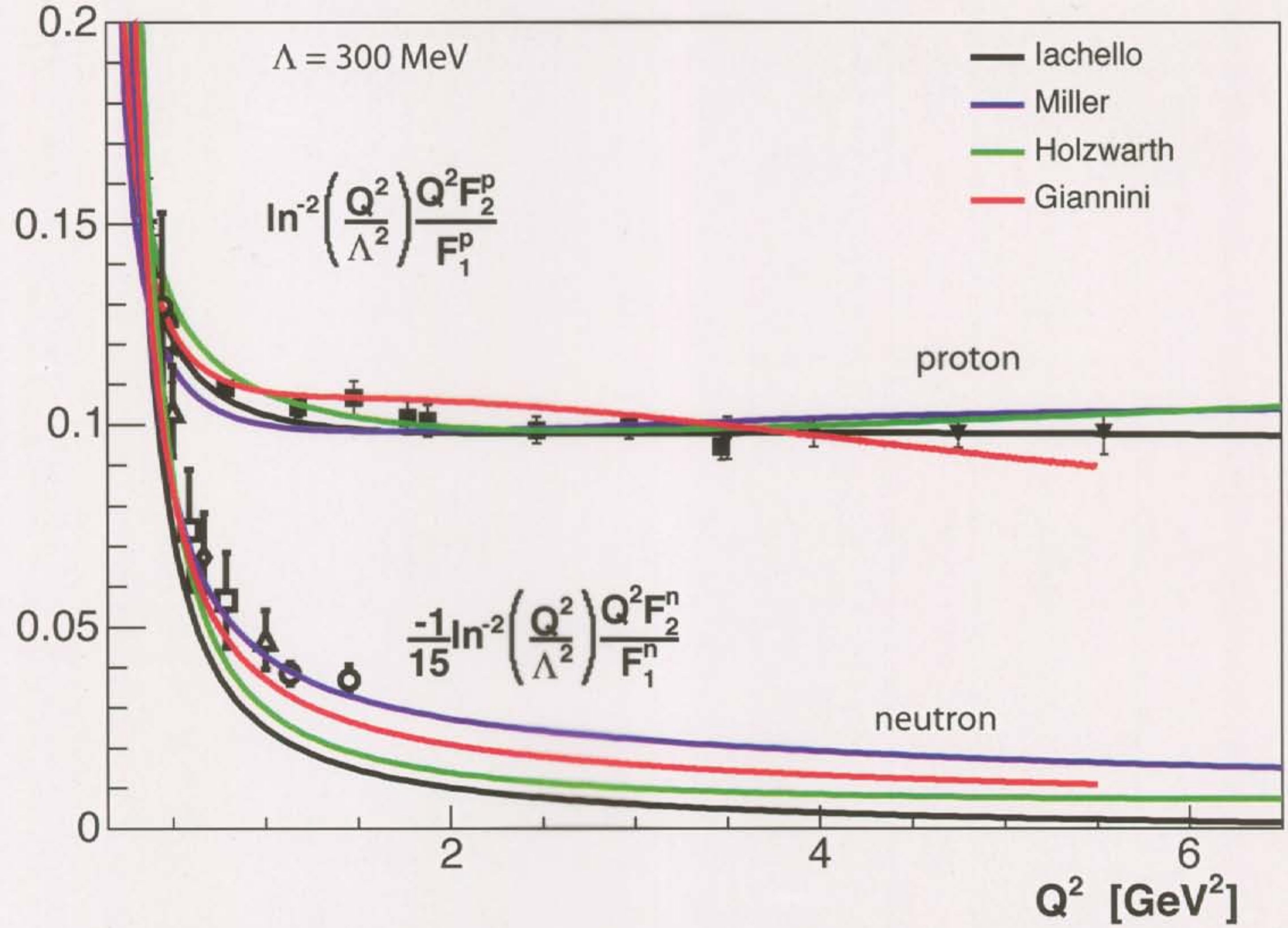
Maldacena

Polchinski + Strassler

Duncan Mueller

Sudakov Suppression of Landshoff Pinch Sing: fixed $\alpha_s$


JLab Hall A
SLAC E101
Deuteron Form Factor
$F_d(Q^2) \equiv A(Q^2)^{1/2}$
$(Q^2)^5\ F_d(Q^2)$
$Q^2$ [(GeV/c)$^2$]
1
0.1
0.01
0.001
0
1
2
3
4
5
6
7

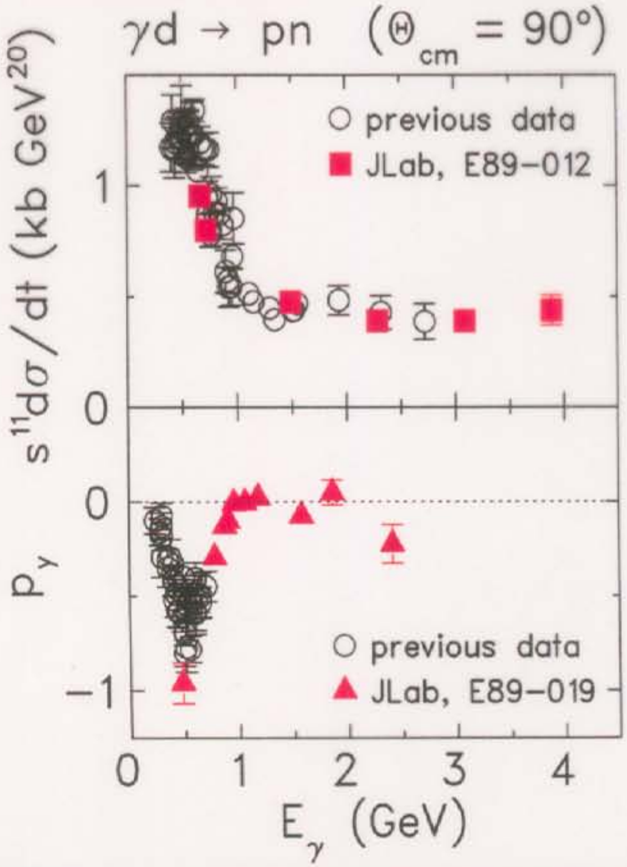


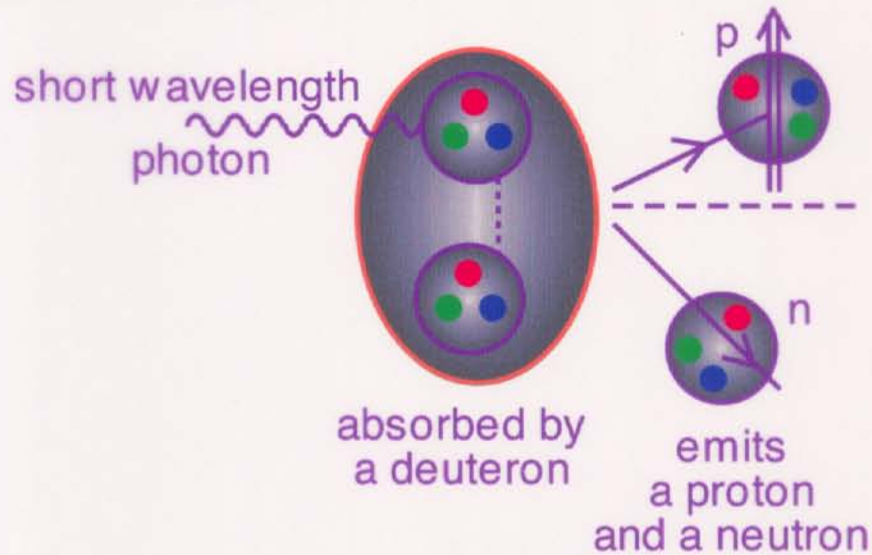
0.2
0.15
0.1
0.05
0
2
4
6
$Q^2$ [GeV$^2$]
$\Lambda = 300$ MeV
Iachello
Miller
Holzwarth
Giannini
$\ln^{-2}\left(\frac{Q^2}{\Lambda^2}\right)\frac{Q^2F_2^p}{F_1^p}$
proton
$\frac{-1}{15}\ln^{-2}\left(\frac{Q^2}{\Lambda^2}\right)\frac{Q^2F_2^n}{F_1^n}$
neutron

# SHORT-DISTANCE STRUCTURE of the DEUTERON

Jefferson Lab (E89 - 012, E89 - 019)

**Do we see the effects of quarks and gluons in a nuclear reaction ?**




- **Reaction probability is consistent with quark counting rules at high photon energy.**
- **Polarization vanishes at same photon energy that reaction probability begins scaling.**
- **First glimpse of the transition region.**

P. Rossi
CLAS
hep-ph/0405207

Scaling in deuteron photodisintegration

$$\frac{d\sigma}{dt}(\gamma d \to np)$$



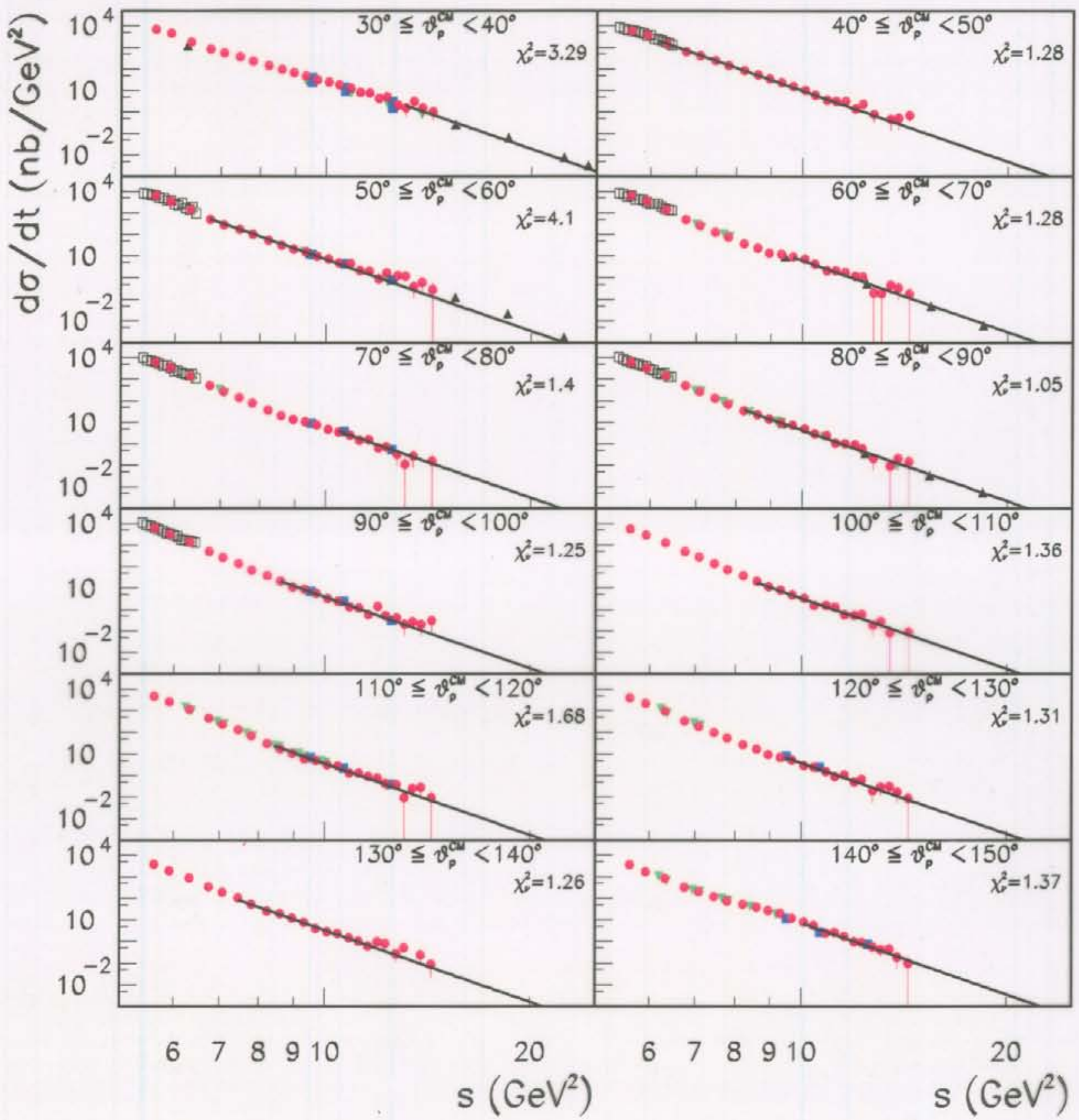



FIG. 2: Fits of the cross sections $d\sigma/dt$ to $s^{-11}$ for $P_T \geq P_T^{th}$ and proton angles between 30° and 150° (solid lines). Data are from CLAS [12] (full/red circles), Mainz [15] (open/black squares), SLAC [5, 6, 7] (full-down/green triangles), JLab Hall A [11] (full/blue squares) and Hall C [8, 9] (full-up/black triangles). Also shown in each panel is the $\chi^2_\nu$ value of the fit.

$$\boxed{\frac{d\sigma}{dt} = \frac{1}{s^{11}} f(\theta_{cm})}$$

# Tests of QCD Physics of Nuclei 12

* PQCD / Conformal scaling laws

$$s^{11} \frac{d\sigma}{dt}(\gamma d \to np)$$

* Reduced amplitude scaling

$$F_d(Q^2) \sim \frac{1}{Q^2}, \quad f_{He^3} \sim \left(\frac{1}{Q^2}\right)^2$$

* Leading twist hadron-helicity conservation

$$\lambda_a + \lambda_b = \lambda_c + \lambda_d$$

* High x nuclear structure functions

$$q_A(x) \sim (1-x)^{2n_s-1} \qquad x \to 1$$

$$x = \frac{k^+}{p^+_A}$$

$$q_d(x) \sim (1-x)^9$$

normalize to 1580 $Q^2 F_d$

# Counting Rules

$\boxed{\text{String Theory}}$

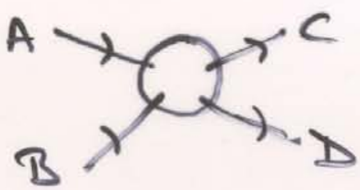
Supergravity dual
of conformal QFT
$AdS_5 \times X_5$

$\boxed{\text{QCD}}$

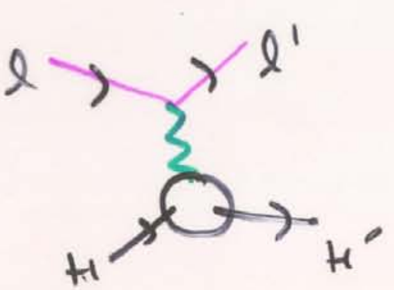
PQCD
Factorization

$-t \gg \Lambda^2$

$$\boxed{\frac{d\sigma}{dt}(AB \to CD) \cong \frac{F_{AB\to CD}(t/s)}{s^{n-2}}}$$




$$n = n_A + n_B + n_C + n_D$$




$$\boxed{F_{\Delta\lambda=0}(t) \cong \left[\frac{\Lambda^2}{t}\right]^{n_i-1}}$$

$n_i$ = minimum # Fock constituents

= dim of lowest twist interpolating op.

Farrar + SJB
Matveev, Muradian, Tavkhelidze

} conformal RGTh fixed coupling

$\Lambda \sim f_\pi \sim$ wf at origin

# Conformal symmetry acts as template

* $$R(s) = \sum_{n=0} C_n \alpha_s^n (Q_n^*)$$

observable — conformal coefficient — absorbs $\beta \neq 0$.

$Q_n^*$ determined by Banks-Zak + BLM

Gardi, Grunberg, Rathsman, SJB

$C_n$ : no $n!$ growth ; no renormalons

* Hadron distribution amplitudes

conformal

- $$\phi_M(x_i, Q) = x_1 x_2 \sum_n a_n C_n^{3/2}(x_1 - x_2)\, e^{-\gamma_n \xi(Q)}$$

$$\xi(Q) = \frac{1}{2\pi} \int^{Q^2} \frac{d\ell^2}{\ell^2} \alpha_s(\ell^2)$$

Lepage SJB

- $$\phi_B(x_i, Q) = x_1 x_2 x_3 \sum_n a_n P_n(x_i)\, e^{-\gamma_n \xi(Q)}$$

Conformal Jacobi polynomials

Braun, Derkachov, Manashov, Korchemsky

* $C_n^{3/2}$, $P_n$ determined from conf. symmetry

* Deviations from conf. symmetry in $\alpha_s(\ell^2)$

$$\boxed{\text{AdS/CFT Correspondence}}$$

Anti de Sitter    conformal field theory

Maldacena (1998)

Remarkable duality between

Supergravity string theory in 10 dimensions

and

Supersymmetric Yang-Mills field theory

in 3+1 Minkowski space-time

$$\boxed{AdS_5 \otimes S^5 \Leftrightarrow SO(4,2) \otimes (\mathcal{N}=4)}$$

5 dim. Sphere

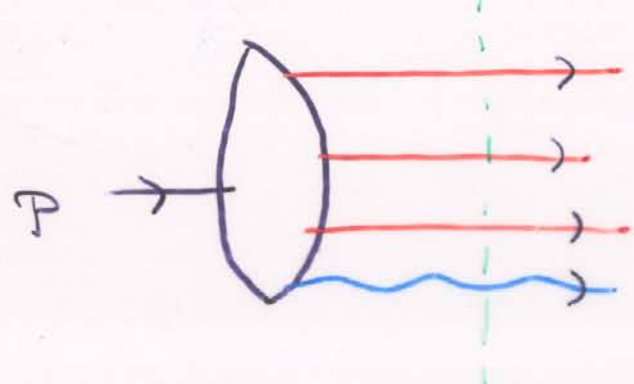
symmetries of Conformal Transformations + Poincare Invariance of Minkowski space

$\mathcal{N}=4$ SUSY

# Light-Front Wavefunctions and QCD Phenomena

Non-Perturbative QCD

$\{\Psi_n\}$ : translation: hadrons $\Rightarrow$ q, g




$$x_i = \frac{k_i^+}{P^+} = \frac{k_i^0 + k_i^z}{P^0 + P^z}$$

fixed $\tau = t + z/c$

Dirac

$$|\Psi\rangle = \sum_n |n\rangle \, \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

free q, g basis

$$\sum_{i=1}^{n} x_i = 1 \ , \quad \sum_{i=1}^{n} \vec{k}_{\perp i} = 0$$

"Light-cone Fock expansion"

boost invariant Frame-indep.

from AdS/CFT

Match $\psi_{LF}$ to $\Phi(r) \sim r^{-\Delta}$

$$\Phi_{LF}^{(n)}(Q) = \int^{Q} [d^2k_\perp]^{n-1} [a^\dagger(k_i)]^n \, \psi_n(k_\perp) \sim Q^{-\Delta}$$

$$\Delta = n + \ell$$

$$\psi_n(k_\perp) \sim \left(\frac{1}{k_\perp^2}\right)^{n-1} \qquad \ell = 0$$

$k_\perp^2 \gg \Lambda_{QCD}^2$ $$\sim \left(\frac{1}{k_\perp^2}\right)^{n+\ell-1} k_\perp^{\ell} \qquad \ell \neq 0$$

Agrees with PQCD Belitsky, Ji, Yuan

Dictated by conformal symmetry

Use above form to model complete LFWF

Confinement potential on LF : Pirner

Form of $\psi_{LF}$ from QCD + Conf. Sym.

(anom dim ignored)

$$\psi_{n/h}(x_i, \vec{k}_{\perp i}, \lambda_i, \ell_{zi})$$

GdT S13

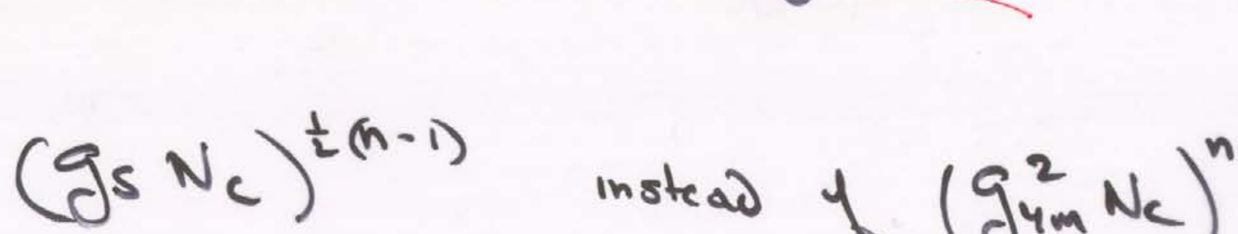
$k_\perp^\pm = k_x \pm i k_y$

$$\sim \frac{(g_s N_c)^{\frac{1}{2}(n-1)}}{\sqrt{N_c}} \prod_{i=1}^{n-1} (k_{\perp i}^\pm)^{|\ell_{zi}|}$$

$g_s = g_{YM}^2$

$$\times \left[ \frac{\Lambda_0}{\mathcal{M}_h^2 - \sum_{i=1}^{n} \frac{(k_\perp^2 + m^2)_i}{x_i} + \Lambda_0^2} \right]^{n+|\ell_z|-1}$$

large $k_\perp$ det by CF




AdS:

$(g_s N_c)^{\frac{1}{2}(n-1)}$ instead of $(g_{YM}^2 N_c)^{n-1}$

S. J. Rey, J. T. Lee (2001)
J. Maldacena (1998)

Parisi
Polchinski, Strassler
de Teramond, SJB

Conformal Symmetry: $\beta = 0$, $m_q = 0$

* AdS/CFT $\Rightarrow$ $\psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$

powerlaw fall-off $\begin{cases} x \to 1 \\ \text{high } k_\perp \end{cases}$ $\left[\frac{1}{m_n^2}\right]^p$

non-perturbative !

agrees with PQCD, QED solns

$\Rightarrow$ predicts

- By scaling
- Dimensional counting rules: $M \sim \frac{F(\theta_{cm})}{s^{n_T-4}}$
- Spectator counting rules $(1-x)^{2n_s-1}$
- OPE, DGLAP, ERBL evol. $(\beta = 0)$

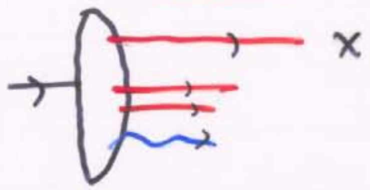
# Manifestations of QCD Quantum Fluctuations

Conformal predictions

Lepage SJB
Burkardt
Schmidt, SJB

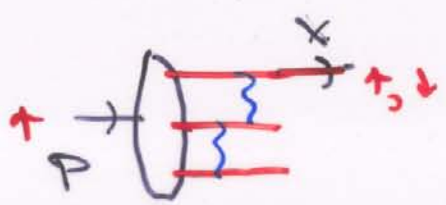
"Counting rules" at $x \to 1$

$$\boxed{F(x) \underset{x \to 1}{\sim} (1-x)^{2n_s - 1 + 2\Delta S_z}}$$



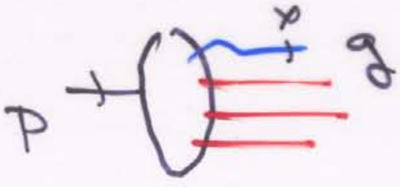

$$k_F^2 \sim \frac{-k_\perp^2 + m^2}{1-x} \to -\infty$$

Examples




$$q_{\uparrow/\uparrow} \sim (1-x)^3$$

$$q_{\downarrow/\uparrow} \sim (1-x)^5$$

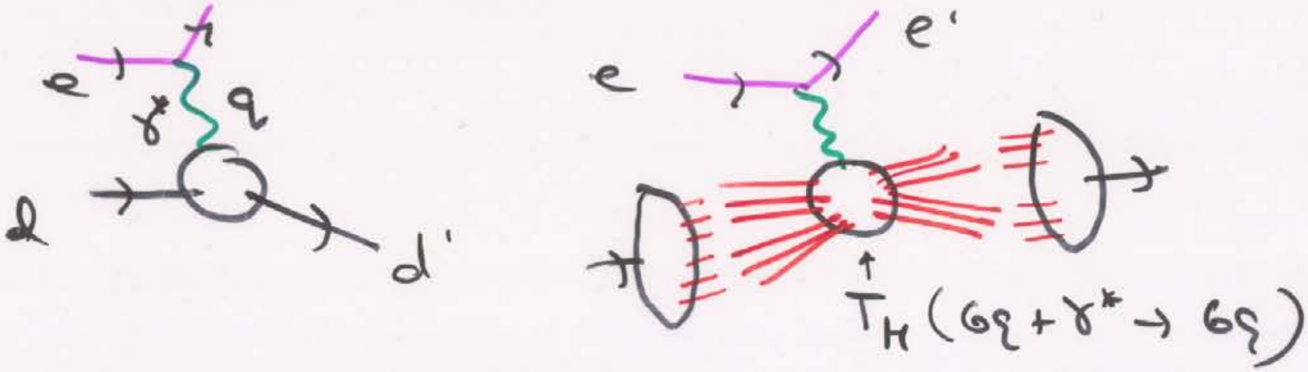



$$g_{\uparrow/\uparrow} \sim (1-x)^4$$

$$g_{\downarrow/\uparrow} \sim (1-x)^6$$

* Rigorous predicts of PQCD, Conformal Sym!
* No DGLAP evol at fixed $W^2$
* Violated by CTEQ6.1 $\quad \frac{g(x)}{q(x)} \overset{x \to 1}{\sim} \frac{1}{(1-x)^{.5}}$

# Deuteron Form Factor in QCD

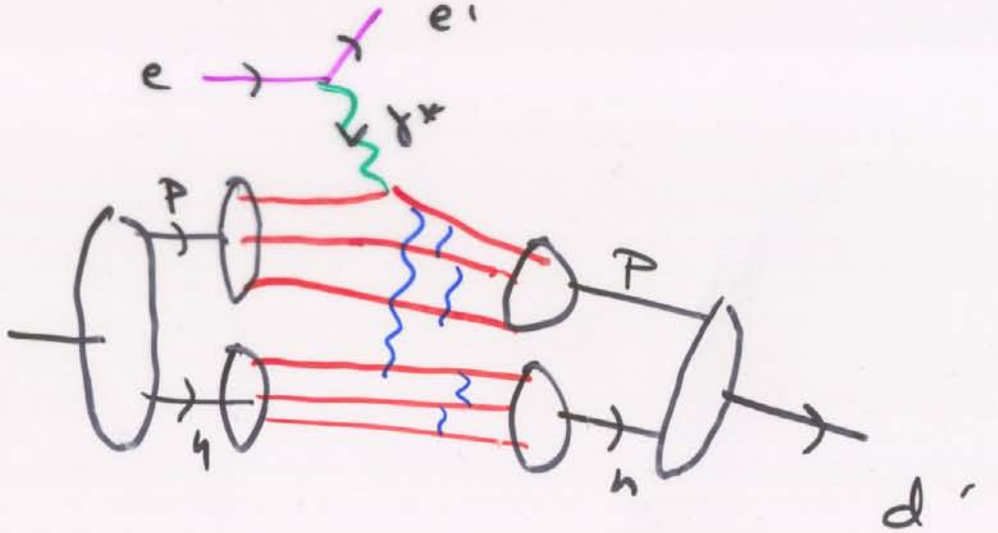


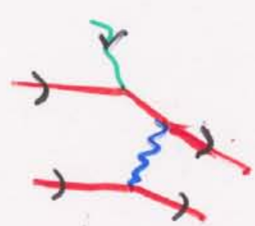

$$\text{PQCD}: \quad F_d(Q^2) \sim \left(\frac{1}{Q^2}\right)^5 \quad \text{large } Q^2$$

$$q^2 = -Q^2$$

# "Reduced Amplitude" formulation

B. Chertok
SJB



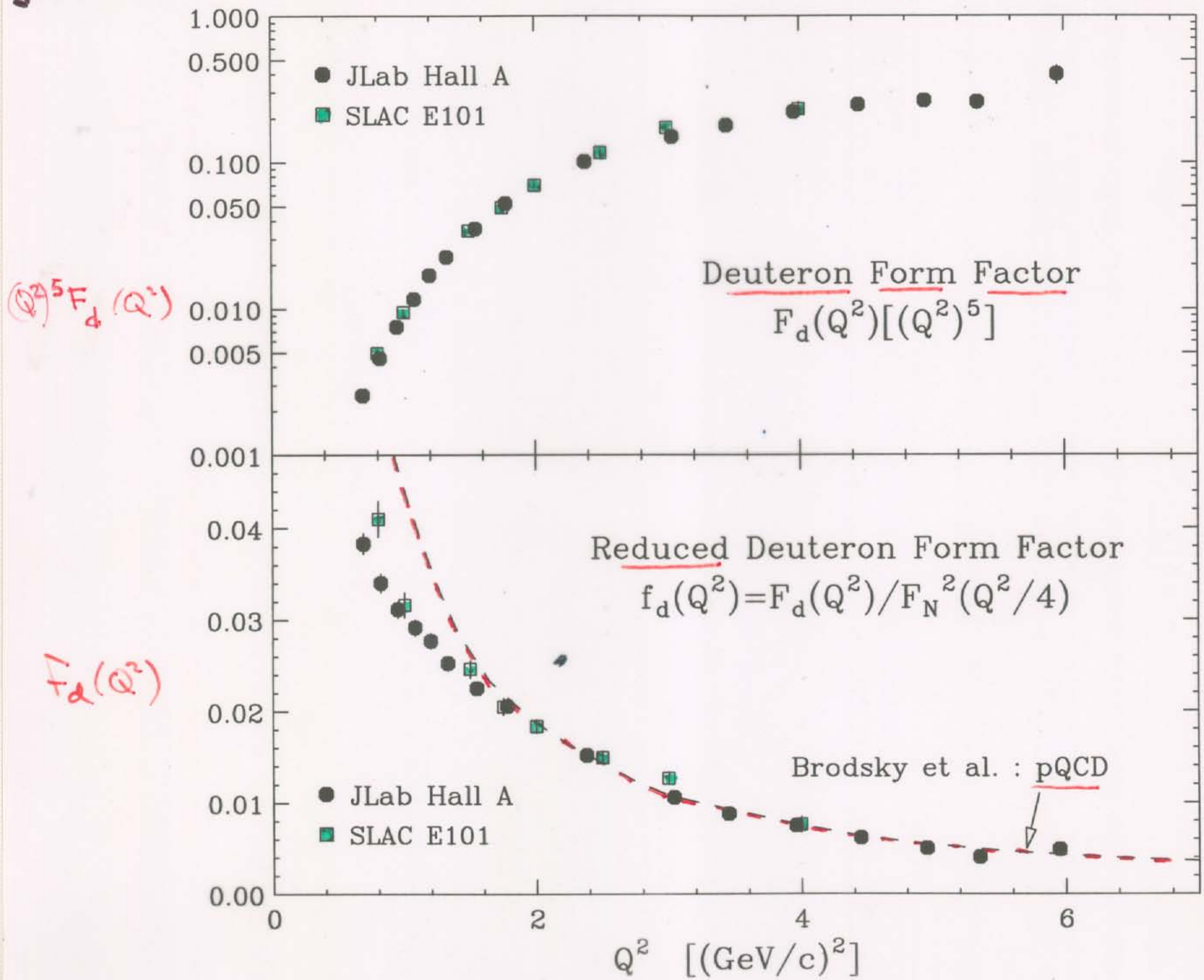
$F_d(Q^2) \sim f_\pi(Q^2)$

$$F_d(Q^2) \equiv F_p\left(\frac{Q^2}{4}\right) F_n\left(\frac{Q^2}{4}\right) f_d(Q^2)$$

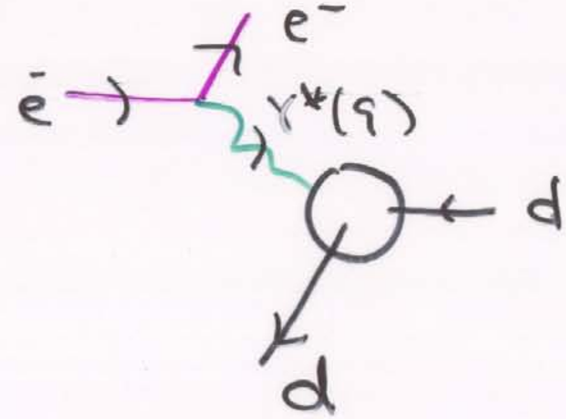
$$\text{PQCD}: \quad \boxed{f_d(Q^2) \sim \frac{1}{Q^2}} \quad \text{large } Q^2$$

18/17

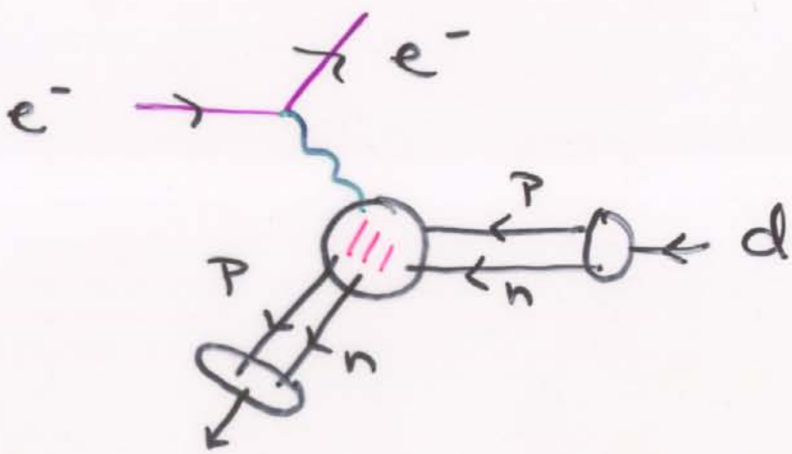
ref: L.C. Alexa, et al, submitted to PRL 10-28-98



# Exclusive Nuclear Processes




measure
deuteron form factors
$F_d(q^2)$ (3)




Chertok
Miller
SJB

Lepage
Ji
SJB

* $$F_d(Q^2) \equiv F_p\left(\frac{Q^2}{4}\right) F_n\left(\frac{Q^2}{4}\right) f_d(Q^2)$$

CFT / PQCD: $$f_d(Q^2) \sim F_\pi(Q^2) \sim \frac{1}{Q^2}$$

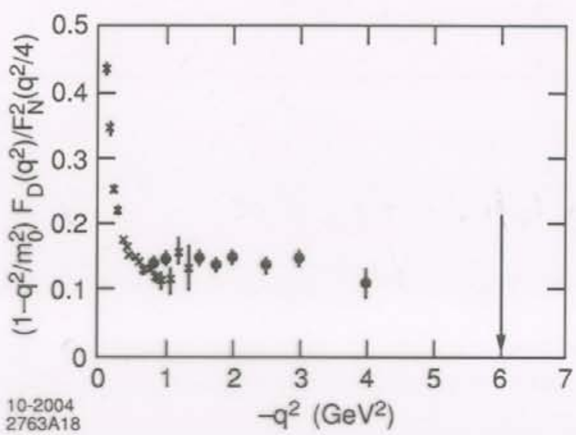
"reduced" nuclear form factor

B. Chertok
SSB

# Scaling of Reduced Form Factor

$$Q^2 F_d(Q^2) \to \text{const}$$

$$\left(1+\frac{Q^2}{M_0^2}\right) F_d(Q^2)$$




$M_0 = 450$ MeV

Two components!

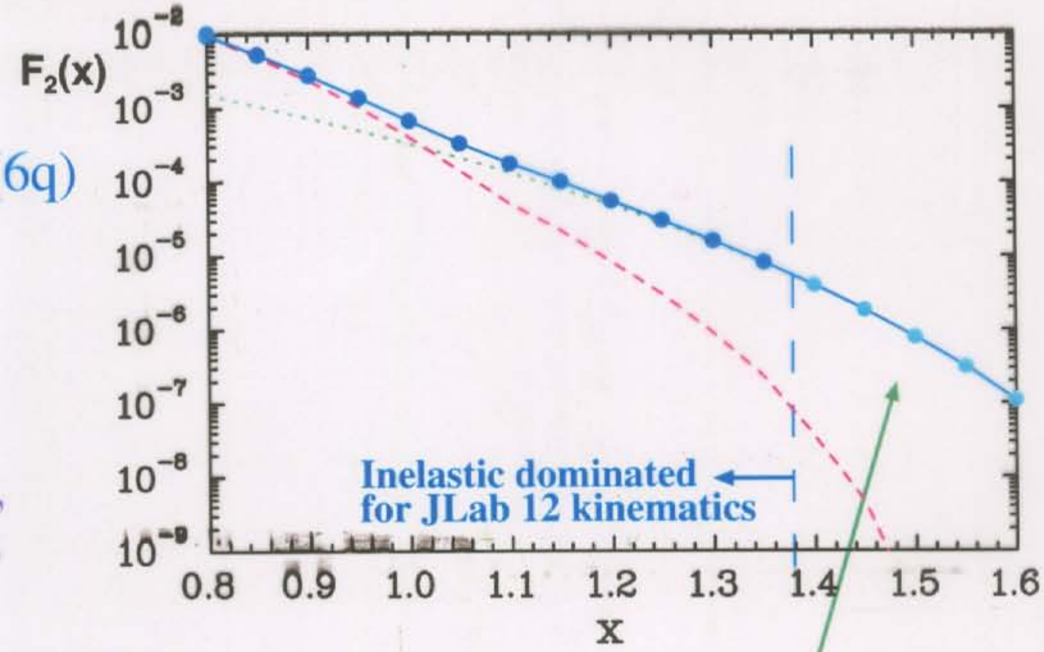
1) Fast falling, characteristic of nuclear size

2) $0.15 \times F_\pi(Q^2)$ ← mostly hidden color

# Quark distributions at x>1

Red curve: $^2H = p + n$

Blue curve: $^2H = 0.85(p+n) + 0.15(6q)$




Deuteron provides ***cleanest*** signature

*(we understand deuteron as p+n)*

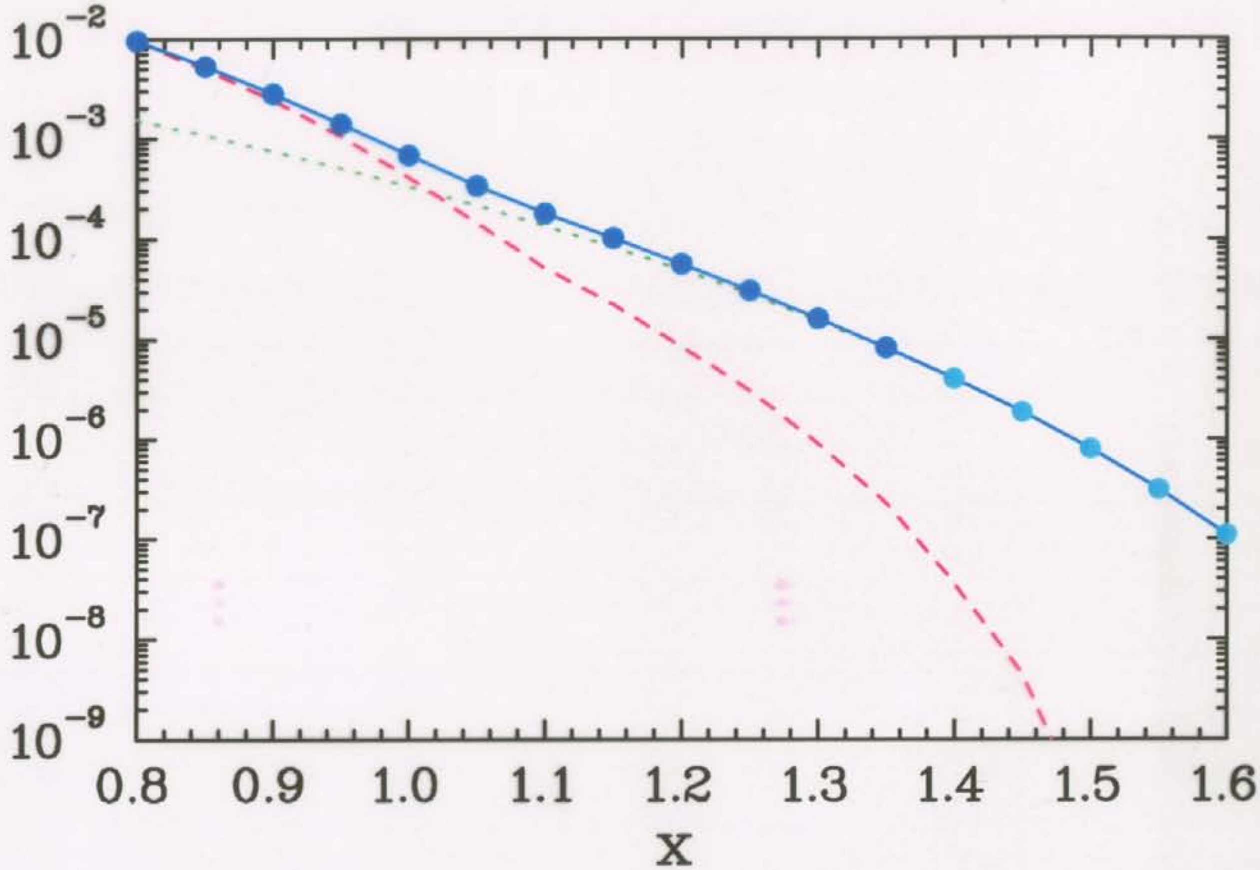
Heavy nuclei may yield ***larger*** signals, but need better understanding of SRCs for hadronic 'baseline'

Such a signal would provide *clear signature of deviation from a purely hadronic picture*

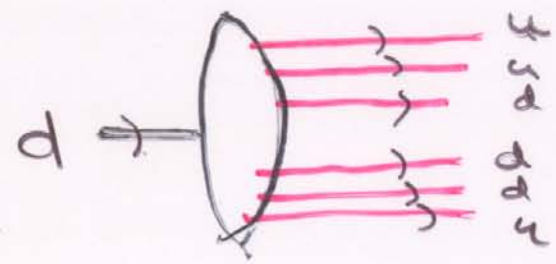
Expect any 'quark-mixing' between nucleons to increase strength at large x

Improved nuclear PDFs provides important input to other experiments

- Hard processes in hadron-hadron collisions
- Sub-threshold particle production measurements



$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
x




$$3_c \otimes 3_c \otimes 3_c \otimes 3_c \otimes 3_c$$
$$= 5 \times 1_c + \cdots$$

Five color-singlet combinations
– one is $n \times p$

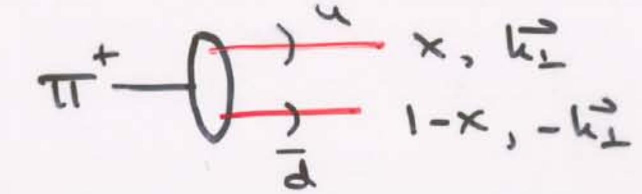



Gluon exchange produces hidden color components.

G.P. Lepage
SLB

# Pion Distribution Amplitude

$$\phi_\pi(x, Q^2) = \int \frac{d^2k_\perp}{16\pi^3}\, \psi^{(Q)}_{q\bar{q}/\pi}(x, \vec{k}_\perp)$$




$$\sim \psi_{q\bar{q}/\pi}\left(x, b_\perp \sim O\left(\tfrac{1}{Q}\right)\right)$$

$$\phi_\pi(x, Q) = \int \frac{dz^- P_\pi^+}{4\pi}\, e^{ix P_\pi^+ z^-/2}$$

$$\langle 0 | \bar{\psi}(0) \frac{\gamma^+\gamma^5}{2\sqrt{2n_c}} \psi(z) | \pi \rangle^{(Q)} \Big|_{z^+ = \vec{z}_\perp = 0}$$

Gauge Invariant!

$$P \exp \int_0^1 ds\, ig\, A(sz)\cdot z = 1 \quad \text{in } A^+ = 0 \text{ gauge}$$

$$= \int \frac{dk^-}{2\pi}\, \psi^{GI}_{BS}(k, p)$$

obeys: OPE, RGE, Evolution Eqs.

Lepage, SJB

NLO: Müller, etc

# Evolution Eqn. for Distribution Amplitudes

$$\phi_M(x,Q) = \int \frac{d^2k_\perp}{16\pi^3} \psi_{q\bar{q}}^{(Q)}(x, \vec{k}_\perp) \, \Theta\left(Q^2 - \frac{k_\perp^2}{x(1-x)}\right)$$

$$= x_1 x_2 \tilde{\phi}$$

$$\boxed{x_1 x_2 \frac{\partial}{\partial \ln Q^2} \tilde{\Phi}_M(x,Q) = \frac{\alpha_s(Q^2)}{4\pi} \int_0^1 dy \, V(x,y) \, \tilde{\phi}_M(y,Q)}$$

$$* \quad V(x,y) = 2C_F \, x_1 y_2 \, \theta(y_1 - x_1)\left(\delta_{h_1 \bar{h}_2} + \frac{\Delta}{y_1 - x_1}\right) + (1 \leftrightarrow 2)$$

$$\Delta\tilde{\phi} = \tilde{\phi}(y_1, Q) - \tilde{\phi}(x_1, Q)$$

$$x_1 = x, \quad x_2 = 1 - x$$

$\delta_{h_1\bar{h}_2} = 1$ opp hel

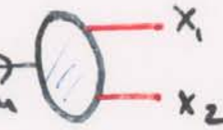
favors opp hel.

For baryons:

$$* \quad V(x_i, y_i) = 2x_1x_2x_3 \sum_{i \neq j} \theta(y_i - x_i)\,\delta(x_k - y_k)\,\frac{y_j}{x_j}\left(\frac{\delta_{h_i \bar{h}_j}}{x_i + x_j} + \frac{\Delta}{y_i - x_i}\right)$$

$\phi_M(x_i, Q)$

## Hadron Distribution Amplitude




$\frac{k_\perp^2}{x(1-x)} < Q^2$

- key non-perturbative input
  to hadronic exclusive processes
  at large momentum transfer

Rigorous results
Lepage, SJB

$$\phi(x_i, Q) \equiv \left(\ln \frac{Q^2}{\Lambda^2}\right)^{-n\gamma_n/2\beta_0}$$

$$\int \prod_{i=1}^{n} \{d^2 k_\perp^{(i)}\, \Theta(Q^2 - m_n^2)\}\, \delta^{(2)}(\Sigma \vec{k}_\perp^{(i)})\, \psi^{\mathrm{val}}(x_i, \vec{k}_\perp^{(i)})$$

$$\phi_M(x_i, Q) = x_1 x_2 \sum_n a_n\, C_n^{3/2}(x_1 - x_2) \left(\ln \frac{Q^2}{\Lambda^2}\right)^{-\gamma_n/2\beta_0}$$

Lepage
SJB
Efremov Radyushkin

non-perturbative input

from conformal symmetry

D. Müller
et al

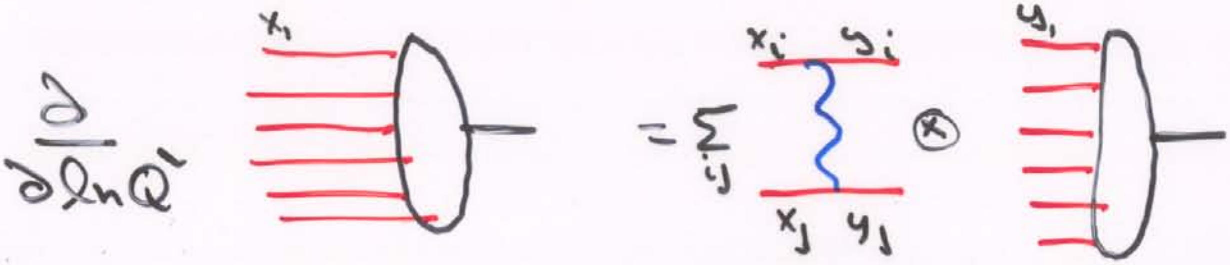
$$\zeta(Q^2) = \frac{1}{4\pi} \int^{Q^2} \frac{d\ell^2}{\ell^2}\, \alpha_s(\ell^2)$$

deviations from conformal symmetry

$$e^{-\gamma_n \zeta(Q^2)} \Rightarrow \left(\ln Q^2/\Lambda^2\right)^{-\gamma_n/2\beta_0}$$

Ji, Lepage, S & B
PRL 51, 83 (1981)

Evolution of deuteron distribution amplitude




$$\tilde{\Phi} = V \otimes \tilde{\Phi}$$

5x1 5x5 5x1

$$\prod x_k \left[\frac{\partial}{\partial \zeta} + \frac{3C_F}{\beta}\right] \tilde{\Phi}(x_i, Q)$$

$$= -\frac{C_d}{\beta} \int_0^1 [dy]\, V(x_i, y_i)\, \tilde{\Phi}(y_i, Q)$$

$$\zeta(Q^2) = \frac{\beta}{4\pi} \int_{Q_0^2}^{Q^2} \frac{dk^2}{k^2}\, \alpha(k^2)$$

$$V(x_i, y_i) = 2 \prod x_k \sum_{i \neq j} \theta(y_i - x_i) \prod_{l \neq i,j} \delta(x_l - y_l)$$

$$\frac{y_j}{x_j}\left(\frac{\delta_{h_i \bar{h}_j}}{x_i + x_j} + \frac{\Delta}{y_i - x_i}\right)$$

$$C_d = \frac{1}{5} S^{d}_{ijklmn} \left(\tfrac{1}{2}\lambda_a\right)_i^{i'} \left(\tfrac{1}{2}\lambda_a\right)_j^{j'} S_d^{i'j'klmn}$$

QCD predictions:

$$\tilde{\Phi}(x_i, Q) \propto \int^{k_{\perp i} < Q} [d^2 k_\perp] \tilde{\Psi}_{qqq\,qqq}(x, \vec{k}_\perp)$$

$5 \times 1$

Evolution in $\log^{\gamma_n} Q^2 \, P_n(x_i)$

Consistent with OPE

$$\Psi(x, k_\perp) \sim \left[\frac{1}{k_\perp^2}\right]^5 \text{ modulo logs}$$

$$k_\perp^2 > \Lambda^2_{QCD}$$

Same ingredients as DGLAP!

Consistent with AdS/CFT

$\gamma_n, P_n$ Determined by conformal symmetry

5 color singlets! 1 is n p

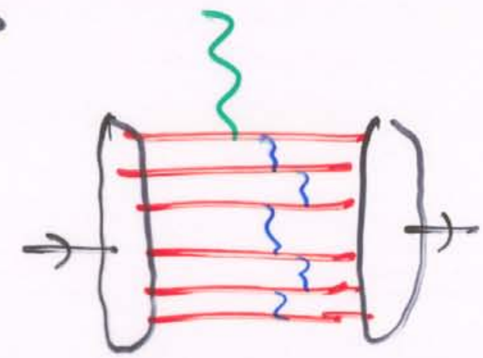
$Q^2 \to \infty$ all equal

$$\Phi \to x_1 x_2 x_3 x_4 x_5 x_6$$

80% Hidden color.

# Phenomenological Consequences of Hidden Color

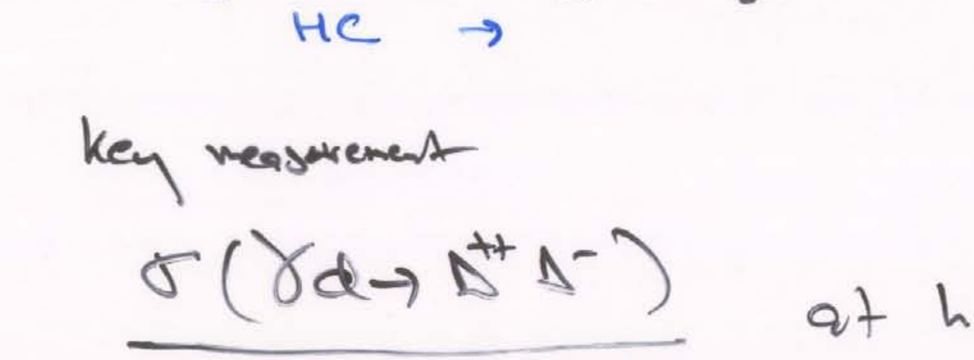
1. Crucial contribution to hard deuteron processes



Normalization of $F_d$ enhanced by H.C.

Farrar et al

2. $\Delta^{++}\Delta^{-}$ contribution comparable to pn at short distance




Key measurement

$$\frac{\sigma(\gamma d \to \Delta^{++}\Delta^{-})}{\sigma(\gamma d \to n p)}$$ at high $p_T$

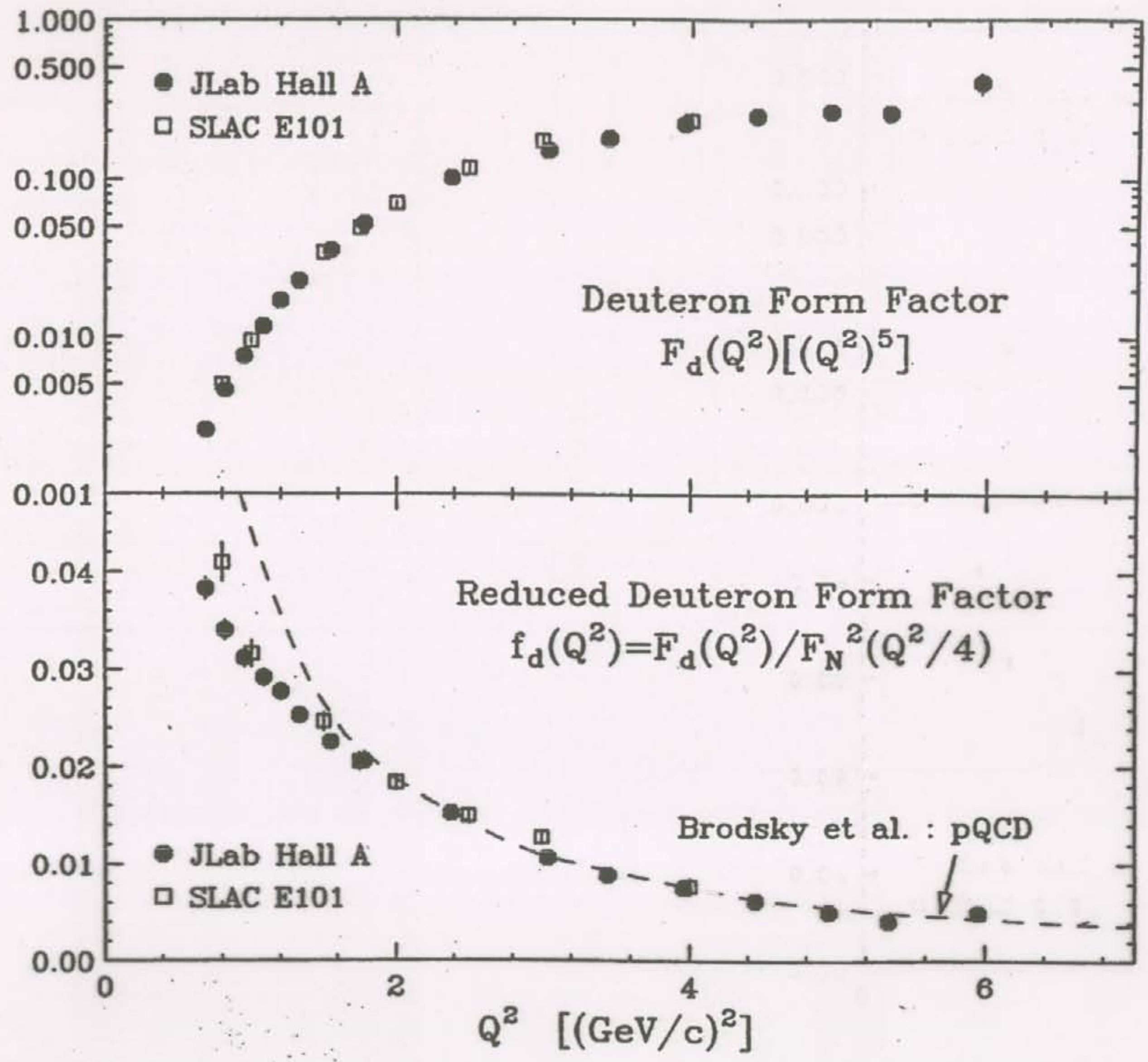
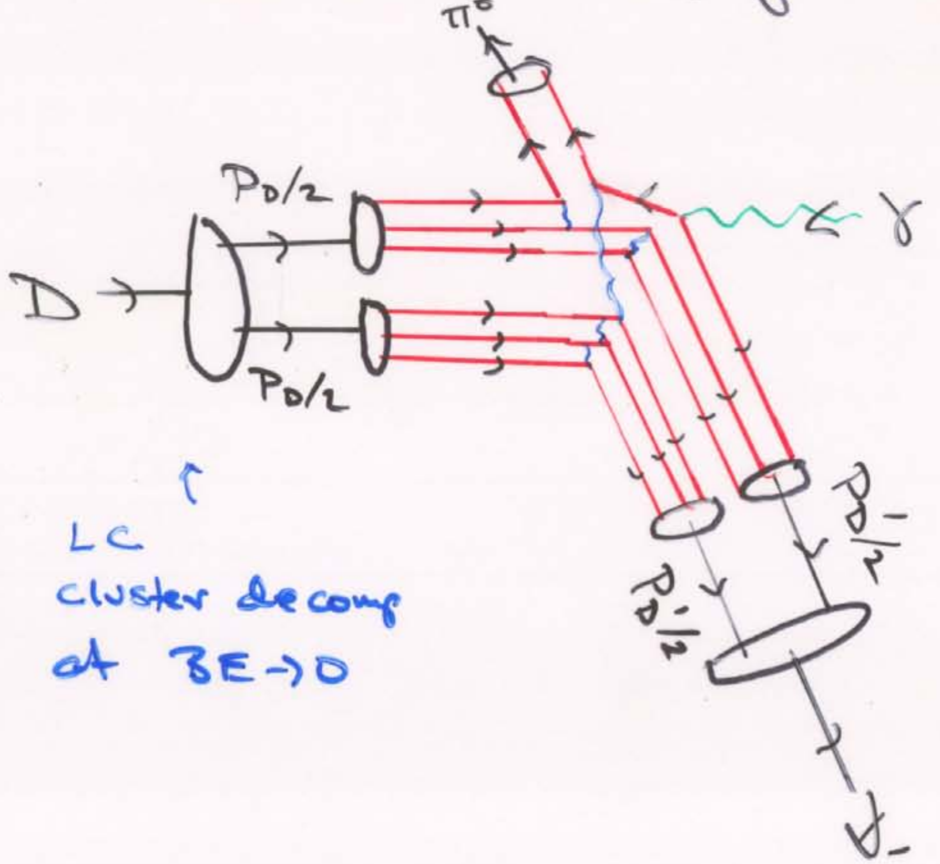



FIG. 4. The deuteron form factor $F_d(Q^2)$ times $(Q^2)^5$ (top) and the reduced deuteron form factor $f_d(Q^2)$ (bottom) from this experiment and from SLAC [4]. The curve is the asymptotic pQCD prediction of Ref. [15] for $\Lambda = 100$ MeV, arbitrarily normalized to the data at $Q^2 = 4$ (GeV$/c)^2$.

L C Alexa et al / PRL 82, 1374 (99)

Hiller Ji
Miller SJB

Reduced Amplitude Scaling for $\gamma D \to \pi^0 D'$




$$\mathcal{M}_{\gamma D \to \pi^0 D}(u,t)$$

$$= F_D(t)\, \mathcal{M}_{\gamma N_1 \to \pi^0 N_1}\left(\tfrac{u}{4}, \tfrac{t}{4}\right) F_{N_2}(t/4)$$

monopole from eD→eD

from data

dipole from eN→eN

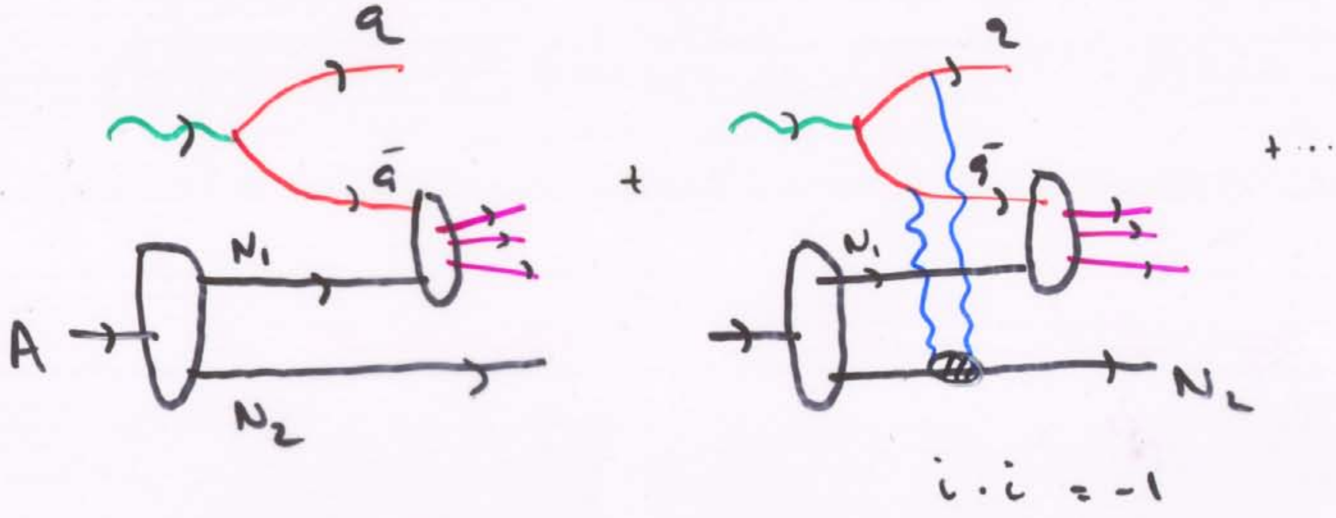
PQCD Scaling: $p_T^{11} \mathcal{M}_{\gamma D \to \pi^0 D}(p_T, \theta_{cm})$

$$= \left(p_T^2 f_D\right)\left(p_T^5\, \mathcal{M}_{\gamma N \to \pi^0 N}\right) p_T^4\, F_N(t/4)$$

$$= \text{const.}$$

# Diffractive Deep Inelastic Scattering

## leads to Nuclear Shadowing ($B_j$-scaling)

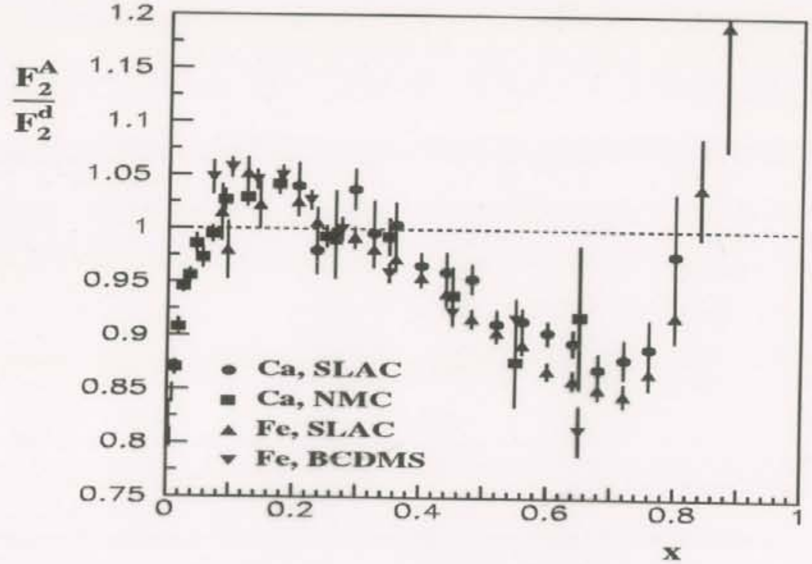



one-step

two-step

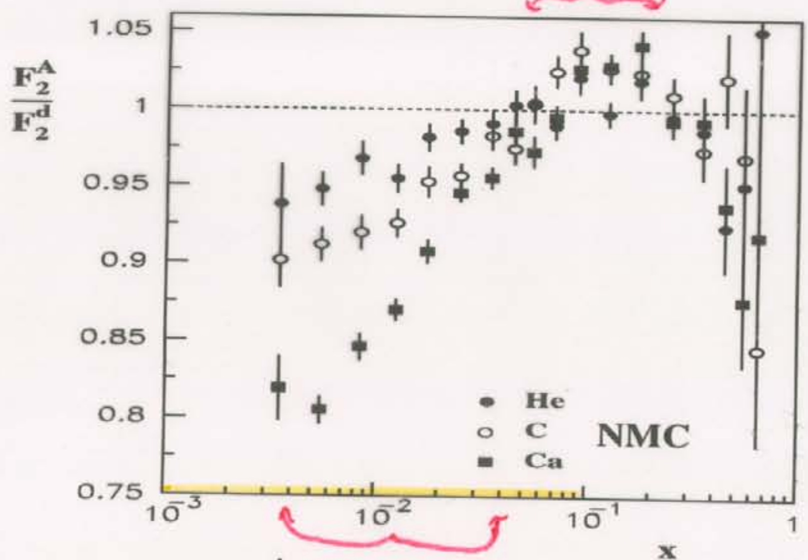
* Amplitudes destructively interfere!
* Flux on back face diminished
* Depletion of $\dfrac{F_{2A}(x)}{A\,F_{2N}(x)}$ at small $x$ (high energy)
* Shadowing not built into $\psi_A(x_i, \vec{k}_{\perp i})$!
* Enhanced by H.C.?

# Nuclear structure functions




antishadowing

$$x = \frac{Q^2}{2p\cdot q} = \frac{Q^2}{2M\nu}$$

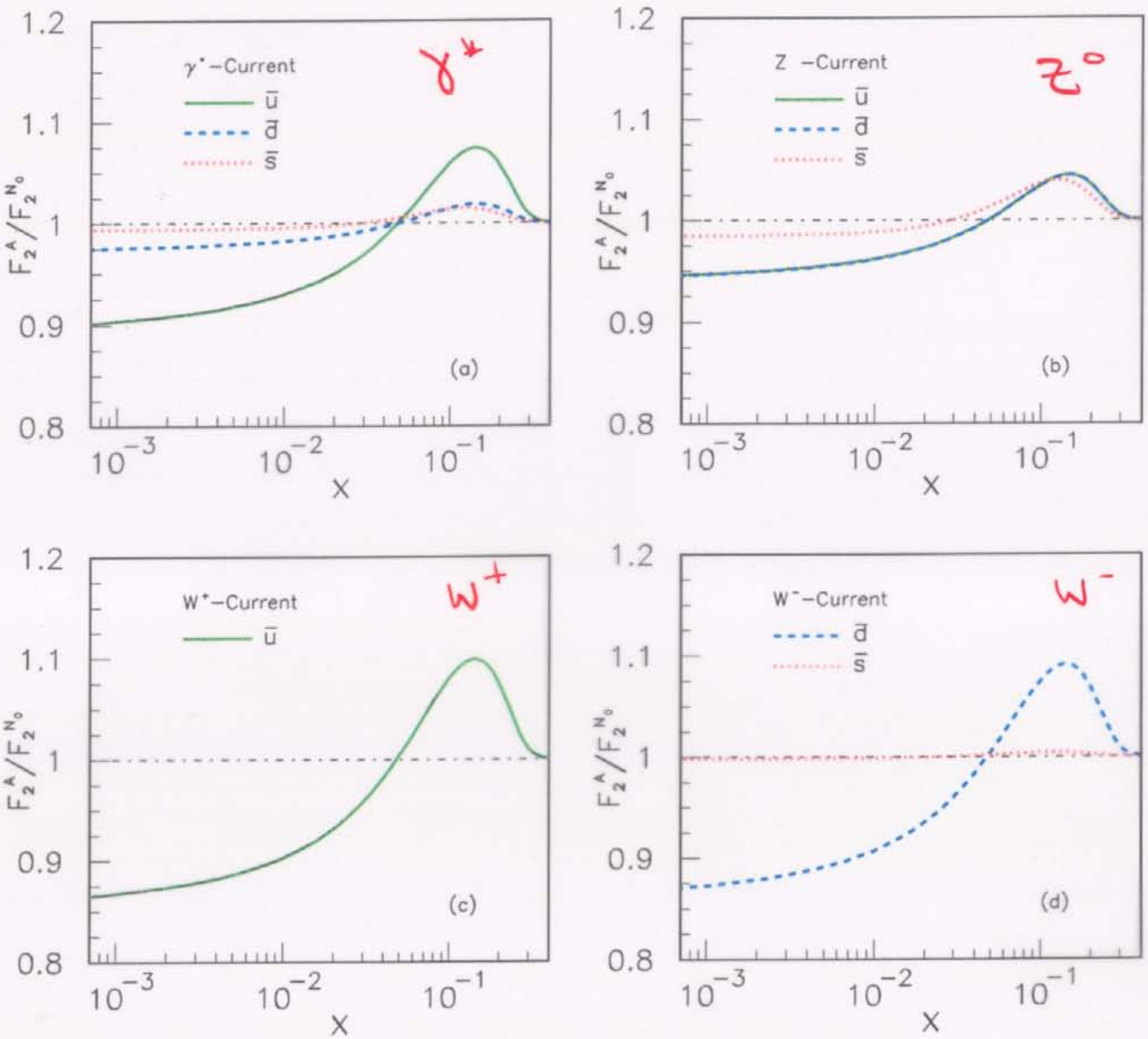


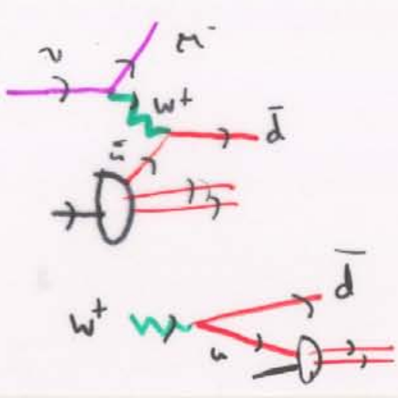

shadowing at small x (high energy)

coherence length of hadronic configurations

$$\lambda \simeq \frac{1}{Mx} > 2\,\mathrm{fm} \leftrightarrow x < 0.1$$

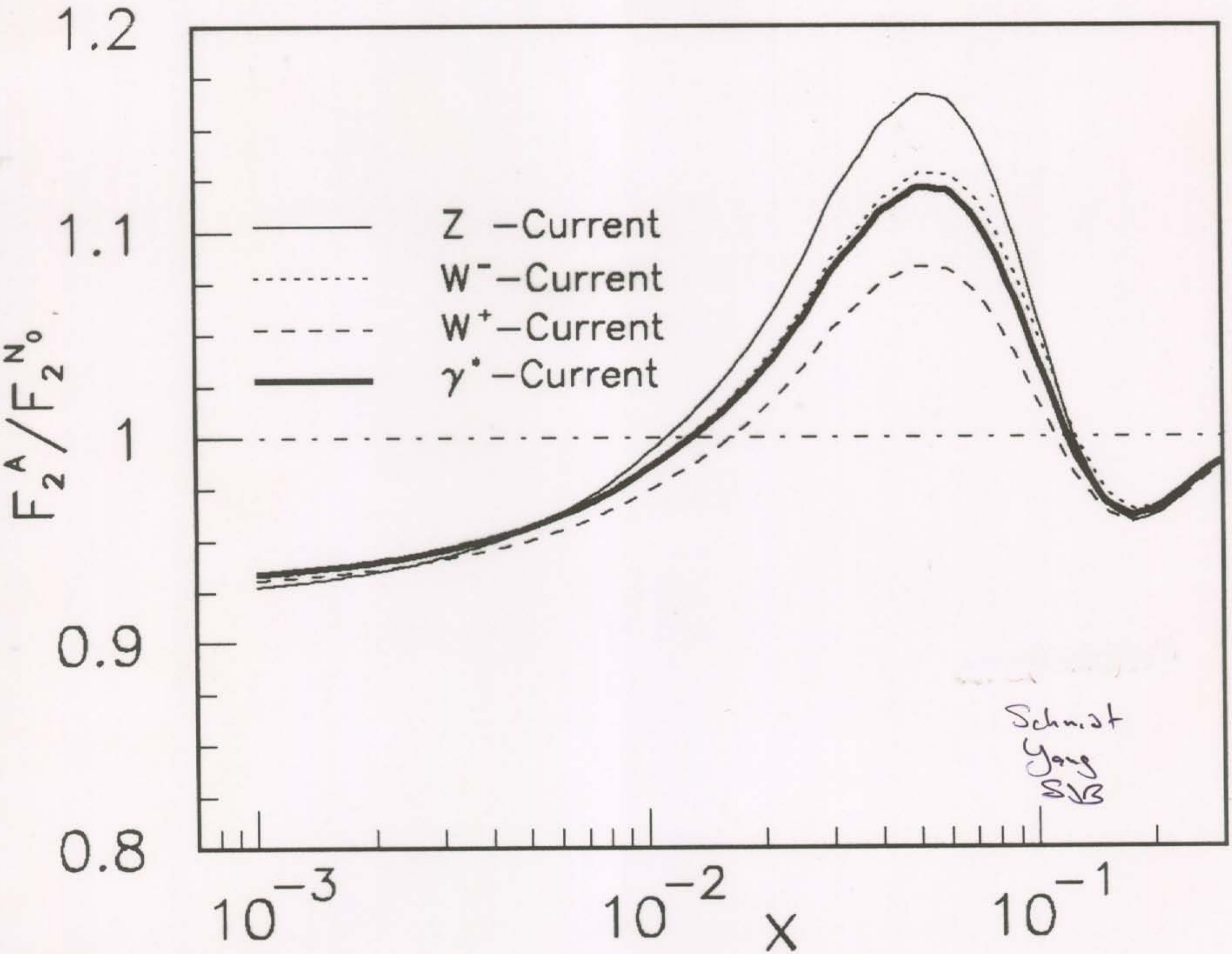
(preliminary)
BSJ




⇒
Lab

Shadowing / antishadowing
depends on current
$\gamma^*$ : $W^\pm$ : $Z^0$


1.2
1.1
1
0.9
0.8
$F_2^A/F_2^{N_0}$
Z -Current
$W^-$-Current
$W^+$-Current
$\gamma^*$-Current
$10^{-3}$
$10^{-2}$
$10^{-1}$
x
Schmidt
Yang
SJB

# Nuclear QCD Effects

* Antishadowing of nuclear structure functions

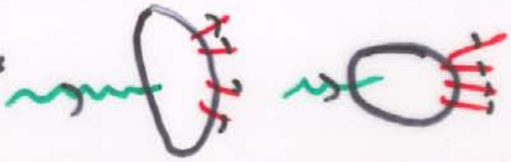
Flavor-dependent?

$\gamma^* A \to \phi X$ test $s, \bar{s}$

Schmidt, Yang SJB

* Anomalous shadowing

$\gamma^* d_\uparrow \to X$




geometrical effect

* Nuclear SSA

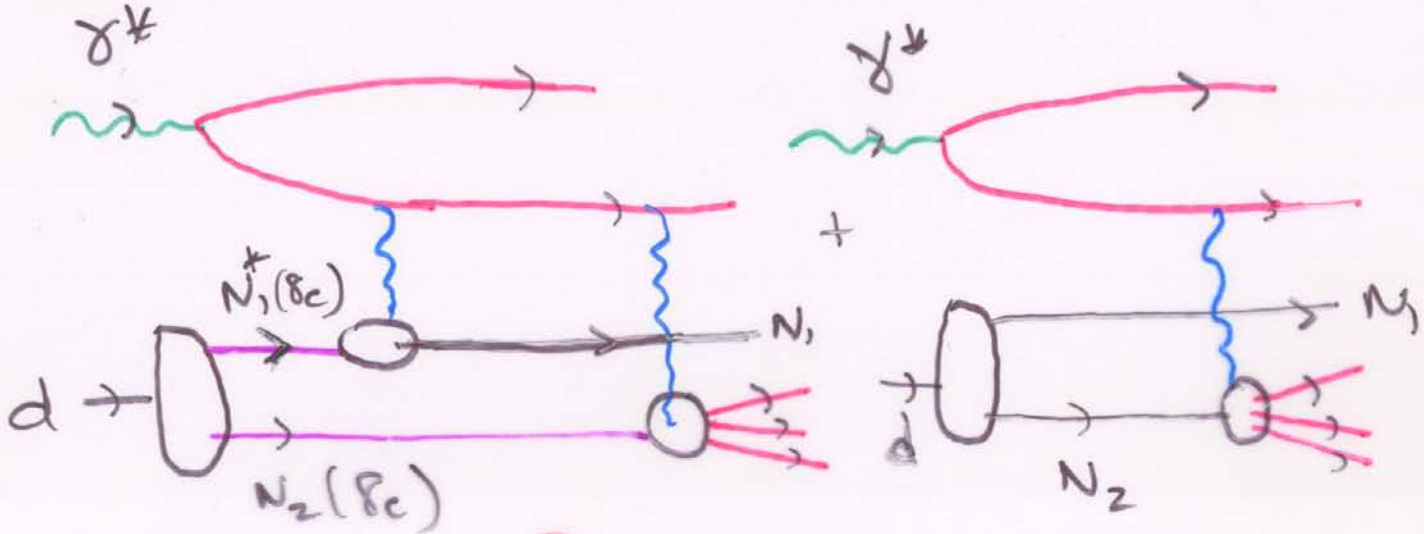
transversity in deut.

$\gamma^* d_\uparrow \to \pi X$

Sivers: enhanced by hidden color?

* Shadowing of $\sigma_L(\gamma^* A)$

# Manifestation of Hidden Color in Deuteron




i

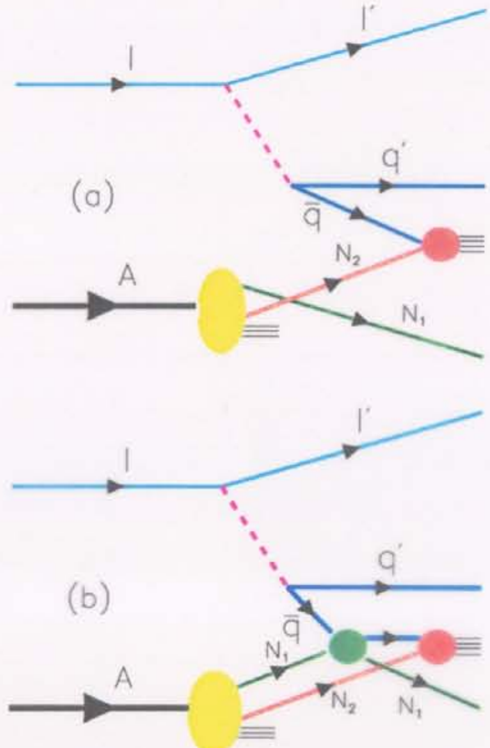
* Same final state but Im × Re

* Single-Spin Asymmetry, Shadowing, antishadowing

$$i \vec{S}_{N_1} \cdot \vec{q} \times \vec{p}_{N_1}$$

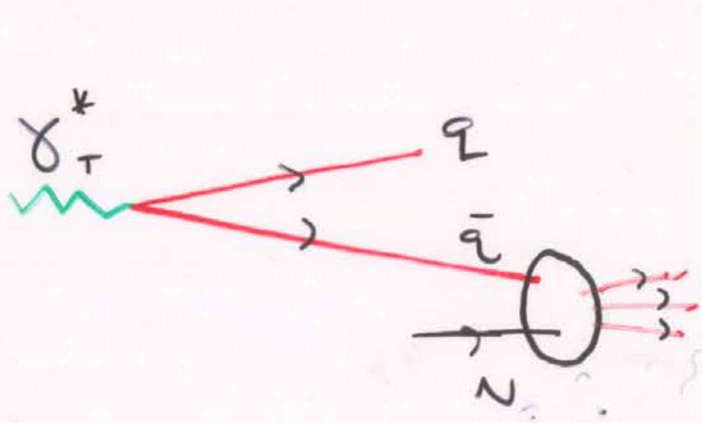
$$i \vec{S}_d \cdot \vec{q} \times \vec{p}_{N_1}$$

* Hidden color needed for $F_d(Q^2)$



l
l′
(a)
q′
q̄
N₂
A
N₁
l
l′
(b)
q′
q̄
N₁
A
N₂
N₁

H. Lu + SJB




aligned jet model

Bjorken

$$q_N(x) = C_1 \frac{x}{1-x} \int ds\, d^2k_\perp \, \mathrm{Im}\, T_{\bar{q}N}(s, \mu^2)$$

$$\mu^2 = -x \frac{(s + k_\perp^2)}{1-x} + x M^2 - k_\perp^2$$

Landshoff
Polkinghorne
Short

Connects $q_N(x)$, $q_A(x)$ to $\sigma_{\bar{q}N}, \bar{q}A$

$$T_{\bar{q}N}(s, \mu^2) = i s \beta_1(\mu^2)$$
$$+ (1-i) s^{1/2} \beta_{1/2}(\mu^2)$$
$$+ i s^{-1} \beta_{-1}(\mu^2)$$

Reproduces $F_{2N}(x)$, Pomeron, Reggeon, Val.
$q(x) \sim \Sigma \beta x^{-\alpha}$

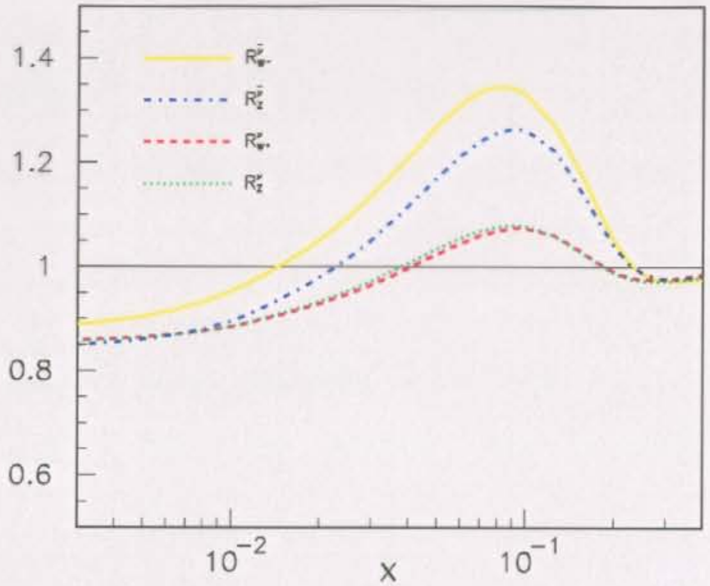



Figure 11: The nuclear effect on the cross sections of CC and NC neutrino-nucleus DIS. The dotted and dashed curves almost overlap.

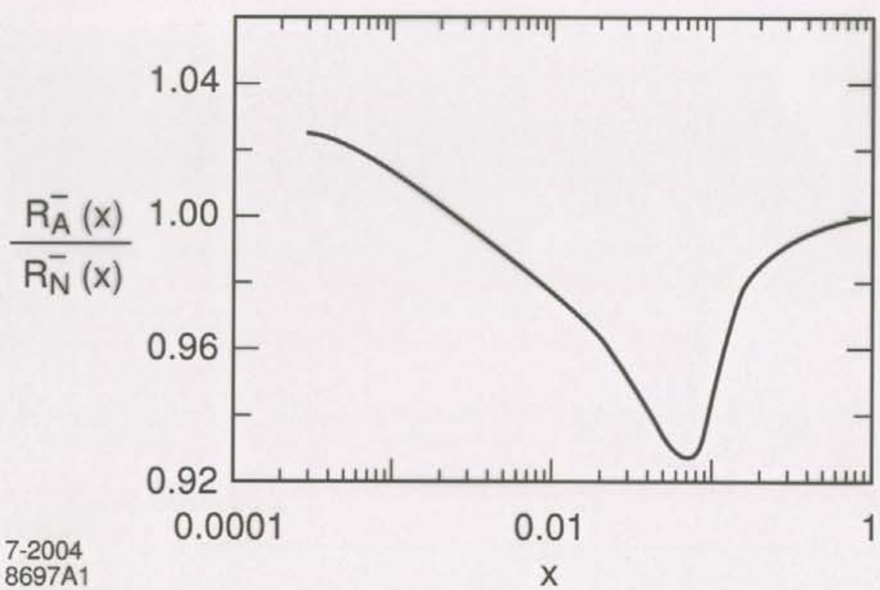



Figure 12: The nuclear effect on the Paschos-Wolfenstein ratio of differential cross sections $R_A^-(x)/R_N^-(x)$.

I. Schmidt
J.J. Yang
SJB

$\boxed{\text{Antishadowing}}$

constructive interference !

* Reggeons (constrained by k-W)
* Odderon
* Pseudoscalar Reggeon
* Hidden color

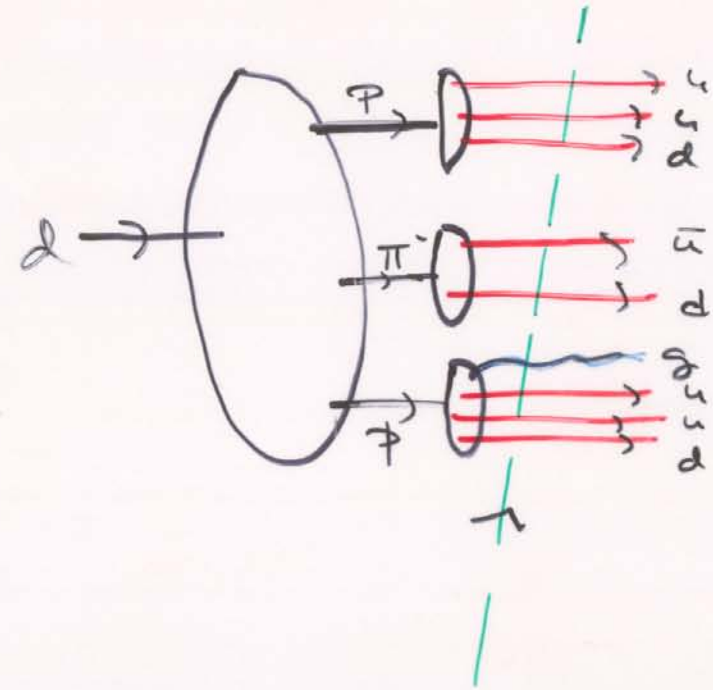
Central point:

$\left\langle \begin{array}{l} \text{Flavor specific} \\ \text{not universal} \end{array} \right\rangle$

Different antishadowing for charged, neutral current !

Affects $\sin^2\theta_W$ extraction !

NuTeV



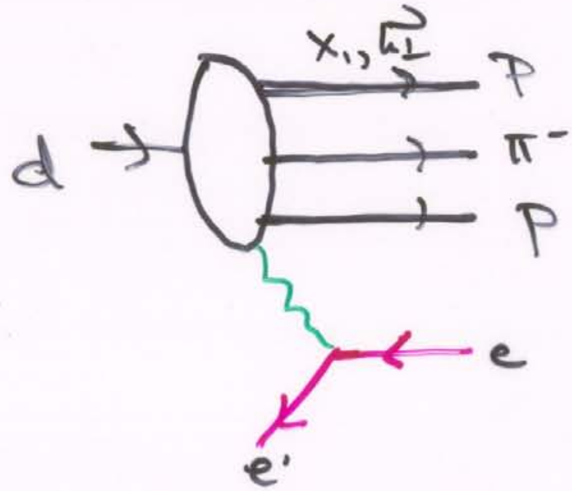

Sample $\Psi_d$ at fixed $\tau = t + z/c$

'Tis a mistake / Time flies not ;
it only hovers on the wing /
Once born the moment dies not /
tis an immortal thing.

Montgomery

Light Front Time !

Coulomb dissociation of nuclear light-front wf




$$\frac{\partial}{\partial k_\perp} \psi_{pp\pi^-/d}(x, \vec{k_\perp})$$

$$x_1 = \frac{k_p^+}{P_d^+} = \frac{k_p^0 + k_p^z}{P_d^0 + P_d^z}$$

fundamental measure of nuclear dynamics

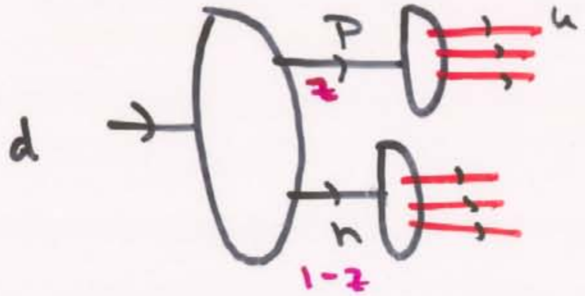
Boost invariant relativistic wavefunctions

$$\gamma^* d \to p p \pi^-, \ldots$$

$$\Delta^{++} \Delta^-$$

exclusive nuclear processes

# Cluster decomposition of nuclear LFWFs




$$\psi_d = \psi_{np/d} \otimes \psi_p \otimes \psi_n$$

convolution

Valid at $z \sim 1/2$, weak binding

⇒ Cluster decomposition theorem ✓ — Namyslowski. Ji + SJB

But: $$k_p^2 = m_p^2 + z\left[M_d^2 - \frac{k_\perp^2+m_p^2}{z} - \frac{k_\perp^2+m_n^2}{1-z}\right]$$

Far off shell at $z \to 1$

$$F_p(Q^2, k_p^2) = \frac{1}{\left[Q^2 + m_\rho^2 + m_p^2 - k_p^2\right]^2}$$

medium dep. form factors

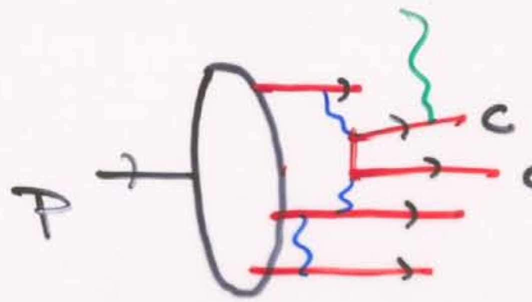
- Slow fall-off at large $|k_p^2|$
- smaller magnitude at large $|k_p^2|$
- EMC Effect? $q_A(x, Q^2)$

Chudakov
Hoyt
SJB
Laget

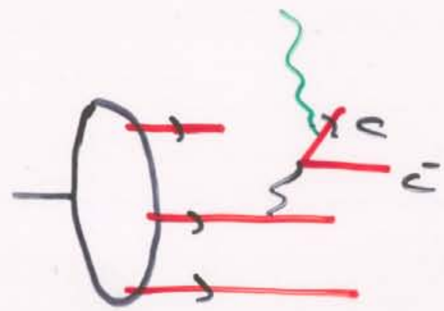
# $\boxed{\text{Charm Production near Threshold}}$

$$\gamma p \to J/\psi\, X \quad , \quad \Lambda_c D$$

$$\gamma A \to J/\psi\, X$$




intrinsic
high $x_c$




extrinsic
small $x_c$
(inefficient near threshold)

$P_{IC} \sim \frac{1}{m_c^2}$ non-abelian only

Nuclei:

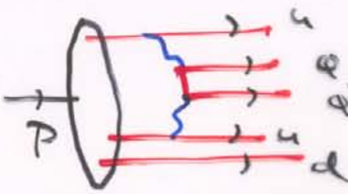
enhanced by Fermi motion
hidden color

Hunt at Cornell

PQCD, Conformal symmetry (AdS/CFT)

$\Rightarrow$ power-law fall-off at large $\mathcal{M}^2$

$$\mathbb{P}(\mathcal{M}^2) \sim \frac{1}{\mathcal{M}^2}$$




∴ Important Fock states have minimal $\mathcal{M}^2$

$$\mathcal{M}_n^2 = \sum_{i=1}^{n} \frac{m_{\perp i}^2}{x_i} \Rightarrow x_i \sim \frac{m_{\perp i}}{\sum_{j=1}^{n} m_{\perp j}}$$

* Corresponds to small rel $v_i$ in rest frame

equal $y_i$ in moving frame

*** heavy quarks have maximal $x$ !

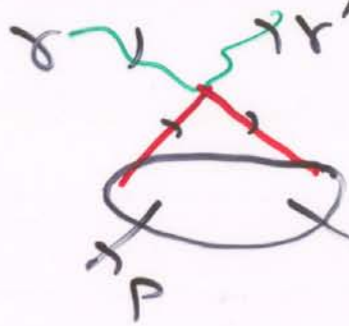
$$\boxed{x_Q \sim \frac{m_{\perp Q}}{\sum_{j=1}^{5} m_{\perp j}}}$$

Damashek + Gilman
SJB; Close, Gunion

# Compton Scattering

J=0 Sum Rule:

not mimicked by duality



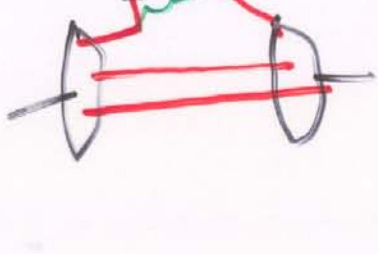

$$s^0 F(t)$$

$$F(t) = \sum e_q^2 \langle \tfrac{1}{x} \rangle$$

$$\alpha_R(t) = 0 \quad \text{all } t \ !$$

all $q^2$

Distinctive property of local interactions

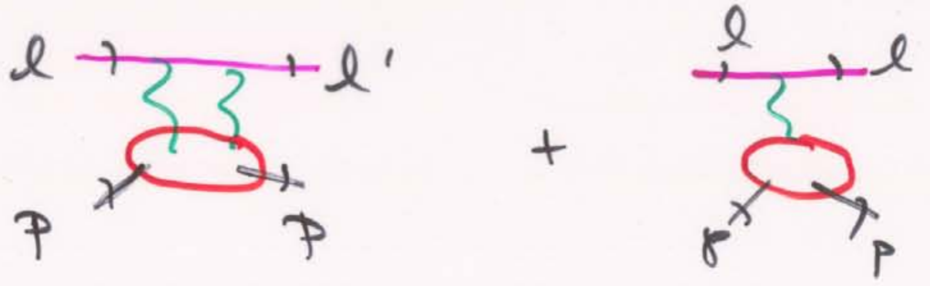


Instantaneous fermion exchange

$$\gamma^i \frac{\gamma^+}{k^+} \gamma^j$$

Test in $\gamma p \to \gamma p$, $\gamma d \to \gamma d$

$\gamma^* p \to \gamma p$, $\gamma^* p \to \gamma \gamma^*$



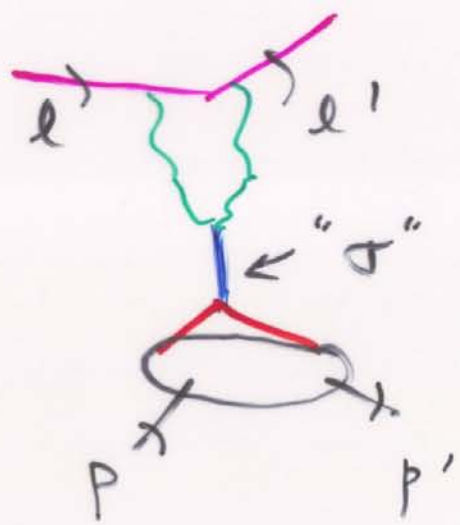

complicated Rosenbluth sep.

Nuclear case?

Blunden
Melnitchouk

Afanasev
Carlson
Vanderhaeghen
S,B

J=0 :




elementary
spin 0

Regge expansion $\sum_k \beta_k(t)\, \alpha_k(t)\, \xi(t)$

$\alpha_J(0) = 0$ all $t$

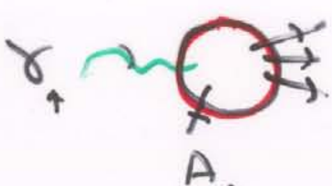
# DHG Sum Rule

$$8\pi^2 \mu_A^2 = \int_{\nu_{Th}}^{\infty} \left[\sigma^P_{\gamma A} - \sigma^A_{\gamma A}\right] \frac{d\nu}{\nu}$$

DHG
valid for nuclei!

Primak, S & B

Why is the sum rule
unaffected by nuclear shadowing?




absorption on
front surface

Color transparency ⇒ gauge principle

$\frac{d\sigma}{dt}(\gamma p \to \pi^+ n)$ in nuclei

Quark hadronization in nuclear environment

$$D^{A}_{\pi/q}(z, Q^2) \to D_{\pi/q}(z, Q^2) + O\left(\frac{1}{\nu}\right)$$

from e+e- → X

Formation length

color transparency

LPM $\Delta E \sim \text{const} \times L^2$, not $\Delta E \propto E$

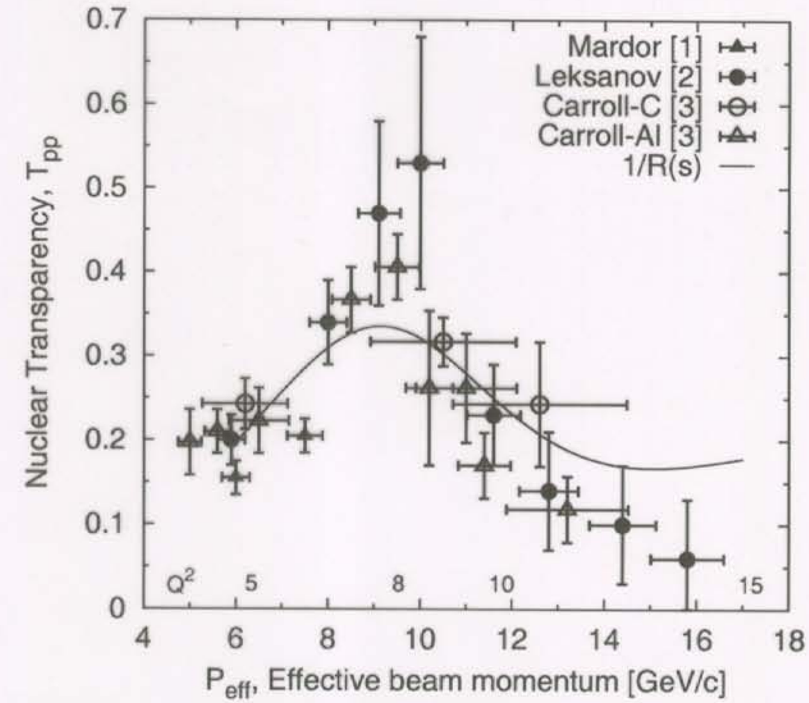
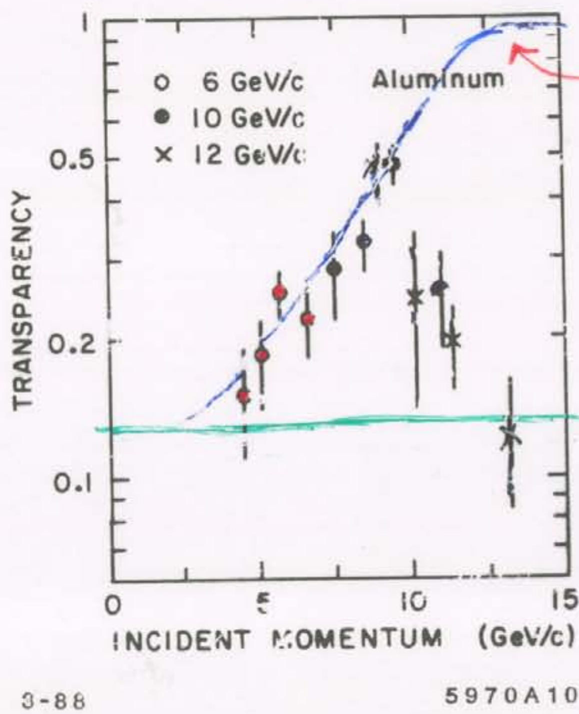



FIG. 18: The $T_{pp}$ values for Carbon and the aluminum (scaled by $(27/12)^{1/3}$) are plotted versus their $P_{eff}$ values. For a single incident beam momentum, $P_1$, a range of $P_{eff}$ values is obtained by using Equation 6. This allows us to place more points on the nuclear transparency curve and extend the range of momenta. The curved line is the inverse of R(s) defined by Equation 24, and adjusted with an amplitude for a best fit to the magnitudes of the measured transparencies. The horizontal error bars represent the total spread in effective momentum resulting from the accepted $\alpha_0$ range. A $Q^2$ $[(GeV/c)^2]$ scale is included at the bottom of the figure.

Test of Color Transparency

quasi-elastic $pp \to pp$ in Al

$\frac{Z_{eff}}{Z}$




QCD expectation (schematic)

"Glauber" energy independent!

$\sigma_{pN} = 36$ mb

{ Heppelman
{ Lee + Miller

$$\frac{Z_{eff}}{Z} = \frac{\frac{d\sigma}{dt}\left(pA \to pp(A-1)\right)}{Z\,\frac{d\sigma}{dt}(pp \to pp)}$$

Expt: BNL

Carroll, Heppelman, et al.

Explanation of decrease at 12 GeV/c

SJB + de Teramond : charm threshold

Ralston + Pire : pinch singularity

## Nuclear Physics + QCD

A Scientific Revolution!

### Nuclear Properties

* PQCD Predictions for hard nuclear amplitudes
* "Reduced Nuclear Amplitude" ← AdS/CFT
* "Hidden Color" of Nuclear Wavefunctions
* Nuclear-Bound Quarkonium
* Quark-Gluon Plasma - Gluon Avalanche

+ pentaquarks, octoquarks, gluonium

### Nuclear Testing Ground for QCD

* Factorization Theorems
* Color Transparency - Fluctuating State
* Diffraction of Hadrons to Jets
* Shadowing / Anti-shadowing, Diffraction
* Energy Loss - LPM Effect
* Single-Spin Asymmetries - FSI ISI

### Nuclear Physics ⇔ QCD Interface

$\chi$ Effective Theory ⇔ $\mathcal{L}_{QCD}$

$\chi SSB$

# Novel Aspects of QCD:

* Exotic hadronic spectra
  - Gluonia $gg$ $ggg$
  - Hybrids $\bar{q}qg$
  - Pentaquarks $qqqq\bar{q}$
  - Octoquarks $qqqqqq Q\bar{Q}$
  - Nuclear-bound quarkonia
* Hidden Color in Nuclei
* Color Transparency
* Single Spin Asymmetries, $A_{NN}$
* Diffraction: DDIS, Pomeron, Odderon
* Intrinsic Charm, Bottom, Strangeness
* Shadowing, Anti-shadowing
* $q, g$ plasma; new phases