Probing high x structure of nuclei with EIC

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#motivations:

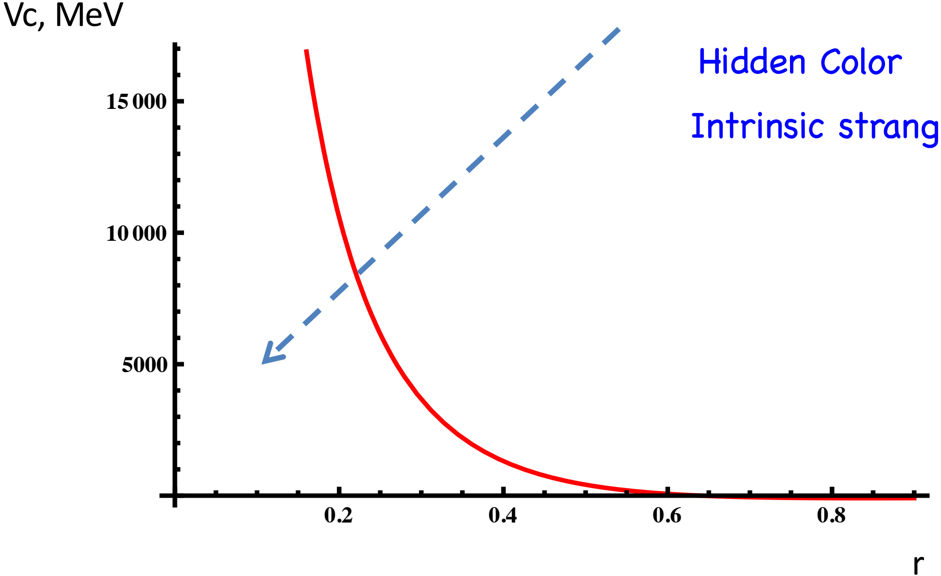
- Baryon-Quark transition in Cold Nuclear Matter

  (Origin of nuclear forces at short distances)

  - Origin of the repulsive NN core
  - Color non-singlet/hidden color states
  - Gluonic content of NN core

Existence of cold quark-matter

NN potential



Perturbative QCD

Hidden Color

Intrinsic strangeness/charm

~80% hidden color

Brodsky,Ji, Lepage, PRL 83

Probing the Deuteron at Short Distances

$$\Psi_d = \Psi_{pn} + \Psi_{\Delta\Delta} + \Psi_{NN^*} + \Psi_{hc} \cdots$$

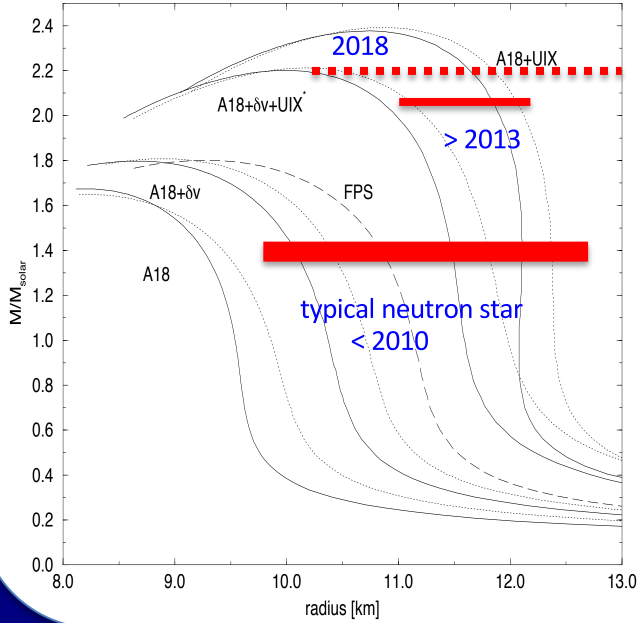
$$\Psi_{hc} = \Psi_{N_c,N_c}$$ ~80%

The NN core can be due to the orthogonality of

$$\langle \Psi_{N_c,N_c} \mid \Psi_{N,N} \rangle = 0$$

“Unreasonable” Persistence of the Nucleons

for 3Ms Black Hole $r_{NN} \lesssim 0.4\text{fm}$



2018

> 2013

typical neutron star
< 2010

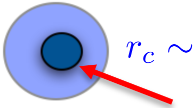
Neutron star masses
> 2 Solar Masses
> 2010

$r_{NN} \sim 0.6 - 0.8 fm$

Typical Neutron star masses
1.4 Solar Masses

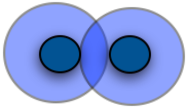
$r_{NN} \sim 0.7 - 1 fm$

H.Heiselberg
V. Pandharipande
ARNPS 2000



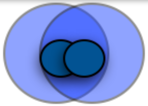
$r_c \sim 0.3 fm$

color singlet(cs) core



two color singlet “nucleons”

New Physics



hidden color
gluons

Conceptually: How to probe nuclei at such a short nucleon separations

- probe bound nucleons at large internal momenta >300MeV/c
- needs high energy probe to resolve such nucleons in nuclei
- considering quasielastic $A(e,e')X,\ A(e,e',N_f,N_r)X$ *and* $A(p,p',N_f,N_r)X$
- several novel observations: *JLab produced 2 Science and 2 Nature papers*

Limitations

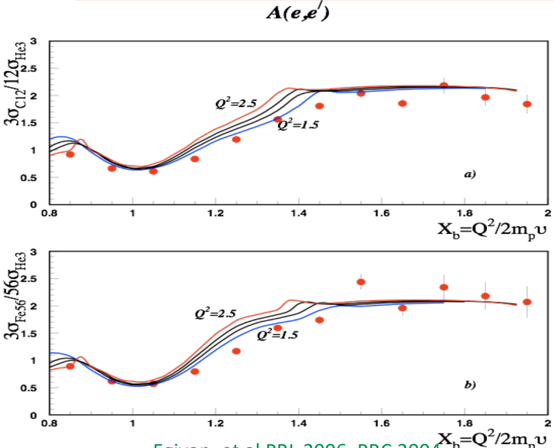
- to probe larger internal momenta larger Q^2 is needed
- nucleon form factors drop $1/Q^8$

1. Locality/Factorization of NN Short Range Correlations in the Nuclear Wave Function

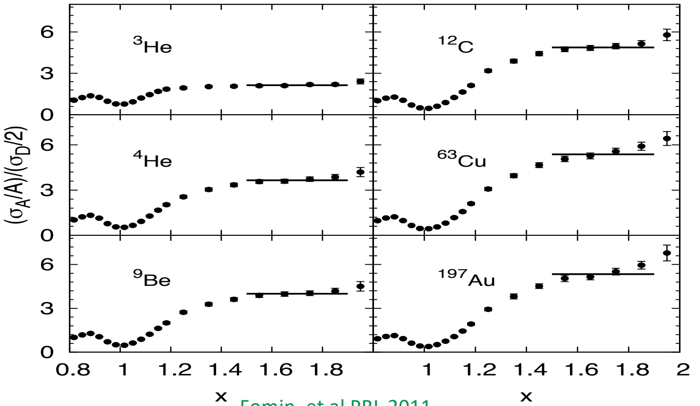
$$\boxed{R = \frac{A_2\sigma[A_1(e,e')X]}{A_1\sigma[A_2(e,e')X]}}$$

Day, Frankfurt, MS, Strikman, PRC 1993

$$\text{For } 1 < x < 2 \ R \approx \frac{a_2(A_1)}{a_2(A_2)}$$



Egiyan, et al PRL 2006, PRC 2004



Fomin, et al PRL 2011

2. Dominance of the (pn) component of SRC

$$P_{pn/pX} = 0.92^{+0.08}_{-0.18}$$

$$\frac{P_{pp}}{P_{pn}} \le \frac{1}{2}(1 - P_{pn/pX}) = 0.04^{+0.09}_{-0.04}.$$

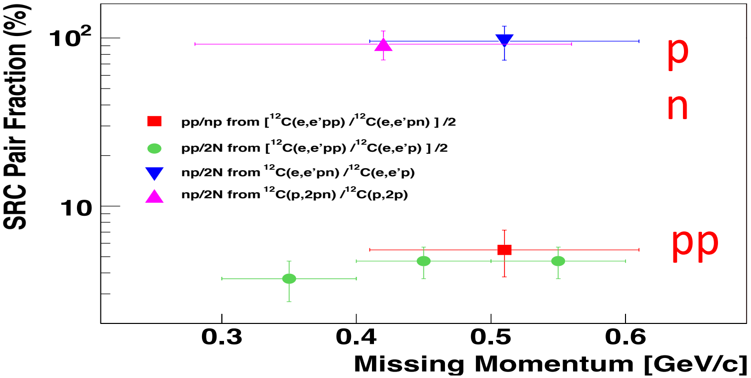
Theoretical analysis of BNL Data $A(p,2p)X$ reaction

E. Piasetzky, MS, L. Frankfurt, M. Strikman, J. Watson PRL , 2006

$$P_{pp/pn} = 0.056 \pm 0.018$$

Direct Measurement at JLab

R.Subedi, et al Science , 2008

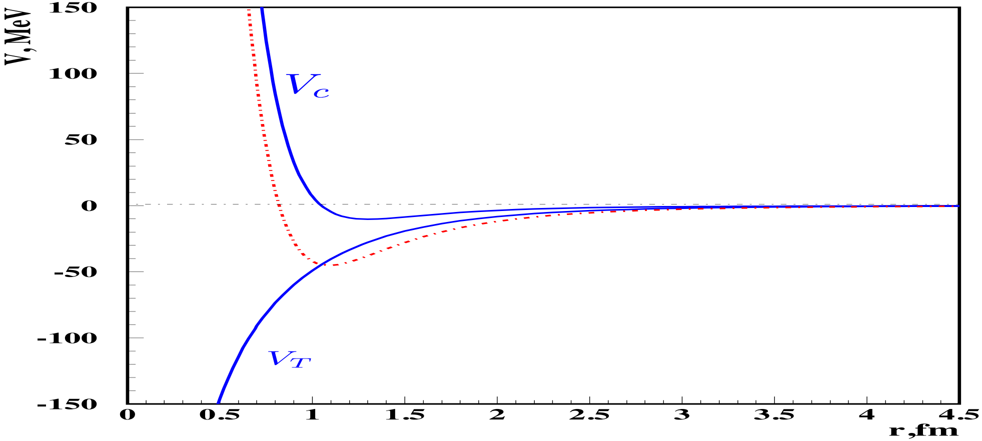


Factor of 20

Expected 4
(Wigner counting)

Theoretical Interpretation

$$\phi_A^{(1)}(k_1,\cdots,k_i=p,\cdots,k_j\approx -p,\cdots,k_A)\sim \frac{V_{NN}(p)}{p^2}f(k_1,\cdots{}'\cdots{}'\cdots\ )$$



3. Momentum Sharing of Nucleons in SRC

MS,arXiv:1210.3280 (2012), Phys. Rev. C 2014

Two new properties of high momentum distributions in nuclei was predicted:

- Approximate Scaling Relation:

$$\boxed{\frac{Z}{A} n_p^A(p) \approx \frac{(A-Z)}{Z} n_n^A(p)}$$

- Inverse Fractional Dependence of High Momentum Component

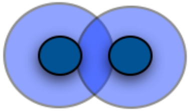
$$\boxed{n^A_{p/n}(p) \approx \frac{1}{2x_{p/n}} a_2(A,y) \cdot n_d(p)}$$

Confirmed
in different theoretical calculations: R.B. Wiringa et al,Phys. Rev. C 2014

J. Ryckebusch, W.Cosyn M. Vanhalst., J.Phys 2015

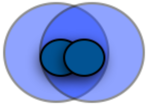
experimentally: O. Hen, et.al. Science, 2014, Duer et al, Nature 2018

to summarize…



two color singlet “nucleons”

- Is being currently investigated in quasielastic channel primarily at JLab, JSA, JINR

To probe 

- Needs significantly higher Q^2 and quasielastic processes are less effecteive

- Alternative approach is to explore x>1 in Nuclear Deep Inelastic Processes

Probing SuperFast Quarks in Nuclei

Studies of nuclear partonic distributions at $x>1$

- $x > 1$ requires a momentum transfer from the nearby nucleon or the quark from the nearby nucleon.

- $x>1$ “super-fast quarks”

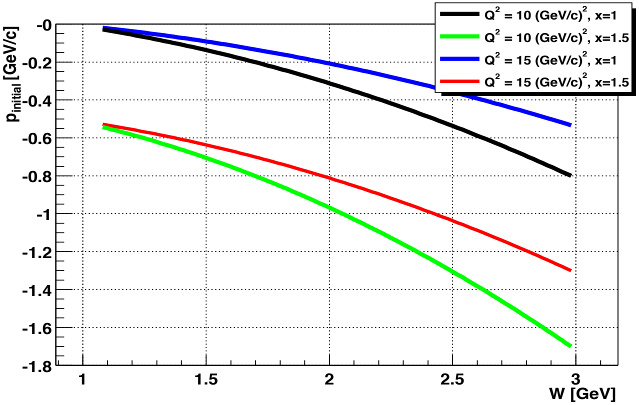
SuperFast quarks - short distance probes in nuclei

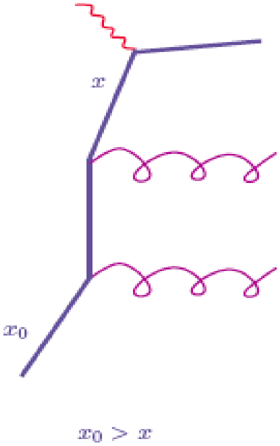
$$x = \frac{Q^2}{2m_N q_0} > 1$$

Two factors driving nucleons close together

Kinematic $p_{min} \equiv p_z = m_N \left(1 - x - x\left[\frac{W_N^2 - m_N^2}{Q^2}\right]\right)$

Dynamical:QCD evolution





Existing and Planned Inclusive Experiments:

1. BCDMS Collaboration 1994 (CERN): $52 \leq Q^2 \leq 200 \text{ GeV}^2$

2. CCFR Collaboration 2000 (FermiLab): $Q^2 = 120 \text{ GeV}^2$

3. E02-019 Experiment 2010 (JLab) $Q^2_{AV} = 7.4 \text{ GeV}^2$

4. Approved Experiments at JLab12: $e + A \rightarrow e' + X, \;\; Q^2 \geq 10 \text{ GeV}^2$

Alternative Studies:

5. Semi-inclusive 2jet production: p+A -> 2 jets + X

Adam Freese, M.S.
M.Strikman, EPJ 2015

6. Electron Ion Collider:

- Inclusive scattering $e + A \to e' + X$ $x_{Bj} > 1,\ Q^2 \geq 20\ \mathrm{GeV}^2$
- Single jet/N/h production $e + A \to e' + jet/N/h + X,$ $\boldsymbol{x_h > 1}$
- Double jet/N/h production $\gamma + A \to jet_f/h_f + jet_b/h_b + X$

QCD Evolution Equation for Nuclear Partonic Distributions

Adam Freese, Wim Cosyn,
MS, Phys. Rev D 2019

$$
\begin{aligned}
\frac{dq_{i,A}(x,Q^2)}{d\log Q^2} &= \frac{\alpha_s}{2\pi}\left\{2\left(1+\frac{4}{3}\log(1-\frac{x}{A})\right)q_{i,A}(x,Q^2)\right.\\
&+\left.\frac{4}{3}\int\limits_{x/A}^{1}\frac{dz}{1-z}\left(\frac{1+z^2}{z}q_{i,A}(\frac{x}{z},Q^2)-2q_{i,A}(x,Q^2)\right)+\int\limits_{x/A}^{1}dz\frac{(1-z)^2+z^2}{2z}G_A(\frac{x}{z},Q^2)\right\}
\end{aligned}
$$

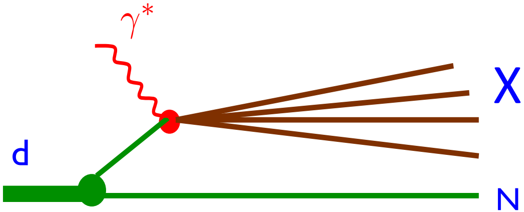
$$
F_{2A}(x,Q^2)=\sum_i e_i^2 x q_{i,A}(x,Q^2),
$$

$$
\begin{aligned}
\frac{dF_{2A}(x,Q^2)}{d\log Q^2} &= \frac{\alpha_s}{2\pi}\left\{2\left(1+\frac{4}{3}\log(1-\frac{x}{A})\right)F_{2,A}(x,Q^2)\right.\\
&+\left.\frac{4}{3}\int\limits_{x/A}^{1}\frac{dz}{1-z}\left(\frac{1+z^2}{z}F_{2A}(\frac{x}{z},Q^2)-2F_{2A}(x,Q^2)\right)+\frac{f_Q}{2}\int\limits_{x/A}^{1}dz[(1-z)^2+z^2]\frac{x}{z}G_A(\frac{x}{z},Q^2)\right\}
\end{aligned}
$$

- Dynamics of generation of superfast quarks in nuclei

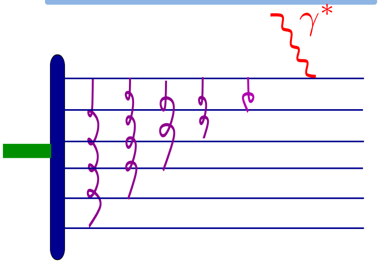
In inclusive d(ee')X proceses

1. Convolution Model



$$F_{2d} = \int_x^2 \rho_d^N(\alpha, p_t) F_{2N}\left(\frac{x}{\alpha}, Q^2\right) \frac{d^2\alpha}{\alpha} d^2 p_t$$

2. Six-Quark Model

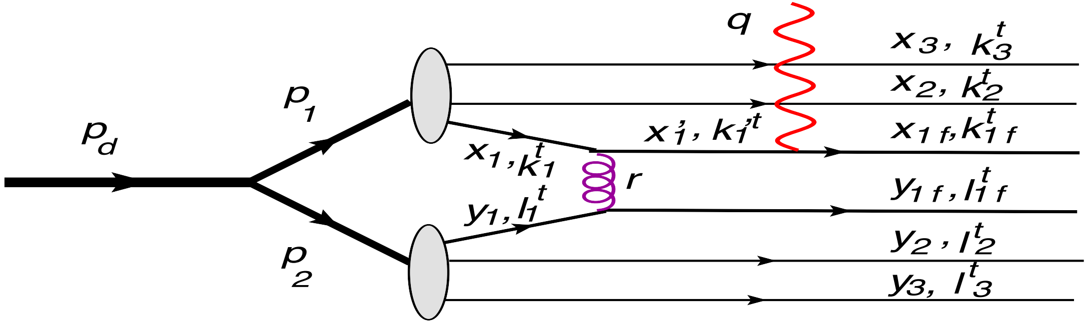


$$F_{2D} = F_{2,(6q)} \sim \left(1 - \frac{x}{2}\right)^{10}$$

$$x_N = \frac{x}{\alpha}$$

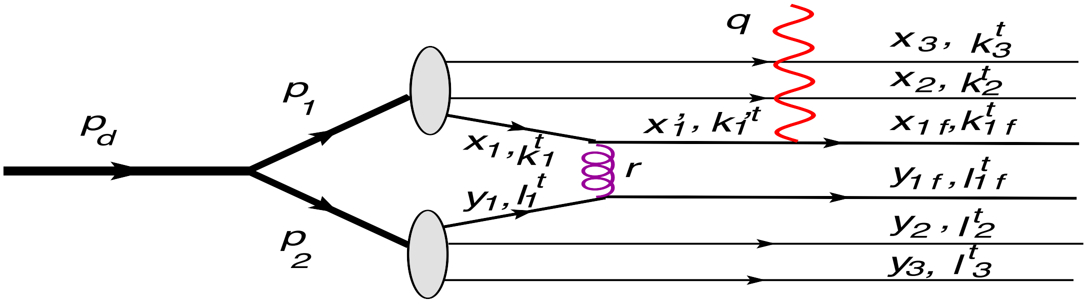
3. Hard Gluon Exchange

MS in progress



$$A^\sigma = \sum_{h_1,h_2} \int \frac{d\alpha}{\alpha} \frac{d^2 p_2}{2(2\pi)^3}$$

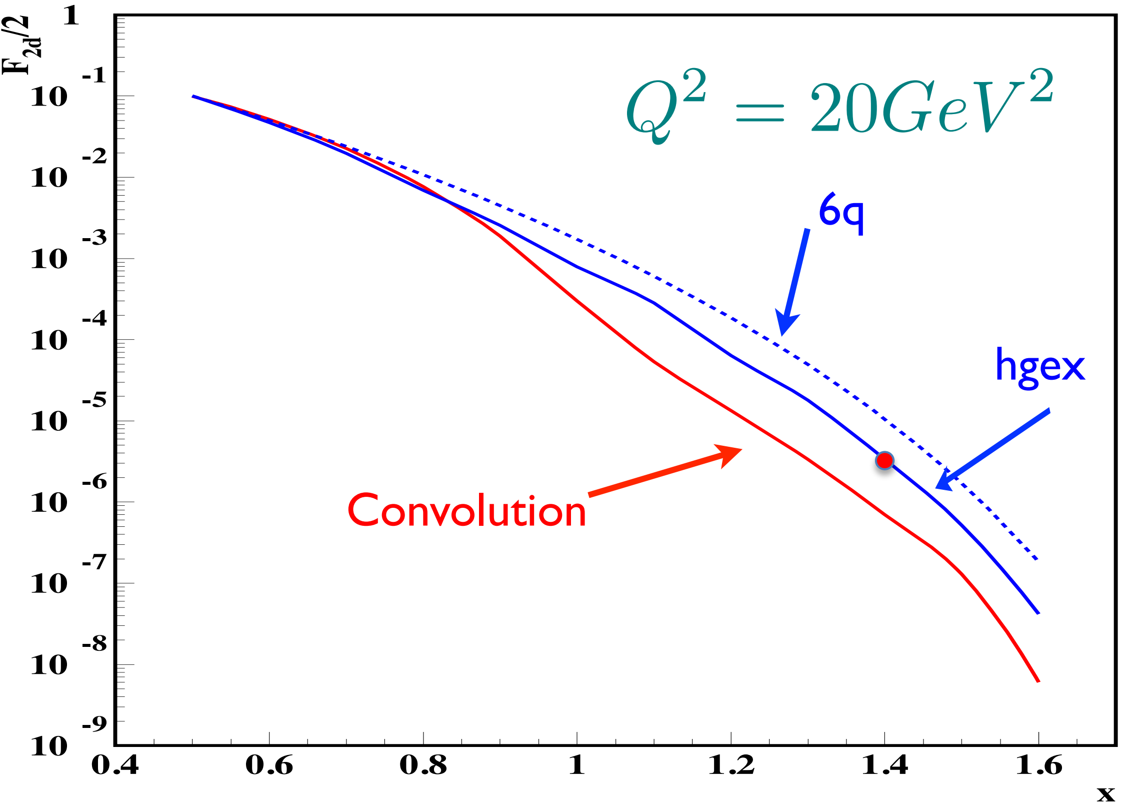
$$\left\{ \sum_{\eta_1,\lambda_1} H^\sigma_{(\eta_{1f},\eta_1),(\lambda_{1f},\lambda_1)} \frac{\psi_N^{h_1}(k_1,\eta_1;k_2,\eta_2;k_3,\eta_3)}{x_1\sqrt{2(2\pi)^3}} \frac{\psi_N^{h_2}(l_1,\lambda_1;l_2,\lambda_2;l_3,\lambda_3)}{y_1\sqrt{2(2\pi)^3}} \right\} \frac{\Psi_d^{h_1,h_2,m_d}(p_1,p_2)}{(1-\alpha)\sqrt{2(2\pi)^3}}$$



$$F_{2d}(x_{Bj},Q^2) = \sum_{i,j} x_{Bj} e_i^2 \int dx_1 dy_1 \frac{d^2 l_{1f,t}}{2(2\pi)^3} \frac{8\alpha_{QCD}}{l_{1f,t}^4} f_i(x_1,Q^2) f_j(y_1, l^2_{1f,t}) \times$$

$$\frac{1}{y_1^2}\left[1-\frac{x_{Bj}}{x_1+y_1}\right]^2 \Theta(x_1+y_1-x_{Bj}) \left[\sum_{h_1,h2}\int \frac{\Psi_d(\alpha,p_t)}{\alpha(1-\alpha)}\frac{d\alpha}{\sqrt{2(2\pi)^3}}\frac{d^2p_t}{(2\pi)^2}\right]^2$$

where $x_{Bj} = \frac{Q^2}{2m_N\nu}$.

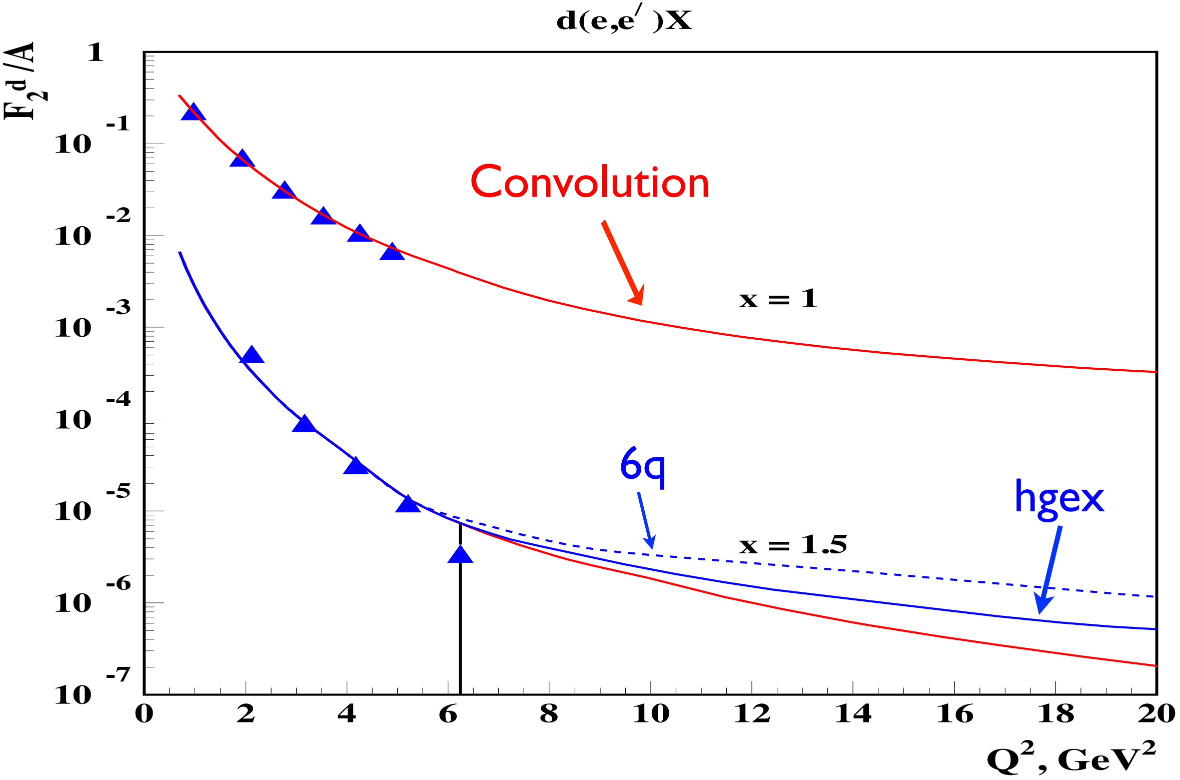


$s = 65\text{GeV}$
$x = 1.4$

rate

$$0.23 - 2.3 \; \frac{\text{events}}{\text{hour}} \frac{GeV^2}{dQ^2dx}$$

(M.S & Weiss,in progress)

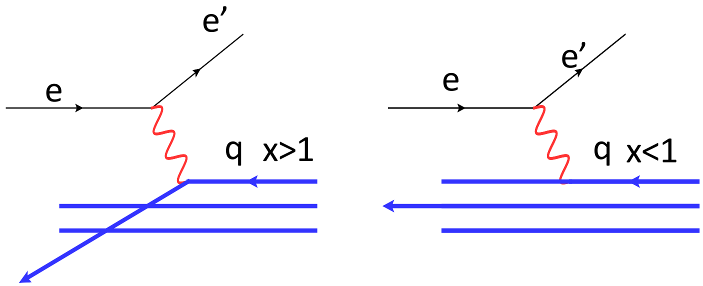

d(e,e′)X
F_2^d/A
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
2
4
6
8
10
12
14
16
18
20
Q^2, GeV^2
Convolution
x = 1
6q
hgex
x = 1.5

6. Electron Ion Collider:

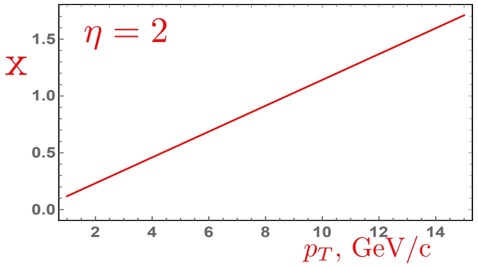
$\gamma + A \to e' + X,\qquad x_{Bj} > 1,\ Q^2 \geq 20\ \mathrm{GeV}^2$

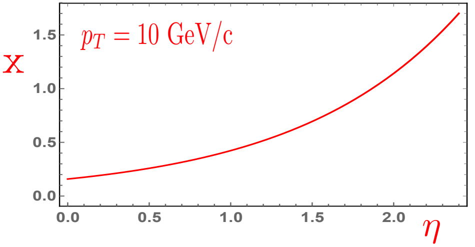
- For A=2 – core physics
- For A>2 – 3N physics

$$e + A \to e' + jet/N/h + X,$$



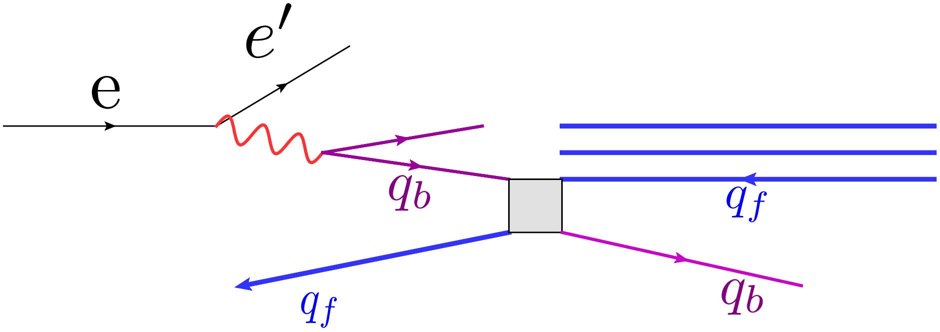
$$x = \frac{p_T}{2E_n}e^{\eta} + \frac{Q^2}{4E_iE_n}$$





6. Electron Ion Collider:

$$\gamma + A \rightarrow jet_f/h_f + jet_b/h_b + X$$



$$x = \frac{p_T}{2E_n}\left(e^{\eta_f} + e^{-\eta_b}\right)$$

Summary & Outlook

- Set of reactions such as: $e + A \to e' + X$

$$e + A \to e' + jet/N/h + X,$$

$$\gamma + A \to jet_f/h_f + jet_b/h_b + X$$

Will allow to reach practically unexplored x>1 region

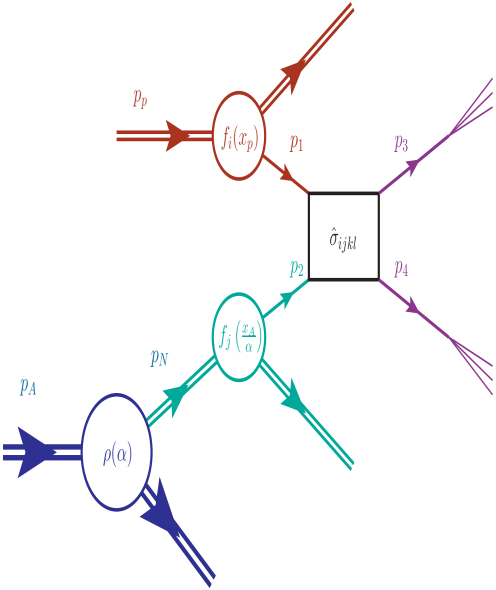
- Cross section in these kinematics is sensitive to the nuclear structure at very short distances: deuteron case for core studies, A>2 case for core vs multinucleon (such as 3N SRC) dynamics.

5. Probing Superfast quarks in p+A -> 2 jets + X reaction

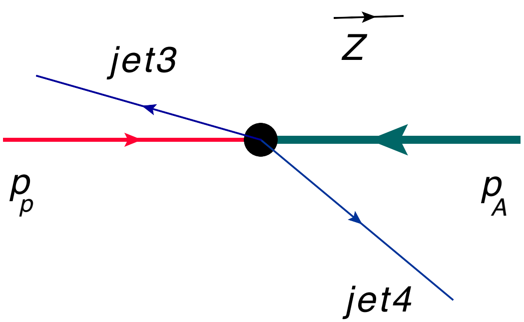
Adam Freese, M.S.
M.Strikman, EPJ 2015

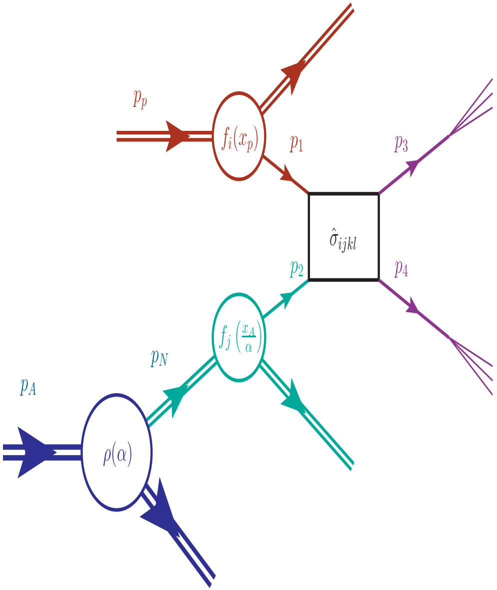
$$p + A \to \text{dijet} + X$$

- Reaction is treated in <u>Leading Twist Approximation</u>
- Jets are produced in <u>two-body parton-parton scattering</u>
- one <u>parton from the probe</u> – <u>other from the nucleus</u>
- <u>nuclear parton</u> originated from the bound nucleon



Jet - kinematics

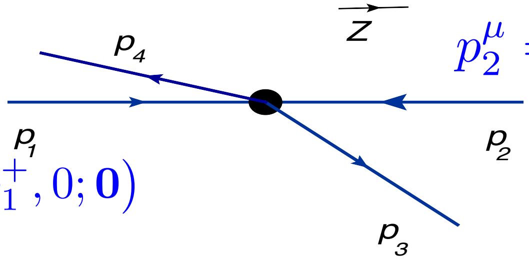




$$p_p^\mu = \left(p_p^+, \frac{m_p^2}{p_p^+}, \mathbf{0}_T\right) = (2E_0, 0, \mathbf{0}_T) = \left(\sqrt{\frac{A s_{NN}^{\text{avg.}}}{Z}}, 0, \mathbf{0}_T\right)$$

$$p_A^\mu = \left(\frac{M_A^2}{p_A^-}, p_A^-, \mathbf{0}_T\right) = (0, 2ZE_0, \mathbf{0}_T) = \left(0, \sqrt{AZ s_{NN}^{\text{avg.}}}, \mathbf{0}_T\right)$$

Parton - kinematics

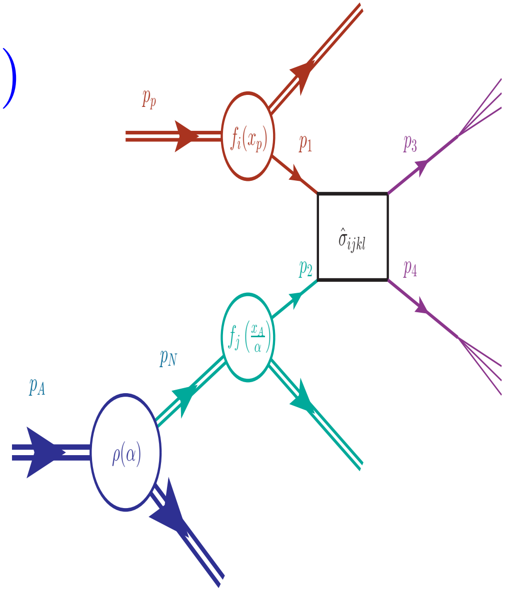


$$p_2^\mu = \left(0, p_2^- ; \mathbf{0}\right)$$

$$p_1^\mu = \left(p_1^+, 0; \mathbf{0}\right)$$

$$x_p = \frac{p_1^+}{p_p^+} = \sqrt{\frac{Z}{A}}\,\frac{p_1^+}{\sqrt{s_{NN}^{\text{avg.}}}}$$

$$\boxed{x_A = A\frac{p_2^-}{p_A^-} = \sqrt{\frac{A}{Z}}\,\frac{p_2^-}{\sqrt{s_{NN}^{\text{avg.}}}}}$$



$$p_1^\mu = (p_1^+, 0; \mathbf{0}) \qquad x_p = \frac{p_1^+}{p_p^+}$$

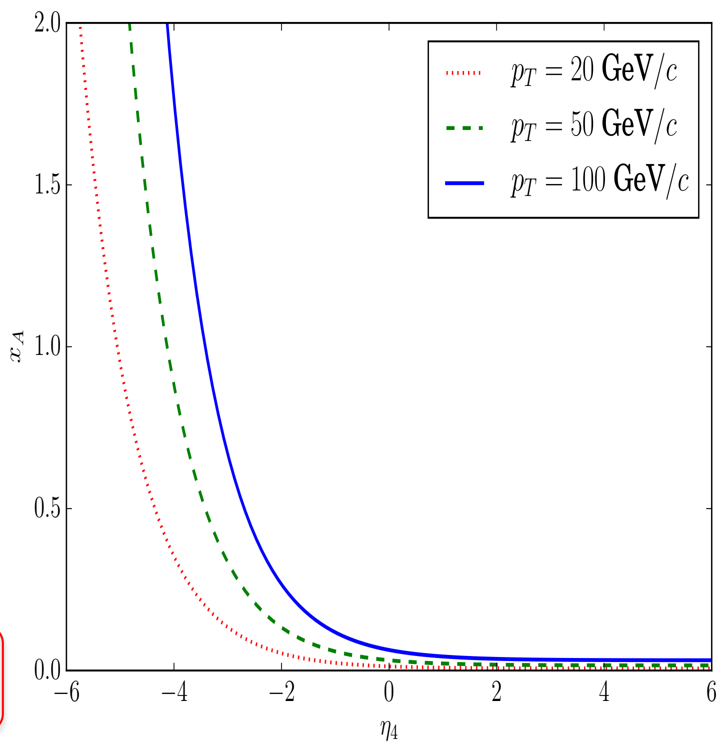
$$p_2^\mu = (0, p_2^-; \mathbf{0}) \qquad x_A = A\frac{p_2^-}{p_A^-}$$

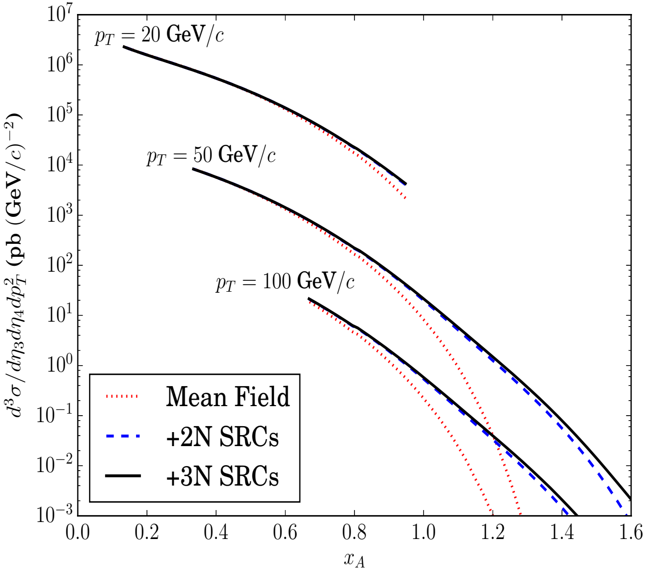
$$p_1^\mu + p_2^\mu = p_3^\mu + p_4^\mu$$

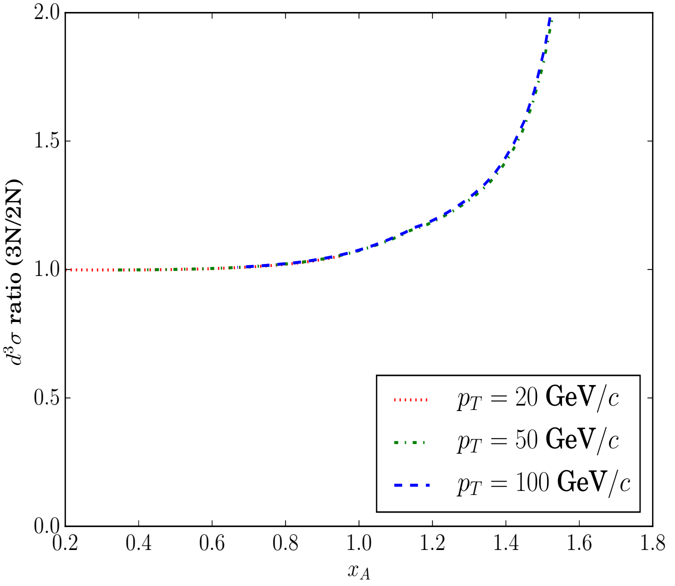
$$\eta = \frac{1}{2}\log\left(\frac{p^+}{p^-}\right)$$

$$x_p = \sqrt{\frac{Z}{A}}\,\frac{p_T}{\sqrt{s_{NN}^{\text{avg.}}}}\left(e^{\eta_3} + e^{\eta_4}\right)$$

$$\boxed{x_A = \sqrt{\frac{A}{Z}}\,\frac{p_T}{\sqrt{s_{NN}^{\text{avg.}}}}\,(e^{-\eta_3} + e^{-\eta_4}}$$




$p_T = 20$ GeV/c
$p_T = 50$ GeV/c
$p_T = 100$ GeV/c
Mean Field
+2N SRCs
+3N SRCs
$d^3\sigma/d\eta_3 d\eta_4 dp_T^2$ (pb (GeV/c)$^{-2}$)
x_A
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6


$d^3\sigma$ ratio (3N/2N)
x_A
$p_T = 20$ GeV/c
$p_T = 50$ GeV/c
$p_T = 100$ GeV/c
2.0
1.5
1.0
0.5
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8