Large x Physics in UPCs and EIC

Misak Sargsian
Florida International University, Miami

Probing QCD in Photon-Nucleus Interactions at RHIC and the LHC -> EIC
Feb, 13-17, 2017, INT, UW, Seattle

(I) Probing Nuclear Dynamics at Very Short Distances

- r < 0.5 fm (> 1GeV)

- Physics of Nuclear Core
  - We know why nuclei are bound
  - We don't know why they are stable

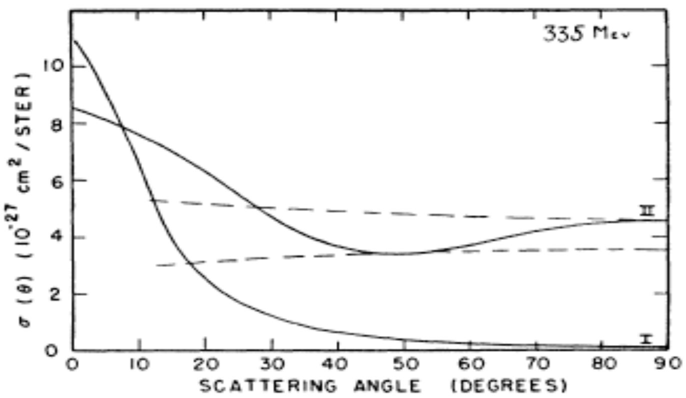
- Hadron- quark/gluon transition
- Color non-singlet states
- Gluonic content of NN core
- Delta-Delta NN* components

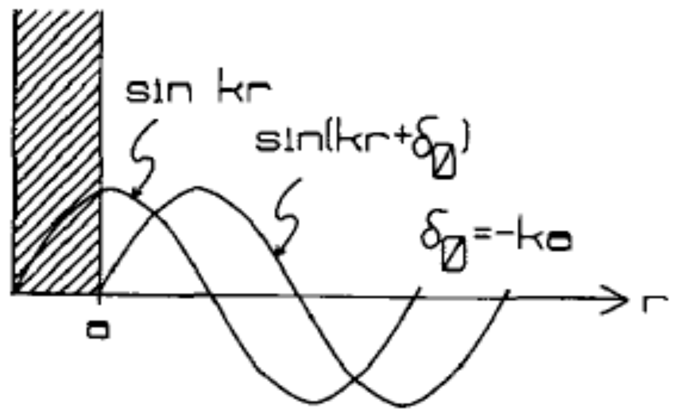
(II) Probing Nuclear Partonic Distributions at large x

- Physics of the EMC Effect
- Modification of parton distributions in the bound nucleon
- Dependence of modification on local densities/momenta
- x and Q^2 dependence of parton modifications

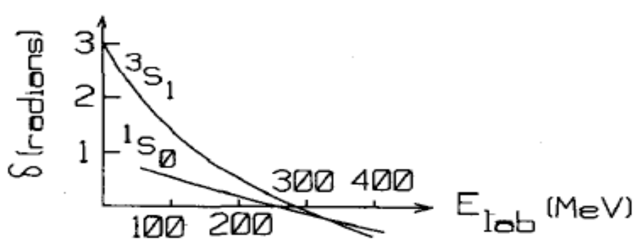
(I) Probing Nuclear Dynamics at very short distances: NN repulsive core

Jastrow 1951 assumed the existence of the hard core to explain the angular distribution of pp cross section at 340 MeV (r_0=0.6fm)





r_0 = 0.4fm



Stability Theorem: Nuclei will Collapse without Repulsive interaction 1950s Weisskopf, Blatt

Modern NN Potentials

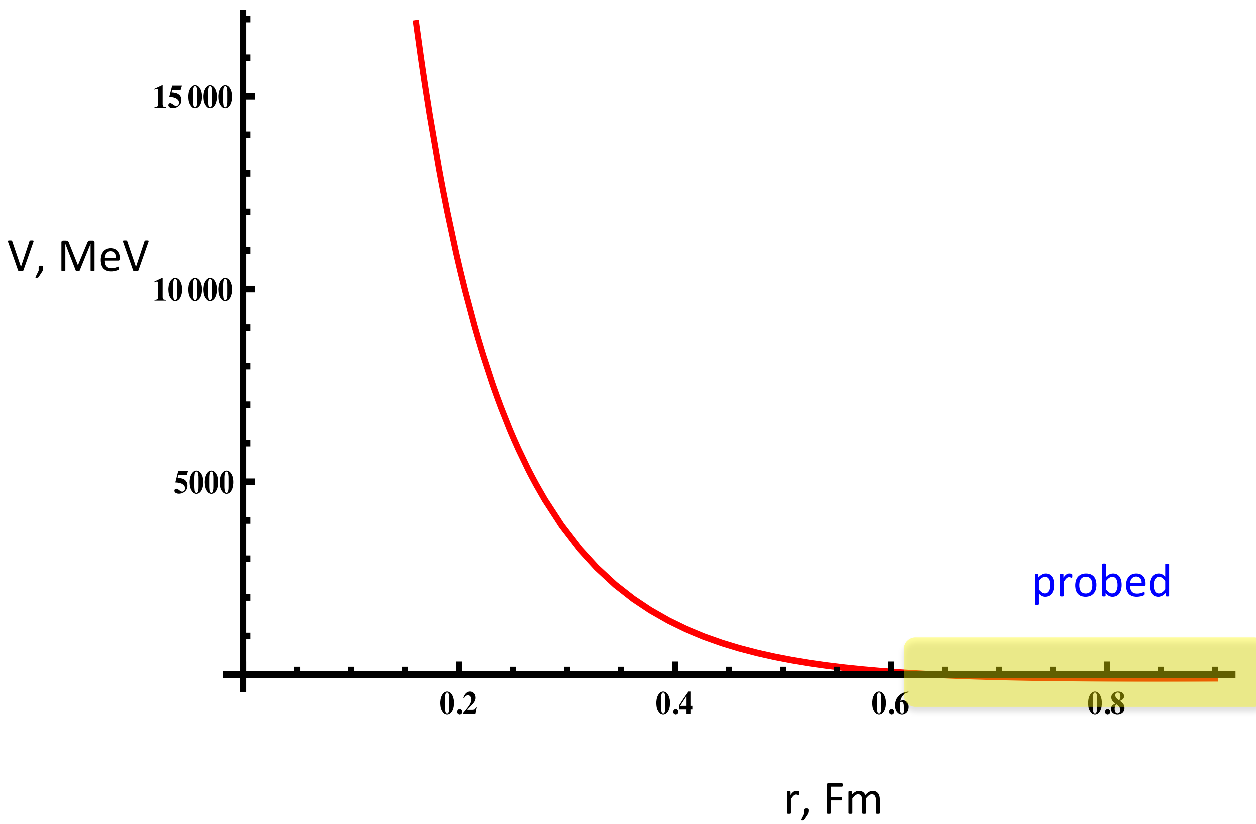
$$V^{2N} = V_{EM}^{2N} + V_{\pi}^{2N} + V_{R}^{2N}$$

$$V_R^{2N} = V^c + V^{l2} L^2 + V^t S_{12} + V^{ls} L \cdot S + v^{ls2} (L \cdot S)^2$$

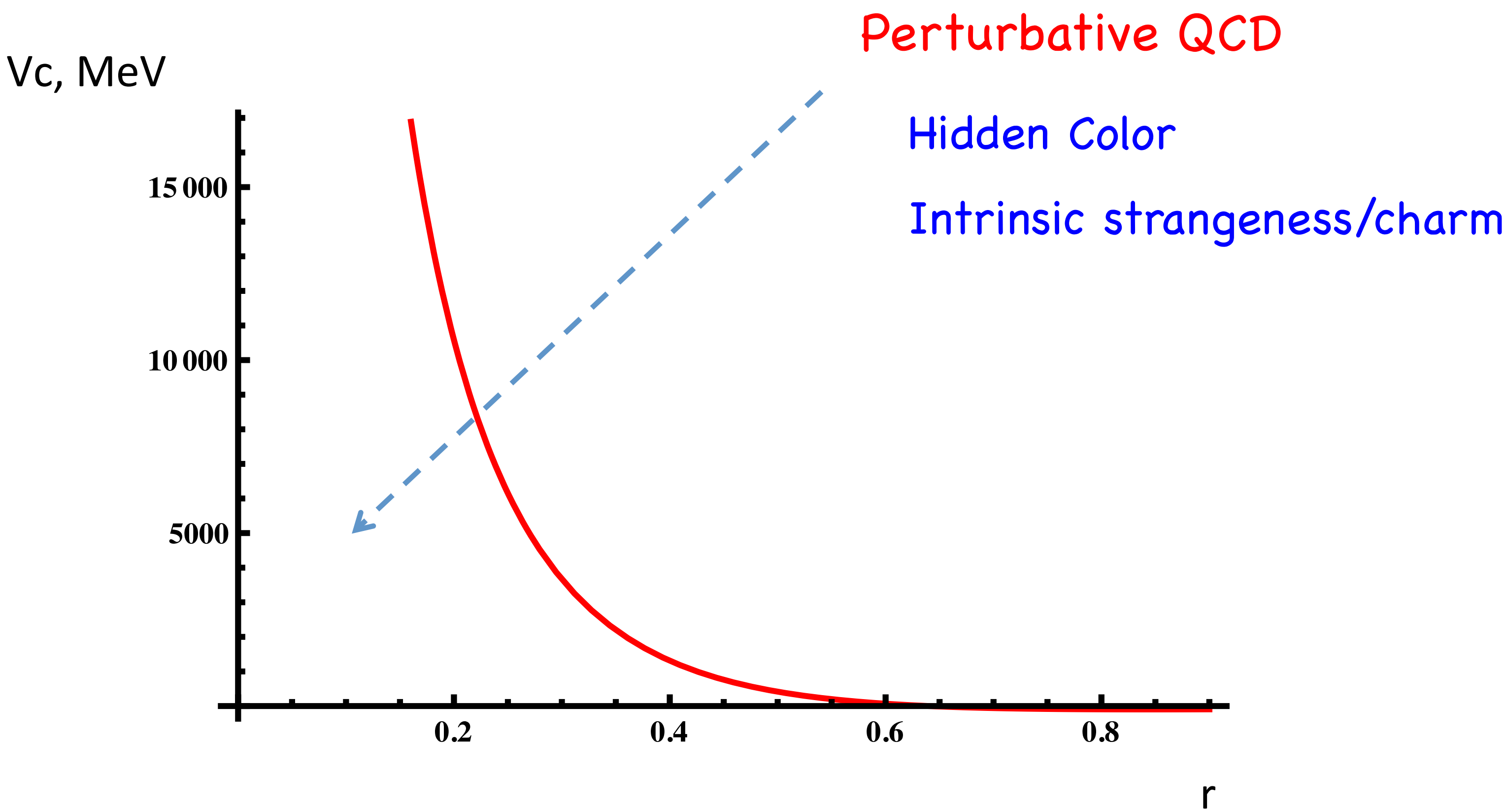
$$V^i = V_{int,R} + V_{core}$$

$$V_{core} = \left[1 + e^{\frac{r - r_0}{a}} \right]^{-1}$$

60's



V, MeV
15 000
10 000
5000
probed
0.2
0.4
0.6
0.8
r, Fm



~80% hidden color

(II) Nuclear Medium Modifications of PDFs (EMC Effect)

$$R_{EMC} = \frac{2\sigma_A}{A\sigma_D} \cdot f_{iso}$$

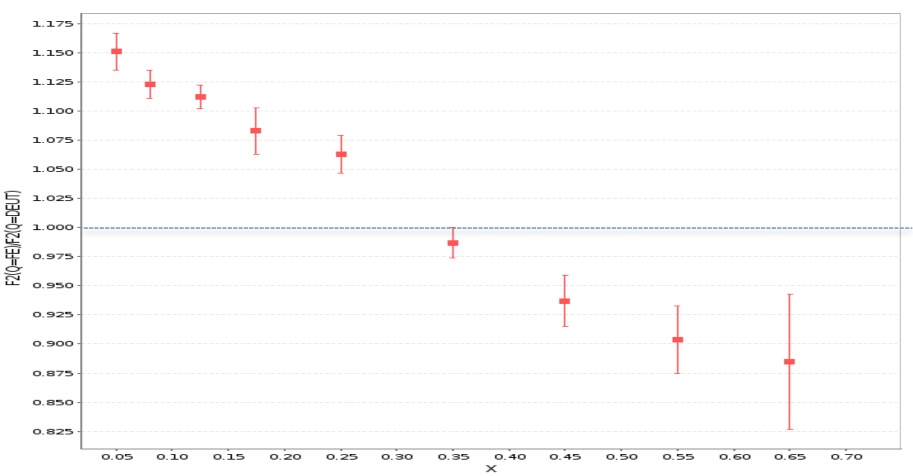
$$\sigma_{eA} = \frac{d\sigma}{d\Omega dE'}$$

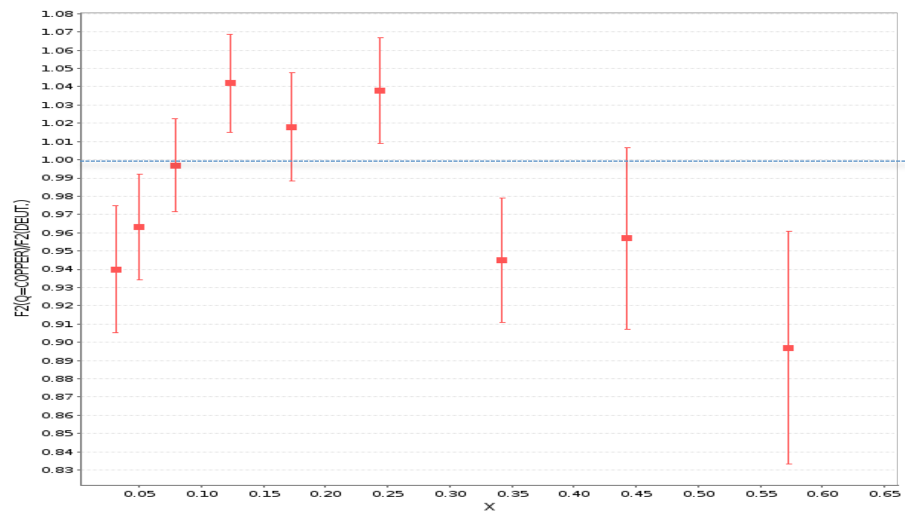
and

$$f_{iso} = \frac{\sigma_p + \sigma_n}{\frac{2Z}{A}\sigma_p + \frac{2(A-Z)}{A}\sigma_n}$$

Expected $R = 1 \text{ in DIS region}$

CERN 1983-1988





$$R_{EMC} = \frac{2\sigma_A}{A\sigma_D} \cdot f_{iso}$$

SLAC 1994: Gomez et al

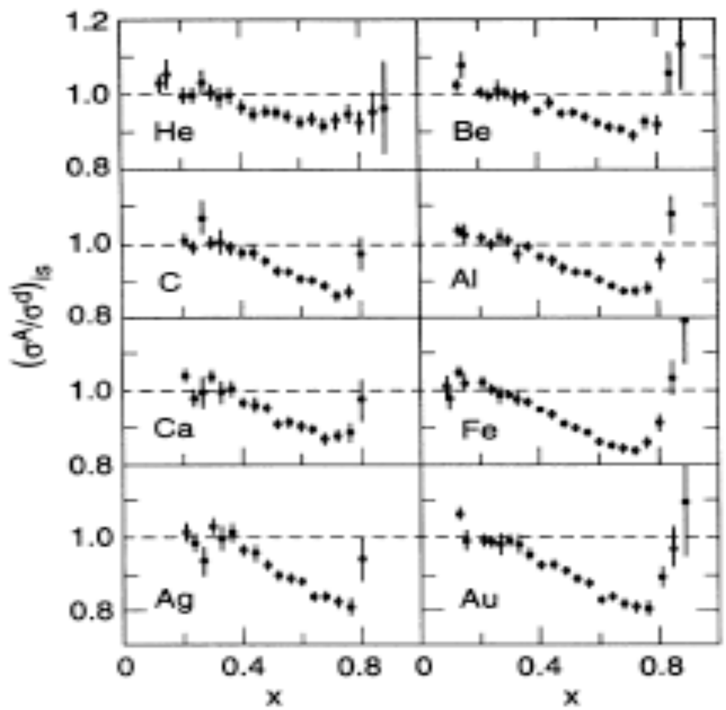


FIG. 15. Q^2-averaged $(\sigma^A/\sigma^d)_{is}$ ratios for isoscalar nuclei a a function of x. The data have been binned in fine x bins. Er rors are the same as in Fig. 14.

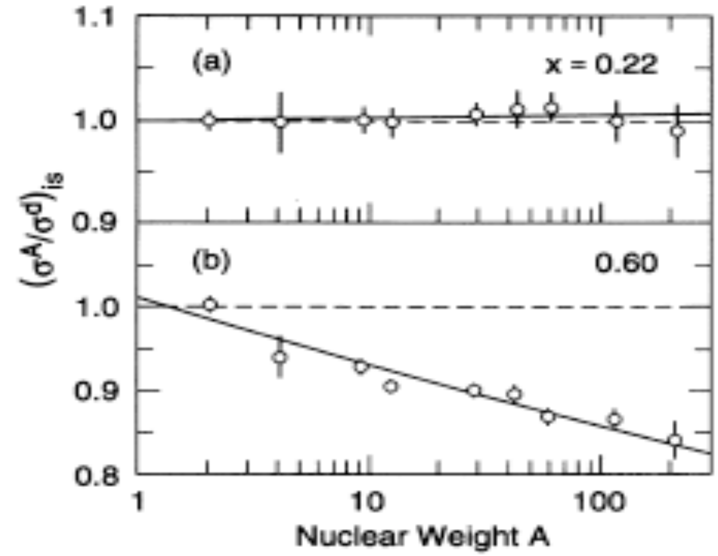


FIG. 18. Ratios $(\sigma^A/\sigma^d)_{is}$ versus atomic weight A at (a) $x=0.220$ and (b) $x=0.600$. The solid lines are a parametrization of the data in terms of $(\sigma^A/\sigma^d)_{is}=C(x)A^{\alpha(x)}$. The errors shown include statistical, point-to-point systematic, and target-to-target errors. The overall uncertainty due to the deuterium target is included only at the $A=2$ point.

$$R_{EMC} = \frac{2\sigma_A}{A\sigma_D} \cdot f_{iso}$$

SLAC 1994: Gomez et al

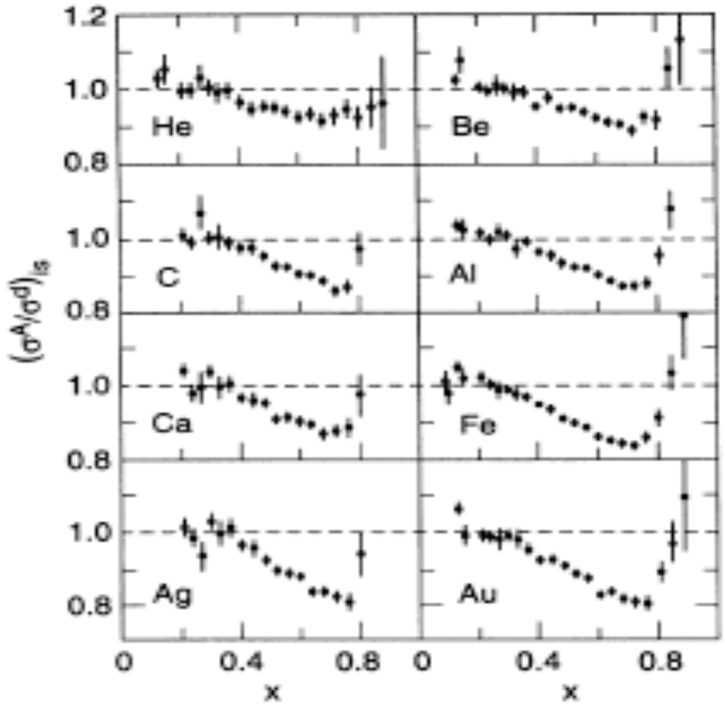


FIG. 15. Q^2-averaged $(\sigma^A/\sigma^d)_{is}$ ratios for isoscalar nuc a function of x. The data have been binned in fine x bins rors are the same as in Fig. 14.

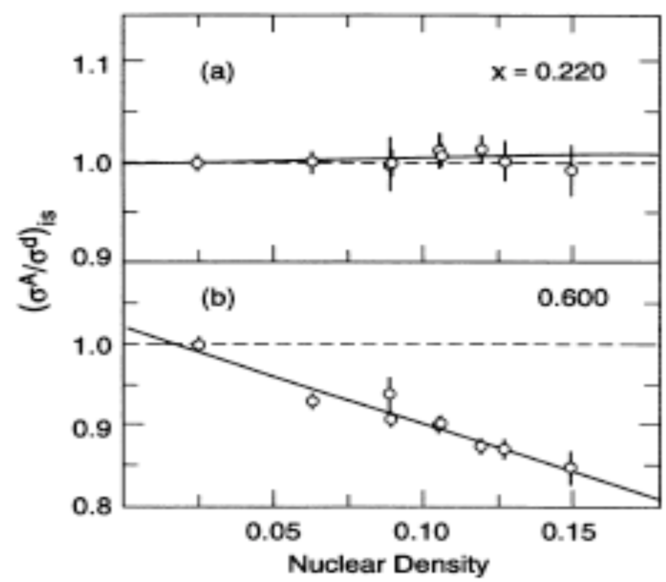
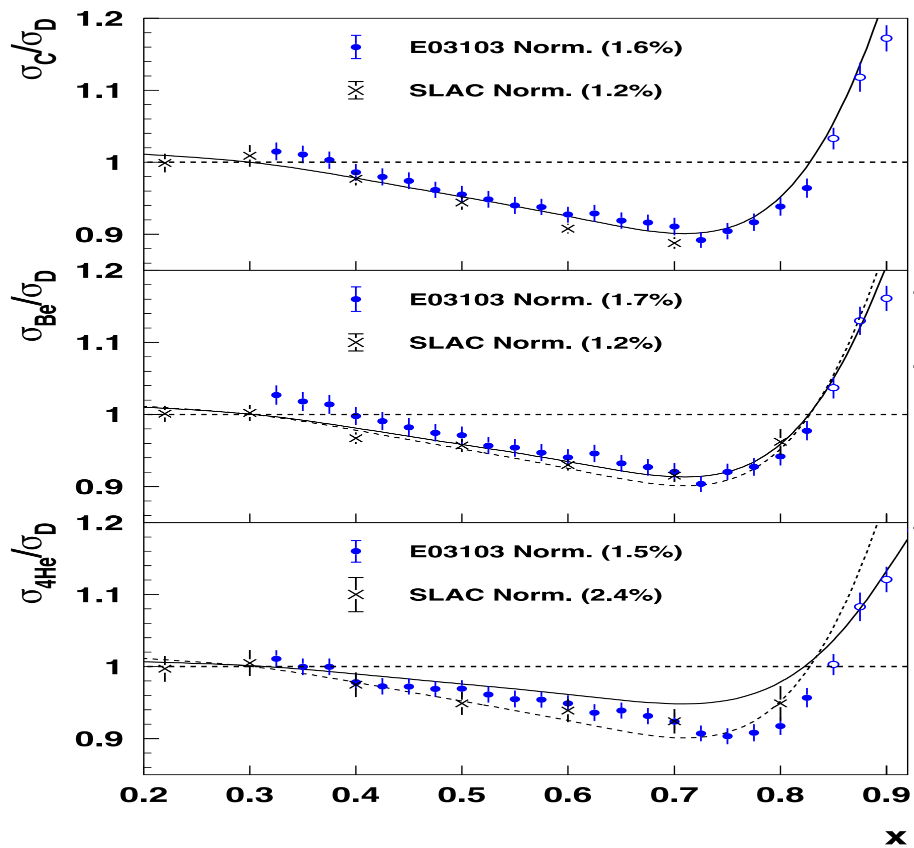


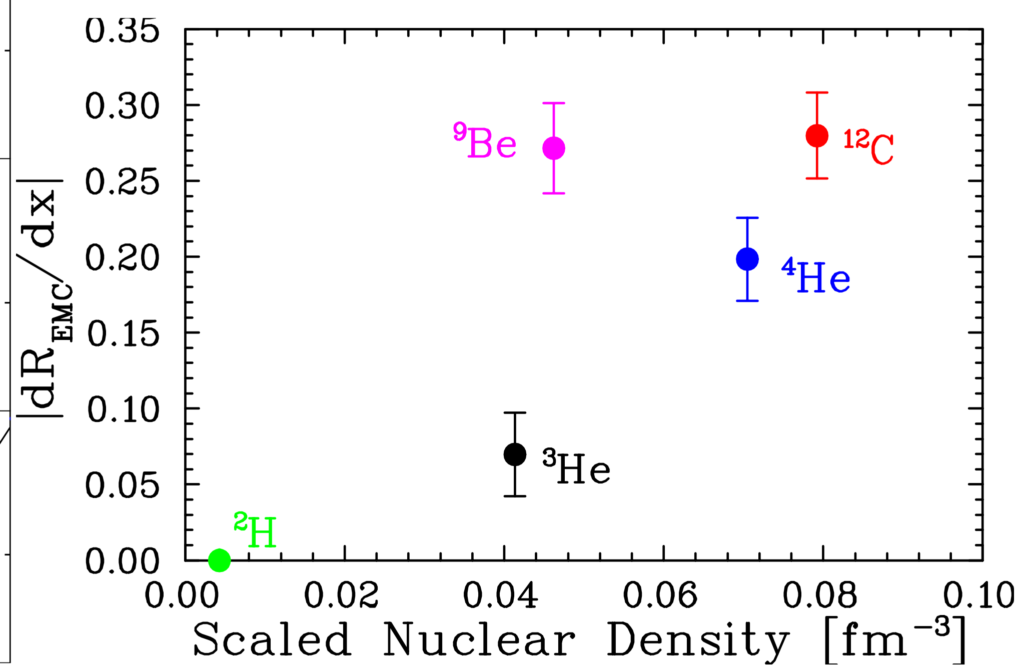
FIG. 20. Ratios $(\sigma^A/\sigma^d)_{is}$ versus nuclear density at (a) $x=0.220$ and (b) $x=0.600$. The solid lines represent the parametrization $(\sigma^A/\sigma^d)_{is}=d(x)[1+\beta(x)\rho(A)]$. The errors shown include statistical, point-to-point systematic, and target-to-target errors. The overall uncertainty due to the deuterium target is included only at the $A=2$ point.

EMC Effect

JLAB 2009: Silly et al PRL09

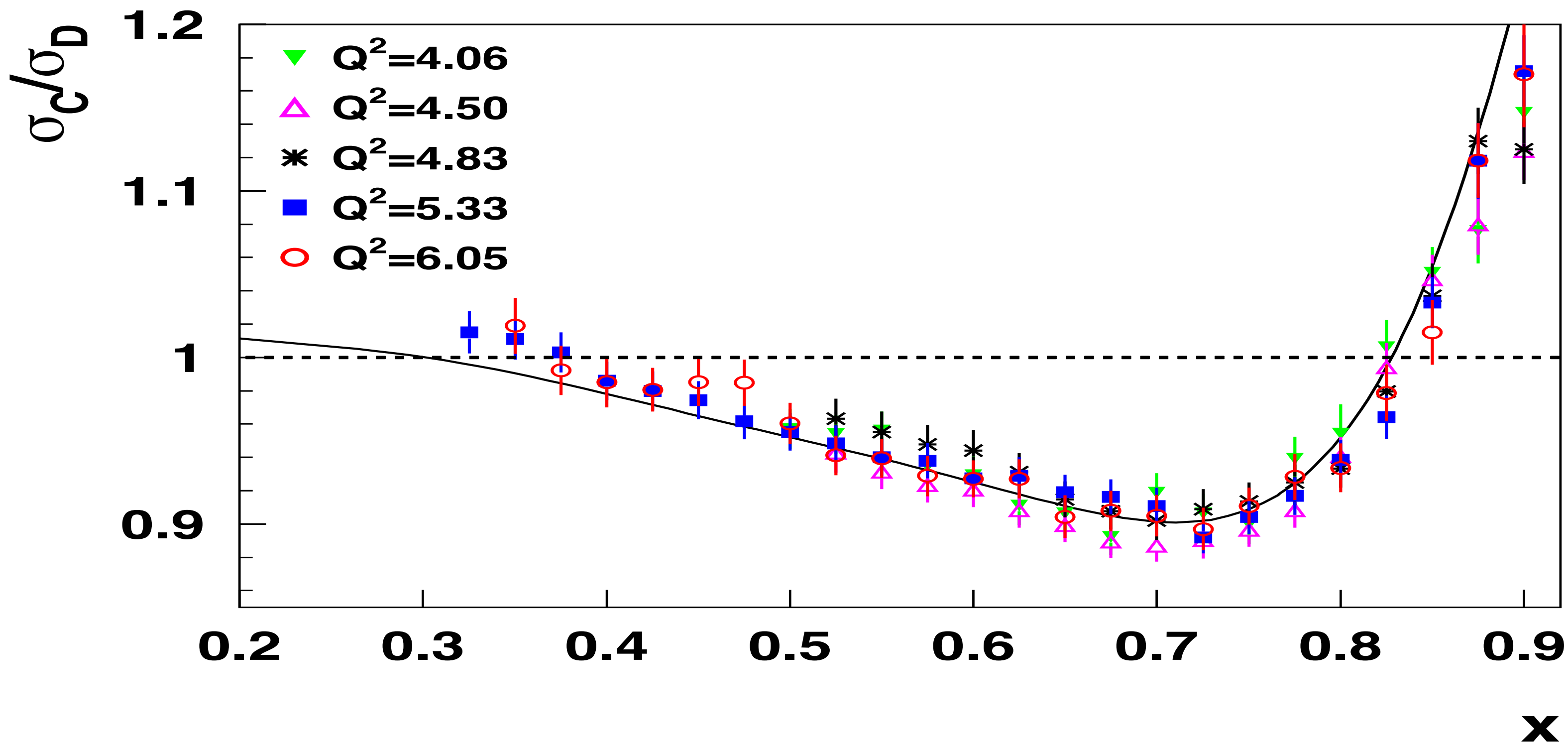
$$R_{EMC} = \frac{2\sigma_A}{A\sigma_D} \cdot f_{iso}$$





EMC Effect **JLAB 2009**

$$R_{EMC} = \frac{2\sigma_A}{A\sigma_D} \cdot f_{iso}$$



EMC - SRC - Correlation

SLAC 1993:Day Frankfurt, MS, Strikman PRC93

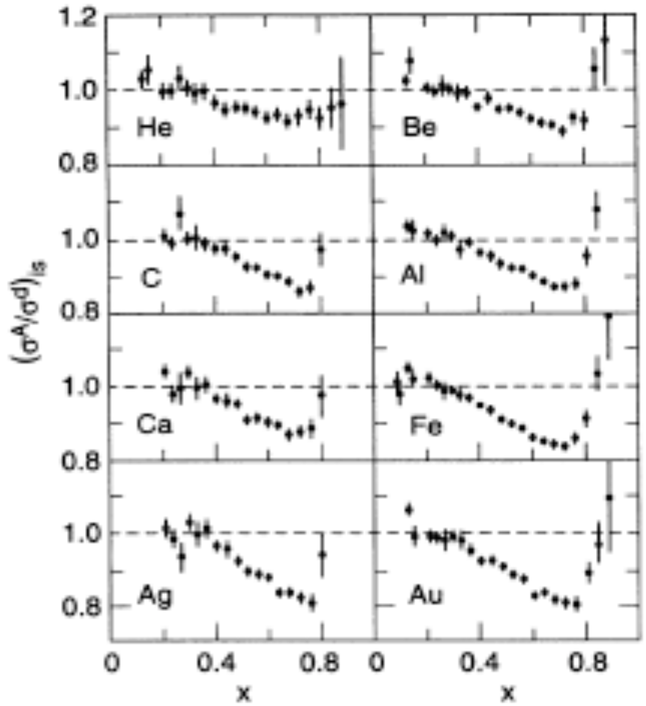
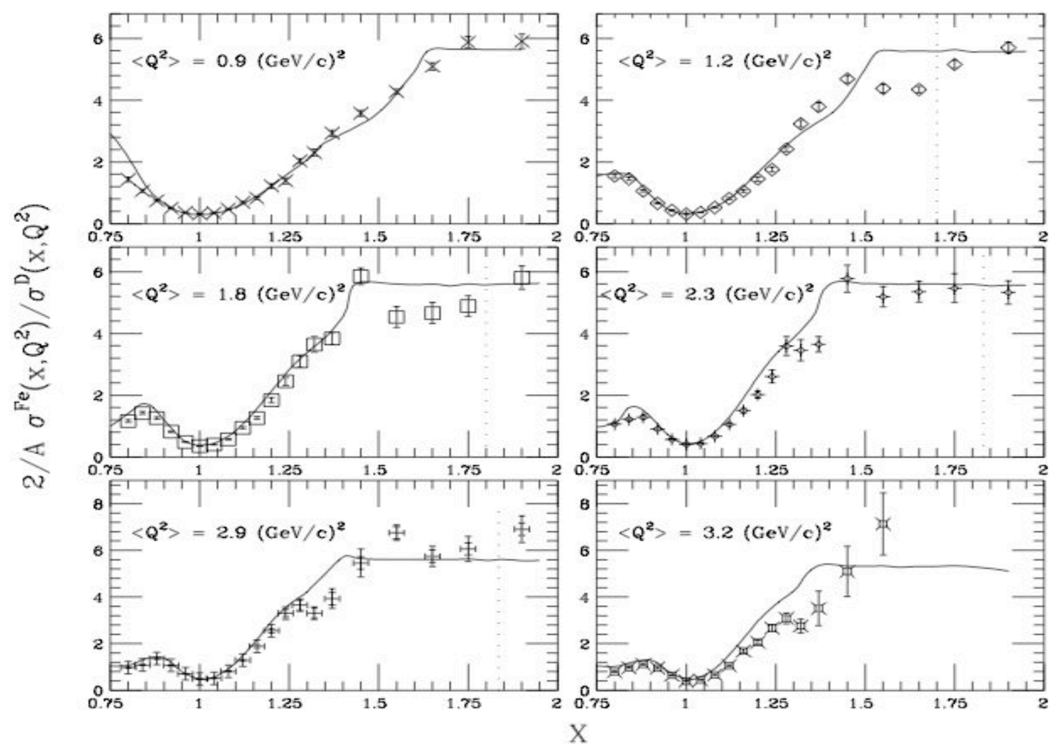


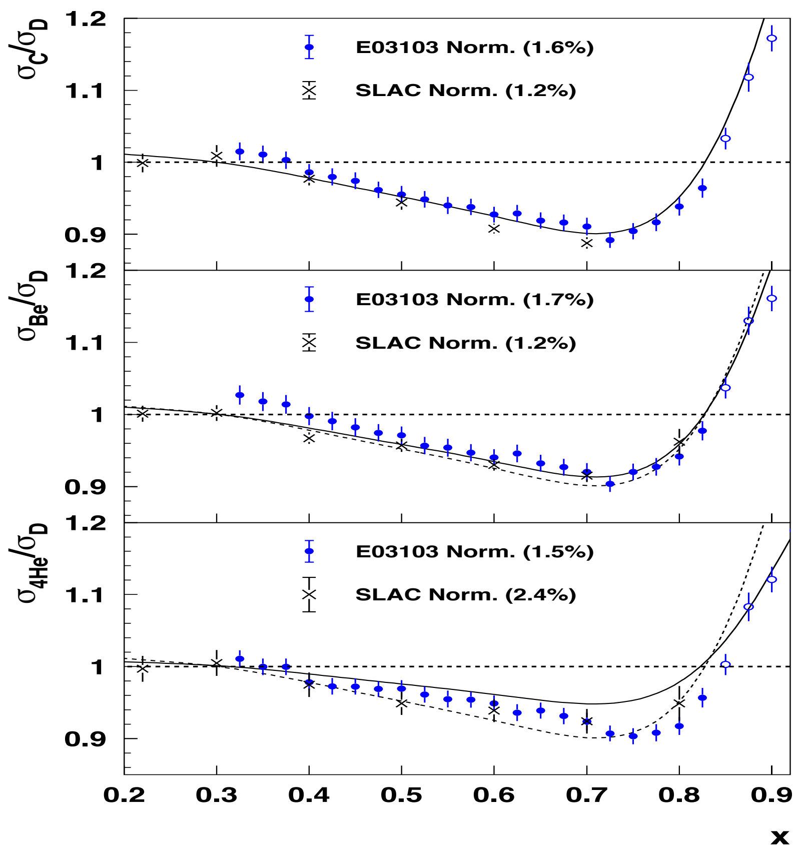
FIG. 15. Q^2-averaged $(\sigma^A/\sigma^d)_{is}$ ratios for isoscalar nuclei as a function of x. The data have been binned in fine x bins. Errors are the same as in Fig. 14.

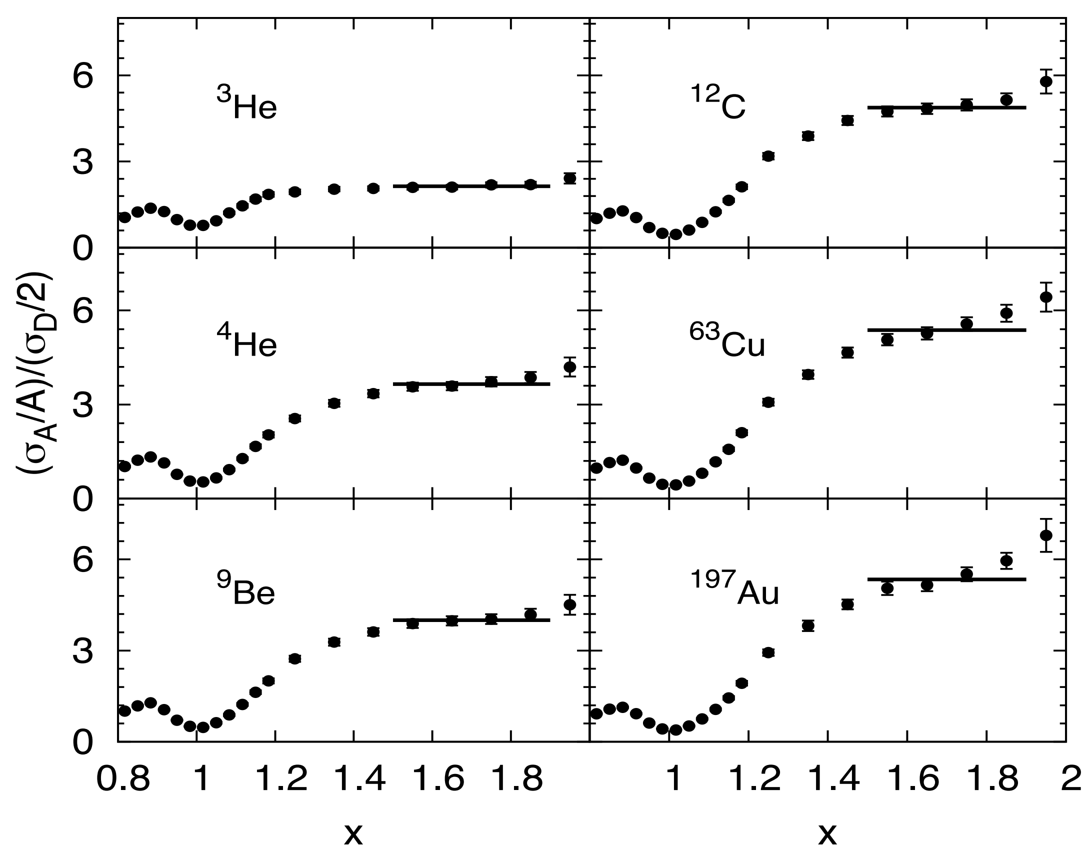


EMC - SRC - Correlation

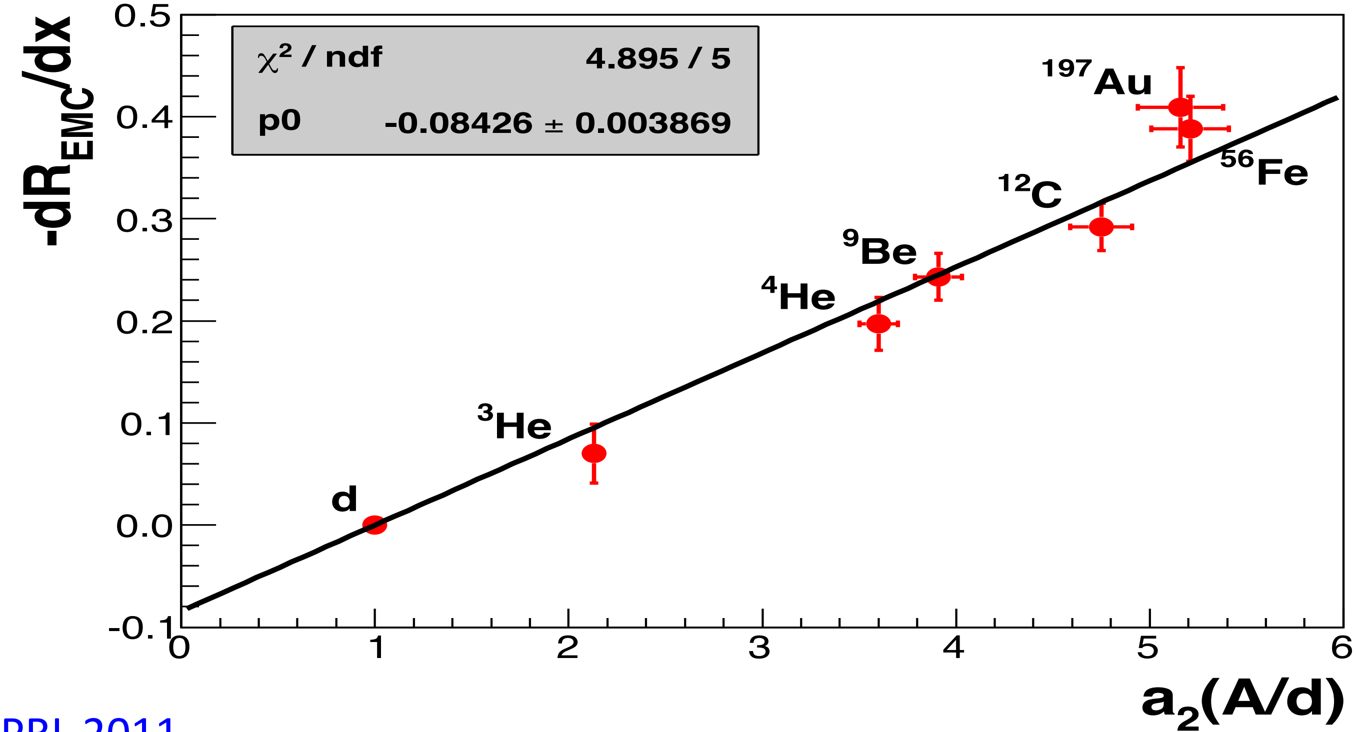
Jlab 2012

Fomin et al, PRL 2012





EMC-SRC Correlations



-Weinstein et al PRL 2011,
arxiv 2012

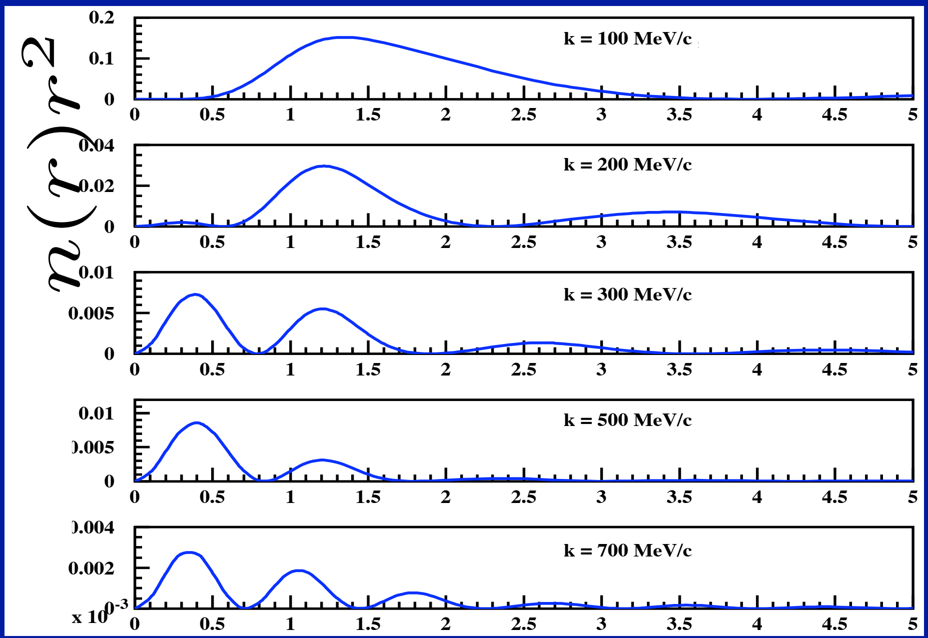
Conceptually: How to probe nuclei at short nucleon separations

❑ How to probe small distances in nuclei *for NN-system (Deuteron)*

1. Probe nucleon with large virtuality

$$\frac{1}{k^2 - m^2 + i\epsilon} \sim \frac{1}{m(\frac{k^2}{2m} + |\epsilon_B| - i\epsilon)}$$

2. Probe large relative momenta



$$E_m \sim \frac{k^2}{2m} \gtrsim 100 \ \ \mathrm{MeV}$$

$$k \gtrsim 300 \ \mathrm{MeV/c}$$

High Density Fluctuations

Emergence of Short-Range Correlations

- start with A-body Schroedinger equation interacting by two body potential only

$$\left[-\sum_i \frac{\nabla_i^2}{2m} + \frac{1}{2}\sum_{i,j} V(x_i - x_j)\right]\psi(x_1,\cdots,x_A) = E\psi(x_1,\cdots,x_A)$$

- Introducing

$$\psi(x_1,\cdots,x_A) = \int \Phi(k_1,\cdots k_A)e^{i\sum_i k_i x_i}\prod_i \frac{d^3k_i}{(2\pi)^{3/2}}$$

$$V(x_i - x_j) = \int U(q)e^{iq(x_i-x_j)}d^3q$$

$$\left(\sum_i \frac{k_i^2}{2m} - E_b\right)\Phi(k_1,\cdots,k_A) = -\frac{1}{2}\sum_{i,j}\int U(q)\,\Phi(k_1,\cdots,k_i-q,\cdots k_j+q,\cdots,k_A)d^3q$$

- Assume: system is dilute

$$\left(\sum_i \frac{k_i^2}{2m} - E_b\right)\Phi(k_1,\cdots,k_A) = -\frac{1}{2}\sum_{i,j}\int U(q)\,\Phi(k_1,\cdots,k_i - q,\cdots k_j + q,\cdots,k_A)d^3q$$

- then the k dependence of the wave function for $k^2/2m_N \gg |E_B|$

Amado, 1976

$$\Phi^{(1)}(k_1,\cdots,k_c,\cdots,-k_c,\cdots,k_A) \approx \frac{U_{NN}(k_c)}{k_c^2}F_A(k_1,\cdots'\cdots',\cdots,k_A)$$

- Assume: $U_{NN}(q) \sim \frac{1}{q^n}$ with $n > 1$

$$\Phi^{(2)}(\cdots k_c,\cdots) \sim \frac{1}{k_c^{2+n}}\int \frac{1}{q^n}dq \sim \frac{U_{NN}(k_c)}{k_c^2}\int_{q_{min}} \frac{1}{q^n}dq$$

- For large k_c $\Phi^{(2)}(k_c) \ll \Phi^{(1)}(k_c)$

Frankfurt, Strikman 1981
Frankfurt, MS, Strikman 2008

- 3N SRCs are parametrically smaller than 2N SRC

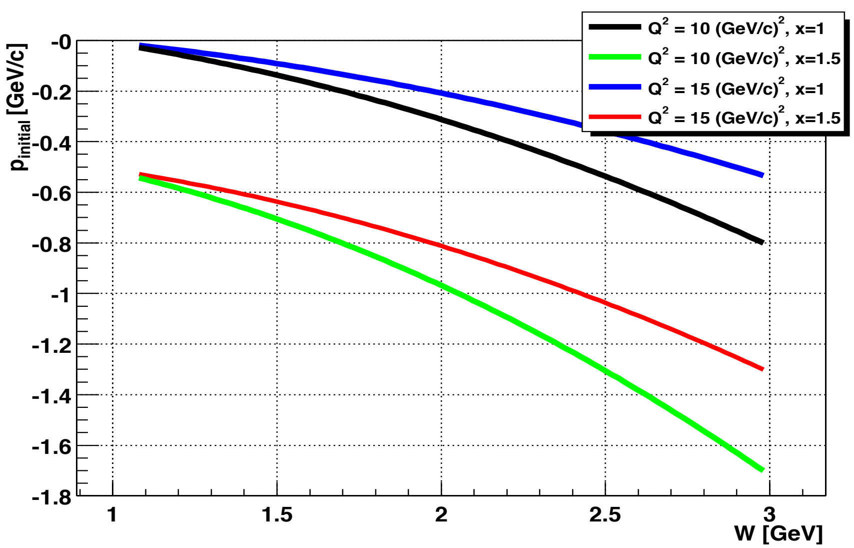
SuperFast quarks - short distance probes in nuclei

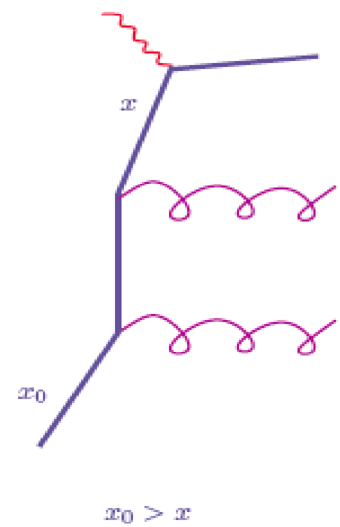
$$x = \frac{Q^2}{2m_N q_0} > 1$$

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 Experiments:

1. BCDMS Collaboration 1994 (CERN): $52 \leq Q^2 \leq 200\ \mathrm{GeV}^2$
2. CCFR Collaboration 2000 (FermiLab): $Q^2 = 120\ \mathrm{GeV}^2$
3. E02-019 Experiment 2010 (JLab) $Q^2_{AV} = 7.4\ \mathrm{GeV}^2$
4. Approved Experiments at JLab12
5. Alternative Studies at LHC p+A -> 2 jets + X
6. Ultra Peripheral Collision: $\gamma + A \to 2jets + X$?
7. Electron Ion Collider: $e + A \to e' + (N) + X$?

1. BCDMS Collaboration 1994 (CERN):

Z.Phys C63 1994

Structure function of Carbon in deep-inelastic scattering of 200GeV muons

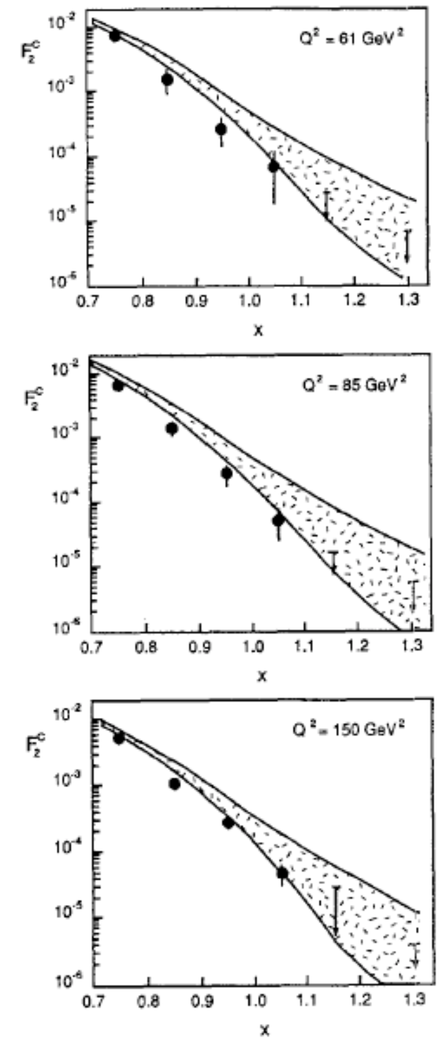
$$Q^2 = 61,\ 85 \text{ and } 150 \text{ GeV}^2$$

$$x = 0.85,\ 0.95,\ 1.05,\ 1.15 \text{ and } 1.3$$

$$F_{2A}(x,Q^2) = F_{2A}(x_0 = 0.75, Q^2)e^{-s(x-0.75)}$$

$$s = 16.5 \pm 0.6$$

More than Fermi Gas but very marginal high momentum component



2. CCFR Collaboration 2000 (FermiLab):

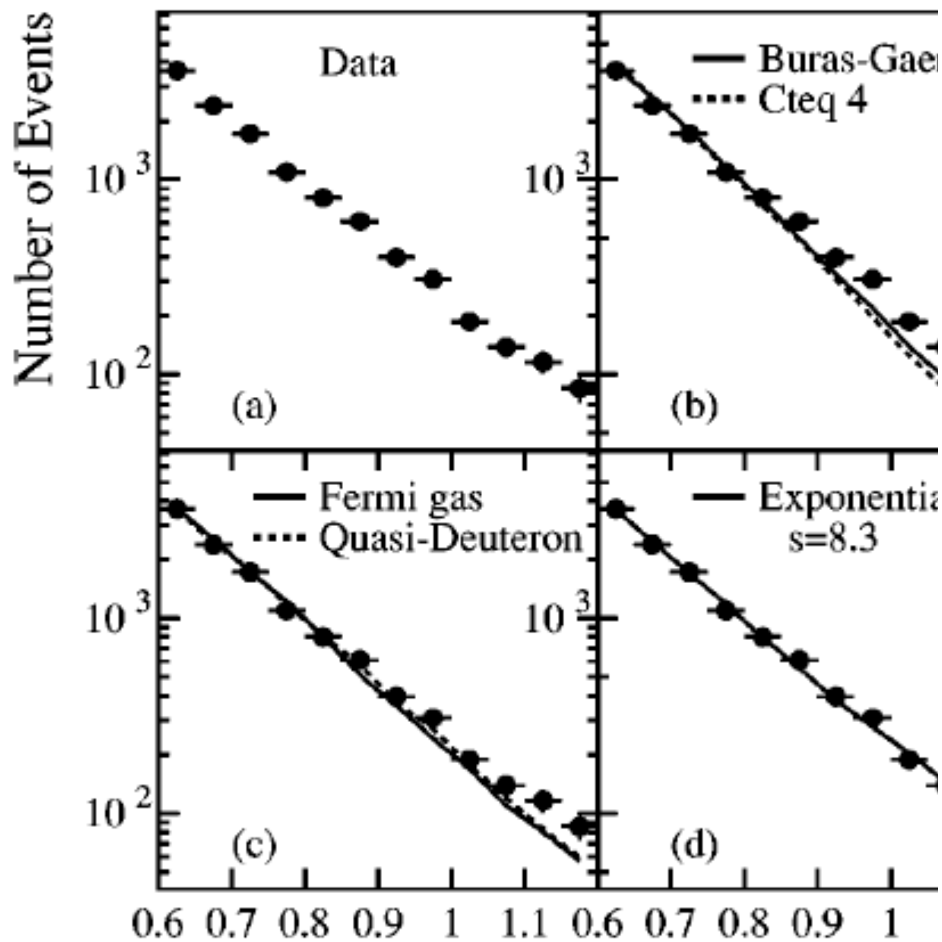
Phys. Rev. D61 2000

Using the neutrino and antineutrino beams in which structure function Iron was measured in the charged current sector for average

$$Q^2 = 120\ \mathrm{GeV}^2 \text{ and } 0.6 \le x \le 1.2.$$

$$F_{2A} \sim e^{-s(x-x_0)}$$

$$s = 8.3 \pm 0.7(stat) \pm 0.7(sys$$



3. E02-019 Experiment 2010 (JLab)

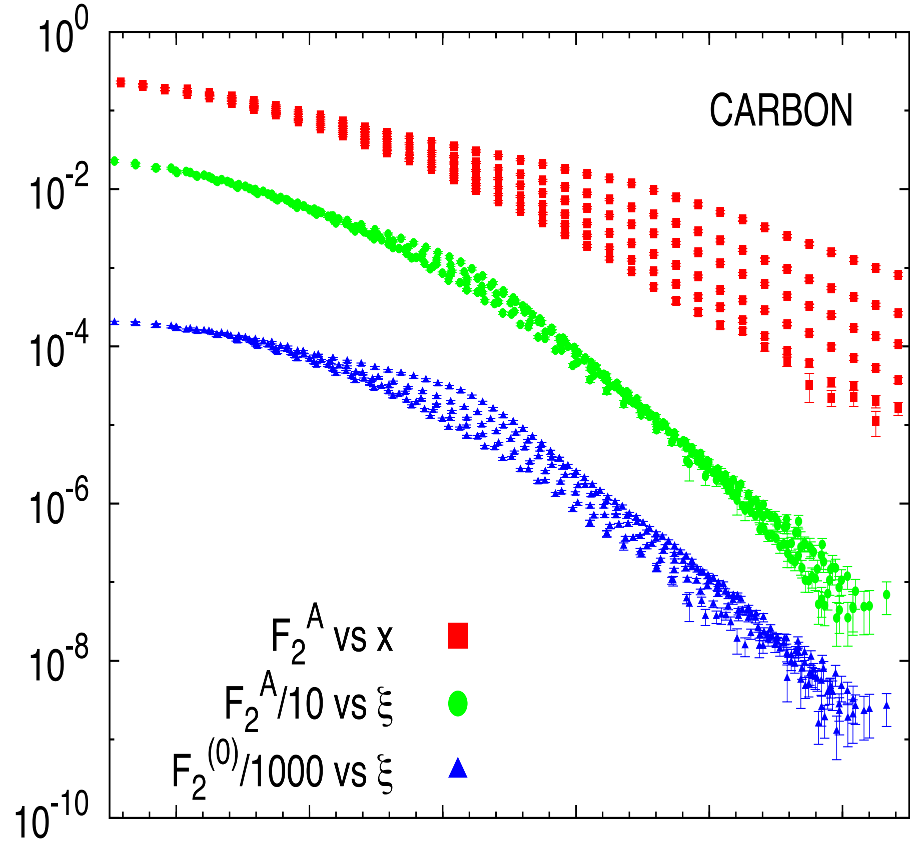
Phys.Rev.Lett 204 2010

(ee') scattering of

$^{2}H,\ ^{3}He,\ ^{4}He,\ ^{9}Be,\ ^{12}C,\ ^{64}Cu$ and ^{197}Au

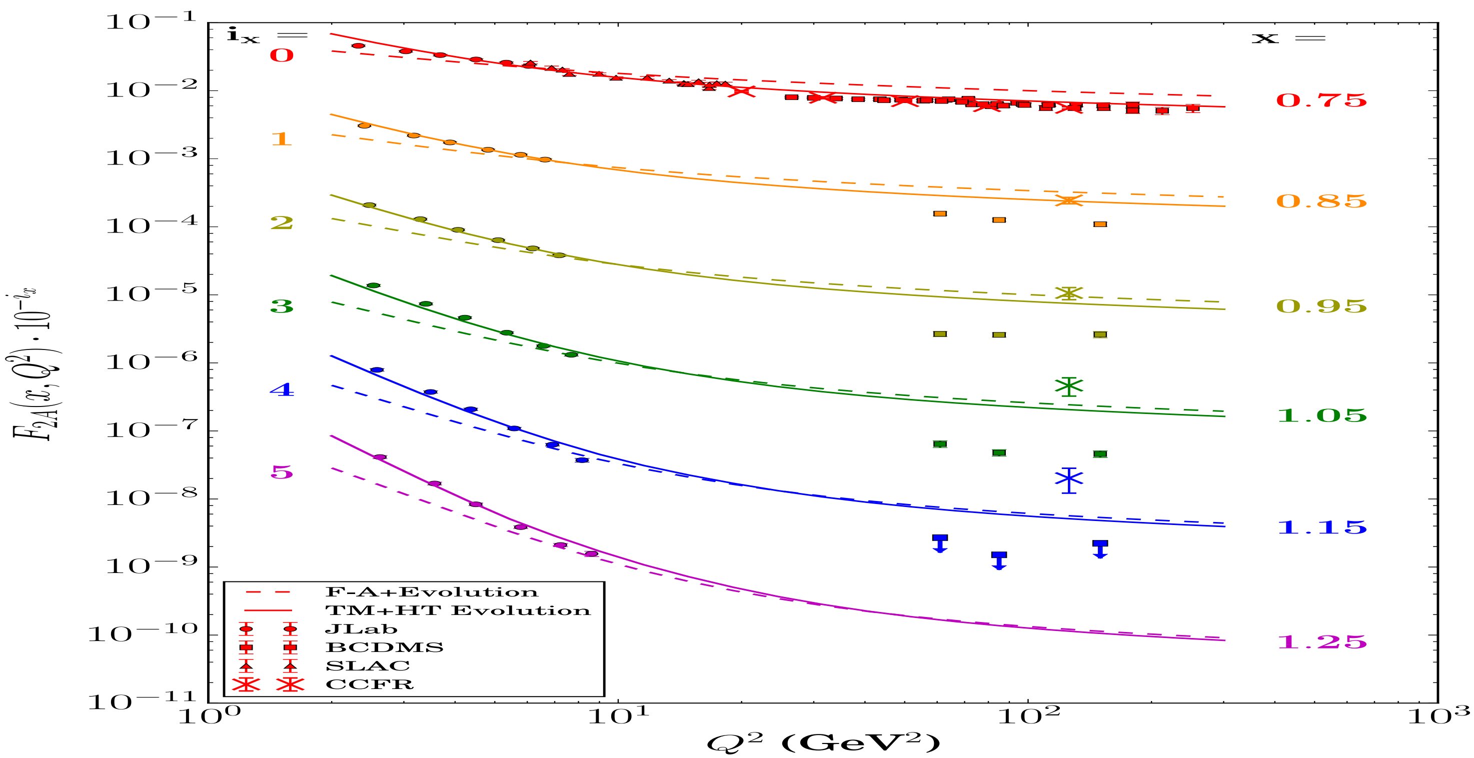
$$6 < Q^2 < 9\ \mathrm{GeV}^2$$

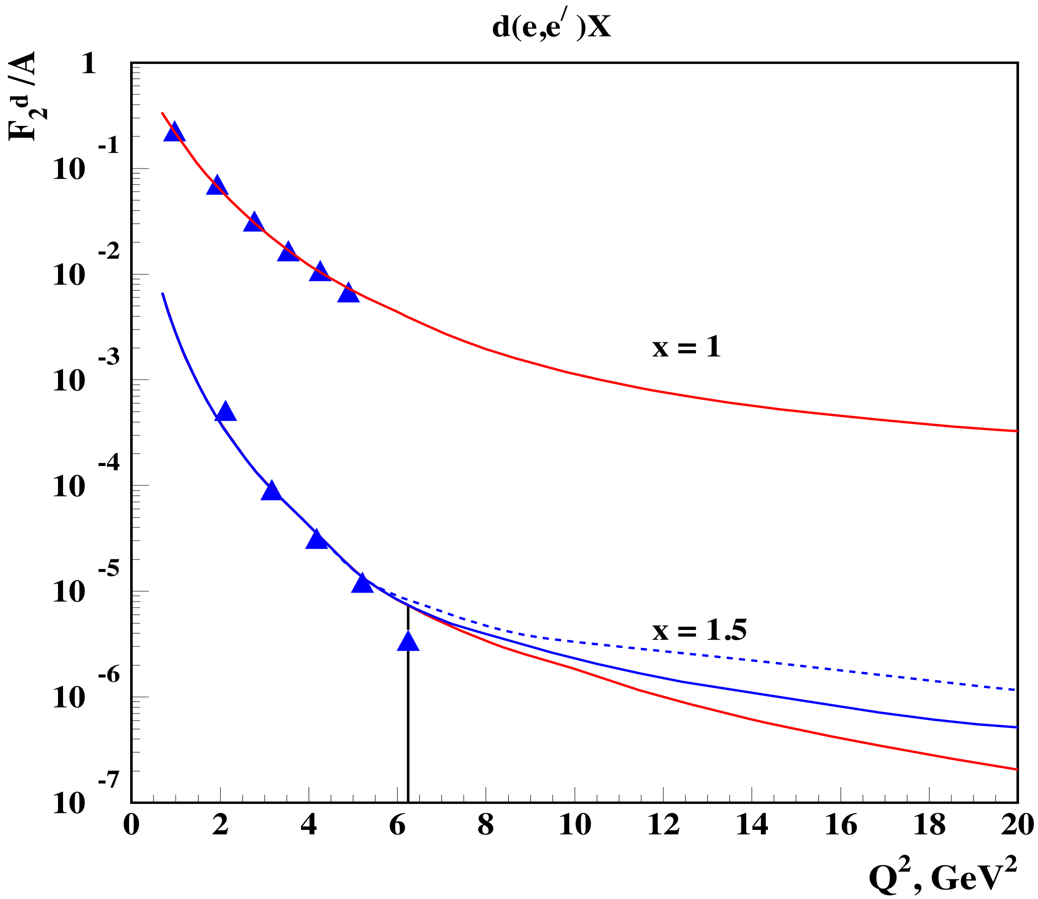
$$\xi = \frac{2x}{(1+r)} \text{ where } r = \sqrt{1 + \frac{4M_N^2 x^2}{Q^2}}$$

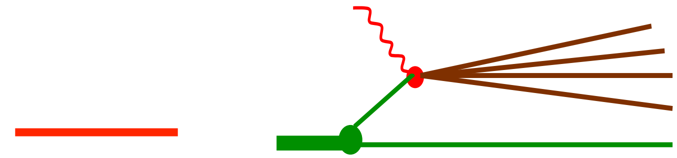


$$\frac{dF_{2A}(x,Q^2)}{d\log Q^2} = \frac{\alpha_s}{2\pi}\left\{2\left(1+\frac{4}{3}\log(1-\frac{x}{A})\right)F_{2,A}(x,Q^2) + \frac{4}{3}\int_{x/A}^{1}\frac{dz}{1-z}\left(\frac{1+z^2}{z}F_{2A}(\frac{x}{z},Q^2) - 2F_{2A}(x,Q^2)\right)\right\}.$$

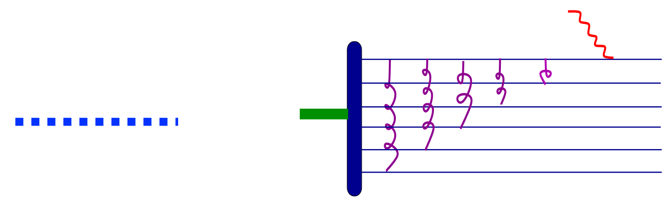
A.Freese & M.S
ArXiv 2016



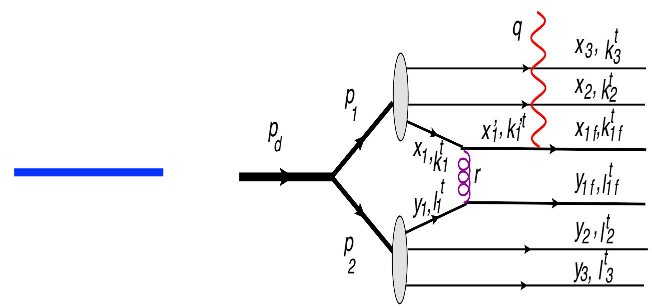




$$F_{2d} = \int_x^2 \rho_d^N(\alpha, p_t) F_{2N}\left(\frac{x}{\alpha}, Q^2\right) \frac{d^2\alpha}{\alpha} d^2 p_t$$



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



$$F_{2d}(x_{Bj}, Q^2) \sim \sum_{i,j} x_{Bj} e_i^2 \int dx_1 dy_1 f_i(x_1, Q^2) f_j(y_1, l_{1f,t}^2) \frac{1}{y_1^2} \left[1 - \frac{x_{Bj}}{x_1 + y_1}\right]^2 \Theta(x_1 + y_1 - x_{Bj})$$

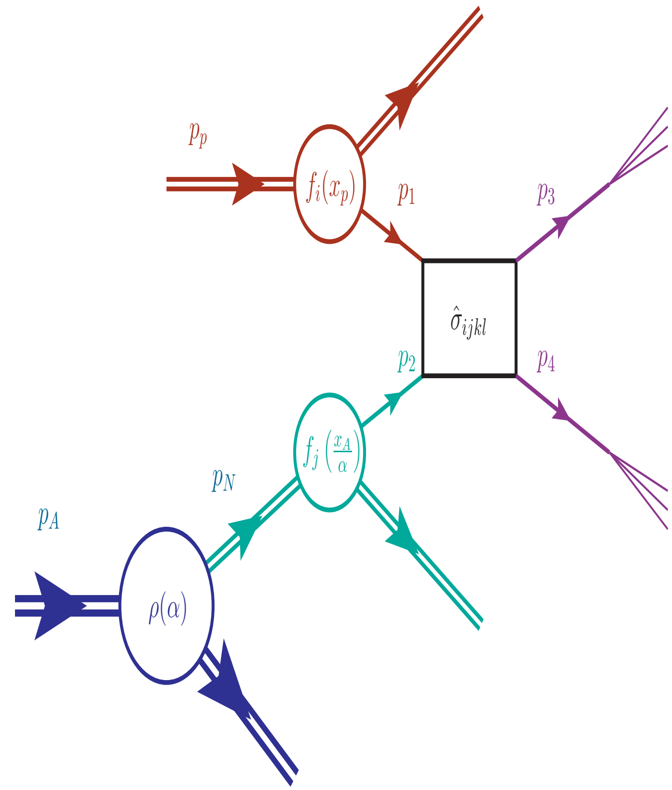
MS, in progress

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

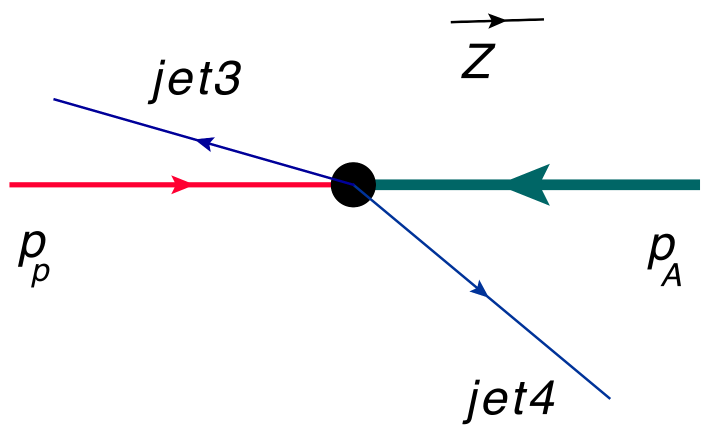
A.Freese, M.S.
M.Strikman, EPJ 2015

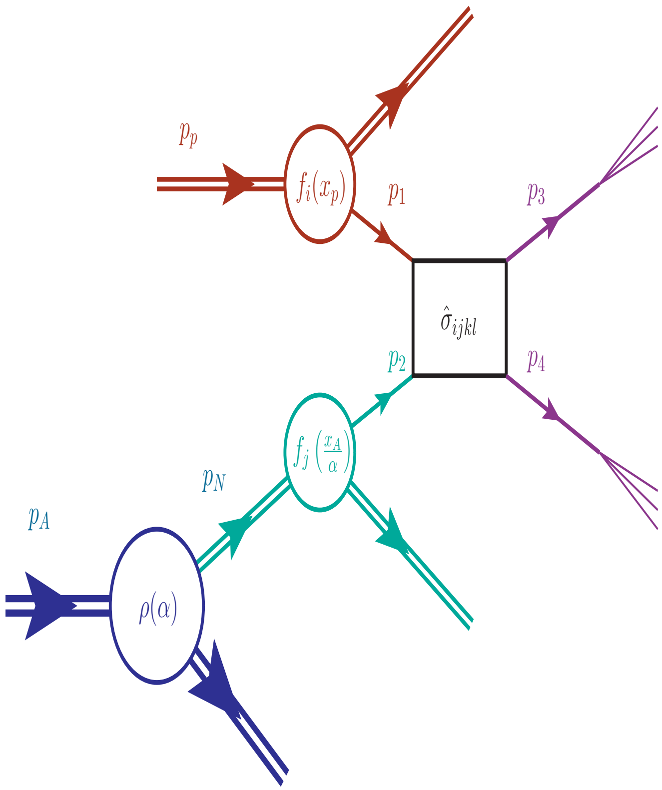
$$p + A \to \text{dijet} + X$$

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



Jet - kinematics

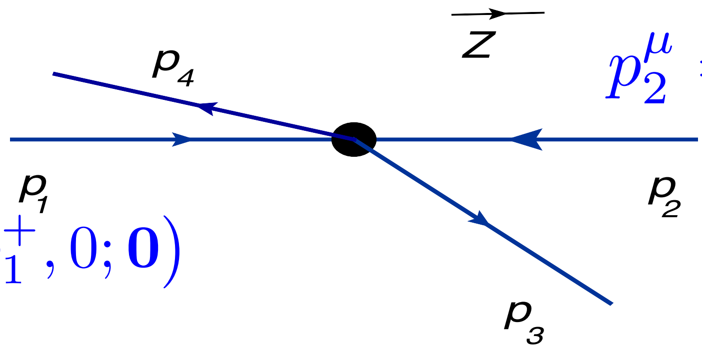




$$p_p^\mu = \left(p_p^+, \frac{m_p^2}{p_p^+}, \mathbf{0}_T\right) = (2E_0, 0, \mathbf{0}_T) = \left(\sqrt{\frac{As_{NN}^{\text{avg.}}}{Z}}, 0, \mathbf{0}_T\right)$$

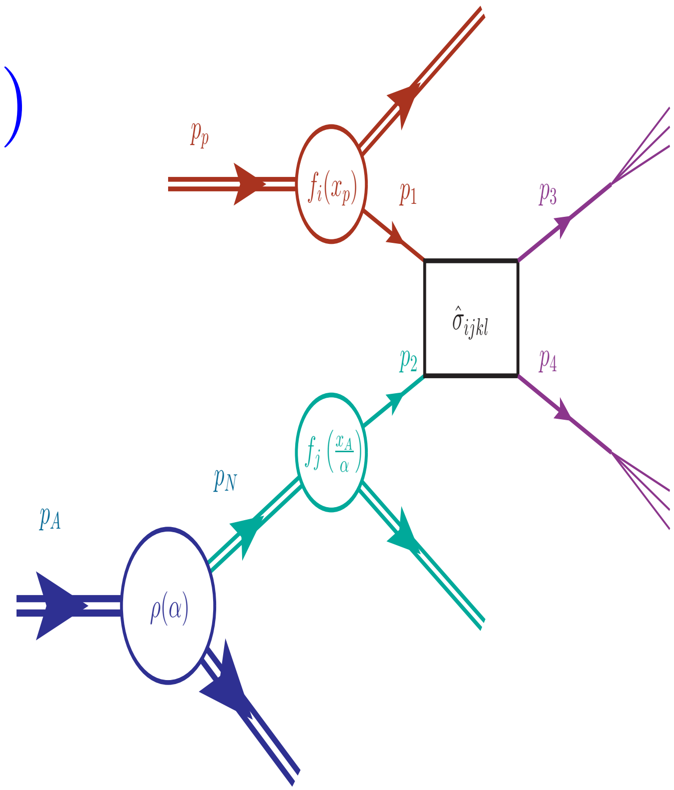
$$p_A^\mu = \left(\frac{M_A^2}{p_A^-}, p_A^-, \mathbf{0}_T\right) = (0, 2ZE_0, \mathbf{0}_T) = \left(0, \sqrt{AZs_{NN}^{\text{avg.}}}, \mathbf{0}_T\right)$$

Parton - kinematics



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

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



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

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

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

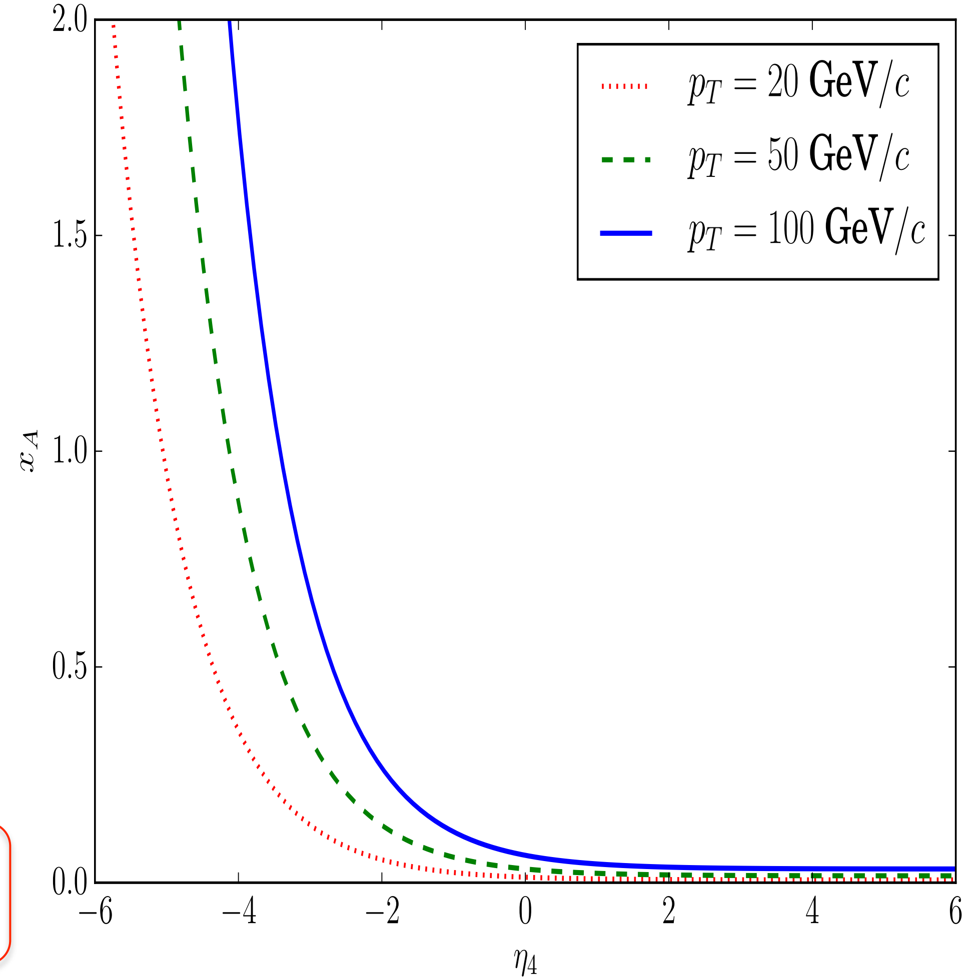
$$p_2^\mu = (0, p_2^-; \mathbf{0}) \qquad x_A = A\frac{p_2^-}{p_A^-}$$

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

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

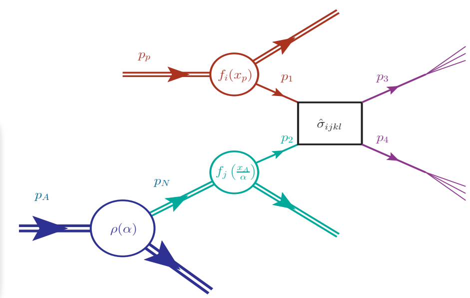
$$x_p = \sqrt{\frac{Z}{A}}\frac{p_T}{\sqrt{s_{NN}^{\text{avg.}}}}\left(e^{\eta_3} + e^{\eta_4}\right)$$

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



Differential Cross Section of the Reaction

$$\frac{d^3\sigma}{d\eta_3 d\eta_4 dp_T^2} = \sum_{ijkl} \frac{1}{16\pi (s_{NN}^{\text{avg.}})^2} \frac{f_{i/p}(x_p, Q^2)}{x_p} \frac{f_{j/A}(x_A, Q^2)}{x_A} \frac{\overline{|\mathcal{M}_{ij\to kl}|^2}}{1+\delta_{kl}}$$



$$s_{NN}^{\text{avg}} = \frac{p_p^+ p_A^-}{A}$$

$$Q^2 = -(p_1 - p_3)^2 \approx p_T^2$$

$$f_{i/p}(x_p, Q^2)$$

$$f_{j/A}(x_A, Q^2)$$

Subprocess	$\frac{\overline{\lvert\mathcal{M}\rvert^2}}{g_s^4}$
$q_j + q_k \to q_j + q_k$	$\frac{4}{9}\frac{s^2+u^2}{t^2}$
$q_j + q_j \to q_j + q_j$	$\frac{4}{9}\left(\frac{s^2+u^2}{t^2} + \frac{s^2+t^2}{u^2}\right) - \frac{8}{27}\frac{s^2}{ut}$
$q_j + \bar{q}_j \to q_k + \bar{q}_k$	$\frac{4}{9}\frac{t^2+u^2}{s^2}$
$q_j + \bar{q}_j \to q_j + \bar{q}_j$	$\frac{4}{9}\left(\frac{s^2+u^2}{t^2} + \frac{t^2+u^2}{s^2}\right) - \frac{8}{27}\frac{u^2}{st}$
$q_j + \bar{q}_j \to g + g$	$\frac{32}{27}\frac{u^2+t^2}{ut} - \frac{8}{3}\frac{u^2+t^2}{s^2}$
$g + g \to q_j + \bar{q}_j$	$\frac{1}{6}\frac{u^2+t^2}{ut} - \frac{3}{8}\frac{u^2+t^2}{s^2}$
$q_j + g \to q_j + g$	$-\frac{4}{9}\frac{u^2+s^2}{us} + \frac{8}{3}\frac{u^2+s^2}{t^2}$
$g + g \to g + g$	$\frac{9}{2}\left(3 - \frac{ut}{s^2} - \frac{us}{t^2} - \frac{st}{u^2}\right)$

Nuclear Partonic Distributions

$$f_{i/A}(x_A, Q^2) = \sum_N \int_{x_A}^{A} \frac{d\alpha}{\alpha} \int d^2\mathbf{p}_T f_{N/A}(\alpha, \mathbf{p}_T) f_{i/N}^{(b)}\left(\frac{x_A}{\alpha}, \alpha, \mathbf{p}_T, Q^2\right)$$

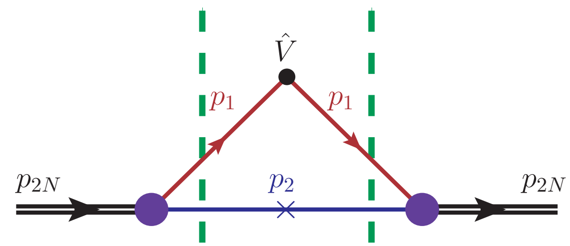
$f_{N/A}(\alpha, \mathbf{p}_T)$ Light-Front fractional distribution of nucleon in the nucleus

$f_{i/N}^{(b)}\left(\frac{x_A}{\alpha_N}, \alpha_N, \mathbf{p}_{N,T}, Q^2\right)$ i-parton distribution in the bound nucleon N

Light-Front Distribution of Nucleon in the Nucleus

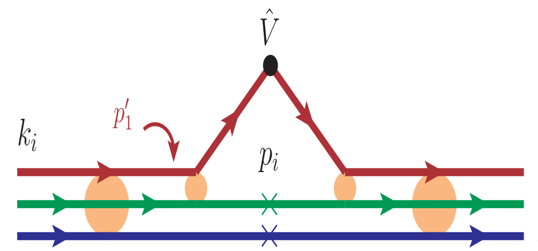
$$f_{N/A}(\alpha, \mathbf{p}_T) = f^{(MF)}_{N/A}(\alpha, \mathbf{p}_T) + f^{(2)}_{N/A}(\alpha, \mathbf{p}_{NT}) + f^{(3)}_{N/A}(\alpha, \mathbf{p}_{NT}) \cdots$$

$$f^{(MF)}_{N/A}(\alpha, \mathbf{p}_T) = \frac{m_A}{A} \left| \Psi^{(N)}_{MF}(p) \right|^2$$



$$f^{(2)}_{N/A}(\alpha, \mathbf{p}_T) = \frac{a_2(A)}{2\chi_N} \frac{\overline{|\psi_d(k)|^2}}{\alpha(2-\alpha)} \Theta(k - k_F)$$

$$f^{(3)}_{N/A}(\alpha, \mathbf{p}_T) = \{a_2(A)\}^2 \frac{1}{\alpha} \int \frac{d\alpha_3 d^2\mathbf{p}_{3T}}{\alpha_3(3-\alpha-\alpha_3)} \left\{ \frac{3-\alpha_3}{2(2-\alpha_3)} \right\}^2 \overline{|\psi_d(k_{12})|^2}\, \Theta(k_{12} - k_F)\, \overline{|\psi_d(k_{23})|^2}\, \Theta(k_{23} - k_F)$$



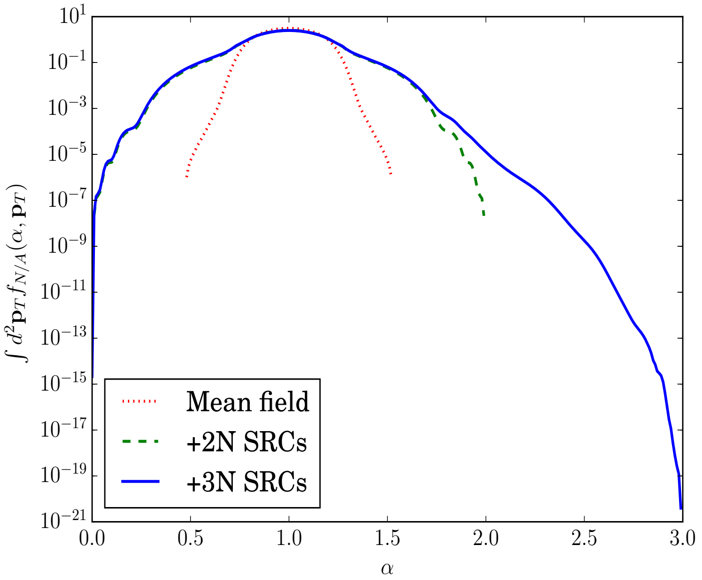
Light-Front Distribution of Nucleon in the Nucleus

$$f_{N/A}(\alpha,\mathbf{p}_T) = f^{(MF)}_{N/A}(\alpha,\mathbf{p}_T) + f^{(2)}_{N/A}(\alpha,\mathbf{p}_{NT}) + f^{(3)}_{N/A}(\alpha,\mathbf{p}_{NT})\cdots$$

$$f^{(MF)}_{N/A}(\alpha,\mathbf{p}_T) = \frac{m_A}{A}\left|\Psi^{(N)}_{MF}(p)\right|^2$$

$$f^{(2)}_{N/A}(\alpha,\mathbf{p}_T) = \frac{a_2(A)}{2\chi_N}\frac{\overline{|\psi_d(k)|^2}}{\alpha(2-\alpha)}\Theta(k-k_F)$$

$$f^{(3)}_{N/A}(\alpha,\mathbf{p}_T) = \{a_2(A)\}^2\frac{1}{\alpha}\int\frac{d\alpha_3 d^2\mathbf{p}_{3T}}{\alpha_3(3-\alpha-\alpha_3)}\left\{\frac{3-\alpha_3}{2(2-\alpha_3)}\right\}^2 \overline{|\psi_d(k_{12})|^2}\,\Theta(k_{12}-k_F)\,\overline{|\psi_d(k_{23})|^2}\,\Theta(k_{23}-k_F$$

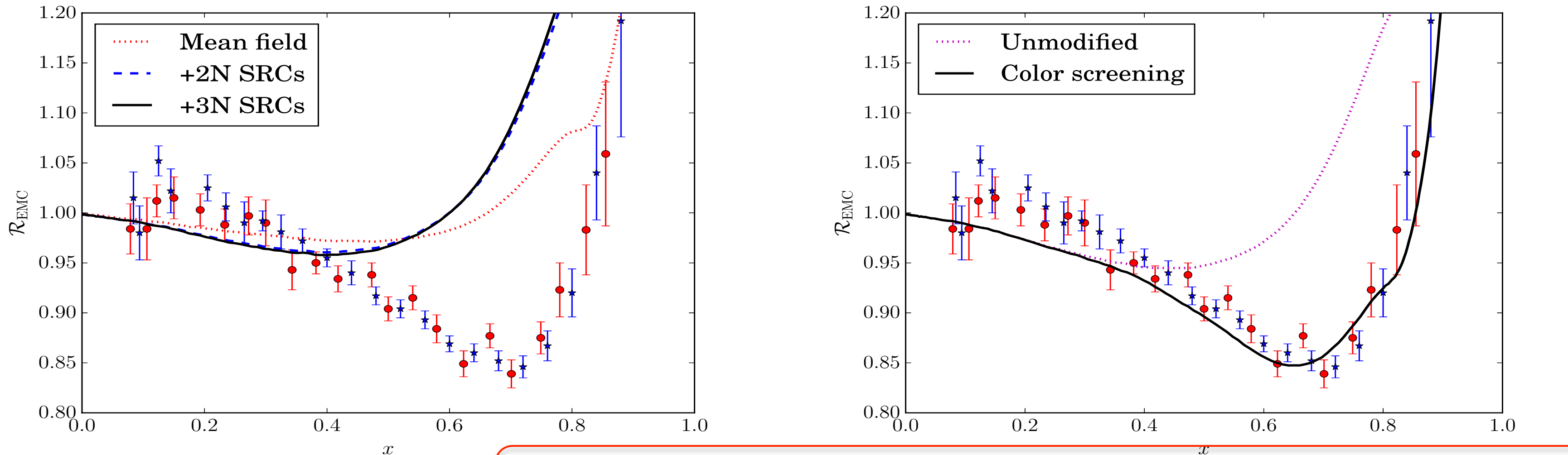


Partonic distribution in the bound nucleon: Medium Modification effects

$$F_2^{(A)}(x,Q^2) = \sum_N \int_x^A d\alpha \int d^2\mathbf{p}_T f_{N/A}(\alpha,\mathbf{p}_T) F_2^{(N,b)}\left(\frac{x}{\alpha},\alpha,\mathbf{p}_T,Q^2\right)$$

$$\mathcal{R}_{\mathrm{EMC}}(x,Q^2) = \frac{2}{A}\frac{\sigma_{eA}}{\sigma_{ed}} f_{iso} \approx \frac{2}{A}\frac{F_2^{(A)}(x,Q^2)}{F_2^{(d)}(x,Q^2)} f_{iso}$$

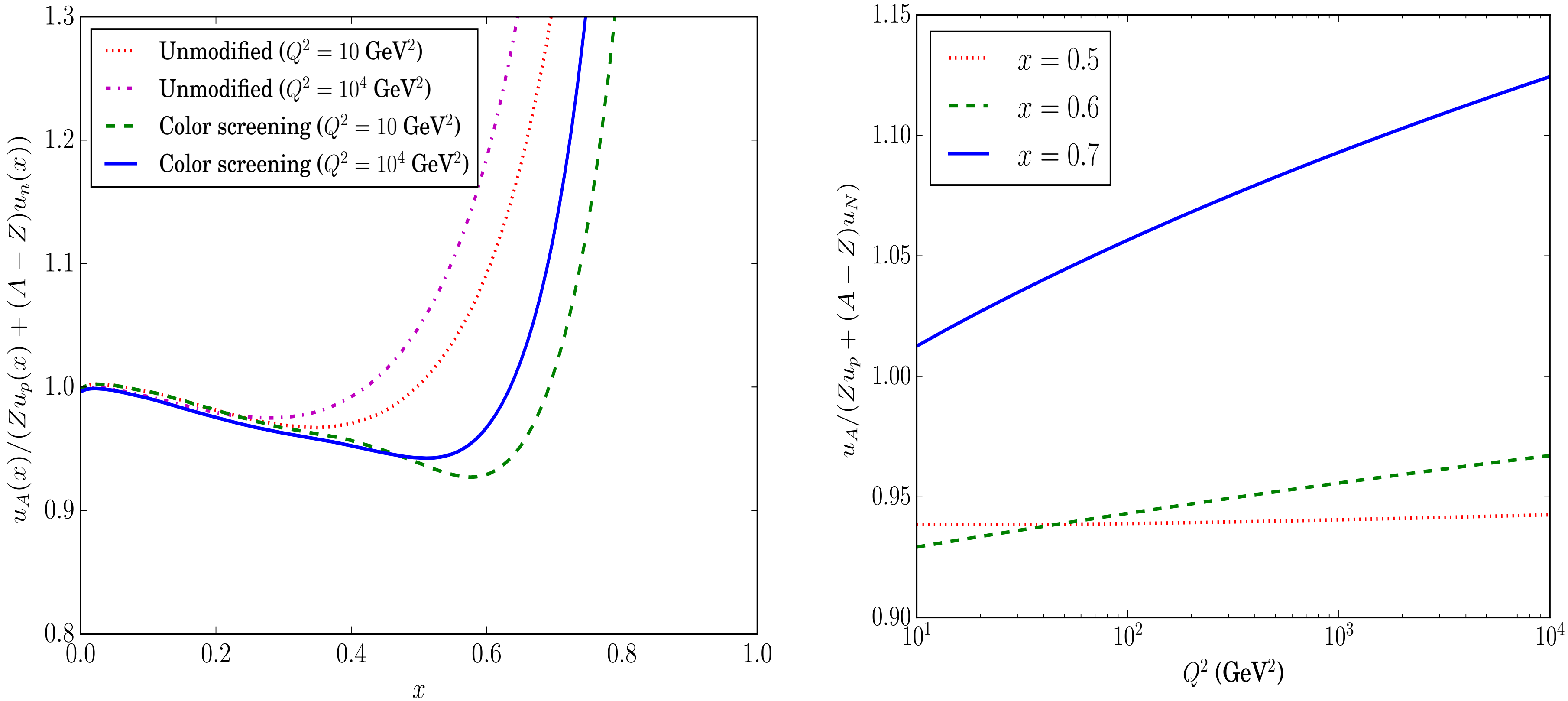
$$Q^2 = 10\ \mathrm{GeV}^2$$



Color Screening Model ->

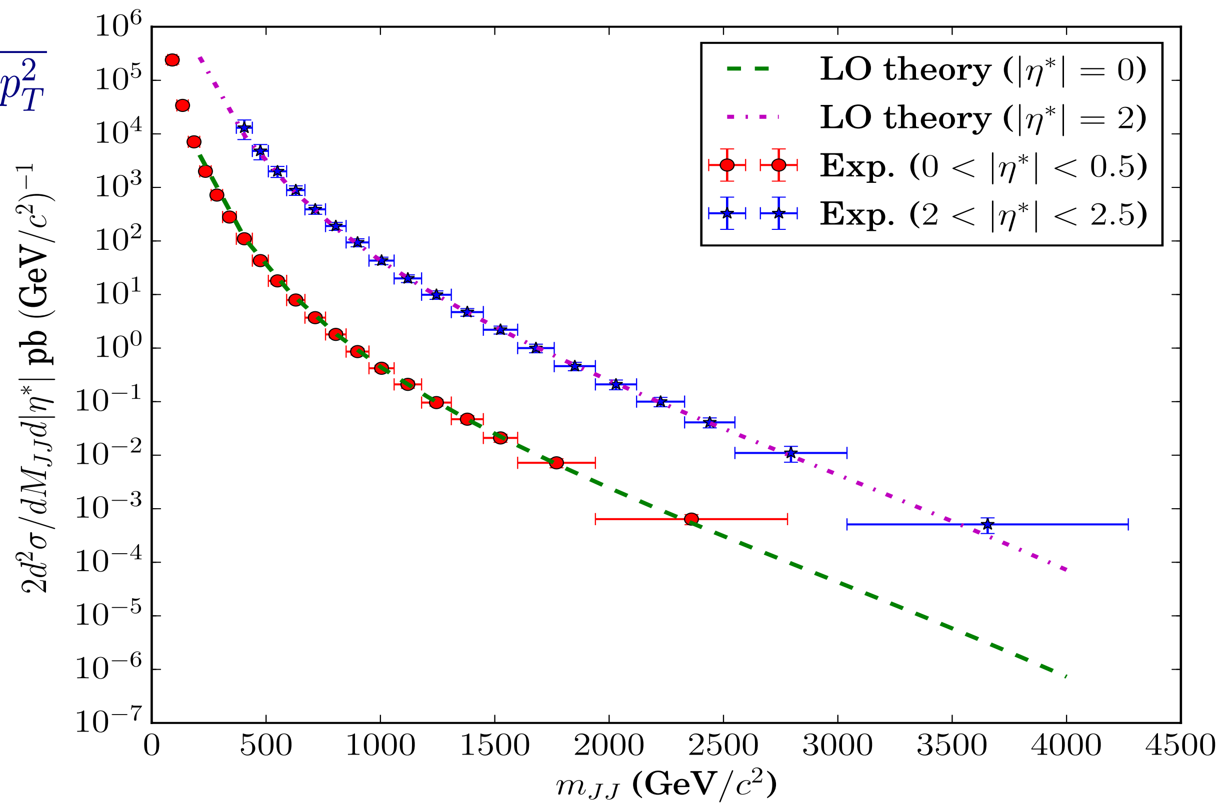
$$F_2^{(N,b)}\left(\frac{x}{\alpha},\alpha,\mathbf{p}_T,Q^2\right) = F_2^{(N)}\left(\frac{x}{\alpha},Q^2\right)\delta\left(k^2(\alpha,\mathbf{p}_T),\frac{x}{\alpha}\right)$$

QCD Evolution of Medium Modifications

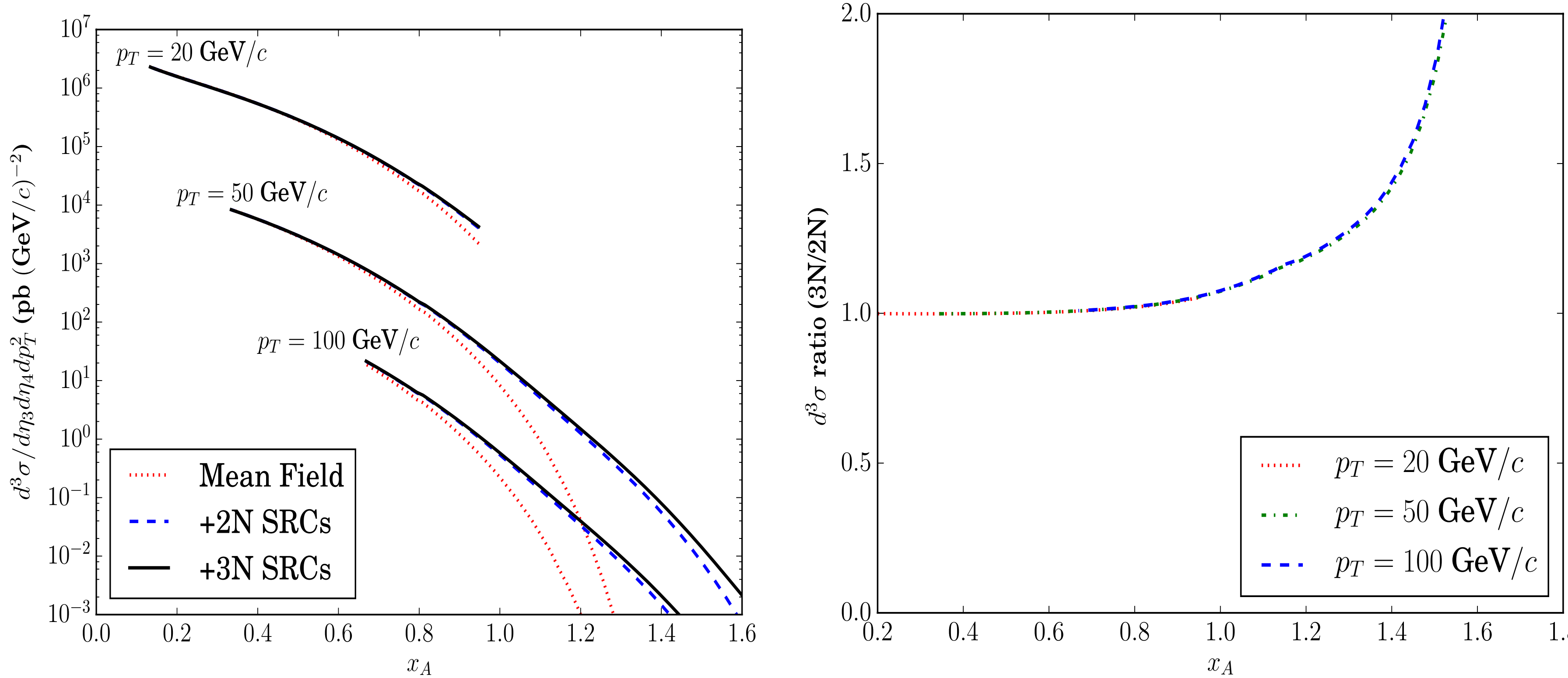


Checking Calculation for "Conventional" kinematics

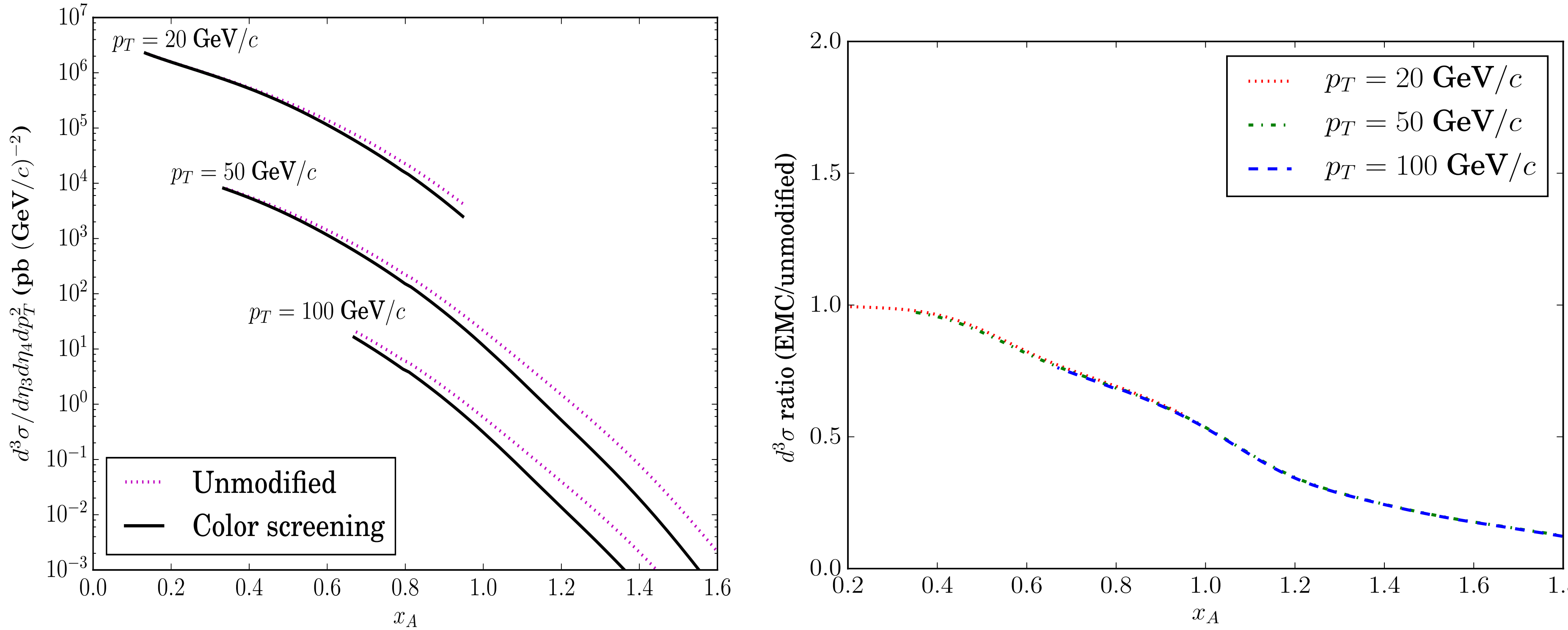
$$\frac{2d^2\sigma}{dm_{JJ}d\eta^*} = \frac{4p_T}{\cosh(\eta^*)}\int d\bar{\eta}\frac{d^3\sigma}{d\eta_3 d\eta_4 dp_T^2}$$



G. Aad et al. (ATLAS Collaboration), Phys. Rev. D 86, 014022(2012).

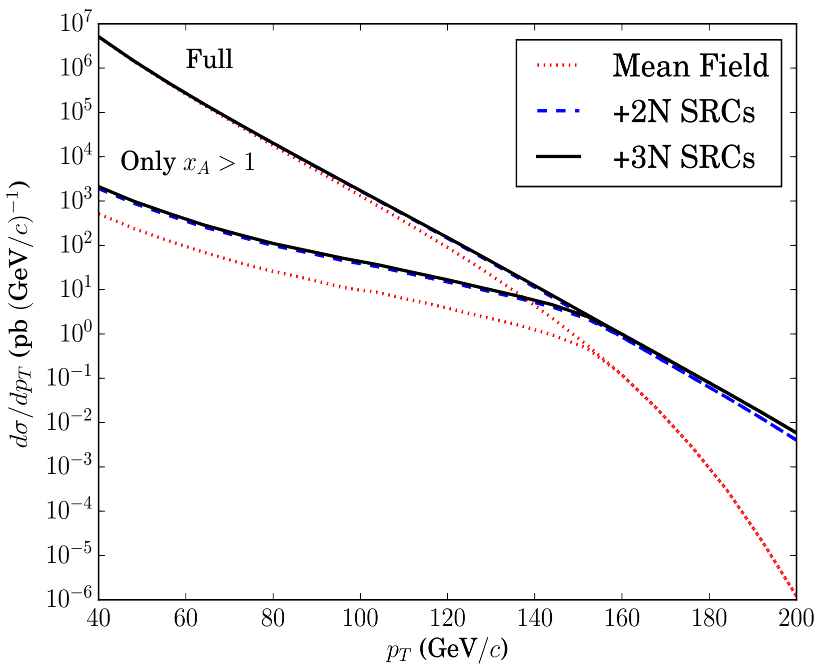


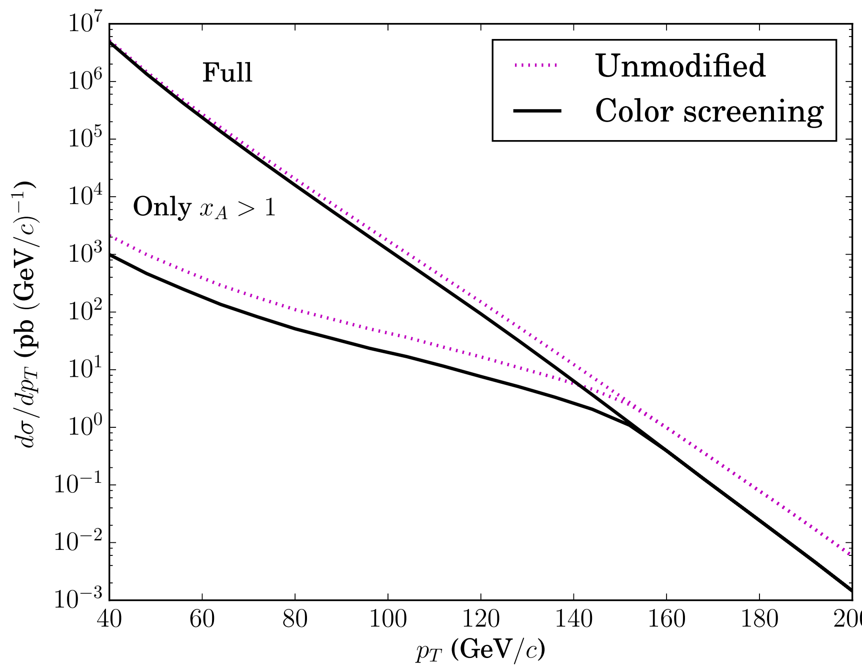
$p_T = 20$ GeV/c
$p_T = 50$ GeV/c
$p_T = 100$ GeV/c
Mean Field
+2N SRCs
+3N SRCs
$d^3\sigma/d\eta_3 d\eta_4 dp_T^2$ (pb (GeV/c)$^{-2}$)
x_A
$d^3\sigma$ ratio (3N/2N)
x_A
$p_T = 20$ GeV/c
$p_T = 50$ GeV/c
$p_T = 100$ GeV/c



$p_T = 20$ GeV/c
$p_T = 50$ GeV/c
$p_T = 100$ GeV/c
Unmodified
Color screening
$d^3\sigma/d\eta_3 d\eta_4 dp_T^2$ (pb (GeV/c)$^{-2}$)
x_A
$p_T = 20$ GeV/c
$p_T = 50$ GeV/c
$p_T = 100$ GeV/c
$d^3\sigma$ ratio (EMC/unmodified)
x_A

$$\frac{d\sigma(x_A > 1)}{dp_T} = \int_{-2.5}^{2.5} d\eta_3 \int_{-5}^{-3} d\eta_4 \frac{2p_T d^3\sigma}{d\eta_3 d\eta_4 dp_T^2} \Theta(x_A - 1)$$





Integrated cross section at 7TeV per proton

$$\frac{d\sigma(x_{max} > x_A > x_{min})}{dp_T} = \int_{50GeV/c} dp_T \int_{-2.5}^{2.5} d\eta_3 \int_{-5}^{-3} d\eta_4 \frac{2p_T d^3\sigma}{d\eta_3 d\eta_4 dp_T^2} \Theta(x_A - x_{min})\Theta(x_{max} - x_A)$$

	Unmodified (SRCs)	Modified (no SRCs)	Modified (SRCs)
All x_A	58 μb	55 μb	55 μb
$0.6 < x_A < 0.7$	1.7 μb	1.2 μb	1.3 μb
$0.7 < x_A < 0.8$	0.60 μb	0.37 μb	0.43 μb
$0.8 < x_A < 0.9$	0.20 μb	0.11 μb	0.13 μb
$0.9 < x_A < 1$	59 nb	20 nb	33 nb
$1 < x_A$	21 nb	3.0 nb	9.3 nb

The expected yield for $x_A > 1$ events at the LHC is 326 events for a month of run time based on previously achieved luminosity of 35.5/nb.

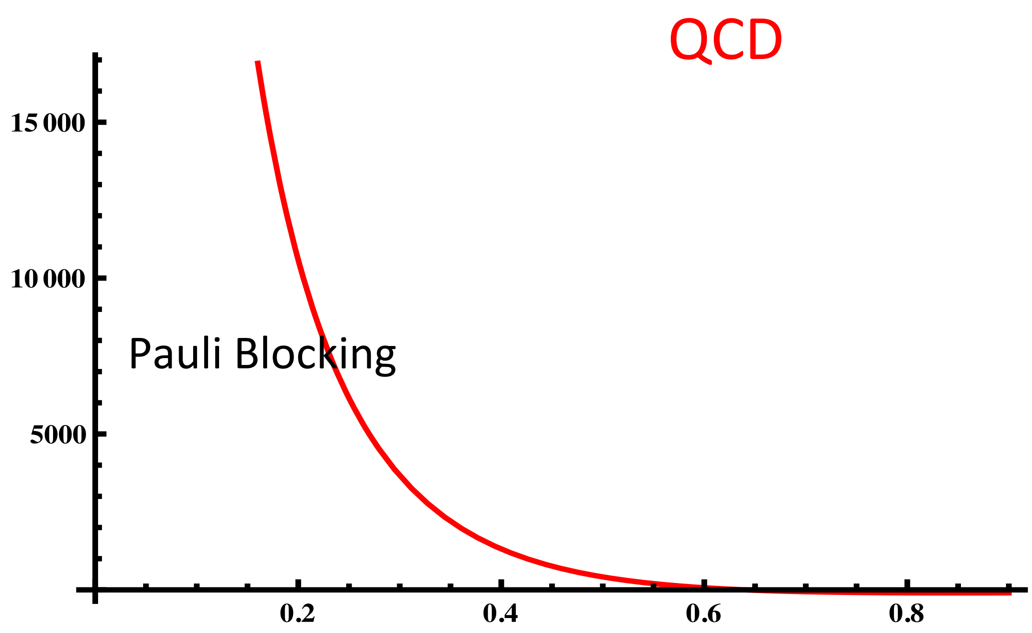
Summary & Outlook

- p+A -> 2jets+X at large p_T allow to reach practically unexplored x>1 region

- Cross section in these kinematics is sensitive to the nuclear structure at very short distances

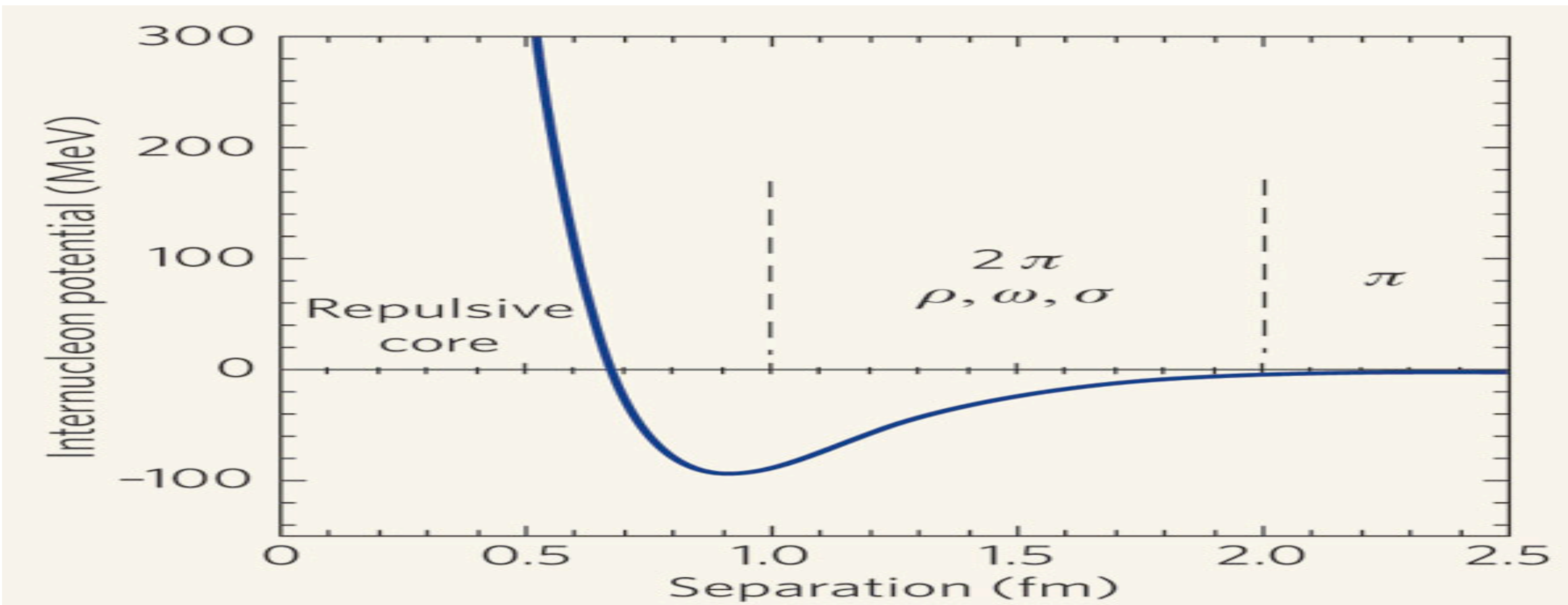
- It is sensitive also to the medium modification effects of PDFs allowing to study its x and Q^2 dependences

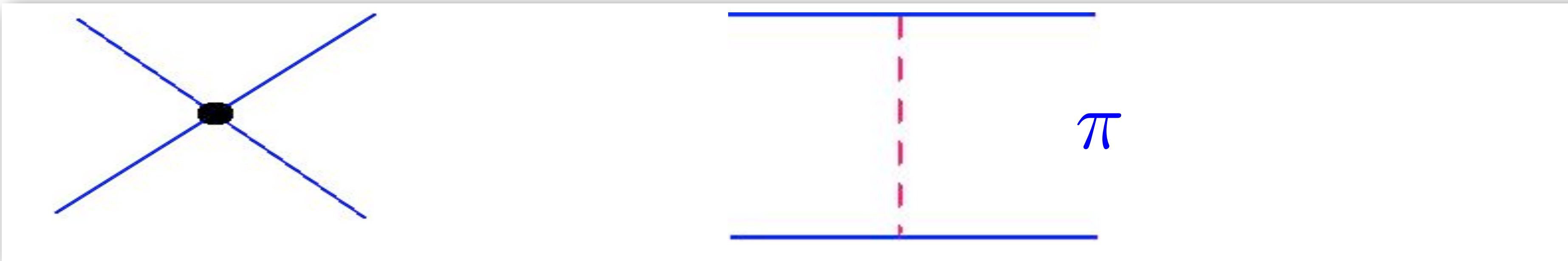
- Special care shout be given in separating above to phenomena

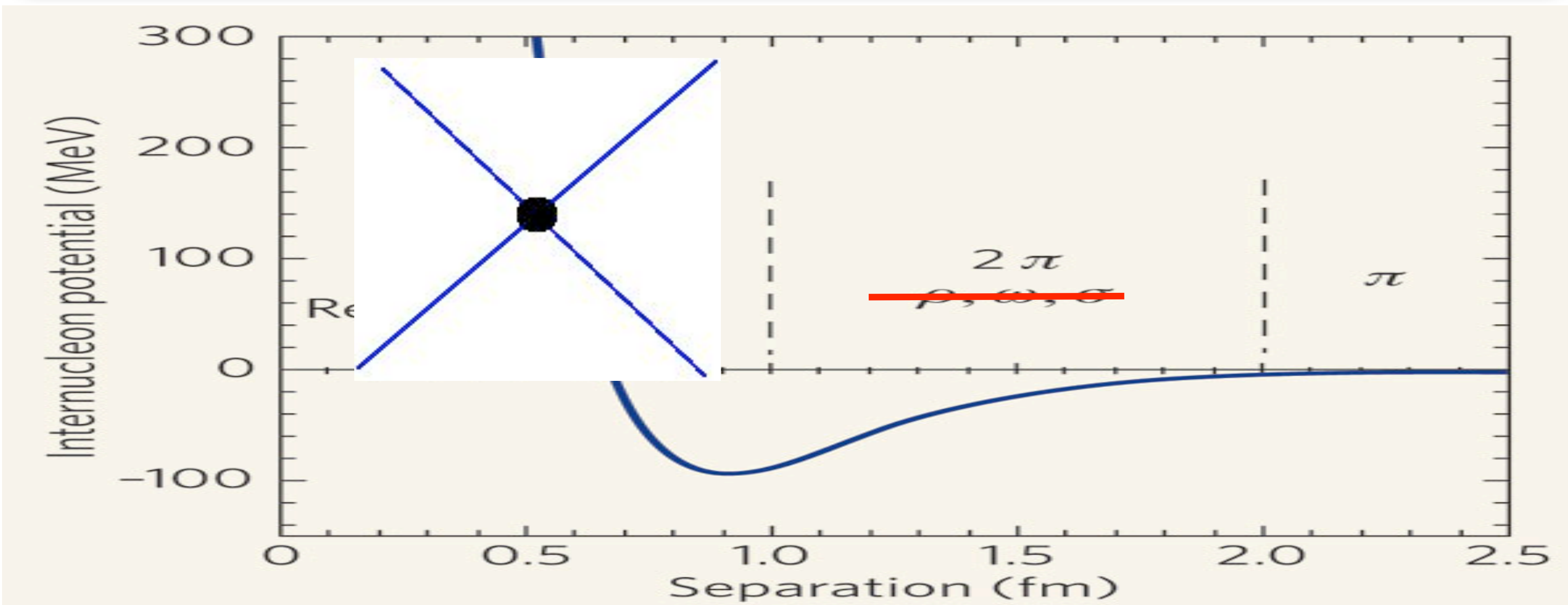


Contradicts Neutron Star Observations:
will predict masses not more than 0.1 - 0.6 Solar mass

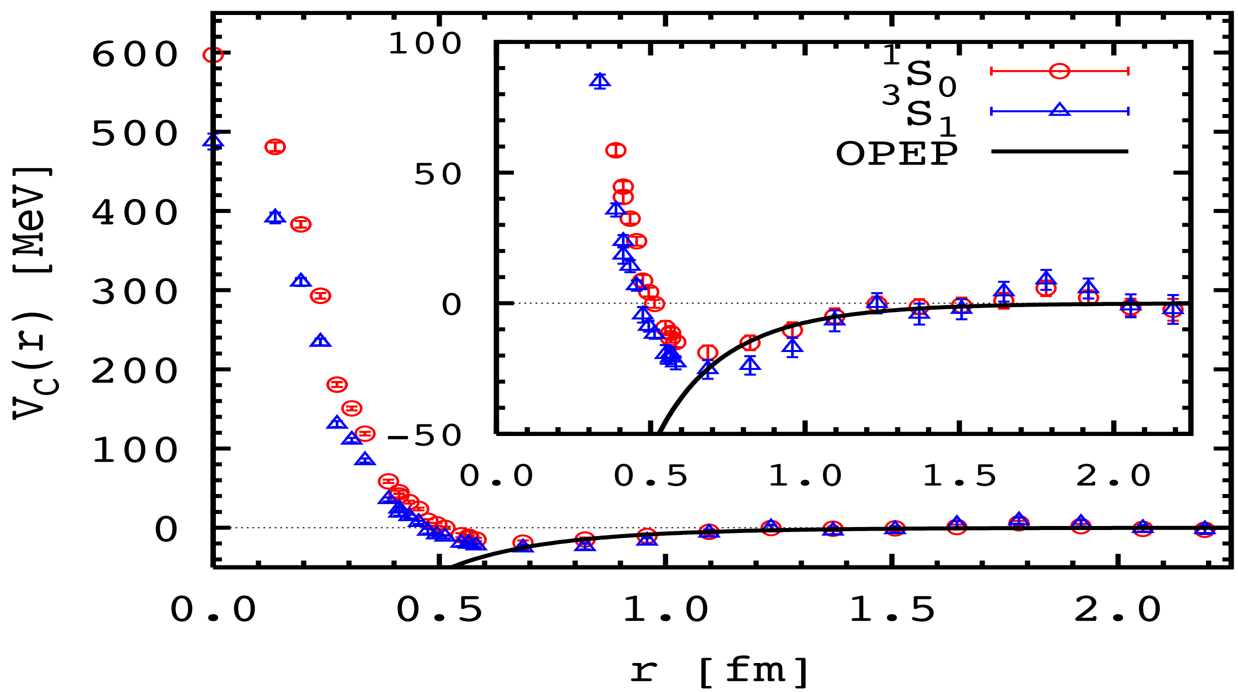
$\sigma, \quad \pi, \quad \rho, \quad \omega, \ldots$




π


300
200
100
0
−100
Internucleon potential (MeV)
0
0.5
1.0
1.5
2.0
2.5
Separation (fm)
2 π
ρ, ω, σ
π

Lattice Calculations



How to probe high density fluctuations in nuclei *for A > 2*

Probe large pre-existing relative momenta of nucleons in the nucleus

$$(E_B - \frac{k^2}{2m} - \sum_{i=2,..A} T_i)\psi_A = \sum_{i=2,...A} \int V(k-k_i')\psi_A(k, k_i', ...k_j, ...k_A)\frac{d^3k_i'}{(2\pi)^3} + \sum_{i=2,...A} \int V(k_i - k_i')\psi_A(k, k_i', ...k_j, ..., k_A)\frac{d^3k_i'}{(2\pi)^3},$$

If at large k, $V_{NN}(k) \sim \frac{1}{k^n}$ and $n > 1$

Frankfurt M.S. Strikman IJMP 08

in $k^2/2m_N \gg |E_B|$ limit

$$\psi_A \sim \frac{V_{NN}(k)}{k^2} f(k_3, ...k_A),$$

where $f(k_3, ...k_A)$ is a smooth function of spectator nucleon's momenta with $k_2 \sim -k$.