Probing Nuclear Structure at Extreme Conditions

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Short Range Nuclear Dynamics

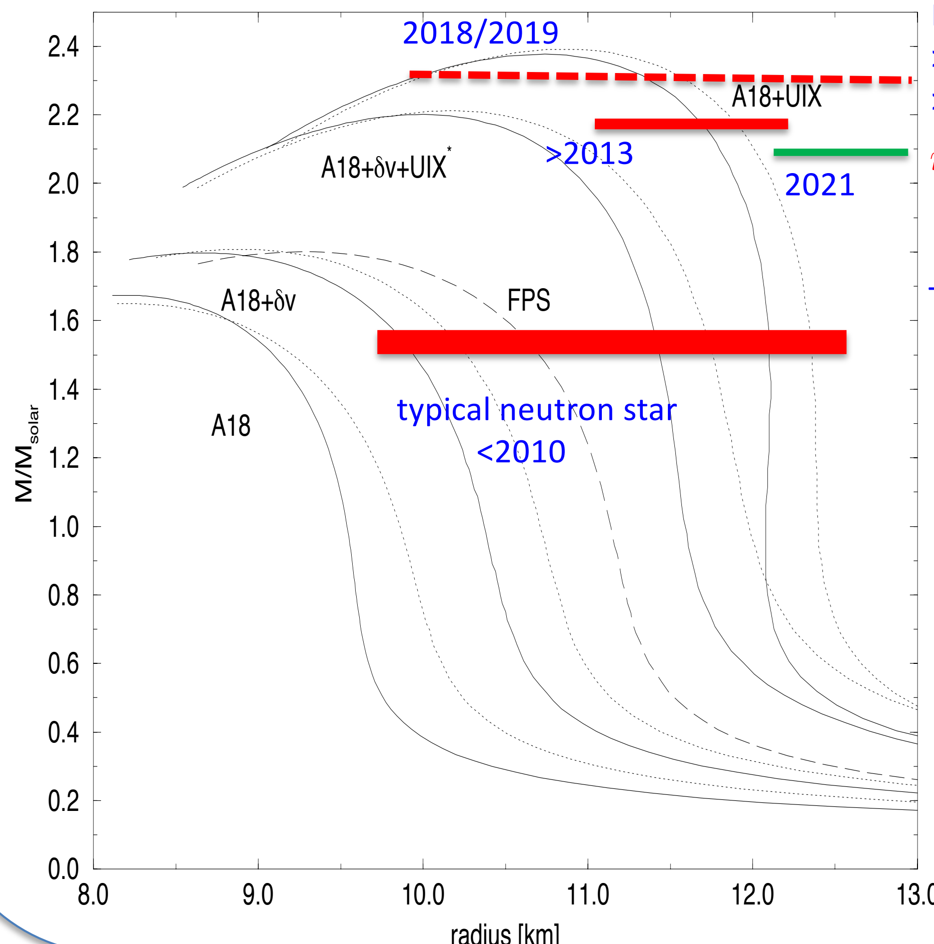
1. Structure in Universe Exists because of Atomic Nuclei

2. Atomic Nuclei Exist because of specifics of strong interaction at short distances (<= 1f)

3. These specifics include (a) correlated nature of nuclear structure at short distances (b) existence of strong tensor component and repulsive core of the NN interaction

4. The research is relevant for understanding the core of neutron stars, their merging as well as structure disappearance in black-holes

"Unreasonable" Persistence of Nucleons



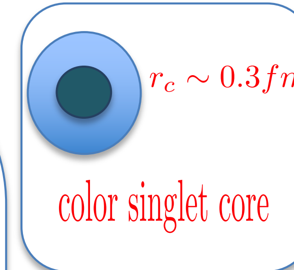
Neutron star masses
>2 solar masses
>2010

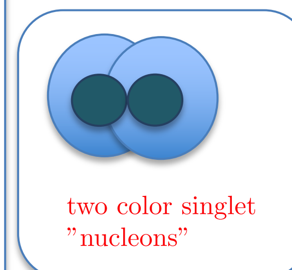
$r_{NN} \sim 0.6 - 0.8 fm$

Typical neutron star
1.4 Solar mass

$r_{NN} \sim 0.7 - 1.0 fm$

H. Heiselberg,
V.Pandharipande
ARNPS 2000





Methodology

High Energy and Momentum Transfer Electronuclear Processes – Large Q^2

Quasielastic

Inclusive $e + A \to e' + X$

Semi-Inclusive $e + A \to e' + N_F + X$ $e + A \to e' + N_F + N_R + X$

$e + A \to e' + h_R + X$

Exclusive $e + d \to e' + N_F + (N_R)$

Deep-Inelastic

Inclusive $e + A \to e' + X$ $x_B > 1$

Semi-Inclusive $e + A \to e' + h_R + X$ Tagged hadrons

Short Range Dynamics in Nuclei at 6 GeV:

1. Probing NN interaction at 1Fm

- *Measurement of "genuine" deuteron momentum distribution for up to 550 MeV/c;*

2. 2N SRC research in the domain of tensor-forces

- *x>1 QE Nuclear Scaling ;*
- *extraction of a2 parameter for various A*
- *discovery of pn dominance*
- *observation of "momentum sharing effects"*

3. Exploring Hadron-Quark Transition in Nuclei

- *Hard break-up of two-nucleons*
- *Apparent correlation between EMC and SRC effects*
- *First probes of superfast quarks*
- *FSI in SemiDIS in the deuteron*

- New Properties of High Momentum Distribution of Nucleons in Asymmetric Nuclei — MS,arXiv:1210.3280.2012 Phys. Rev. C 2014

- Protons are more Energetic in Neutron Rich High Density Nuclear Matter — M. McGauley, MS arXiv:1102.3973,2011

- First Experimental Indication — O. Hen, et.al. Science, 2014, Nature 2016

- Confirmed by VMC calculations for A<12 — R.B. Wiringa et al, Phys. Rev. C 2014

- For Nuclear Matter — W. Dickhoff et al Phys. Rev. C 2014

- For Medium/Heavy Nuclei — J. Ryckebusch, W.Cosyn M. Vanhalst., J.Phys 2015

- In Light-Cone Approximation: — O.Artiles, M.S. Phys. Rev. C 2016

- *Dominance of pn short range correlations as compared to pp and nn SRCS*

2006-2008s

- *Dominance of NN Tensor as compared to the NN Central Forces at <= 1fm*

2011- present

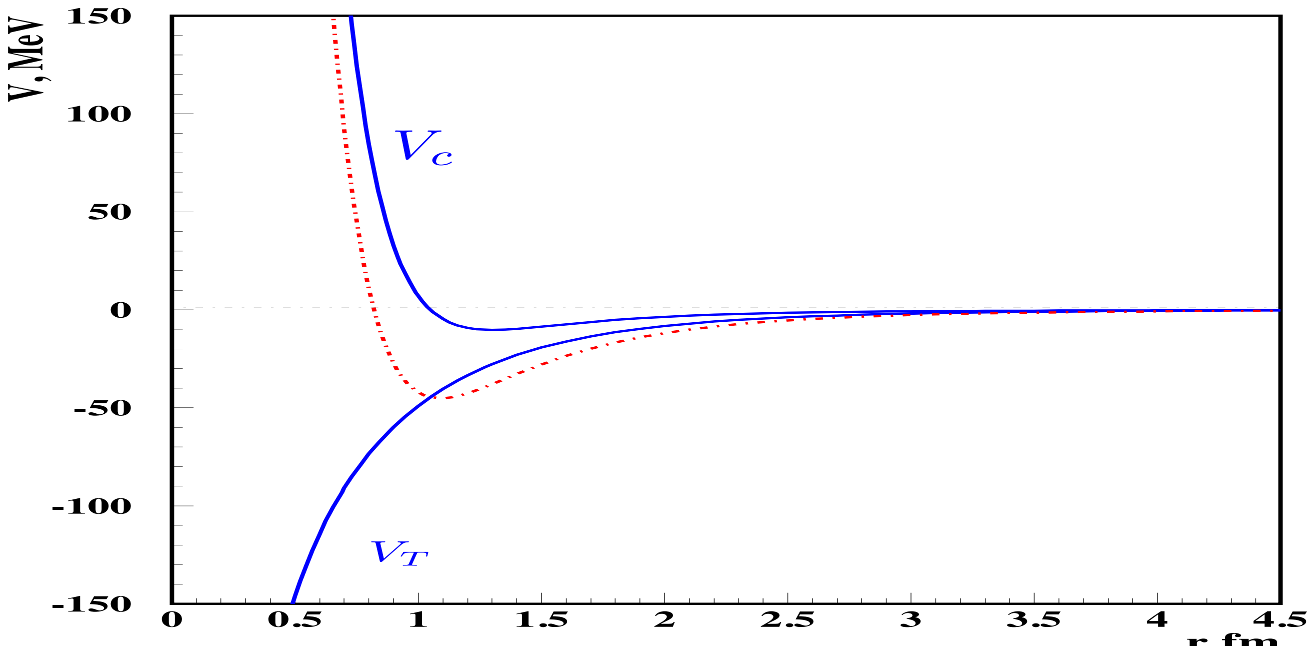
- Two New Properties of High Momentum Component

- Energetic Protons in Neutron Rich Nuclei

2. Theoretical Foundation of 2N SRCS

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

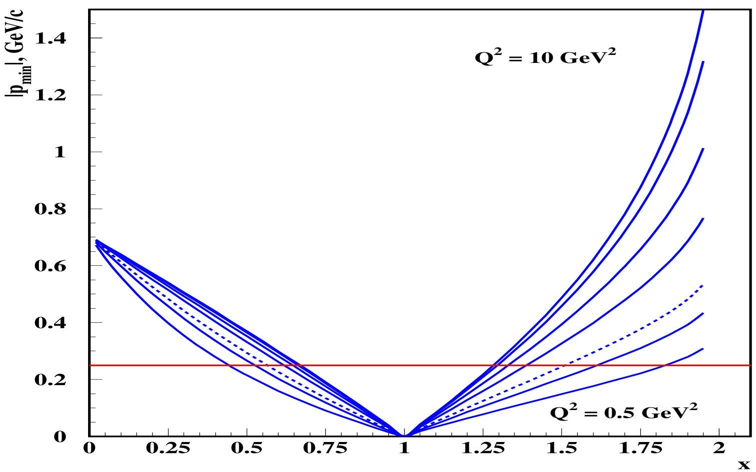
$$n_A(k) \approx a_{NN}(A) n_{NN}(k)$$

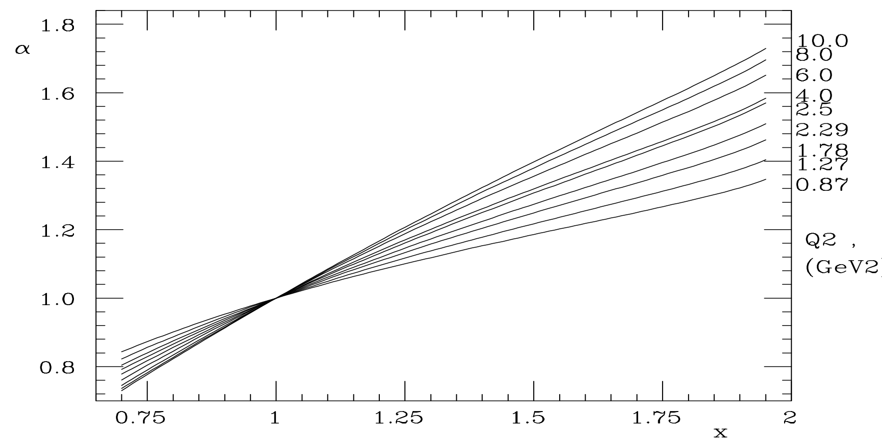


Proper Variables of 2N SRC are

- the Light Front Momentum Fraction: $\alpha = \frac{p_N^+}{p_{NN}^+}$
- transverse momentum: $p_\perp$

For Inclusive A(ee')X QE Processes $\alpha_{2N} = 2 - \frac{q_- + 2m_N}{2m_N}\left(1 + \frac{\sqrt{W_{2N}^2 - 4m_N^2}}{W_{2N}}\right)$





Prediction of Nuclear Scaling at x>1 and large Q^2

Day, Frankfurt, MS, Strikman, PRC 1993

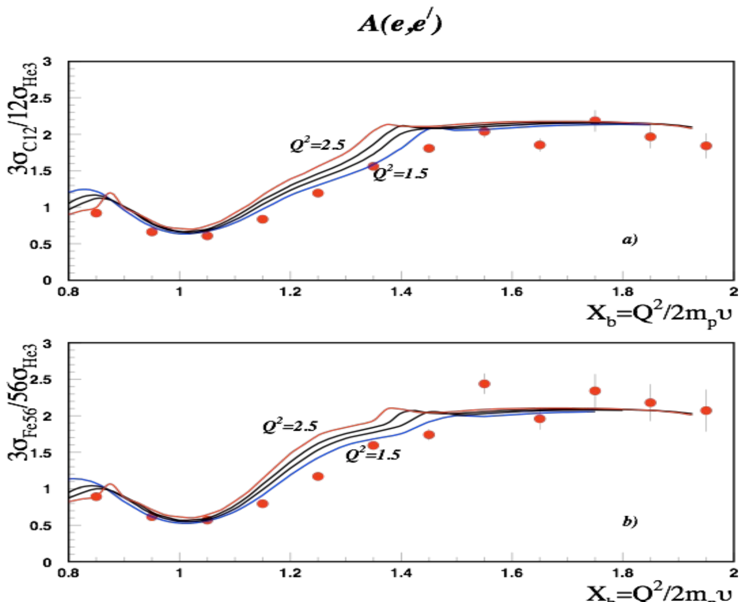
1. Extraction of a2(A,Z) for wide range of Nuclei

Day, Frankfurt, MS, Strikman, PRC 1993

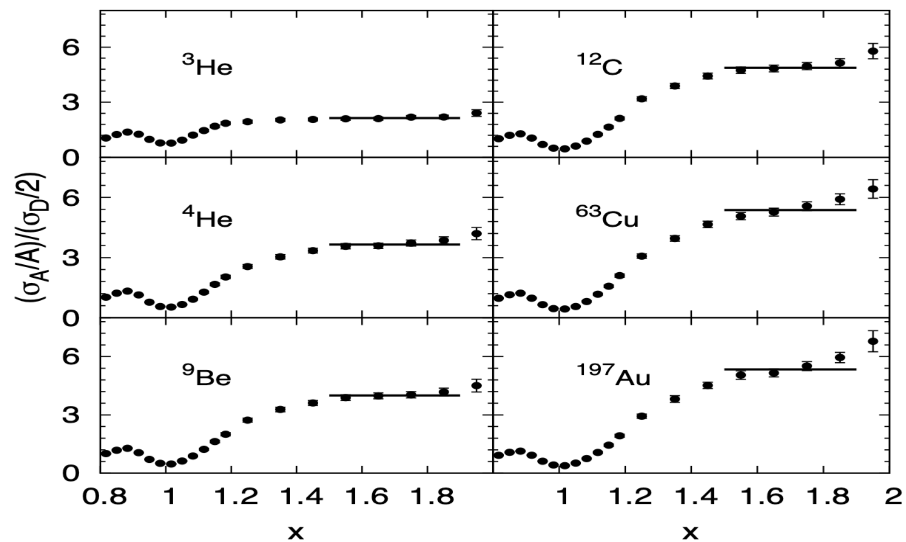
Frankfurt, MS, Strikman, IJMP A 2008

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

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



Egiyan, et al PRC 2004



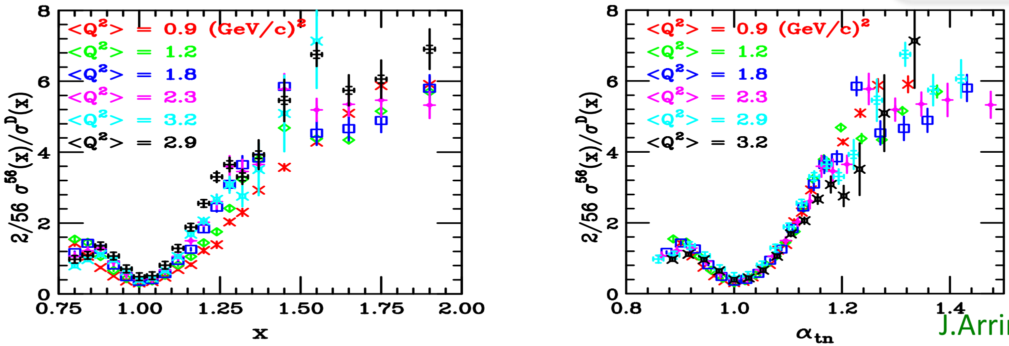
Fomin et al PRL 2011

$$\sigma_{eA} = \sum \sigma_{eN} \cdot \rho_A(\alpha) \quad \text{where} \quad \rho_A(\alpha) = \int \rho_A(\alpha, p_\perp) d^2 p_\perp$$

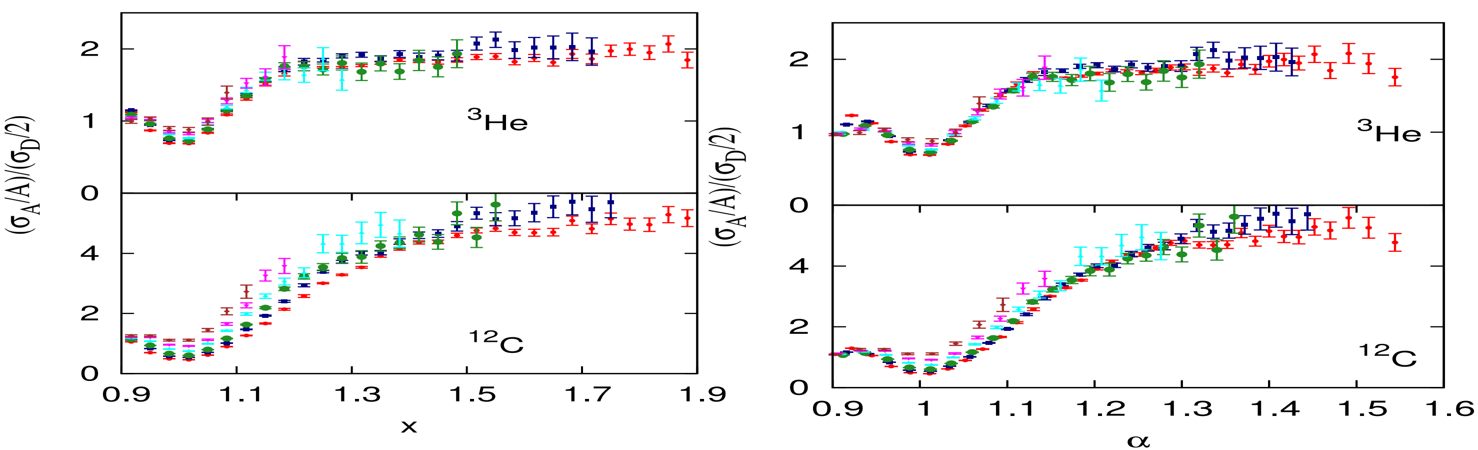
$$1.3 \leq \alpha_{2N} \leq 1.5$$

$$\alpha_{2N} = 2 - \frac{q_- + 2m_N}{2m_N}\left(1 + \frac{\sqrt{W_{2N}^2 - 4m_N^2}}{W_{2N}}\right)$$

$$\alpha\ |_{Q^2 \to \infty} \to x$$
$$\alpha\ |_{x \to 1} \to 1$$



J.Arrington, D.Higinbotham
G.Rosner, M.S. Prog. PNP 2012



N.Fomin, D.Higinbotham
M.S., P.Sovignon ARNPS, 2017

a_2's as relative probability of 2N SRCs

Table 1: The results for $a_2(A, y)$

A	y	This Work	Frankfurt et al	Egiyan et al	Famin et al
^{3}He	0.33	2.07±0.08	1.7±0.3		2.13±0.04
^{4}He	0	3.51±0.03	3.3±0.5	3.38±0.2	3.60±0.10
^{9}Be	0.11	3.92±0.03			3.91±0.12
^{12}C	0	4.19±0.02	5.0±0.5	4.32±0.4	4.75±0.16
^{27}Al	0.037	4.50±0.12	5.3±0.6		
^{56}Fe	0.071	4.95±0.07	5.6±0.9	4.99±0.5	
^{64}Cu	0.094	5.02±0.04			5.21±0.20
^{197}Au	0.198	4.56±0.03	4.8±0.7		5.16±0.22

- Dominance of the (pn) component of SRC

for large $k > k_{Fermi}$

$$n_A(k) \approx a_{NN}(A) n_{NN}(k)$$

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

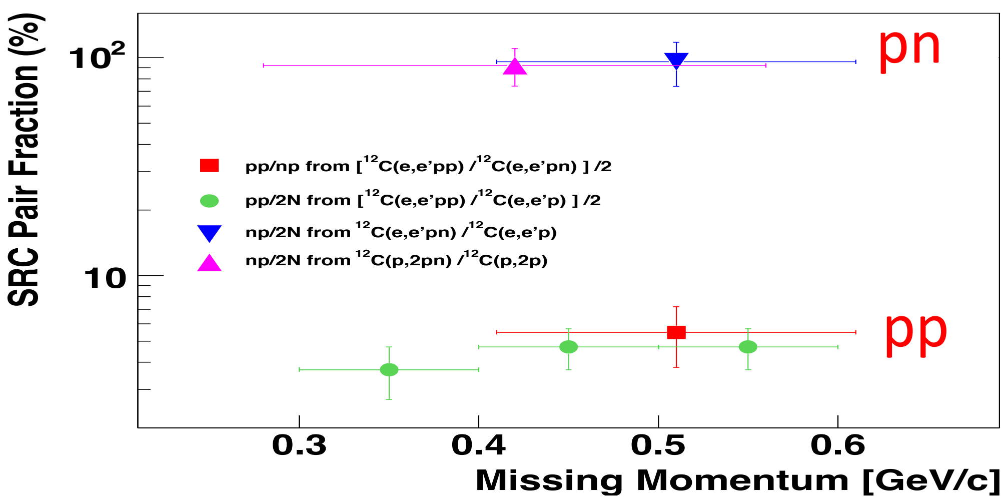
Theoretical analysis of BNL Data

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

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

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

Direct Measurement at JLab R.Subdei, et al Science , 2008



Factor of 20

Expected 4
(Wigner counting)

Predictions: Energetic Protons in Neutron Rich Matter

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

$$P_{p/n}(A,y) = \frac{1}{2x_{p/n}} a_2(A,y) \int_{k_F}^{\infty} n_d(p) d^3p$$

$$y = |x_p - x_n|$$

A	Pp(%)	Pn(%)
12	20	20
27	23	22
56	27	23
197	31	20

Requires dominance of pn SRCs
in heavy neutron reach nuclei

O. Hen et.al. Science, 2014

VMC Estimates: Robert Wiringa

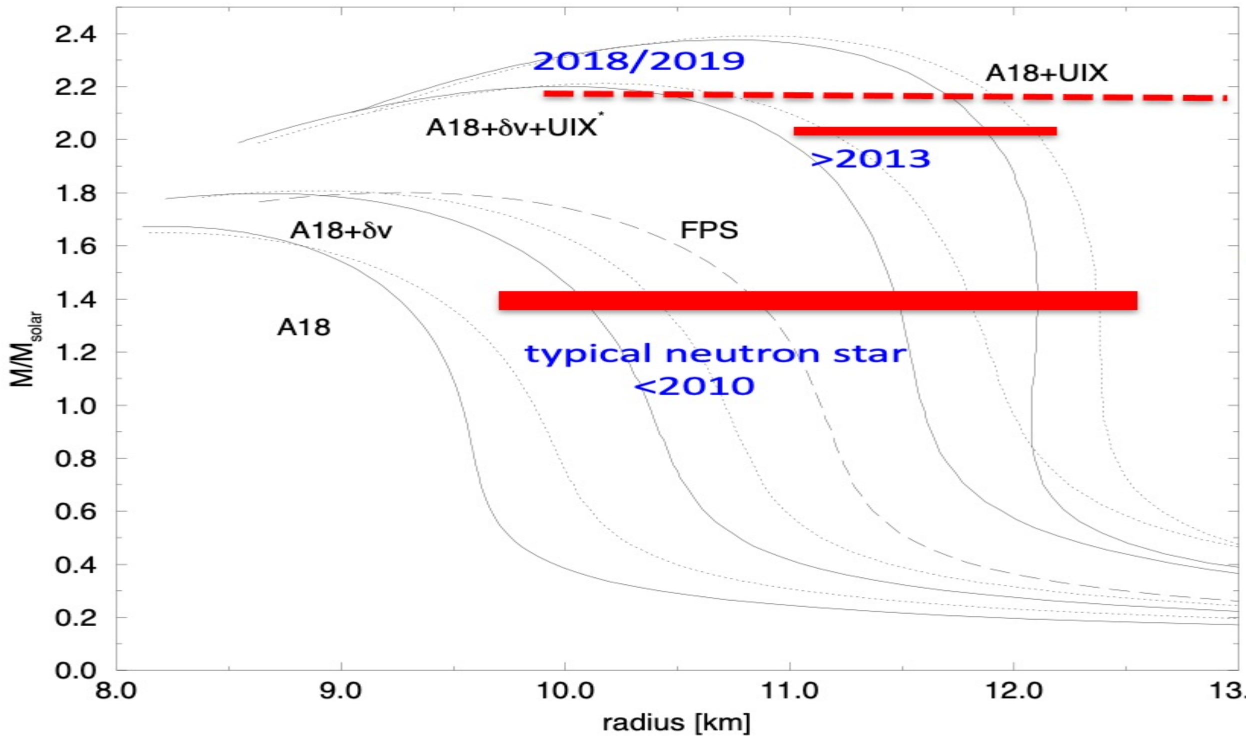
Wiringa, et al PRC 2014

Table 1: Kinetic energies (in MeV) of proton and neutron

A	y	E^p_{kin}	E^n_{kin}	$E^p_{kin} - E^n_{kin}$
^{8}He	0.50	30.13	18.60	11.53
^{6}He	0.33	27.66	19.06	8.60
^{9}Li	0.33	31.39	24.91	6.48
^{3}He	0.33	14.71	19.35	-4.64
^{3}H	0.33	19.61	14.96	4.65
^{8}Li	0.25	28.95	23.98	4.97
^{10}Be	0.2	30.20	25.95	4.25
^{7}Li	0.14	26.88	24.54	2.34
^{9}Be	0.11	29.82	27.09	2.73
^{11}B	0.09	33.40	31.75	1.65

Summarizing: Intensive studies of NN SRCs during last 2 decades

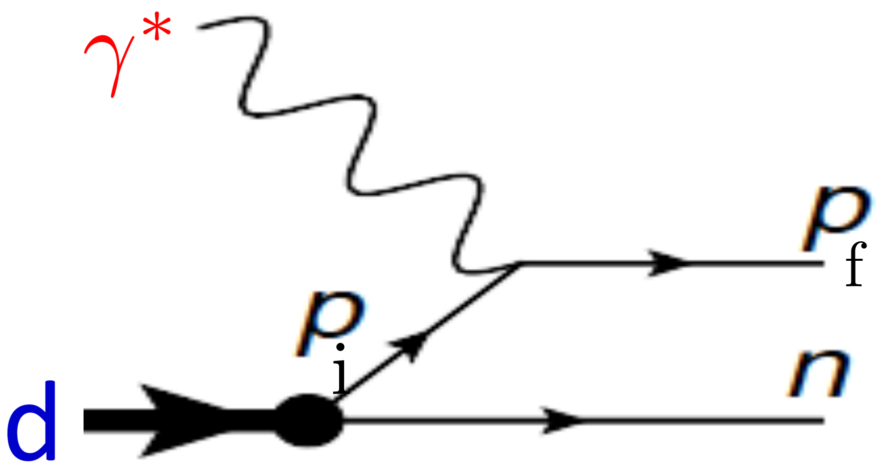
Next: Probing NNN- SRCs as well as SRCs with non-nucleonic component



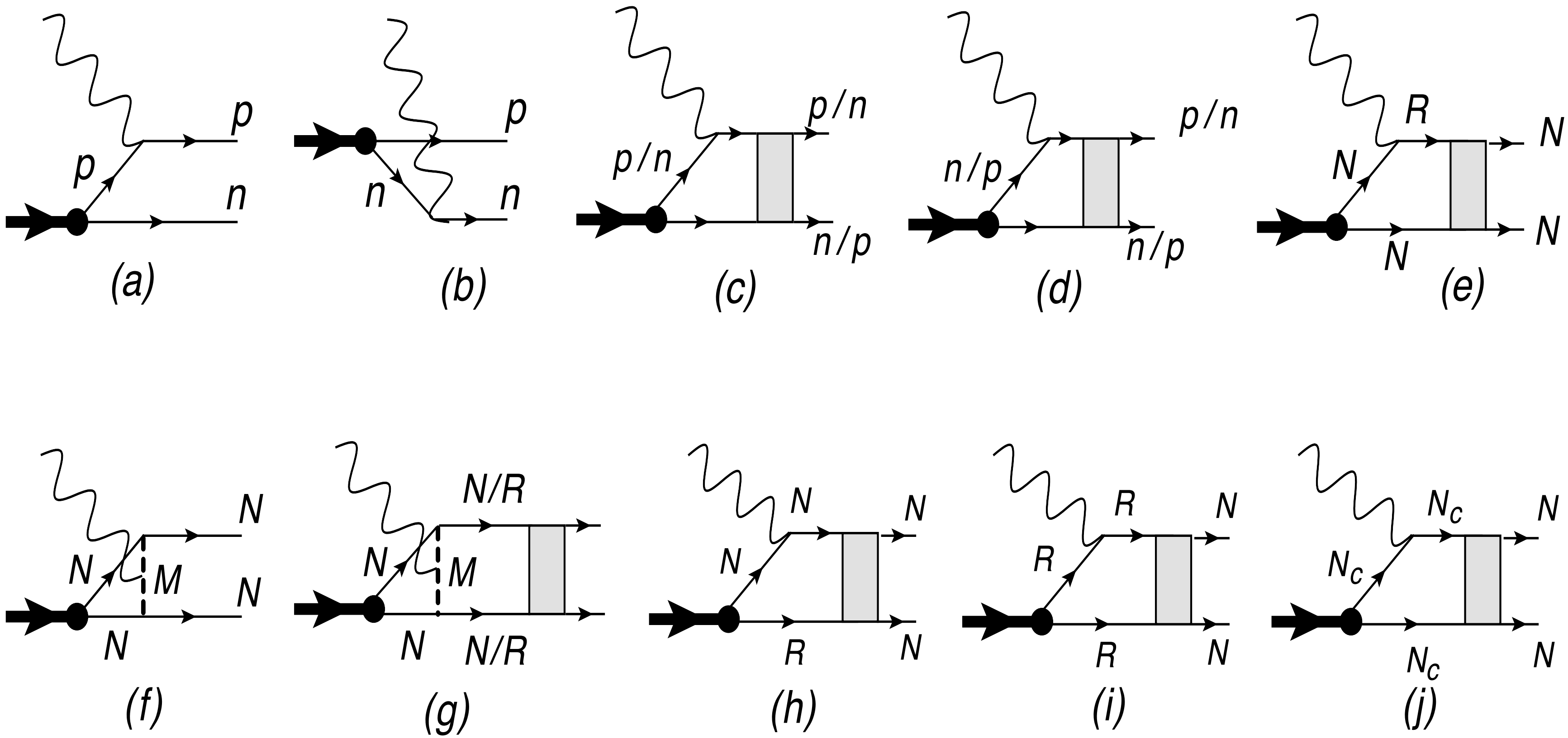
(II) Probing NN interaction at short distances

Considering reaction: $e + d \rightarrow e' + p_f + n$

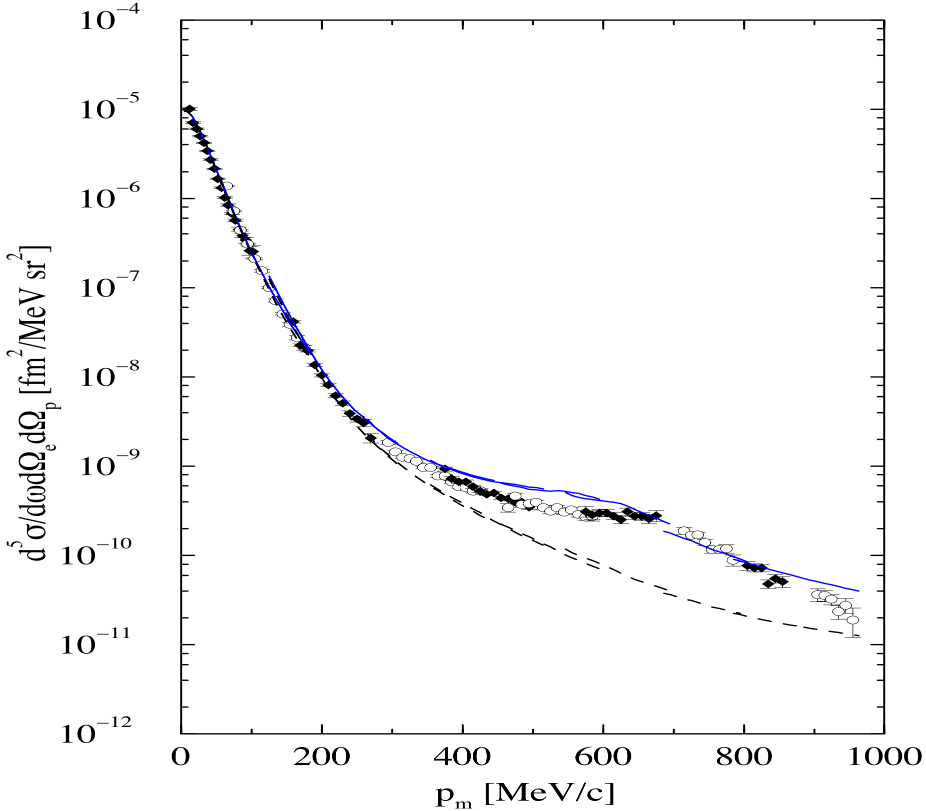
$$|p_i| = |p_f - q| > 300 \text{ MeV/c}$$



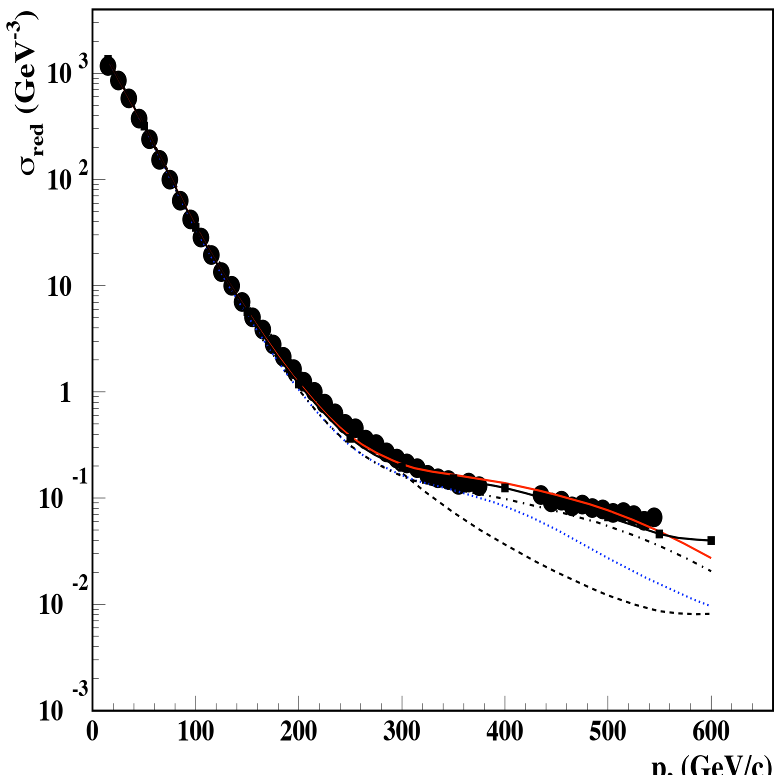
Impossibility to Probe Deuteron at Small Distances at low Q^2



Impossibility to Probe Deuteron at Small Distances at low Q^2

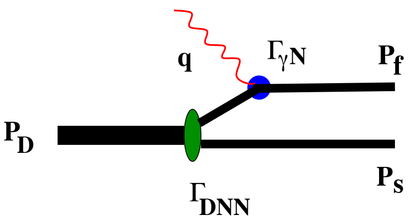


Mainz, $Q^2 = 0.33$ GeV^2

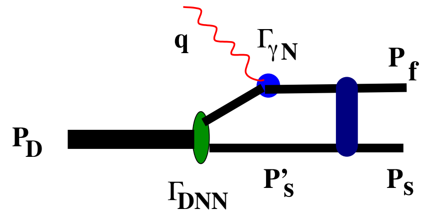


JLab, $Q^2 = 0.66$ GeV^2

At Large $Q^2 > 1\text{-}2\ GeV^2$ Eikonal Regime is Established)



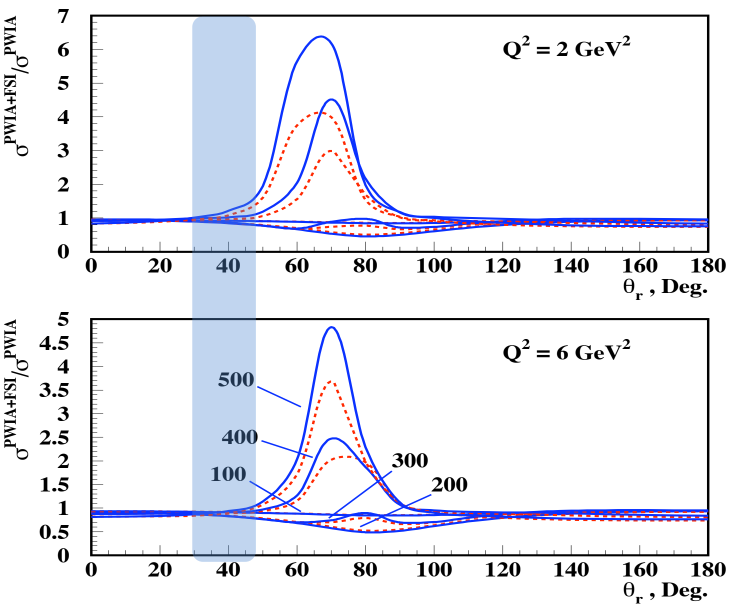
(a)

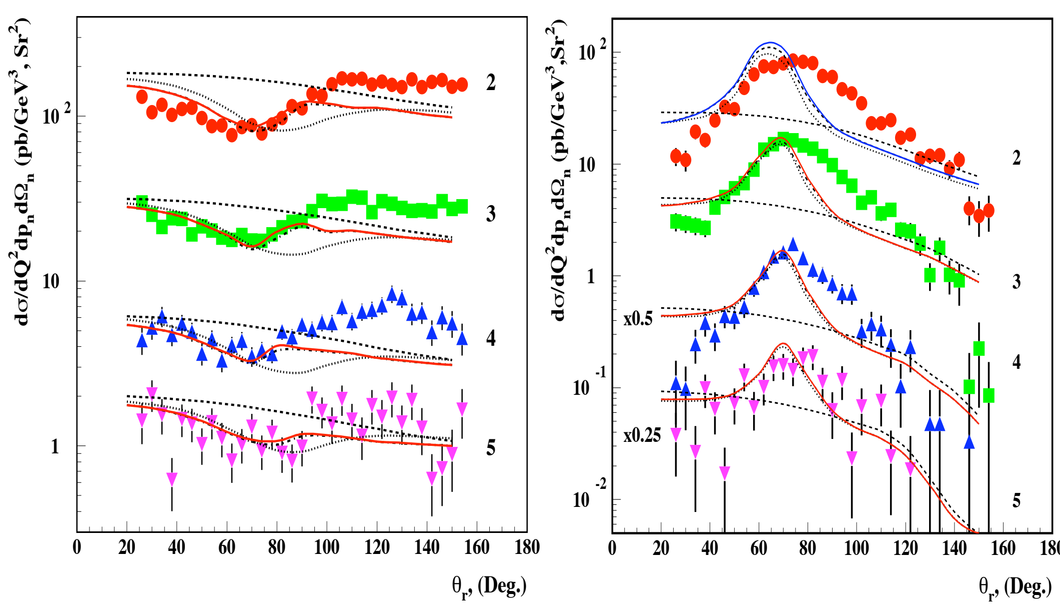


(b)

For the case of
$e + d \rightarrow e' + p_f + p_s$

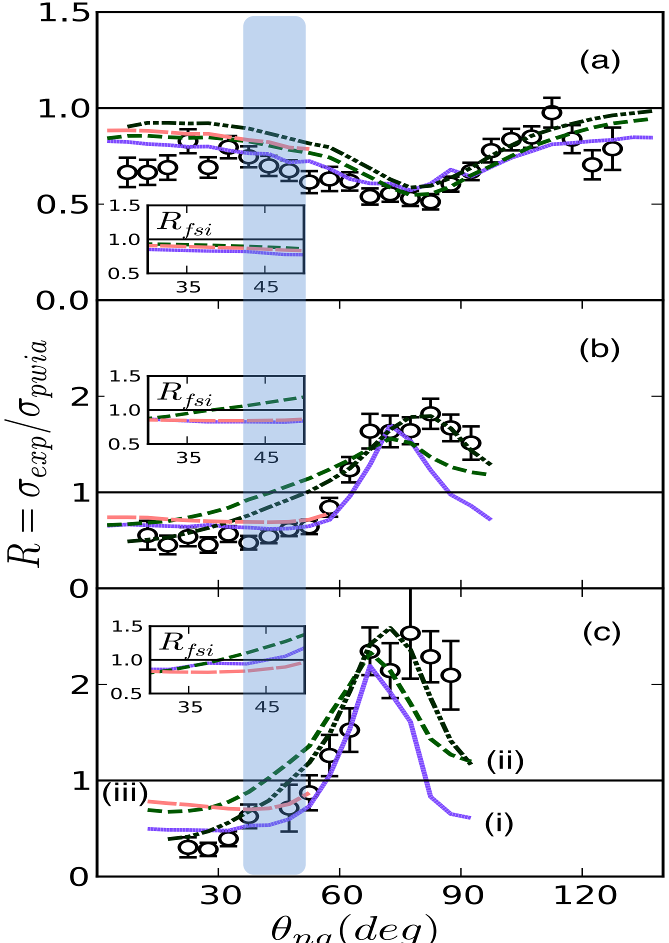
K.Egiyan at al 2008



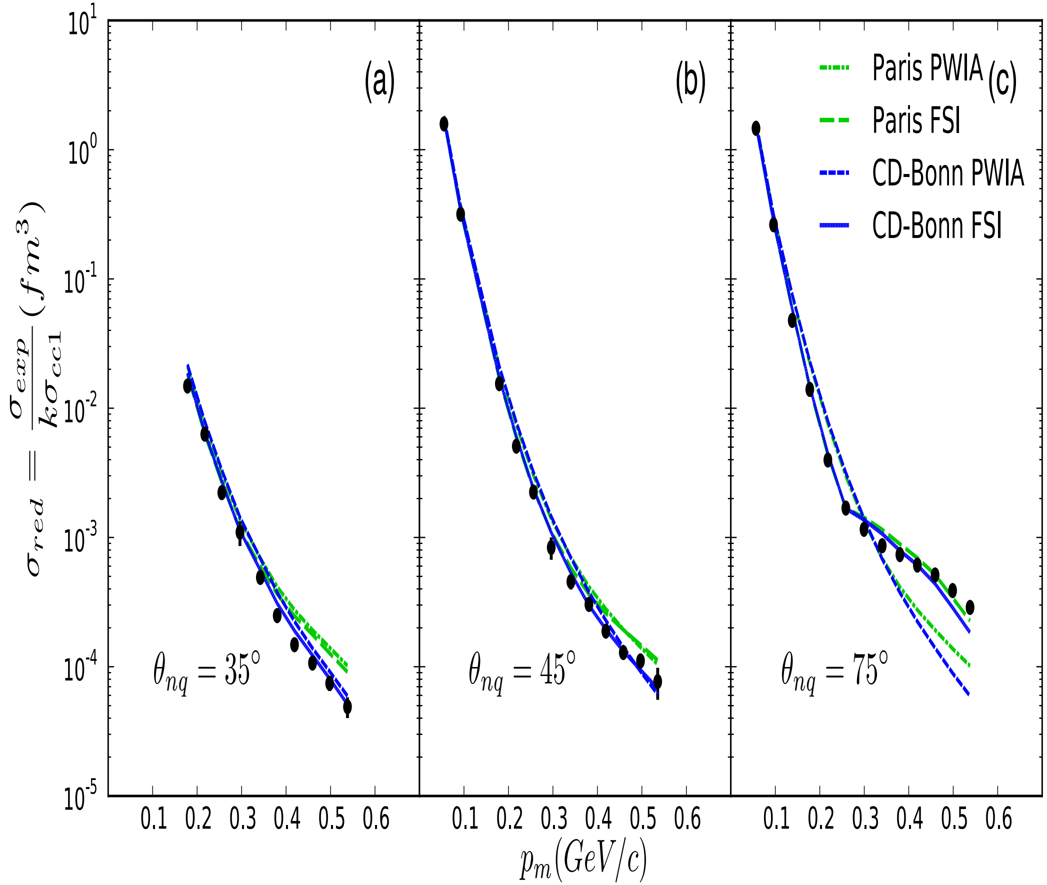


M.Sargsian, PRC 2010

Probing Deuteron at Small Distances at large Q^2

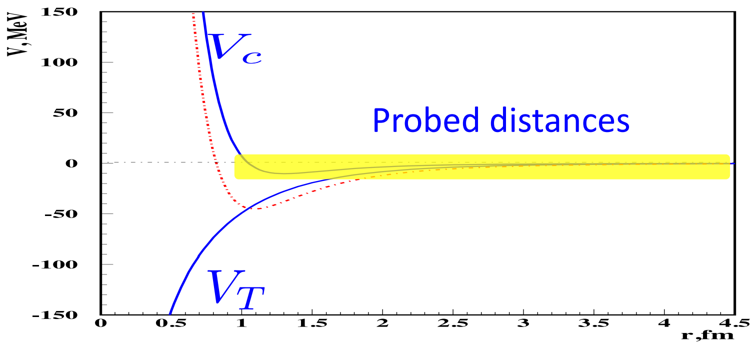


JLab, $Q^2 = 3.5$ GeV^2

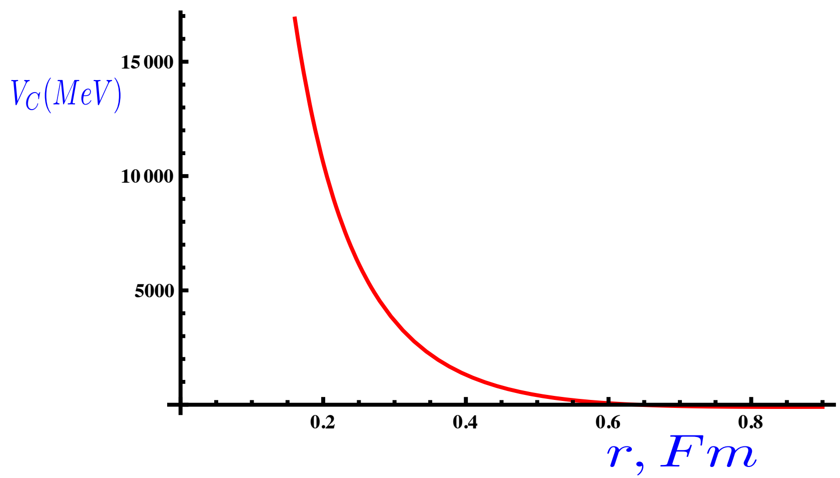


Boeglin et al PRL 2011, deuteron probed at up to 550MeV/c

Summarizing: Probed NN structure up to > 0.8fm



Next: NN – Repulsive Core



Short Range Dynamics in Nuclei at 24 GeV:

1. Probing NN Repulsive Core

- *strength of the core;*
- *isospin dependence of repulsive core*
- *non-nucleonic components, hidden color, gluons*

2. Discovering 3N Short-Range Correlations

- *can they be observed?*
- *strength of 3N SRCs?*
- *isospin composition*
- *role of the genuine 3N forces*

3. Exploring Hadron-Quark Transition in Nuclei

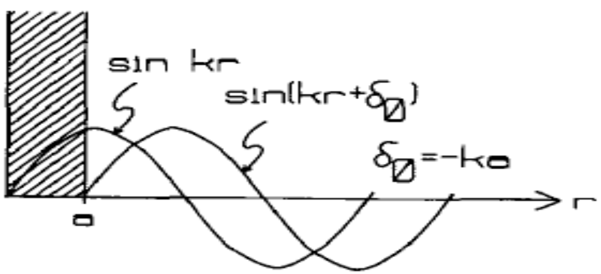
- *is EMC effect a short-range phenomenon?*
- *flavor dependence of EMC effect*
- *probing superfast quarks (x>1) in nuclei;*
- *hadronization in the deuteron*

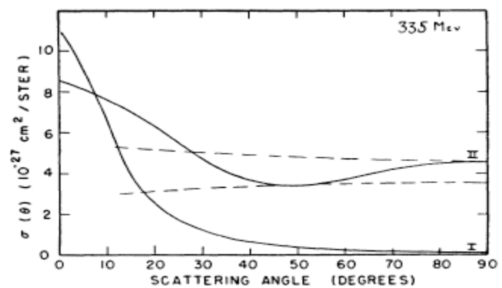
Probing NN Repulsive Core

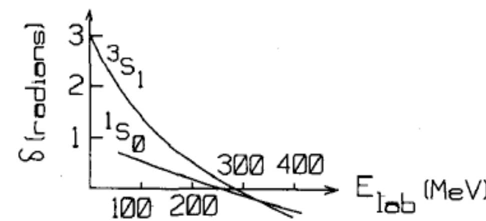
"If the two-body forces are everywhere attractive and if many-body forces are neglected then the nucleon pairs are sufficiently close to take advantage of attractive interactions and a collapsed state of nuclear matter results "

G. Breit and E.P. Wigner, Phys. Rev. 53, 998 (1938).

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







Non-monotonic NN central potential with the repulsive core was introduced: Brueckner & Watson 1953 to obtain nuclear density saturation.

Modern NN Potentials

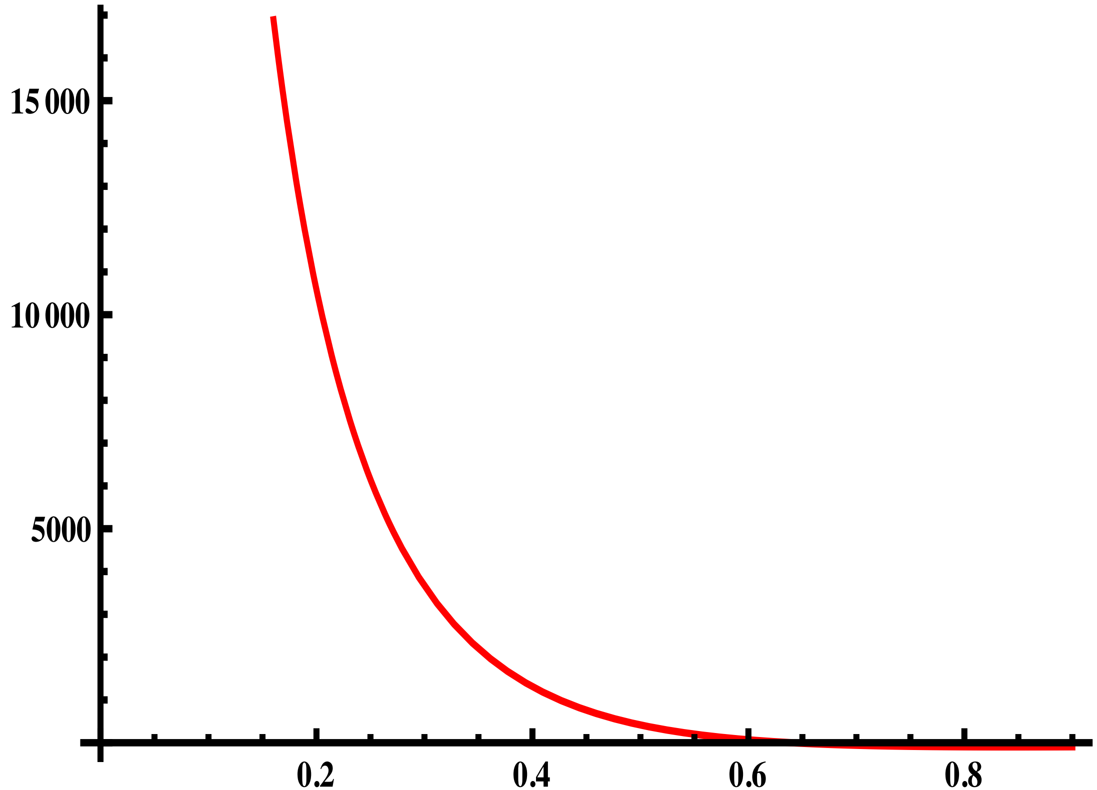
$$V^{2N} = V_{EM}^{2N} + V_{\pi}^{2N} + V_{R}^{2N}$$

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

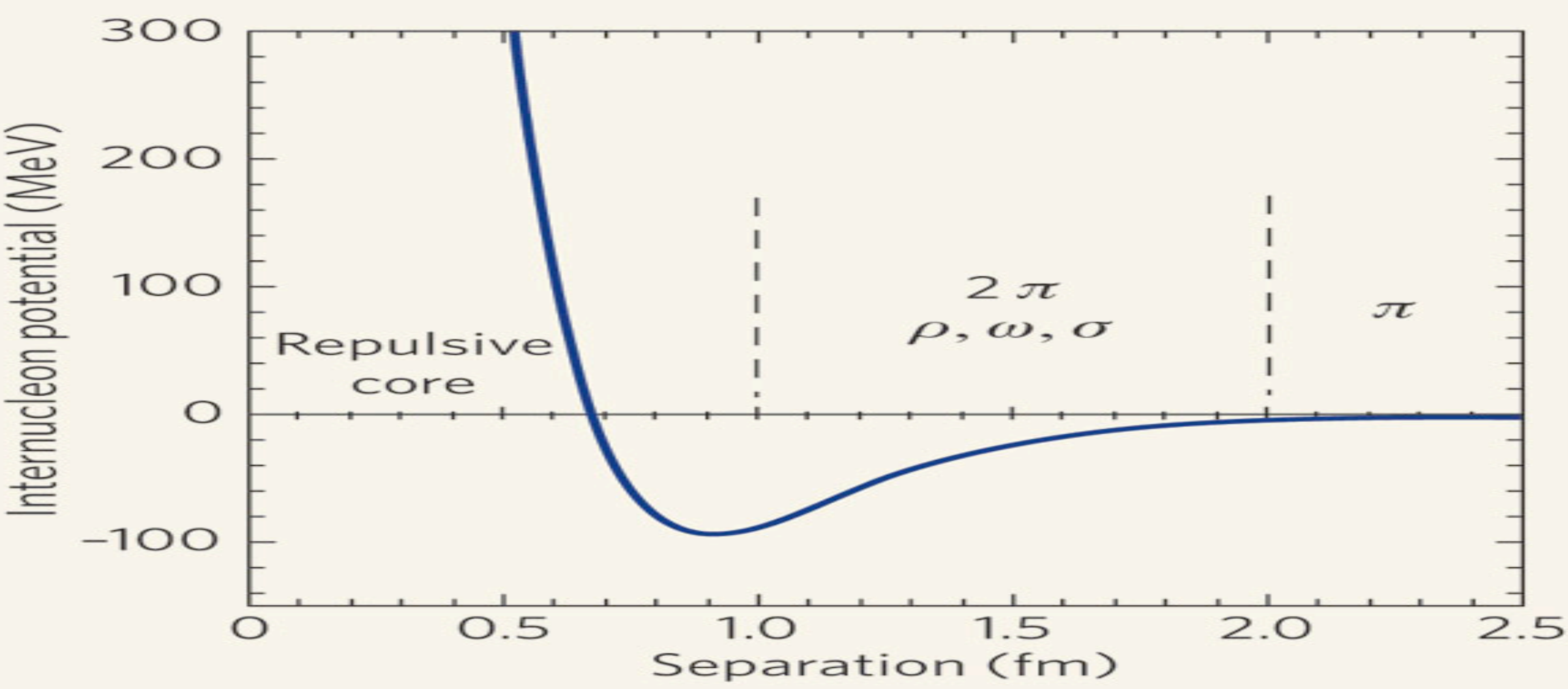
$$V^i = V_{int,R} + V_{core}$$

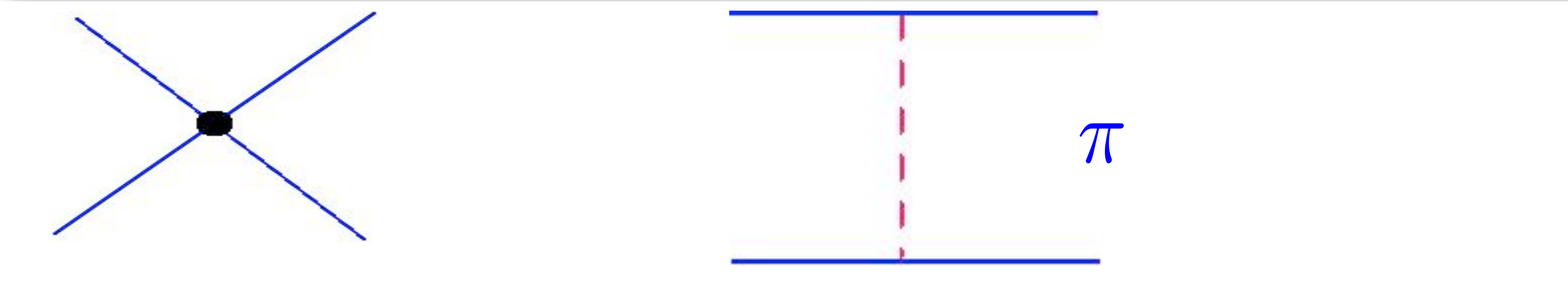
$$V_{core} = \left[1 + e^{\frac{r - r_0}{a}}\right]^{-1}$$

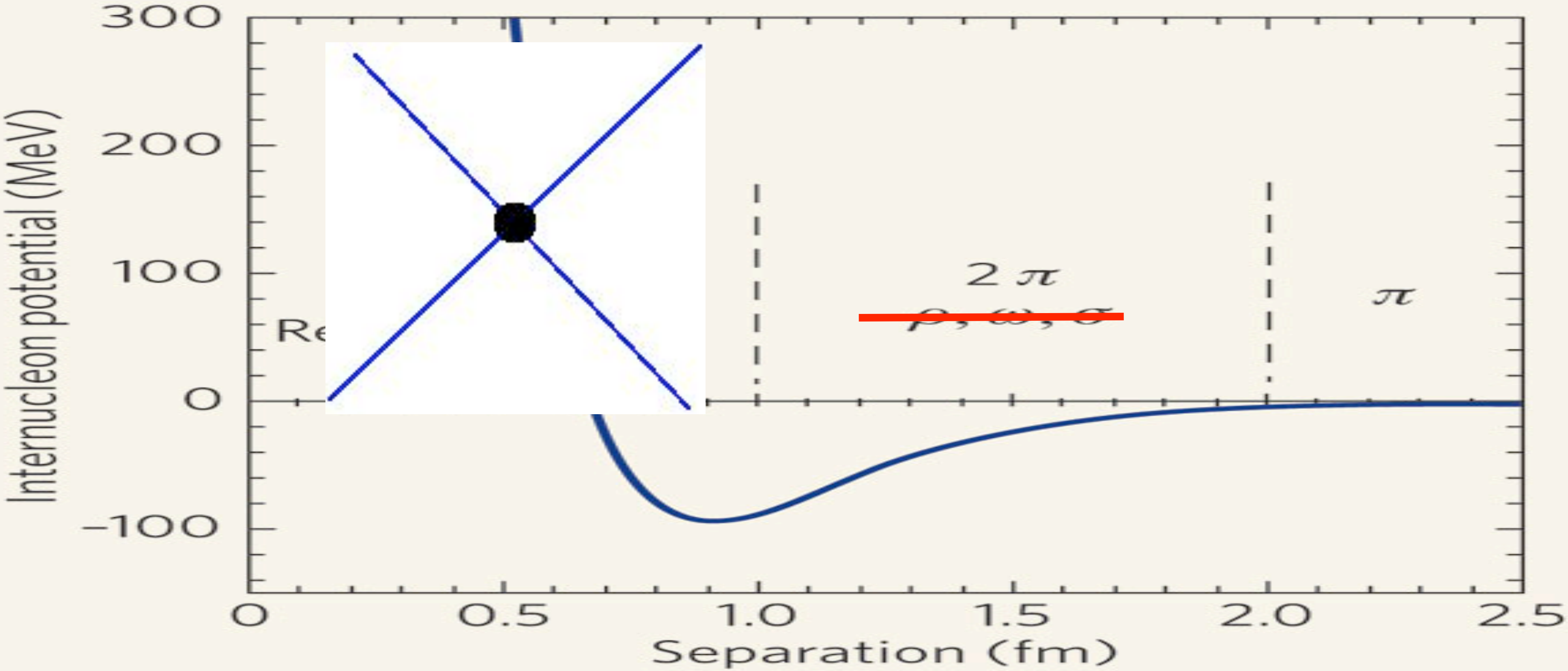
60's


15 000
10 000
5000
0.2
0.4
0.6
0.8

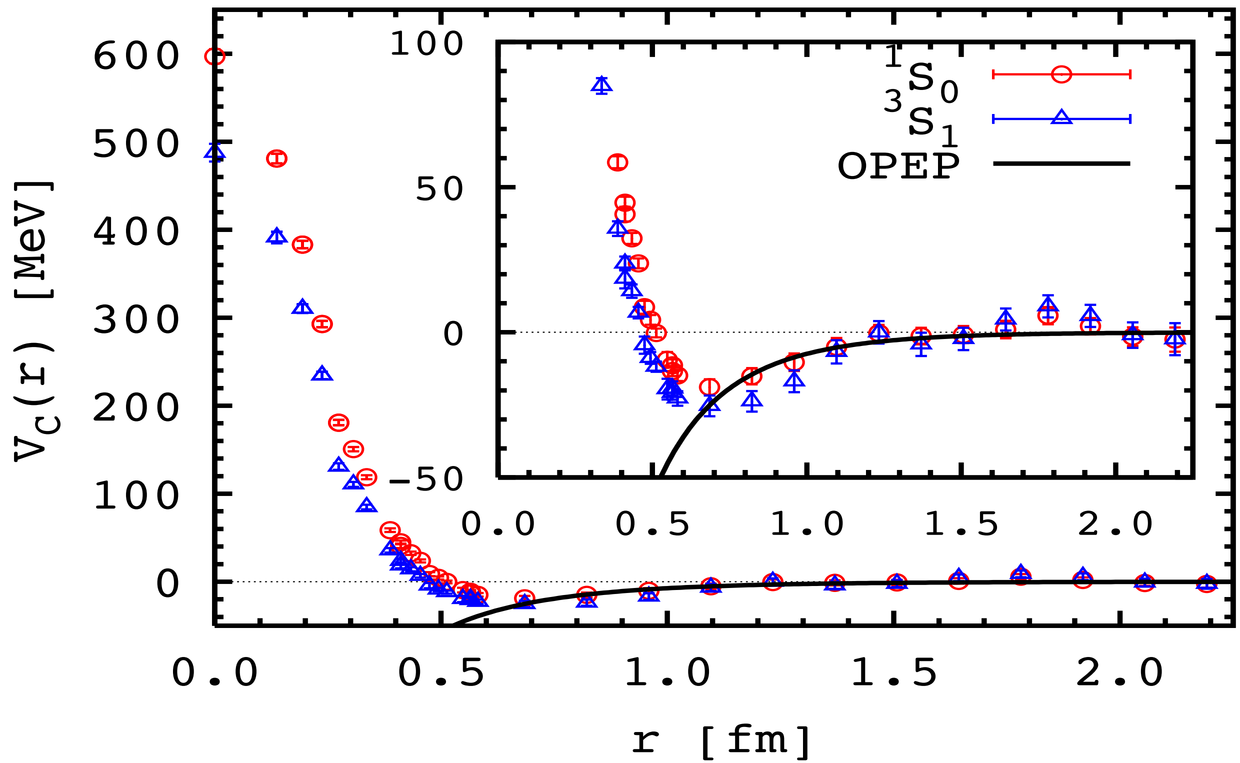
$\sigma, \quad \pi, \quad \rho, \quad \omega, \ldots$



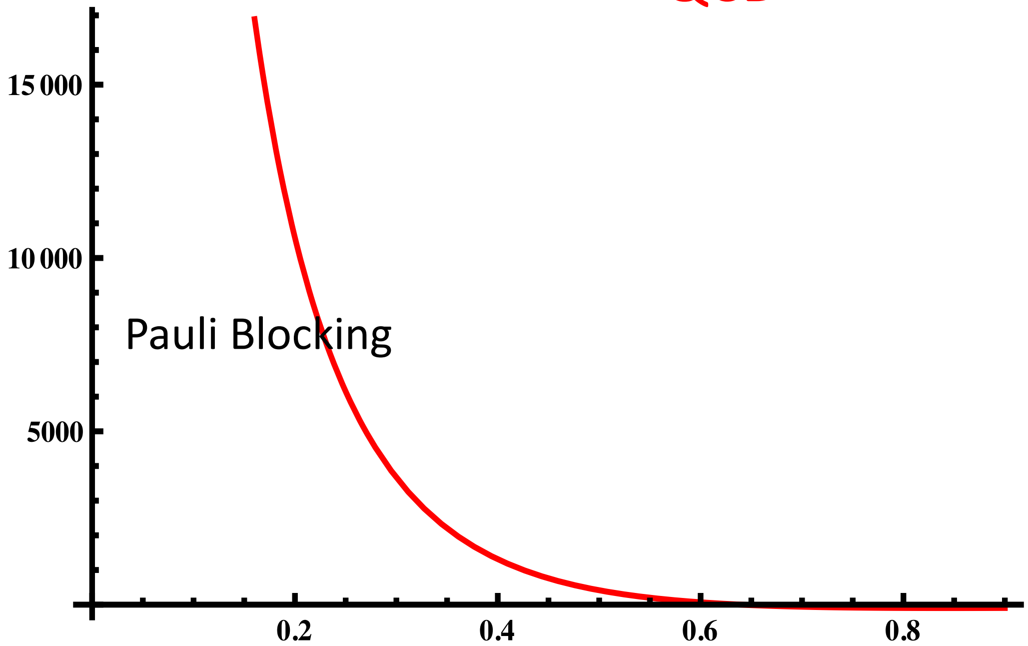

π


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

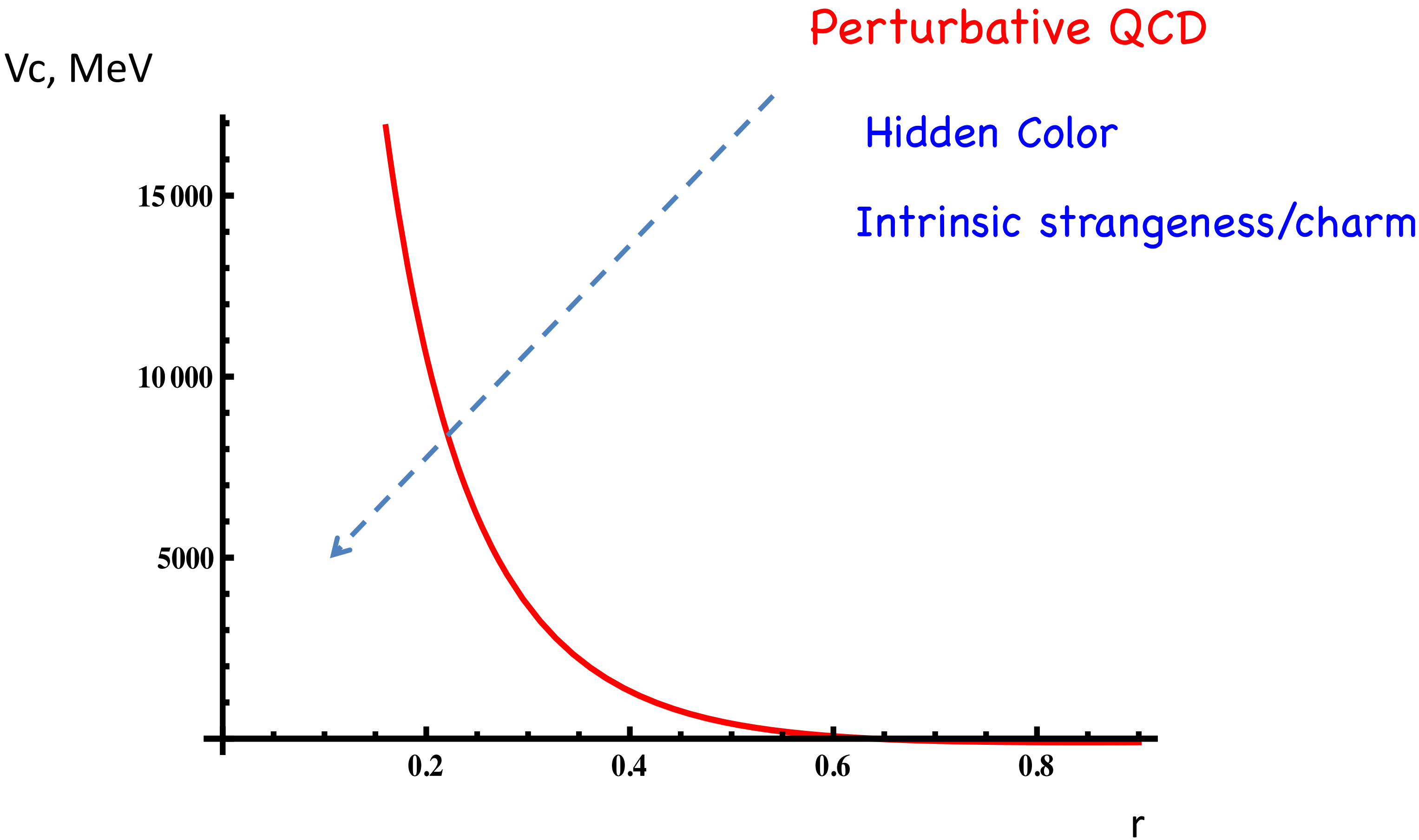
Lattice Calculations



QCD



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



~80% hidden color

Brodsky,Ji, Lepage, PRL 83

For the Deuteron it means, at Short Distances

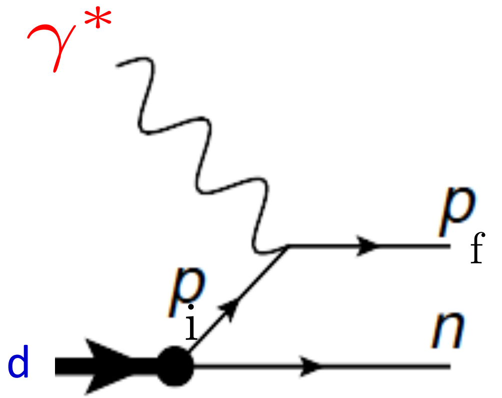
$$\Psi_d = \Psi_{pn} + \Psi_{\Delta\Delta} + \Psi_{NN^*} + \Psi_{hc} \cdots$$

$$\Psi_{hc} = \Psi_{N_c,N_c}$$

The NN repulsive core can be due to the orthogonality of

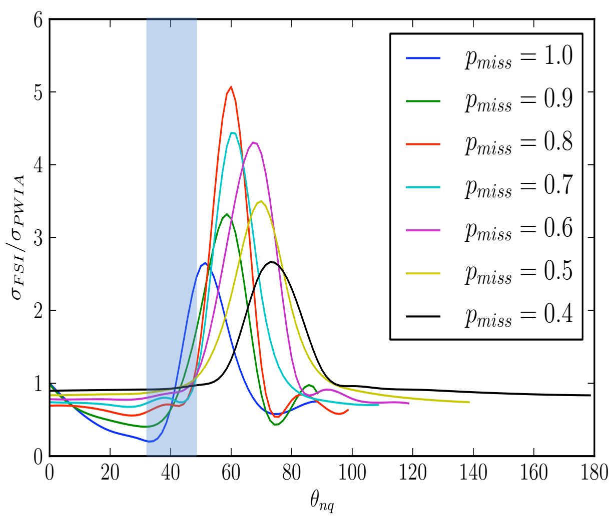
$$\langle \Psi_{N_c,N_c} \mid \Psi_{N,N} \rangle = 0$$

Considering reaction: $e + d \to e' + p_f + n$



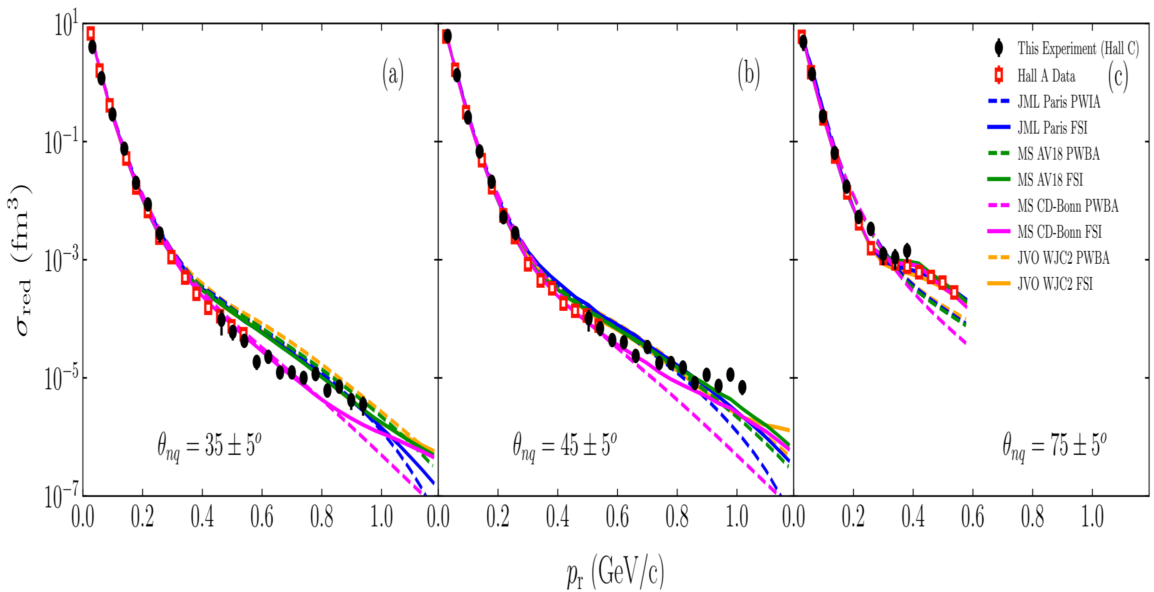
$$|p_i| = |p_f - q| > 300 \text{ MeV/c}$$

$$|p_i| = |p_f - q| \gtrsim 800 \text{MeV/c}$$



W. Boeglin, M.S *Int.J.Mod.Phys.E* 24 (2015) 03

JLab experiment $Q^2 = 4$ GeV^2



C. Yero, et al *Phys.Rev.Lett.* 125 (2020) 26, 262501

New Structure in the Deuteron and possible non-nucleonic components

M.S & Frank Vera, in progress

Paradigm shift:

- consider a deuteron not a nucleus that consist of proton and neutron
- but ***pseudovector composite particle*** from which we ***extract*** proton and neutron

- on the light-front the vertex that describes such a transition in the most general form can be written through 6 vertex functions as:

$$\Gamma_d^\mu = \Gamma_1 \gamma^\mu + \Gamma_2 \frac{(p_1 - p_2)^\mu}{2m_N} + \Gamma_3 \frac{\Delta^\mu}{2m_N} + \Gamma_4 \frac{(p_1 - p_2)^\mu \not{\Delta}}{4m_N^2}$$
$$+ i\Gamma_5 \frac{1}{4m_N^3} \gamma_5 \epsilon^{\mu\nu\rho\gamma} (p_d)_\nu (p_1 - p_2)_\rho (\Delta)_\gamma + \Gamma_6 \frac{\Delta^\mu \not{\Delta}}{4m_N^2}$$

$$\psi_d^{\lambda_d}(\alpha_i, p_\perp, \lambda_1 \lambda_2) = -\frac{\bar{u}(p_2, \lambda_2)\bar{u}(p_1, \lambda_1)\Gamma_d \chi^{\lambda_d}}{\frac{1}{2}\left(m_d^2 - 4\frac{m_N^2 + p_\perp^2}{\alpha_i(2-\alpha_i)}\right)\sqrt{2(2\pi)^3}}$$

$$\Delta^\mu \equiv p_1^\mu + p_2^\mu - p_d^\mu \equiv (\Delta^-, \Delta^+, \Delta_\perp) = (\Delta^-, 0, 0),$$

where

$$\Delta^- = p_1^- + p_2^- - p_d^- = \frac{m_N^2 + k_\perp^2}{p_1^+} + \frac{m_N^2 + k_\perp^2}{p_2^+} - \frac{M_d^2}{p_d^+}$$
$$= \frac{1}{p_d^+}\left[\frac{4(m_N^2 + k_\perp^2)}{\alpha_1(2-\alpha_1)} - M_d^2\right] = \frac{4}{p_d^+}\left[m_N^2 - \frac{M_d^2}{4} + k^2\right].$$

In high Q^2 limit $\quad \frac{\Delta^-}{2m_N} \ll 1$

$$\Gamma_d^\mu = \Gamma_1 \gamma^\mu + \Gamma_2 \frac{(p_1 - p_2)^\mu}{2m_N} + \Gamma_3 \frac{\Delta^\mu}{2m_N} + \Gamma_4 \frac{(p_1 - p_2)^\mu \not{\Delta}}{4m_N^2}$$
$$+ i\Gamma_5 \frac{1}{4m_N^3} \gamma_5 \epsilon^{\mu\nu\rho\gamma} (p_d)_\nu (p_1 - p_2)_\rho (\Delta)_\gamma + \Gamma_6 \frac{\Delta^\mu \not{\Delta}}{4m_N^2}$$

$$\psi_d^{\lambda_d}(\alpha_i,k_\perp) = -\sum_{\lambda_2,\lambda_1,\lambda_1'} \bar{u}(-k,\lambda_2)\left\{\Gamma_1\gamma^\mu + \Gamma_2\frac{\tilde{k}^\mu}{m_N} + \sum_{i=1}^{2} i\Gamma_5\frac{1}{8m_N^3}\epsilon^{\mu+i-}p_d'^{+}k_i\Delta'^{-}\right\}\gamma_5\frac{\epsilon_{\lambda_1,\lambda_i'}}{\sqrt{2}}u(k,\lambda_1')s_\mu^{\lambda_d}$$

$$\psi_d^{\lambda_d}(\alpha_1,k_t,\lambda_1,\lambda_2) = \sum_{\lambda_1'}\phi_{\lambda_2}^\dagger\sqrt{E_k}\left[\frac{U(k)}{\sqrt{4\pi}}\sigma\mathbf{s}_\mathbf{d}^{\lambda_\mathbf{d}} - \frac{W(k)}{\sqrt{4\pi}\sqrt{2}}\left(\frac{3(\sigma\mathbf{k})(\mathbf{k}\mathbf{s}_\mathbf{d}^\lambda)}{k^2} - \sigma\mathbf{s}_\mathbf{d}^\lambda\right) + (-1)^{\frac{1+\lambda_d}{2}}P(k)Y_1^{\lambda_d}(\theta,\phi)\delta^{1,|\lambda_d|}\right]\frac{\epsilon_{\lambda_1,\lambda_1'}}{\sqrt{2}}\phi_{\lambda_1'}$$

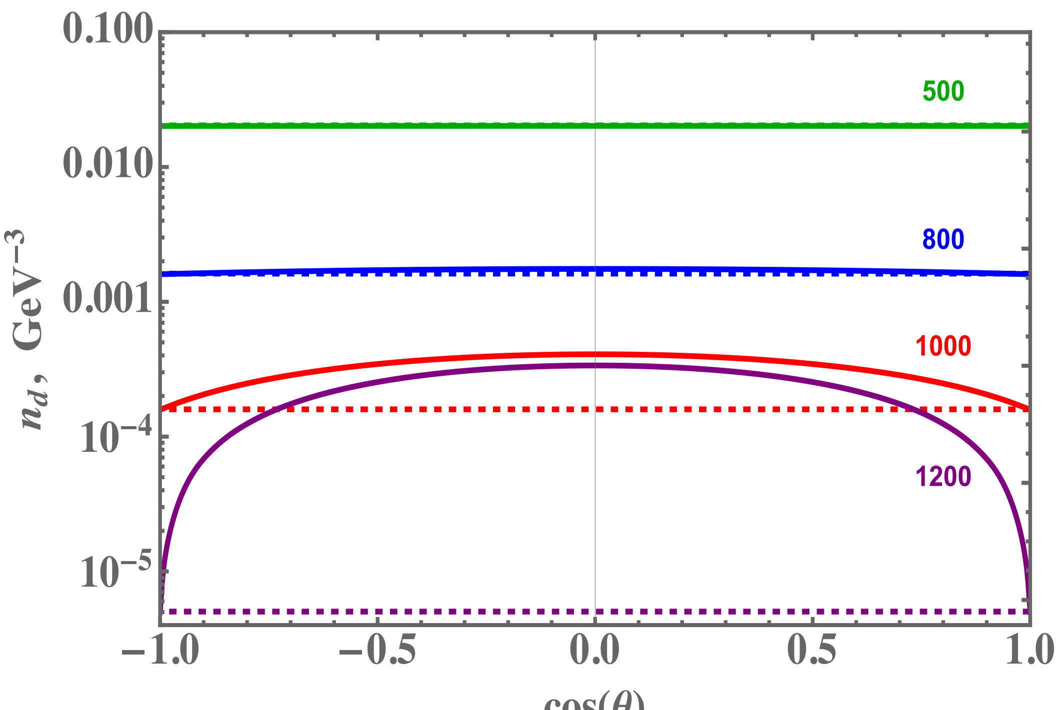
$$U(k) = \frac{2\sqrt{4\pi}\sqrt{E_k}}{3}\left[\Gamma_1(2+\frac{m_N}{E_k}) + \Gamma_2\frac{k^2}{m_N E_k}\right]$$

$$P(k) = \sqrt{4\pi}\frac{\Gamma_5(k)\sqrt{E_k}}{\sqrt{3}}\frac{k^3}{m_N^3}$$

$$W(k) = \frac{2\sqrt{4\pi}\sqrt{2E_k}}{3}\left[\Gamma_1(1-\frac{m_N}{E_k}) - \Gamma_2\frac{k^2}{m_N E_k}\right] \qquad Y_1^{\pm}(\theta,\phi) = \mp i\sqrt{\frac{3}{4\pi}}\sum_{i=1}^{2}\frac{(k\times s_d^{\pm 1})_z}{k}$$

$$n_d(k, k_\perp) = \frac{1}{3} \sum_{\lambda_d=-1}^{1} \mid \psi_d^{\lambda_d}(\alpha, k_\perp) \mid^2 = \frac{1}{4\pi} \left(U(k)^2 + W(k)^2 + \frac{k_\perp^2}{k^2} P^2(k) \right)$$

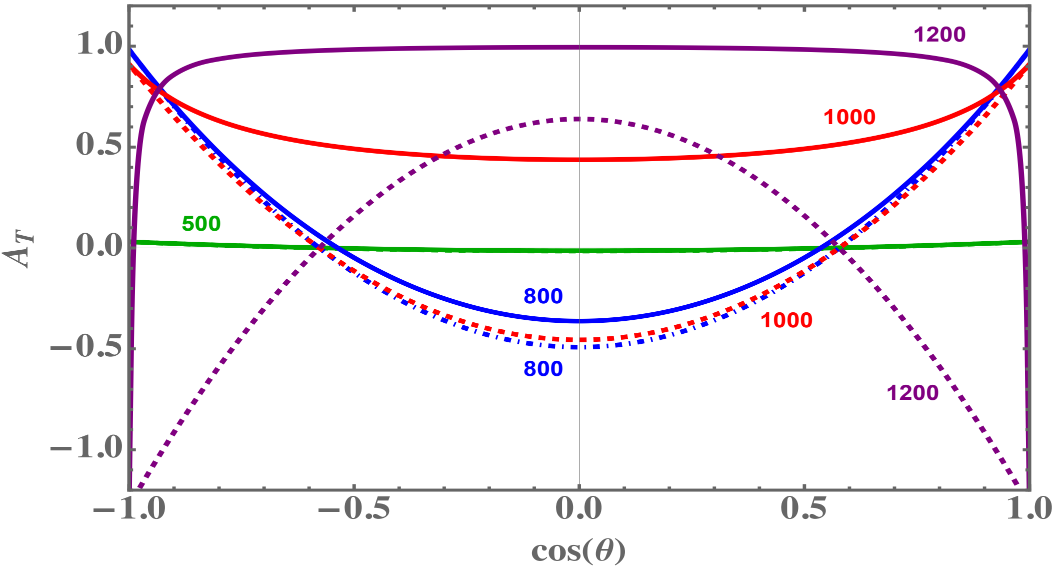
Such a possibility could exist only if proton and neutron emerged from non-nucleonic component



For a case of $N_C N_C \to pn$ transition

$$P(k) = \sqrt{4\pi} \frac{\Gamma_5(k)\sqrt{E_k}}{\sqrt{3}} \frac{k^3}{m_N^3}$$

Predicting angular dependence of momentum distribution



Tensor polarization dramatically changes

- Measuring angular dependence at larger momenta will require at least 6 x beam time

- Currently approved experiment can measure one angle for up to 1 GeV/c for 25 days

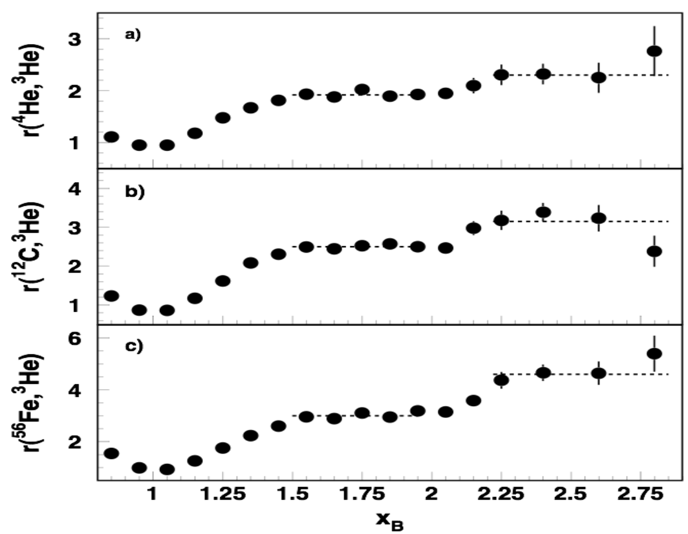
- Preliminary estimate is that at 24 GeV cross section and efficiently allows to reduce the beam time by at least 5 times

(2) Probing Three Nucleon Short Range Correlations

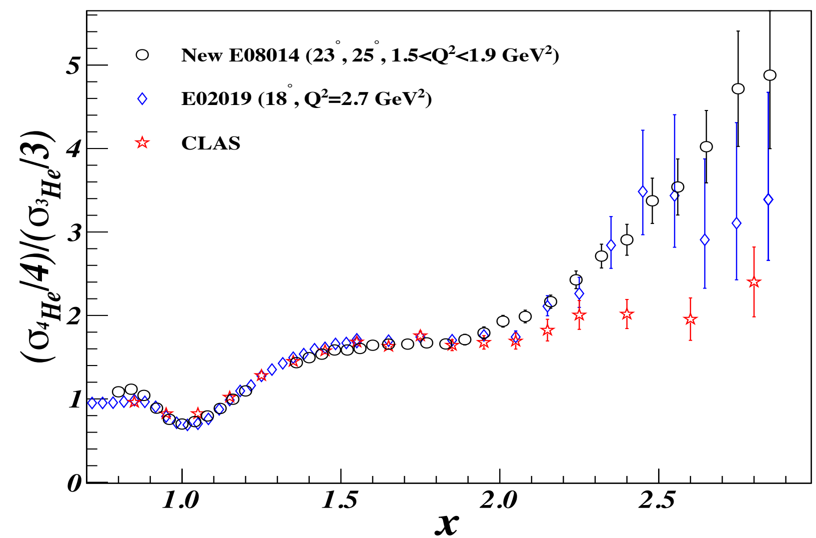
Looking for the Plateau in Inclusive Cross Section Ratios x>2

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

For $2 < x < 3$ $R \approx \frac{a_3(A_1)}{a_3(A_2)}$



Egiyan, et al PRL 2006

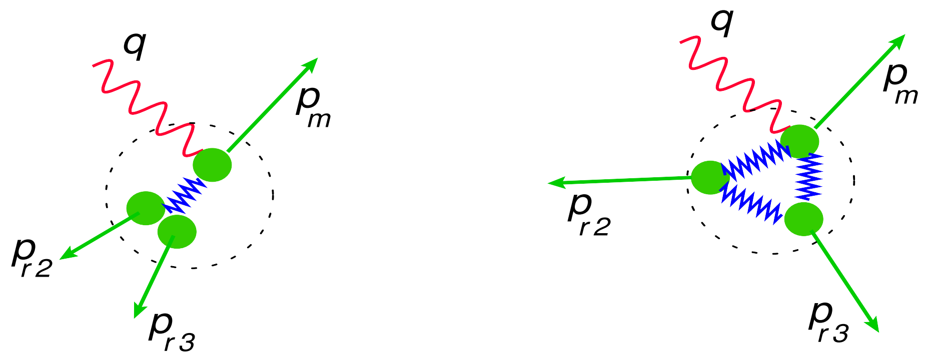


Z. Ye, at al, 2017

3N SRCs:

Proper Variables of 3N SRC are

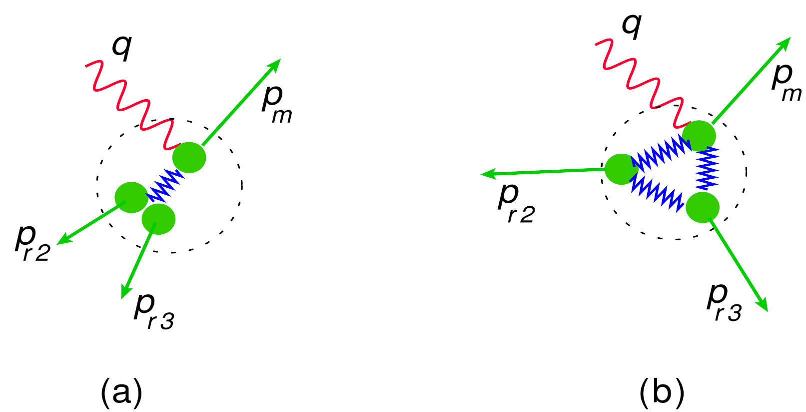
- the Light Front Momentum Fraction: $\alpha = \frac{p_N^+}{p_{3N}^+}$
- transverse momentum: $p_\perp$

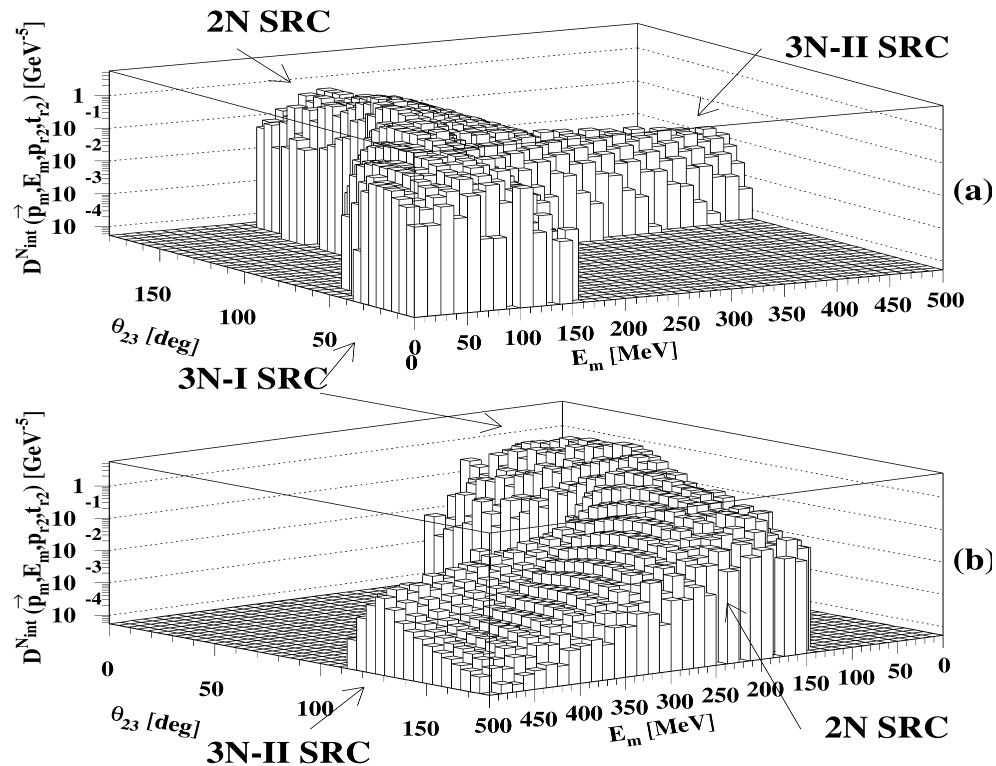


(a) (b)

3N SRCs in Inclusive A(e,e')X Reactions

$$\sigma_{eA} = \sum \sigma_{eN} \cdot \rho_A(\alpha) \quad \text{where} \quad \rho_A(\alpha) = \int \rho_A(\alpha, p_\perp) d^2 p_\perp$$





M.S. Abrahamyan, Frankfurt, Strikman ,Phys. Rev. C 2005

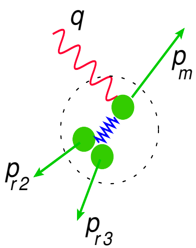
3N SRC model

$$\sigma_{eA} = \sum \sigma_{eN} \cdot \rho_A(\alpha) \quad \text{where} \quad \rho_A(\alpha) = \int \rho_A(\alpha, p_\perp) d^2 p_\perp$$

$$1.6 \le \alpha_{3N} < 3$$

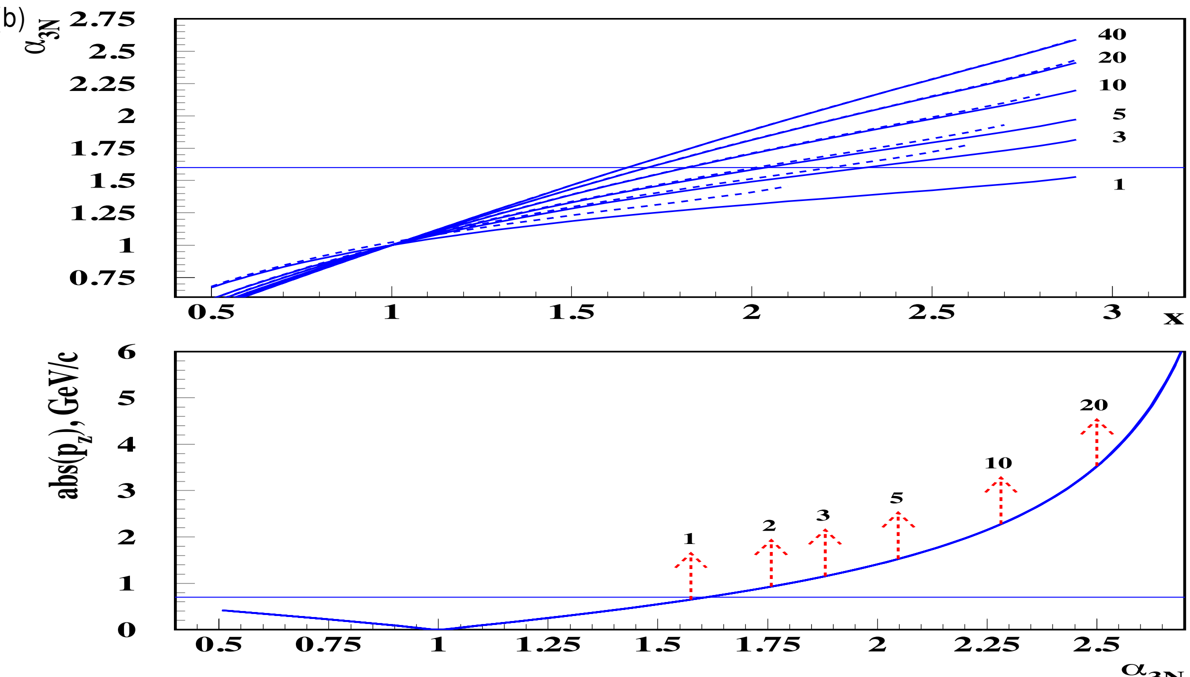
$$q + 3m_N = p_f + p_s$$

$$\alpha_{3N} = 3 - \frac{q_- + 3m_N}{2m_N}\left[1 + \frac{m_S^2 - m_N^2}{W_{3N}^2} + \sqrt{\left(1 - \frac{(m_S+m_n)^2}{W_{3N}^2}\right)\left(1 - \frac{(m_S-m_n)^2}{W_{3N}^2}\right.}\right.$$



(a)

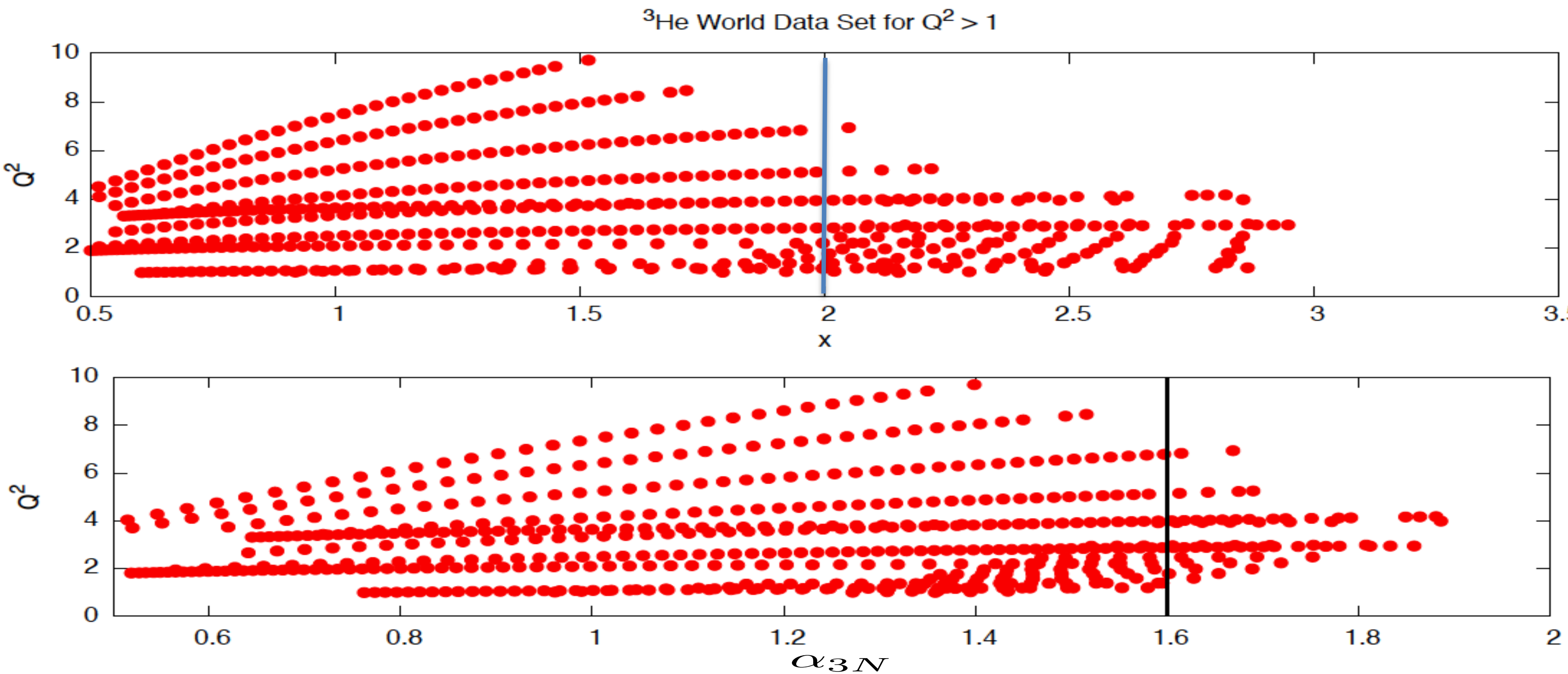
(b)



D.Day, M.S. L.Frankfurt, M.Strikman, ArXiV 2022

3N SRC model $\sigma_{eA} = \sum \sigma_{eN} \cdot \rho_A(\alpha)$ where $\rho_A(\alpha) = \int \rho_A(\alpha, p_\perp) d^2 p_\perp$

$$1.6 \leq \alpha_{3N} < 3$$

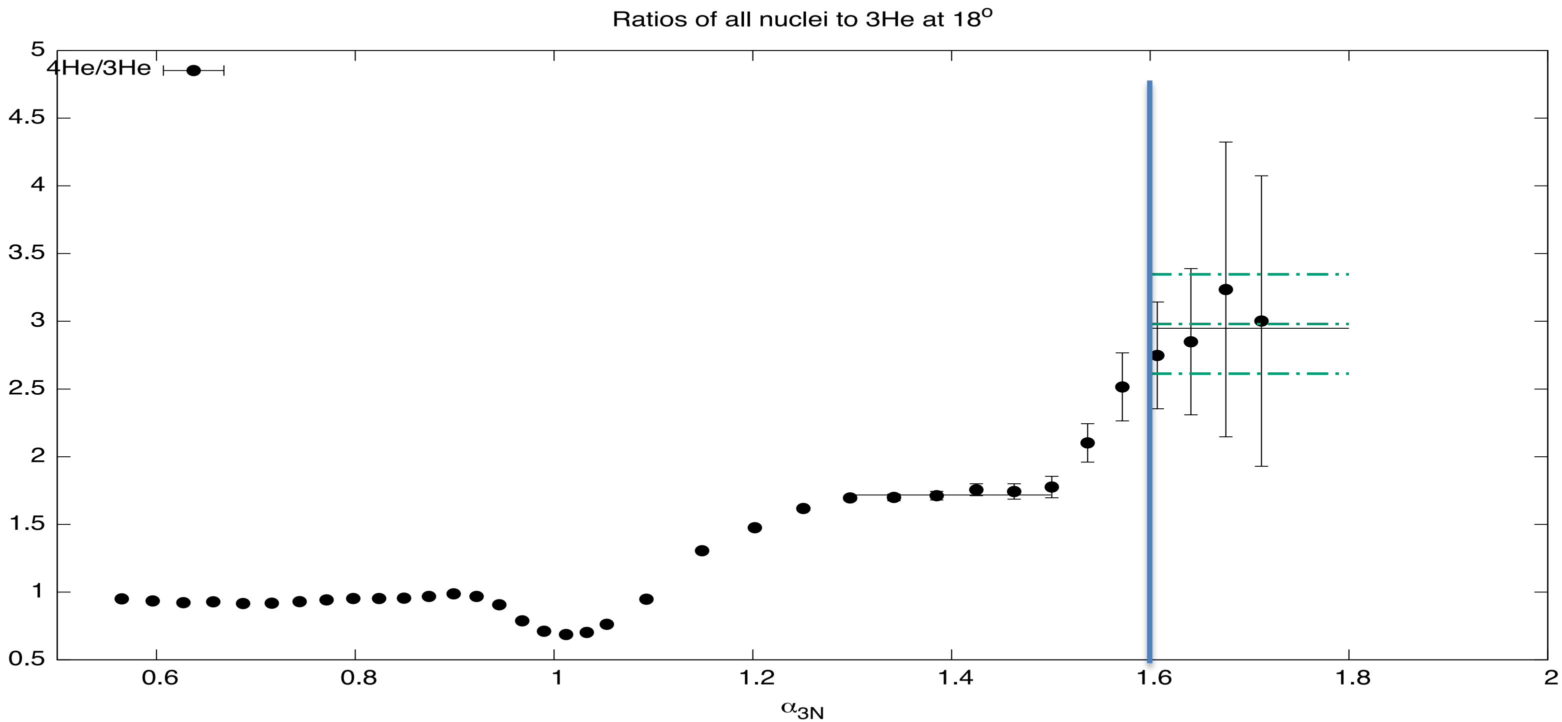


D.Day, M.S. L.Frankfurt, M.Strikman, ArXiV 2018,2022

3N SRCs

$$\sigma_{eA} = \sum \sigma_{eN} \cdot \rho_A(\alpha) \quad \text{where} \quad \rho_A(\alpha) = \int \rho_A(\alpha, p_\perp) d^2 p_\perp$$

$$1.6 \leq \alpha_{3N} < 3$$



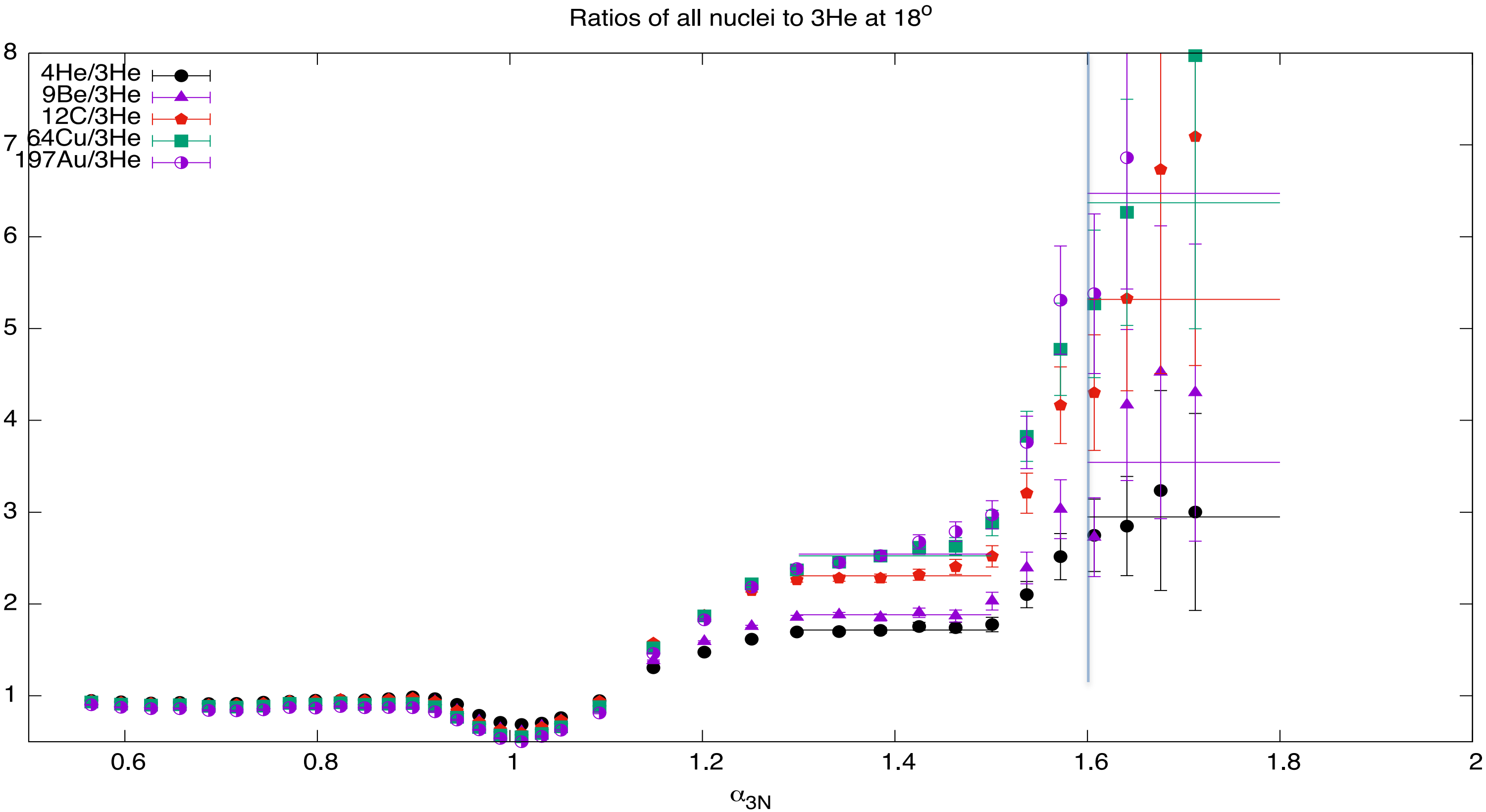
JLab - E02019 - Data

M.S. D.Day. L.Frankfurt, M.Strikman, PRC 2019

3N SRC scaling

$$\sigma_{eA} = \sum \sigma_{eN} \cdot \rho_A(\alpha) \quad \text{where} \quad \rho_A(\alpha) = \int \rho_A(\alpha, p_\perp) d^2 p_\perp$$

$$1.6 \leq \alpha_{3N} < 3$$



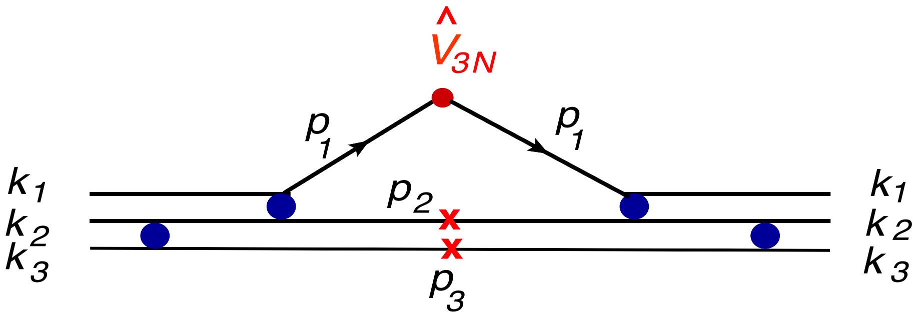
D.Day, M.S. L.Frankfurt, M.Strikman, ArXiV 2018,2022

JLab - E02019 - Data

3N SRC: Light-Cone Momentum Fraction Distribution

A.Freese, M.S., M.Strikman, Eur. Phys. J 2015

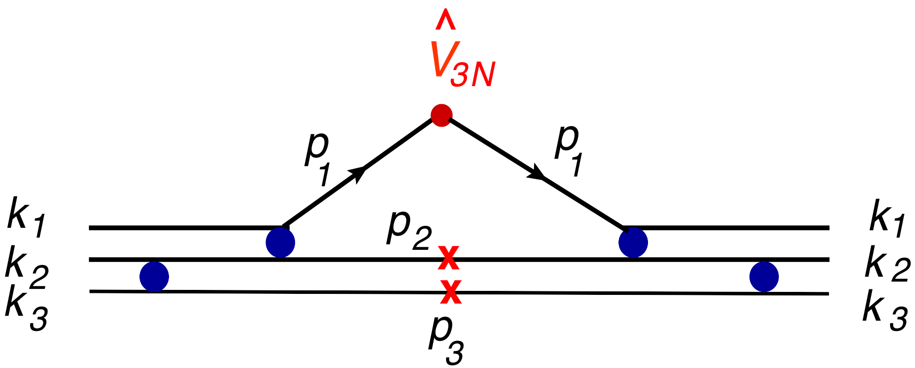
O. Artiles M.S. Phys. Rev. C 2016



$$P^N_{A,3N}(\alpha_1, p_{1,\perp}, s_1, \tilde{M}_N) = \sum_{s_2,s_3,s_{2'},\tilde{s}_{2'}} \int \bar{u}(k_1)\bar{u}(k_2)\bar{u}(k_3)\Gamma^\dagger_{NN\to NN}\frac{u(p_{2'},\tilde{s}_{2'})\bar{u}(p_{2'},\tilde{s}_{2'})}{p^2_{2'} - M^2_N}$$
$$\times \Gamma^\dagger_{NN\to NN}\frac{u(p_1,s_1)}{p_1^2 - M_N^2}u(p_2,s_2)\left[2\alpha_1^2\delta(\alpha_1+\alpha_2+\alpha_3-3)\delta^2(p_{1\perp}+p_{2\perp}+p_{3\perp})\delta(\tilde{M}_N^2 - M_N^{3N,2})\right]$$
$$\times \bar{u}(p_2,s_2)\frac{\bar{u}(p_1,s_1)}{p_1^2 - M_N^2}\Gamma_{NN\to NN}\frac{u(p_{2'},s_{2'})\bar{u}(p_{2'},s_{2'})}{p^2_{2'} - M^2_N}u(p_3,s_3)\bar{u}(p_3,s_3)\Gamma^\dagger_{NN\to NN}u(k_1)u(k_2)u(k_3)$$
$$\times \frac{d\alpha_2}{\alpha_2}\frac{d^2p_{2\perp}}{2(2\pi)^3}\frac{d\alpha_3}{\alpha_3}\frac{d^2p_{3\perp}}{2(2\pi)^3}, \qquad (1)$$

$$P^N_{A,3N}(\alpha_1, p_{1,\perp}, \tilde{M}_N) = \int \frac{3-\alpha_3}{2(2-\alpha_3)^2}\boxed{\rho_{NN}(\beta_3, p_{3\perp})\rho_{NN}(\beta_1, \tilde{k}_{1\perp})}2\delta(\alpha_1+\alpha_2+\alpha_3-3)$$
$$\delta^2(p_{1\perp}+p_{2\perp}+p_{3\perp})\delta(\tilde{M}_N^2 - M_N^{3N,2})d\alpha_2 d^2p_{2\perp}d\alpha_3 d^2p_{3\perp}, \qquad (1)$$

3N SRC: Light-Cone Momentum Fraction Distribution

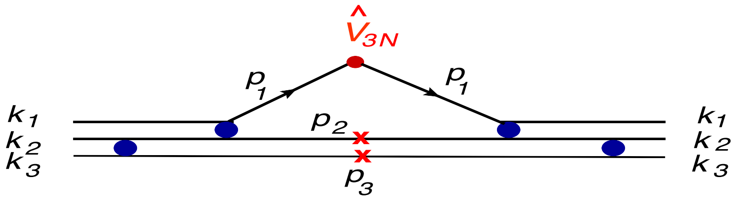


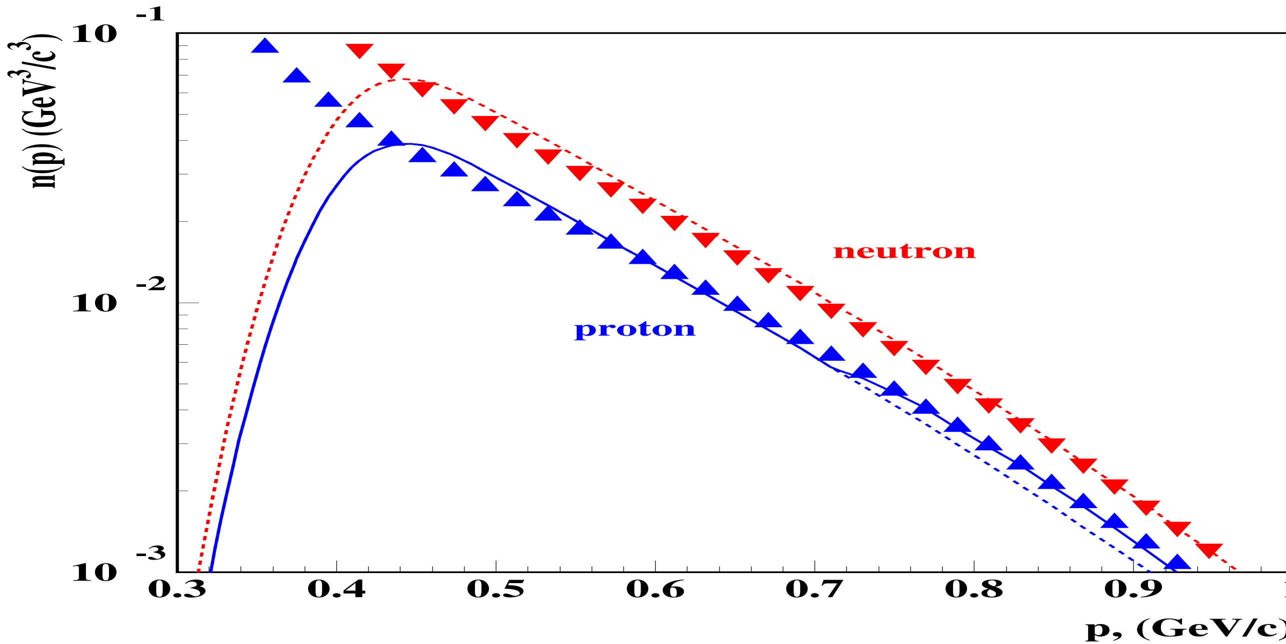
$$\rho_{3N}(\alpha_1) = \int \frac{1}{4}\Big[\frac{3-\alpha_3}{(2-\alpha_3)^3}\rho_{pn}(\alpha_3, p_{3\perp})\,\rho_{pn}\left(\frac{2\alpha_2}{3-\alpha_3}, p_{2\perp}+\frac{\alpha_1}{3-\alpha_3}p_{3\perp}\right) + \frac{3-\alpha_2}{(2-\alpha_2)^3}\rho_{pn}(\alpha_2, p_{2\perp})\,\rho_{pn}\left(\frac{2\alpha_3}{3-\alpha_2}, p_{3\perp}+\frac{\alpha_1}{3-\alpha_2}p_{2\perp}\right)\Big]\delta\Big(\sum_{i=1}^{3}\alpha_i - 3\Big) d\alpha_2 d^2p_{2\perp} d\alpha_3 d^2p_{3\perp}, \quad (1)$$

$$\rho_{pn}(\alpha, p_\perp) \approx a_2(A)\rho_d(\alpha, p_\perp)$$

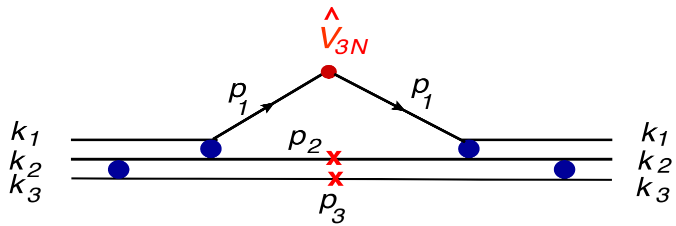
3N SRC: Light-Cone Momentum Fraction Distribution

O. Artiles M.S. Phys. Rev. C 2016





3N SRC: Light-Cone Momentum Fraction Distribution



$$-\rho_{3N} \sim a_2(A,z)^2$$

- For A(e,e') X reactions: $\sigma_{eA} = \sum_N \sigma_{eN}\rho_{3N}(\alpha_{3N})$

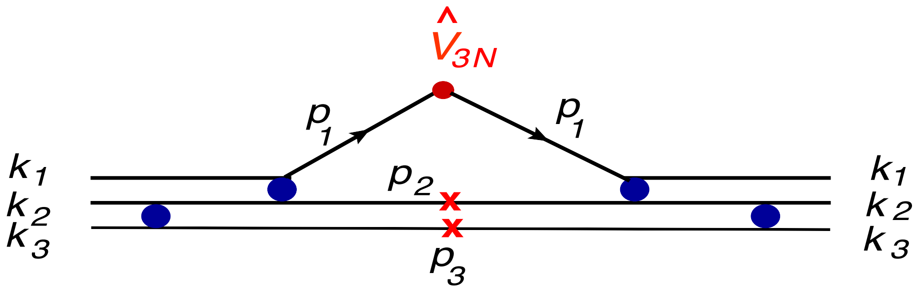
- Defining: $R_3(A,Z) = \frac{3\sigma_{eA}}{A\sigma_{e^3He}}\Big|_{\alpha_{3N}\geq\alpha^0_{3N}}$

- We predict:

$$R_3(A,Z) = \frac{9}{8}\frac{(\sigma_{ep}+\sigma_{en})/2}{(2\sigma_{ep}+\sigma_{en})/3}\left(\frac{a_2(A,Z)}{a_2(^3He)}\right)^2 = \frac{9}{8}\frac{(\sigma_{ep}+\sigma_{en})/2}{(2\sigma_{ep}+\sigma_{en})/3} \boxed{R_2^2(A,Z)},$$

- Where: $R_2(A,Z) = \frac{3\sigma_{eA}}{A\sigma_{e^3He}}\Big|_{1.3\leq\alpha_{3N}\leq1.5}$ where: $\alpha_{3N} \approx \alpha_{2N}$

3N SRC: Predictions



- $\rho_{3N} \sim a_2(A,z)^2$
- *ppp* and *nnn* strongly suppressed compared with *ppn* or *pnn*
- pp/nn recoil state is suppressed compared with pn

$$R_3(A,Z) \quad = \quad \frac{9}{8}\frac{(\sigma_{ep}+\sigma_{en})/2}{(2\sigma_{ep}+\sigma_{en})/3}\left(\frac{a_2(A,Z)}{a_2(^3He)}\right)^2 = \frac{9}{8}\frac{(\sigma_{ep}+\sigma_{en})/2}{(2\sigma_{ep}+\sigma_{en})/3}R_2^2(A,Z),$$

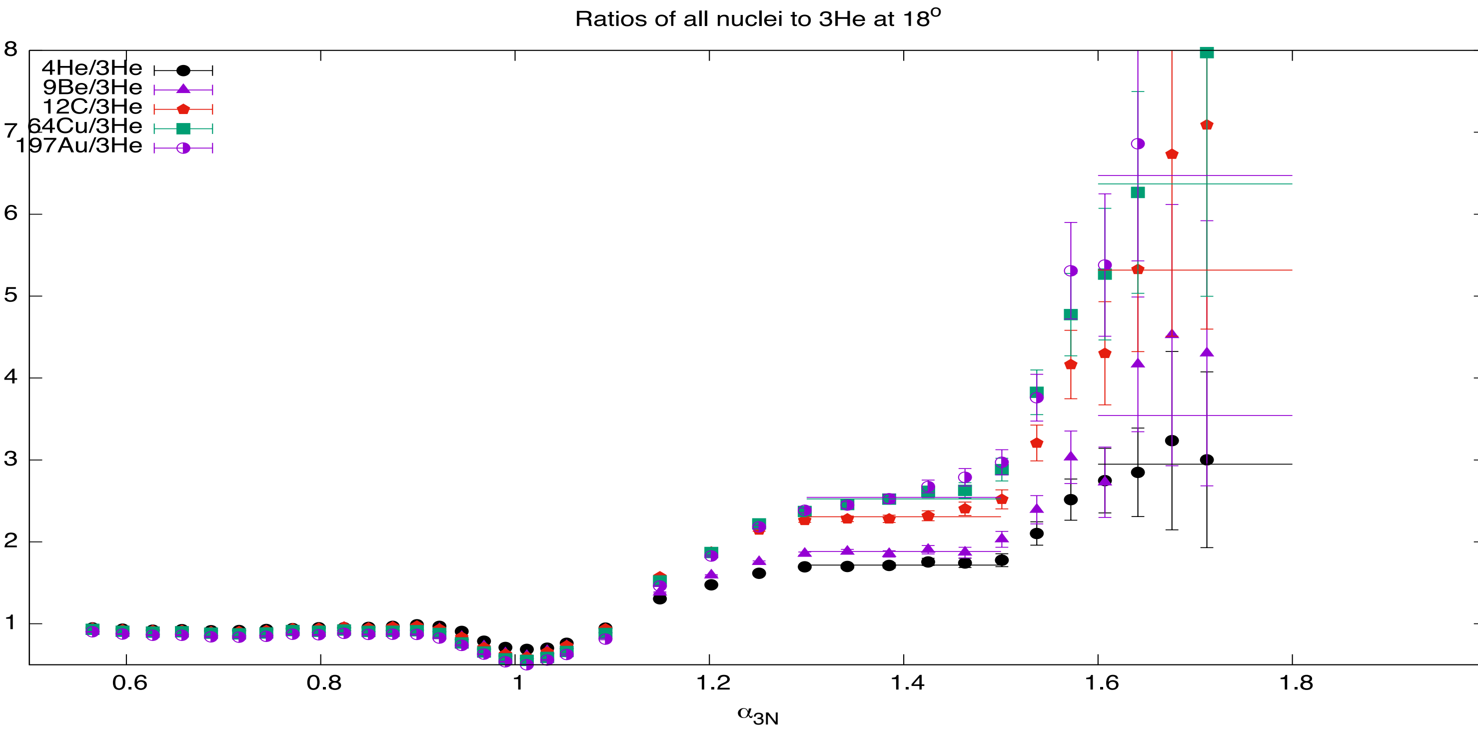
3N SRC model

$$R_2 = \frac{3\sigma_{eA}(\alpha_{3N})}{A\sigma_{3A}(\alpha_{3N})} \quad 1.3 \le \alpha_{3N} \le 1.5$$

$$1.6 \le \alpha_{3N} < 3$$

$$R_3 = \frac{3\sigma_{eA}(\alpha_{3N})}{A\sigma_{3A}(\alpha_{3N})} \quad 1.6 \le \alpha_{3N} \le 1.8$$

$$R_3(A,Z) \approx R_2(A,Z)^2$$



3N SRC model: Prediction

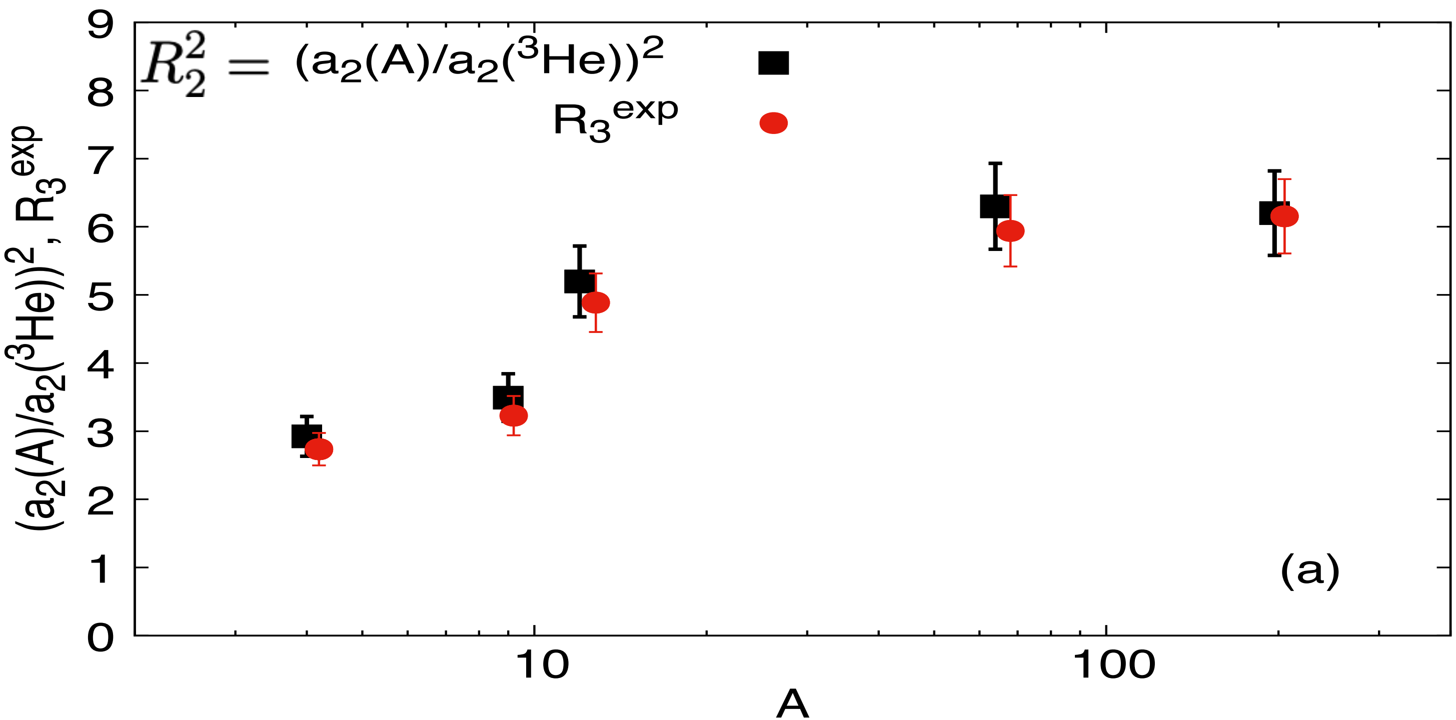
$$R_2 = \frac{3\sigma_{eA}(\alpha_{3N})}{A\sigma_{3A}(\alpha_{3N})} \quad 1.3 \leq \alpha_{3N} \leq 1.5$$

$$R_3 = \frac{3\sigma_{eA}(\alpha_{3N})}{A\sigma_{3A}(\alpha_{3N})} \quad 1.6 \leq \alpha_{3N} \leq 1.8$$

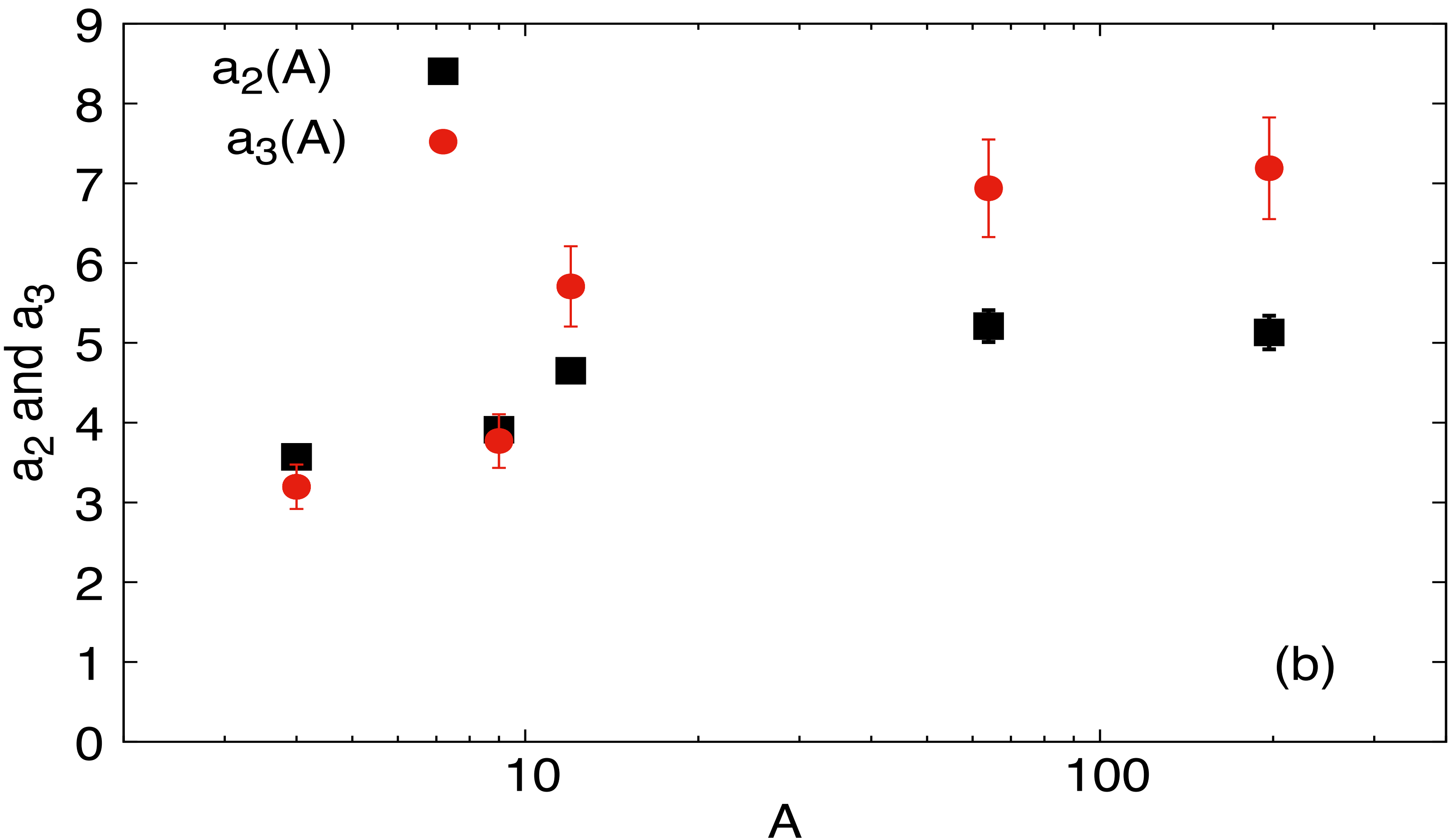
$$1.6 \leq \alpha_{3N} < 3$$

$$R_3(A) = R_2(A)^2$$

M.S. D.Day, L.Frankfurt,M.S, M.Strikman, PRC 2019



One of the goals: Extrapolating to infinite nuclear matter



3N SRC Summary & Outlook

- Proper variable for studies of 2N and 3N SRS are Light-Cone momentum fractions: α_{2N}, α_{3N}

- It seems we observed first signatures of 3N SRCs in the form of the "scaling"

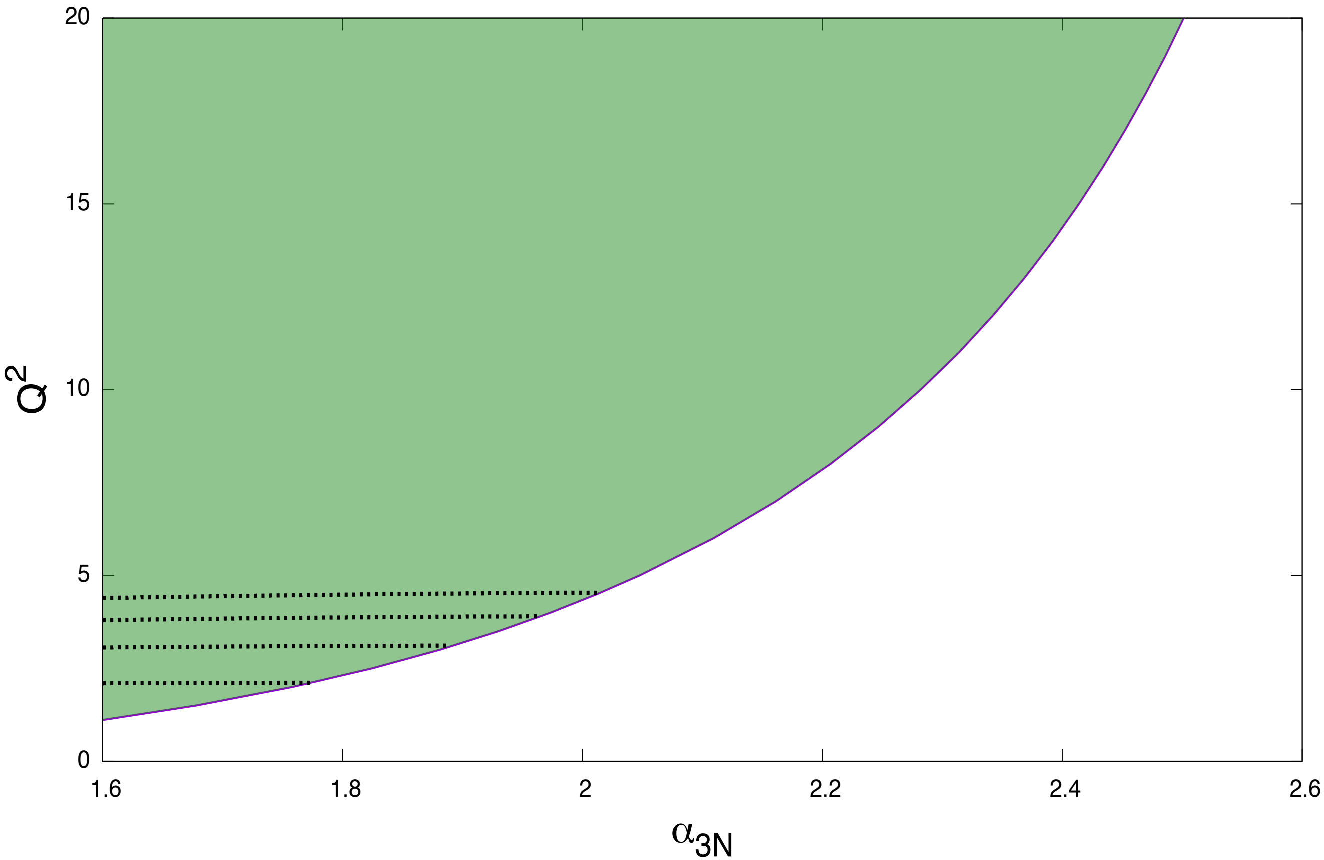
- Existing data in agreement with the prediction of: $R_3(A,Z) \approx R_2(A,Z)^2$

- Unambiguous verification will require larger Q2 data to cover larger α_{3N} region

- Reaching Q2 > 5 GeV2 will allow to reach: $\alpha_{3N} > 2$

3N SRC Outlook

^3He at $Q^2 = 5$ GeV^2 $\alpha_{3N} = 2$



$E = 12$ GeV, 30 days

$E = 24$ GeV, 6 days

Probing 3N SRCs in Inclusive Scattering:

$$\frac{2\sigma(eA \to e'X)}{A\sigma(ed \to e'X)} = \frac{\rho_A(\alpha_{2N})}{\rho_d(\alpha_{2N})} = a_2(A)$$ For $1 < \alpha_{2N} < 2$

$$q + 2m = p_f + p_s$$

$$\alpha_{2N} = 2 - \frac{q_- + 2m_N}{2m_N}\left(1 + \frac{\sqrt{W_{2N}^2 - 4m_N^2}}{W_{2N}^2}\right)$$

$$\frac{3\sigma(eA \to e'X)}{A\sigma(e^3He \to e'X)} = \frac{\rho_A(\alpha_{3N})}{\rho_{^3He}(\alpha_{3N})} = a_3(A)$$ For $2 < \alpha_{3N} < 3$

$$q + 3m = p_f + p_s$$

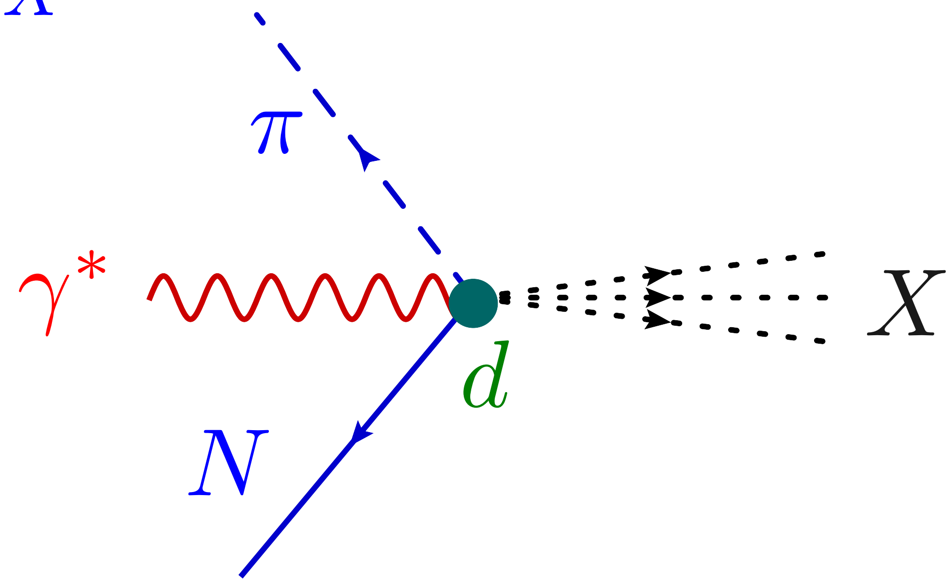
$$\alpha_{3N} = 3 - \frac{q_- + 3m_N}{2m_N}\left[1 + \frac{m_S^2 - m_N^2}{W_{3N}^2} + \sqrt{\left(1 - \frac{(m_S + m_n)^2}{W_{3N}^2}\right)\left(1 - \frac{(m_S - m_n)^2}{W_{3N}^2}\right)}\right]$$

Probing Deuteron at Core Distances at large Q^2

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

$$e + d \to e' + \Delta_{backward} + X$$

$$e + d \to e' + N^*_{backward} + X$$



3. Probing SuperFast Quarks in Nuclei

Studies of nuclear partonic distributions at x>1

Bjorken $$x = \frac{Q^2}{2m_N\nu}$$

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

- x>1 "super-fast quarks"

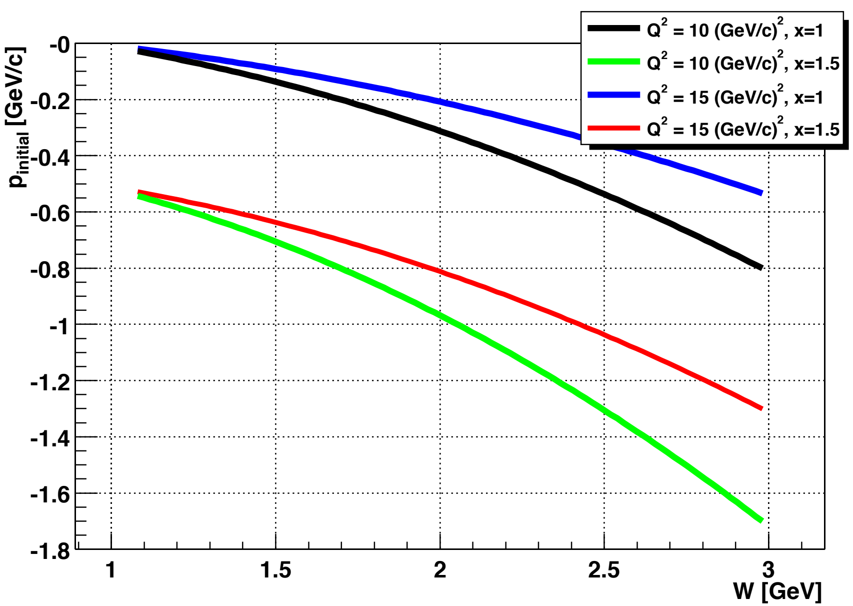
SuperFast quarks - short distance probes in nuclei

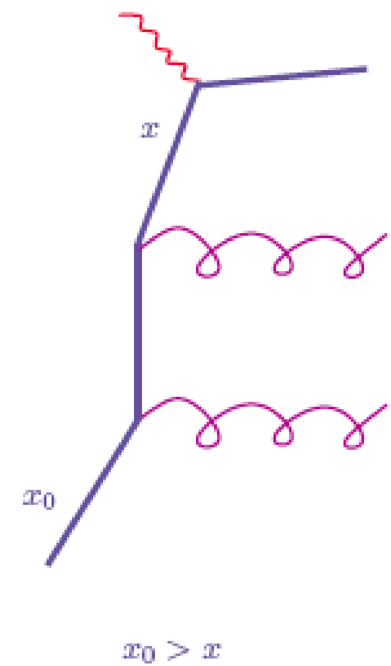
$$x = \frac{Q^2}{2m_N q_0} > 1$$

Two factors driving nucleons close together

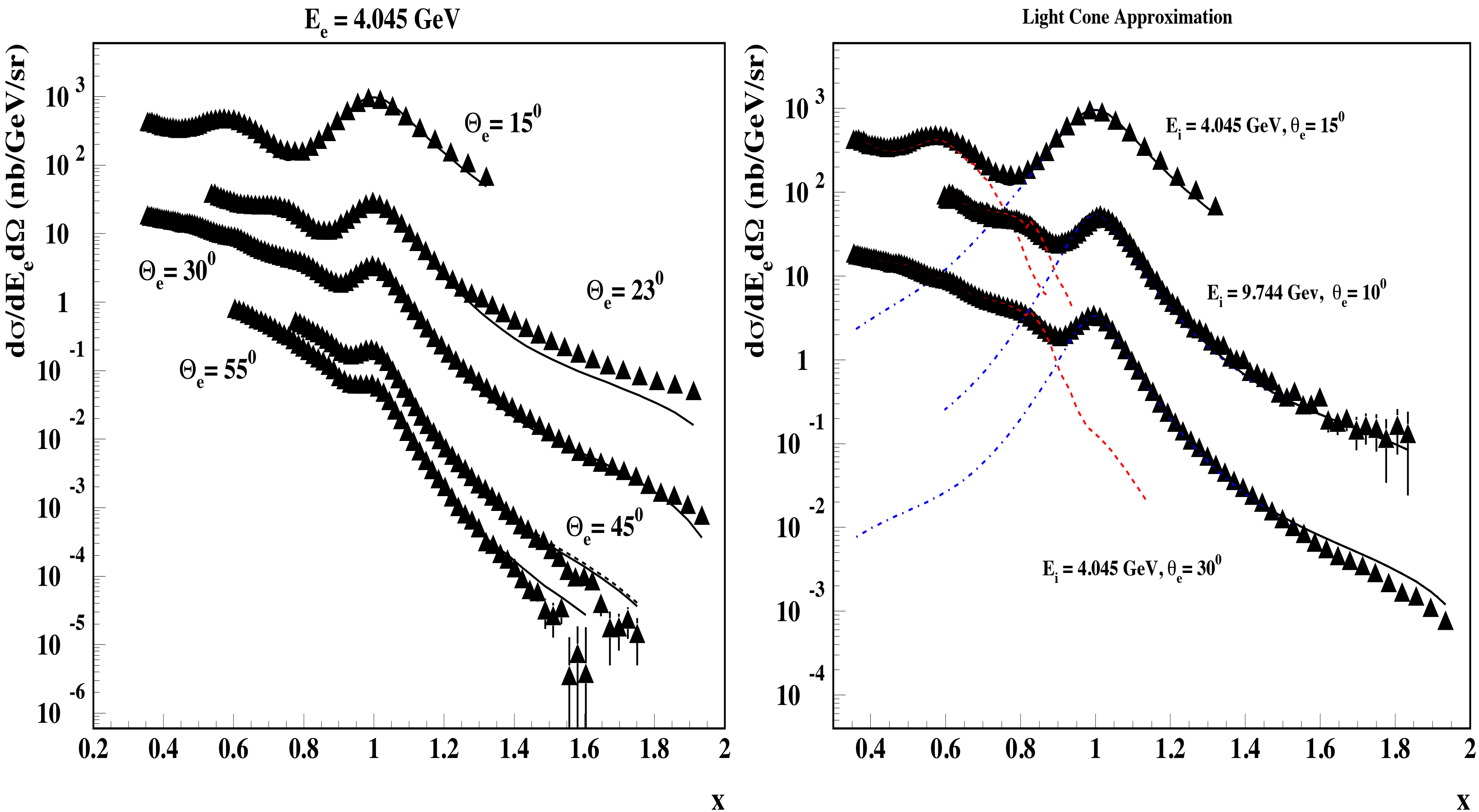
Kinematic $p_{min} \equiv p_z = m_N \left(1 - x - x\left[\frac{W_N^2 - m_N^2}{Q^2}\right]\right)$

Dynamical:QCD evolution





Inclusive $d(e,e')X$



Existing 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: $e + A \to e' + X, \; Q^2 \geq 10 \text{ GeV}^2$

5. Alternative Studies at LHC: p+A -> 2 jets + X

6. Electron Ion Collider: $\gamma + A \longrightarrow e' + X,$ $x_{Bj} > 1, Q^2 \geq 20 \text{ GeV}^2$

$$e + A \to e' + jet/N/h + X, \qquad x_h > 1$$

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

1. BCDMS Collaboration 1994 (CERN):

Z.Phys C63 1994

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

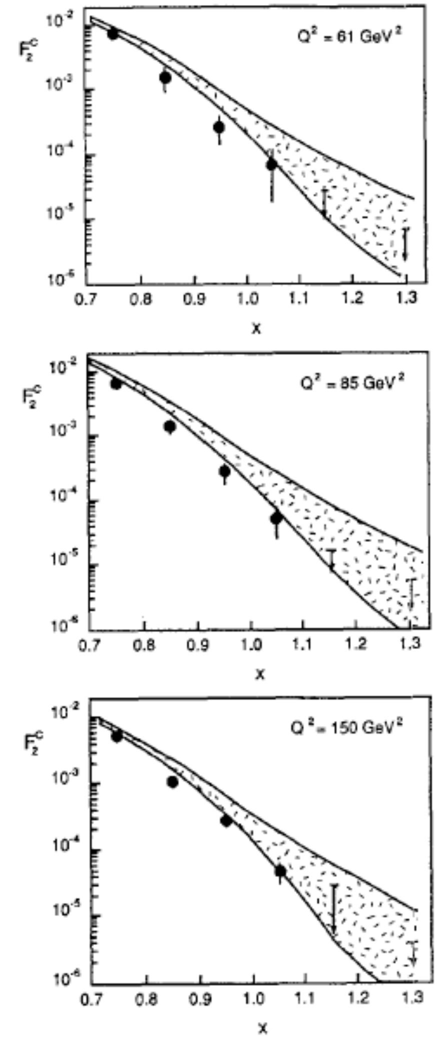
$$Q^2 = 61,\ 85 \text{ and } 150 \text{ GeV}^2$$

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

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

$$s = 16.5 \pm 0.6$$

More than Fermi Gas but very marginal high momentum component



2. CCFR Collaboration 2000 (FermiLab):

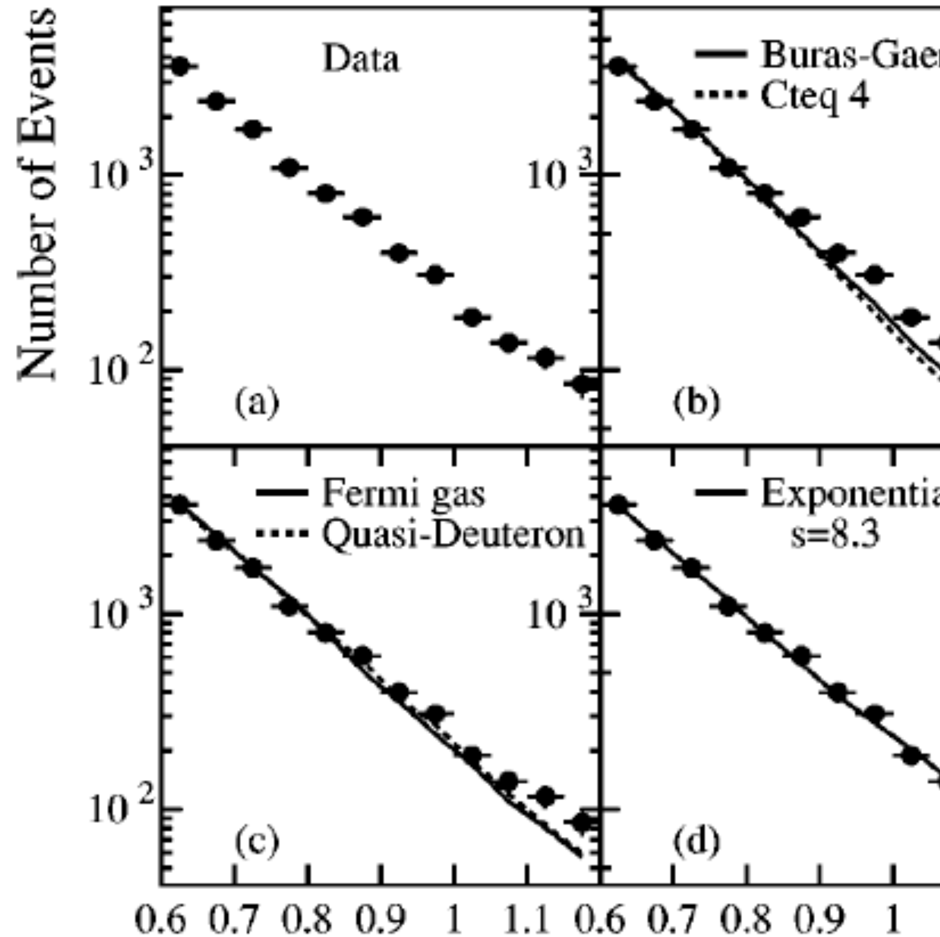
Phys. Rev. D61 2000

Using the neutrino and antineutrino beams in which structure function of 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)

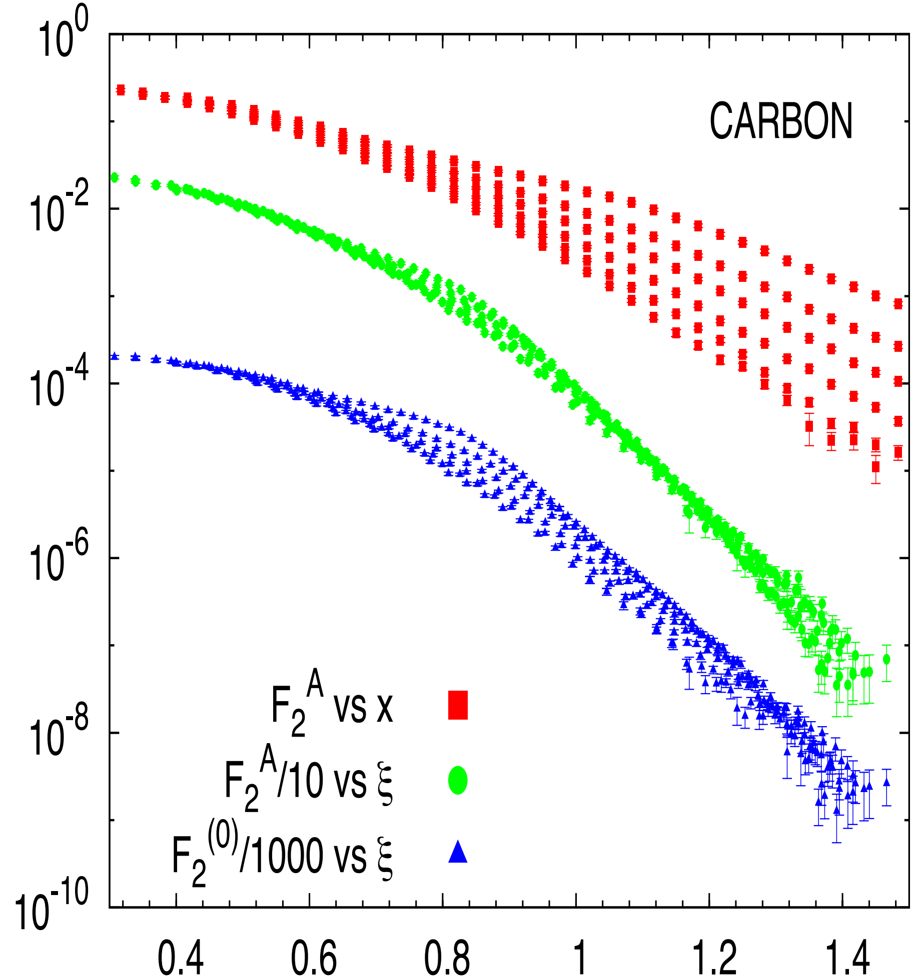
Fomin, Arrington, hys.Rev.Lett 204 2010

(ee') scattering of

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

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

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



QCD Evolution Equation for Nuclear Partonic Distributions

Adam Freese, MS
ArXiv 2015

$$\frac{dq_{i,A}(x,Q^2)}{d\log Q^2} = \frac{\alpha_s}{2\pi}\left\{2\left(1+\frac{4}{3}\log(1-\frac{x}{A})\right)q_{i,A}(x,Q^2)\right.$$

$$\left. + \frac{4}{3}\int\limits_{x/A}^{1}\frac{dz}{1-z}\left(\frac{1+z^2}{z}q_{i,A}(\frac{x}{z},Q^2) - 2q_{i,A}(x,Q^2)\right) + \int\limits_{x/A}^{1} dz\frac{(1-z)^2+z^2}{2z}G_A(\frac{x}{z},Q^2)\right\}$$

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

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

$$\left. + \frac{4}{3}\int\limits_{x/A}^{1}\frac{dz}{1-z}\left(\frac{1+z^2}{z}F_{2A}(\frac{x}{z},Q^2) - 2F_{2A}(x,Q^2)\right) + \frac{f_Q}{2}\int\limits_{x/A}^{1} dz[(1-z)^2+z^2]\frac{x}{z}G_A(\frac{x}{z},Q^2)\right\}$$

Neglecting $G_A(x, Q^2)$

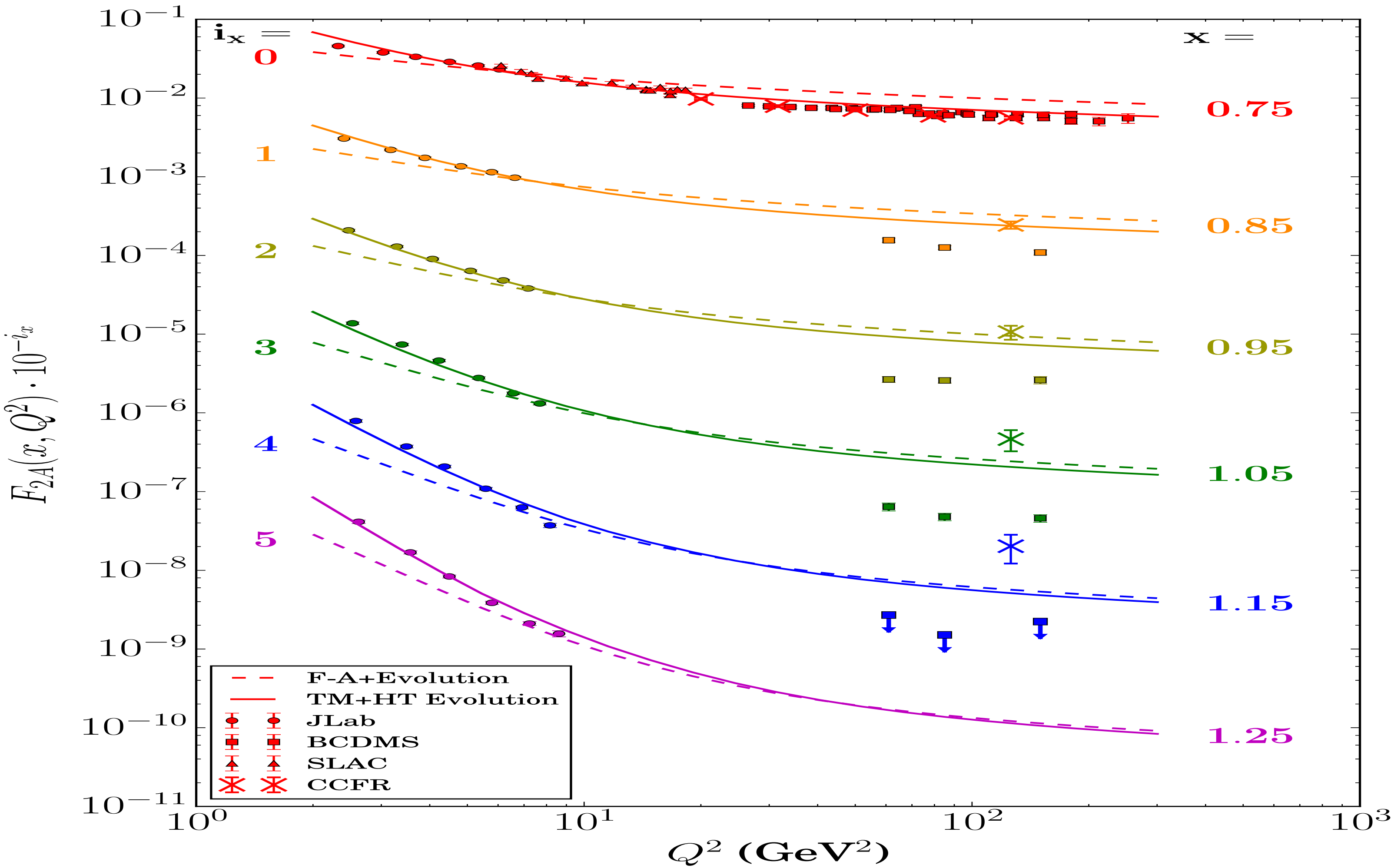
$$\frac{dF_{2A}(x,Q^2)}{d\log Q^2} = \frac{\alpha_s}{2\pi}\left\{2\left(1+\frac{4}{3}\log(1-\frac{x}{A})\right)F_{2,A}(x,Q^2) + \frac{4}{3}\int_{x/A}^{1}\frac{dz}{1-z}\left(\frac{1+z^2}{z}F_{2A}(\frac{x}{z},Q^2) - 2F_{2A}(x,Q^2)\right)\right\}$$

Using input $F_{2A}^{(0)}(\xi, Q^2)$ from JLab analysis at $Q^2 = 7.4\ \text{GeV}^2$

and calculate the evolution to Q^2 region of CCFR and BCDMS

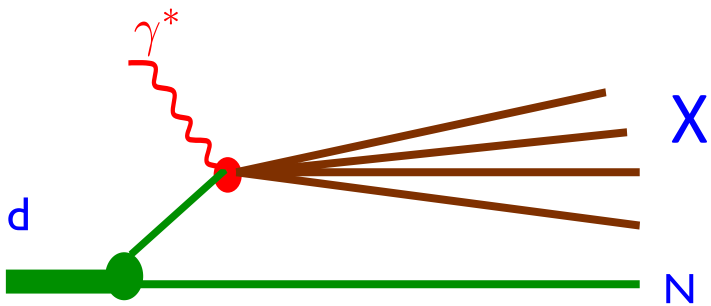
$Q^2 = 120\ \text{GeV}^2$ $\quad 52 \leq Q^2 \leq 200\ \text{GeV}^2$

A.Freese & M.S
ArXiv 2015



- Dynamics of generation of superfast quarks in nuclei

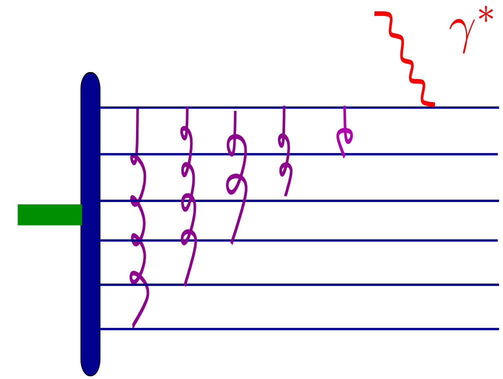
1. Convolution Model



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

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

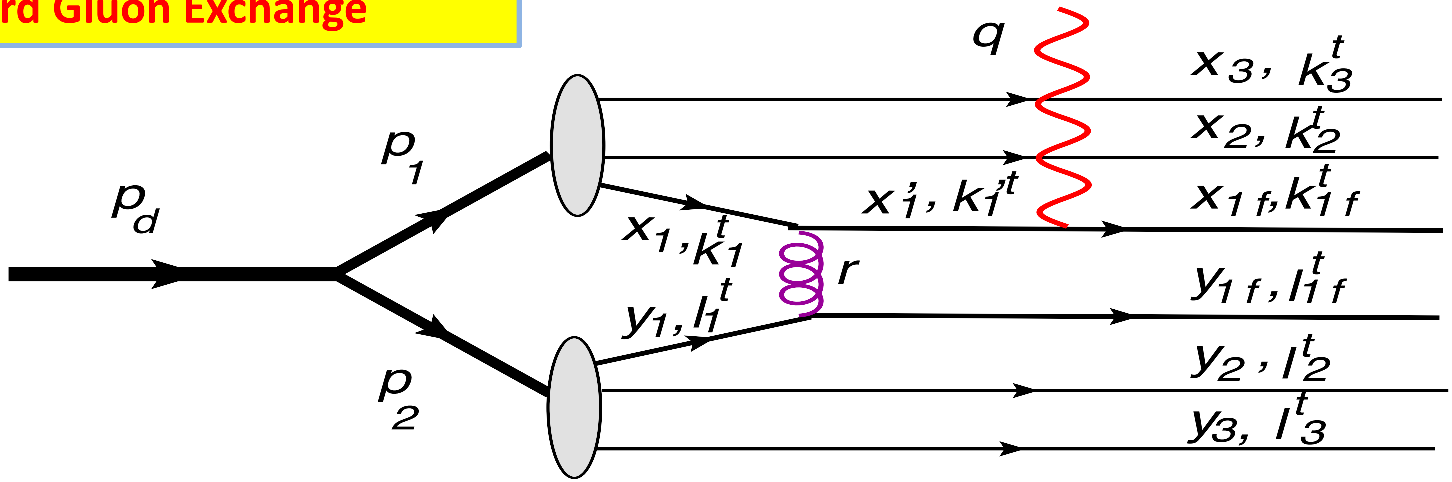
2. Six-Quark Model



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

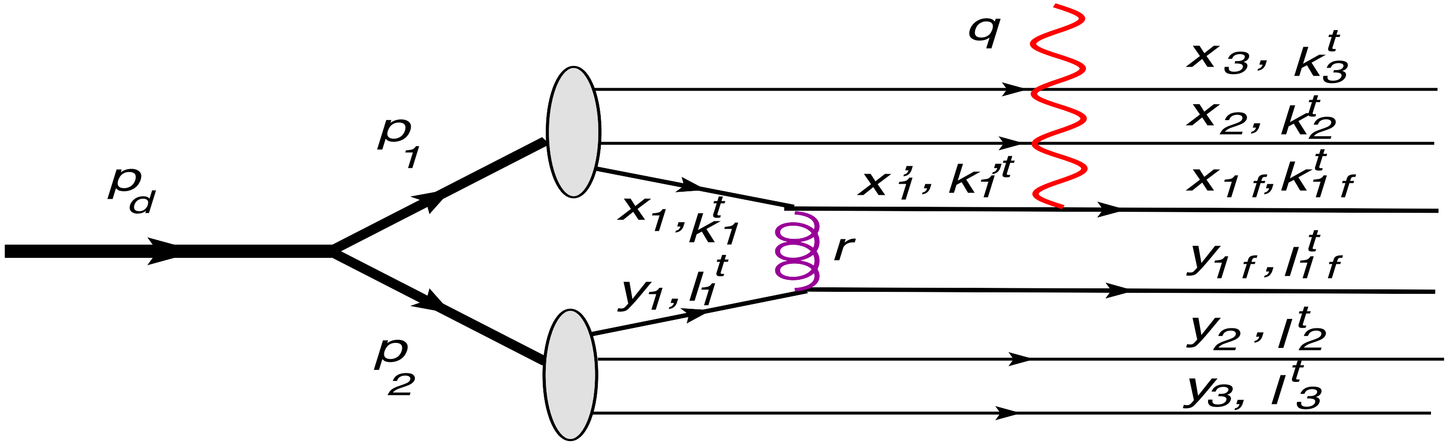
3. Hard Gluon Exchange

MS in progress



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

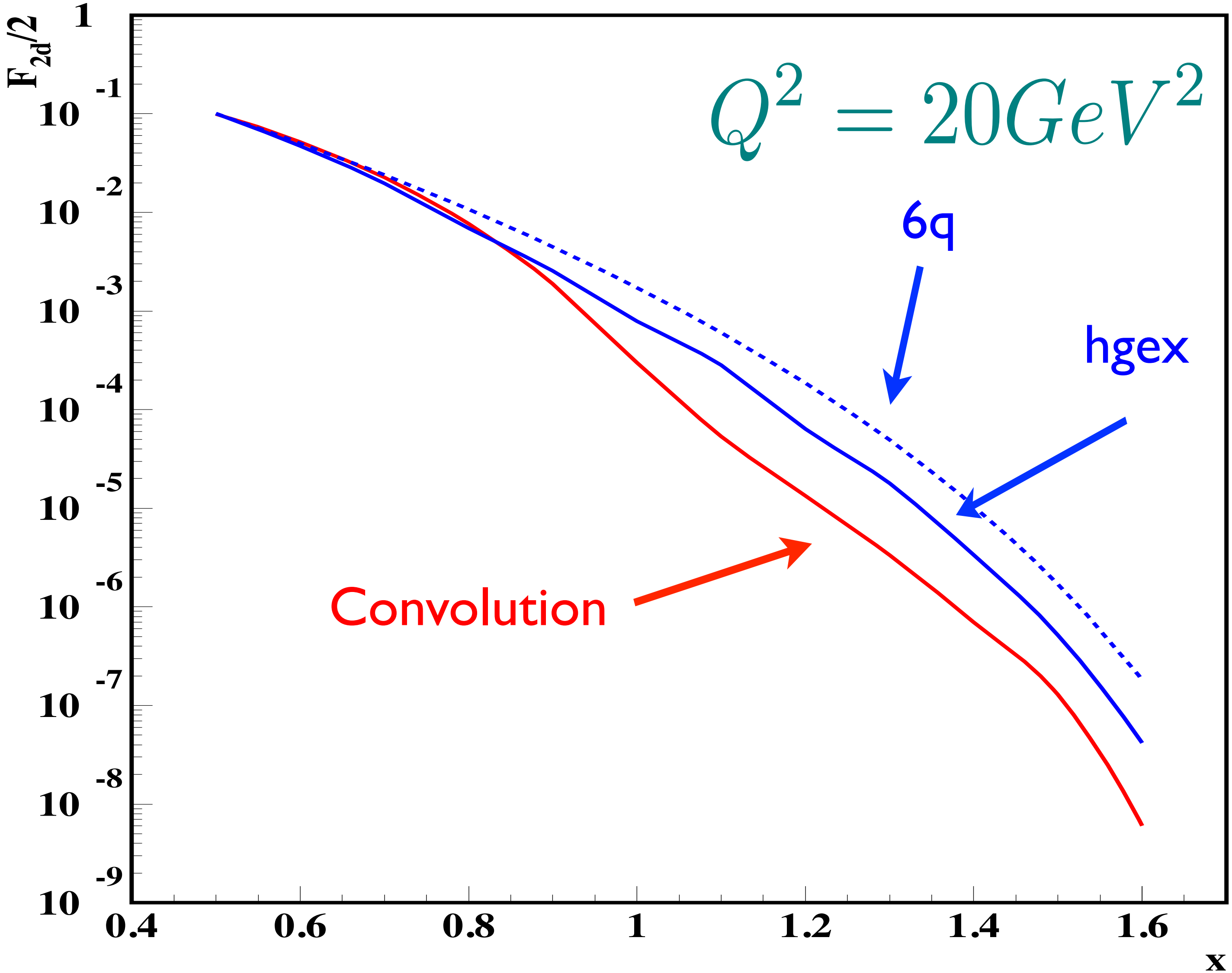
$$\left\{ \sum_{\eta_1,\lambda_1} H^\sigma_{(\eta_{1f},\eta_1),(\lambda_{1f},\lambda_1)} \frac{\psi_N^{h_1}(k_1,\eta_1;k_2,\eta_2;k_3,\eta_3)}{x_1\sqrt{2(2\pi)^3}} \frac{\psi_N^{h_2}(l_1,\lambda_1;l_2,\lambda_2;l_3,\lambda_3)}{y_1\sqrt{2(2\pi)^3}} \right\} \frac{\Psi_d^{h_1,h_2,m_d}(p_1,p_2)}{(1-\alpha)\sqrt{2(2\pi)^3}}$$



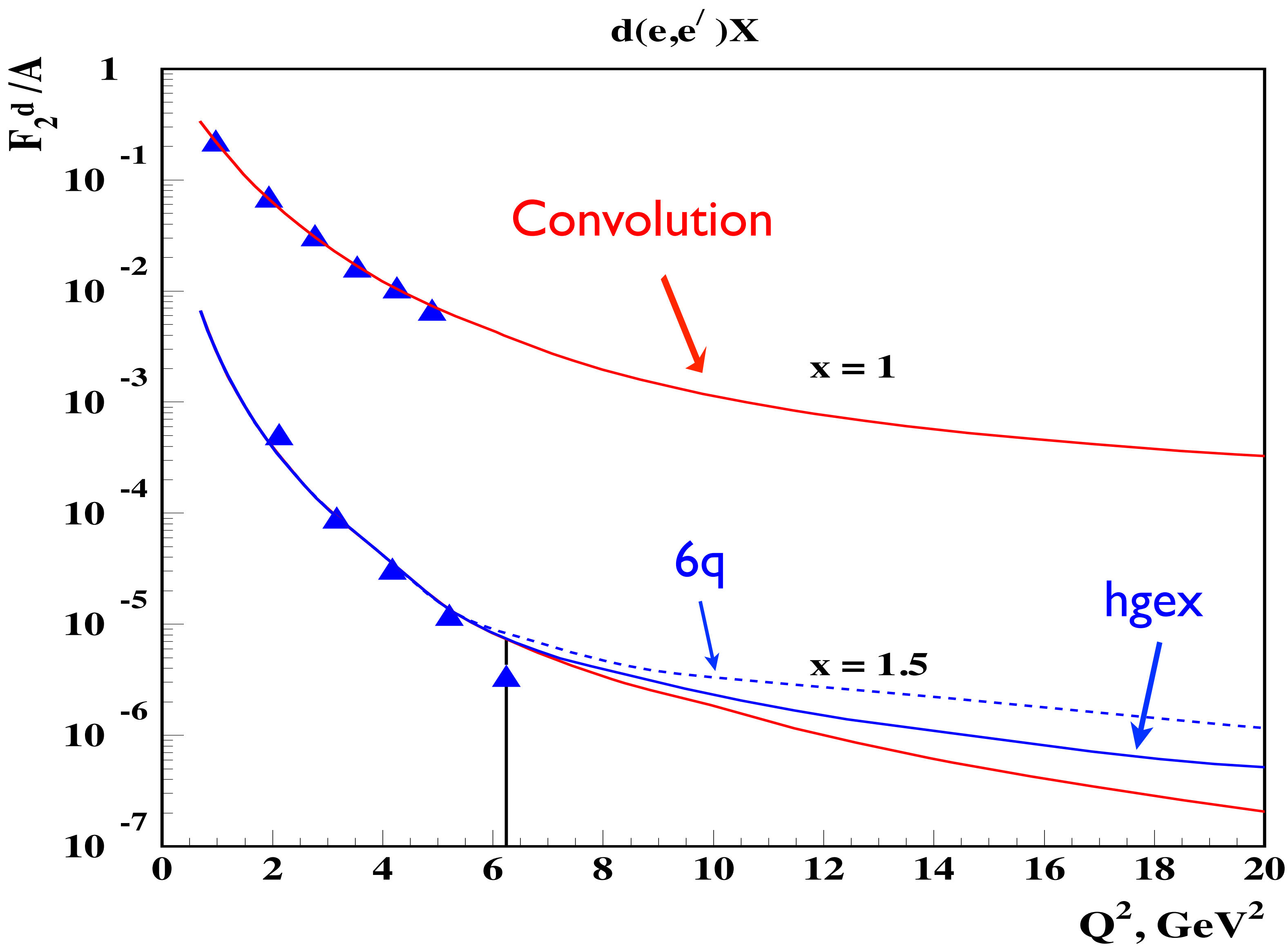
$$F_{2d}(x_{Bj},Q^2) = \sum_{i,j} x_{Bj} e_i^2 \int dx_1 dy_1 \frac{d^2 l_{1f,t}}{2(2\pi)^3} \frac{8\alpha_{QCD}}{l_{1f,t}^4} f_i(x_1,Q^2) f_j(y_1, l_{1f,t}^2) \times$$

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

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



$F_{2d}/2$
$Q^2 = 20GeV^2$
6q
hgex
Convolution
x
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0.4
0.6
0.8
1
1.2
1.4
1.6



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

Conclusions and Outlook

- Dedicated studies of deuteron will allow for the first time to probe the NN core
- 3He, 3H and other asymmetric nuclei allow to verify momentum sharing effects
- Q2 = 5 GeV2 is optimal for searching 3N SRC plateau in inclusive cross section ratiosat x>2
- pp correlations can be used to isolate 3N SRCs
- Superfast quark distributions may allow verify the dynamics of quark-hadron transition

- all the processes have small cross sections…