New Properties of High Momentum Component of Asymmetric Nuclei

Misak Sargsian
Florida International University, Miami

Nuclear Structure and Dynamics at Short Distances
Feb 11 – 22 INT, University of Washington

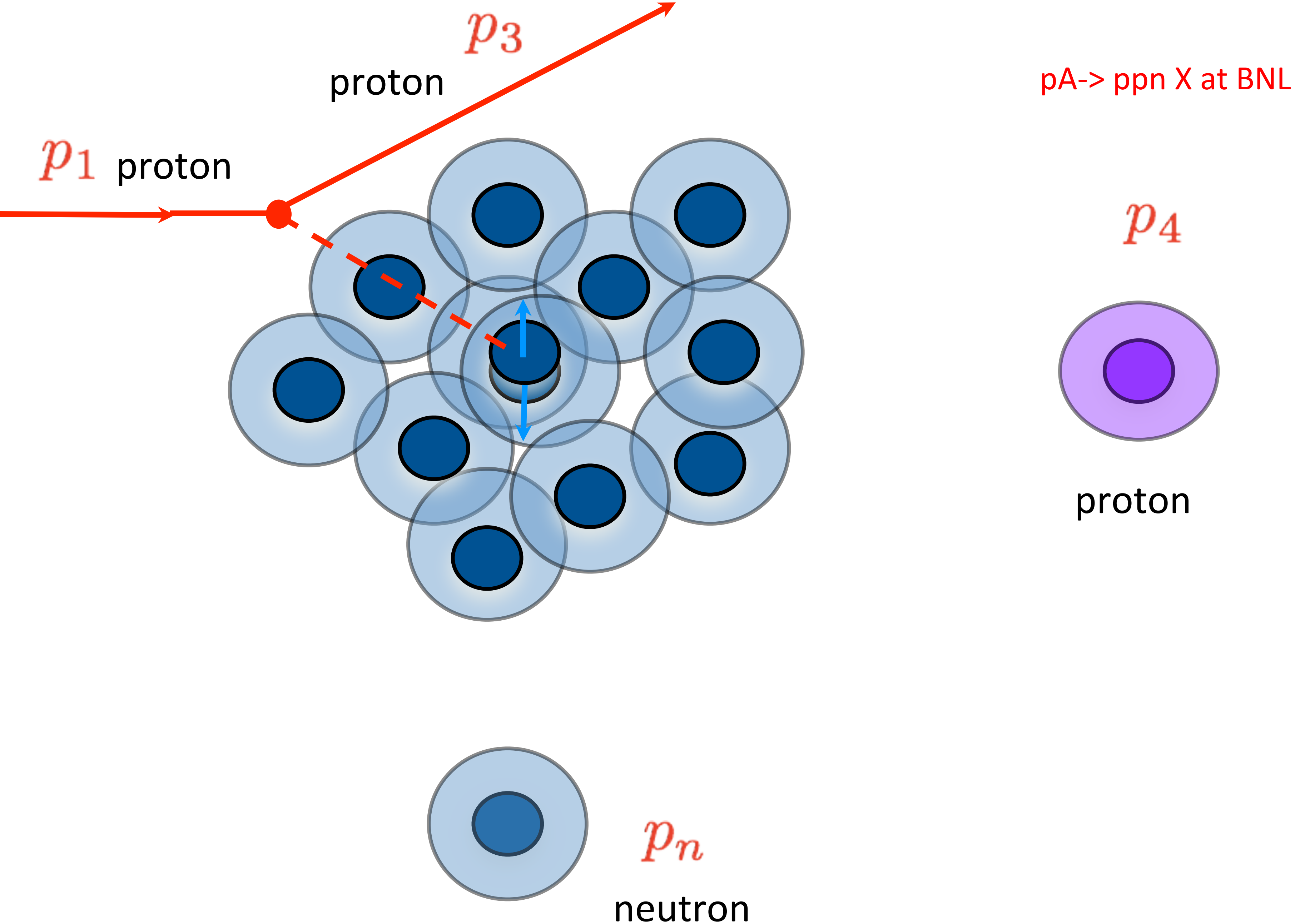
- Dominance of pn short range correlations as compared to pp and nn SRCS

- Dominance of NN Tensor as compared to the NN Central Forces

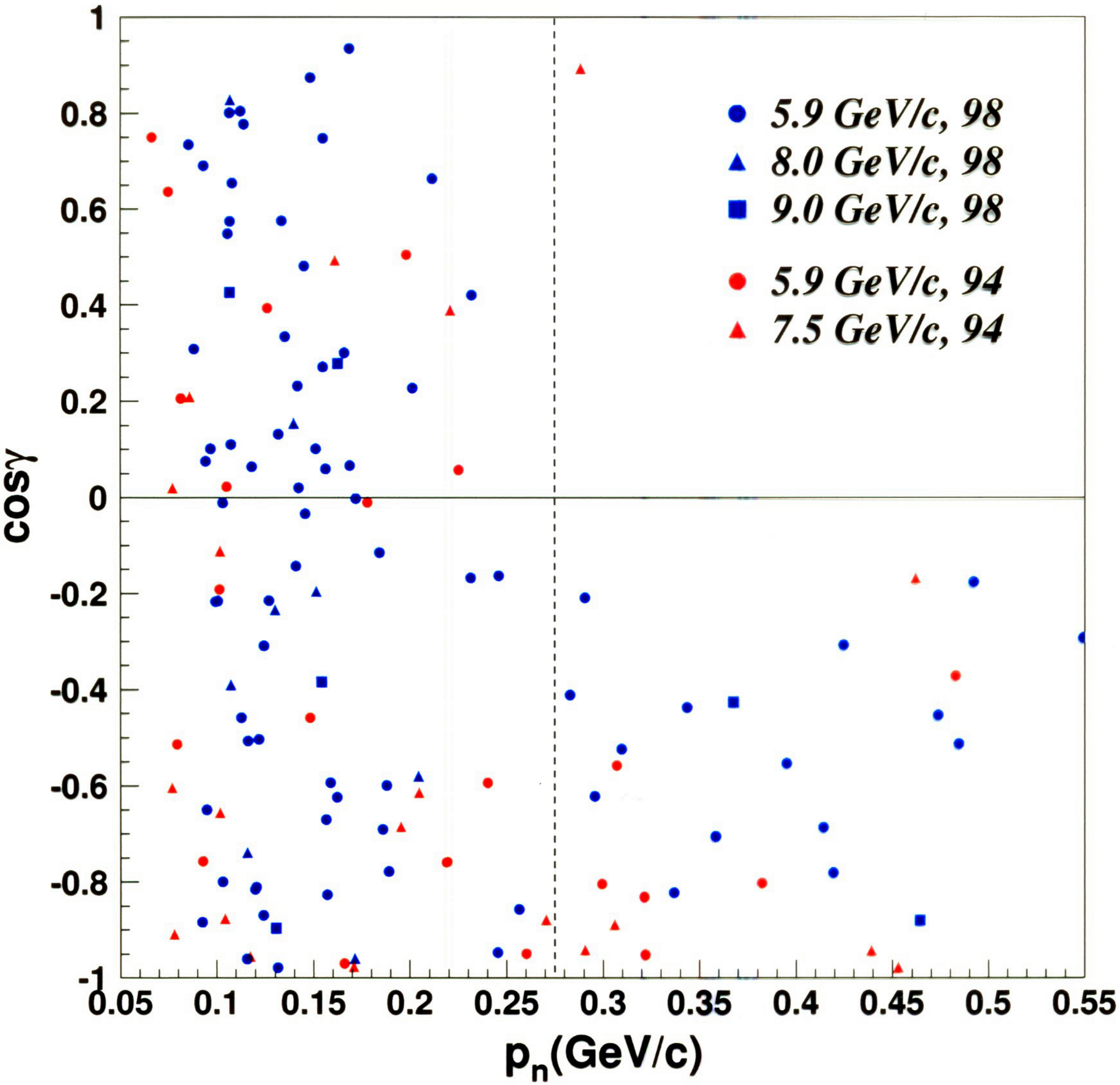
- Two New Properties of High Momentum Component

- Energetic Protons in Asymmetric Nuclei

- Implications



p_3
proton
pA-> ppn X at BNL
p_1 proton
p_4
proton
p_n
neutron



A. Tang et al, PRL 2003

Brookhaven Experiment

A. Tang et al, PRL 2003

$$F = \frac{\text{Number of (p,ppn) events } (p_i, p_n > k_F)}{\text{Number of (p,pp) events } (p_i > k_F)},$$

$$F = 0.43^{+0.11}_{-0.07} \qquad \text{for } 275 \le p_i, p_n \le 550 \text{ MeV/c}$$

Theoretical Analysis

Piasetzky, MS, Frankfurt, Strikman, Watson PRL 2007

$$P_{pn/pX} = \frac{F}{T_n R}$$

relative probability of finding pn SRC in the "pX" configuration that contains a proton with $p_i > k_F$.

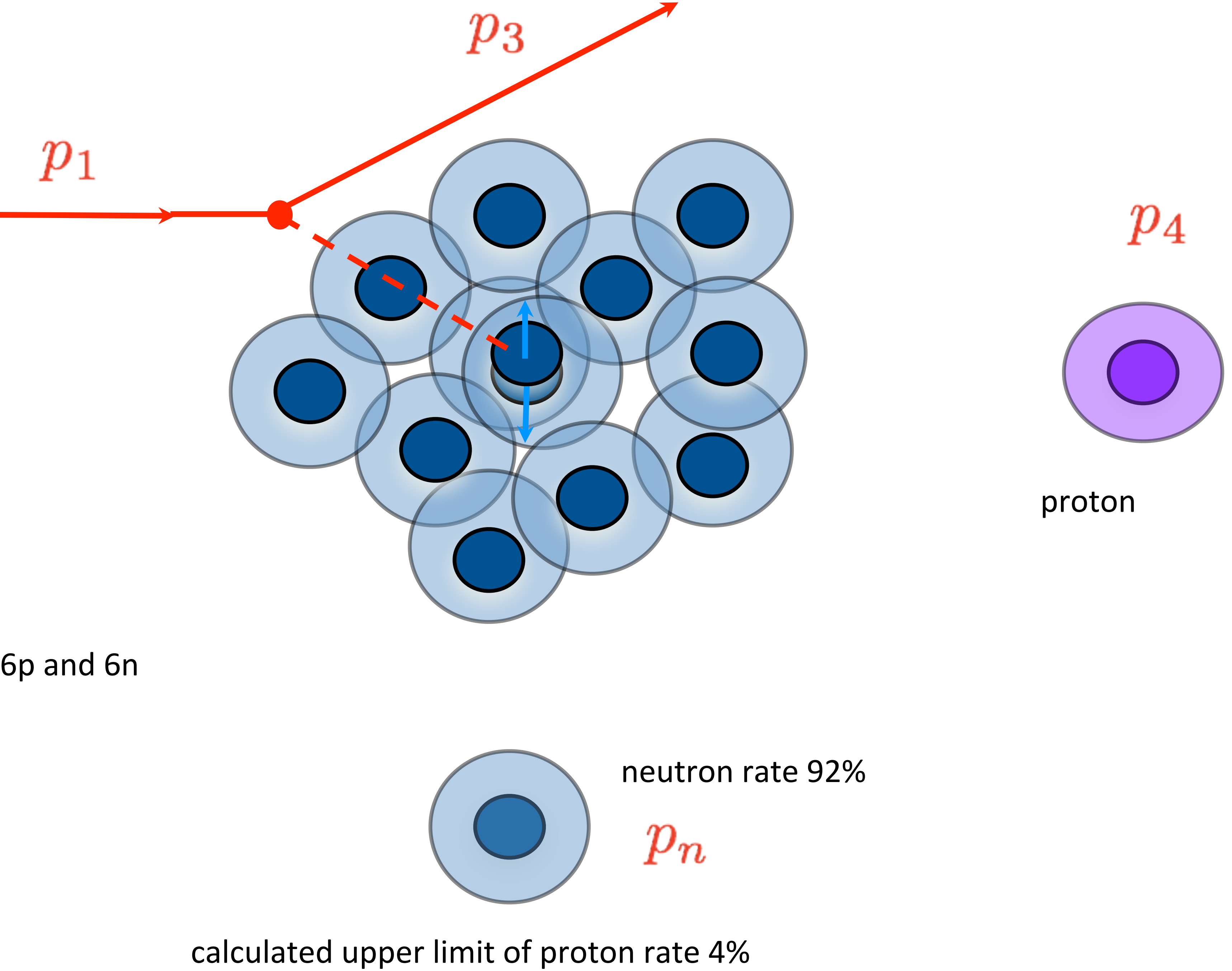
$$R \equiv \frac{\int_{\alpha_i^{min}}^{\alpha_i^{max}} \int_{p_{ti}^{min}}^{p_{ti}^{max}} \int_{\alpha_n^{min}}^{\alpha_n^{max}} \int_{p_{tn}^{min}}^{p_{tn}^{max}} D^{pn}(\alpha_i, p_{ti}, \alpha_n, p_{nt}, P_{R+}) \frac{d\alpha}{\alpha} d^2p_t \frac{d\alpha_n}{\alpha_n} d^2p_{tn} dP_{R+}}{\int_{\alpha_i^{min}}^{\alpha_i^{max}} \int_{p_{ti}^{min}}^{p_{ti}^{max}} S^{pn}((\alpha_i, p_{ti}, P_{R+}) \frac{d\alpha}{\alpha} d^2p_t dP_{R+}}.$$

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

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

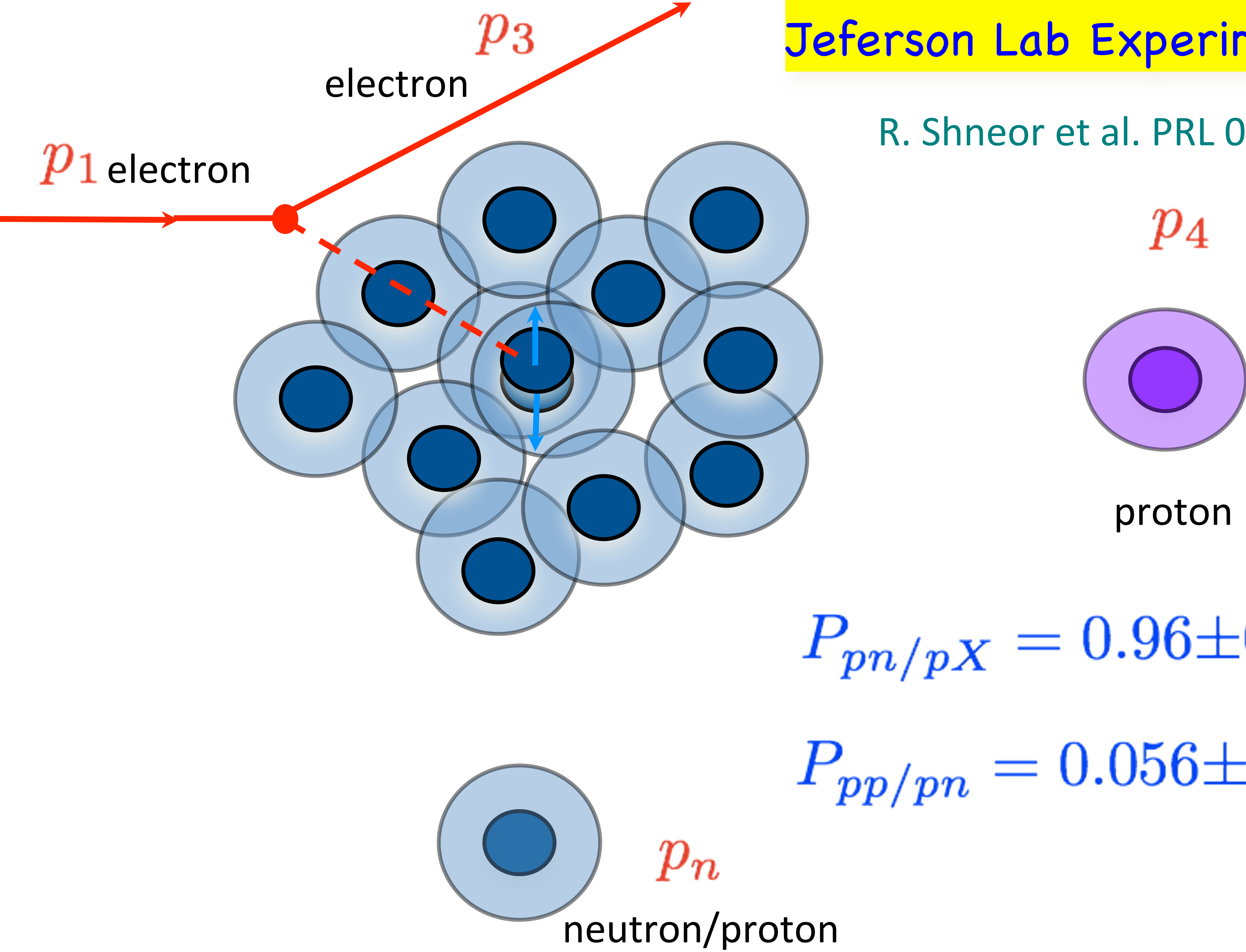
- 92% of the time two-nucleon high density fluctuations are proton and neutron

- at most 4% of the time proton-proton or neutron-neutron


p_1
p_3
p_4
proton
6p and 6n
neutron rate 92%
p_n
calculated upper limit of proton rate 4%

Jeferson Lab Experiment

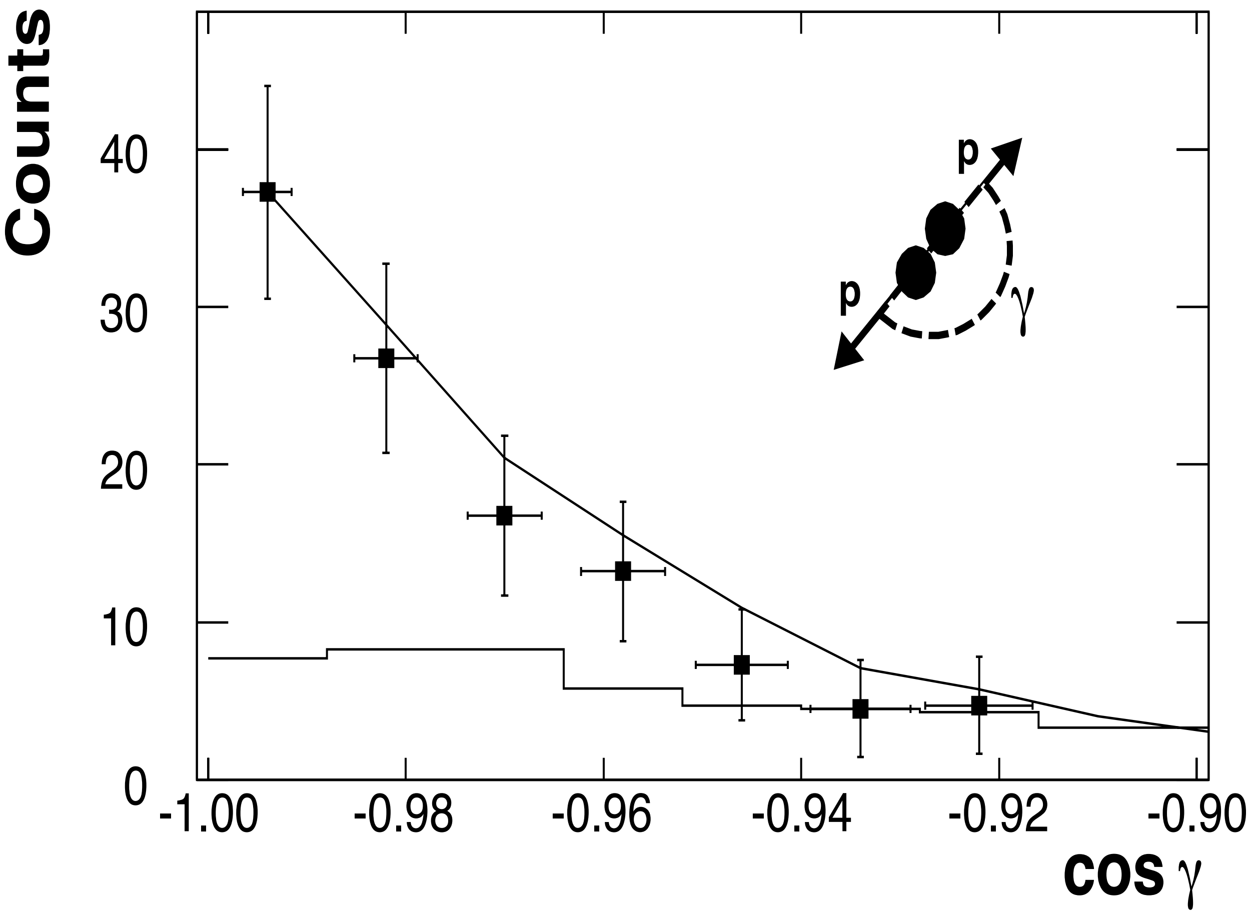
R. Shneor et al. PRL 07



$$P_{pn/pX} = 0.96 \pm 0.22$$

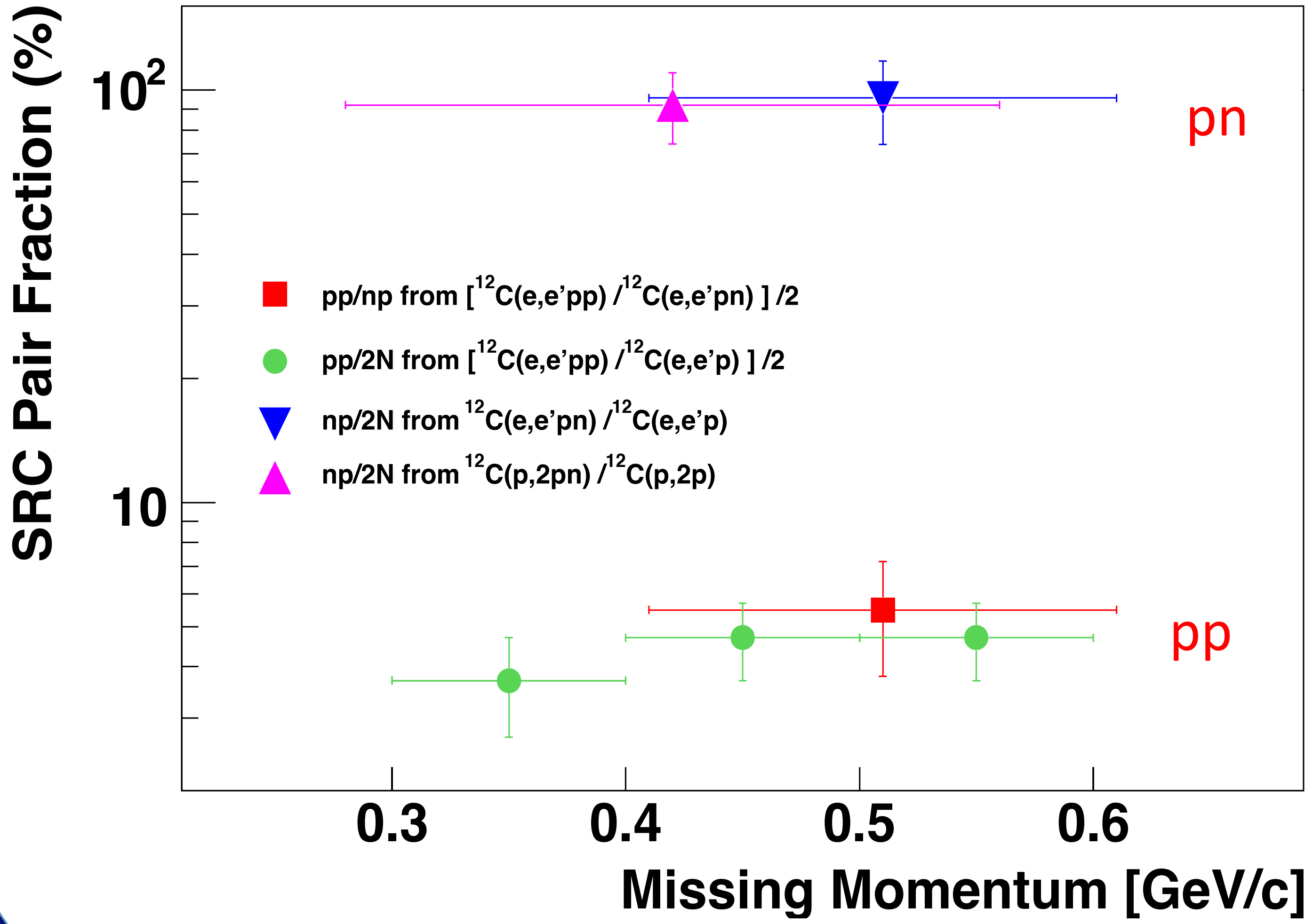
$$P_{pp/pn} = 0.056 \pm 0.018$$

R.Shneor, et al PRL , 2007



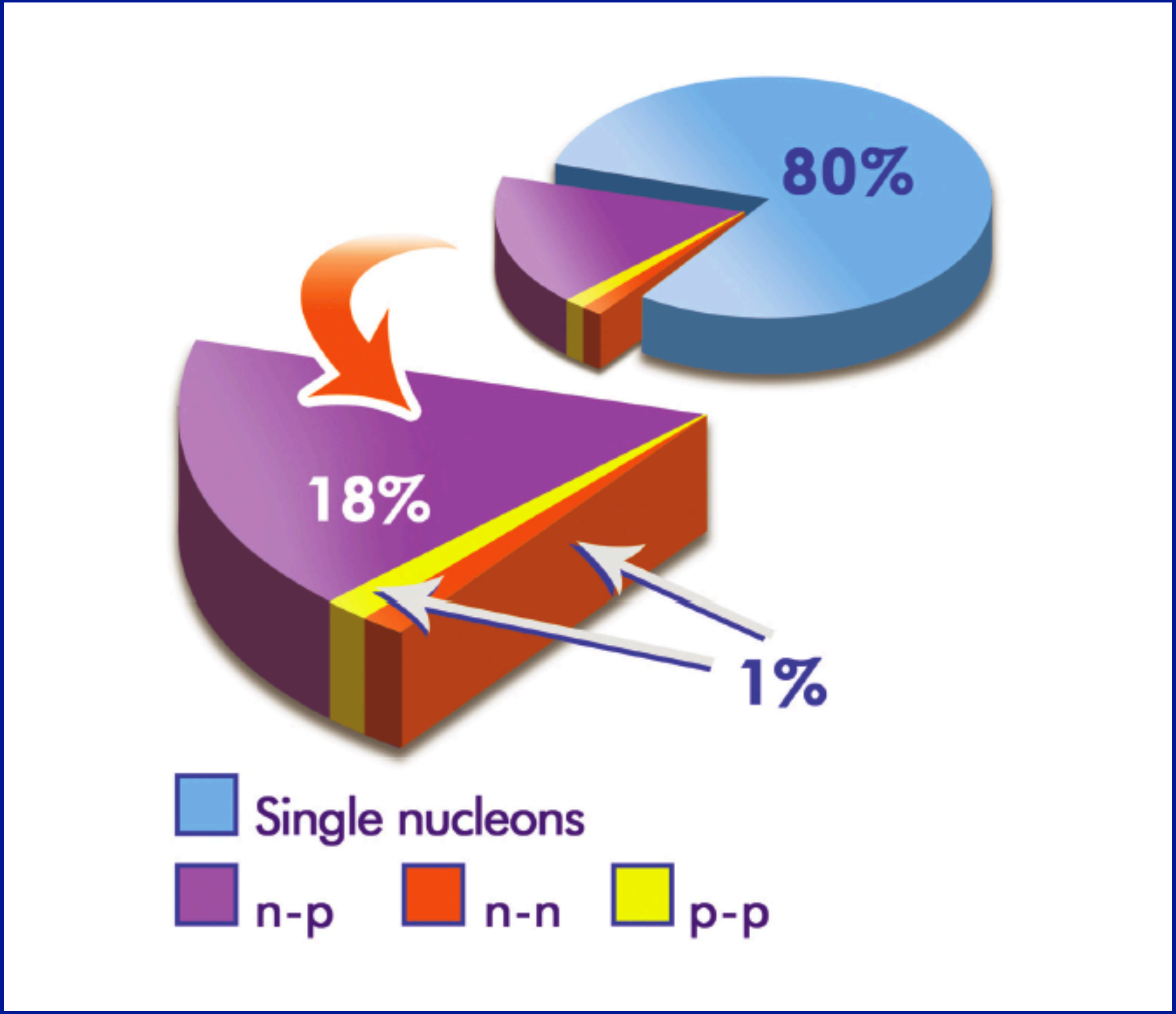
Combined Analysis

R.Subdei, et al Science , 2008



Combined Analysis

R.Subdei, et al Science , 2008



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

BNL data on A(p,2pn)X

Piasetzky, MS, Frankfurt, Strikman, Watson PRL 2007

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

- 92% of the time two-nucleon high density fluctuations are proton and neutron
- at most 4% of the time proton-proton or neutron-neutron

JLAB data A(e,e'pn)X

$$P_{pn/pX} = 0.96 \pm 0.22$$

R. Shneor et al. PRL 07

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

Second:

- Nuclear momentum distribution at $k > k_F$ should reflect the dynamics of V_{NN} rather than V_{Nucl}

$$V_{NN}(r) \approx V_c(r) + V_t(r) \cdot S_{12}(r) + V_{LS} \cdot \vec{L}\vec{S}$$

$$S_{12} = 3(\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) - \sigma_1\sigma_2$$

$$S_{12}|pp\rangle = 0$$

$$S_{12}|nn\rangle = 0$$

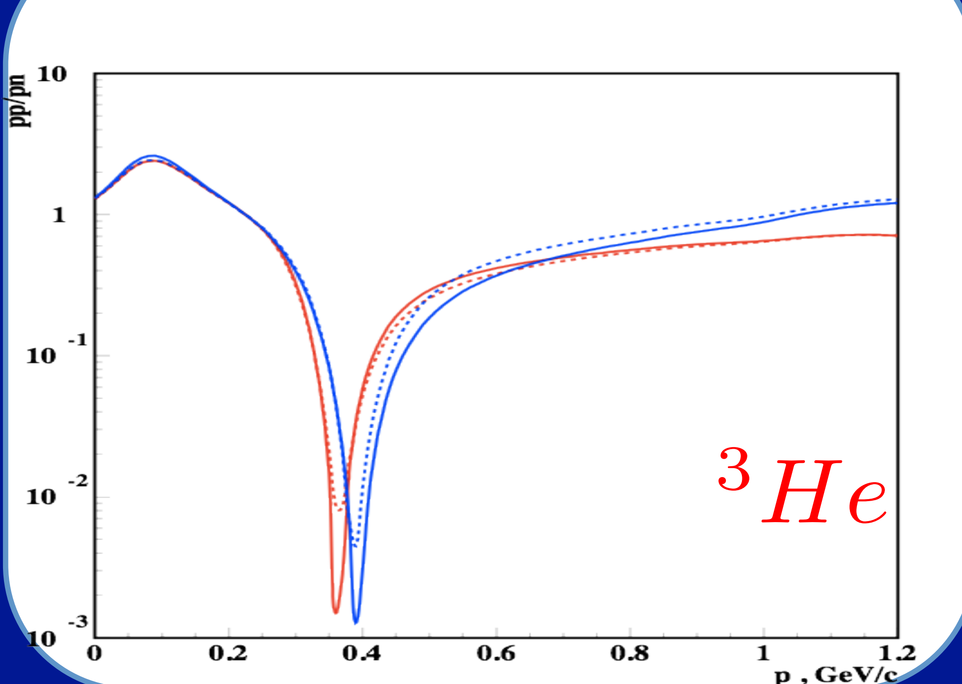
$$S_{12}|pn\rangle = 0$$

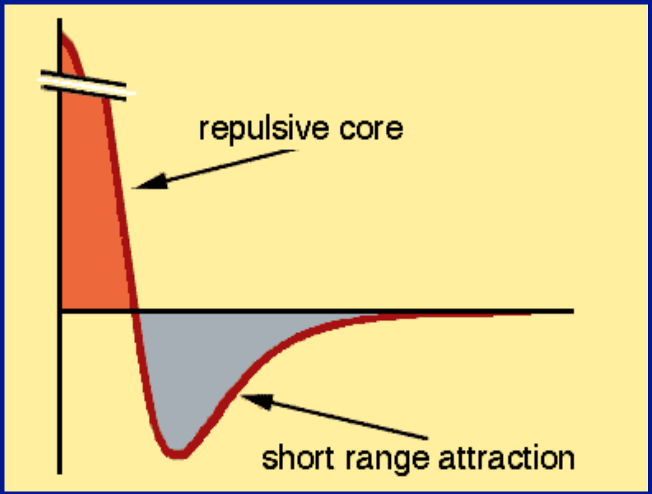
Isospin 1 states

$$S_{12}|pn\rangle \neq 0$$

Isospin 0 states

M.S, Abrahamyan, Frankfurt,Strikman PRC,2005





Second:

- Nuclear momentum distribution at $k > k_F$ should reflect the dynamics of V_{NN} rather than V_{Nucl}

$$V_{NN}(r) \approx V_c(r) + V_t(r) \cdot S_{12}(r) + V_{LS} \cdot \vec{L}\vec{S}$$

$$S_{12} = 3(\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) - \sigma_1\sigma_2$$

$$S_{12}|pp\rangle = 0$$

$$S_{12}|nn\rangle = 0$$

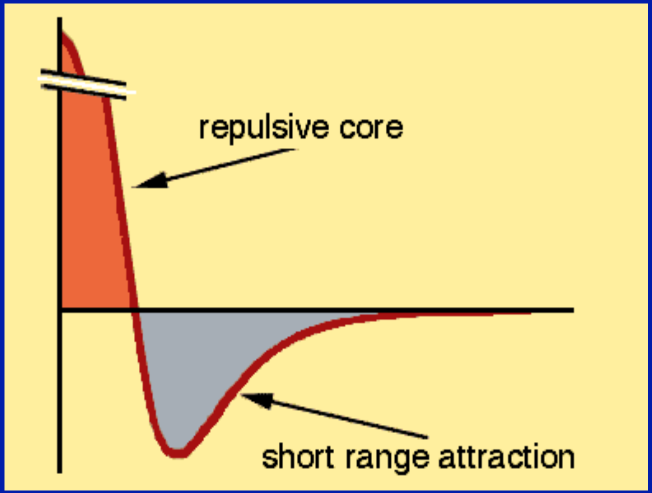
$$S_{12}|pn\rangle = 0$$

Isospin 1 states

$$S_{12}|pn\rangle \neq 0$$

Isospin 0 states

Thomas Neff



New Properties of High Momentum Component

- Dominance of NN Correlations

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

-if the potential decreases at large k, like $V(k) \sim \frac{1}{k^n}$ and $n > 1$

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

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

- From $\psi_A \sim \frac{V_{NN}(k)}{k^2} f(k_3, \ldots k_A)$ follows

at $p > k_F$

$$n^A(p) \sim a_{NN}(A) \cdot n_{NN}(p) \quad (1)$$

- Dominance of NN Correlations

$$n_{NN}(p) \approx n_{pn}(p) \approx n_{(d)}(p) \quad (2)$$

- Define momentum distribution of proton & neutron

$$n^A(p) = \frac{Z}{A} n_p^A(p) + \frac{A-Z}{A} n_n^A(p) \quad (3)$$

$$\int n^A_{p/n}(p) d^3p = 1$$

First Property: Approximate Scaling Relation

- if contributions by pp and nn SRCs are neglected

- the high momentum distribution strengths of proton and neutron weighted by their fractions in the given nucleus will be defined by the same probability of being in the pn SRC

- for $\sim k_F - 600$ MeV/c region:

$$x_p \cdot n_p^A(p) \approx x_n \cdot n_n^A(p)$$

where $x_p = \frac{Z}{A}$ and $x_n = \frac{A-Z}{A}$.

Second Property: Fractional Dependence of High Momentum Component

Combining: Eqs.1,2 &3

$$x_p \cdot n_p^A(p) \approx x_n \cdot n_n^A(p) \approx n_A(p) \approx a_{NN}(A,y) n_d(p)$$

where $y = |1 - 2x_p| = |x_n - x_p|$

- $a_{NN}(A,0)$ corresponds to the probability of pn SRC in symmetric nuclei

- $a_{NN}(A,1) = 0$ according to our approximation of neglecting pp/nn SRCs

Second Property: Fractional Dependence of High Momentum Component

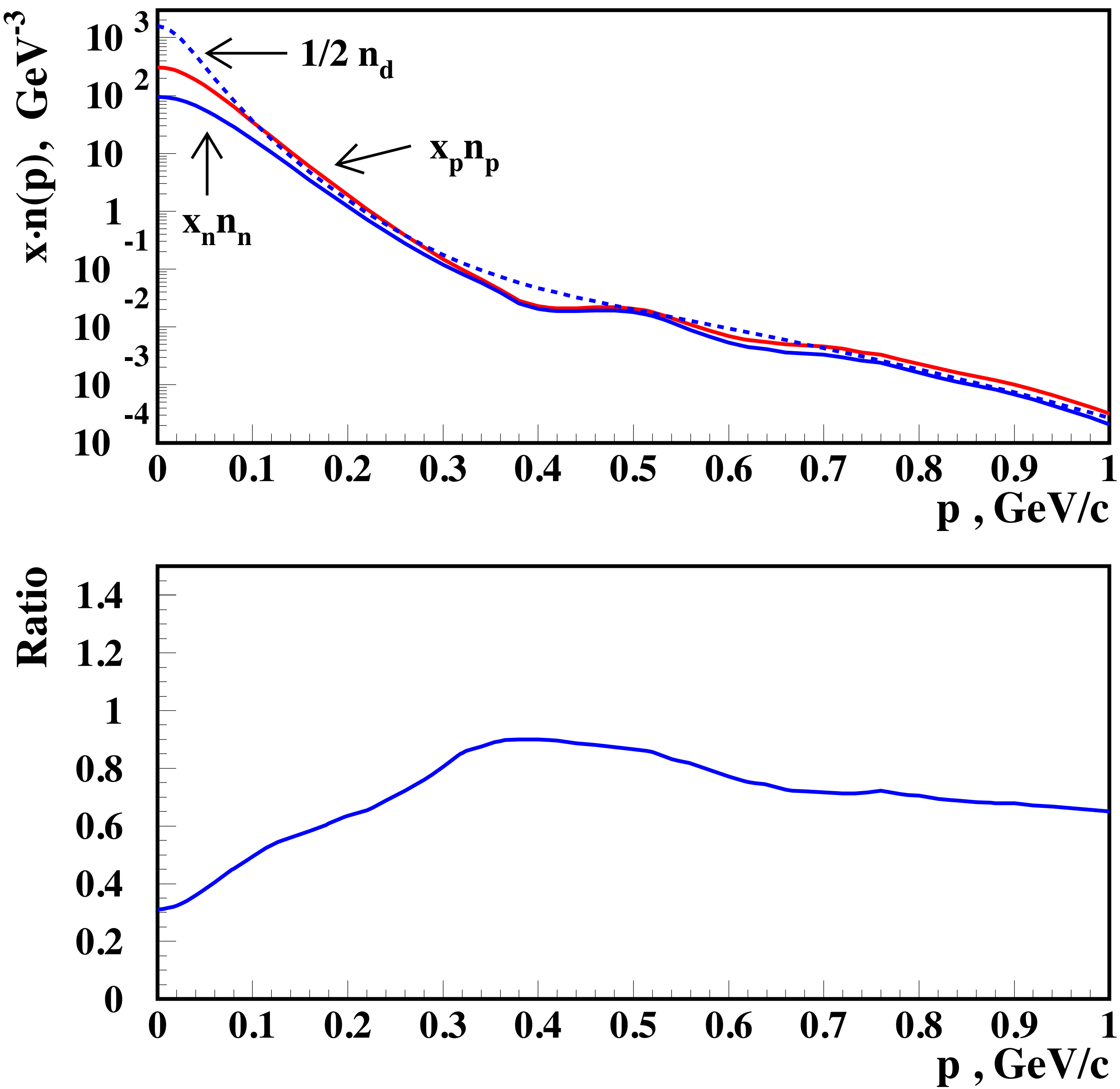
$$a_{NN}(A,y) \approx a_{NN}(A,0) \cdot f(y)$$ with $f(0) = 1 \text{ and } f(1) = 0$

$$f(|x_p - x_n|) = 1 - \sum_{j=1}^{n} b_i |x_p - x_x|^i \text{ with } \sum_{j=1}^{n} b_i = 0$$

In the limit $\sum_{j=1}^{n} b_i |x_p - x_x|^i \ll 1$ Momentum distributions of p & n are inverse proportional to their fractions

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

Realistic 3He Wave Function:



Observations: High Momentum Fractions

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

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

Observations: High Momentum Fractions

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

Checking for He3

Energetic Neutron

$$E^p_{kin} = 14 \text{ MeV (p= 157 MeV/c)}$$

$$E^n_{kin} = 19 \text{ MeV (p= 182 MeV/c)}$$

Implications: Energetic Protons in Large A Nuclei

- EMC Effect

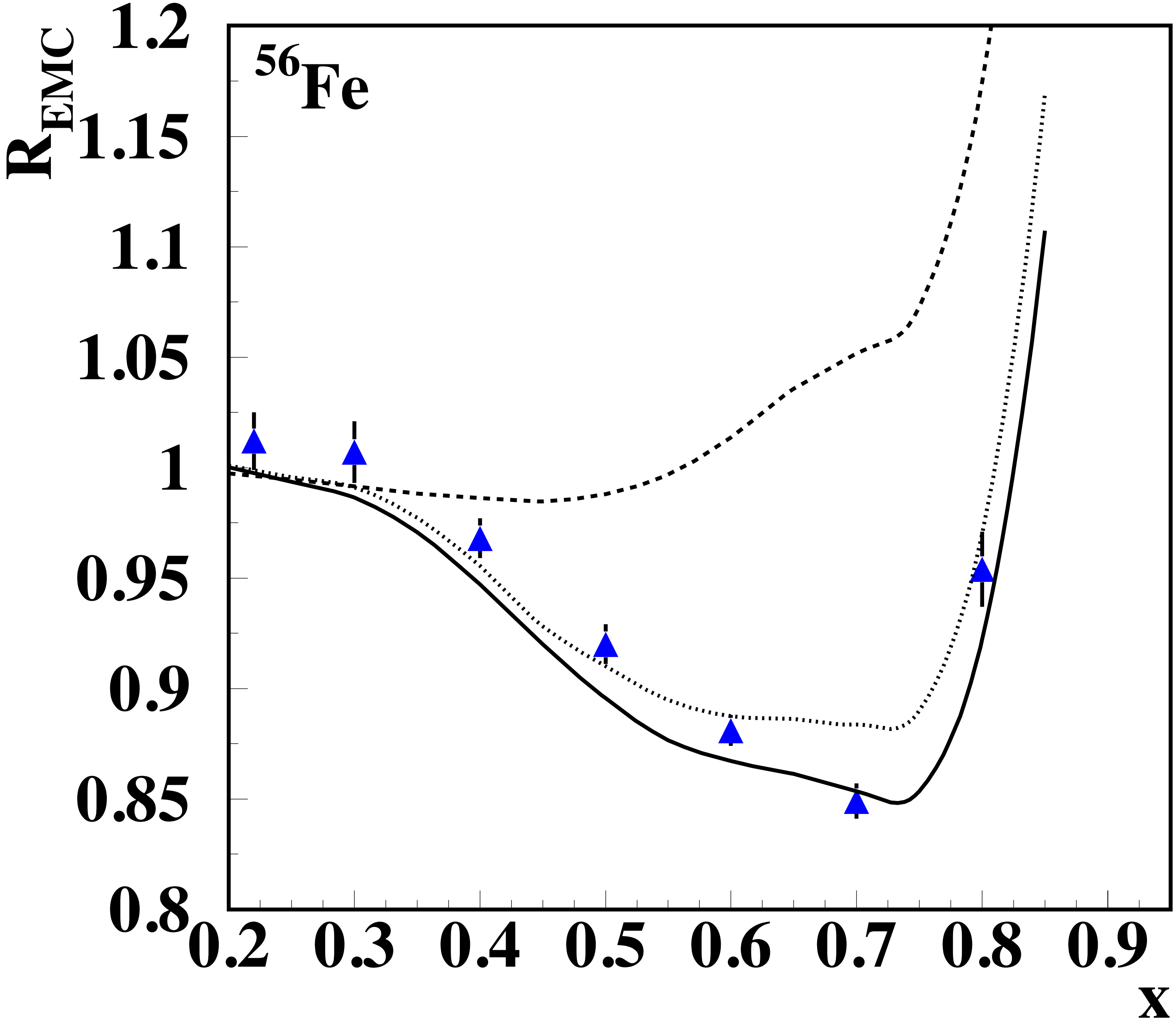
$$F_{2A} = (A - Z) \int_x^A F_{2n}(\tfrac{x}{\alpha}) \rho_n(\alpha, p_t) \frac{d\alpha}{\alpha} d^2 p_t$$

$$+ \; Z \int_x^A F_{2p}(\tfrac{x}{\alpha}) \rho_p(\alpha, p_t) \frac{d\alpha}{\alpha} d^2 p_t$$

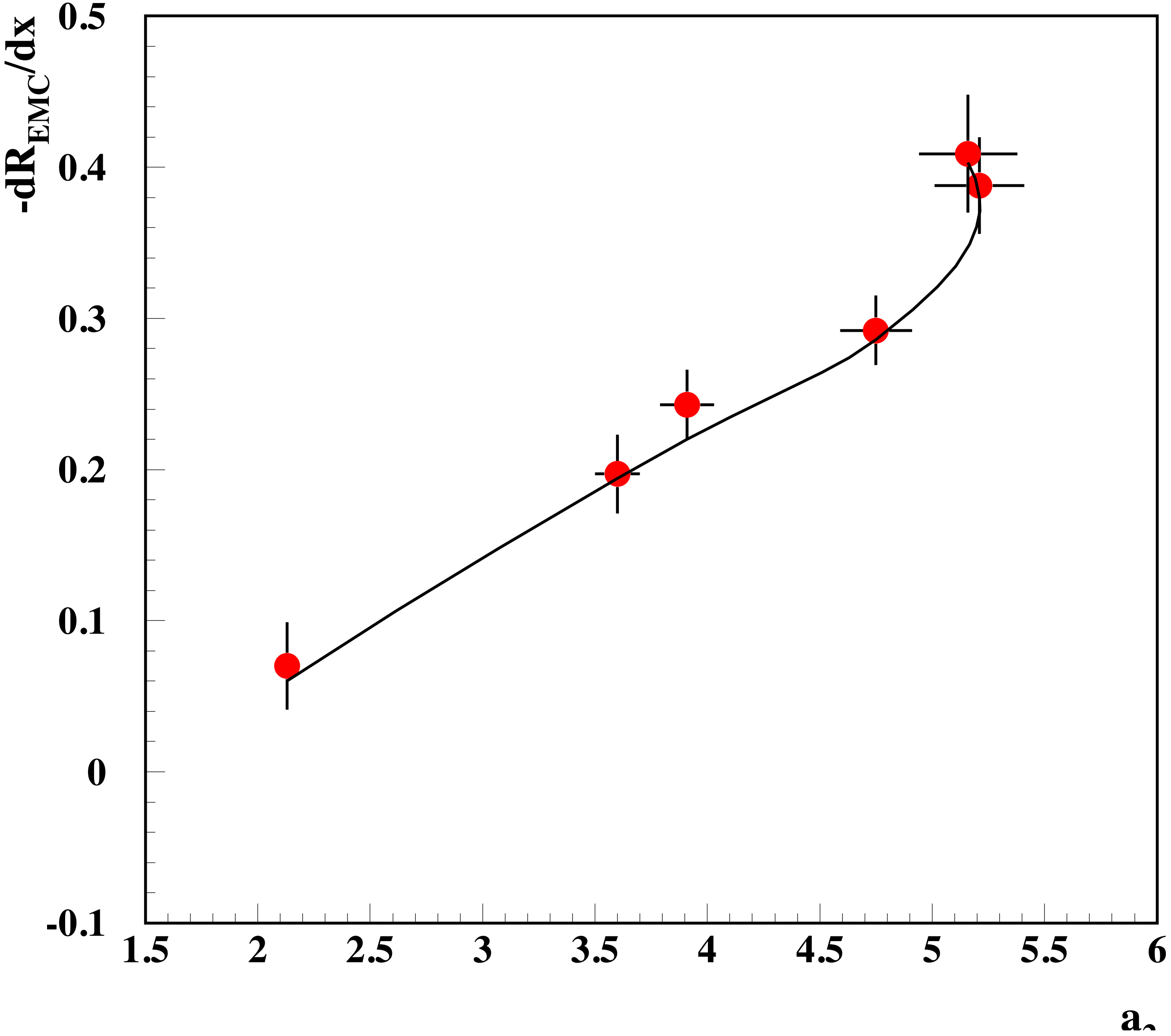
Color Screening Model: Frankfrut Strikman 1987

$$F_{2N}^{eff}(\tfrac{x}{\alpha}, p_k) = F_{2N}(\tfrac{x}{\alpha}) \Delta(p_k^2 - m^2)$$

- EMC Effect



- EMC Effect



Implications: Protons are more modified in Large A Nuclei

u-quarks are more modified then d quarks in Large A Nuclei

- Different explanation of NuTev Puzzle

- Can be checked in neutrino-nuclei or in pvDIS processes

Implications: Protons are more modified in Large A Nuclei

- Effect contributes to the Neutron Skin Effect

Implications: For Nuclear Matter

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

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

Implications: For Nuclear Matter

Our Goal

$$a_2(A, y) = a_2(\rho, y)$$

$$a_2(\rho, y)\ |_{\rho\to\infty} = ?$$

$$a_2(A,y) \equiv a_2(\rho,y)\,,\; y = |1-2x_p|\,,\; x_p \equiv \frac{Z}{A}$$

(1) $$a_2(A,y) = a_2^{sym}(A)\cdot f(y)$$

Parametric Form

(2) For $a_2^{sym}(A)$ we analyze data for symmetric nuclei

and for other A's use the relation

$$a_2^{sym}(A) = C\cdot\langle\rho^2_{A,sym}\rangle$$

where

$$\langle\rho^2_{A,sym}\rangle = \frac{1}{A}\int\rho_{A,sym}(r)^2 d^3r$$

(3) Neglecting contributions due to pp and nn SRCs one obtains boundary conditions

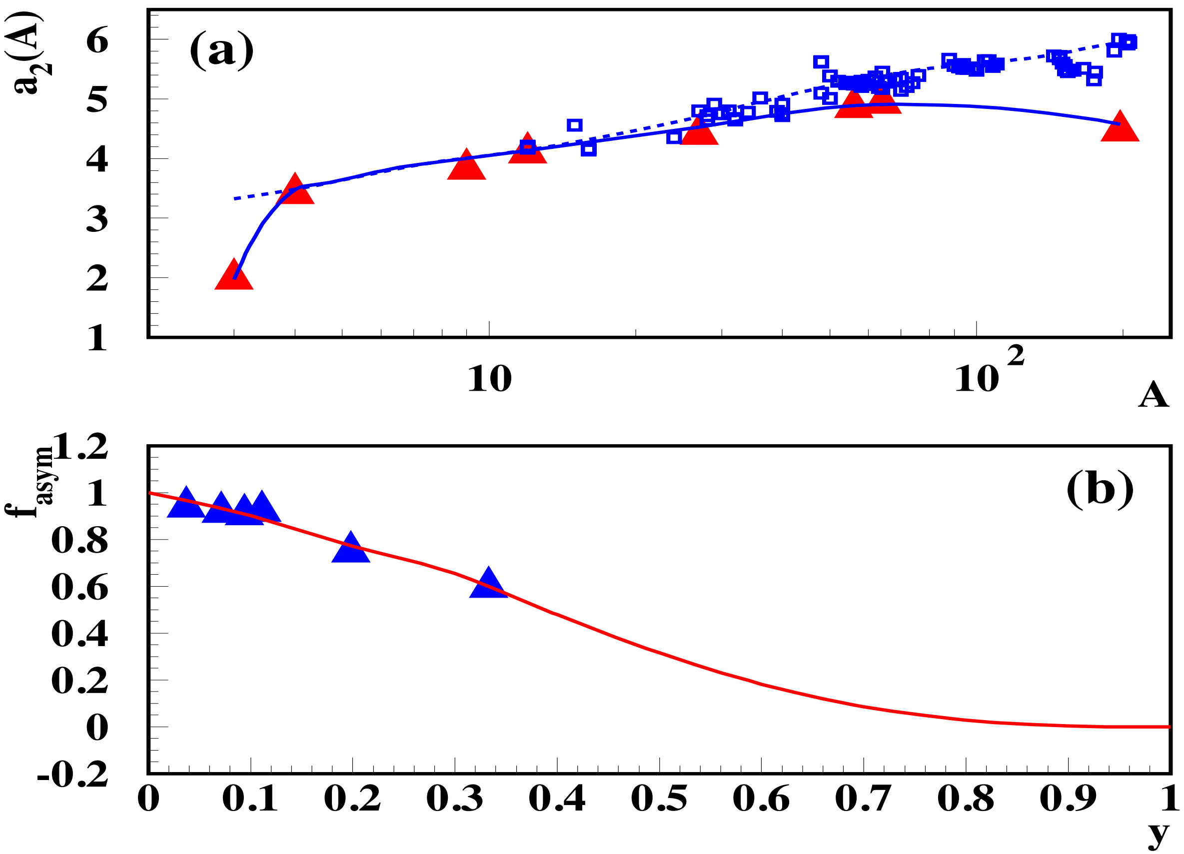
$$f(0) = 1 \text{ and } f(1) = 0$$

M. McGauley, MS Feb. 2011
arxiv 1102.3973

Implications: For Nuclear Matter

$$a_2(A,y) = a_2(A,0)f(y)$$

$$a_2(A,0) = C\int \rho_A^2(r)d^3r$$



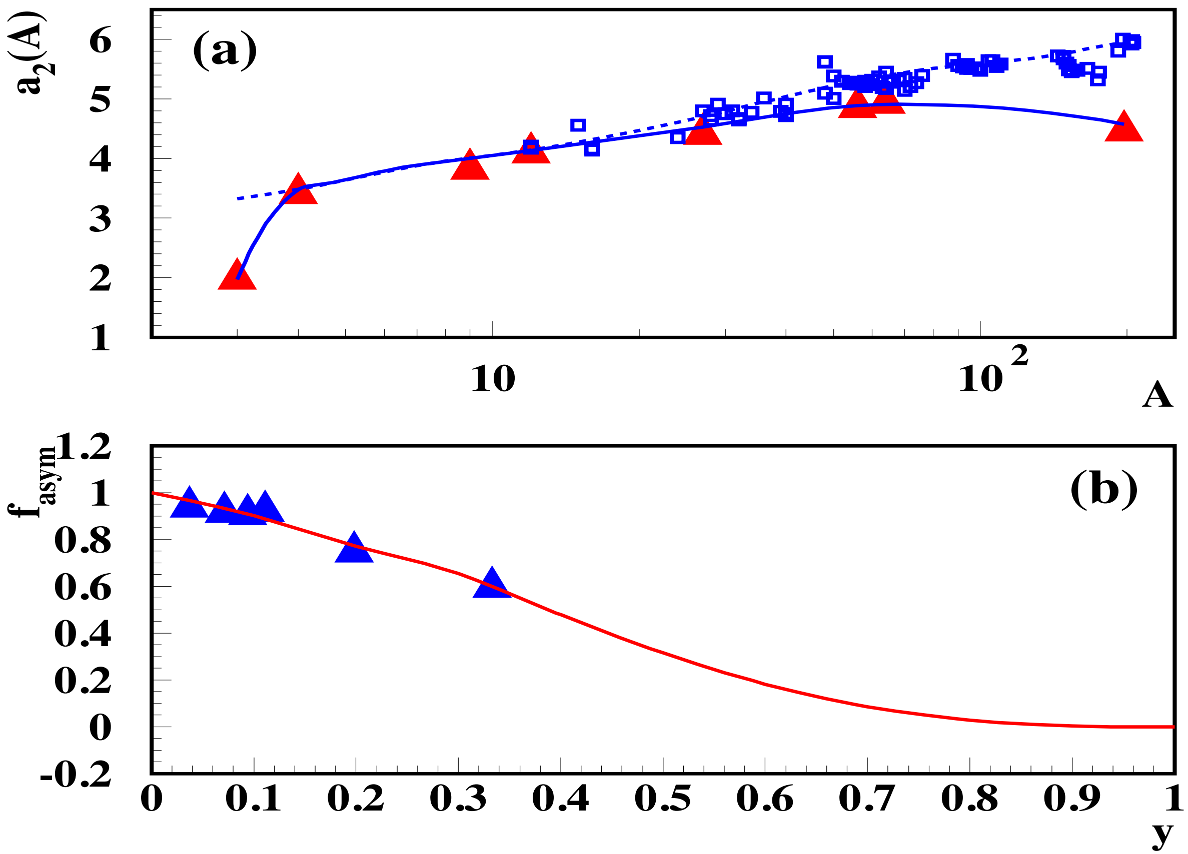
$$C = 49.1 \pm 2.6$$

Implications: For Nuclear Matter

$$a_2(A, y) = a_2(A, 0) f(y)$$

Fitting $f(y)$

- 4 data points



- 2 boundary conditions due to the neglection of pp/nn SRCs

$f(0) = 1$ and $f(1) = 0$

-2 more boundary conditions due to

$y \to 1$ and $y \to 0$ corresponds to $A \to \infty$

$f'(0) = f'(1) = 0$

-1 more positiveness of f(y)

$$f(y) \approx (1 + (b-3)y^2 + 2(1-b)y^3 + by^4) \qquad b \approx 3$$

Extrapolation to infinite and superdense nuclear matter

$$a_2(A,y) = a_2^{sym}(A) \cdot f(y)$$ with $$a_2^{sym}(A) = C \cdot \langle \rho^2_{A,sym} \rangle$$

For the symmetric nuclear matter at saturation densities ρ_0
using: $R = r_0 \cdot A^{\frac{1}{3}}$ we obtain:

$$\langle \rho^2 \rangle_{sym}^{INM} = \frac{1}{A} \int \rho^2_{A,sym}(r) d^3r = \frac{4\pi}{3} \rho_0^2 r_0^3 \approx 0.143 \ fm^{-3}$$

$$a_2(\rho_0, 0) \approx 7.03 \pm 0.41$$

compare

$$a_2(\rho_0, 0) \approx 8 \pm 1.24$$

C.Ciofi degli Atti, E. Pace, G.Salme, PRC 1991

Asymmetric and superdense nuclear matter:

$$a_2(\rho, y) = \langle \rho^2 \rangle_{sym}^{INM} \cdot f(y)$$

Consider β equilibrium $e - p - n$ superdense asymmetric nuclear matter at the threshold of URCA processes $x_p = \frac{1}{9}$ $(y = \frac{7}{9})$.

At $x_p < \frac{1}{9}$ the URCA processes

$$n \to p + e^- + \bar{\nu}_e, \quad p + e^- \to n + \nu_e$$

will stop in the standard model of superdense nuclear matter consisting of degenerate protons and neutrons.

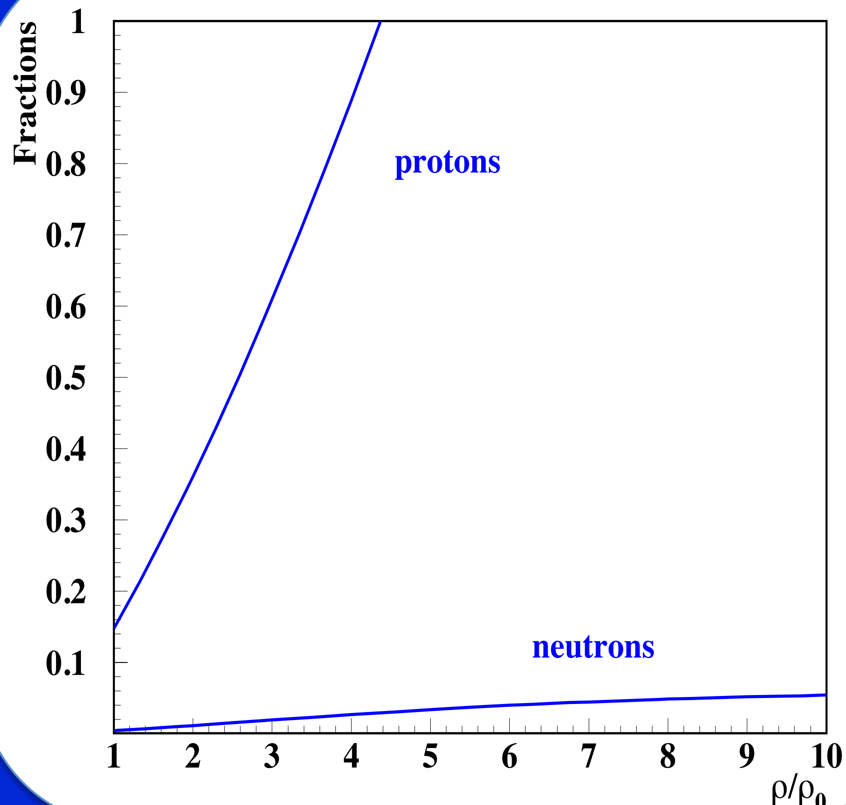
Implications: For Nuclear Matter

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

For $x_p = \frac{1}{9}$ and $y = \frac{7}{9}$
and using $k_{F,N} = (3\pi^2 x_N \rho)^{\frac{1}{3}}$

For $x_p = \frac{1}{9}$ and $y = \frac{7}{9}$
and using $k_{F,N} = (3\pi^2 x_N \rho)^{\frac{1}{3}}$

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



Some Possible Implication of our Results

Cooling of Neutron Star:

Large concentration of the protons above the Fermi momentum will allow the condition for Direct URCA processes $p_p + p_e > p_n$ to be satisfied even if $x_p < \frac{1}{9}$. This will allow a situation in which intensive cooling of the neutron stars will be continued well beyond the critical point $x_p = \frac{1}{9}$.

Superfluidity of Protons in the Neutron Stars:

Transition of protons to the high momentum spectrum will smear out the energy gap which will remove the superfluidity condition for the protons. This will also result in significant changes in the mechanism of generation of neutron star magnetic fields.

Protons in the Neutron Star Cores:

The concentration of protons in the high momentum tail will result in proton densities $\rho_p \sim p_p^3 \gg k_{F,p}^3$. This will result in an equilibrium condition with "neutron skin" effect in which large concentration of protons will populate the core rather than the crust of the neutron star. This situation may provide very different dynamical conditions for generation of magnetic fields of the stars.

Isospin Locking and Large Masses of Neutron Stars

With an increase of the densities more and more protons move to the high momentum tail where they are in short range tensor correlations with neutrons. In this case on will expect that high density nuclear matter will be dominated by configurations with quantum numbers of tensor correlations $S = 1$ and $I = 0$. In such scenario protons and neutrons at large densities will be locked in the NN iso-singlet state. Such situation will double the threshold of inelastic excitation from $NN \to N\Delta$ to $NN \to \Delta\Delta(NN^*)$ transition thereby stiffening the equation of the state. This situation my explain the observed neutron star masses in Ref.[?] which are in agreement with the calculation of equation state that include only nucleonic degrees of freedom

Limitation of the Model

- *pp/nn Correlations are neglected*

- *pn SRC is at Rest*

- *3N SRCS*

- *non-nucleonic component of SRCs*

Identical Effects on proton and neutron distributions?

$$x_p^\gamma \cdot n_p^A(p) \approx x_n^\gamma \cdot n_n^A(p)$$

$$\gamma < 1$$

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

Is the Observed Effect Universal for Two Component Asymmetric Fermi Systems?

- *Start with Two Component Asymmetric Degenerate Fermi Gas*

- *Asymmetric:* $\rho_1 << \rho_2$

- *Switch on the short-range interaction between two-component*

- *While interaction between each components is weak*

- *Spectrum of the small component gas will strongly deforme*

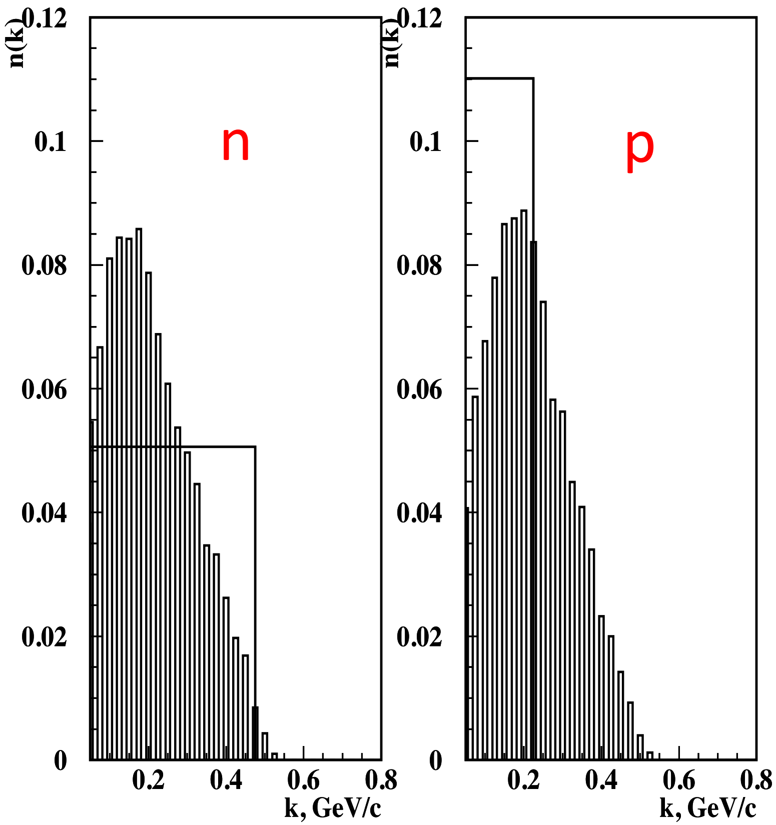
Cold Atoms

A. Bulgac, and M.M. Forbes, Zero Temperature Thermodynamics of Asymmetric Fermi Gases at Unitarity, Phys. Rev. A 75, 031605(R) (2007),

Finite T Nuclear Gas

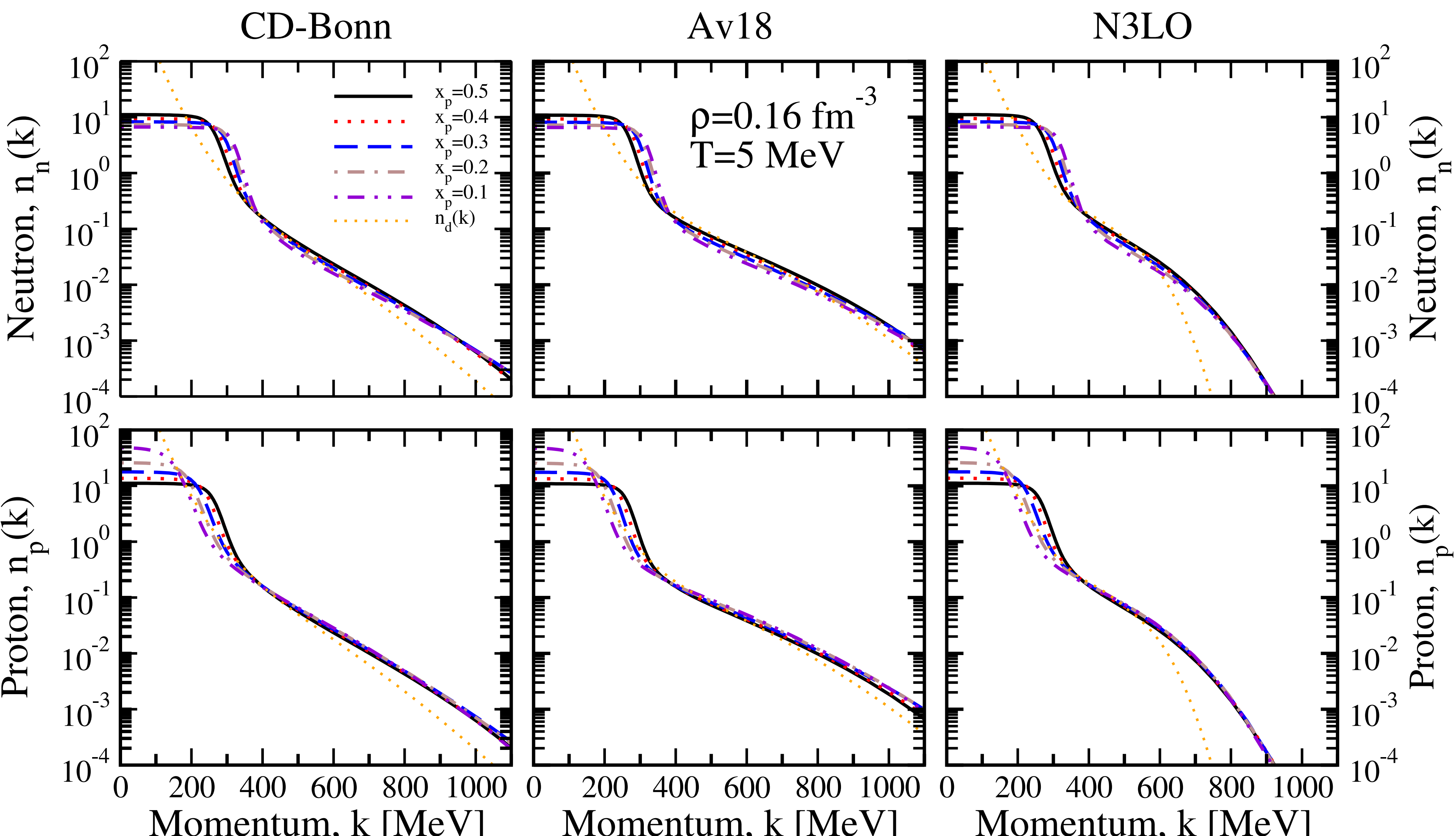
A. Rios, A. Polls and W. H. Dickhoff, Depletion of Nuclear Fermi Gas Phys. Rev. C 79, 064308 (2009).

Is the Observed Effect Universal to Two Component Asymetric Fermi Systems?



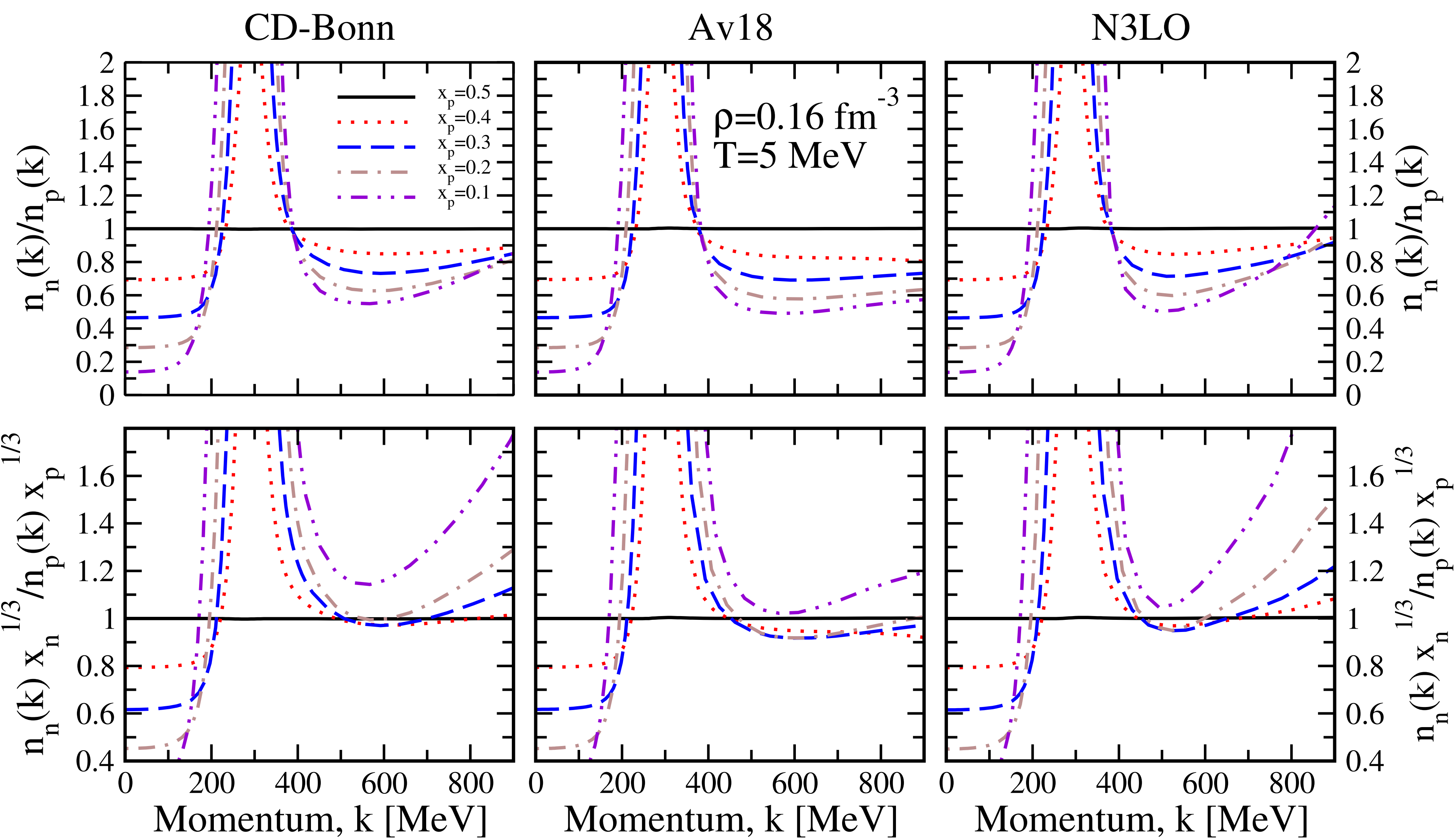
Is the Observed Effect Universal to Two Component Asymetric Fermi Systems?

A.Rios, A. Polls and W. H. Dickhoff, PRC 79, 064308 (2009).

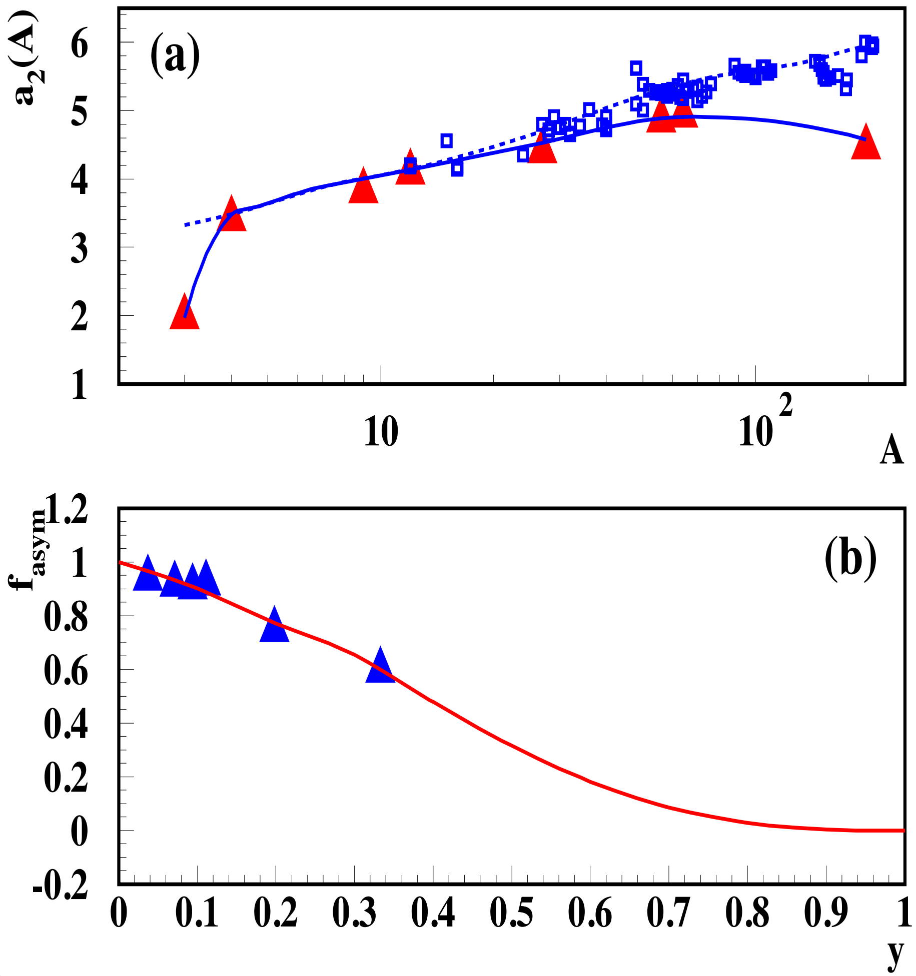


Is the Observed Effect Universal to Two Component Asymetric Fermi Systems?

A.Rios, A. Polls and W. H. Dickhoff, PRC 79, 064308 (2009).



Some Outlook



- *More Symmetric Nuclei*
- *Measurements of pp/nn*
- *3N SRCS*
- *Nuclei with large asymmetry parameters*
- *Break-down of nucleon framework*