

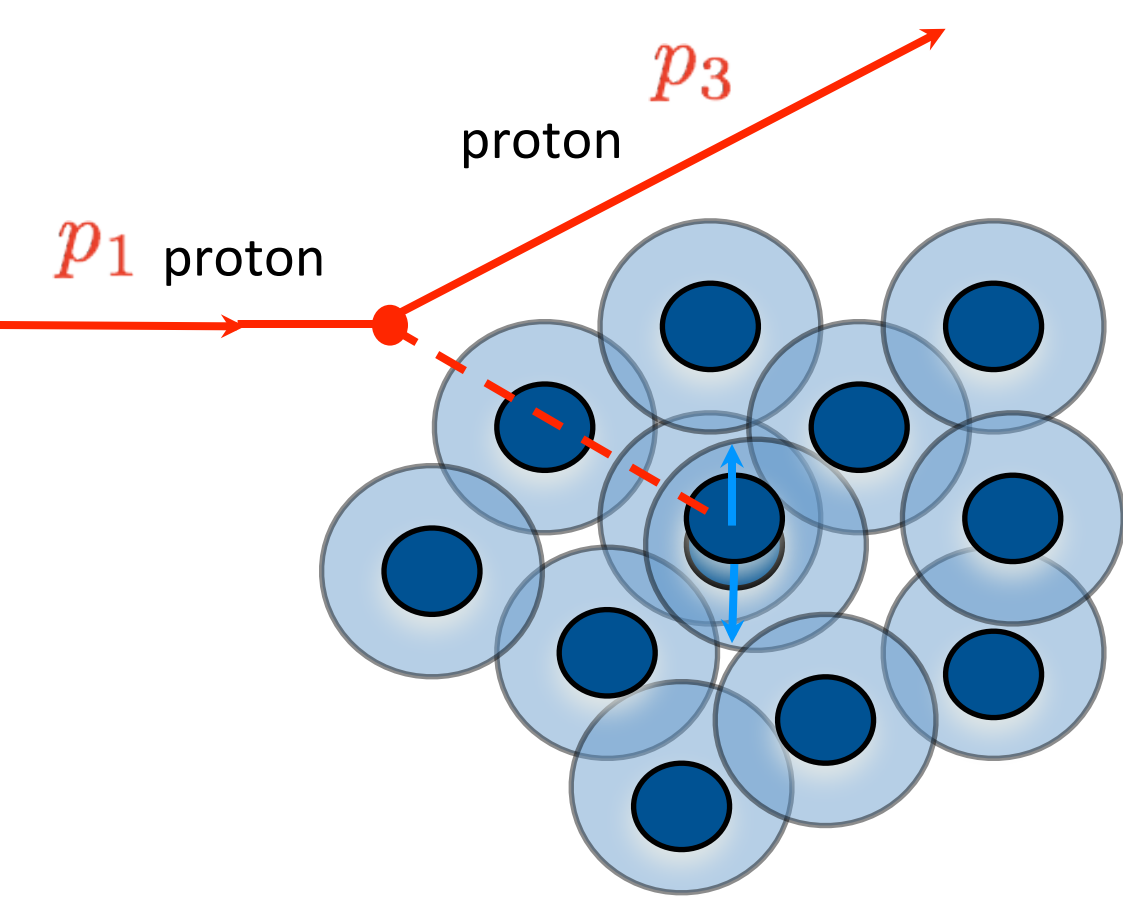
New Properties of High Momentum Distribution of Nucleons and their Implication for Nuclear Matter

Misak Sargsian
Florida International University, Miami

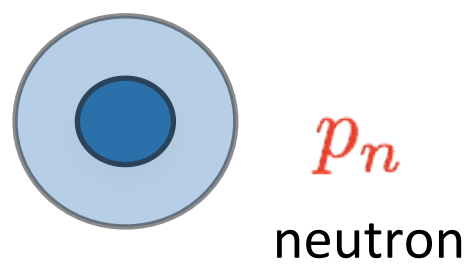
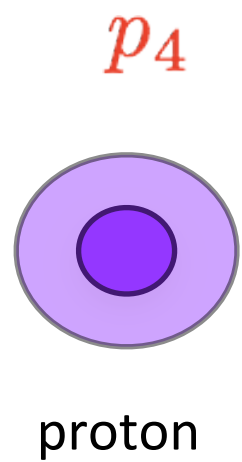


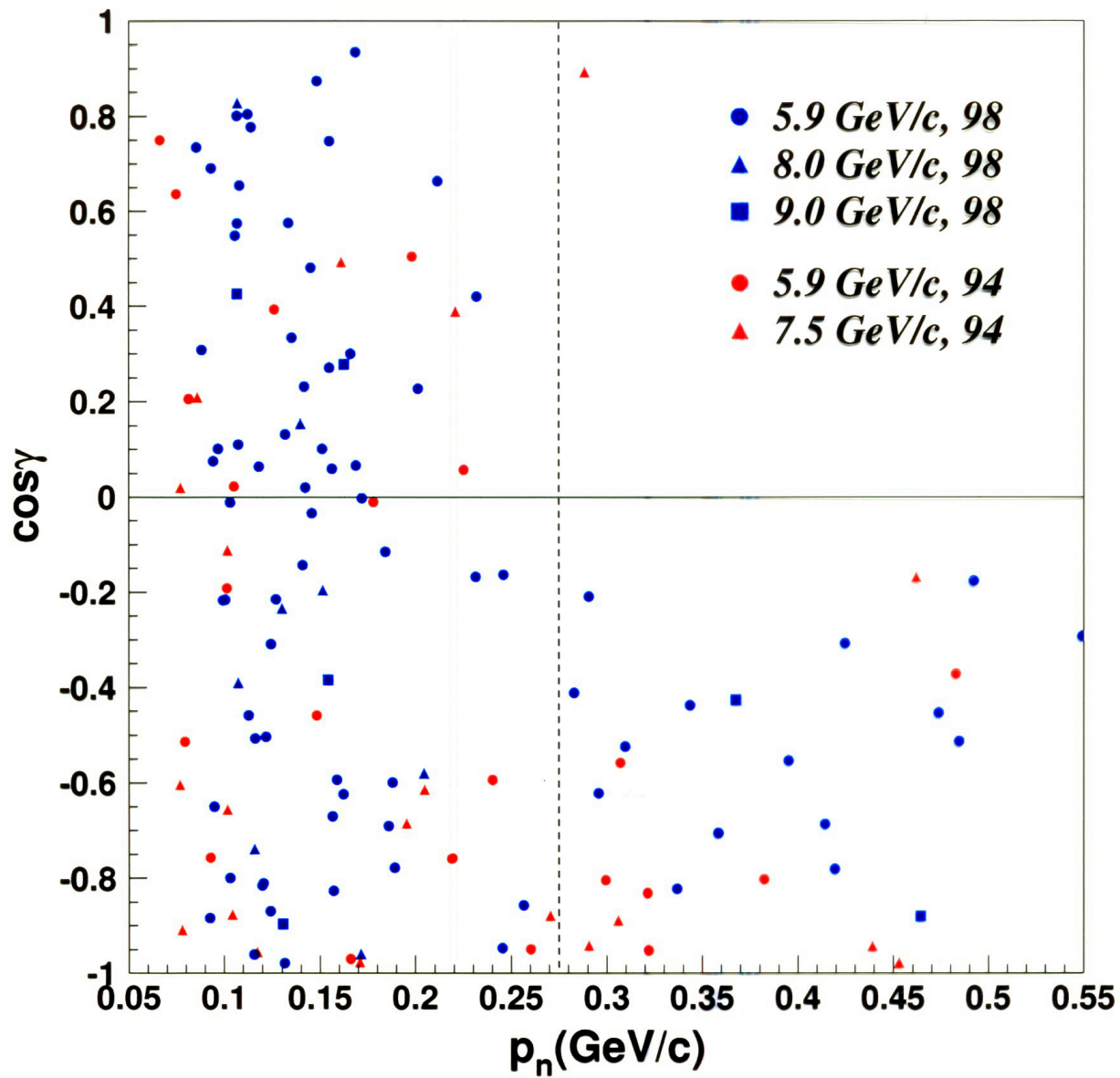
Nuclear Structure and Dynamics at Short Distances
Feb 11 – 22 INT, University of Washington

- 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



$pA \rightarrow ppn X$ at BNL





A. Tang et al, PRL 2003

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

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

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 $p_i > k_F$.

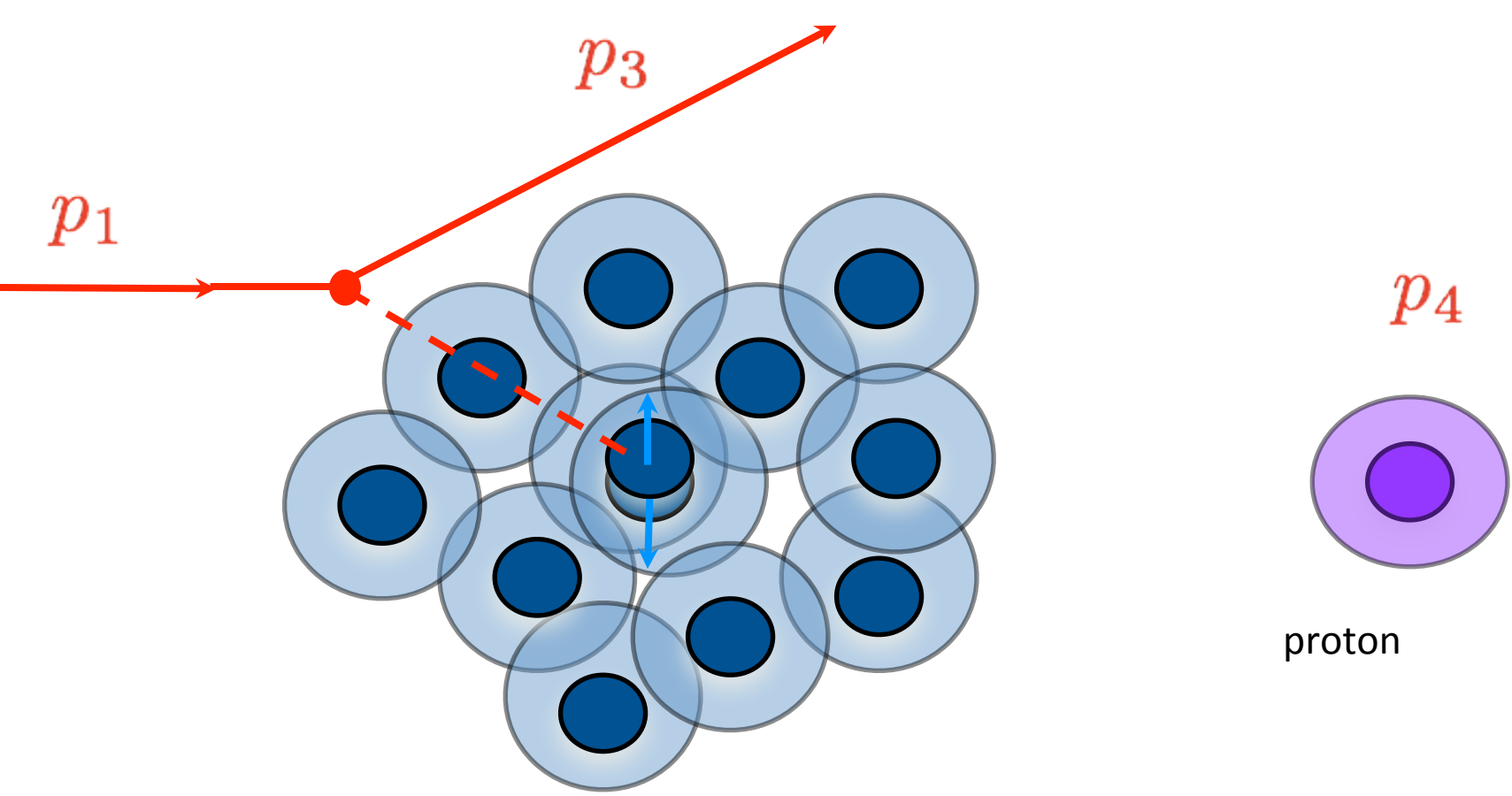
$$R \equiv \frac{\int_{\alpha_i^{\min}}^{\alpha_i^{\max}} \int_{p_{ti}^{\min}}^{p_{ti}^{\max}} \int_{\alpha_n^{\min}}^{\alpha_n^{\max}} \int_{p_{tn}^{\min}}^{p_{tn}^{\max}} D^{pn}(\alpha_i, p_{ti}, \alpha_n, p_{tn}, P_{R+}) \frac{d\alpha}{\alpha} d^2 p_t \frac{d\alpha_n}{\alpha_n} d^2 p_{tn} dP_{R+}}{\int_{\alpha_i^{\min}}^{\alpha_i^{\max}}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

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

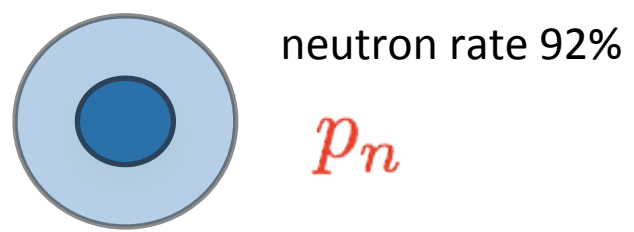
$$\frac{P_{pp}}{P_{pn}} \leq \frac{1}{2}(1 - P_{pn/pX}) = 0.04^{+0.09}_{-0.04}.$$

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

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



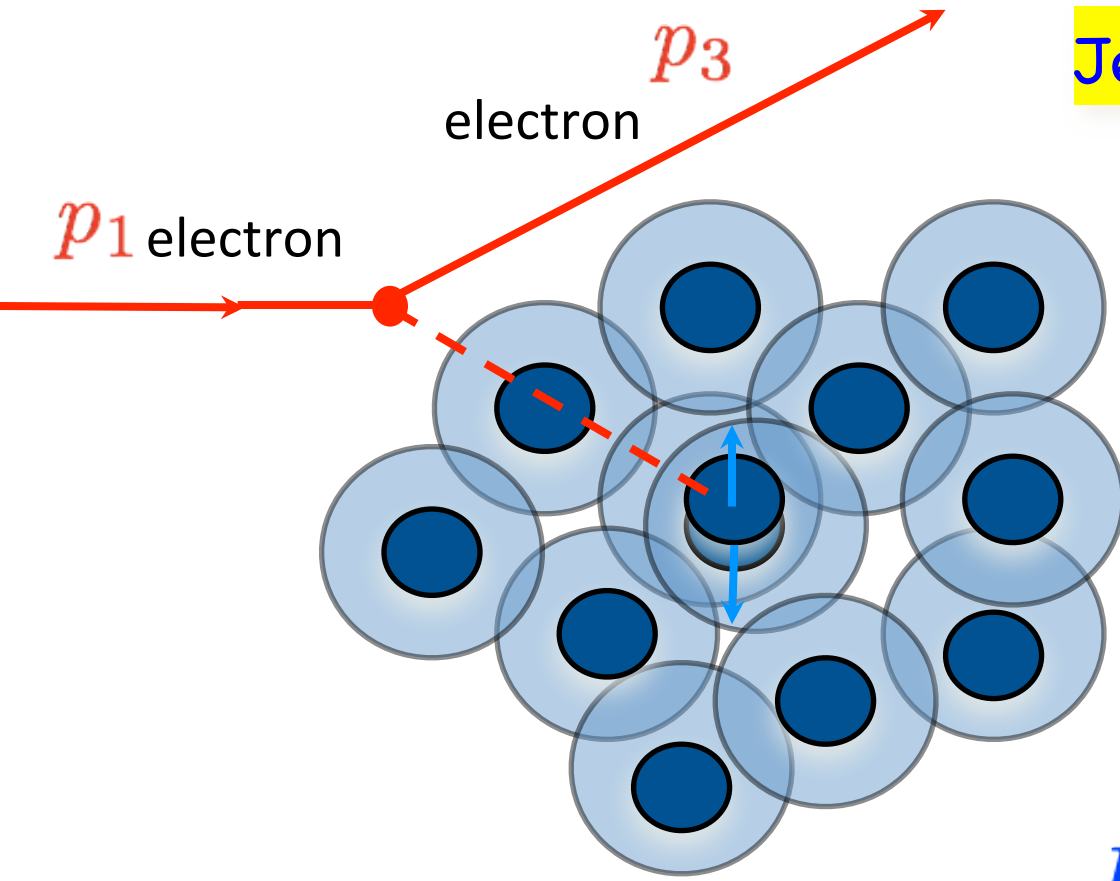
6p and 6n



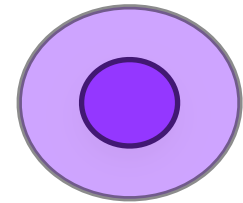
calculated upper limit of proton rate 4%

Jeferson Lab Experiment

R. Shneor et al. PRL 07



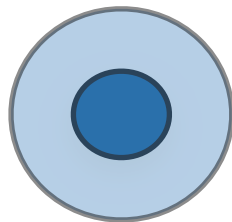
p_4



proton

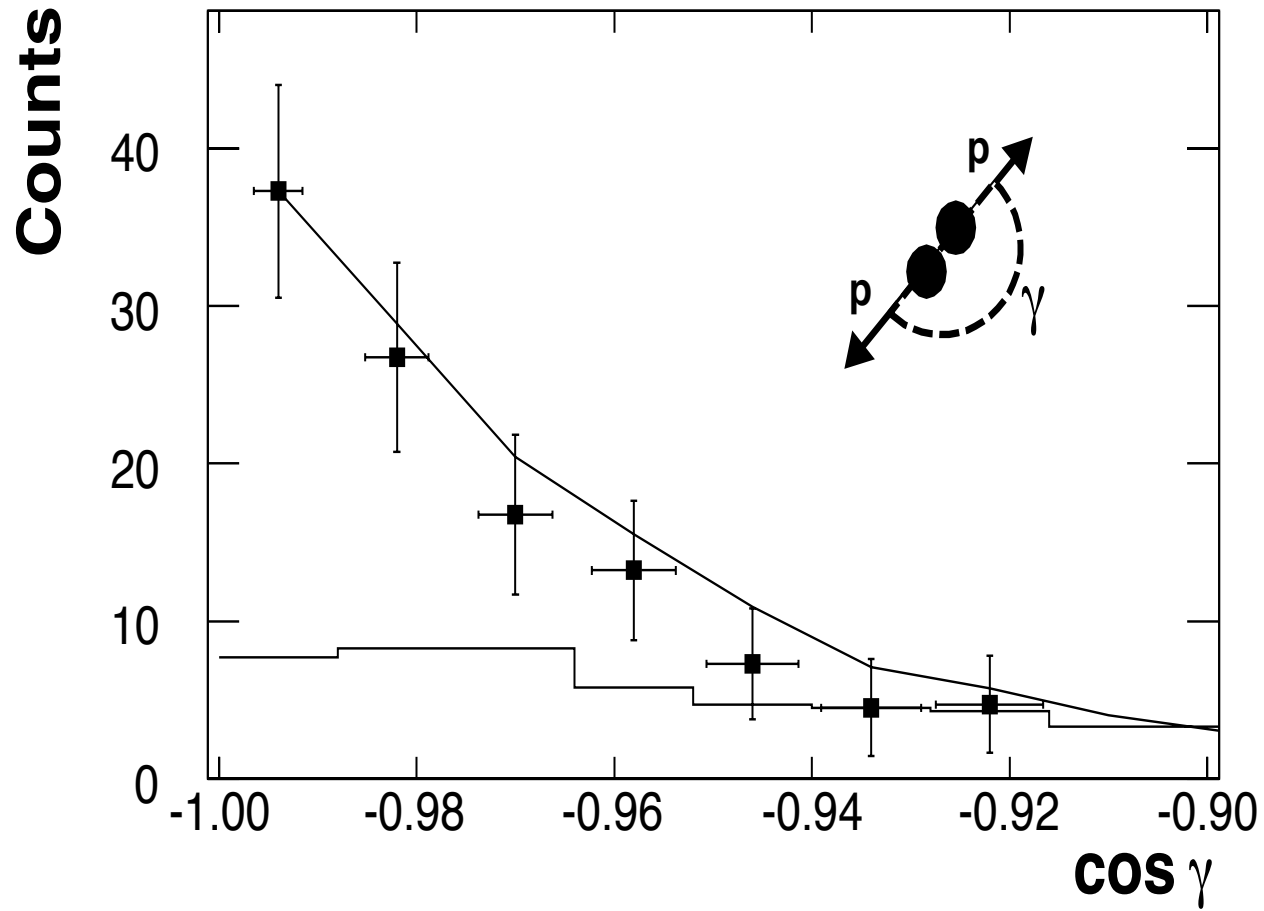
$$P_{pn/pX} = 0.96 \pm 0.22$$

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



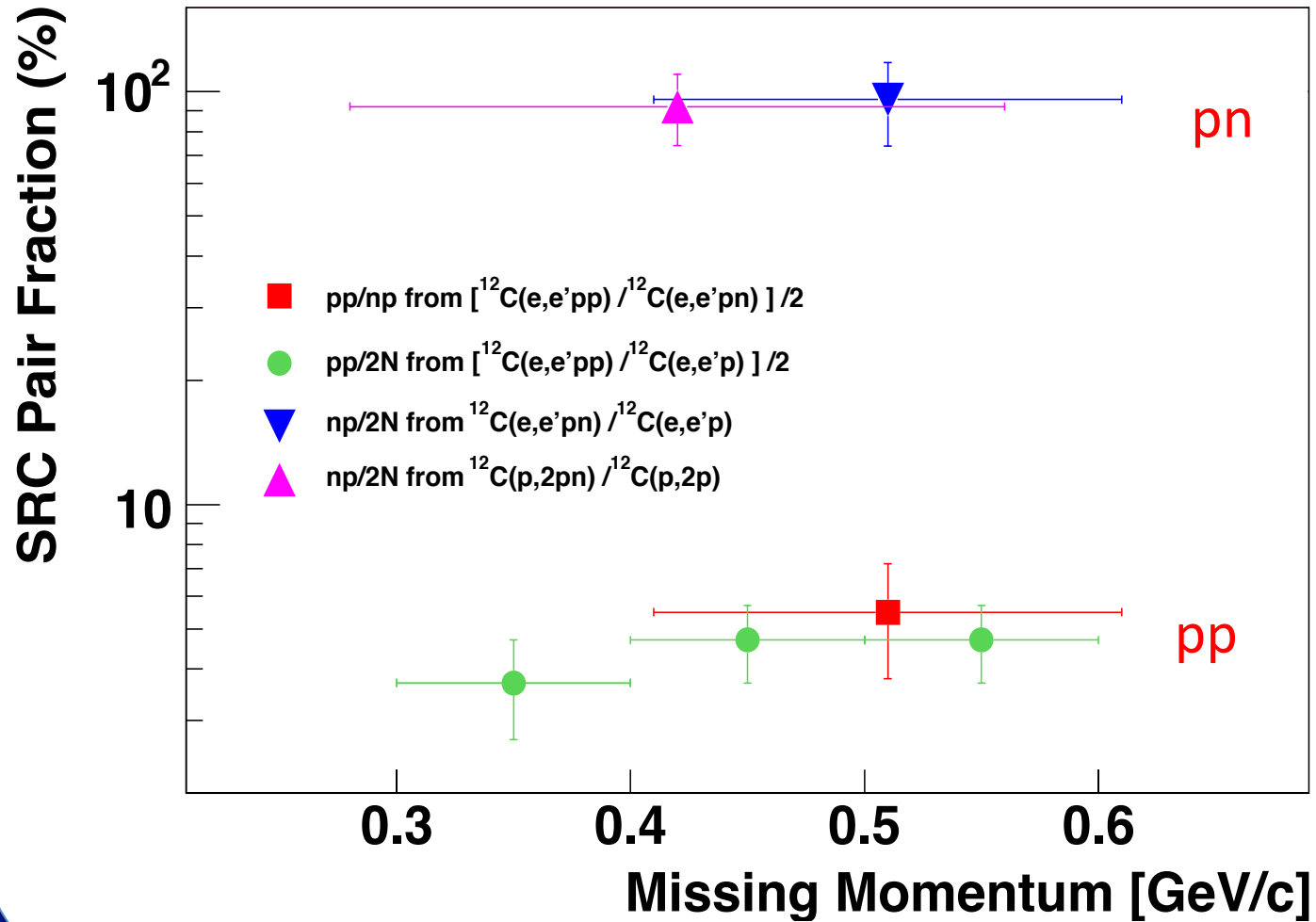
p_n

neutron/proton



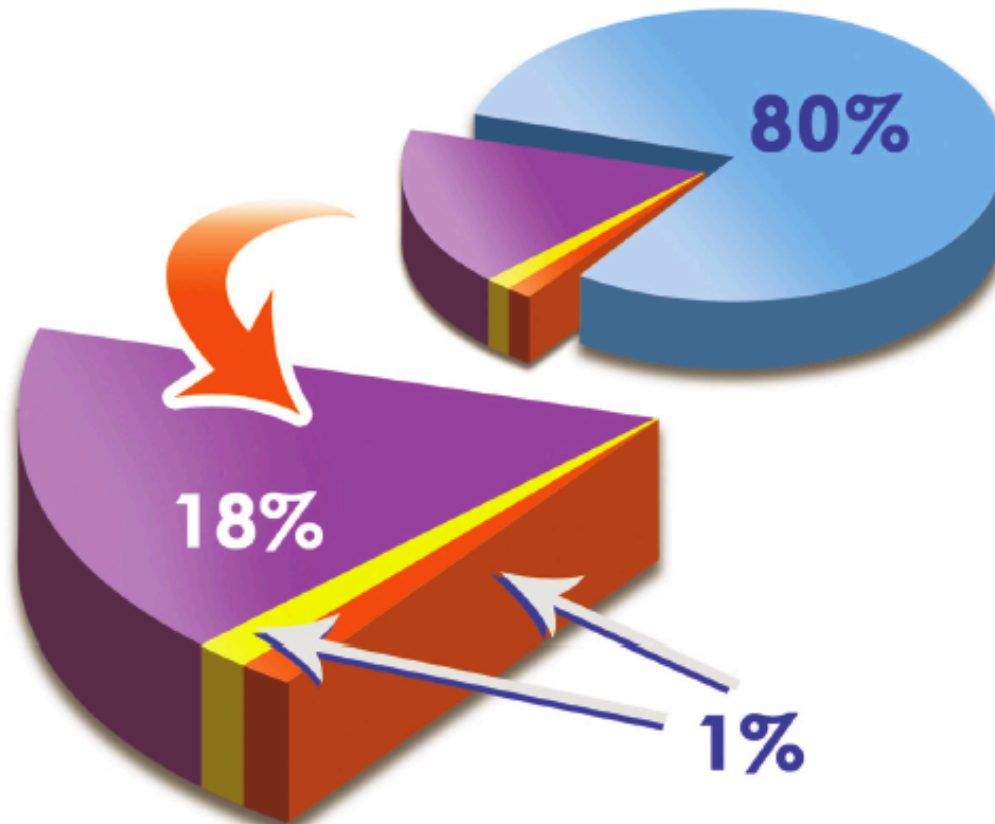
Combined Analysis

R.Subdei, et al Science , 2008



Combined Analysis

R.Subdei, et al Science , 2008



Single nucleons

n-p

n-n

p-p

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

BNL data on $A(p,2pn)X$

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

Piasezky, MS, Frankfurt,
Strikman, Watson PRL 2007

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

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

JLAB data $A(e,e'pn)X$

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

R. Shneor et al. PRL 07

Second:

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

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

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

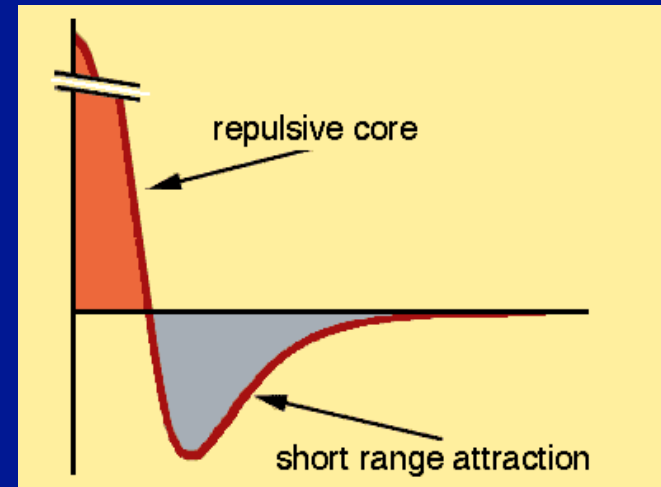
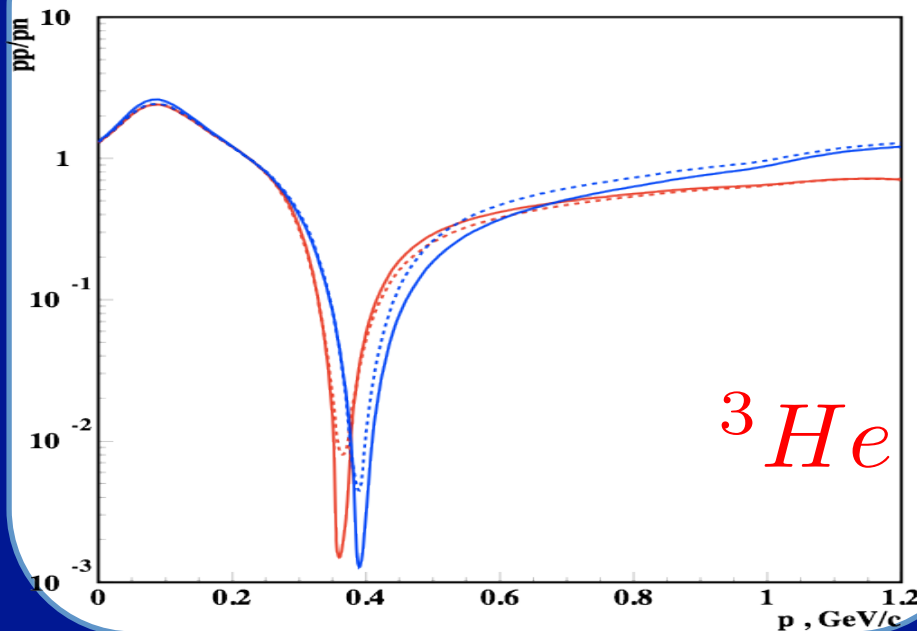
$$S_{12}|pp\rangle = 0$$

$$S_{12}|nn\rangle = 0 \quad \text{Isospin 1 states}$$

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

$$S_{12}|pn\rangle \neq 0 \quad \text{Isospin 0 states}$$

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



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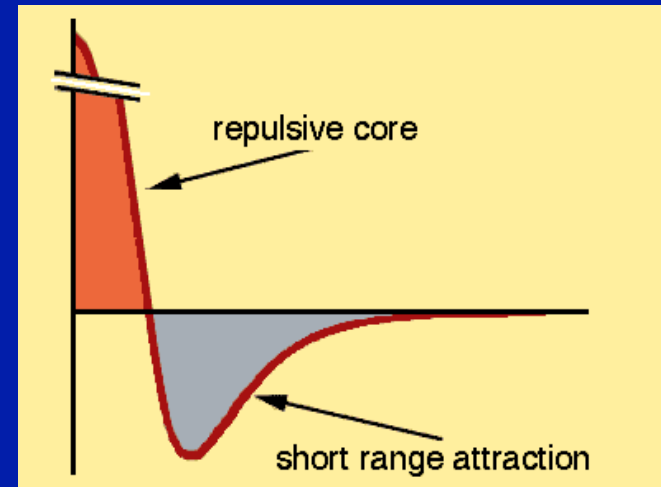
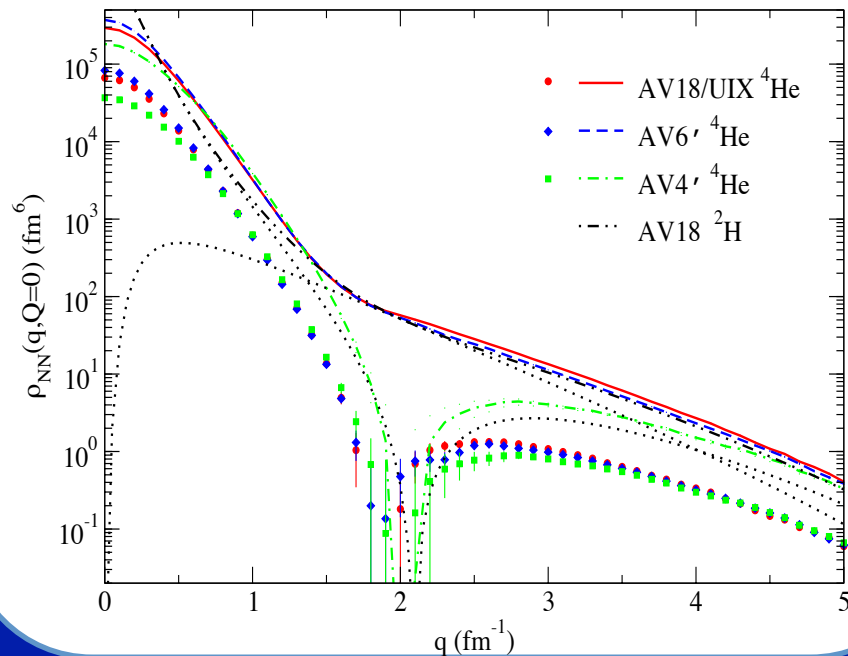
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Sciavilla, Wiringa, Pieper, Carls PRL,2007



New Properties of High Momentum Component

- Dominance of NN Correlations

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

-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 $k^2/2m_N \gg |E_B|$

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

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

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

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

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

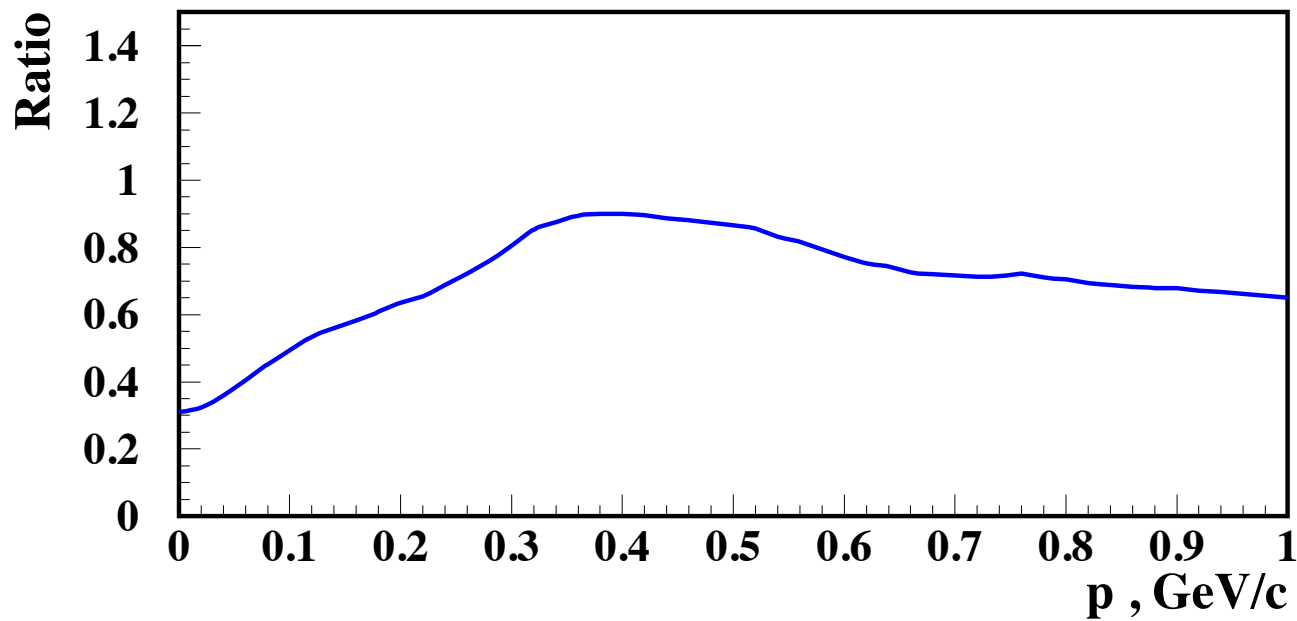
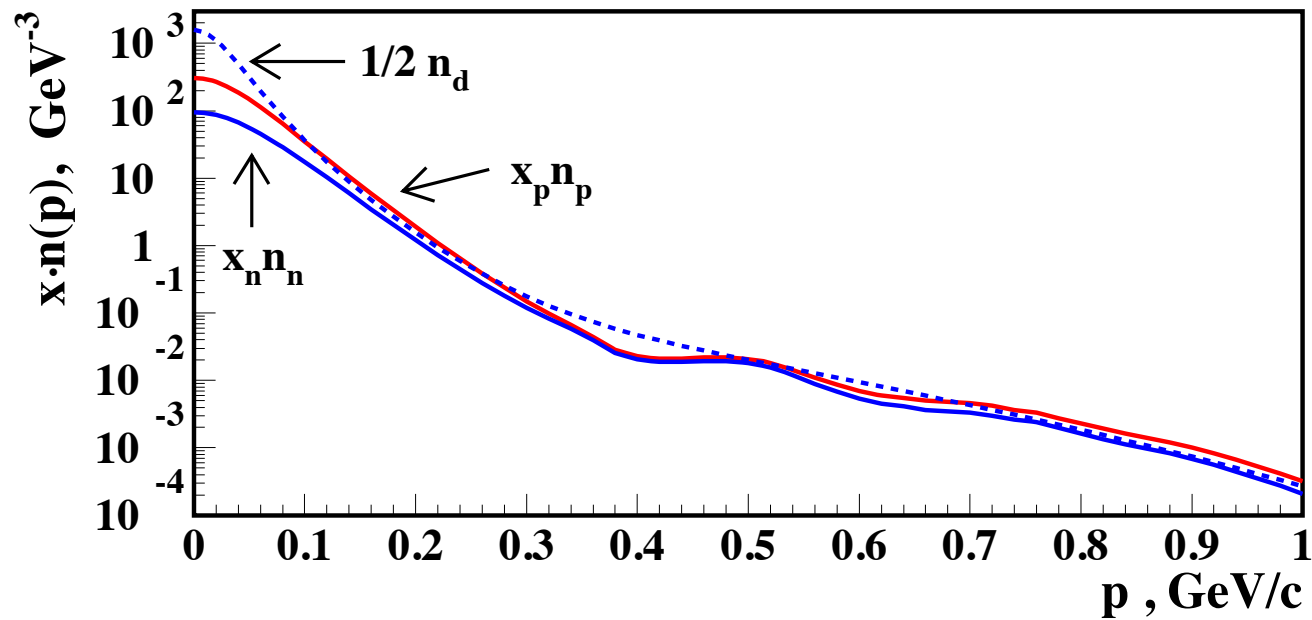
$$a_{NN}(A, y) \approx a_{NN}(A, 0) \cdot f(y) \quad \text{with } f(0) = 1 \text{ and } f(1) = 0$$

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

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

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

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

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

$$E_{kin}^n = 19 \text{ MeV} \quad (p = 182 \text{ MeV}/c)$$

Implications: Energetic Protons in Large A Nuclei

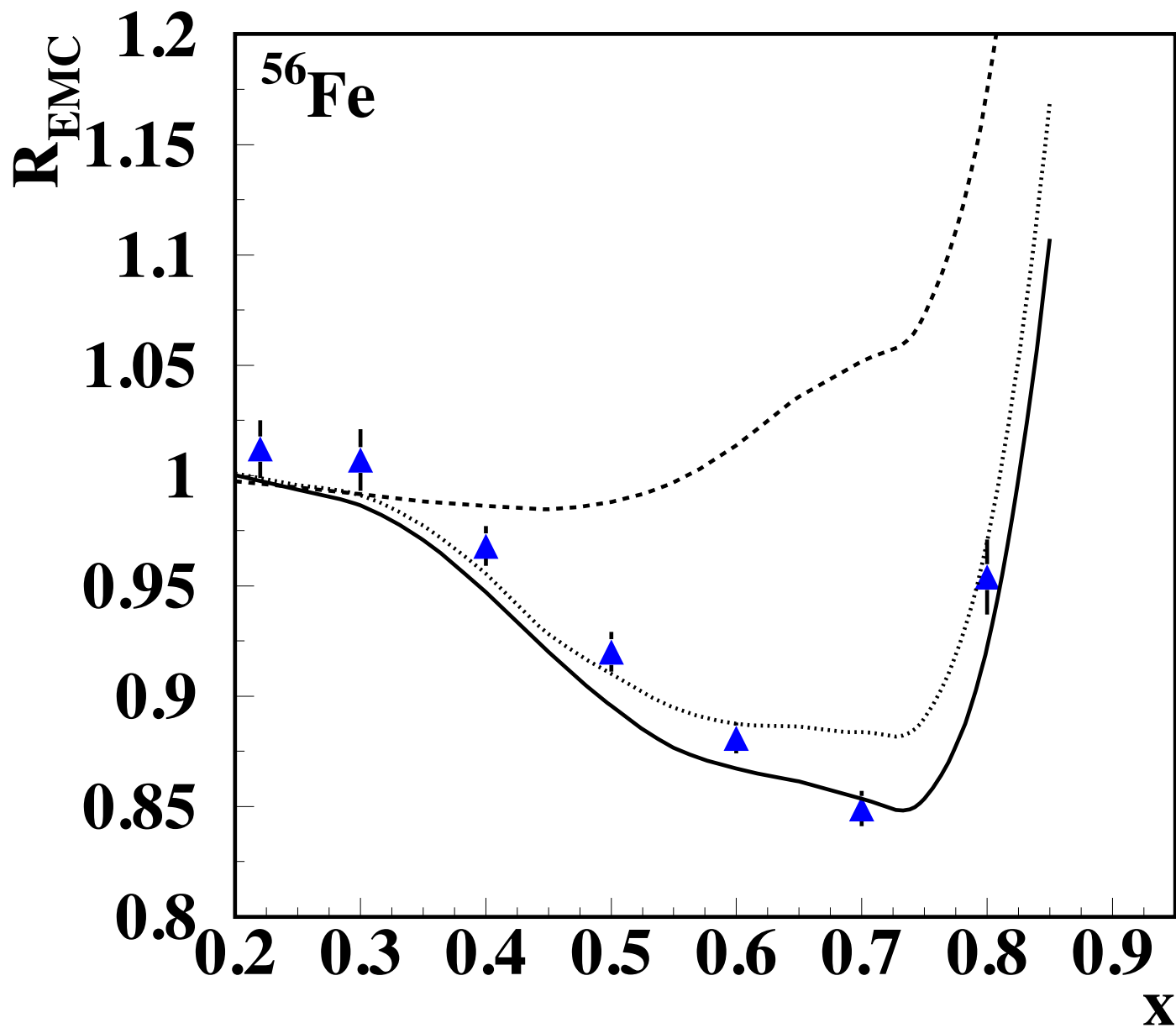
- EMC Effect

$$F_{2A} = (A - Z) \int_x^A F_{2n}\left(\frac{x}{\alpha}\right) \rho_n(\alpha, p_t) \frac{d\alpha}{\alpha} d^2 p_t \\ + Z \int_x^A F_{2p}\left(\frac{x}{\alpha}\right) \rho_p(\alpha, p_t) \frac{d\alpha}{\alpha} d^2 p_t$$

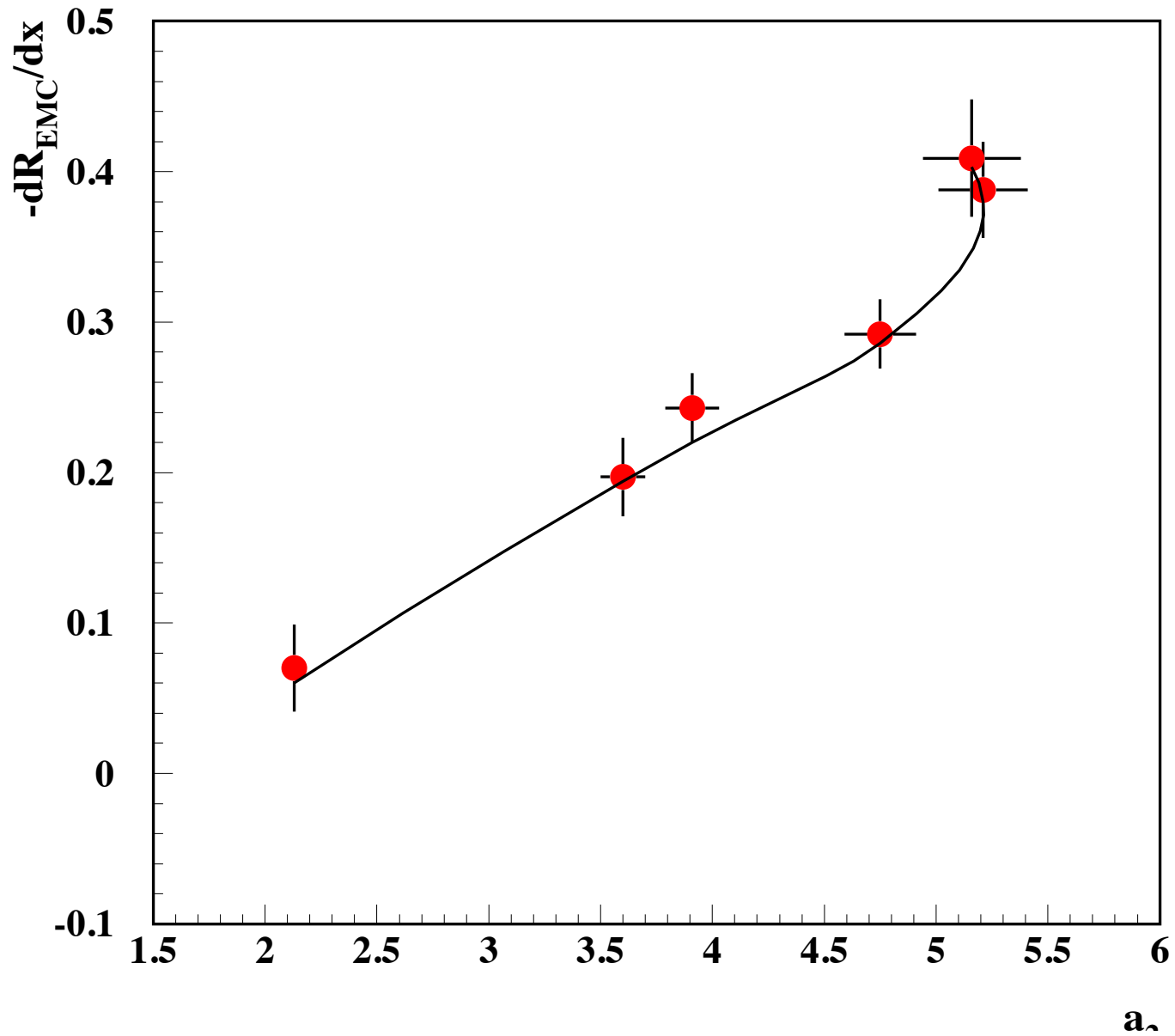
Color Screening Model: Frankfurt Strikman 1987

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

- EMC Effect



- EMC Effect



Implications: Protons are more modified in
Large A Nuclei

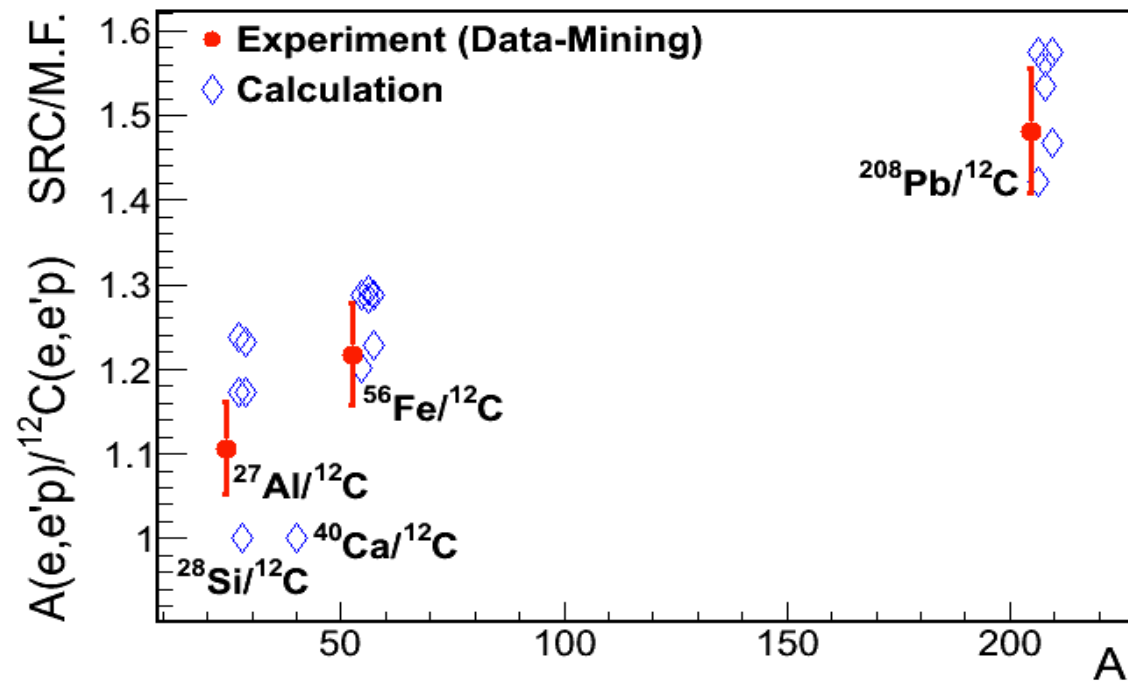
u-quarks are more modified than
d quarks in Large A Nuclei

- Different explanation of NuTeV Puzzle
- Can be checked in neutrino-nuclei or
in pvDIS processes

Implications: Protons are more modified in Large A Nuclei

- Can be checked in $A(e, e'p)$ Reaction (Or Hen & Eli Piassetzky)

$$R_A = \frac{\int_{k_F}^{\infty} \sigma_A(p_{in}) d^3 p_{in}}{\int_0^{k_F} \sigma_A(p_{in}) d^3 p_{in}} \quad R = \frac{R_A}{R_{C12}}$$



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

Implications: For Nuclear Matter

Our Goal

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

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

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

(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

where

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

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

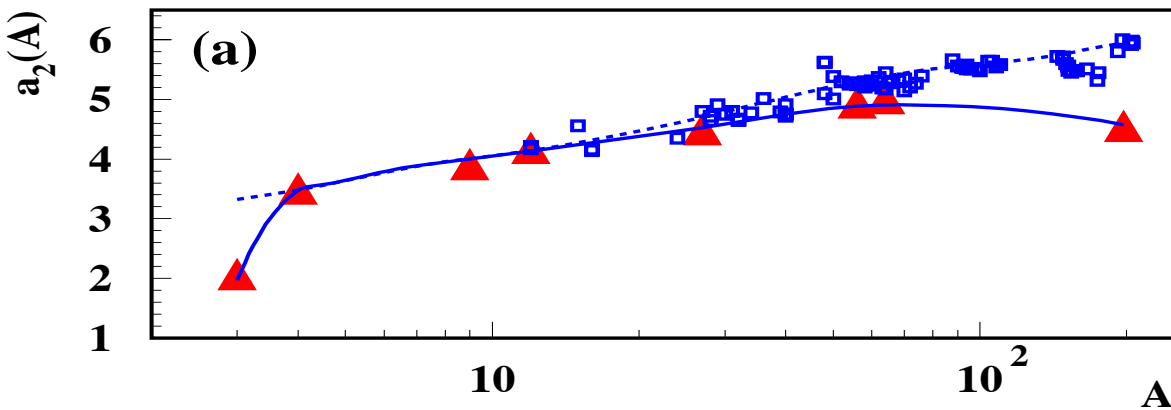
(3) Neglecting contributions due to **pp** and **nn** SRCs one obtains boundary conditions

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

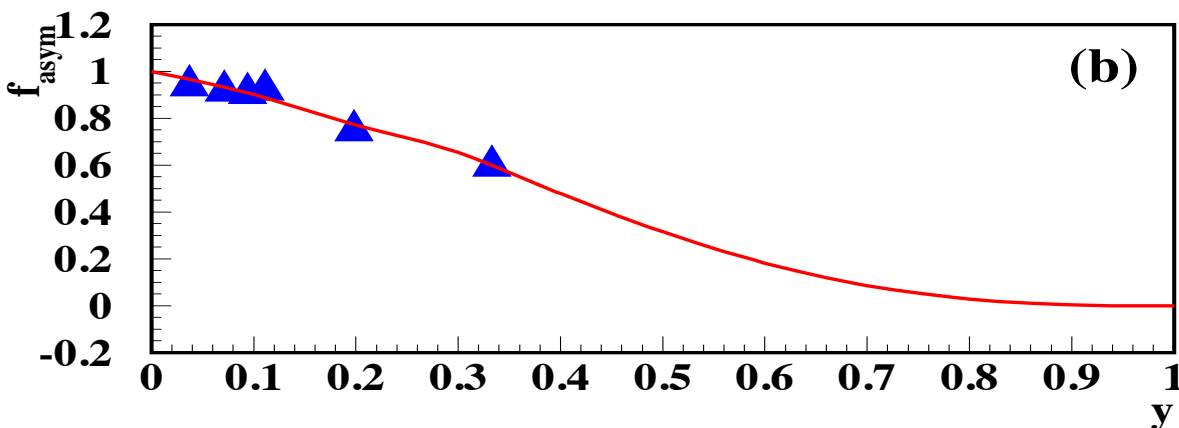
Implications: For Nuclear Matter

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

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



$$C = 49.1 \pm 2.6$$

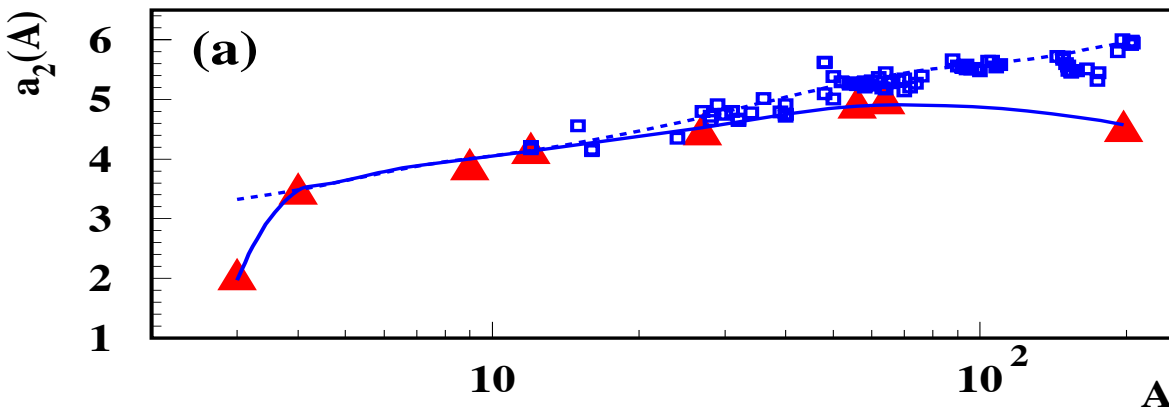


Implications: For Nuclear Matter

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

Fitting $f(y)$

- 4 data points



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

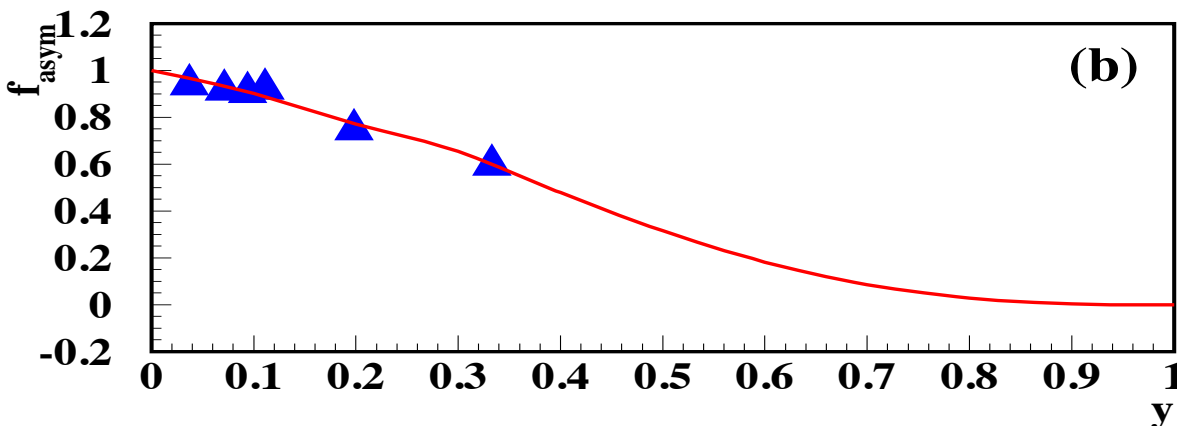
$$f(0) = 1 \text{ and } f(1) = 0$$

- 2 more boundary conditions due to

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

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

- 1 more positiveness of $f(y)$



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

Extrapolation to infinite and superdense nuclear matter

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

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

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

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

compare

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

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



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

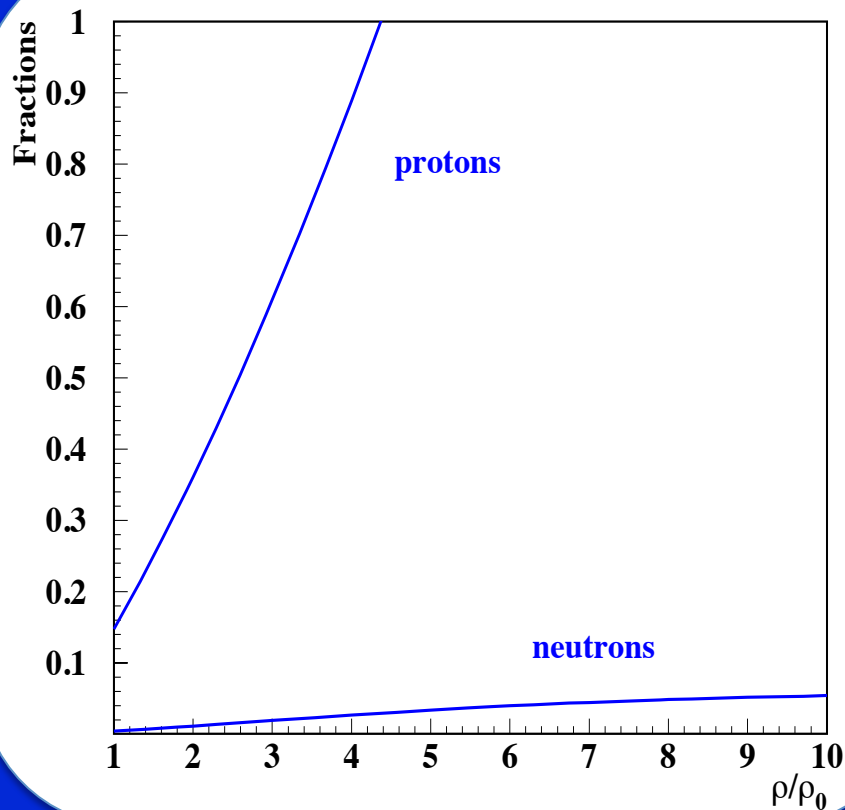
Implications: For Nuclear Matter

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

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 one 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 isosinglet state. Such situation will double the threshold of inelastic excitation from $NN \rightarrow N\Delta$ to $NN \rightarrow \Delta\Delta(NN^*)$ transition thereby stiffening the equation of state. This situation may explain the observed neutron star masses in Ref.[?] which are in agreement with the calculation of equation of 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: $\rho_1 \ll \rho_2$*
- *Switch on the short-range interaction between two-component*
- *While interaction between each components is weak*
- *Spectrum of the small component gas will strongly deform*

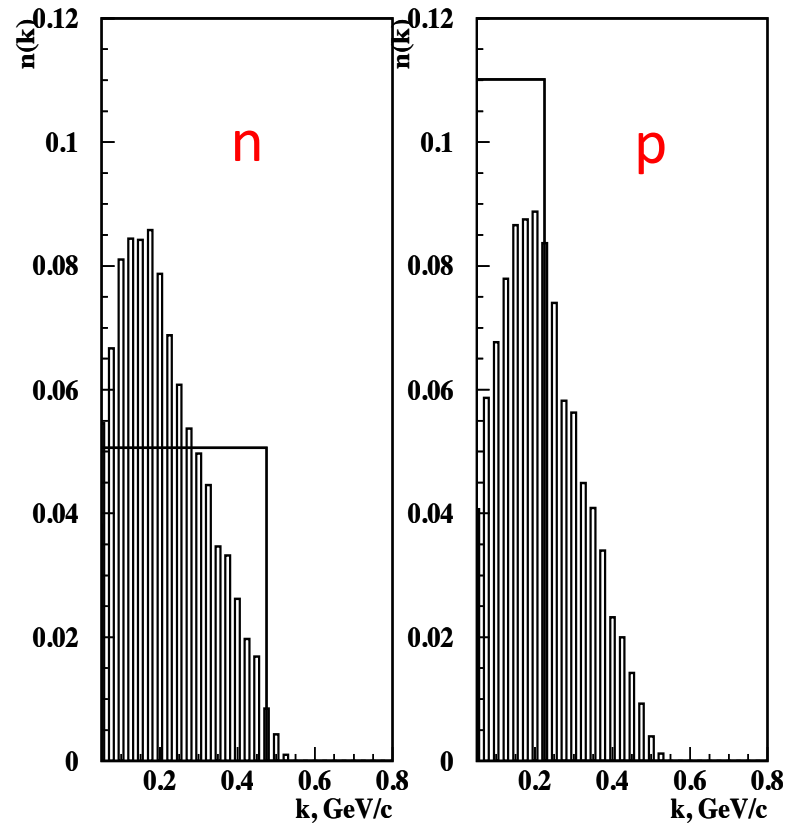
Cold Atoms

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

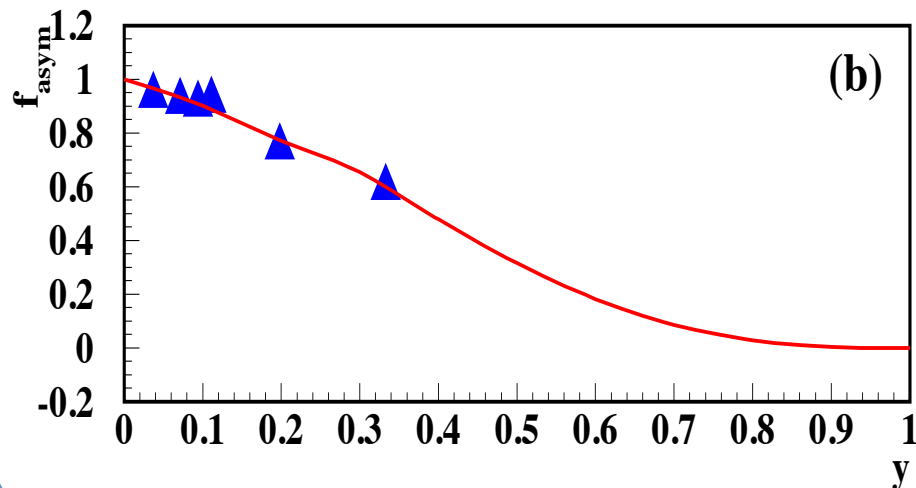
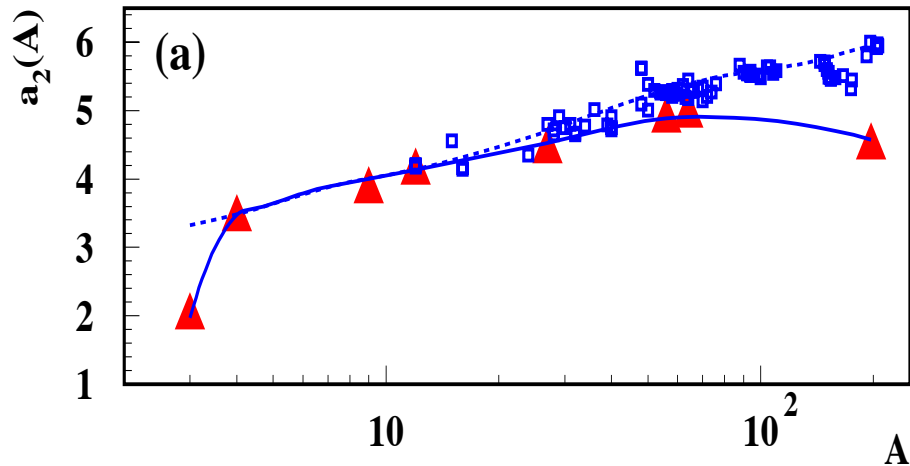
Finite T Nuclear Gas

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 Asymmetric Fermi Systems?



Where we would like go from here ?



- More Symmetric Nuclei

- Measurements of pp/nn

- $3N$ SRCs

- Nuclei with large asymmetry parameters

- Break-down of nucleon framework

