

# Hadrons in the Nuclear Medium

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## TOPICAL REVIEW

## Hadrons in the nuclear medium

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### Abstract

Quantum chromodynamics (QCD), the microscopic theory of strong interactions, has not yet been applied to the calculation of nuclear wavefunctions. However, it certainly provokes a number of specific questions and suggests the existence of novel phenomena in nuclear physics which are not part of the traditional framework of the meson–nucleon description of nuclei. Many of these phenomena are related to high nuclear densities and the role of colour in nucleonic interactions. Quantum fluctuations in the spatial separation between nucleons may lead to local high-density configurations of cold nuclear matter in nuclei, up to four times larger than typical nuclear densities. We argue here that experiments utilizing the higher energies available upon completion of the Jefferson Laboratory energy upgrade will be able to probe the quark–gluon structure of such high-density configurations and therefore elucidate the fundamental nature of nuclear matter. We review three key experimental programmes: quasi-elastic electro-disintegration of light nuclei, deep inelastic scattering from nuclei at  $x > 1$  and the measurement of tagged structure functions. These interrelated programmes are all aimed at the exploration of the quark structure of high-density nuclear configurations.

The study of the QCD dynamics of elementary hard processes is another important research direction and nuclei provide a unique avenue to explore

## High Density Nuclear Physics

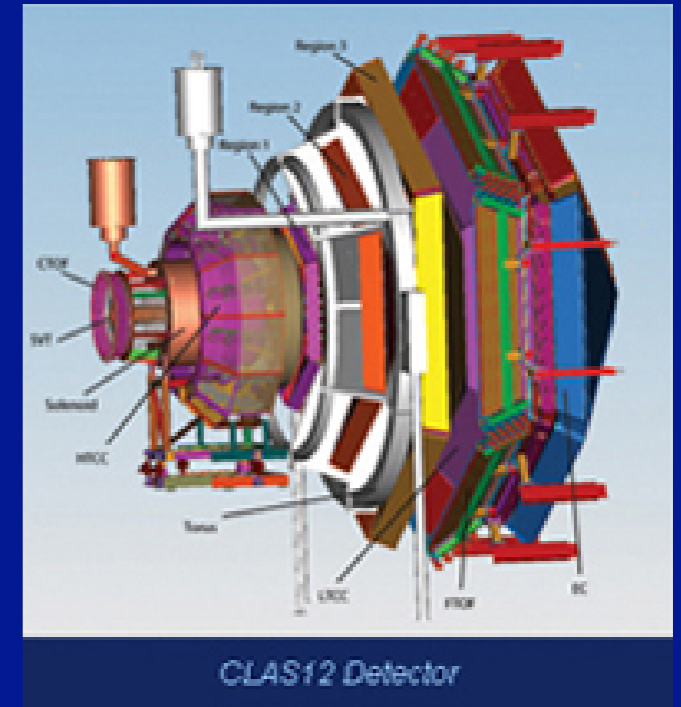
- Short Range Nucleon Correlations
- Nuclear DIS at  $x > 1$

## Properties of QCD from Nuclear Medium

- Modification of Bound Nucleon Structure - EMC effect
- Color Transparency
- Hadronization
- Signatures of Chiral Symmetry Restoration

## QCD Dynamics of Hadronic Interaction

- hard break-up of hadrons from the light nuclei
- quasireal secondary Hadronic "Beams"



## - Potential Models

Nuclear Hamiltonian

$$H = - \sum_i \frac{\nabla_i^2}{2m} + \sum_{i < j} V_{ij}^{2N} + \sum_{i < j < k} V_{i,j,k}^{3N} + \dots$$

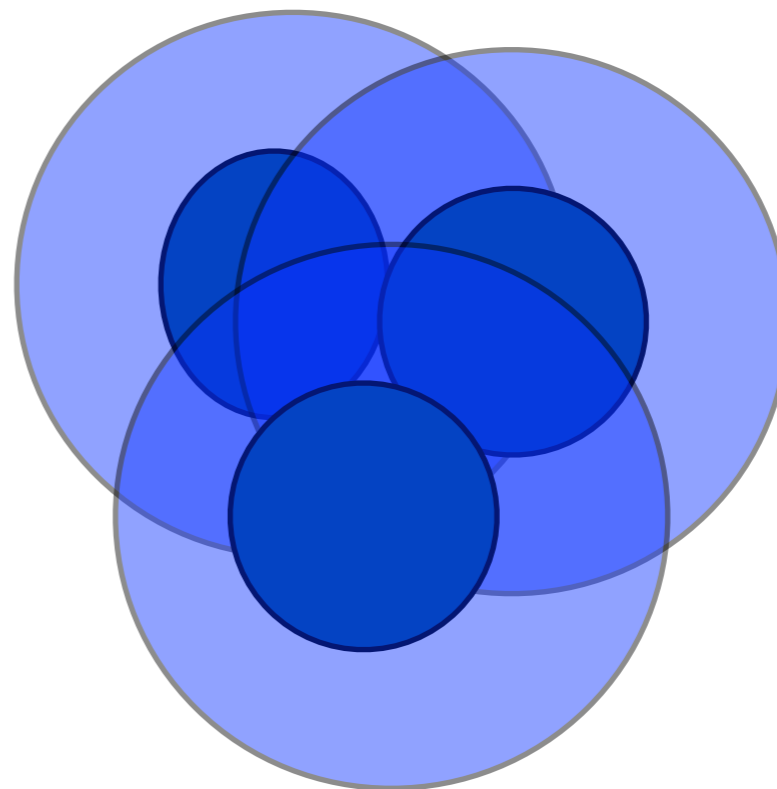
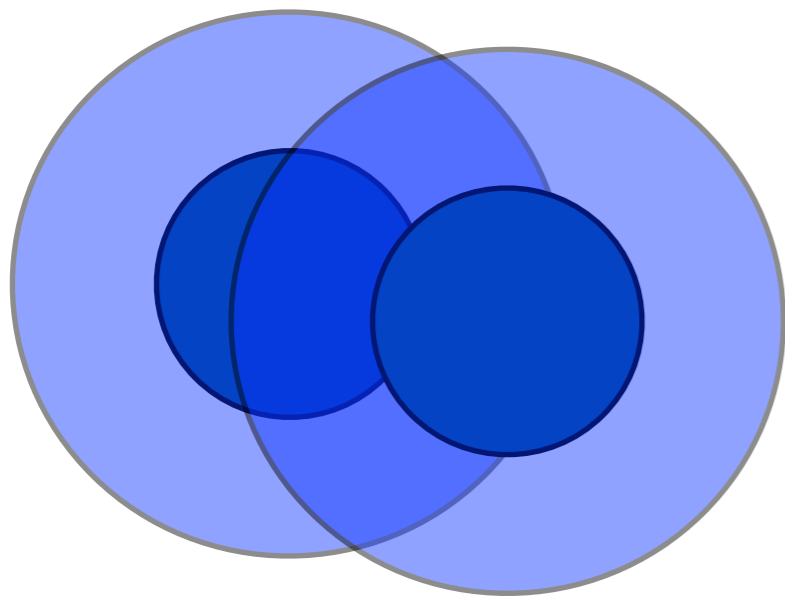
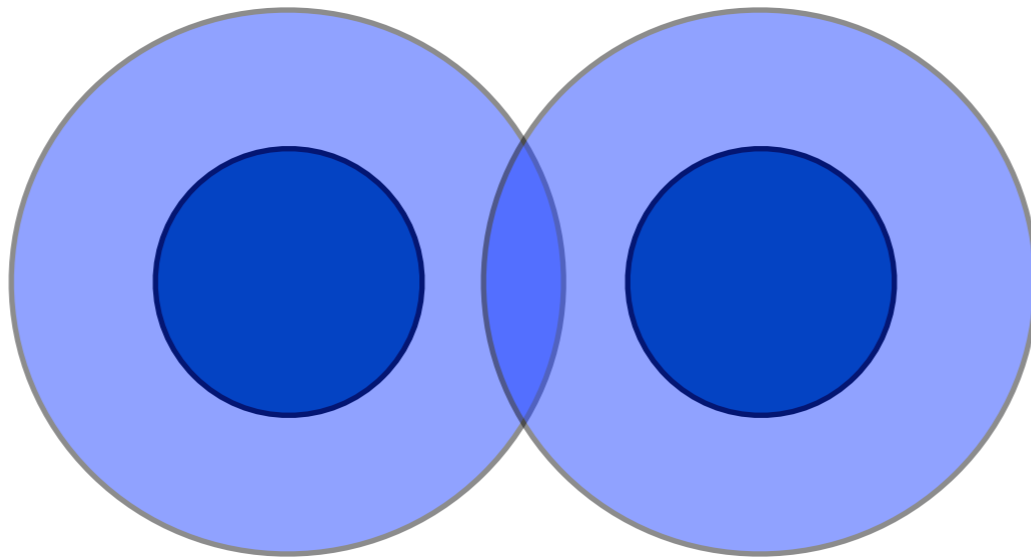
$$H \Psi_A(r_1, \dots, r_A) = E \Psi_A(r_1, \dots, r_A)$$

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

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

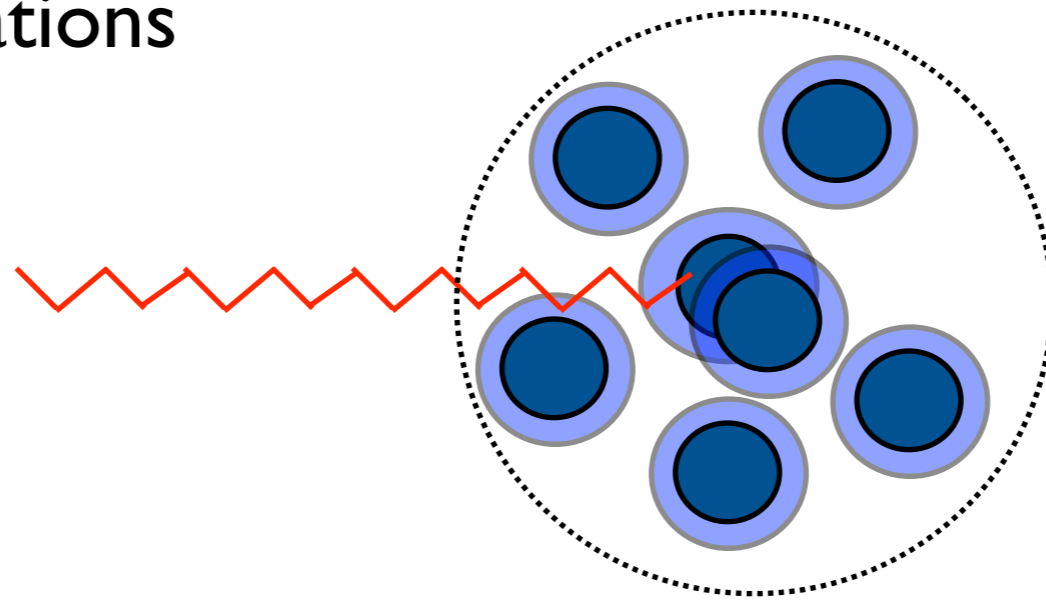
$$V^i = V_{int,R} + V_{core}$$

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

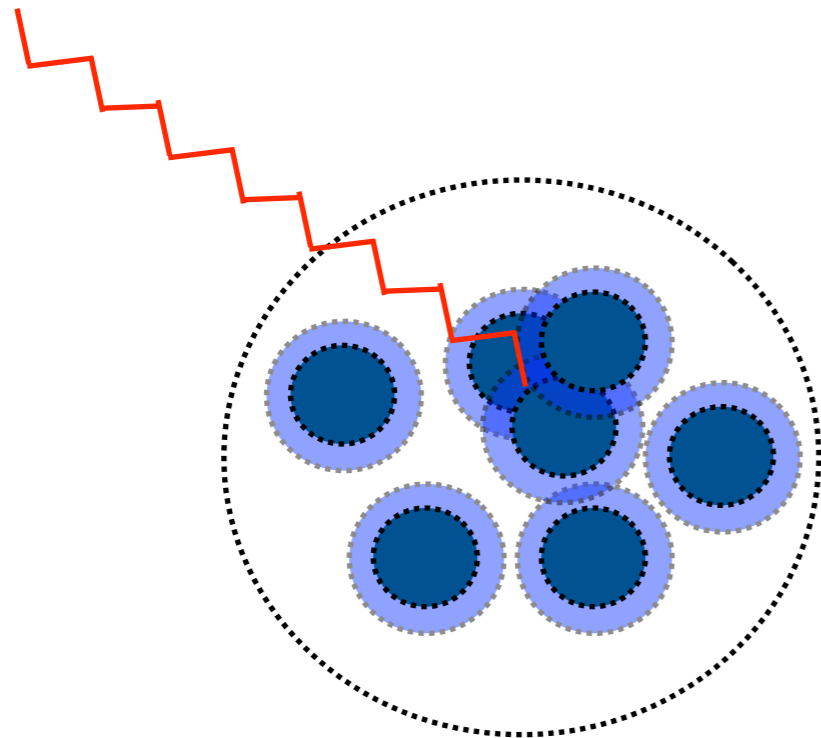


# Probing Short Range Nucleon Correlations

## Two Nucleon Correlations



## Three Nucleon Correlations

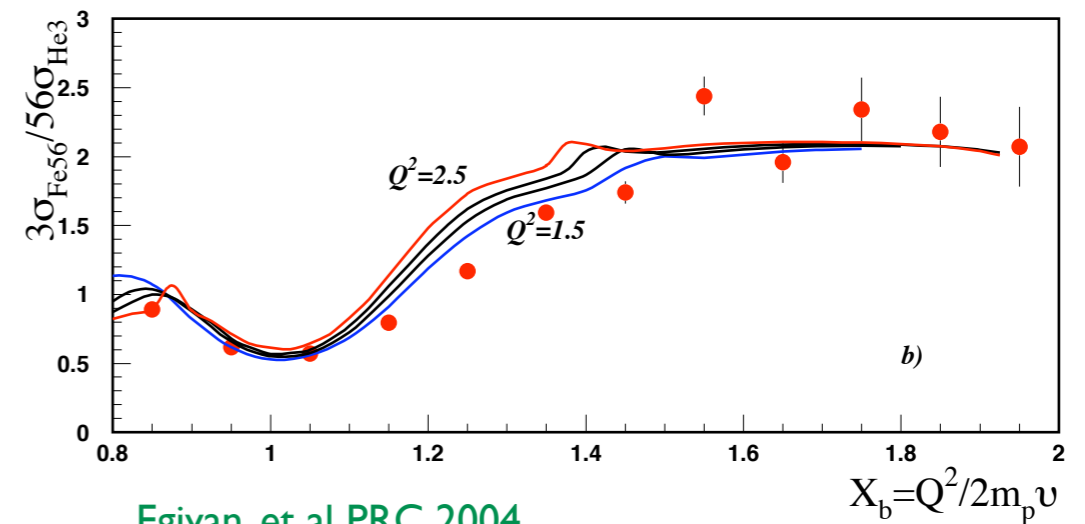
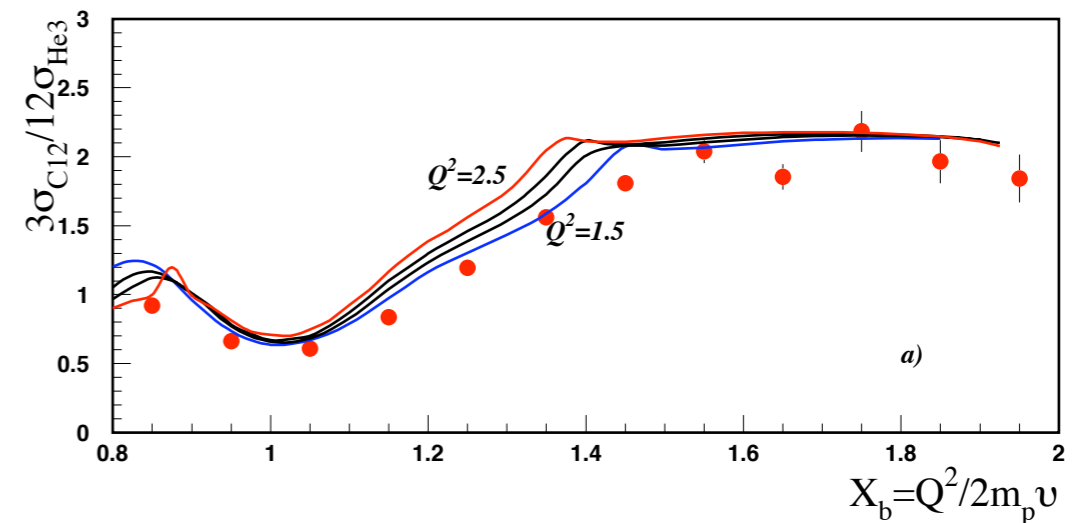
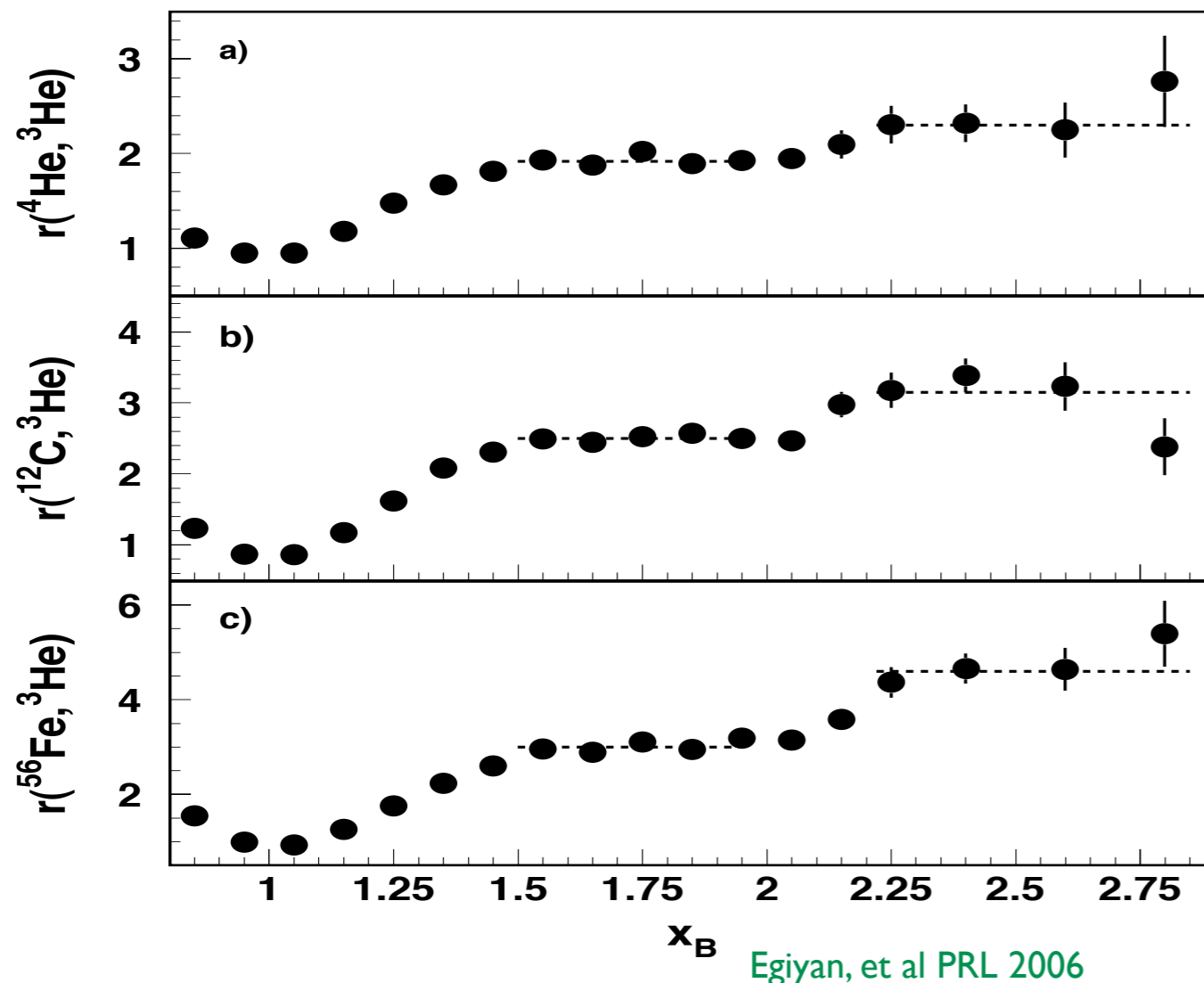


# Scaling of Inclusive Cross Section Ratios

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

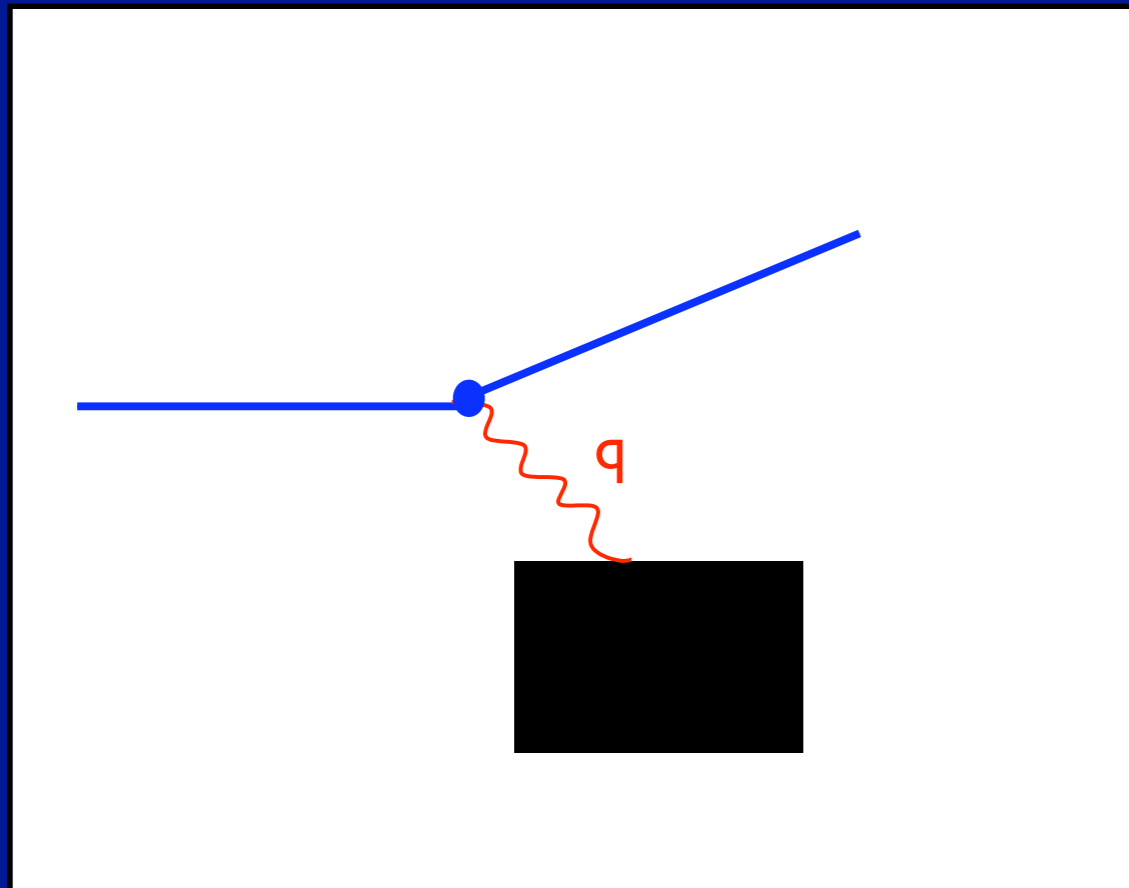
For  $2 < x < 3$   $R \approx \frac{a_3(A_1)}{a_3(A_2)}$

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



# Inclusive Scattering

## Inclusive Scattering From the Black Box



What we can learn  
about BB without detecting it ?

- the Black Box has constituents
- the probe knocks-out one of such constituents without breaking it
- the remnant of the BB was a spectator to this action



$$p_i = P_{BB} - P_R$$

$$(q + p_i)^2 = m_c^2$$

$$-Q^2 + 2qp_i + m_i^2 = m_c^2$$

$$-Q^2 + q_+p_{i-} + q_-p_{i+} + m_i^2 = m_c^2$$

$$p_{i-} = \frac{Q^2}{q_+} - \frac{q_-}{q_+}p_{i+} + \frac{m_c^2 - m_i^2}{q_+}$$

$$p_{i-} = \frac{Q^2}{q_+} = \frac{Q^2}{2q_0}$$

$$z || q$$

$$p_{i\pm} = E_i \pm p_{iz}$$

$$q_{\pm} = q_0 \pm q$$

$$\frac{Q^2}{q_+} = \text{fixed}$$

$$q_0 \rightarrow \infty$$

$$q_+ \rightarrow 2q_0$$

$$\frac{q_-}{q_+} = -\frac{\text{fixed}}{q_+} \rightarrow 0$$

$$p_{i-} = \frac{Q^2}{q_+} = \frac{Q^2}{2q_0}$$

$p_{i-} = ?$   $\longrightarrow$   $\frac{p_{i-}}{P_{BB-}}$  Invariant with respect to Lorentz transformation in z

$$\frac{p_{i-}}{P_{BB-}} \Big|_{LAB} = \frac{Q^2}{2q_0 M_{BB}}$$

$$\frac{p_{i-}}{P_{BB-}} \Big|_{IMF} = \left( \frac{E_i + p_i^z}{E_{BB} + P_{BB}^z} \right)_{IMF} \approx \left( \frac{p_i^z}{P_{BB}^z} \right)_{IMF}$$

$$p_{i\perp} \ll p_{iz}^{IMF}$$

If BB = nucleus

knocked out constituent is nucleon

Correlation Parameter

$$\alpha = A \frac{p_-}{p_{BB-}}$$

**Momentum Fraction of Nucleus  
carried by the constituent nucleon**

$\alpha_i > j$  corresponds to  $j$ -nucleons involved in the scattering

For finite  $Q^2$

$$x = \frac{\alpha - \frac{m_N^2 - m_i^2}{2mq_0}}{\left(1 + \frac{p_{i+}}{q_+}\right) \frac{2q_0}{q_+}}$$

# signatures for short range correlations

$x > 1$  at least 2 nucleons are needed

$x > 2$  at least 3 nucleons are needed

$x > j$  at least  $j+1$  nucleons are needed

## Prediction for Scaling

$x > 1$  if only 2 nucleons then  $\frac{\sigma_A}{\sigma_D}$  scales

$x > 2$  if only 3 nucleons then  $\frac{\sigma_A}{\sigma_{A=3}}$  scales

$x > j$  if only  $j+1$  nucleons then  $\frac{\sigma_A}{\sigma_{j+1}}$  scales

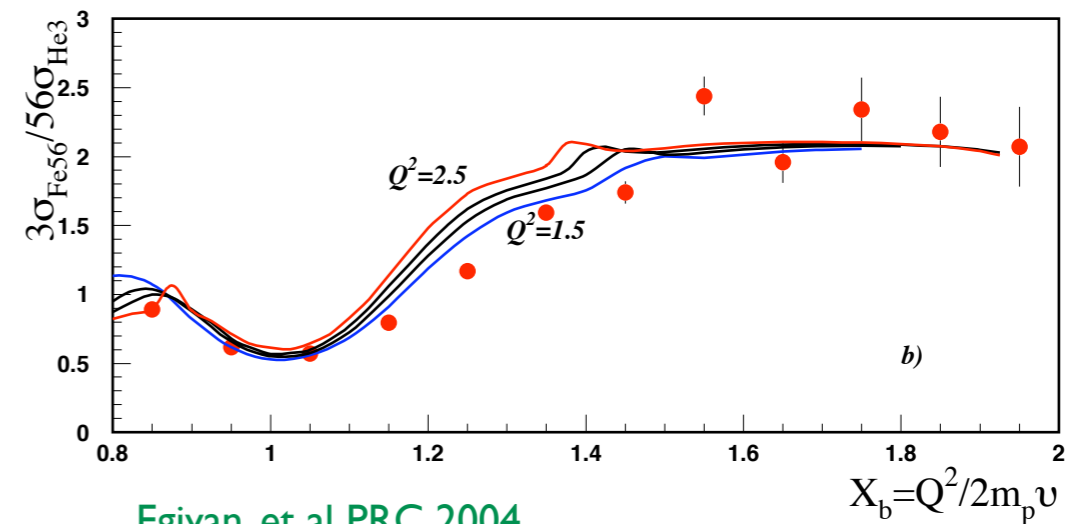
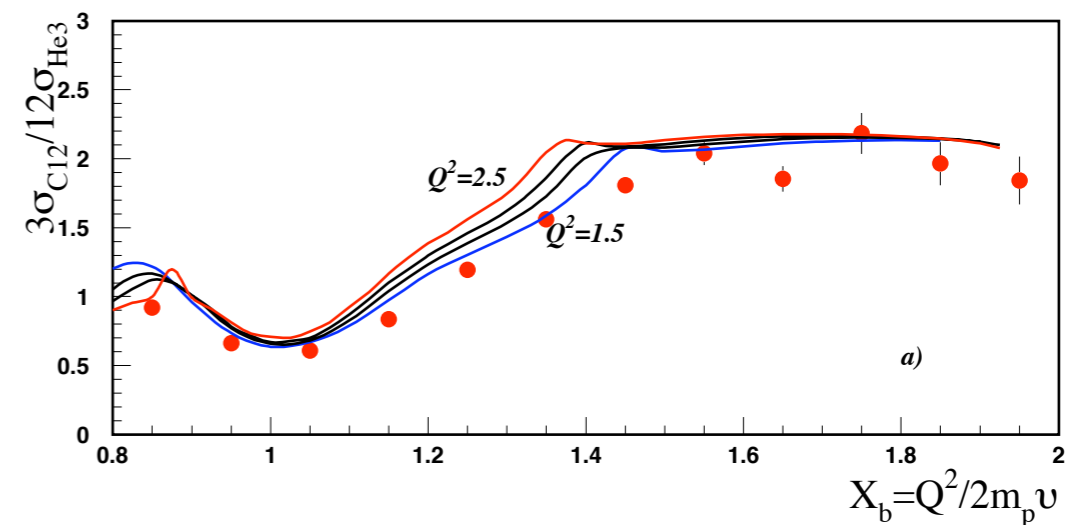
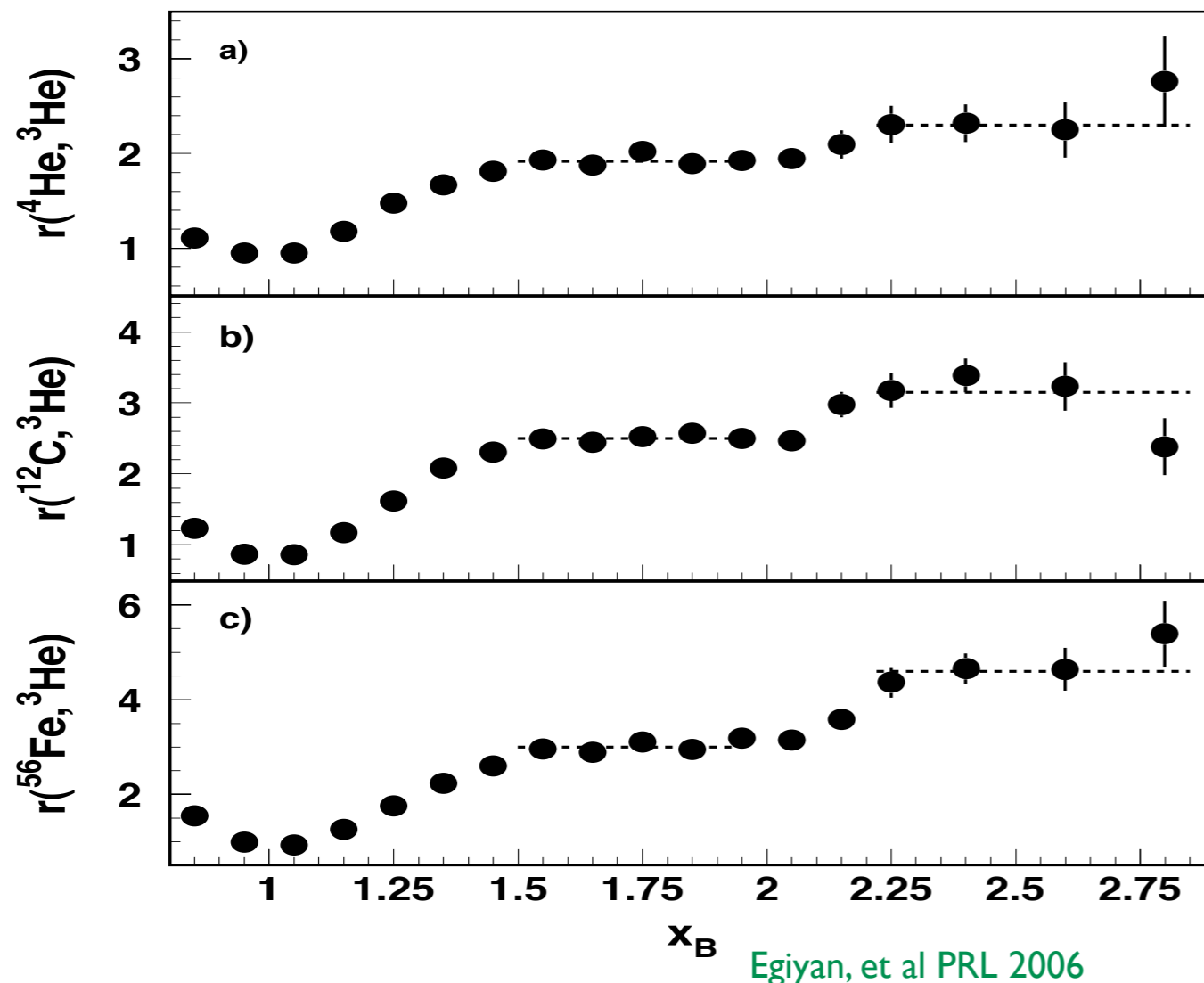
# Meaning of the scaling values

$$R = \frac{F_{A_1}(\alpha)}{F_{A_2}(\alpha)}$$

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

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

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



# What we Learned from $A(e,e')X$ Reactions

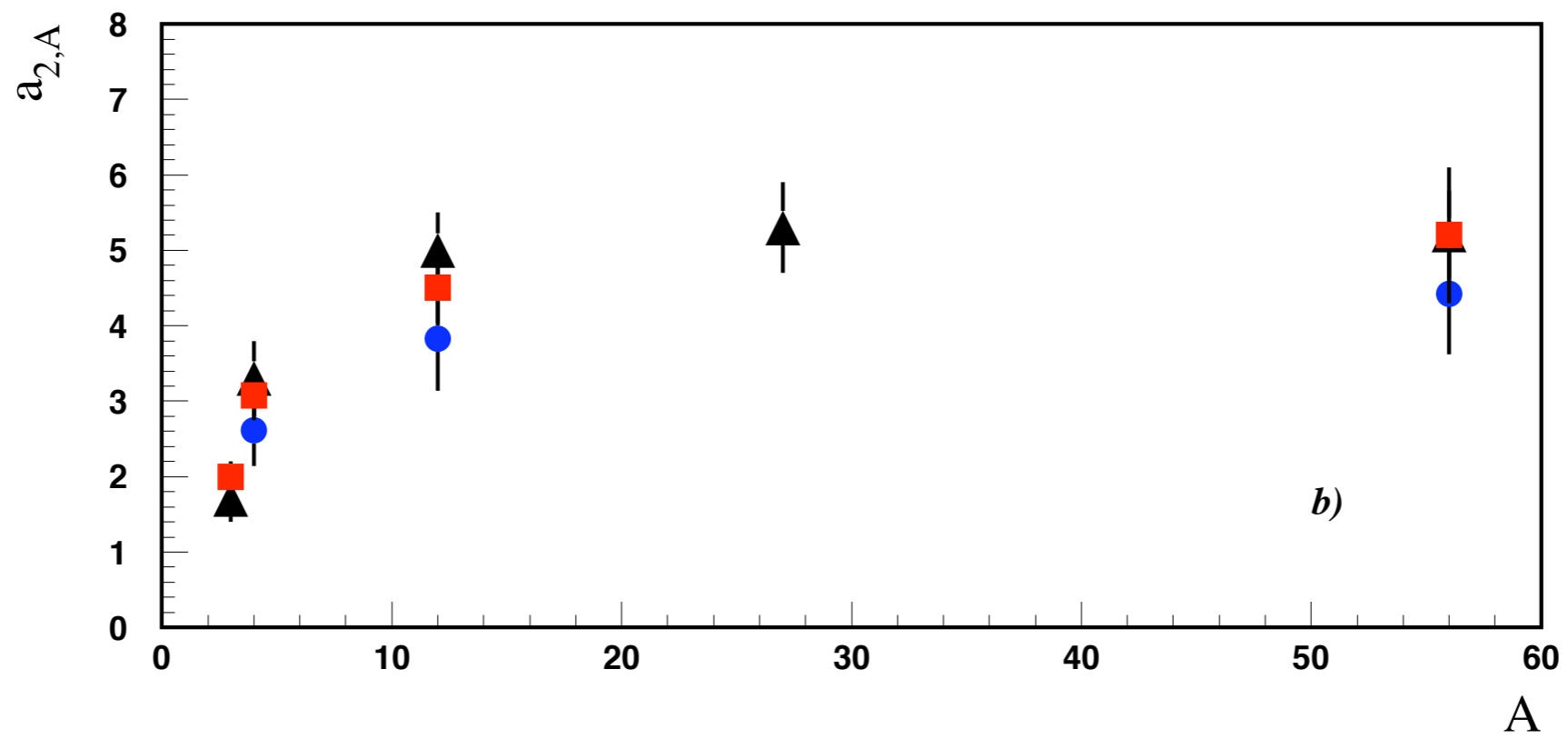
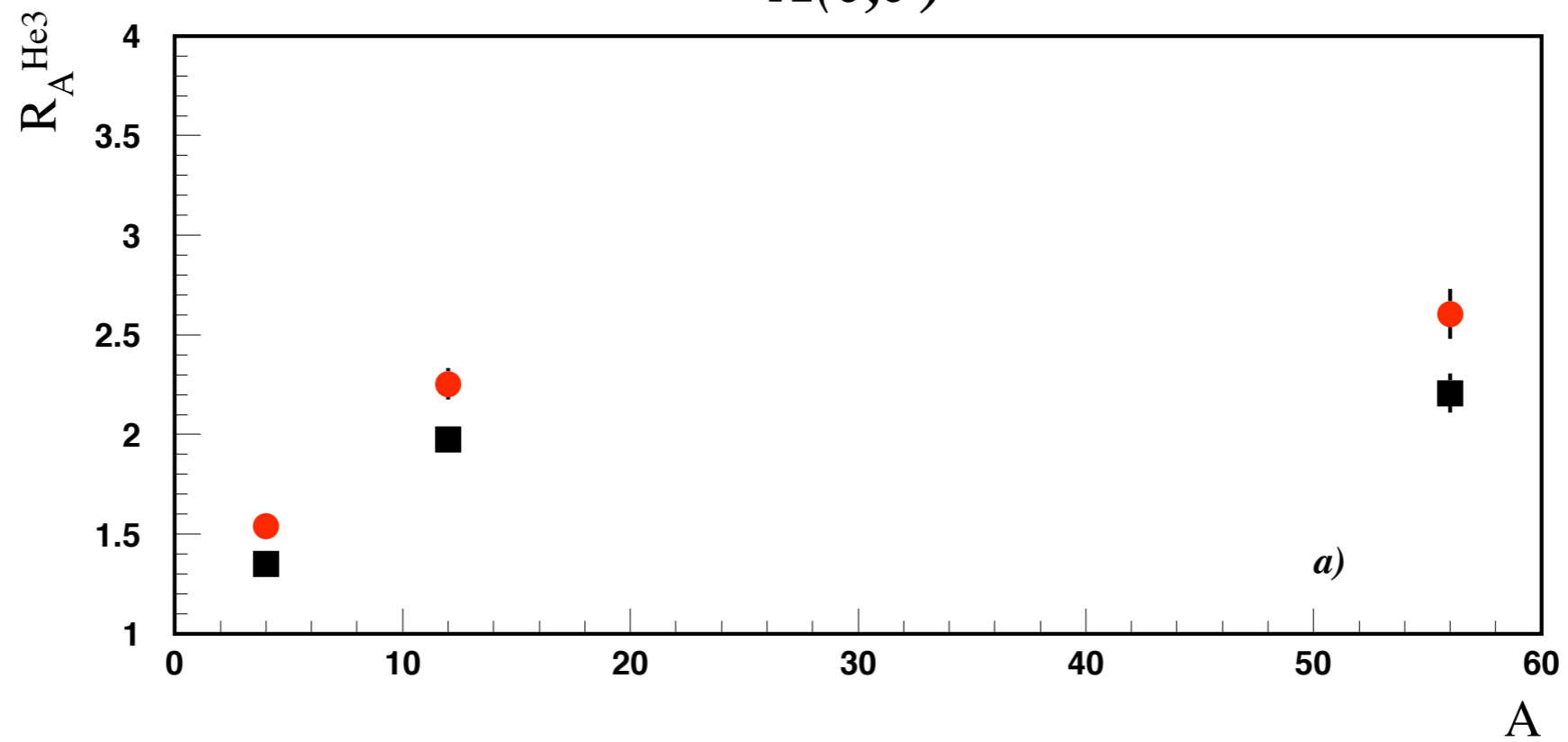
	$a_{2N}(A)$	$a_{3N}(A)$
${}^3\text{He}$	$0.080 \pm 0.000 \pm 0.004$	$0.0018 \pm 0.0000 \pm 0.0006$
${}^4\text{He}$	$0.154 \pm 0.002 \pm 0.033$	$0.0042 \pm 0.0002 \pm 0.0014$
${}^{12}\text{C}$	$0.193 \pm 0.002 \pm 0.041$	$0.0055 \pm 0.0003 \pm 0.0017$
${}^{56}\text{Fe}$	$0.227 \pm 0.002 \pm 0.047$	$0.0079 \pm 0.0003 \pm 0.0025$

$$a_2({}^{12}\text{C}) = 0.194\%$$

$$a_3({}^{12}\text{C}) = 0.0055\%$$

$$a_2({}^{56}\text{Fe}) = 0.227\%$$

$$a_3({}^{56}\text{Fe}) = 0.0079\%$$

$A(e, e')$ 

What  $a_2(A)$  and  $a_3(A)$  can tell us

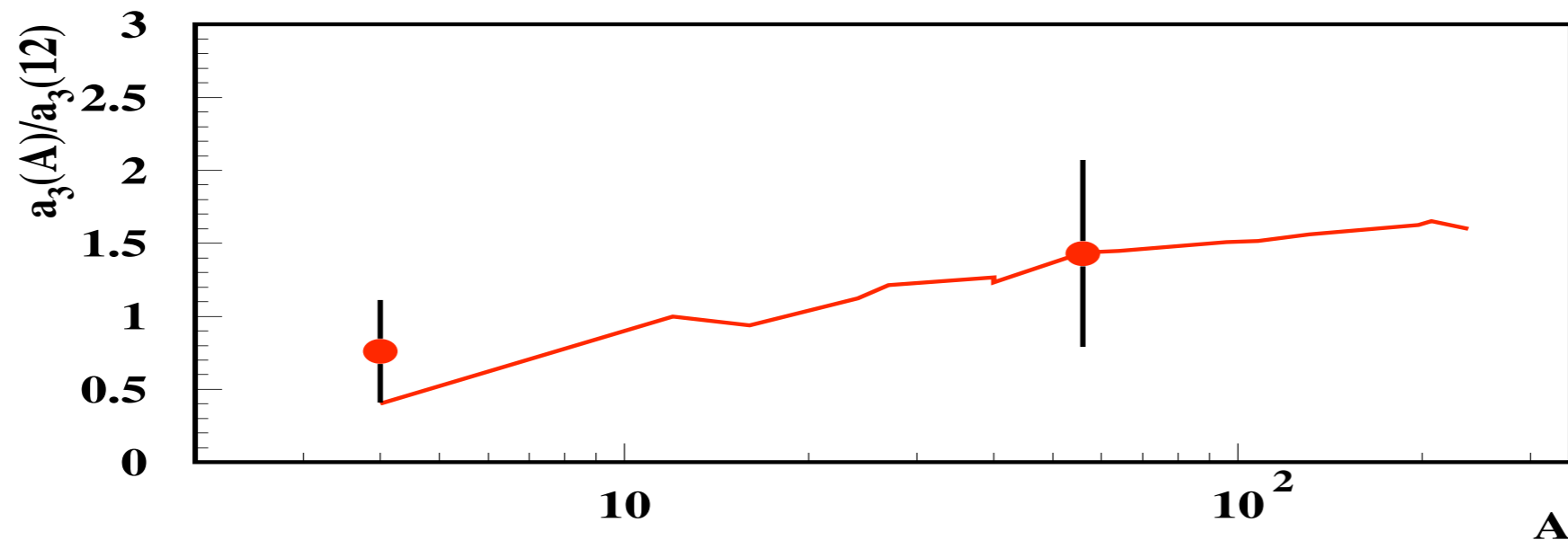
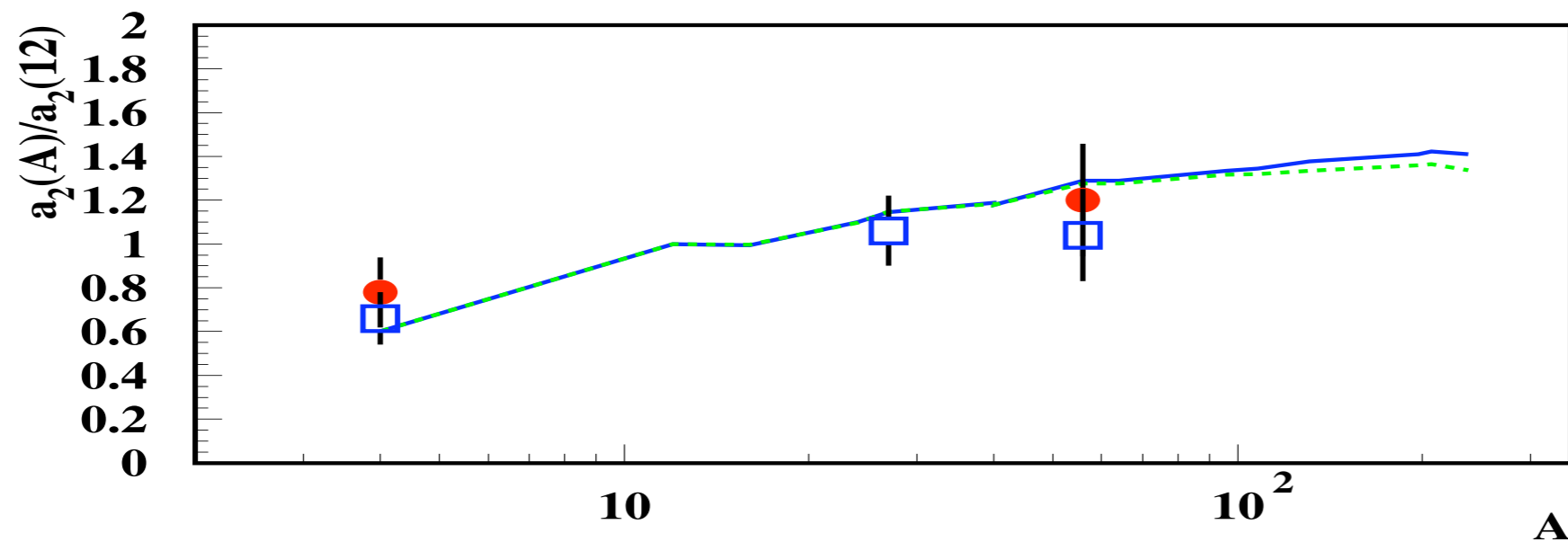
are they really fluctuations?



# Estimating density fluctuations

Frankfurt, MS, Strikman  
IJMA review, 2008

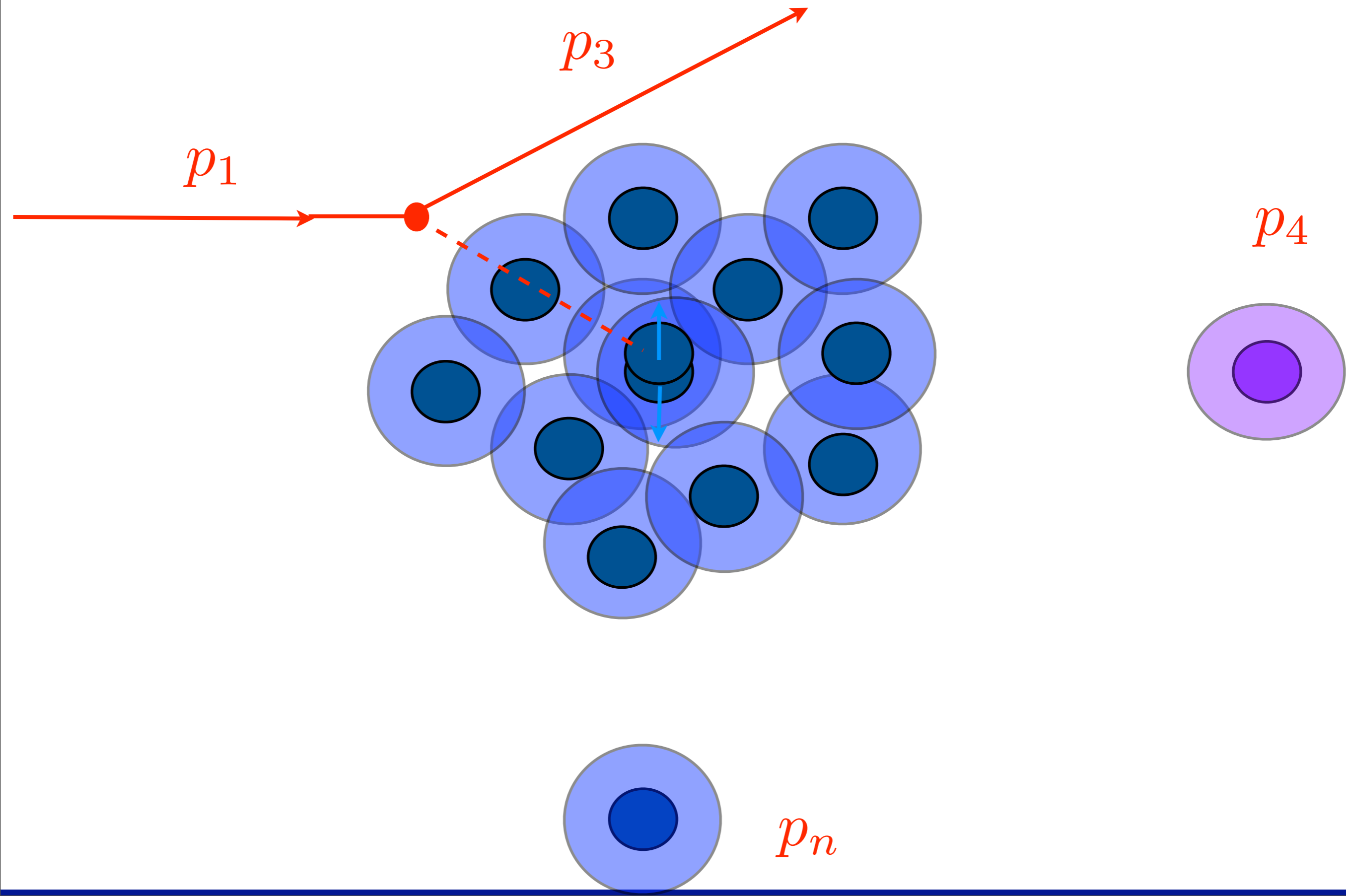
$$a_j(A) \propto \int \rho_A(r)^j d^3r \approx \int \rho_{A,mf}^j \left(1 + j \frac{\rho_{A,src}}{\rho_{A,mf}}\right) d^3r$$

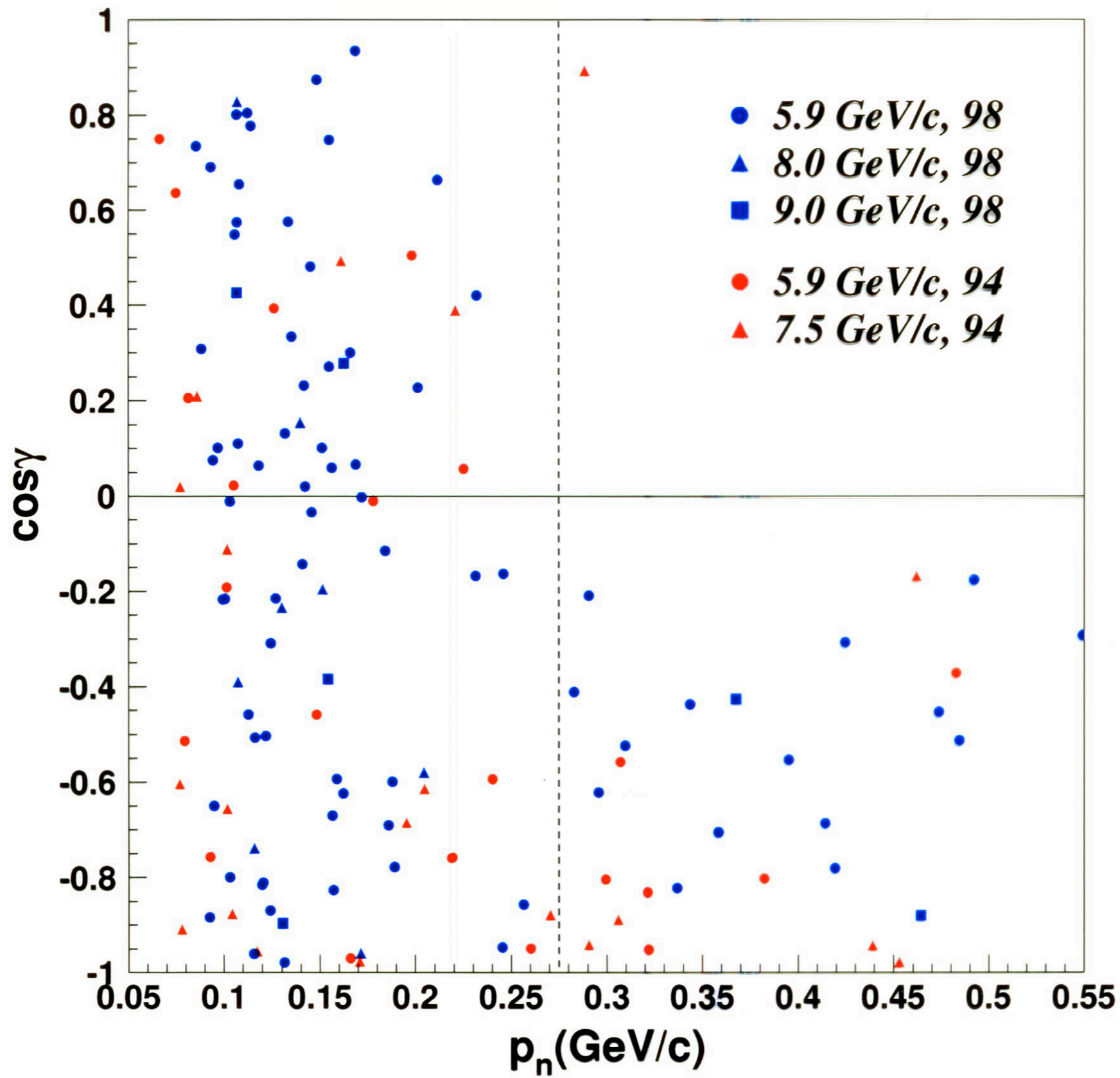


■ high energy inclusive probe at  $x > 1$  and large  $Q^2$   
can detect high density fluctuations

■ and measure their probabilities  $a_2(A)$   $a_3(A)$

# What are these correlations/fluctuations made of





A.Tang et al, PRL 2003

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

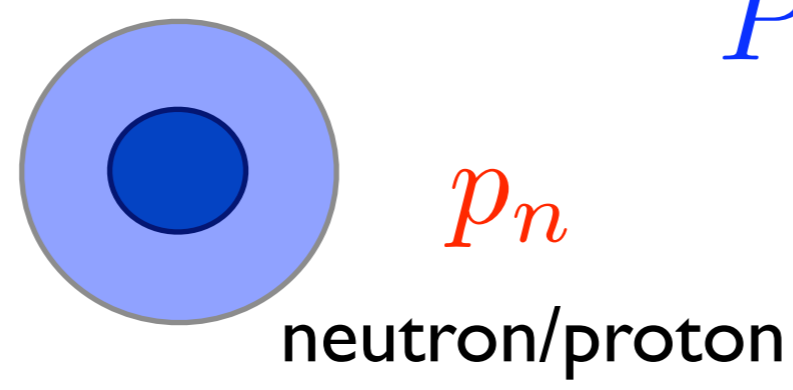
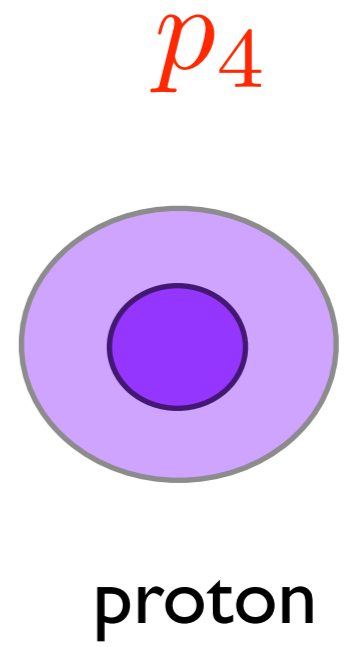
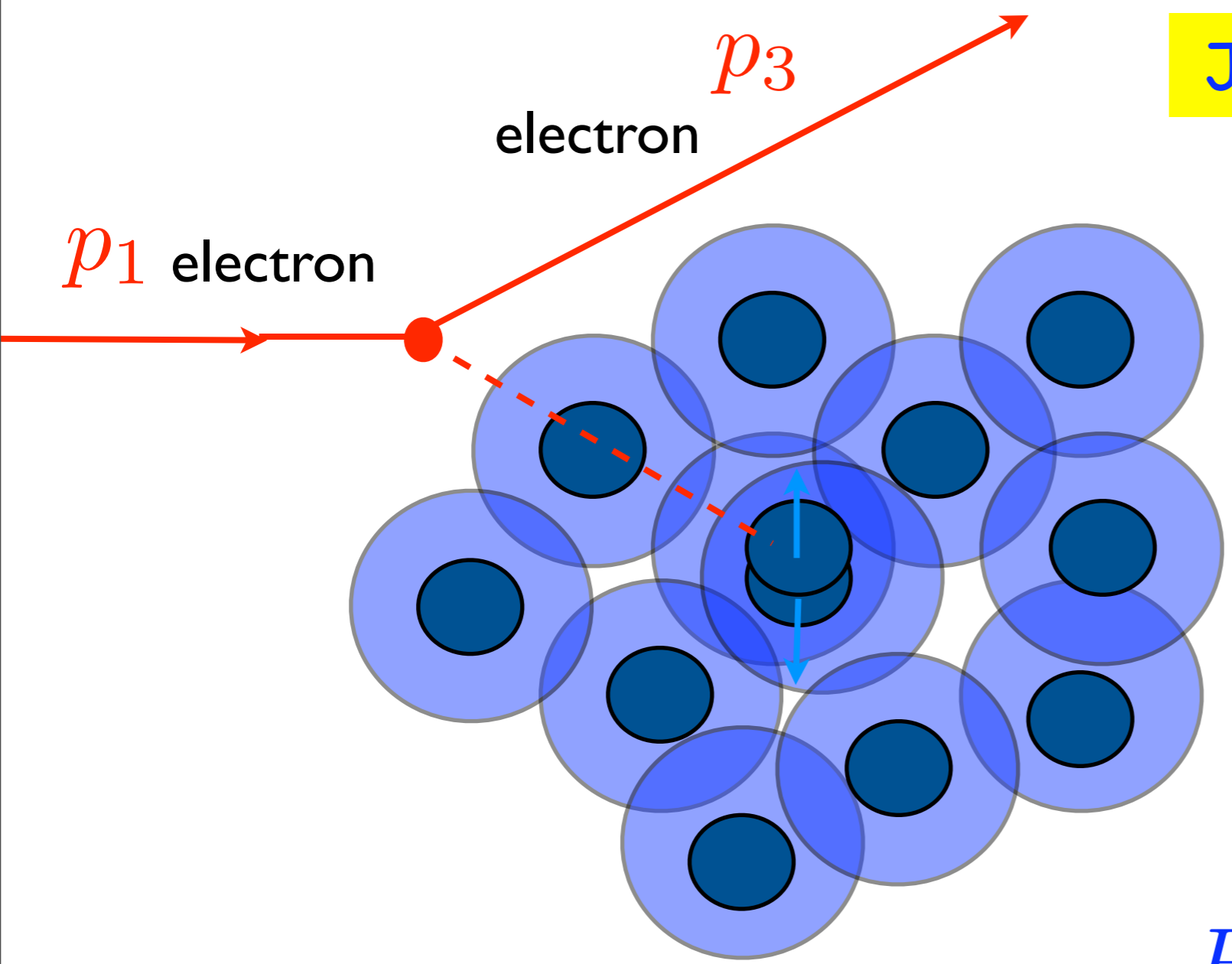
Piasezky, MS, Frankfurt,  
Strikman, Watson PRL 2007

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

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

# Jeferson Lab Experiment

R. Shneor et al. PRL 07

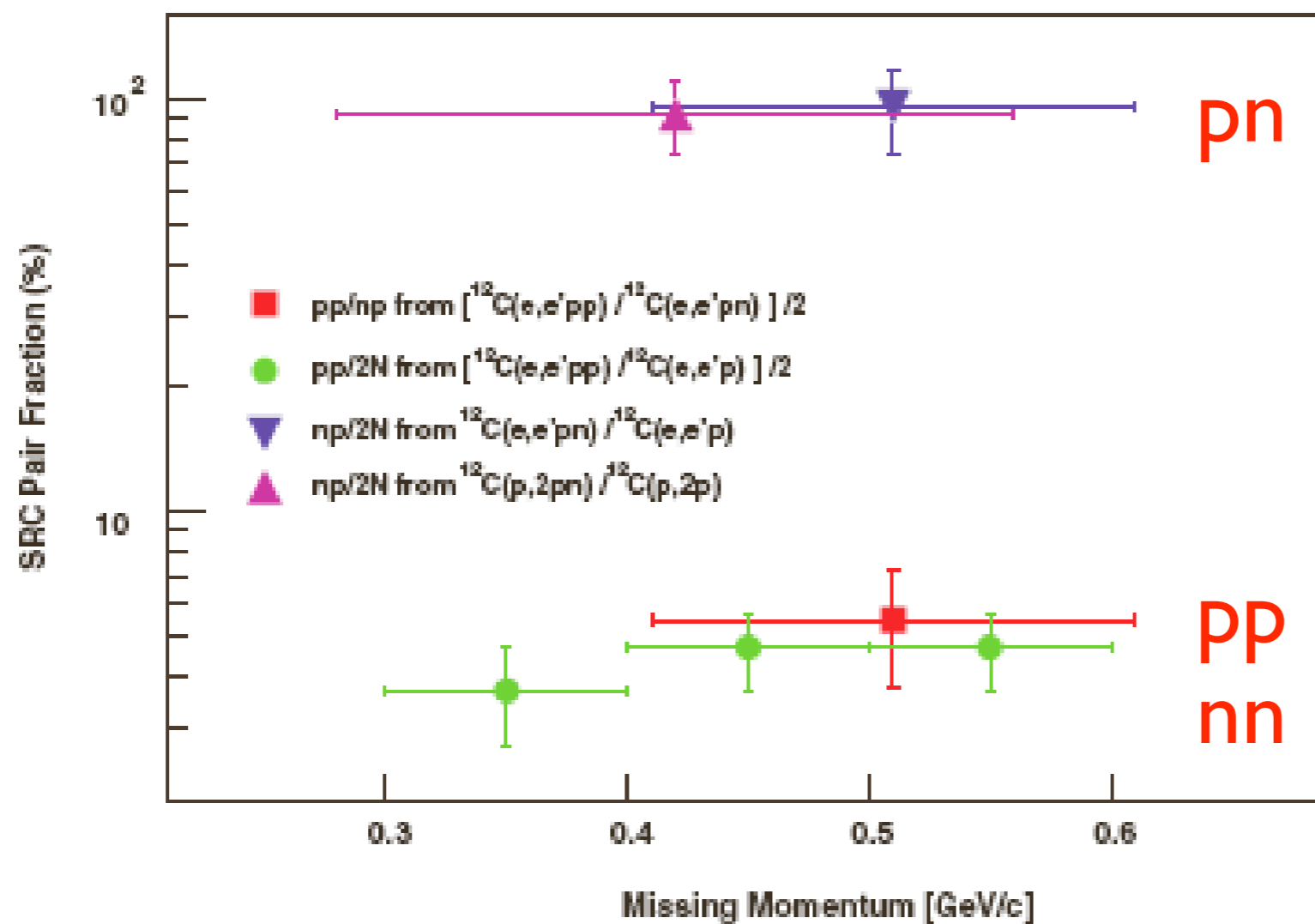


$$P_{pn/pX} = 0.96 \pm 0.22$$

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

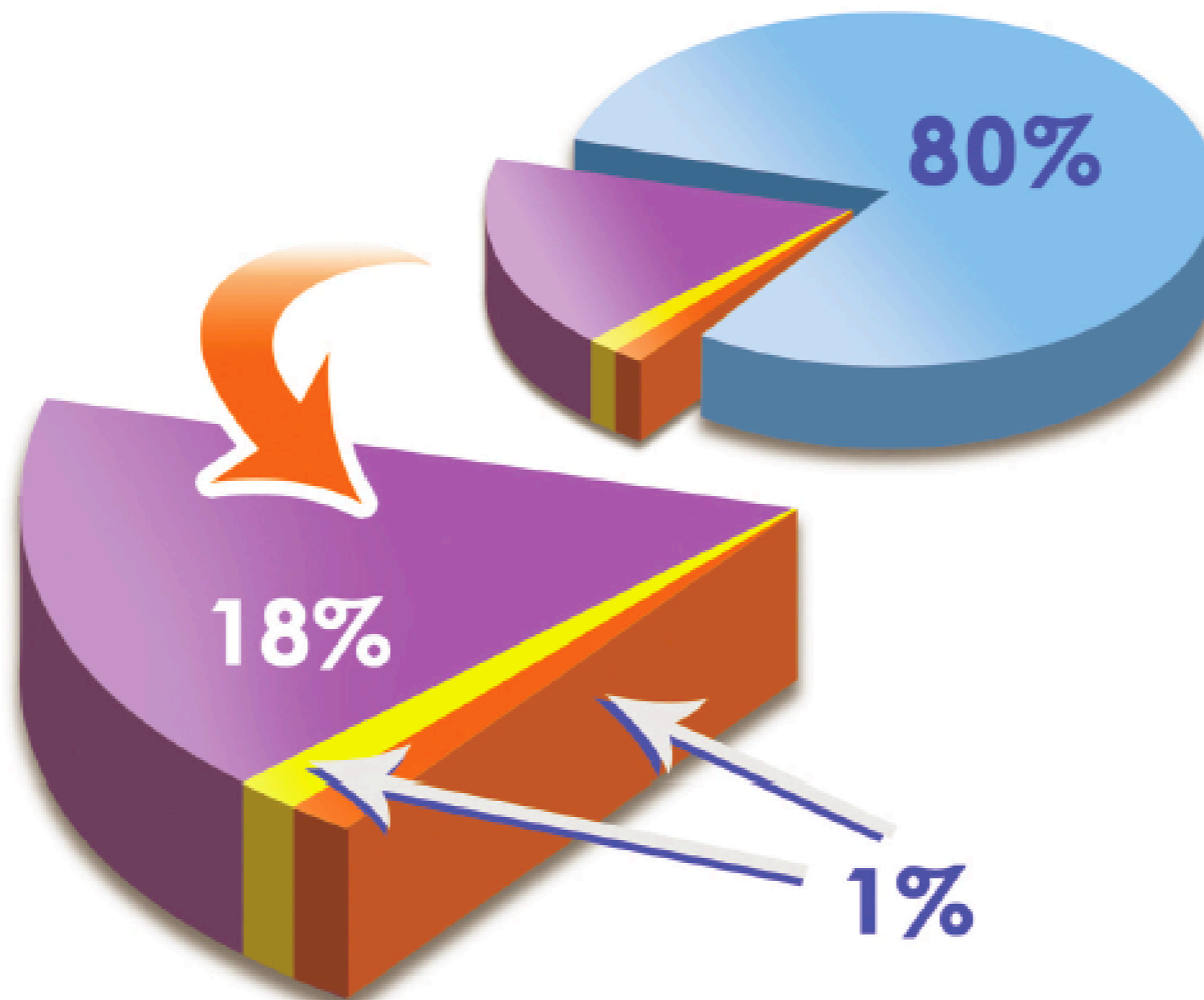
# Combined Analysis

R.Subdei, et al Science , 2008



# Combined Analysis

R.Subdei, et al Science , 2008



Single nucleons

n-p

n-n

p-p



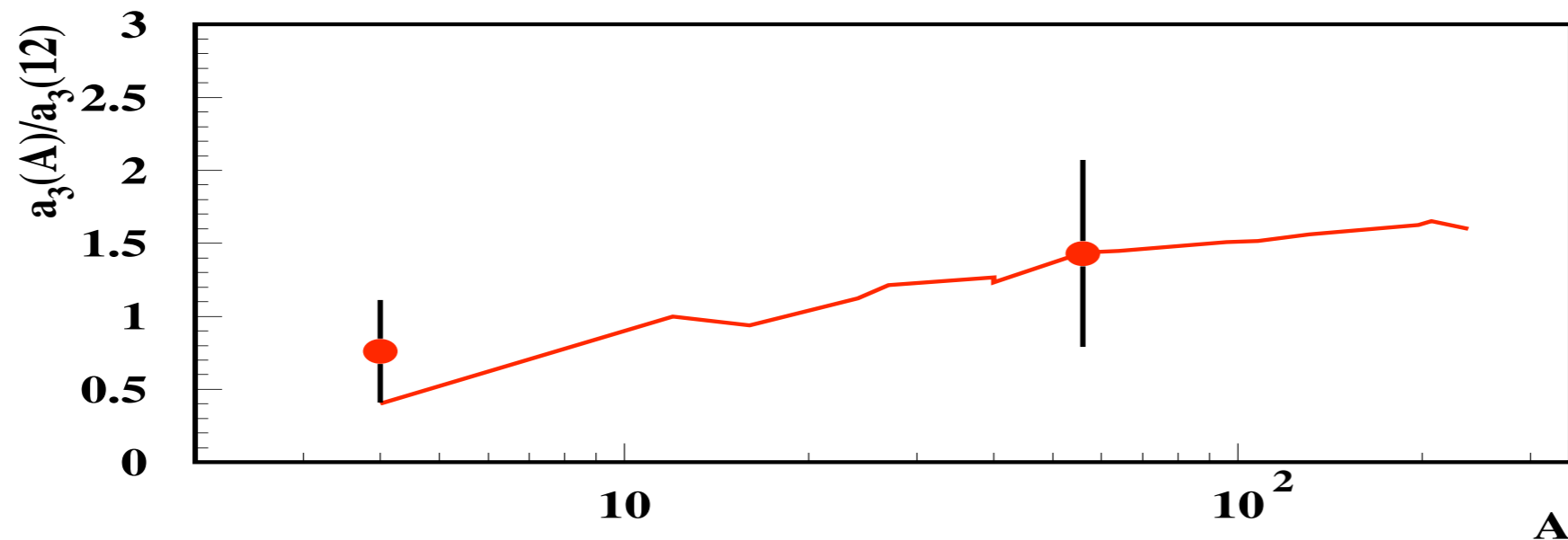
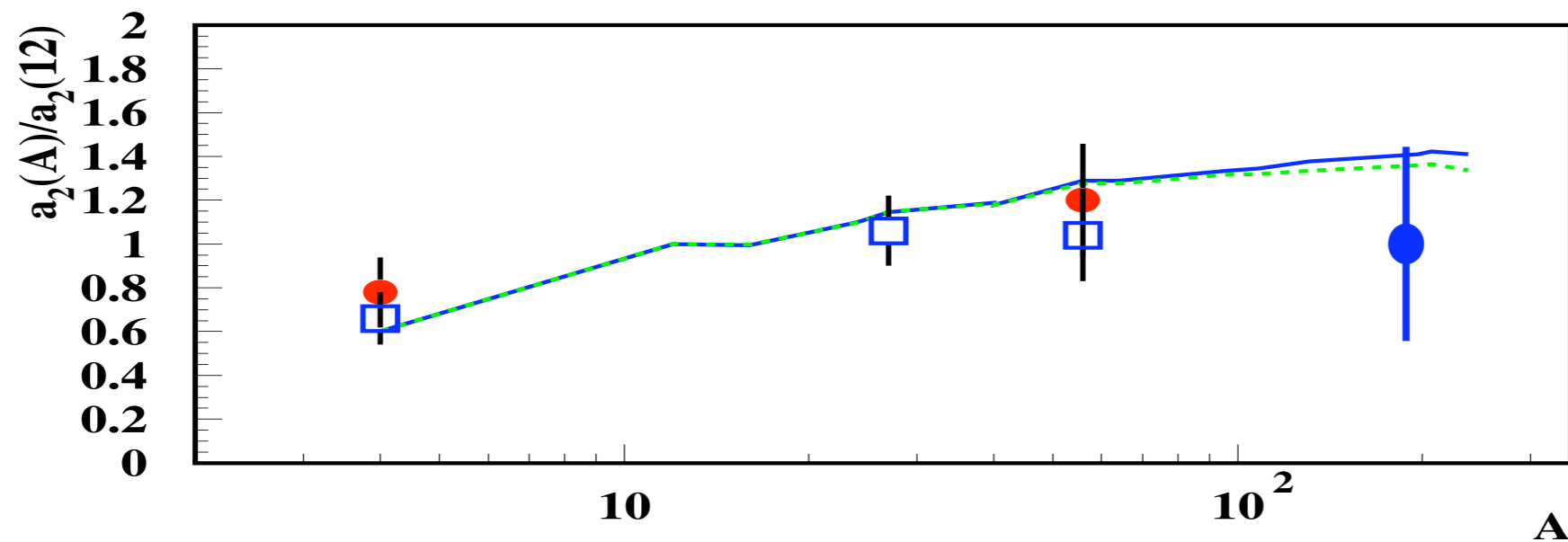
# What these observations suggest us for the future studies

- Drop of the magnitude of extracted  $a_2$  for neutron reach matter

# Estimating density fluctuations

Frankfurt, MS, Strikman  
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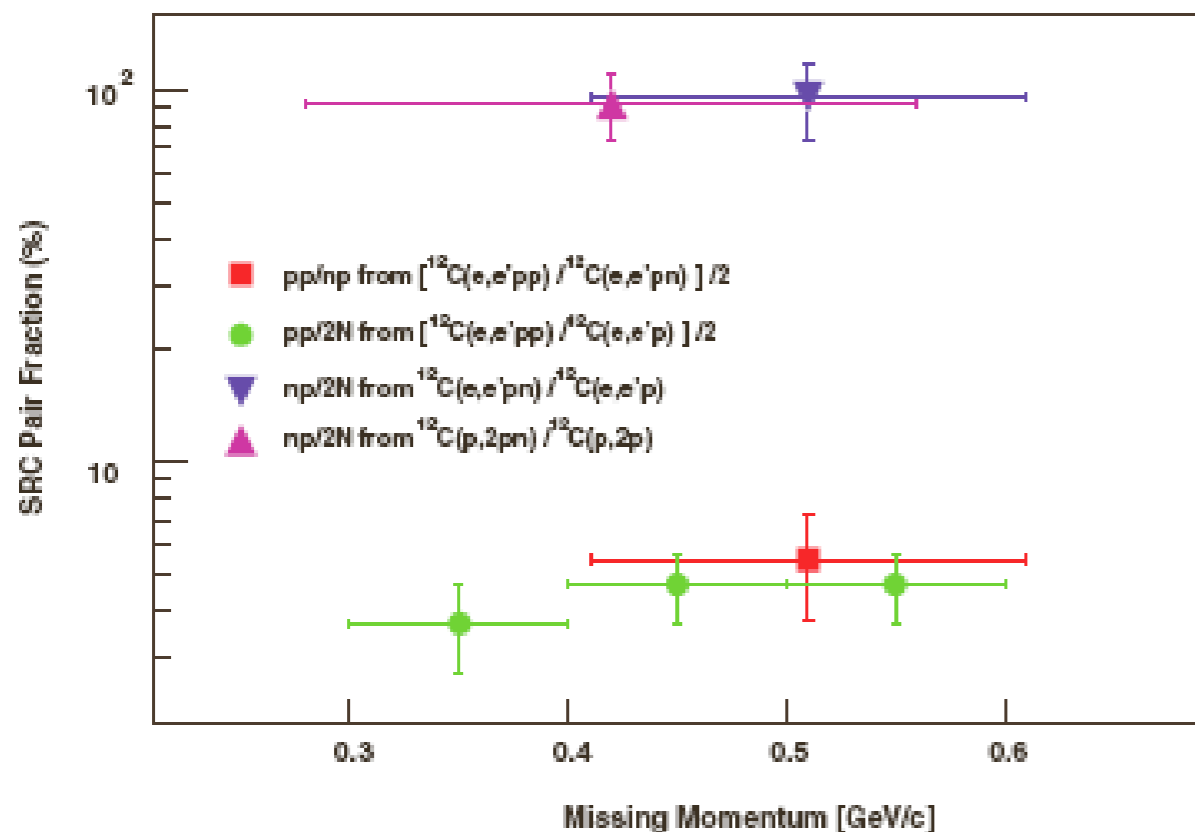
$$a_j(A) \propto \int \rho_A(r)^j d^3r \approx \int \rho_{A,mf}^j \left(1 + j \frac{\rho_{A,src}}{\rho_{A,mf}}\right) d^3r$$



# What these observations suggest us for the future studies

- Drop of the extracted  $a_2$  for neutron rich matter
- When the transition from hadronic to quark degrees of freedom in high density nuclear matter happens?

# Transition from hadronic to quark degrees of freedom in high density nuclear matter



$$P_{pn} + P_{pp} + P_{nn} = 1$$

as a function of initial momentum of nucleon

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

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

T=0 is dominant: inelasticities appear at

$$2(M_{\Delta} - M_N) \approx 300 \text{ MeV}$$

$$k \sim 700 \text{ MeV}/c$$

- Transition from hadronic to quark degrees of freedom in high density nuclear matter

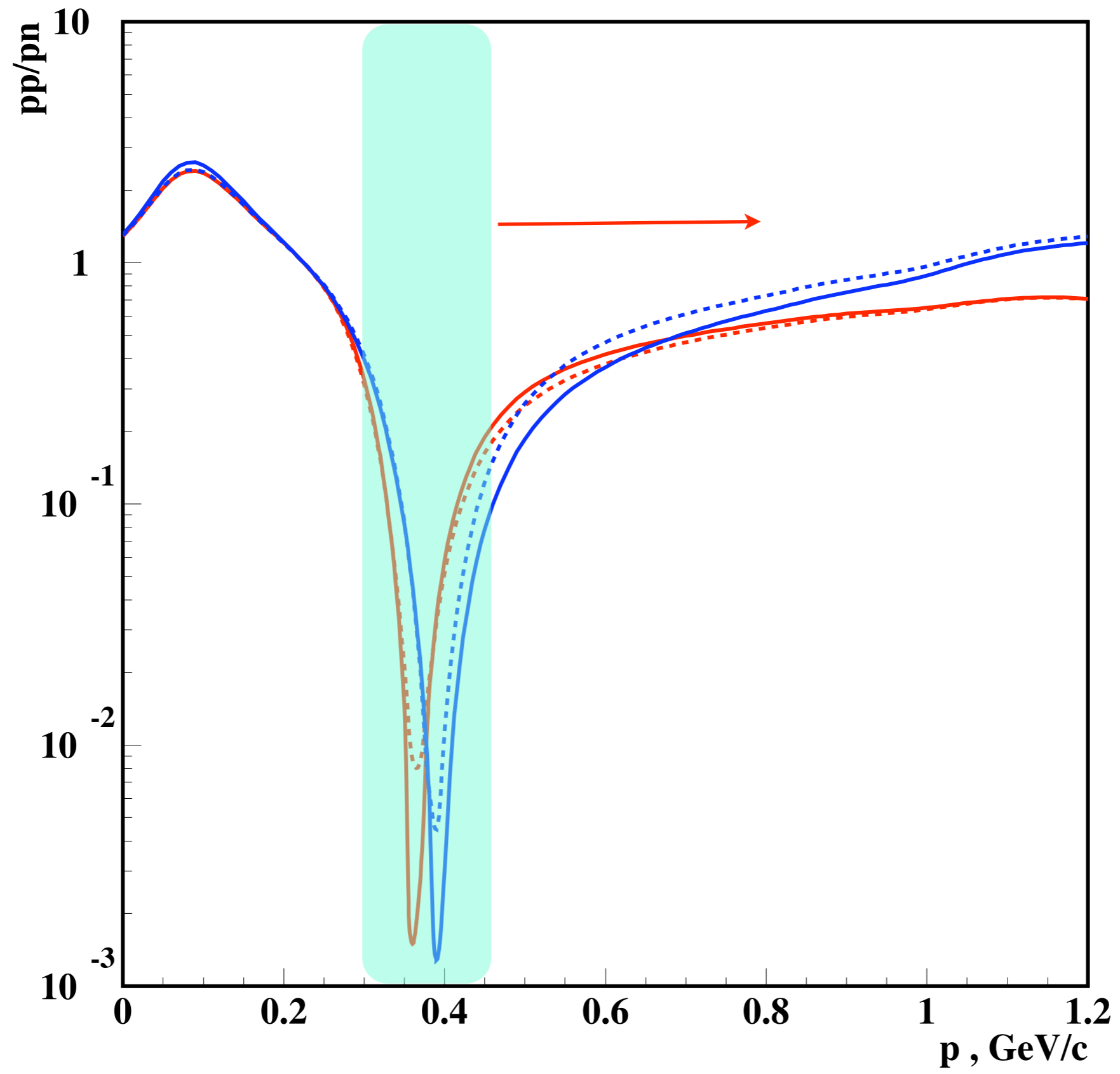
**Alternative measurements will be to measure  $P_{NX}$**

$$e + A \rightarrow e' + N + X_{back} + X'$$

$$X_{back} = \Delta, N^*, \dots$$

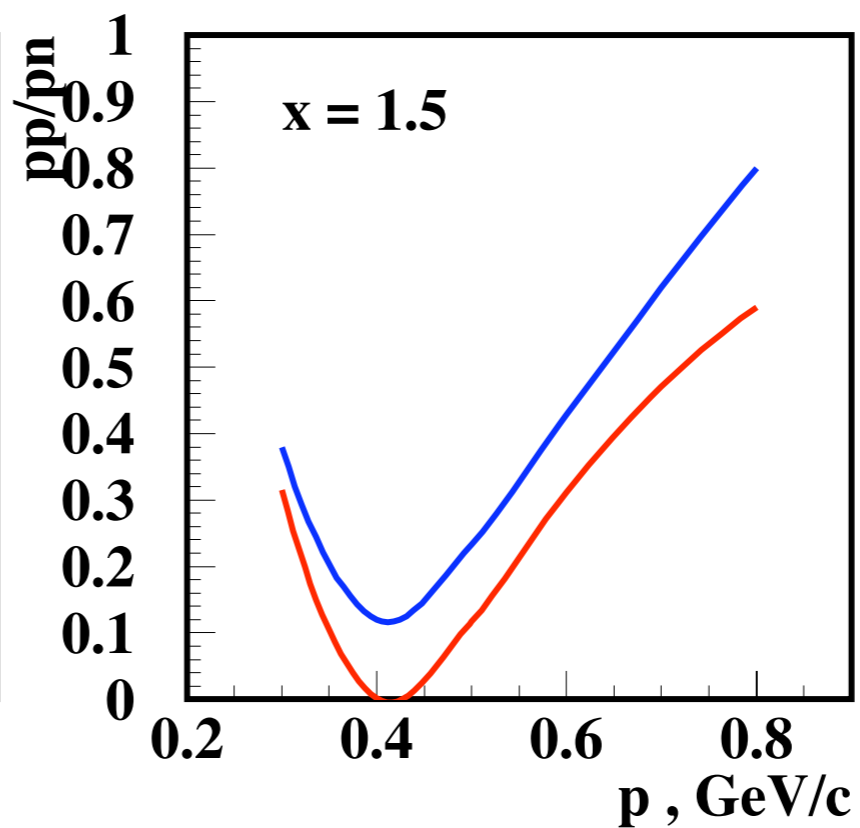
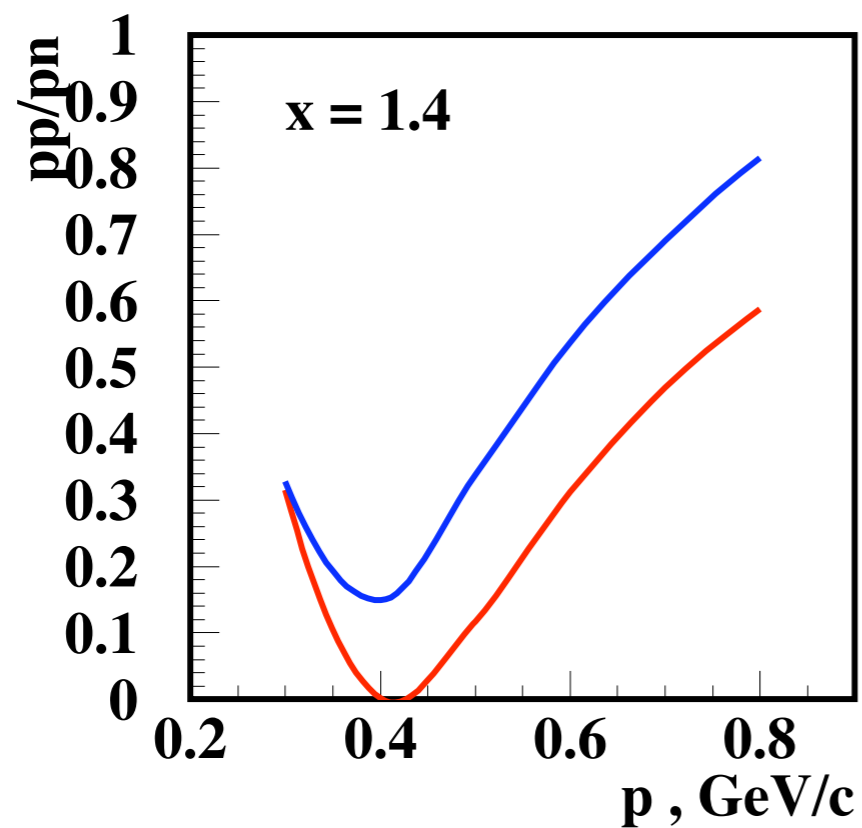
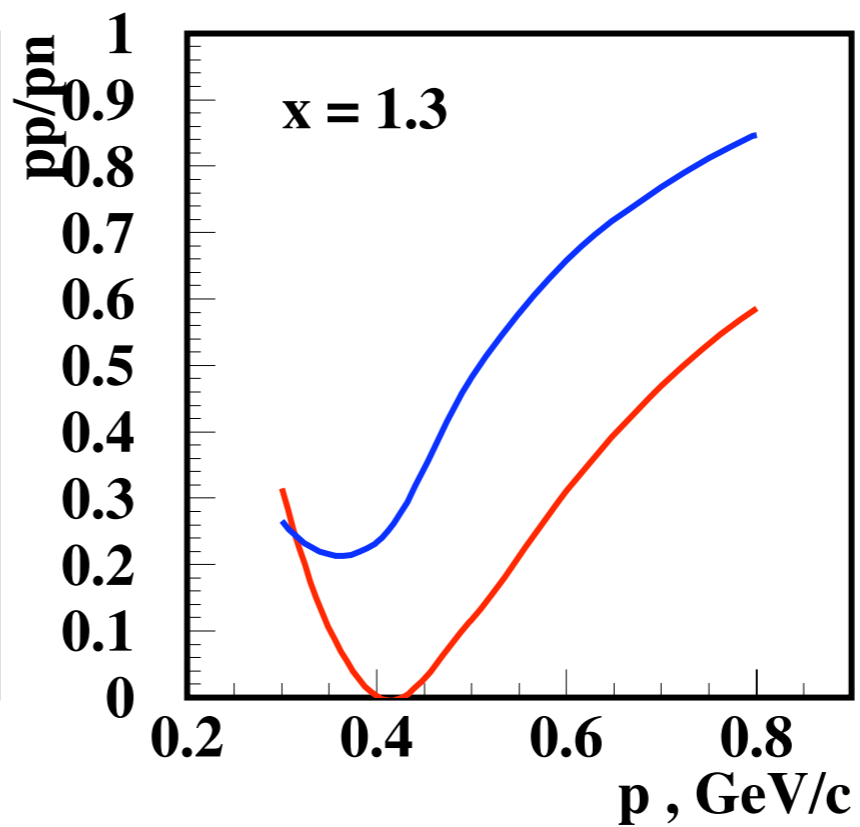
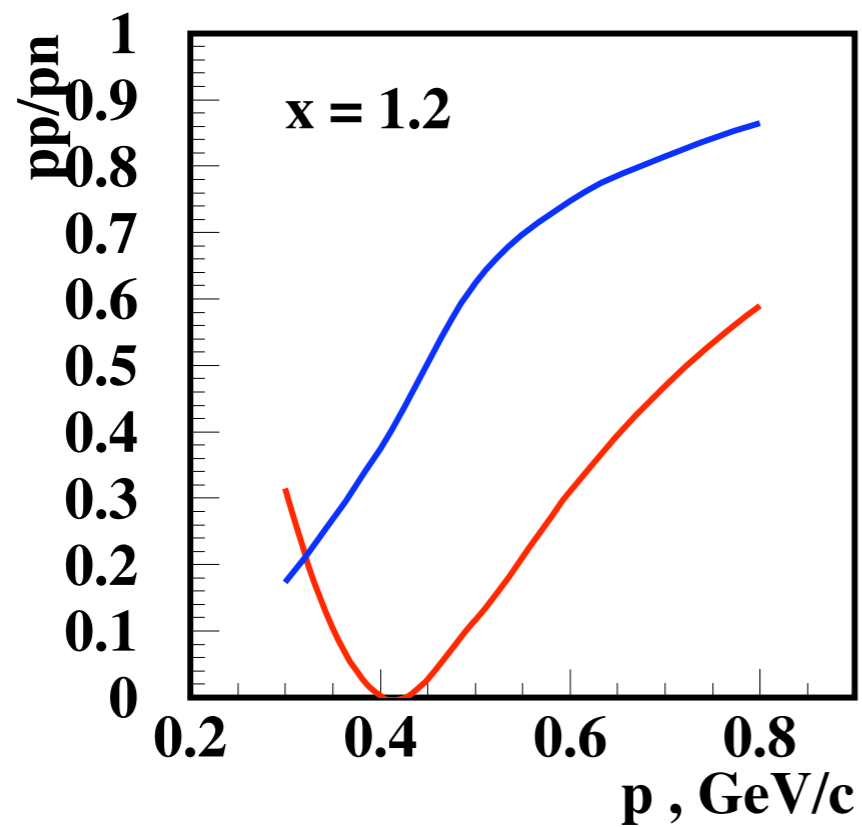
# What these observations suggest us for the future studies

- Drop of the extracted  $a_2$  for neutron rich matter
- When the transition from hadronic to quark degrees of freedom in high density nuclear matter happens?
- Studying the properties of the NN core



# For Quasielastic Channel

$$Q^2 = 2 \text{ GeV}^2$$





## For Inelastic Channel

$$e + d \rightarrow e' + R_{backward} + X$$

### Chiral Symmetry Restoration and Hidden Color Degrees of Freedom effects

In the world where chiral symmetry is broken the Deuteron ( $t=0$  and  $S=1$ ) consists of two separately color neutral nucleons

*In the world where chiral symmetry is unbroken*

$$\psi_{t=0,s=1}^{6q} = \sqrt{\frac{1}{9}}\psi_{NN} + \sqrt{\frac{4}{45}}\psi_{\Delta\Delta} + \sqrt{\frac{4}{5}}\psi_{CC}$$

$$e + d \rightarrow e' + \Delta(N)_{backward} + X$$

$$\frac{yield_{\Delta_{back}}}{yield_{N_{back}}} \text{ from few \% to 1}$$

with an increase of internal momentum in the deuteron

$$e + d \rightarrow e + \pi_{back}(K_{back}) + N + X$$

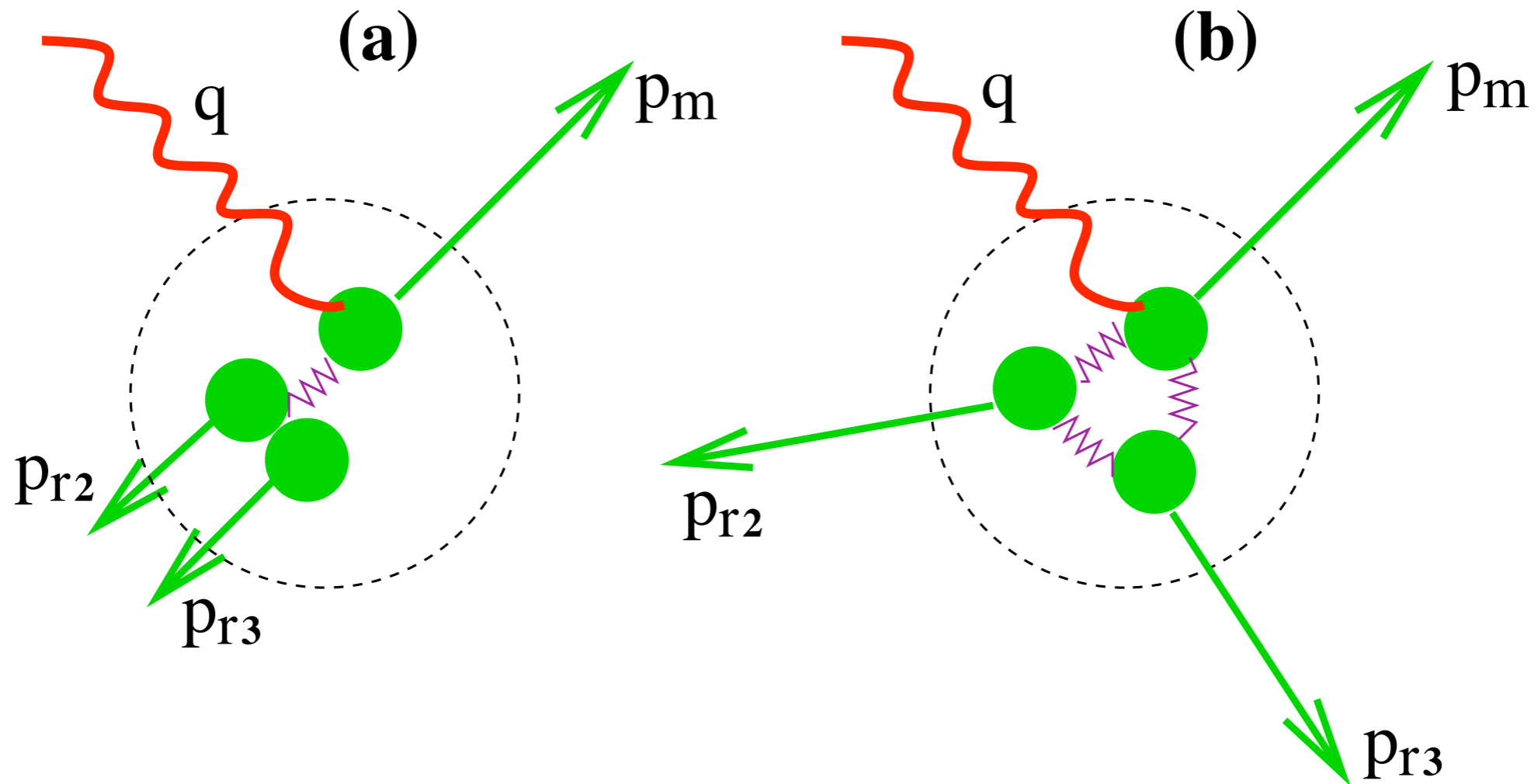
$$\frac{yield_{K_{back}}}{yield_{\pi_{back}}} \text{ from few percent} \rightarrow 1$$

with an increase of internal momentum in the deuteron

# What these observations suggest us for the future studies

- Drop of the extracted  $a_2$  for neutron rich matter
- When the transition from hadronic to quark degrees of freedom in high density nuclear matter happens?
- Studying the properties of the NN core
- Studying NNN correlations

# Studying the properties of the NN core

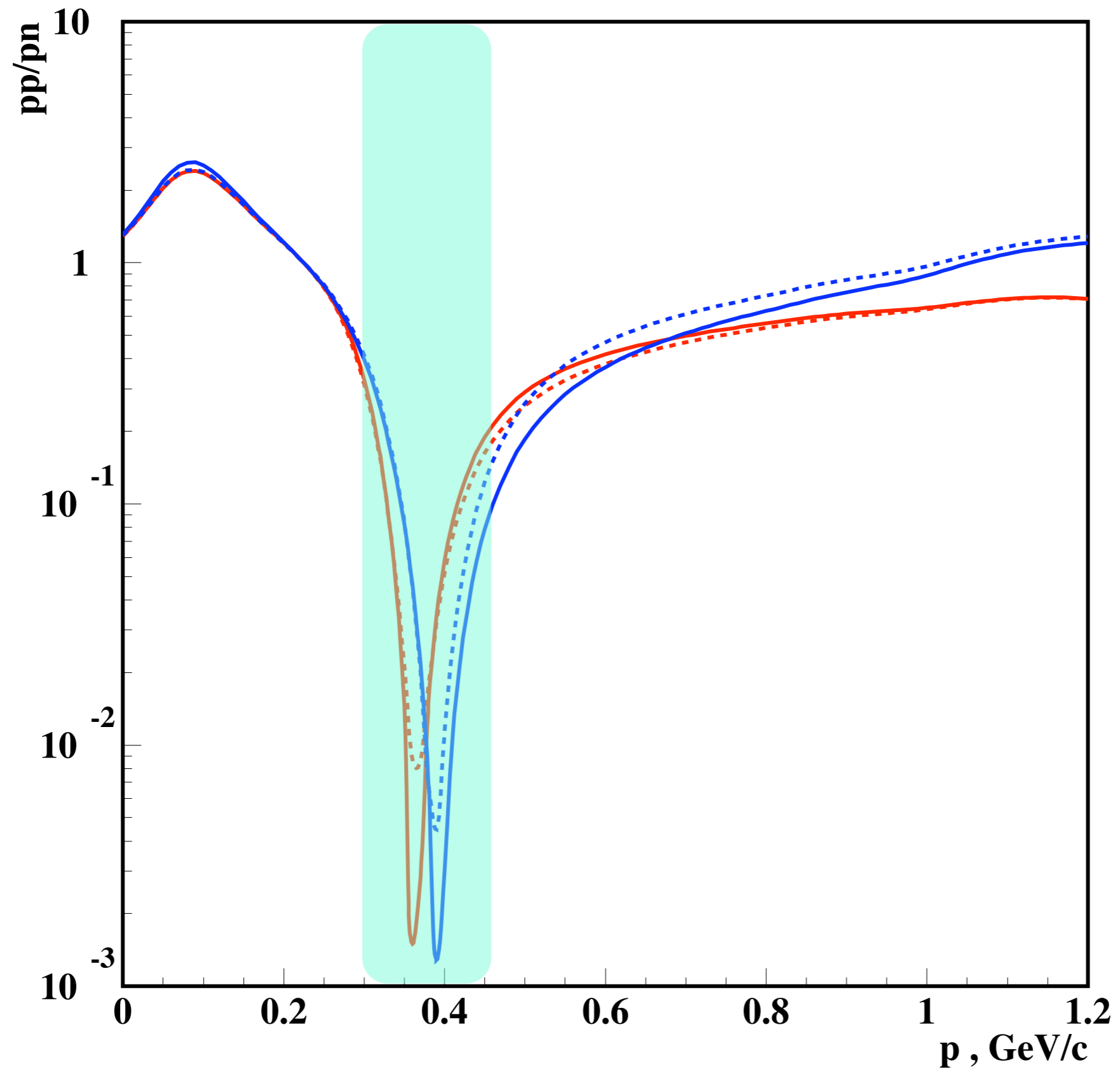


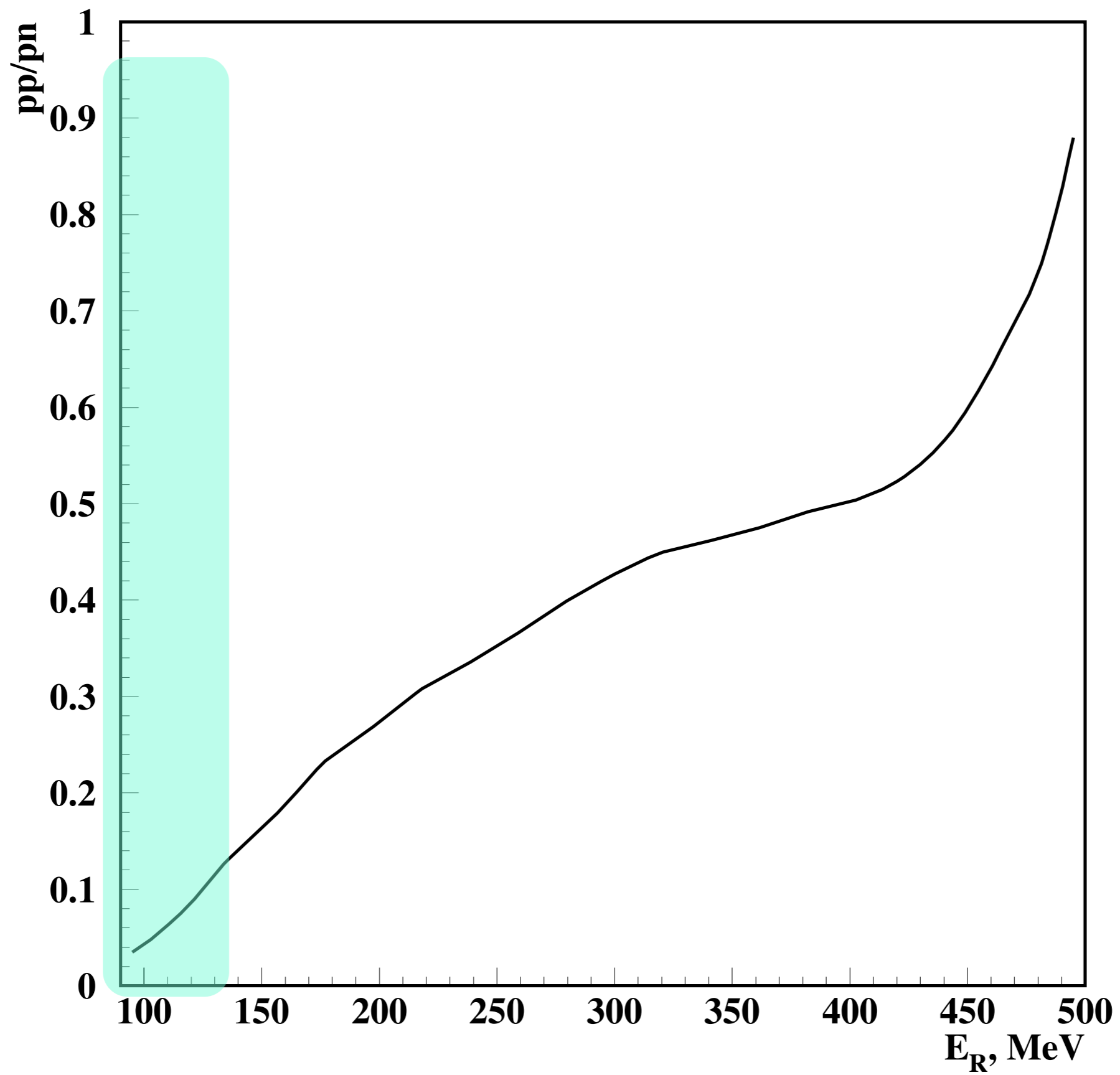
Measuring large

$p_{NN,cm}$

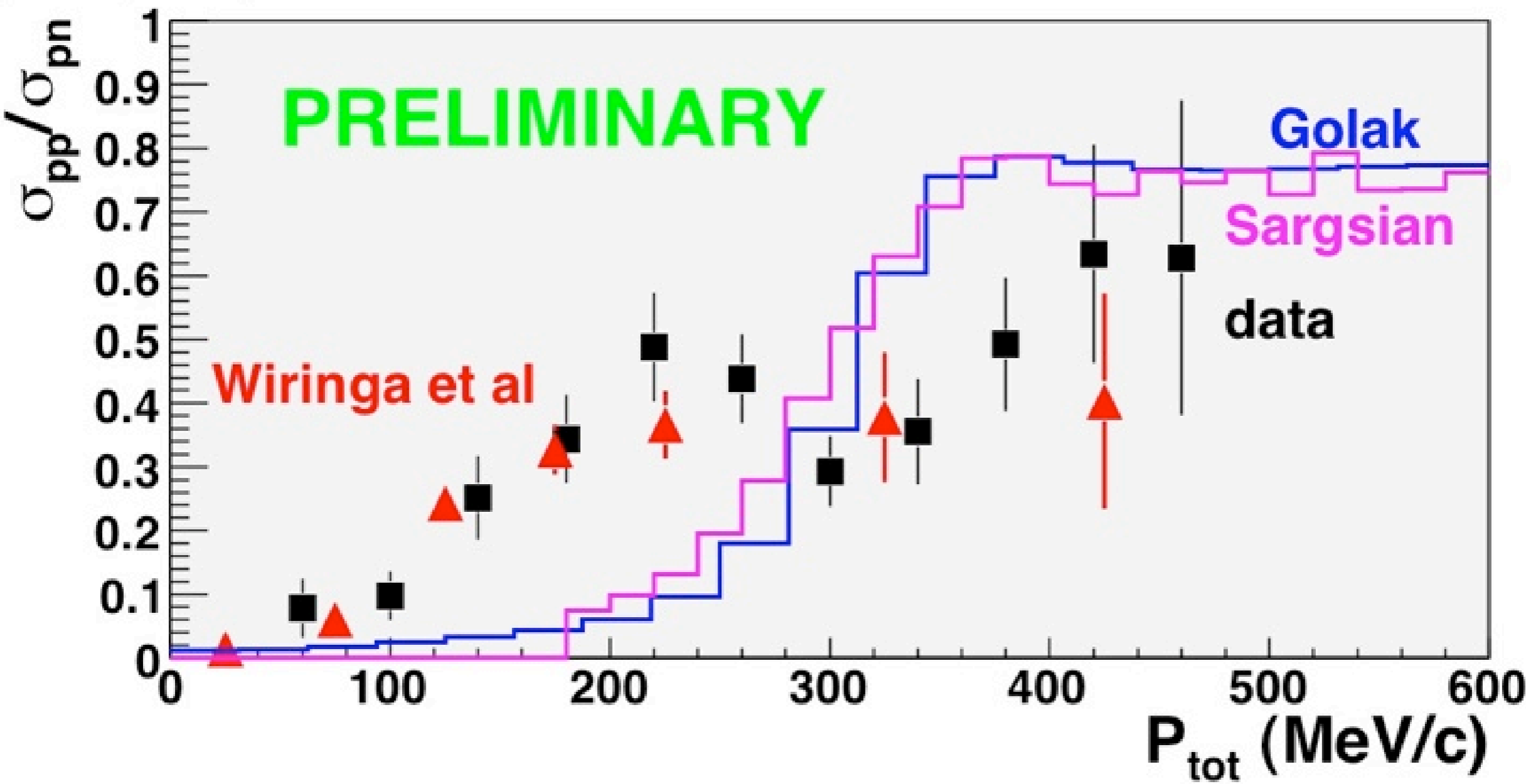
or

$E_R$





$0.3 < P_{rel} < 0.5$



L. Weinstein

## High Density Nuclear Physics

- Short Range Nucleon Correlations
- Nuclear DIS at  $x > 1$

## Properties of QCD from Nuclear Medium

- Modification of Bound Nucleon Structure - EMC effect
- **Color Transparency**
- Hadronization
- Signatures of Chiral Symmetry Restoration

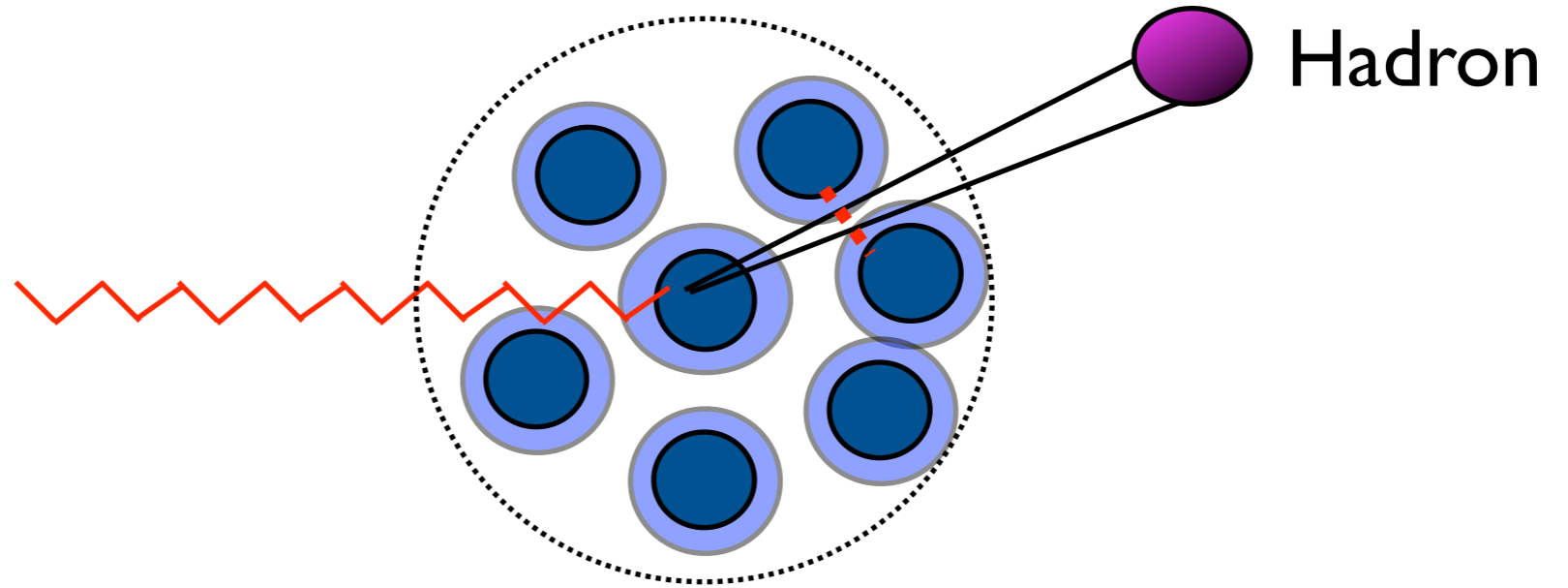
## QCD Dynamics of Hadronic Interaction

- hard break-up of hadrons from the light nuclei
- quasireal secondary Hadronic "Beams"

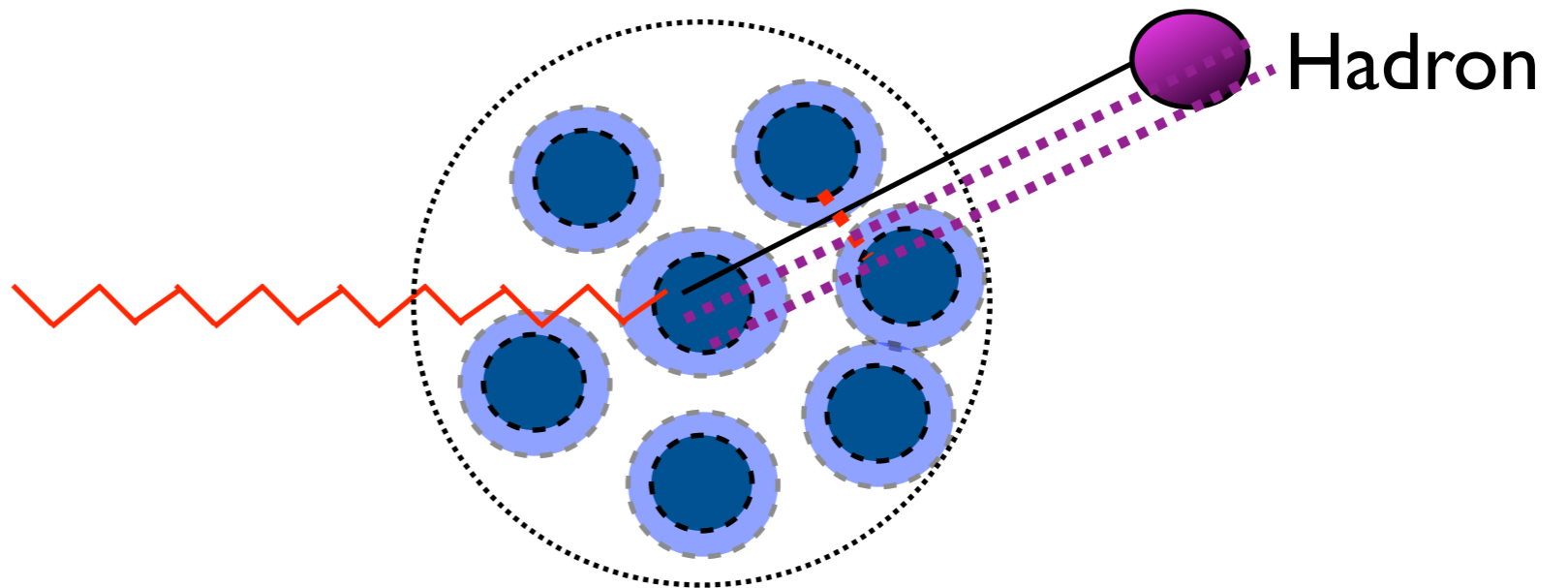


# Color Transparency

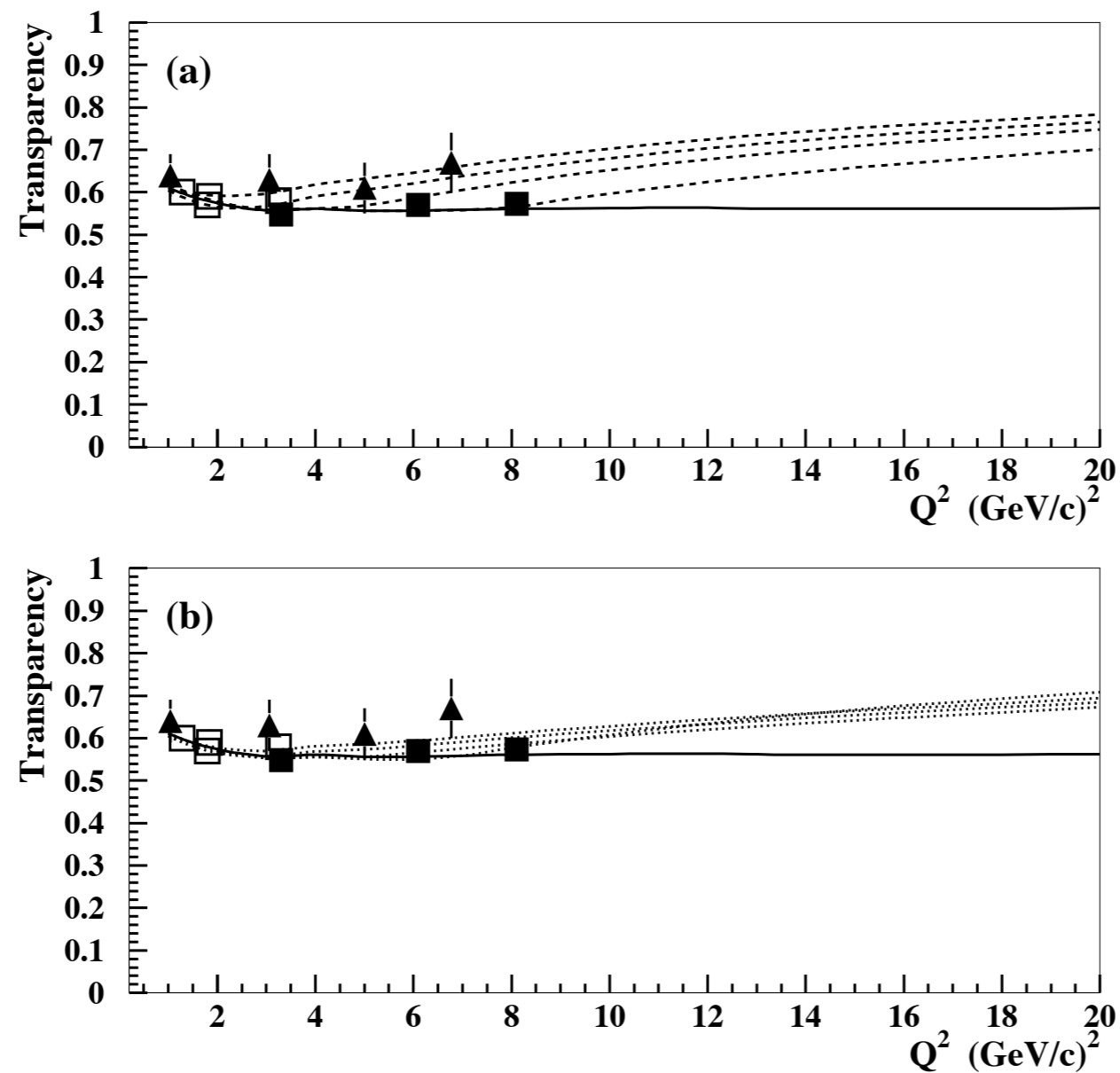
Minimal Fock  
Component



Feynman Mechanism

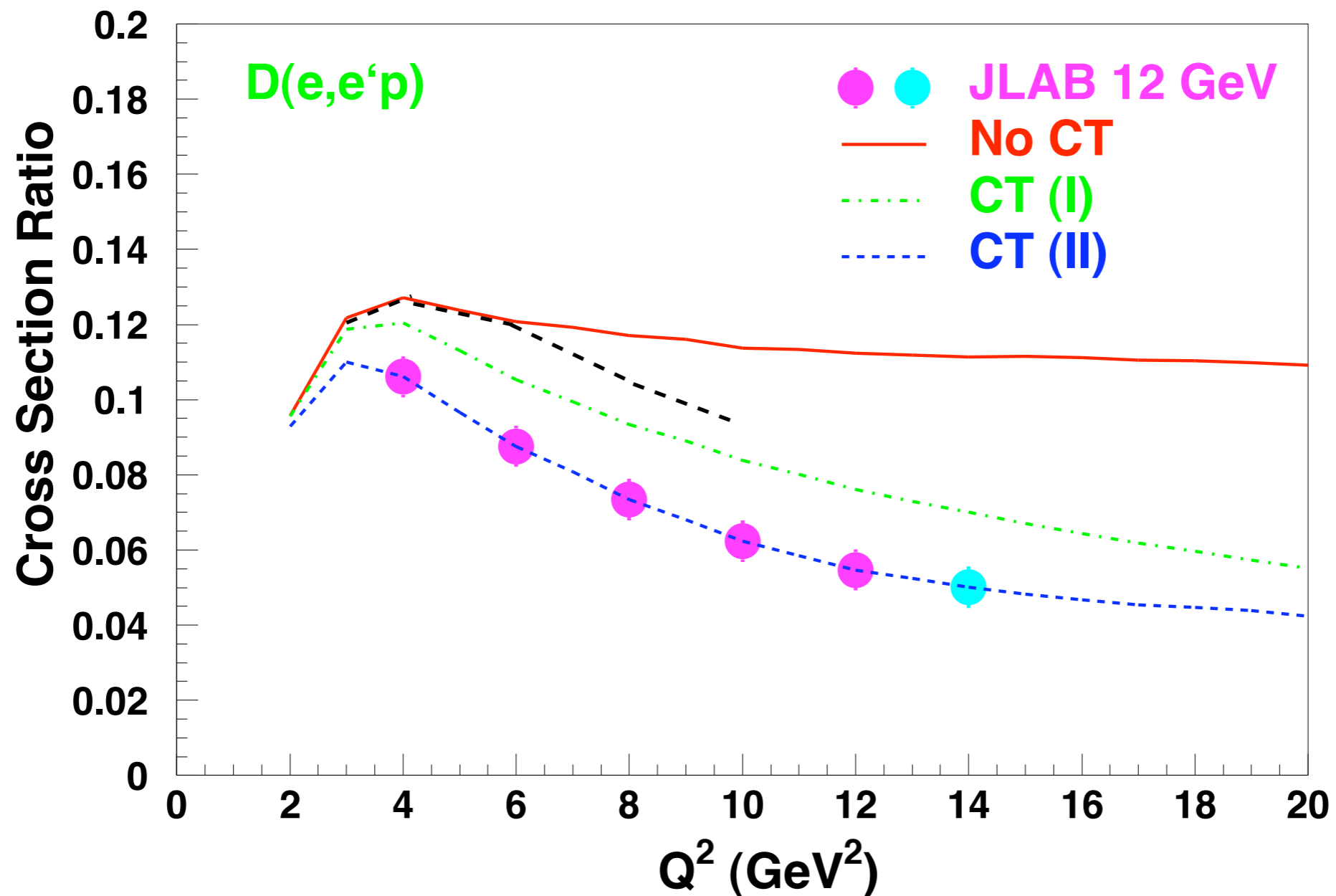


# Color Transparency as an increased probability for produced hadron to propagate the nuclear medium unscattered



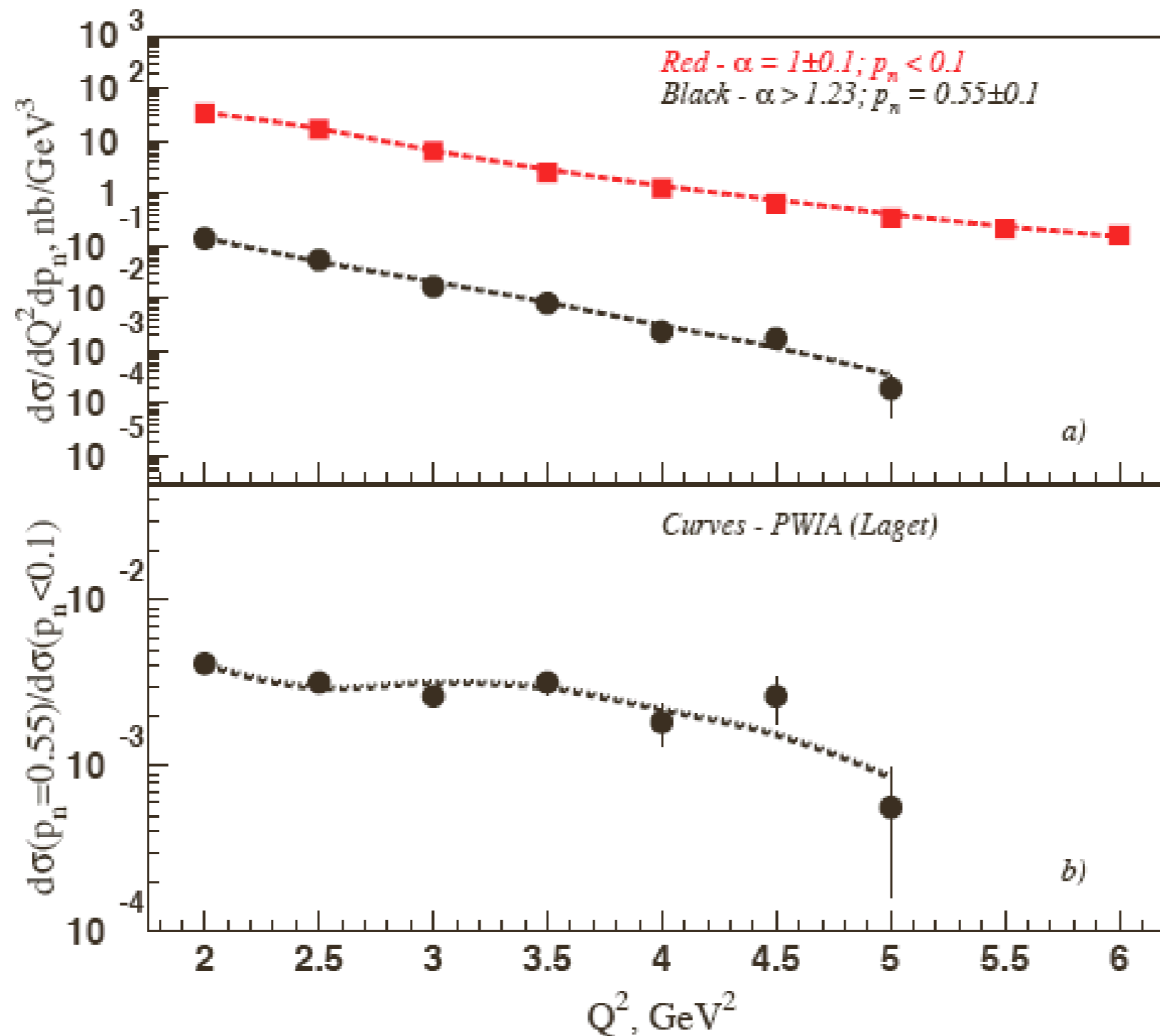
**Figure 14.** The  $Q^2$ -dependence of  $T$ . The solid line is the prediction of the Glauber approximation. In (a) dashed curves correspond to the CT prediction with  $\Delta M^2 = 0.7 \text{ GeV}^2$  and with  $Q_0^2 = 1$  (upper curve), 2, 4, 6 and 8  $\text{GeV}^2$  (lower curve). In (b) dotted curves correspond to the CT prediction with  $\Delta M^2 = 1.1 \text{ GeV}^2$  and with  $Q_0^2 = 1$  (upper curve), 2, 4 and 6  $\text{GeV}^2$  (lower curve). All calculations are normalized to the data at  $Q^2 = 1 \text{ GeV}^2$ . The data are the same as in Fig. 13.

Color Transparency as a **decreased** probability for produced hadron to propagate the nuclear medium being **rescattered**

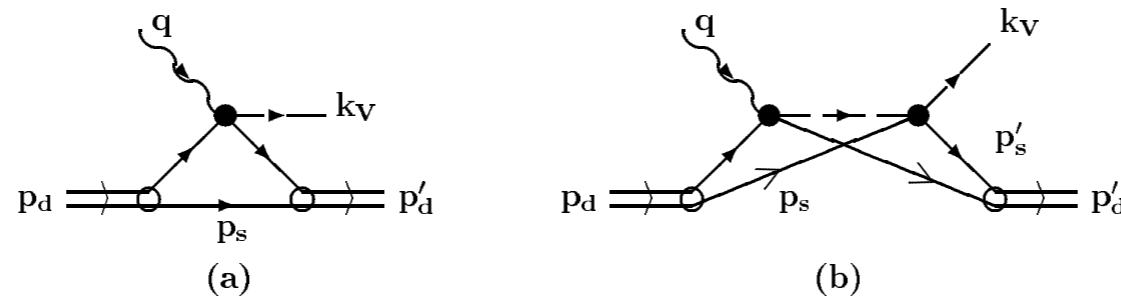


# Q<sup>2</sup> dependence of d(e,e'p)n

## Preliminary

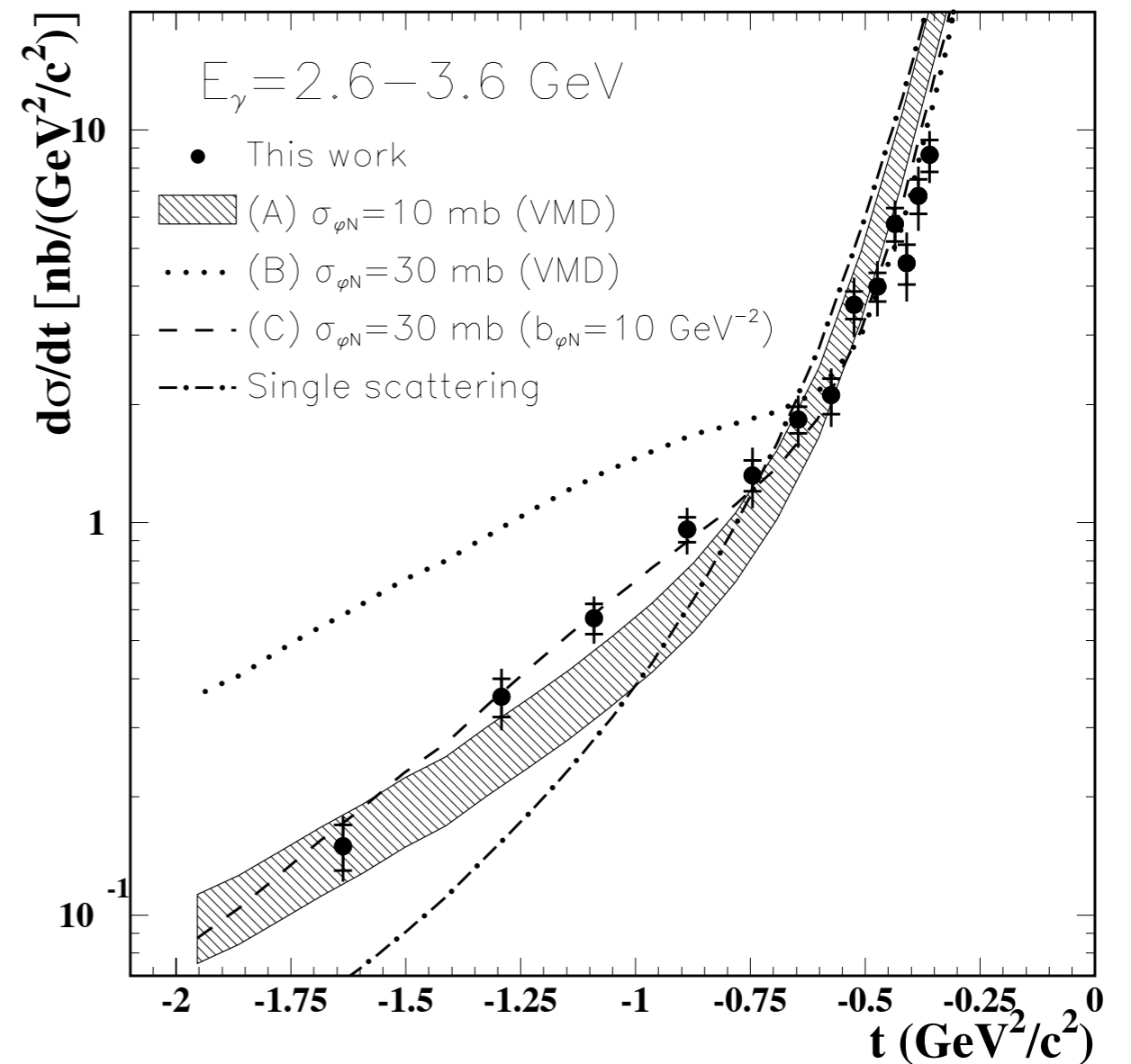
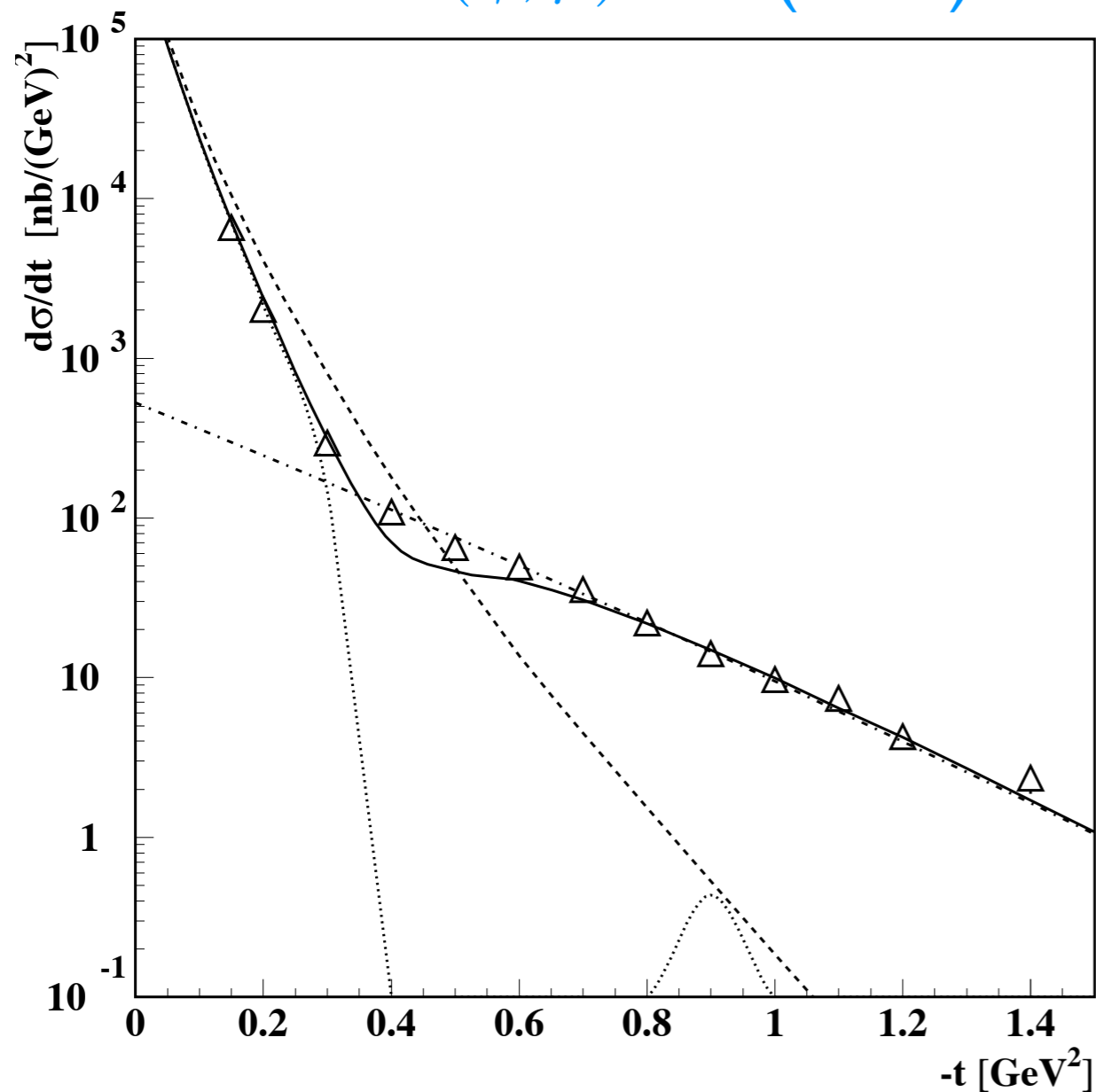


# Q2 dependence of $d(e,e'\nu)d'$ at large $-t$

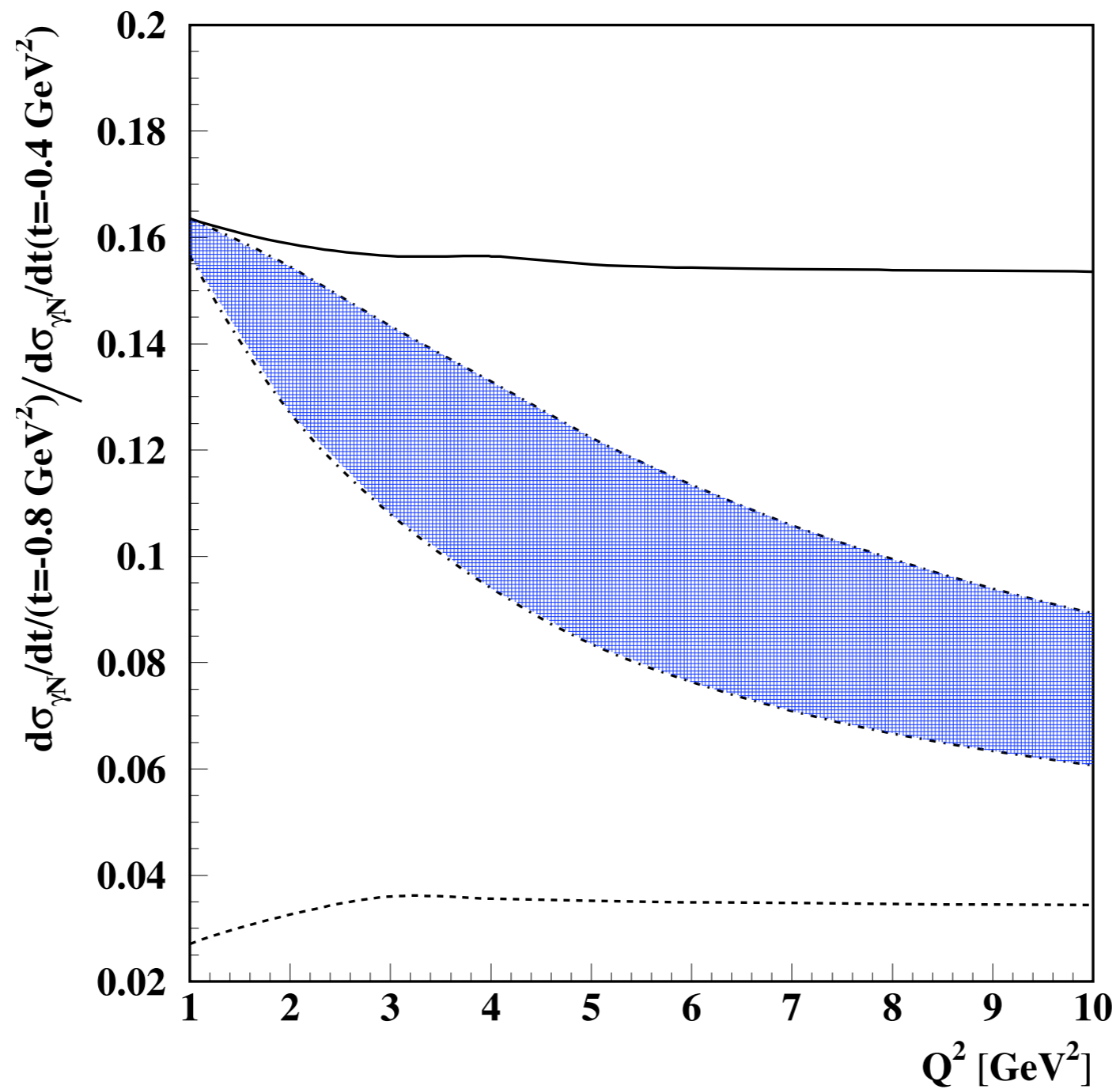


$d(\gamma, \rho)d'$  (1971)

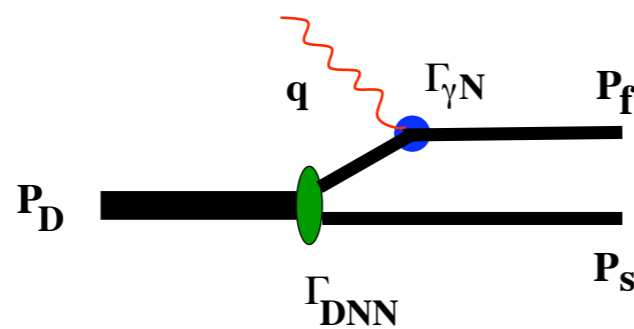
$d(\gamma, \phi)d'$  (2007)



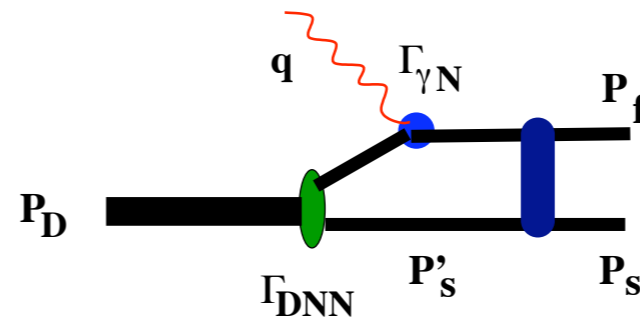
# $Q^2$ dependence of $d(e,e'\nu)d'$ at large $-t$



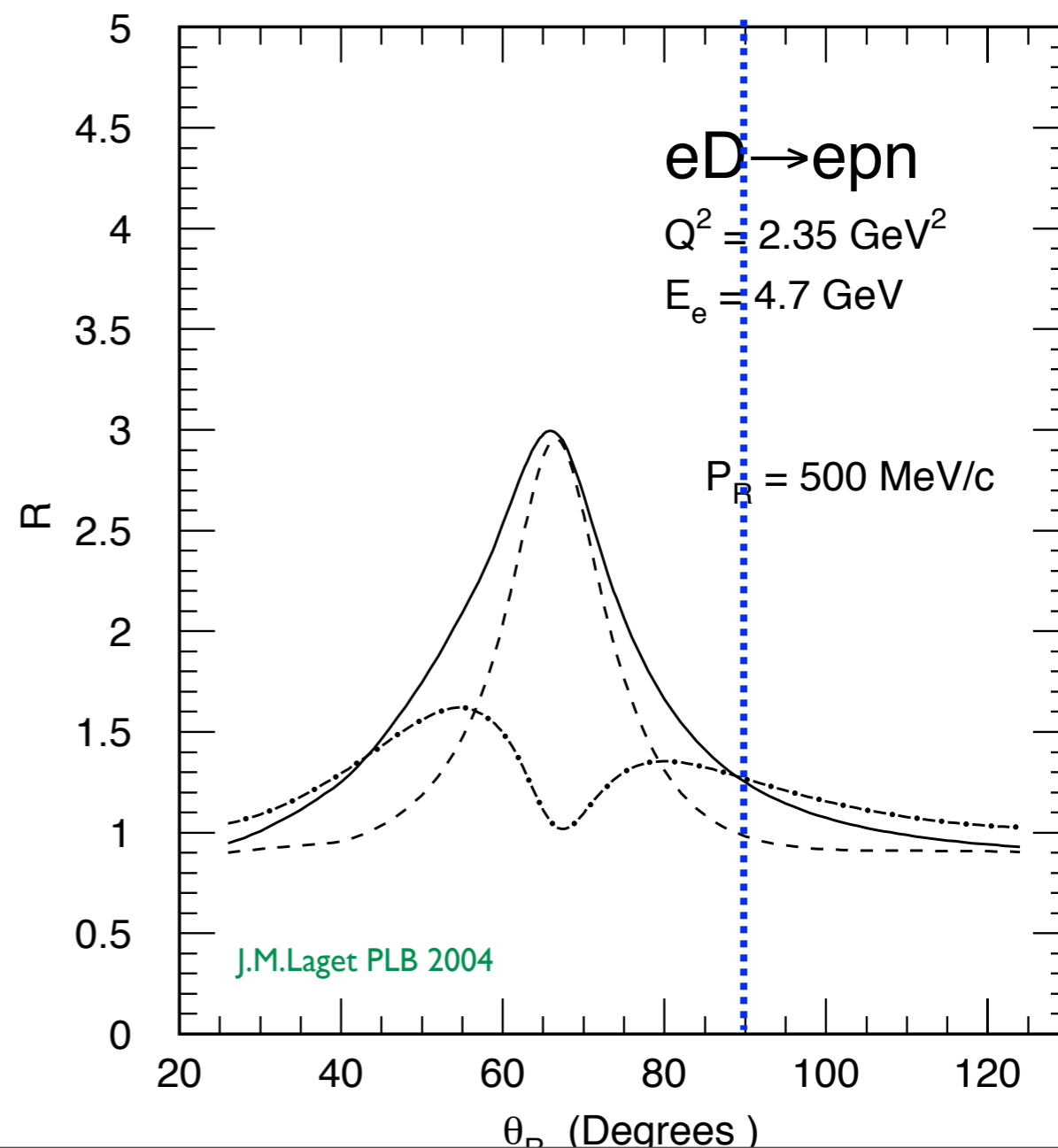
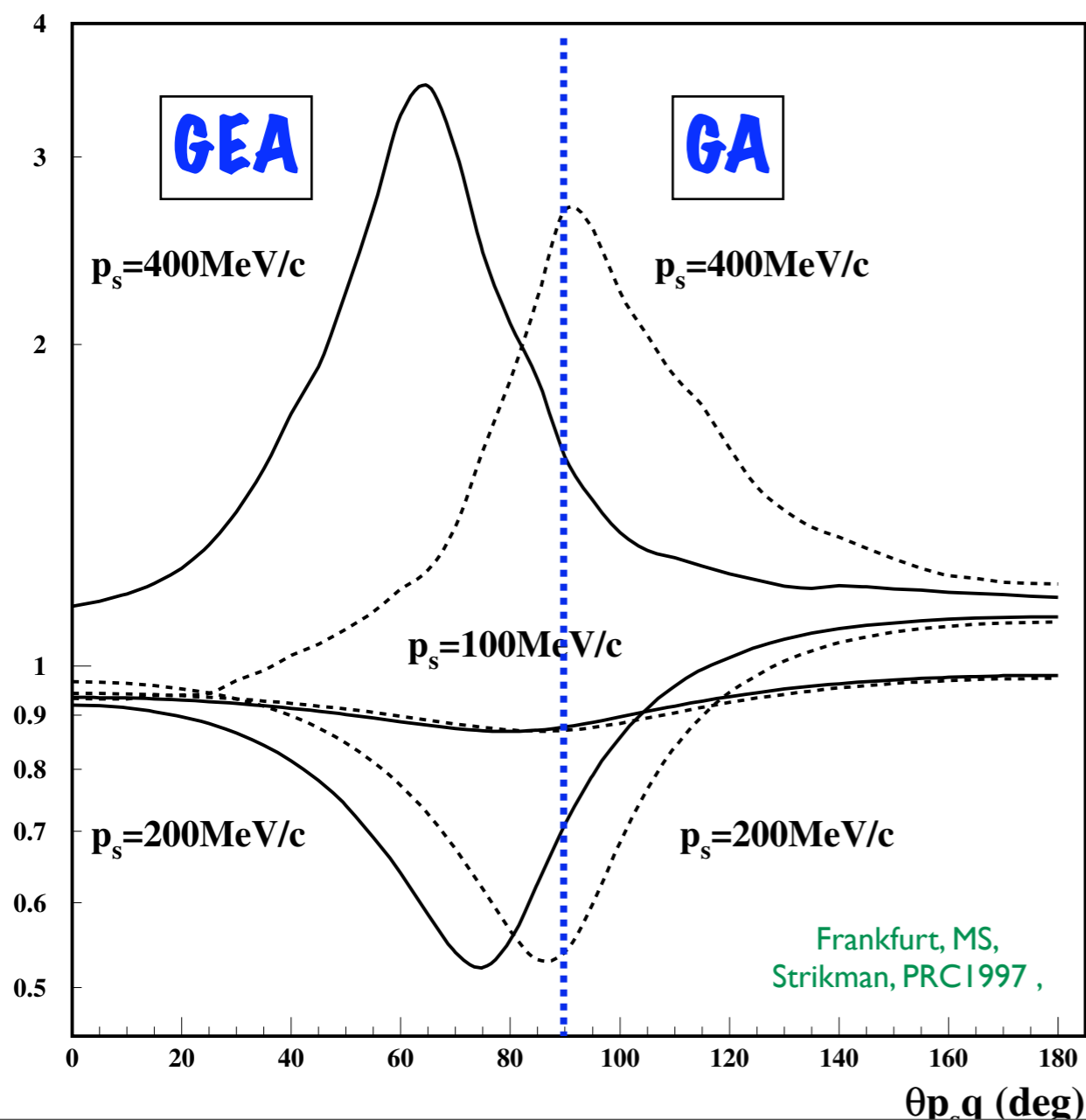
# Back to $Q^2$ dependence of $d(e,e'p)n$



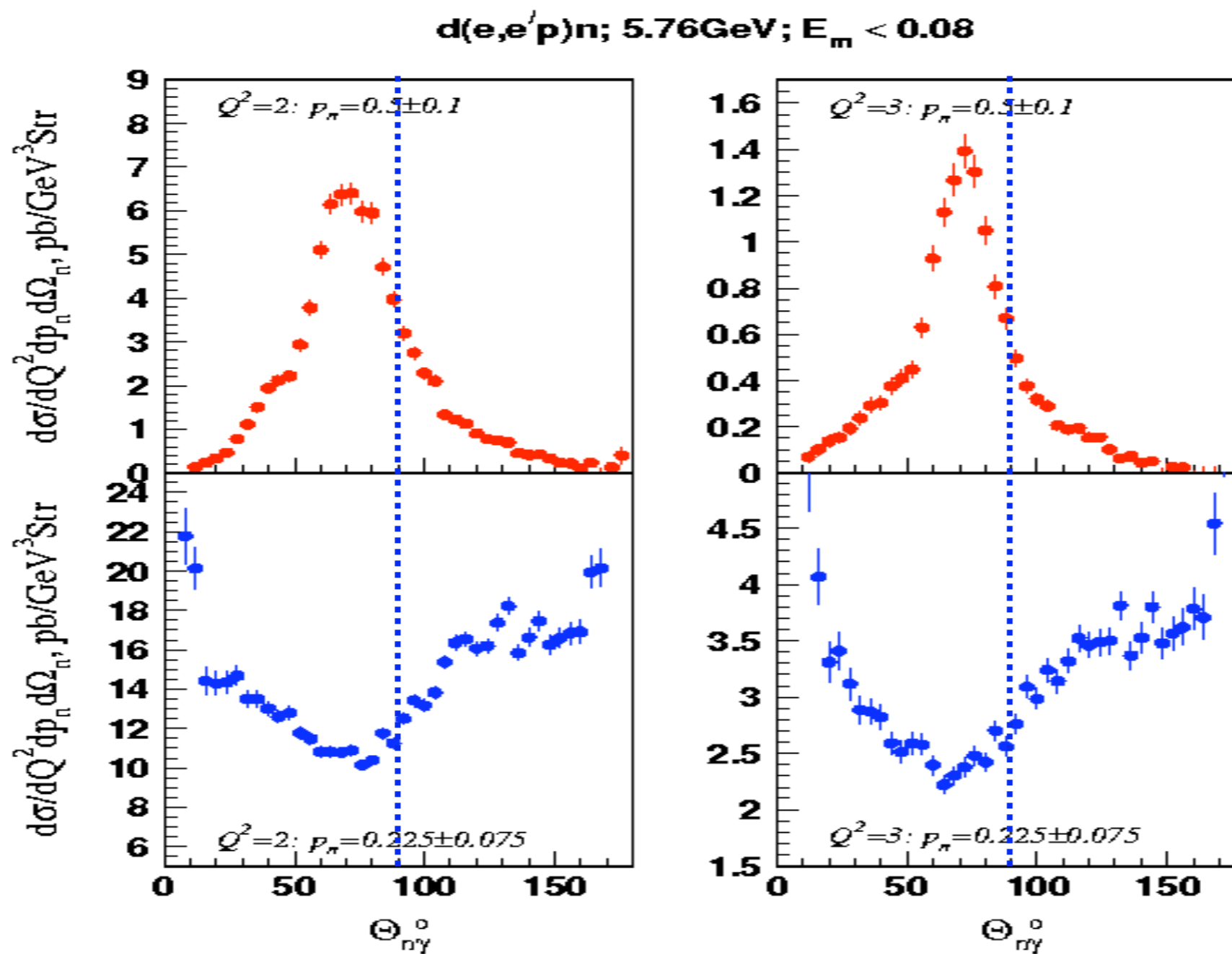
(a)



(b)



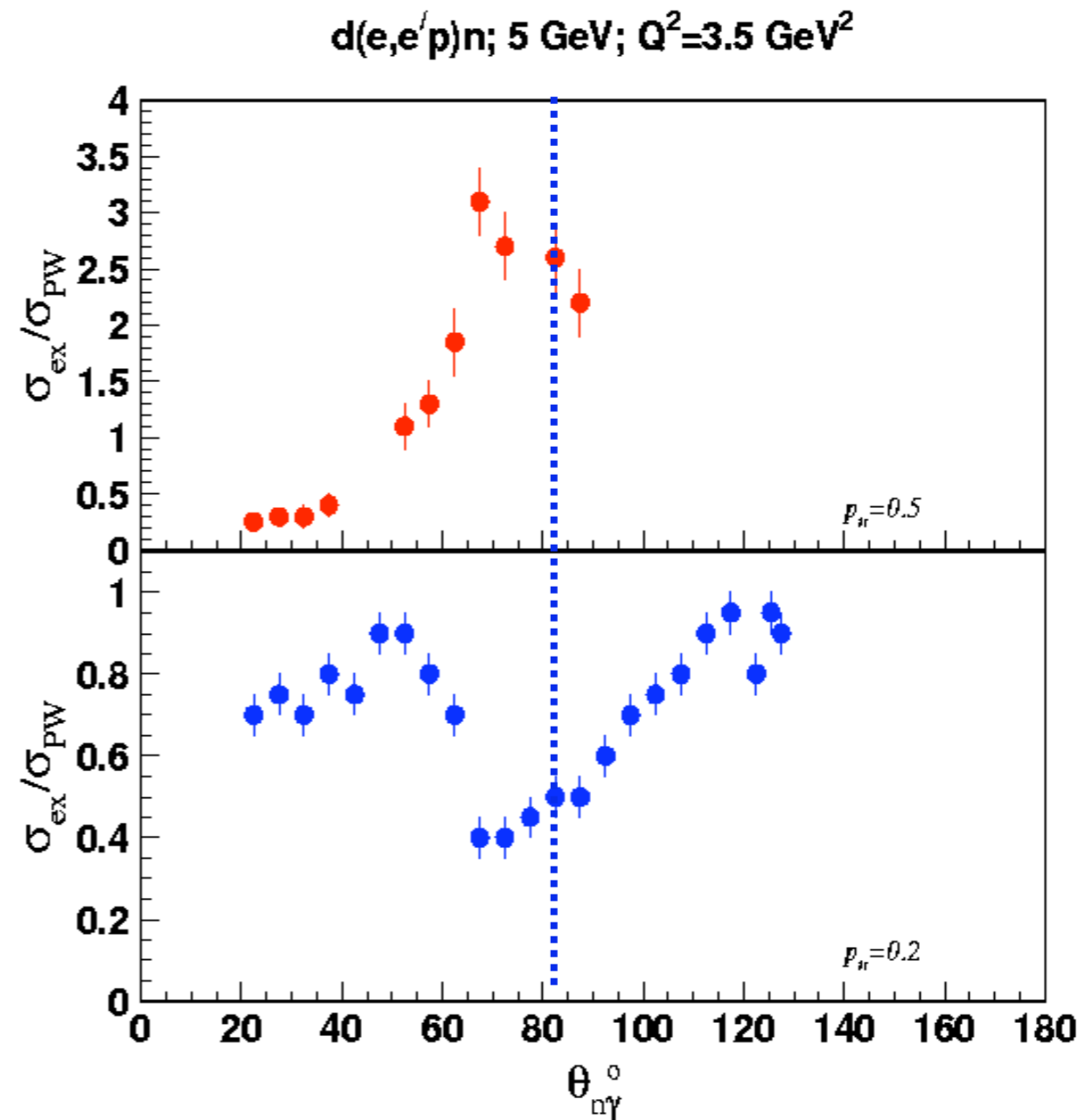
# Recoil-Neutron's Angular Distributions - I





# Recoil-Neutron Angular Distributions; Hall A Exp.

Werner Boeglin  
Luminita Coman, PhD 2007



PRELIMINARY

## High Density Nuclear Physics

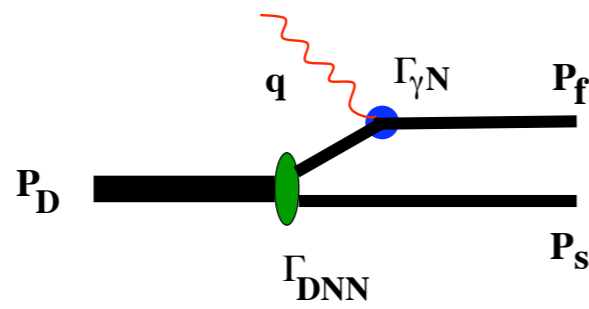
- Short Range Nucleon Correlations
- Nuclear DIS at  $x > 1$

## Properties of QCD from Nuclear Medium

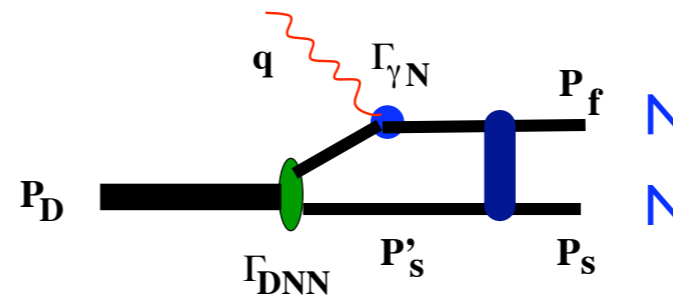
- Modification of Bound Nucleon Structure - EMC effect
- Color Transparency
- Hadronization
- Signatures of Chiral Symmetry Restoration

## QCD Dynamics of Hadronic Interaction

- hard break-up of hadrons from the light nuclei
- **quasireal secondary Hadronic "Beams"**



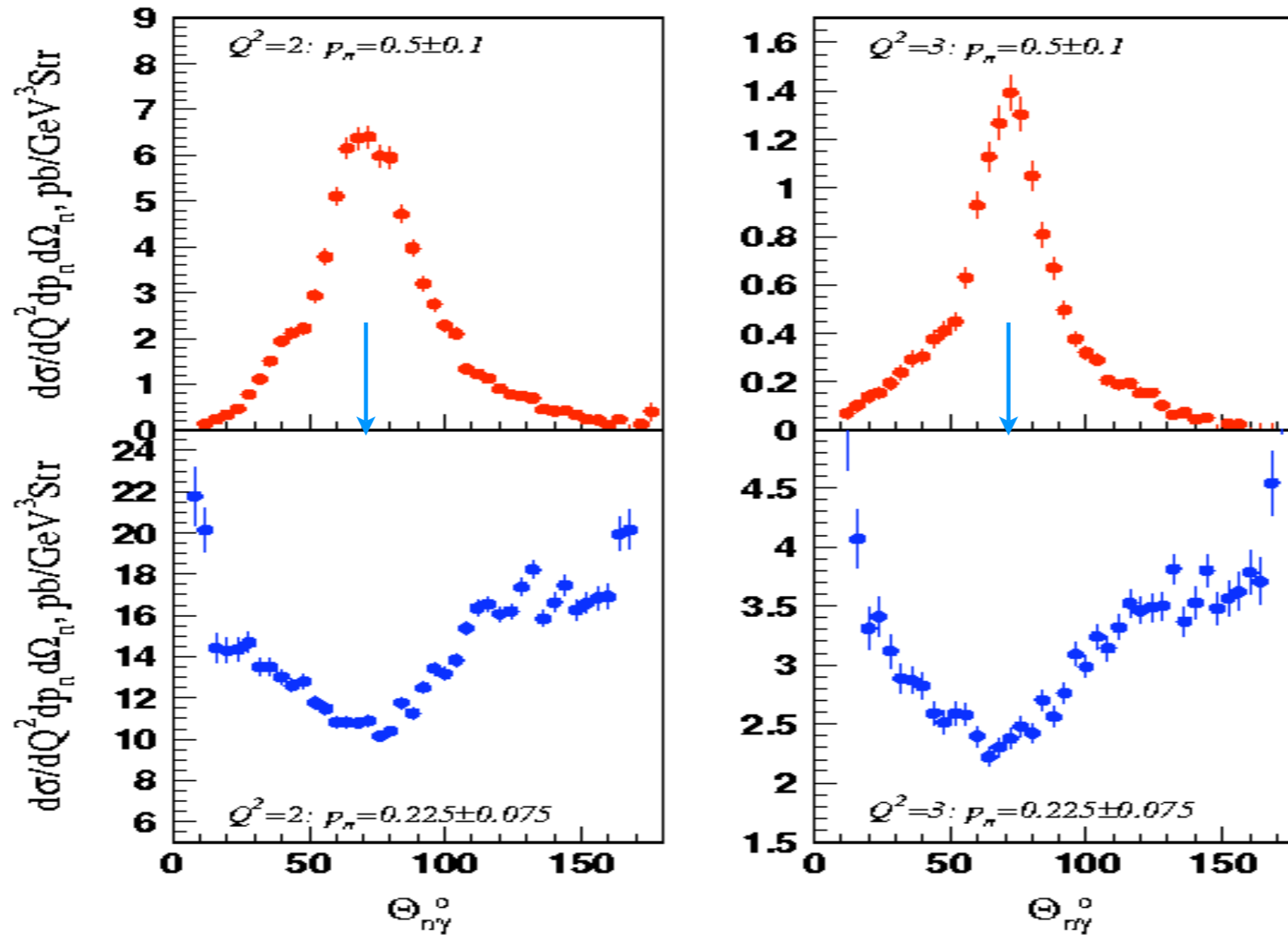
(a)



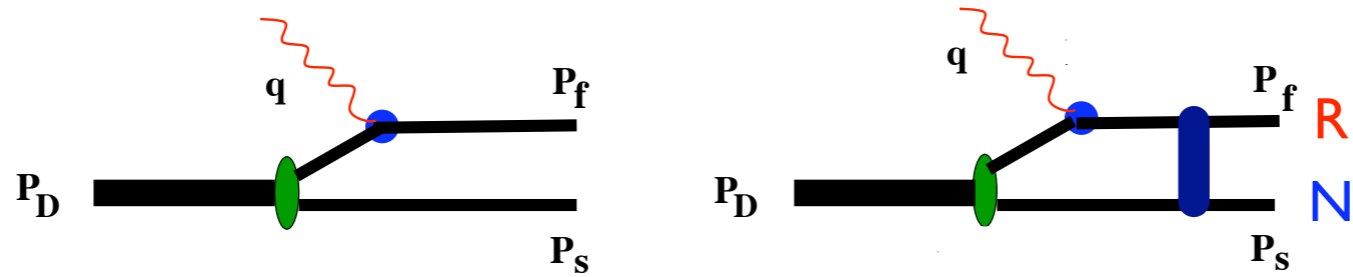
(b)

$$x_N = \frac{Q^2}{2q_0 m_N}$$

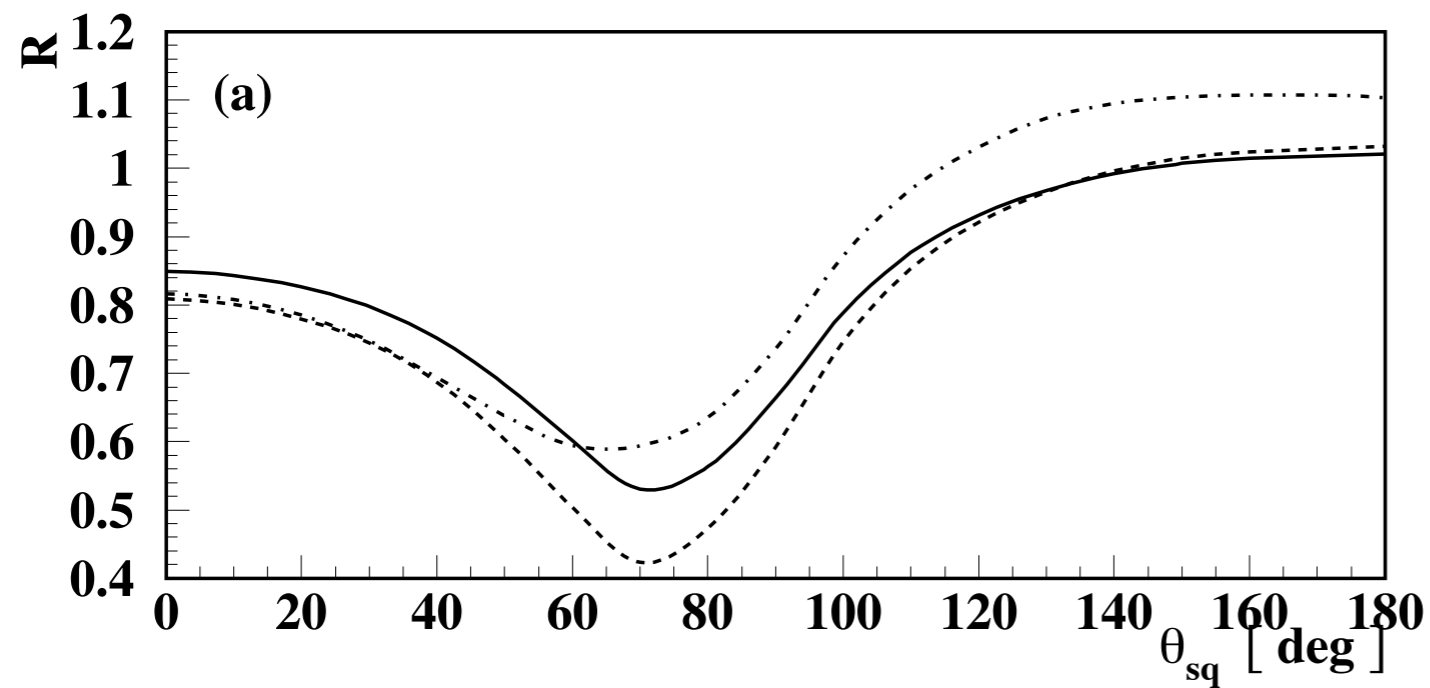
$d(e, e' p)n; 5.76 \text{ GeV}; E_m < 0.08$



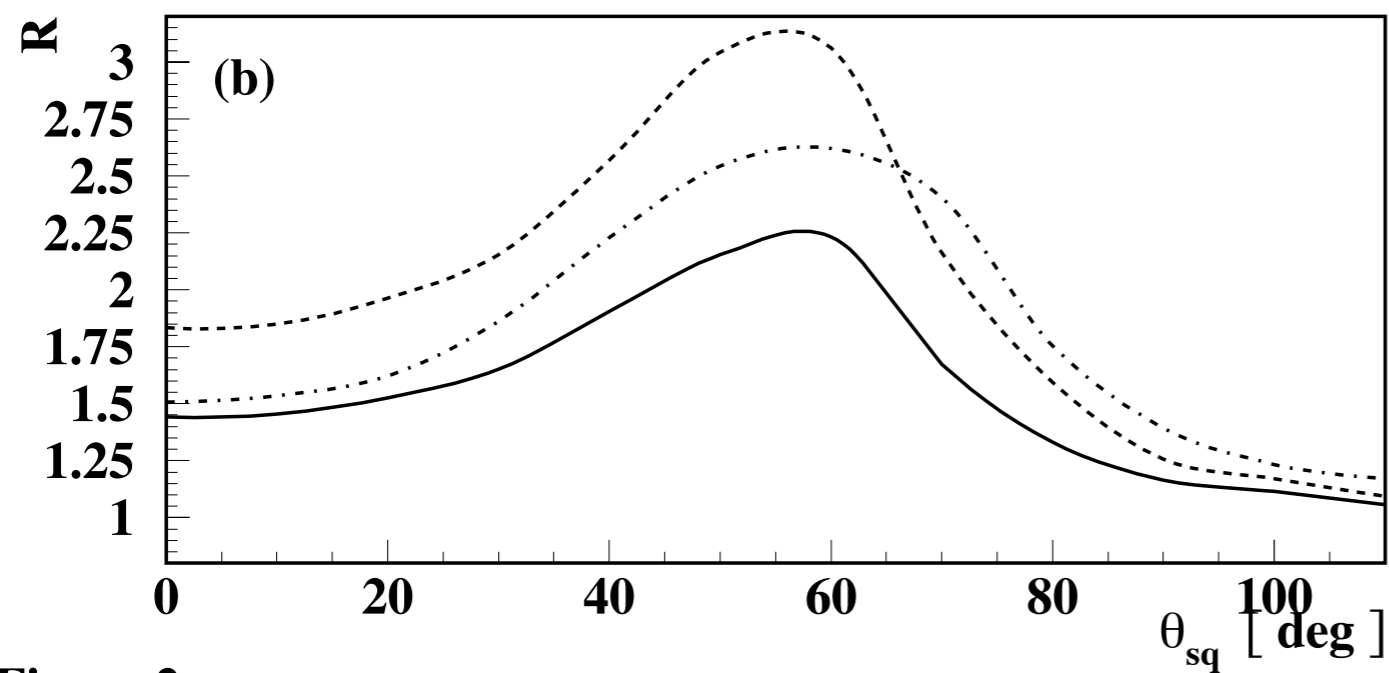
Y



$$x_N = \frac{Q^2}{2q_0 m_R}$$



$$d(e, e' N^*) N$$



Frankfurt, Johnson, MS,  
Strikman, Weise  
PRC1998,

Figure 2

## High Density Nuclear Physics

### - Short Range Nucleon Correlations

$$e + A \rightarrow e' + N_{back} + N_{forw} + X$$

### - Nuclear DIS at $x > 1$

## Properties of QCD from Nuclear Medium

### - Modification of Bound Nucleon Structure - EMC effect

### - Color Transparency

$$e + A \rightarrow e' + N(V)_{resc} + N_{recoil} + X$$

### - Hadronization

### - Signatures of Chiral Symmetry Restoration

$$e + A \rightarrow e' + h_{back} + h_{forw} + X$$

## QCD Dynamics of Hadronic Interaction

### - hard break-up of hadrons from the light nuclei

### - quasireal secondary Hadronic "Beams"

$$e + A \rightarrow e' + R_{forw} + N_{recoil} + X$$