Dynamics of Cold Dense Nuclear Matter

Misak Sargsian
Florida International University

JLab User Meeting, 18-20, June 2007

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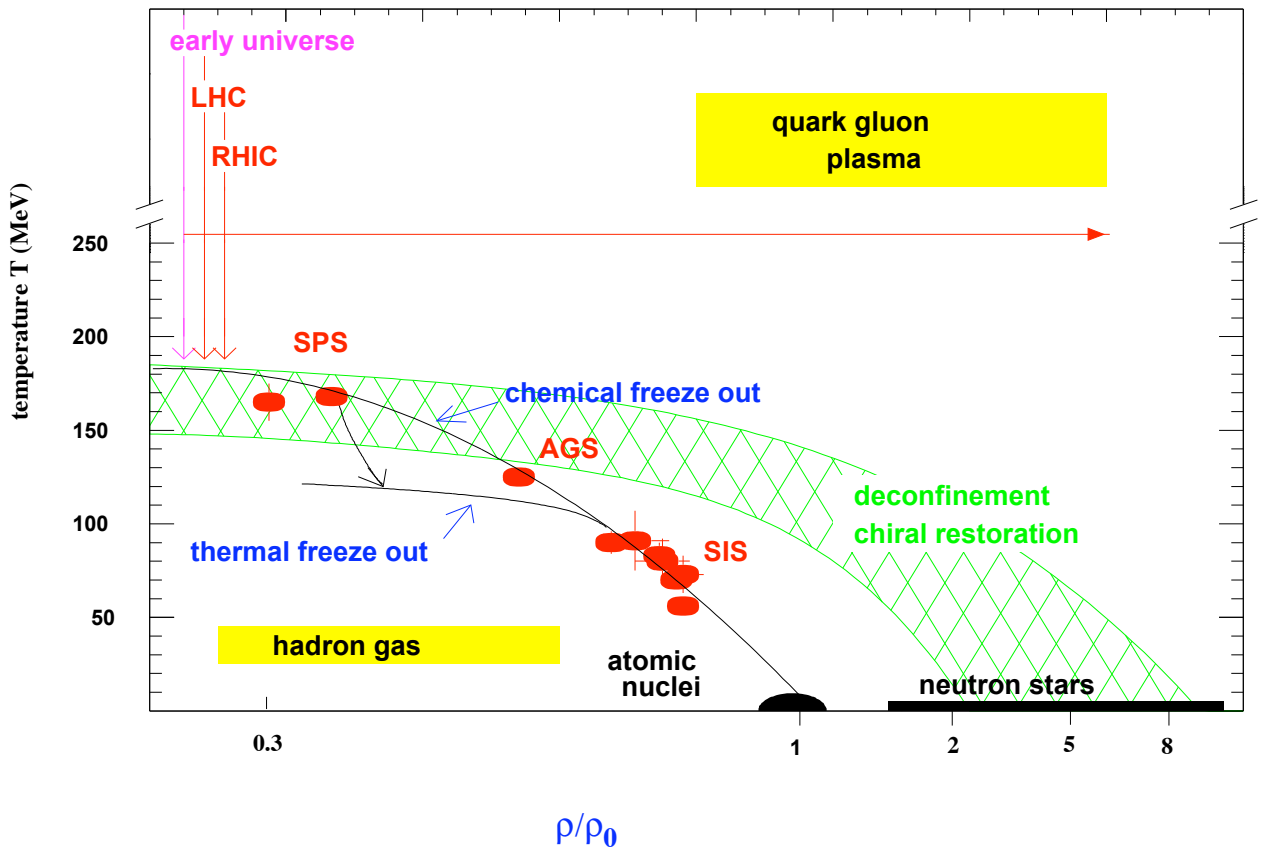

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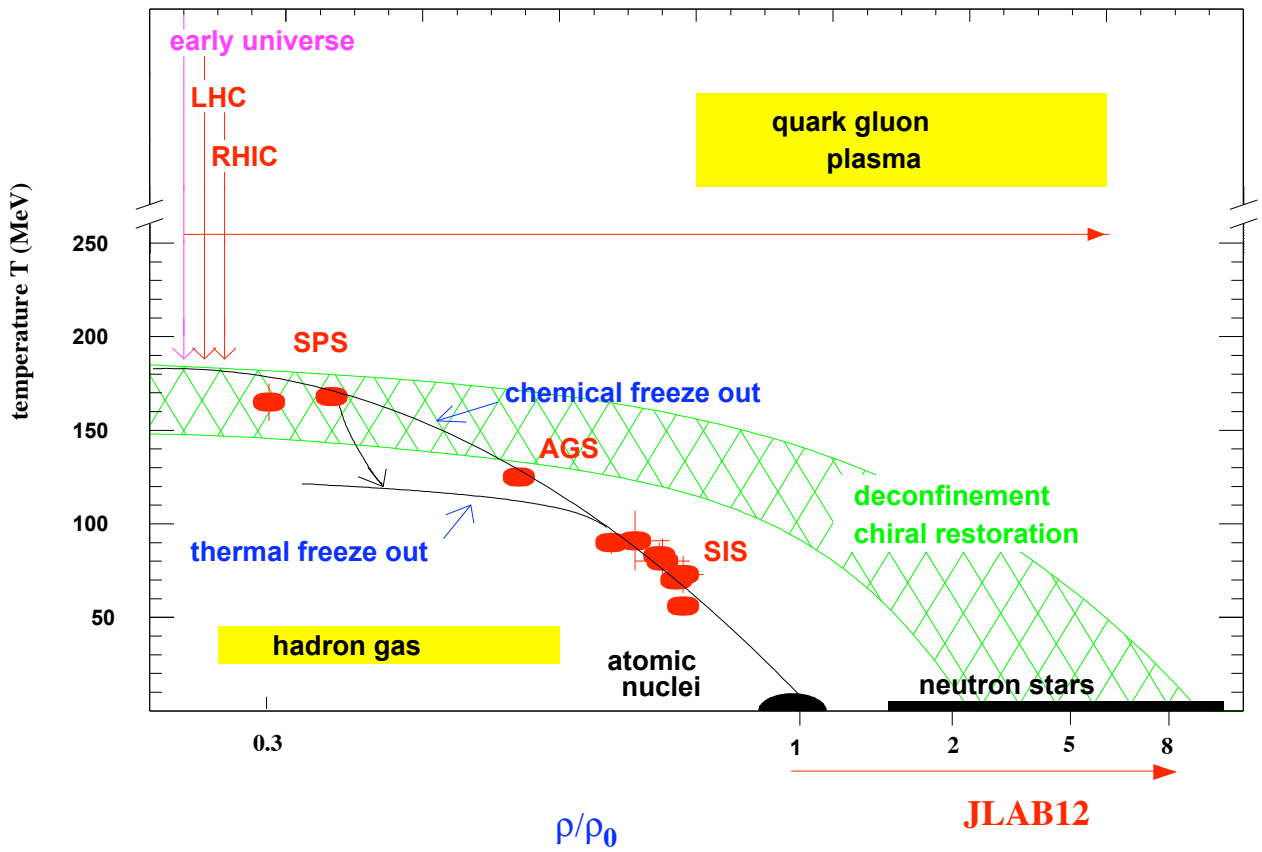

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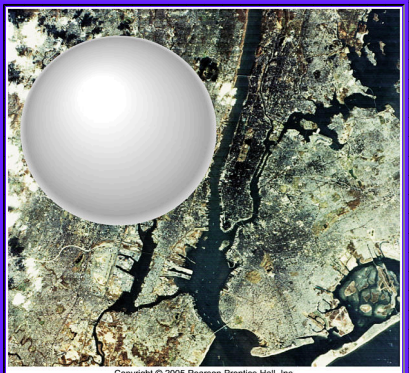
Winter Retreat on

Cold Dense Nuclear Matter

15-17
February, 2007

Florida
International
University

Miami



Winter Retreat on

Cold Dense Nuclear Matter

15-17
February, 20

Florida
Internationa
University

Miami

International Workshop on

Dense and Cold Nuclear Matter and Hard Exclusive Processes

Het Pand, Ghent University, Belgium
Monday August 20, through Friday August 24, 2007

Microscopic Structure of NN Interaction and properties of Dense Nuclear Matter

Oppenheimer-Volkoff model, 1939

Degenerate neutron and electron Fermi Gas

$$\sim 0.7 M_S$$

Observational $\sim 1.36 M_S$

Microscopic Structure of NN , NNN, ... Interactions

$$H = -\sum_i \frac{1}{2m}\nabla_i^2 + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \cdots,$$

NN interaction

$$\begin{aligned} v_{ij}^{\pi} &= \frac{f_{\pi NN}^2}{4\pi}\,\frac{m_\pi}{3}\,X_{ij}\,\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j\ , \\ X_{ij} &= Y_\pi(r_{ij})\,\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j\ +\ T_\pi(r_{ij})\,S_{ij}\ . \end{aligned}$$

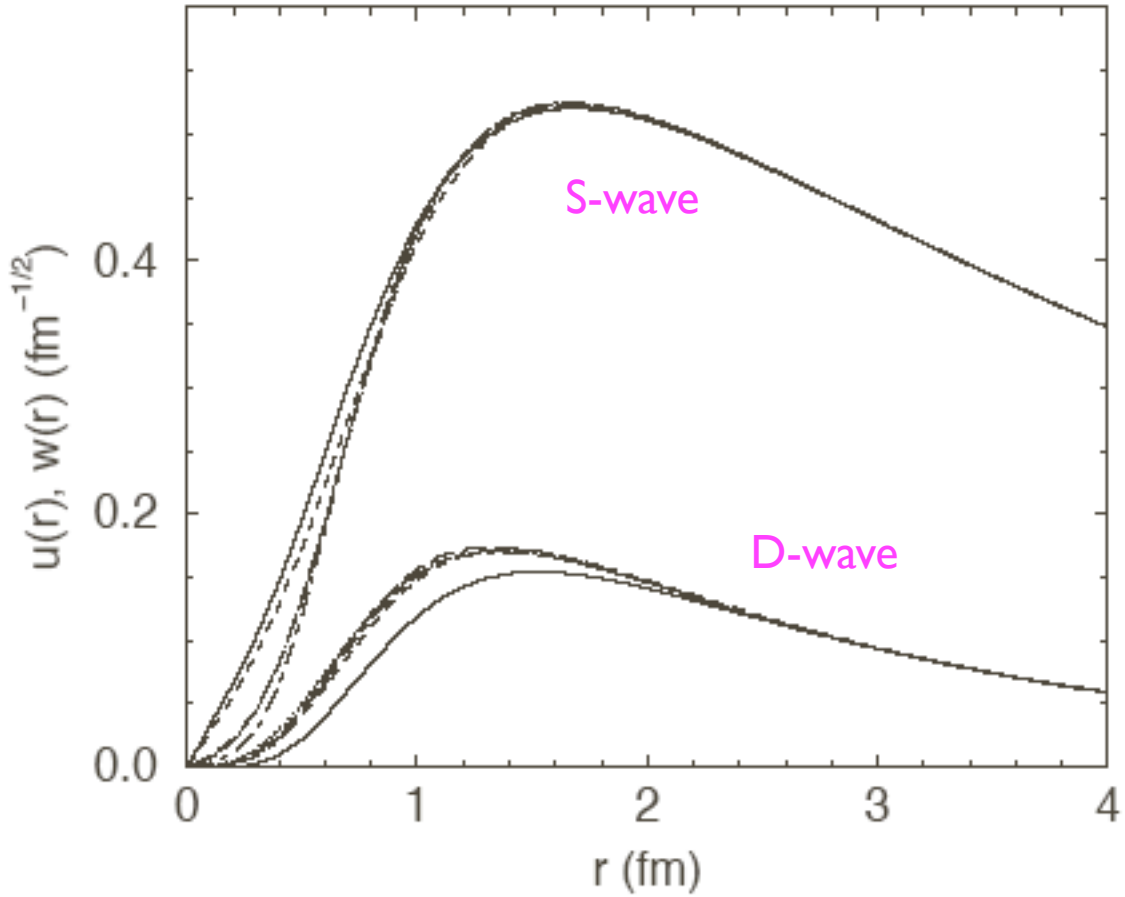
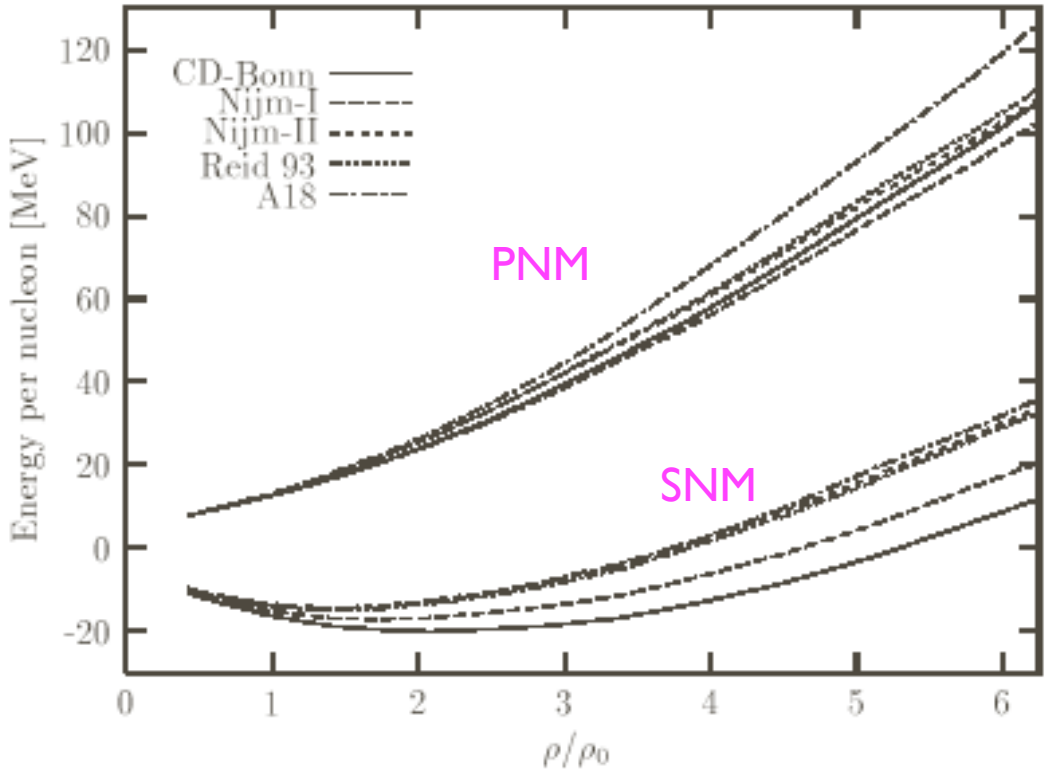


Figure 2: Deuteron radial wave-functions, $^3S_1$ u(r) (upper curves) and $^3D_1$ w(r) (lower curves) predicted by modern NN interactions: CD-Bonn (solid), Nijm-I (dashed), Nijm-II (dash-dotted), Reid 93 (dotted) and A18 (long-dashed).



Heiselberg, Pandharipande, 2000

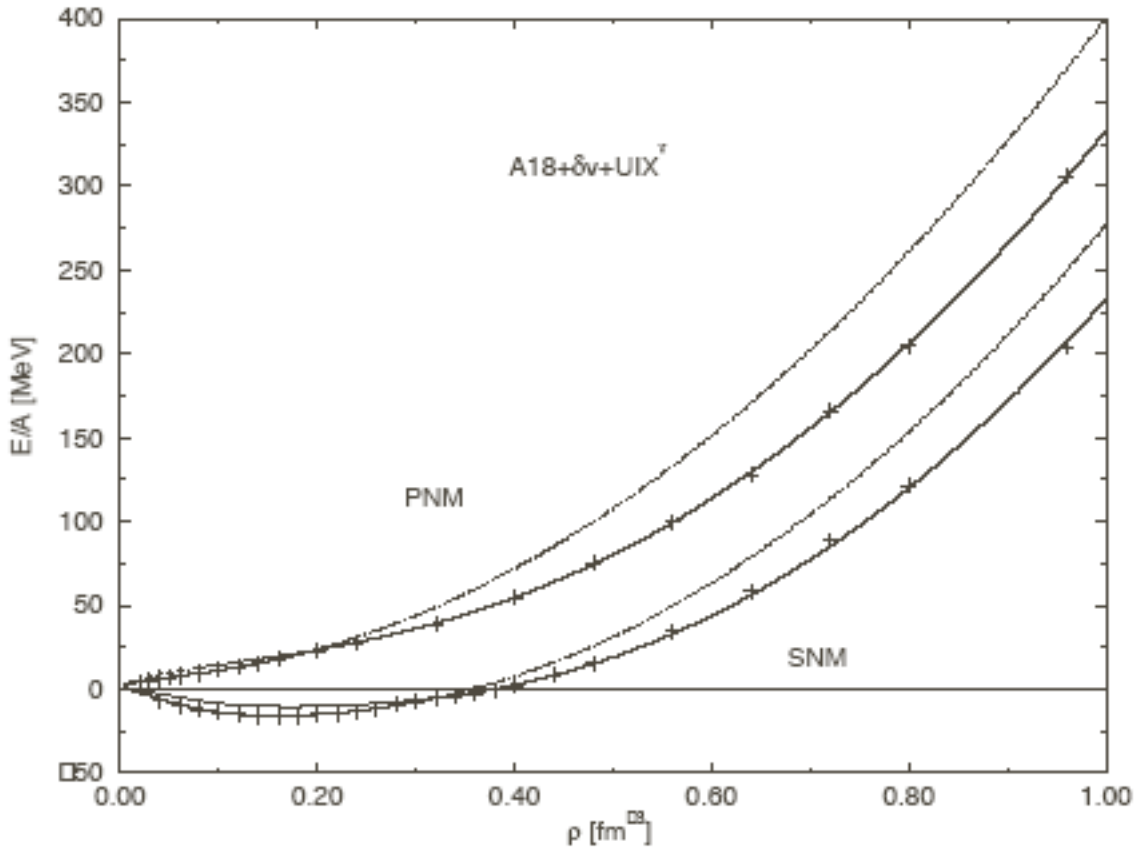
3N Interaction

$$V_{ijk} = V_{ijk}^{2\pi} + V_{ijk}^{R}$$

Relativistic Effects

Effectively Repulsive ?

Gross, Stadler 2007



Heiselberg, Pandharipande, 2000

Chemical Potential and Quantum Field

Classical Thermodynamics for Open Systems

Added energy due to N_i matter introduced to the system

$$\mu_i N_i$$

$$\mu_i = \sqrt{m_i^2 + k_{Fi}^2}$$

$$U = ST - PV + \sum \mu_i N_i$$

Diffusive Equilibrium

$$\mu_A = \mu_B$$

Particles in the Cold Dense Matter

Everything may change when kinetic energy of NN system exceeds 300 MeV

$$N + N \rightarrow N + \Delta$$

$$N + N \rightarrow N + \Lambda + K$$

The system becomes effectively open

$$\mu_A = \mu_B$$

Particles which leave the star do not contribute in μ

$$K^- \rightarrow \mu^- + \bar{\nu} \qquad \mu_{K^-} = \mu_{\mu^-}$$

Kaon Condensation

$$n \leftrightarrow p + e^- + \bar{\nu}_e \qquad \mu_p = \mu_n - \mu_e$$

$$e \leftrightarrow \mu^- + \nu_e + \bar{\nu}_\mu \qquad \mu_e = \mu_\mu$$

$$e^- \rightarrow K^- + \nu_e$$

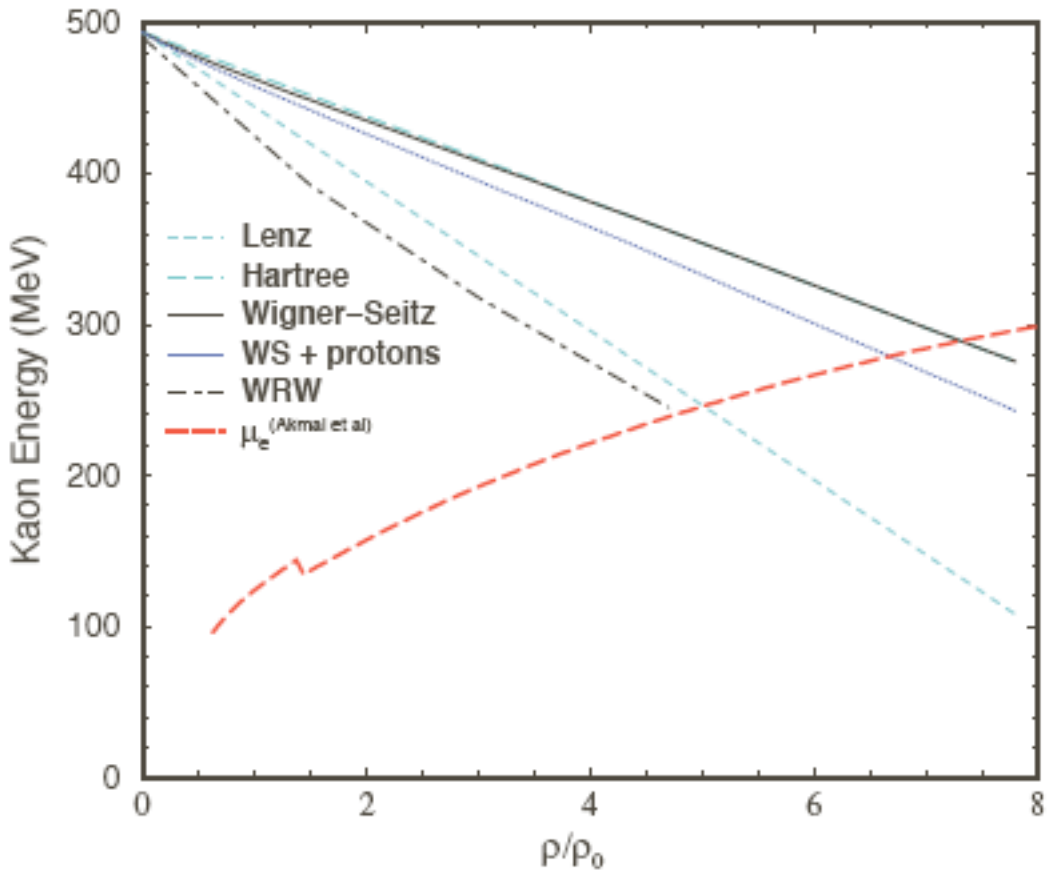
$$\mu_{e^-} = \mu_{K^-}$$

$K^- n$ Interaction is attractive kaon energy decreases with density

Strangeness Enhancement

$$\mu_\Lambda = \mu_n$$

$$\mu_{\Sigma^+} = \mu_n - \mu_e = \mu_p$$



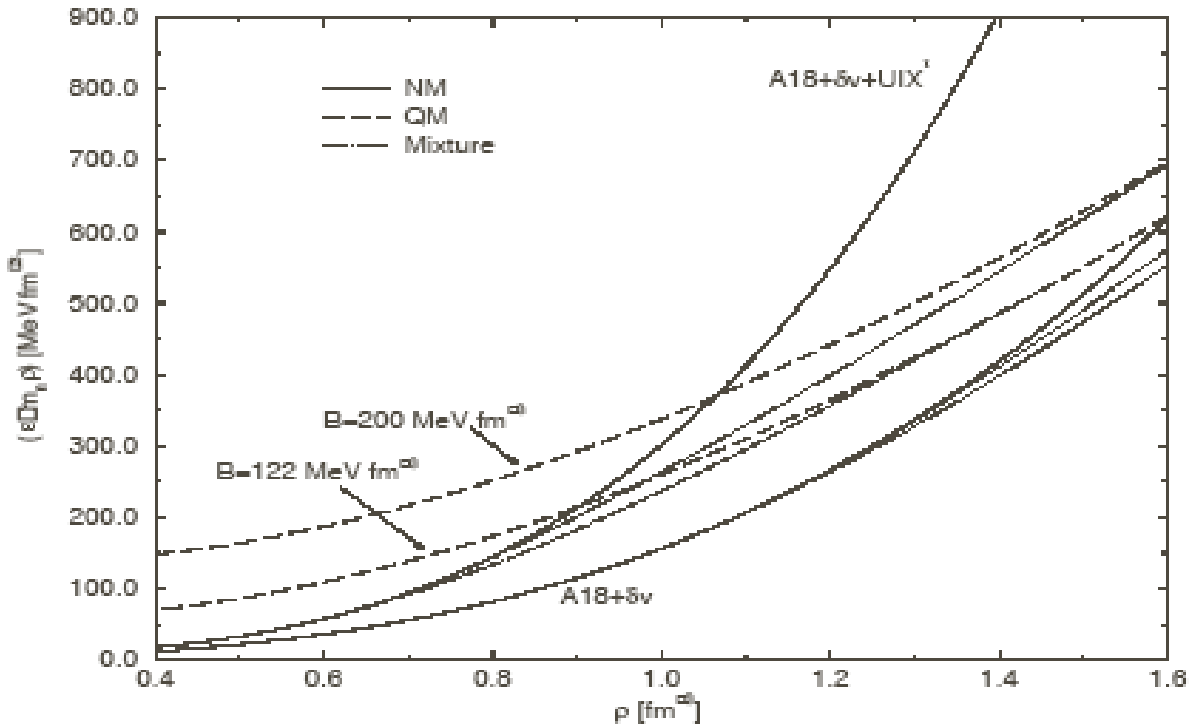
Heiselberg, Pandharipande, 2000

Quark Matter

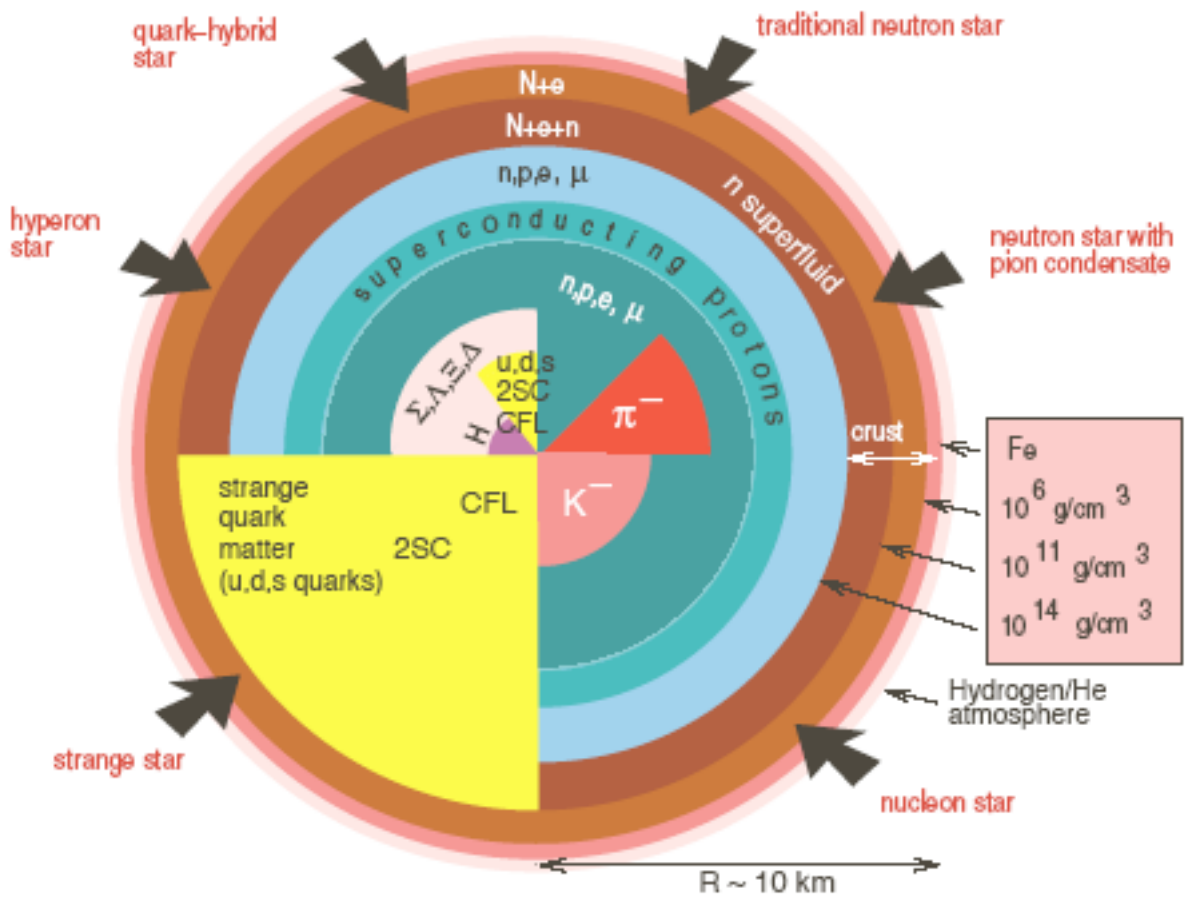
$$\mu_u + \mu_e = \mu_d = \mu_s$$

In the core of the neutron star nucleons may melt

Astro-EMC effect

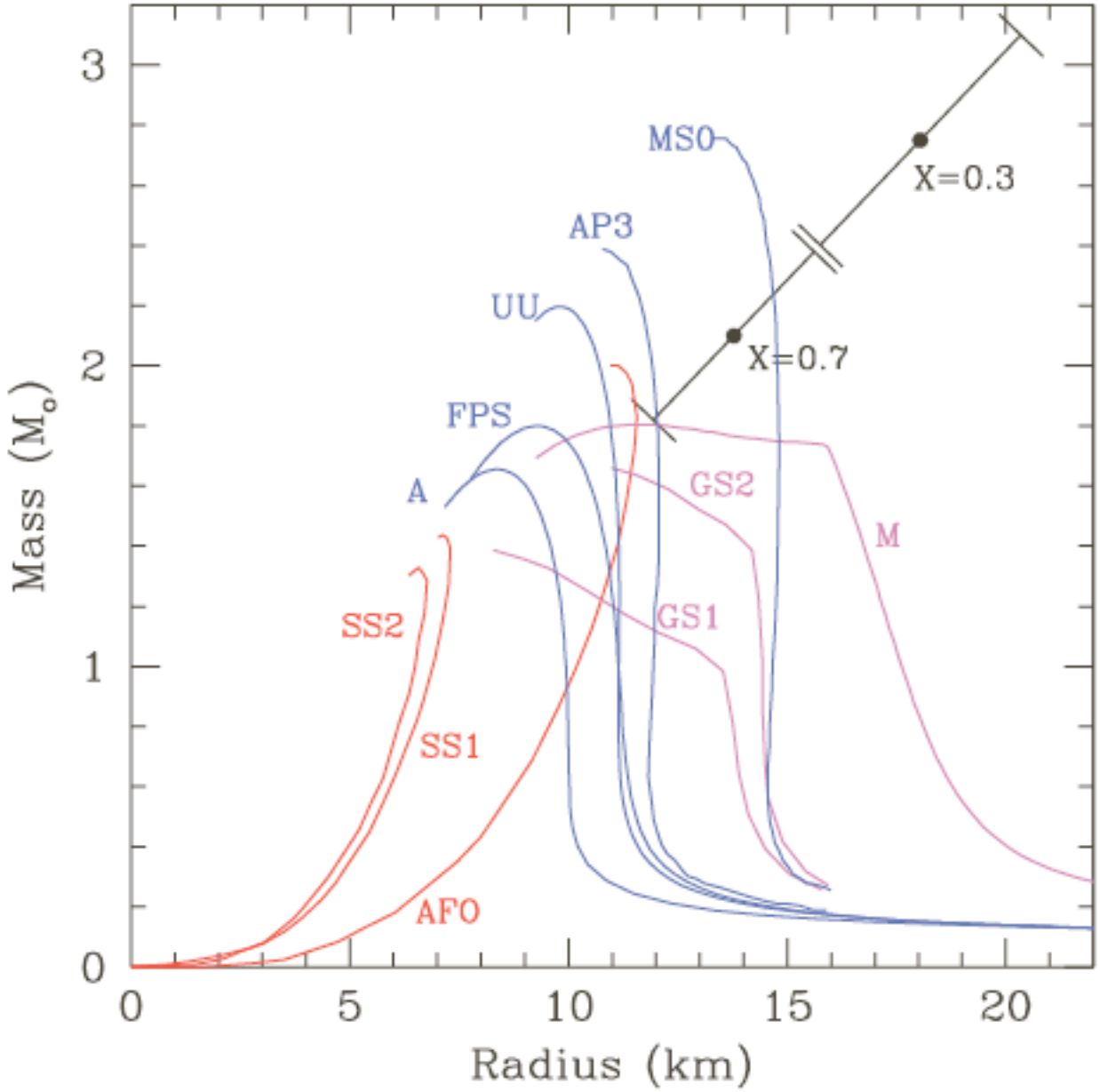


Heiselberg, Pandharipande, 2000



Weber, Negreiros, Rosenfield, 2007

- Short Range properties of NN interaction
- 3N forces
- Relativism and core of the NN interaction
- Relative importance of protons
- Non-Nucleonic Degrees of Freedom
- Quark-Hadron Transition
- Strangeness
- . . .



The Mass and Radius estimate of EXO-0748-676 provides the evidence for stiff Equation of State

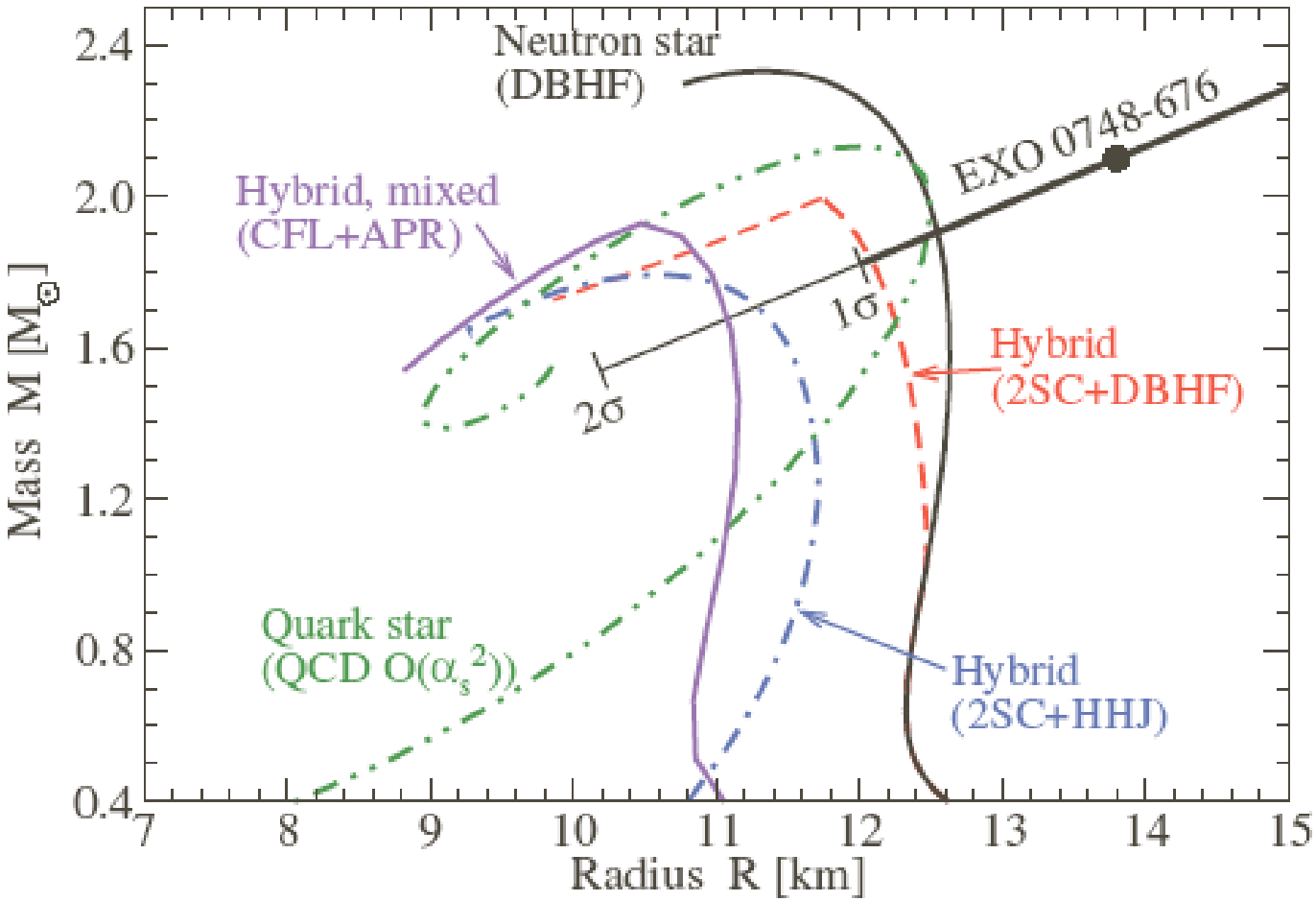
- Measured NS masses in binaries are clustered around the value $1.4M_\odot$ (canonical mass).
- for PSR J0751+1807 the mass measurement gives $M = 2M_\odot$ with an error $\pm 0.2M_\odot$.
- Mass and radius measurement for EXO 0748-676: large masses and large radii
  - Strong evidence for significant repulsive short-range correlations.
  - Purely nucleonic NS are viable candidates, but where are the other constituents?
  - We hope that they are there ... since otherwise neutron stars will be much less interesting objects to study

Sedrakian, Winter Retreat, FIU 2007

Özel, in a recent reanalysis of EXO 0748-676 observational data, concluded that quark matter probably does not exist in the center of neutron stars [1]. However, her analysis only considered relatively old equations of state for quark matter. In this comment we compare the observational limits with more recent calculations of the possible structure of quark and hybrid stars.

Özel's analysis leads to lower-limit values on the mass $M = 2.1 \pm 0.28\ M_\odot$ and radius $R = 13.8 \pm 1.8$ km. These are shown in Figure 1, along with M-R relations for various quark matter and nuclear matter equations of state. Özel assumes that ruling out soft equations of state means ruling out quark matter, but overlooks the fact that, because of finite-density QCD corrections and color-superconducting gaps, quark matter can be as stiff as nuclear matter. This has been shown using the MIT bag model [2], perturbative corrections to QCD [3], and the Nambu–Jona-Lasinio model [4]. Thus, as the figure illustrates, Özel's values are actually compatible with nucleonic, hybrid and quark stars.

Alford, Blaschke et al 2006


Neutron star
(DBHF)
EXO 0748-676
Hybrid, mixed
(CFL+APR)
1σ
2σ
Hybrid
(2SC+DBHF)
Quark star
(QCD O(α_s^2))
Hybrid
(2SC+HHJ)
Mass M [M_⊙]
Radius R [km]
2.4
2.0
1.6
1.2
0.8
0.4
7
8
9
10
11
12
13
14
15

- Short Range properties of NN interaction
- 3N forces
- Relativism and core of the NN interaction
- Relative importance of protons
- Non-Nucleonic Degrees of Freedom
- Quark-Hadron Transition
- Strangeness
- . . .

How to Generate High Densities in Nuclei ?

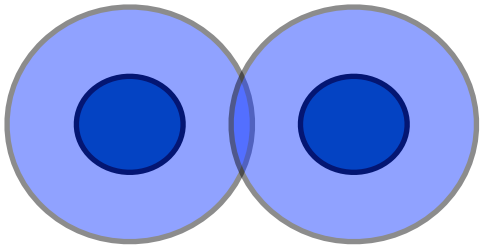
- Probe large virtualities in nuclei: distances ~ propagator $\sim \frac{1}{p^2 - m^2}$

- virtualities $\sim \frac{p^2}{2m}$

- large internal momenta and excitation energies

- However by nature these high densities are fluctuations

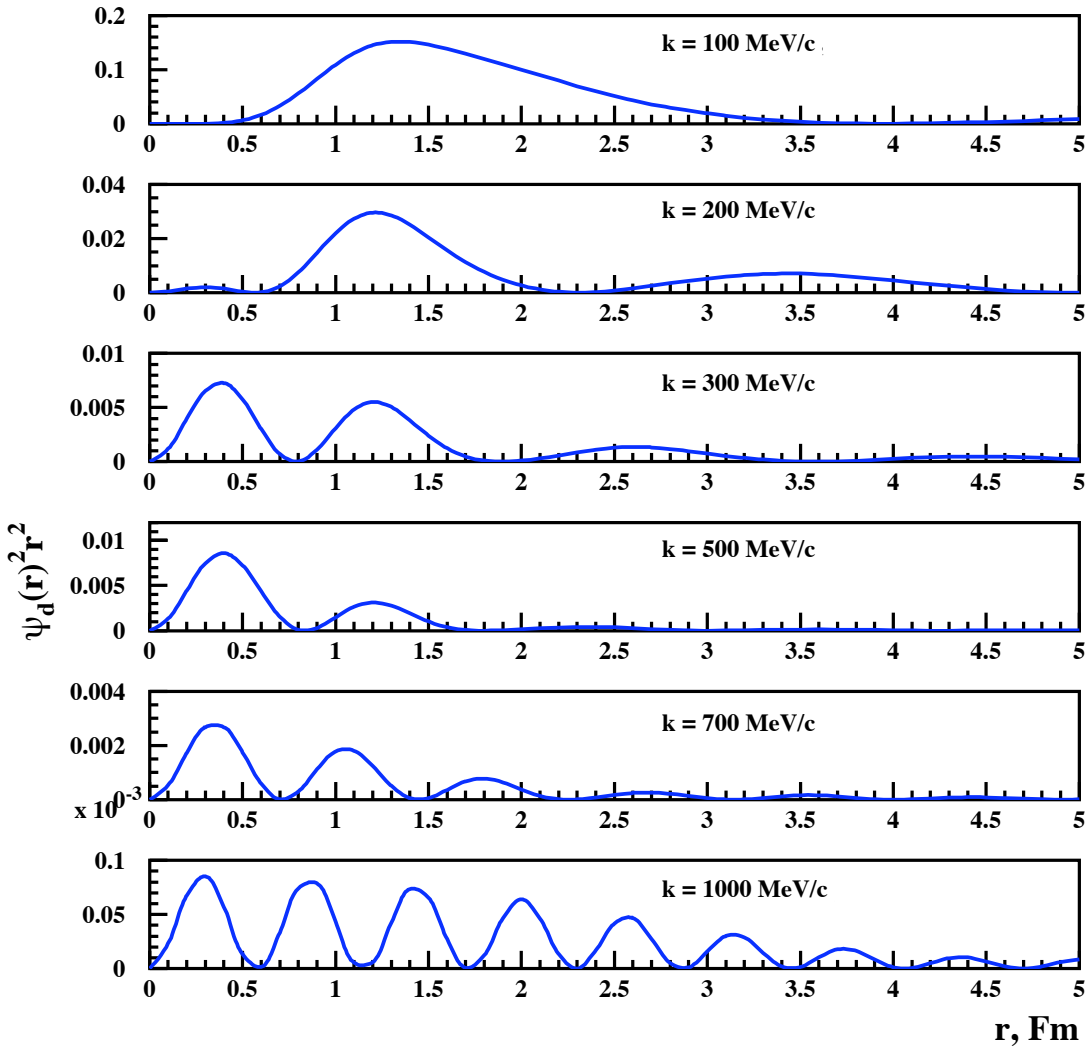
Short Range properties of NN interaction

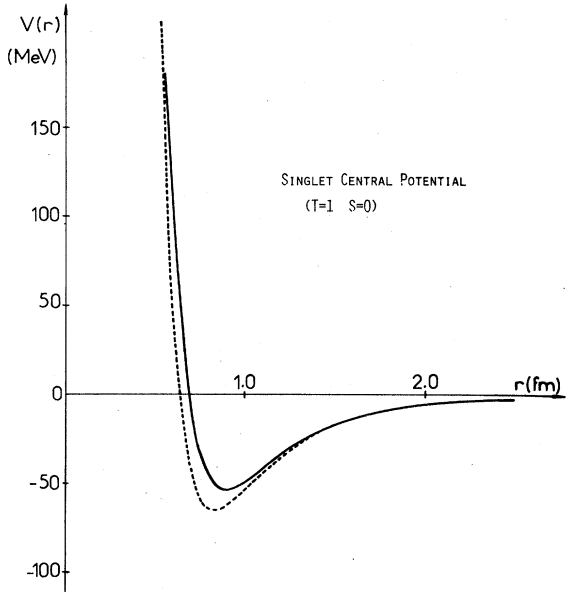


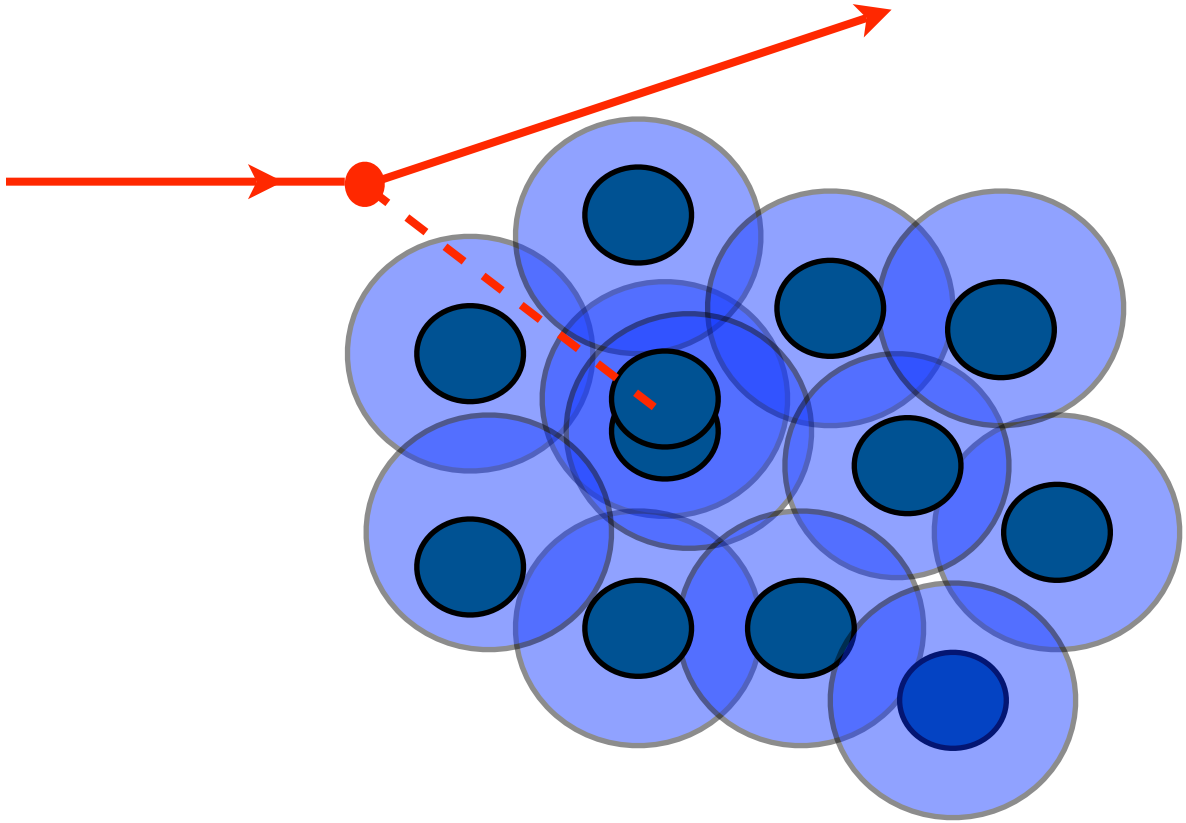
How to get nucleons close together

Probing at large relative momenta

$$r \sim \frac{1}{k}$$





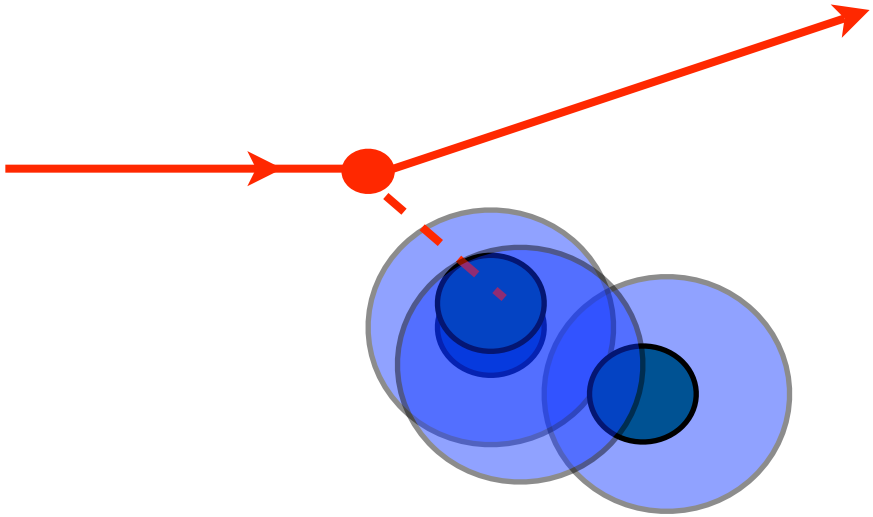


$p_1 \geq 300 - 350 MeV/c$

$x_{Bj} > 1.5 \quad Q^2 \geq 1.4 GeV^2$

$$^{12}C(e,e')X$$

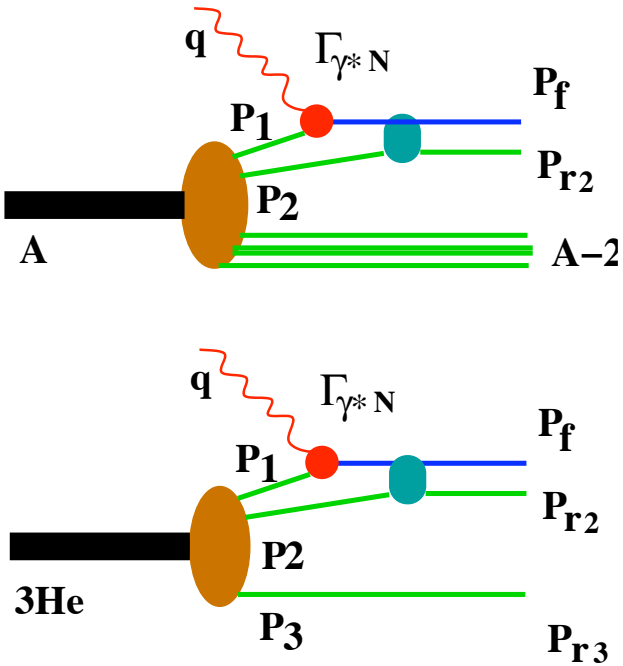
$$\frac{\sigma_{^{12}C}}{12}$$

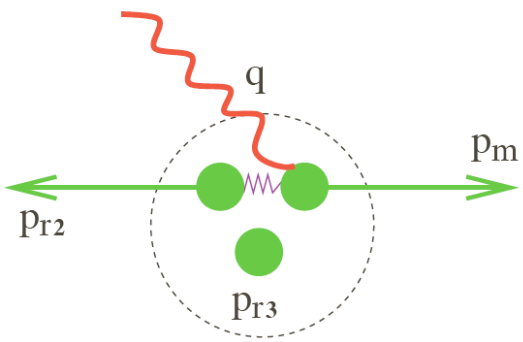


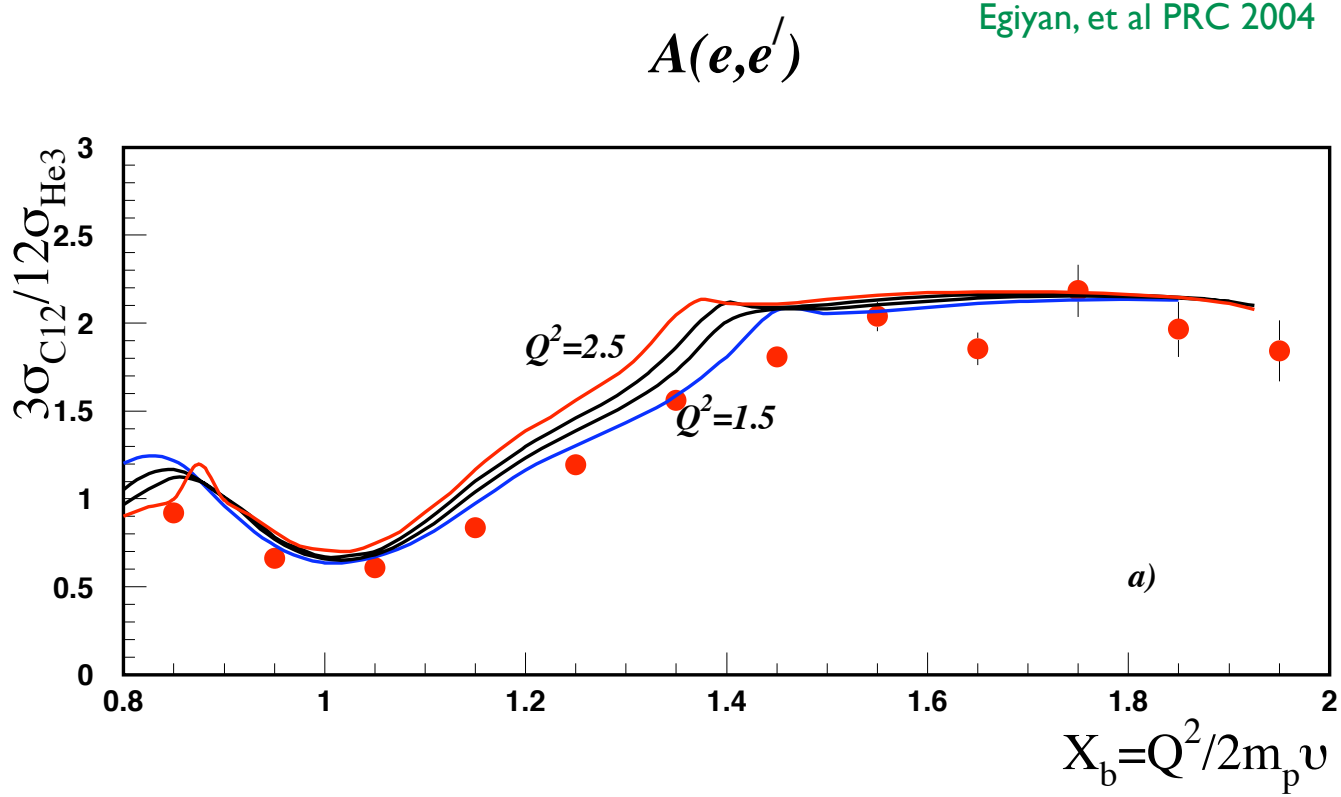
$$^{3}He(e,e')X$$

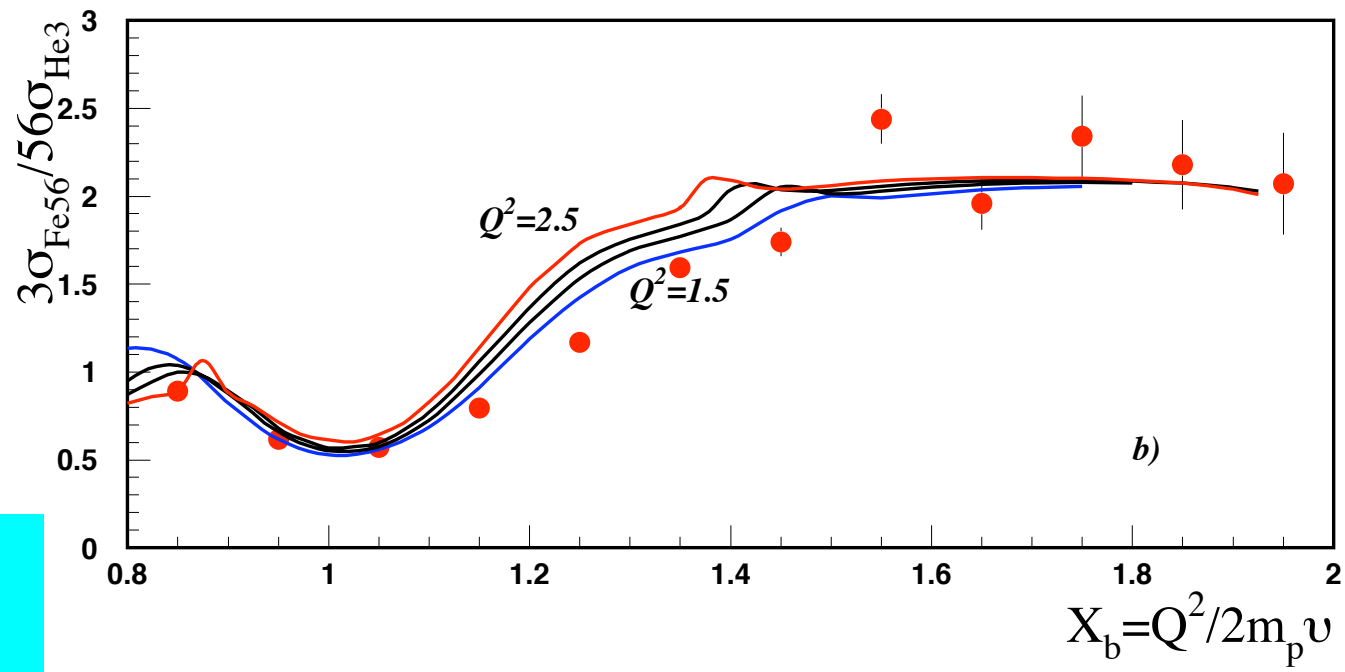
$$\frac{\sigma_{^{3}He}}{3}$$

Egiyan, et al PRC 2004







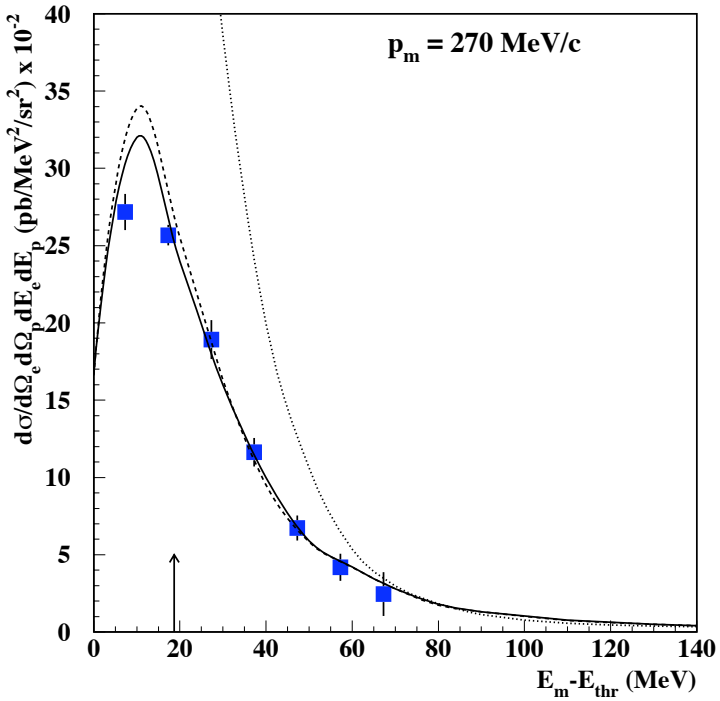


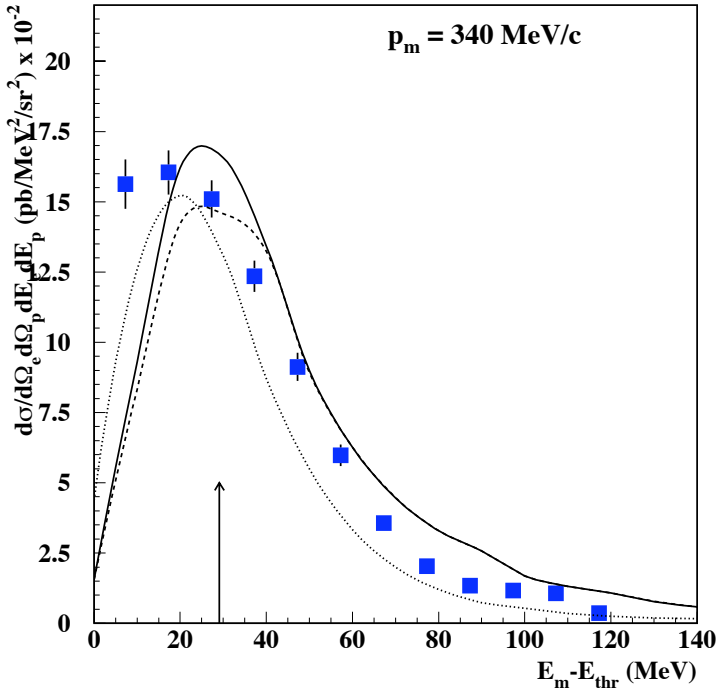
FSI predominantly happens in SRC

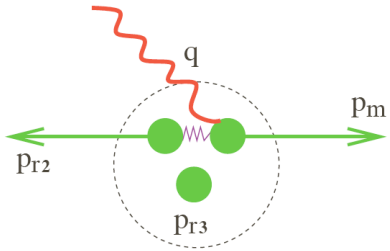
Three Body Break-up (e,e'p)pn Reaction

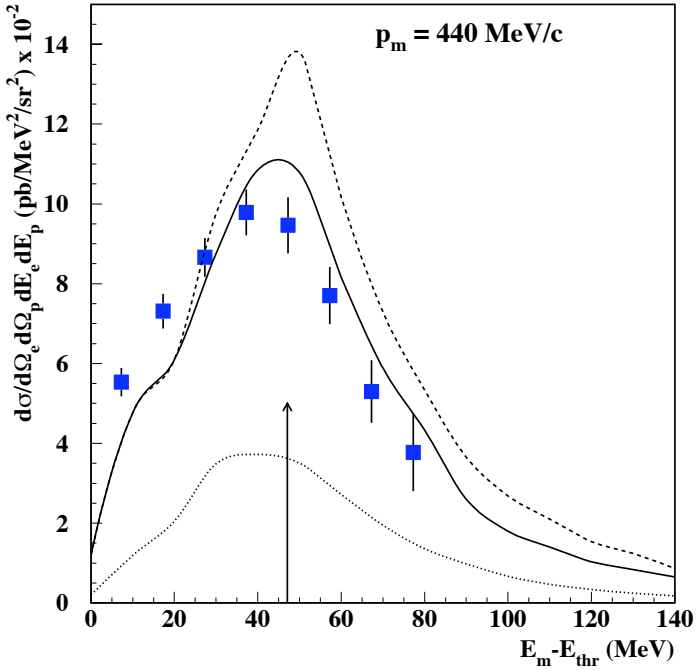
$Q^2 = 1.55\ \mathrm{GeV}^2$

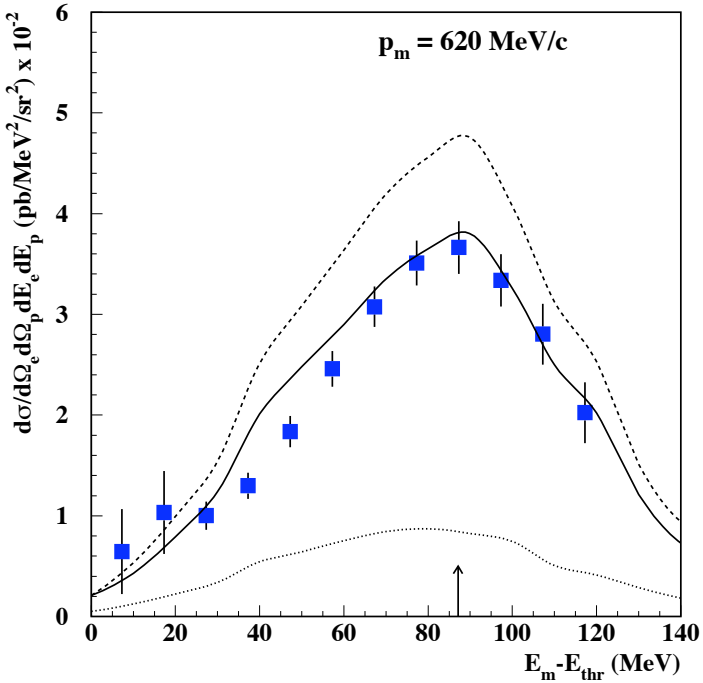
Benmokhtar, et al PRL 2005



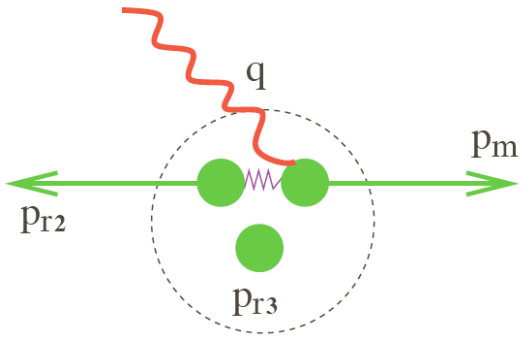




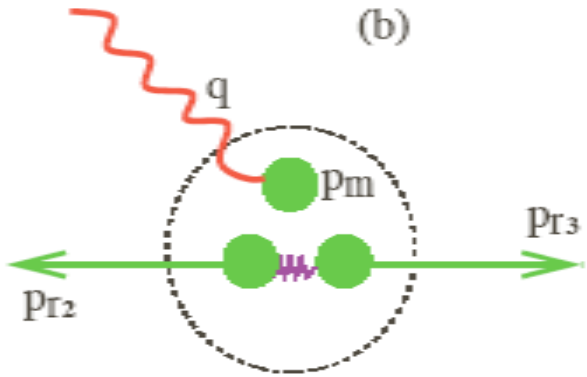




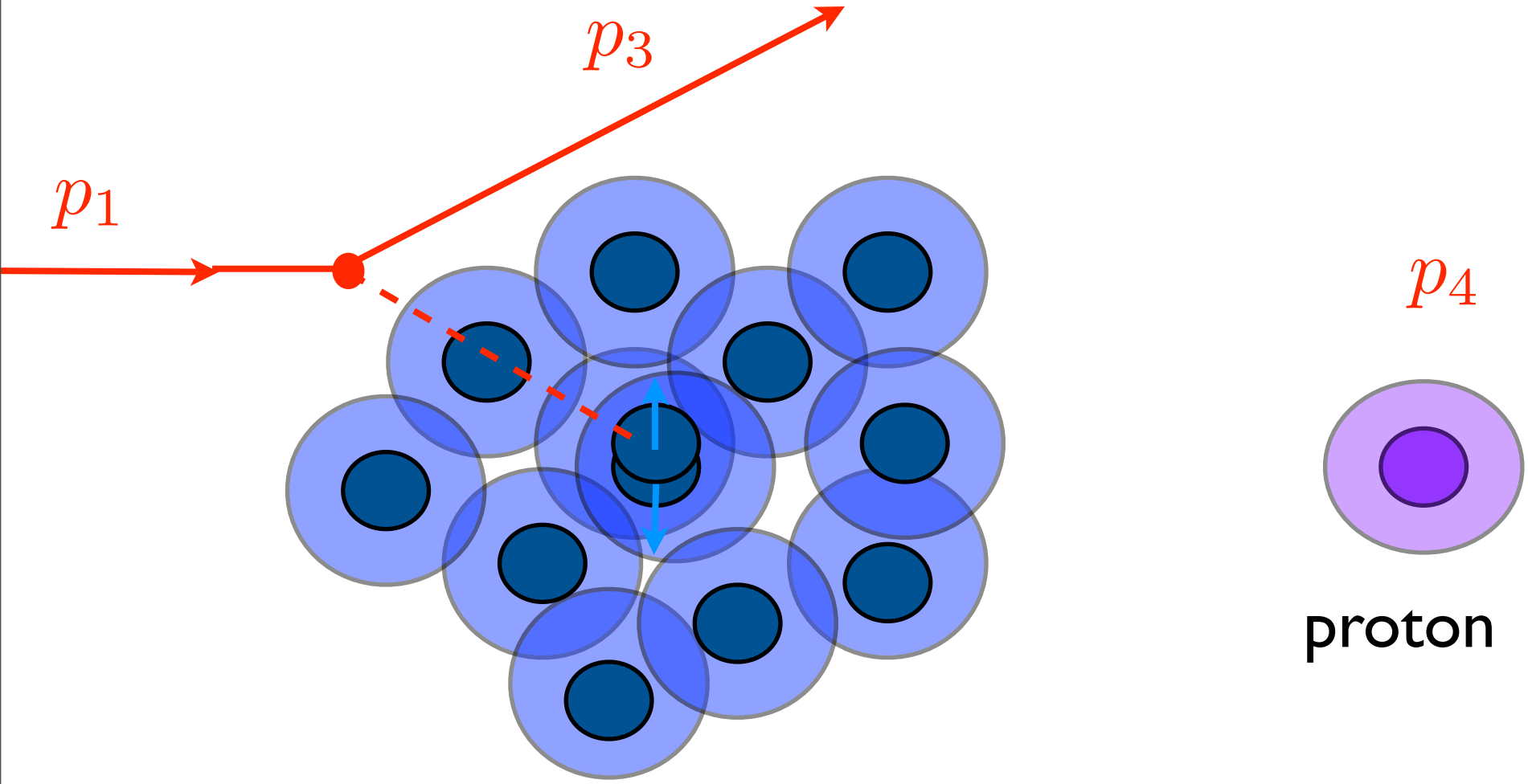
GEA model, M.S. 06



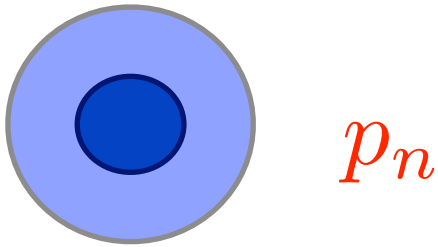
Piasetzky & Co



Weinstein & Co



6p and 6n



p_n neutron rate

calculate the expected proton rate

$$p + A \rightarrow p + p/n + X$$

92% of the time two-nucleon high density fluctuations

are proton and neutron

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

Important Implication for the structure of the neutron stars

Piasetzky, MS, Strikman, Frankfurt, Watson
PRL 2006

$$e + A \rightarrow e' + p + p/n + X$$

R. Shneor et al. 07

Confirmed

Schiavilla, Wiringa, Pieper, Carlson
PRL 2007

Conclusions on Short Range NN

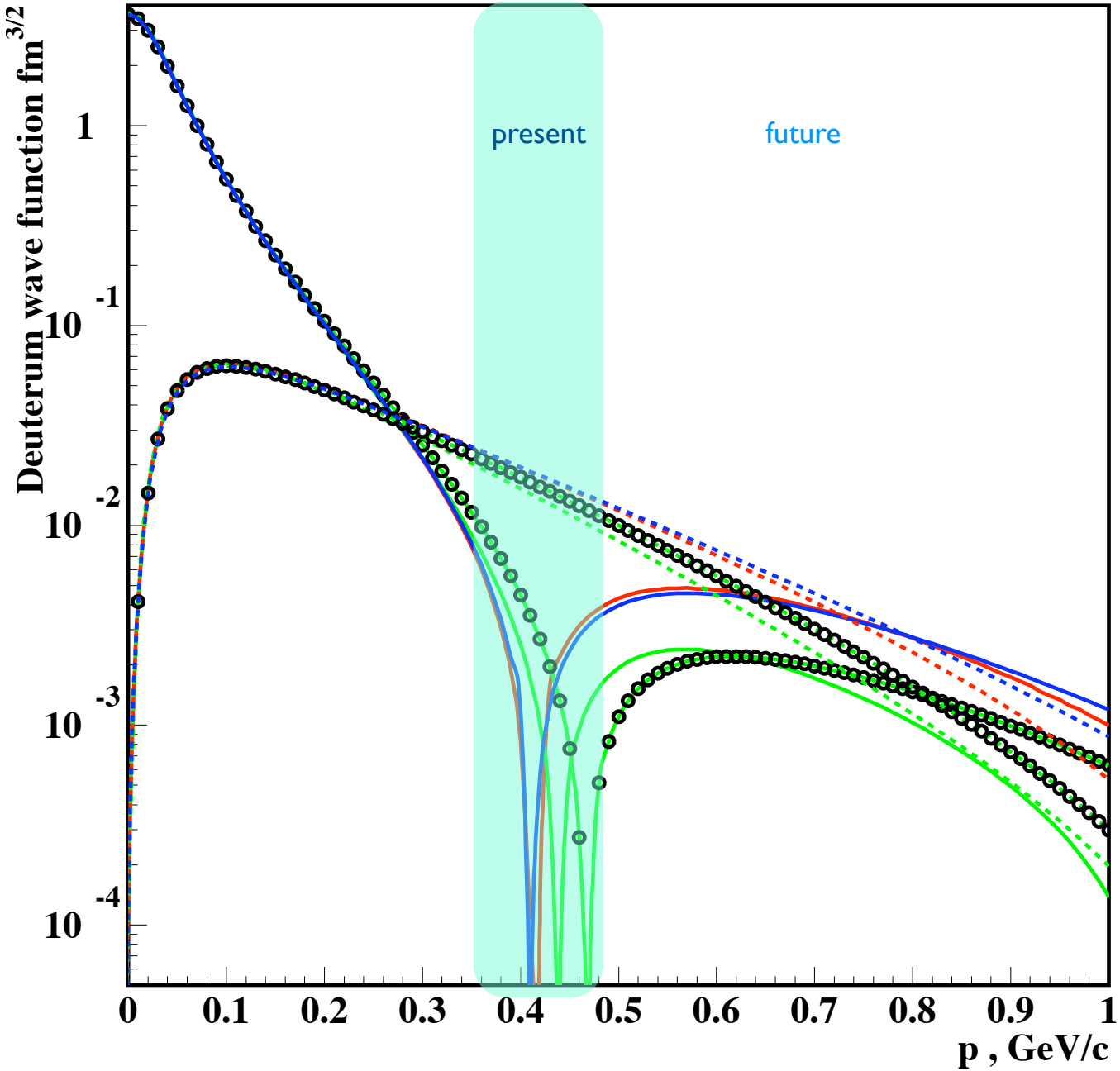
- We can localize 2N SRCs in Nuclei with relative momenta up to 600 MeV/c

- Final State Interaction is localized in SRC

- There is a strong suppression of pp and nn SRC's as compared to pn -> dominance of the tensor forces

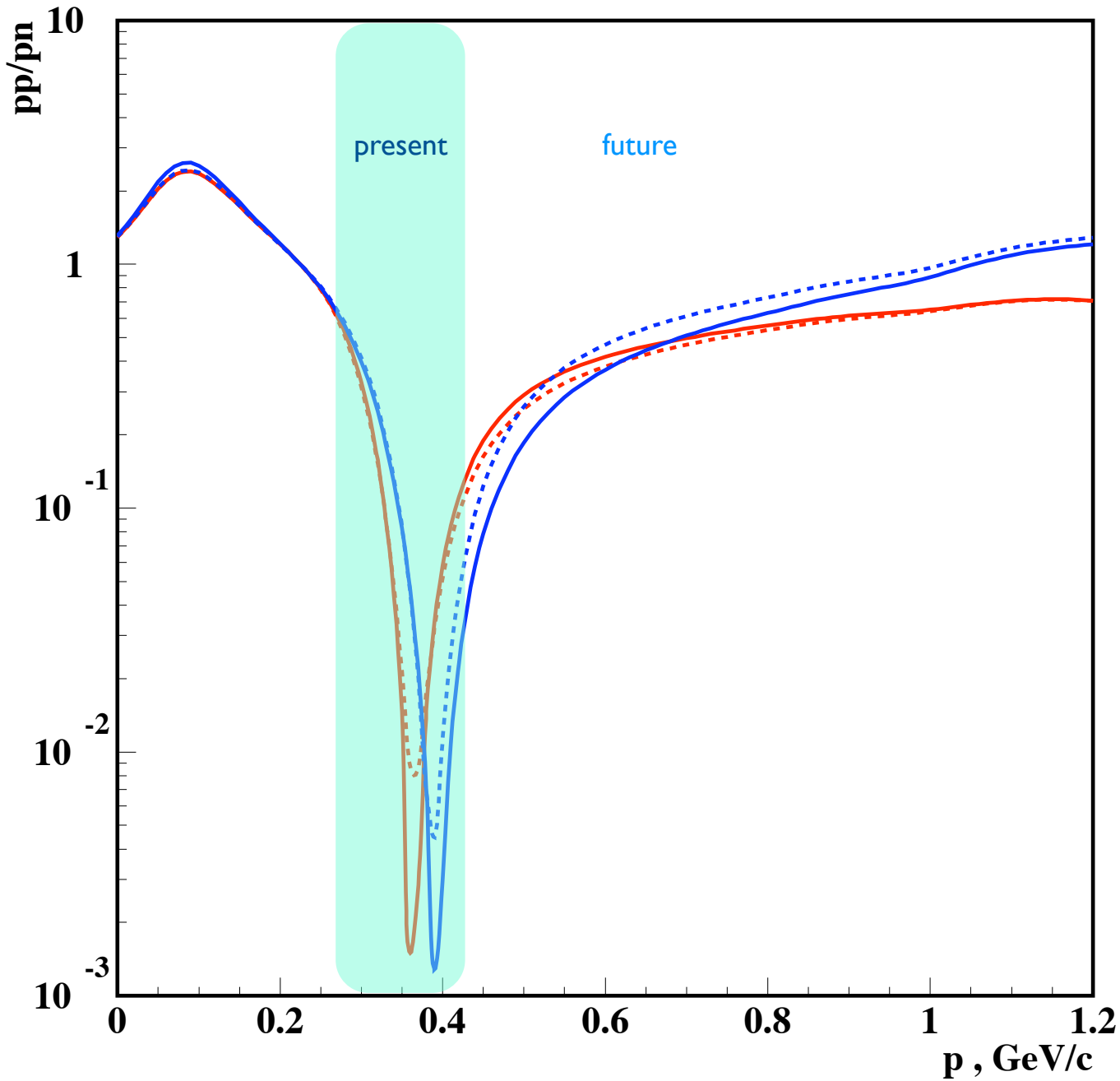
- the Fermi distribution of protons in the neutron stars will be strongly deformed due to larger strength of pn interaction as compared to nn

Relativism and core of the NN interaction



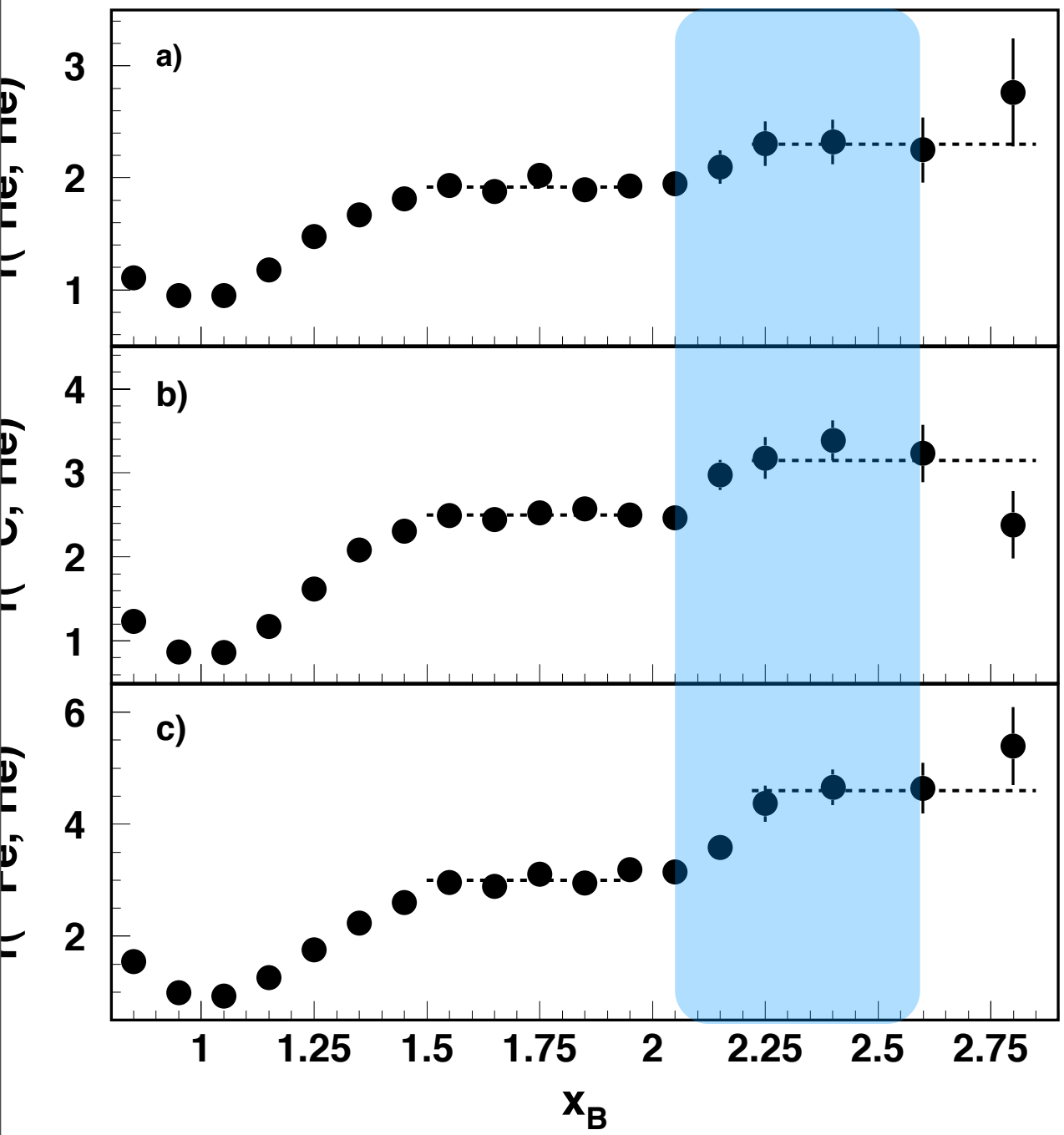
Deuteron

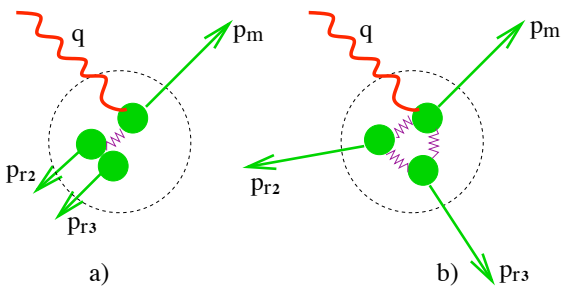
Relativism and core of the NN interaction



Helium 3

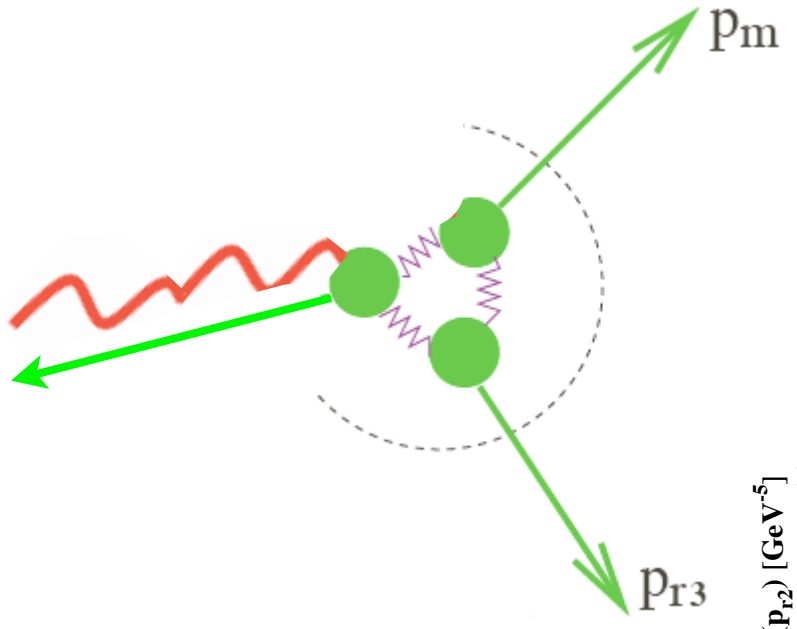
3N forces



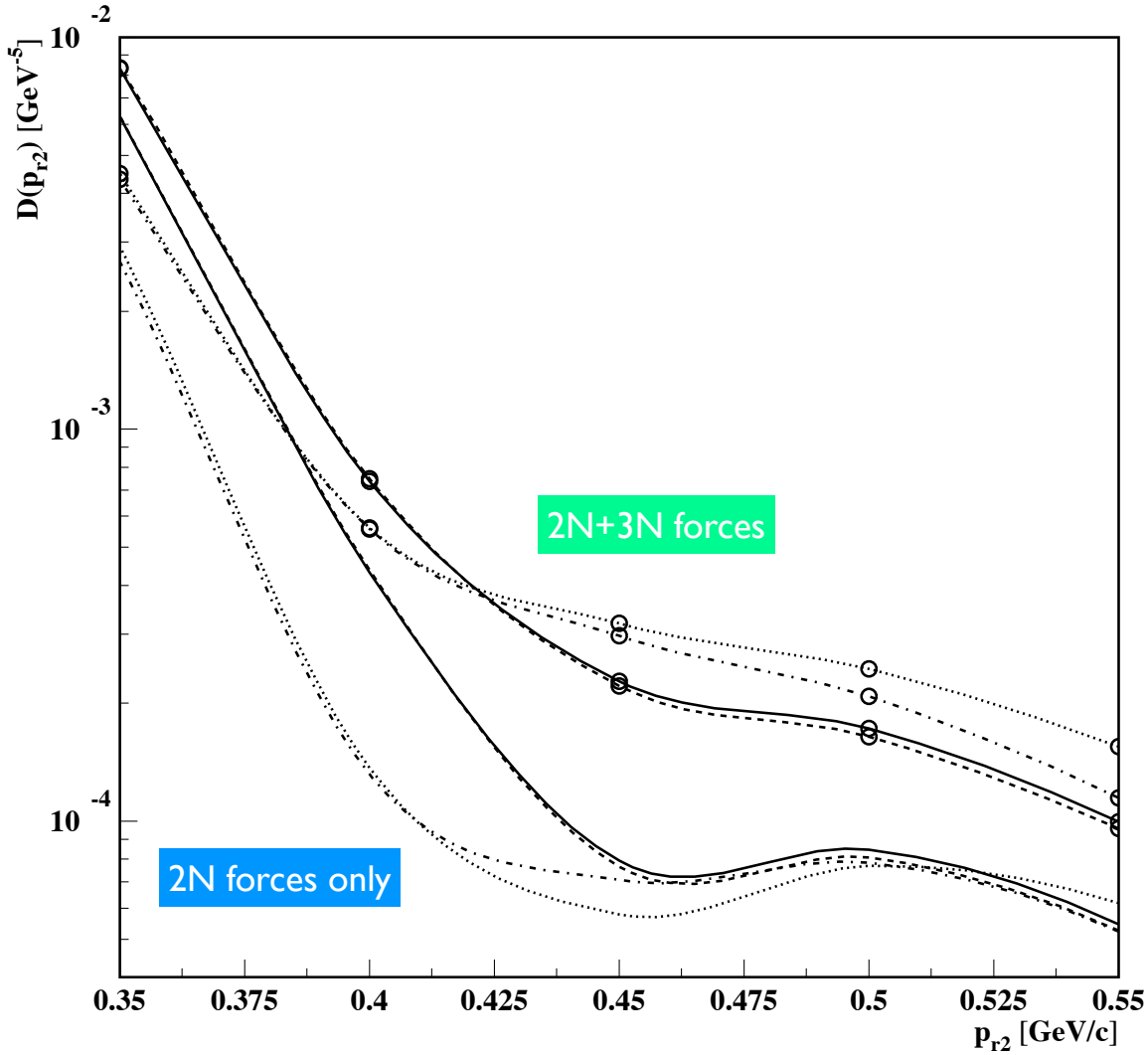


Egiyan et al, PRL2006

Three Nucleon Forces

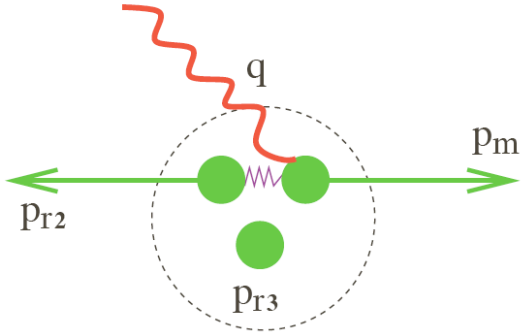


$$E_m^{3N} = 2\sqrt{m^2 + p_m^2} - 2m - \sqrt{4m^2 + p_m^2}$$

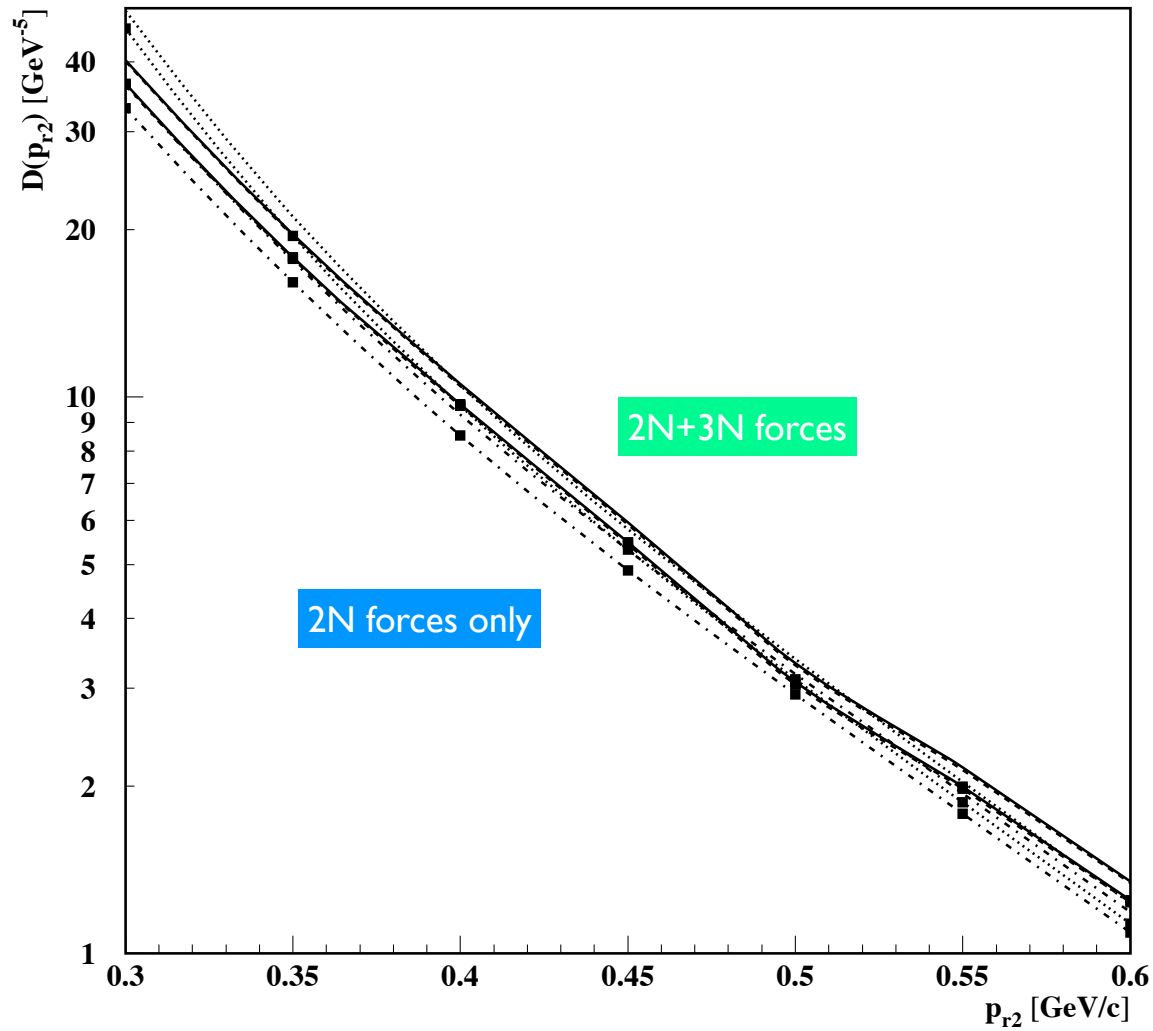


MS, Abrahamyan, Frankfurt, Strikman, PRC05

2N correlation kinematics



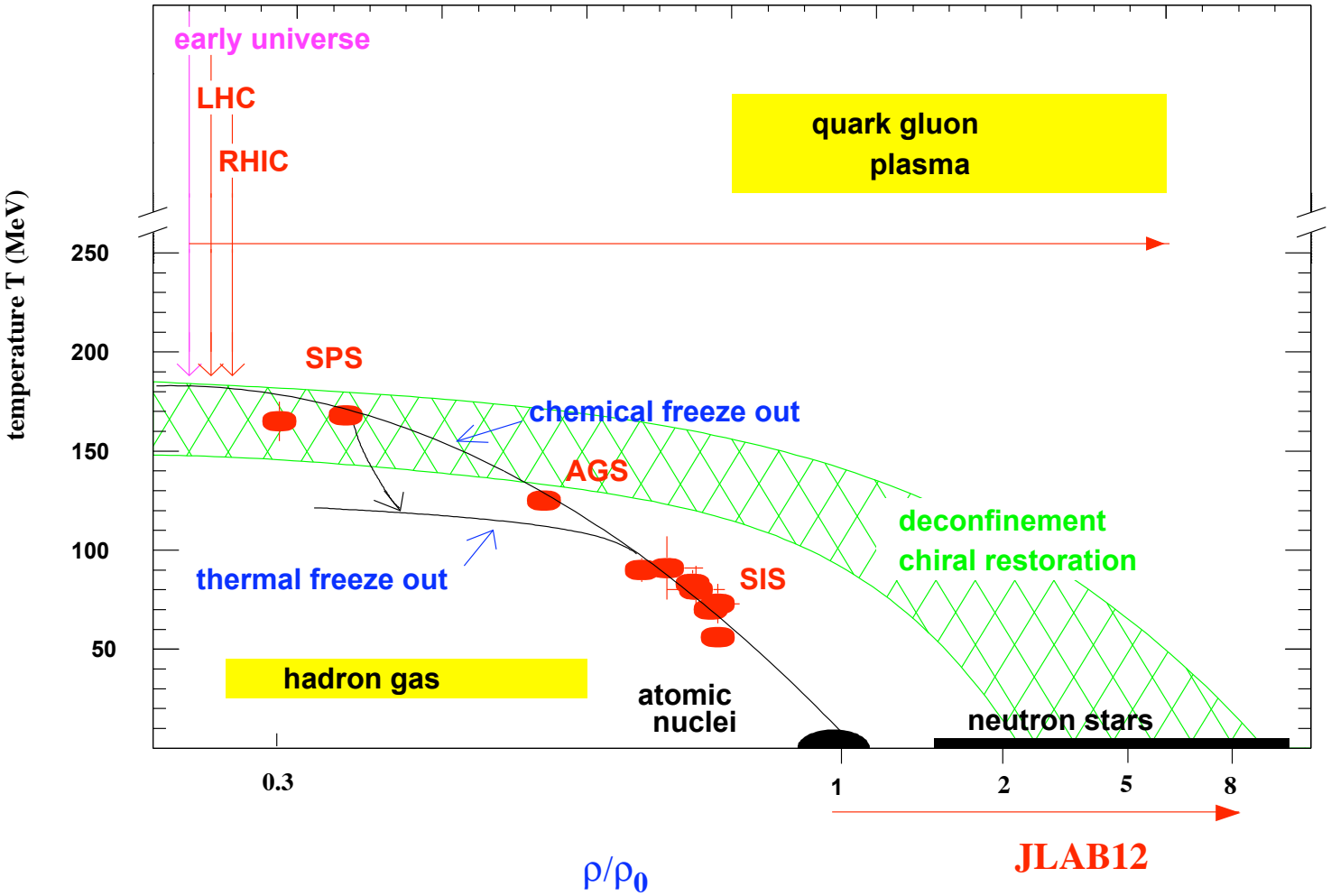
$$E_m^{2N} = \sqrt{m^2 + p_m^2} - m - \sqrt{4m^2 + p_m^2}$$



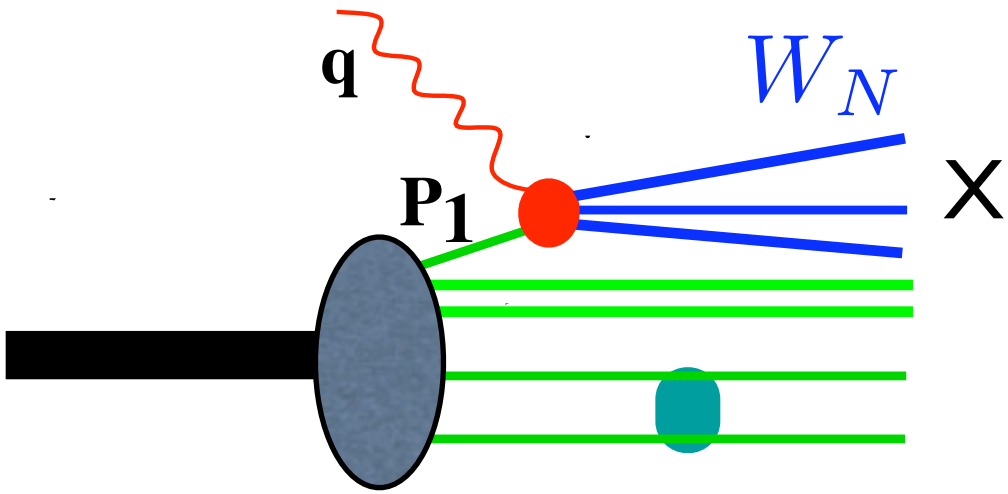
MS, Abrahamyan, Frankfurt, Strikman, PRC05

quark-hadron transition

quark-hadron transition



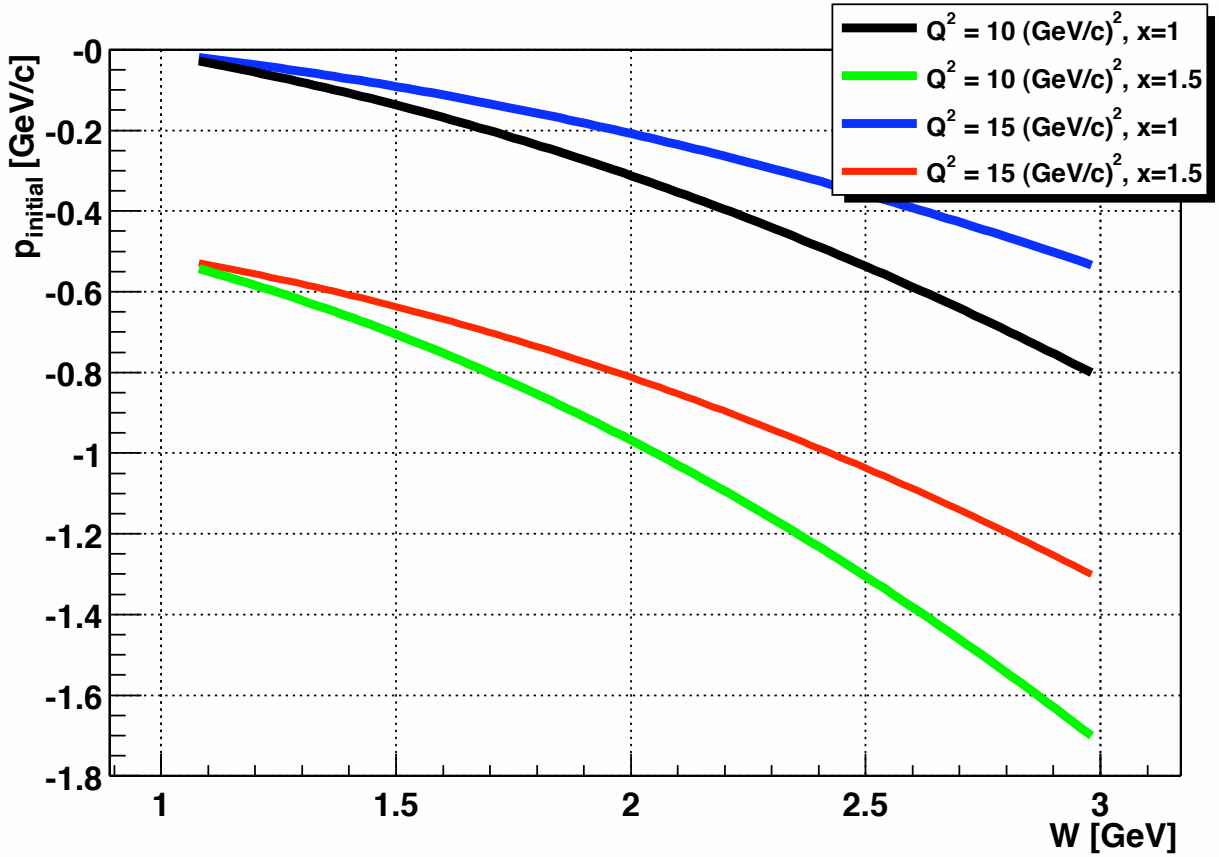
Deep Inelastic $A(e,e')X$ Scattering at x>1



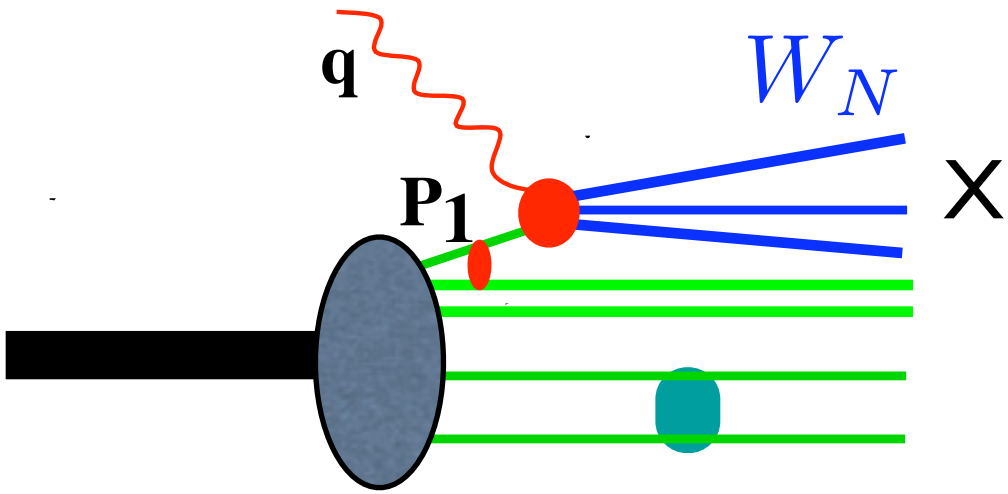
Two processes driving nucleons close together

First: Kinematics

$$p_1^z = m\left(1 - x - x\left[\frac{W_N^2 - m^2}{Q^2}\right]\right)$$



Deep Inelastic $A(e,e')X$ Scattering at x>1



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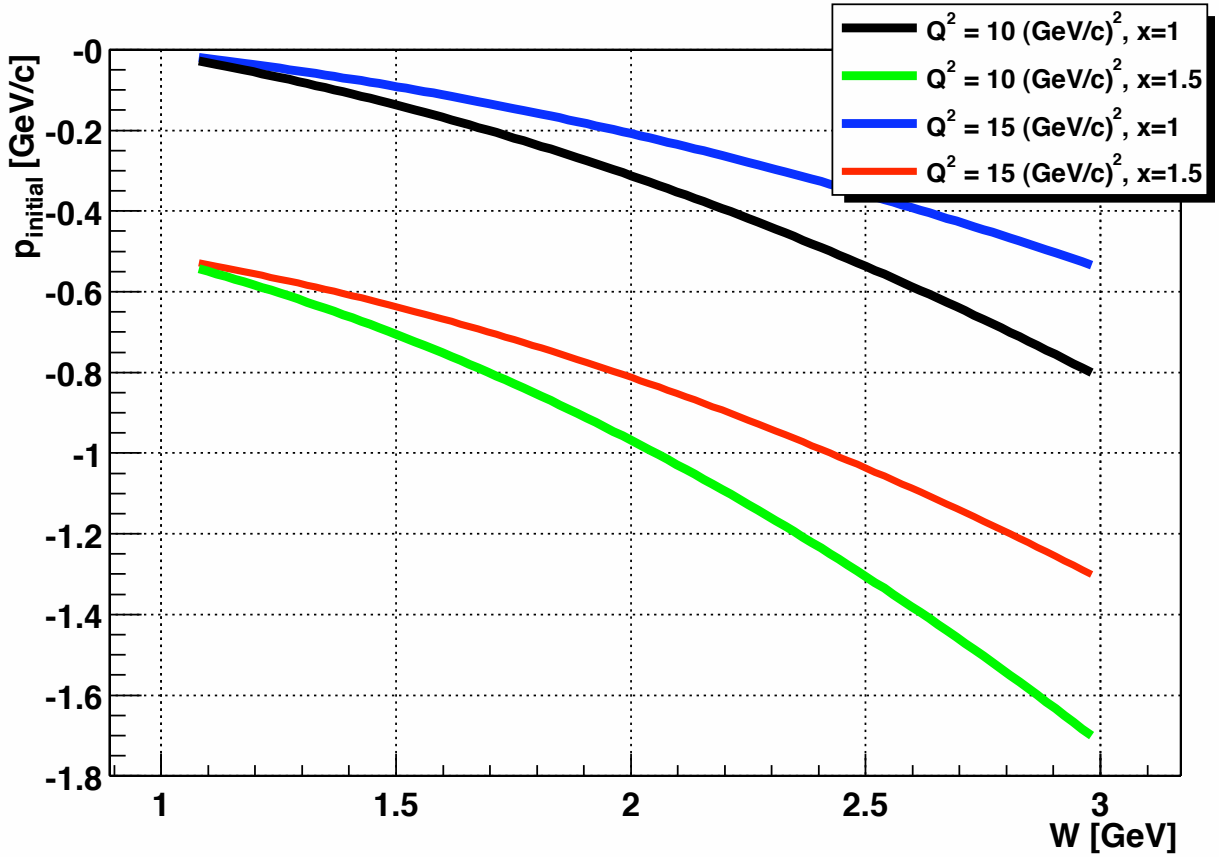
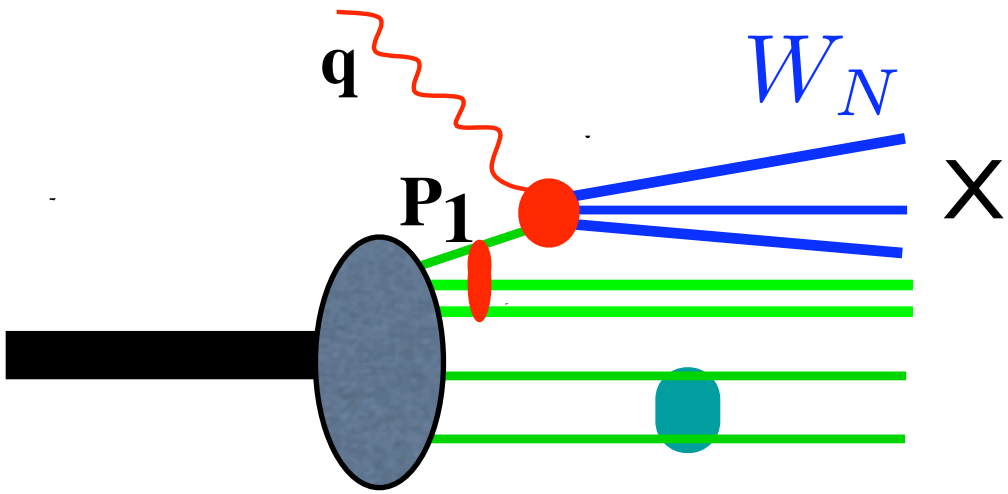


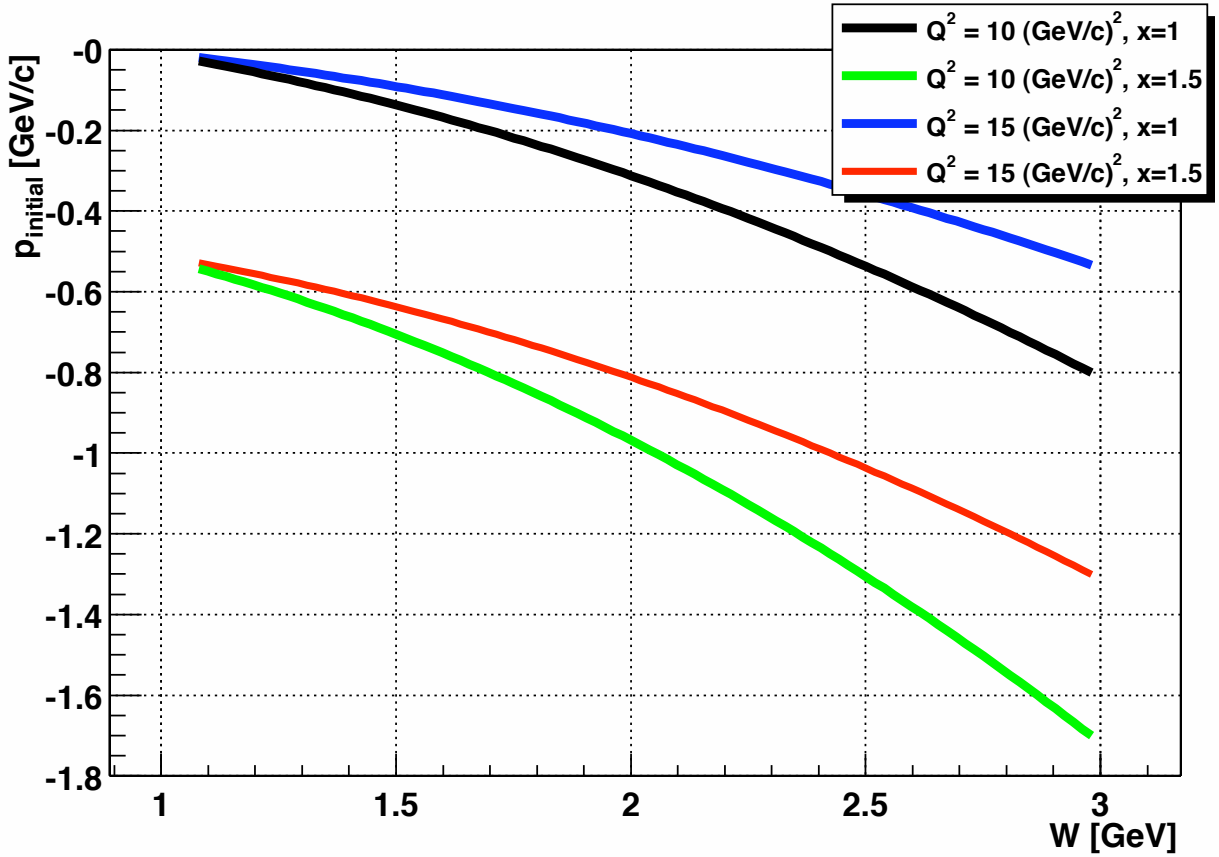
Deep Inelastic $A(e,e')X$ Scattering at x>1



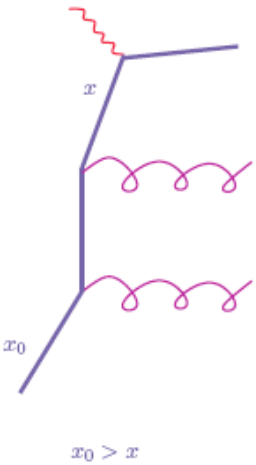
Two processes driving nucleons close together

First: Kinematics

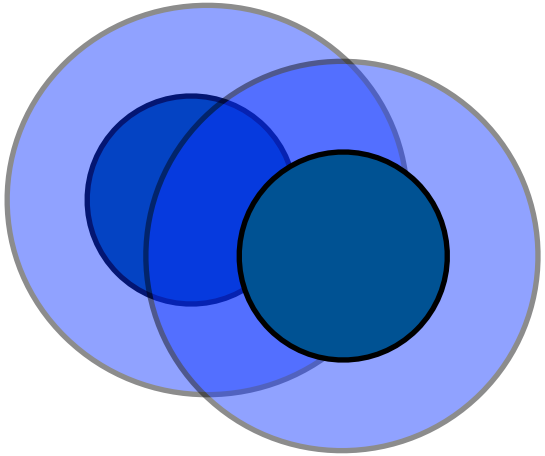
$$p_1^z = m\left(1 - x - x\left[\frac{W_N^2 - m^2}{Q^2}\right]\right)$$

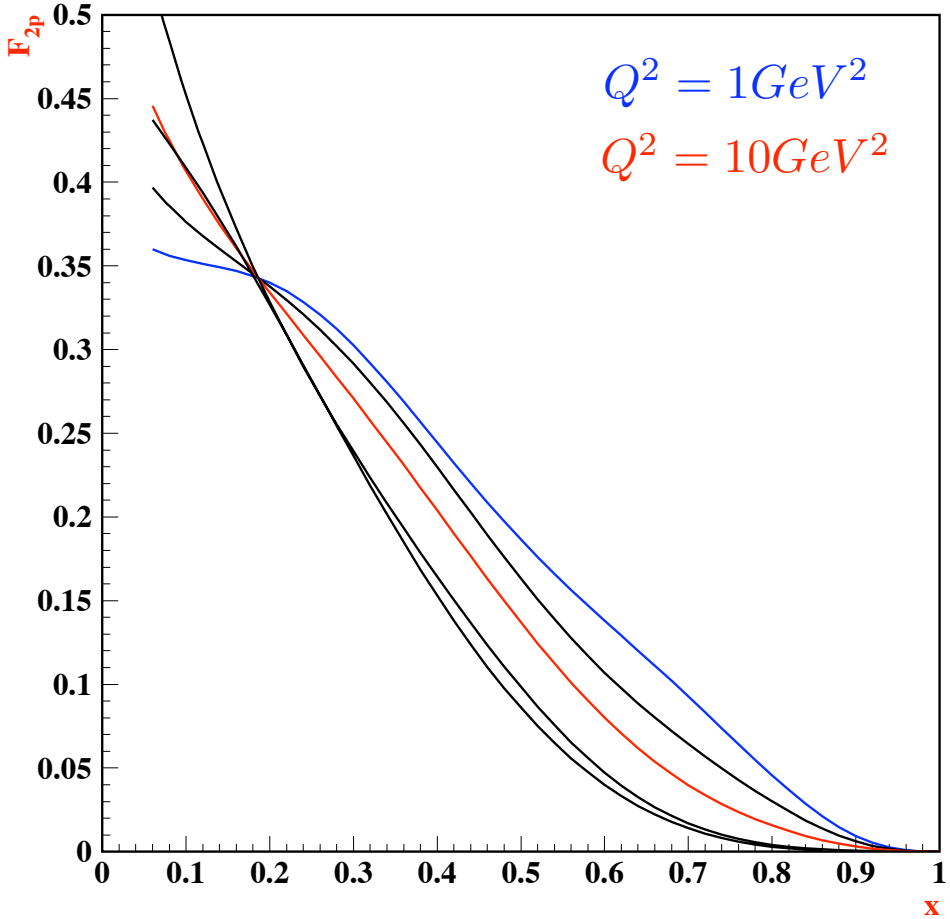


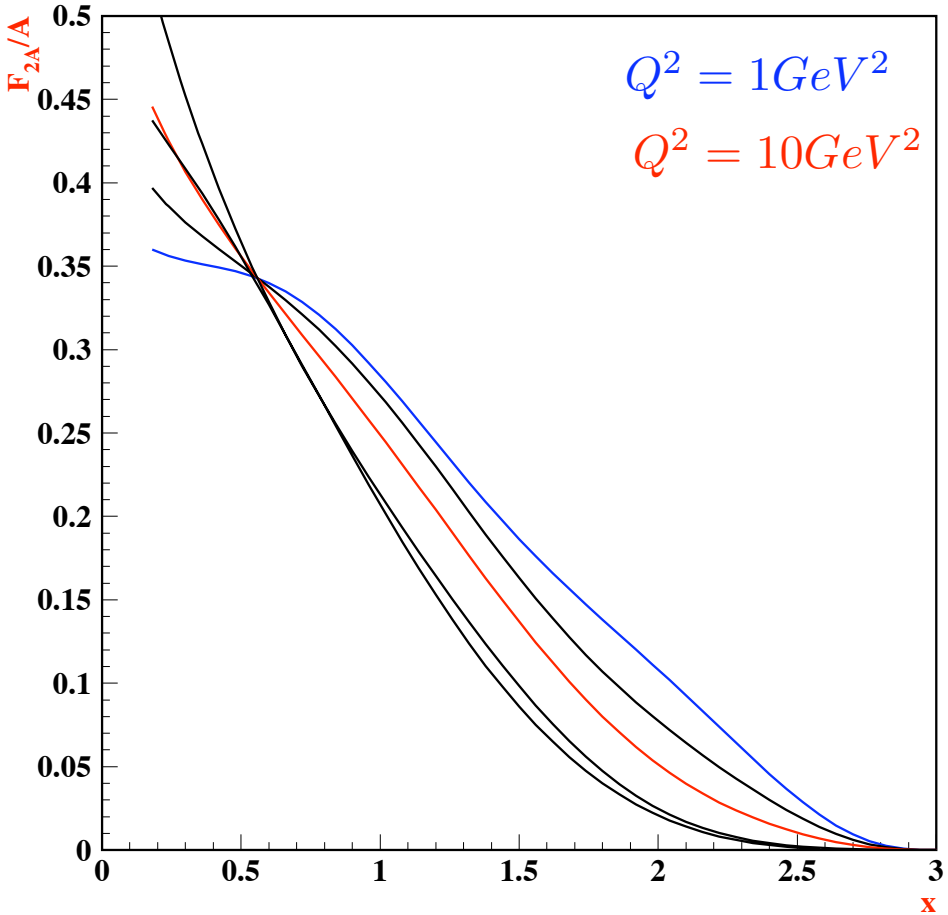
Second: Dynamics



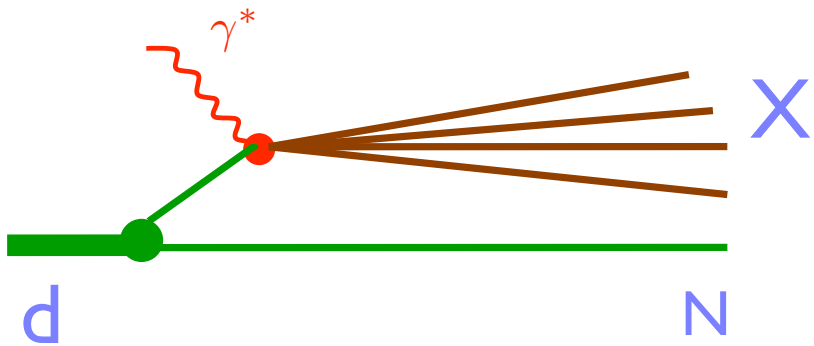
Consider: Deuteron





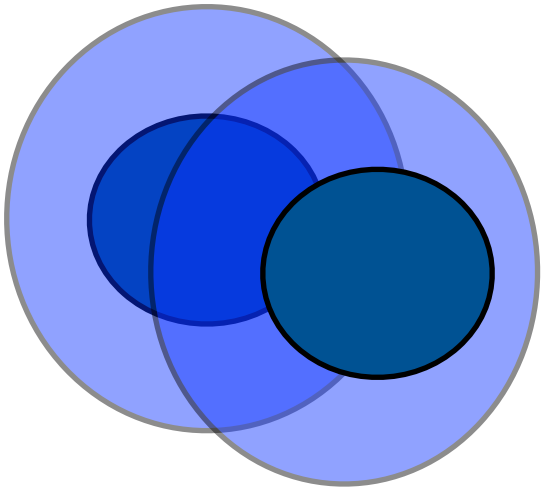


Convolution Model

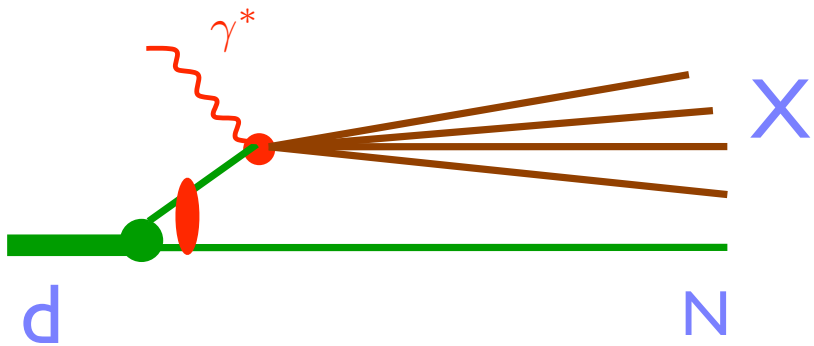


$$F_{2d} = \int_x^2 \rho_d^N(\alpha, p_t) F_{2N}(\frac{x}{\alpha}, Q^2) \frac{d^2\alpha}{\alpha} d^2 p_t$$

$$F_{2N} \longrightarrow F_{2N}^{mod}$$



Convolution Model



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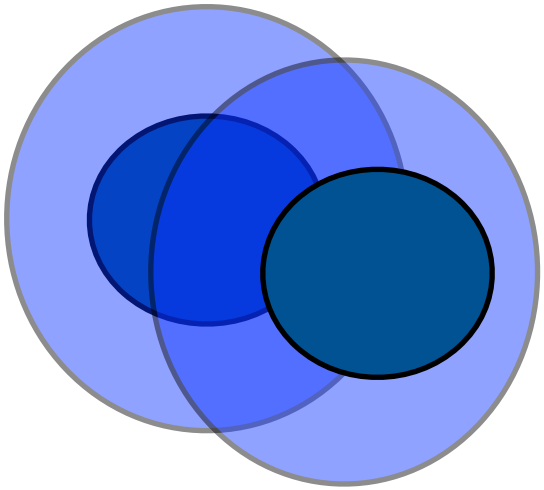
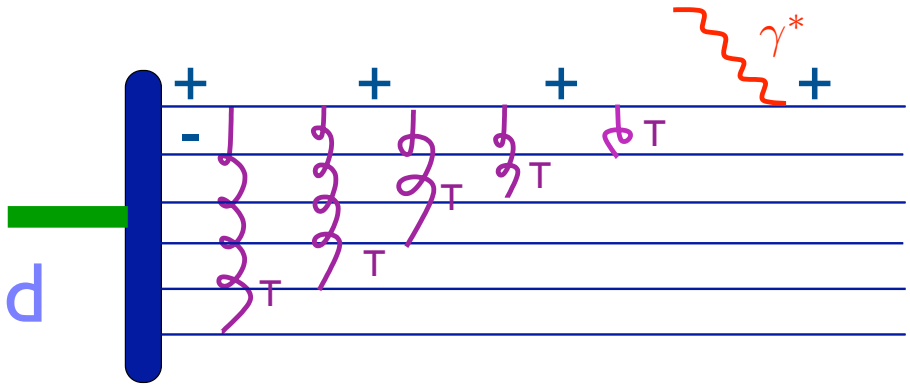


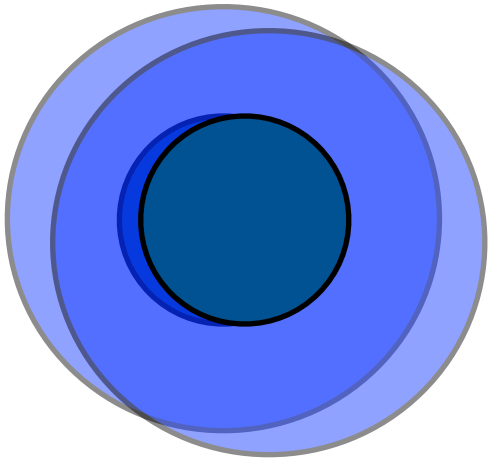
Quark-Cluster - 6q - Model



$$F_2 \sim (1-x)^{2N-3+2|\Delta\lambda|}$$

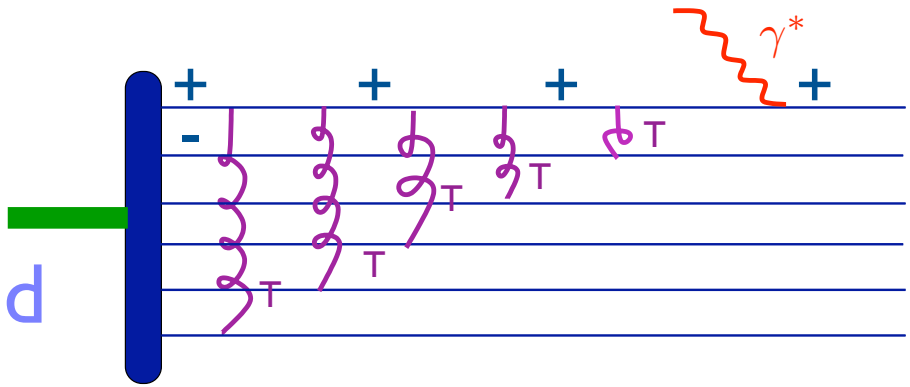
Gunion, Nason, Blankenbecler, PRD 1984

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



Carlson, Lassila, Sukhatme, PLB 1988,1991

Quark-Cluster - 6q - Model



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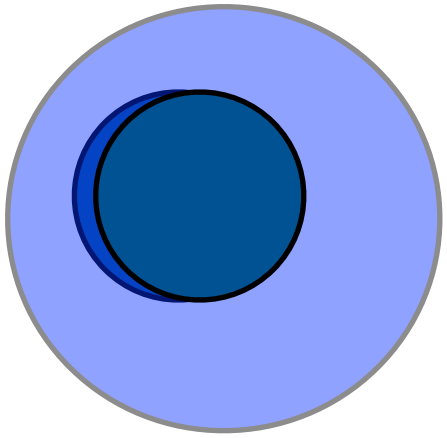
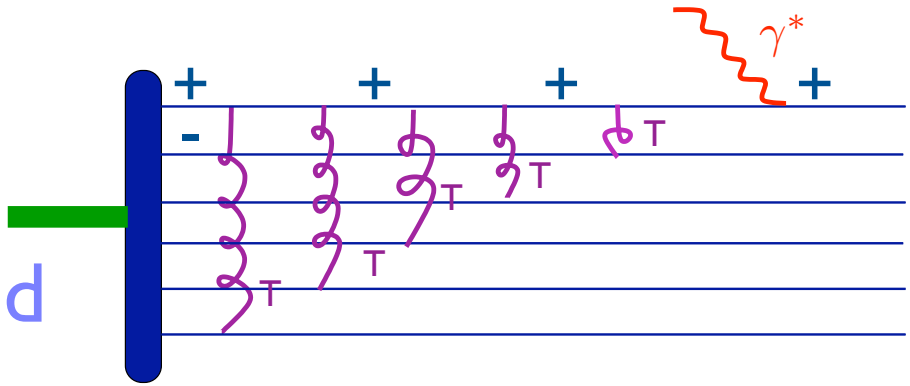


Carlson, Lassila, Sukhatme, PLB 1988,1991

Quark-Cluster - 6q - Model



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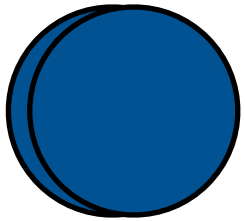
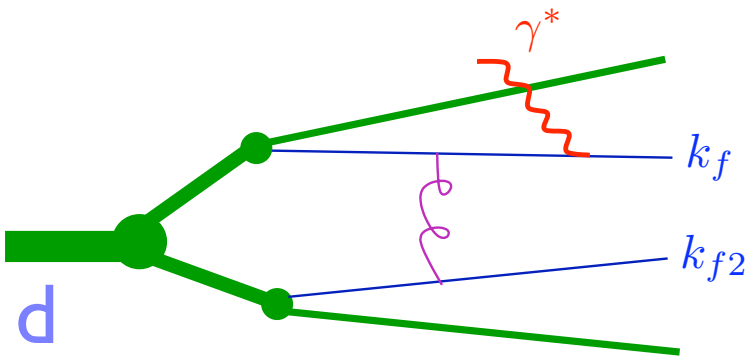
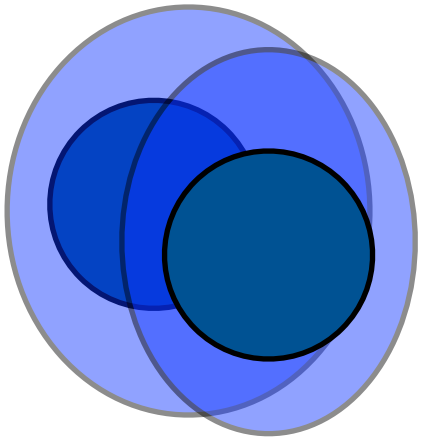


Carlson, Lassila, Sukhatme, PLB 1988,1991

Hard Gluon-Exchange Model



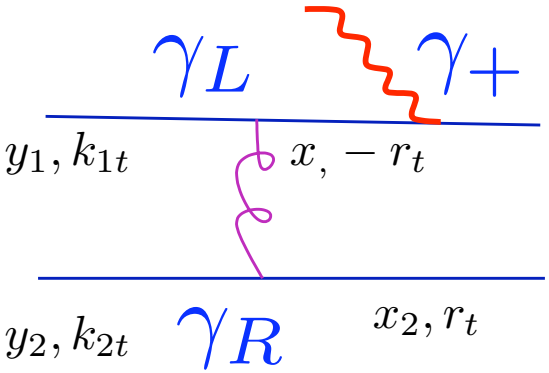


$$\mathcal{M}^\mu = \int \frac{\Psi_d(\alpha, p_t)}{(1-\alpha)} \frac{d\alpha}{\alpha} \frac{d^2 p_t}{2(2\pi)^3} \times$$

$$\bar{u}(k_f)[e_q \gamma^\mu] u_{\zeta'}(k_f - q) \frac{1}{(k_f - q)^2 - m_q^2} \bar{u}_{\zeta'}(k_f - q)[g T^a \gamma^{\nu_1}] u_\zeta(k_1) \frac{\psi_N(y_1, k_{1t})}{y_1}$$

$$\bar{u}_{\eta'}(k_{f2})[g T^b \gamma^{\nu_2}] u_\eta(k_2) \frac{\psi_N(y_2, k_{2t})}{y_2} \frac{d^{\nu_1,\nu_2} \delta_{ab}}{(k_2 - k_{f2})^2}$$

$$F_{2d} = W^{++} \cdot \nu \left(\frac{m_N}{p_{d+}} \right)^2 \qquad W^{++} = \frac{1}{4\pi m_d} \int |\mathcal{M}^+|^2 dQ$$



$$\gamma_{R,L} = \gamma_x \pm \gamma_y$$

$$\gamma_\pm = \gamma_0 \pm \gamma_z$$

Reference Frame

$$q_+ = 0$$

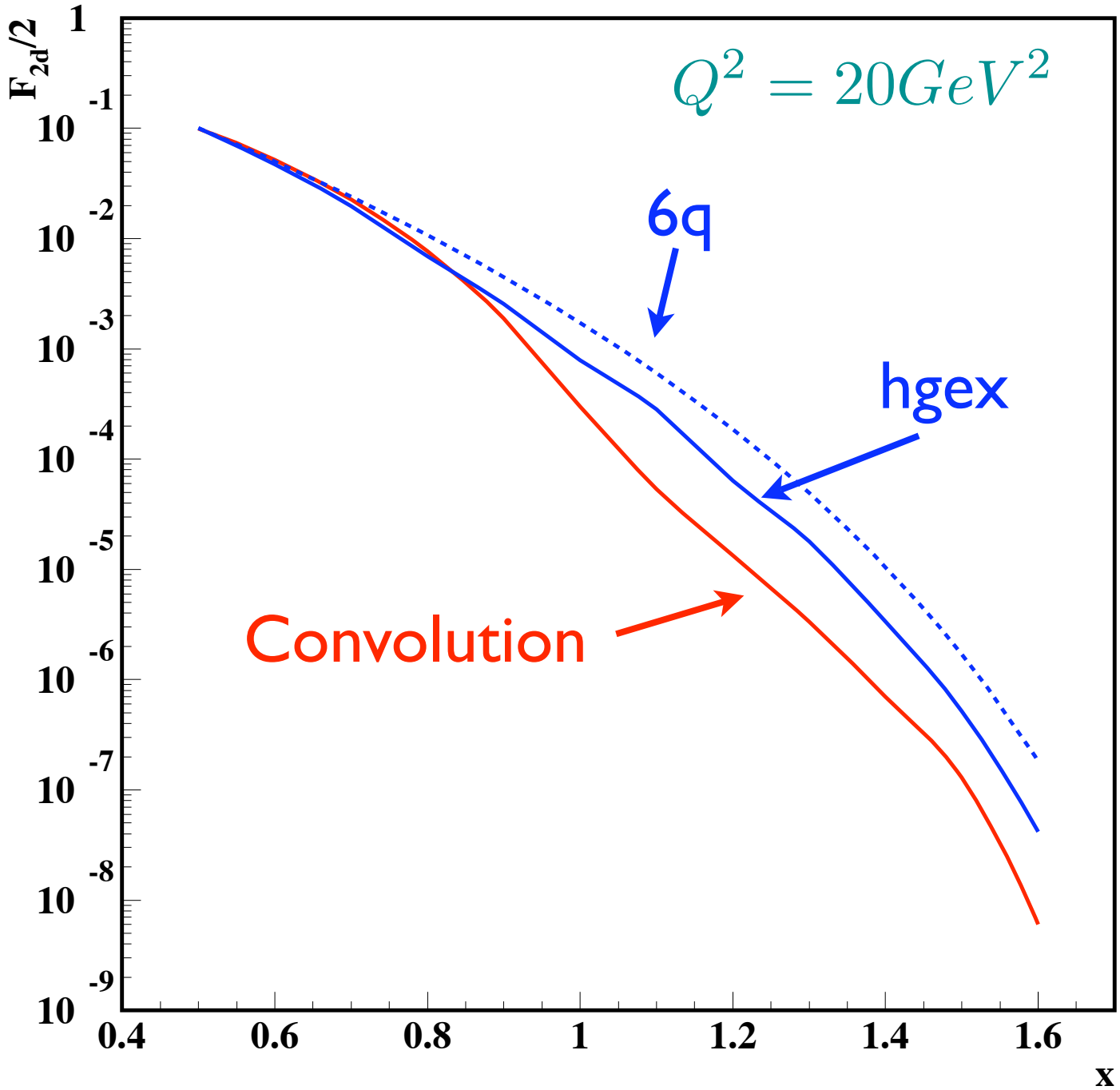
$$q = (0, \frac{2\nu m_d}{p_{d+}}, \sqrt{Q^2})$$

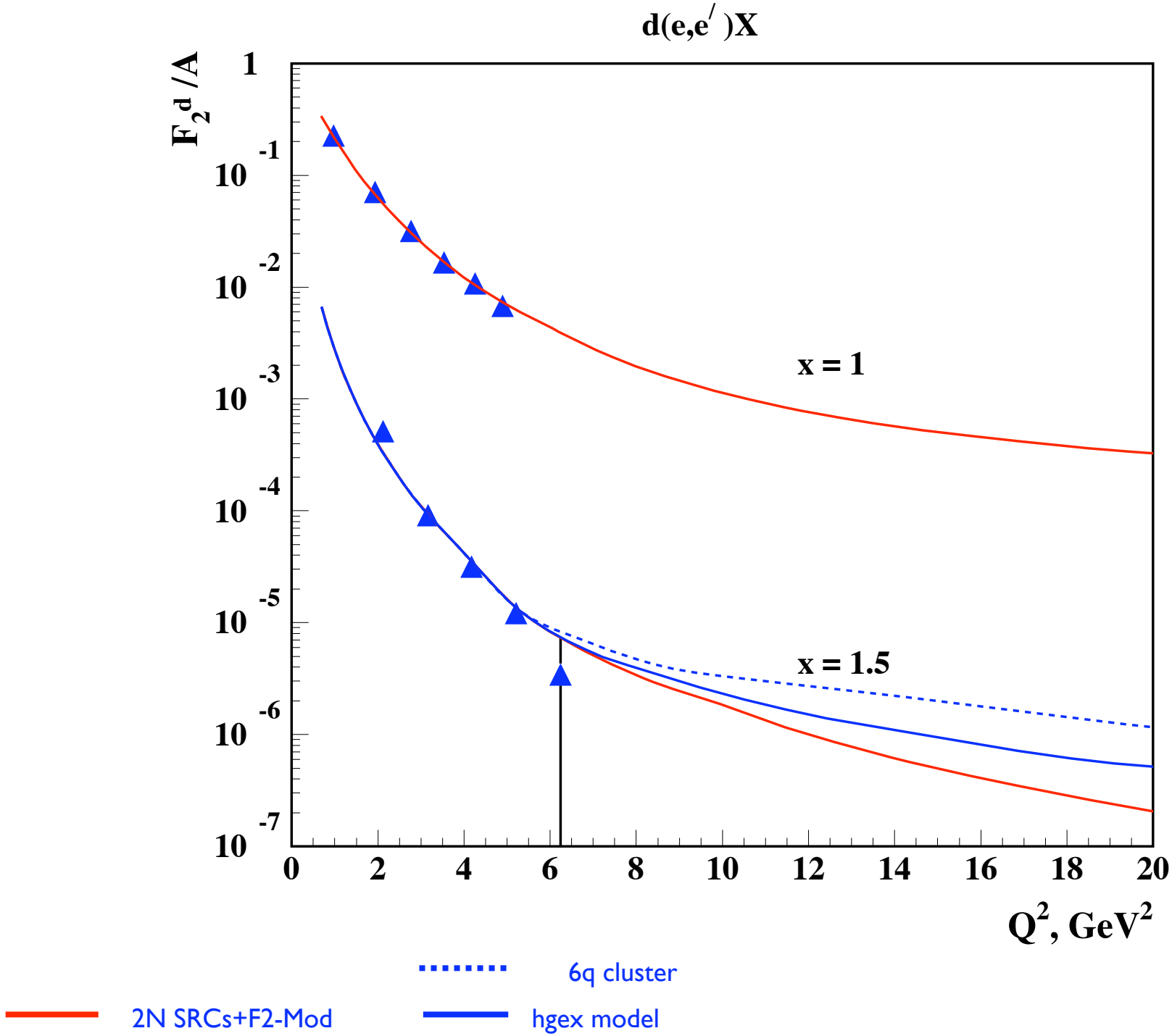
$$p_d = (p_{d+}, \frac{m_d^2}{p_{d+}}, 0)$$

$$kernel = \sqrt{x x_2}(1-\alpha)\alpha(1 - \frac{x}{y_1 + y_2})\frac{8 p_{d+}}{((1-\alpha)y_1 + \alpha y_2) r_t^2}$$

$$F_{2D} \approx N \int \frac{d\alpha}{\alpha} \left[\psi_d(\dot{\alpha}, p_t) \frac{d^2 p_t}{(2\pi)^2} \right]^2 \times$$

$$\times \int_0^1 \int_0^1 \left(1 - \frac{x}{2(y_1\alpha + y_2(1-\alpha))} \right)^4 \Theta(y_1\alpha + y_2(1-\alpha) - \frac{x}{2}) f_N(y_1) f_N(y_2) dy_1 dy_2$$

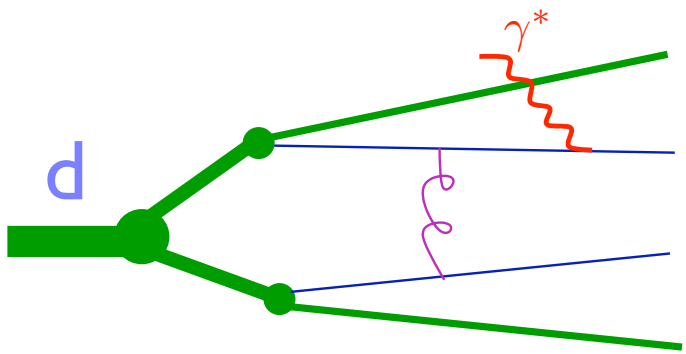

$F_{2d}/2$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0.4
0.6
0.8
1
1.2
1.4
1.6
x
$Q^2 = 20GeV^2$
6q
hgex
Convolution

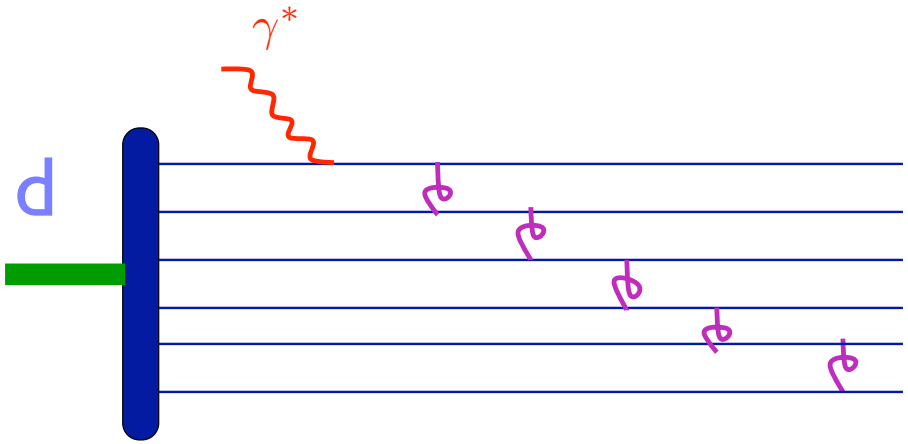

d(e,e/)X
F2d /A
1
10-1
10-2
10-3
10-4
10-5
10-6
10-7
0
2
4
6
8
10
12
14
16
18
20
Q2, GeV2
x = 1
x = 1.5
6q cluster
2N SRCs+F2-Mod
hgex model

- softening of x distribution

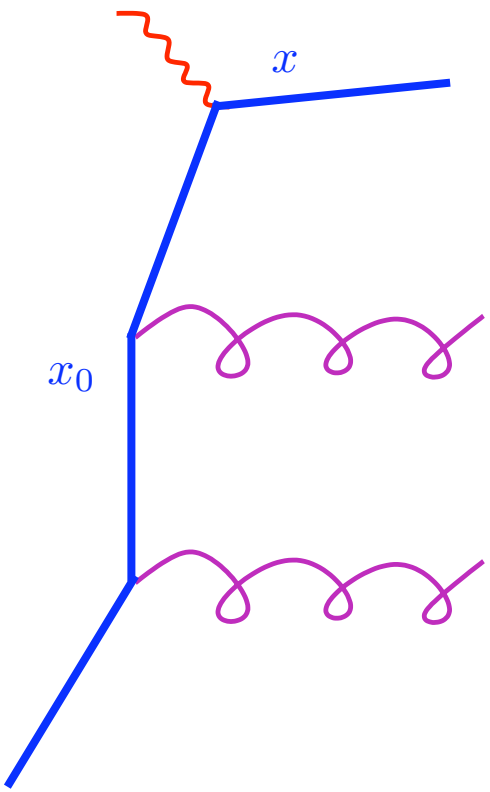
- hgex model predicts less soft than 6q and less hard than NN

- observation of hgex like scenario will indicate on existence of mixed quark- hadron phase in NS

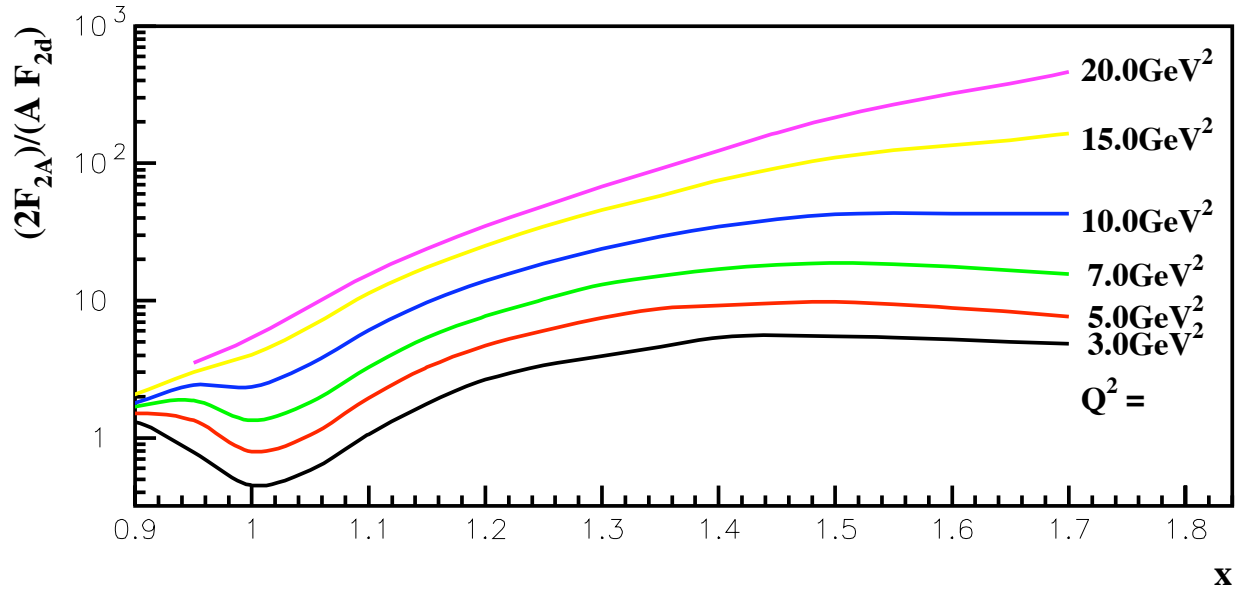




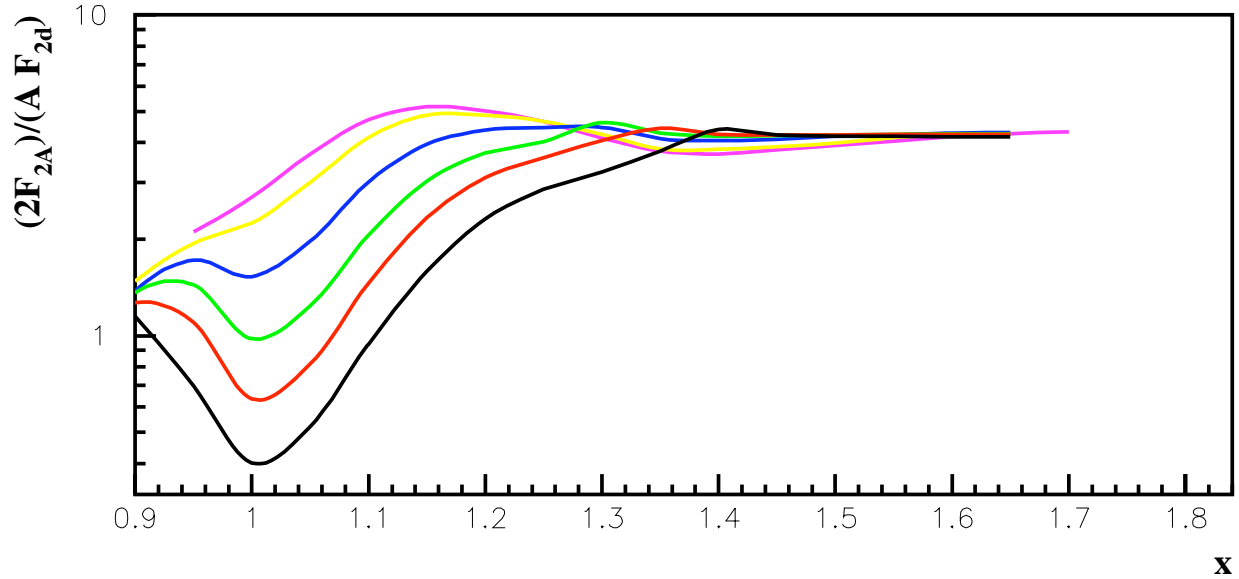
A/d Ratios with Parton Evalution



$x_0 > x$



2N+3N models



2N models only

Highlighting Other Processes

$$N + N \rightarrow HigherMasses$$

Chiral Restoration

The role of Δ in High Density Fluctuations

Role of the Strangeness in High Density Fluctuations

Hyperon N interaction

Survey Experiments → Chiral Restoration and Hidden Color

S. Brodsky, 05

In the world where chiral symmetry is broken

Deuteron (t=0,s=1) two nucleons two-separately color neutral objects

In the world where chiral symmetry is unbroken

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

Signature of Chiral Simmetry Restoration

$\frac{\psi_d(NN)}{\psi_d(\Delta\Delta)}$ $0 \rightarrow 1$ with an increase of internal momenum in the deuteron

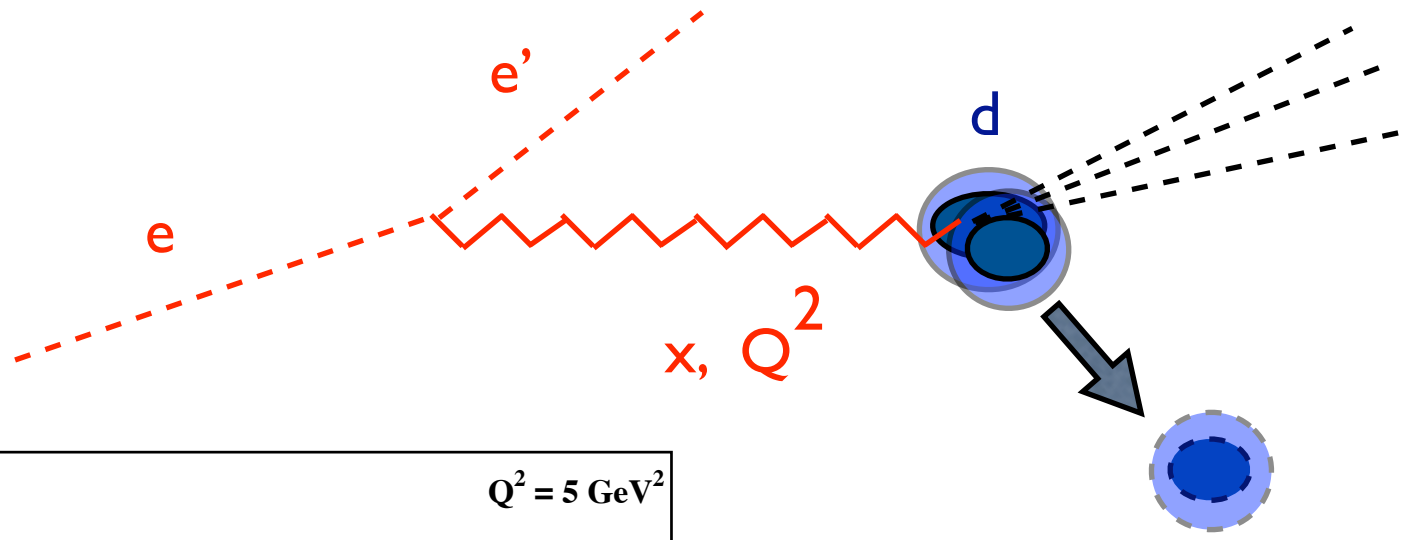
$$e + d \rightarrow e + N_{back}(\Delta_{back}) + X$$

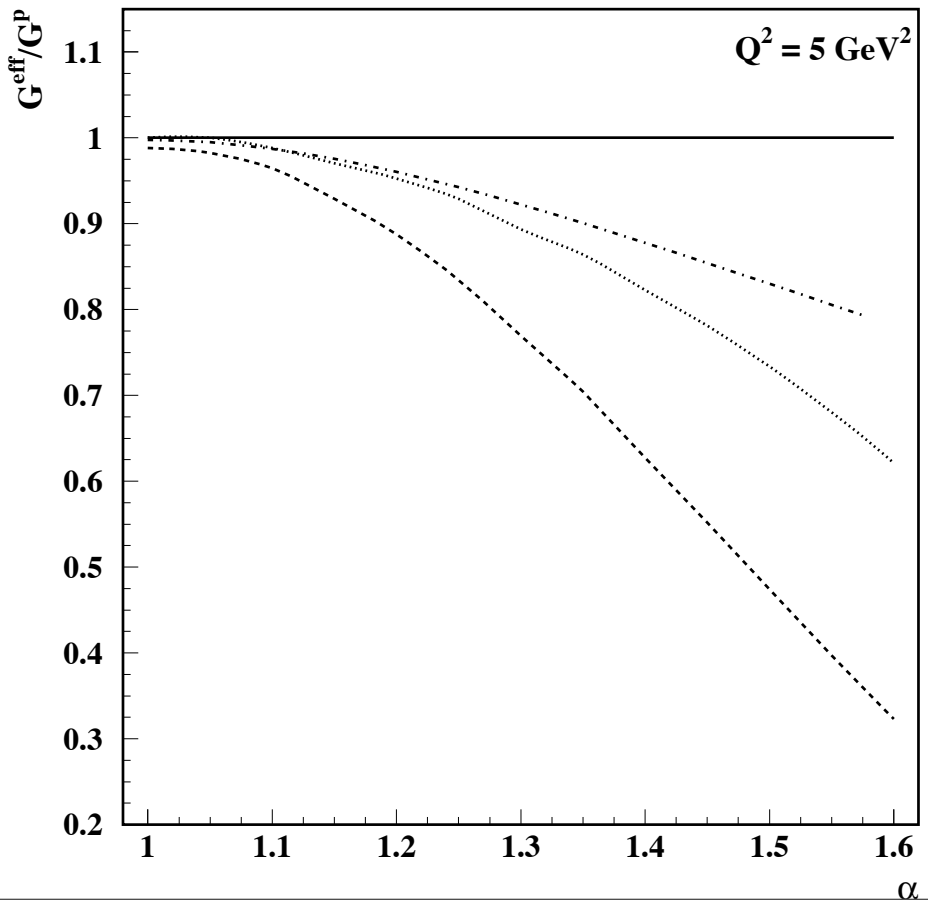
$\frac{\mathbf{yield_{K_{back}}}}{\mathbf{yield_{\pi_{back}}}}$ **from few percent $\rightarrow$ 1**

with an increase of internal momenum in the deuteron

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

Modification of quark distributions in nuclei (EMC effect)





α, p_t

controls the virtuality of bound nucleon in the Deuteron

Melnitchouk, MS, Strikman 97

Griffioen, Kuhn 94 Experiment

Conclusions/ Outlook

- Systematic framework can be developed for an earthbound nuclear physics studies that can advance our understanding of the structure of Dense Nuclear matter

- Emerging Results on SRC from JLab demonstrates very well the feasibility of such program

- 12 GeV upgrade will allow to carry out systematic studies of
  - structure of the nuclear core
  - 3N forces
  - relativistic effects
  - hadron-quark transition
  - .....

- All these experiments will require long running time ...

- Some of them will have a survey character ...