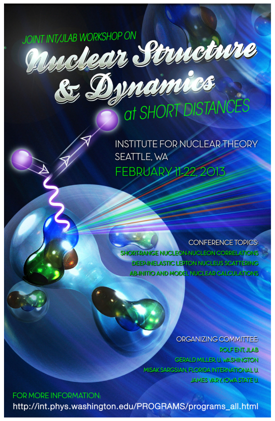
Role of short-range (and tensor) correlations in finite nuclei and nuclear matter



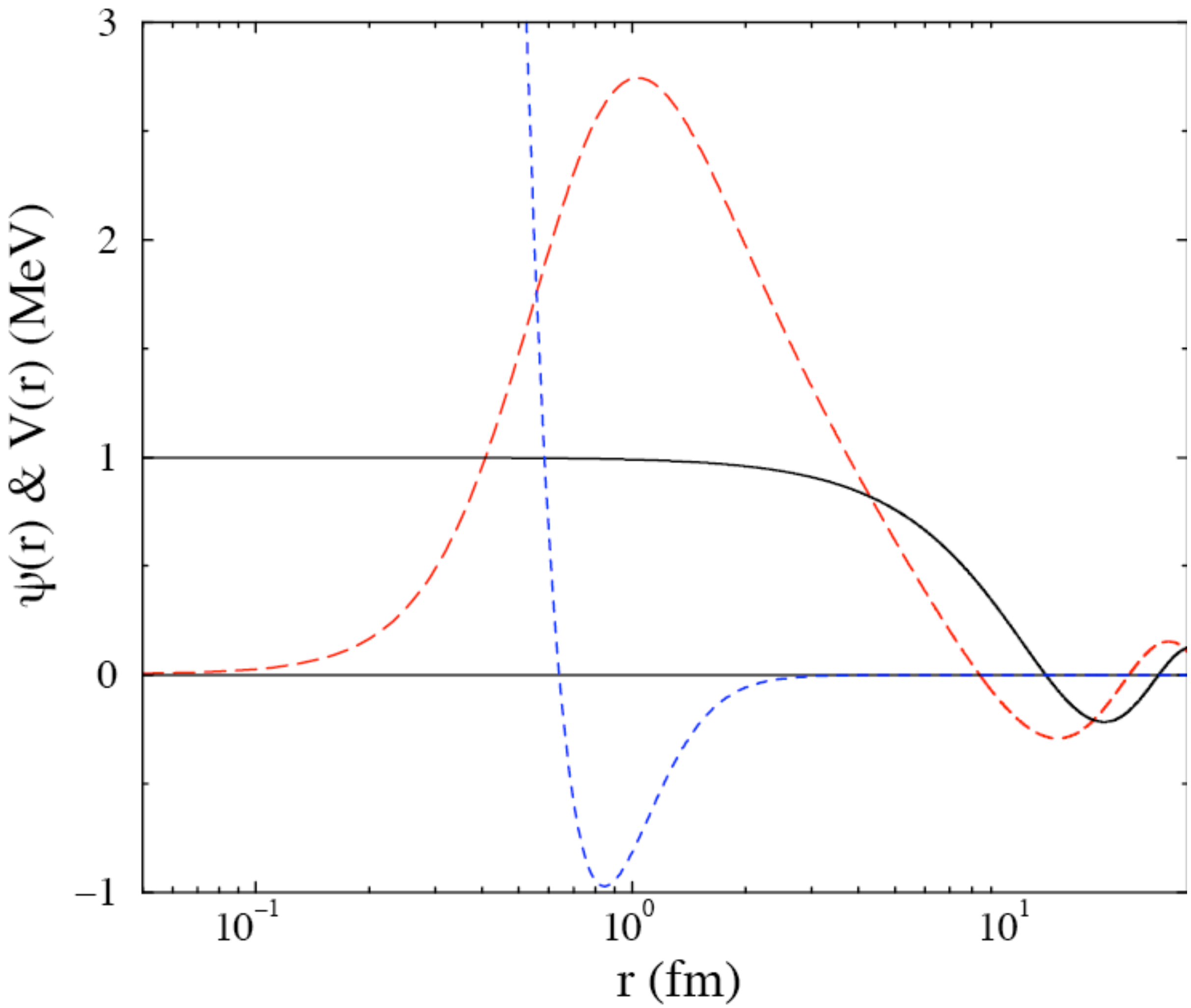
Arnau Rios (Surrey)
Arturo Polls (Barcelona)

Dimitri Van Neck (Ghent)
Herbert Müther (Tübingen)

<u>WashU in St. Louis</u>
Hossein Mahzoon
Seth Waldecker
Helber Dussan
Bob Charity
Wim Dickhoff

- SRC for two nucleons
- Review of older insights
- Recent self-consistent Green's functions calculations at finite T
  - Nuclear matter: symmetric and pure neutron matter
  - Asymmetric matter
- Finite nuclei with SRC from a Green's function calculation
  - Ab initio
- Dispersive Optical Model (Framework of Green's functions <--> data)
- Conclusions and Outlook

Repulsive core and wave function ⇒ high-momenta



Reid $^1S_0$

$k_0 = 0.25\ fm^{-1}$

~ few MeV

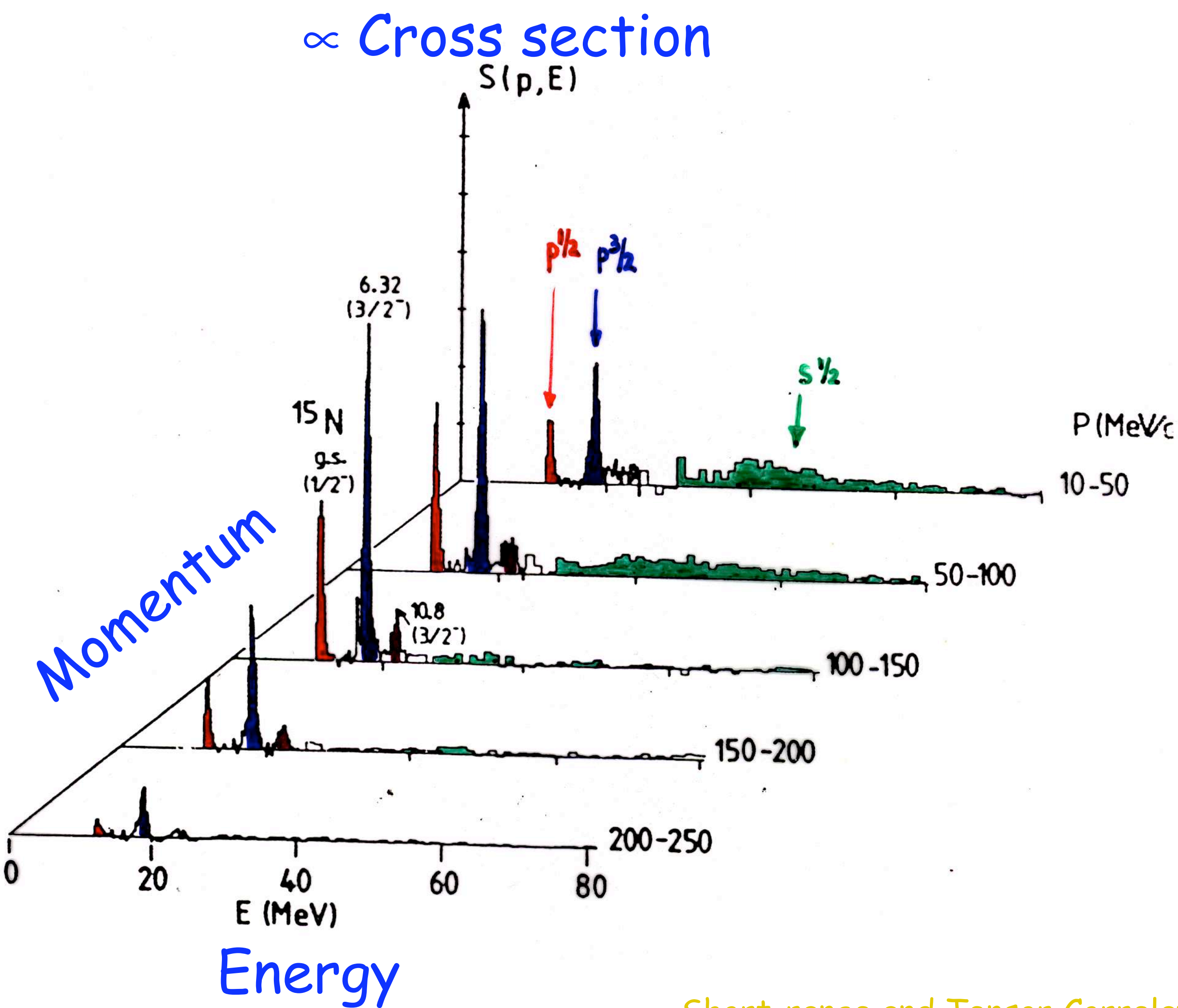
V(r)/100

$\sin(k_0 r)/k_0 r$

correlated wf for a "hard" interaction

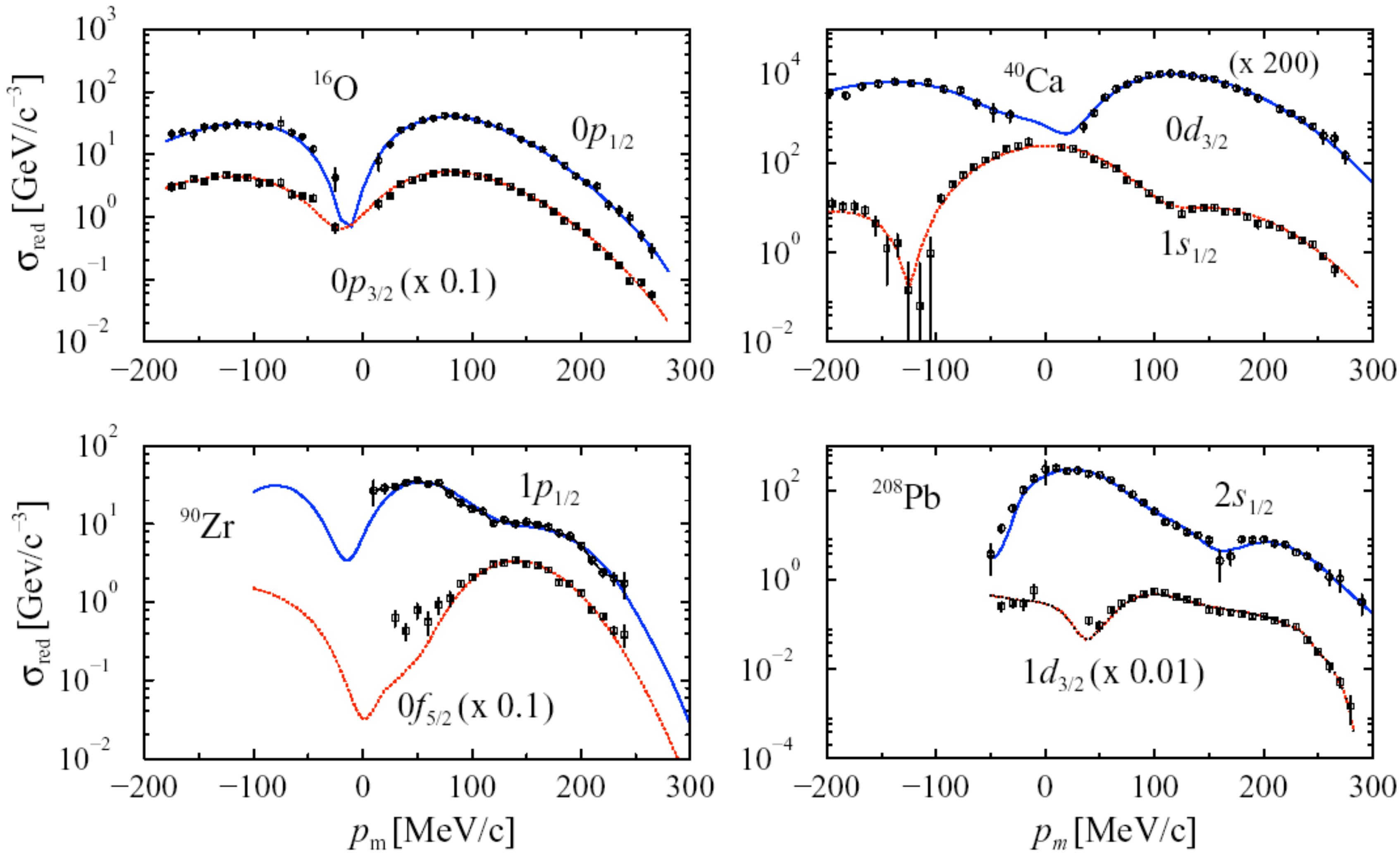
Mougey et al., Nucl. Phys. A335, 35 (1980)

$^{16}O(e,e'p)$



Nuclei (e,e'p) reaction

NIKHEF data, L. Lapikás, Nucl. Phys. *A553*, 297c (1993)



Wave functions as expected, except .... Short-range and Tensor Correlations

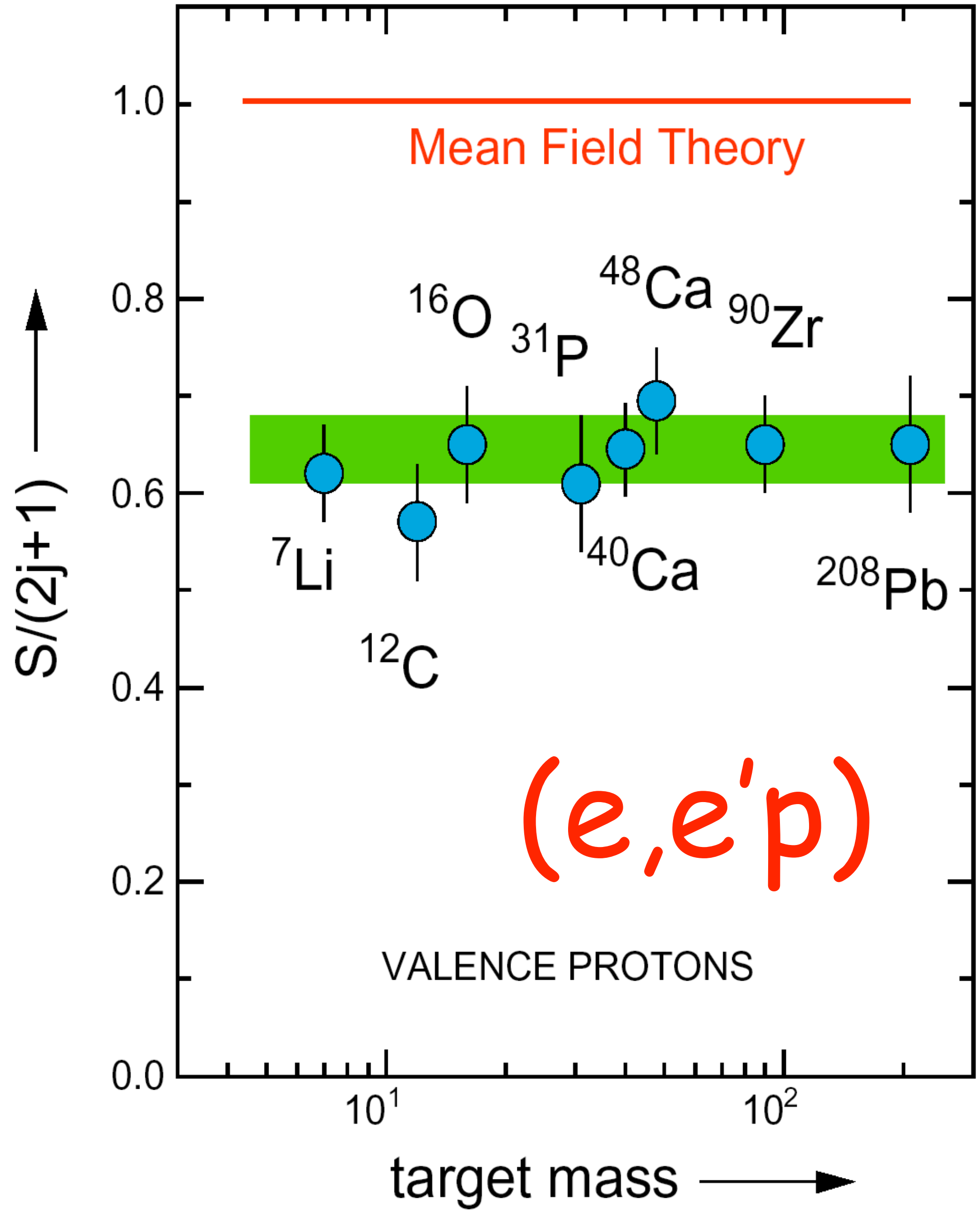
Removal probability for valence protons from NIKHEF data

L. Lapikás, Nucl. Phys. A553,297c (1993)

S ≈ 0.65 for valence protons
Reduction ⇒ both SRC and LRC

Weak probe but propagation in the nucleus of removed proton using standard optical potentials to generate distorted wave --> associated uncertainty ~ 5-10%

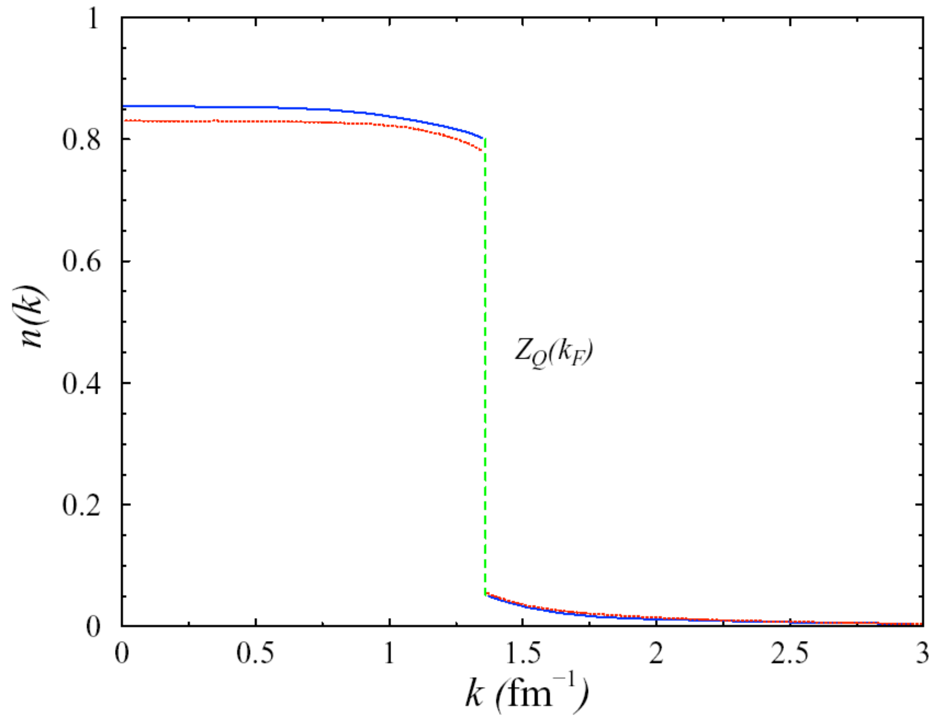
Why: details of the interior scattering wave function uncertain since non-locality is not constrained (so far)



Short-range correlations in nuclear matter and n(k)

n(k = 0) = 0.83 / 0.85 ⇒ finite nuclei

$$n(k) = \int_{-\infty}^{\varepsilon_F} dE\, S_h(k;E)$$



Reid soft core k_F = 1.36 fm^{-1}

Old prediction!

Self-consistent result

$Z_Q(k_F)$=0.72

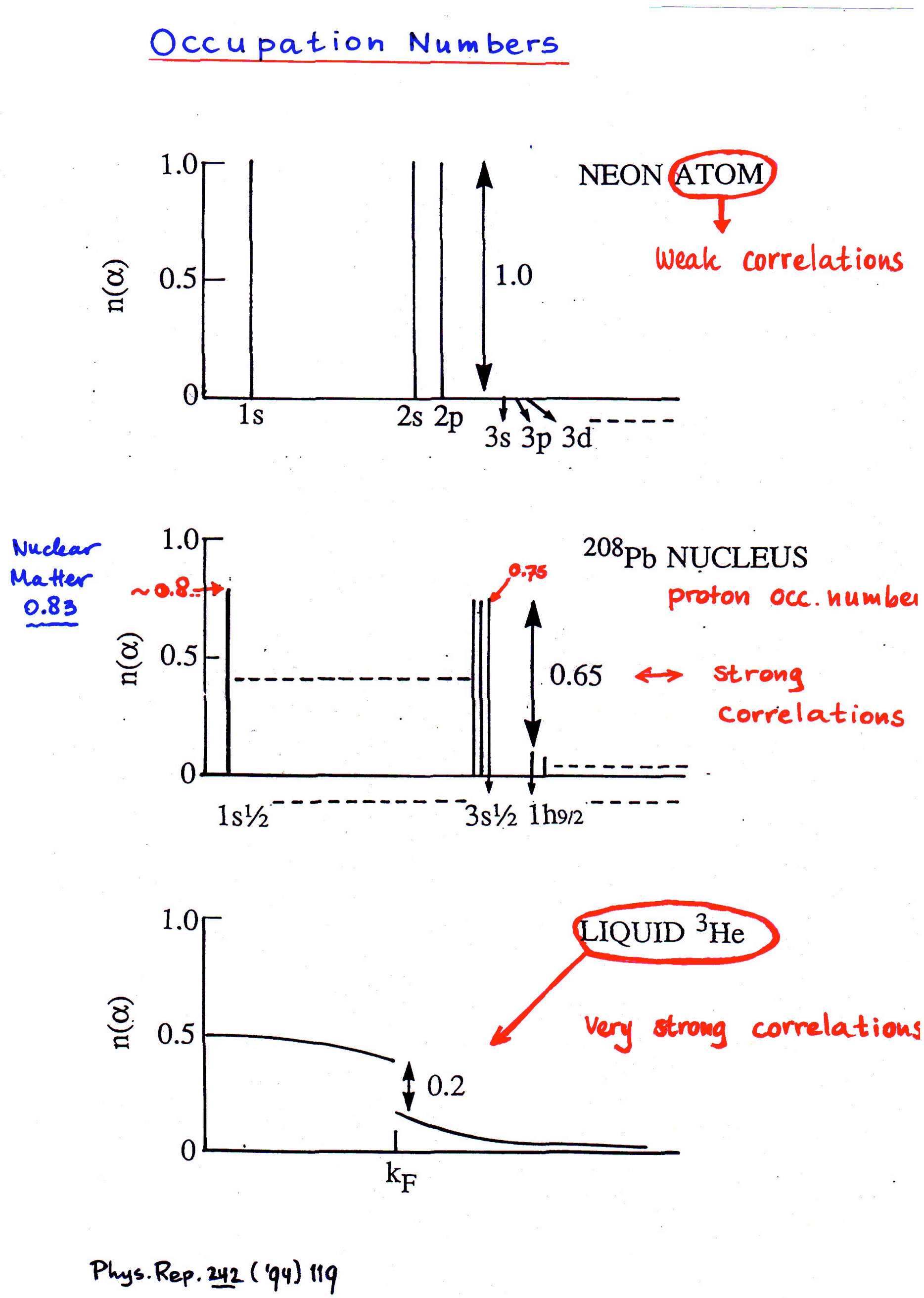
$Z_Q(k_F)$=0.75

k < k_F : 17% > ε_F with 13% above 100 MeV (7% above 500 MeV)

Without tensor force only 10.5% above ε_F

B.E.Vonderfecht et al. Nucl. Phys. A555, 1 (1993)
E.R.Stoddard, thesis WU 2000 (self-consistent ladders)

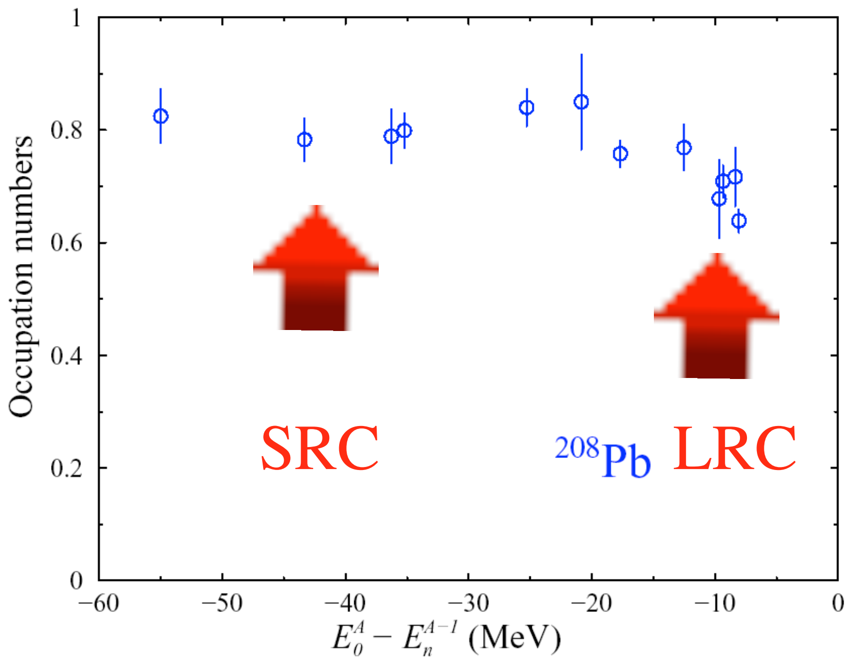
slide from 20 years ago ...



M. van Batenburg & L. Lapikás from ^{208}Pb (e,e´p) ^{207}Tl

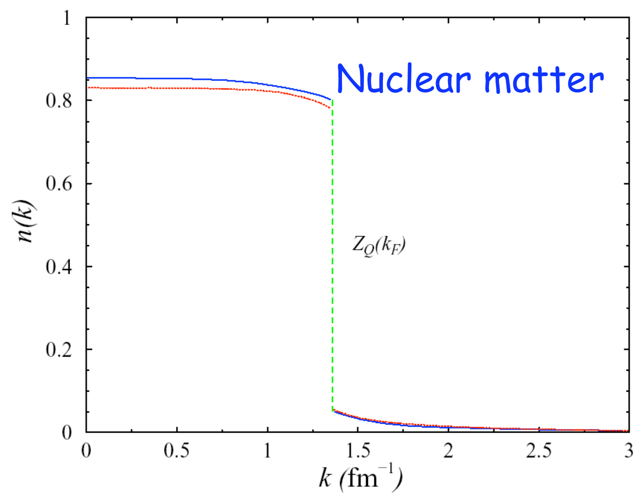
NIKHEF 2001 data (one of the last experiments)

Occupation of deeply-bound proton levels from **EXPERIMENT**



Up to 100 MeV missing energy and 270 MeV/c missing momentum

Covers the whole mean-field domain for the FIRST time!!



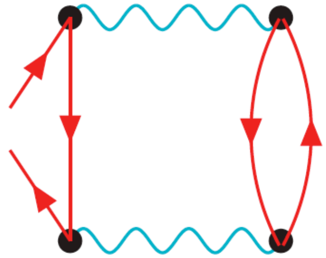
Short-range and Tensor Correlations

Confirms predictions for depletion

n(0) ⇒ 0.85 Reid
0.87 Argonne V18
0.89 CDBonn/N3LO

Location of high-momentum components

high momenta



require specific intermediate states

External line **k** (large).

Intermediate holes < k_F, say total momentum ~ 0.

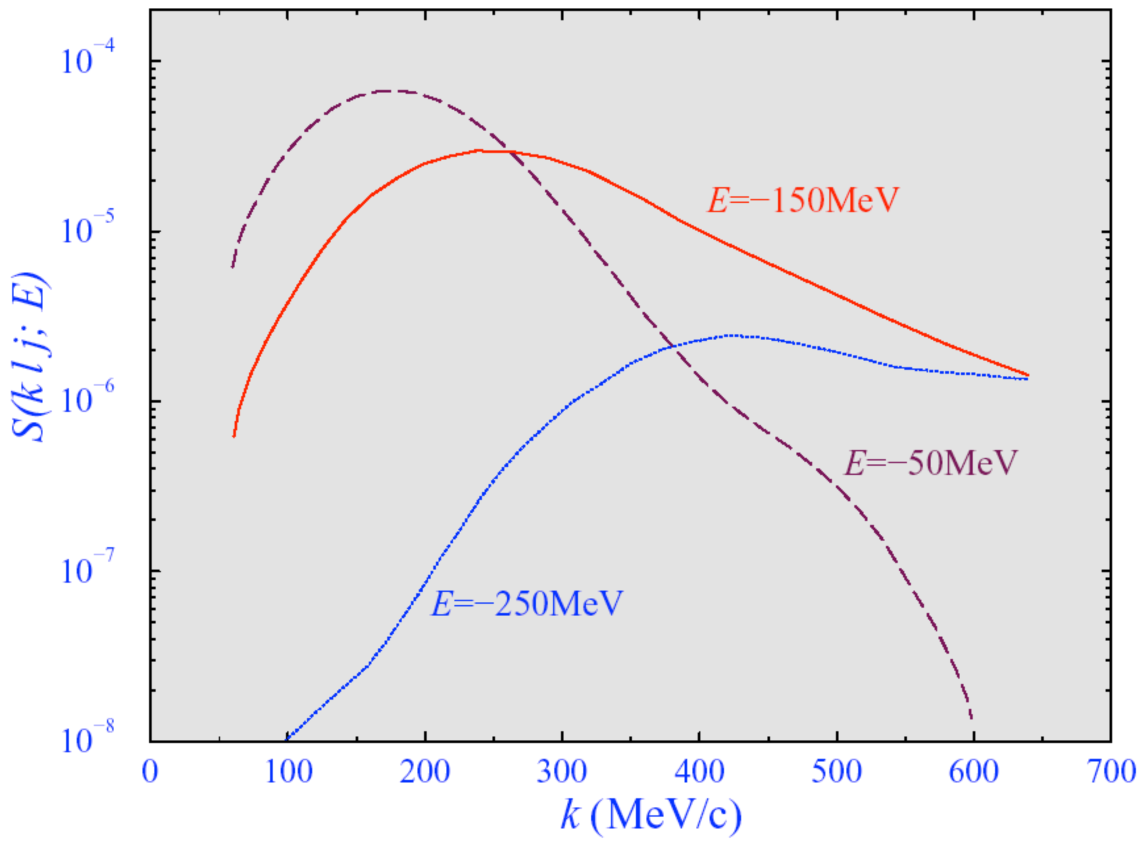
Momentum conservation: intermediate particle -**k**

$\Rightarrow$ Energy intermediate state ~ $\langle\varepsilon_{2h}\rangle - \varepsilon(\mathbf{k})$

$\Rightarrow$ the higher k the more negative the location of its strength

$\Rightarrow$ no high-momentum components near ε_F

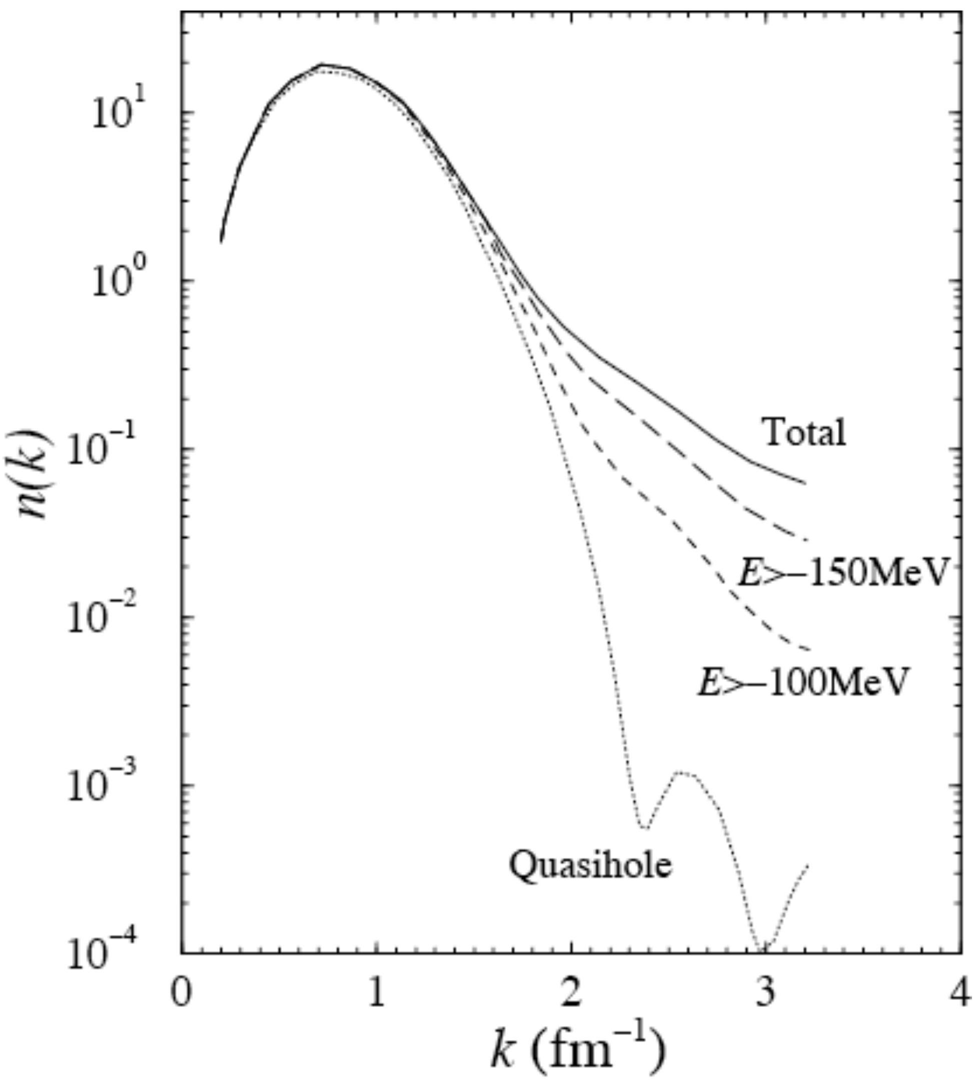
Prediction of high-momentum components calculated for ^{16}O



$p_{1/2}$ spectral function at fixed energies in ^{16}O

Phys. Rev. C49, R17 (1994)

Momentum distribution ^{16}O

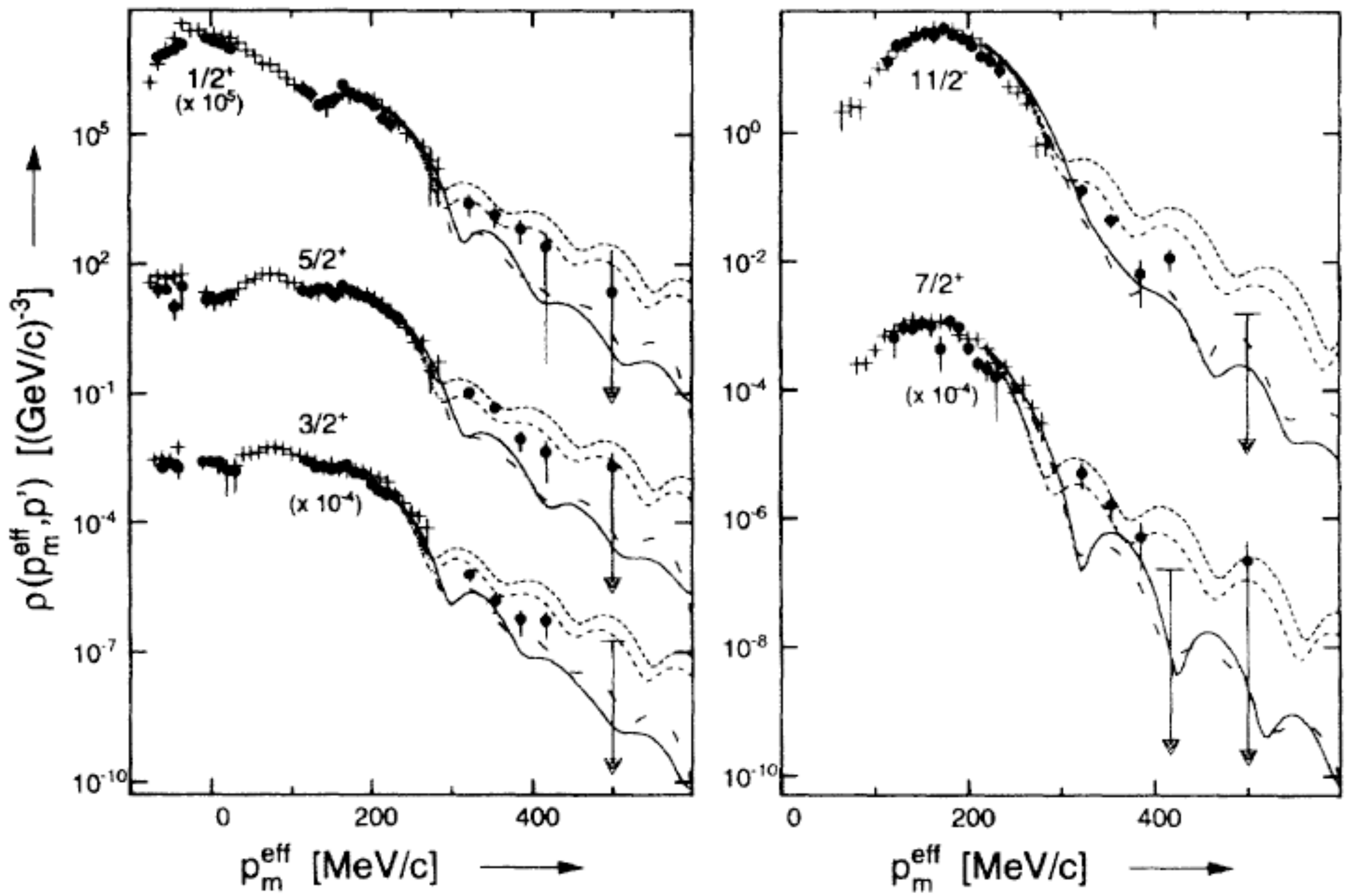


Confirms expectation:

High momentum nucleons can be found at large negative energies

Phys. Rev. C51, 3040 (1995)

High-momenta near ε_F?

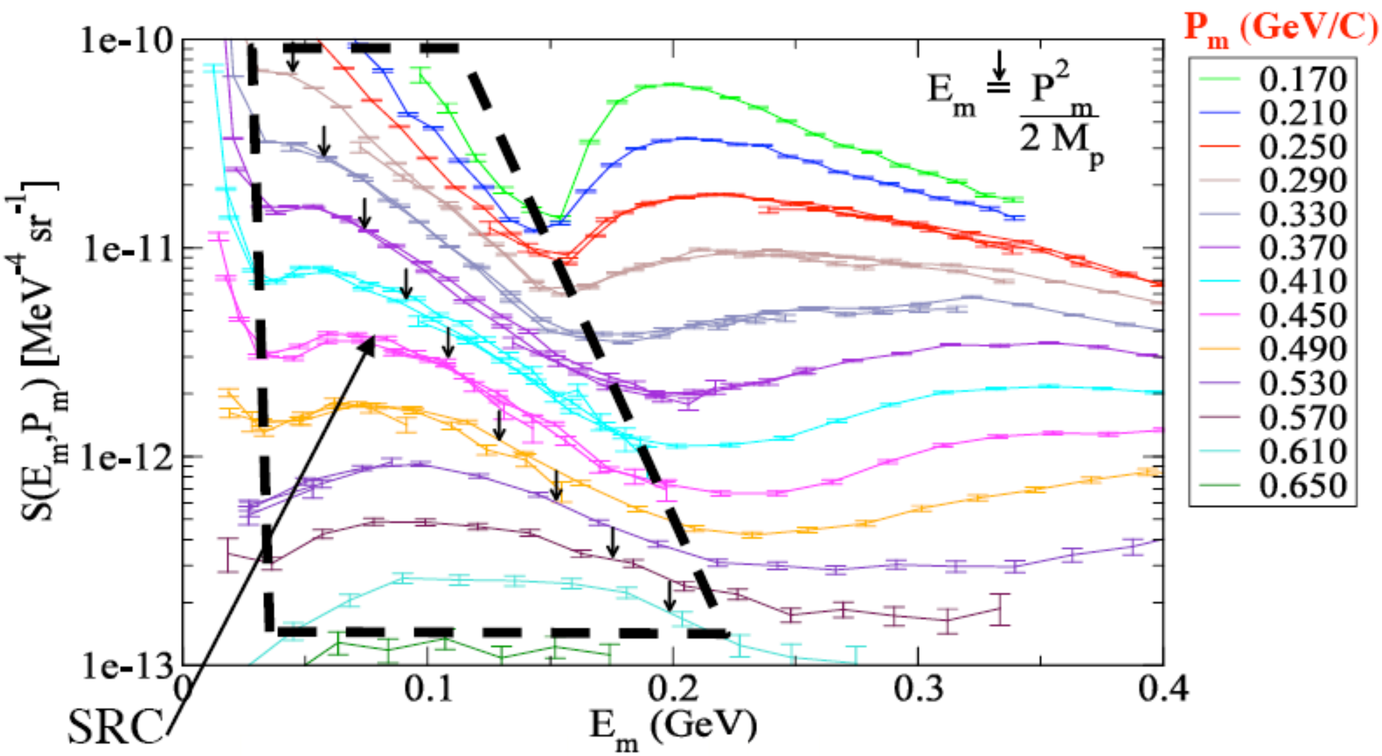


NO!

I. Bobeldijk et al., Phys. Rev. Lett. **73**, 2684 (1994)

High-momentum protons have been seen in nuclei!

Jlab E97-006 Phys. Rev. Lett. 93, 182501 (2004) D. Rohe et al.



^{12}C

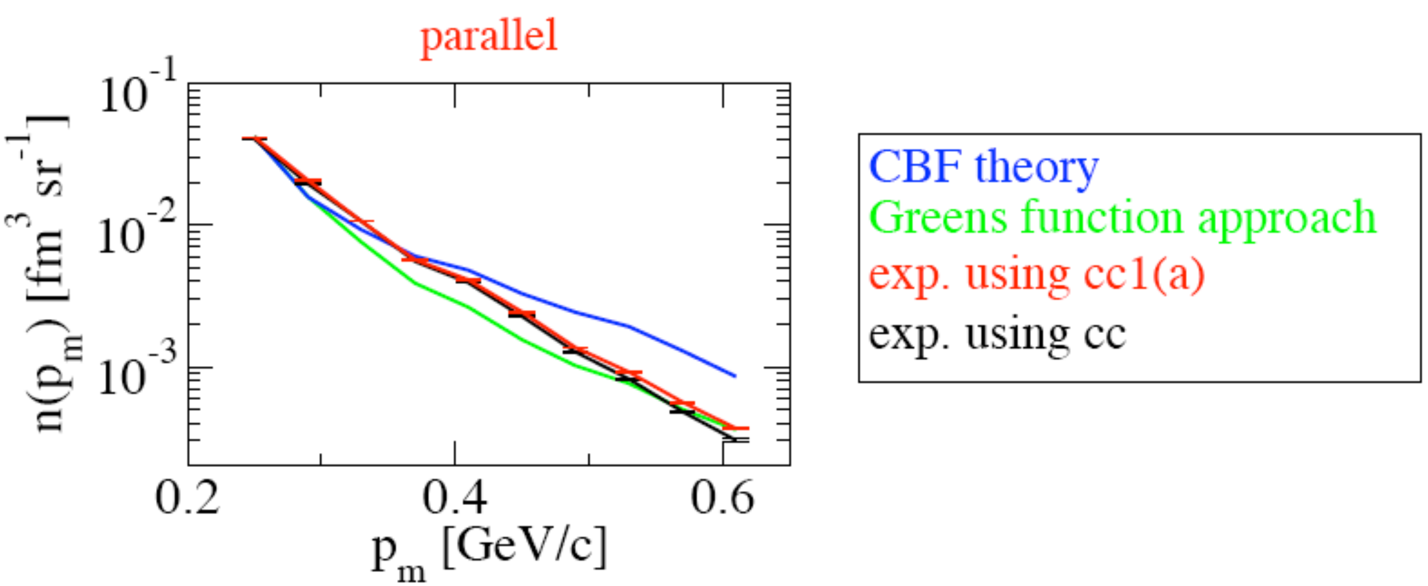
- Location of high-momentum components
- Integrated strength agrees with theoretical prediction Phys. Rev. C49, R17 (1994)

$\Rightarrow$ ~0.6 protons for ^{12}C $\Rightarrow$ **~10%**

Short-range and Tensor Correlations

Integrated strength ⇒ n(k)

momentum dependence



→ theory and experiment ± agree

From: Sick, ECT* workshop July 2007
Daniela Rohe, Habilitation 2004, Basel

Reviewed in Prog. Part. Nucl. Phys. 52 (2004) 377-496

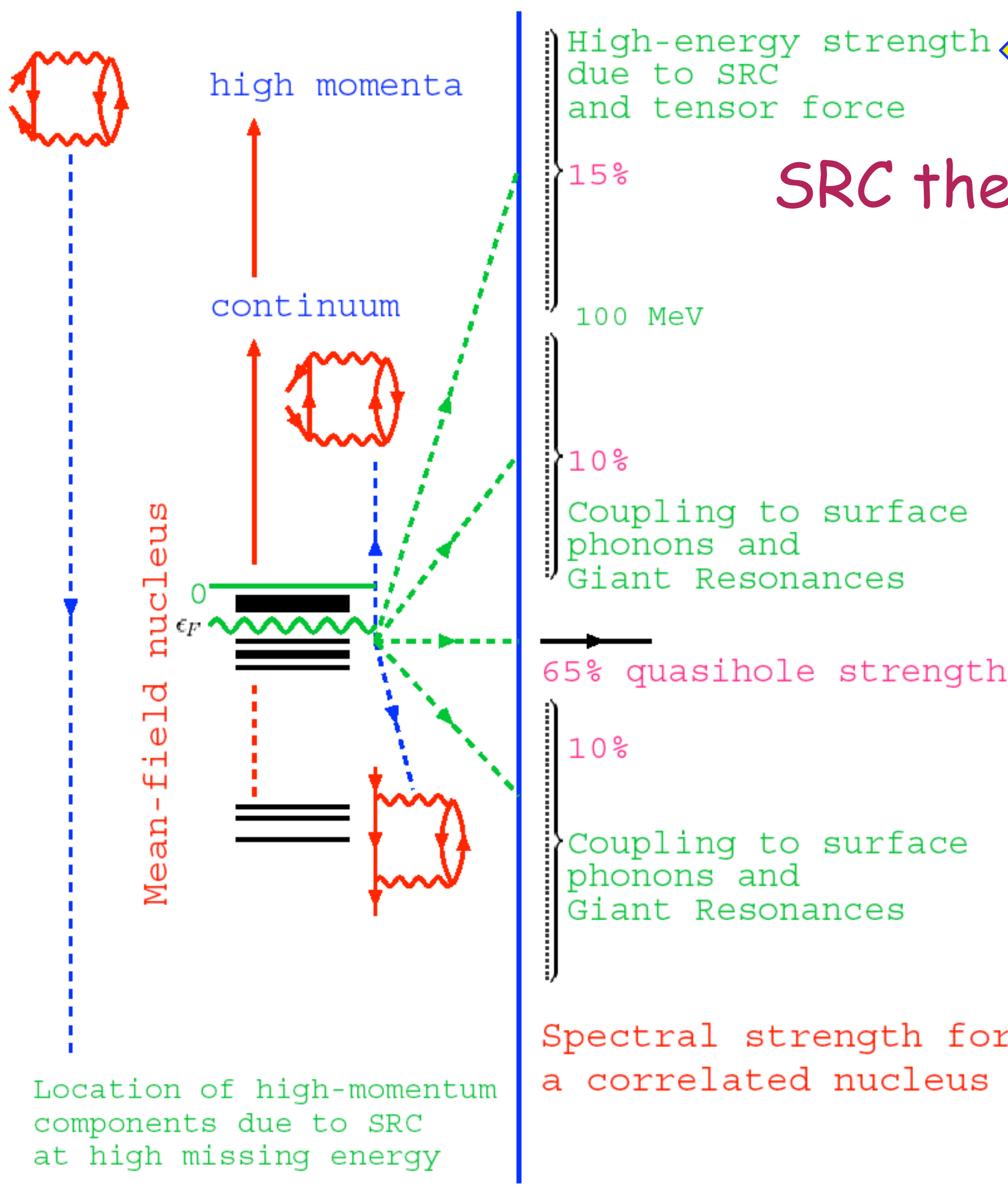
Location of single-particle strength in closed-shell (stable) nuclei

For example: protons in ^{208}Pb

SRC

JLab E97-006

Phys. Rev. Lett. 93, 182501 (2004) D. Rohe et al.



SRC theory

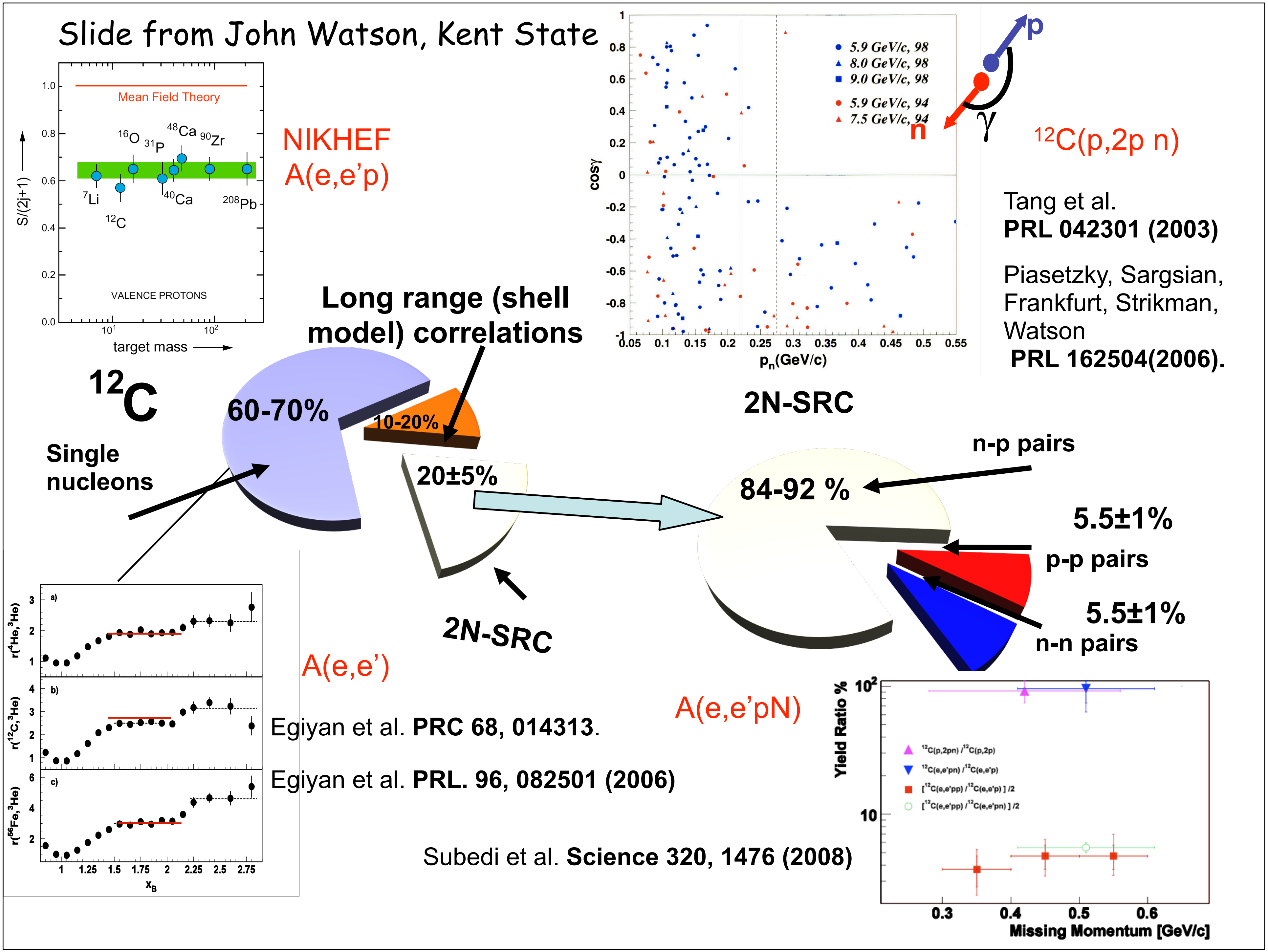
Elastic nucleon scattering

NIKHEF (e,e'p) data

L. Lapikás

Nucl. Phys. A553,297c (1993)

Short-range and Tensor Correlations

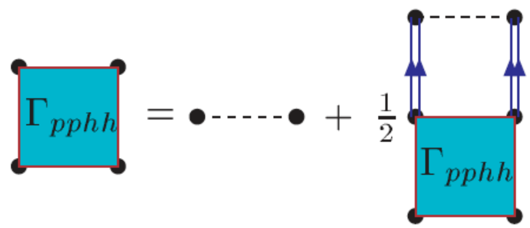

Slide from John Watson, Kent State
Mean Field Theory
VALENCE PROTONS
S/(2j+1)
target mass
NIKHEF
A(e,e'p)
12C(p,2p n)
Tang et al.
PRL 042301 (2003)
Piasetzky, Sargsian, Frankfurt, Strikman, Watson
PRL 162504(2006).
5.9 GeV/c, 98
8.0 GeV/c, 98
9.0 GeV/c, 98
5.9 GeV/c, 94
7.5 GeV/c, 94
cosγ
pn(GeV/c)
Long range (shell model) correlations
12C
60-70%
10-20%
20±5%
Single nucleons
2N-SRC
2N-SRC
84-92 %
n-p pairs
5.5±1%
p-p pairs
5.5±1%
n-n pairs
A(e,e')
Egiyan et al. PRC 68, 014313.
Egiyan et al. PRL. 96, 082501 (2006)
A(e,e'pN)
Subedi et al. Science 320, 1476 (2008)
Yield Ratio %
Missing Momentum [GeV/c]

Full off-shell propagation in infinite matter

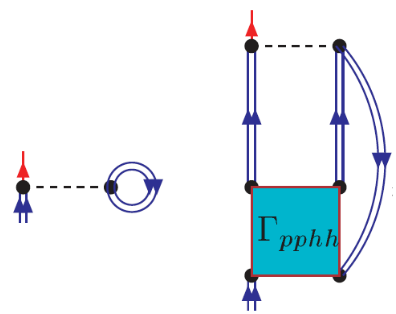
SCGF:
self-consistent
Green's functions
for SRC and tensor
effects

self-consistency
=> thermodynamically consistent

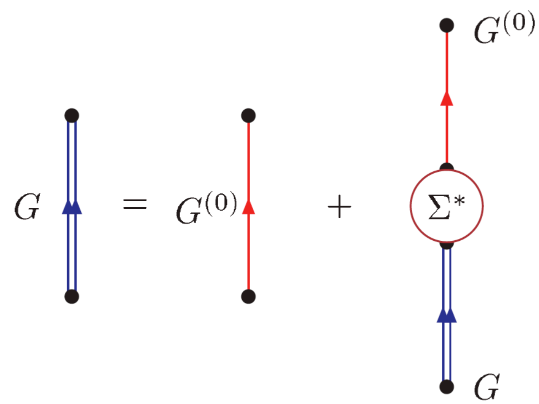
Arnau Rios
Arturo Polls
W.D.
finite T avoids pairing



Interaction in the medium properly treating short-range and tensor correlations



Self-energy = complex potential in nuclear matter



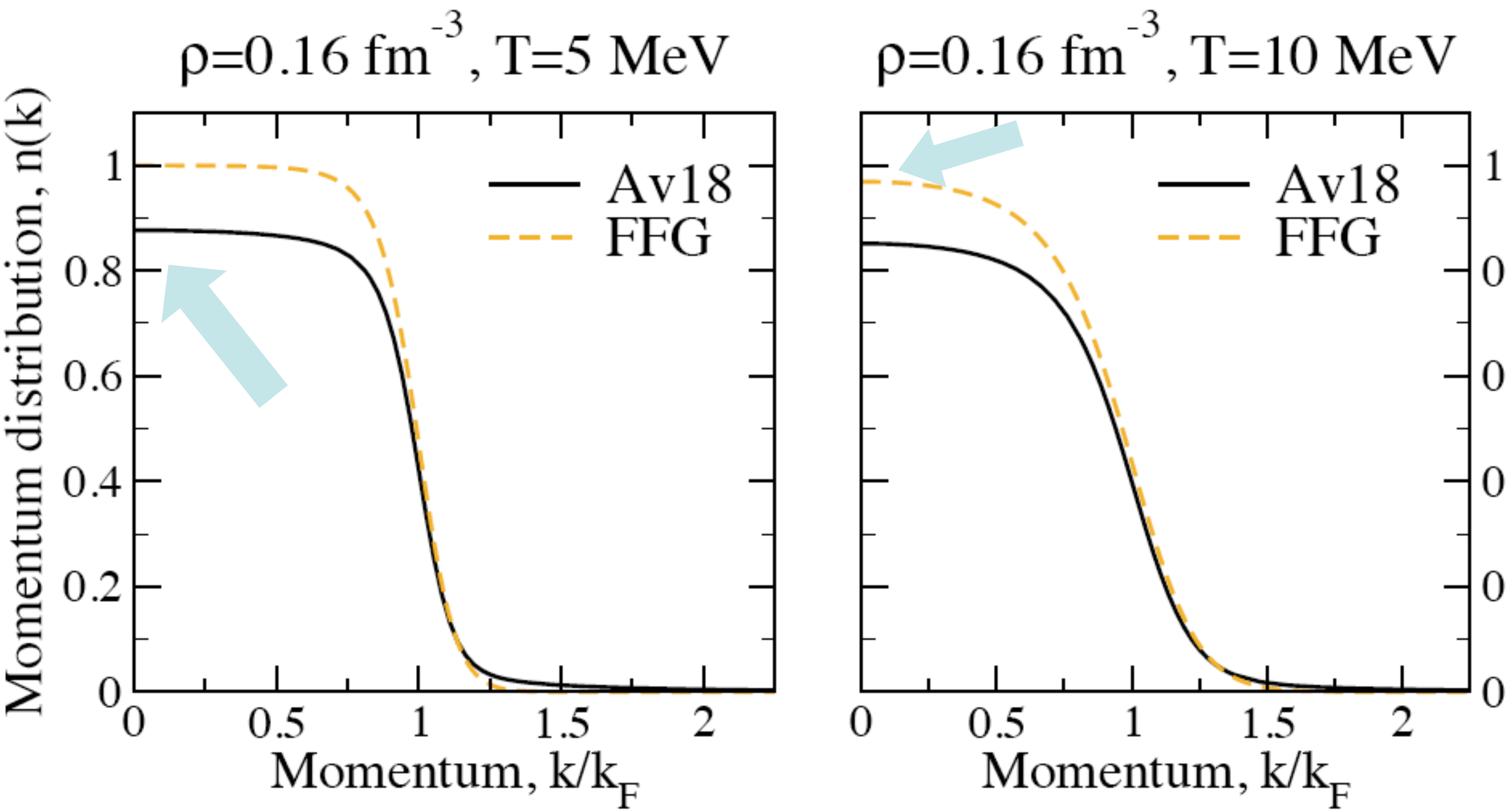
Dyson equation ⇒ Schrödinger equation for dressed nucleons

Some results infinite matter

- Effect of temperature vs. SRC & tensor correlations
- Effect of density
- Choice of interaction: CDBonn & Argonne v18
- Symmetric nuclear matter vs. neutron matter
- Depletion vs. high-momentum components
- Asymmetric nuclear matter
- Temperature, Interaction
- Tensor, tensor, tensor ⇒ pion, pion, pion
- Recent results also for N3LO

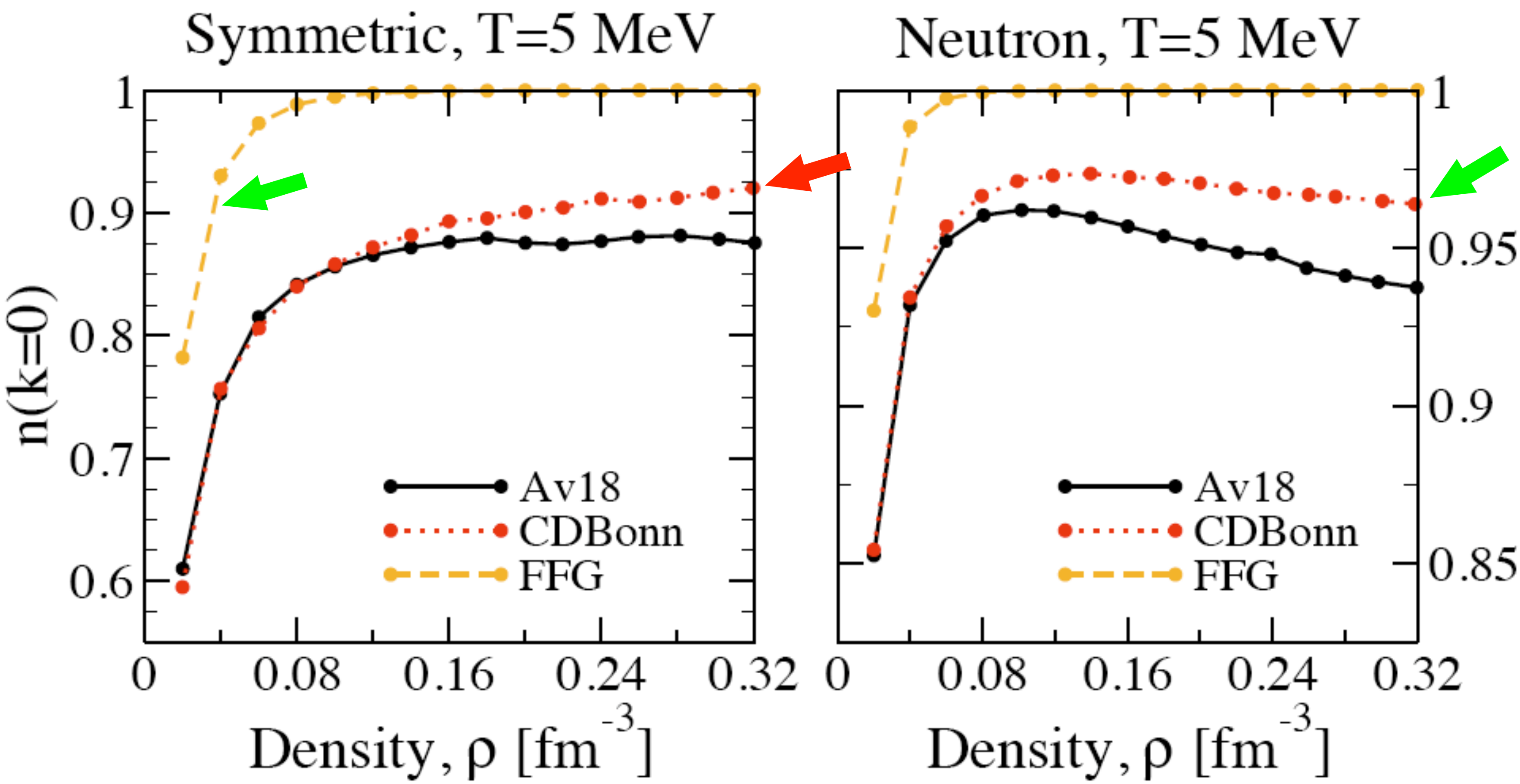
A. Rios, A. Polls, and W. H. Dickhoff
Depletion of the nuclear Fermi sea.
Phys. Rev. C79, 064308 (2009).

Temperature vs. correlations



Symmetric nuclear matter

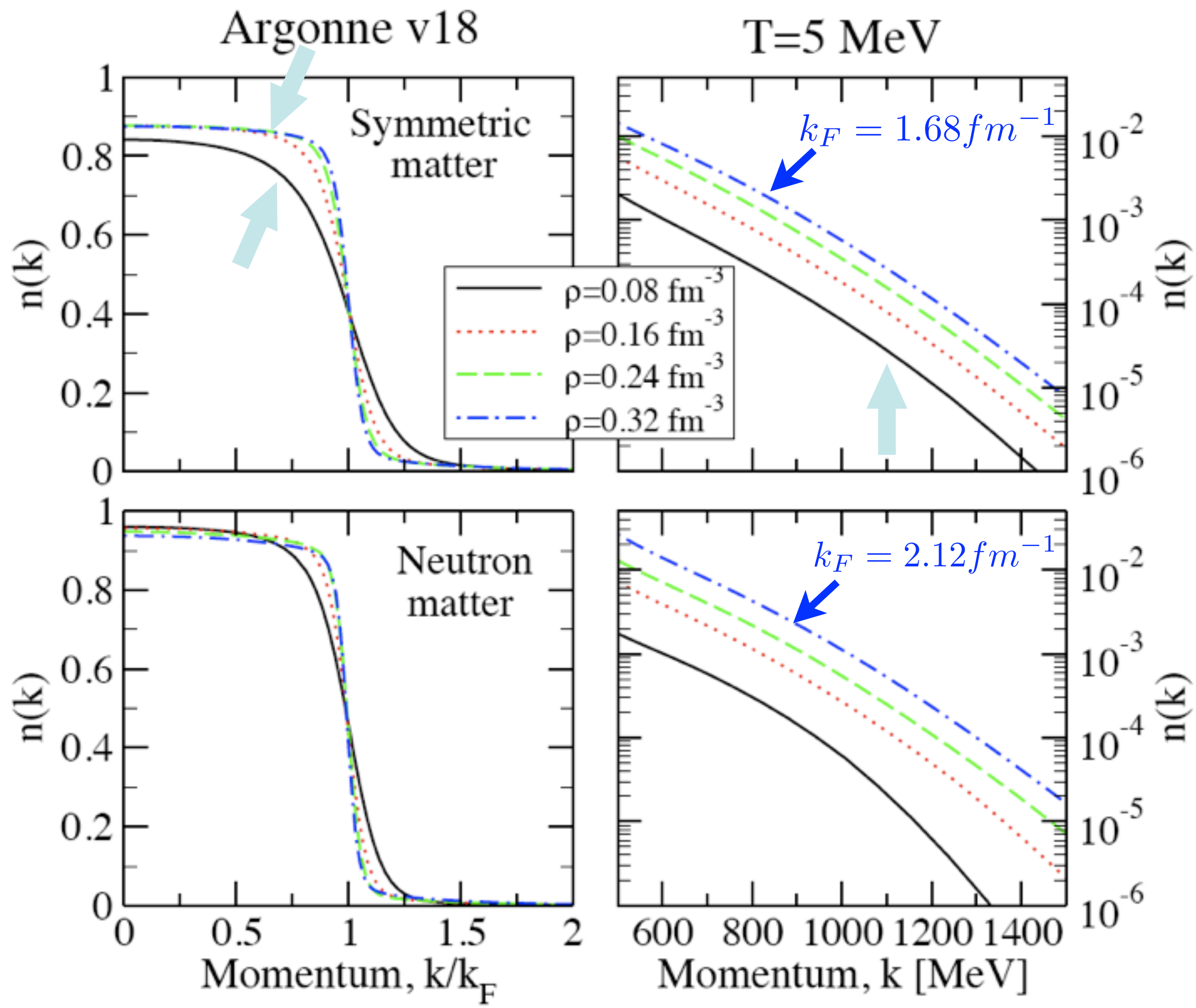
Density dependence n(0) for SNM & PNM



Different behavior for different interactions

Momentum distribution & density

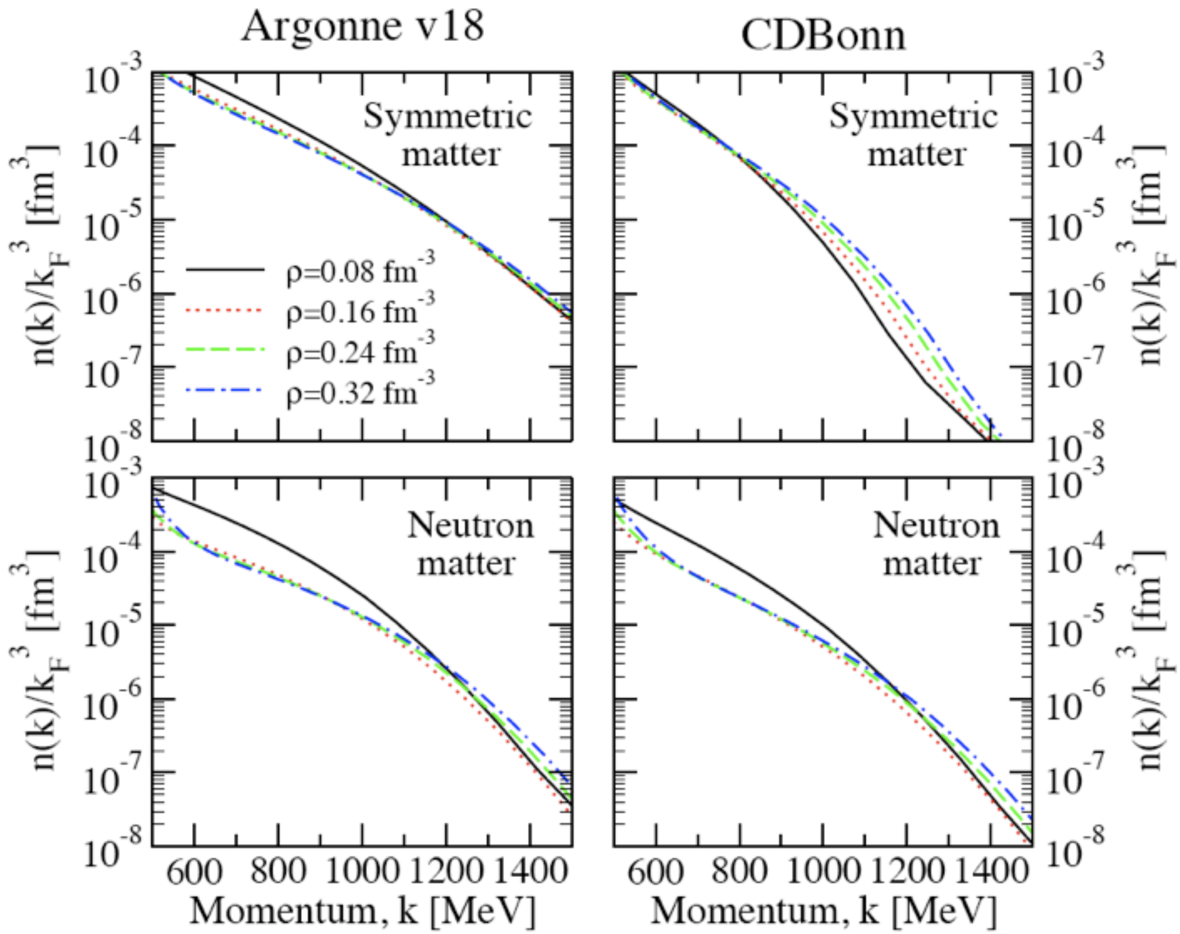
$$\rho = \frac{\nu}{6\pi^2} k_F^3$$



$\nu = 4$

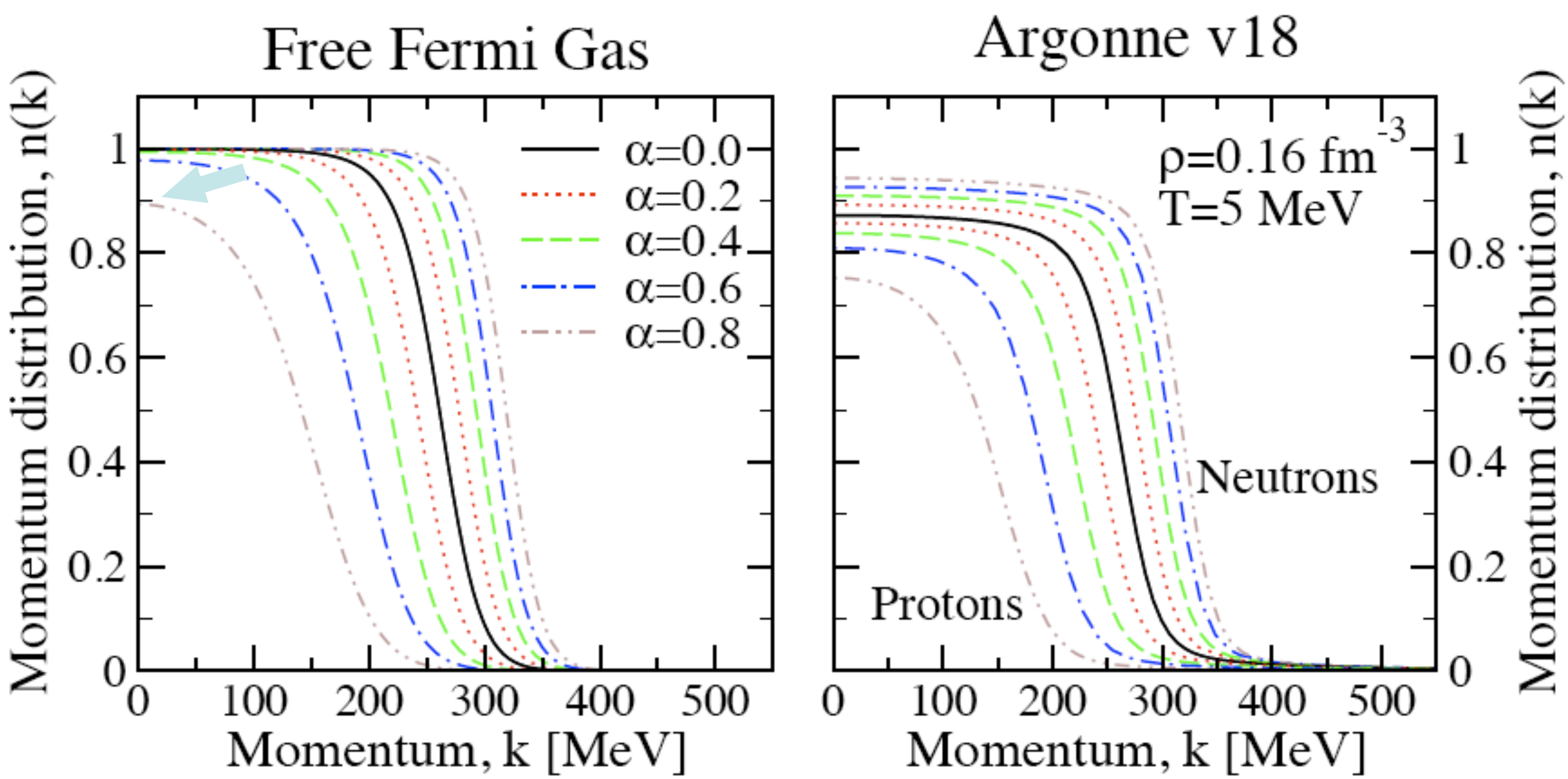
$\nu = 2$

High-momentum scaling ~ $(k_F)^3$



Harder interactions scale with $(k_F)^5$

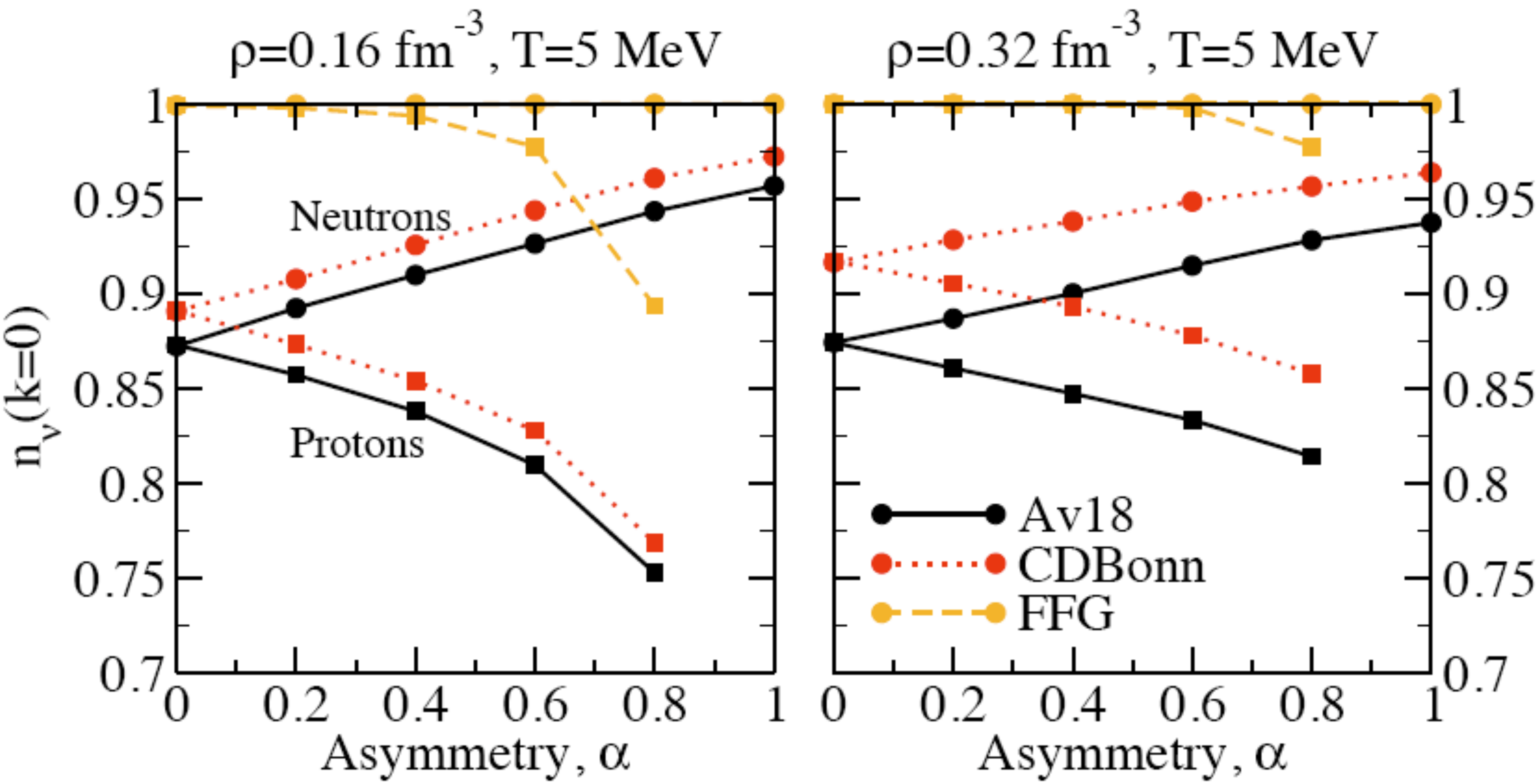
Asymmetric nuclear matter



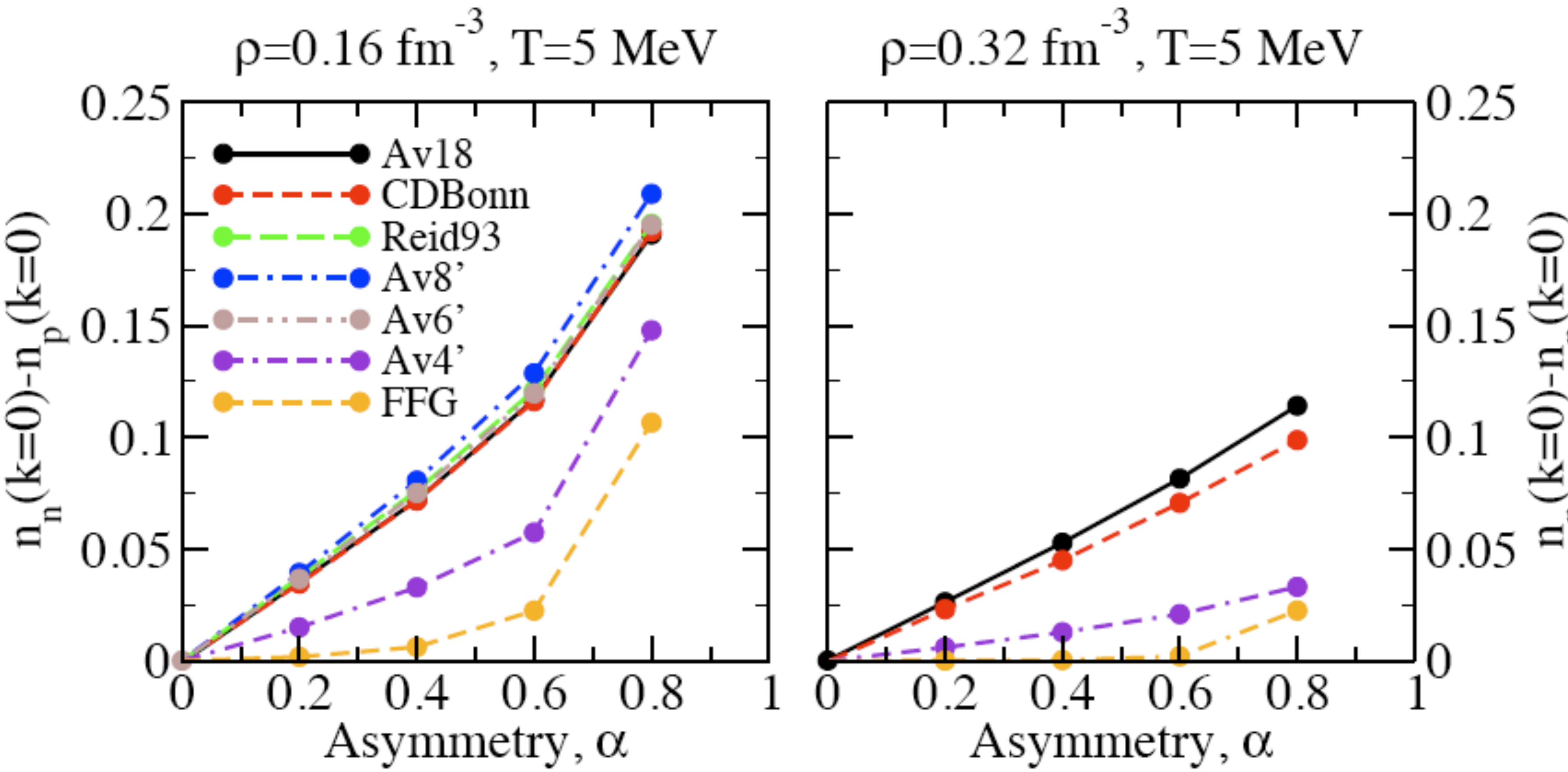
$$\alpha = \frac{N-Z}{N+Z}$$

Short-range and Tensor Correlations

Depletion as a function of asymmetry



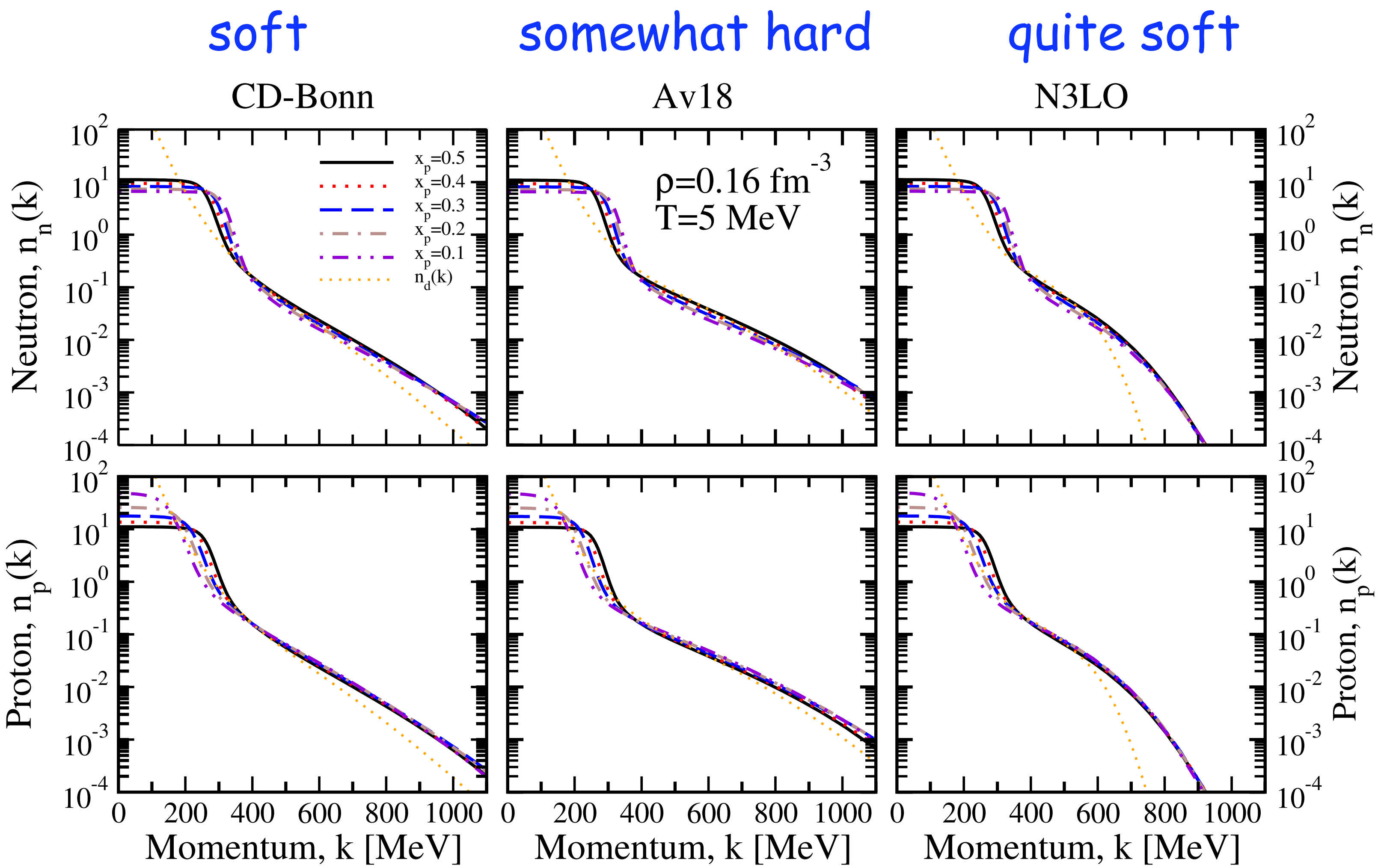
Difference $n_n(k=0)-n_p(k=0)$



Apparently determined by phase shifts!

Tensor! Note Av4'

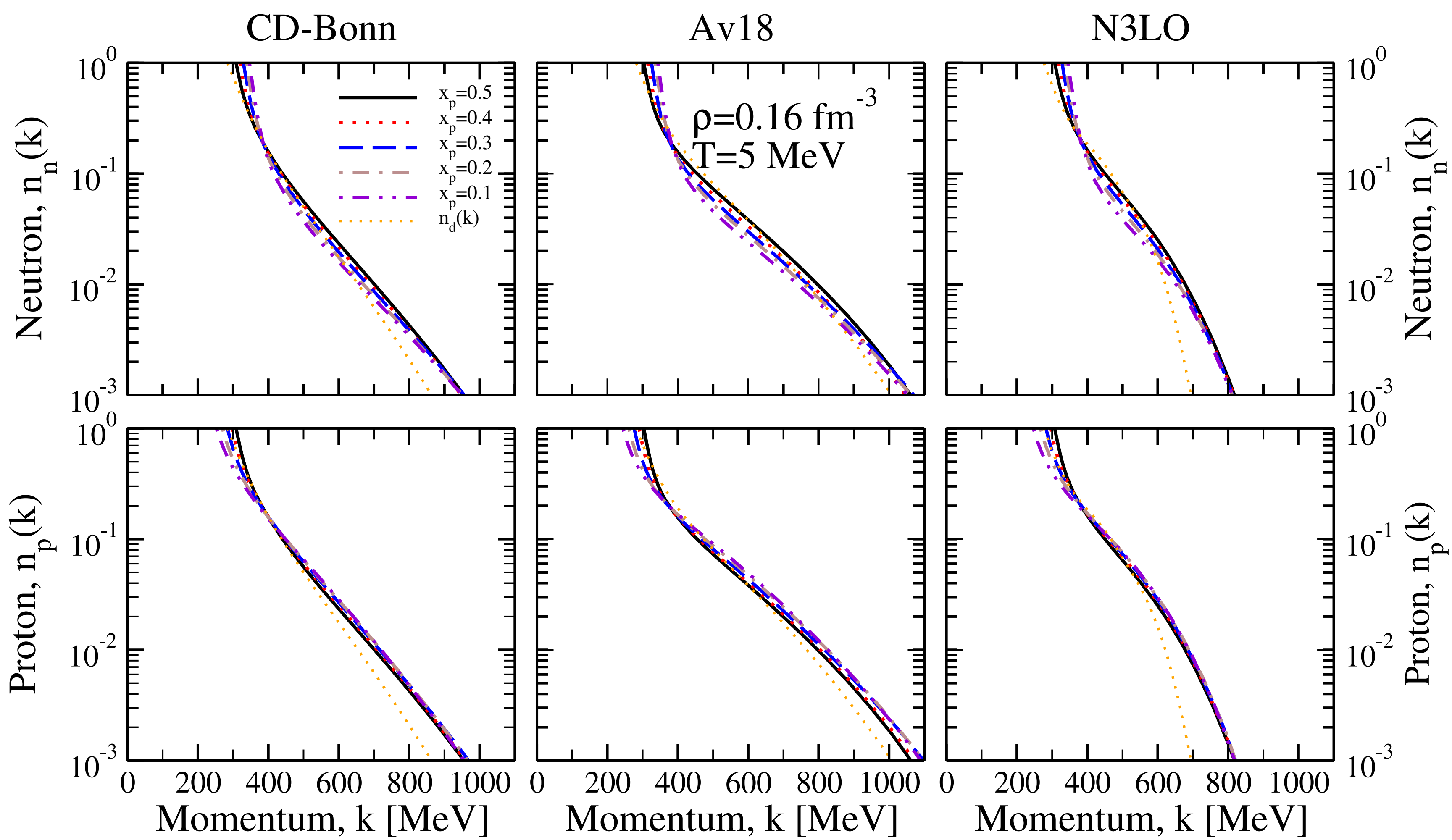
Three different interactions (just calculated)



- Normalization of n(k) --> 1 (not density)

Focus on the tails in asymmetric matter

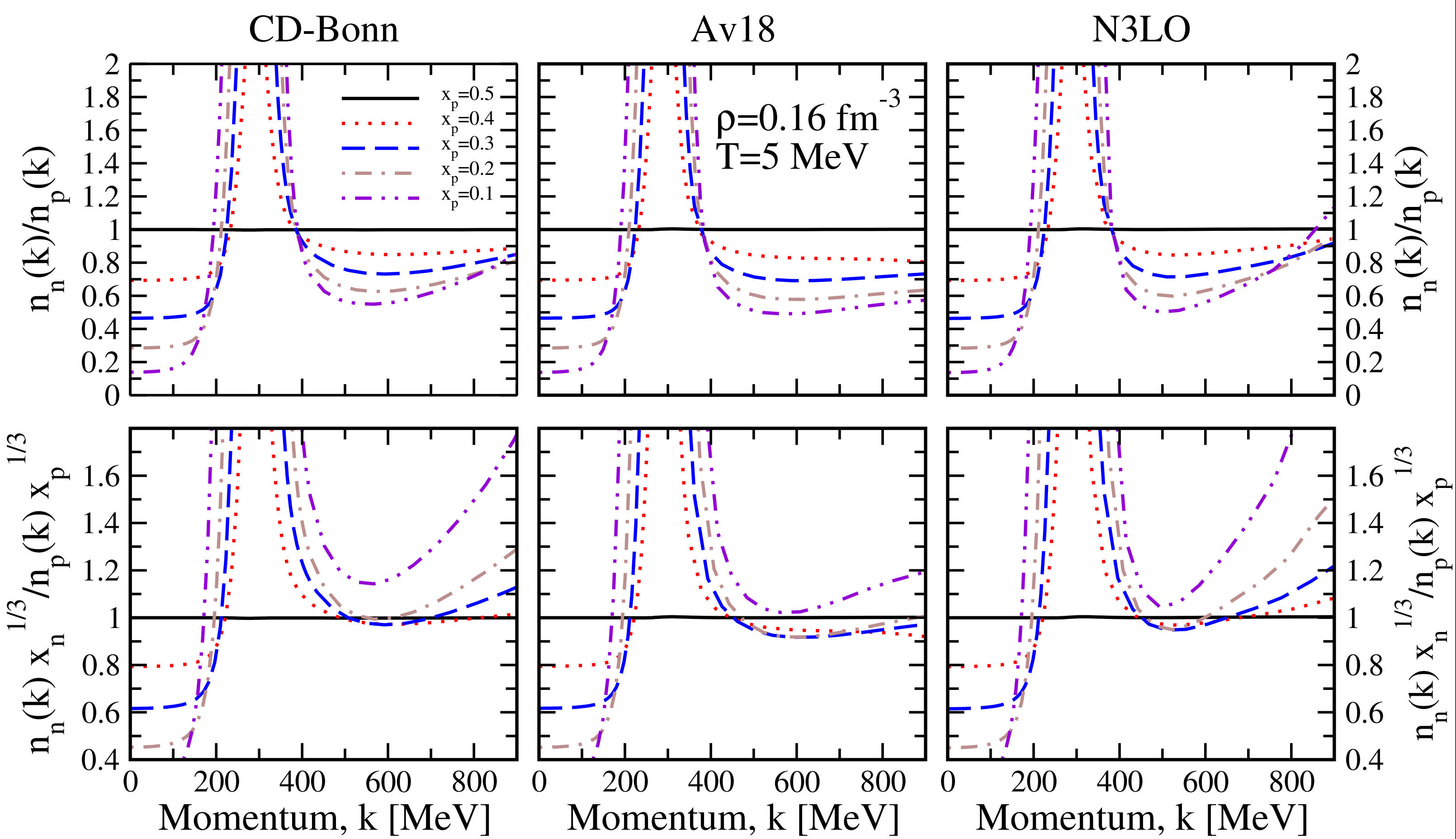
- Normalization of n(k) --> 1



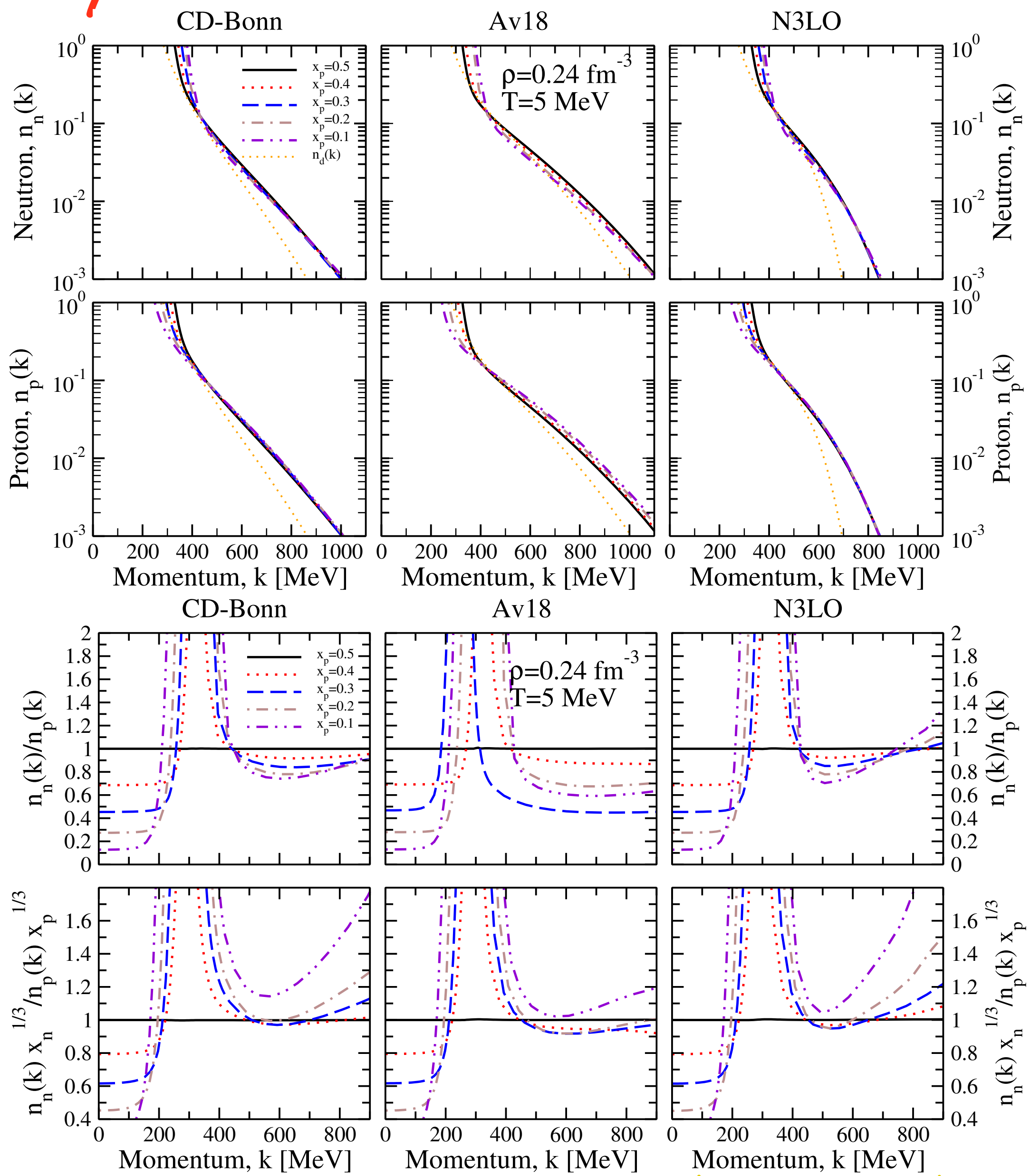
Short-range and Tensor Correlations

Comparing neutrons and protons

- Ratio
- Scaled

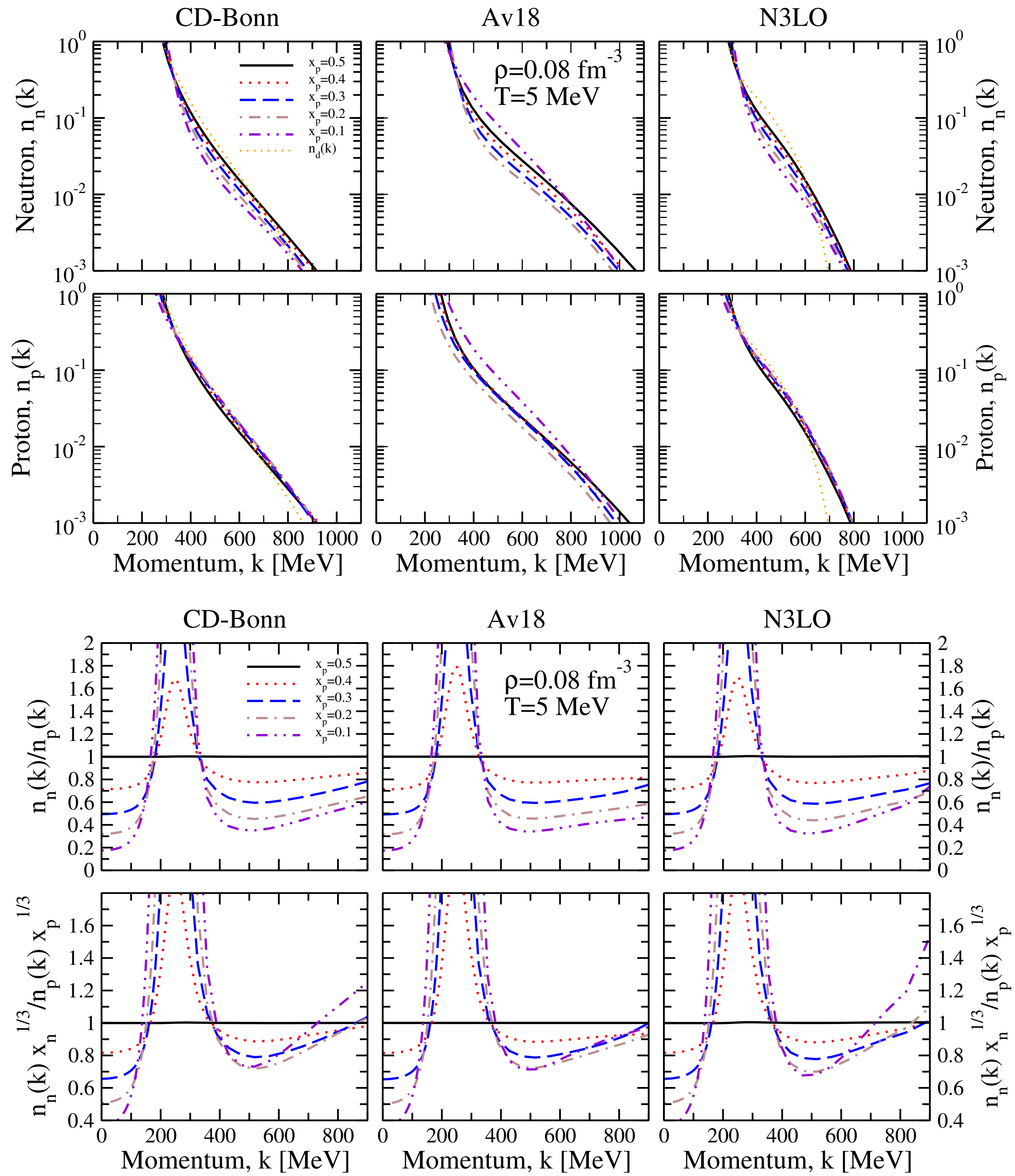


Higher density



Short-range and Tensor Correlations

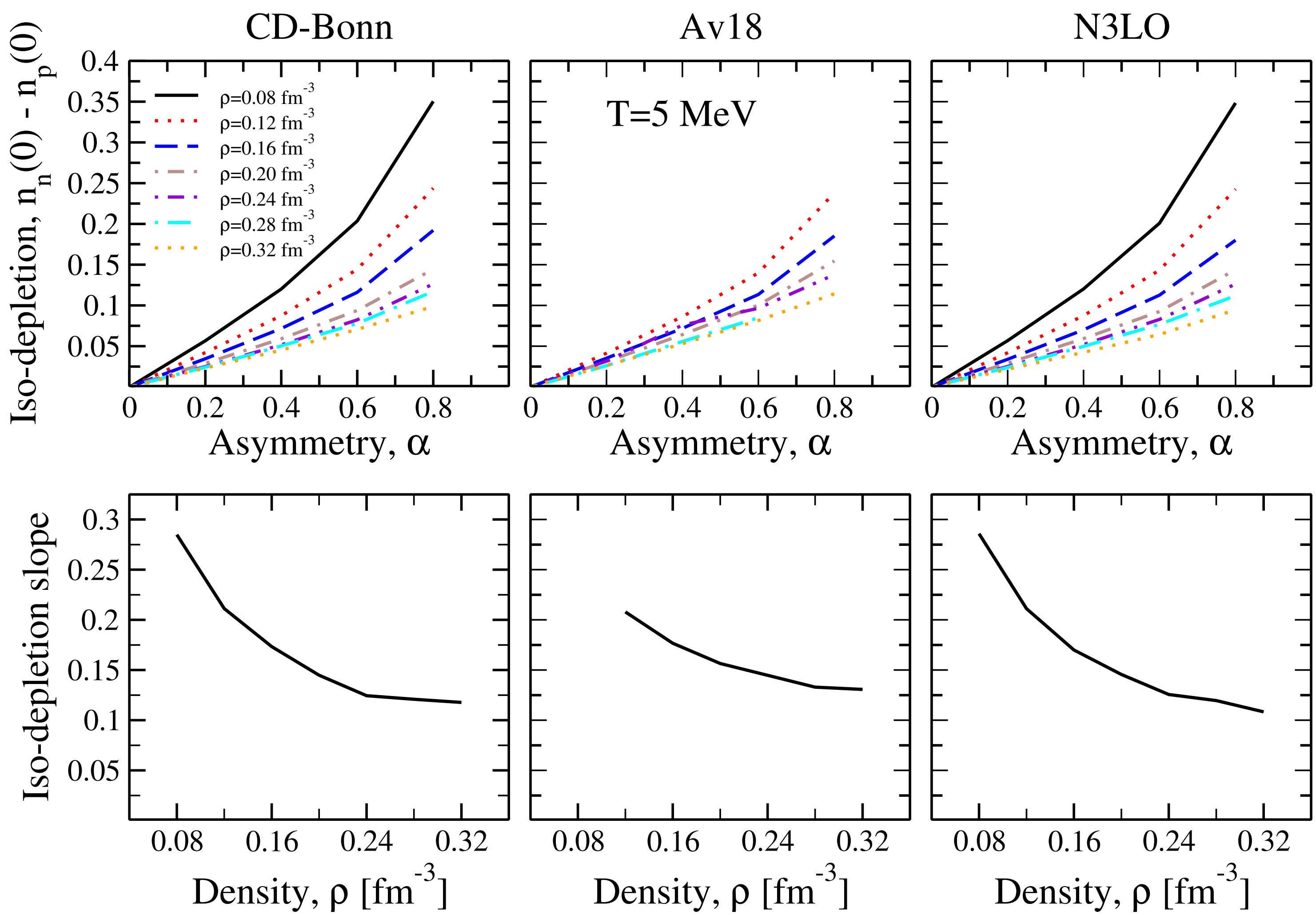
Lower density



Short-range and Tensor Correlations

"Iso-depletion"

- Constraint by data?!

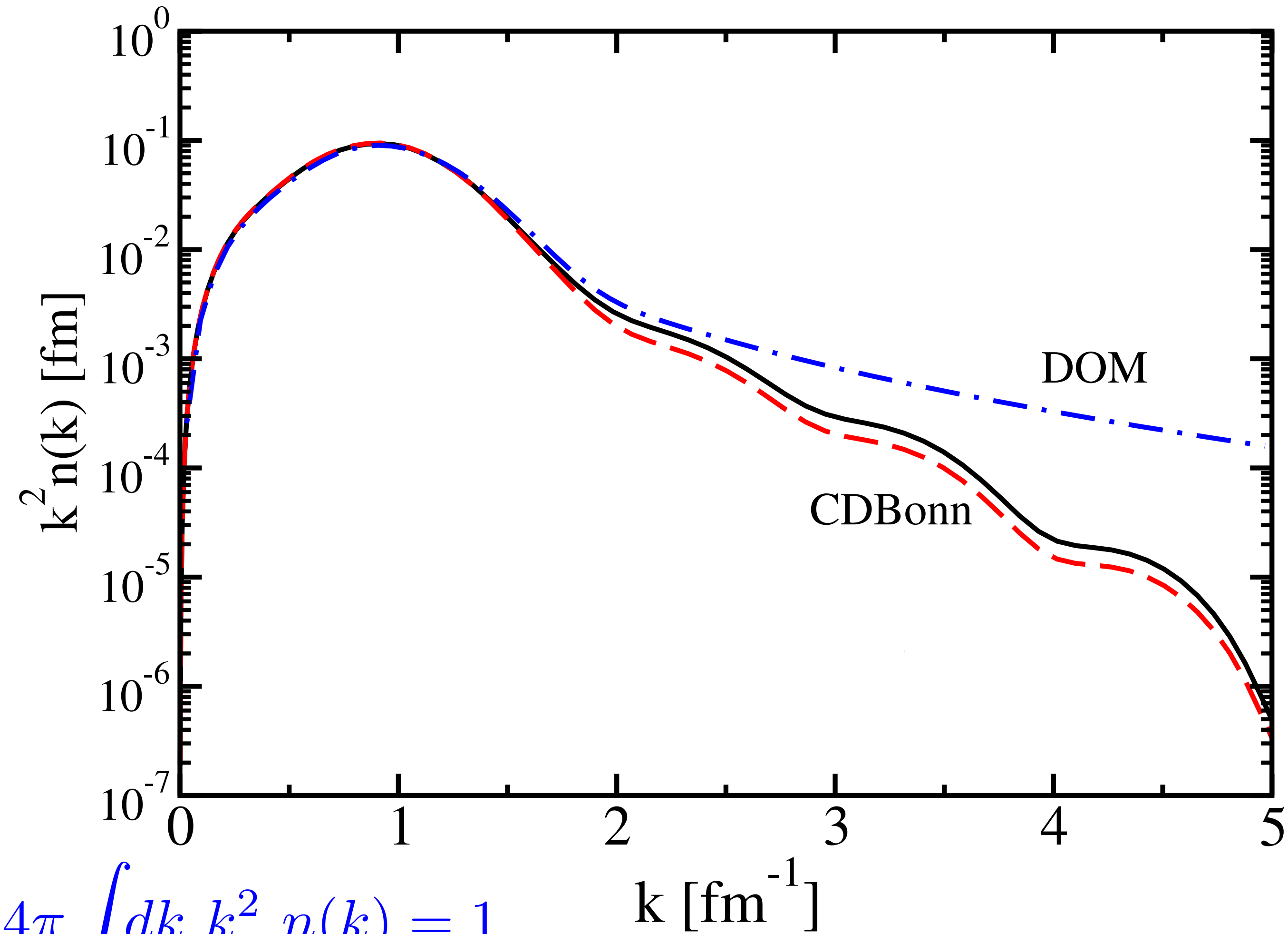


High-momenta ab initio for heavier nuclei

- In the beginning stages of proper sophistication…
- But in progress!

Ab initio with CDBonn for ^{40}Ca

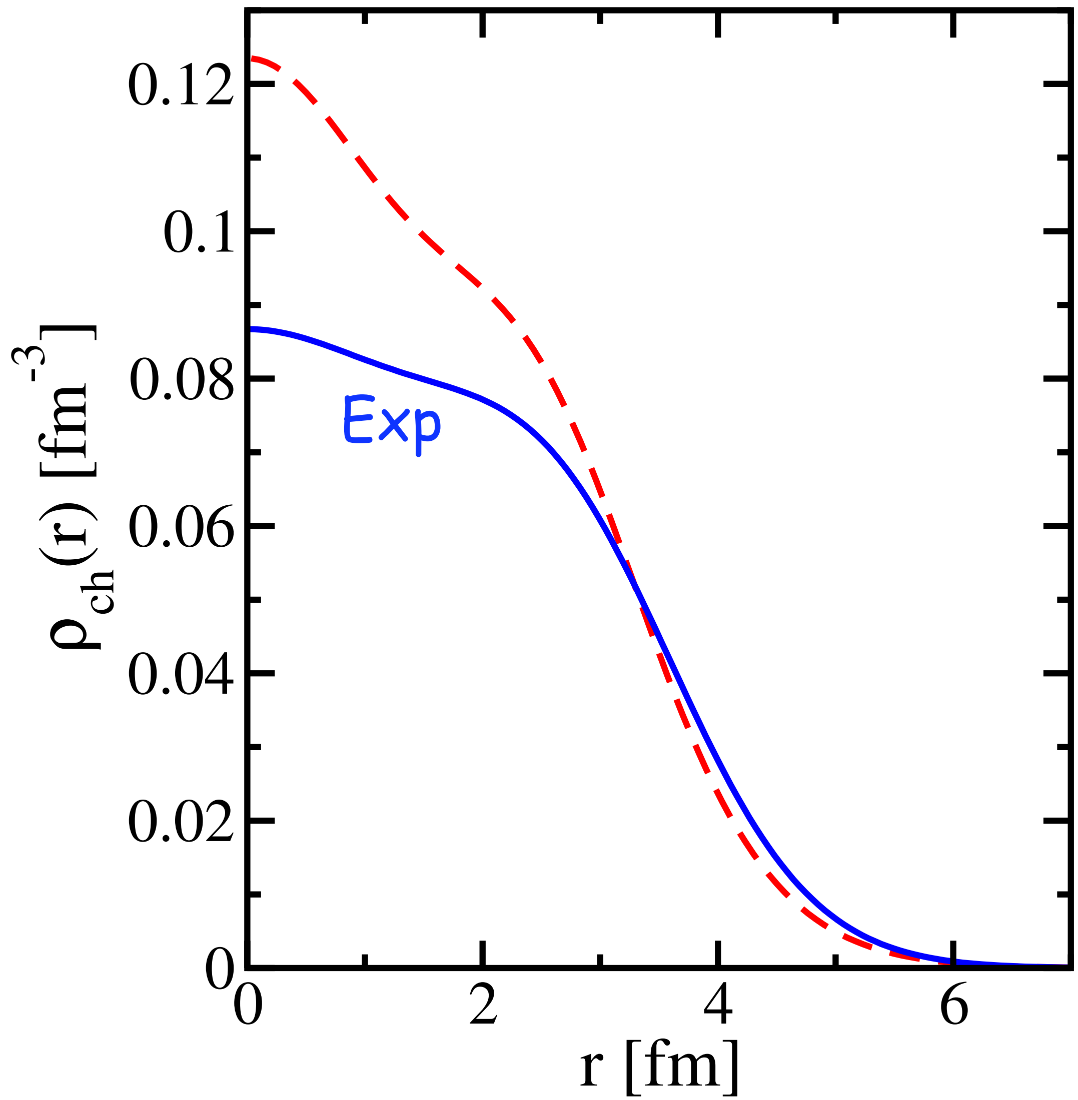
- Dussan et al. PRC84, 044319 (2011); spectral functions available



$$4\pi \int dk\; k^2\; n(k) = 1$$

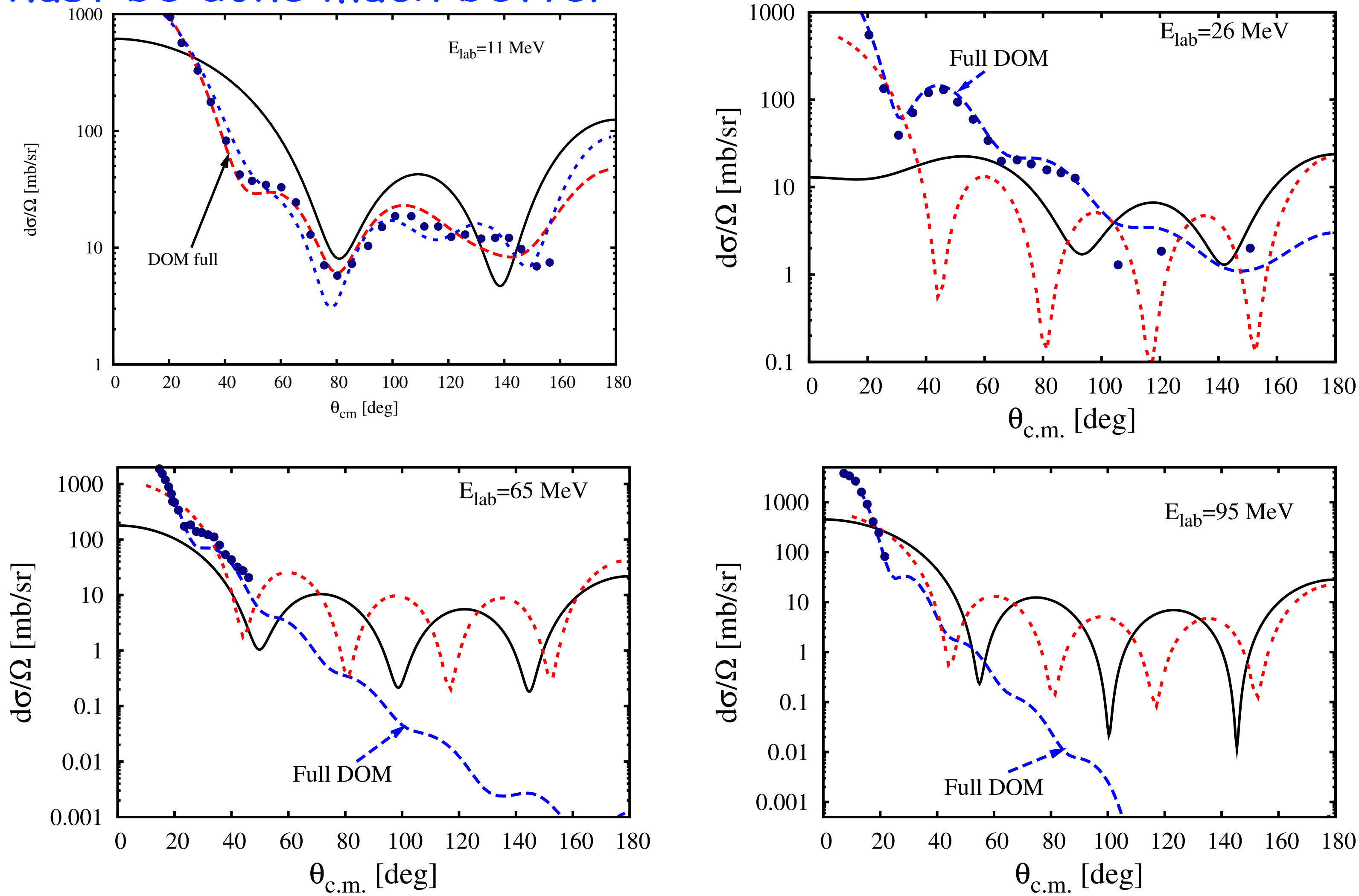
CDBonn

- Density ....



Ab initio description of elastic scattering

- Must be done much better



Drip-line nuclear physics

- Many reactions necessarily involve strongly interacting particles
  - (p,2p) perhaps (p,pn)
  - (d,p) or (p,d)
  - HI knock-out reactions
- Interactions of "projectiles" with "target" are not experimentally constrained at this time --> no unambiguous information

- Empirical Green's function project: Dispersive Optical Model (DOM)
  - intends to provide a frame work for such constraints
  - simultaneous treatment of negative (structure) and positive energies (reactions) for nucleons PLUS a reaction description
  - linking information below and above the Fermi energy such as elastic scattering cross sections, level structure, charge densities, knock-out cross sections etc. ---> constrained description of p or n distorted waves

DOM = Dispersive Optical Model

C. Mahaux and R. Sartor, Adv. Nucl. Phys. **20**, 1 (1991)

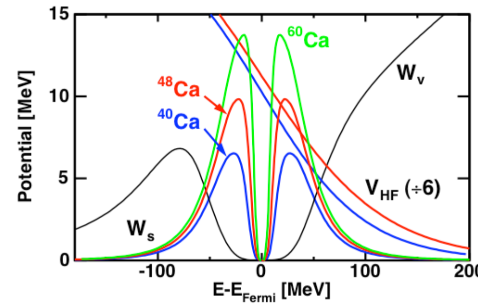
Goal: extract "propagator"/"self-energy" from data

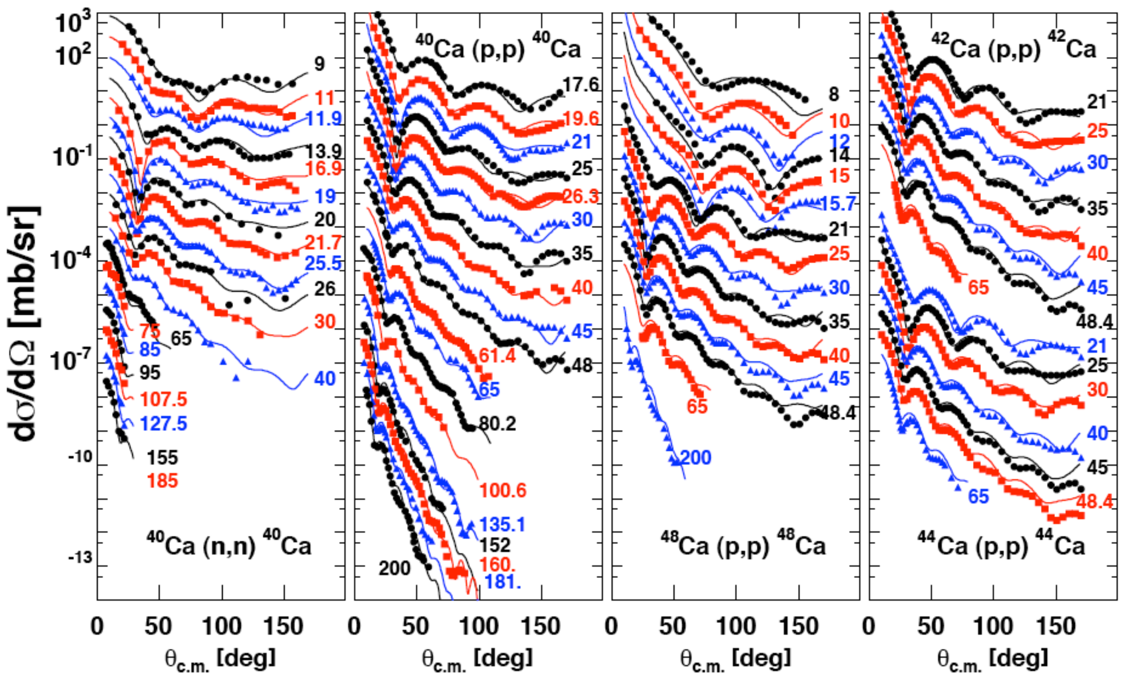
Vehicle for data-driven extrapolations / predictions to the drip lines

Combined analysis of protons/neutrons in ^{40}Ca and ^{48}Ca

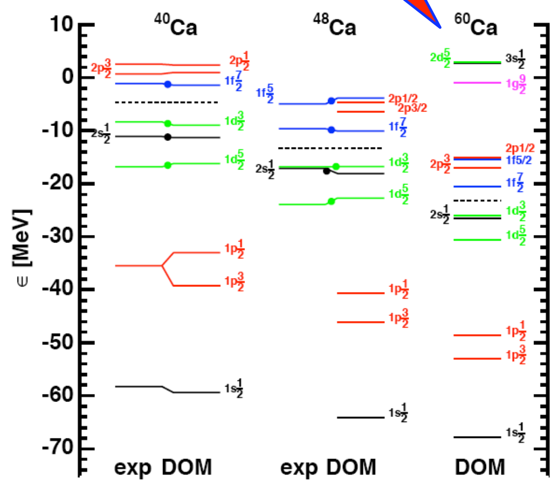
Charity, Sobotka, & WD, PRL **97**, 162503 (2006)

Charity, Mueller, Sobotka, & WD, PRC**76**, 044314 (2007)





Predict



Short-range and Tensor Correlations

Flurry of recent DOM activity

W. H. Dickhoff, D. Van Neck, S. J. Waldecker, R. J. Charity, and L. G. Sobotka
Nonlocal extension of the dispersive-optical-model to describe data below the Fermi energy
Phys. Rev. C82, 054306 (2010), 1-12.

J. M. Mueller, R. J. Charity, R. Shane, L. G. Sobotka, S. J. Waldecker, W. H. Dickhoff, A. S. Crowell, J. H. Esterline, B. Fallin, C. R. Howell, C. Westerfeldt, M. Youngs, B. J. Crowe, III, and R. S. Pedroni
Asymmetry dependence of nucleon correlations in spherical nuclei extracted from a dispersive-optical-model analysis.
Phys. Rev. C83, 064605 (2011), 1-32.

S. J. Waldecker, C. Barbieri and W. H. Dickhoff
Microscopic self-energy calculations and dispersive-optical-model potentials.
Phys. Rev. C84, 034616 (2011), 1-11.

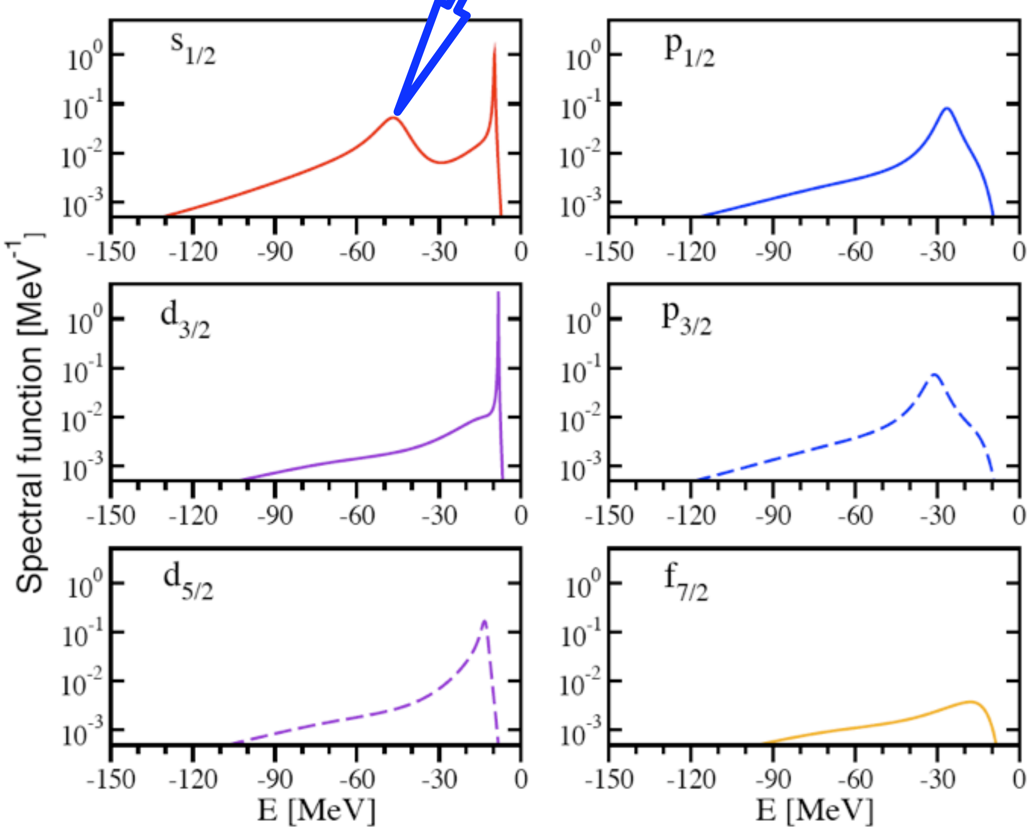
N. B. Nguyen, S. J. Waldecker, F. M. Nuñes, R. J. Charity, and W. H. Dickhoff
Transfer reactions and the dispersive optical-model.
Phys. Rev. C84, 044611 (2011), 1-9.

H. Dussan, S. J. Waldecker, W. H. Dickhoff, H. Müther, and A. Polls
Microscopic self-energy of ^{40}Ca from the charge-dependent Bonn potential.
Phys. Rev. C84, 044319 (2011), 1-16.

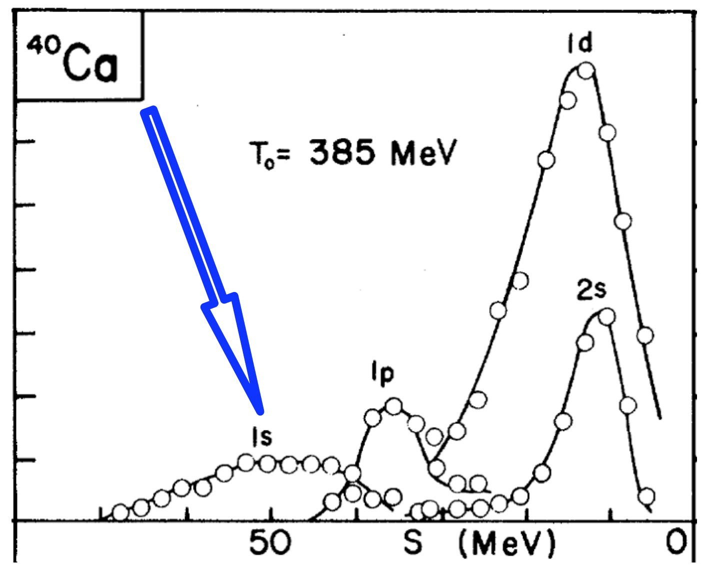
Below ε_F

^{40}Ca spectral function

Recent theoretical development:
nonlocal "HF" self-energy --> below the Fermi energy
WD, Van Neck, Charity, Sobotka, Waldecker, PRC82, 054306 (2010)



Old (p,2p) data from Liverpool

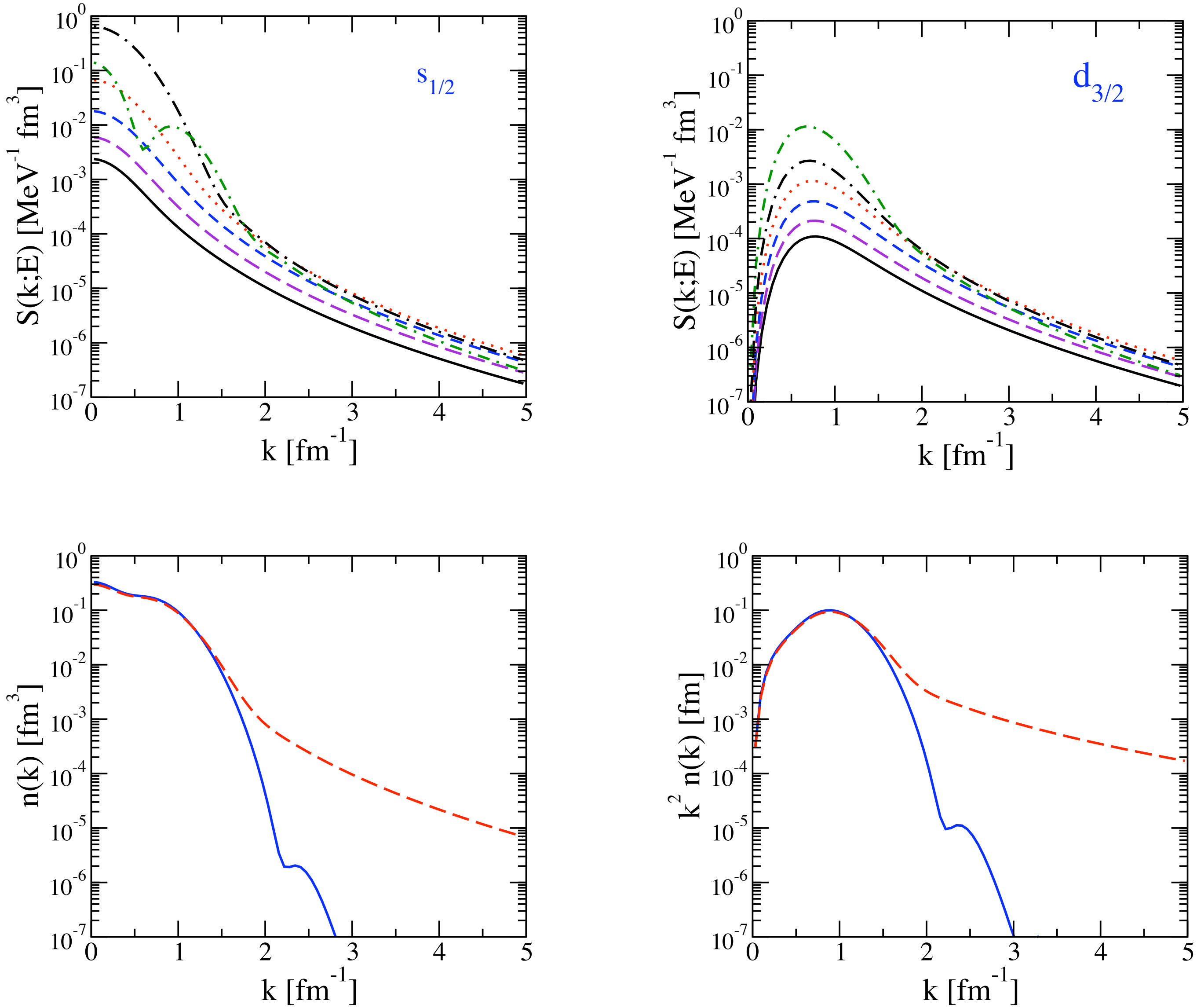


Short-range and Tensor Correlations

Spectral functions and momentum distributions

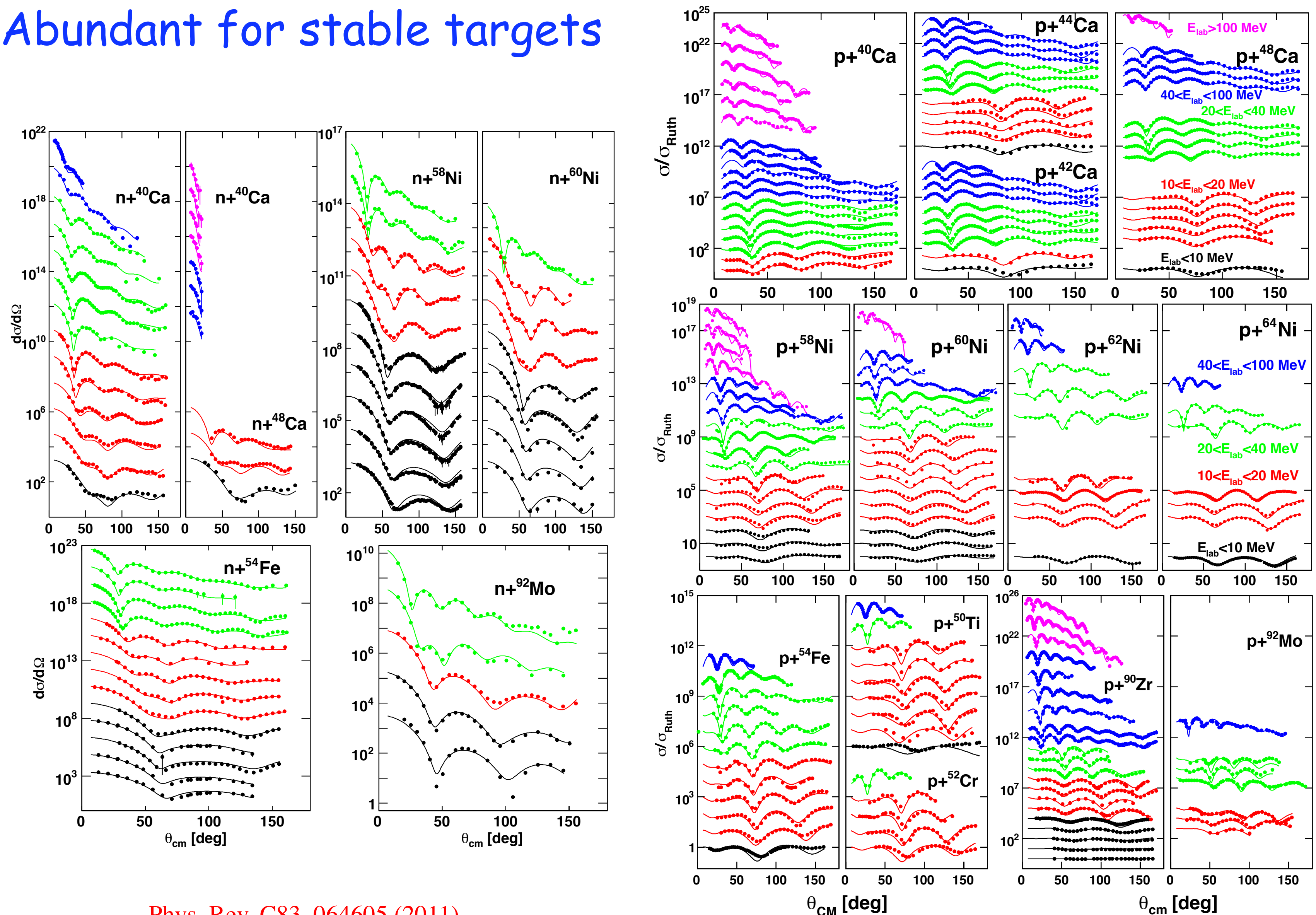
- ^{40}Ca

PRC 82, 054306 (2010)



Elastic scattering data for protons and neutrons

- Abundant for stable targets



Phys. Rev. C83, 064605 (2011)

Short-range and Tensor Correlations

New DOM implementation in progress

- Particle number --> **nonlocal** imaginary part
- Microscopic FRPA & SRC --> different nonlocal properties above and below the Fermi energy
- Include charge density in fit
- Describe high-momentum nucleons <--> (e,e'p) data from JLab

Implications

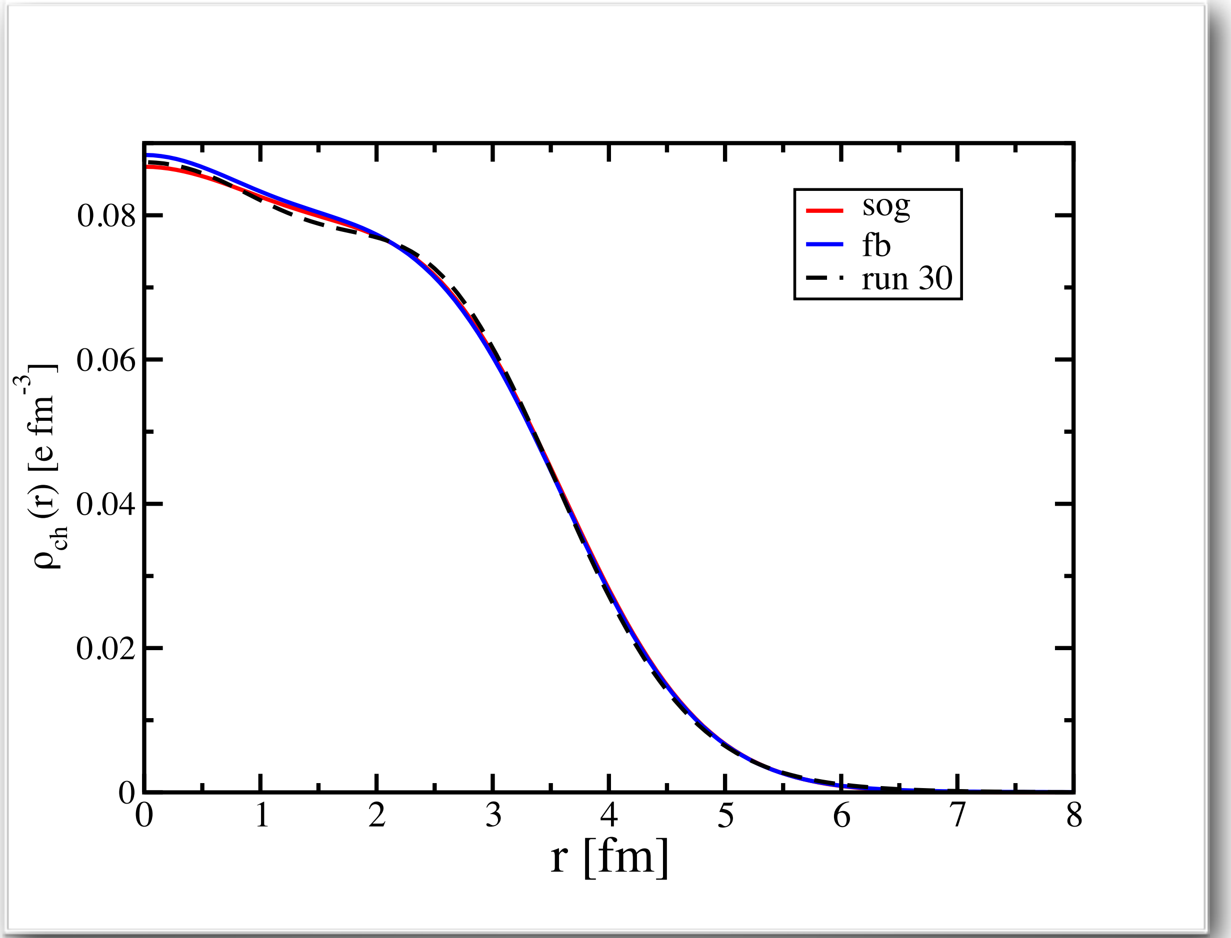
- Changes the description of hadronic reactions because interior nucleon wave functions depend on non-locality
- Consistency test of the interpretation of (e,e'p) possible
- Independent "experimental" statement on size of three-body contribution to the energy of the ground state--> two-body only:

$$E/A = \frac{1}{2A}\sum_{\ell j}(2j+1)\int_0^\infty dk k^2 \frac{k^2}{2m} n_{\ell j}(k) + \frac{1}{2A}\sum_{\ell j}(2j+1)\int_0^\infty dk k^2 \int_{-\infty}^{\varepsilon_F} dE\ E S_{\ell j}(k;E)$$

Short-range and Tensor Correlations

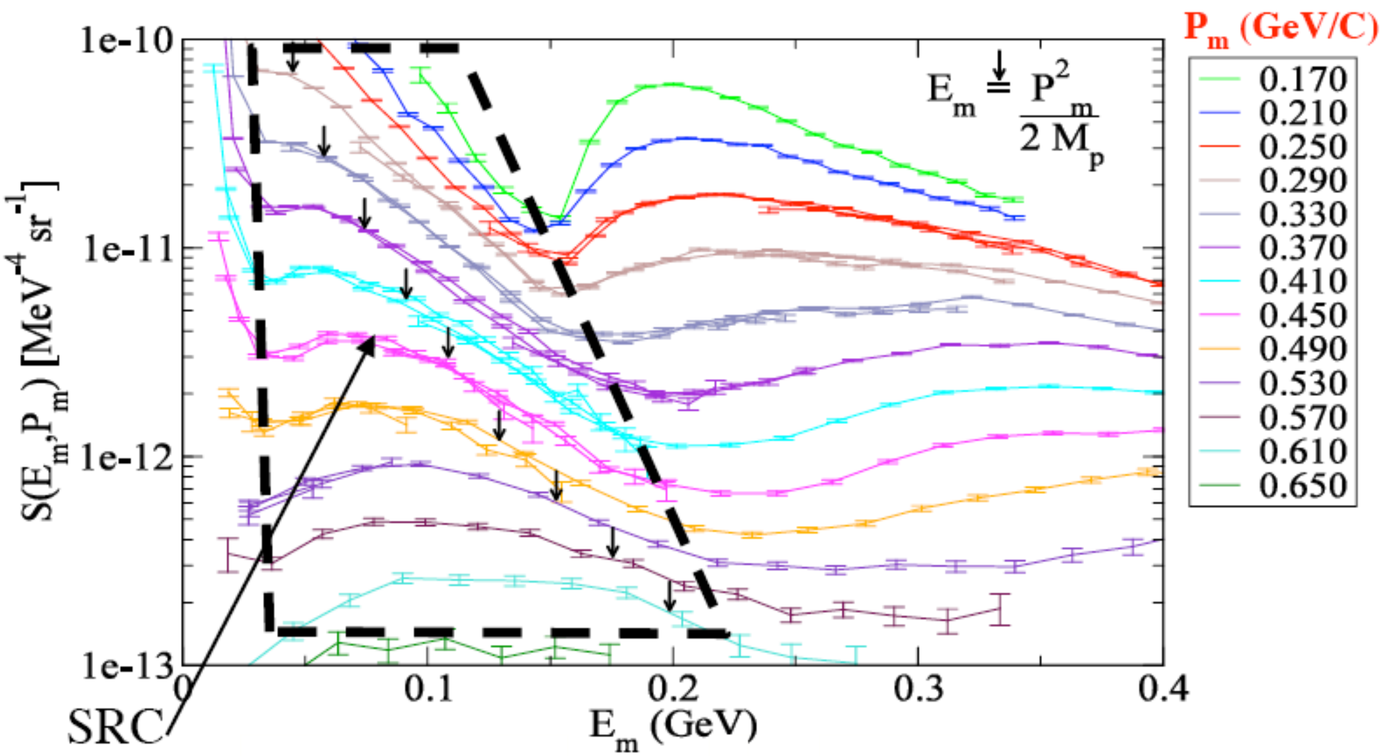
Critical experimental data

Charge density ^{40}Ca



High-momentum protons have been seen in nuclei!

Jlab E97-006 Phys. Rev. Lett. 93, 182501 (2004) D. Rohe et al.



^{12}C

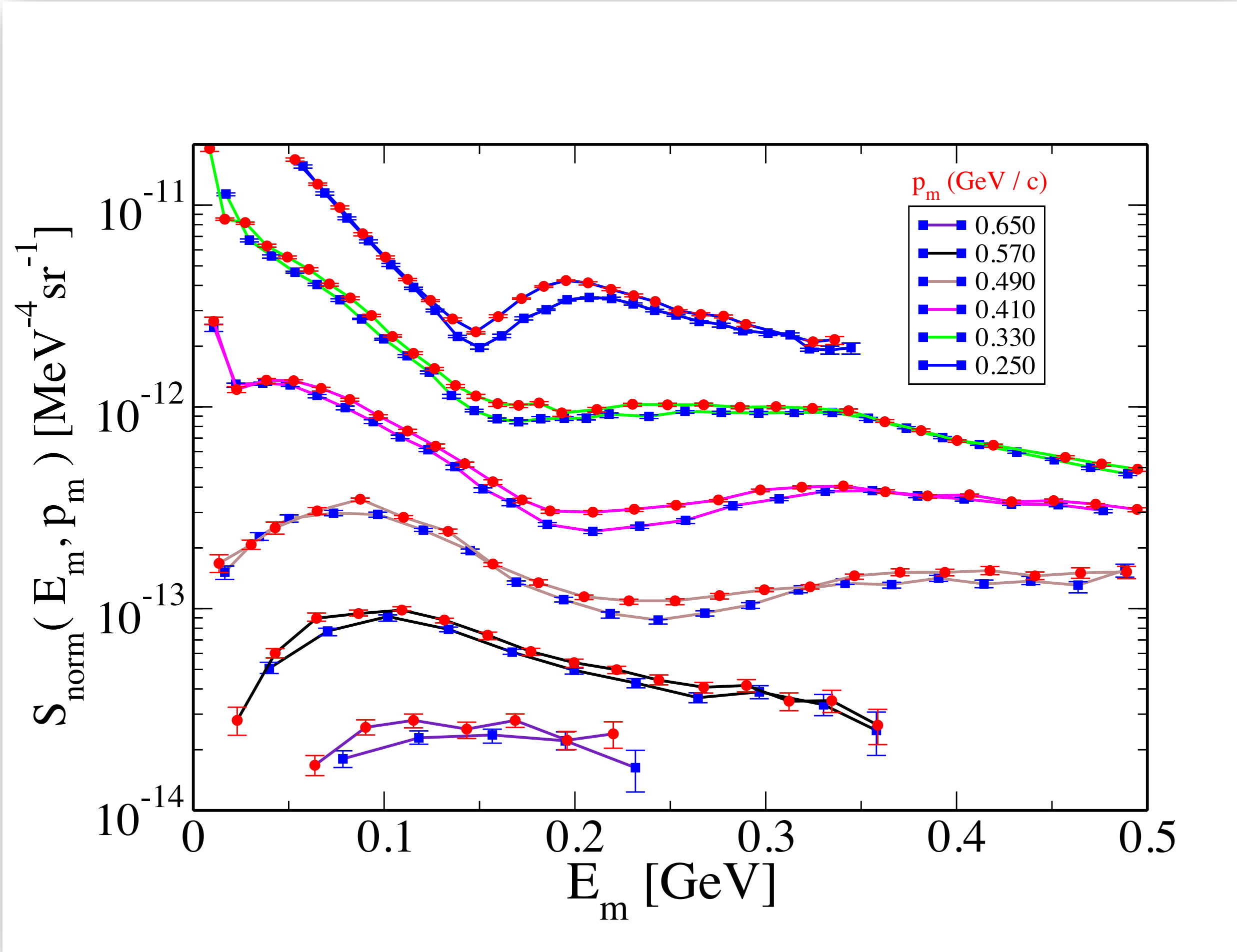
- Location of high-momentum components
- Integrated strength agrees with theoretical prediction Phys. Rev. C49, R17 (1994)

$\Rightarrow$ ~0.6 protons for ^{12}C $\Rightarrow$ **~10%**

Short-range and Tensor Correlations

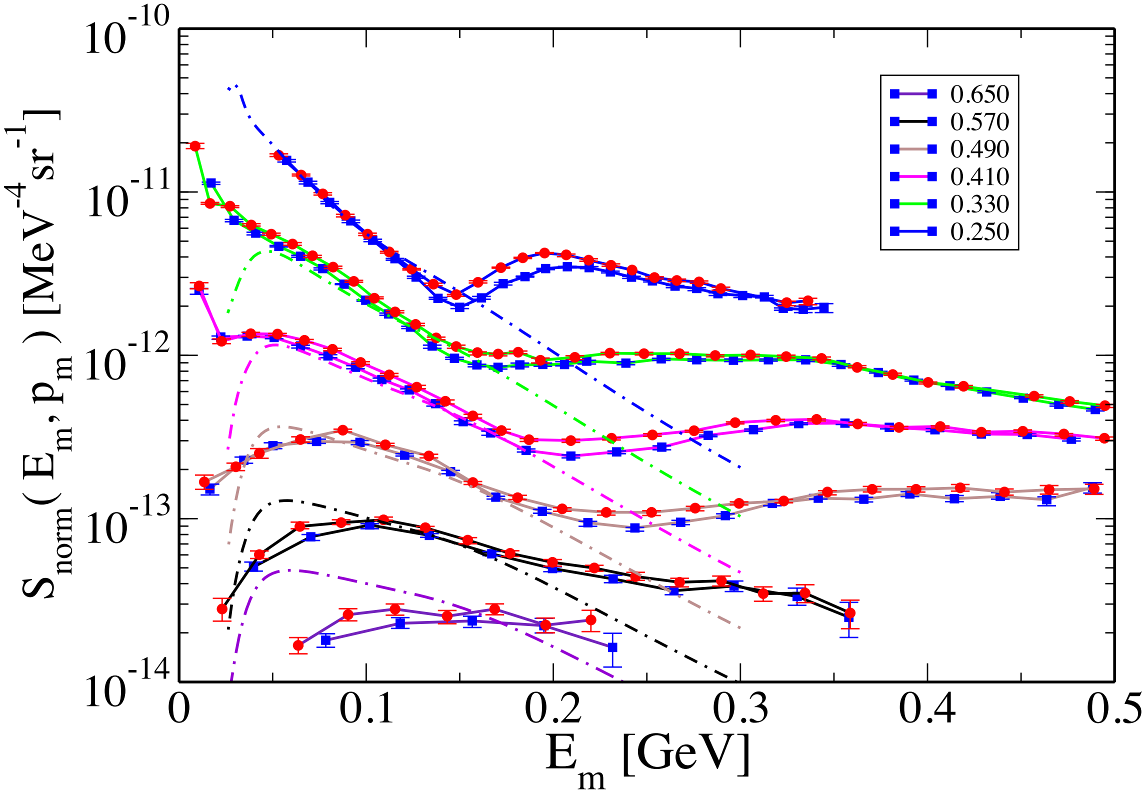
High-momentum components

Rohe, Sick et al. Al and Fe (e,e′p) data per proton



Preliminary results

- Mahzoon, Waldecker, Charity, Dussan, WD (2013)



Note: their location in energy yields an important contribution to the energy of the ground state

$$E/A = \frac{1}{2A}\sum_{\ell j}(2j+1)\int_0^\infty dk k^2 \frac{k^2}{2m} n_{\ell j}(k) + \frac{1}{2A}\sum_{\ell j}(2j+1)\int_0^\infty dk k^2 \int_{-\infty}^{\varepsilon_F} dE\ E S_{\ell j}(k;E)$$

Short-range and Tensor Correlations

Conclusions and Outlook

- Given a realistic NN interaction, its implications for the role of short-range and tensor correlations can be calculated reliably for infinite matter of any nucleon asymmetry, density, and temperature
  - Two-body spectral function and momentum distributions this year
- For finite nuclei this is not the case but some efforts have been made
  - Is a difficult challenge but in progress right now...
- Alternative approach for finite nuclei: correlate a lot of data --> DOM --> drip line
  - Will be a tool for FRIB physics as well