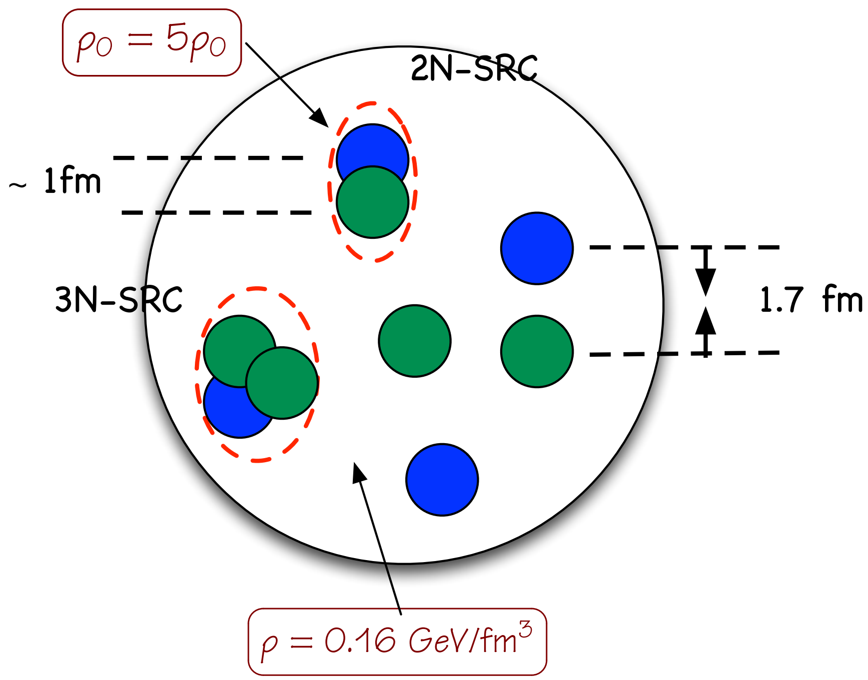
Short Range Correlations in Nuclei
A Survey

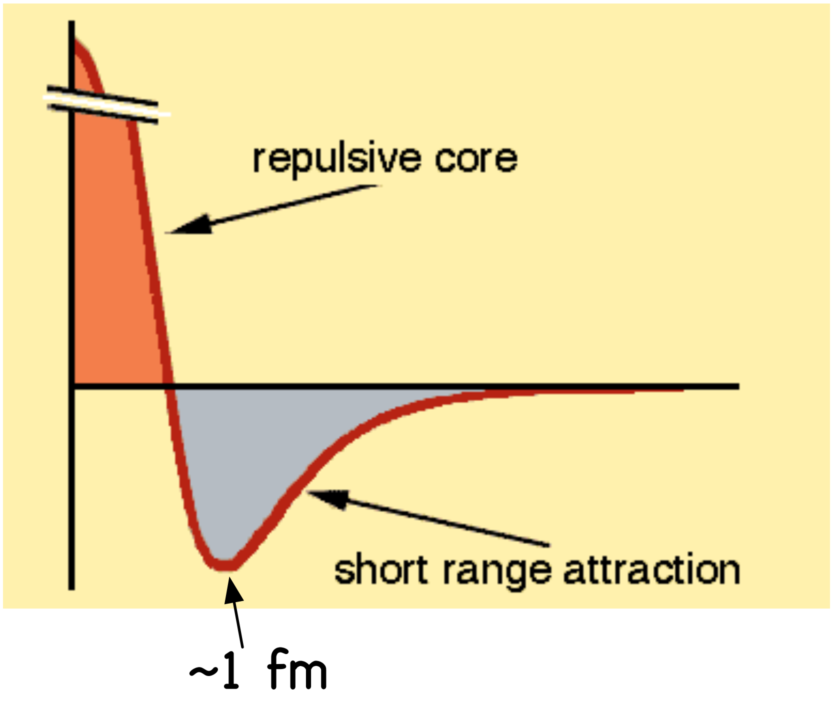
Donal Day
University of Virginia

- Short range Correlations Exist!
  - Old Subject
  - Studied via knock-out reactions
    - Inclusive
      - Ratios
    - Exclusive
      - Isospin dependence
- Source is the Nuclear Potential
  - Some details
- Future Prospects

Structure of the nucleus



Nucleon separation is limited by the short range repulsive core

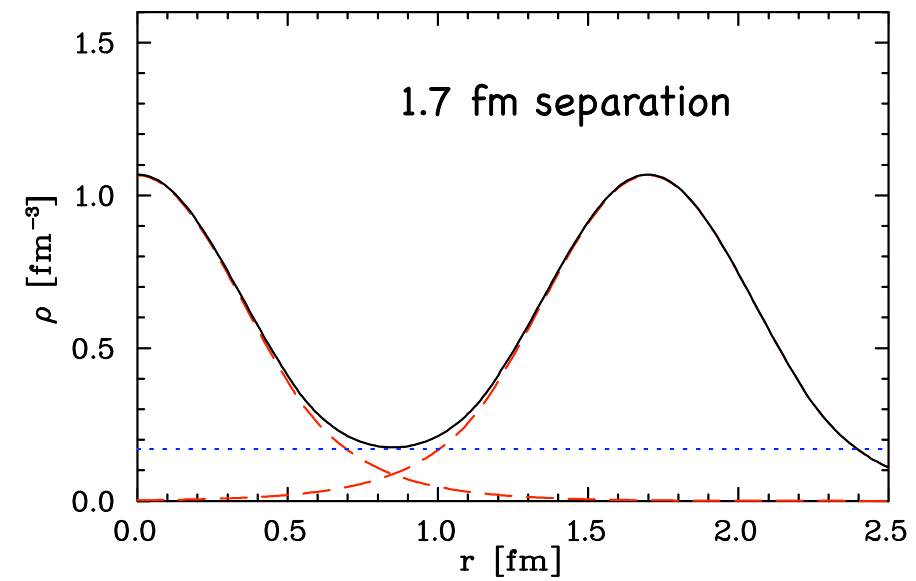


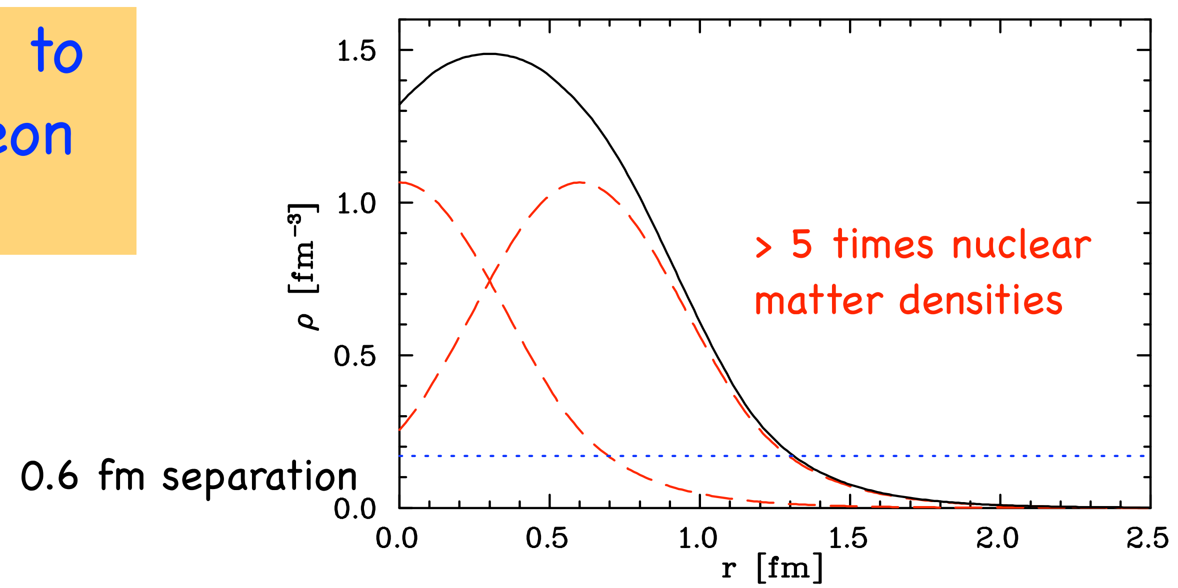
Determined by N-N potential

- nucleons are bound
  - energy (E) distribution
  - shell structure
- nucleons are not static
  - momentum (k) distribution

Densely packed - at small distances multiples of NM

High enough to modify nucleon structure?





Correlations - when 2N are at small r_{12}. How is this manifested?

Correlations - Old Topic

J.H. Smith, Phys Rev 95, 271, 1954 "Nuclear Scattering of High-Energy Electrons"

"The differential cross section for inelastic scattering summed over nuclear energy levels, is found to depend on the relative location of pairs of particles. Information on possible regularities in the internal "construction" of nuclei might be obtained from this quantity."

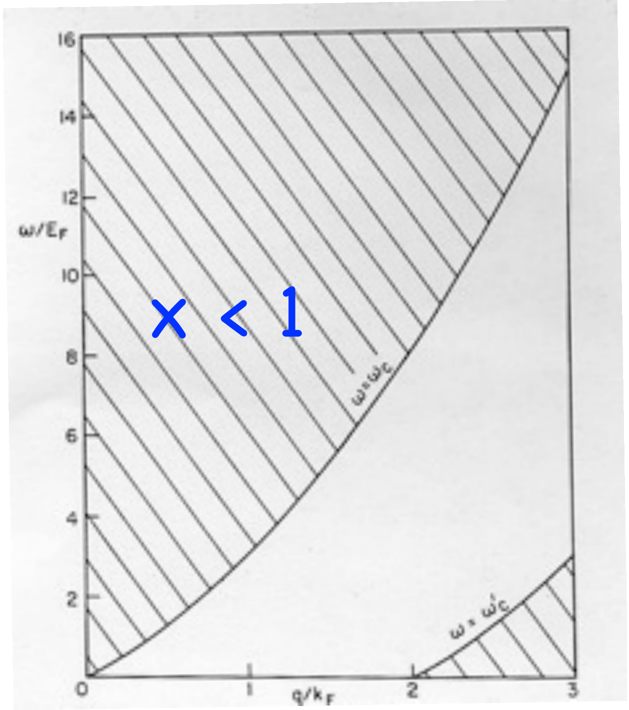
The author related a quantity, ϕ, which

" integrated over all of the coordinates save two to give a "two-particle density" which characterizes the correlation in location of pairs of protons" --- **spatial correlations**

The determination of the nuclear pair correlation function and momentum distribution
Kurt Gottfried
Annals of Physics 21, 29 (1963).

Inelastic electron scattering from fluctuations in the nuclear charge distribution
Wieslaw Czyż and Kurt Gottfried
Annals of Physics 21, 47 (1963)

Shaded domain where scattering is restricted solely to correlations

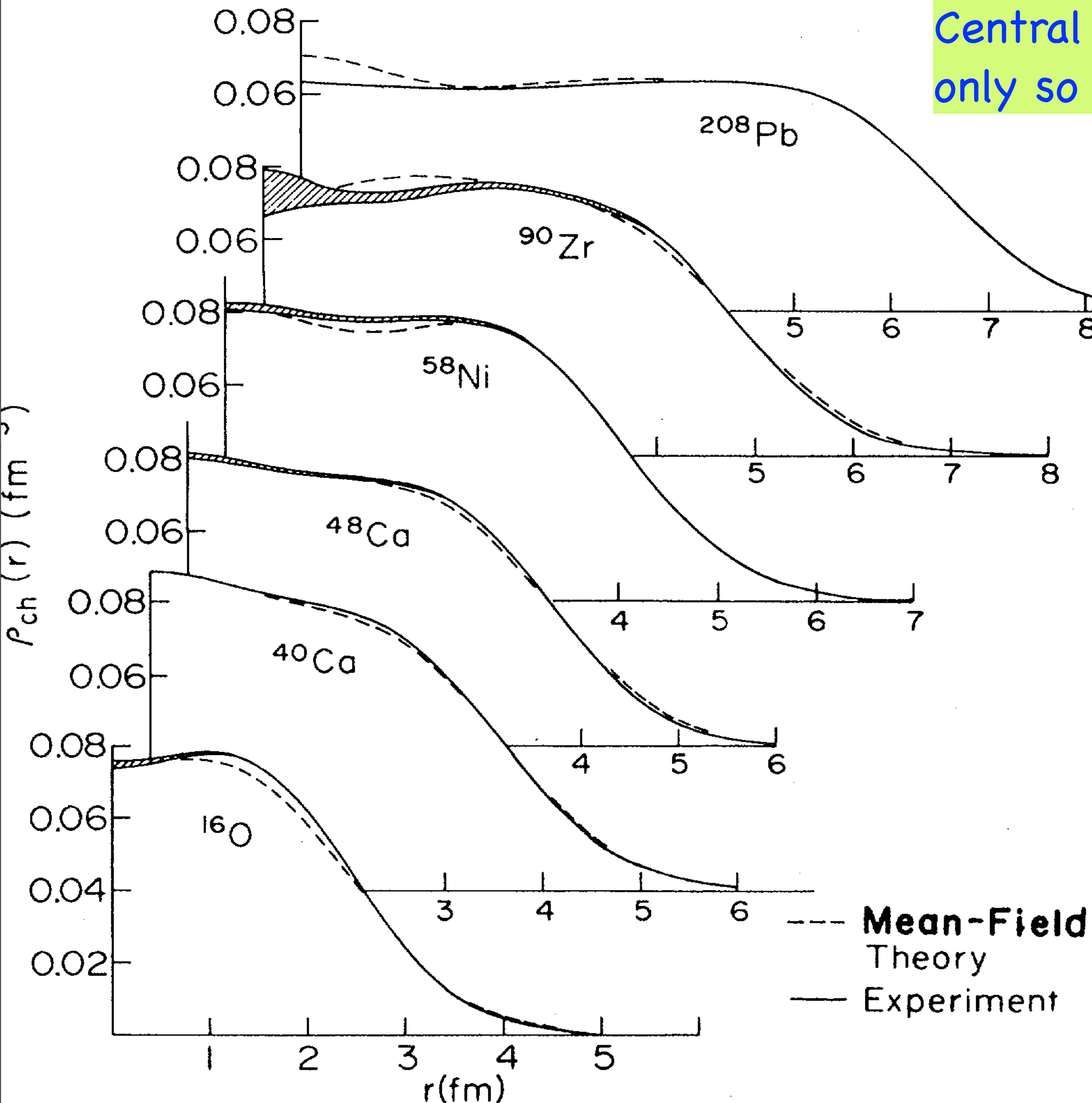


$$\omega_c = \frac{(k+q)^2}{2m} + \frac{q^2}{2m}$$

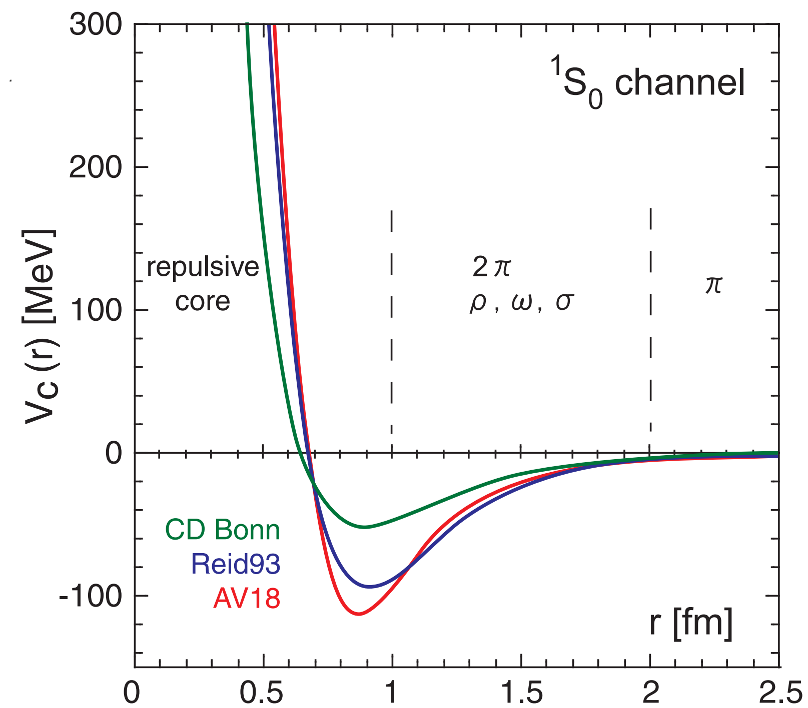
$$\omega_c' = \frac{q^2}{2m} - \frac{qk_f}{2m}$$

x > 1, low ω side of qep

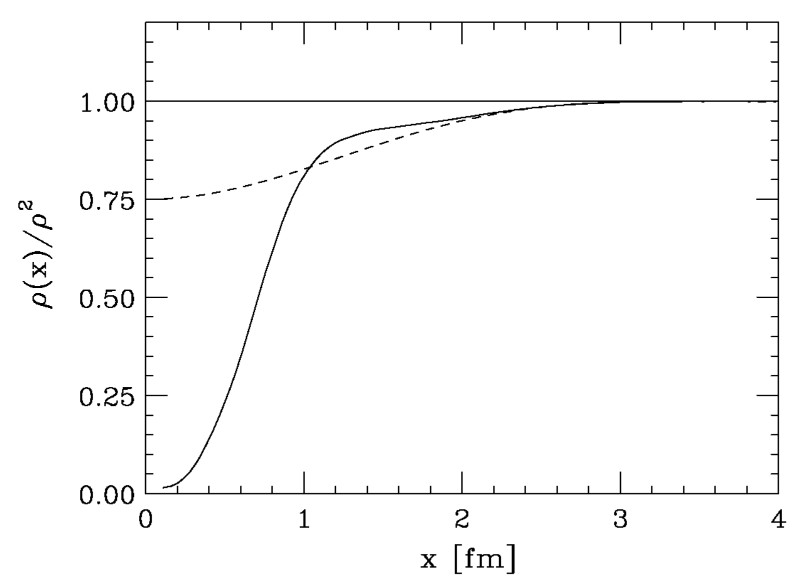
We know short range correlations exist.



Central density is saturated - nucleons can be packed only so close together: ρ_{ch} * (A/Z) = constant



$$\rho(x, x') = \rho(x)\rho(x')g(x, x')$$



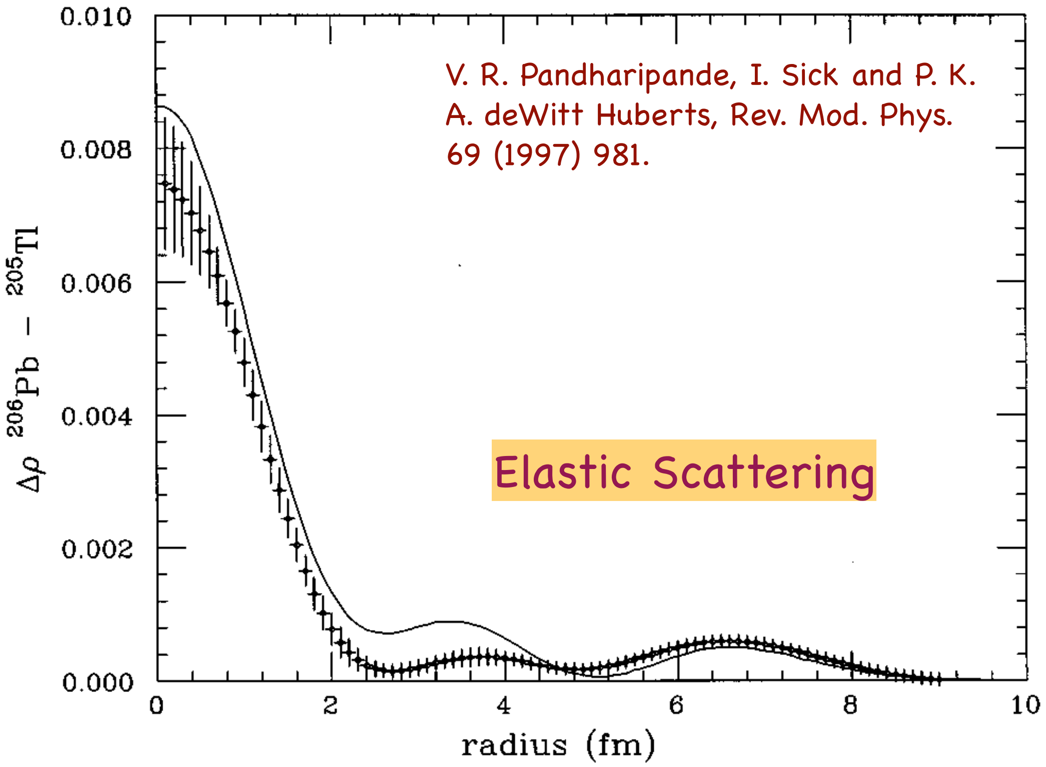
$$|x - x'| \lesssim r_c \Longrightarrow g(x, x') \ll 1$$

Spatial correlations

O. Benhar, AIP Conf.Proc. 1189 (2009) 43-50

J.W. Negele RMP 54 (913) 1982

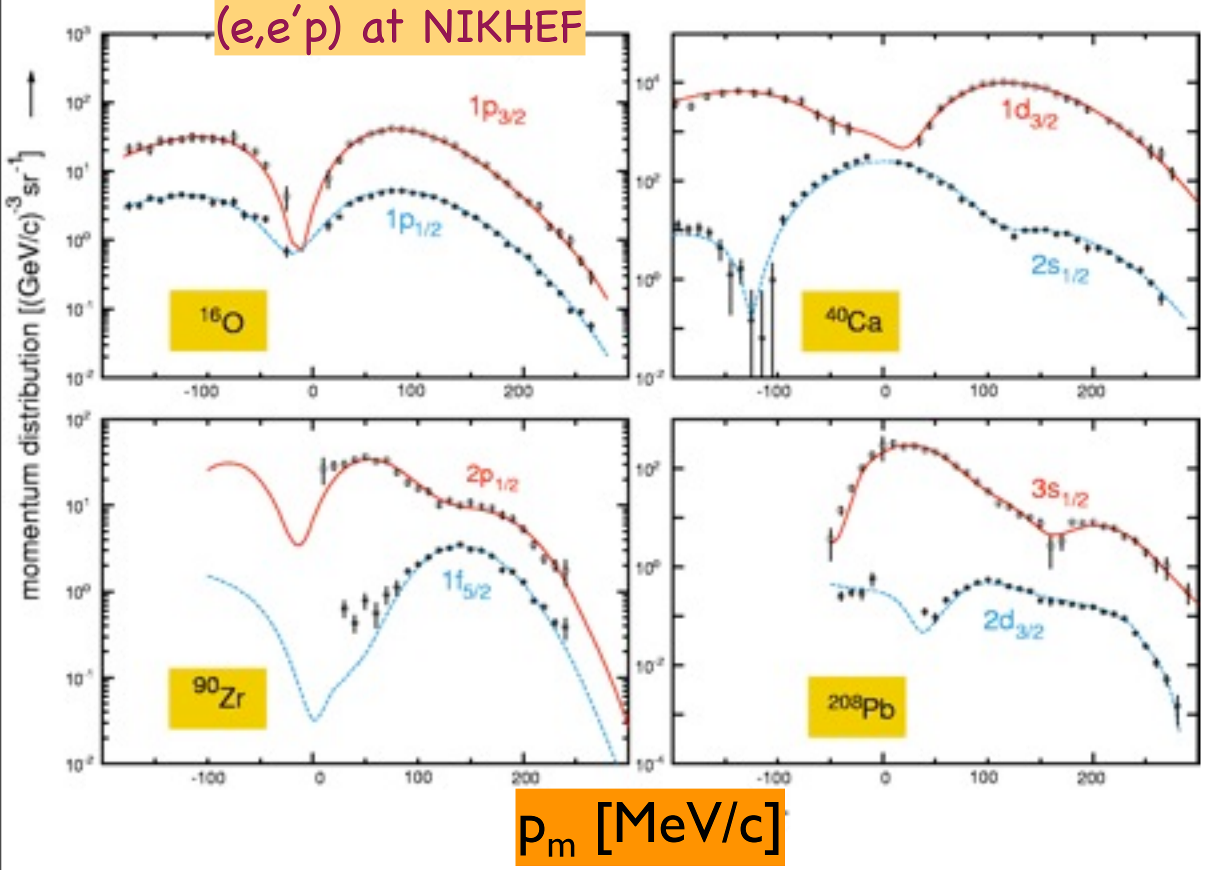
What else? Occupation Numbers



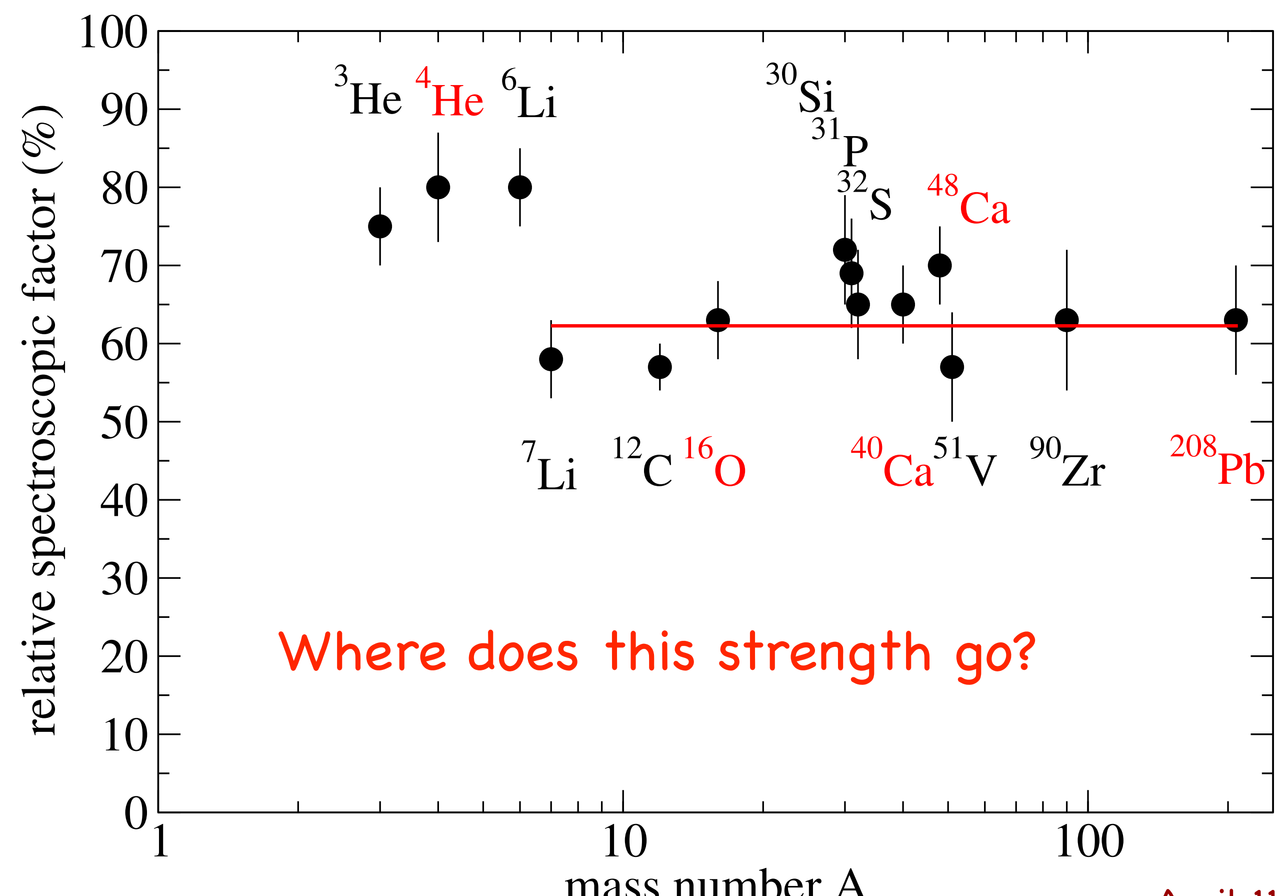
Density difference between ^{206}Pb and ^{205}Tl.

Experiment - Cavedon et al (1982)
Theory: Hartree-Fock orbitals with adjusted occupation numbers is given by the curve.

The shape of the $3s^{1/2}$ orbit is very well given by the mean field calculation.



Occupation numbers scaled down by a factor ~0.65.

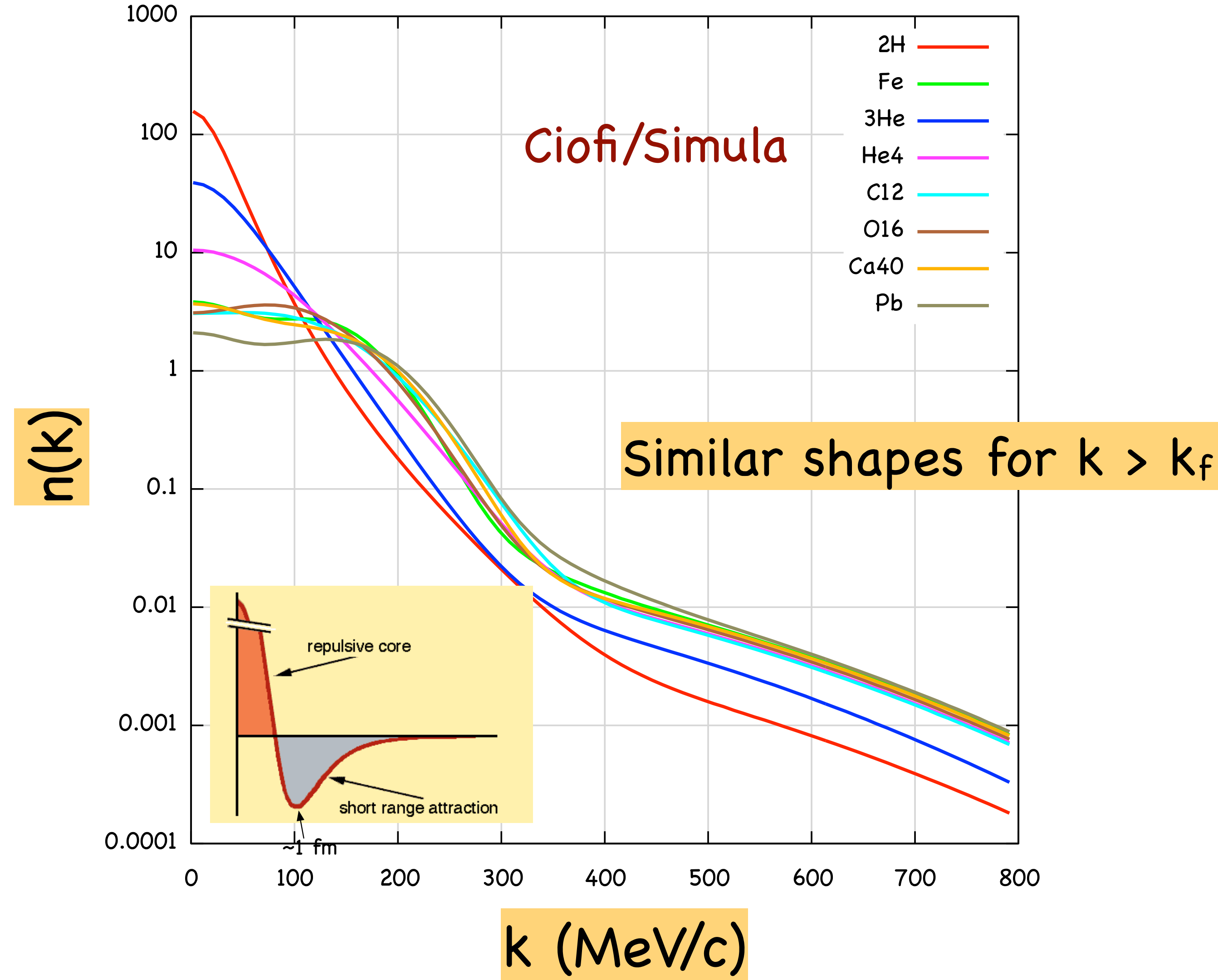


Short Range Correlations reveal themselves in momentum distributions

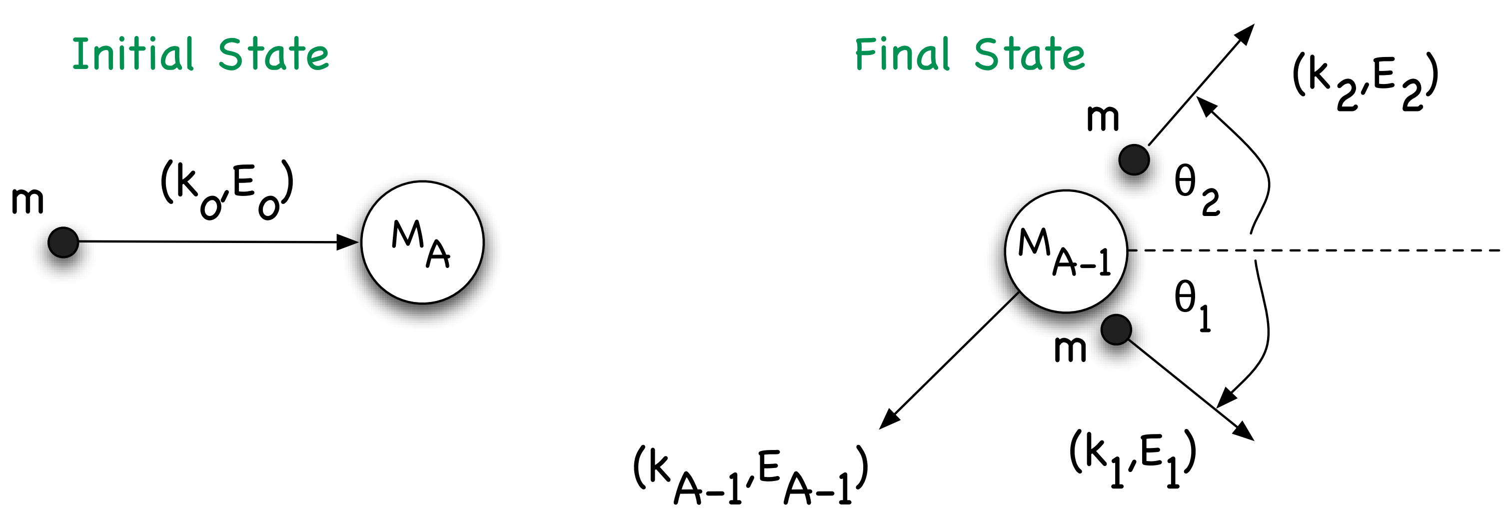
Mean field contributions: $k < k_F$ Well understood, SF Factors ≈ 0.65

High momentum tails: $k > k_F$

- Calculable for few-body nuclei, nuclear matter
- Dominated by two-nucleon short range correlations
- Poorly understood part of nuclear structure
- Sign. fraction have $k > k_F$



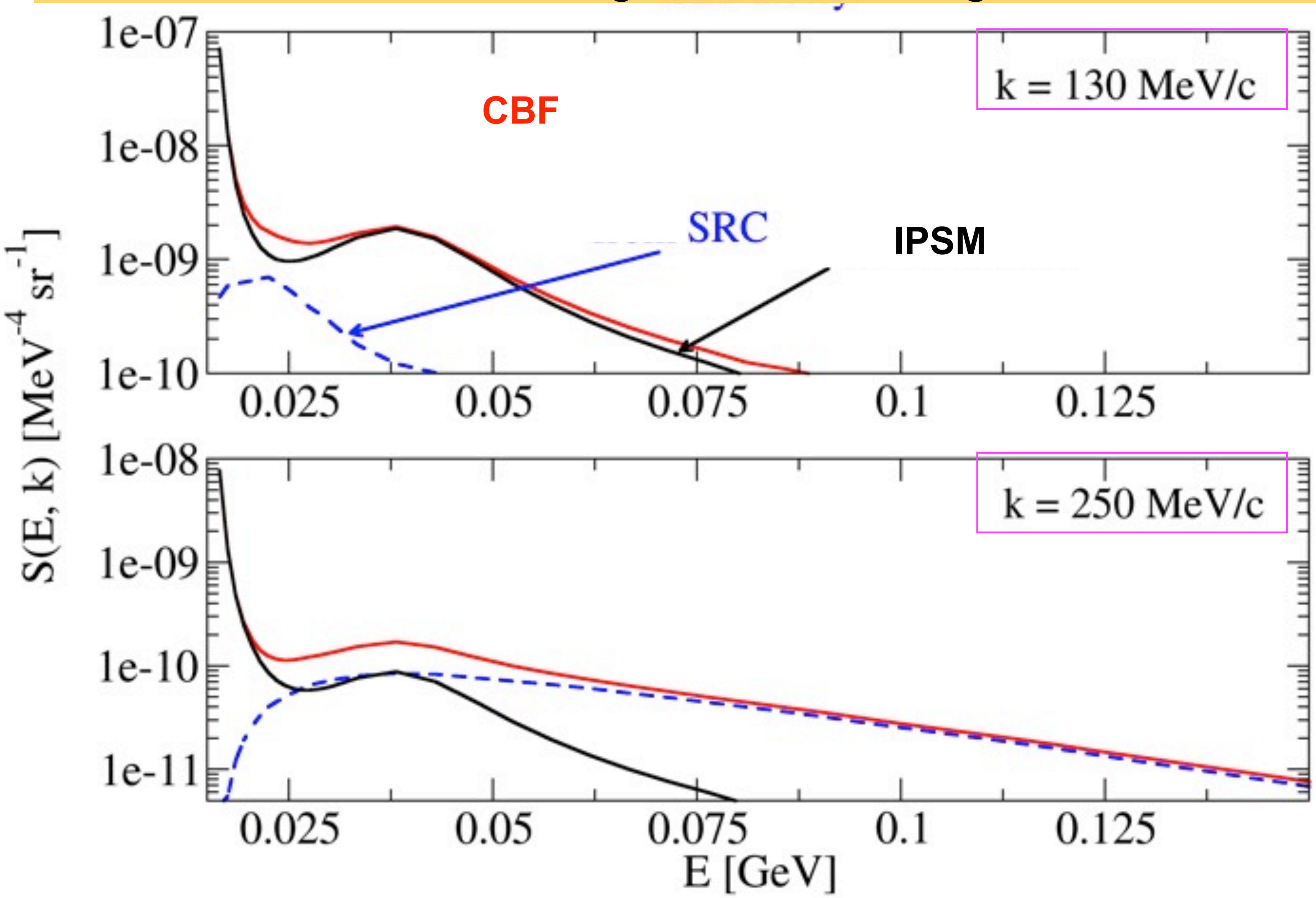
Quasi free Knockout Reactions



proton, pions, electrons

inclusive, exclusive

Realistic many body calculations of the spectral function contain correlated strength and it is significant



Benhar via Rohe ^{12}C

$\approx k_F$

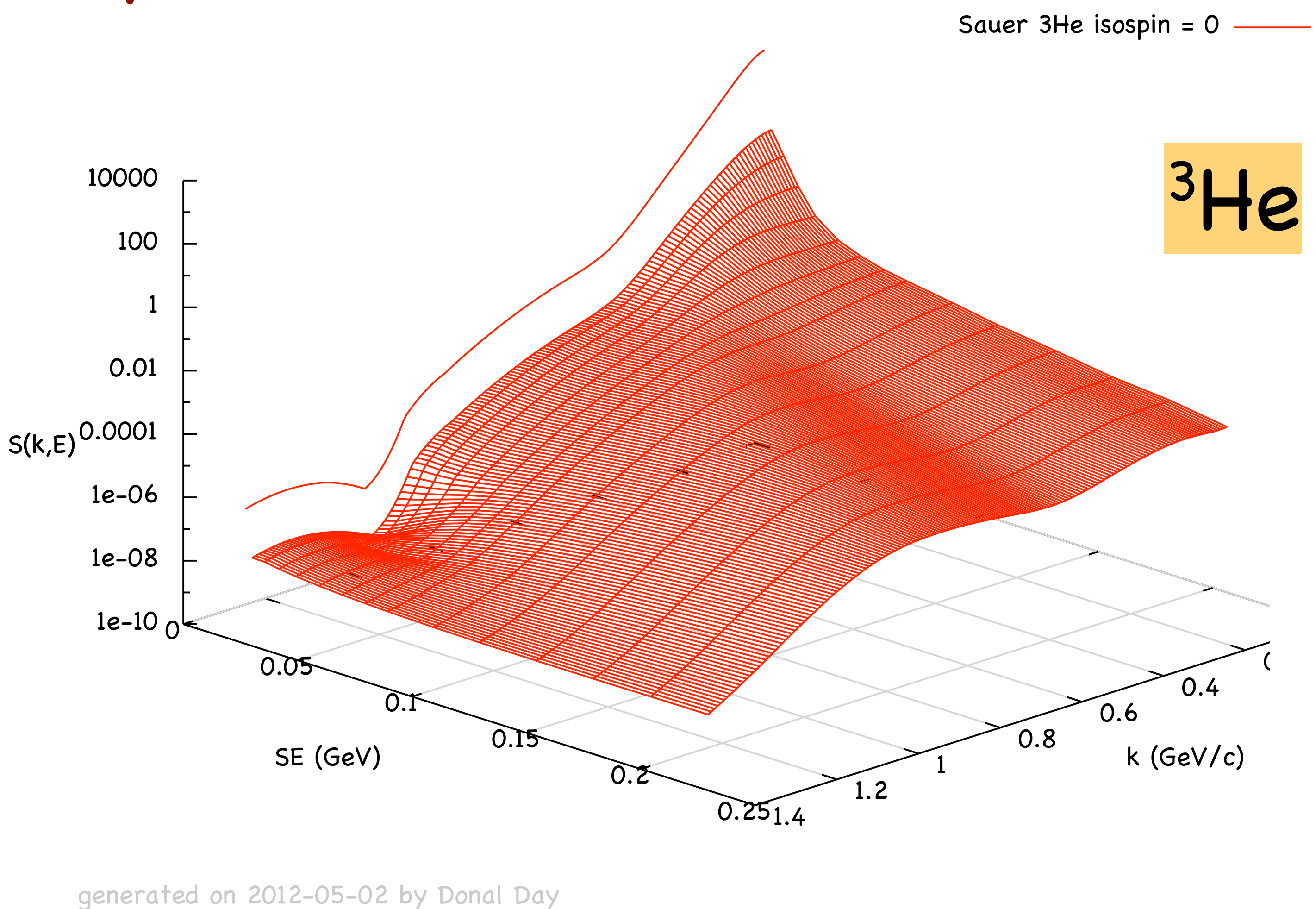
$k < k_F$: single-particle contribution dominates

$k \approx k_F$: SRC already dominates for E > 50 MeV

$k > k_F$: single-particle negligible

Spectral Function

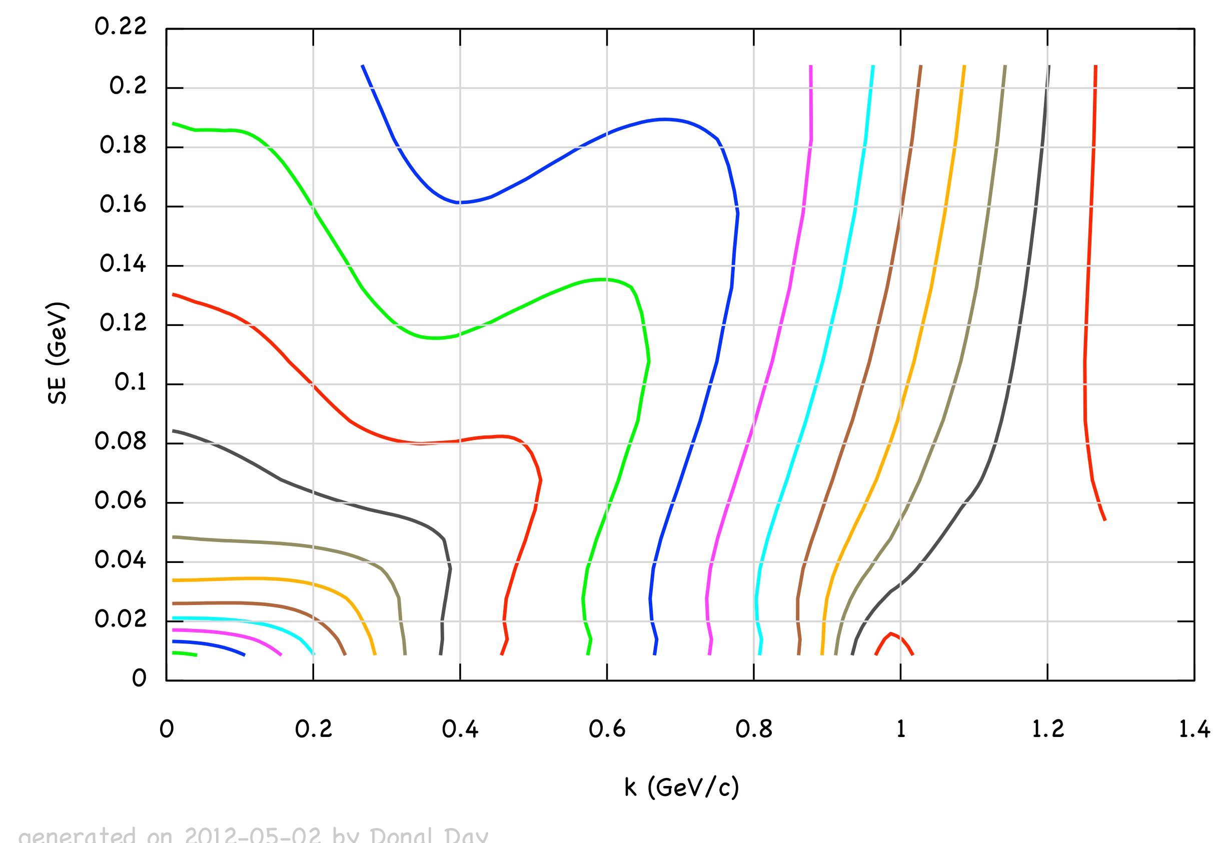
probability to remove a nucleon leaving the residual system with energy $E_R = M_A - m + E = (k^2 + M_R^2)^{1/2}$



^{3}He

$$n(k) = \int S(E_s, k)\, dE_s$$

Strength is spread out in E, all of which must be integrated over to get n(k)

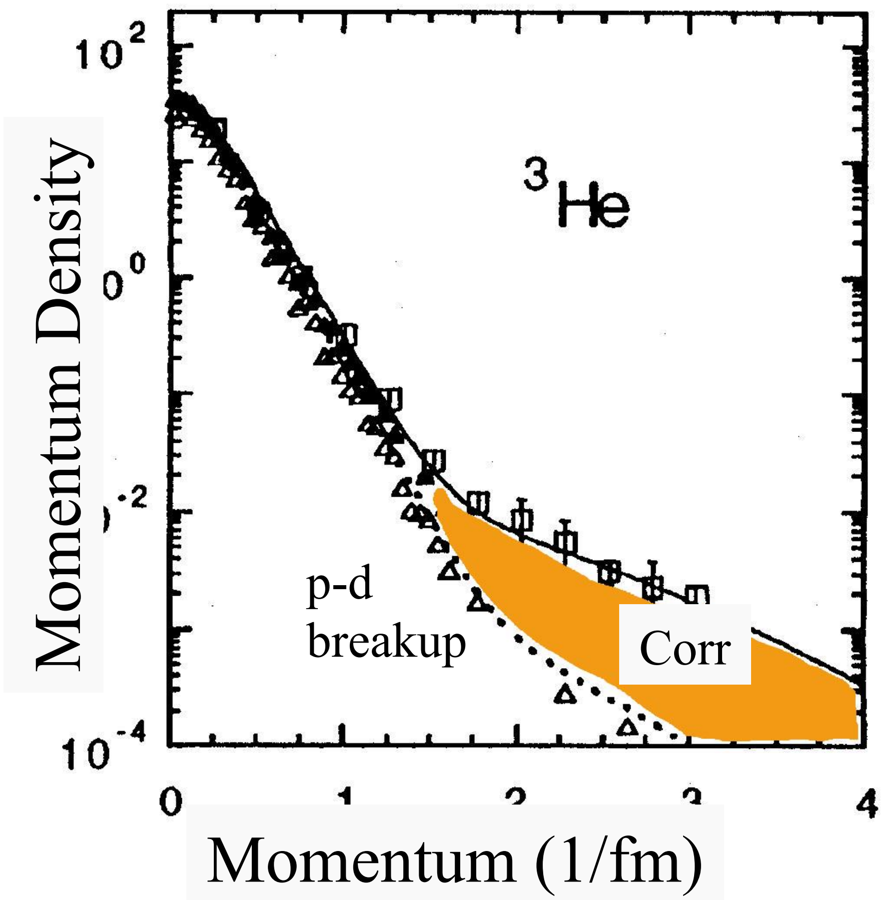


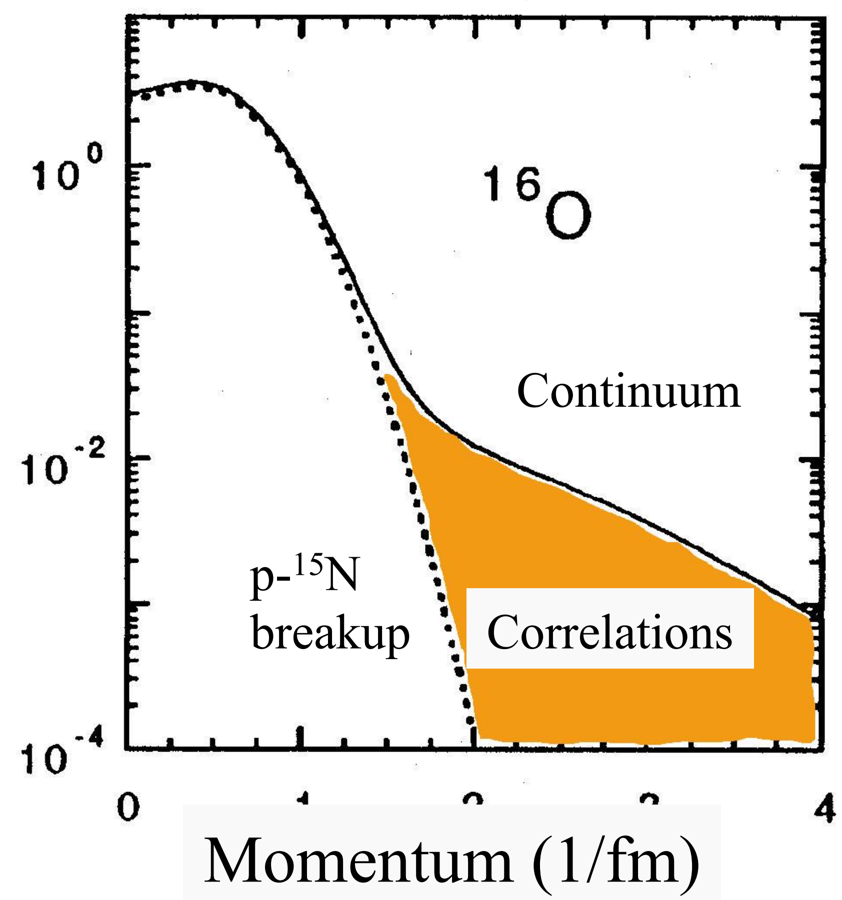
A ridge at approx $E = k^2/2/m$ reflects the correlation in the gs

How to gain access to short range correlations?

^{3}He(e,e'p)d , ^{3}He(e,e'p)np

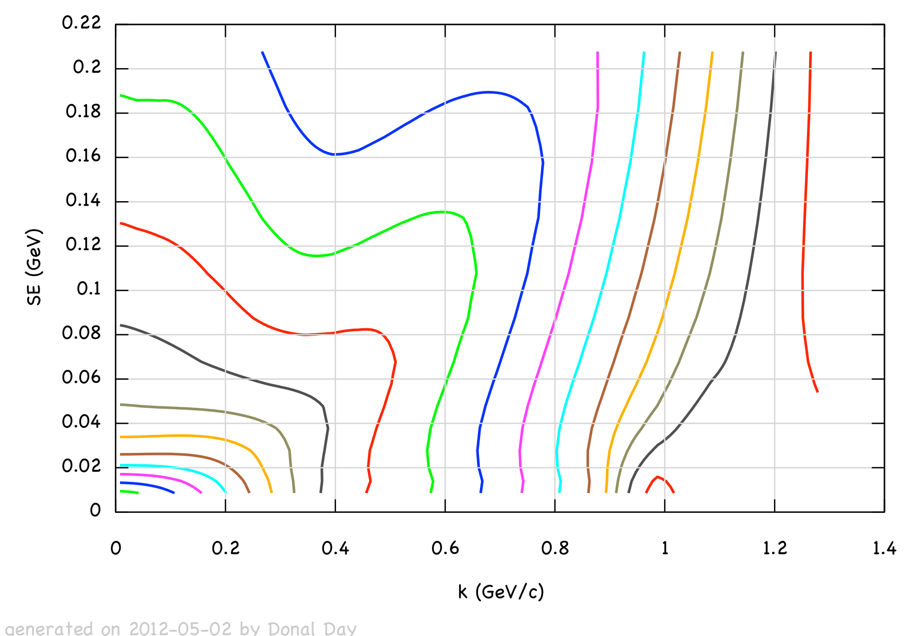
Exclusive reactions



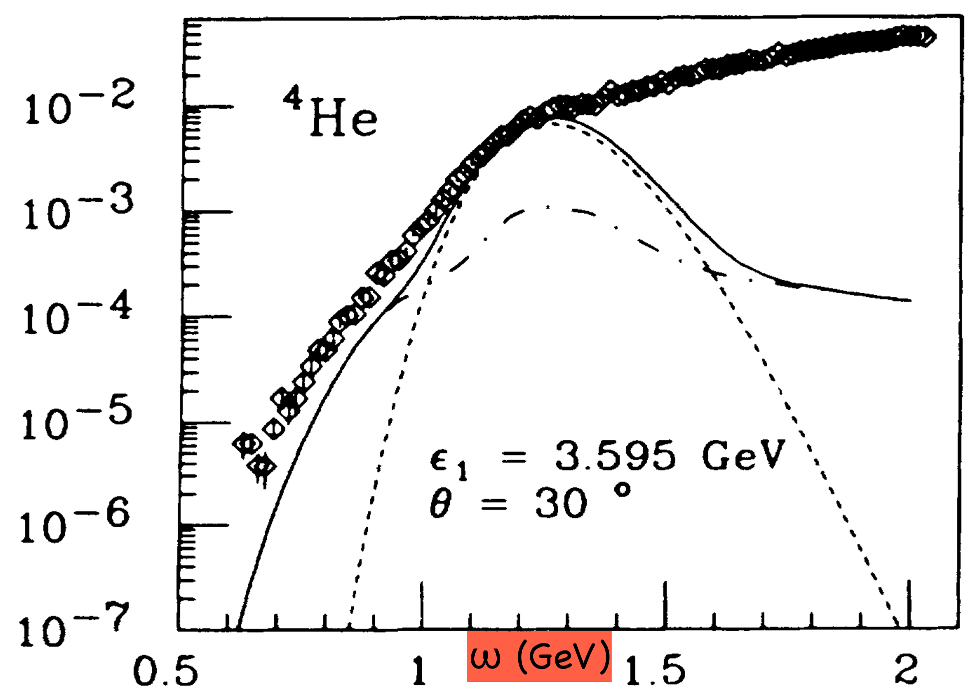


Ciofi degli Atti, PRC 53 (1996) 1689

Marchand et al. Phys. Rev. Lett. 60, 1703–1706 (1988)



^{4}He(e,e') inclusive

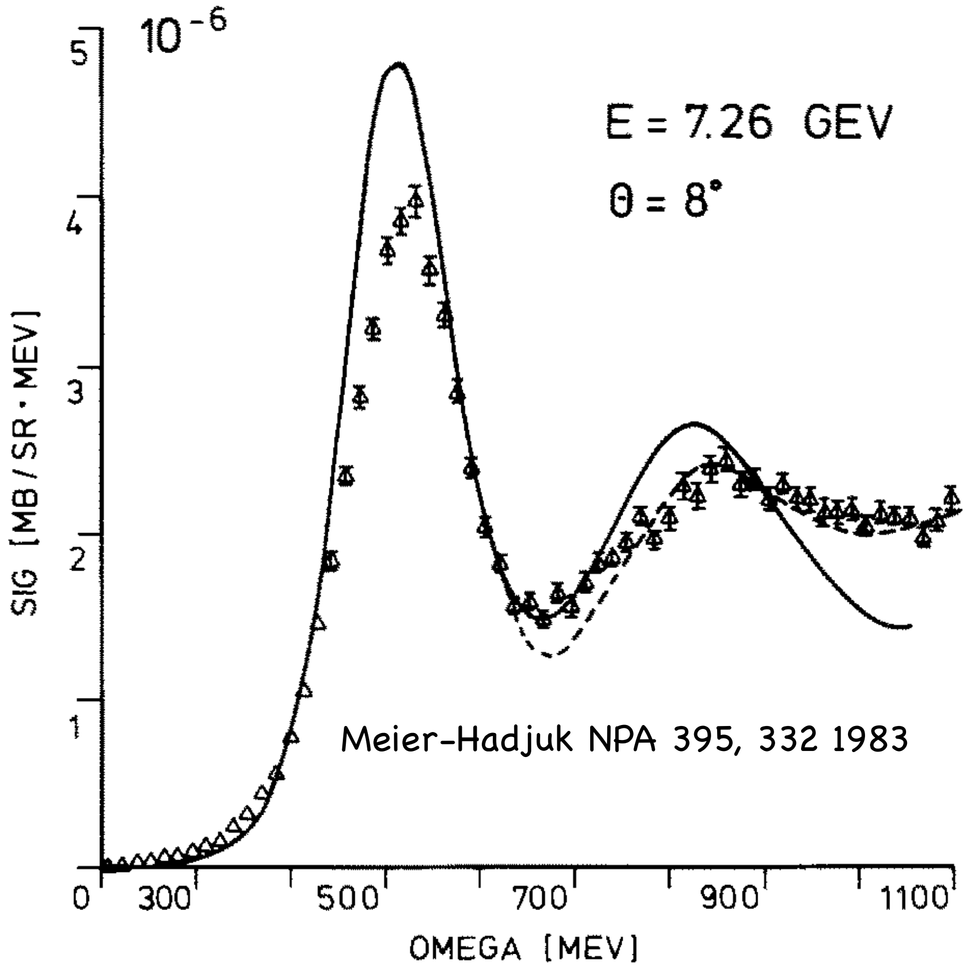


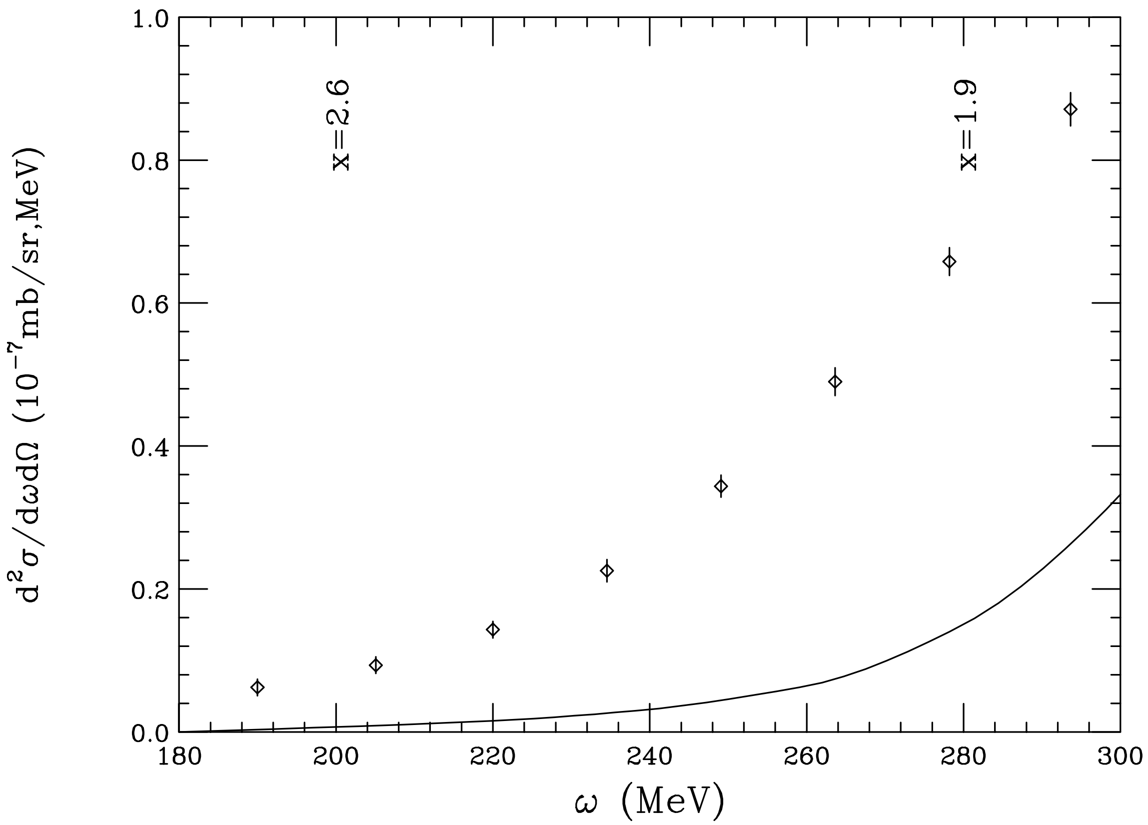
CdA, Day, Liuti, PRC 46 (1045) 1992

One problem with cross section - FSI

In (e,e′p) flux of outgoing protons strongly suppressed: 20-40% in C, 50-70% in Au

In (e,e′) the failure of IA calculations to explain dσ at small energy loss





Some of this could be resolved by a rearrangement of strength in SE

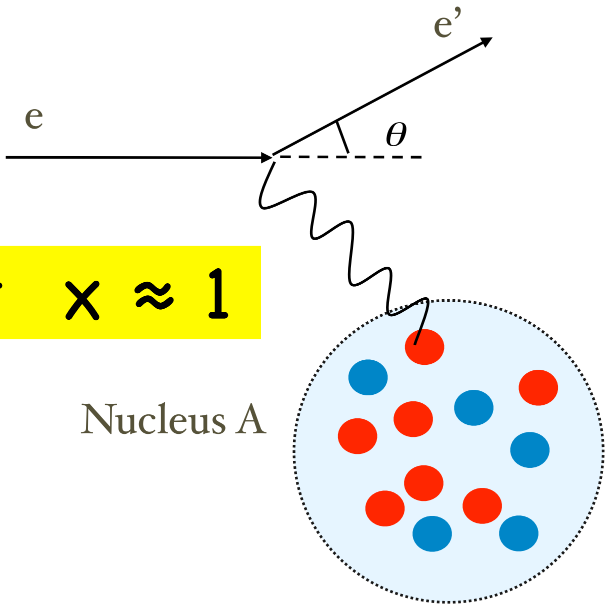
Old problem: real/complex optical potential. Real part generates a shift, imaginary part a folding of cs, reduction of qep.

Role of SRC on Lorentzian tail?? Off-shell effects on NN interaction??

Can they ever be neglected?

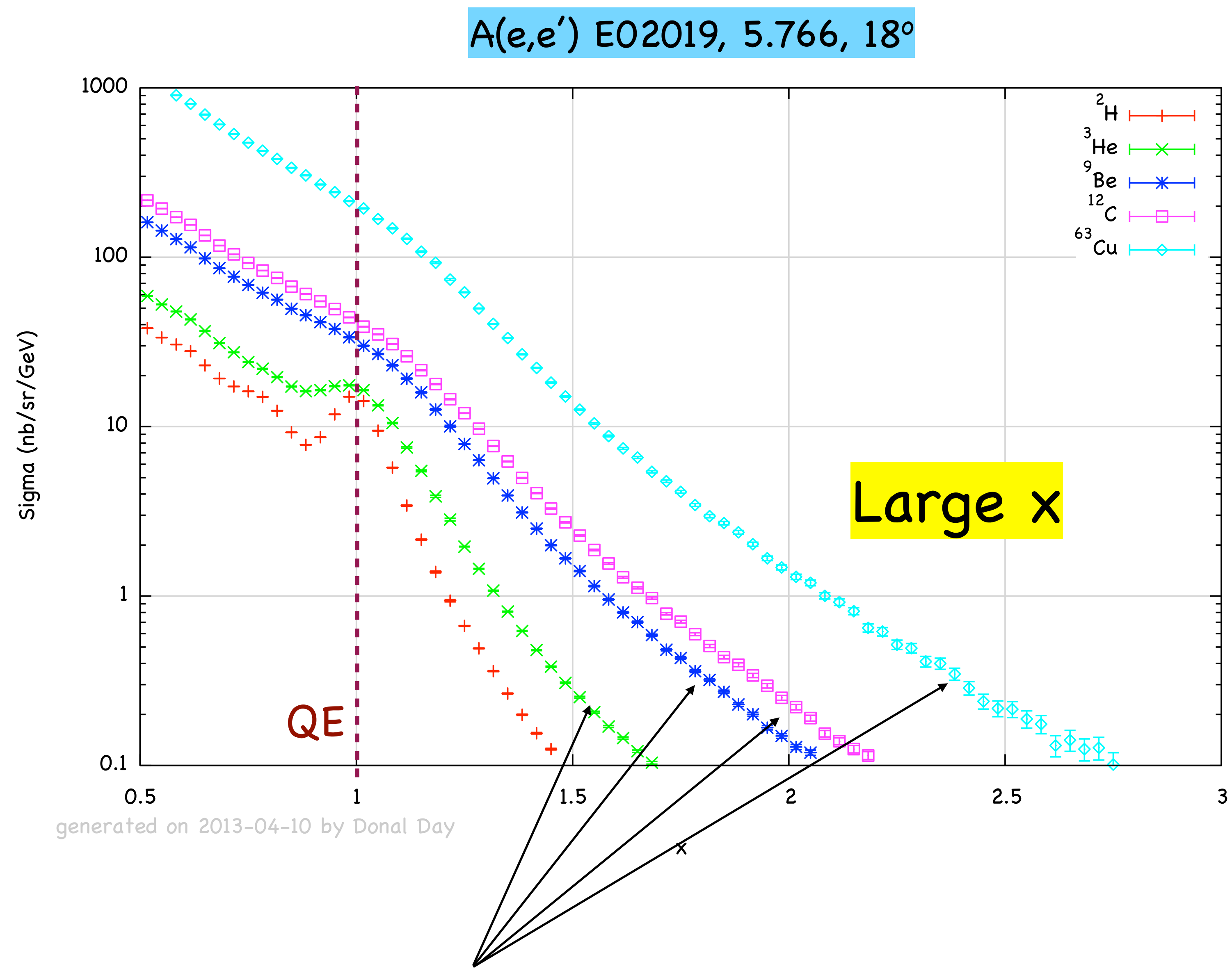
Inclusive scattering at large x

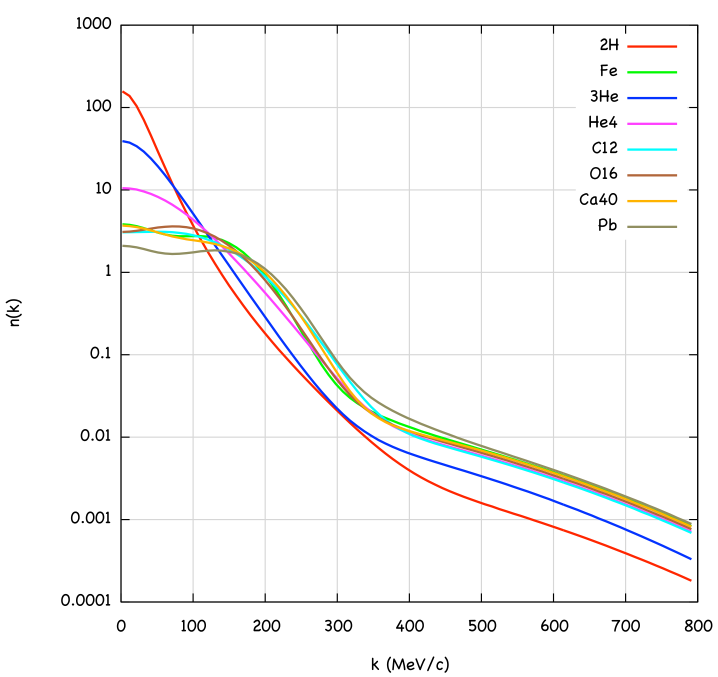
At $x \approx 1$



➡ Motion of nucleon in the nucleus broadens the peak.

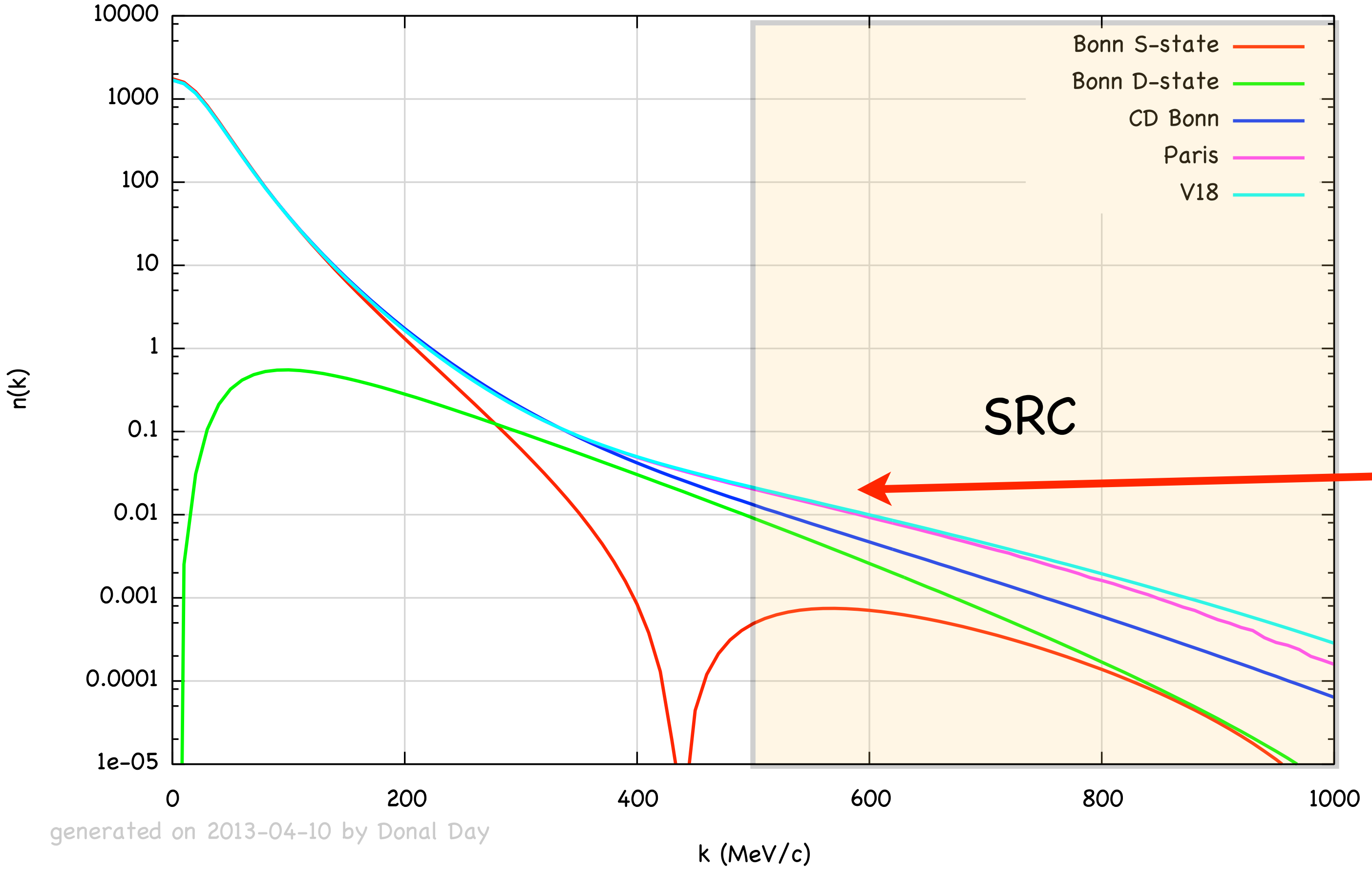
➡ little strength from QE above $x \approx 1.3$.





High momentum tails should yield constant ratio if seeing SRC

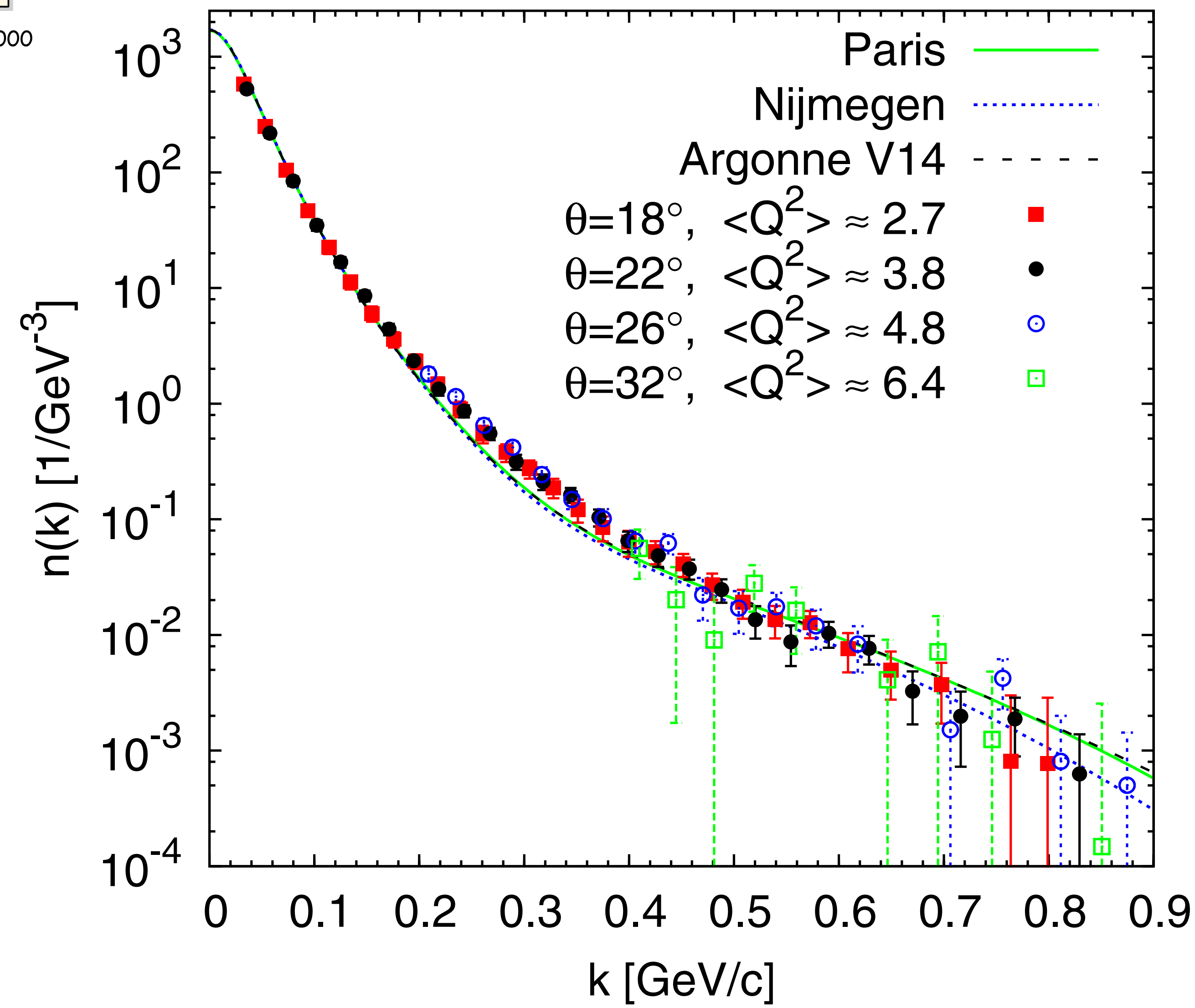
Deuteron momentum distribution



Virtually no experimental d(e,ep)n data exist for p_m > 0.5 GeV/c without large contributions of FSI, MEC and IC

large k dominated by D-state

E02019: Fomin et al. PRL 108, 092502 (2012)



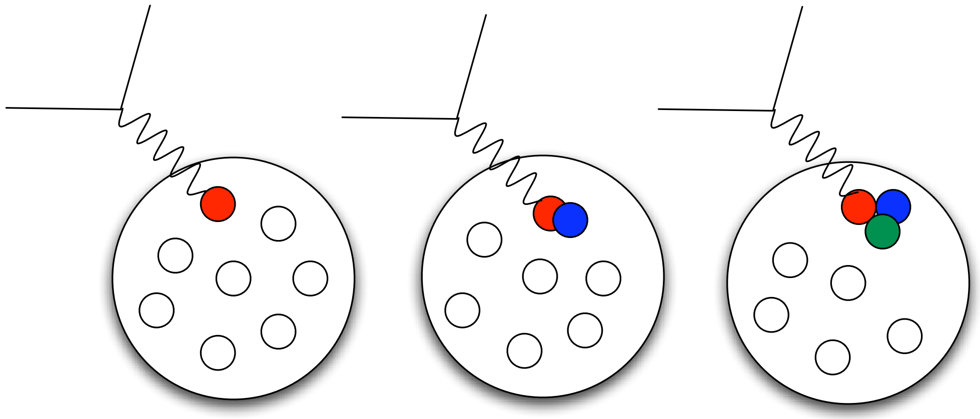
Inclusive D(e,e′) via y-scaling provides n(k) well into the SRC region

$$n(k) = -\frac{1}{2\pi y}\frac{dF(y)}{dy}$$

A(e,e') CS Ratios and SRC

In the region where correlations should dominate, large x,

$$\sigma(x,Q^2) = \sum_{j=1}^{A} A\frac{1}{j}a_j(A)\sigma_j(x,Q^2)$$
$$= \frac{A}{2}a_2(A)\sigma_2(x,Q^2) + \frac{A}{3}a_3(A)\sigma_3(x,Q^2) + \vdots$$



$a_j(A)$ are proportional to finding a nucleon in a j-nucleon correlation. It should fall rapidly with j as nuclei are dilute.

$$\sigma_2(x,Q^2) = \sigma_{eD}(x,Q^2) \text{ and } \sigma_j(x,Q^2) = 0 \text{ for } x > j.$$

$$\Rightarrow \quad \frac{2}{A}\frac{\sigma_A(x,Q^2)}{\sigma_D(x,Q^2)} = a_2(A)\Big|_{1<x\leq 2}$$

$$\frac{3}{A}\frac{\sigma_A(x,Q^2)}{\sigma_{A=3}(x,Q^2)} = a_3(A)\Big|_{2<x\leq 3}$$

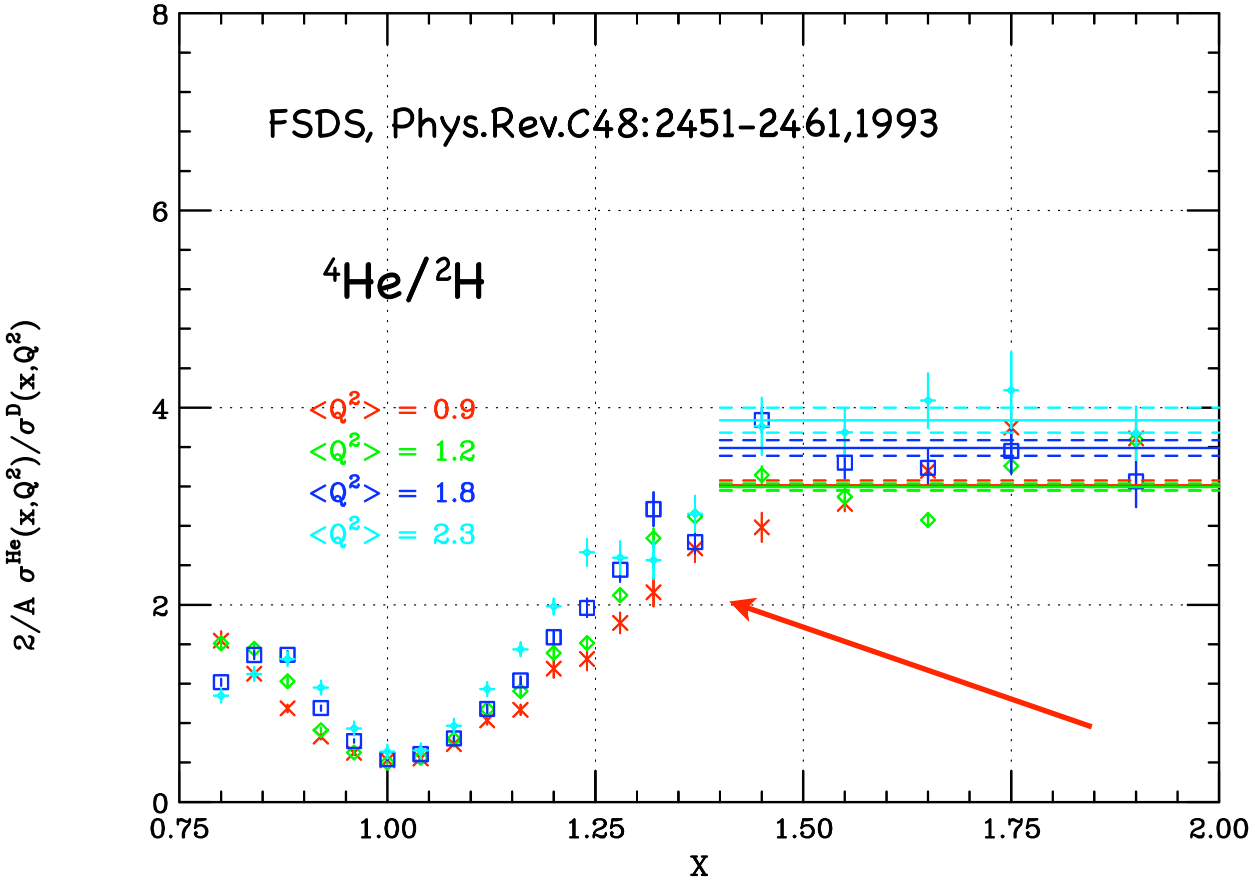
Assumption is that in the ratios, off-shell effects and FSI largely cancel.

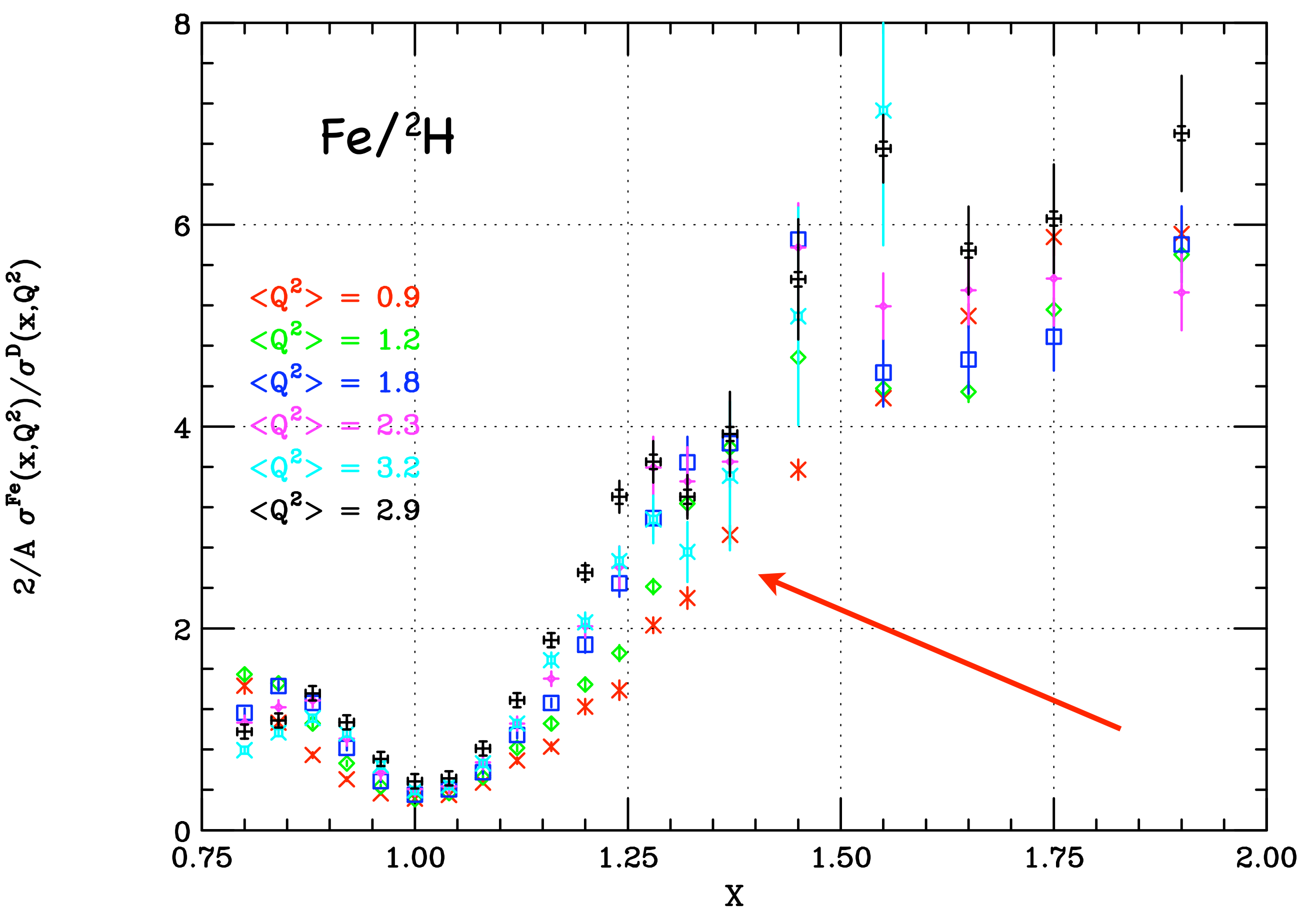
$a_j(A)$ is proportional to probability of finding a j-nucleon correlation

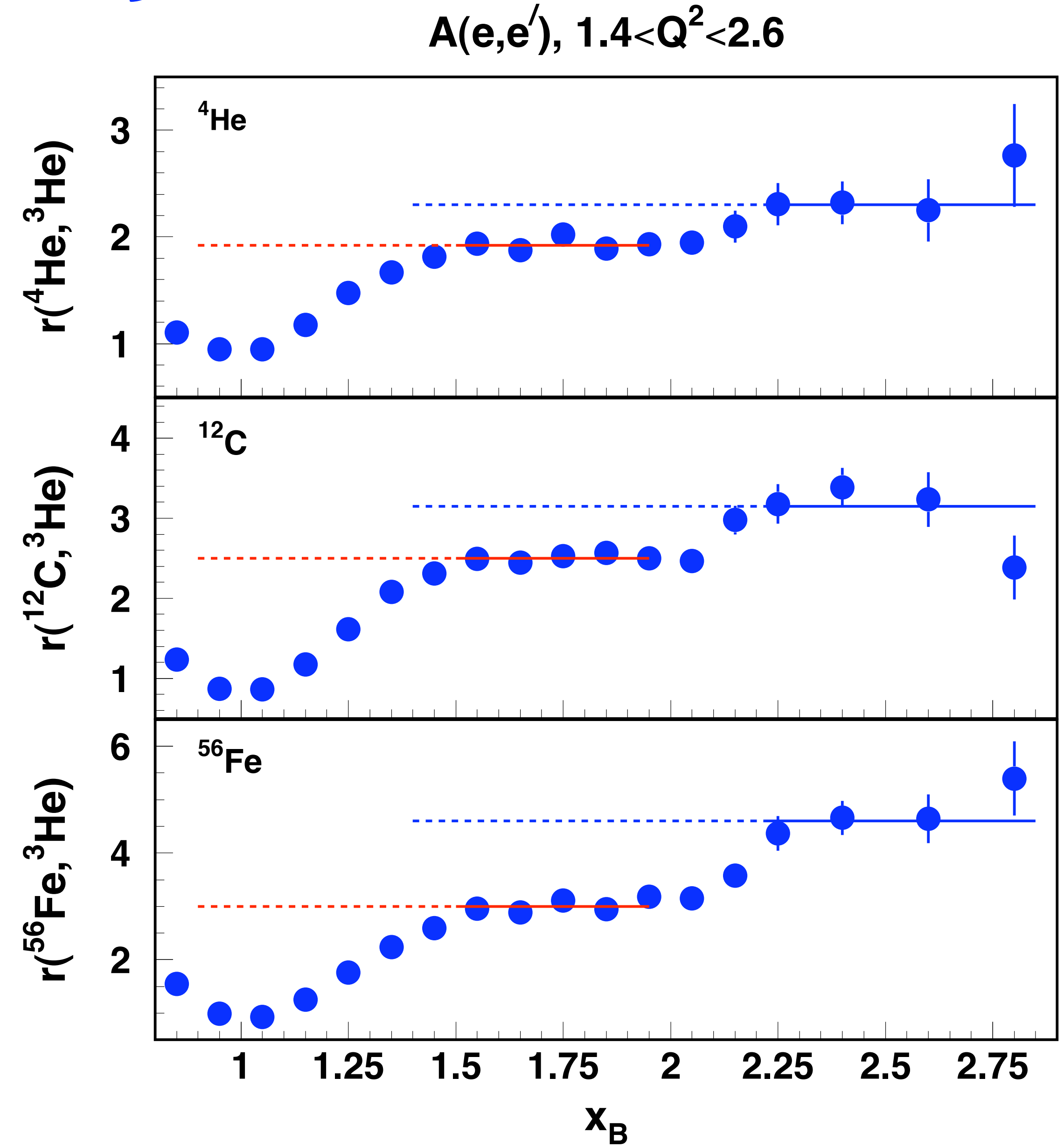
F&S

Ratios, SRC's and Q^2 scaling

$$\frac{2}{A}\frac{\sigma_A}{\sigma_D} = a_2(A);\ (1.4 < x < 2.0)$$







$\alpha_{2N} \approx 20\%$

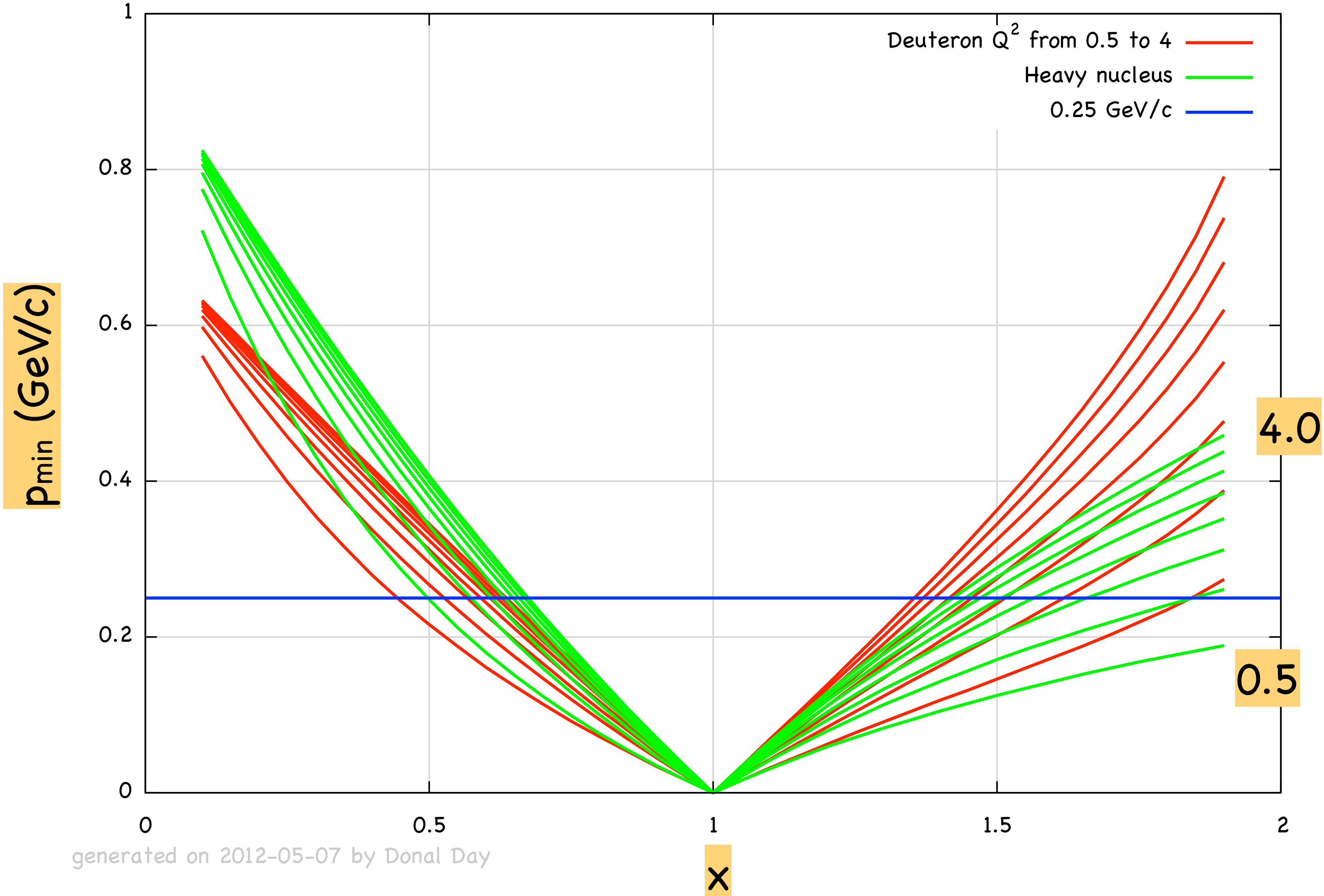
$\alpha_{3N} \approx 1\%$

CLAS data

Egiyan et al., PRL 96, 082501, 2006

$a_j(A)$ is probability of finding a j-nucleon correlation

Selection by kinematics



Appearance of plateaus is A dependent.

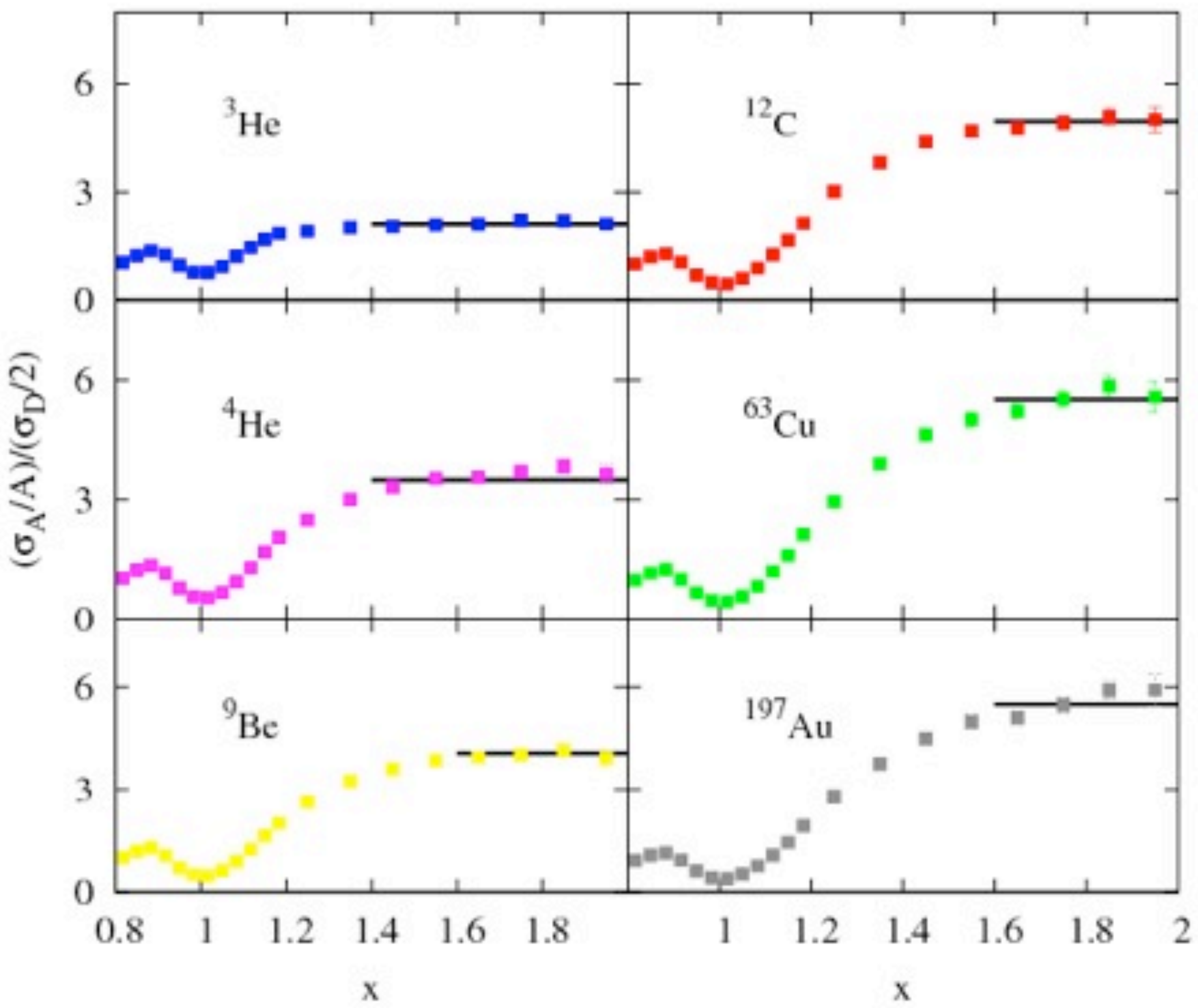
Kinematics: heavier recoil systems do not require as much energy to balance momentum of struck nucleon - hence p_{min} for a given x and Q^2 is smaller.

Dynamics: mean field part in heavy nuclei persist in x to larger values

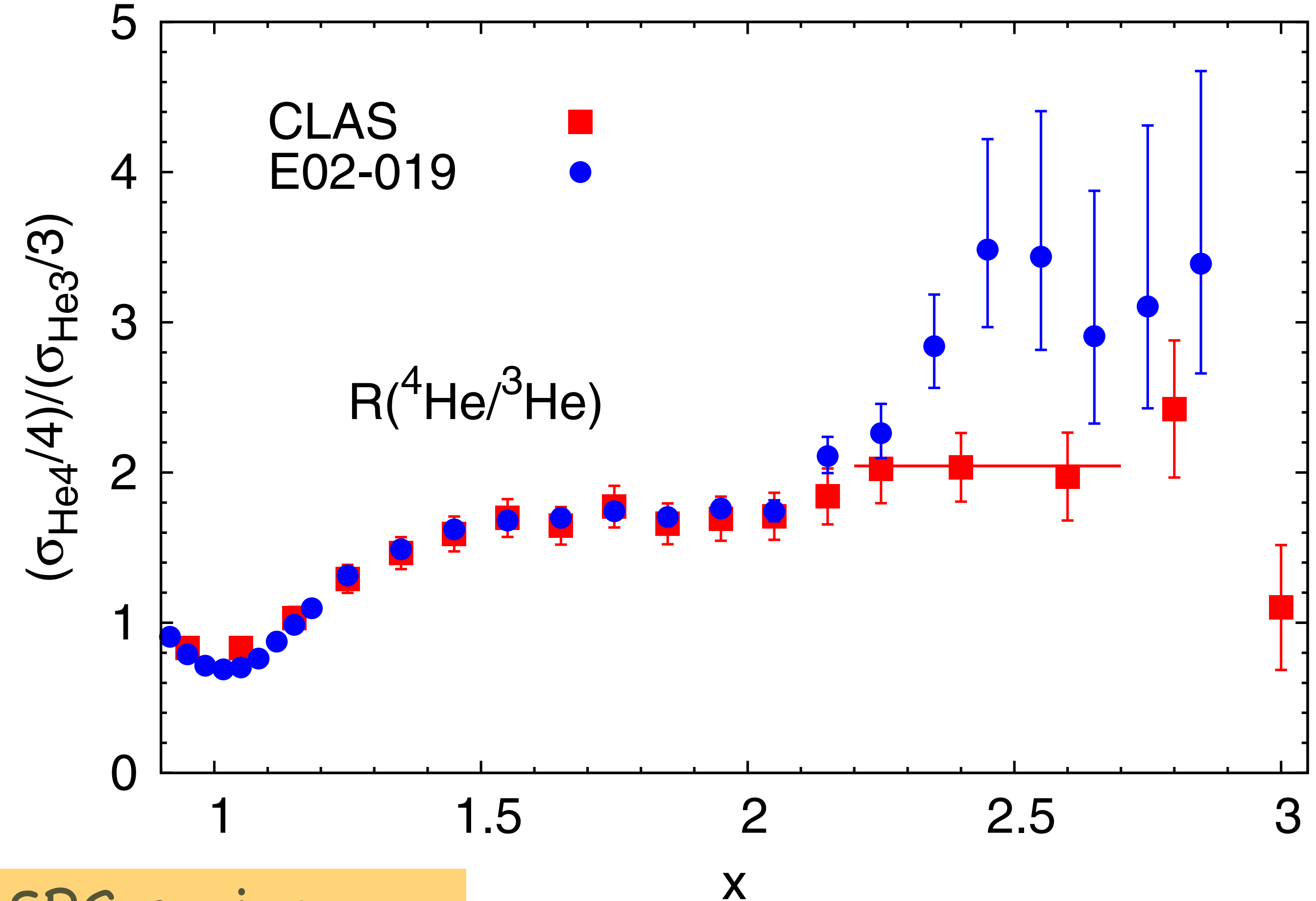
Have to go to higher x or Q^2 to insure scattering is not from mean-field nucleon

SRC evidence at JLAB

N. Fomin et al., Phys. Rev. Lett. 108, 092502 (2012)



A	R_{2N} (E02-019)	SLAC	Ciofi/Simula
^{3}He	1.93 ± 0.10	1.8 ± 0.3	1.9
^{4}He	3.02 ± 0.17	2.8 ± 0.4	3.8
Be	3.37 ± 0.17	...	
C	4.00 ± 0.24	4.2 ± 0.5	4.0
Cu(Fe)	4.33 ± 0.28	(4.3 ± 0.8)	4.5
Au	4.26 ± 0.29	4.0 ± 0.6	4.8 (^{208}Pb)
$\langle Q^2 \rangle$	~2.7 GeV^2	~1.2 GeV^2	
$x_{\min}$	1.5	...	
$\alpha_{\min}$	1.275	1.25	

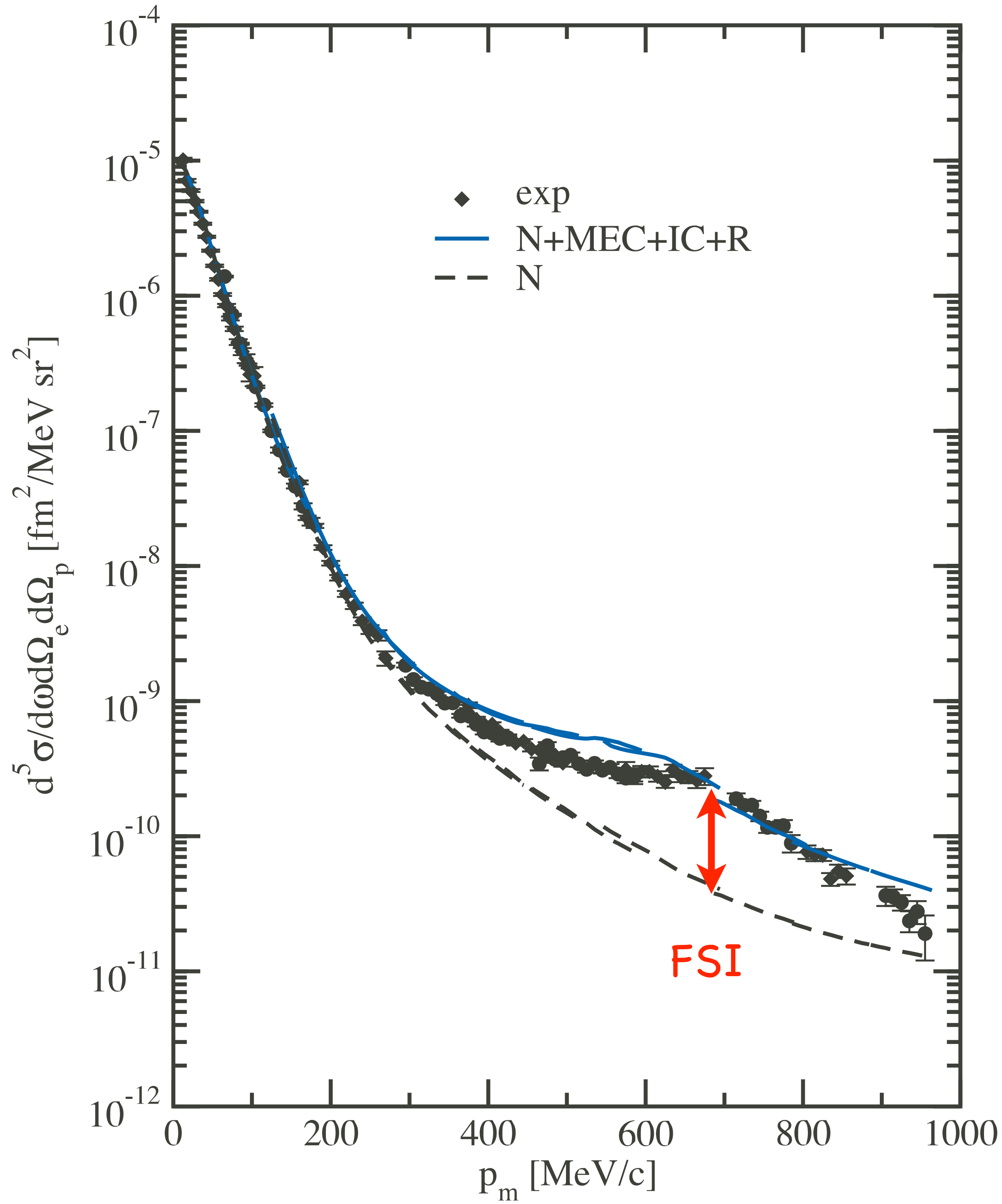


Good agreement in the 2N-SRC region

but potential difference in the 3N-SRC region

Exclusive A(e,e'p)

Deuteron



High momentum(!!) strength in proton knockout in (e,e'p)

^{2}H(ee'p)n Mainz

Boeglin et al, Phys. Rev. C 78, 054001 (2008)

Blomqvist et al, Phys Lett B, (1998), 33-38

E = .855

θ = 45

E' = .657

Q^2 = 0.33

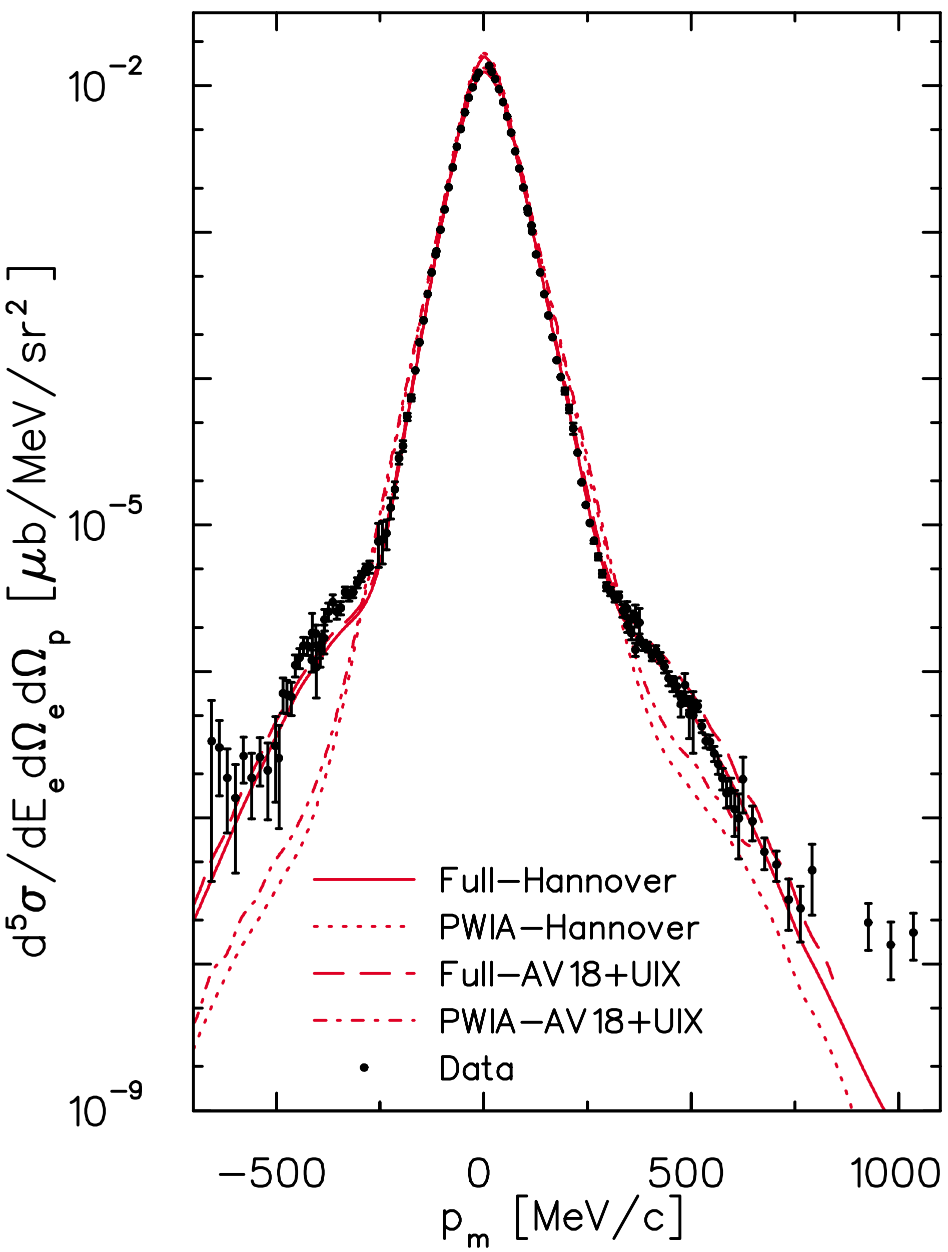
x = .88

Not the best place to look for SRCs - Δs, MECs FSI dominate

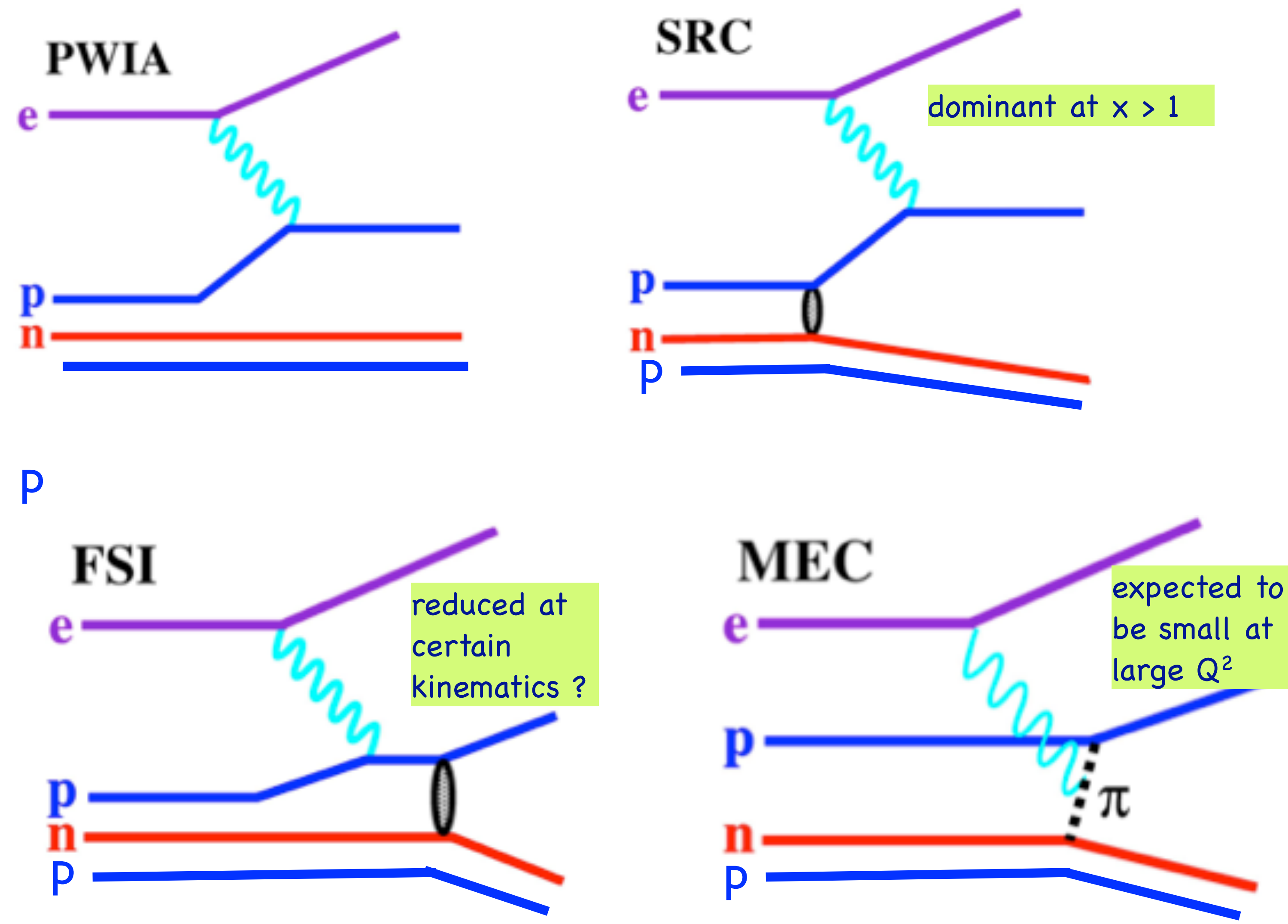
large IC+MEC

Exclusive A(e,e′p)

^{3}He(e,e′p)d E89-044, Hall A



x = 1



Measured far into high momentum tail: Cross section is ~5-10x expectation

High momentum pair can come from SRC (initial state)

OR

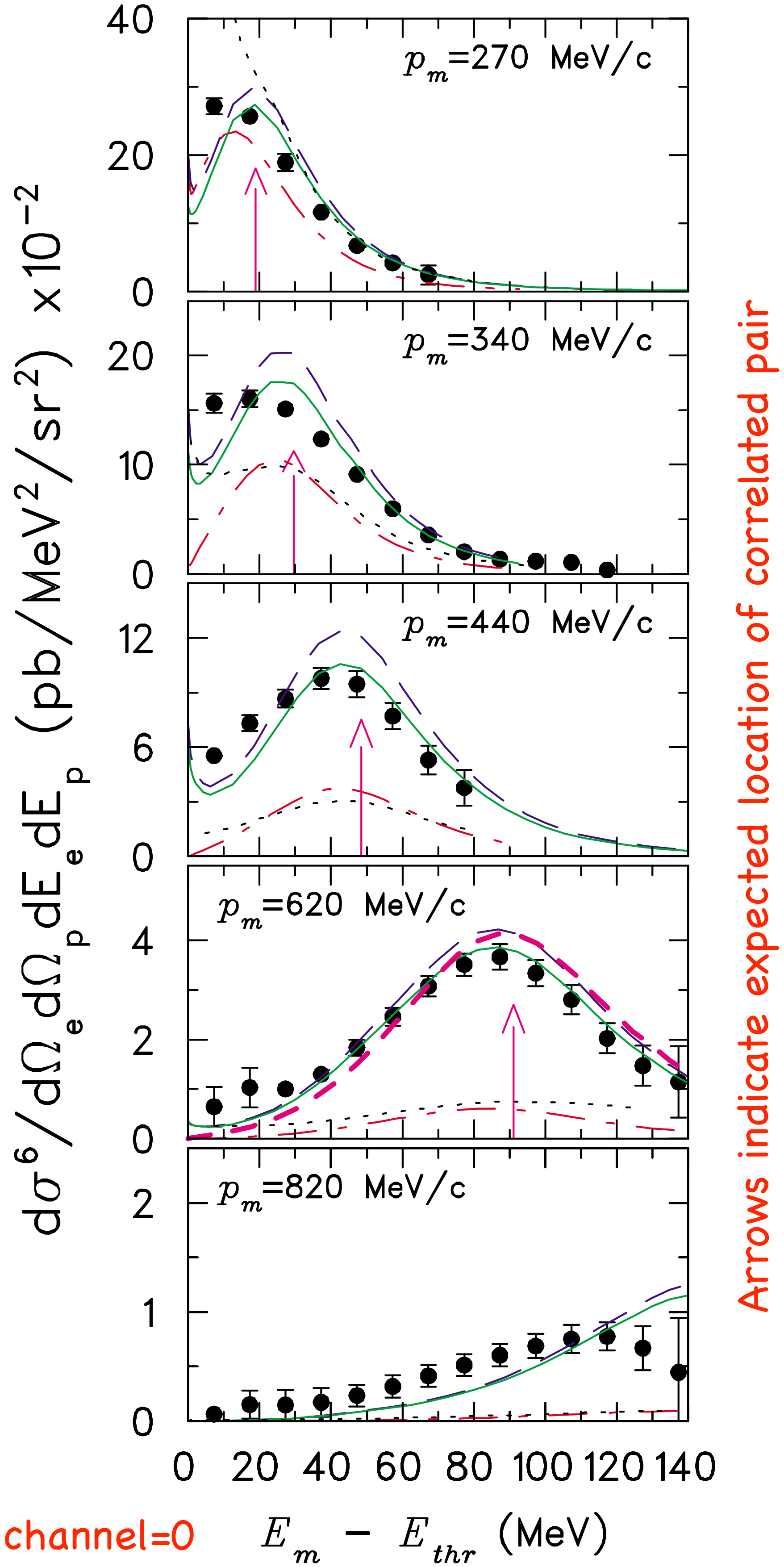
Final State Interactions (FSI) and Meson Exchange Contributions (MEC), Δ's

M. M. Rvachev et al. PRL 94, 192302 (2005)

Exclusive A(e,e'p)

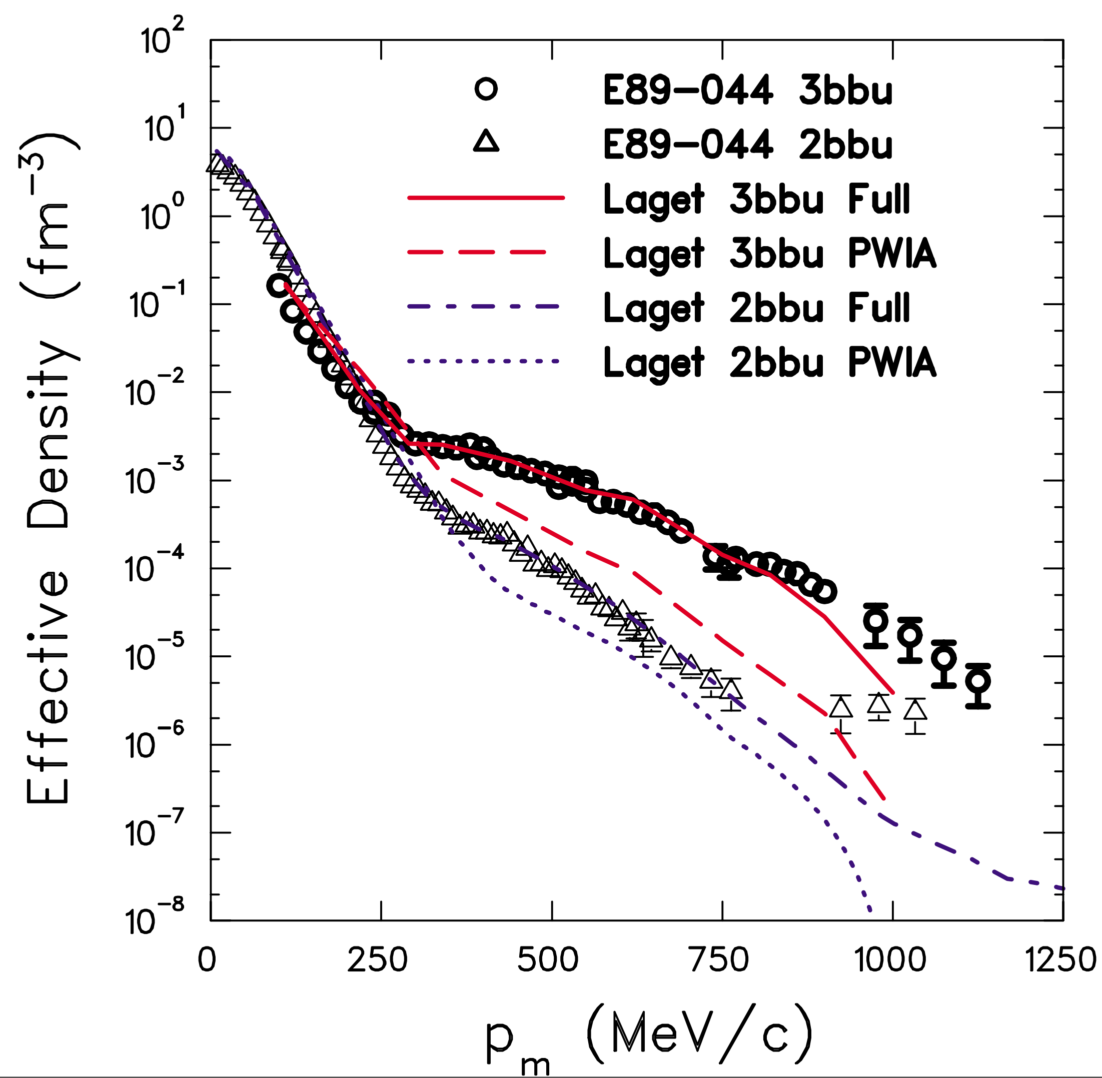
^{3}He(e,e'p)pn E89-044, Hall A

^{3}He(e,e'p)np F. Benmokhtar et al. , PRL 94, 082305 (2005)



3bbu channel=0

- dotted line PWIA
- dash-dot: Laget (PWIA)
- FSI (long dashed line) to full calculation (solid line), including meson-exchange current and final-state interactions: Laget
- In the 620 MeV/c panel
  - short dashed curve is a calculation with PWIA + FSI only within the correlated pair.

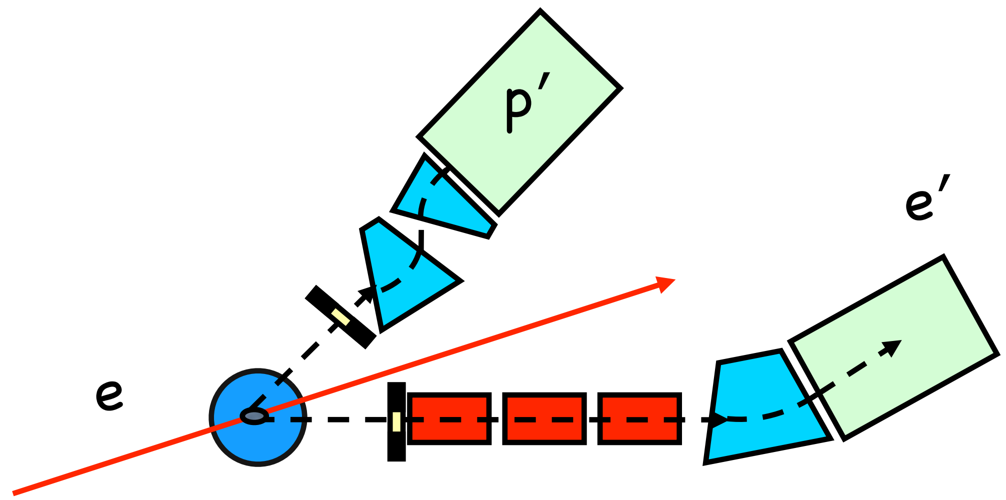


x = 1

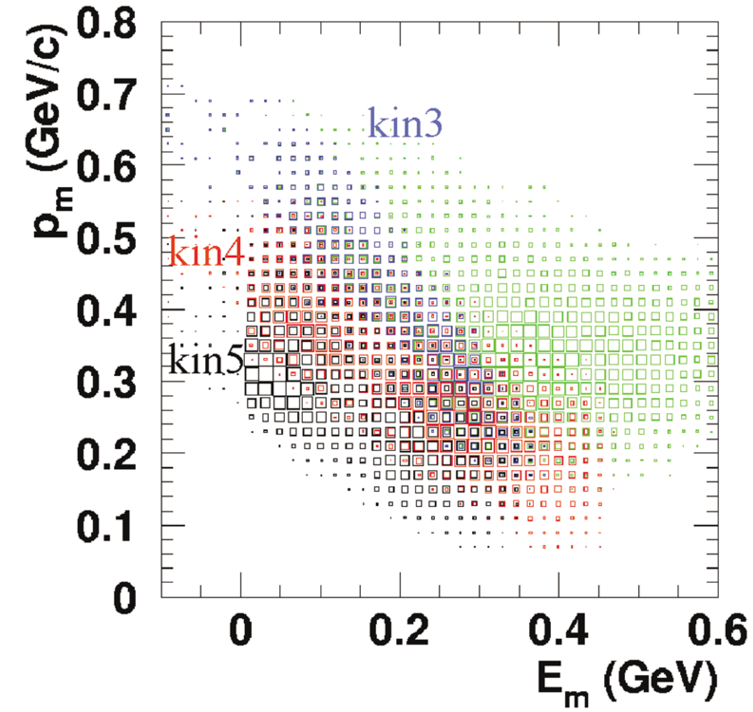
E97-006 Correlated Spectral Function and (e,e'p) Reaction Mechanism

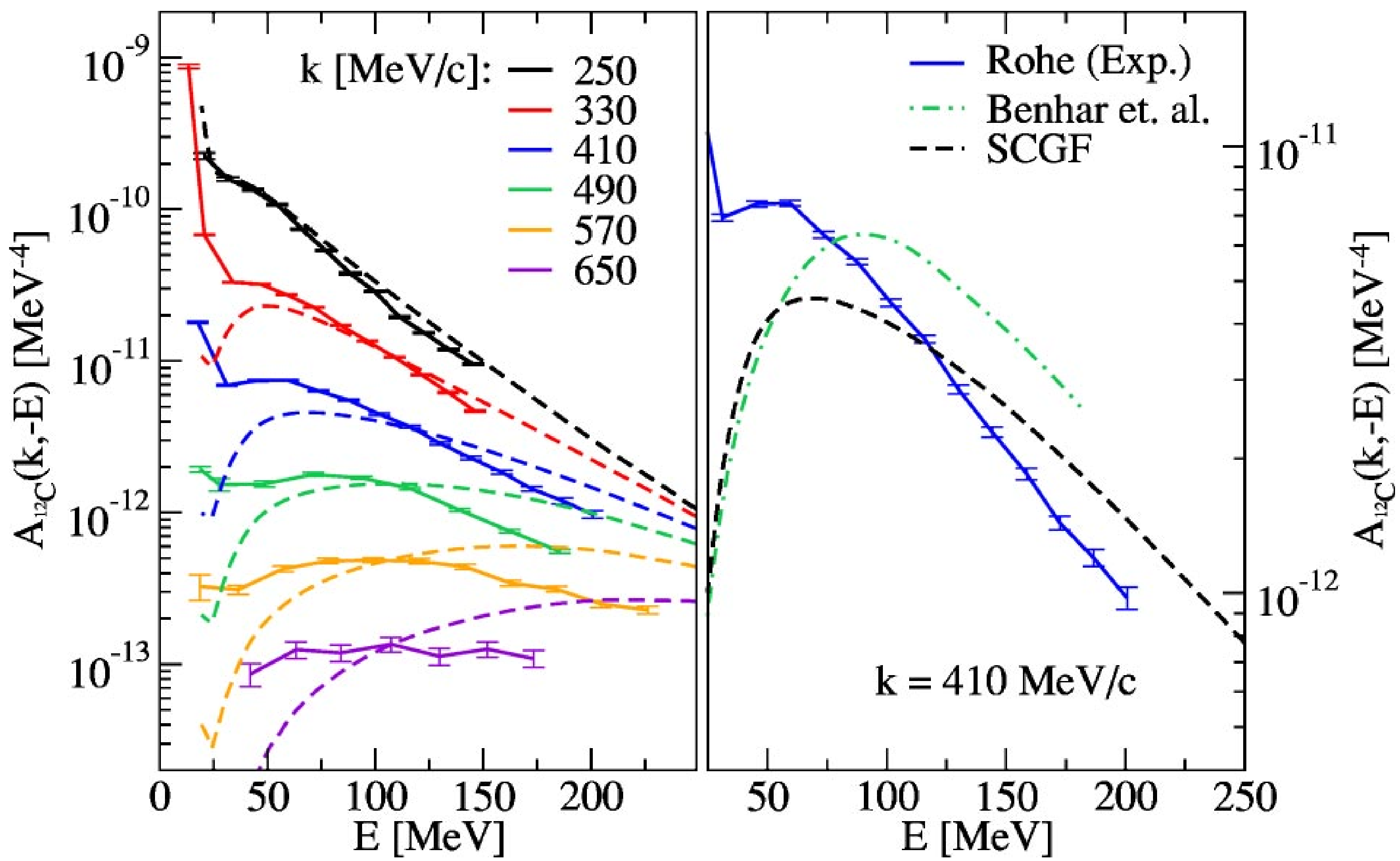
D. Rohe, et al. Phys. Rev Lett. 93 182501

Parallel kinematics selected to minimize FSI



SOS and HMS in Hall C





Data suggests more SRC strength at smaller E than theory

Frick et al. PRC 70, 024309 (2004)

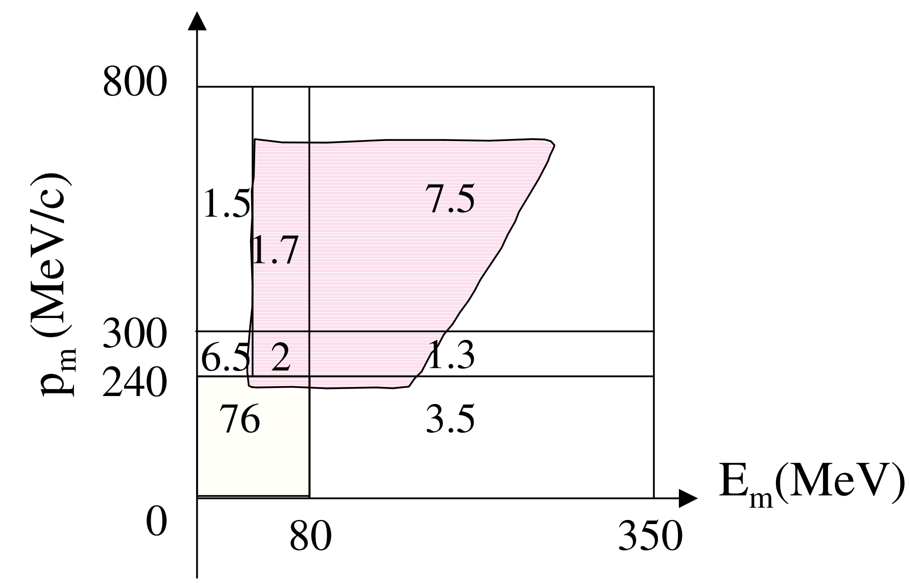
Self consistent Green's Function (SCGF)

Integrated strength in the covered E_m-p_m region:

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

$$Z_c = 4\pi \int_{130}^{670} dp\, p_m^2 \int dE_m S(E_m, p_m)$$

"correlated strength" in the chosen E_m-p_m region:



In terms of # of protons in ^{12}C

^{12}C	exp.	CBF theory	G.F. 2.order	self-consistent G.F.
experimental area	0.61	0.64 ≈ 10 %	0.46	0.61
in total (correlated part)		22 %	12%	≈20%

contribution from FSI: -4 %

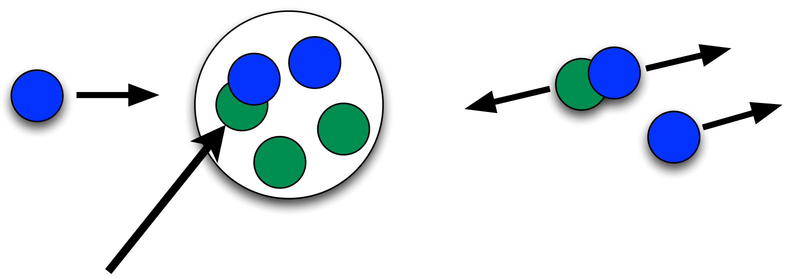
- ≈ 10% of the protons in ^{12}C at high p_m, E_m found
- first time directly measured

comparing to theory leads to conclusion that
≈ 20% of the protons in Carbon are beyond the IPSM region

Triple Coincidence SRC Measurements

n-p Short-Range Correlations from (p,2p + n)

A. Tang, J. W. Watson et al. Phys. Rev. Lett. 90, 042301 (2003)



Correlated pair have equal and opposite momenta

"That neutrons emitted into the backward hemisphere with $p_n > k_F$ come from n-p SRC, since SRC is a natural mechanism to explain such momentum-correlated pairs"

49 ± 13% of events with $|p_f| > k_F$ had directionally correlated neutrons with $|p_n| > k_F$

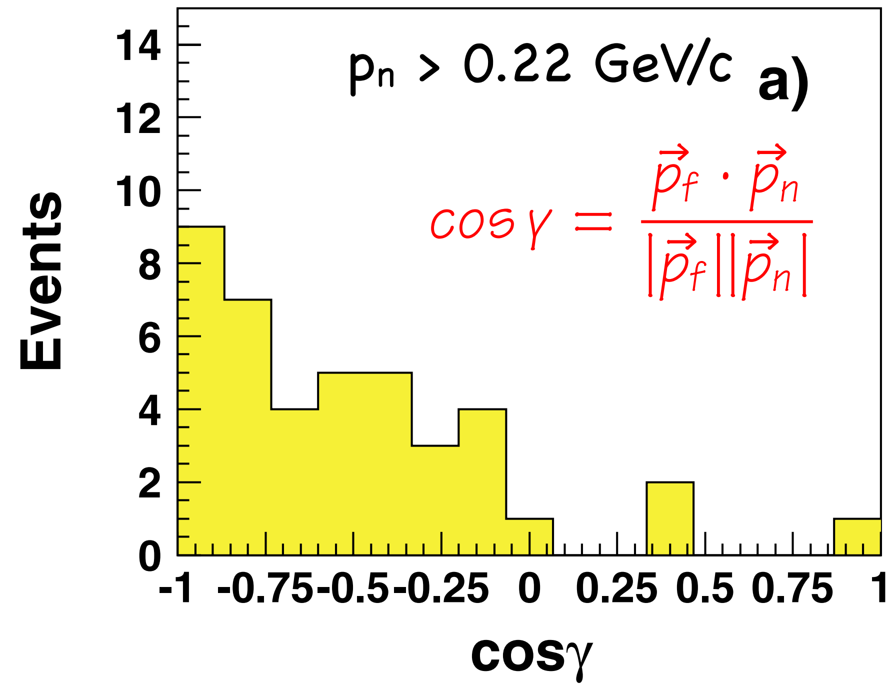
Also measured, for first time, the CM motion of 2N pair

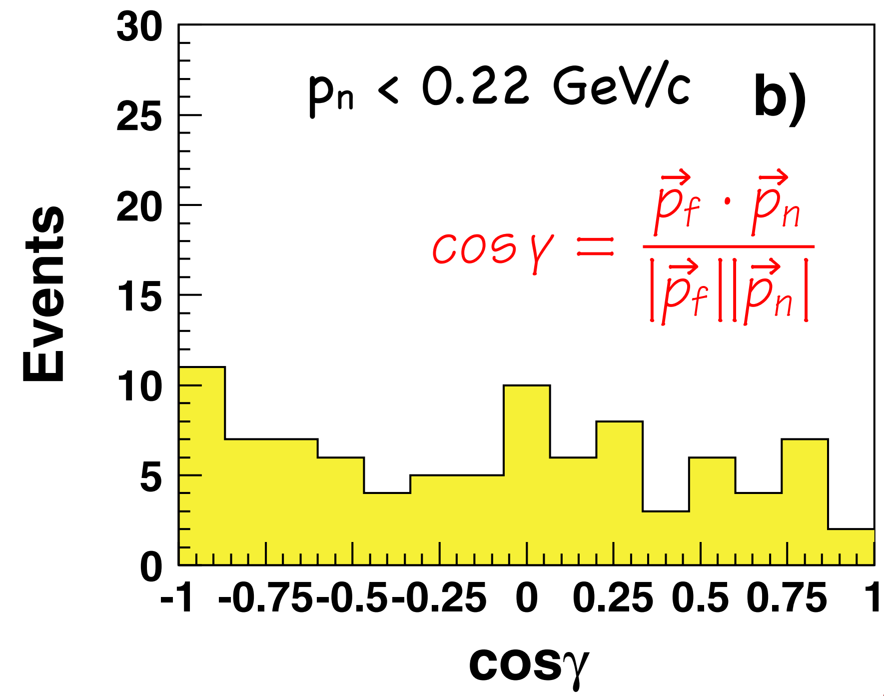
Isospin dependence unstated but SRCs must be the source of high-k

Reconstruct the struck proton before scattering

$$\vec{p}_f = \vec{p}_1 + \vec{p}_2 - \vec{p}_0$$

Detect 2 protons along with emerging neutron





But what of neutron absorption as it moves through the (A-2) system?

Significant possibility that the neutron momentum falls below k_f

Analysis E. Piasetzky, M. Sargsian, L. Frankfurt, M. Strikman, and J. W. Watson, Phys. Rev. Lett. 97, 162504 (2006)

- Modeling of the spectral and decay functions of the reaction in light cone approximation
- Extraction of the quantity $P_{pn/px}$

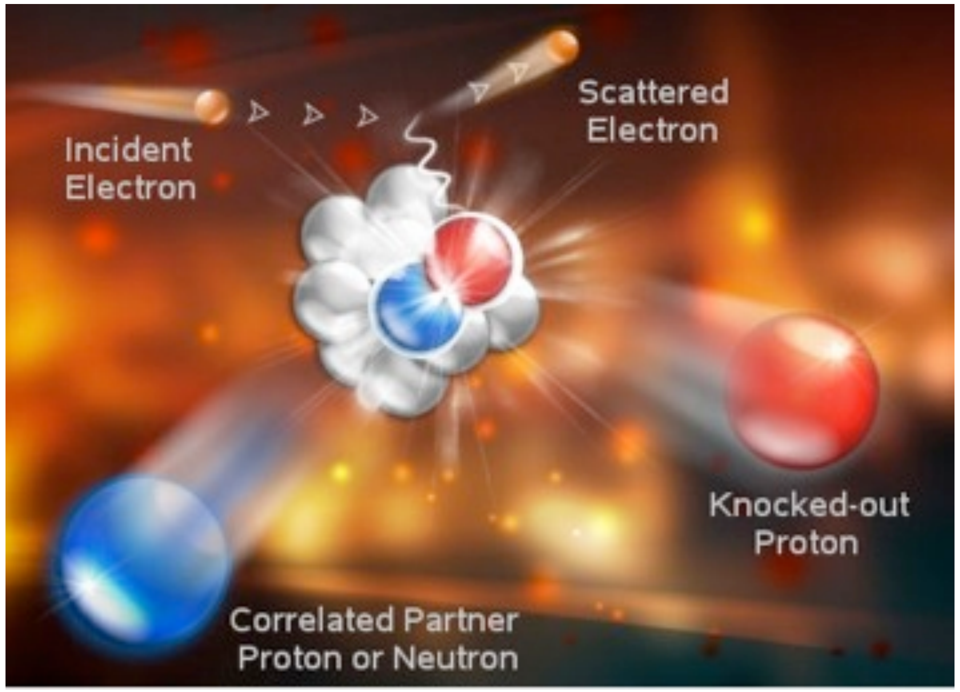
  $P_{pn/px}$: the probability of finding a pn correlation in the "pX" configuration that is defined by the presence of at least one proton with $p > k_{Fermi}$.
- Results: removal of a proton from the nucleus with initial 275<p>550 MeV/c is associated by the emission of a correlated neutron with equal and opposite momentum of the proton 92 (+8/-18)% of the time.

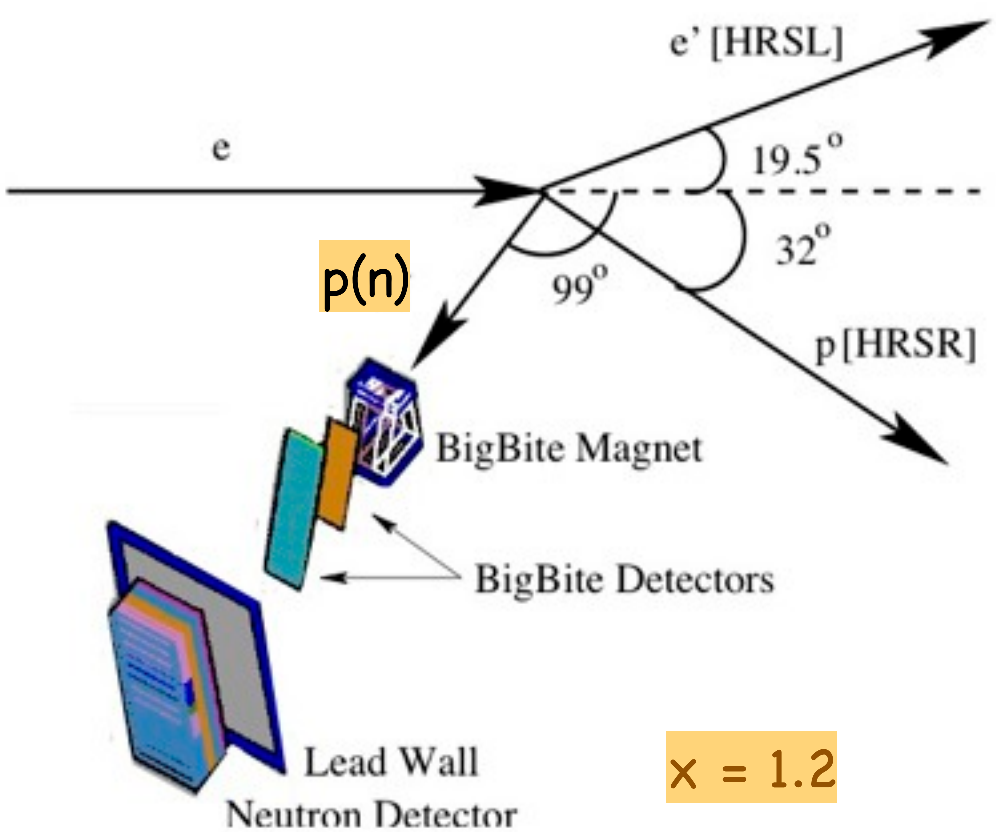
- Proton recoils (eg A(p,pp)n) were not detected but an estimate could be made

  Probabilities of pp or nn SRCs in the nucleus are at least a factor of 6 smaller than that of pn SRCs.

Isospin dependence of SRC

JLAB Experiment E01-015





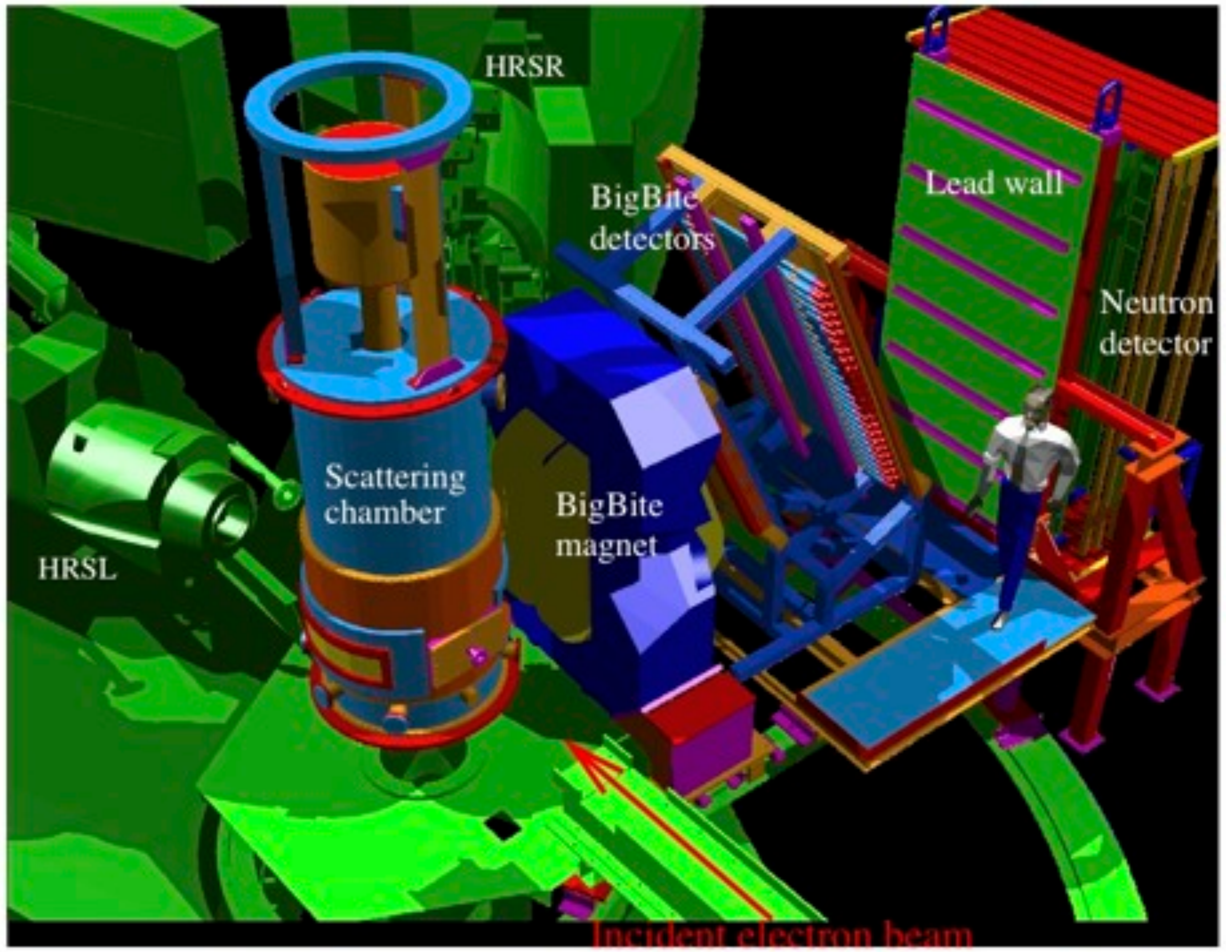
x = 1.2

Simultaneous measurements of the (e,e′p), (e,e′pp), and (e,e′pn) reactions

Use $^{12}C(e,e'p)$ as a tag to measure $^{12}C(e,e'pN)/^{12}C(e,e'p)$

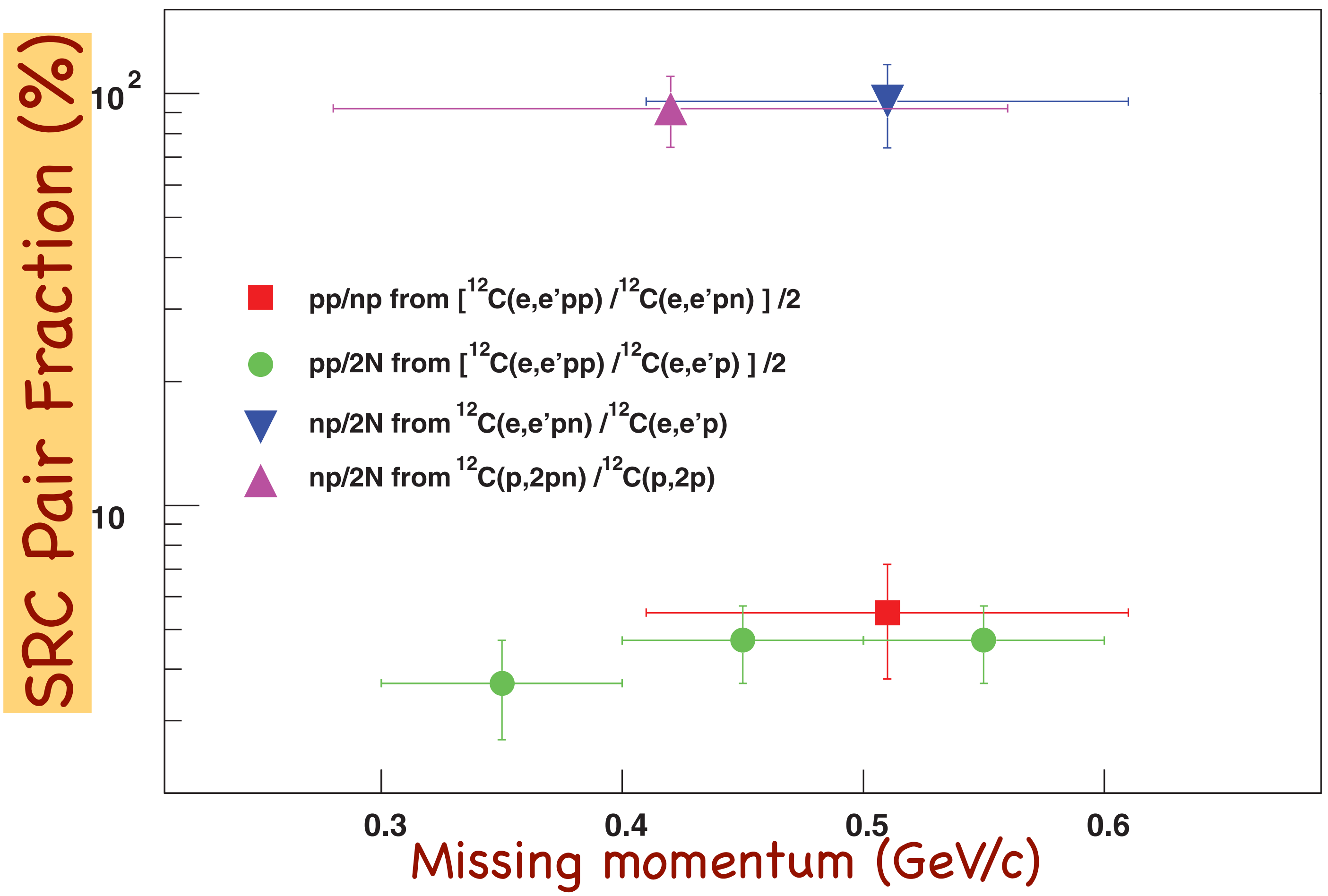
Optimized kinematics:

$Q^2 \approx 2.0$ $x_B \approx 1.2$ "Semi anti-parallel" kinematics

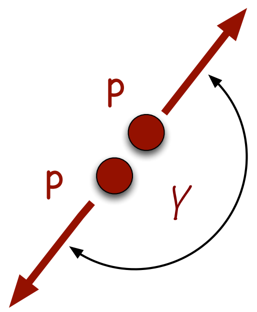


R. Shneor, et al., Phys. Rev. Lett. 99 (2007) 072501.
R. Subedi, et al., Science 320 (2008) 1476-1478.

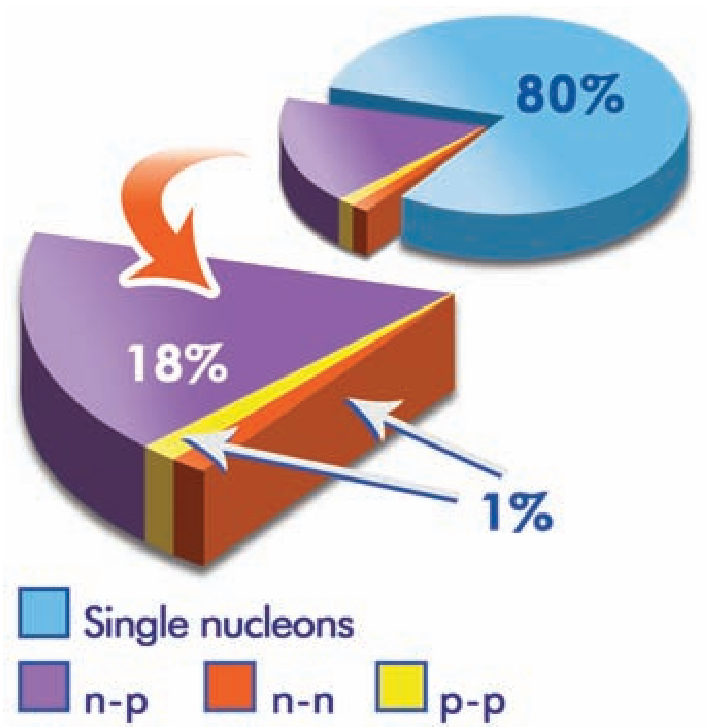
JLAB Experiment E01-015



Findings



- Almost all protons with $p_i > k_F$ in $^{12}C(e,e'p)$ have a paired proton or neutron with similar momentum in opposite direction!
- CM momentum of pair σ_{CM}= 136±20 MeV/c
  - (BNL)=143±17
  - (Ciofi degli Atti&Simula)=139 MeV/c



Data show large asymmetry between np, pp pairs.
Qualitative agreement with calculations; effect of tensor force

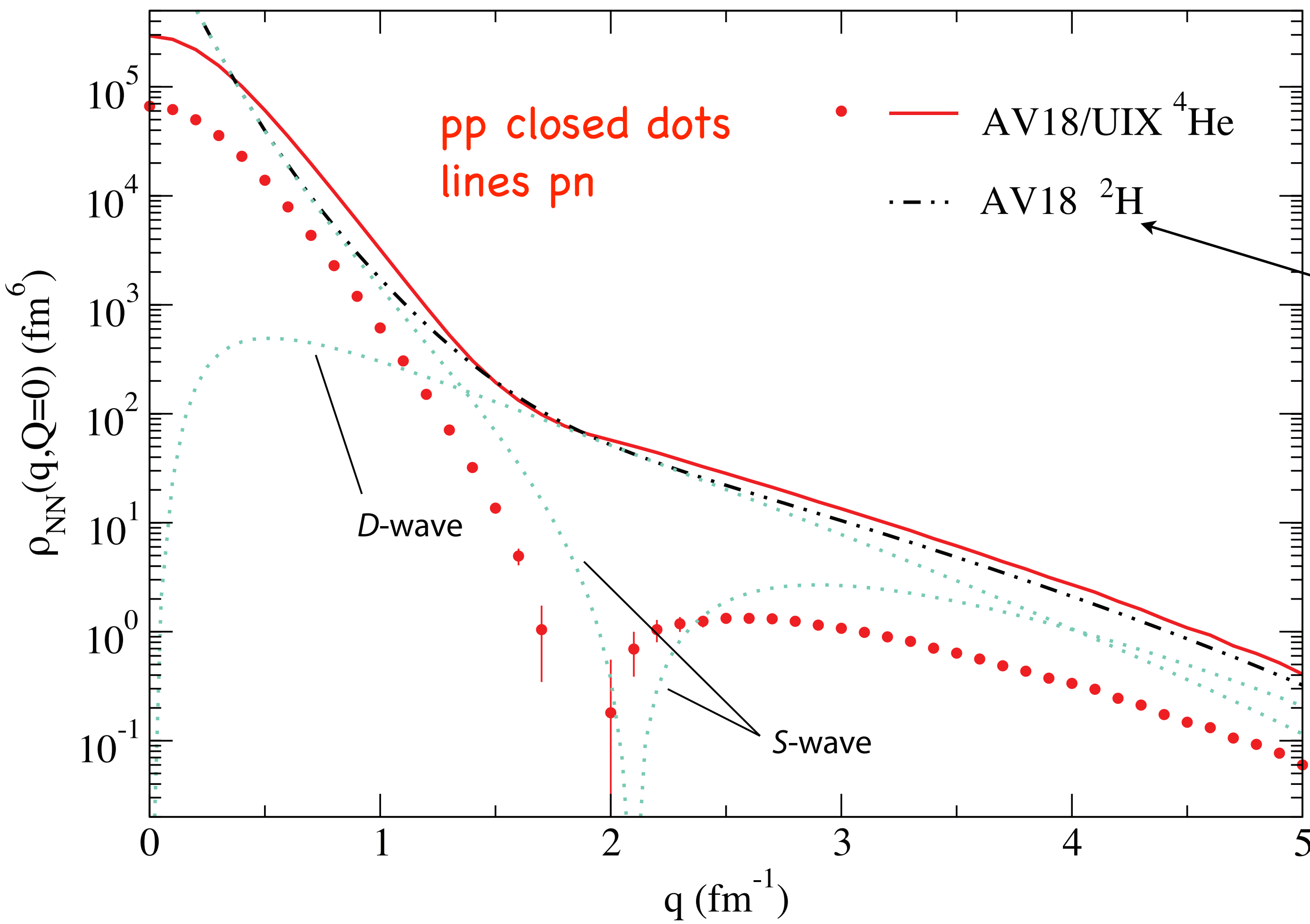
$$\frac{^{12}C(e,e'pp)}{^{12}C(e,e'p)} = 9.5 \pm 2\%$$

$$\frac{^{12}C(e,e'pn)}{^{12}C(e,e'p)} = 96^{+4}_{-23}\%$$

$$\frac{^{12}C(e,e'pn)}{^{12}C(e,e'pp)} = 9.0 \pm 2.5\%$$

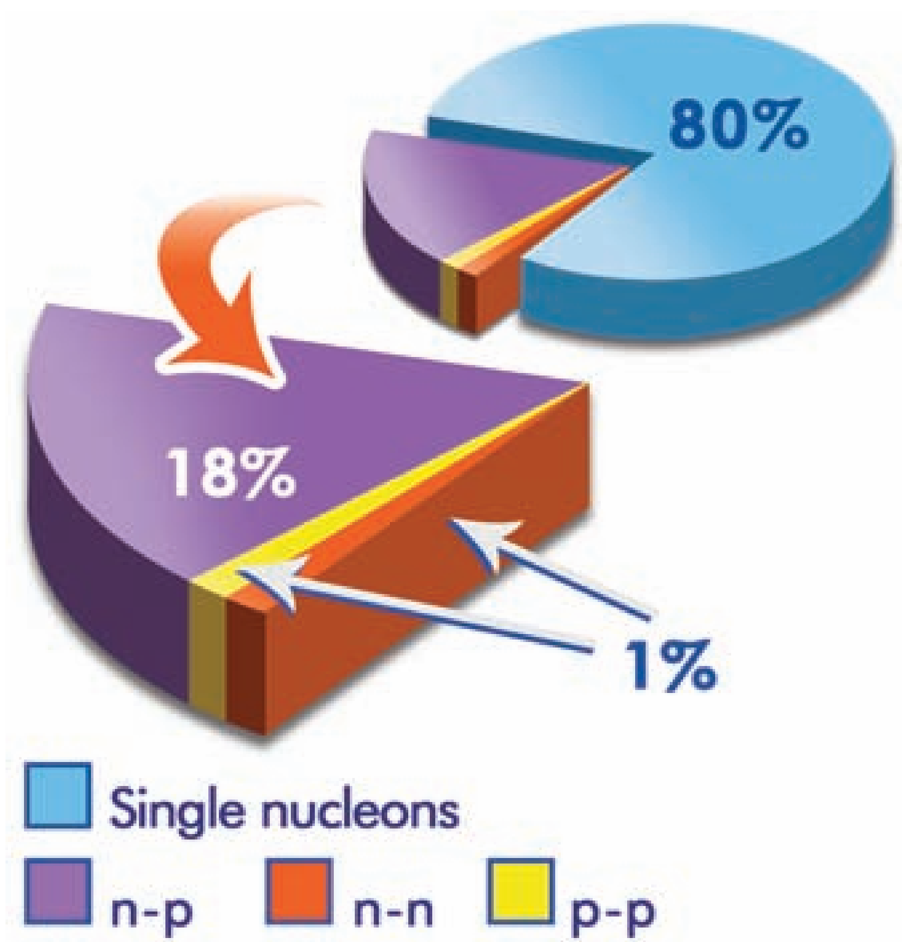
Isospin dependence of SRC

Tensor force responsible for dominant part of SRC and correlations are largely of pn pairs



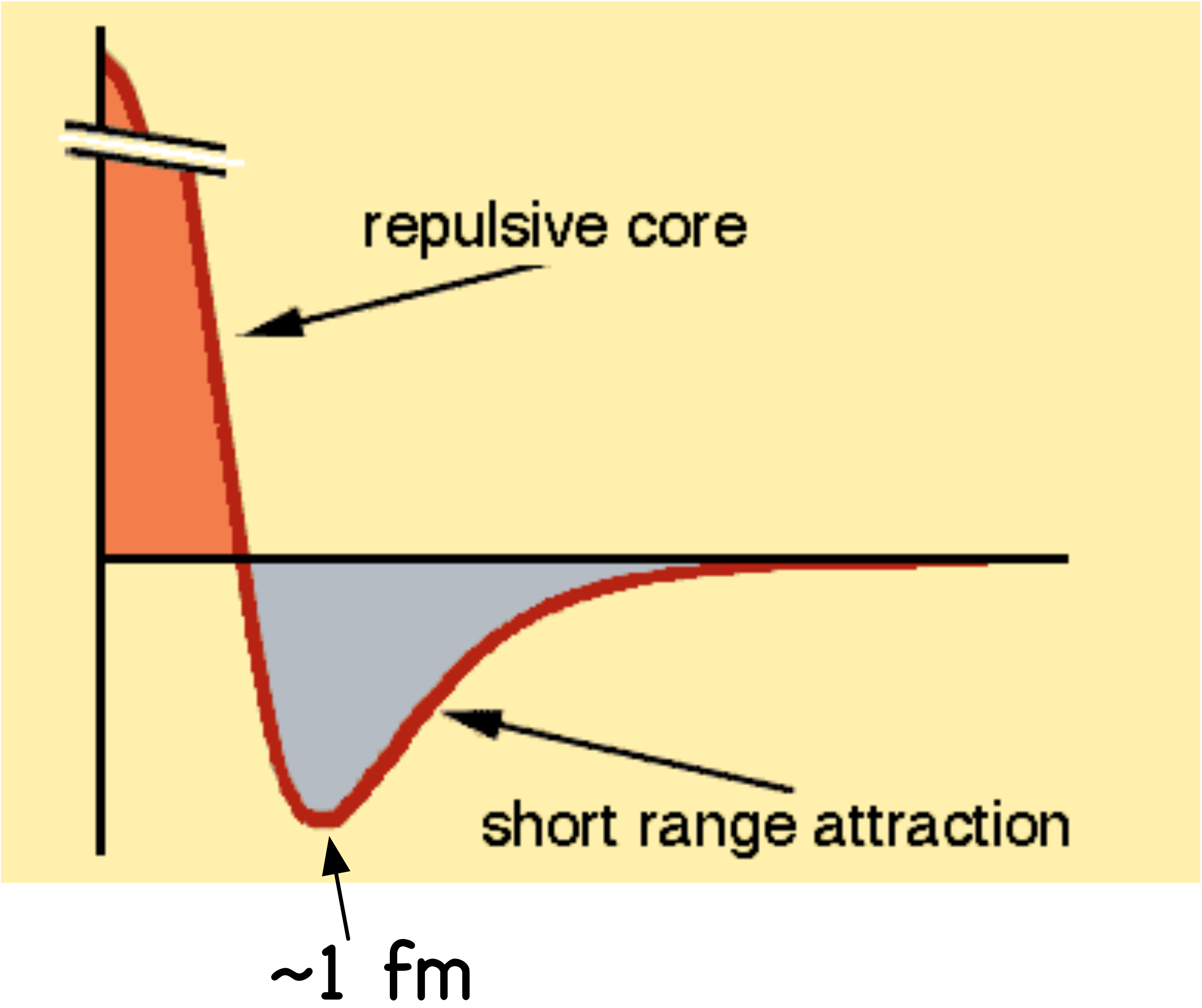
Schiavilla et al. PRL 98, 132501 (2007), VMC and AV18/UIX

Scaled momentum distribution of the deuteron



JLAB A(e,e′NN) data from Hall A
R. Subedi et al.
Science 320, 1476 (2008)

Nucleon-Nucleon Potential



How can two nucleons combine?

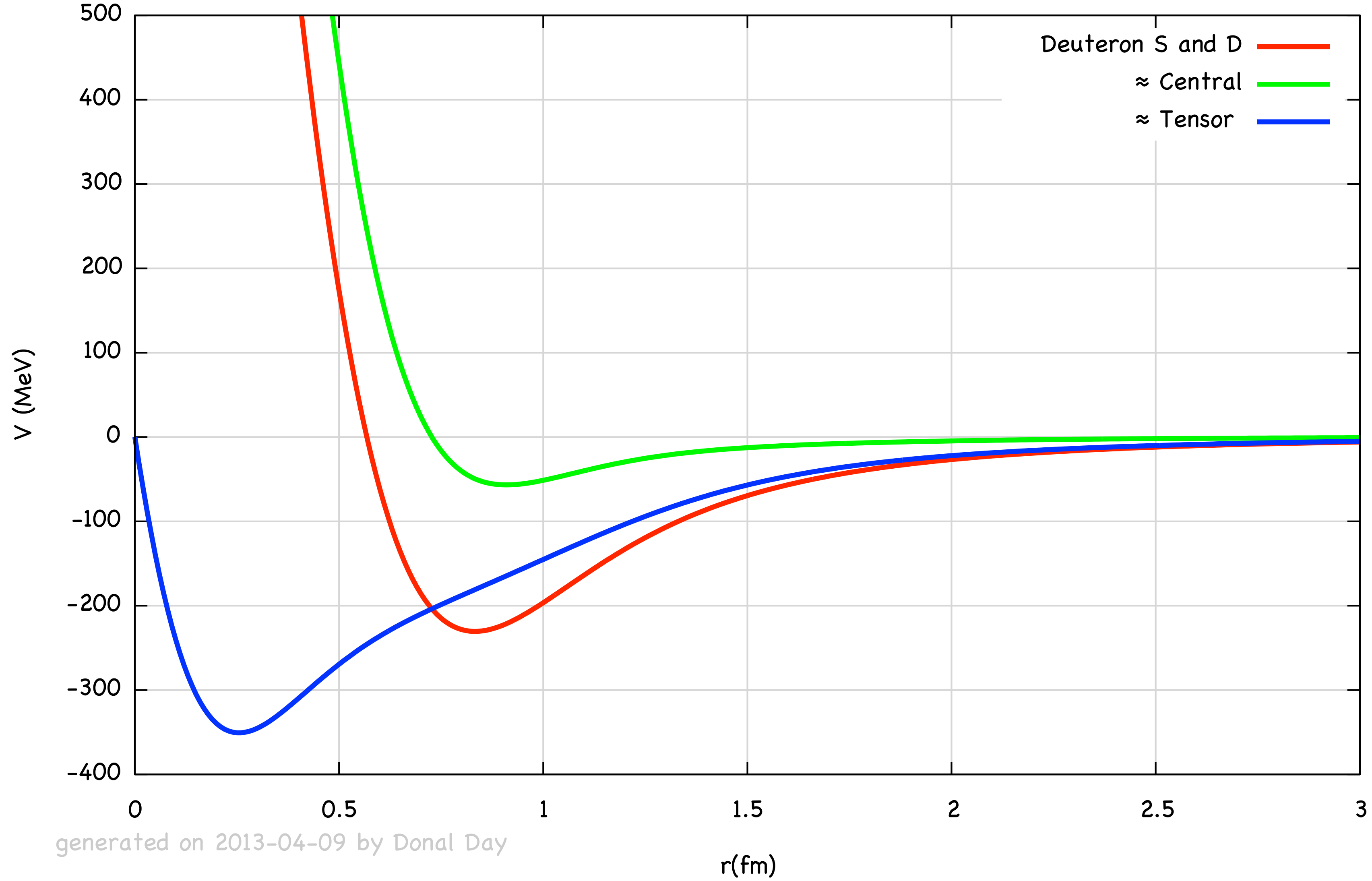
The Pauli principle requires that two-nucleon states be antisymmetric wrt to exchange of the nucleons' space, spin, and isospin coordinates

L	S	J	$\pi = -1^L$	T(L+S+T odd)	$^{2S+1}L_J$
0	0	0	+	1	$^1S_0$
0	1	1	+	0	$^3S_1$
1	0	1	-	0	$^1P_1$
1	1	0	-	1	$^3P_0$
1	1	1	-	1	$^3P_1$
1	1	2	-	1	$^3P_2$
2	0	2	+	1	$^1D_2$
2	1	1	+	0	$^3D_1$
2	1	2	+	0	$^3D_2$
2	1	3	+	0	$^3D_3$

Two-nucleon states

Without the tensor contribution the deuteron would not be bound

And it only contributes to T=0 2N states



Possible Two Nucleon states

L	S	J	$\pi = -1^L$	T(L+S+T odd)	$^{2S+1}L_J$
0	0	0	+	1	$^1S_0$
0	1	1	+	0	$^3S_1$
1	0	1	-	0	$^1P_1$
1	1	0	-	1	$^3P_0$
1	1	1	-	1	$^3P_1$
1	1	2	-	1	$^3P_2$
2	0	2	+	1	$^1D_2$
2	1	1	+	0	$^3D_1$
2	1	2	+	0	$^3D_2$
2	1	3	+	0	$^3D_3$

Two-nucleon states

Symmetric triplet $T = 1$

$^3(T)_1 = |p_1\rangle\,|p_2\rangle$ proton-proton state

$^3(T)_{-1} = |n_1\rangle\,|n_2\rangle$ neutron-neutron state

$^3(T)_0 = \frac{1}{\sqrt{2}}(|p_1\rangle\,|n_2\rangle + |p_2\rangle\,|n_1\rangle)$ neutron-proton state

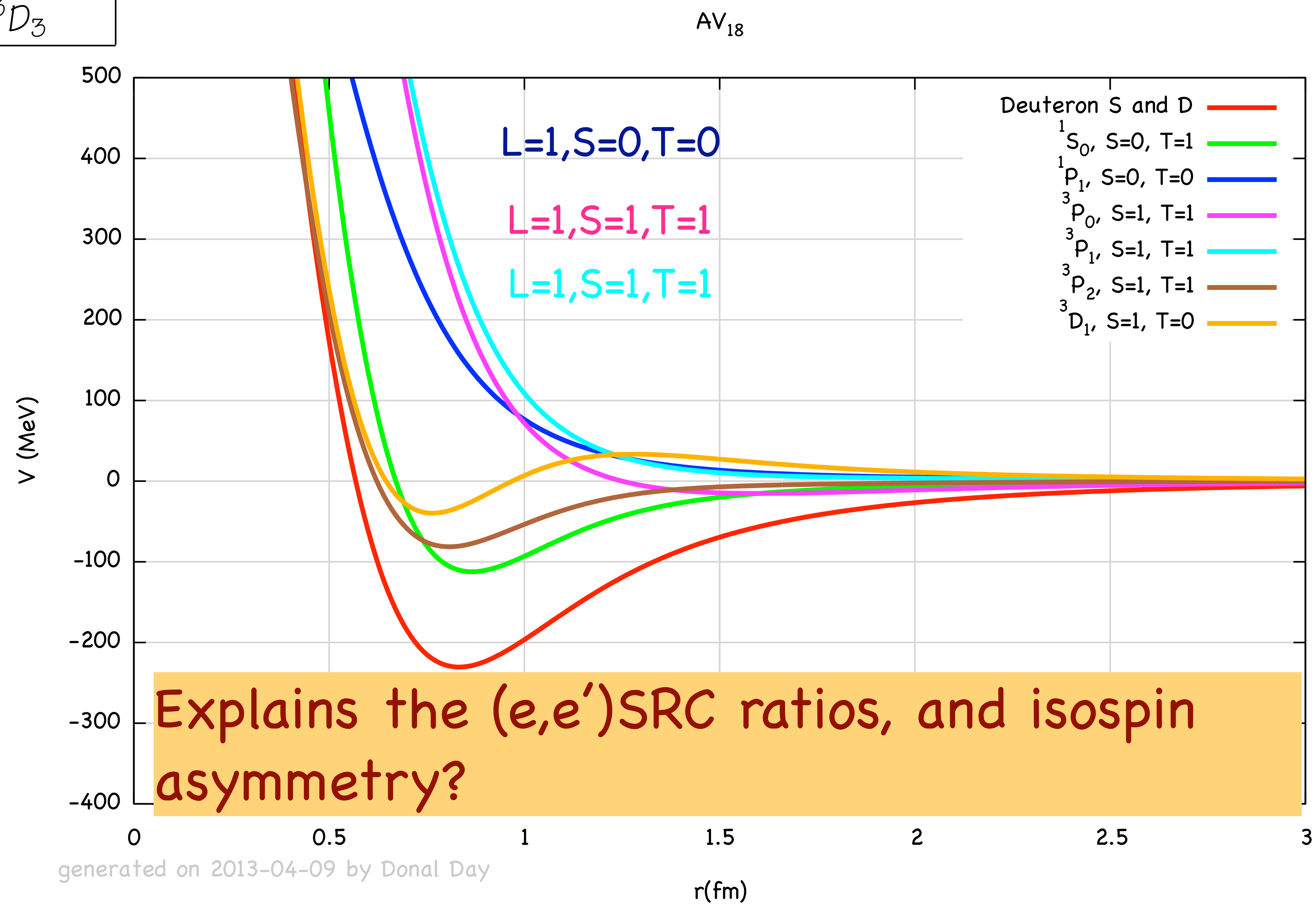
Antisymmetric singlet $T = 0$

$^1(T)_0 = \frac{1}{\sqrt{2}}(|p_1\rangle\,|n_2\rangle - |p_2\rangle\,|n_1\rangle)$ neutron-proton state

The SR NN attraction dominated by tensor interaction, which yields high-momentum isosinglet (np) pairs.

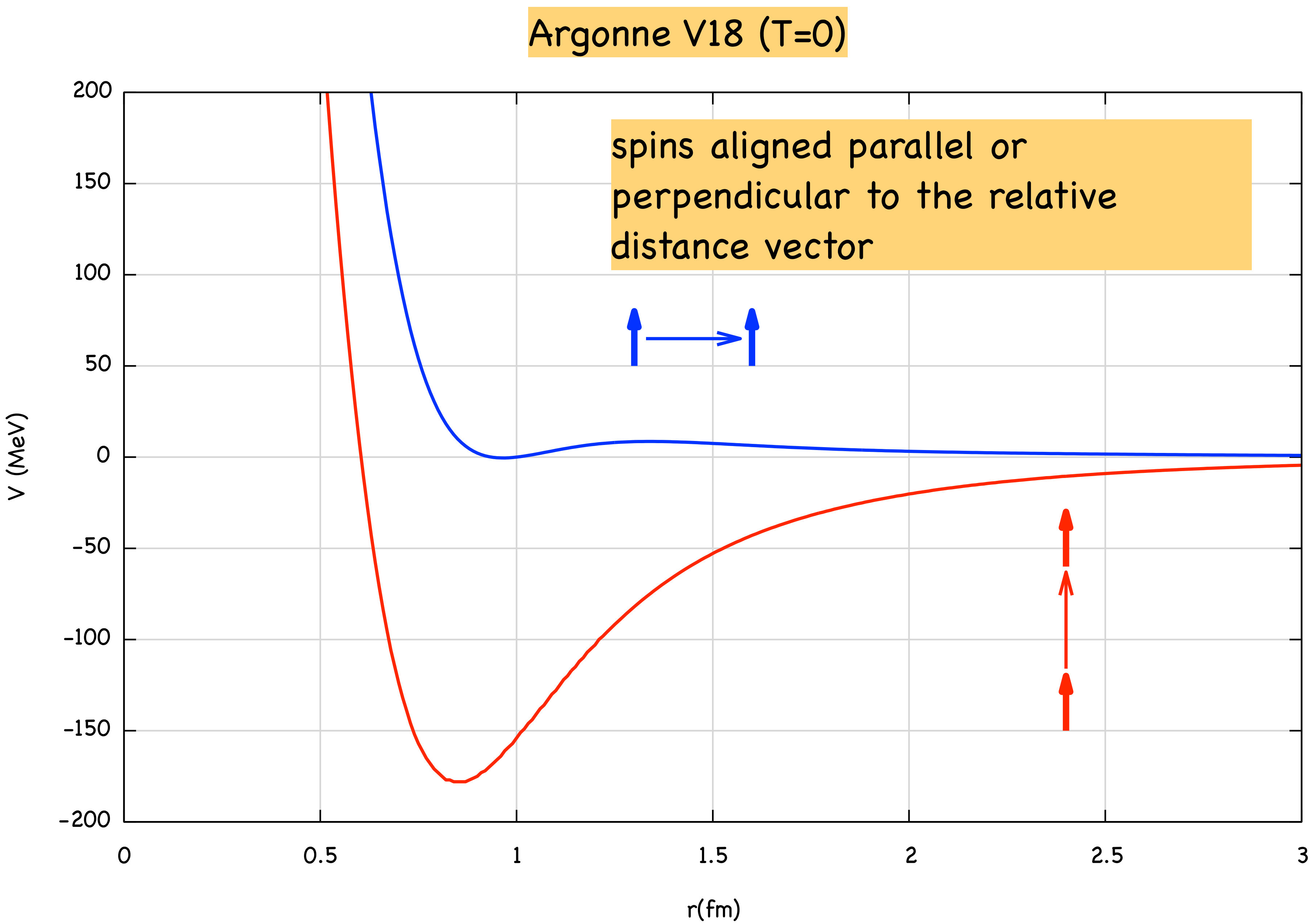
Absent in the isotriplet channel (pp, nn, np).

2-body distribution in nucleus should be identical to the deuteron and ratio of scattering cross sections between a heavy nucleus A and the deuteron to yield a_2 (A, Z)



Explains the (e,e')SRC ratios, and isospin asymmetry?

Nuclear Force



strong repulsive core: nucleons can not get closer than ≈ 0.5 fm

➽ central correlations

- strong dependence on the orientation of the spins due to the tensor force

➽ tensor correlations

the nuclear force will induce strong short-range correlations in the nuclear wave function

Coming up

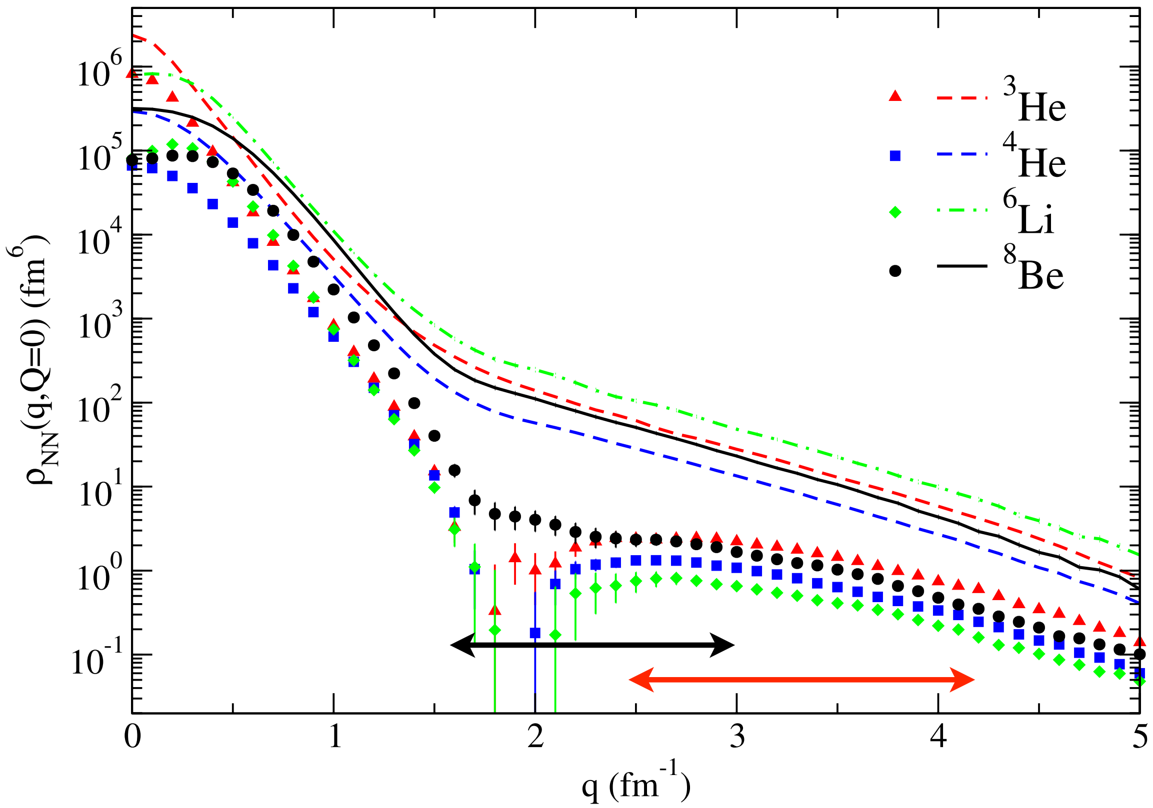
6 GeV (completed in Spring 2011)

[Hall A]

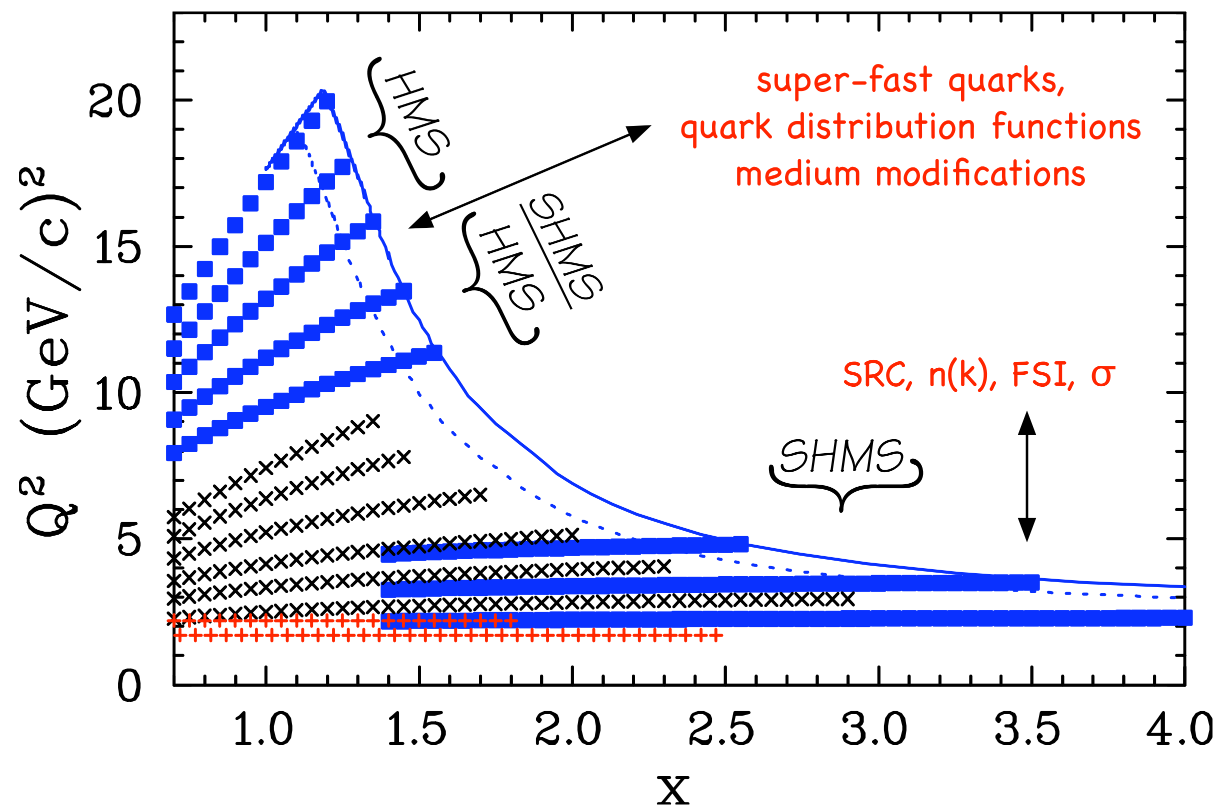
- E-08-014: Three-nucleon short range correlations studies in inclusive scattering for 0.8 < 2.8 $(GeV/c)^2$

^{2}H, ^{3}He, ^{4}He, ^{12}C, ^{40}Ca, ^{48}Ca, isospin dependence

- E07-006: Exclusive X-sctions $^{4}He(e,e'p)$, $^{4}He(e,e'pp)$, $^{4}He(e,e'pn)$, $^{4}He(e,e'p_{recoil})$
  - Does pp/pn ratio change?! Are there signs of repulsive core? Can the reactions be calculated?



- E12-06-105: Inclusive Scattering from Nuclei at x > 1 in the quasielastic and deeply inelastic regimes [Hall C], ^{1}H, ^{2}H, ^{3}He, ^{4}He, $^{6,7}Li$, ^{9}Be, $^{10,11}B$, ^{12}C, ^{40}Ca, ^{48}Ca, Cu, Au



Arrington, DD, Fomin, Solvignon

E12-11-112 Precision measurement of the isospin dependence in the 2N and 3N short range correlation region [Hall A], ^{3}H, ^{3}He 2015?

Physics goals

Isospin-dependence

- ✓ Improved precision: extract R(T=1/T=0) to 3.8%
- ✓ FSI much smaller (inclusive) and expected to cancel in ratio

Improved A-dependence in light and heavy nuclei

- ✓ Average of ^{3}H, ^{3}He --> A=3 “isoscalar” nucleus
- ✓Determine isospin dependence --> improved correction for N>Z nuclei, extrapolation to nuclear matter

Absolute cross sections (and ratios) for ^{2}H, ^{3}H, ^{3}He

test calculations of FSI for simple, well-understood nuclei

P. Solvignon, J.Arrington, DD, D. Higinbotham

Isospin study from 3He/3H ratio

E12-11-112

Simple mean field estimates for 2N-SRC

Isospin independent

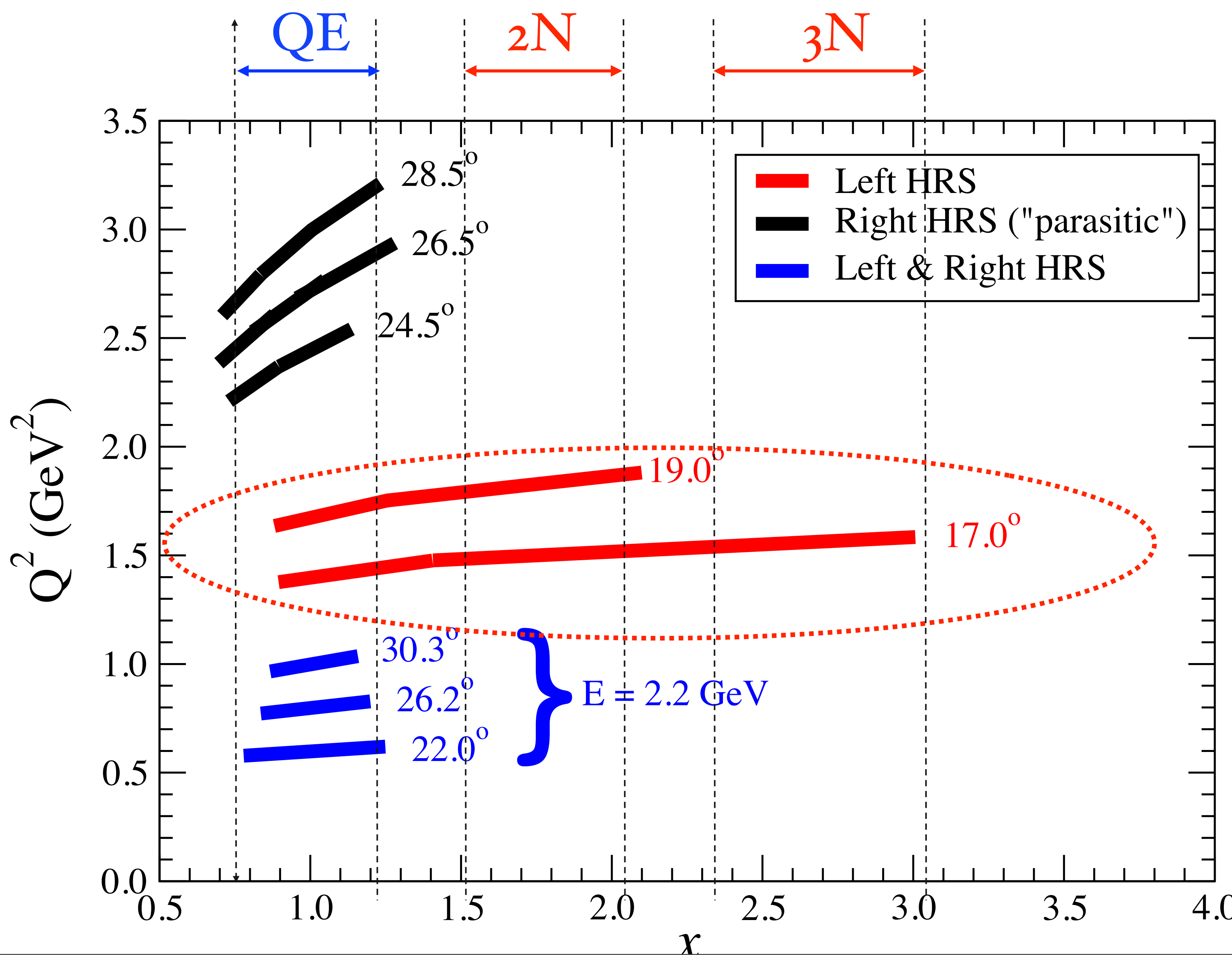
$$\frac{\sigma_{3_{He}}/3}{\sigma_{3_H}/3} = \frac{(2\sigma_p+1\sigma_n)/3}{(1\sigma_p+2\sigma_n)/3}$$

$$\text{with } \sigma_p = 3\sigma_n) \longrightarrow 1.4$$

n-p (T=0) dominance

$$\frac{\sigma_{3_{He}}/3}{\sigma_{3_H}/3} = \frac{(2pn+\cancel{1nn})/3}{(2pn+\cancel{1pp})/3} = 1.0$$

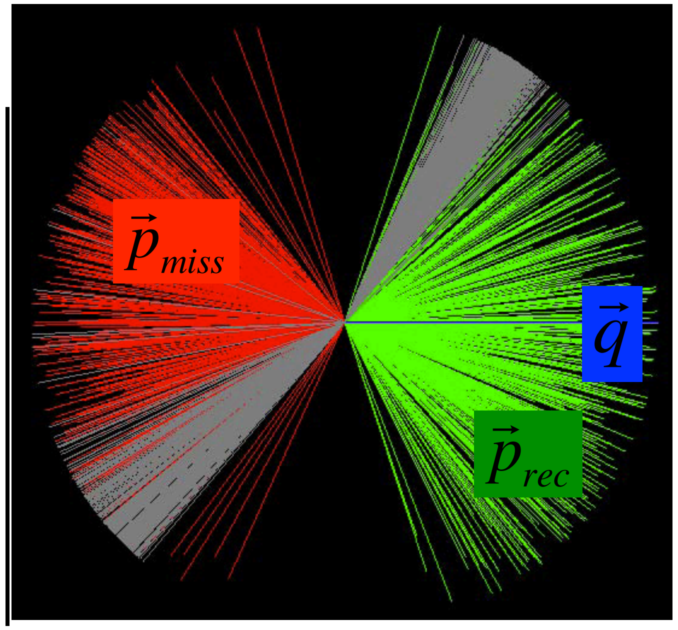
Left HRS running
(380 hours)



Data Mining from CLAS E2

Analysis Goals

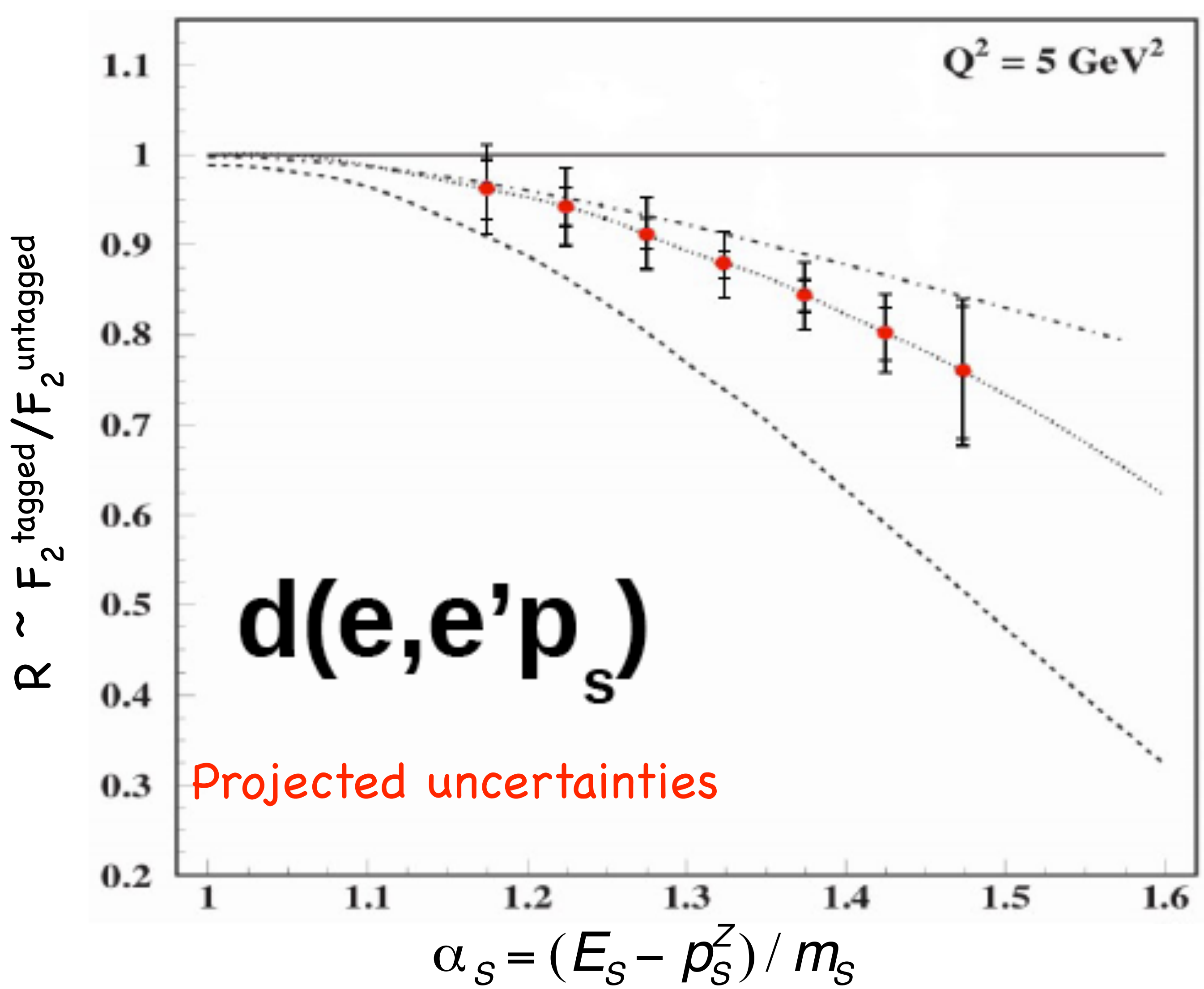
1. pp-SRC universality in large A nuclei
   1. Existence
   2. Characteristics (cm and rel. momentum distributions)
   3. Probabilities
2. Extend $|P_{miss}|$ coverage - transition to scalar force
3. Nuclear transparency - FSI in SRC kinematics
   a. O, Hen et al. Measurement of transparency ratios for protons from short-range correlated pairs, arXiv:1212.5343
4. and more….

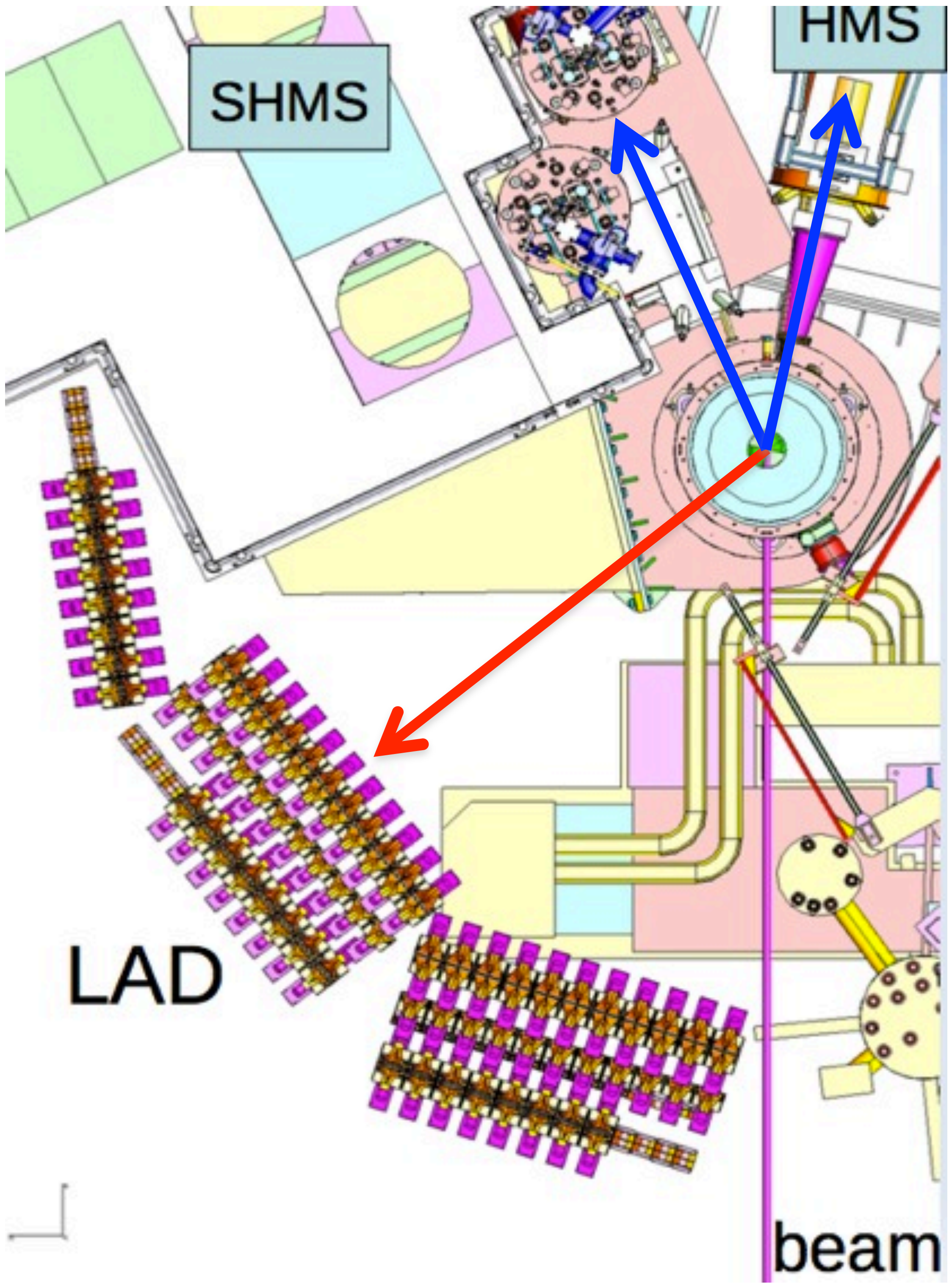


In-Medium Nucleon Structure Functions

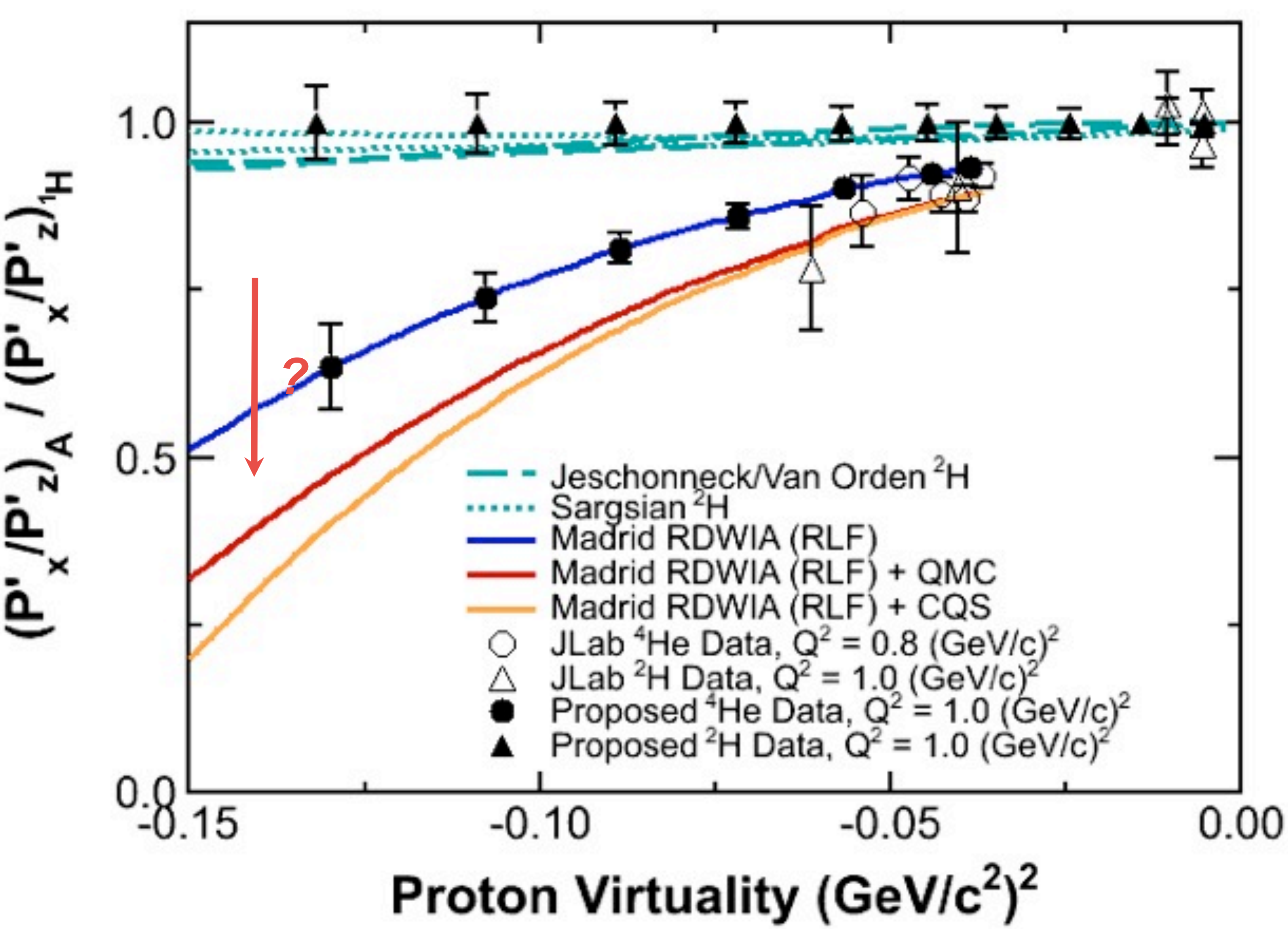
E11-107: O. Hen, L.B. Weinstein, S. Gilad, S.A. Wood

- DIS scattering from nucleon in deuterium
- Tag high-momentum struck nucleons by detecting backward "spectator" nucleon in Large-Angle Detector
- α_s related to initial nucleon momentum





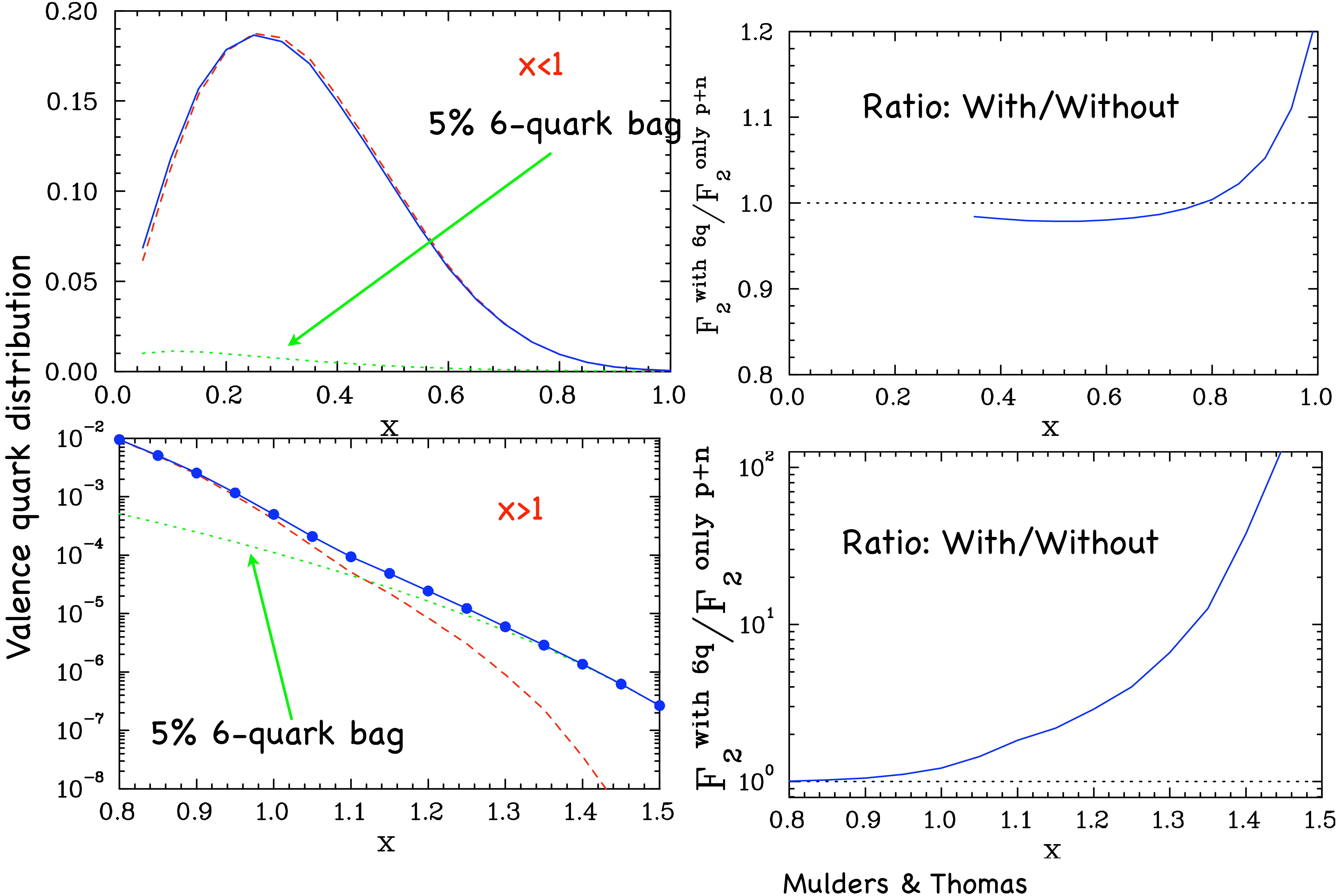
In-Medium Nucleon Form Factors
E11-002: E. Brash, G. M. Huber, R. Ransom, S. Strauch



- Compare proton knock-out from dense and thin nuclei: $^4He(e,e'p)^3H$ and $^2H(e,e'p)n$
- Modern, rigorous $^2H(e,e'p)n$ calculations show reaction-dynamics effects and FSI will change the ratio at most 8%
- QMC model predicts 30% deviation from free nucleon at large virtuality

S. Jeschonnek and J.W. Van Orden, Phys. Rev. C 81, 014008 (2010) and Phys. Rev. C 78, 014007 (2008); M.M. Sargsian, Phys. Rev. C82, 014612 (2010)

Sensitivity to non-hadronic components



Summary

- Evidence for SRC seen in inclusive and exclusive reactions
- Isospin asymmetry established experimentally -> probably should not be a surprise
- New experiments under analysis and approved that should illuminate both the gross and fine features
- SRC demand high densities (momenta) and, if these rare fluctuations can be captured, they should expose, potentially large, medium modifications