Correlations in Few* Body Systems

EMMI Workshop: Cold dense nuclear matter: from short-range nuclear correlations to neutron stars

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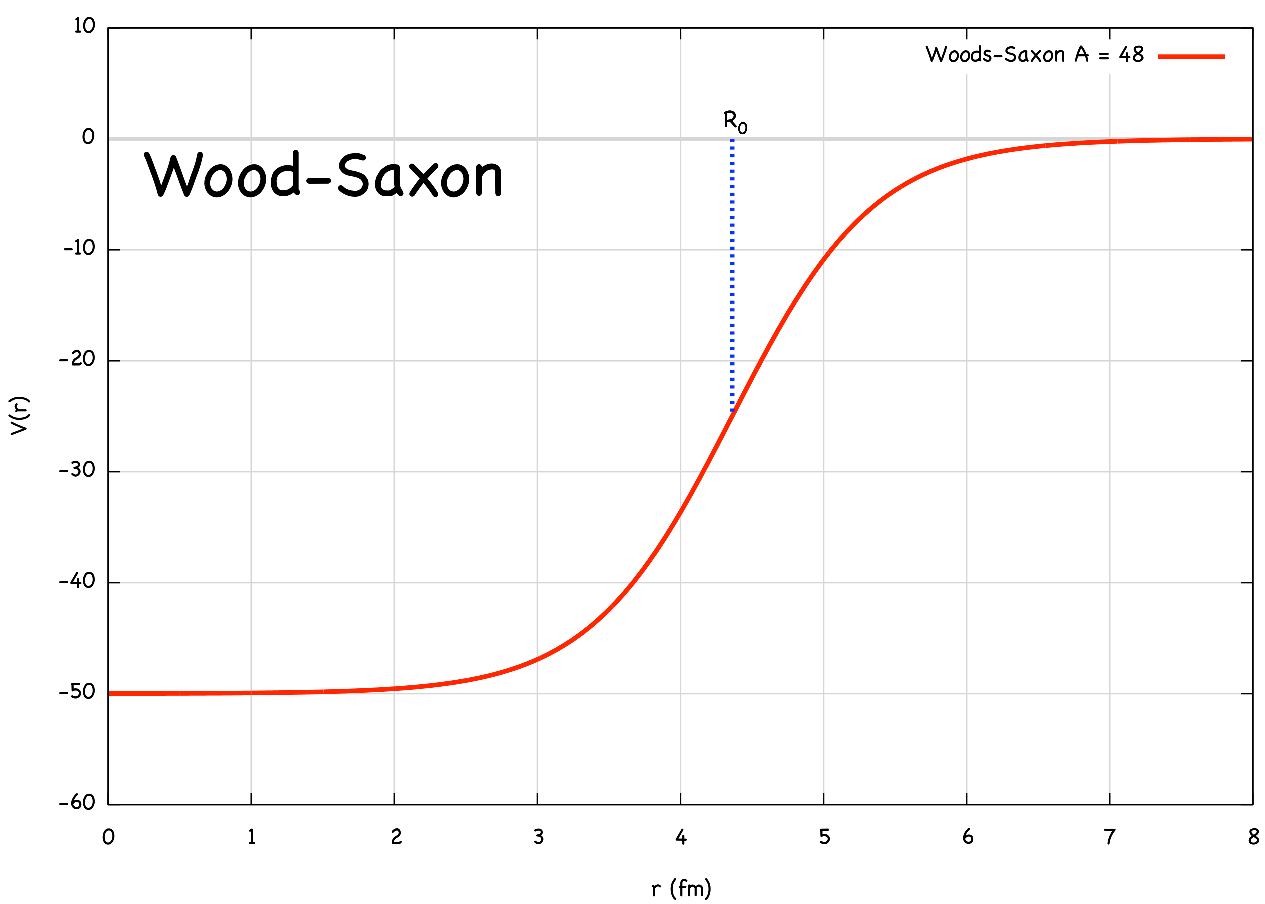
* and heavier

Outline

- Introduction
- NN potential responsible
  - Implications
- Correlations exist
  - Some examples
- Two nucleon correlations
  - Inclusive
  - Exclusive - Few body systems
- 3N correlations
  - 4He/3He
  - 12C/4He etc
- A_{zz}: Scattering from a Tensor Polarized Deuteron
- Finish

Independent Particle Shell Model

- Independent particle states of a uniform potential – a mean field.



- Long mean free paths
- No two-body interactions
- Absence of correlations in ground-state wave function.

$$V_{WS}(r) = \frac{-V_0}{1+e^{(r-R)/a}} - V_{ls}\left(\frac{\hbar}{m_\pi c}\right)^2 \frac{1}{r}\frac{d}{dr}\left(\frac{1}{1+e^{(r-R)/a}}\right)\vec{l}\cdot\vec{\sigma} + V_{Coul}$$

- The single-particle energies ξ_α and wave function Φ_α are the basic quantities – can be accessed in knockout reactions
- The spectral function should exhibit a structure at fixed energies with momentum distributions characteristic of the shell (orbit).

$$S(\vec{p},E) = \sum_a |\Phi_a(p)|^2 \delta(E+\xi_a)$$

- Enormous strong force acting
- So many nucleons to collide with
- How can nucleons possibly complete whole orbits (10^{21}/s) without interacting?

Hard core is small part of the nuclear volume

$$\frac{V_c}{V_{total}} = \left(\frac{c}{2r_o}\right)^3 \approx 1/100$$

Case for Correlations

- The nucleon-nucleon (NN) interaction is singularly repulsive at short distances
  - Difficult to find two nucleons close to each other.
  - Loss in configuration space components signals an increase of high-momentum components
- Both the correlation hole and the high-k components are absent in IPMs
- Taken together the loss of configuration space and the strengthening of high of momentum components are "correlations".
- The NN tensor force also provides high-momentum components; required to obtain the quadrupole moment of the deuteron and predicts a isospin dependence of SRCs.

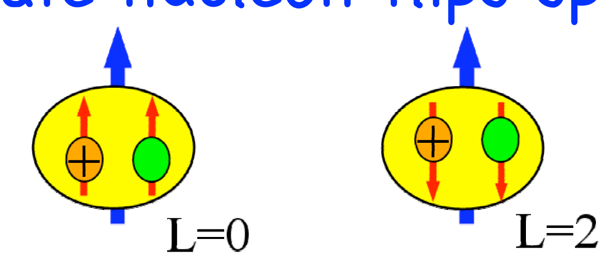
Possible Two Nucleon states

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

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

D-state nucleon flips spin



NN Interaction

Symmetric triplet T = 1

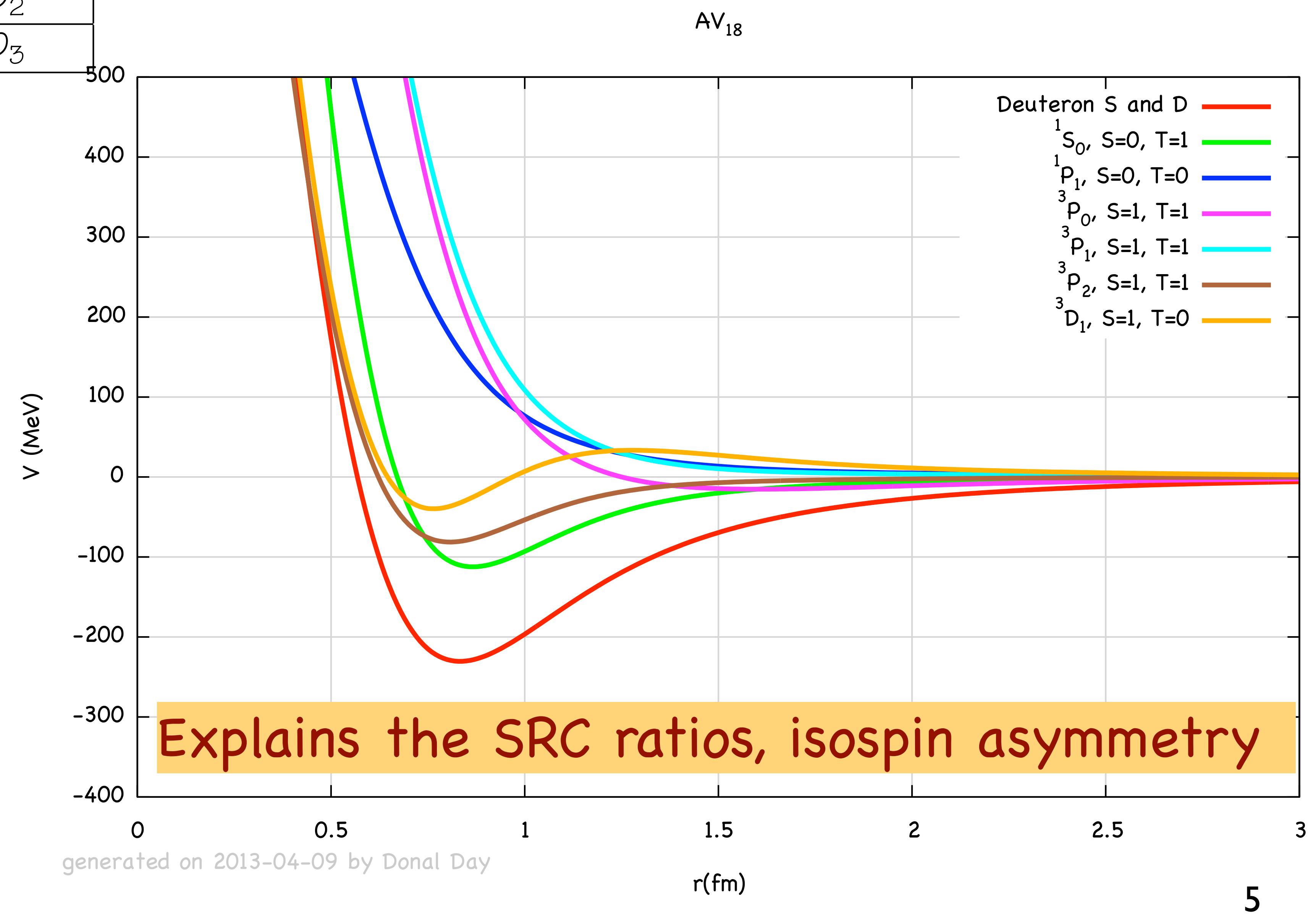
$^3(T)_1 = |p_1\rangle\, |p_2\rangle$ proton-proton state

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



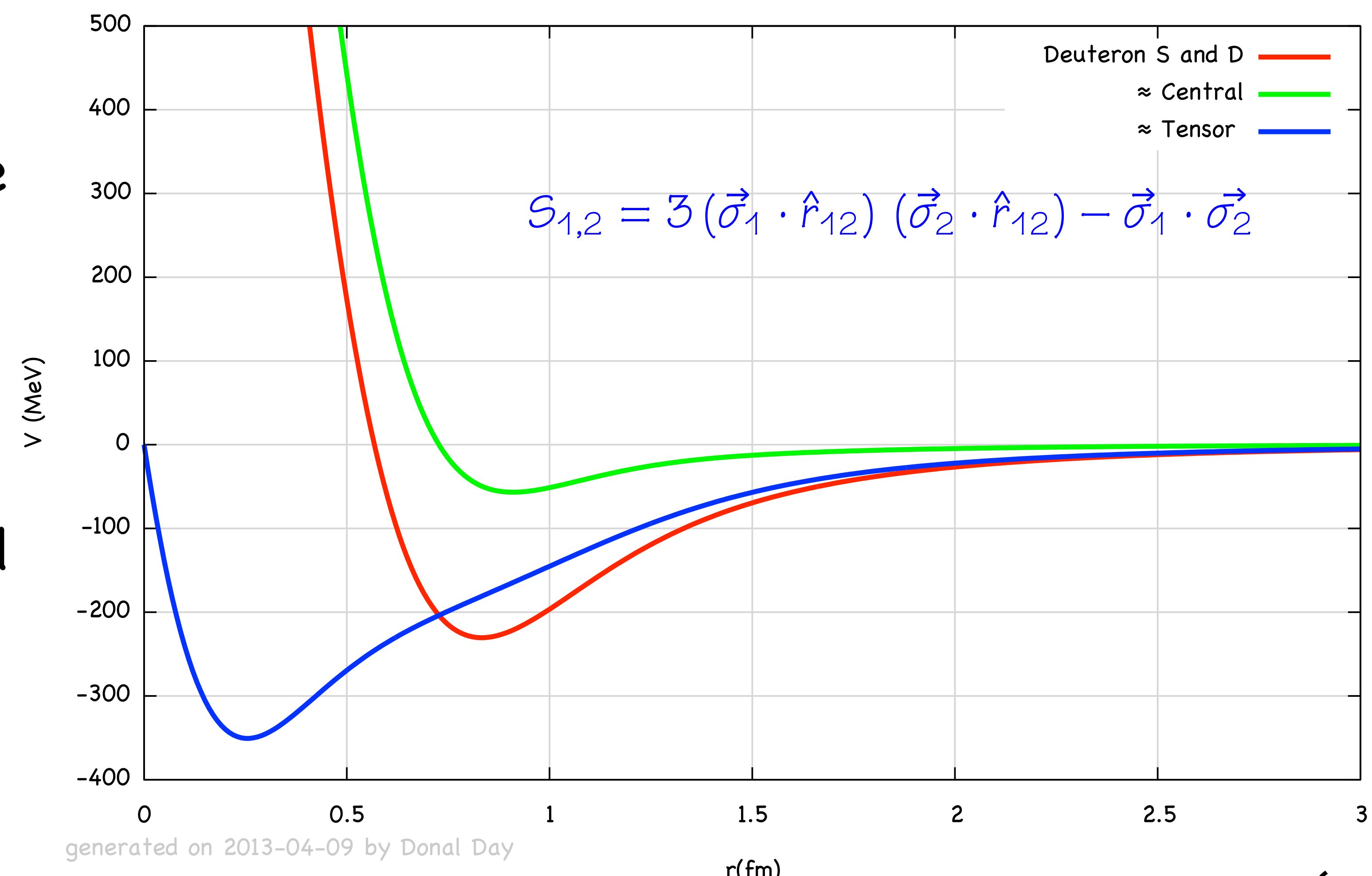
Explains the SRC ratios, isospin asymmetry

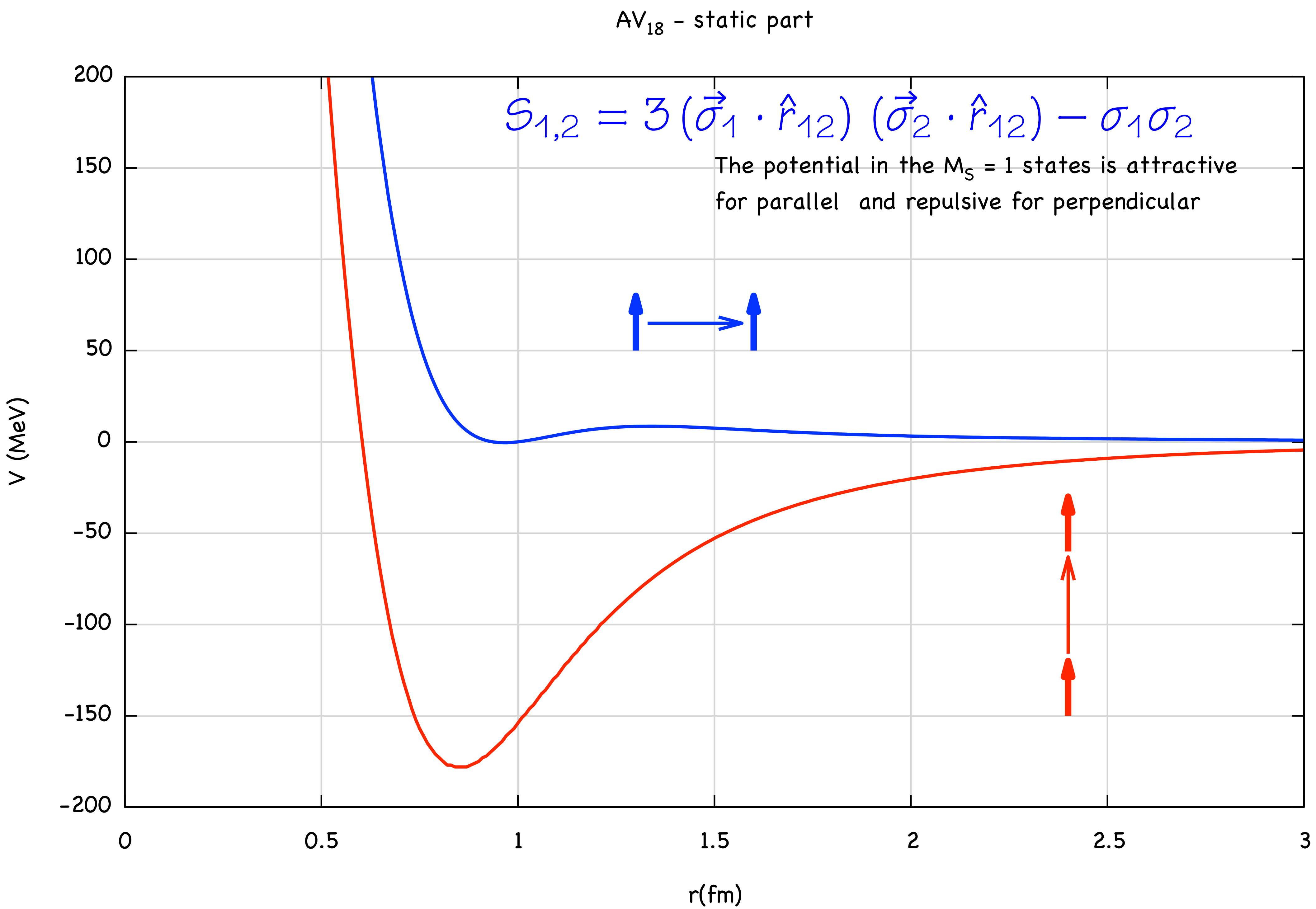
How can two nucleons combine?

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

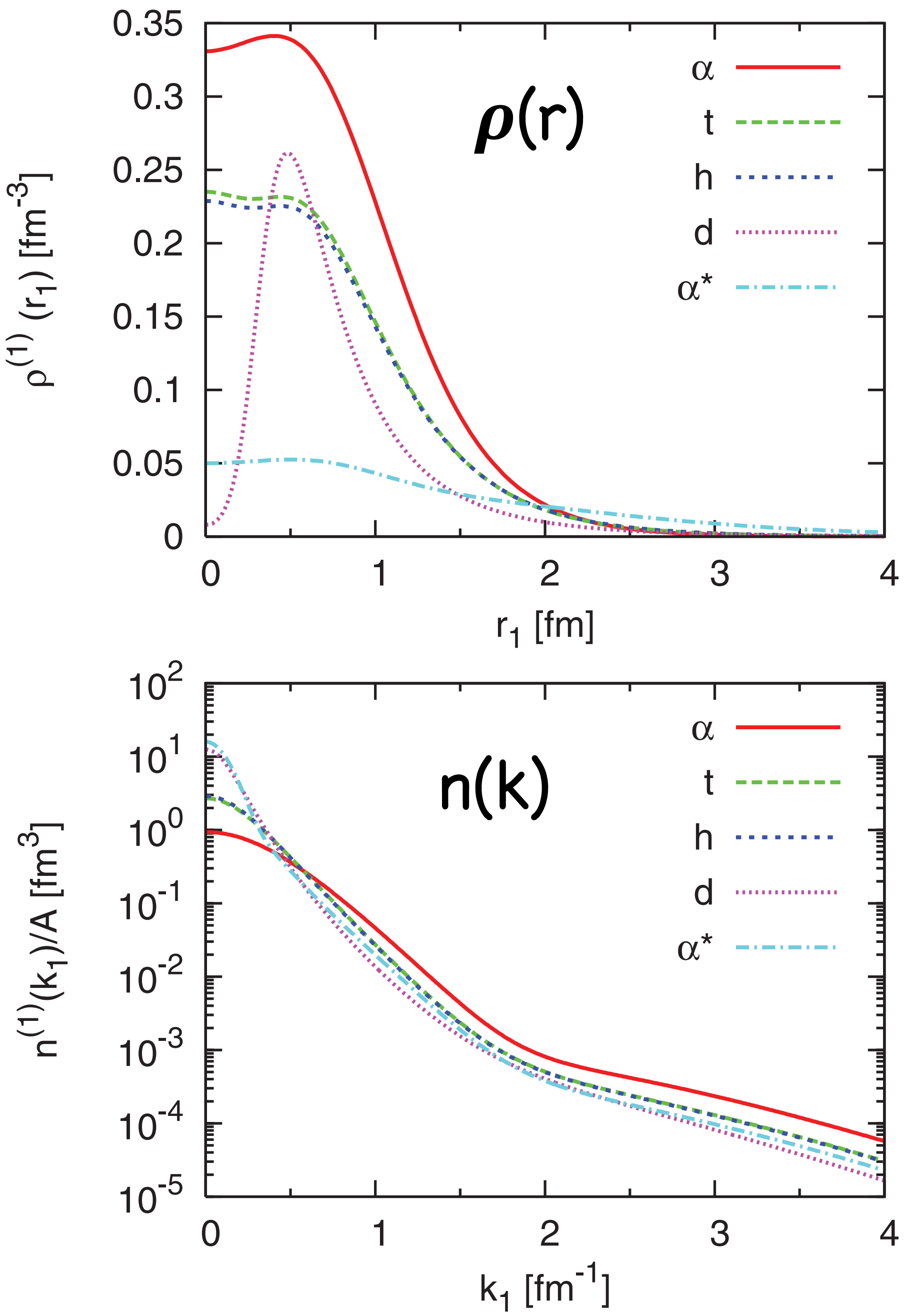
- The SR NN attraction dominated tensor interaction, which yields high momentum iso-singlet (np) pairs.
- Absent in the iso-triplet channel (pp, nn, np).
- The two-body distribution should be identical to the deuteron distribution, $n_2(k) = n_D(k)$, and the ratio of scattering cross sections between a heavy nucleus A and the deuteron to yield a_2 (A, Z)
- Without the tensor contribution the deuteron would not be bound





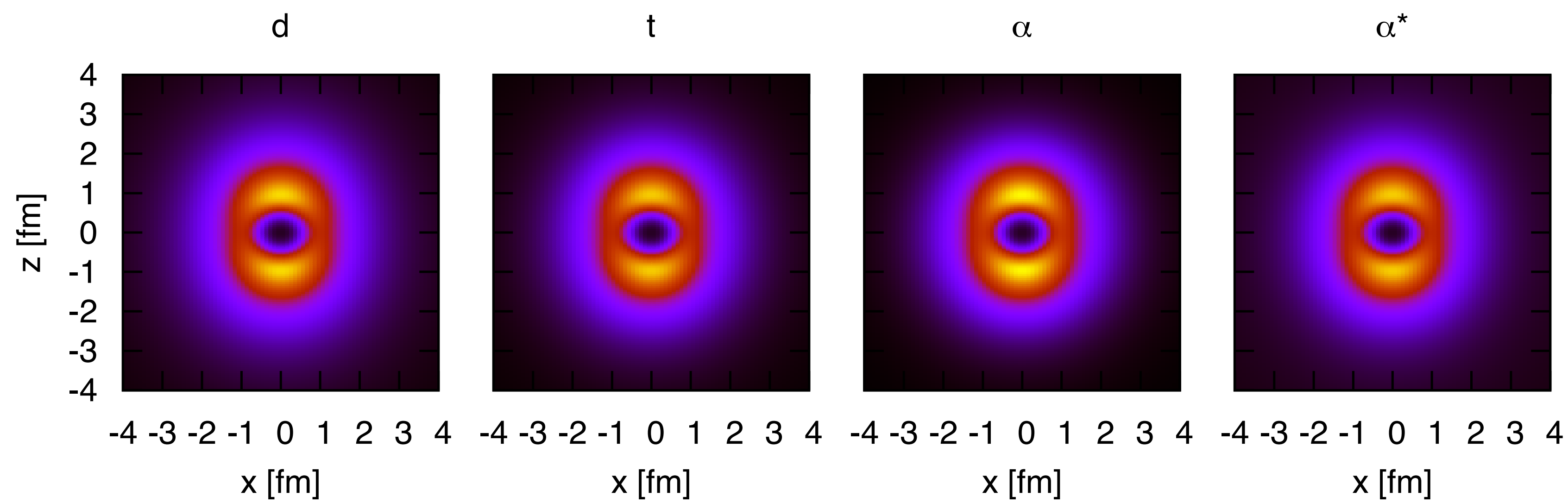
The tensor interaction causes a quadrupole type dependence as a function of the angle between the total spin direction (which we aligned along the z axis) and the direction of the distance vector **r**. The main attraction is obtained when the spins of the nucleons are aligned with the distance vector **r** while almost no attraction exists in the x direction where the spins are orthogonal to **r**.

Configuration and Momentum space



$$\rho^{(1)}(\mathbf{r}_1) = \frac{1}{2J+1} \sum_M \langle \Psi; JM| \sum_{i=1}^{A} \delta^3(\hat{\mathbf{r}}_i - \mathbf{r}_1)|\Psi; JM\rangle$$

$$n^{(1)}(\mathbf{k}_1) = \frac{1}{2J+1} \sum_M \langle \Psi; JM| \sum_{i=1}^{A} \delta^3(\hat{\mathbf{k}}_i - \mathbf{k}_1)|\Psi; JM\rangle$$



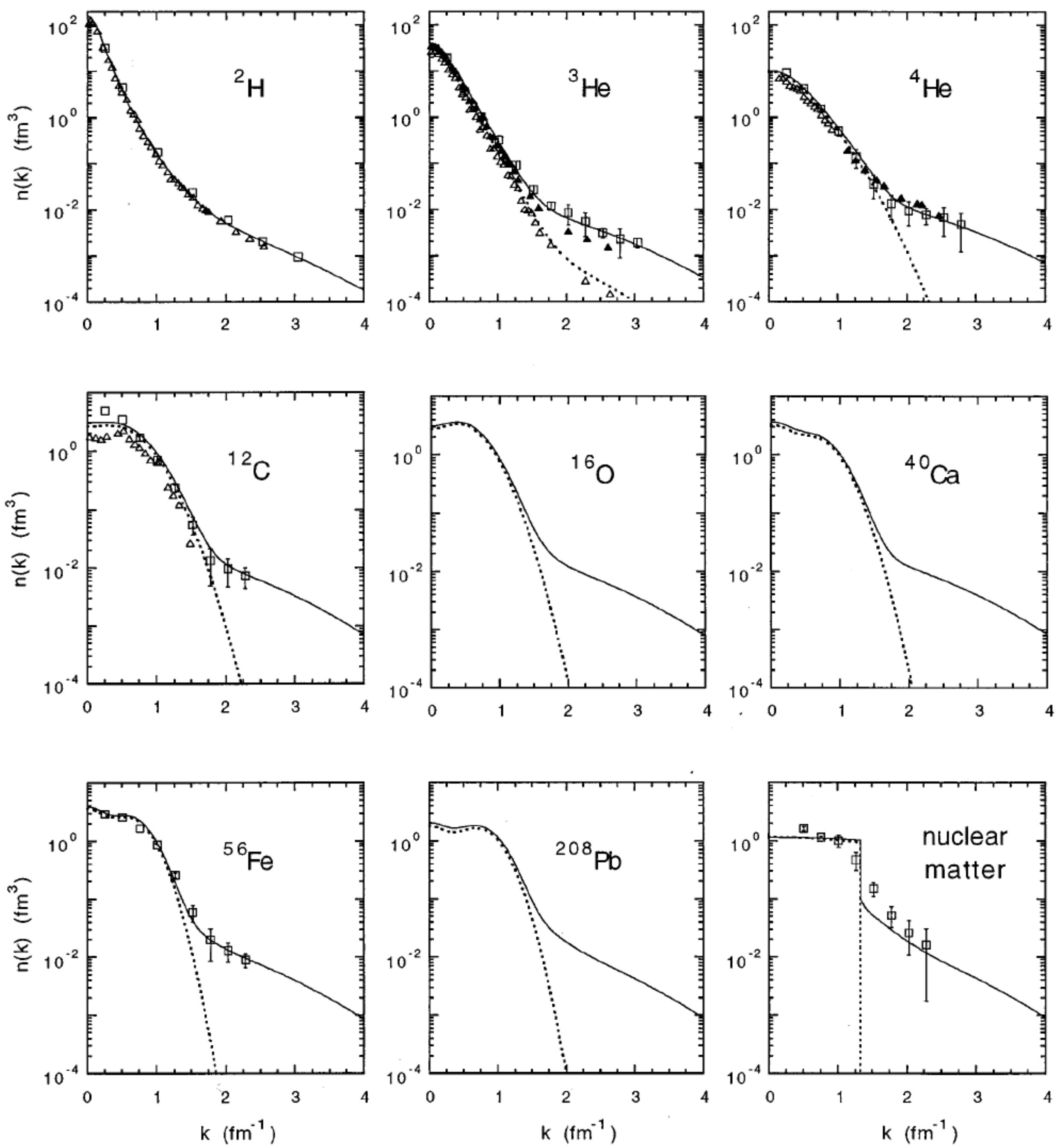
Two-body densities in coordinate space for a pair of nucleons with S = 1, M_S = 1, and T = 0 in the ground states of ^{2}H, ^{3}H, and ^{4}He and the 20.21 MeV excited state of ^{4}He

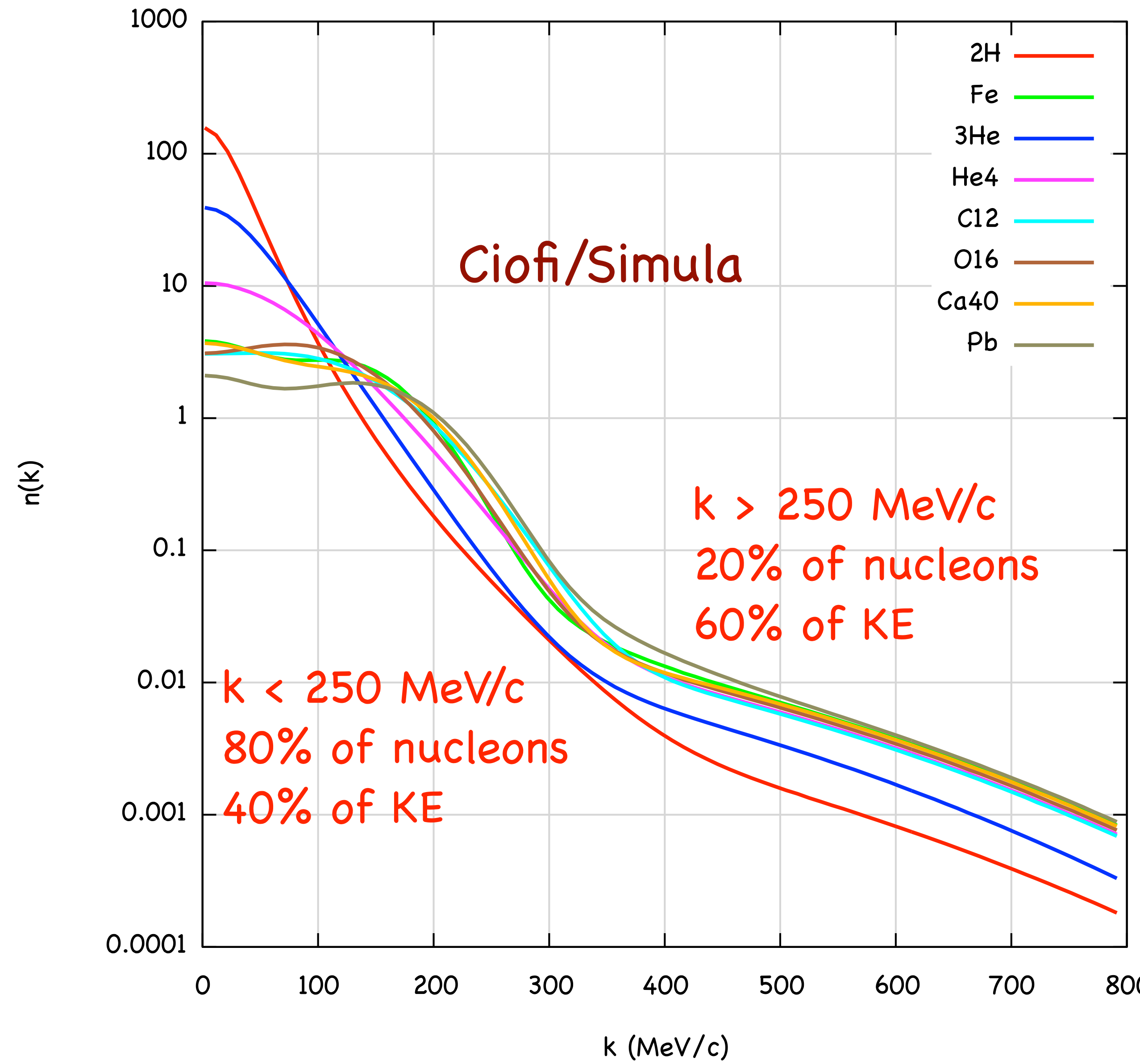
Where the potential is attractive, r ≈ (0,0,±1 fm), the densities are >> and in regions where the interaction is repulsive or close to zero the probability of finding the particle pair is small.

Universality of short-range nucleon-nucleon correlations, Feldmeier, Horiuchi, Neff, Suzuki Physical Review C 84, 054003 (20111)

These correlations can not be represented in a shell model and the two-body densities have their maximum at relative distance r = 0.

Momentum Distributions

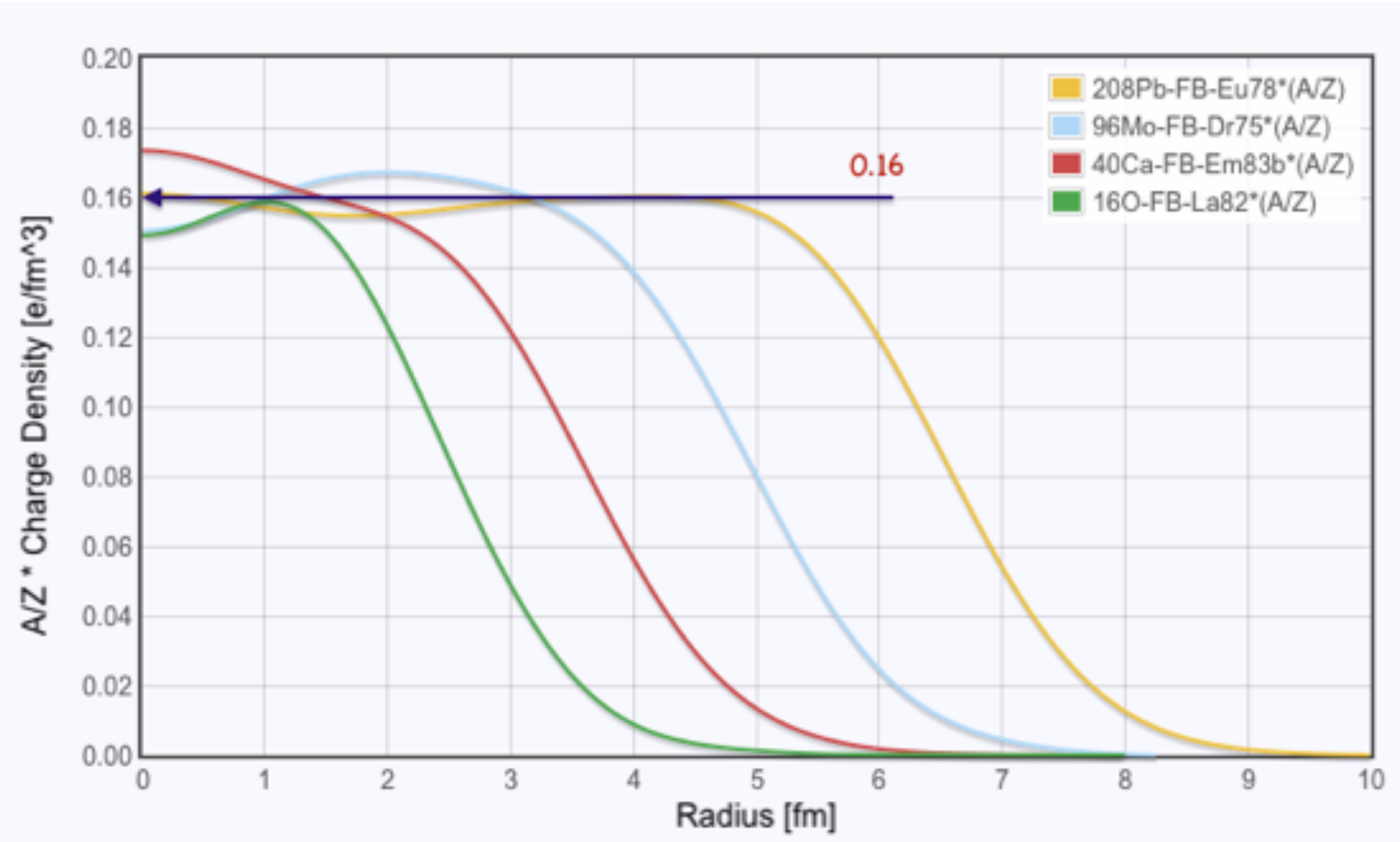




n(k) is dominated by SRCs at large k and n(k) exhibits the same shape for all nuclei for $k>k_{fermi}$

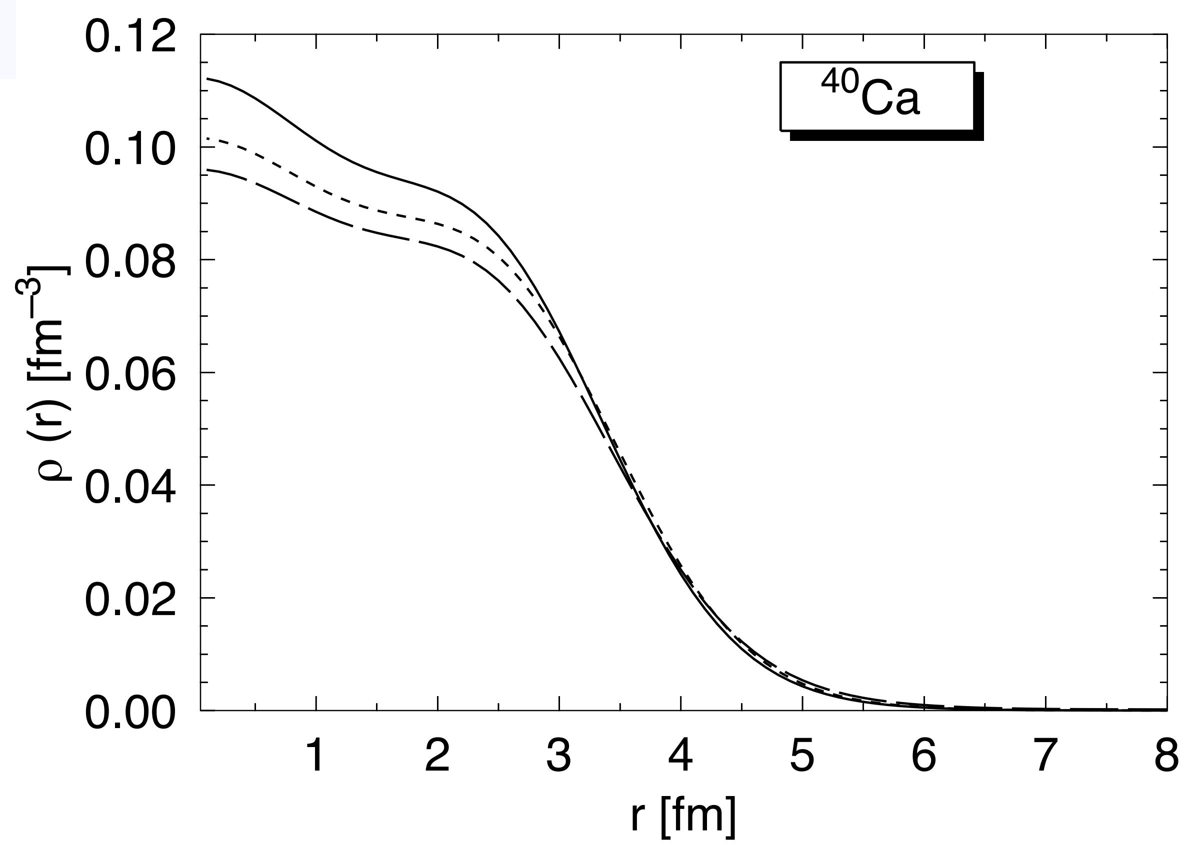
Evidence of SRC

Correlations and charge distributions



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

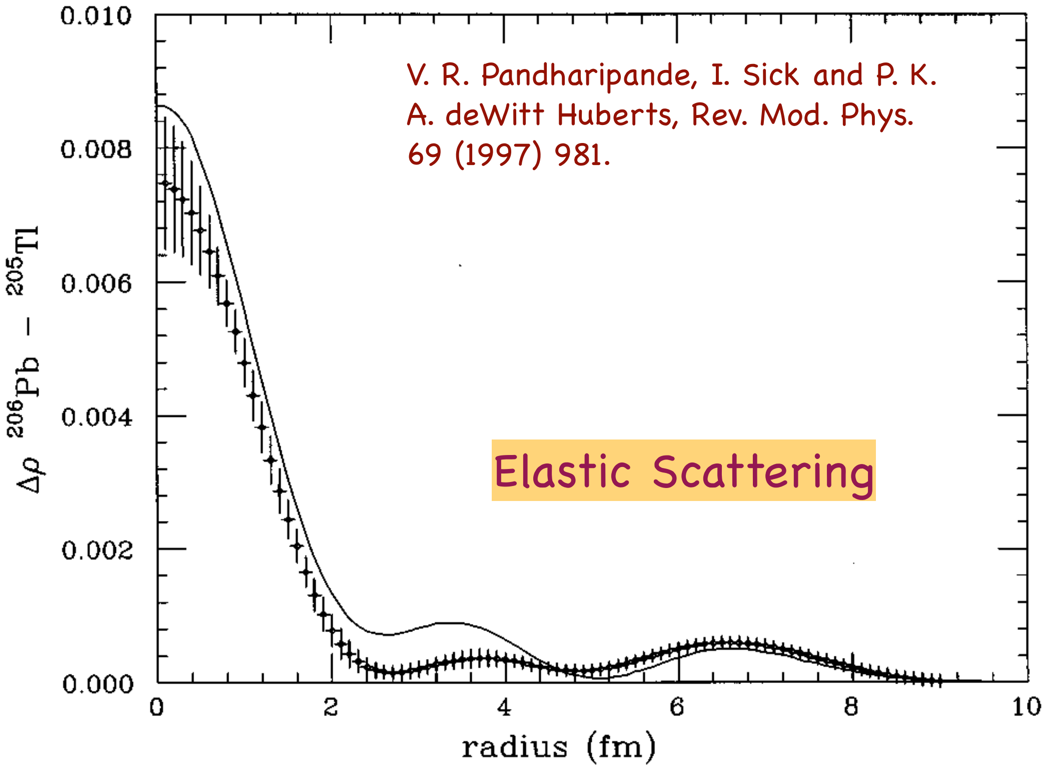
Charge density archive



IPM (full lines), LRC (long dashed lines), SRC (short dashed lines).

Correlations and charge distributions of medium heavy nuclei, Marta Anguiano and Giampaolo Co'

Evidence of SRC

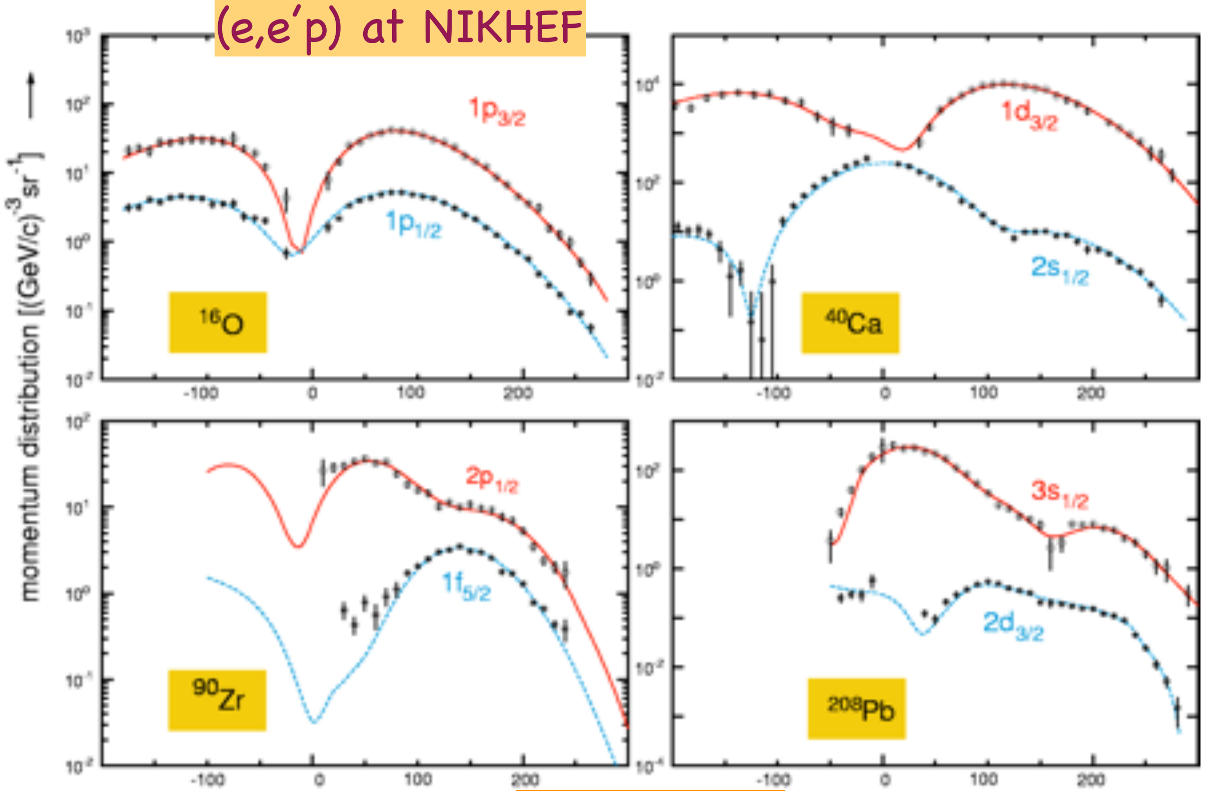


Density difference between ^{206}Pb and ^{205}Tl.: differ by a single $3s^{1/2}$ proton

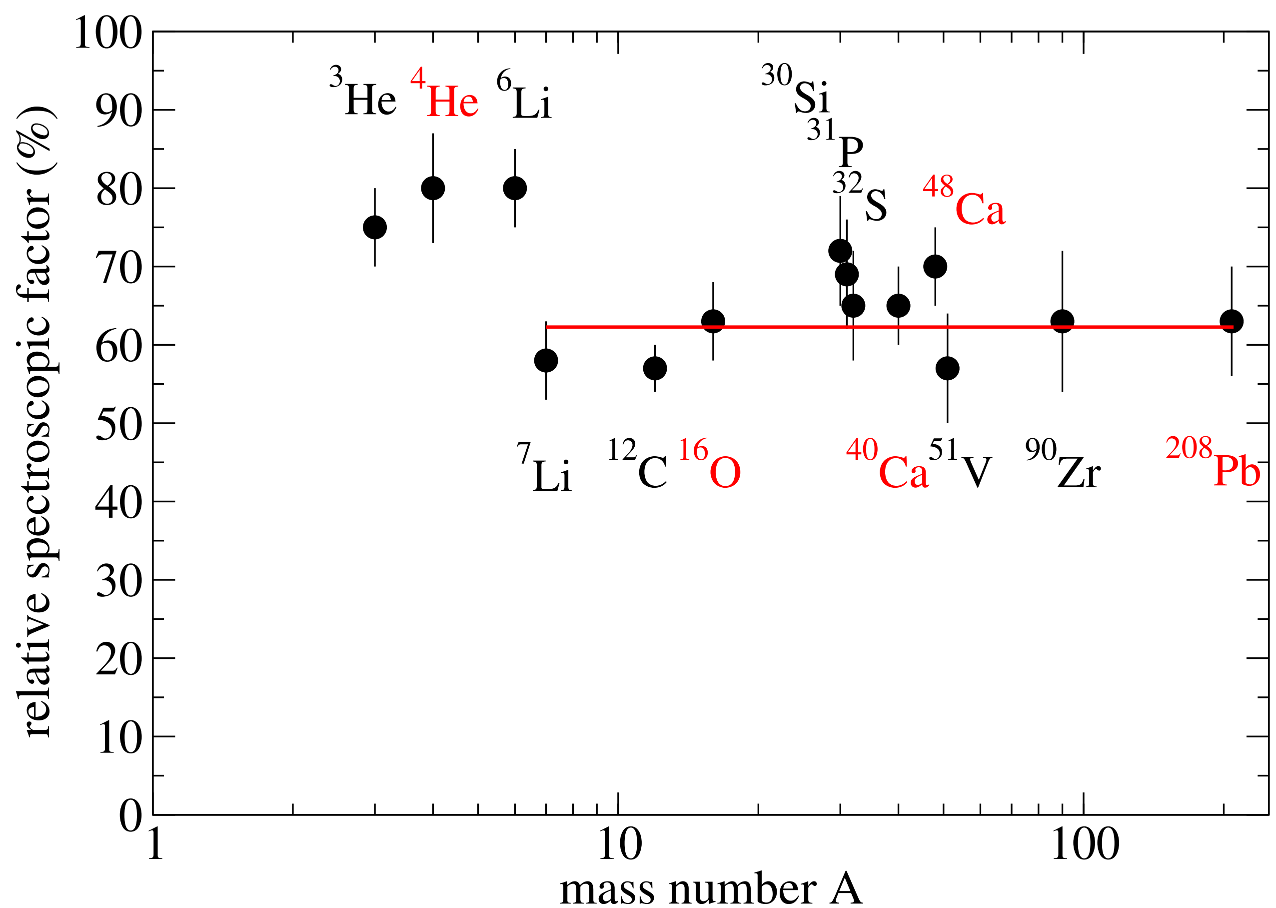
Experiment - Cavedon et al (1982)
Theory: Hartree-Fock orbitals with adjusted occupation numbers describe the shape of the $3s^{1/2}$ orbit.

Occupation numbers scaled down by a factor ~0.65.

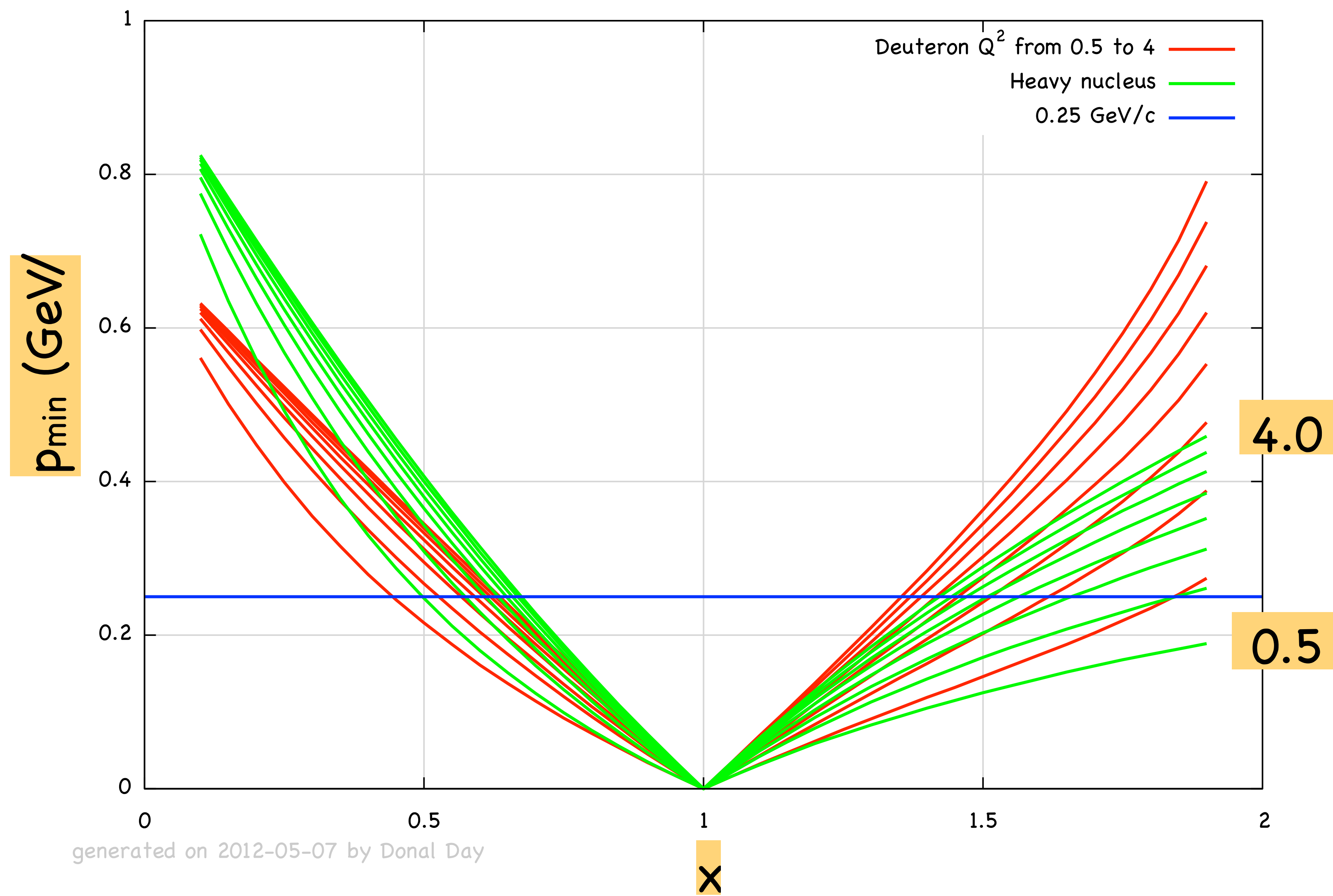
(e,e'p) at NIKHEF

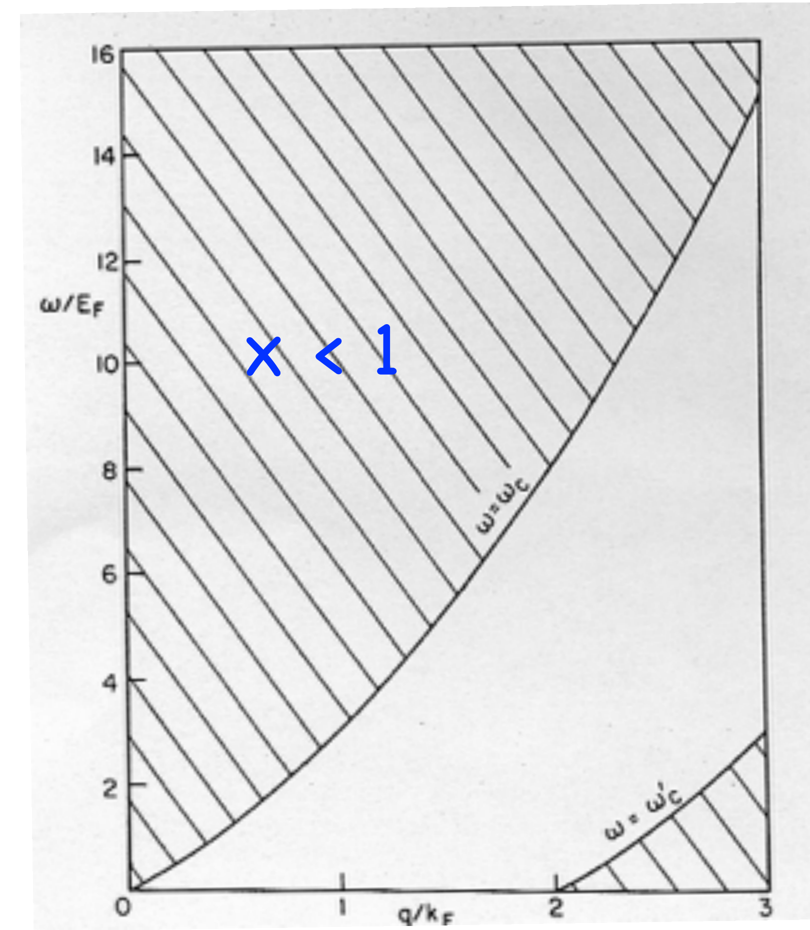


p_m [MeV/c]



Correlations: Where to look in inclusive A(e,e’)





x > 1, low ω side of qep

Inelastic electron scattering from the fluctuations in the nuclear charge distribution

Wieslaw Czyż and Kurt Gottfried

Annals of Physics 21, 47 (1963)

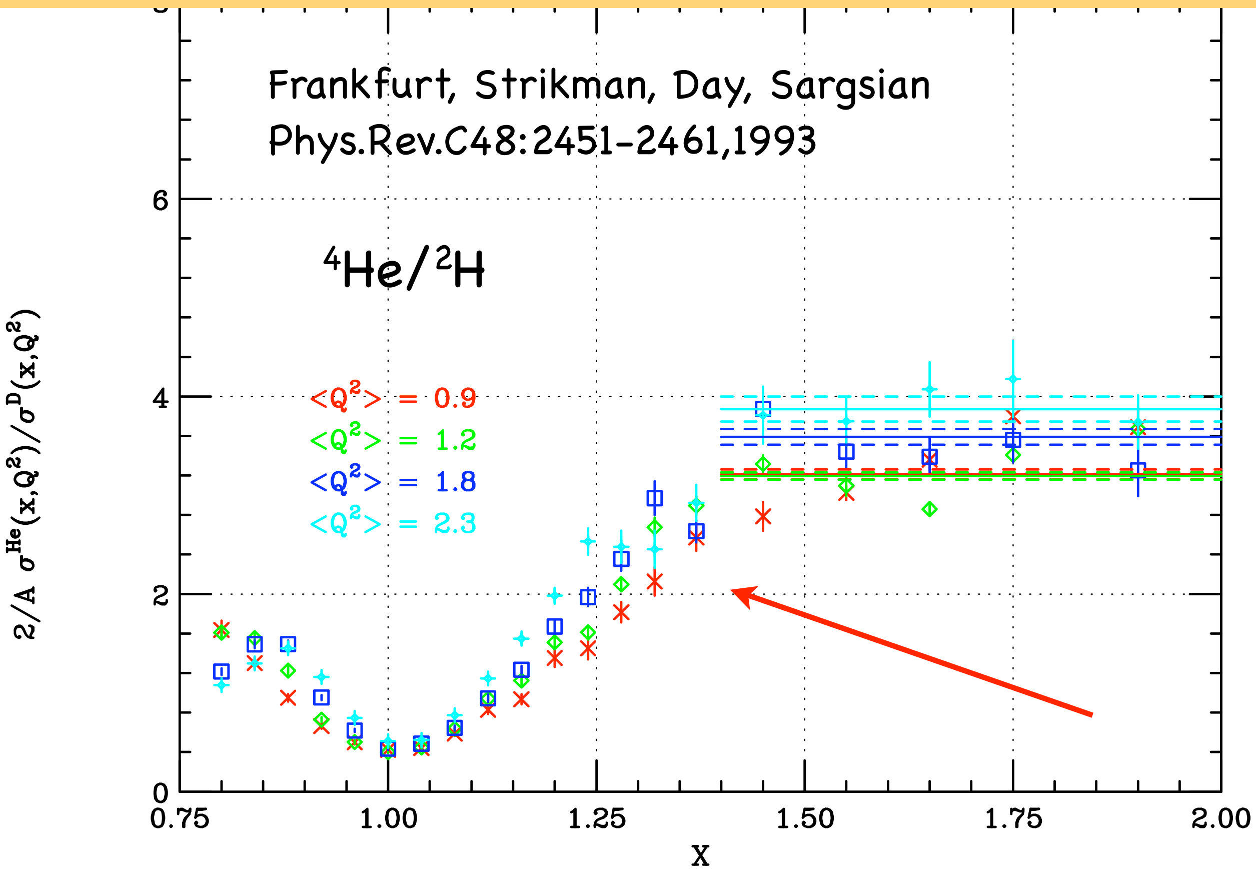
Appearance of plateaus is A dependent.

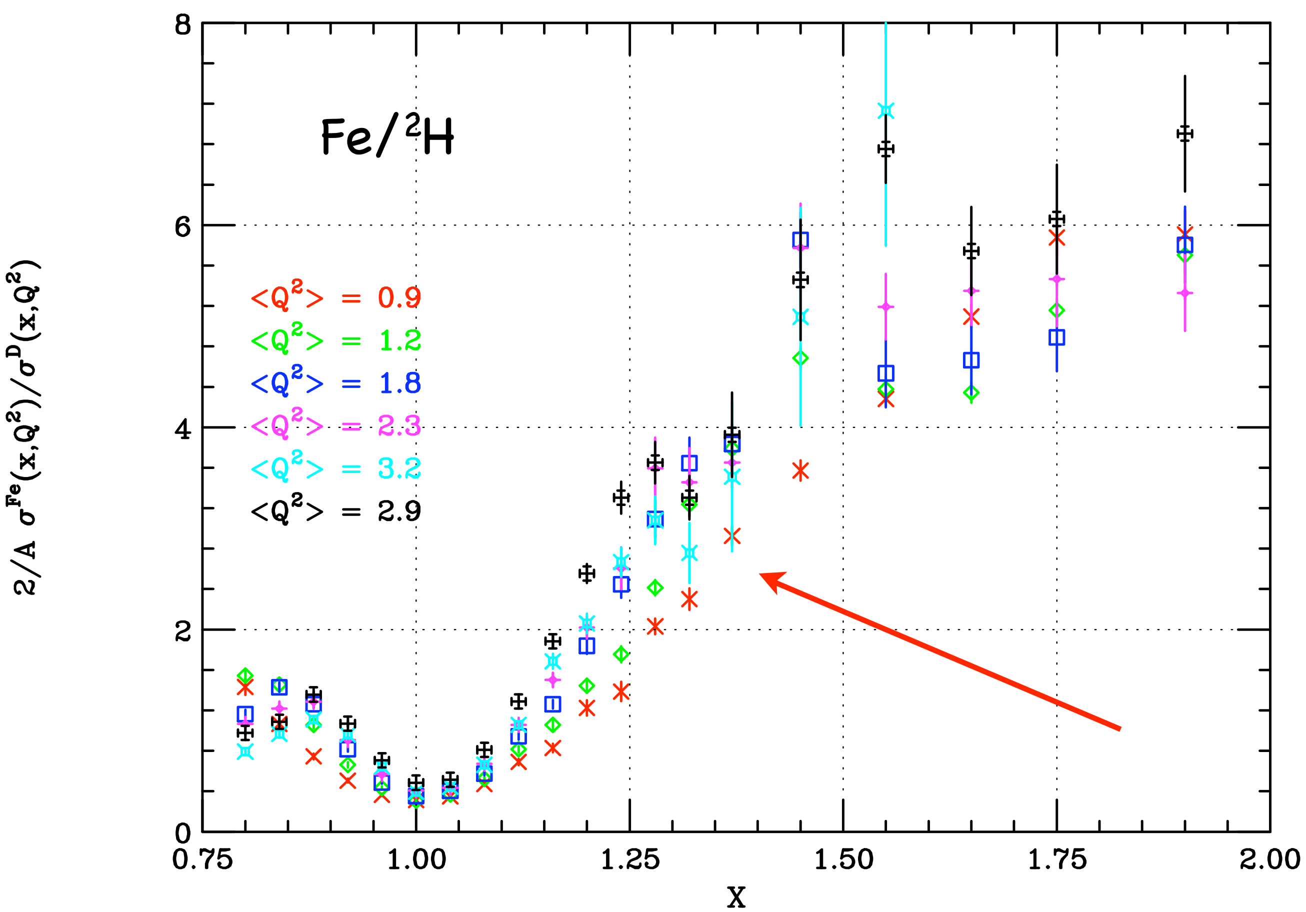
Kinematics: heavier recoil systems do not require as much energy to balance momentum of struck nucleon - hence p_{min} for a given x and Q^2 is smaller.

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

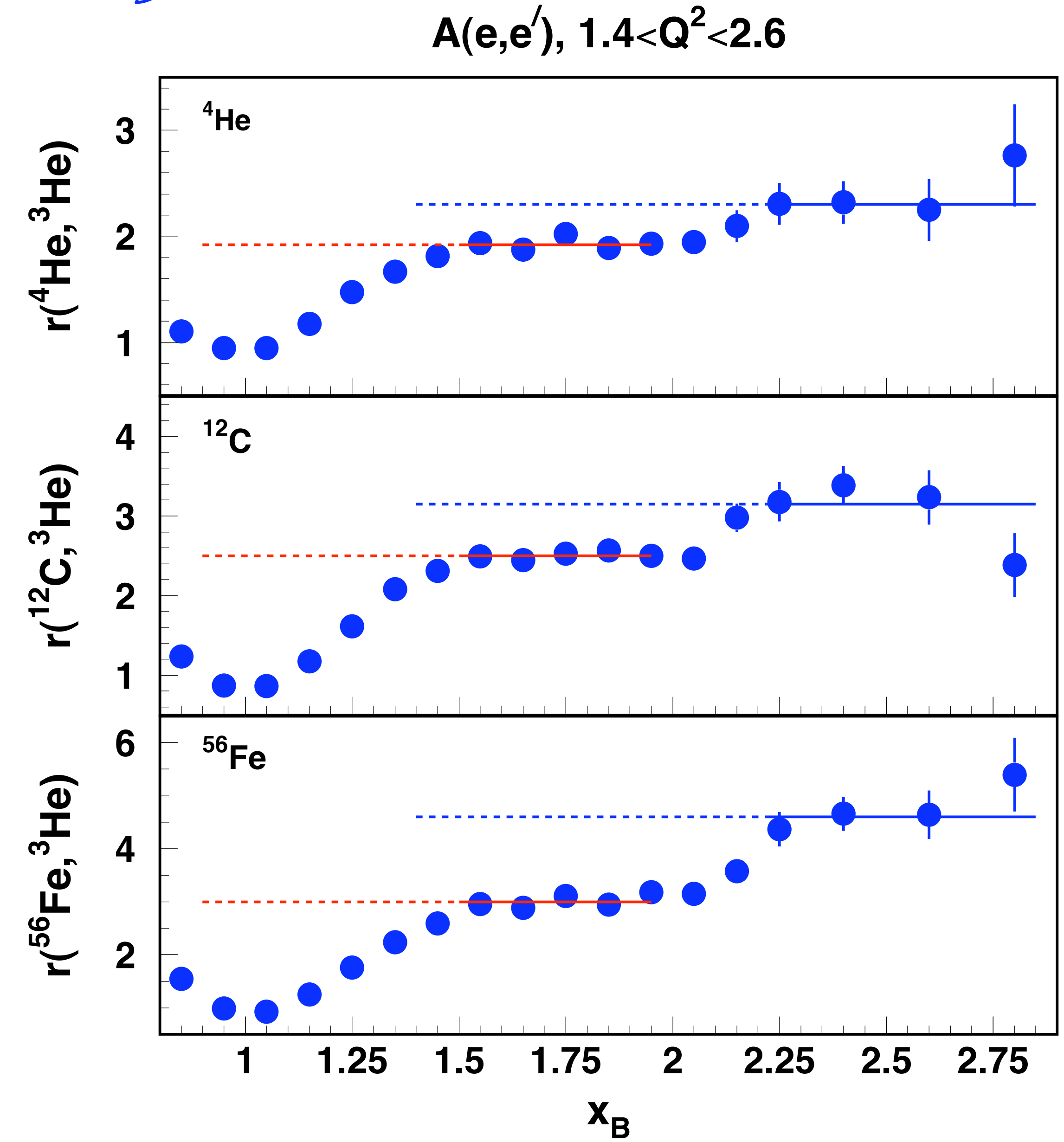
Have to go to higher x or Q^2 to insure scattering is not from mean-field nucleon

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

Ratios and SRC

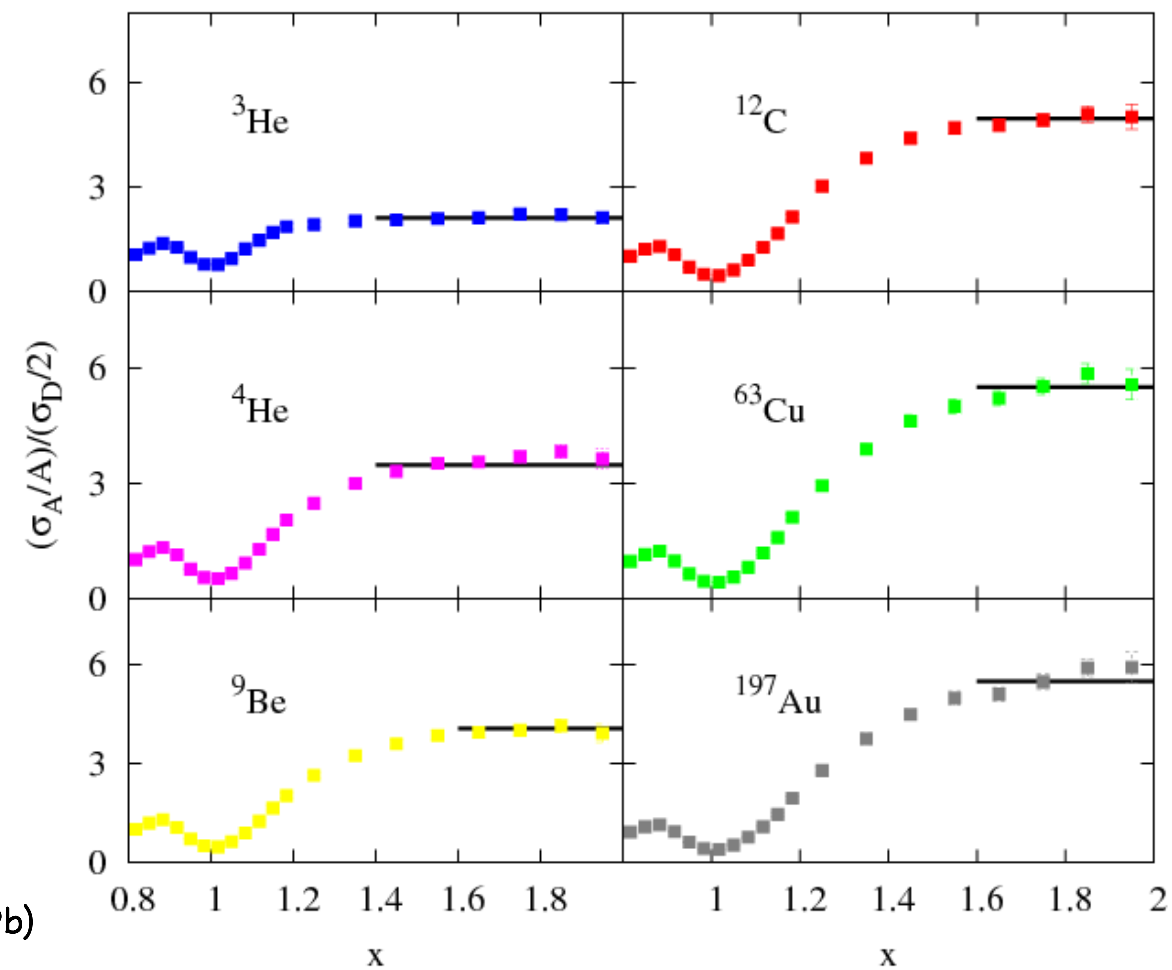
Dominance of np pairs in SRC region leads us to drop the isoscalar correction. We correct for COM motion of pair.

R_{2n} : number of np pairs relative to the deuteron

A	R_{2N} (E02-019)	SLAC	CLAS	F_{CM}	Ciofi/Simula
^{3}He	1.93 ± 0.10	1.8 ± 0.3	⋯	1.10 ± 0.05	1.9
^{4}He	3.02 ± 0.17	2.8 ± 0.4	2.80 ± 0.28	1.19 ± 0.06	3.8
Be	3.37 ± 0.17	⋯	⋯	1.16 ± 0.05	
C	4.00 ± 0.24	4.2 ± 0.5	3.50 ± 0.35	1.19 ± 0.06	4.0
Cu(Fe)	4.33 ± 0.28	(4.3 ± 0.8)	(3.90 ± 0.37)	1.20 ± 0.06 *	4.5
Au	4.26 ± 0.29	4.0 ± 0.6	⋯	1.21 ± 0.06	4.8 (^{208}Pb)
$\langle Q^2 \rangle$	~2.7 GeV^2	~1.2 GeV^2	~2 GeV^2		
$x_{\min}$	1.5	⋯	1.5		
$\alpha_{\min}$	1.275	1.25	1.22–1.26		

Hall C

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

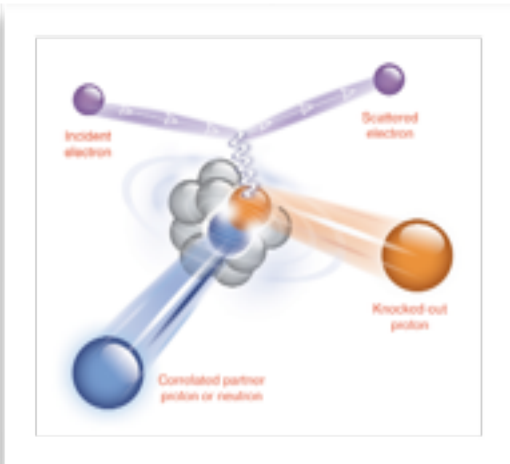


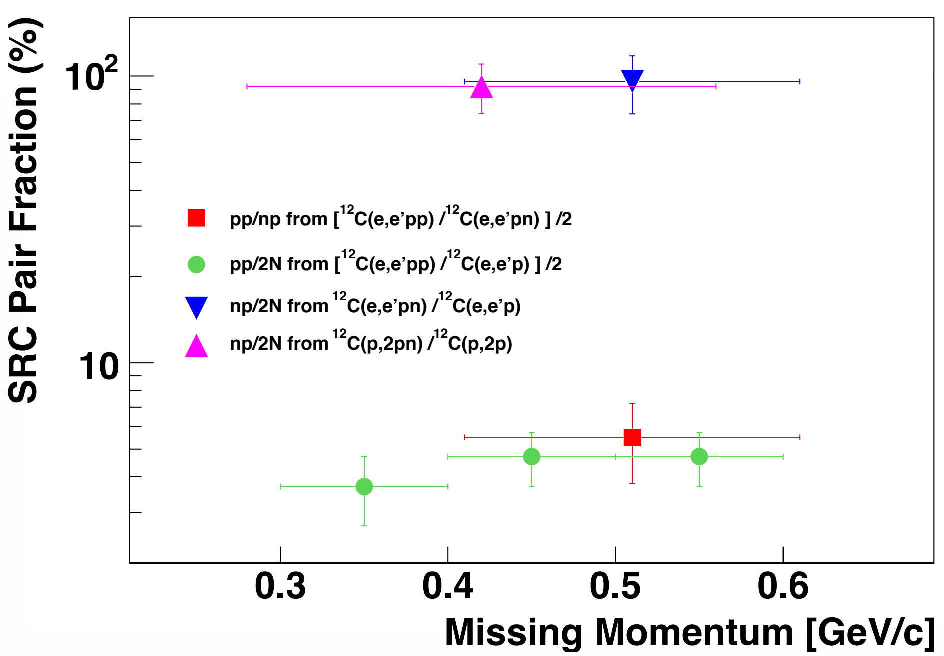
Evidence of 2N-SRC at x>1.5

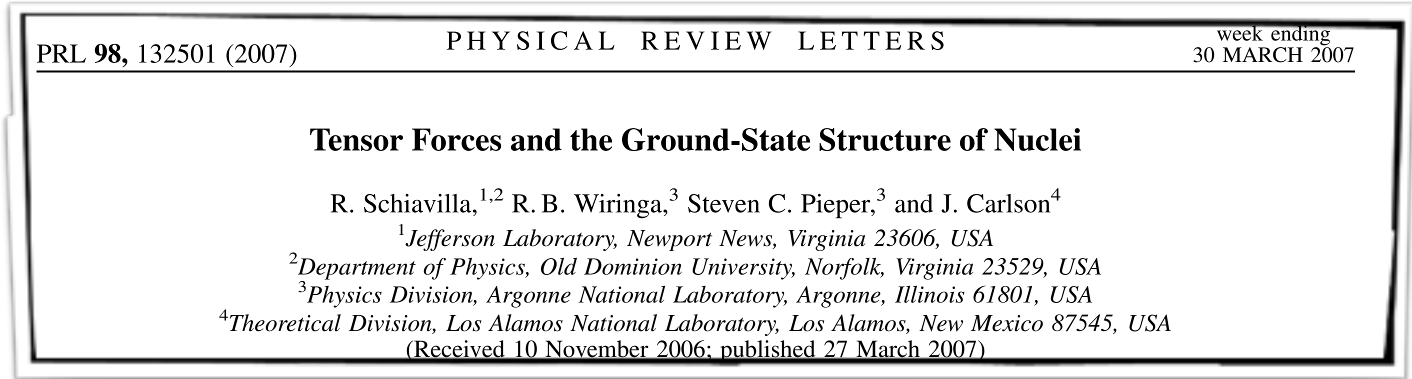
Theory and experiment display isospin dependence

Two-nucleon knock-out experiment

R. Subedi et al, Science 320, 1476(2008)







PRL 98, 132501 (2007) PHYSICAL REVIEW LETTERS week ending 30 MARCH 2007

Tensor Forces and the Ground-State Structure of Nuclei

R. Schiavilla,[1,2] R. B. Wiringa,[3] Steven C. Pieper,[3] and J. Carlson[4]

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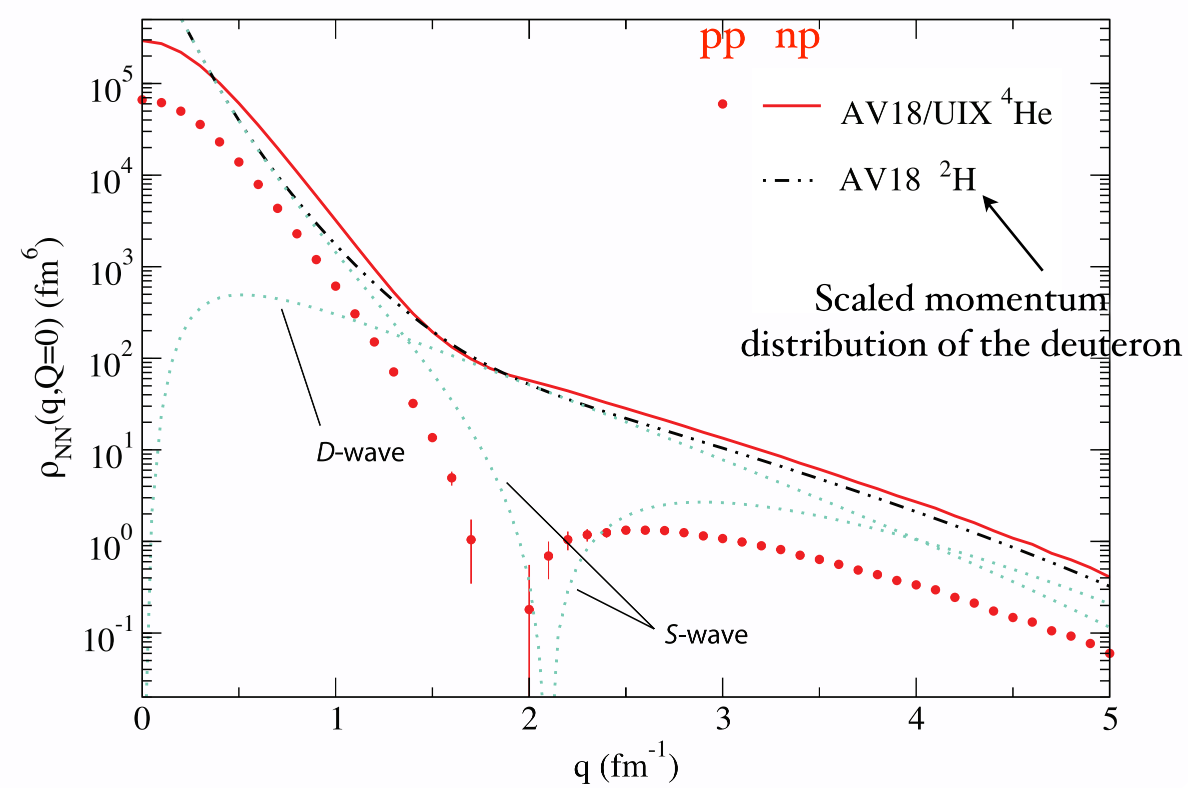
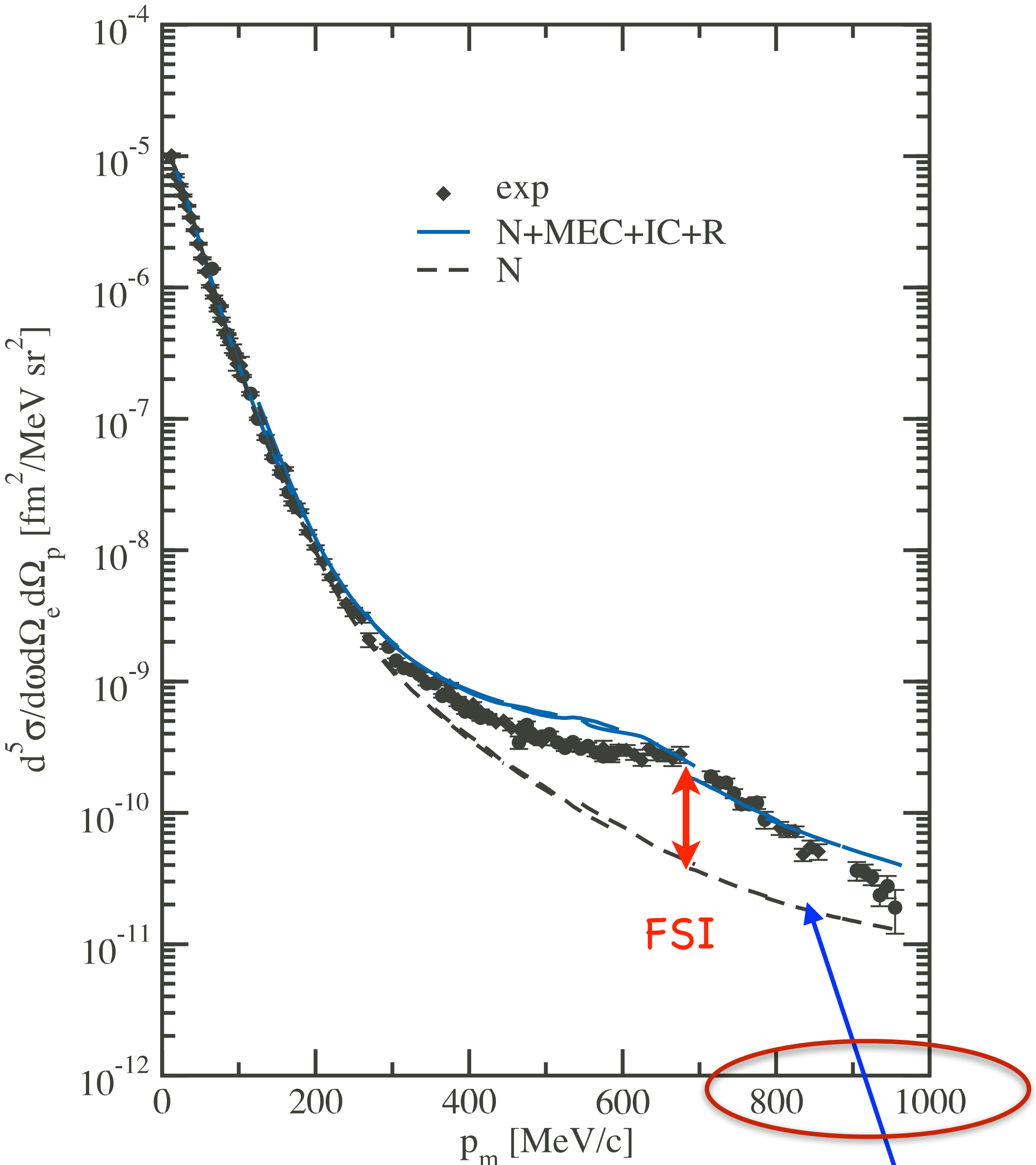


Data show large asymmetry between np, pp pairs:

Qualitative agreement with calculations; effect of tensor force. Huge violation of often assumed isospin symmetry

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

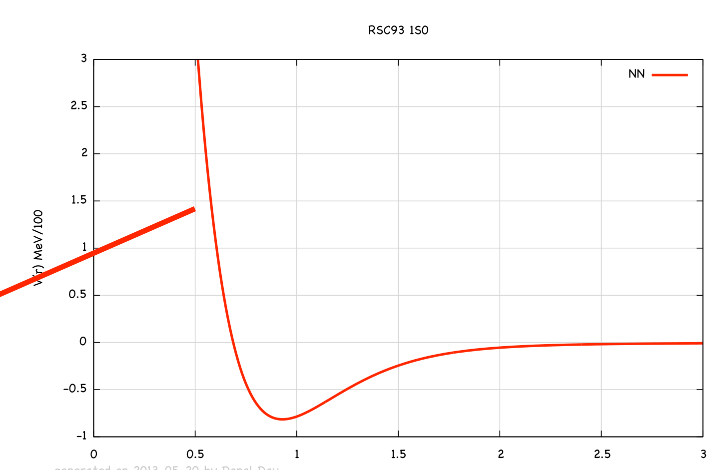
Q^2 = 0.33

x = .88

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

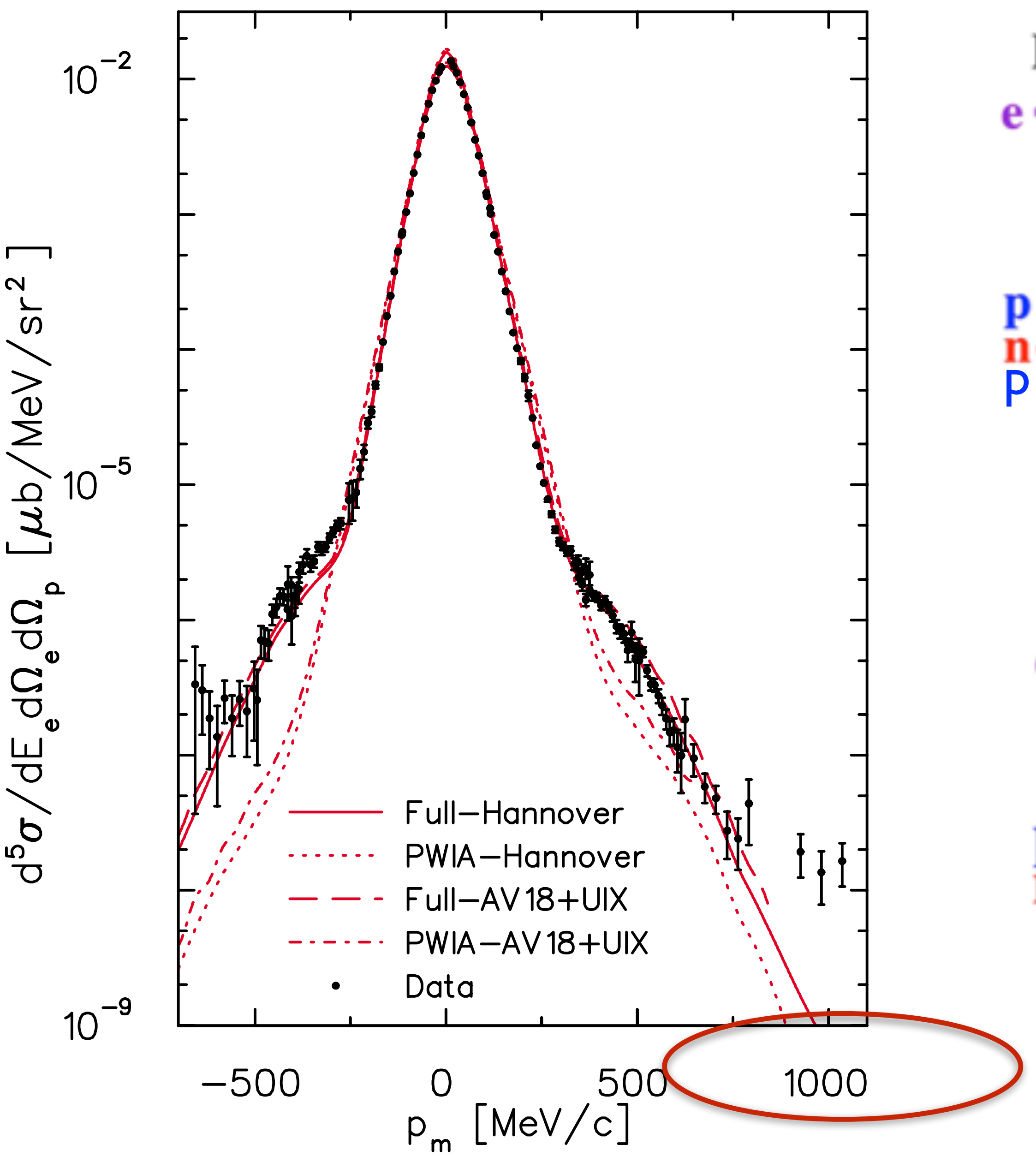
large IC+MEC

hard core

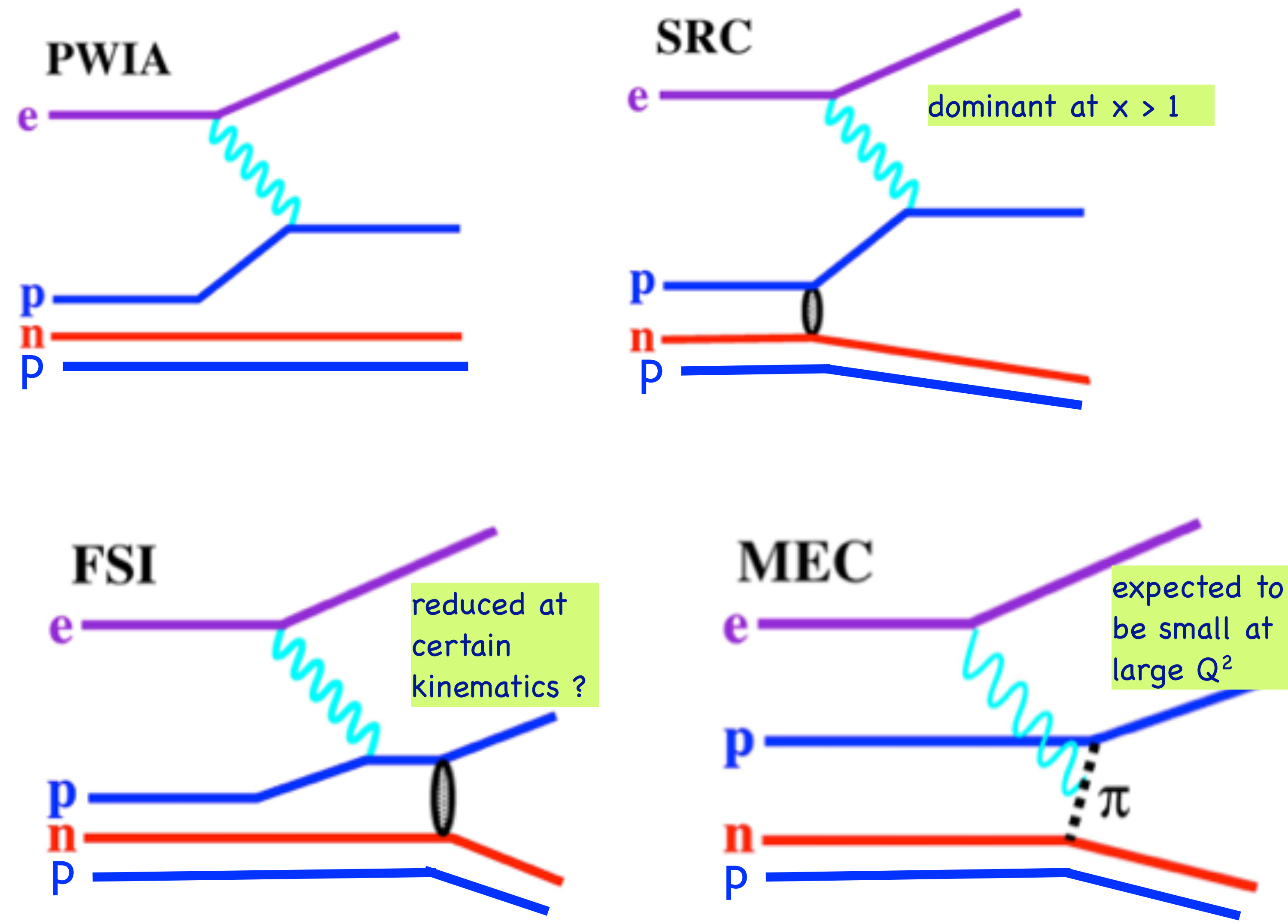


High momentum strength in A(e,e'p)

$^3He(e,e'p)d$ E89-044, Hall A



x = 1



E89-044: $^3He(e,e'p)d$

Measured far into high momentum tail:

Cross section is ~5-10x expectation

High momentum pair can come from SRC (initial state)

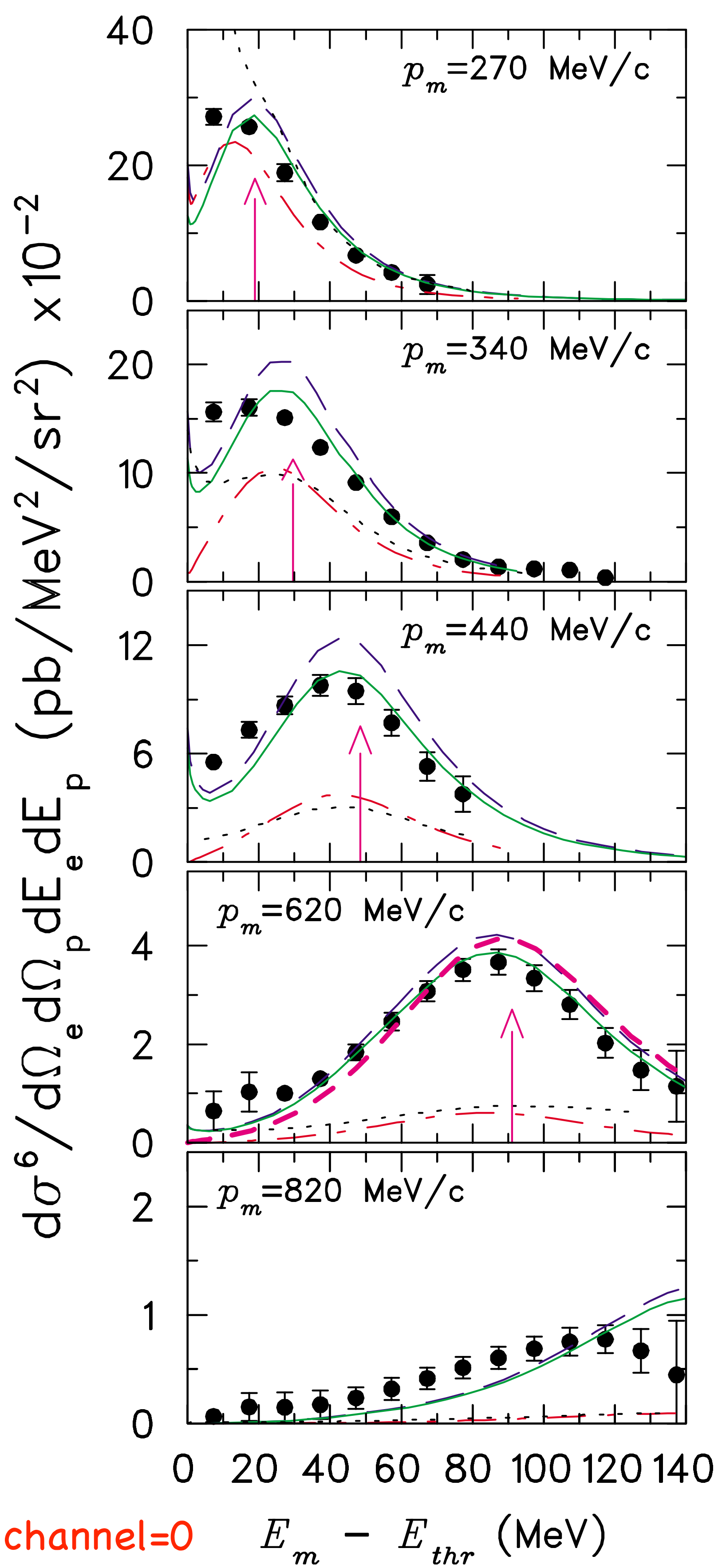
OR

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

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

High momentum strength in A(e,e'p)

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

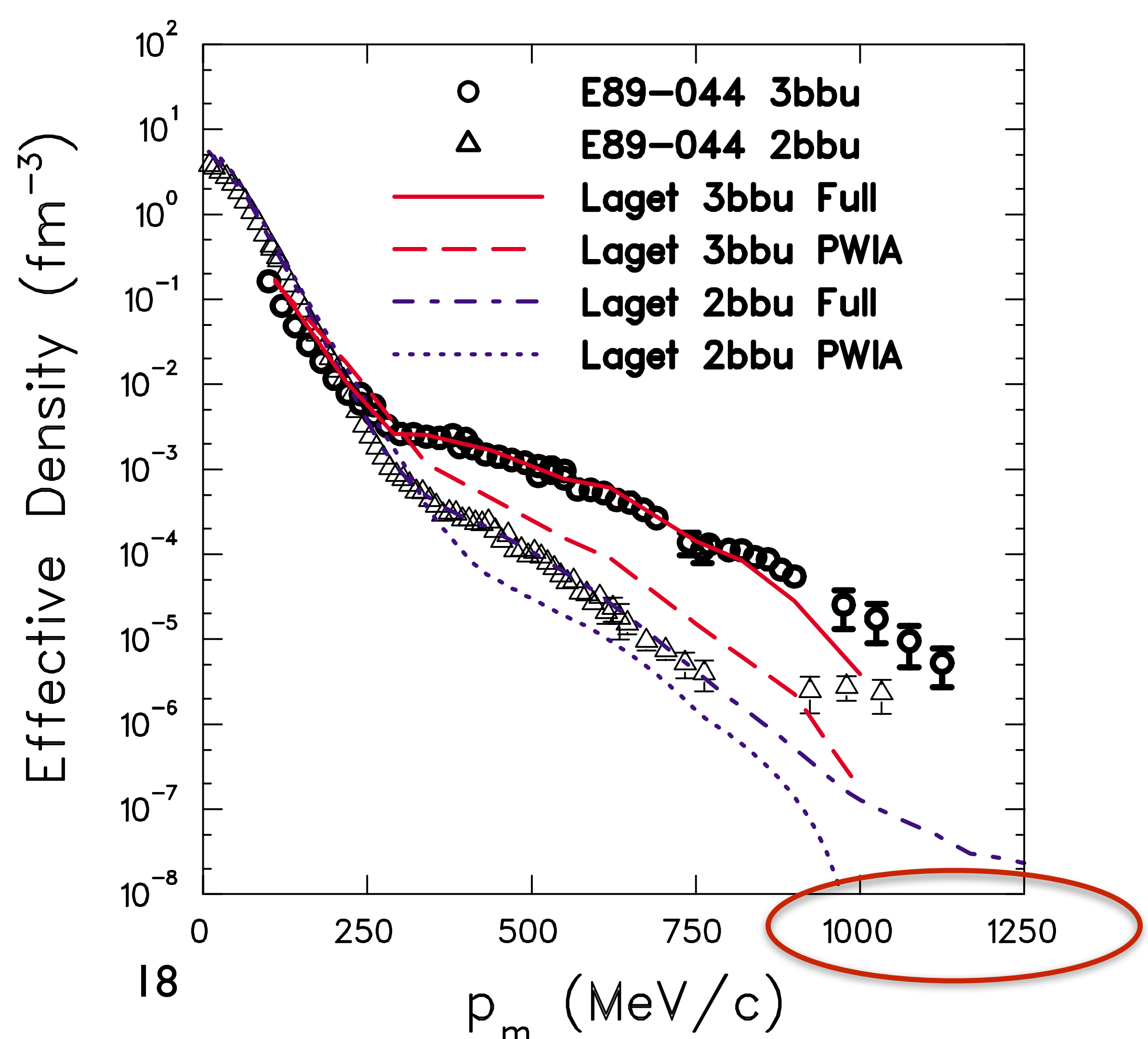


3bbu channel=0

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

Arrows indicate expected location of correlated pair

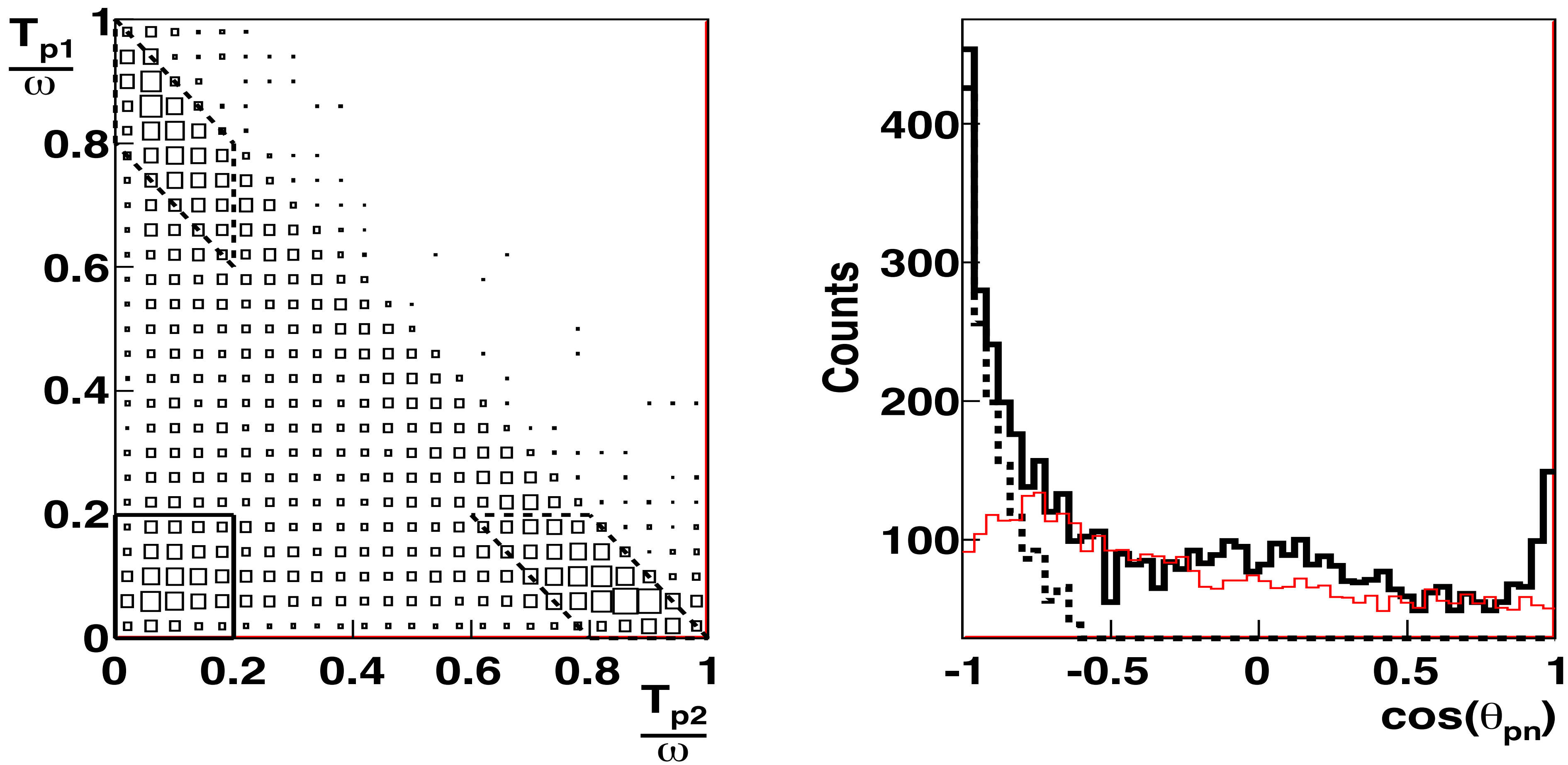
- dotted line PWIA
- dash-dot: Laget (PWIA)
- FSI (long dashed line) to full calculation (solid line), including meson-exchange current and final-state interactions: Laget
- In the 620 MeV/c panel
  - short dashed curve is a calculation with PWIA + FSI only within the correlated pair.



x = 1

Tensor Correlations Measured in $^3He(e,e',pp)n$

H. Baghdasaryan, L. B. Weinstein,et al. PRL 105, 222501 (2010)



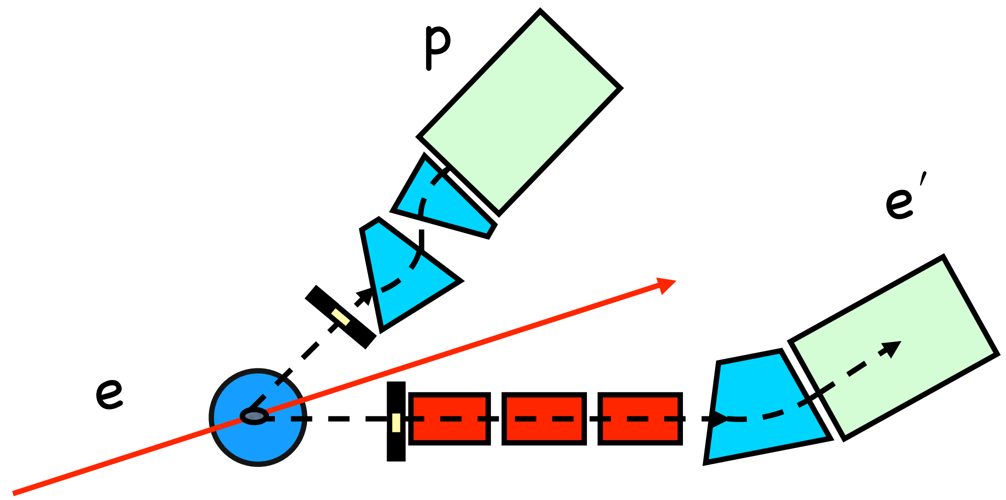
Events with one leading nucleon and a spectator correlated NN pair

- The spectator nucleons each have less than 20% of the transferred energy
- Leading nucleon's momentum perpendicular to $\vec{q}$ be less than 0.3 GeV/c.
- The ratio of pp to pn pair cross sections for $0.3 < p_{rel} < 0.5$ GeV/c is very small at low p_{tot} and rises to approximately 0.5 at large p_{tot}.

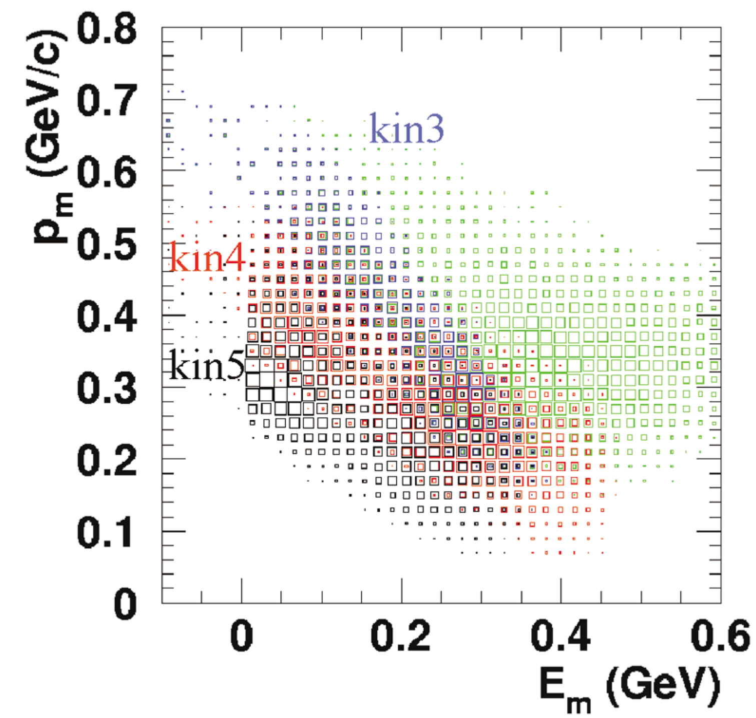
The pp pairs at low p_{tot} are in an s-state, this ratio shows the dominance of tensor over central correlations.

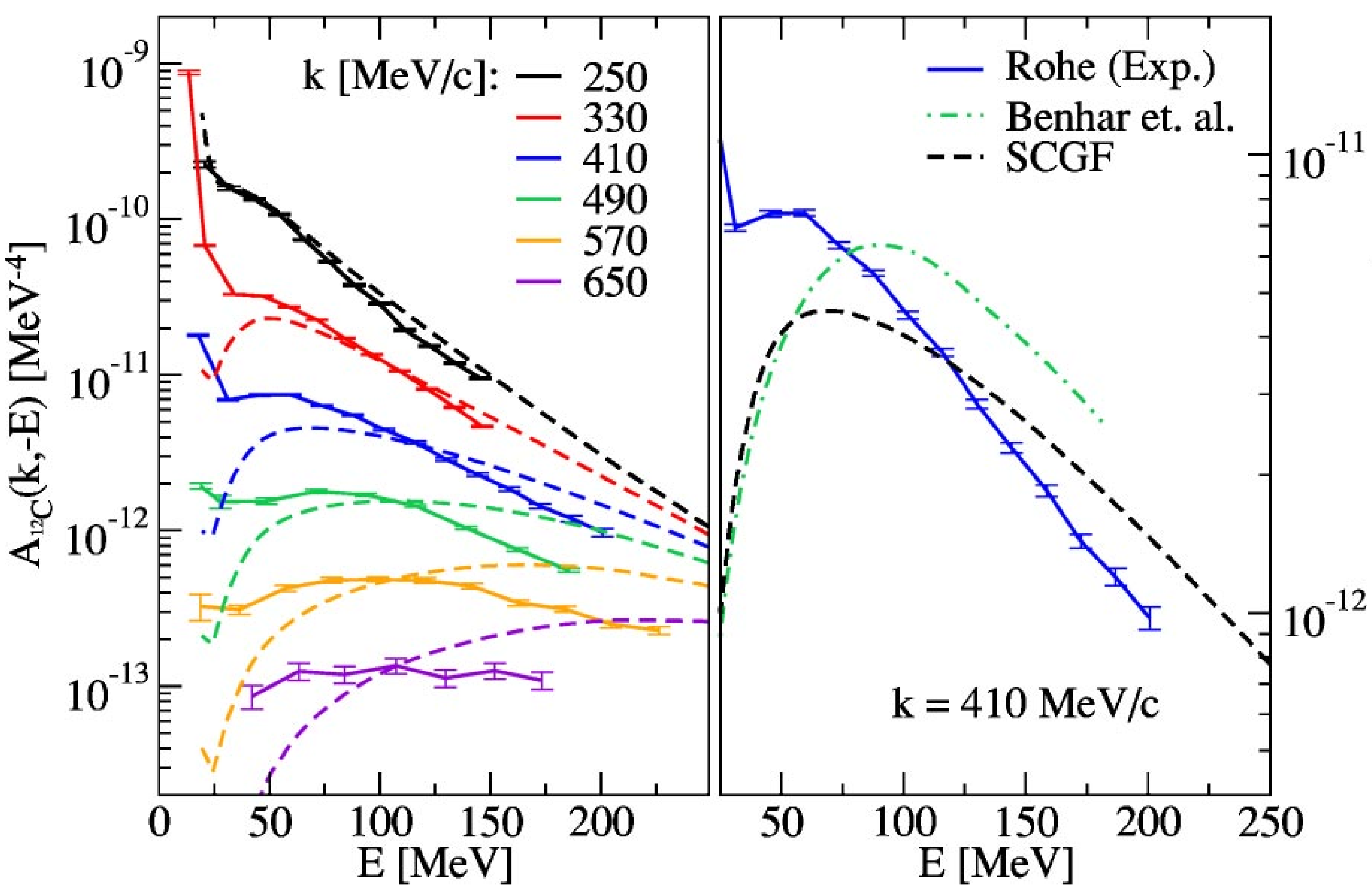
E97-006 Correlated Spectral Function and $^{12}C(e,e'p)$ Reaction Mechanism

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



SOS and HMS in Hall C





Data suggests more strength at smaller E - accessible at large x

Frick et al. PRC 70, 024309 (2004)

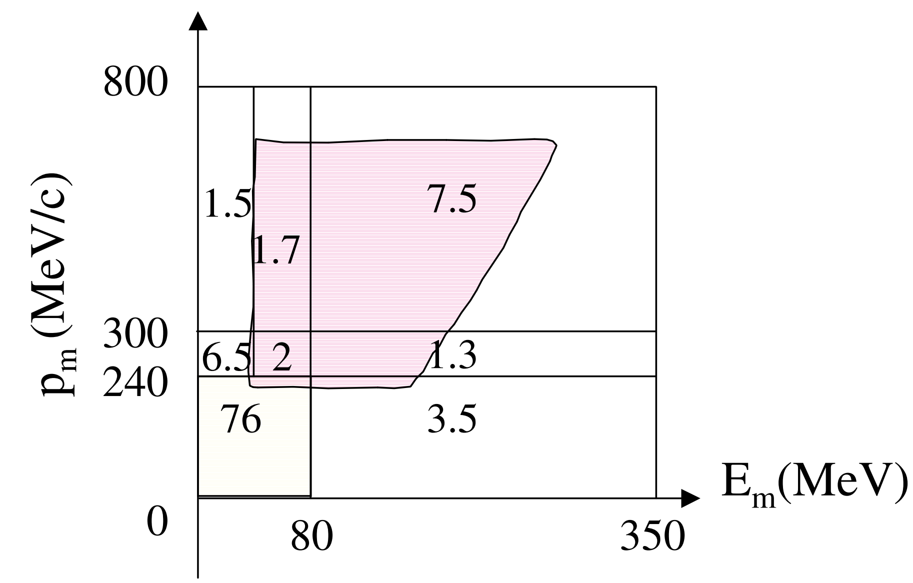
Self consistent Green's Function (SCGF)

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 % (↑ exp.)

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

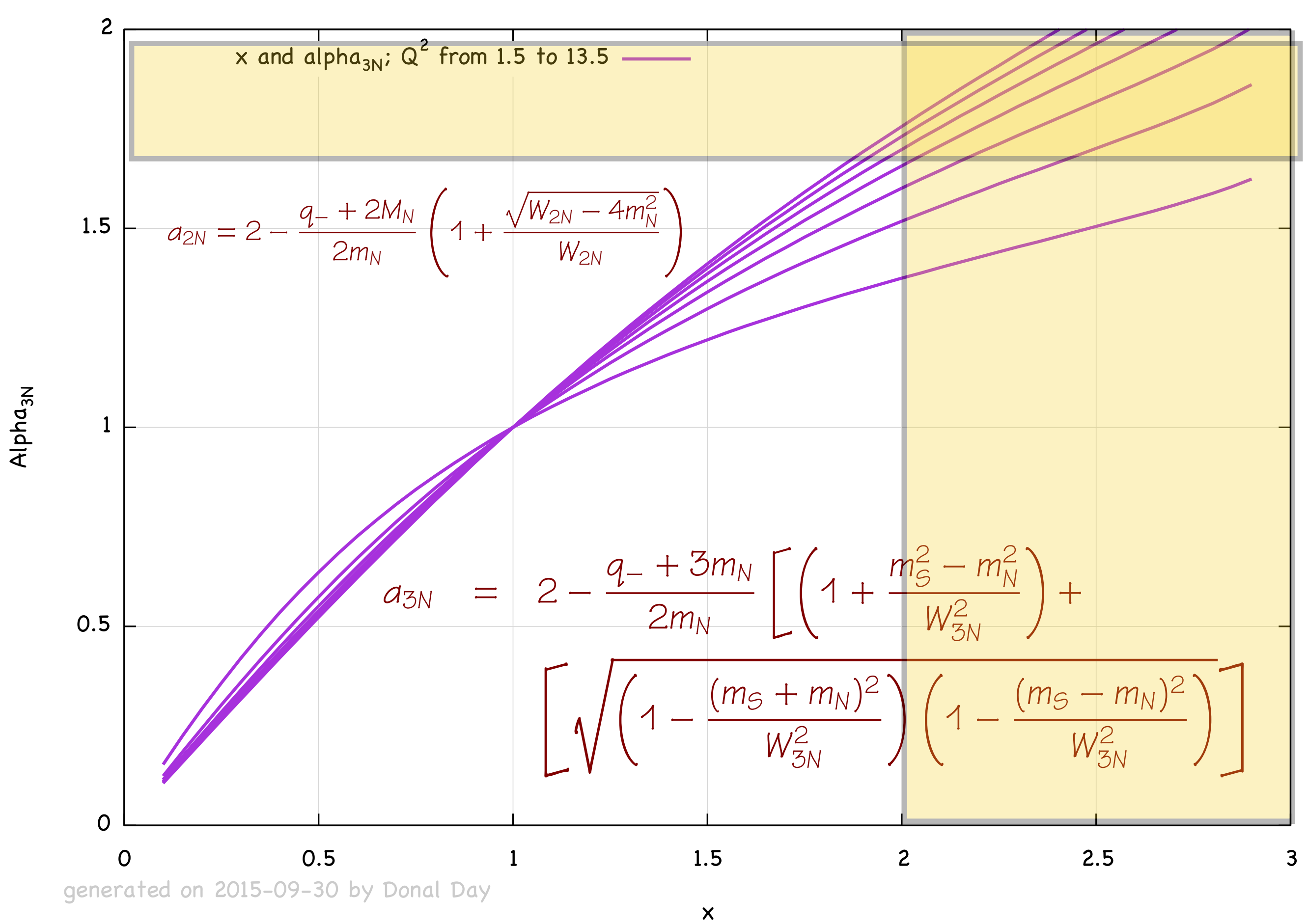
comparing to theory leads to conclusion that
≈ 20% of the protons in Carbon are beyond the IPSM region

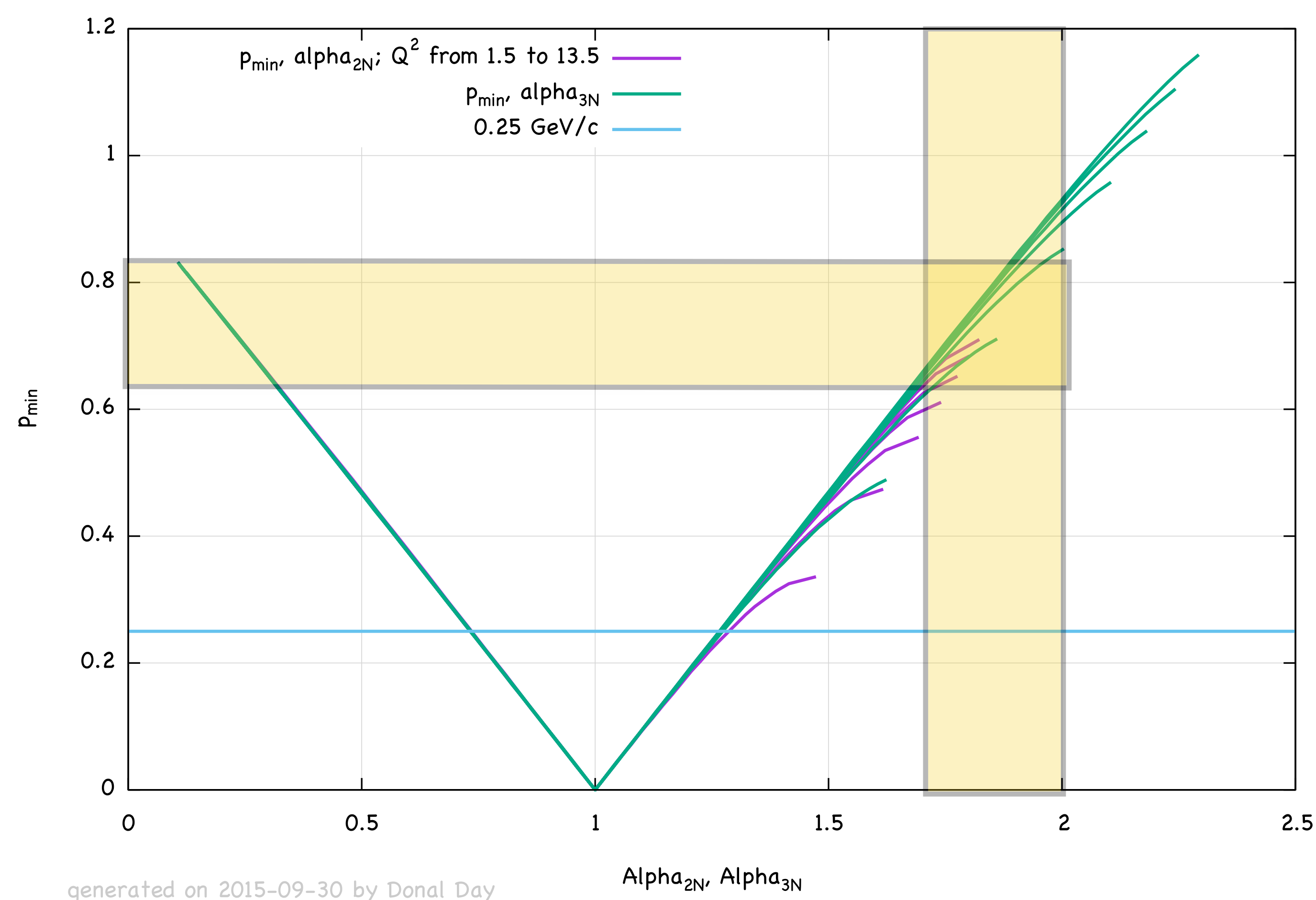
3N Correlations

2N SRC (3N SRC)

- p > k_F i.e. its momentum exceeds characteristic nuclear Fermi momentum, ($k_F \gtrsim$ 250 MeV/c)
- balanced by the momentum of a (two) correlated nucleon(s)
- In both cases the center of mass momentum of the SRC, $p_{cm} \lesssim k_F$

Where to look: >/= 600 MeV/c, Q^2 > 4, x = 2 - 3   Misak's talk





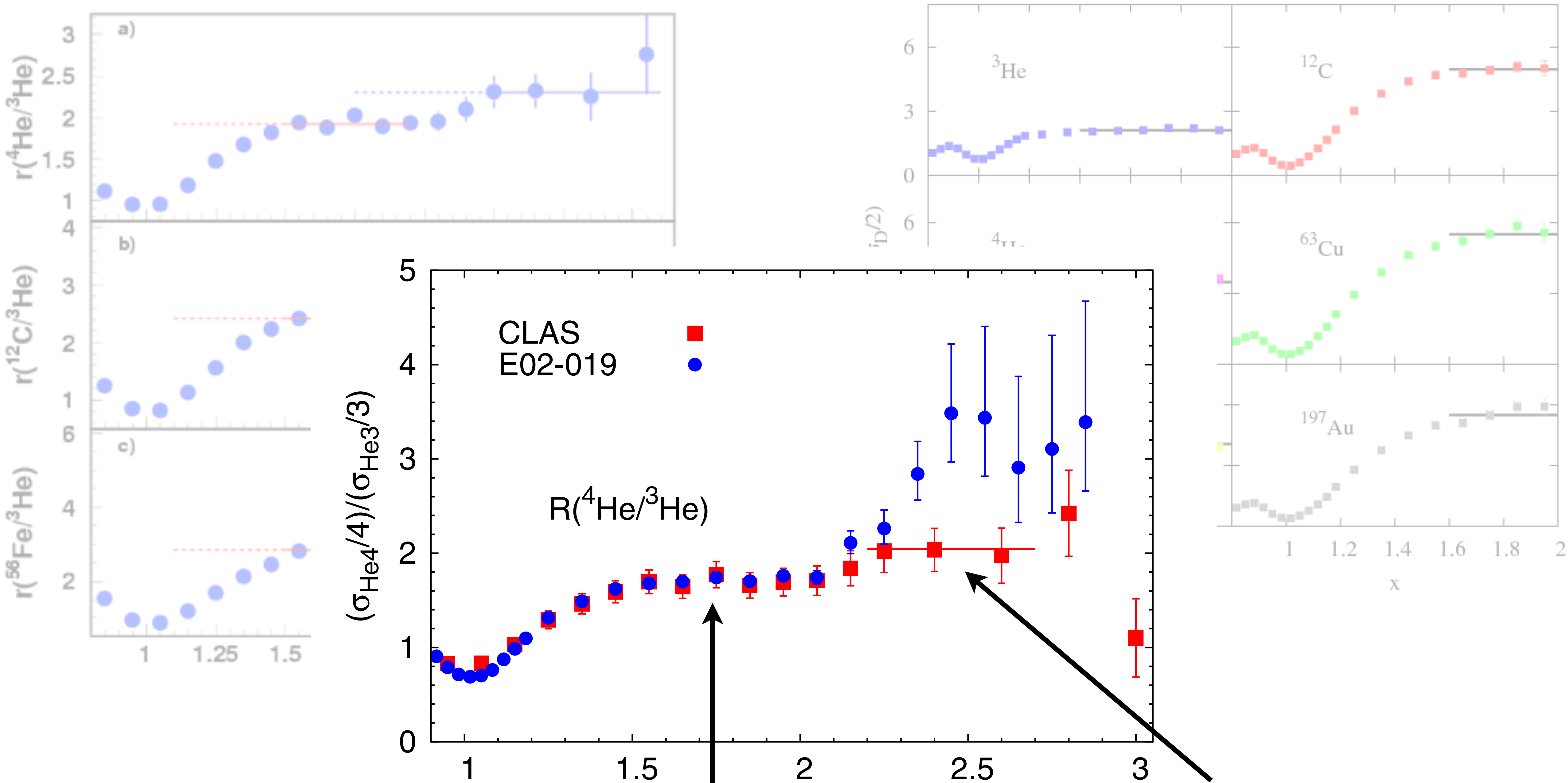
A(e,e') cross section ratios and SRC

Hall B

K. S. Egiyan et al., Phys. Rev. Lett. 96, 082501 (2006)

Hall C

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



Good agreement in the 2N-SRC region

but potential difference in the 3N-SRC region

Data from SLAC

Rock et al, PRC 26, 1593 (1982)

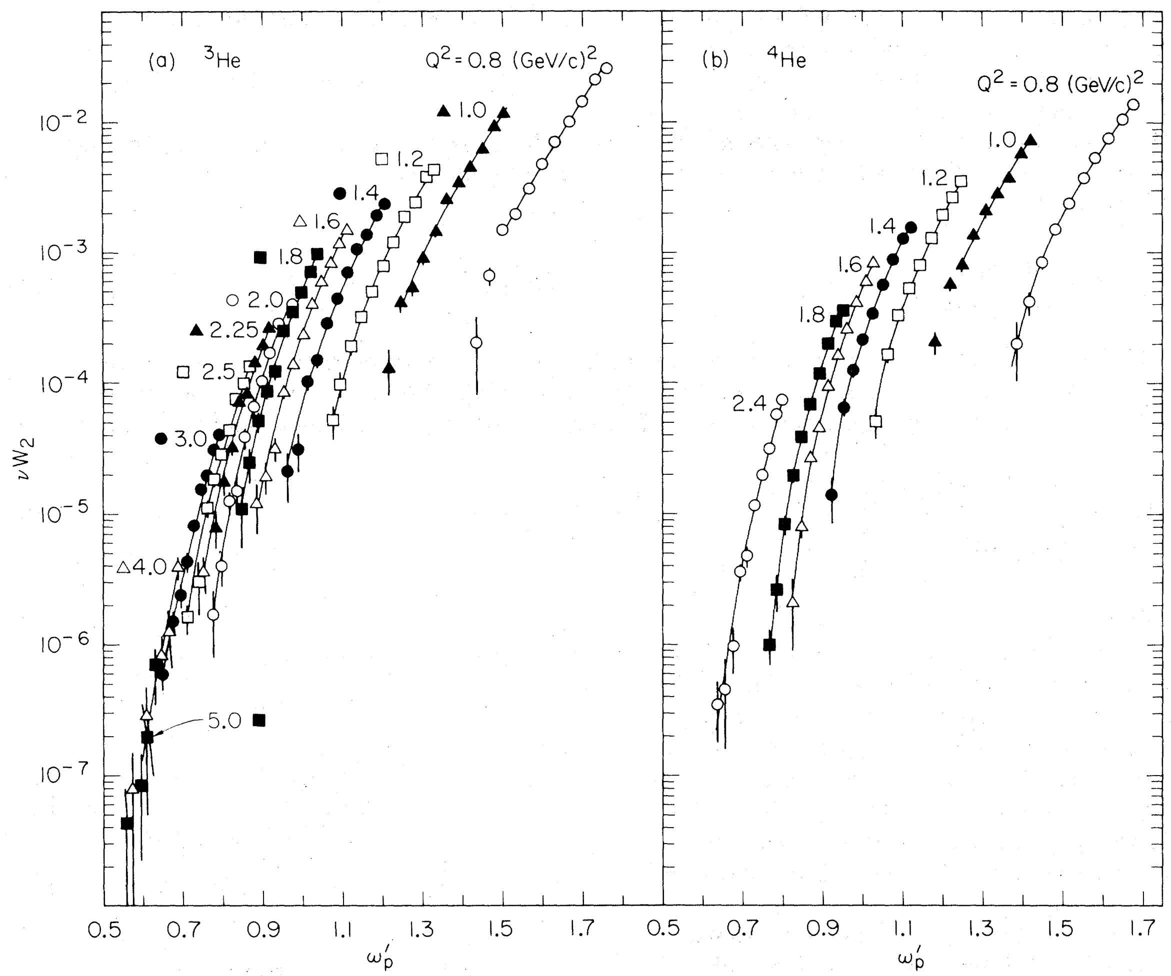
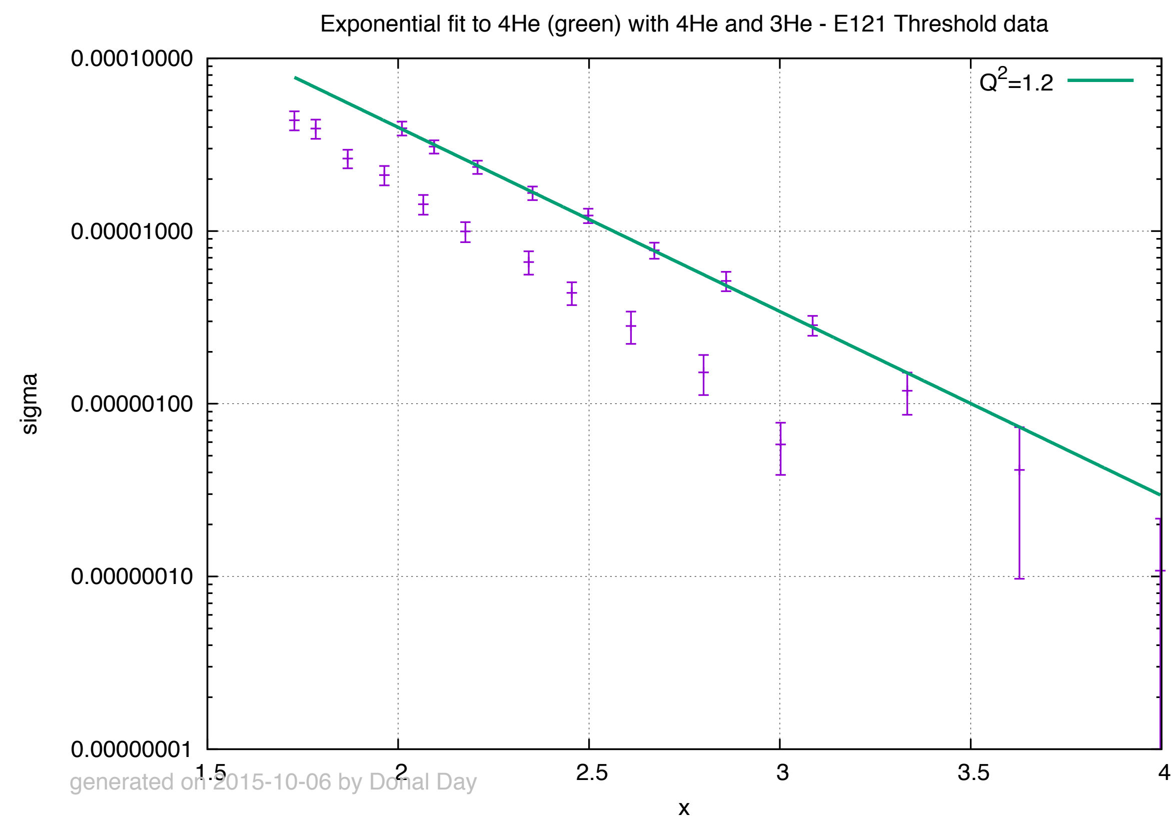
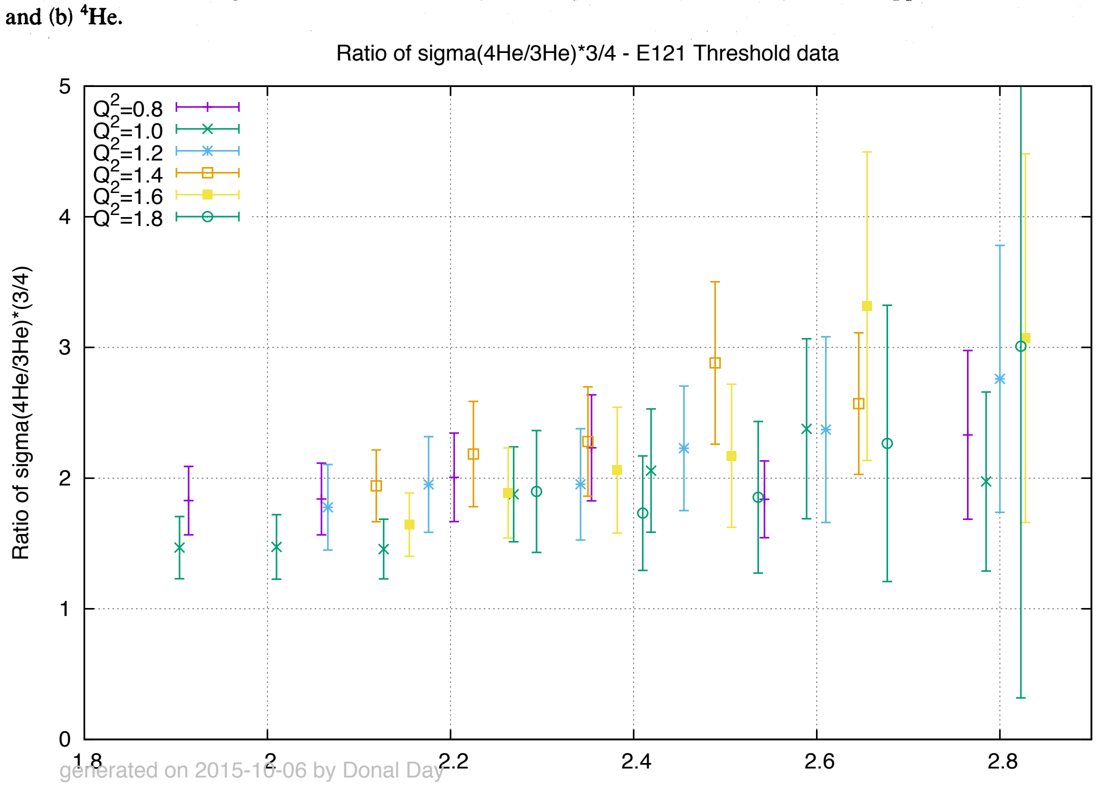
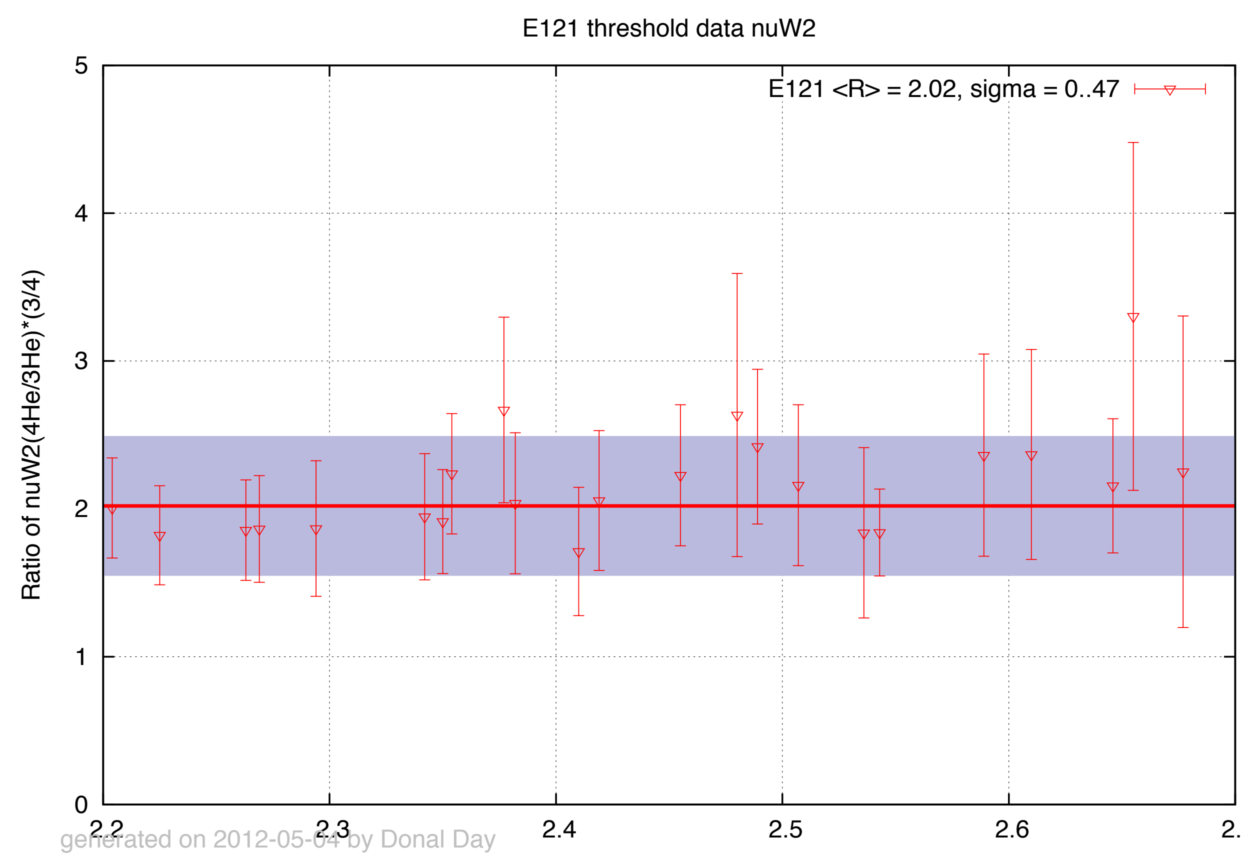


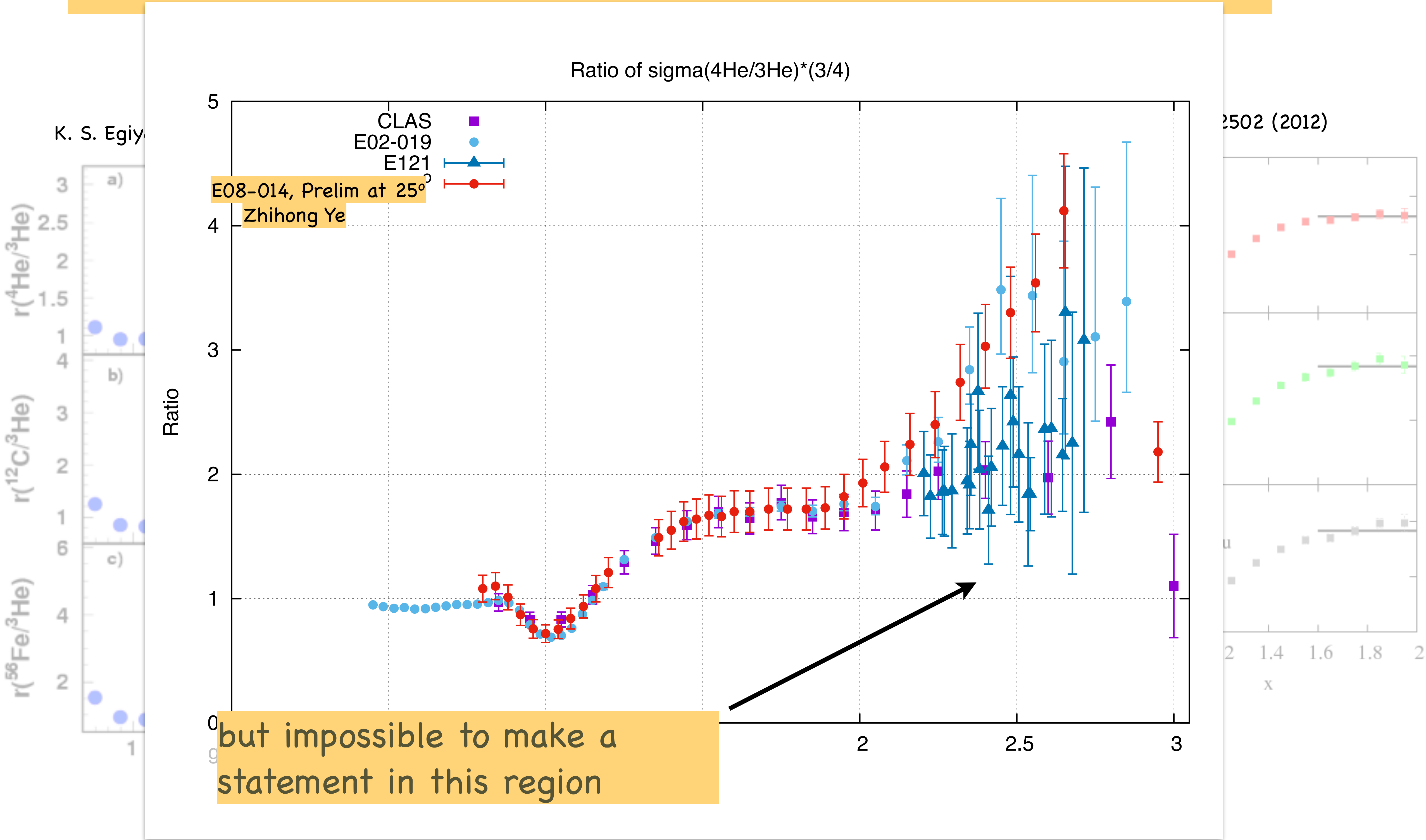
FIG. 7. The inelastic structure function νW_2 as a function of the scaling variable $\omega'_p = 1 + (M_p{}^2 + 2M_p\nu - Q^2)/Q^2$ for several different values of Q^2. The curves at fixed Q^2 are to guide the eye and they seem to approach a common limit, (a) ^{3}He and (b) ^{4}He.





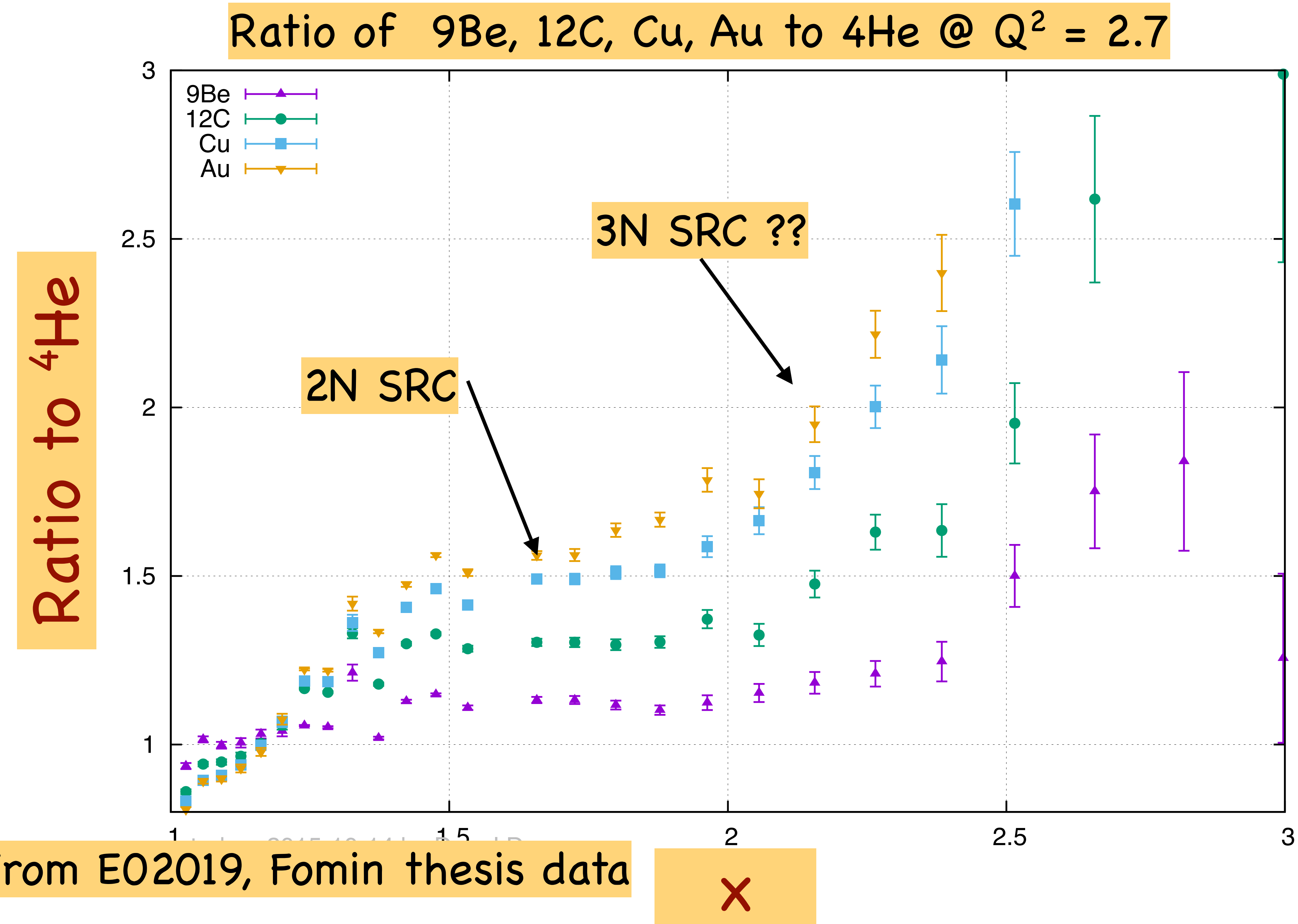


A(e,e') cross section ratios and SRC



More data at larger Q^2 needed, x> 1 at 12 GeV, E12-06-105, , see Arrington, Fomin talks.

A(e,e') cross section ratios and SRC



From E02019, Fomin thesis data

x

Acceptance effects, windows

E12-15-005: Measurements of Quasi-Elastic and Elastic Deuteron Tensor Asymmetries

Probe short-range repulsion and tensor force in nucleon- nucleon interaction through tensor asymmetries from quasi-elastic and elastic deuteron scattering

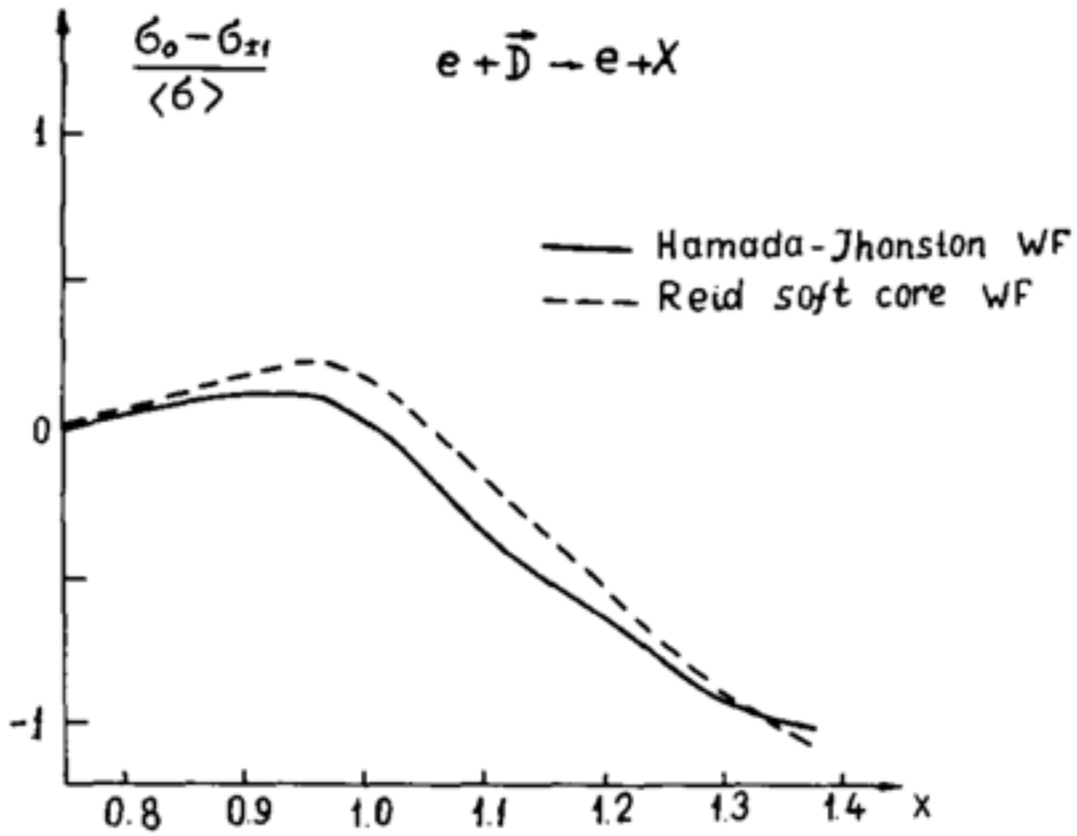
Tensor asymmetries are predicted to be sensitive to the D state probability as well as relativistic effects.

Conditionally Approved (44 days) on improving the tensor polarization and its measurement

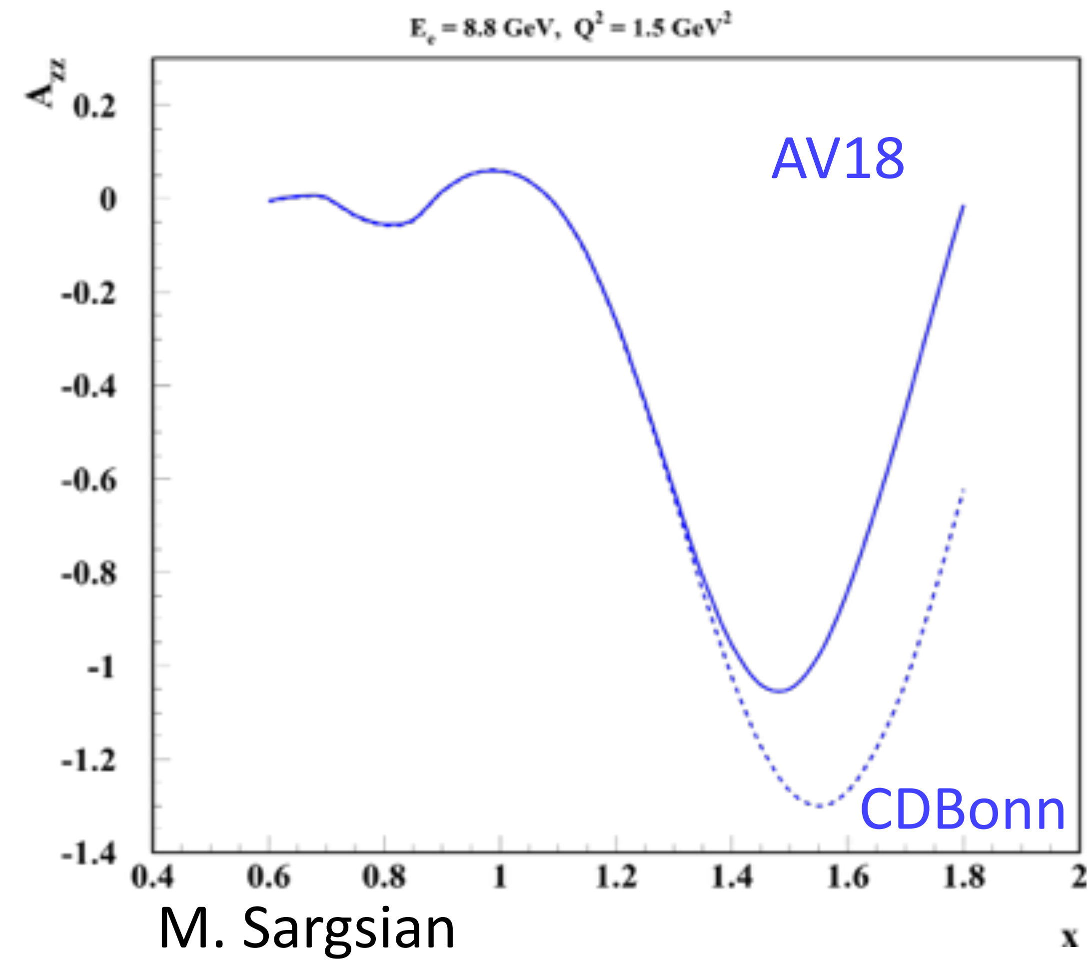
E.Long (UNH), DD, D. Keller, K. Slifer, P. Solvignon, D. Higinbotham

$$A_{zz} = \frac{2}{fP_{zz}}\left(\frac{\sigma_p - \sigma_u}{\sigma_u}\right), \text{ is sensitive to WF admixtures}$$

L.L. Frankfurt, M.I. Strikman, Phys. Rept. 76 (1981) 215



$$A_{zz} \propto \frac{\frac{1}{2}w^2(k) - u(k)w(k)\sqrt{2}}{u^2(k) + w^2(k)}$$



M. Sargsian

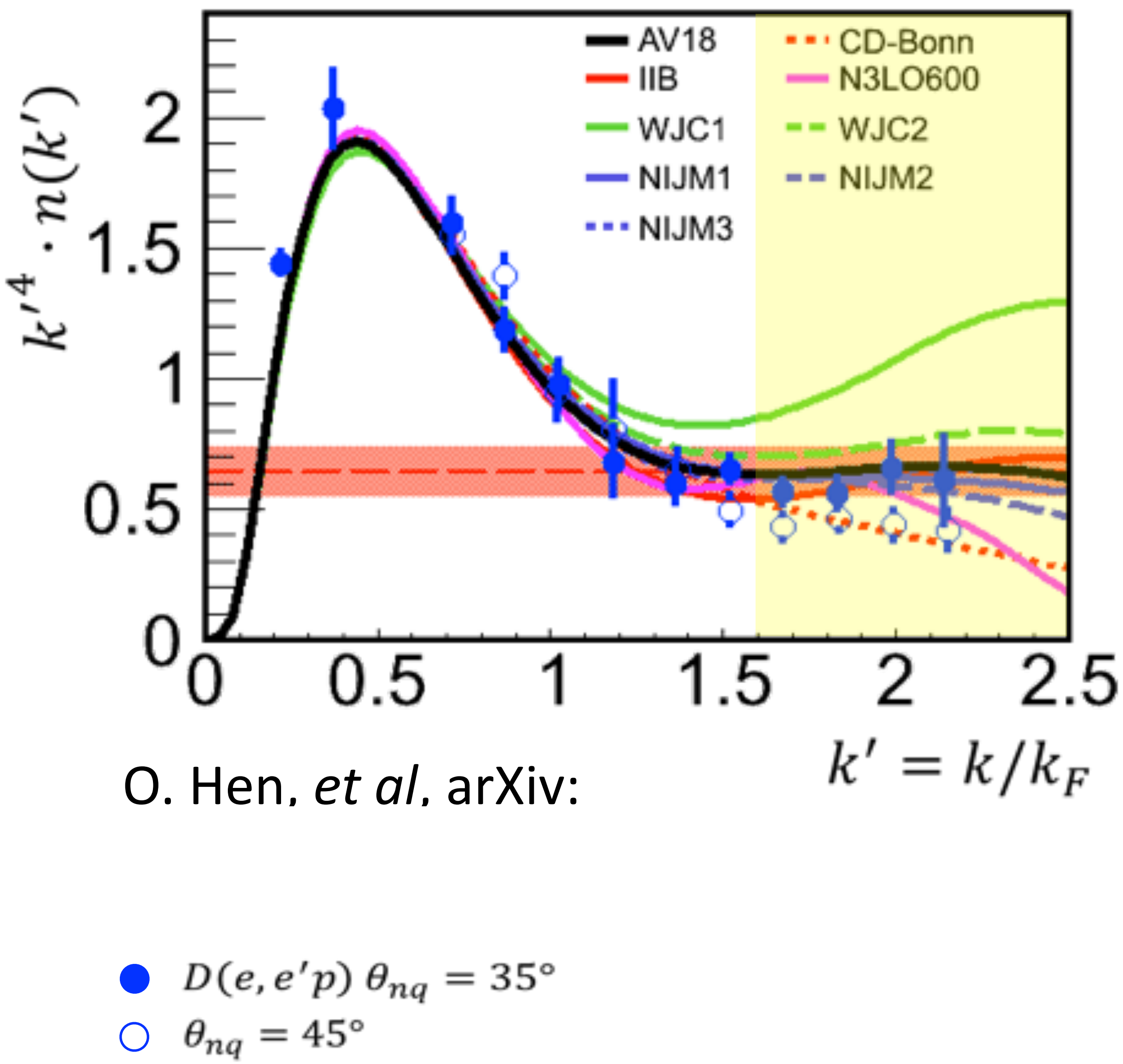
A_{zz} can be used to discriminate between hard and soft wave functions. In impulse approximation A_{zz} is directly related to the S- and D-states which have very different r and p behavior.

Modern calculations indicate a large separation of hard and soft WFs begins above the quasi elastic peak at $x > 1.4$

Deuteron Wave function

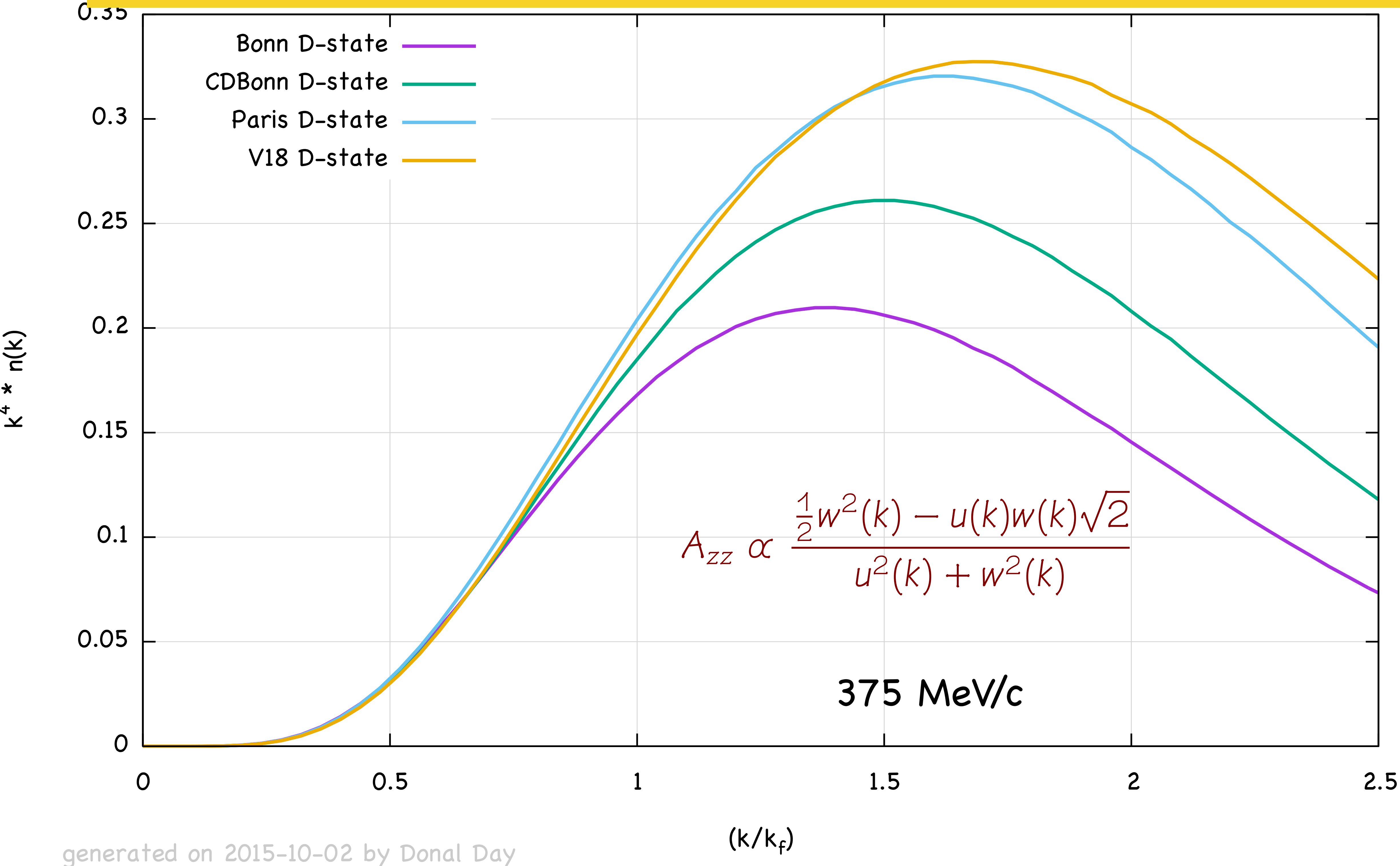
Is the deuteron wave function hard or soft?

- Hard like AV18 or softer like CD Bonn
- Unpolarized deuterons need to be probed at k > 500 MeV/c to distinguish between hard and soft WFs
  - Difficult, absolute cross sections
- At present no unambiguous evidence for hard/soft.
- Tensor polarization exposes the D-state, allowing hard and soft WFs to be distinguished at lower momenta

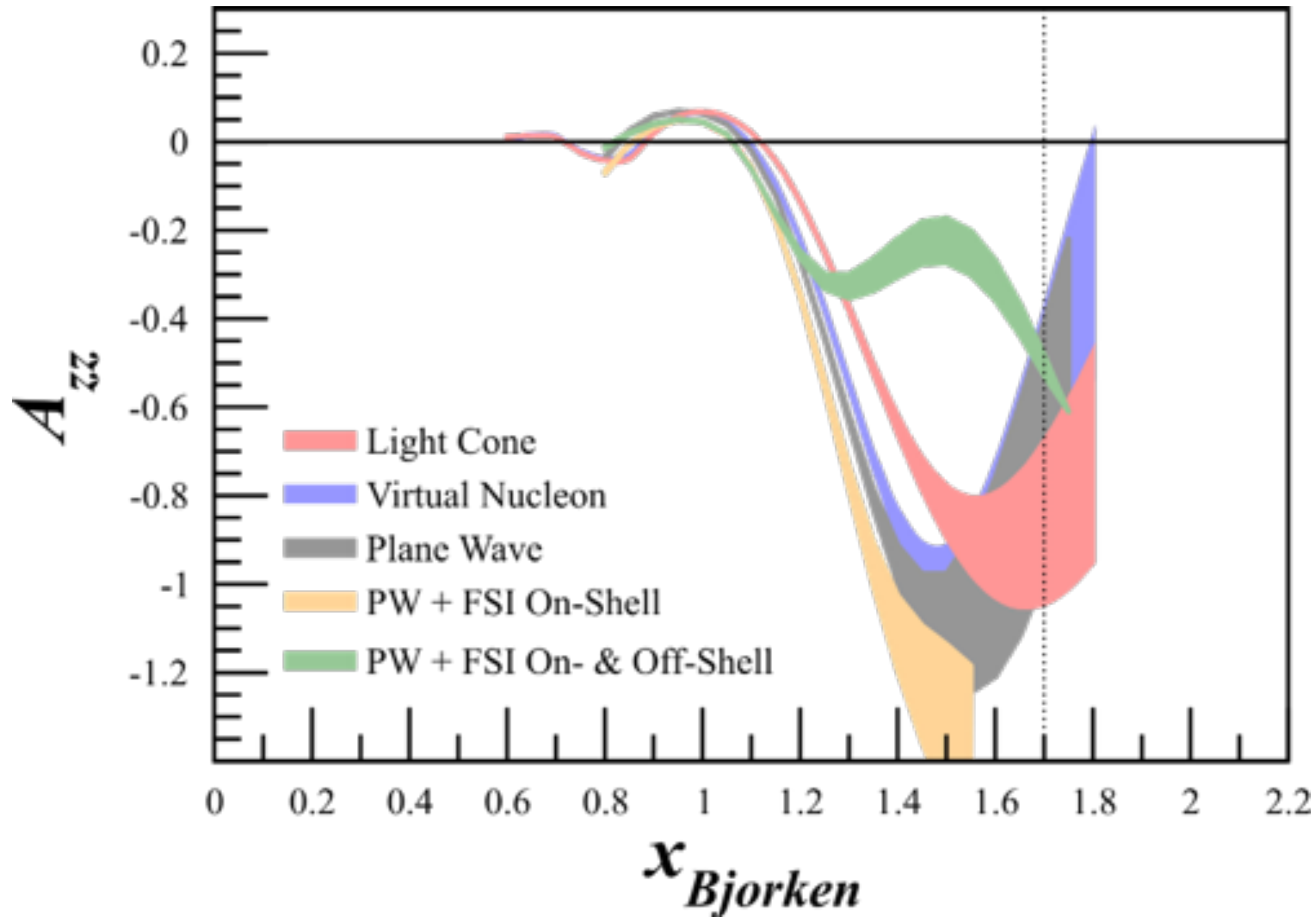


O. Hen, *et al*, arXiv:

Deuteron D-states differ at large k



Measurement of Quasi Elastic A_{zz}



Sensitive to effects that are very difficult to measure with unpolarized deuterons

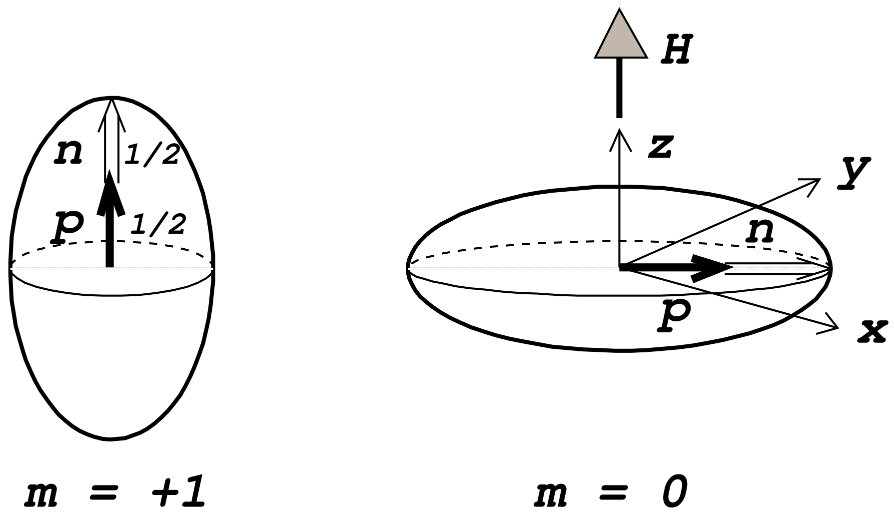
Huge 10-120% asymmetry

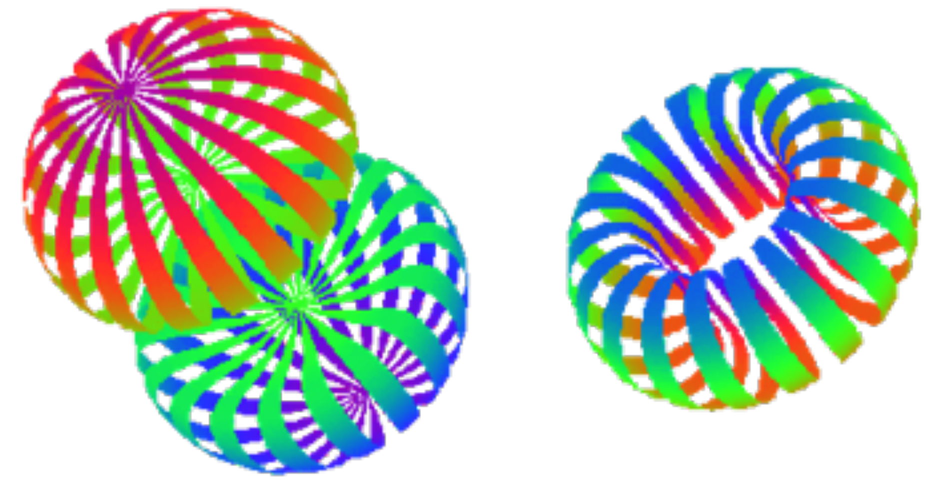
Measuring Azz over a range in x and Q^2 provides insight to

- Nature of NN Forces
- Hard/Soft wf
- Relativistic NN DynamicsOn-Shell/Off-Shell Effect FSI

Decades of theoretical interest that we can only now probe with a high-luminosity tensor-polarized target

Vector and Tensor Polarization of the Deuteron





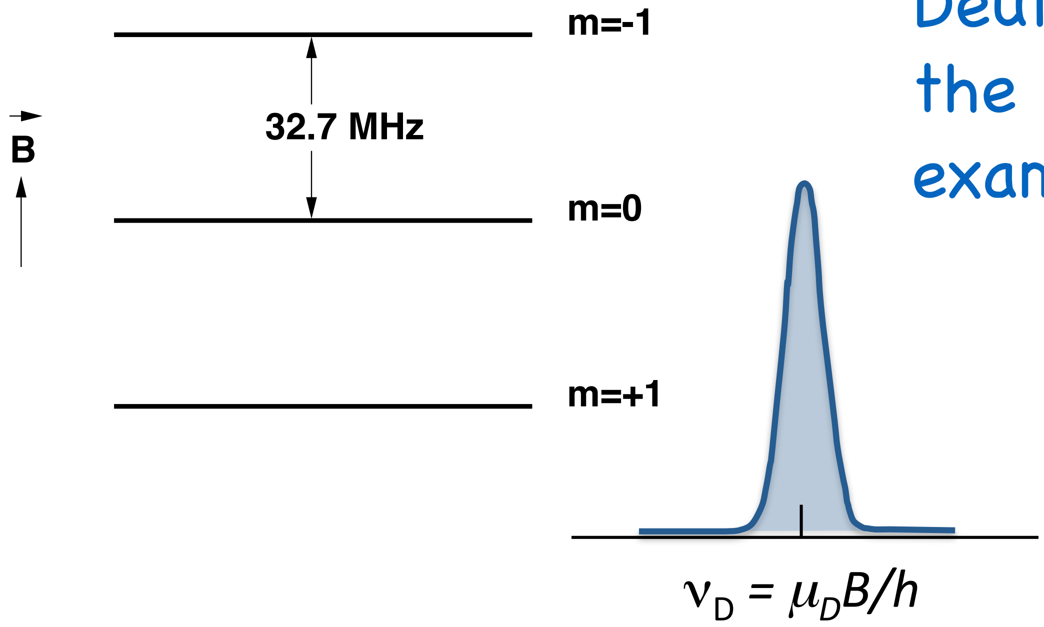
Deuteron in a magnetic field H, spin projection on Z can only take values m_d = +1, 0, −1.

If N_+, N_0, and N_- are the relative numbers in the substates m_d = +1, 0, −1, ($N_+ + N_0 + N_- = 1$), then vector p_Z and tensor p_{ZZ} polarizations of a deuteron target are:

Vector: $p_Z = N_+ - N_-$

Tensor (Alignment) $p_{ZZ} = N_+ + N_- - 2N_0 = 1 - 3N_0$.

Deuteron has quadruple moment that interacts with the electric field gradient in the lattice (in ND_3 for example)



ν_D = deut Lamour freq. (6.54 MHZ/Tesla)

ν_Q = ND_3 quadrupole freq (335.6 kHZ)

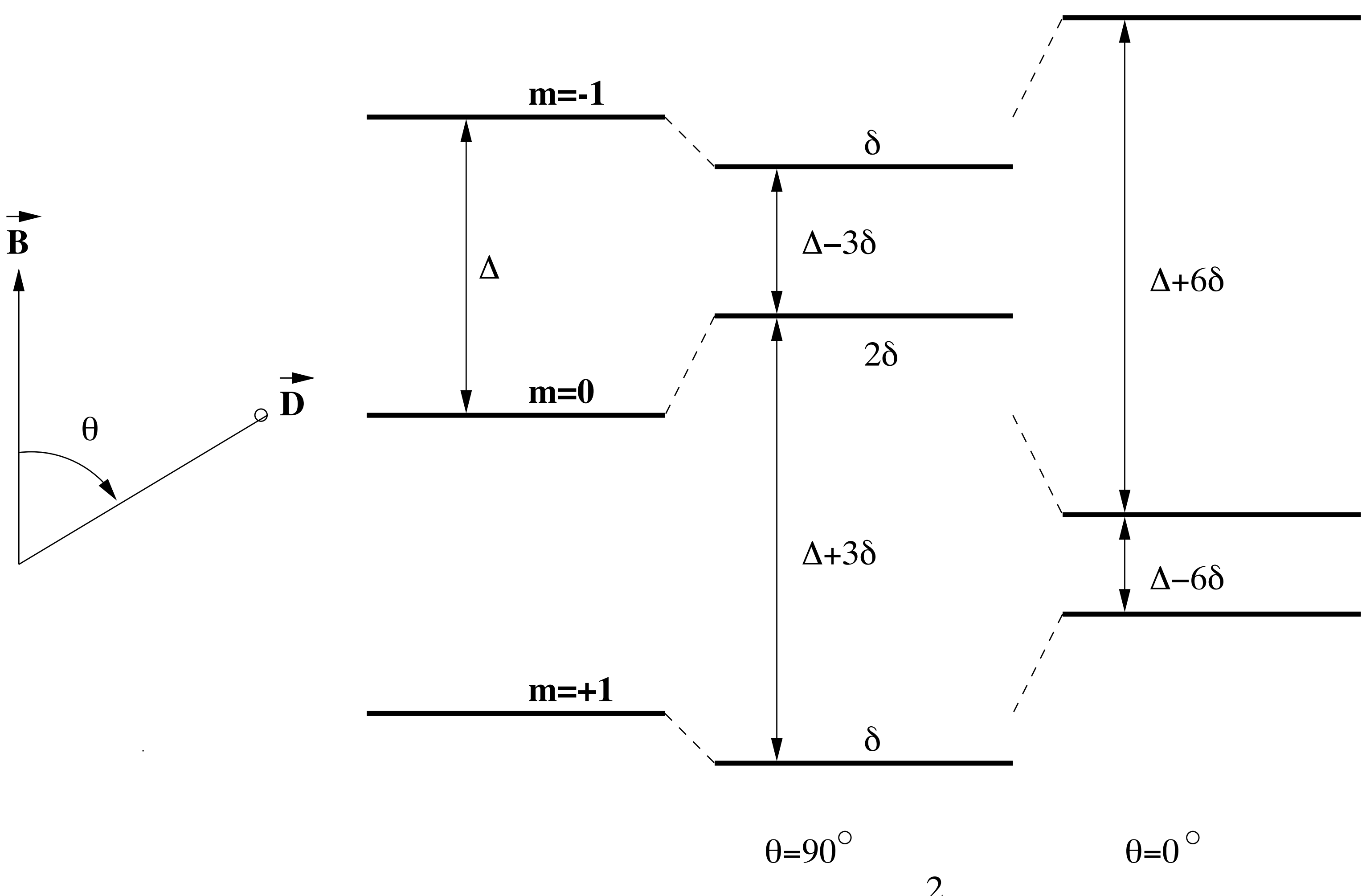
$= \frac{1}{8}\frac{e^2 qQ}{h}$

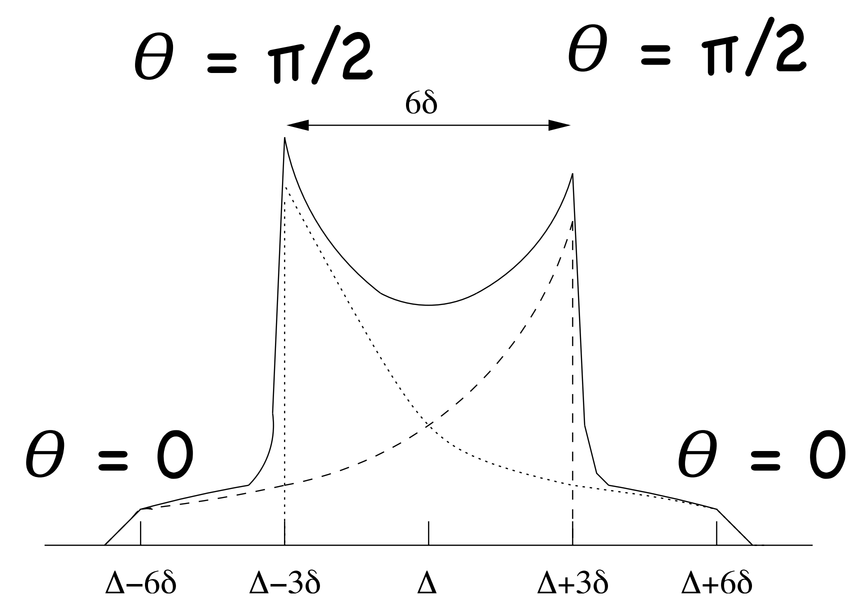
eQ = deuteron quadrupole moment

eq = electric field gradient

θ = angle between eq and B

$$E_m = -h\nu_D m + h\nu_Q[3\cos\theta^2 - 1][3m^2 - I(I+1)]$$



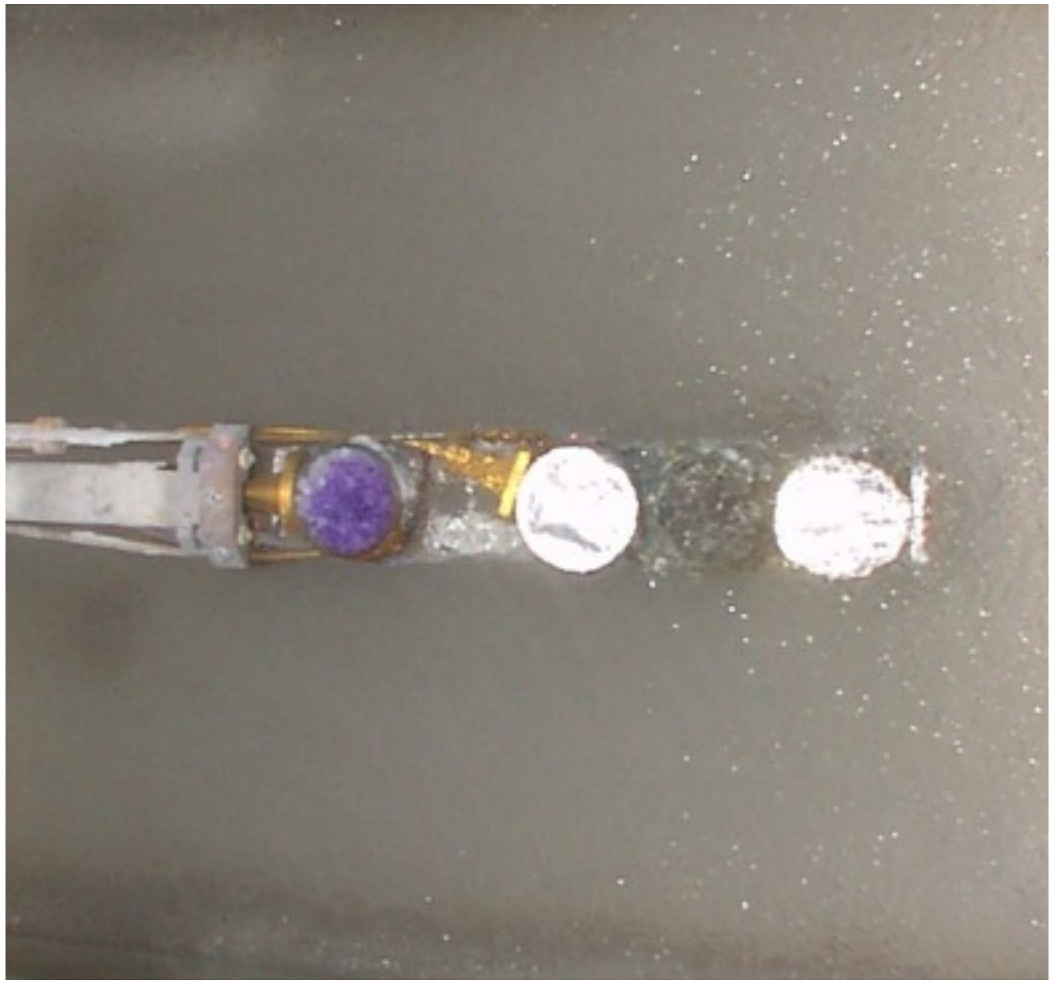


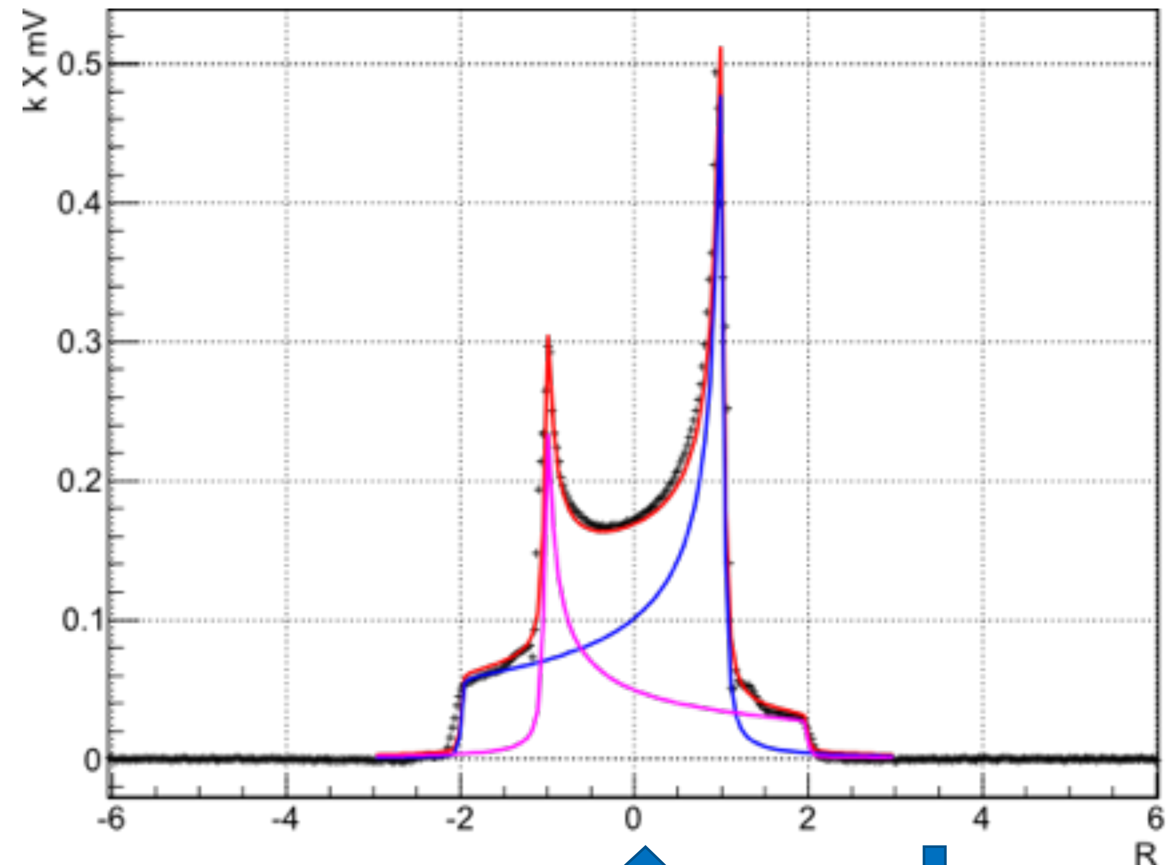
NMR line shape

Dynamic Nuclear Polarization

$$P_{zz} = 2 - \sqrt{4 - 3P_z^2}$$

50% Vector P_z =>> 20% Tensor





5 Tesla at 1K
3cm target length

Vector P_z = $p_+ - p_-$ ↑↑ - ↓↓

Tensor P_{zz} = $(p_+ + p_-) - 2p_0$ ↑↑ + ↓↓ - 2 ↑↓

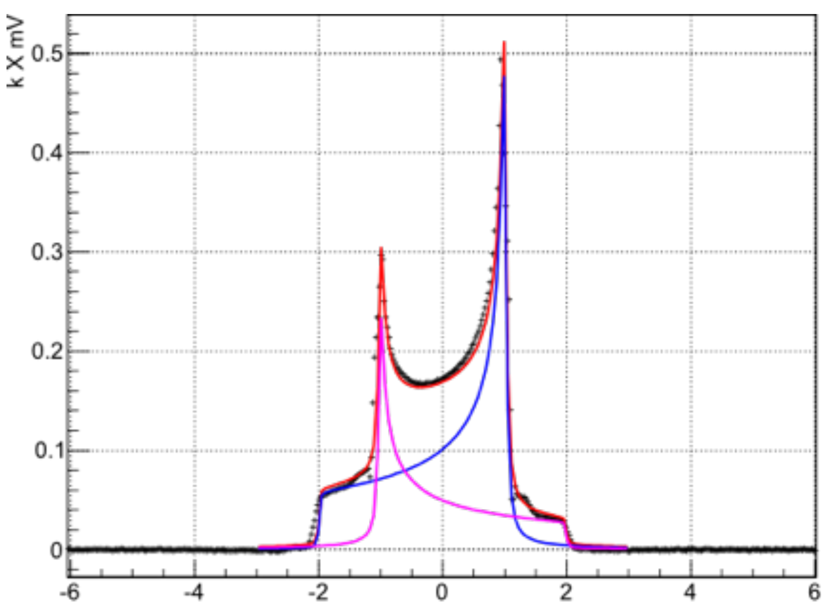
Positive Pzz: fill up the first two and minimize the m_0-state

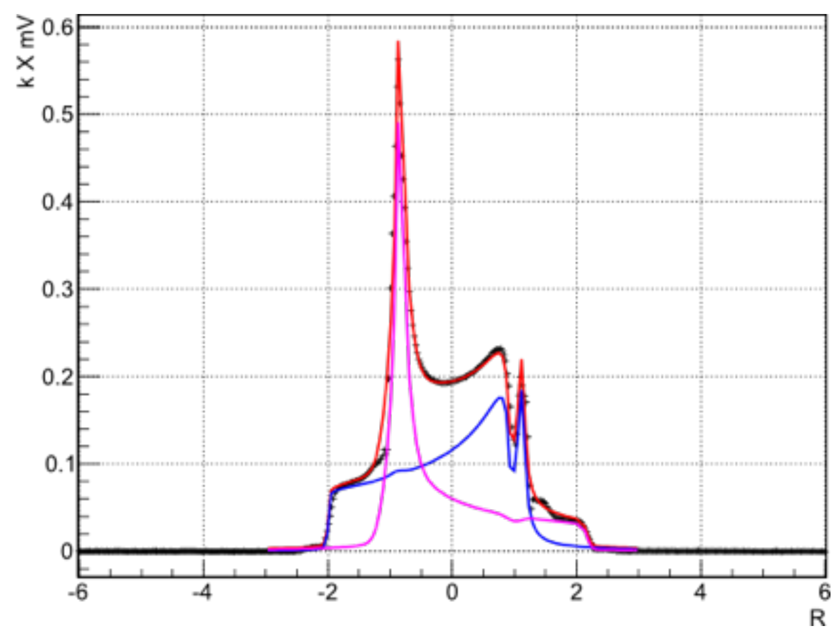
Tensor Polarization Progress

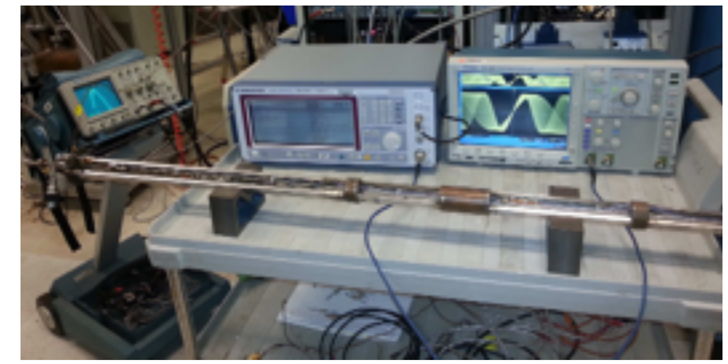
At UVa progress measuring P_{zz} through NMR line-shape analysis advancing (Dustin Keller)

Solid state NMR P_{zz} can be confirmed with elastic (T_{20})

Enhancement through RF hole burning







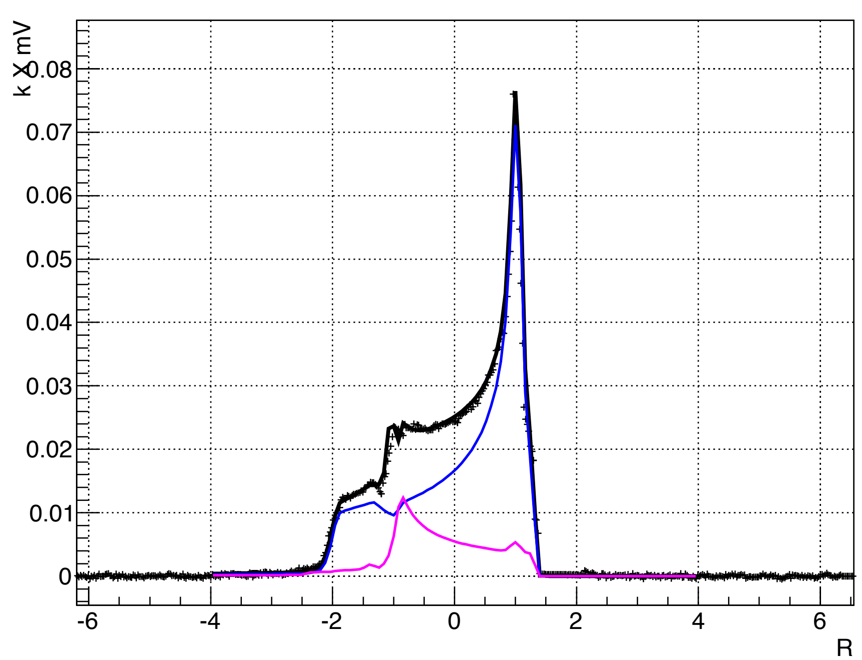
D Keller, PoS(PSTP 2013) 010

D Keller, HiX Workshop (2014)

D Keller, J.Phys.:Conf.Ser. 543, 012015

UVA Tensor Enhancement on Butanol (

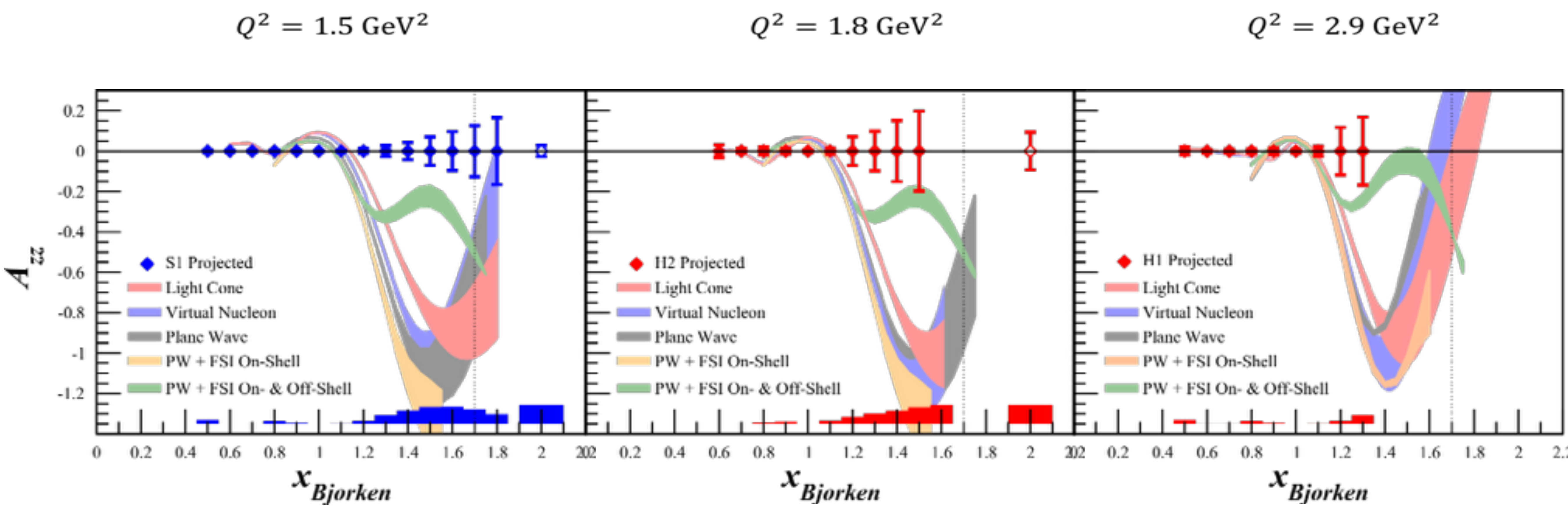
D Keller, PSTP 2015, to be published



$P = 0.503 \rightarrow 0.447$

$P_{zz} = 0.196 \rightarrow 0.325$

A_{zz} for Q^2 > 1 GeV^2 with P_{zz} = 30%



LL Frankfurt, *et al*, PRC **48** 2451 (1993)

Solid = Quasi-elastic
Open = Elastic

Summary

- 2N SRC and their isospin dependence (anticipated by our understanding of the NN interaction, is now firmly established in multiple observables, experiments projectiles, final states and nuclei
- Relation of SRC to EMC established - only lacking are calculations that exposes the underlying connection
- Refined theory and calculation are needed incorporating SRC, FSI, and off-shell behavior will advance understanding
- SRC demand high densities (momenta, virtuality) and, if these rare fluctuations can be captured, they should expose, potentially large, medium modifications
- 3N SRC are as yet unseen in inclusive electron scattering - some sleuthing underway
- Approved experiments across labs with different focuses over next 5-7 years will reveal much
- Next big opportunity in inclusive scattering (in my view) is the transition from QES to DIS at $x > 1$ at very large momenta transfer
- Tensor polarized targets advances will allow exposure of deuteron wf through asymmetry measurements
    - Opportunities exist for experiments with electrons and photons on tensor polarized deuterons