Short-Range Correlations in Nuclei

Or Hen – MIT

NuINT17, June 26th 2017, U. Toronto, Canada.

Nuclear Physics and Neutrino Oscillations

Issue I: Incident neutrino energy reconstruction from the measured final state.

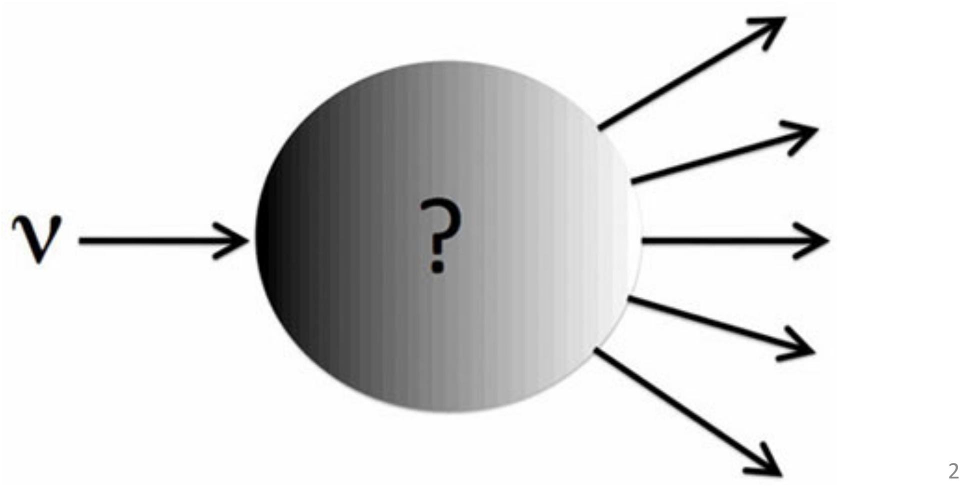
Issue II: Interaction cross-section defines the 'no oscillation' baseline.

Issue III: proton-neutron dynamics can induce non CPV differences between neutrino and anti-neutrino interaction rates.

…

Nuclear Physics Inputs:

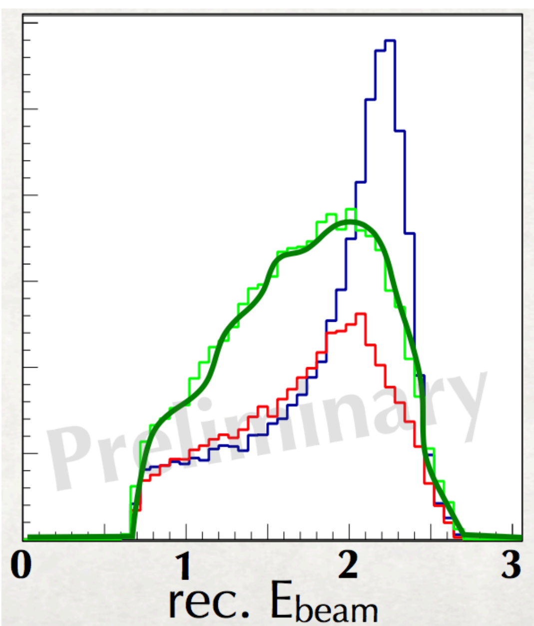
- **Model of the *Nucleus*.**
- **Model of the *Interaction*.**

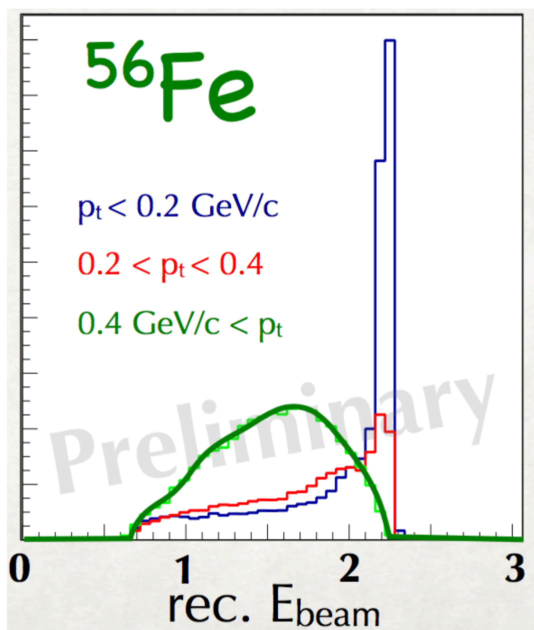


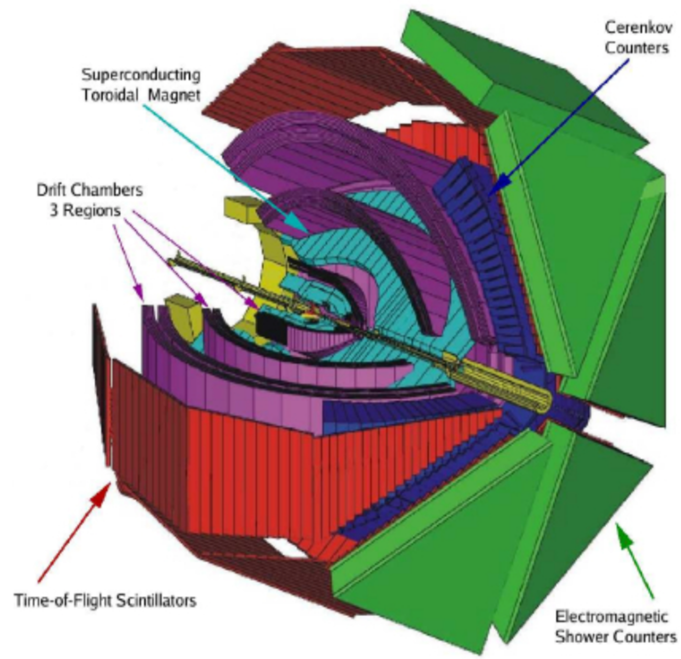
Nuclear Physics and Neutrino Oscillations

Using JLab CLAS **data** to study incident neutrino energy reconstruction and reaction modeling.

See talk by M. Khachatryan and E. Cohen

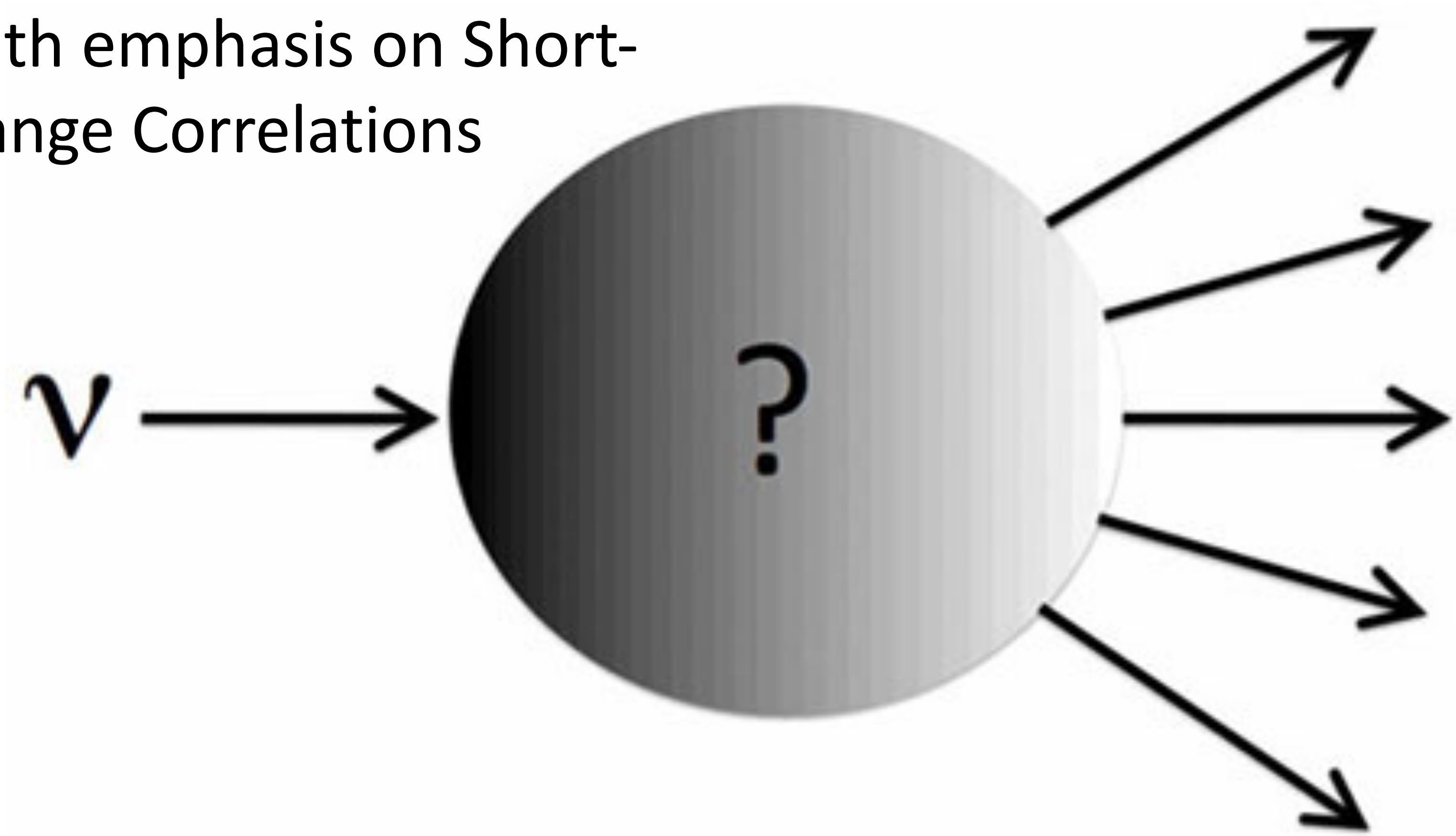






Nuclear Physics and Neutrino Oscillations

Today: Improve modeling of the nuclear ground state, with emphasis on Short-Range Correlations



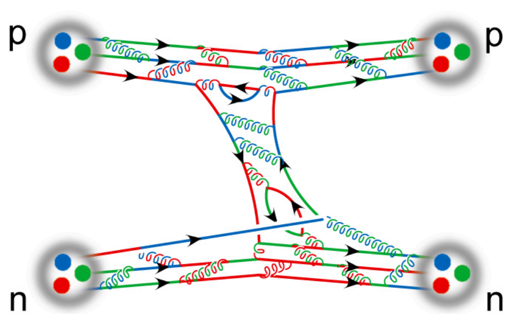
Nuclear Many-Body Challenge

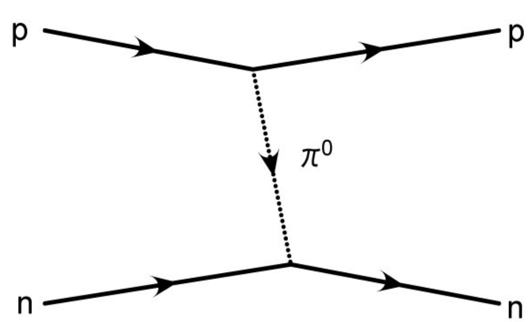
Many-body Schrödinger Equation

$$\sum_i \left\{ -\frac{\hbar^2}{2m_i} \nabla_i^2 \Psi(\vec{r}_1, \ldots, \vec{r}_N, t) \right\} + U(\vec{r}_1, \ldots, \vec{r}_N) \Psi(\vec{r}_1, \ldots, \vec{r}_N, t) = i\hbar \frac{\partial}{\partial t} \Psi(\vec{r}_1, \ldots, \vec{r}_N, t)$$

<u>Main Challenges:</u>

1. No ‘fundamental’ Interaction.
2. Complex phenomenological parametrizations (e.g. over 18 operators)

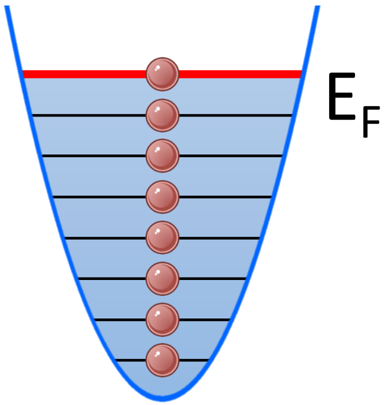




Remarkable progress – see talks by Carlson and Lovato

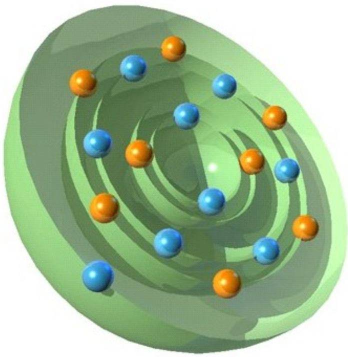
Solution: Effective Theories

Fermi Gas Model

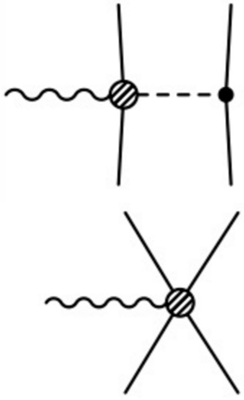


Liquid Drop Model

Shell Model



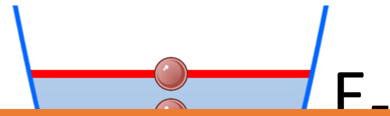
Chiral Perturbation Theory*



* Should converge to exact solution

Solution: Effective Theories

Fermi

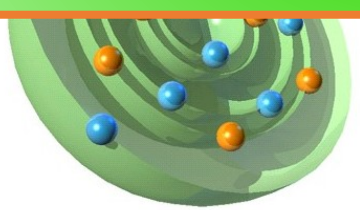


Liquid

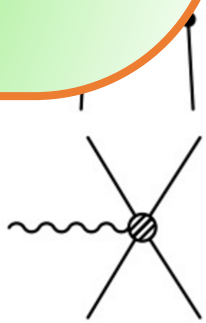
Common idea:

Scale separation of *long* and *short* range dynamics

Model



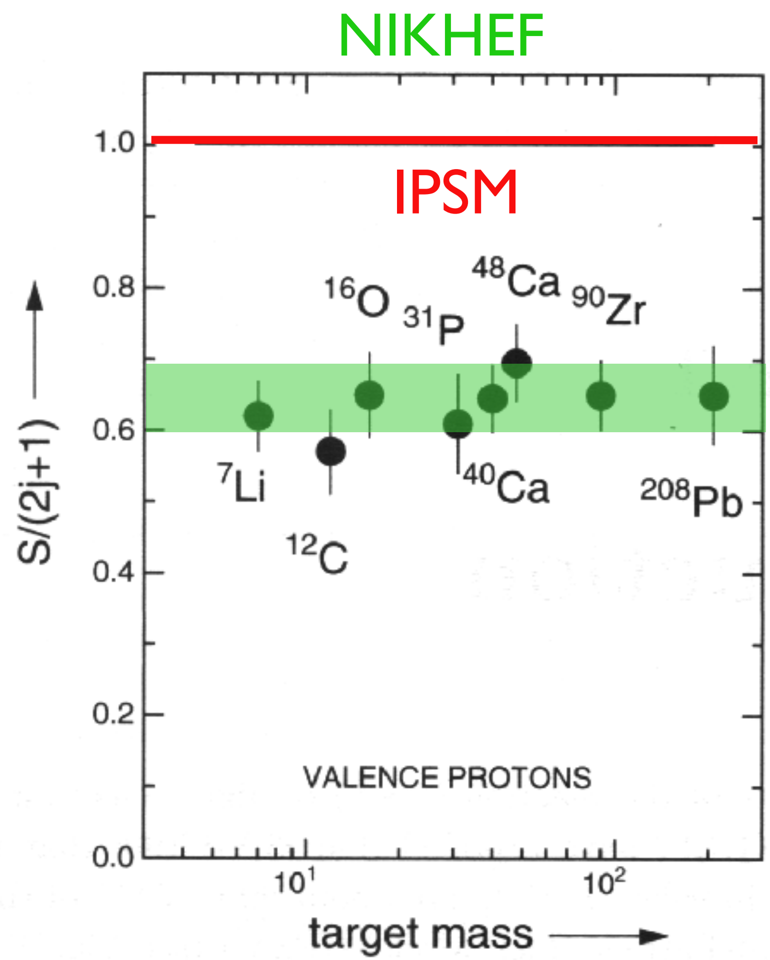
Perturbation Theory*



* Should converge to exact solution

Long-range dynamics

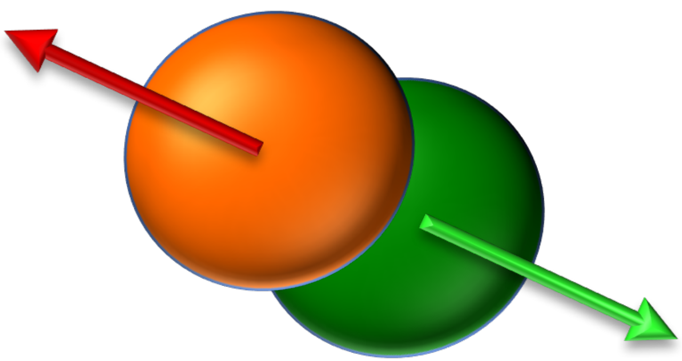
- Described overall well by mean-field models.
- Non negligible pairing effects at long and short distances (/ low and high energy).
- Today's focus is on high-energy, short-range, pairing

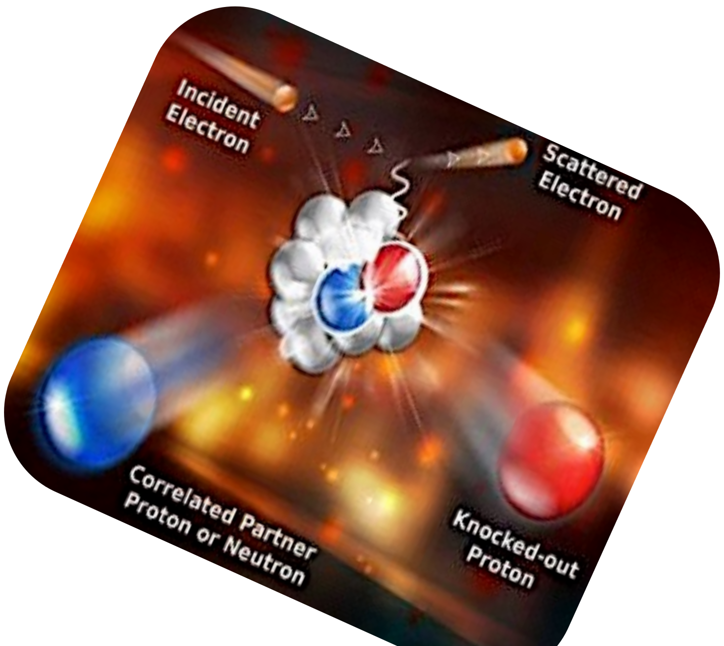


What Are SRC?

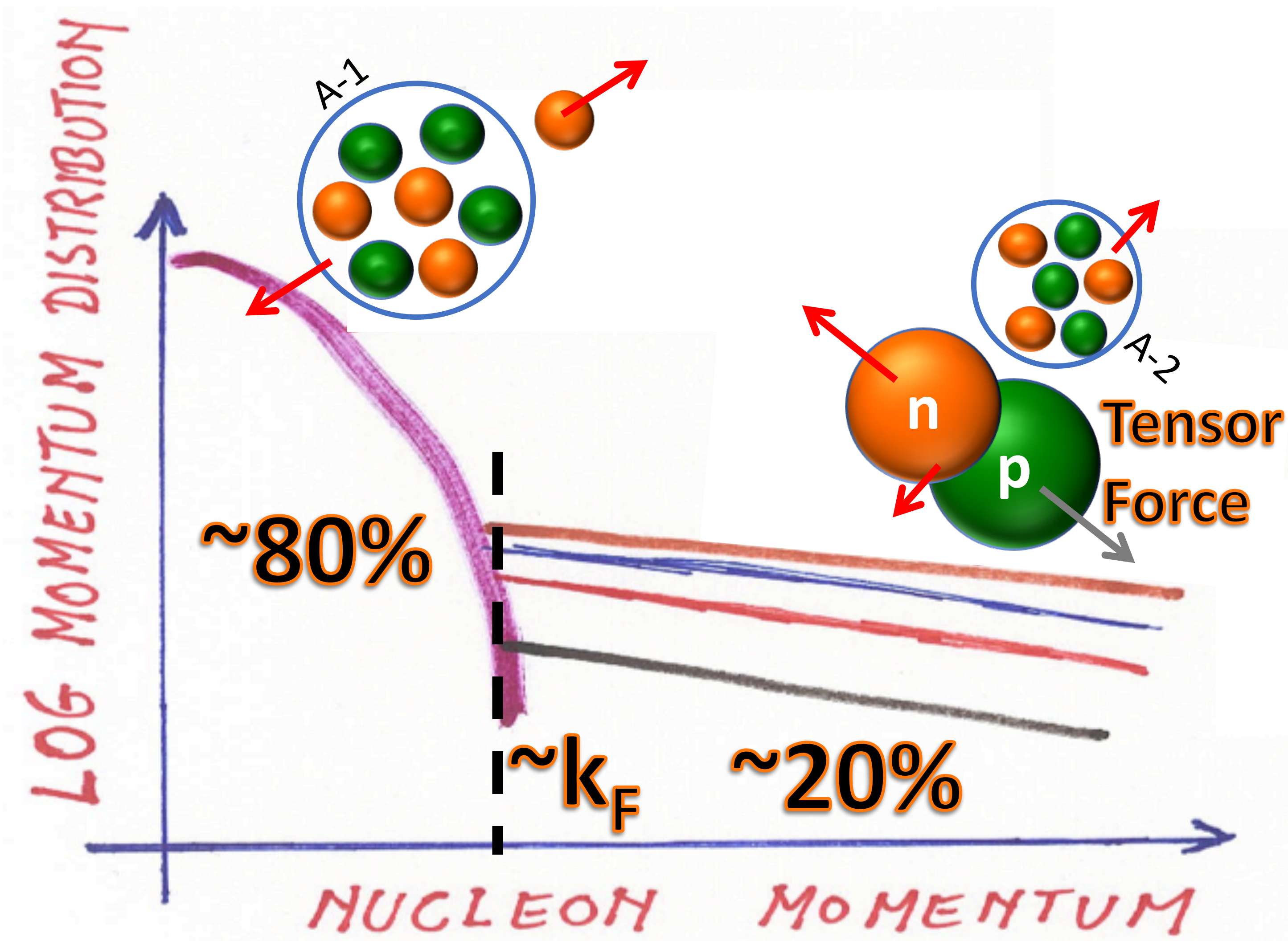
SRC are pairs of nucleon that are close together in the nucleus (wave functions overlap)

=> Momentum space: pairs with *high relative momentum* and *low c.m. momentum* compared to the Fermi momentum (k_F)



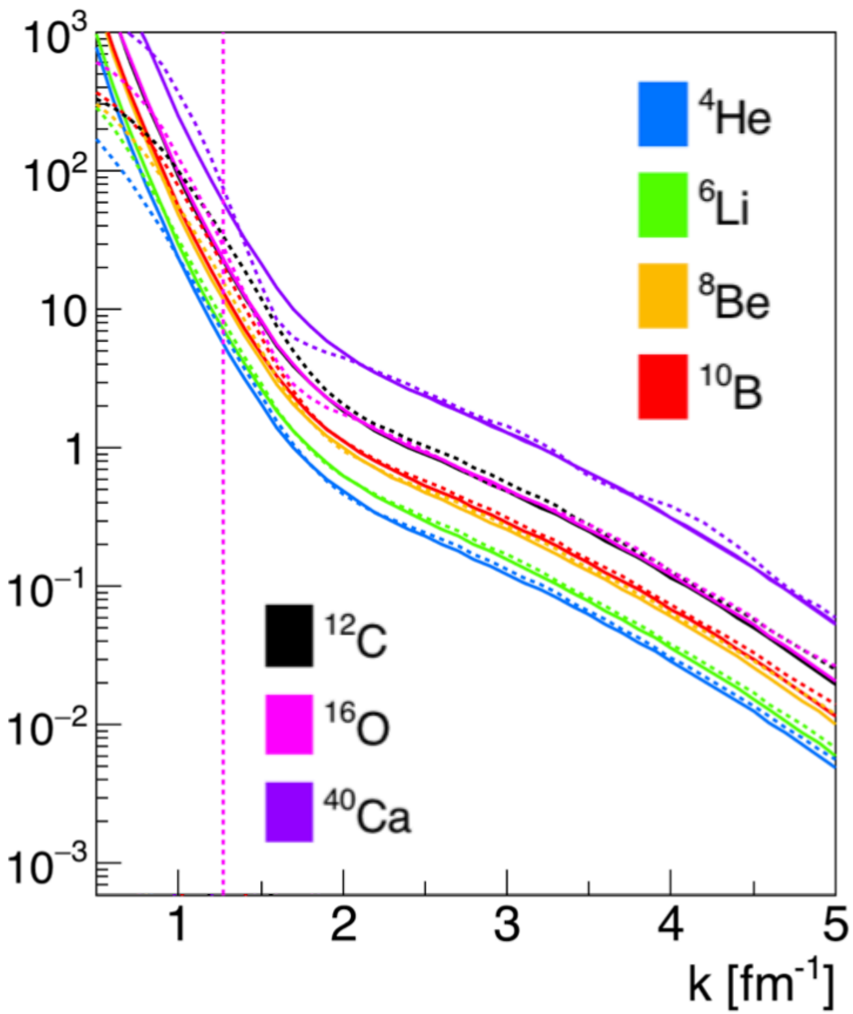


What do we know about SRC



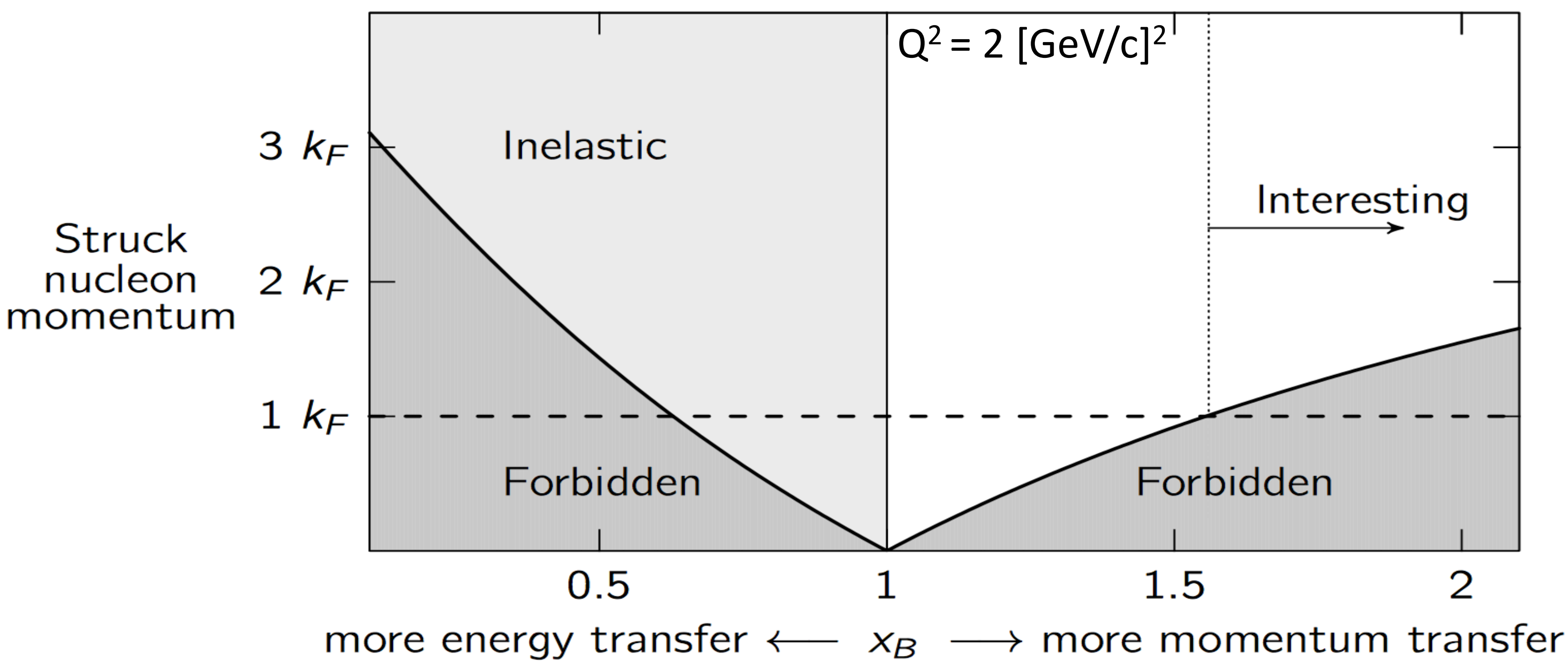
High-Momentum Tails

- Short-range two-body forces create high-momentum tails to the nuclear momentum distribution
- Expected to be due to pairs of short-range correlated nucleons.
- Ongoing experimental program to 'dissect' these high-momentum tails.



Probing High-Momentum Tails

(e,e') cross section at different kinematics are sensitive to different 'parts' of the nuclear momentum distribution.



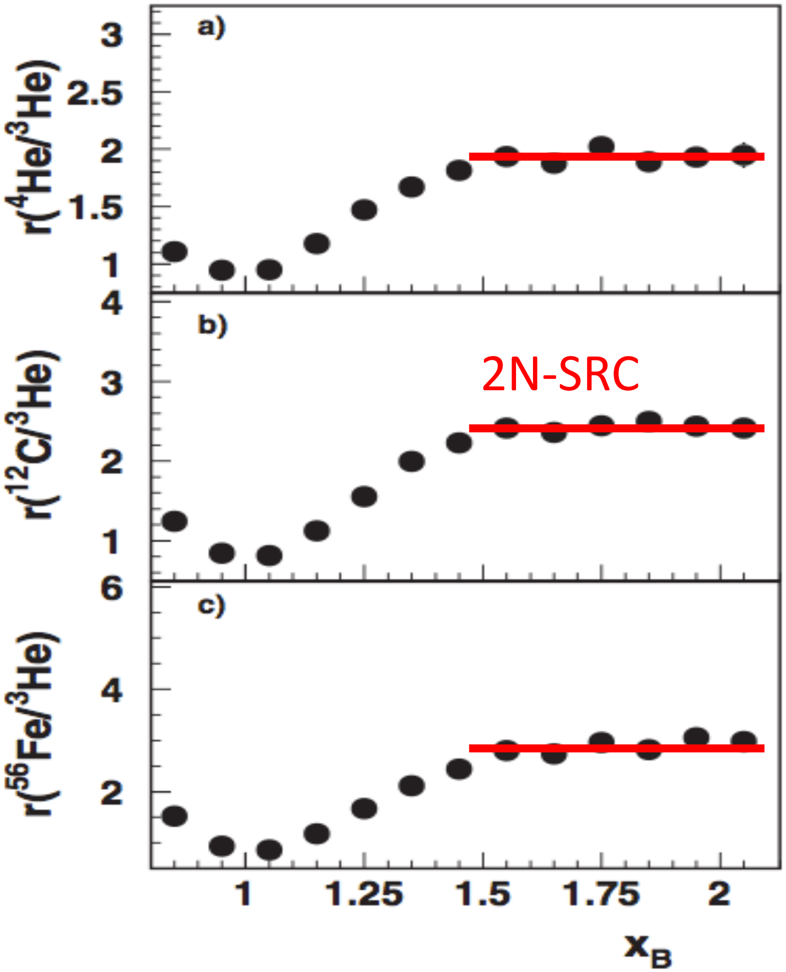
$$(q+p_A-p_{A-1})^2=p_f^2=m_N^2$$

Probing High-Momentum Tails

- A/d (e,e') cross section ratios sensitive to $n_A(k)/n_d(k)$

- Observed scaling for $x_B \geq 1.5$.

$\Rightarrow n_A(k>k_F) = a_2(A) \times n_d(k)$



K. Egiyan et al., PRL **96**, 082501(2006).

L. Frankfurt et al. , Phys. Rev. C **48**, 2451 (1993).
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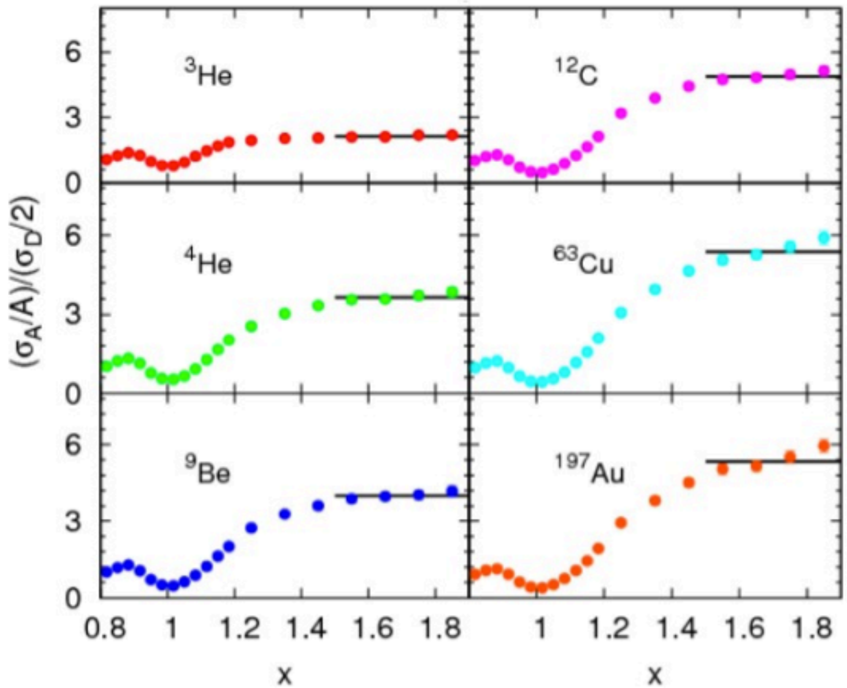

N. Fomin et al., PRL **108**, 092502 (2012)

A	$a_2(A/D)$	A	$a_2(A/D)$
^{3}He	2.1 ± 0.1	^{12}C	4.7 ± 0.2
^{4}He	3.6 ± 0.1	^{63}Cu	5.2 ± 0.2
^{9}Be	3.9 ± 0.1	^{197}Au	5.1 ± 0.2

O. Hen et al., PRC **85**, 047301 (2012)

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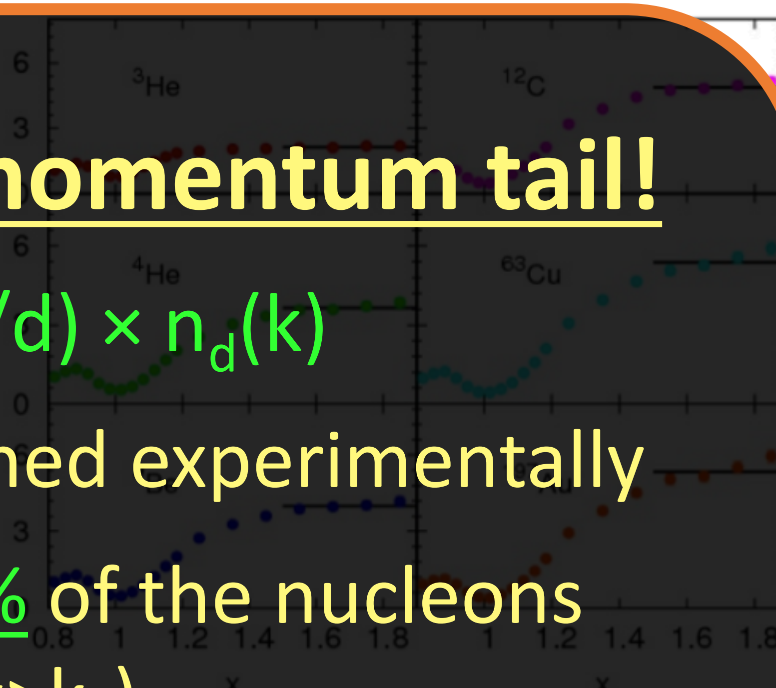
Probing High-Momentum Tails

Nuclei have a high-momentum tail!

1. It scales: $n_A(k>k_F) = a_2(A/d) \times n_d(k)$
2. Scale factor, a_2, determined experimentally
3. In $A \geq 12$ nuclei, 20 – 25% of the nucleons have high-momentum ($k>k_F$).

- A/d (e,e') cross section ratios sensitive to $n_A(k)/n_d(k)$
- Observed scaling for $x_B \geq 1.5$

=> $n_A(k>k_F) = a_2(A)\times n_d(k)$



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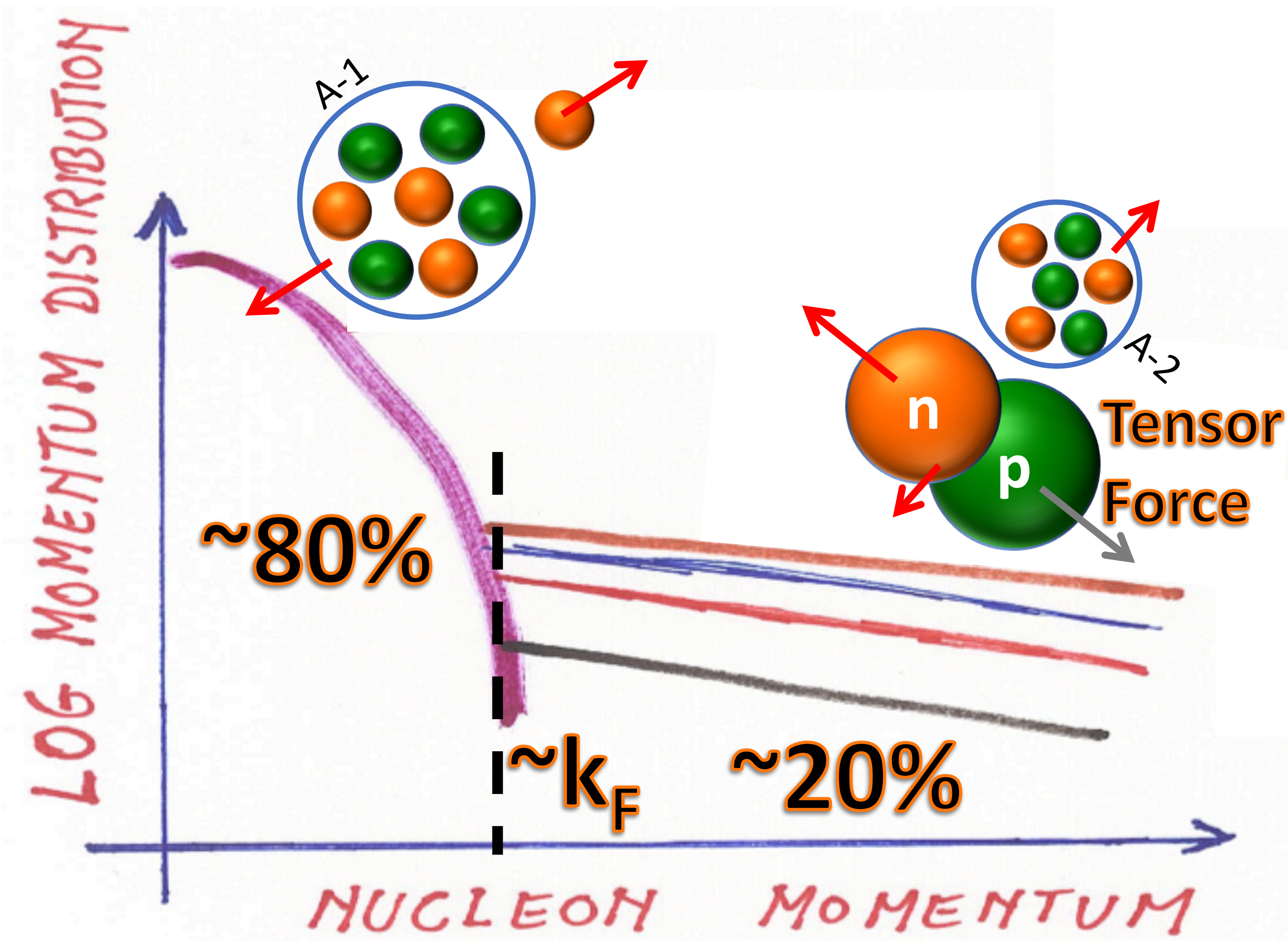
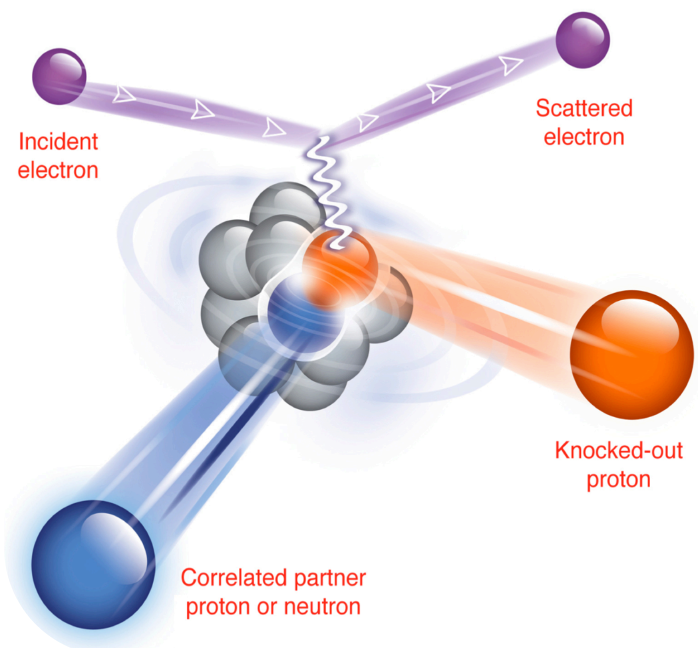
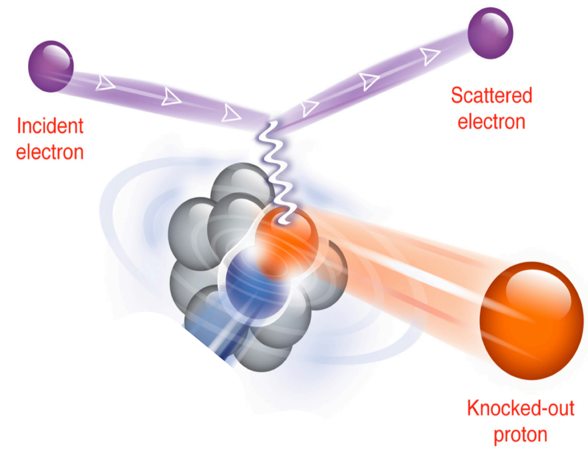
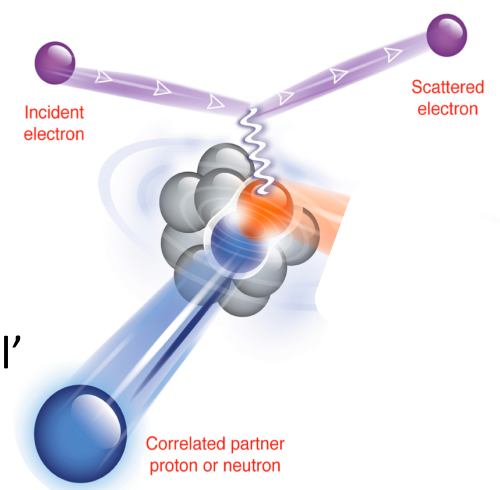


Exclusive probes for SRC structure

Breakup the pair =>
Detect both nucleons =>
Reconstruct ‘initial’ state

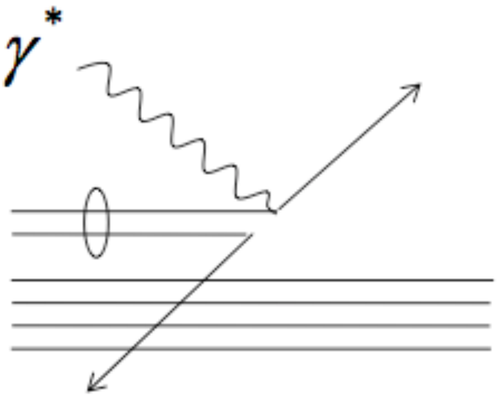






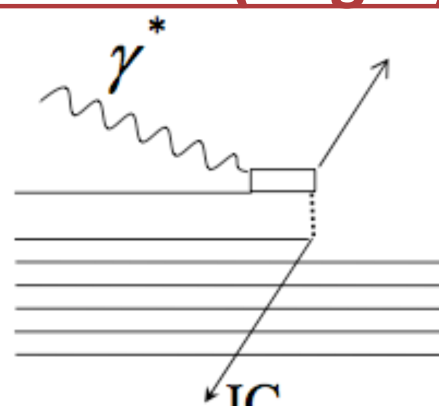
Interlude: Reaction Mechanisms

What we want:

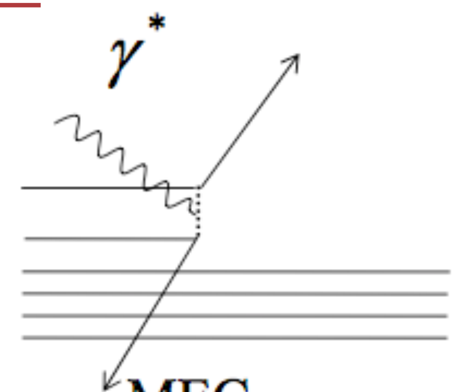


SRC

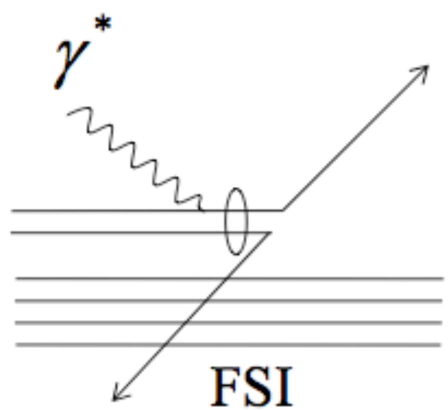
What we (might) get:



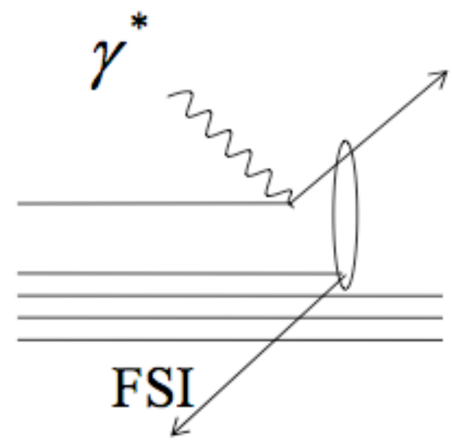
IC



MEC



FSI

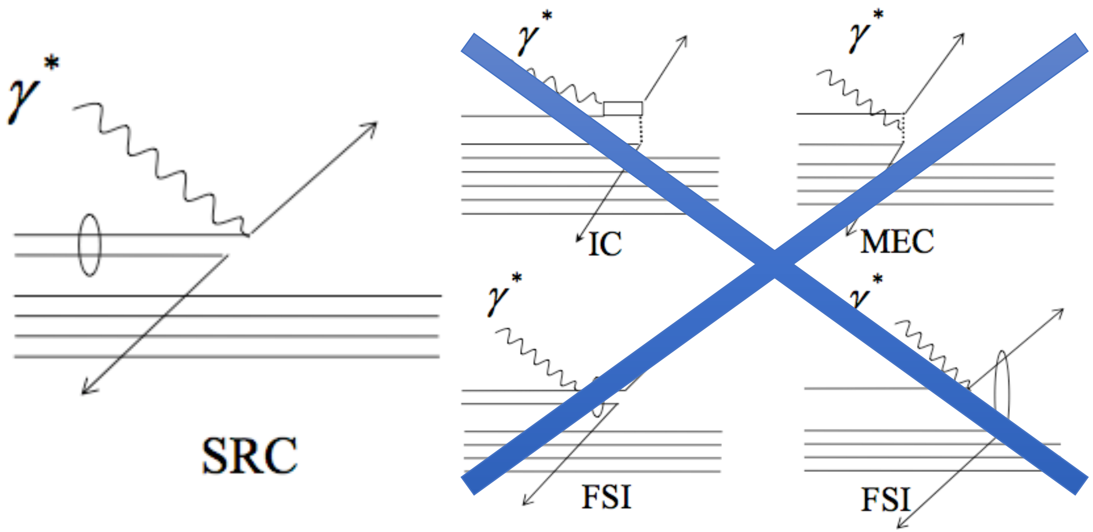


FSI

Interlude: Reaction Mechanisms

Trick: choose 'good' kinematics!

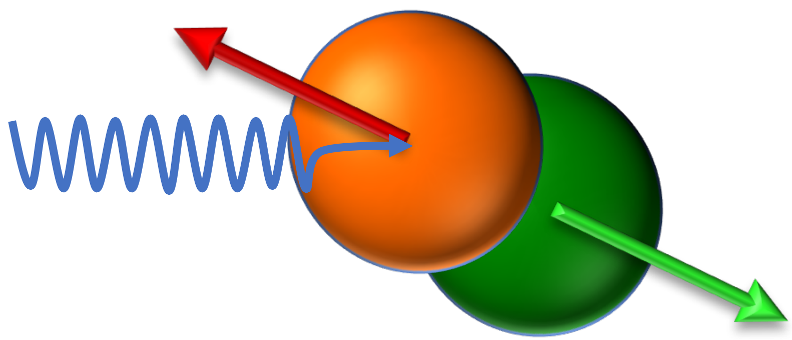
- $x_B > 1.2$
- $Q^2 \sim 2\ (GeV/c^2)$
- Anti-Parallel Kinematics



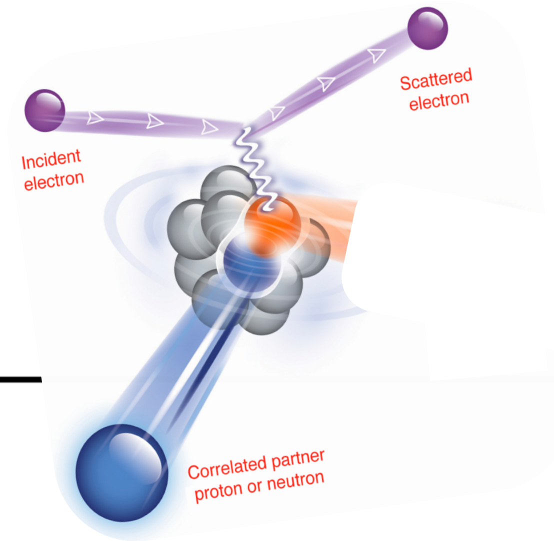
A word on FSI:

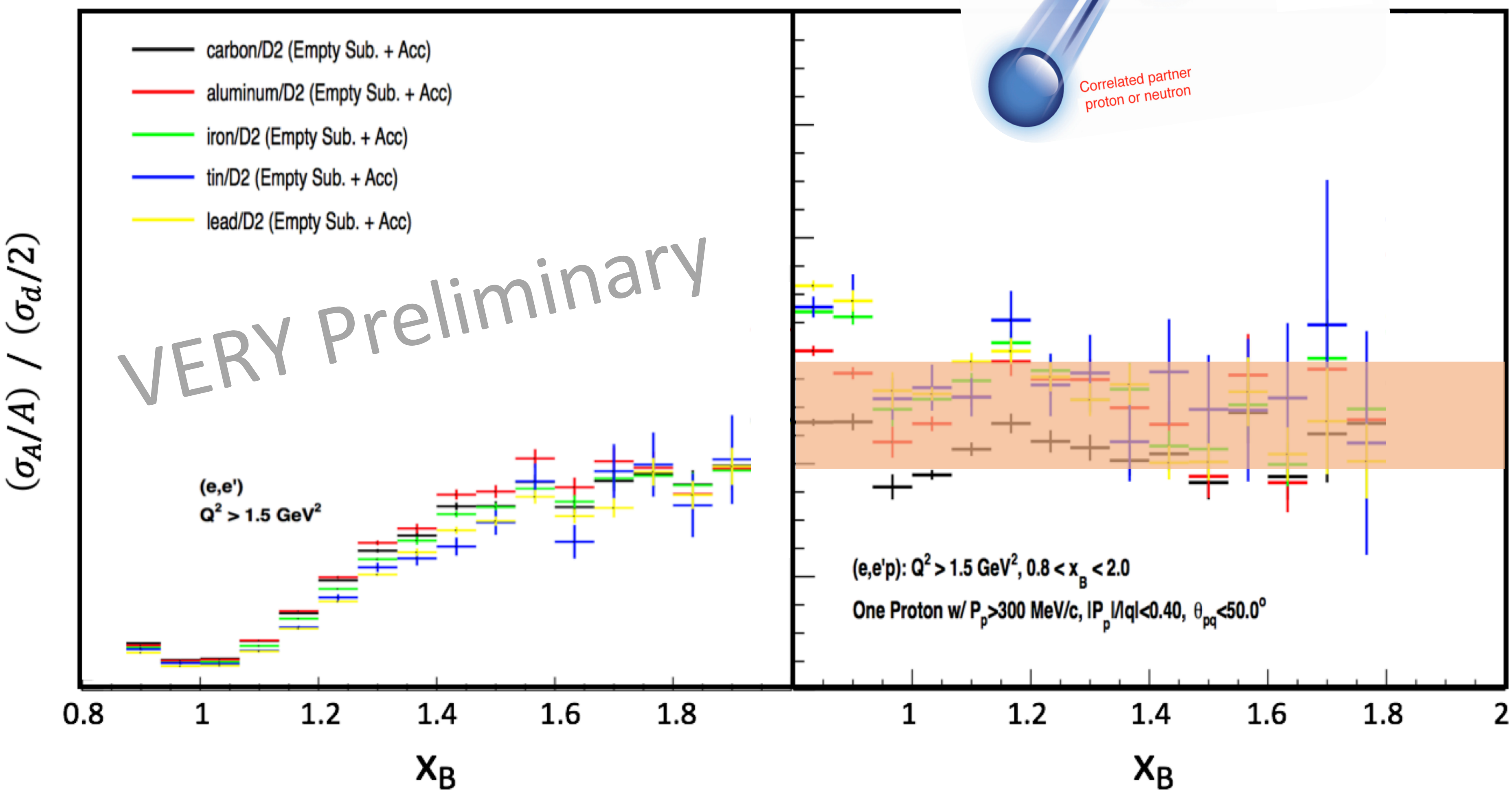
- Large-Q^2 (or $|t,u|$) allows using Eikonal approximation for FSI.
- Combined with $x_B>1$ ensures FSI largely confined to between the nucleons of the pair.

=> Large cancellation in ratios.



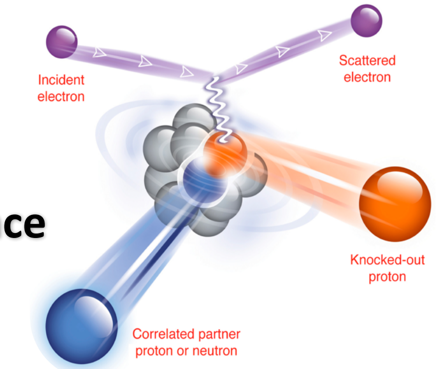
SRC Spectator Tagging

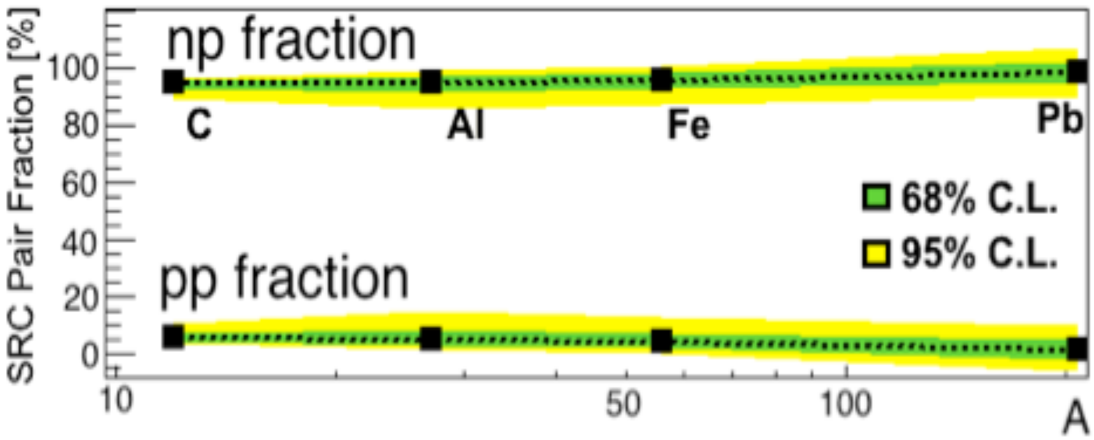




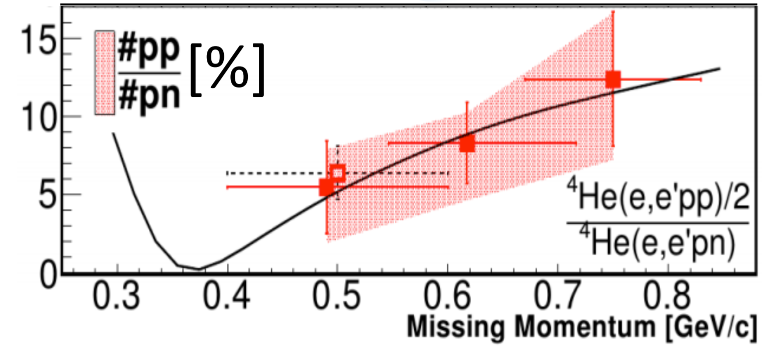
B. Schmookler et al. (CLAS Collaboration), In-Preparation (2017)

np dominance results



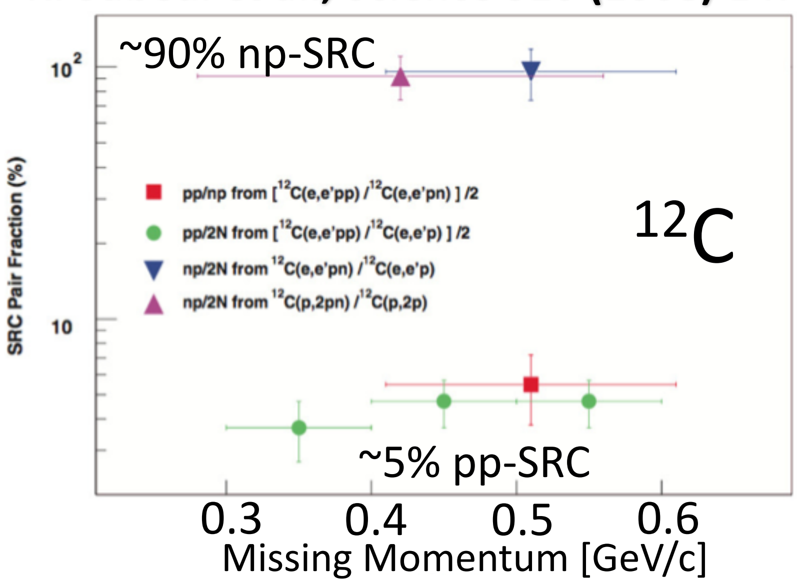


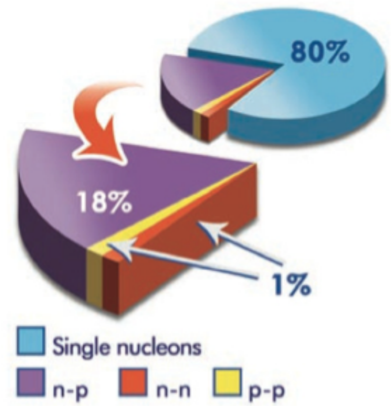
O. Hen et al., Science 364 (2014) 614

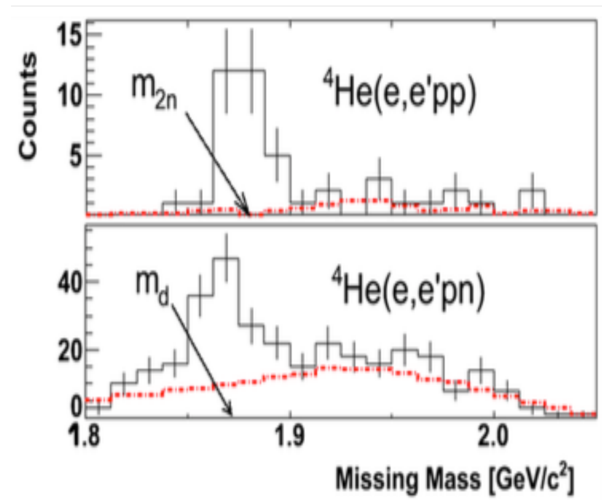


R. Subedi et al., Science 320 (2008) 1476

I. Korover et al., PRL 113 (2014) 022501

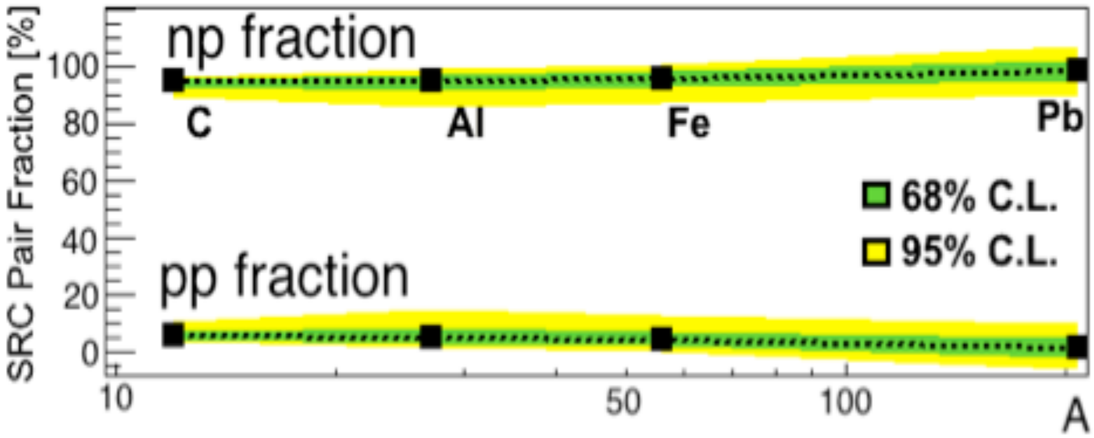






A. Tang et al., PRL (2003); E. Piasetzky et al., PRL (2006); R. Shneor et al., PRL (2007)

np dominance results



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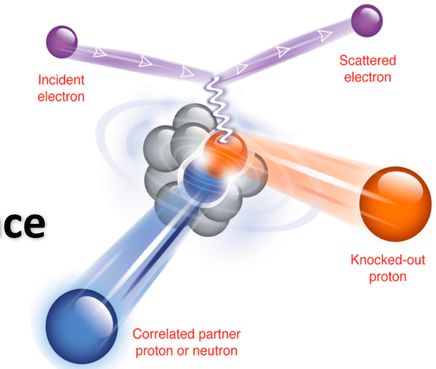

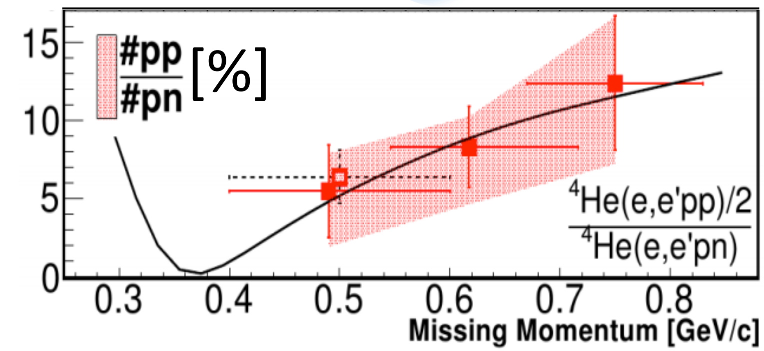

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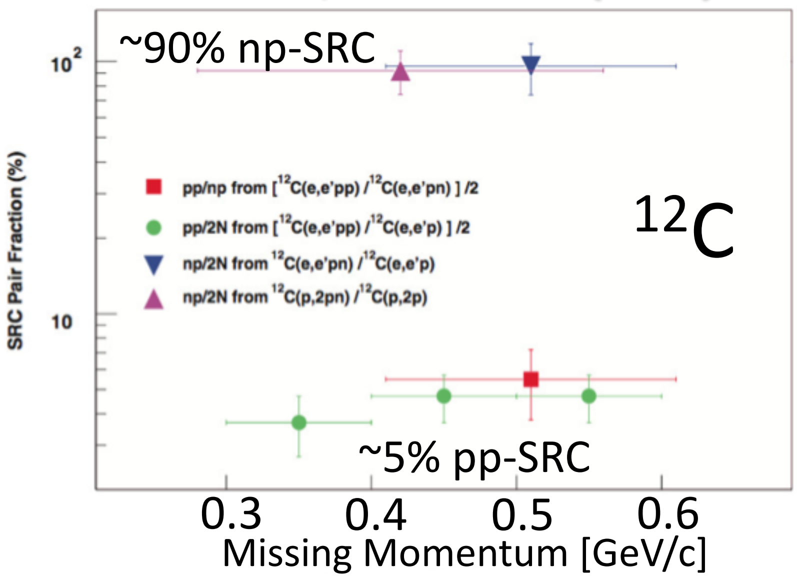
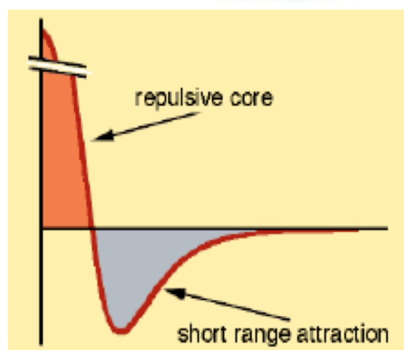
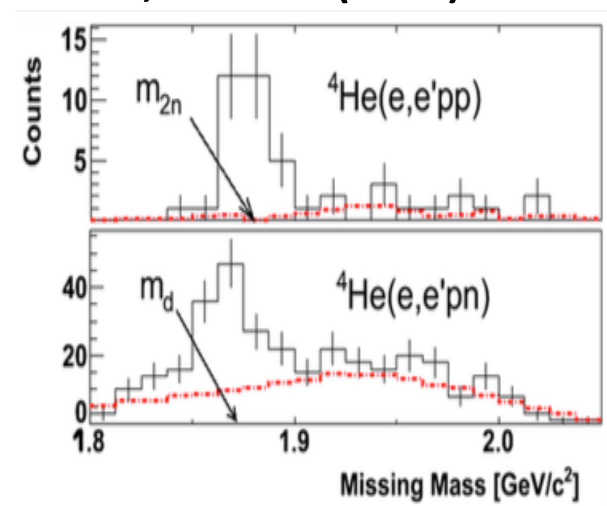


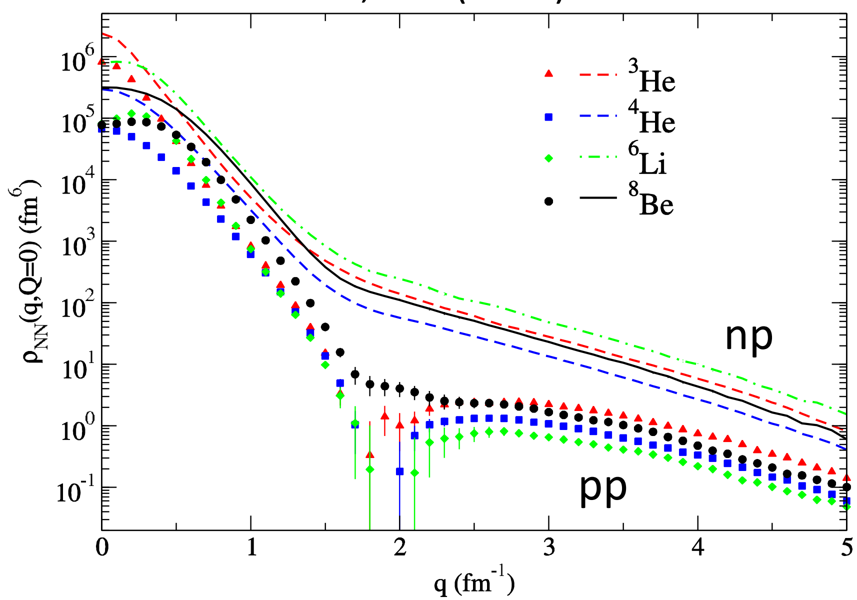




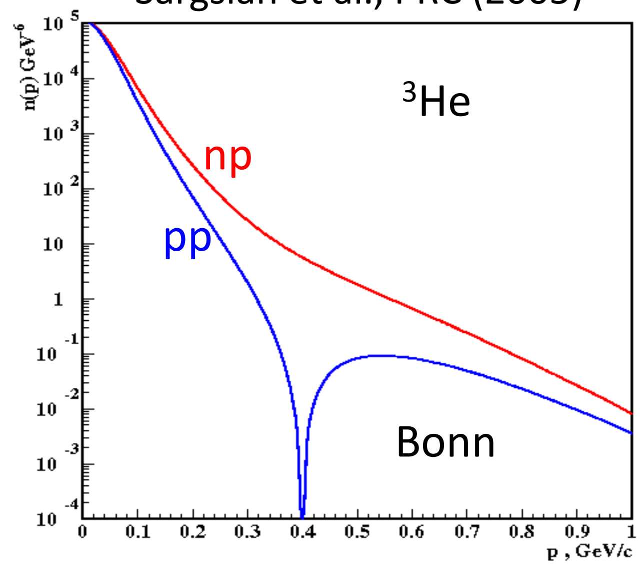
A. Tang et al., PRL (2003); E. Piasetzky et al., PRL (2006); R. Shneor et al., PRL (2007)

Tensor Force Dominance

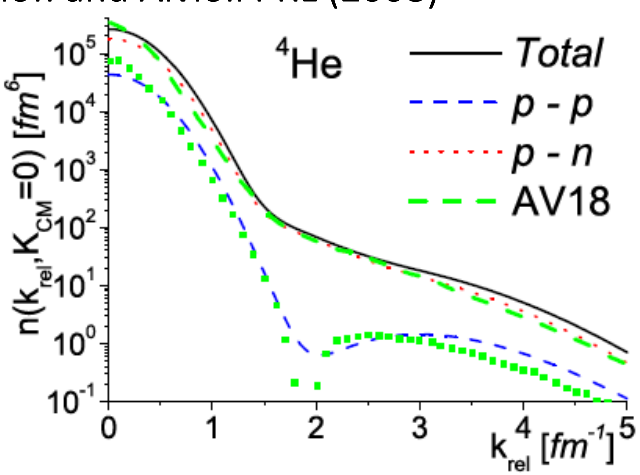
Schiavilla et al., PRL (2007)



Sargsian et al., PRC (2005)

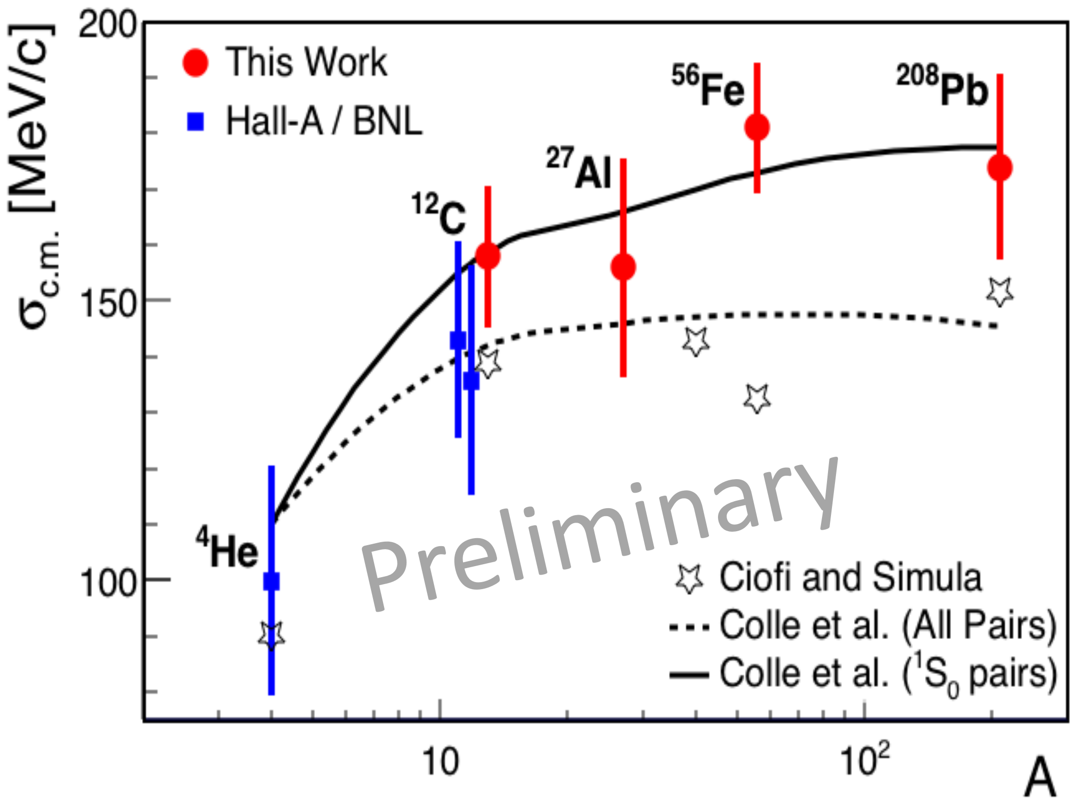


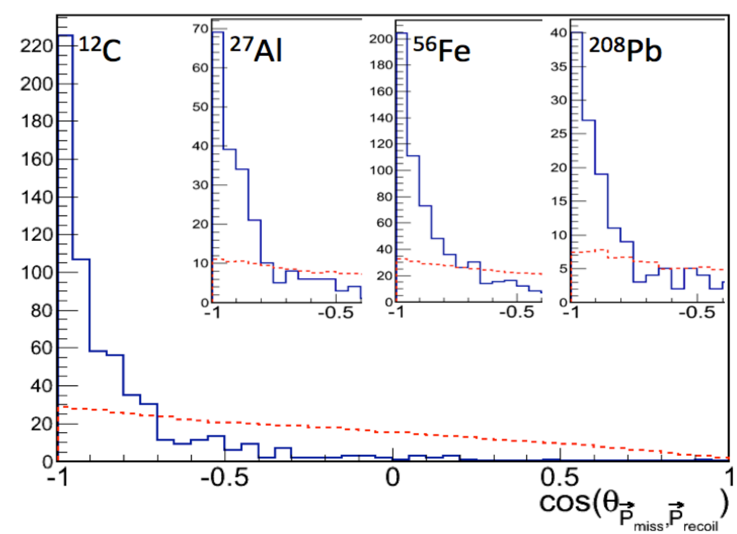
Ciofi and Alvioli PRL (2008)



C.M. Motion and Pairing Mechanisms

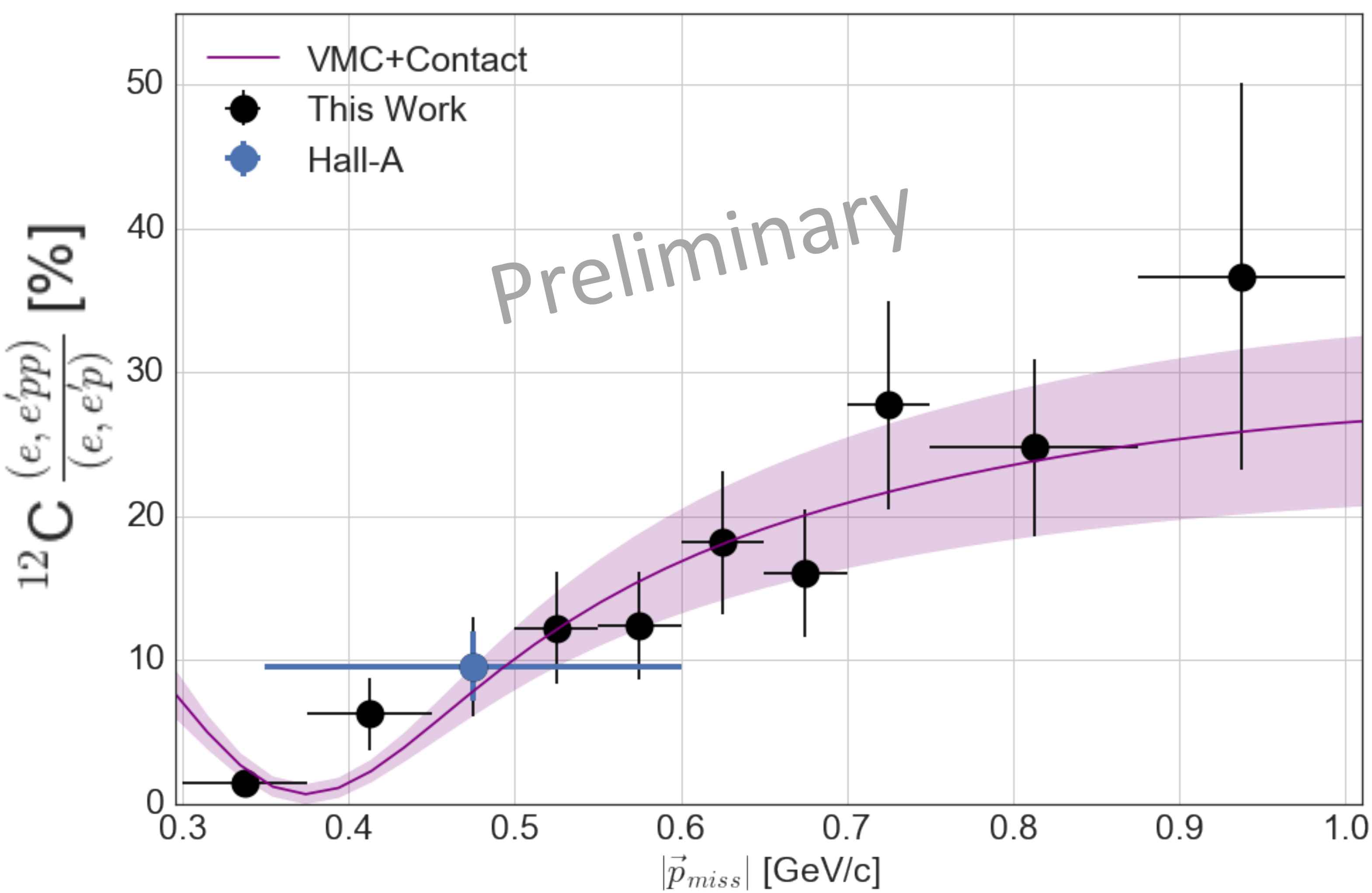
"… *high relative momentum* and ***low c.m. momentum*** compared to the Fermi momentum (k_F)"





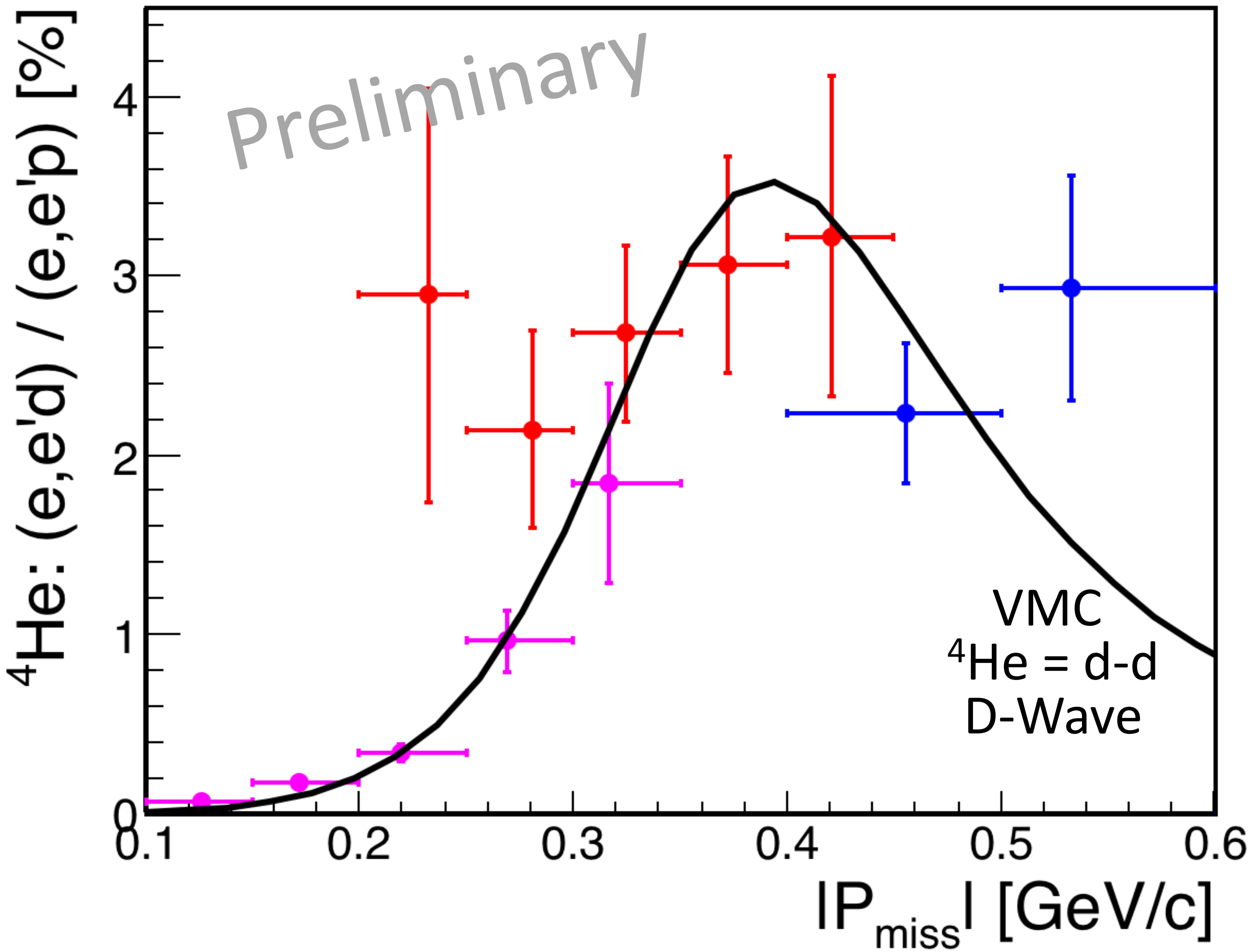
E. Cohen et al. (CLAS Collaboration), In-Preparation (2017)

NN interaction at Short Distances



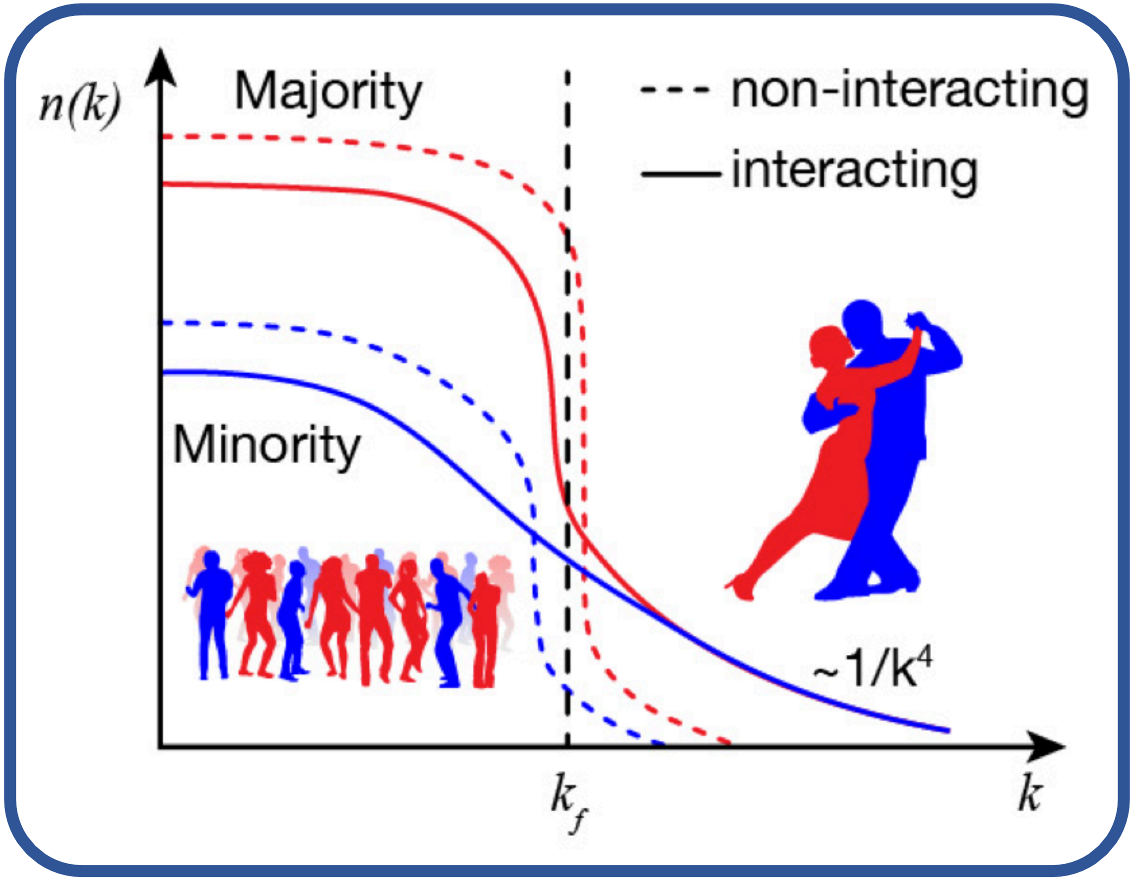
(CLAS Collaboration), In-Preparation (2017)

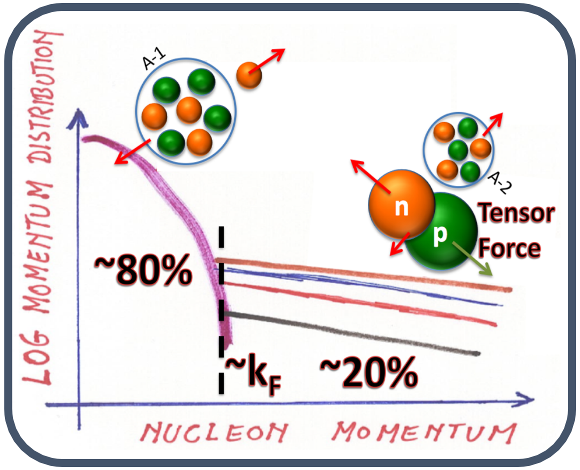
Short-Range Clustering



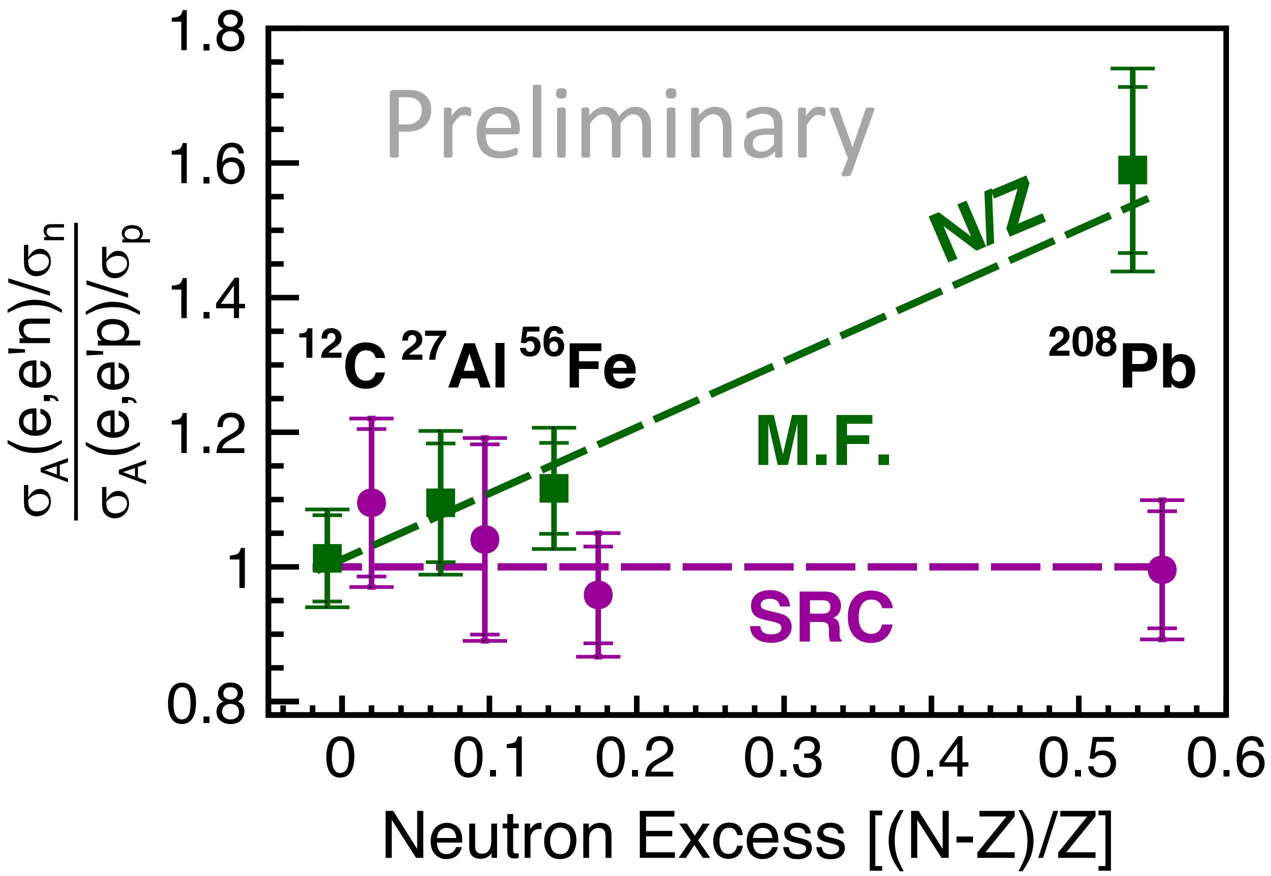
I. Korover et al. (Hall-A Collaboration), In-Preparation (2017)

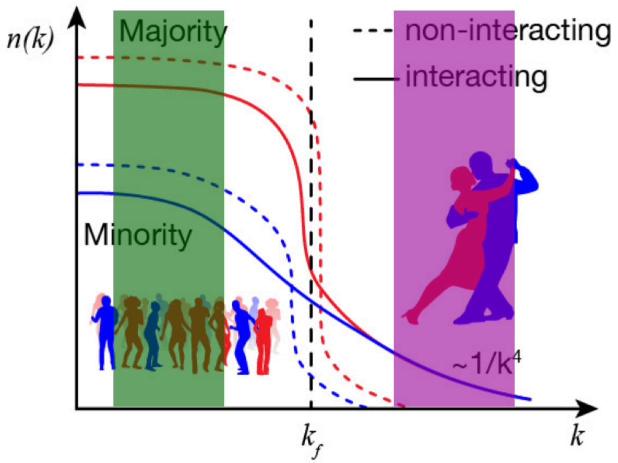
Nuclear Asymmetry Dependence





Nuclear Asymmetry Dependence

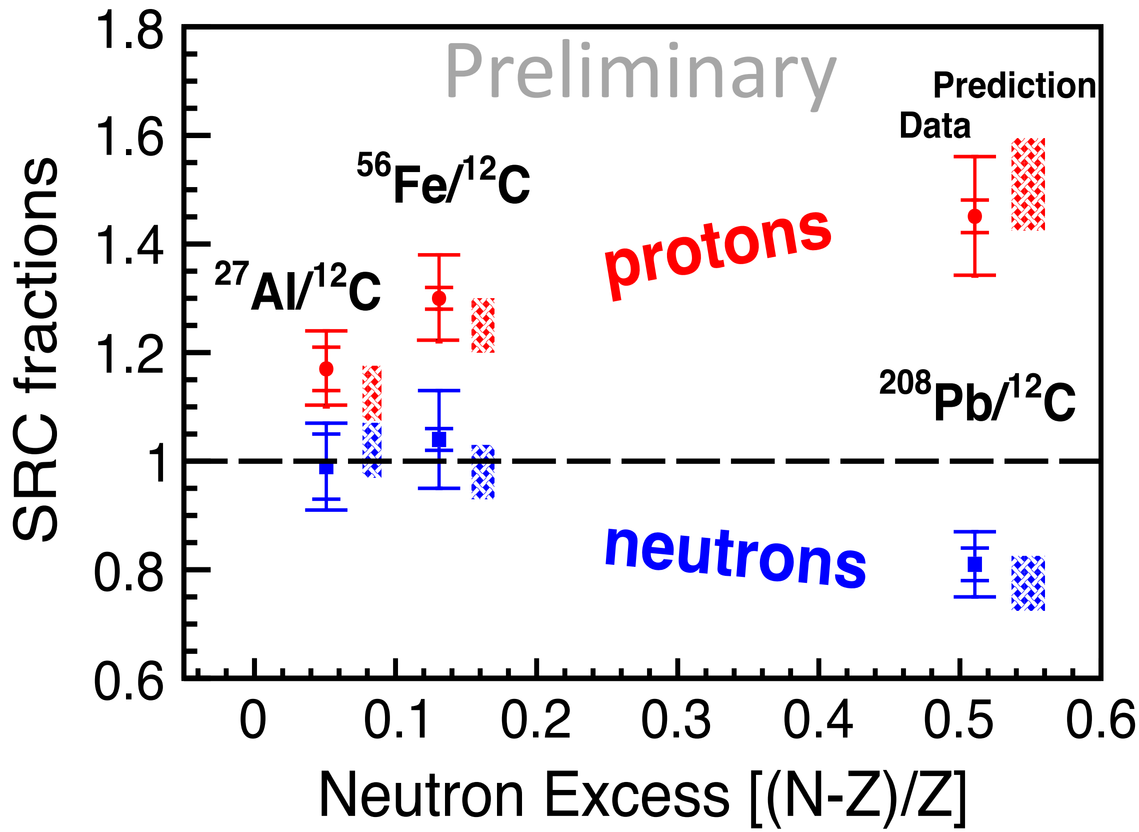




=> *Same* number of high-P protons and neutrons!

M. Duer et al. (CLAS Collaboration), In-Preparation (2017)

Nuclear Asymmetry Dependence



=> Protons more correlated in neutrons rich nuclei!

M. Duer et al. (CLAS Collaboration), In-Preparation (2017)

New Era in SRC Research!

Consistent set of (e,e'), (e,e'p), (e,e'pN) and (p,2pn) measurements allow quantifying SRCs with unprecedented accuracy!

1. SRC Exist in Nuclei (!) and account for:
   - ~ 20% of the nucleons in nuclei.
   - ~100% of the high-p ($k>k_F$) nucleons in nuclei.

2. Have large relative momentum and low c.m. momentum.

3. Predominantly due to np-SRC.

4. Universal for A = 4 – 208 nuclei.

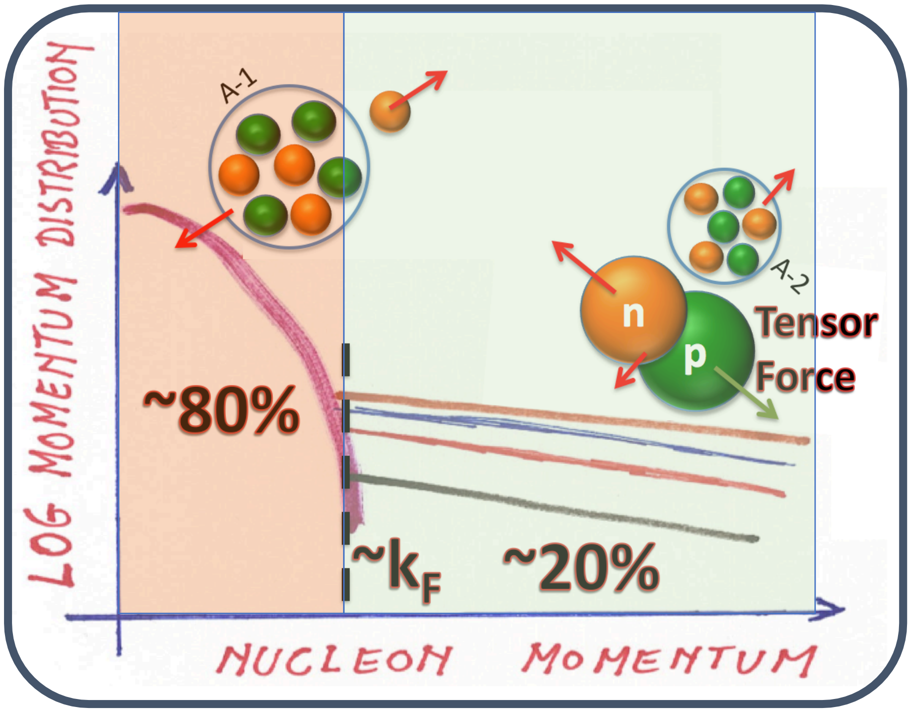
5. np-SRC create a larger fraction of high-momentum protons in neutron rich nuclei!

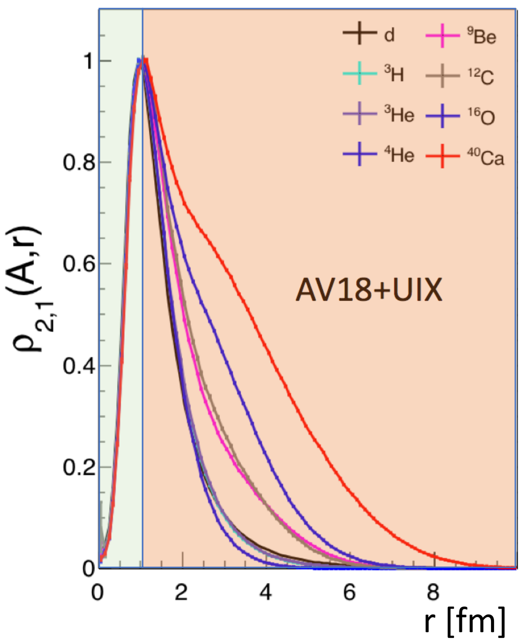
6. Tensor force dominance at short distance.

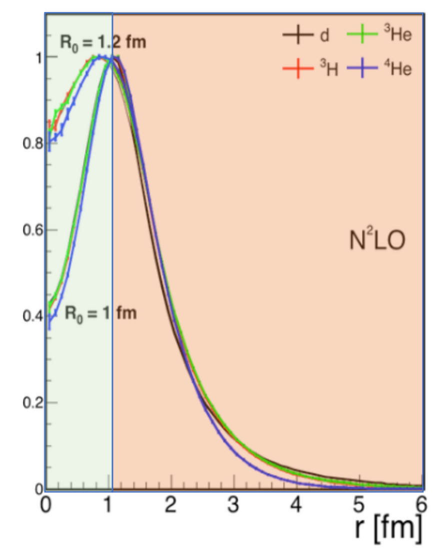
Theory Connection: Momentum Densities

Can we formulate a universal description of SRC (both coordinate and momentum space) without relying on many-body calculations? (YES)

Can we use it to confront theory and experiments? (YES)







Universal Nuclear Structure?

1. Use a factorized ansatz for the short-distance (high-momentum) part of the many-body wave function:

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_{\alpha} \varphi_{\alpha}(\boldsymbol{r}_{ij}) A^{\alpha}_{ij}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}\}_{k\neq ij})$$

- Universal function of the NN interaction.
- Taken as the zero energy solution to the 2 body problem

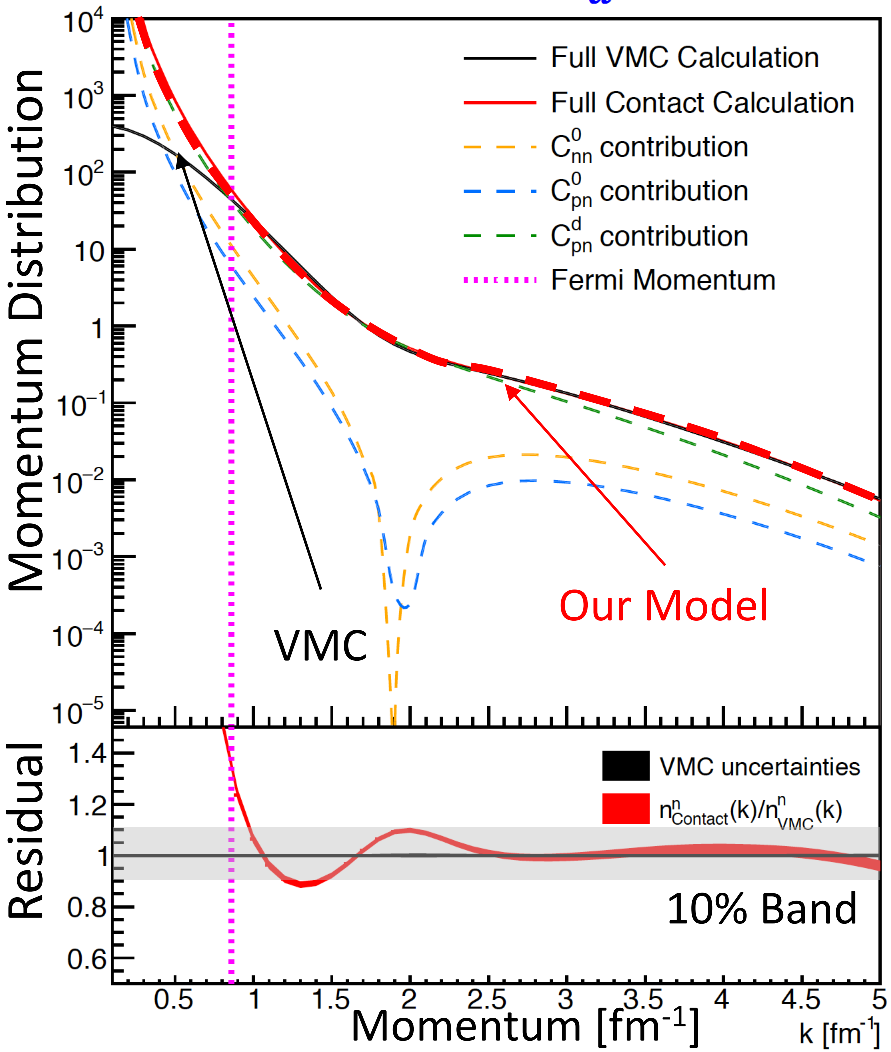
- Nucleus (/ system) specific function
- Depends on all nucleons except the SRC pair (primarily mean-field)

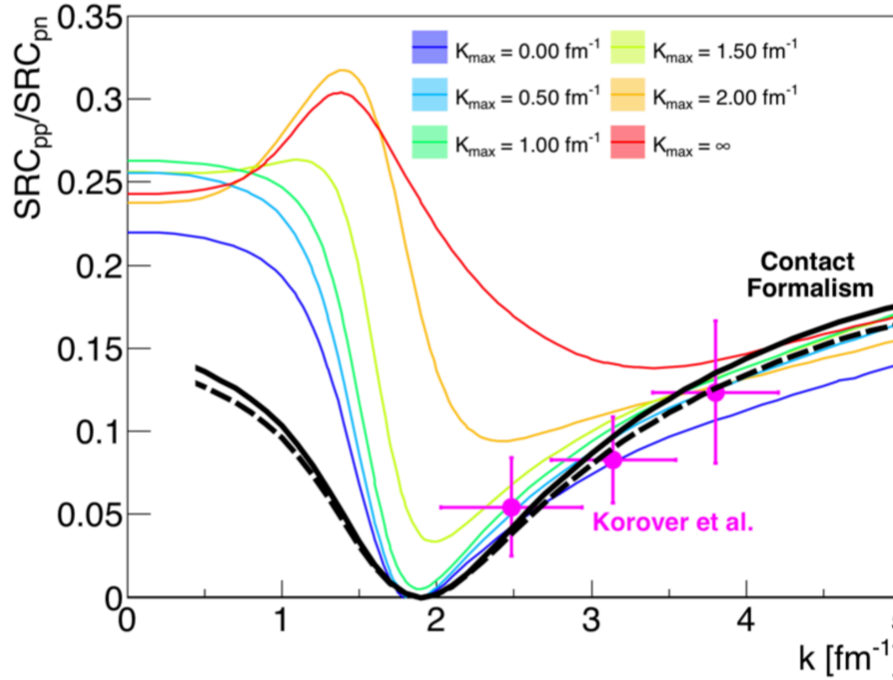
2. Test by comparing to many-body calculations *and* data from hard knockout measurements

Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, arXiv 1612.00923 (2017)

Universal Nuclear Structure!

$$n_p(k) = \sum_\alpha \left|\tilde{\varphi}^\alpha_{pp}(k)\right|^2 2C^\alpha_{pp} + \sum_\alpha \left|\tilde{\varphi}^\alpha_{pn}(k)\right|^2 C^\alpha_{pn}$$





Nuclear contacts can also be extracted from experiment!

Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, arXiv 1612.00923 (2017)

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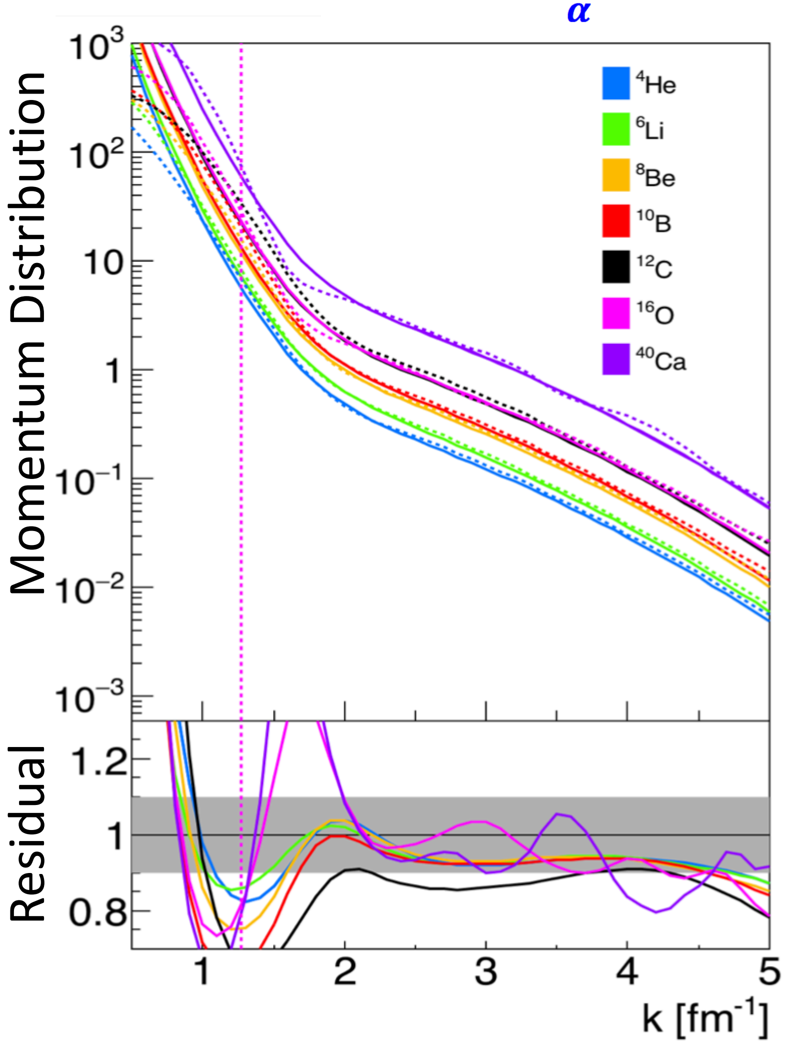

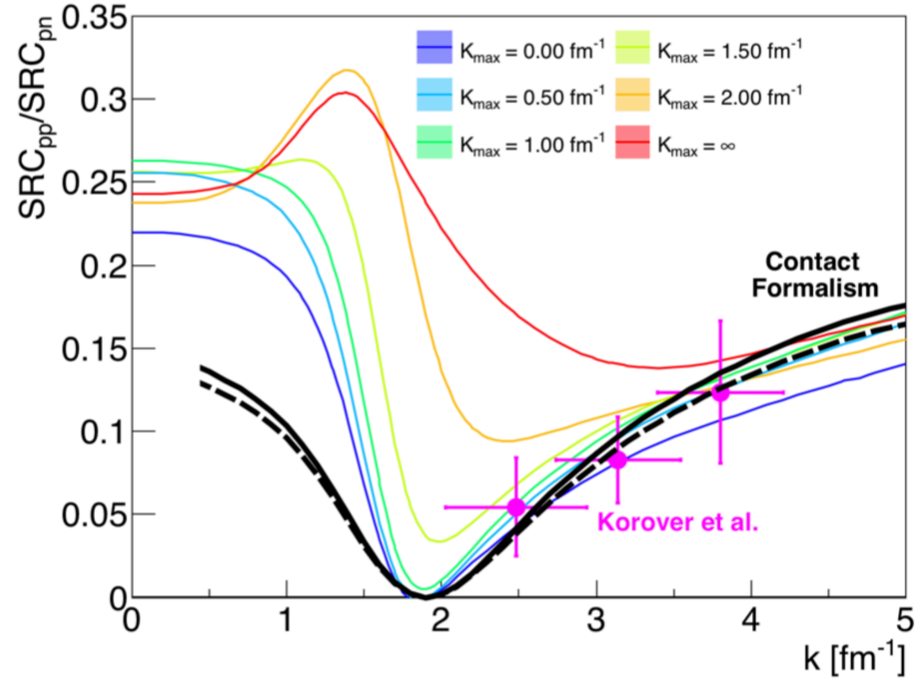

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Nuclear contacts extracted from many-body densities in k- and r-space and from experiment

A	k-space				r-space			
	$C_{pn}^{s=1}$	$C_{pn}^{s=0}$	$C_{nn}^{s=0}$	$C_{pp}^{s=0}$	$C_{pn}^{s=1}$	$C_{pn}^{s=0}$	$C_{nn}^{s=0}$	$C_{pp}^{s=0}$
^{4}He	12.3±0.1	0.69±0.03	0.65±0.03		11.61±0.03	0.567±0.004		
	14.9±0.7 (exp)	0.8±0.2 (exp)						
^{6}Li	10.5±0.1	0.53±0.05	0.49±0.03		10.14±0.04	0.415±0.004		
^{7}Li	10.6 ± 0.1	0.71 ± 0.06	0.78 ± 0.04	0.44 ± 0.03	9.0 ± 2.0	0.6 ± 0.4	0.647 ± 0.004	0.350 ± 0.004
^{8}Be	13.2±0.2	0.86±0.09	0.79±0.07		12.0±0.1	0.603±0.003		
^{9}Be	12.3±0.2	0.90±0.10	0.84±0.07	0.69±0.06	10.0±3.0	0.7±0.7	0.65±0.02	0.524±0.005
^{10}B	11.7±0.2	0.89±0.09	0.79±0.06		10.7±0.2	0.57±0.02		
^{12}C	16.8±0.8	1.4±0.2	1.3±0.2		14.9±0.1	0.83±0.01		
	18±2 (exp)	1.5±0.5 (exp)						

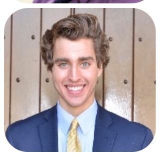
Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, arXiv 1612.00923 (2017)

The Correlations group

- **MIT (Or Hen):**


Barak Schmookler


Reynier Torres


Efrain Segarra


Afroditi Papadopoulou


Axel Schmidt


George Laskaris

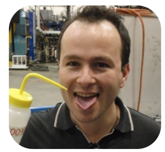

Maria Patsyuk


Adi Ashkenazy

- **TAU (Eli Piasetzky):**


Erez Cohen


Meytal Duer


Igor Korover

- **ODU (Larry Weinstein):**


Mariana Khachatryan


Florian Hauenstein

- **Theory Collaborators (lots!)**