Universality in Short-Range Correlations

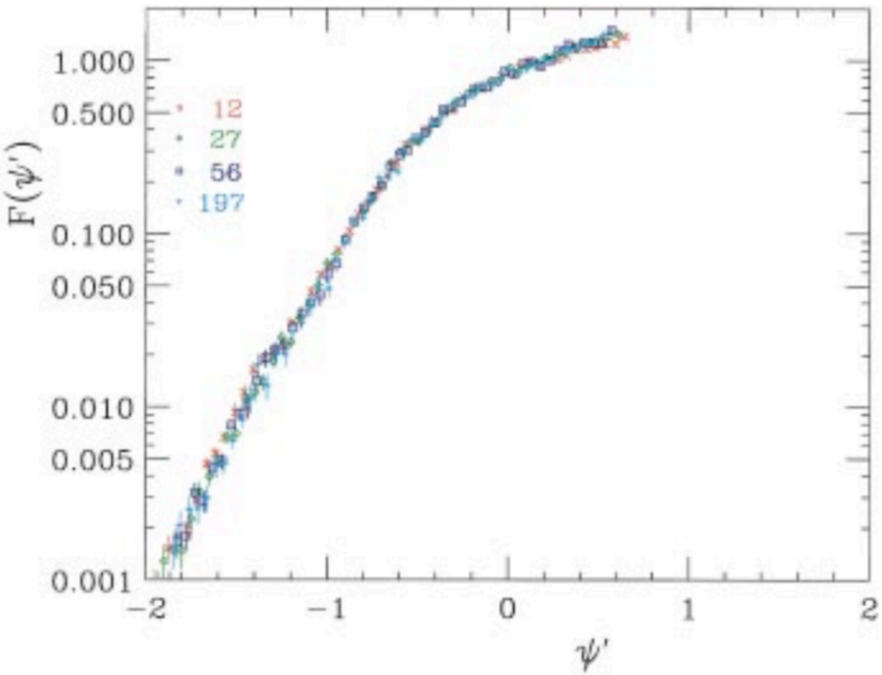
Or Hen – MIT

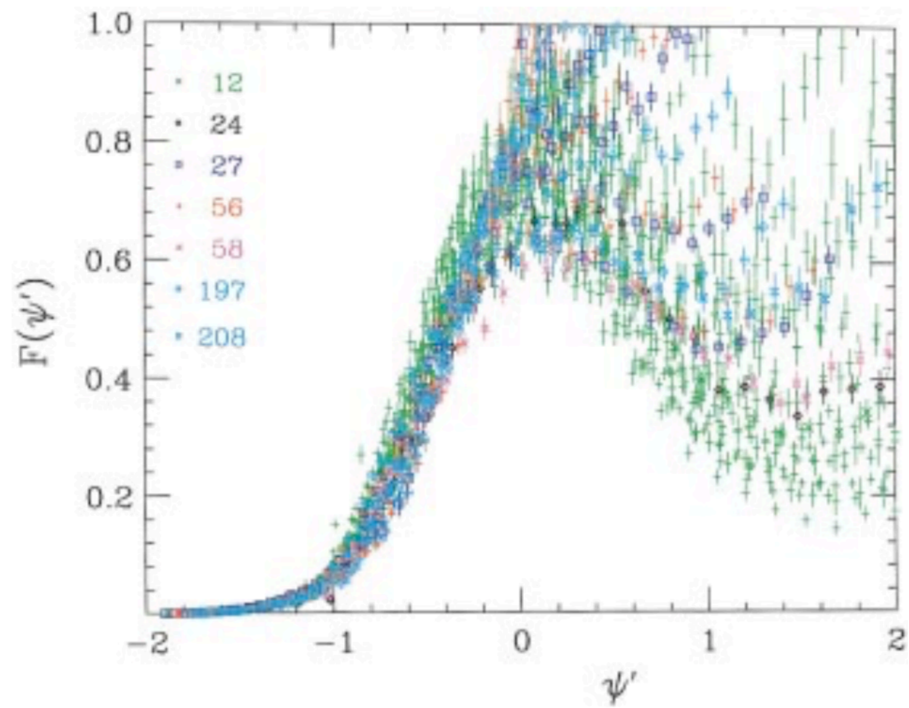
“One model to rule them all;
One parameter to fit it all”

Theoretical Developments in Neutrino-Nucleus Scattering, INT, December 8th 2016

Universality in Nuclear Physics

When discussing "universality" one should separate the ground state from the reaction.





T.W. Donnelly and I. Sick, PRL 82, 3212 (1999)

Universality in Nuclear Physics

<u>My focus (today) is on universality of the ground state:</u>

1. Non interacting fermi gases are universal. One parameter (k_F) essentially determines their properties.
   - *Nuclei in strongly interacting systems…*

2. Dilute two-component fermi gases with a short-ranged interaction are also universal. Two parameters (kF and C) essentially determines their properties.
   - *Nuclei are not dilute…*

My goal is to convince you that nuclei are quite similar to case (2) and present the implications of this understanding.

The Nuclear Challenge

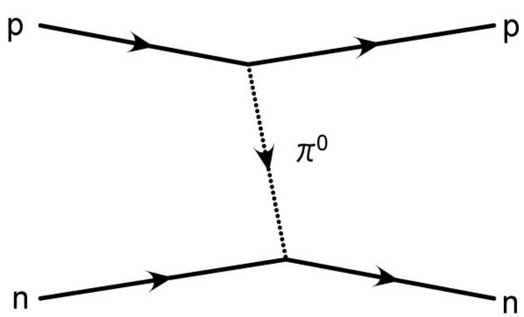
Many-body Schrödinger Equation

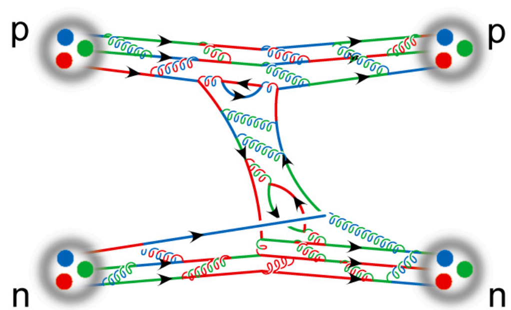
$$\sum_i \left\{ -\frac{\hbar^2}{2m_i} \nabla_i^2 \Psi(\vec{r}_1, \dots, \vec{r}_N, t) \right\} + U(\vec{r}_1, \dots, \vec{r}_N)\Psi(\vec{r}_1, \dots, \vec{r}_N, t) = i\hbar \frac{\partial}{\partial t} \Psi(\vec{r}_1, \dots, \vec{r}_N, t)$$

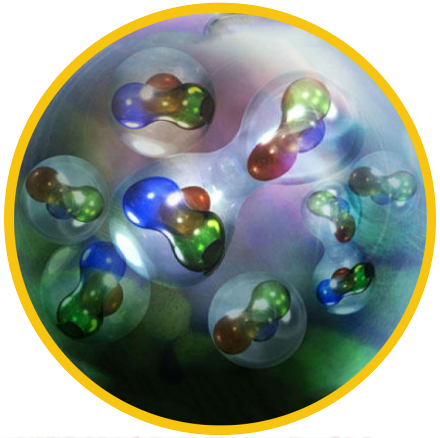
Main Challenges:

1. No 'fundamental' Interaction => residual interaction between quarks that makeup the nucleons.

2. Phenomenological parametrizations are complex! (over 18 operators)

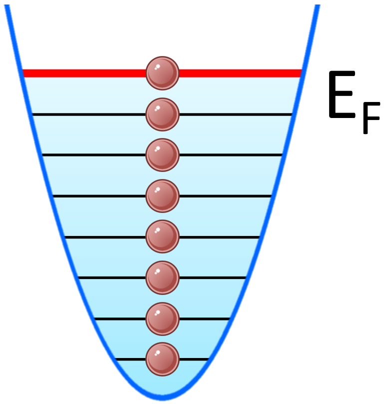






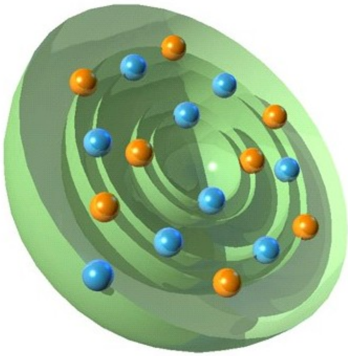
Solution: Effective Theories

Fermi Gas Model

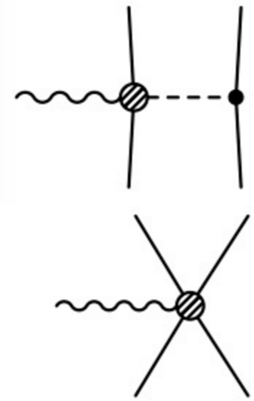


Liquid Drop Model

Shell Model

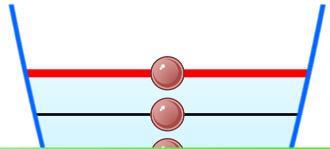


Chiral Perturbation Theory



Solution: Effective Theories

Fermi

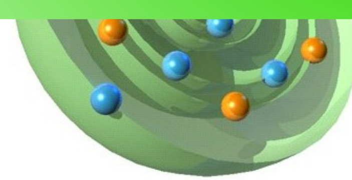


Liquid

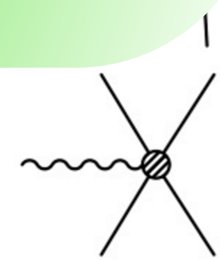
All effective theories relay on the same common idea:

Scale separation of long and short range dynamics in nuclei

Model



Perturbation Theory



Universality of long-range dynamics

Long-range (low-momentum) structure of nuclei was studied for many years and mean-field approaches give a good description of this part of the nuclear ground state.

- Two big questions:
  - How important are details of the short-range structure that are neglected / smeared out?
  - Is there an effective, *universal*, way to add the short-range dynamics for a global description?

Challenge of Correlations

Whole is different from the sum of parts!

$$n_{2N}(k_1, k_2) \neq n_N(k_1) \cdot n_N(k_2)$$
$$\rho_{2N}(\vec{r}_1, \vec{r}_2) \neq \rho_N(\vec{r}_1) \cdot \rho_N(\vec{r}_2)$$

Specifically, in coordinate space:

SRC: $\rho_{2N}(\vec{r}_1, \vec{r}_2) \neq 0$ for $|\vec{r}_1 - \vec{r}_2| \approx R_N$

LRC: $\rho_{2N}(\vec{r}_1, \vec{r}_2) \neq 0$ for $|\vec{r}_1 - \vec{r}_2| \approx R_A$

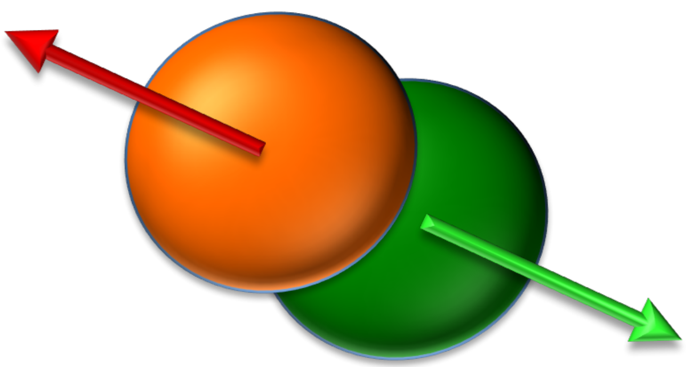
<u>(Some) Interesting questions:</u>

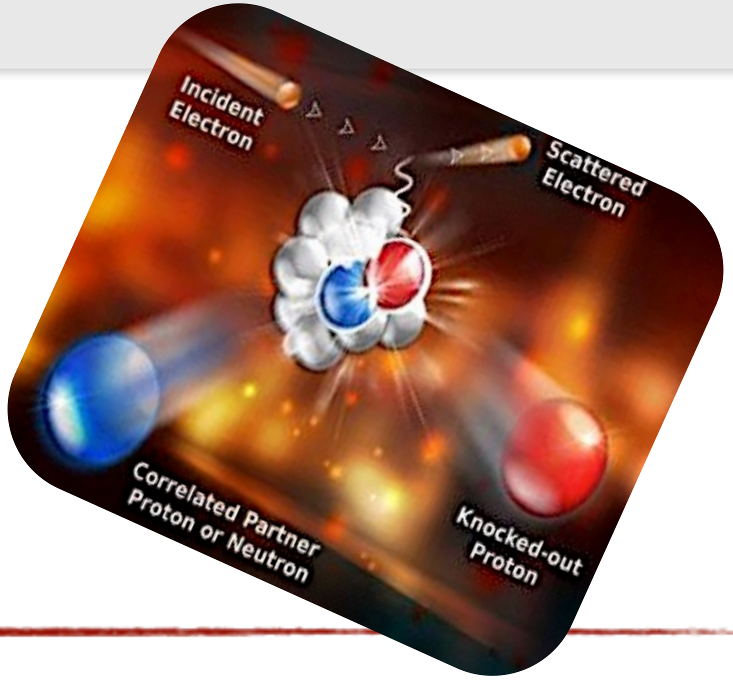
Is there a way to factorize the two-body density? Can we separate the 'mean-field' and 'SRC' effects? Are the SRC effects universal?

SRC 101

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)

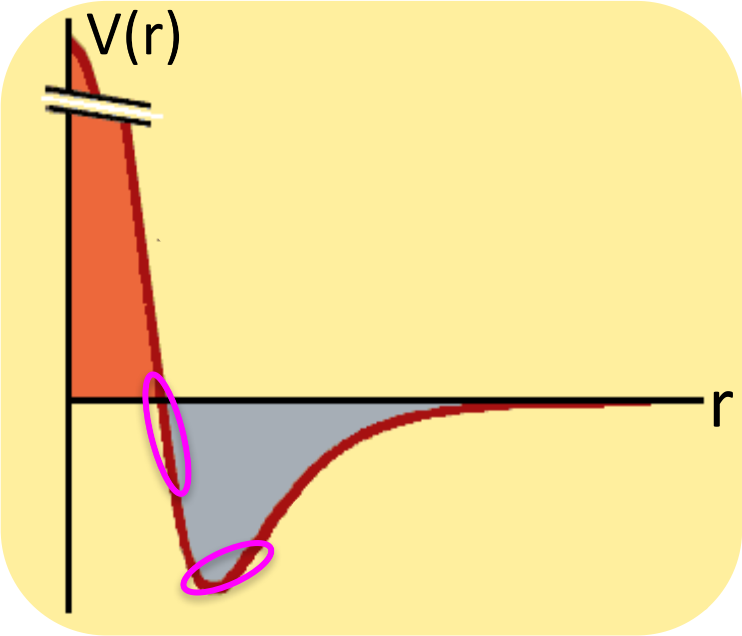




Why SRC?

Nuclear Physics

Better understanding of the
<u>nucleon-nucleon interaction</u> and the
nuclear momentum distribution



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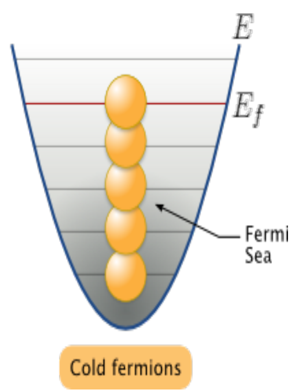

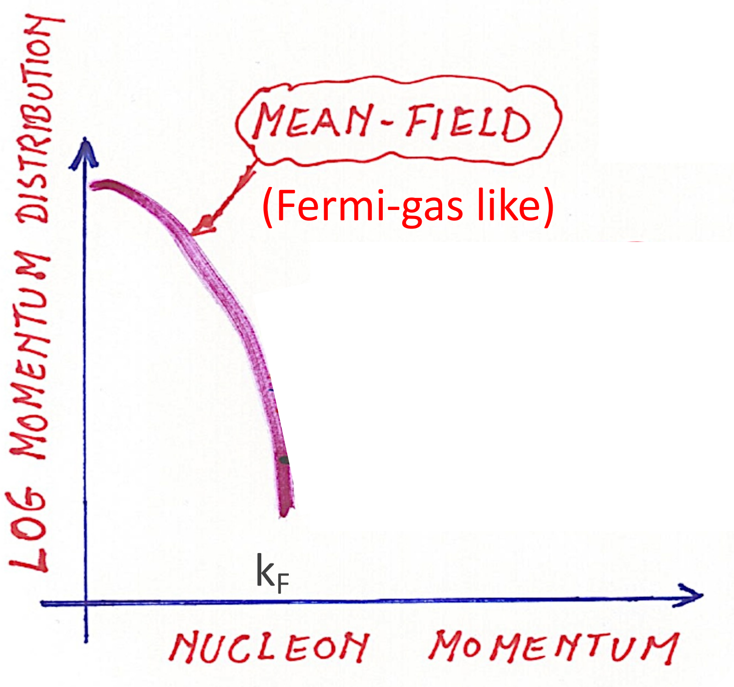

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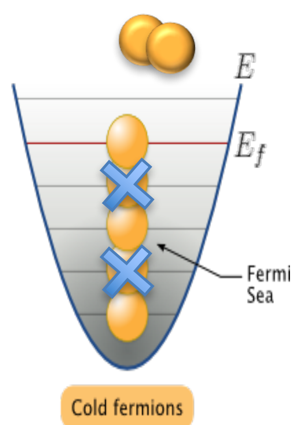
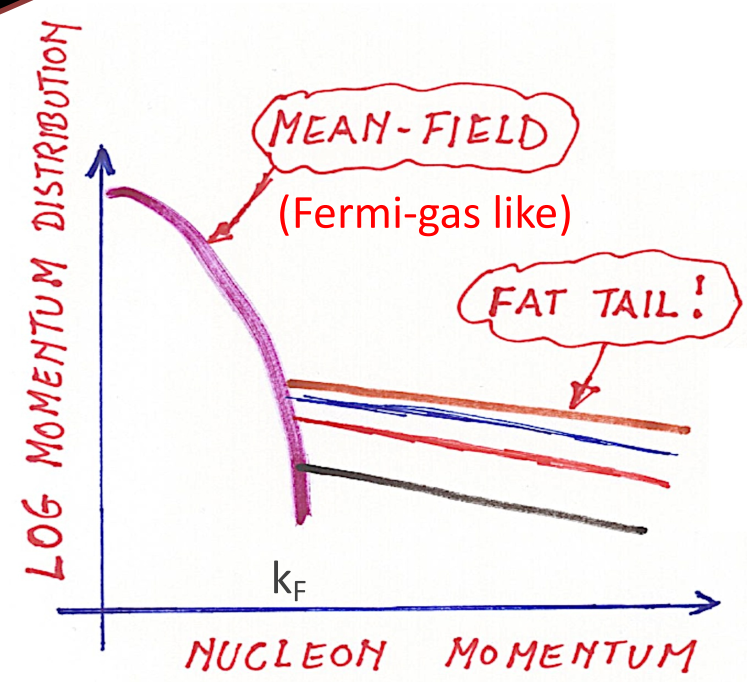




Why SRC?

You can't do nuclei without correlations!

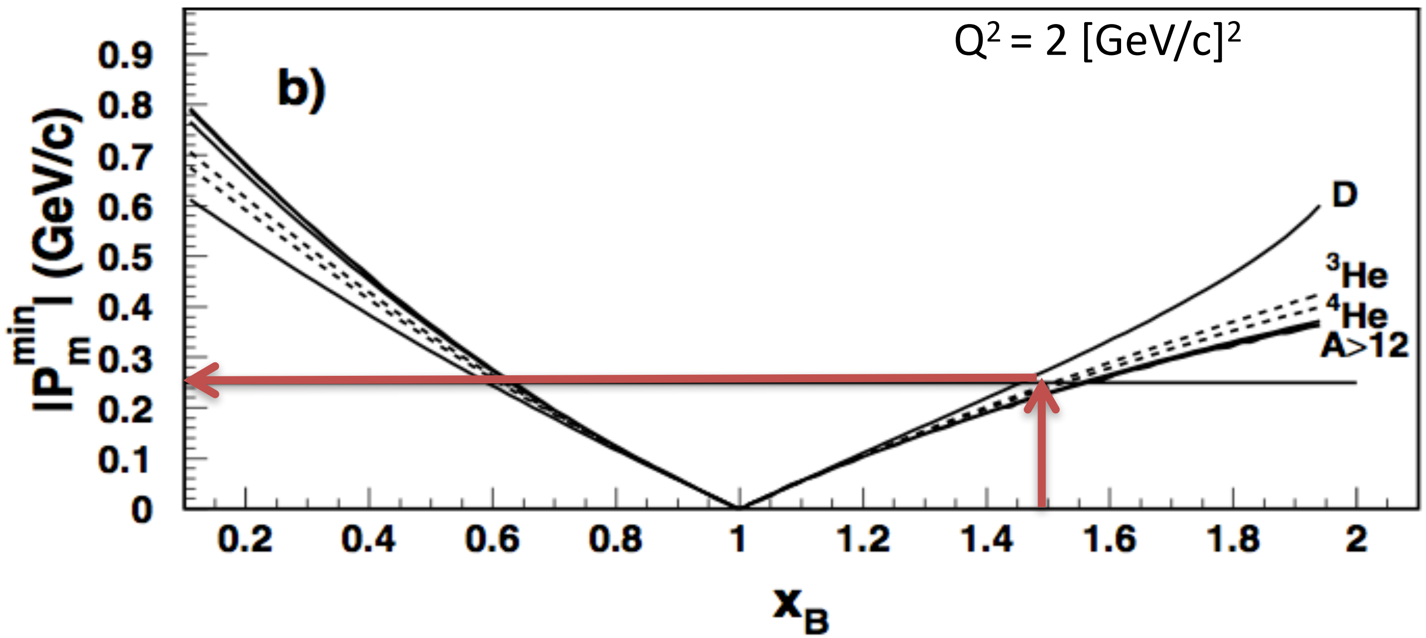
Why SRC?

Today: (short) overview of SRC and a presentation of an effective theory for SRC in nuclei

You can't do nuclei without correlations!

High-Momentum Scaling

(e,e') cross section at different kinematics is sensitive to different 'parts' of the nucleus.

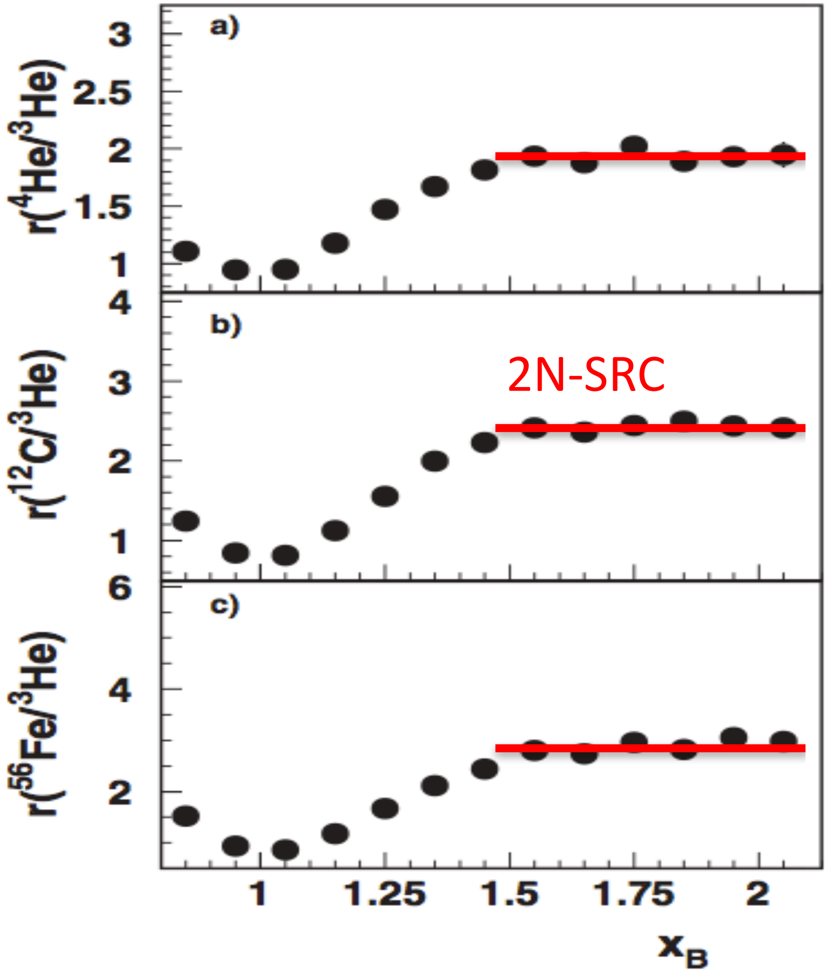


High-Momentum Scaling

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

- Observed scaling in for $x_B \geq 1.5$.

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



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

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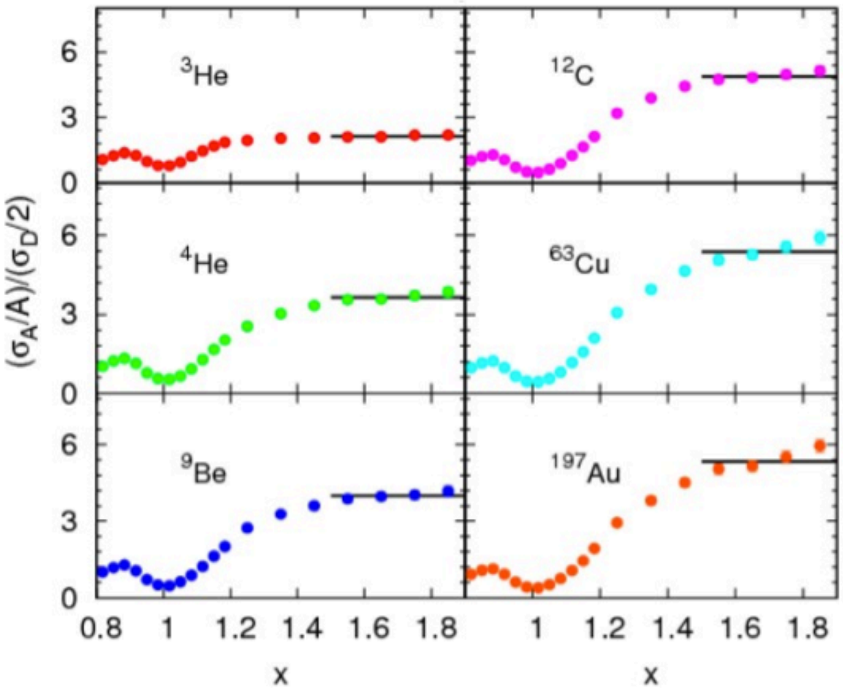

N. Fomin et al., PRL **108**, 092502 (2012)

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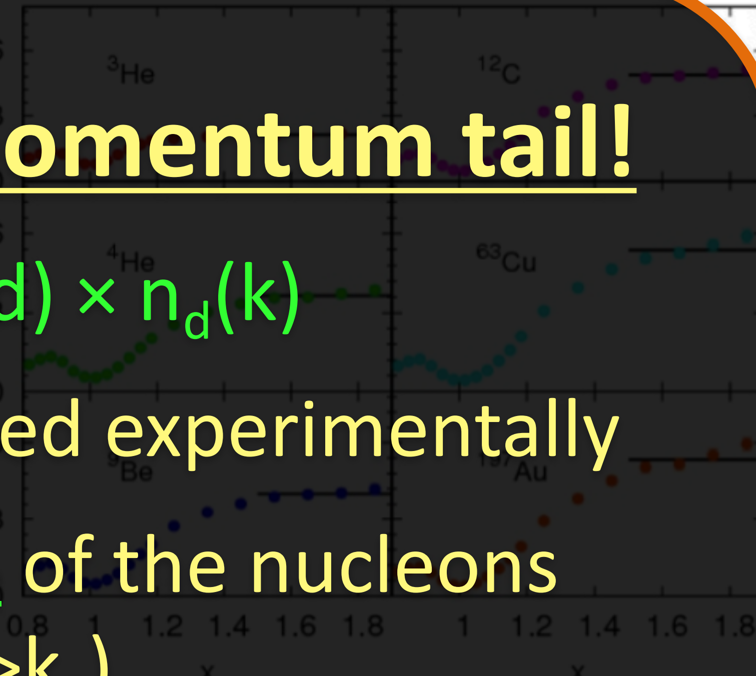
$$n_A(k>k_F) = a_2(A) \times n_d(k)$$

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 ($k>k_F$).



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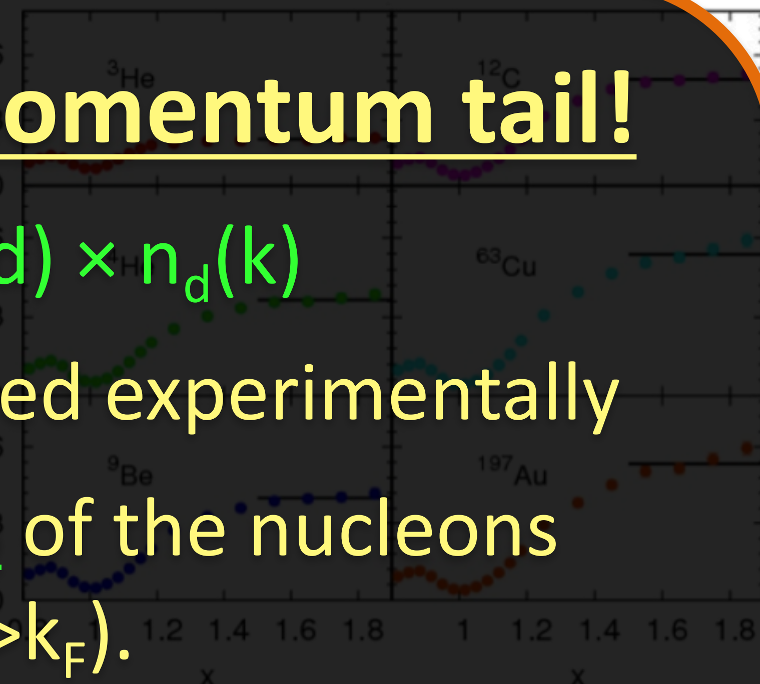
High-Momentum Scaling



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3. In $A \geq 12$ nuclei, 20 – 25% of the nucleons have high-momentum ($k>k_F$).

Do ALL high-momentum nucleons come in pairs? What kind of pairs?

A	$a_2(A/D)$	A	$a_2(A/D)$
^{3}He	[illegible]	^{12}C	4.7 ± 0.2
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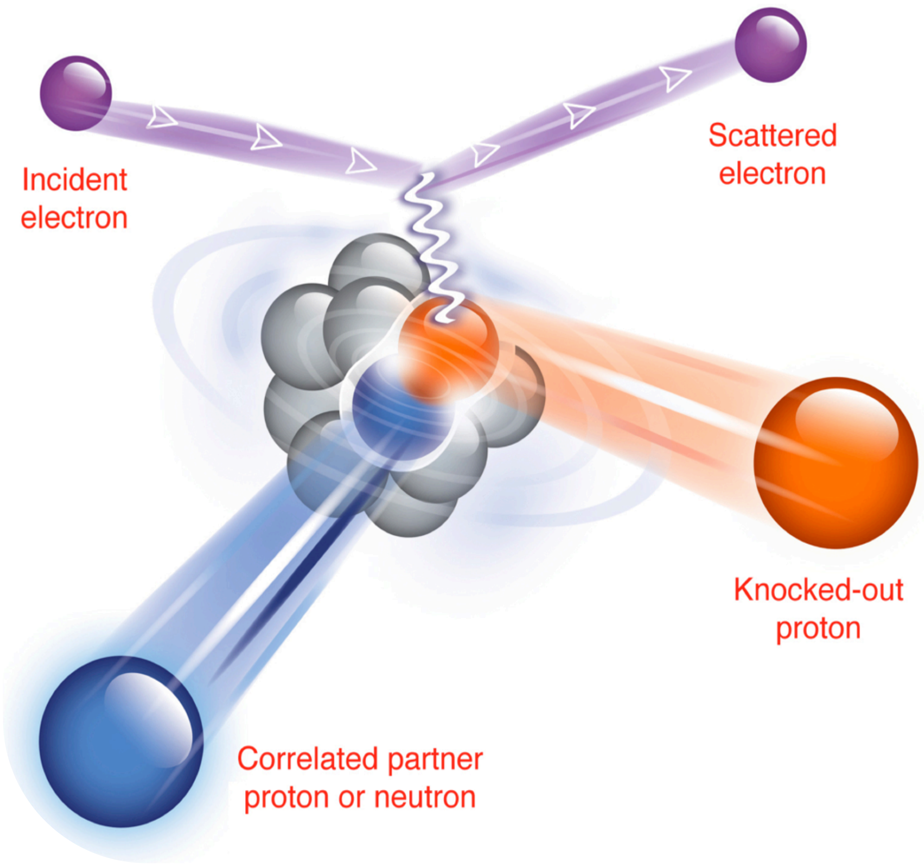
Exclusive 2N-SRC Studies

Breakup the pair =>
Detect both nucleons =>
Reconstruct 'initial' state



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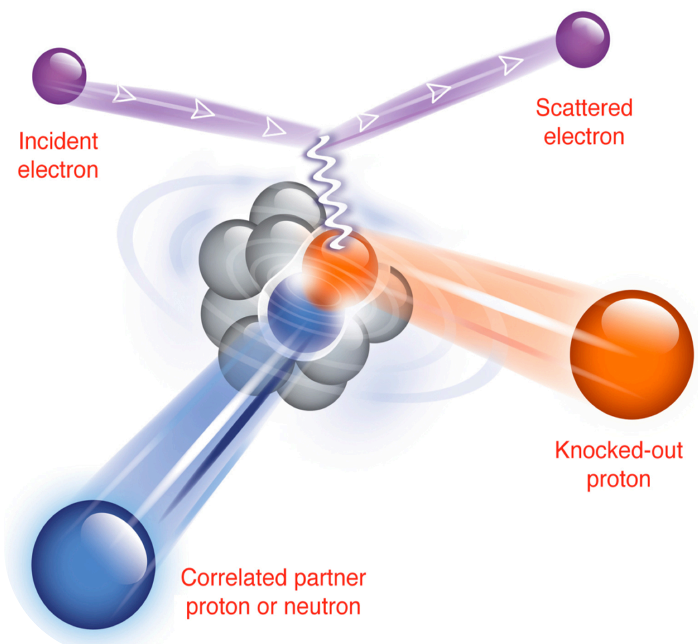
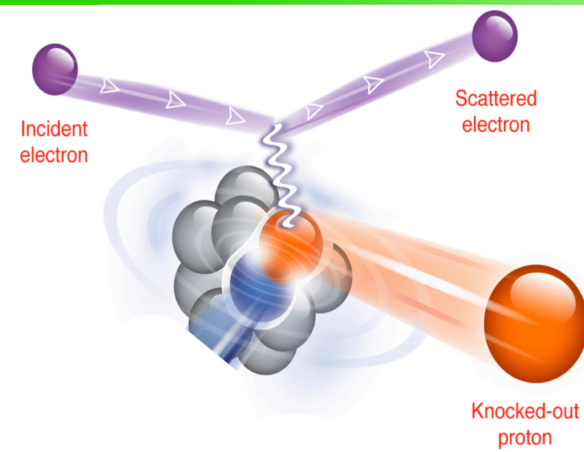
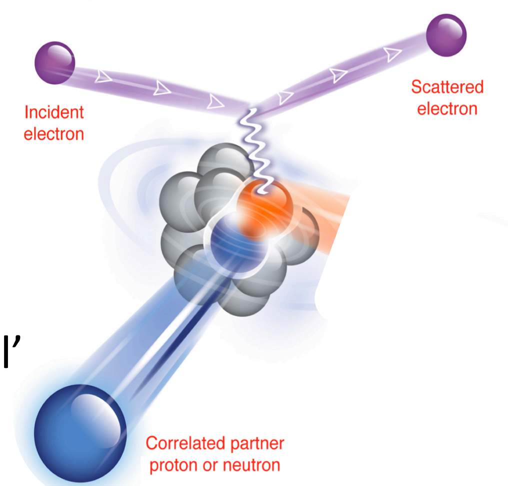




'leading'

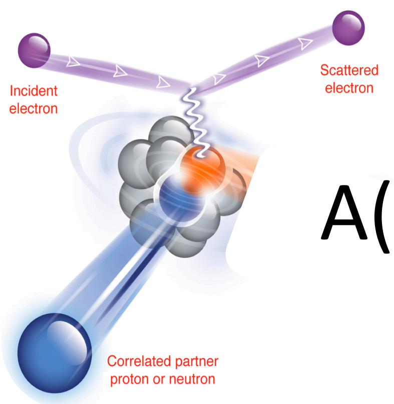
'recoil'



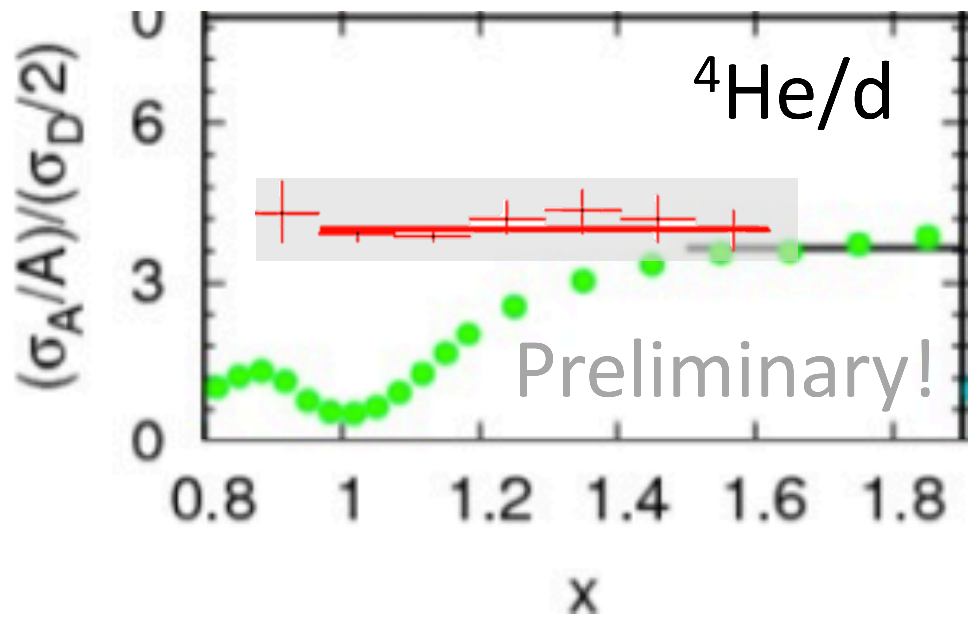
NEW DATA! (1)

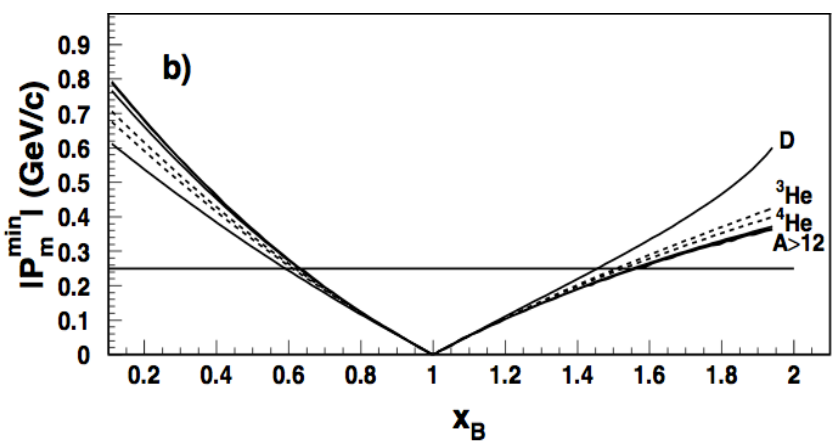
Counting SRCs using spectator tagging.

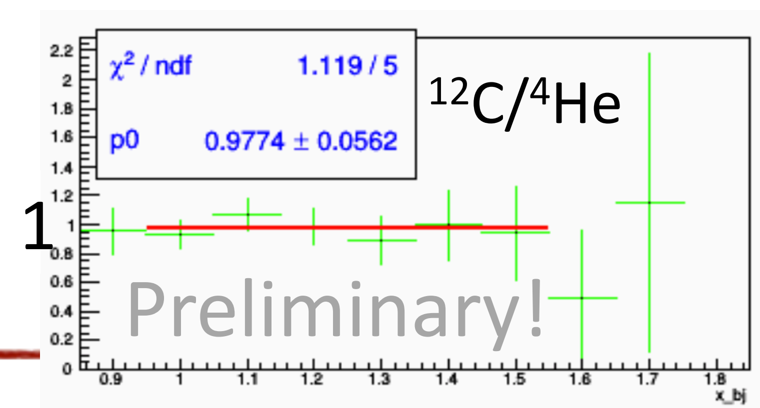
[*Can also be done @ Minerva? (I think so!)*]



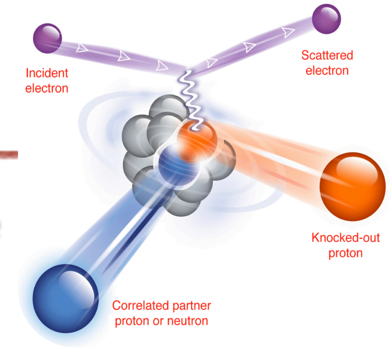
$A(e,e'p_{recoil})$

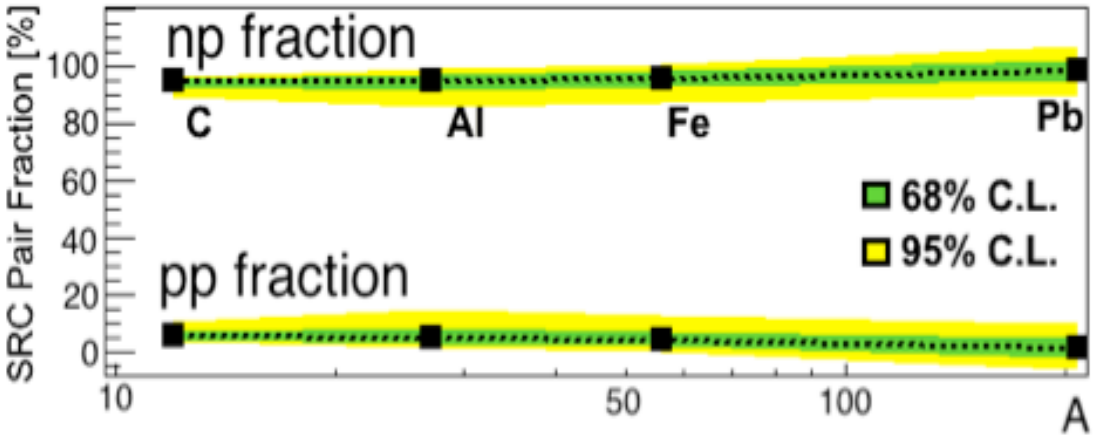




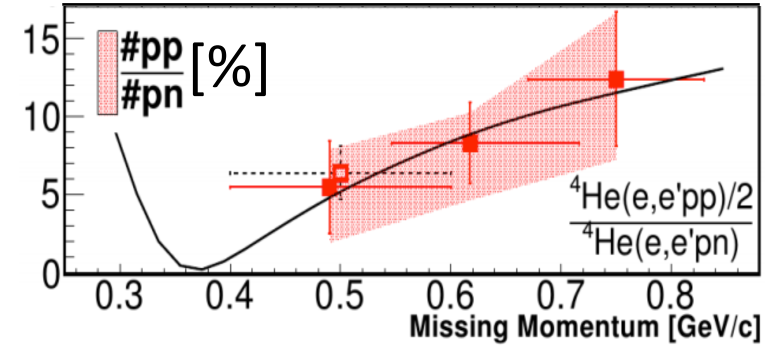


SRC Isospin Structure



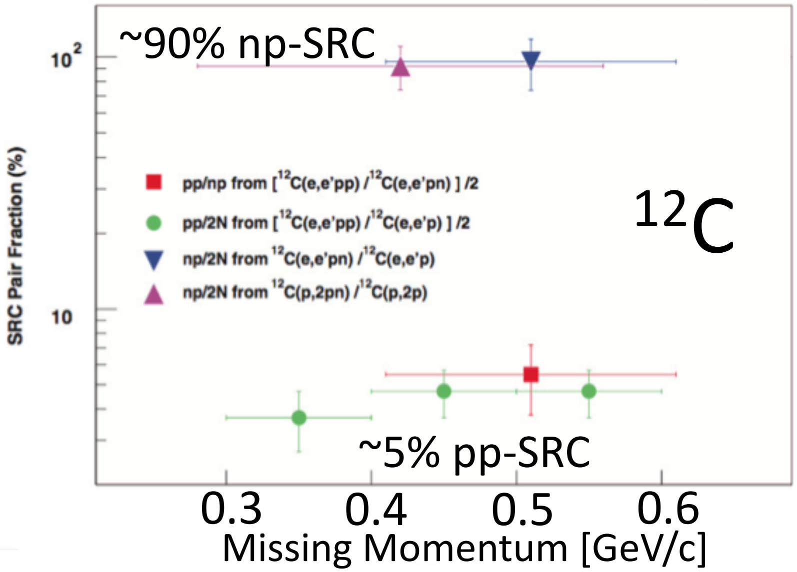


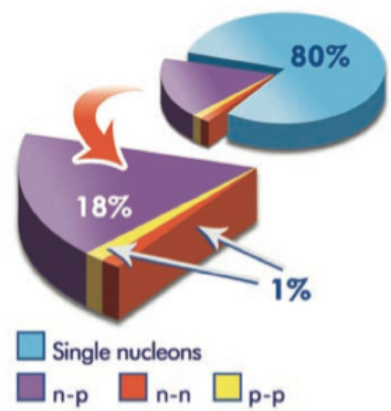
O. Hen et al., Science 364 (2014) 614

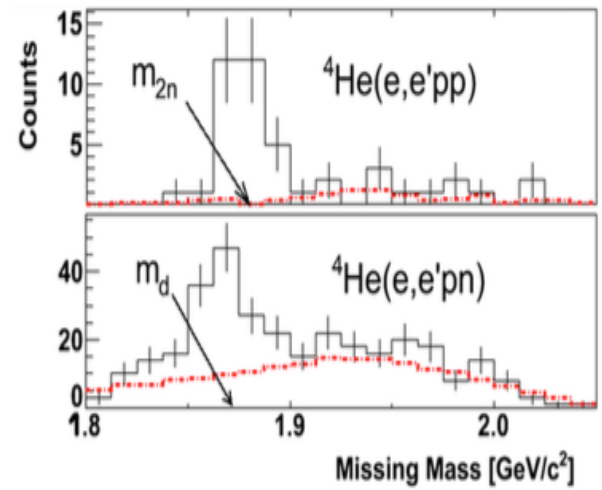


R. Subedi et al., Science 320 (2008) 1476

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



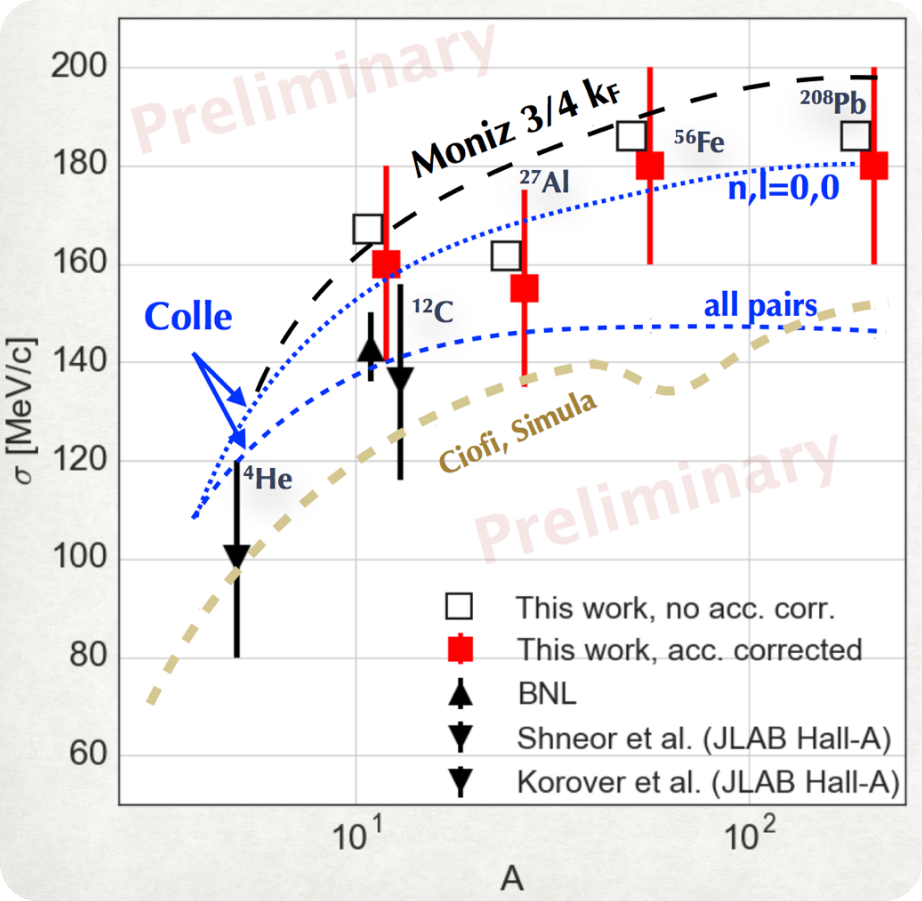


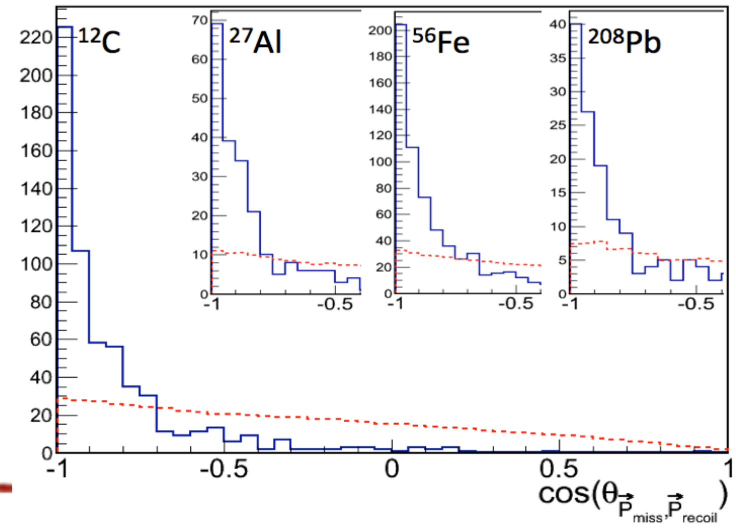


A. Tang et al., PRL (2003); E. Piasetzky et al., PRL (2006); R. Shneor et al., PRL (2007)

NEW DATA! (2)

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





E. Cohen et al. (CLAS Collaboration)

SRC Isospin Structure

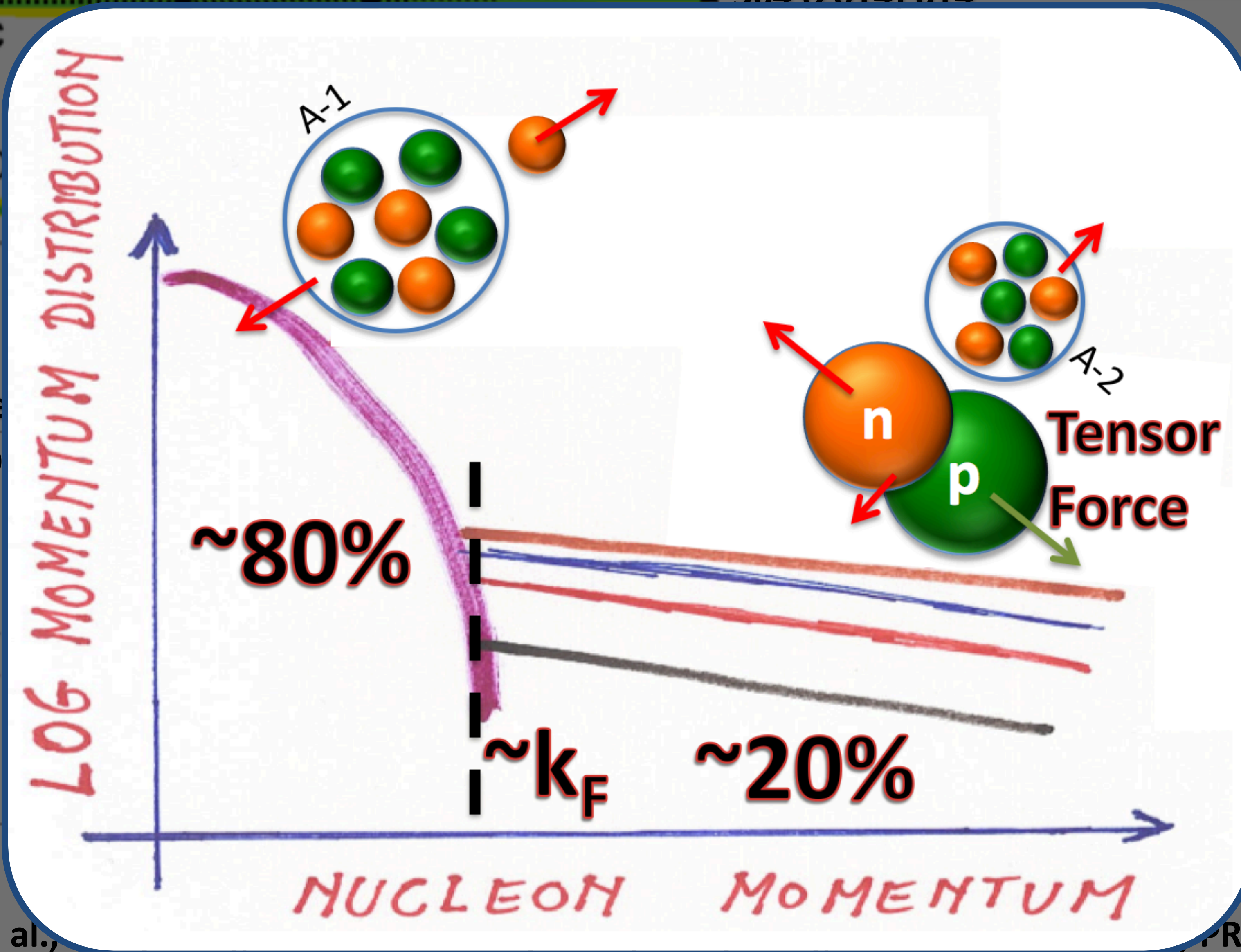
Bottom Line:

- SRCs account for:
  - ~ 20% of the nucleons in nuclei.
  - ~100% of the high-p ($k>k_F$) nucleons in nuclei.
- Predominantly due to np-SRC.
- Universal for A = 4 – 208 nuclei.
- **Tensor force** dominance at short distance.

0.3 0.4 0.5 0.6
Missing Momentum [GeV/c]

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

Universal structure of nuclear momentum distributions



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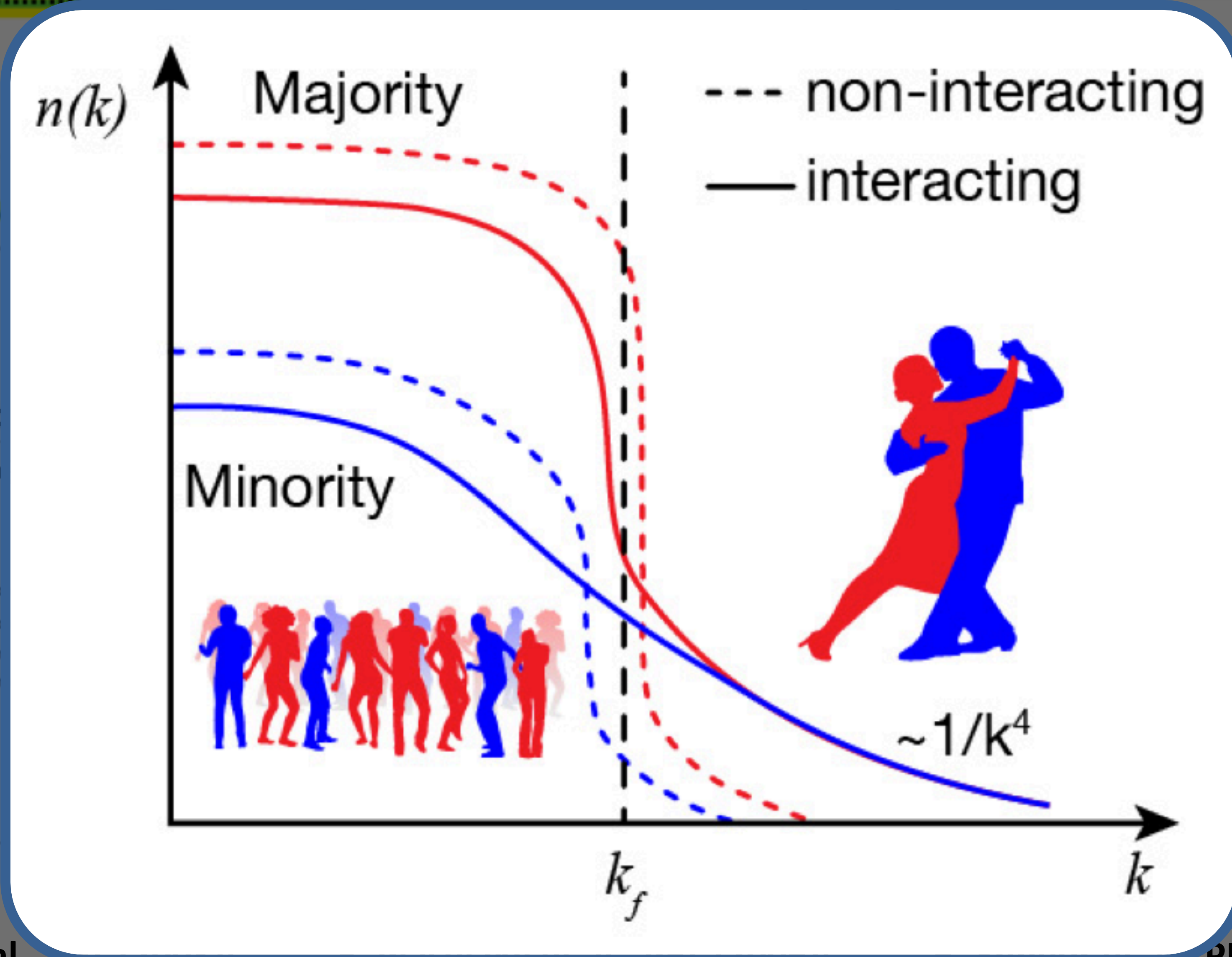
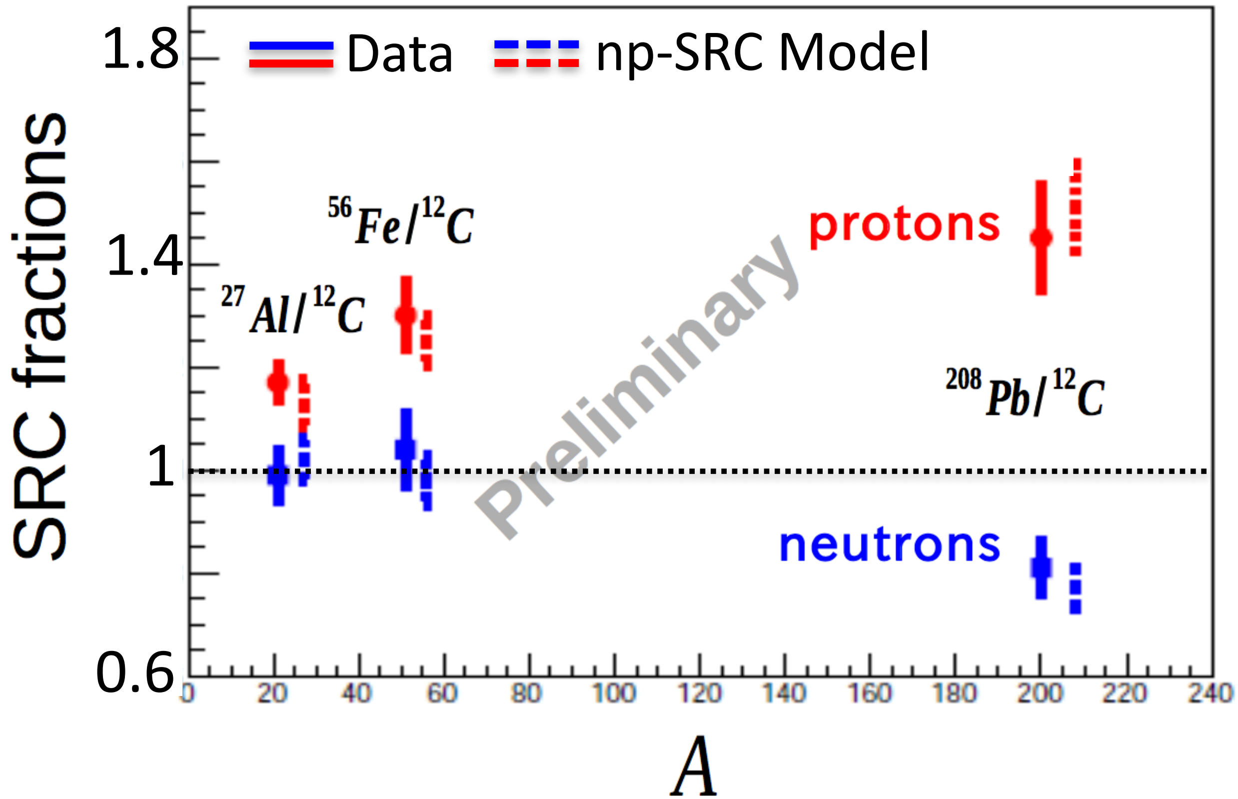
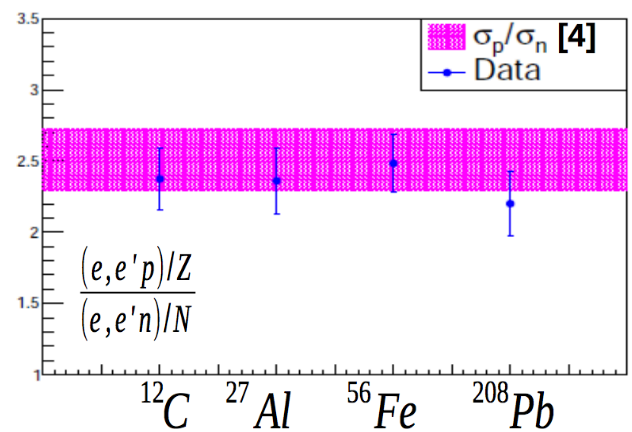


NEW DATA! (3)

Fraction of high-momentum nucleons in asymmetric nuclei



$$\frac{A\,(e,e'N)\,[\text{high-}P_m\,/\,\text{low-}P_m]}{^{12}C(e,e'N)\,[\text{high-}P_m\,/\,\text{low-}P_m]}$$



M. Duer et al. (CLAS Collaboration)

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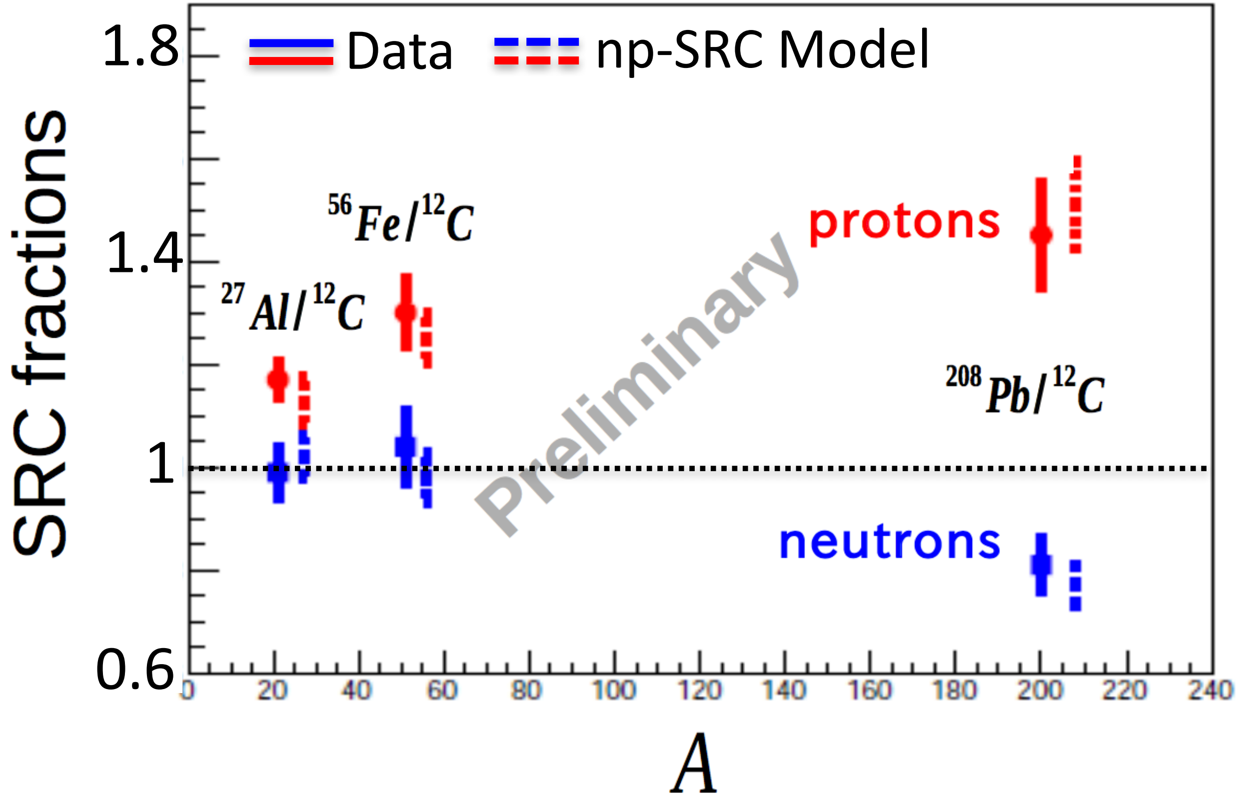


Protons in neutron rich nuclei have higher SRC probability!!

M. Duer et al. (CLAS Collaboration)

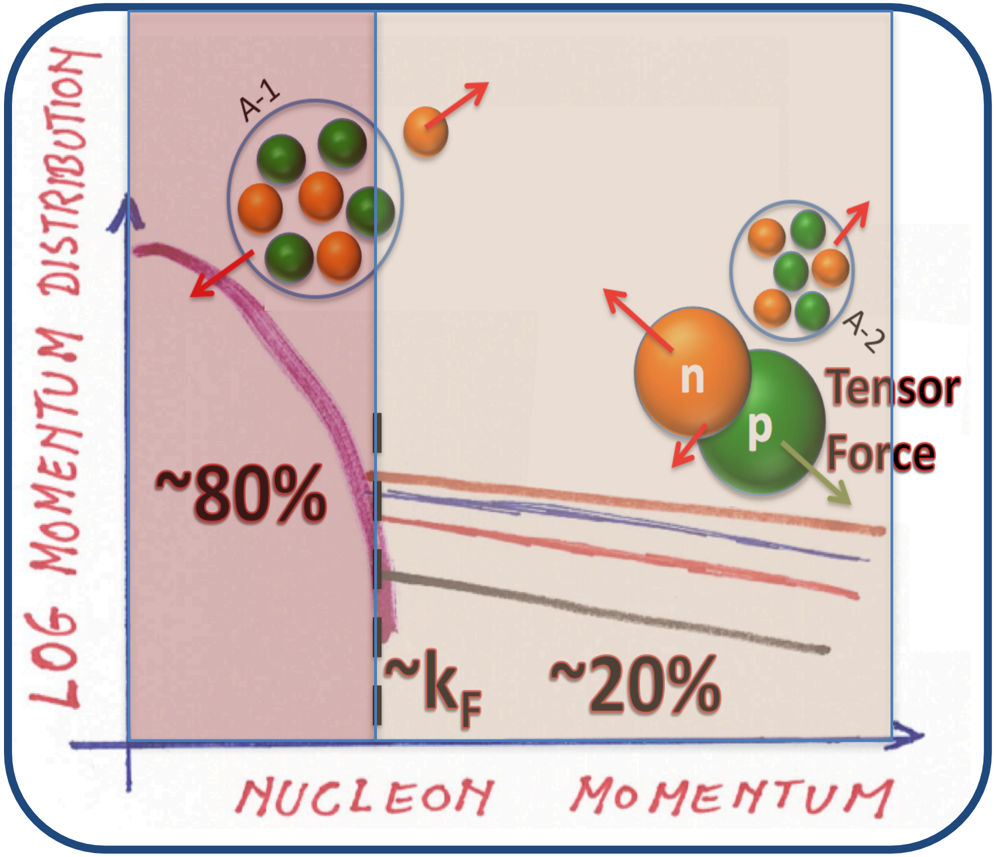
SRC 101

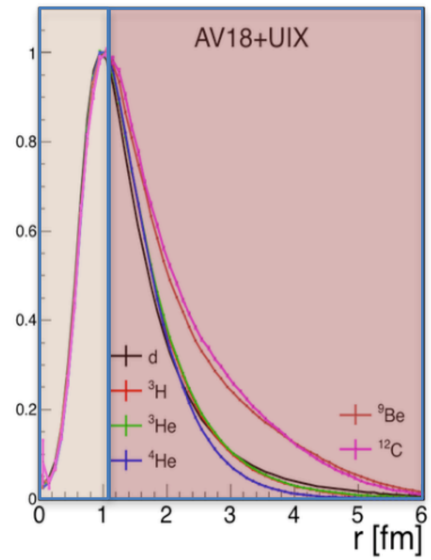
Consistent set of (e,e’), (e,e’p), (e,e’pN) and (p,2pn) measurements, on a variety of nuclei, allow quantifying SRCs with unprecedented accuracy!

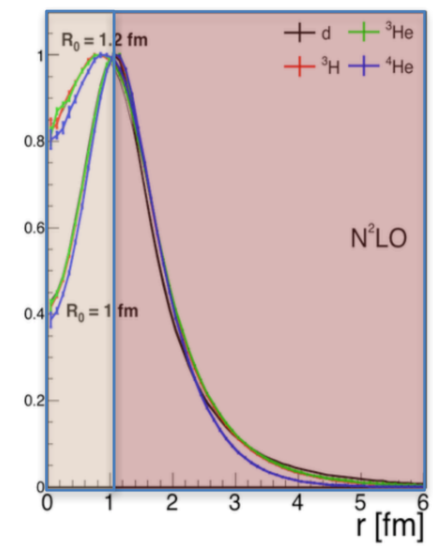
1. SRC Exist in Nuclei (!) and account for:
   - ~ 20% of the nucleons in nuclei.
   - ~100% of the high-p ($k>k_F$) nucleons in nuclei.
2. Have large relative momentum and low c.m. momentum.
3. Predominantly due to np-SRC.
4. Universal for A = 4 – 208 nuclei.
5. np-SRC create a larger fraction of high-momentum protons in neutron rich nuclei!
6. **Tensor force** dominance at short distance.

Universal Nuclear Structure

Can universality help describe the SRC phase of the nucleus in both coordinate and momentum space WITHOUT relaying on many-body calculations? (seems like the answer is YES)





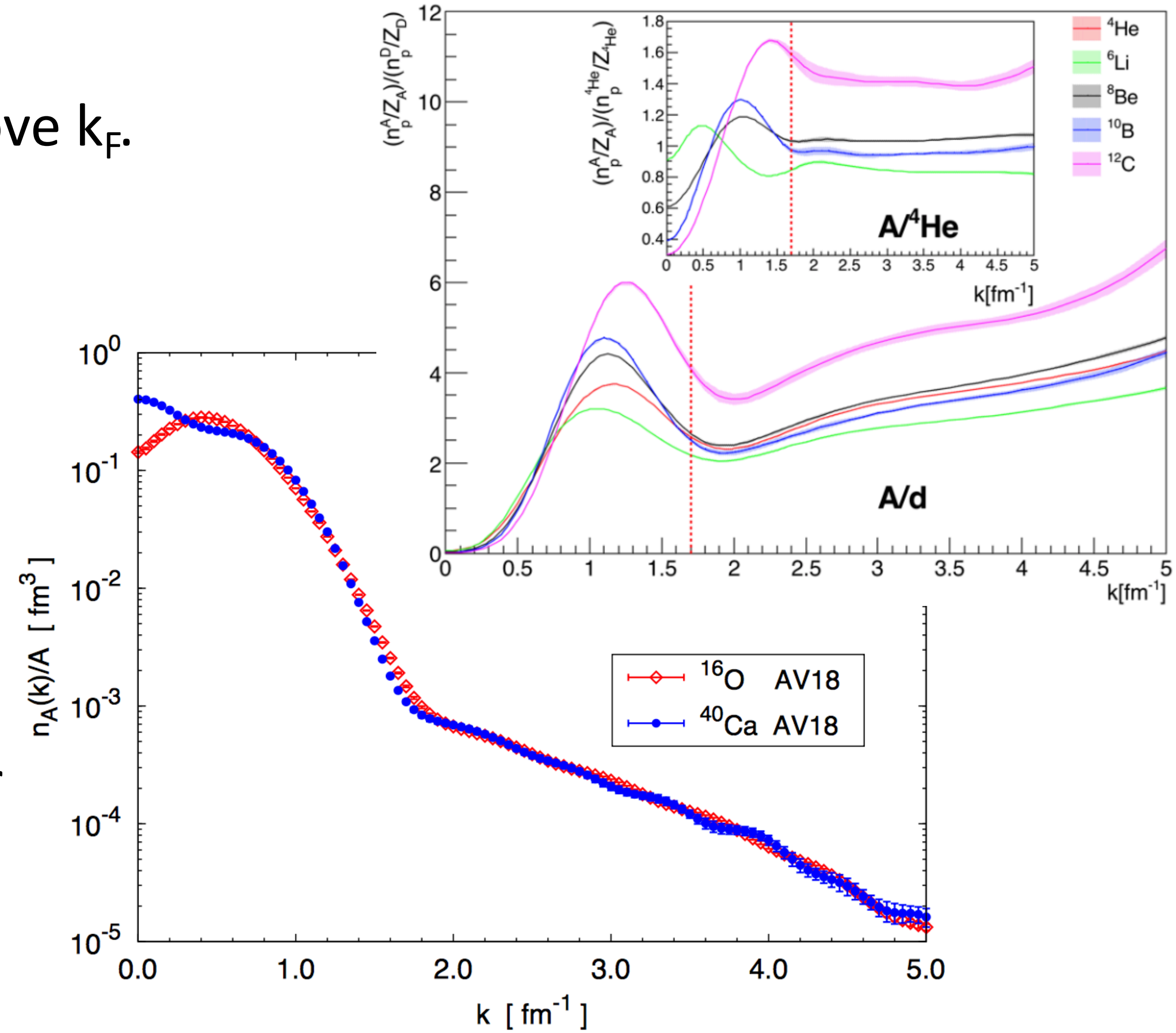


Hints from Many-Body (VMC) ?

- One body momentum distribution scales above k_F.
- Good scaling relative to ^{4}He NOT deuteron.

⇒ Importance of non-deuteron pairs? c.m. motion? Both?

⇒ Why the (e,e') data for A/d scale but the calculations don't?



Two-component interacting Fermi systems

The contact term

Please forget about nuclear physics for a moment

Concept developed for dilute two-component Fermi systems with a short-range (δ-like) interaction.

$$\text{dilute} \equiv r_{eff} << a, d$$

Dilute System

Concept developed for dilute two-component Fermi systems with a short-range (δ-like) interaction.

$$\text{dilute} \equiv r_{eff} << a, d$$

- r_{eff}: Range of interaction
- a: Scattering length
- d: Distance between fermions

Range of interaction much smaller than the other relevant length scales in the problem

Dilute System

S. Tan Annals of Physics 323 (2008) 2952, ibid 2971, ibid 2987

The Contact and Universal Relations

Contact interaction is represented through a boundary condition

Imposing this B.C. on the Schrödinger equation yields an asymptotic wave function when two fermions get very close

$$\Psi \xrightarrow[r_{ij}\to 0]{} \underbrace{(1/r_{ij} - 1/a)}_{\text{Two Body}} \underbrace{A_{ij}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j})}_{\text{A-2}}$$

Two Body A-2

Dilute System → Short Distance Factorization

S. Tan Annals of Physics 323 (2008) 2952, ibid 2971, ibid 2987

The Contact and Universal Relations

$$\Psi \xrightarrow[r_{ij}\to 0]{} (1/r_{ij} - 1/a) A_{ij}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j})$$

$$n(k) = C / k^4 \quad \text{for} \quad k > k_F$$

Dilute System → Short Distance Factorization → **High Momentum Tail**

S. Tan Annals of Physics 323 (2008) 2952, ibid 2971, ibid 2987

The Contact and Universal Relations

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$$n(k) = C / k^4 \quad \text{for} \quad k > k_F$$

<u>Tan's Contact term:</u>

1. Measures the number of SRC different fermion pairs.
2. Determines the thermodynamics through a series of universal relations.

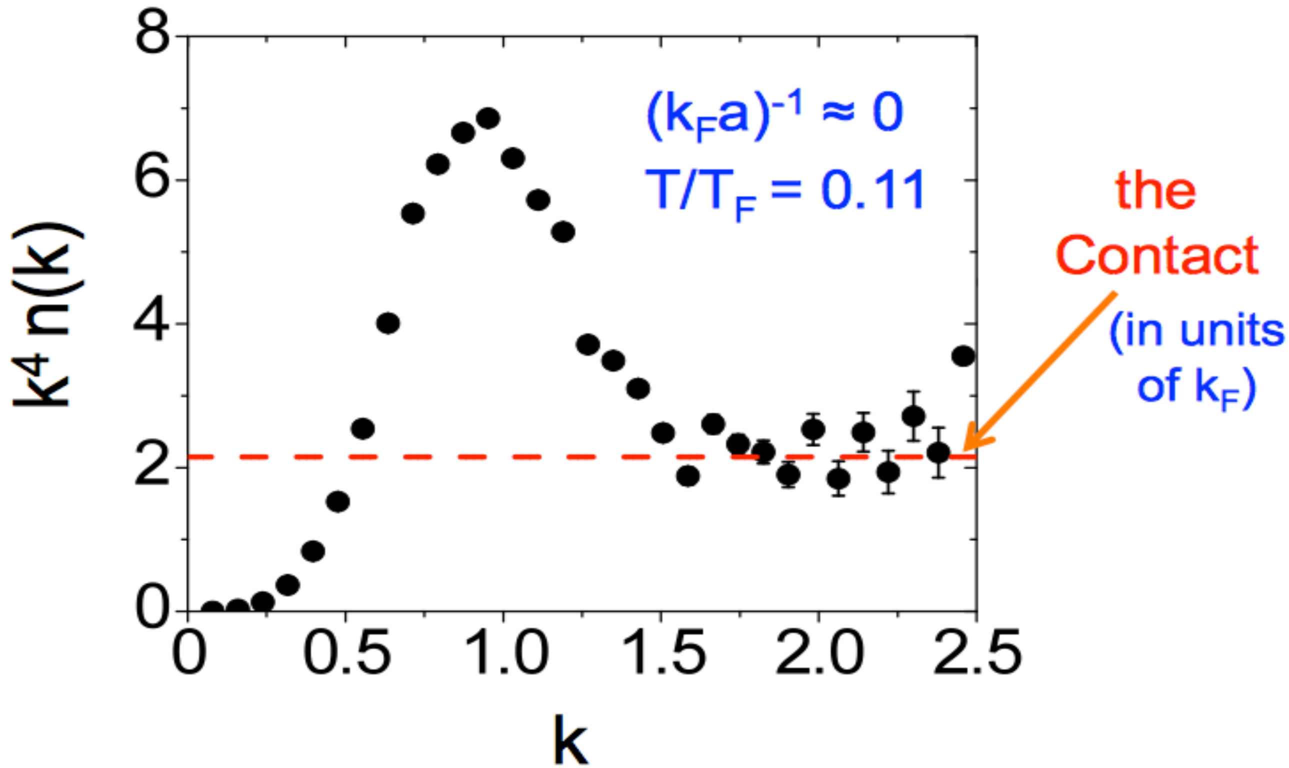
Dilute System → Short Distance Factorization → **High Momentum Tail**

S. Tan Annals of Physics 323 (2008) 2952, ibid 2971, ibid 2987

Experimental Validation

Two spin-state mixtures of ultra-cold ^{40}K and ^{6}Li atomic gas systems.

=> extracted the contact and verified the universal relations



Stewart et al. PRL **104**, 235301 (2010)

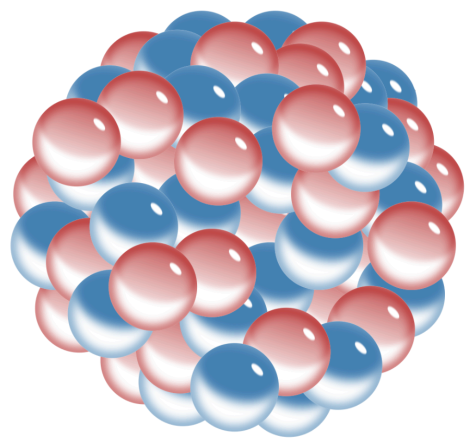
What About a *Nuclear* Contact ?

A Nuclear Contact?

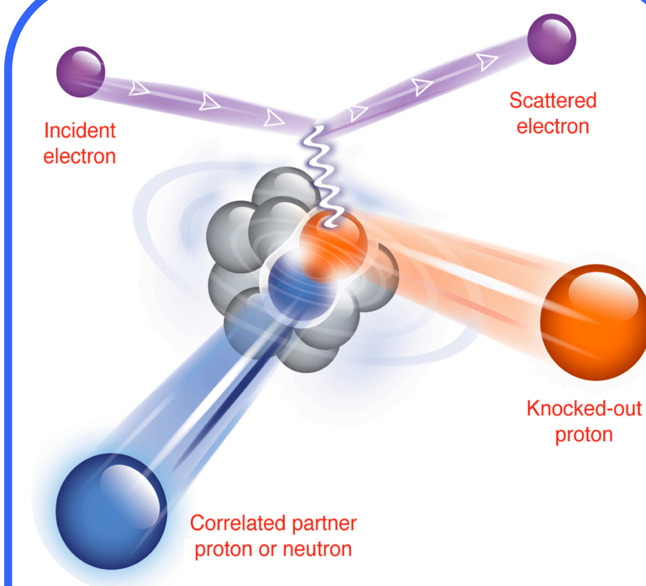
Concept developed for:

dilute two-component Fermi systems with a short-range interaction.

?



protons and neutrons



2N-SRC

Theory Says: not so much

Are nuclei dilute? (i.e. $r_{eff} << a,d$)

$$d = \left(\rho/2\right)^{-1/3} \approx 2.3 \text{ fm}$$

$$r_{eff} \approx \frac{\hbar}{2 \cdot m_\pi \cdot c} \approx 0.7 \text{ fm}$$

[Tensor force]

$$a\left({}^3S_1\right) = 5.42 \text{ fm}$$

$$r_{eff}(0.7 \text{ fm}) < d(2.3 \text{ fm}), a(5.4 \text{ fm})$$

But Experiment Says….

Is there $1/k^4$ scaling regardless?

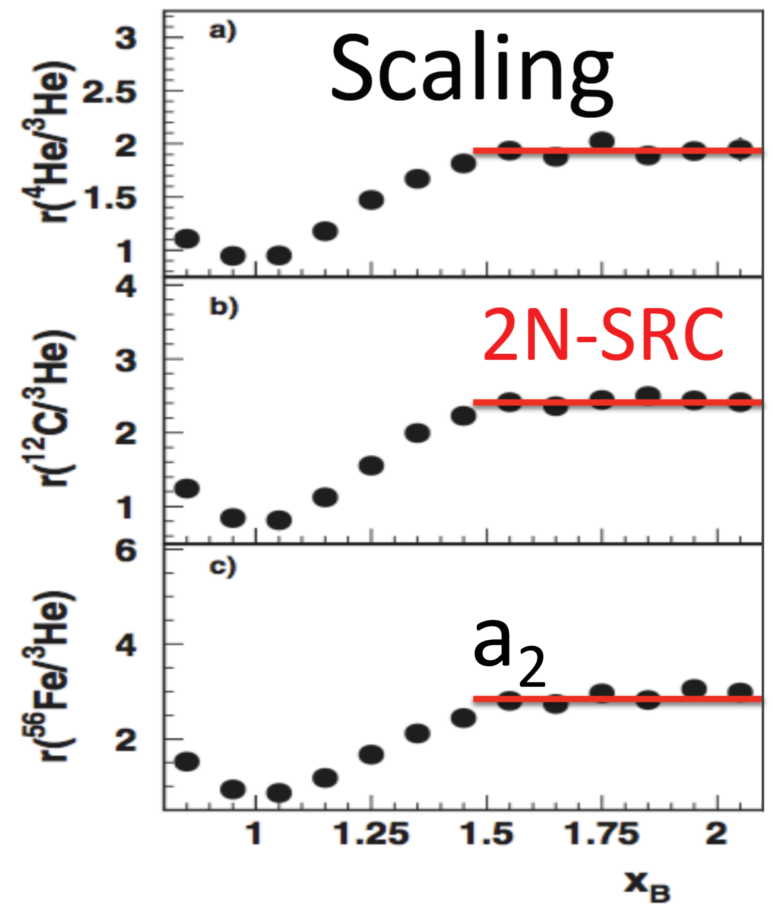
$$1.5k_F < k < 3k_F$$

$$n_A(k) = a_2(A/d) \cdot n_d(k)$$

nucleus A momentum distribution

experimental constant

deuteron momentum distribution



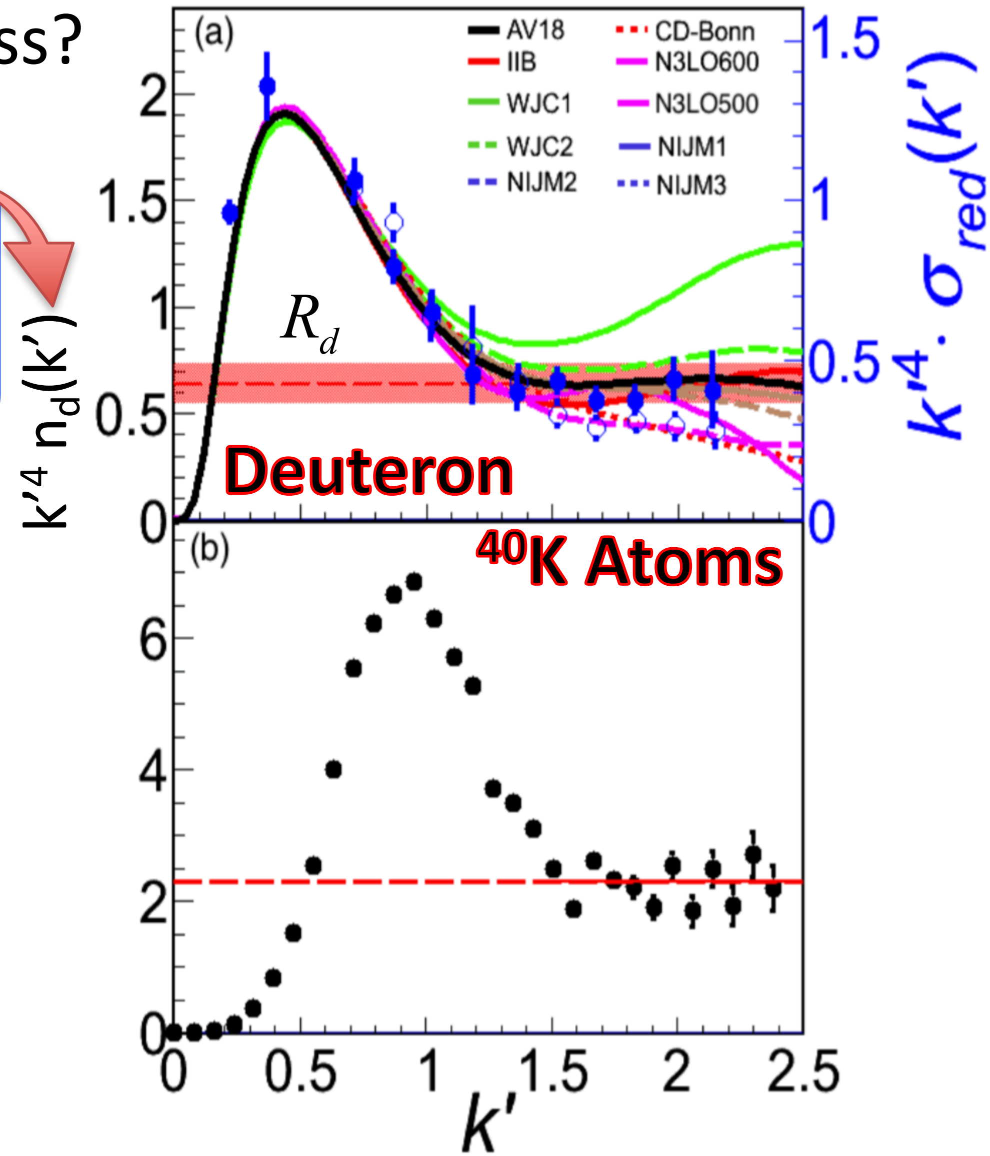
The momentum distribution of nucleons in medium to heavy nuclei is proportional to that of deuteron at high momenta.

But Experiment Says.... **Yes!**

Is there $1/k^4$ scaling regardless?

$$1.5k_F < k < 3k_F$$

$$n_A(k) = a_2(A/d) \cdot n_d(k)$$



O. Hen et al. Phys. Rev. C **92**, 045205 (2015)

But Experiment Says.... Yes! (?)

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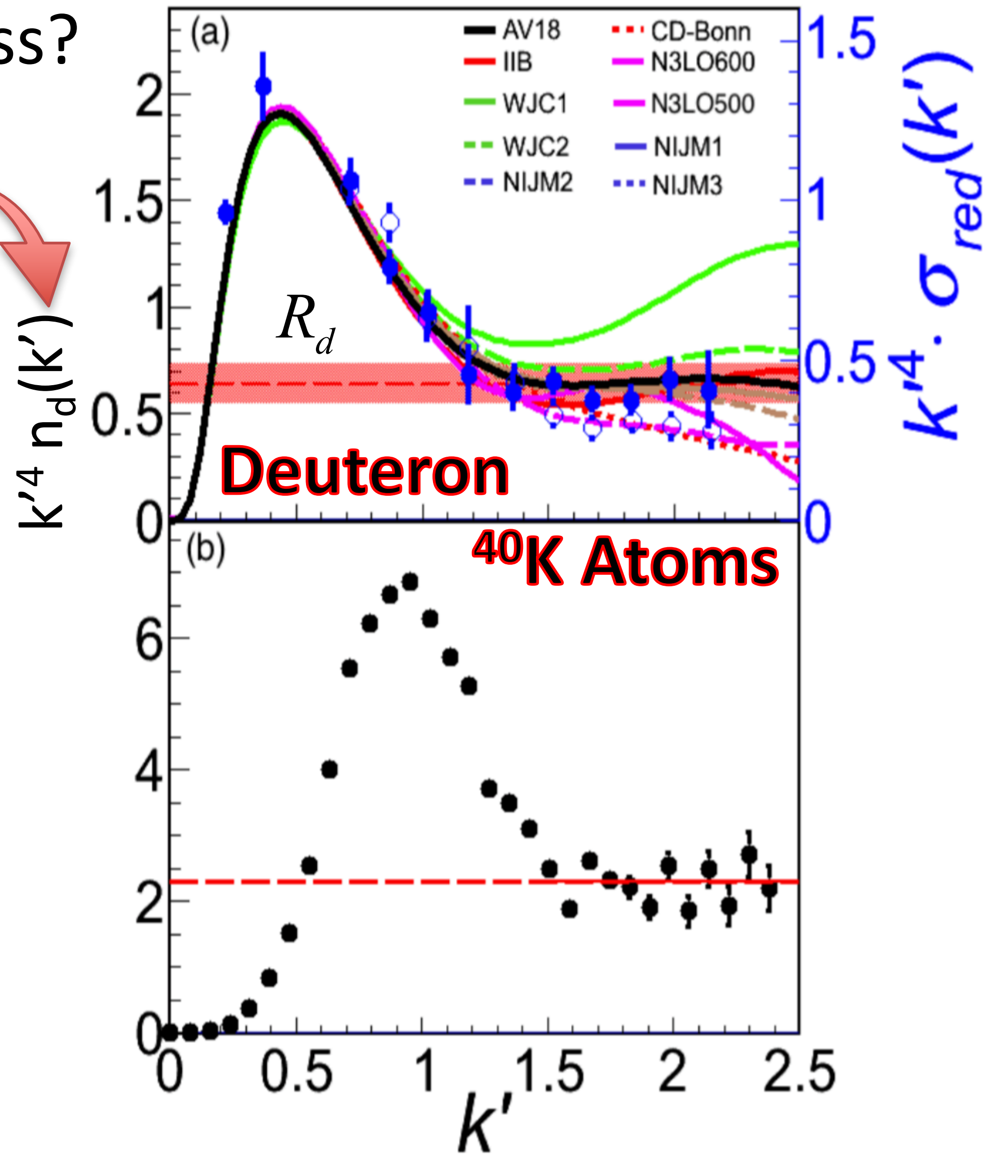


Why $1/k^4$?

Effect of the one pion exchange (OPE) contribution to the tensor potential acting in second order

$$(-B - H_0)|\Psi_D\rangle = V_T|\Psi_S\rangle$$

$$V_{00} = V_T(-B - H_0)^{-1} V_T$$

O. Hen et al. Phys. Rev. C **92**, 045205 (2015)

But Experiment Says…. **Yes! (?)**

Is there $1/k^4$ scaling regardless?

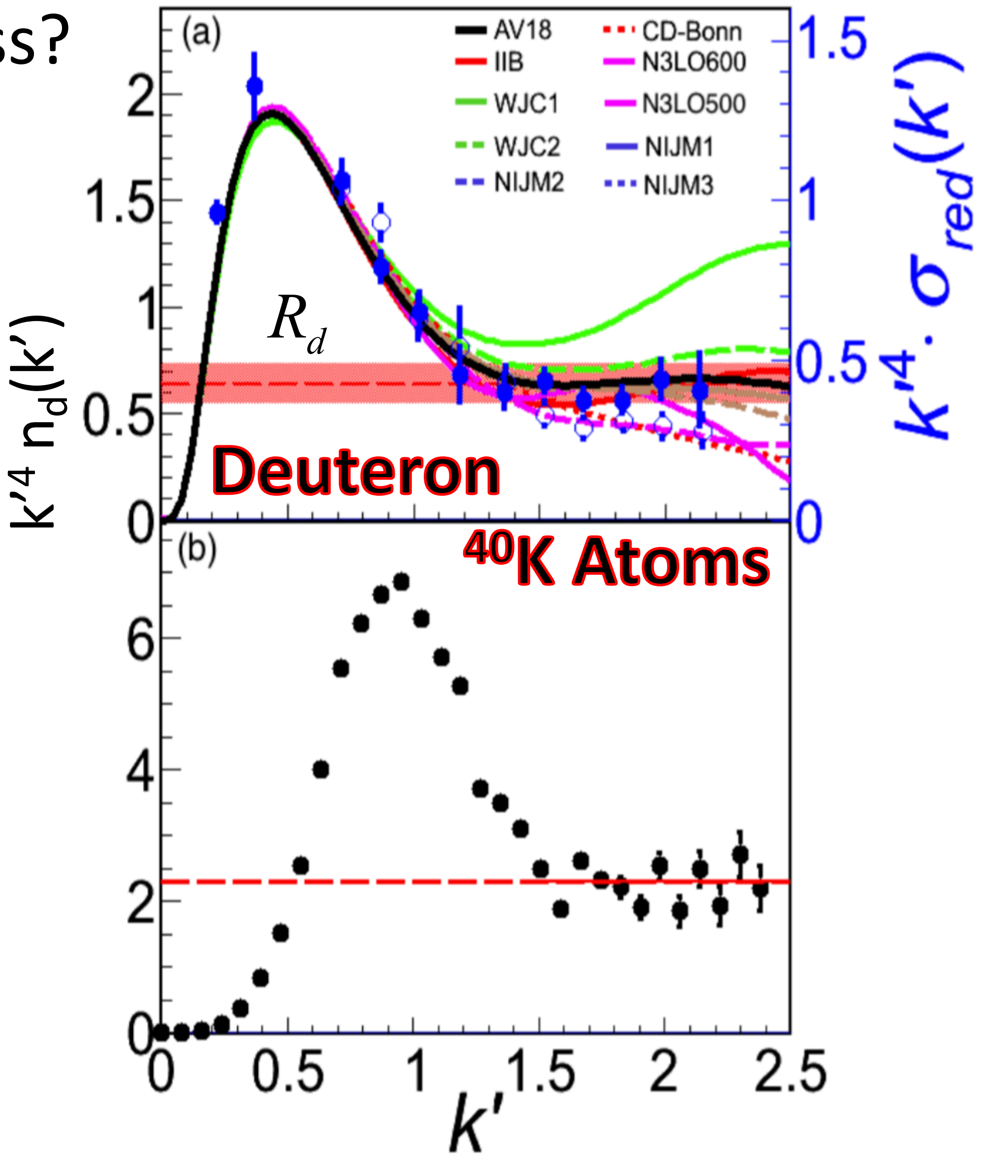
$$1.5k_F < k < 3k_F$$

$$n_A(k) = a_2(A/d) \cdot n_d(k)$$

$$\frac{C}{k_F \cdot A} = a_2(A) \cdot R_d$$

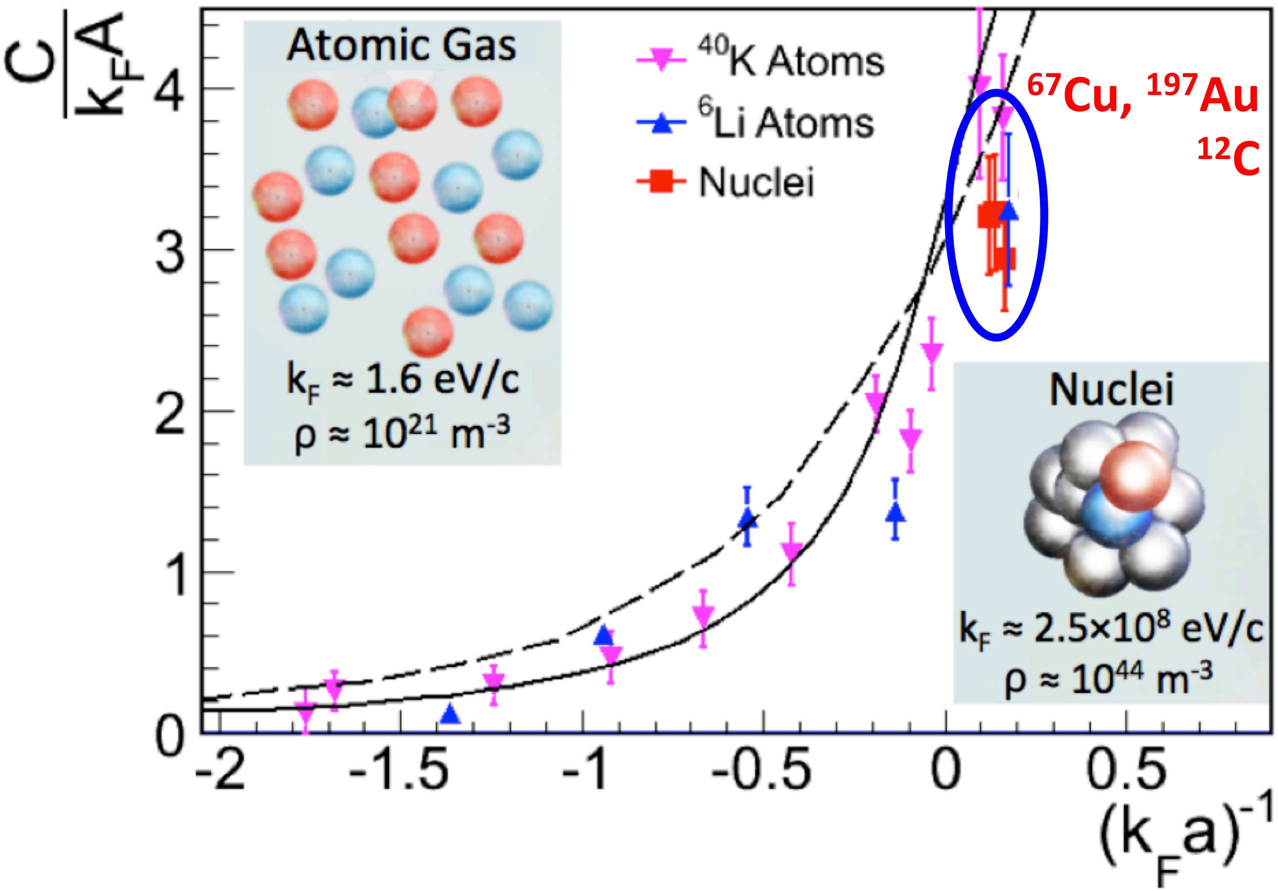
Nucleus	$a_2(A)$	$\frac{C}{k_F A}$
^{12}C	4.75 ± 0.16	3.04 ± 0.49
^{56}Fe	5.21 ± 0.20	3.33 ± 0.54
^{197}Au	5.16 ± 0.22	3.30 ± 0.53

O. Hen et al. Phys. Rev. C **92**, 045205 (2015)



Comparing with atomic systems

Equal contacts for equal interactions strength!



For Nuclei:

$k_F \approx 1.27$ fm^{-1}

$a \approx 5.4$ fm

$(k_F a)^{-1} \approx 0.15$

Nucleus	$\frac{C}{k_F A}$
^{12}C	3.04 ± 0.49
^{56}Fe	3.33 ± 0.54
^{197}Au	3.30 ± 0.53

$$\frac{C}{k_F \cdot A} = a_2(A) \cdot R_d$$

O. Hen et al. Phys. Rev. C **92**, 045205 (2015)
Stewart et al. Phys. Rev. Lett. **104**, 235301 (2010)
Kuhnle et al. Phys. Rev. Lett. **105**, 070402 (2010)

How can we reconcile the experimental observation with theory expectation?

i.e. is there a region in which the nuclear wave function fully factorizes?

Going Back to the Theory…

1. Generalize the contact formalism to nuclear systems.

2. Use it to make specific predictions of nuclear properties.

3. Check using experimental data and full many-body calculations.

The Contact and Universal Relations

Issue: Scale separation does not necessarily work in nuclear systems.

Solution: assume a more general form for the 2-body wavefunction.

Atomic System:

$$\Psi \xrightarrow[r_{ij}\to 0]{} (1/r_{ij} - 1/a) A_{ij}(\mathbf{R}_{ij}, \{\mathbf{r}_k\}_{k\neq i,j})$$

Nuclear System:

$$\Psi \xrightarrow[r_{ij}\to 0]{} \left(\boldsymbol{\varphi}(r)_{ij} \right) A_{ij}(\mathbf{R}_{ij}, \{\mathbf{r}_k\}_{k\neq i,j})$$

The Contact and Universal Relations

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Nuclear System:

$$\Psi \xrightarrow[r_{ij}\to 0]{} \left(\boldsymbol{\varphi(r)_{ij}} \right) A_{ij}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j})$$

known solution for the two-body (nuclear) problem

Factorization in Nuclei

Consider the factorized wave function:

$$\Psi \xrightarrow[r_{ij}\to 0]{} \sum_{\alpha} \varphi_{\alpha}(\boldsymbol{r}_{ij}) A_{ij}^{\alpha}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j})$$

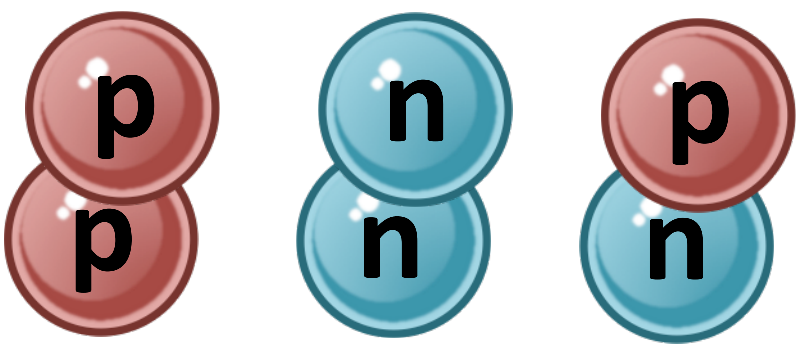
In nuclear physics we have 3 possible types of pairs:

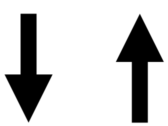
ij = {pp, nn, pn}

+

For each pair we have different channels

α = (s,l)jm





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In nuclear physics we have 3 possible types of pairs:

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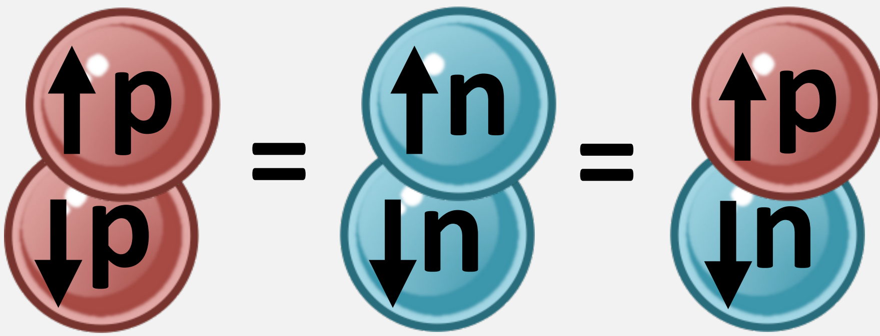
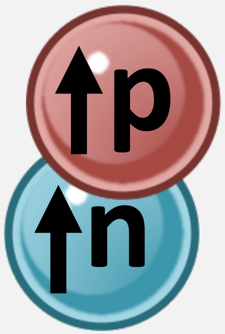
Reduced to 2 contacts by imposing L=0 and symmetry considerations

S=0



S=1



Relating to Momentum Space

$$\Psi \xrightarrow[r_{ij}\to 0]{} \sum_{\alpha} \varphi_{\alpha}(\boldsymbol{r}_{ij}) A_{ij}^{\alpha}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j})$$

One Body:

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

2-Body momentum distributions

- One Body momentum distribution [$n_N(k)$]: Probability to find a nucleon, N, in the nucleus with momentum k.

- Two Body momentum distribution [$n_{NN}(q,Q)$]: Probability to find a NN pair in the nucleus with relative (c.m.) momentum q (Q).

$n_{NN}(q,Q)$ – computational Frontier!

Momentum Space Factorization

$$\Psi \xrightarrow[r_{ij}\to 0]{} \sum_{\alpha} \varphi_\alpha(\boldsymbol{r}_{ij}) A_{ij}^{\alpha}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j})$$

One Body:

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

Two body:

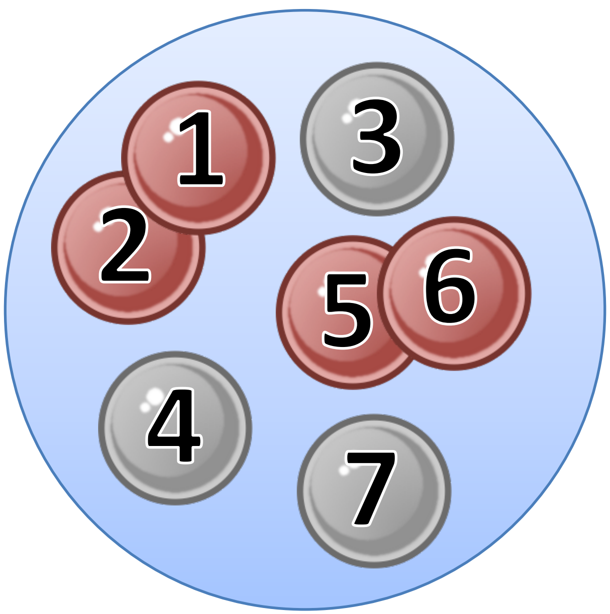
$$\boldsymbol{F_{ij}(k)} = \sum_{\alpha} \left|\tilde{\varphi}_{ij}^{\alpha}(\boldsymbol{k})\right|^2 C_{ij}^{\alpha}$$

Clearly:

$$\boldsymbol{n_p(k)} \xrightarrow[k\to\infty]{} 2\boldsymbol{F_{pp}(k)} + \boldsymbol{F_{pn}(k)}$$

Two-Body Momentum Distributions

- $n_{NN}(q,Q)$ – Mathematical object that counts all possible NN pairs, regardless of their state:

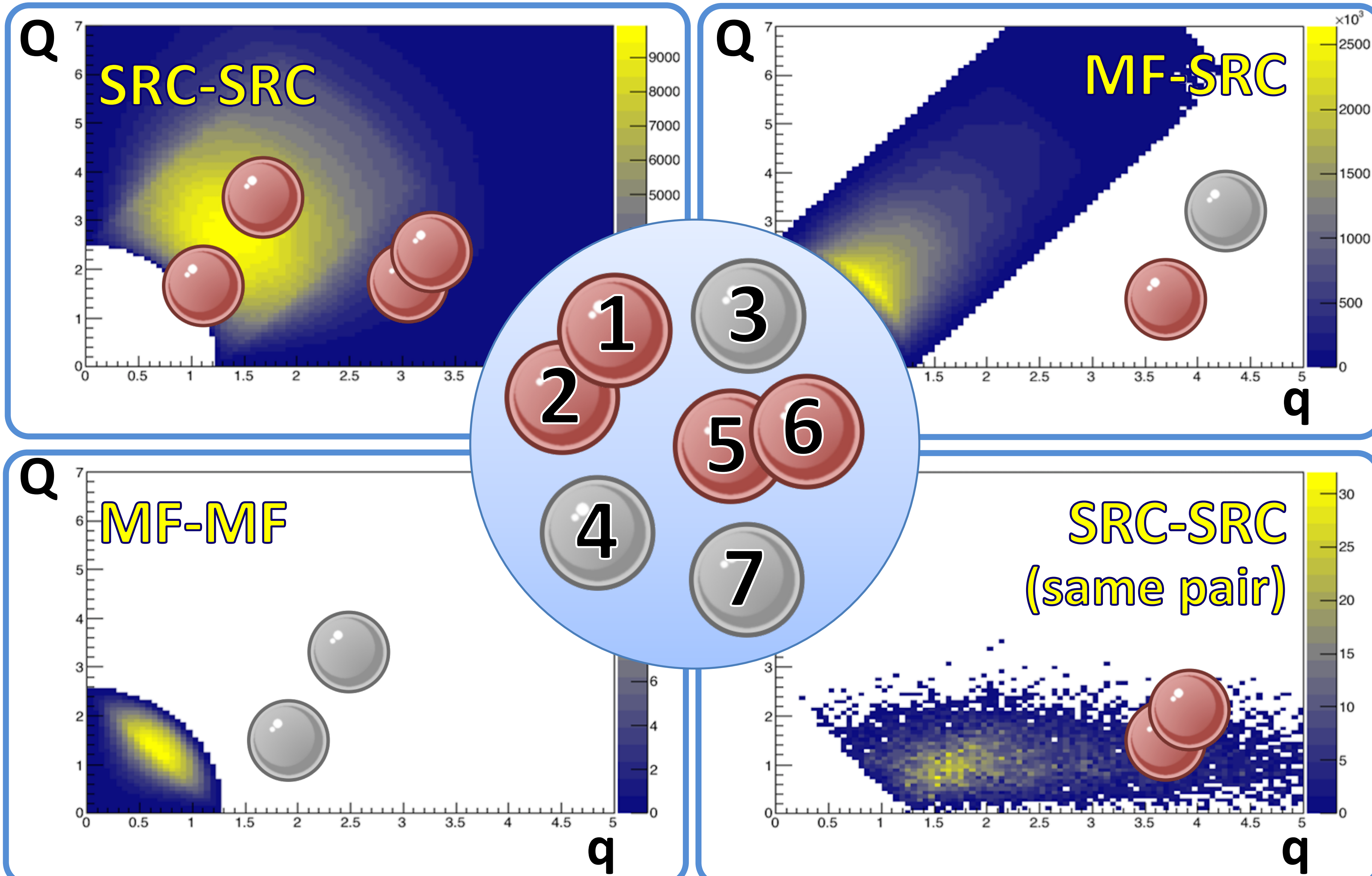


Consider all NN pairs:

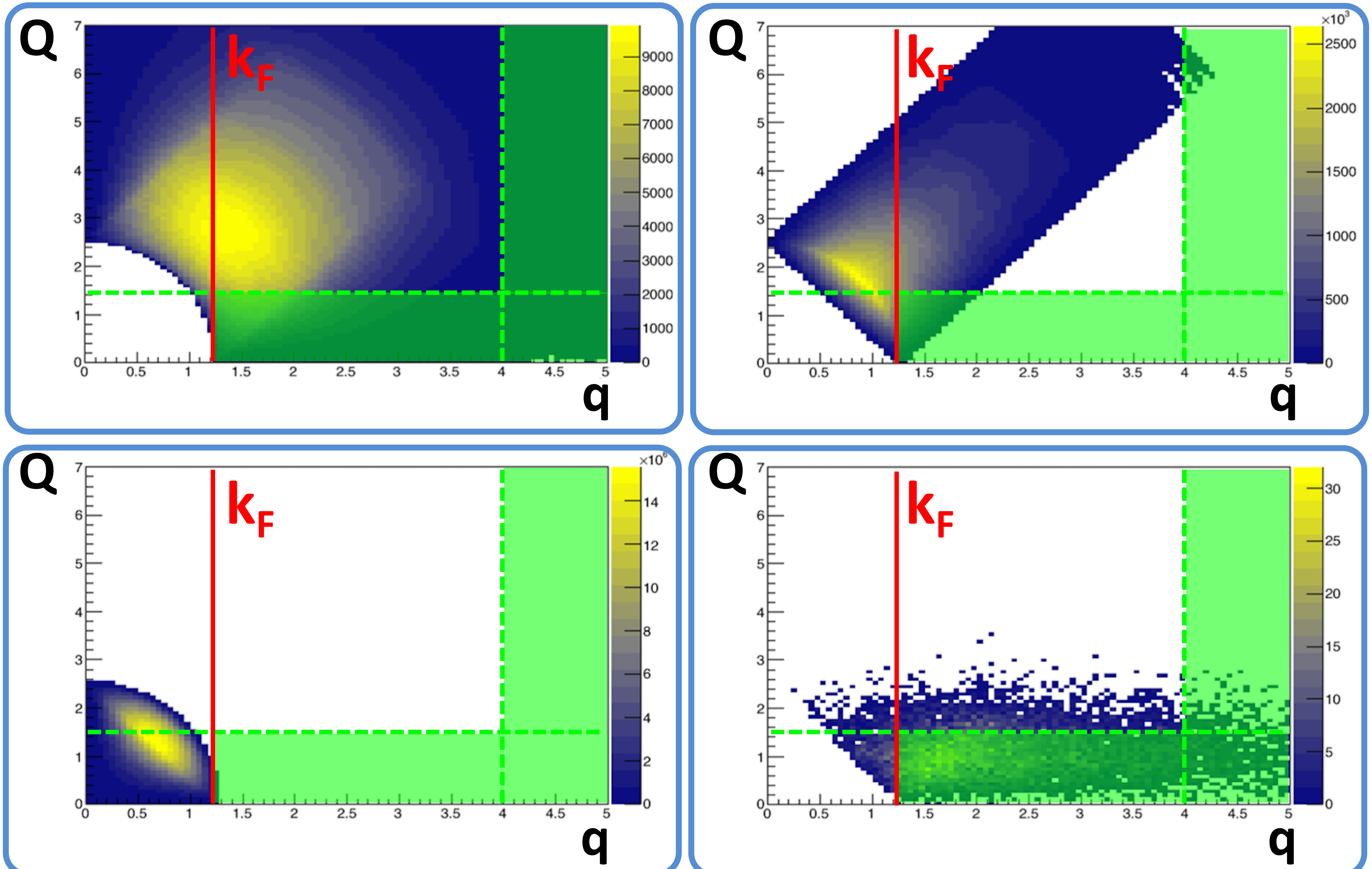
1-2	2-3	3-4	4-5	**5-6**	6-7
1-3	2-4	3-5	4-6	5-7	
1-4	**2-5**	3-6	4-7		
1-5	**2-6**	3-7			
1-6	2-7				
1-7					

$n_{NN}(q,Q)$

Toy model to the rescue

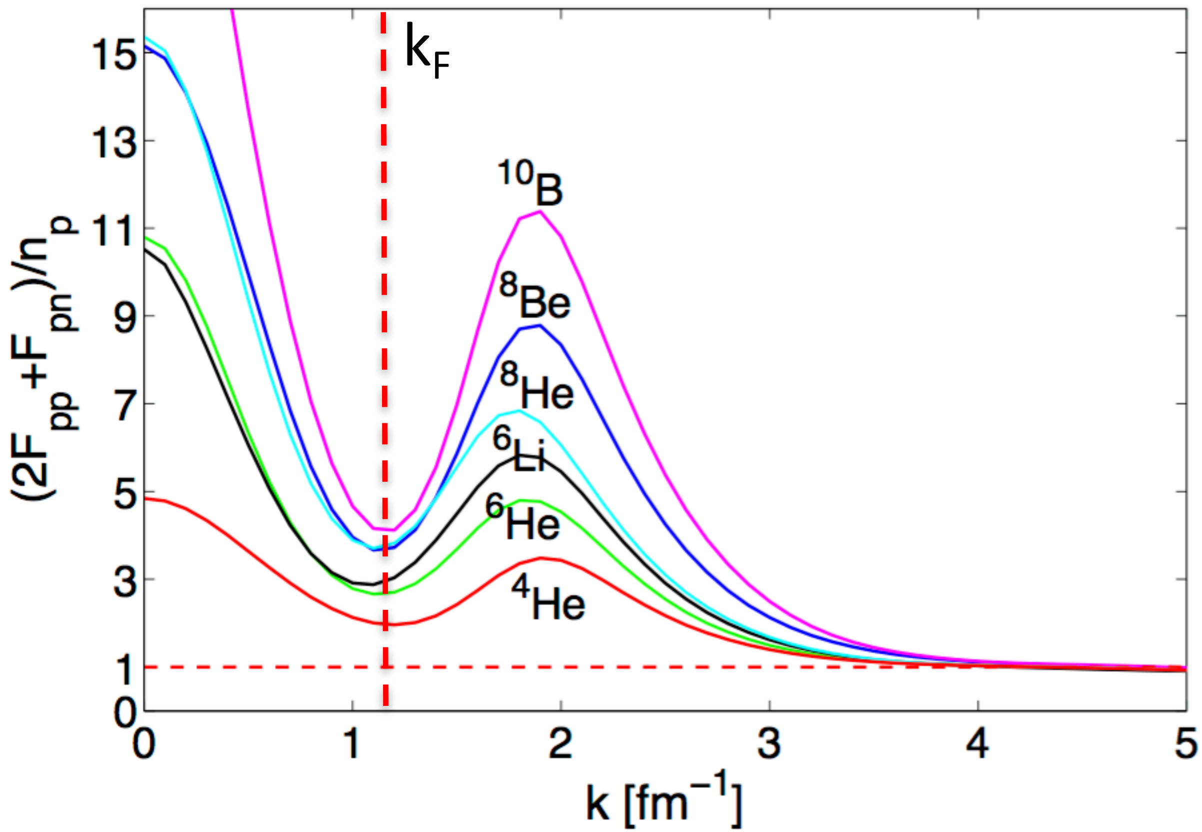


Toy model to the rescue



Two-Body Scaling for **High q**

- Weiss and Barnea (PRC 2015): contact interactions dominate when $n_{pn}(q)+2n_{pp}(q) = n_p(k)$



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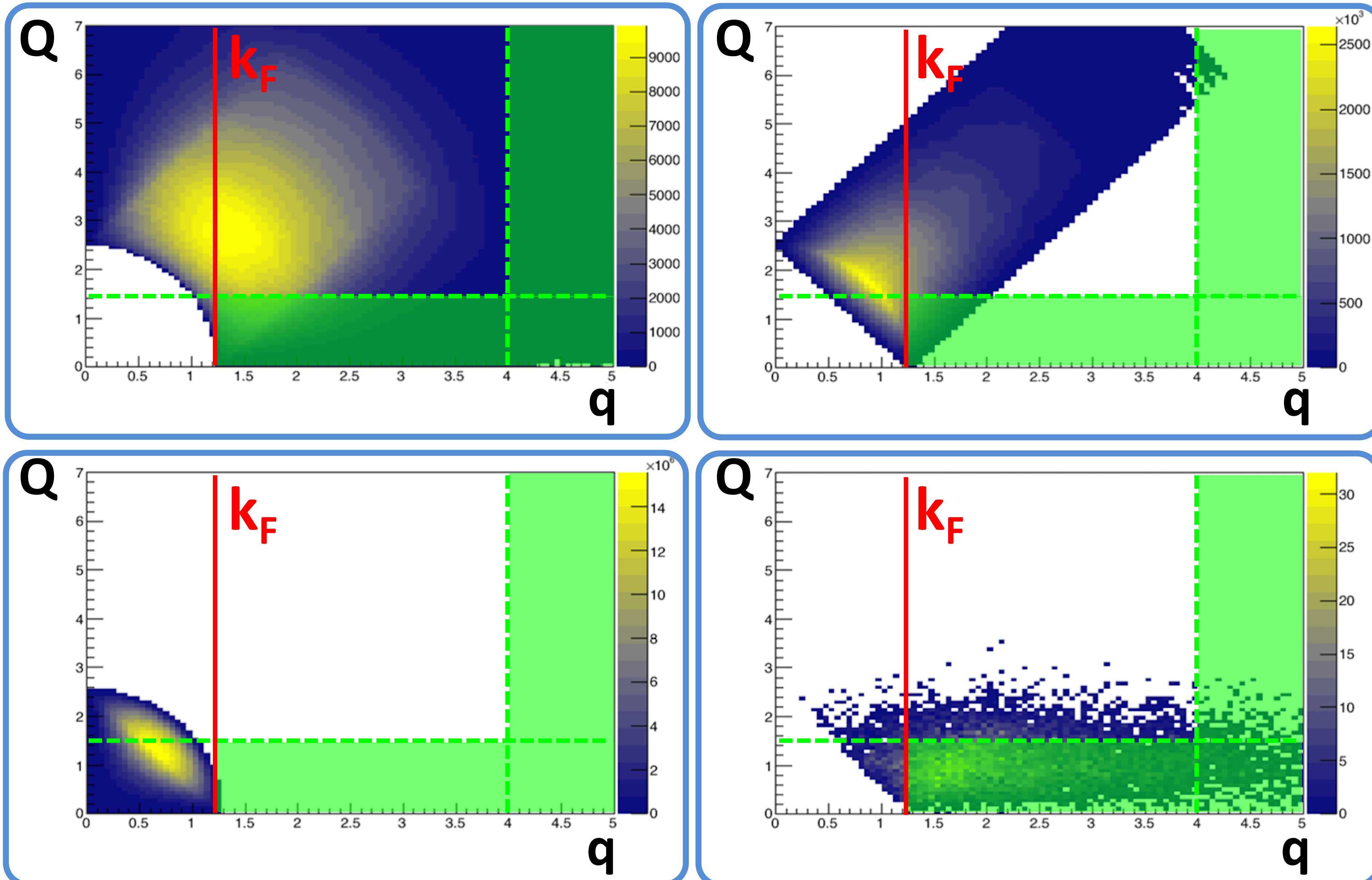
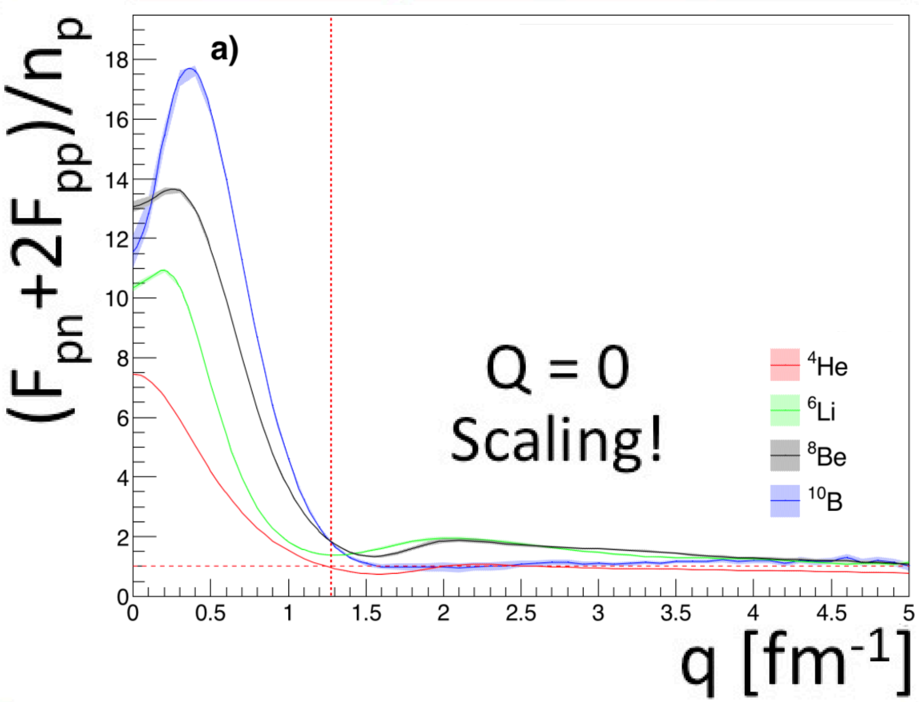
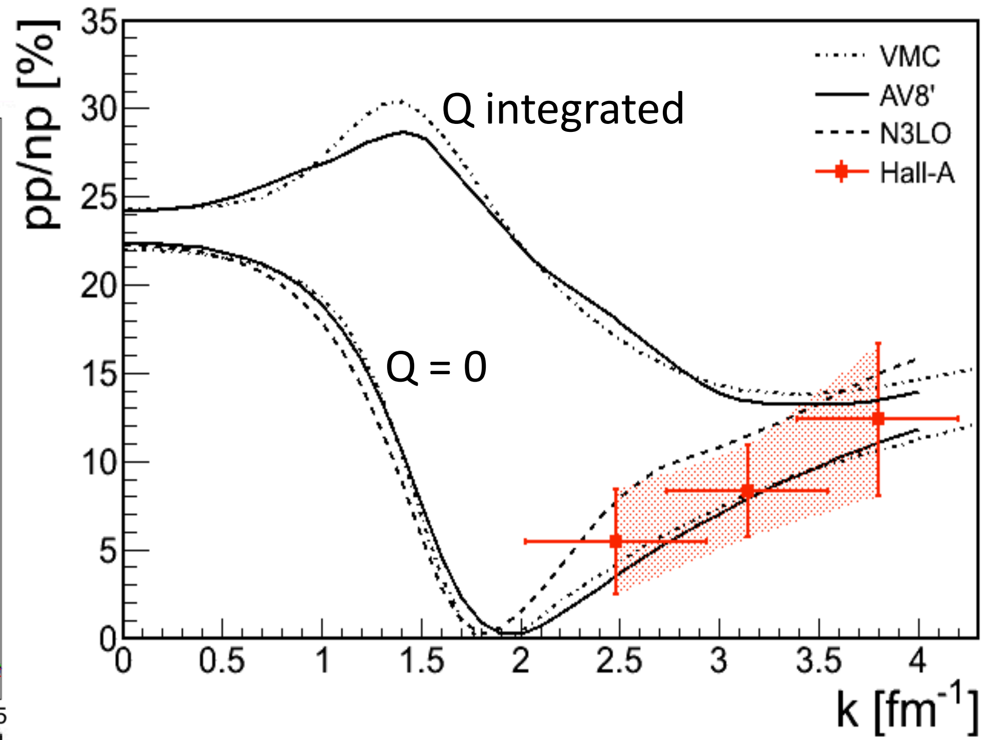


Two-Body Scaling for **Q=0**

- Restricting Q=0 restores scaling starting from $k>k_F$ AND gives consistent results with experimental data!



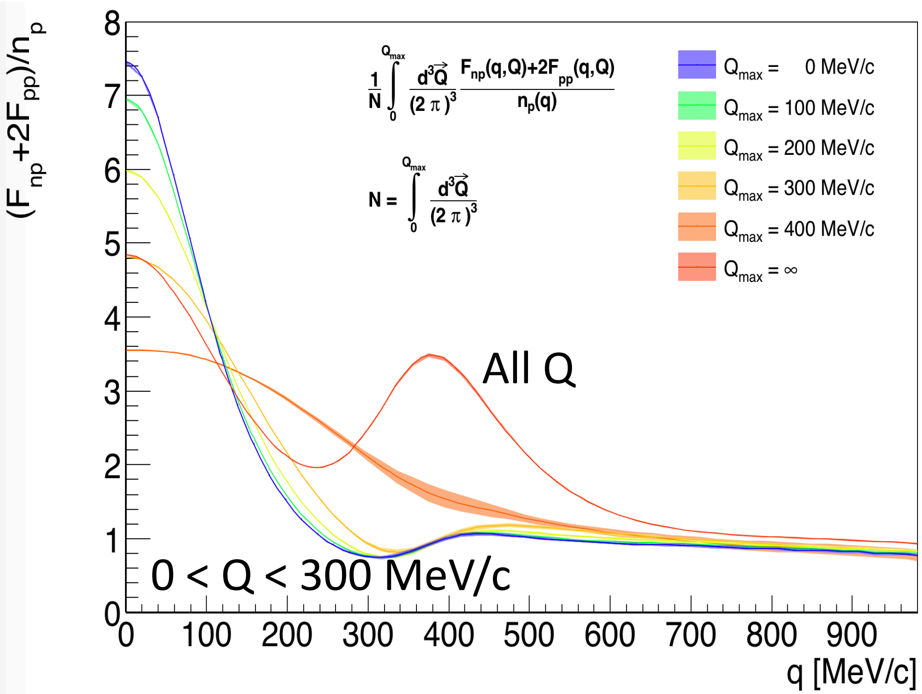


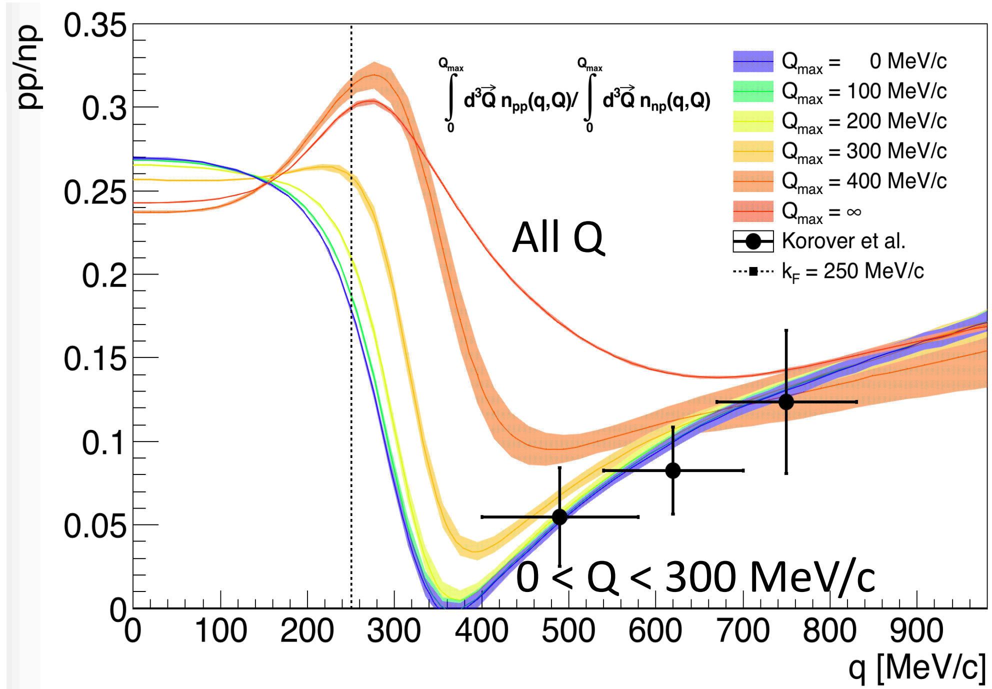
SRC pairs are consistent with Q = 0 *back-to-back* pairs

R. Weiss, **R. Cruz-Torres** et al., In-Preperation (2016)
R. Wiringa et al., Phys. Rev. C 89, 024305 (2014).
T. Neff, H. Feldmeier and W. Horiuchi, Phys. Rev. C 92, 024003 (2015).
I. Korover, N. Muangma, and O. Hen et al., Phys. Rev. Lett 113, 022501 (2014).

Two-Body Scaling for **Low Q**

- Restricting Q=0 restores scaling starting from $k>k_F$ AND gives consistent results with experimental data!





SRC pairs are consistent with $Q \leq k_F$ *back-to-back* pairs

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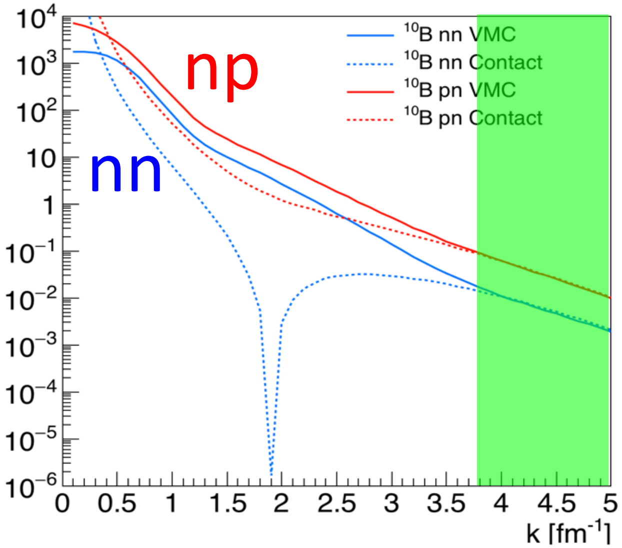
Extracting the nuclear contact(s)

Extracting the Contacts

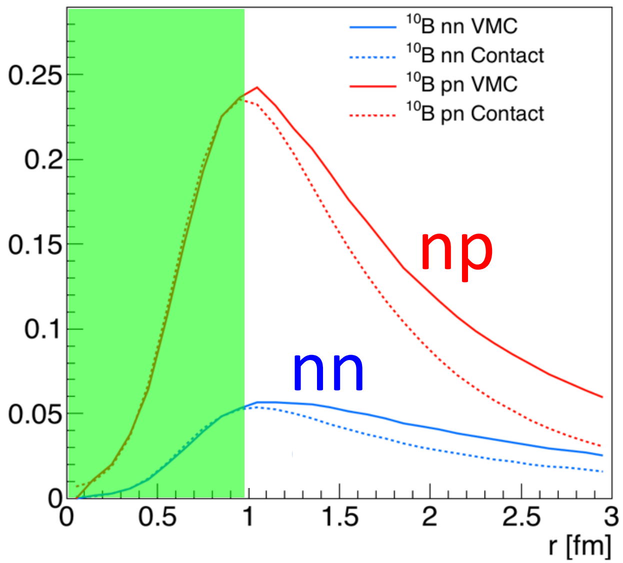


2-Body momentum distributions

$$F_{pn}(k) \xrightarrow[k\to\infty]{} |\varphi^{0}_{pn}(k)|^2 C^{0}_{pn} + |\varphi^{d}_{pn}(k)|^2 C^{d}_{pn}$$

$$F_{nn}(k) \xrightarrow[k\to\infty]{} |\varphi^{0}_{nn}(k)|^2 C^{0}_{nn}$$

Fitting range ~ 4-5 fm^{-1}



2-Body density distributions

$$\rho_{pn}(r) \xrightarrow[r\to 0]{} |\varphi^{0}_{pn}(r)|^2 C^{0}_{pn} + |\varphi^{d}_{pn}(r)|^2 C^{d}_{pn}$$

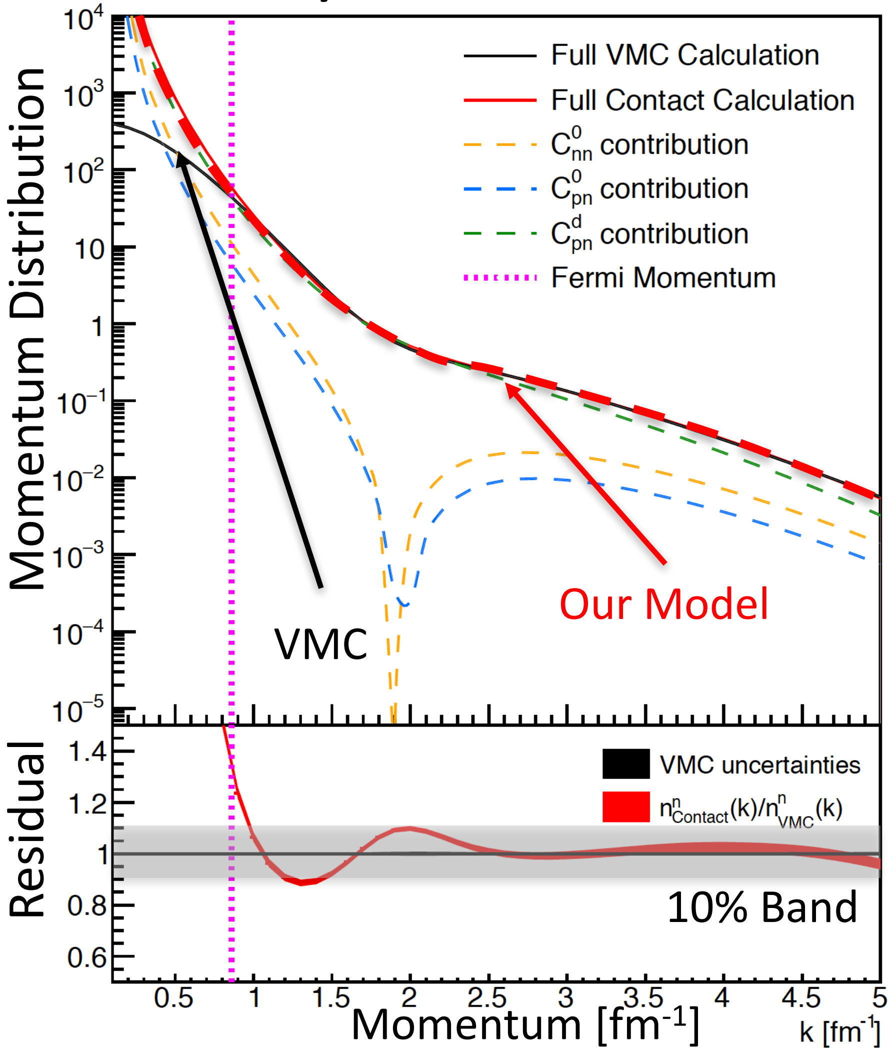
$$\rho_{nn}(r) \xrightarrow[r\to 0]{} |\varphi^{0}_{nn}(r)|^2 C^{0}_{nn}$$

Fitting range ~ 0.25-1 fm

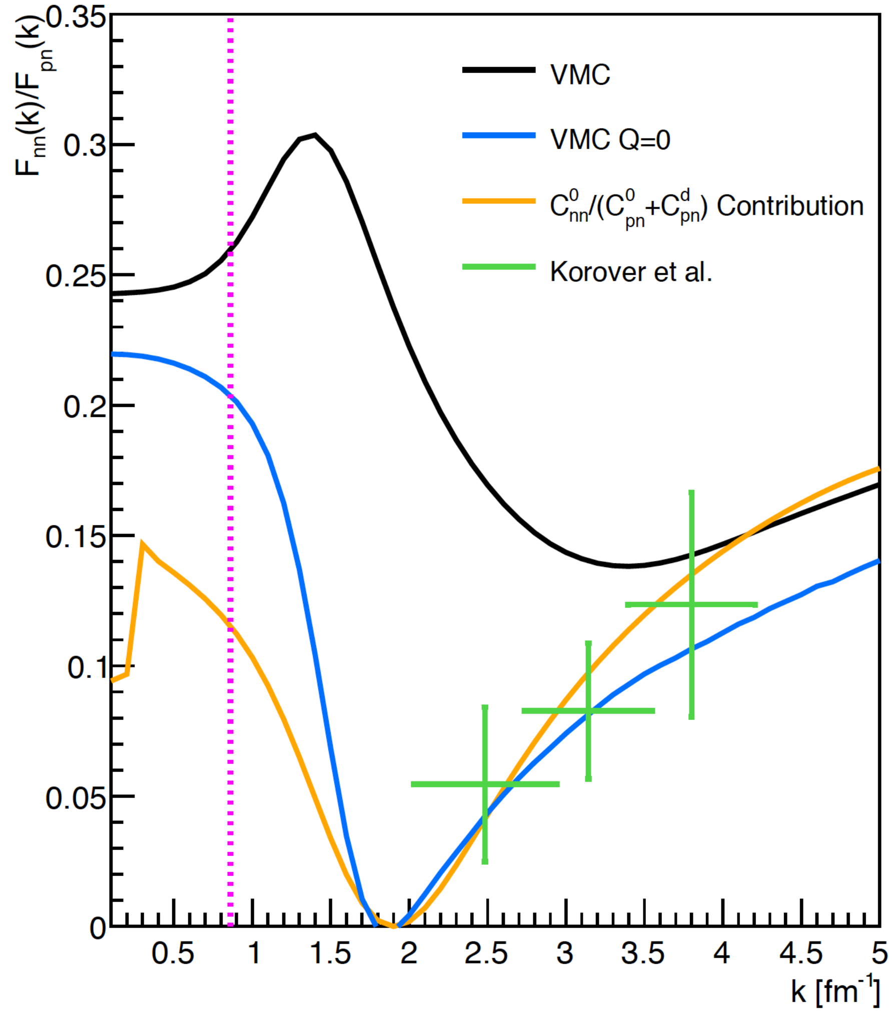
R. B. Wiringa *et al.*, PRC 89, no. 2, 024305 (2014).

^{4}He Results

1-body Momentum dist.

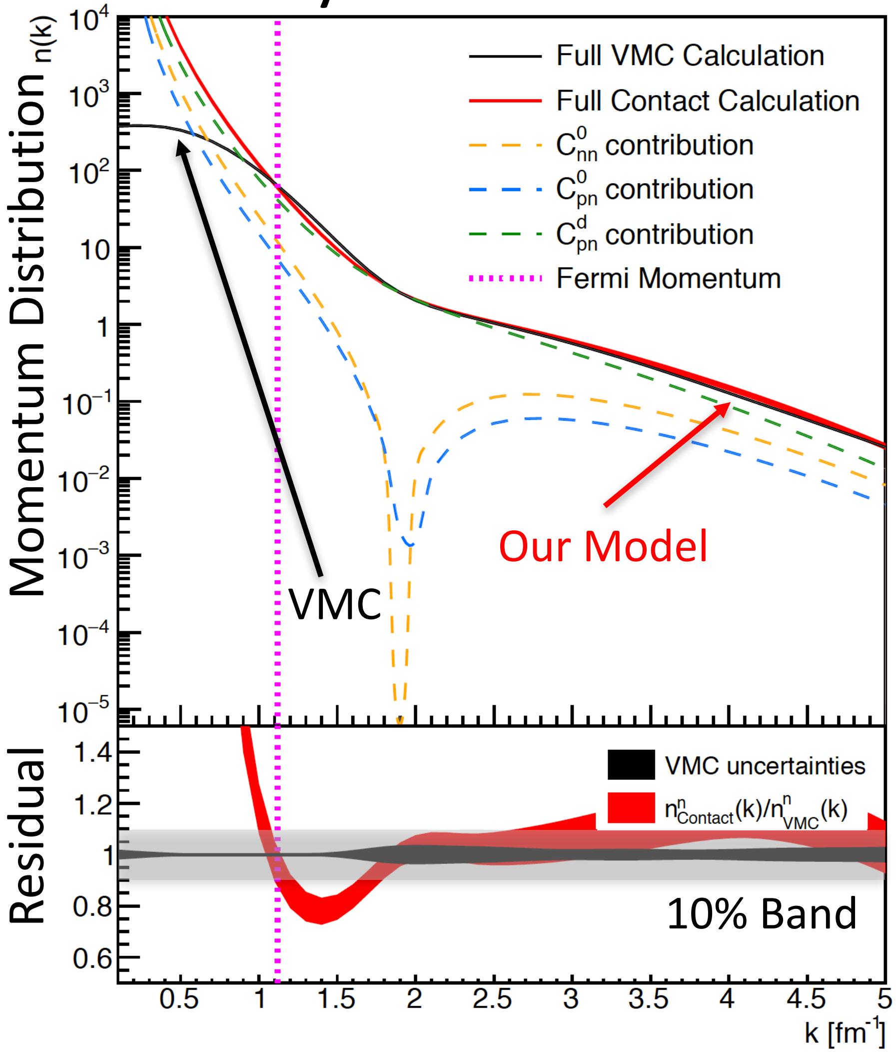


pp / np ratio

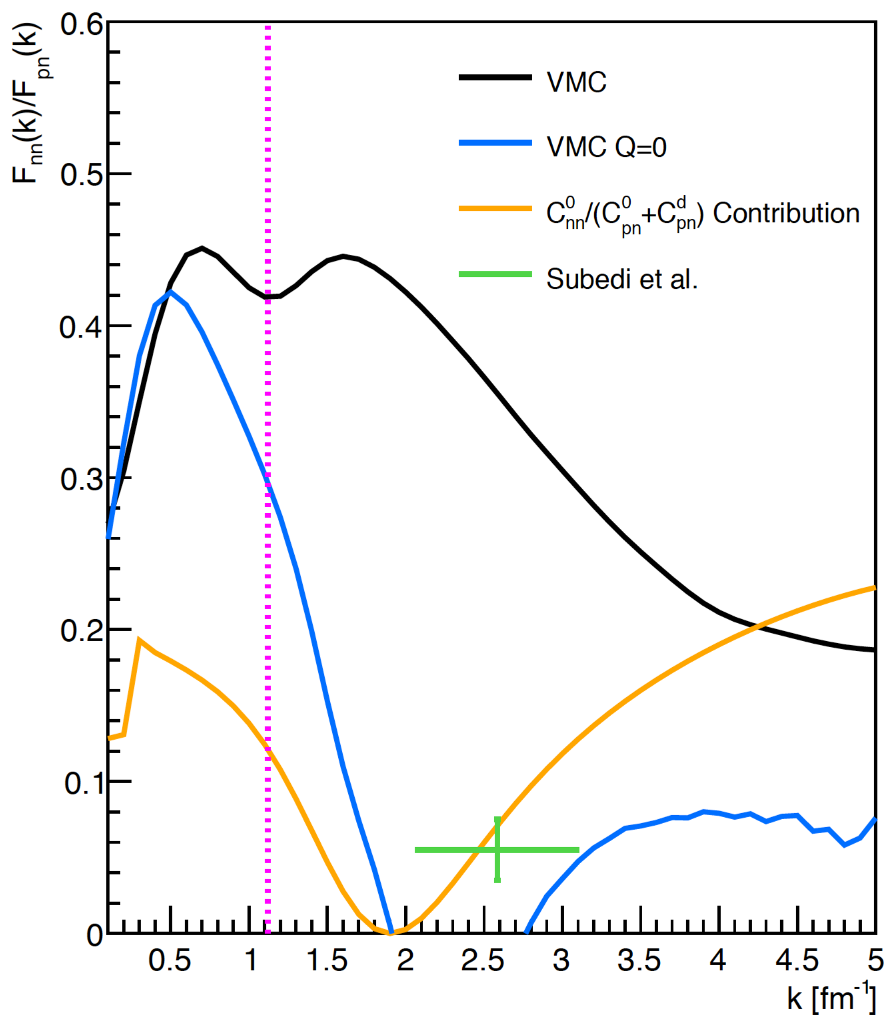


^{12}C Results

1-body Momentum dist.



pp / np ratio



Nuclear Contacts

Consistent nuclear contacts extracted from:

(1) Experimental data,

(2) many-body ***momentum*** space calculations,

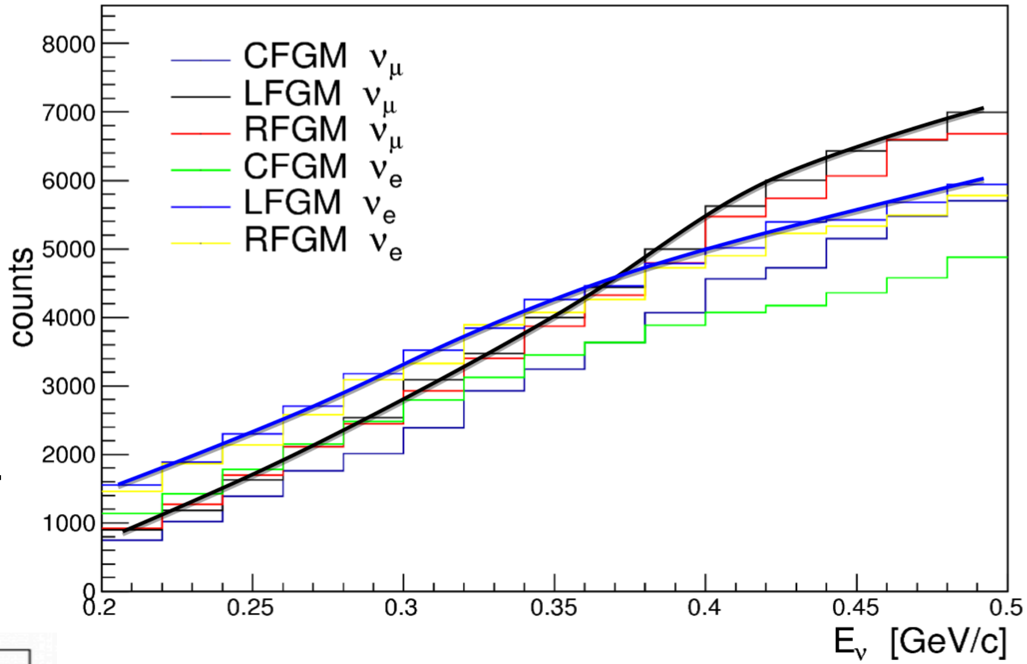
(3) many-body ***coordinate*** space calculations.

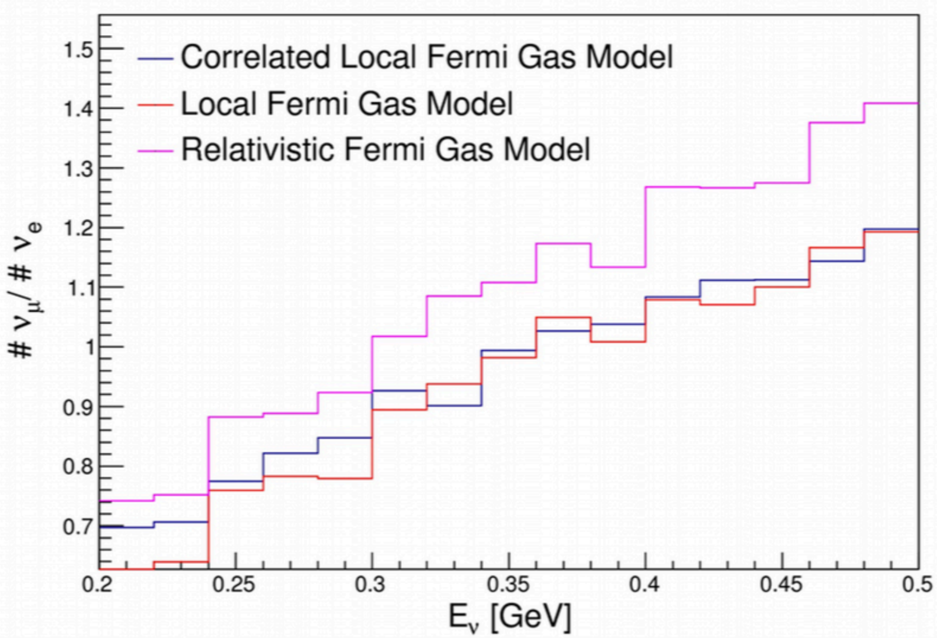
A	**k-space**				**r-space**			
	$C_{pn}^{s=1}$	$C_{pn}^{s=0}$	$C_{nn}^{s=0}$	$C_{pp}^{s=0}$	$C_{pn}^{s=1}$	$C_{pn}^{s=0}$	$C_{nn}^{s=0}$	$C_{pp}^{s=0}$
^{4}**He**	12.3±0.1	0.69±0.03	0.65±0.03		11.61±0.03	0.567±0.004		
	14.9±0.7 (exp)	0.8±0.2 (exp)						
^{6}**Li**	10.5±0.1	0.53±0.05	0.49±0.03		10.14±0.04	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)						

Relevance To Neutrino Scattering?

1. Initial implementation of SRCs in GENIE's Local Fermi-Gas Model.

2. Examination of model dependence of 1-lepton 1-proton CCQE predictions





3. Correlation effects reduced for ν_μ / ν_e ratios!

4. Next step: contact formalism implementation and then using spectral and decay functions.

Relevance To Neutrino Scattering?

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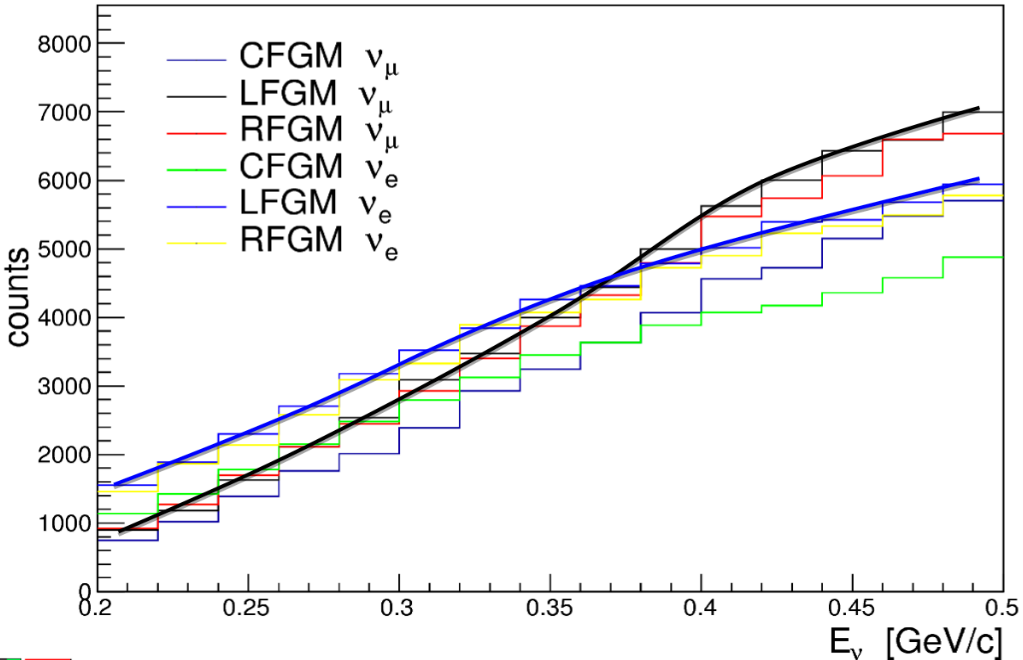
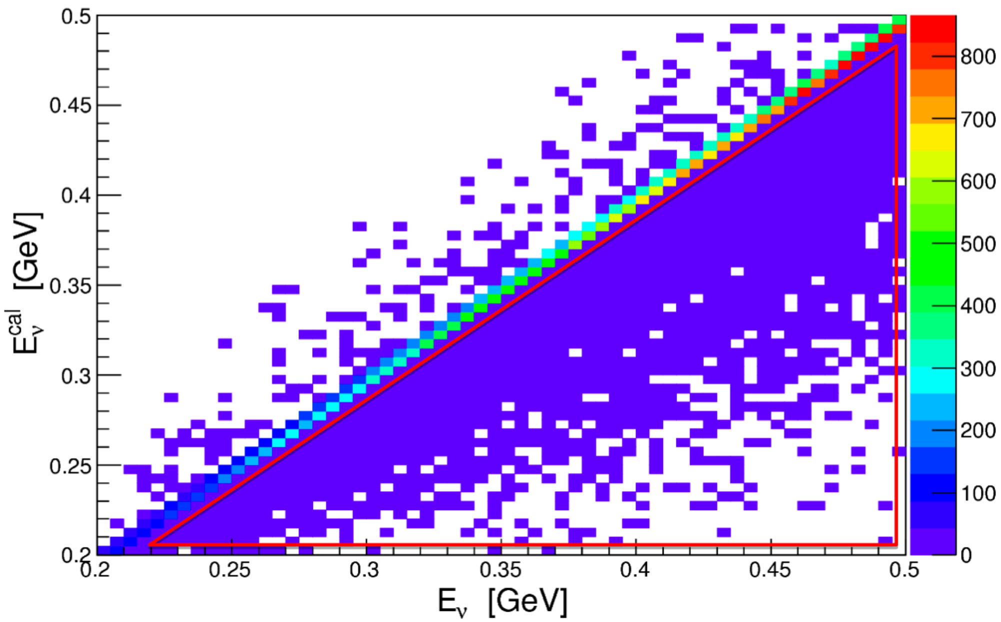




Calorimetric energy reconstruction works well for parts of the phase-space.

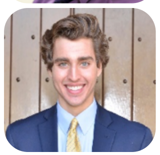
Should we focus on these parts? uB data forthcoming!

The Correlations group

- **MIT (Or Hen):**


Barak Schmookler


Reynier Torres


Efrain Segarra


Afroditi Papadopoulou

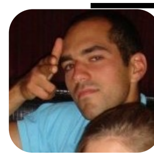

Axel Schmidt


George Laskaris


Maria Patsyuk


Taofeng Wang (*visiting scientist)

- **TAU (Eli Piasetzky):**

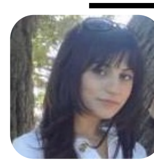

Erez Cohen


Meytal Duer


Igor Korover


Adi Ashkenazy

- **ODU (Larry Weinstein):**

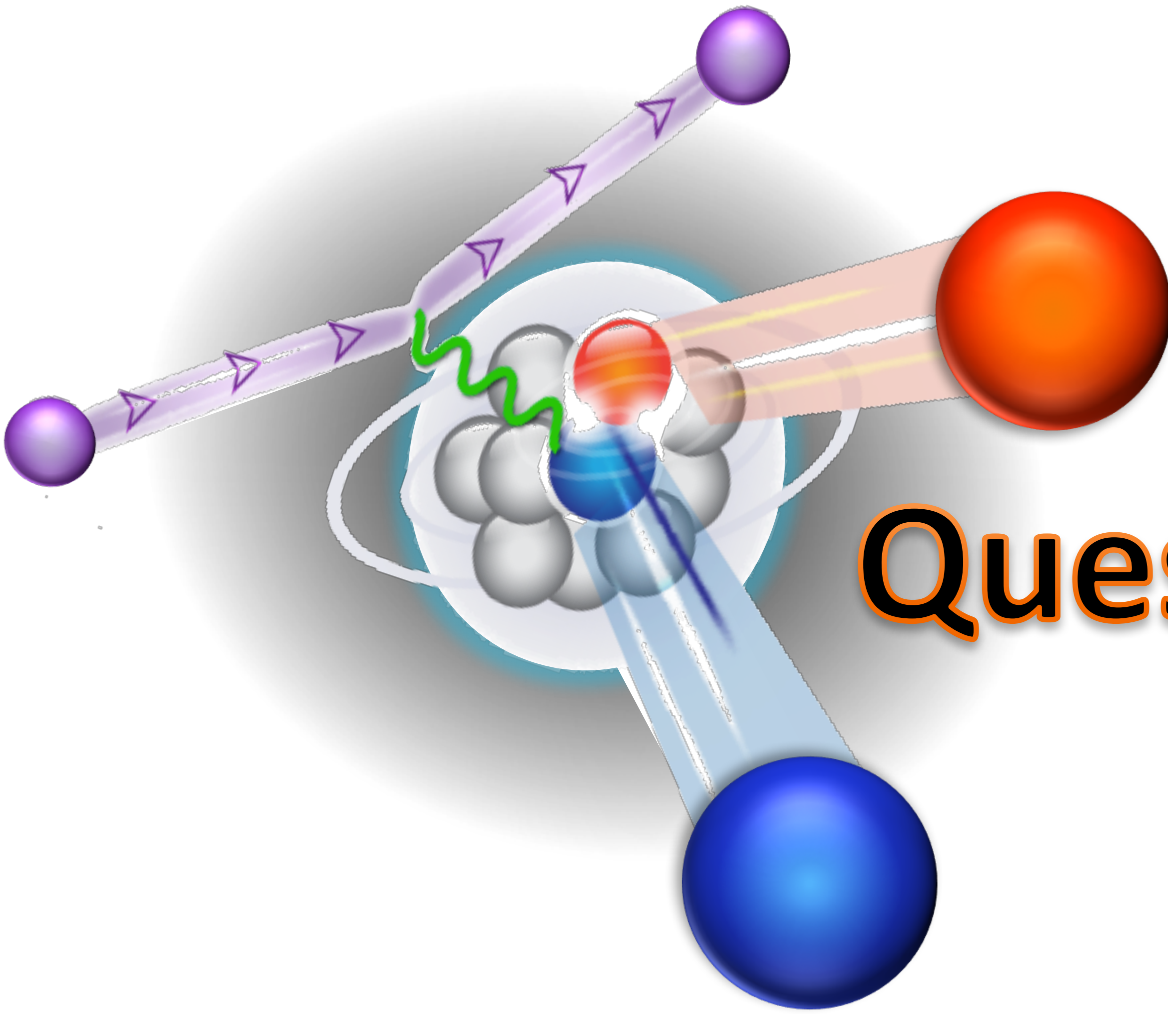

Mariana Khachatryan


Florian Hauenstein

- **Theory Collaborators** (lots!)

Contact works: G. Miller, N. Barnea and R. Weiss

Thank You!



Questions?