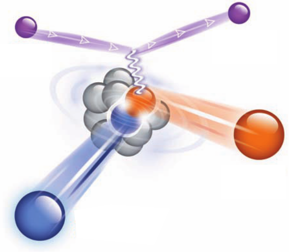
Exclusive Studies of Short-Range Correlations in Nuclei using CLAS-12

Proposal PR12-18-003

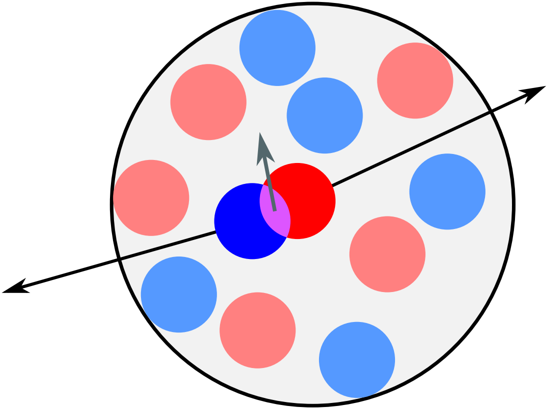
Spokespersons:

O. Hen, A. Schmidt (MIT)
L.B. Weinstein (ODU),
E. Piasetzky (TAU),
S. Stepanyan, H. Szumila-Vance (Jlab)



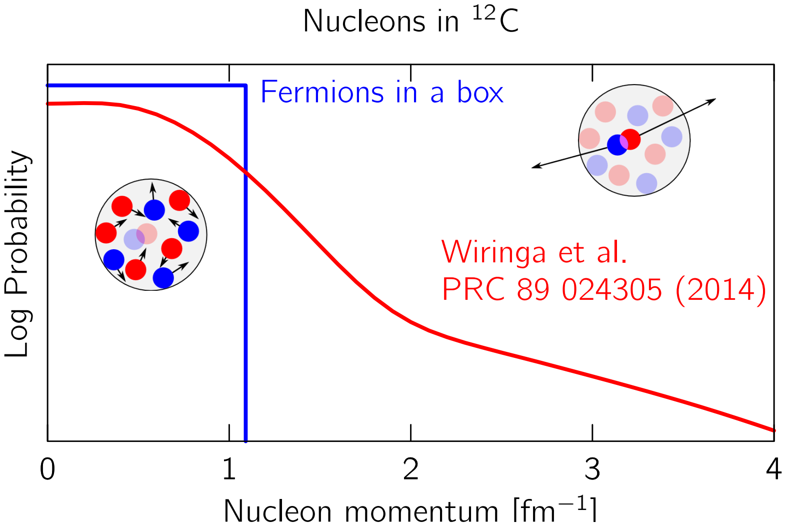
Jefferson Lab PAC-46, July 17th, 2018

Short-range correlations are a universal property of nuclei.

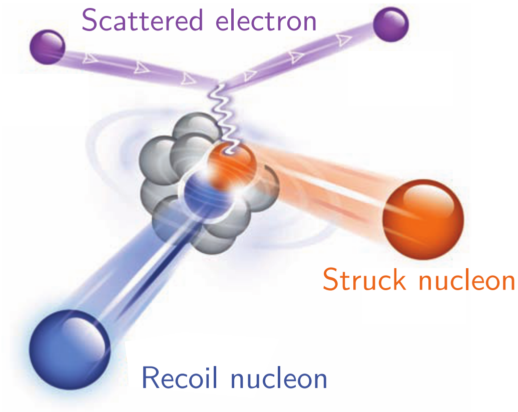


- Relative momentum: > 300 MeV/c
- CoM momentum: $\mathcal{O}(150$ MeV/$c)$

Short-range correlations produce high-momentum tails.



Break up the pair, detect both nucleons
$\longrightarrow$ *reconstruct initial state*



Many discoveries from remarkably little data

1. High-impact results

2. Advances in theory and ab initio methods

3. Connections to other fields
   - Strongly-interacting Fermi systems
   - EMC effect
   - Neutron stars

4. We need more data!

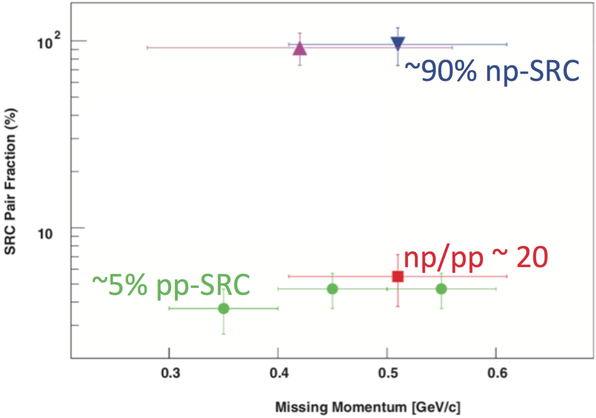
A new experimental program is needed to:

1. Move from qualitative to quantitative.
2. Put reaction theory on solid ground.
3. Pursue high-impact avenues
   - *NN*-interaction
   - Asymmetry dependence
   - 3*N* Correlations
   - Reaction dynamics

In this talk:

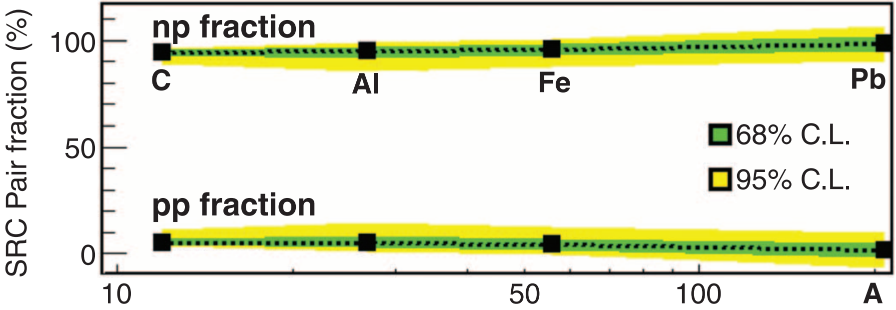
1. Past success
   - High-impact exclusive SRC measurements
2. Unanswered Questions
   - More high-impact physics to come
3. Proposed program
   - Designed for maximum impact

^{12}C: SRC pairs are far more likely to be neutron-proton, than proton-proton.



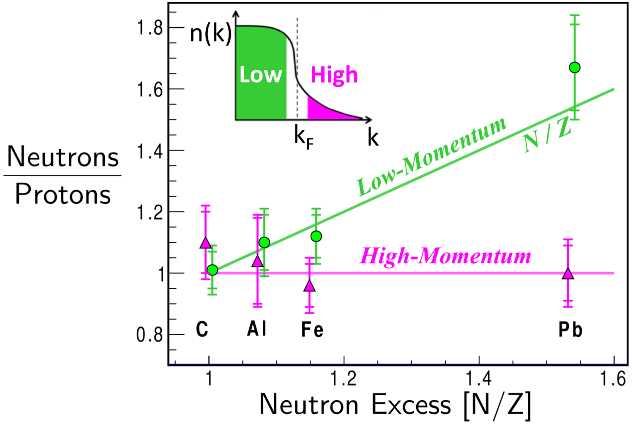
Subedi et al., Science 320 p. 1476 (2008)

np-dominance persists in asymmetric nuclei.



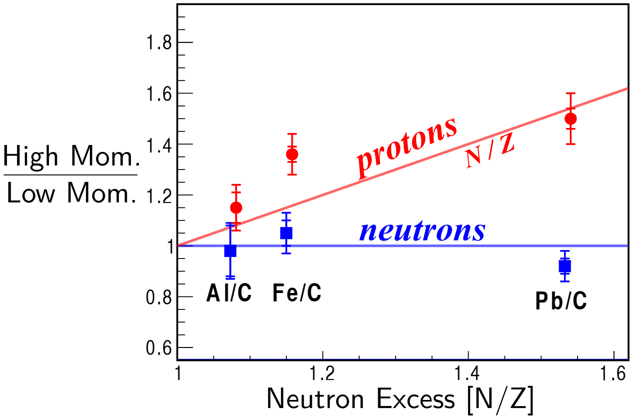
Hen et al., Science 346 p. 614 (2014)

This leads to new effects in neutron-rich nuclei.



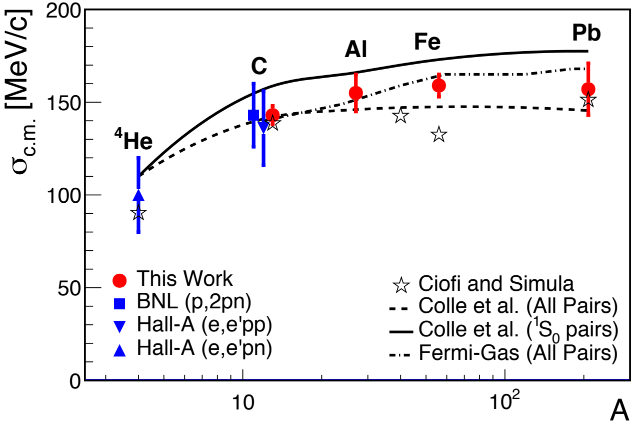
Duer et al., to appear in Nature (2018)

Correlation Probabilities:
Neutrons saturate, Protons grow



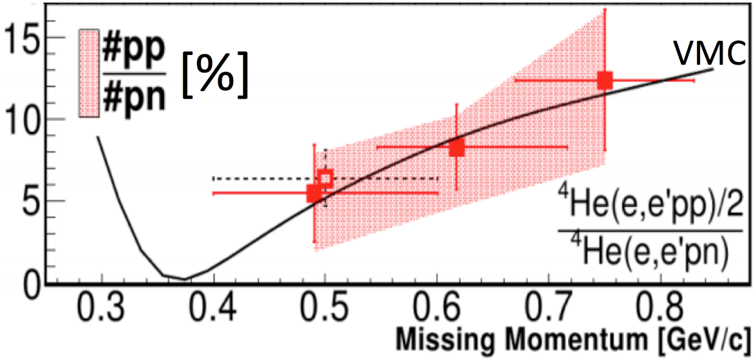
Duer et al., to appear in Nature (2018)

The center-of-mass momentum distribution offers first glimpse of formation mechanism.



Cohen et al., to appear in PRL (2018)

The evolution of *np*-dominance may be a sign of the repulsive core.



Korover et al., PRL 113 022501 (2014)

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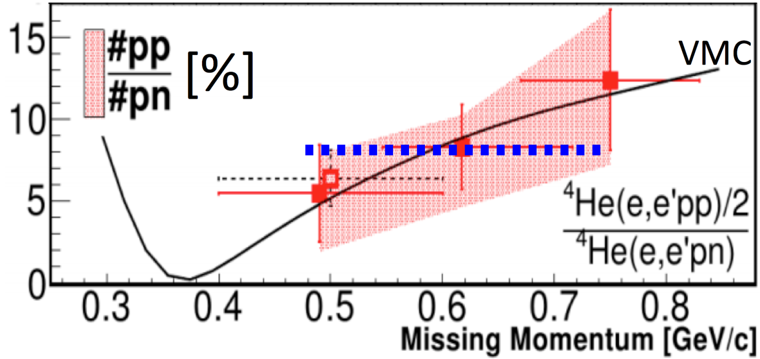

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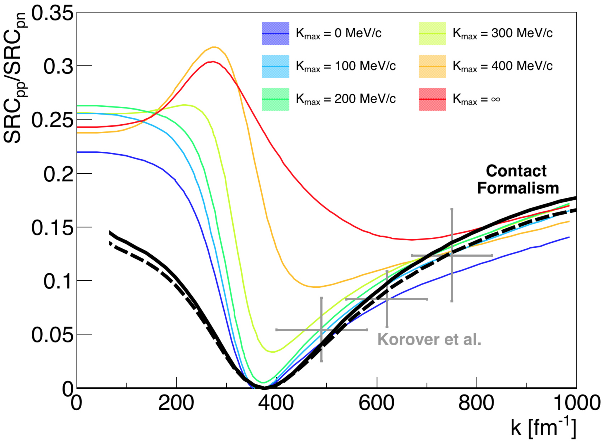

Weiss, Cruz-Torres, et al., PLB 780, 211 (2018)

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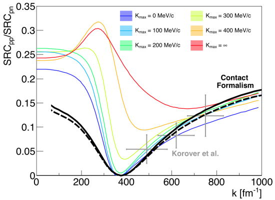

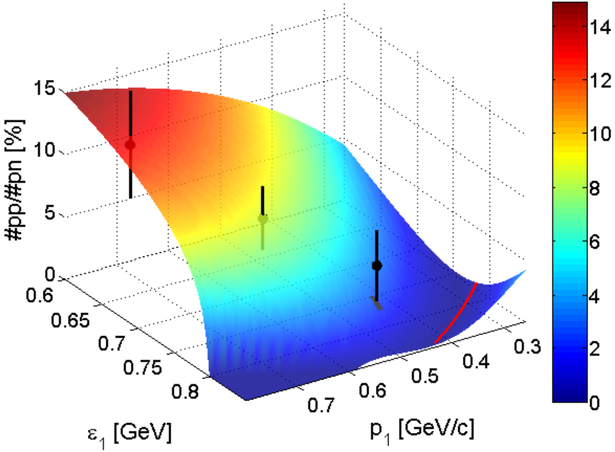

Weiss et al., arXiv:1806.10217 (2018)

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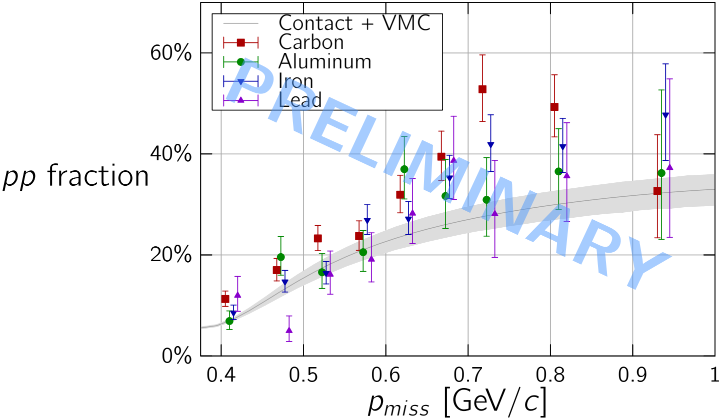
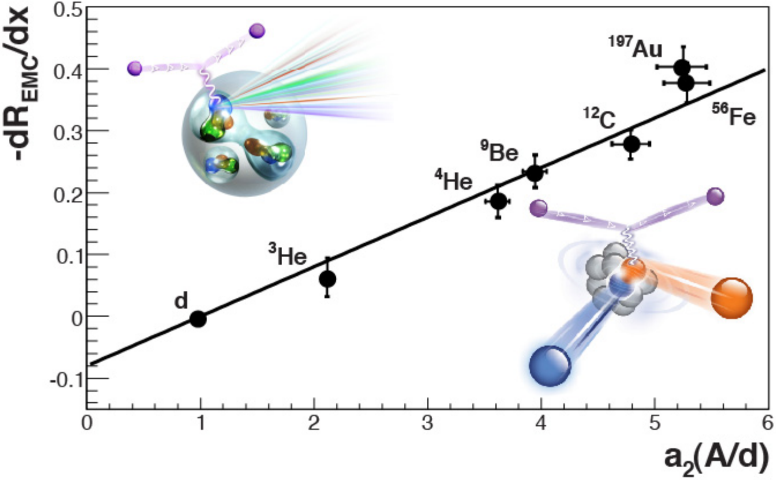


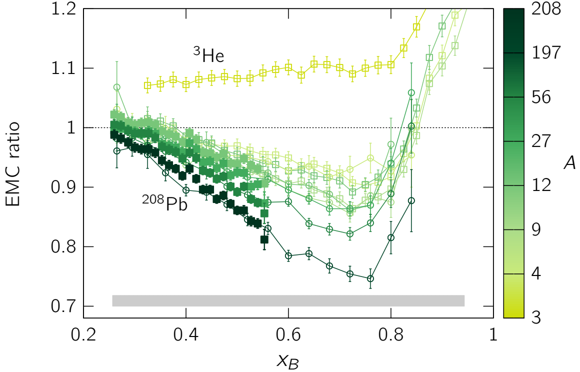
Schmidt et al., in preparation

SRCs may be the cause of the EMC effect.



CLAS-6 data led us to build a consistent phenomenological model.

$$F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A(\Delta F_2^p + \Delta F_2^n)$$



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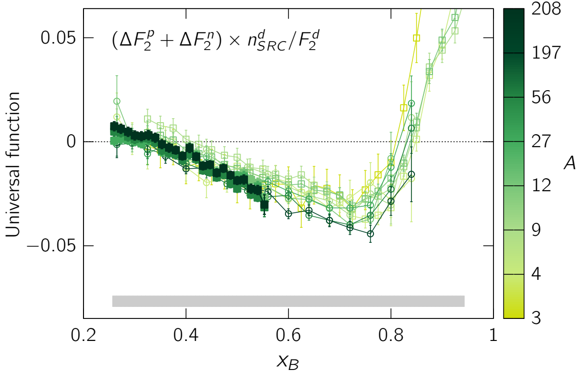

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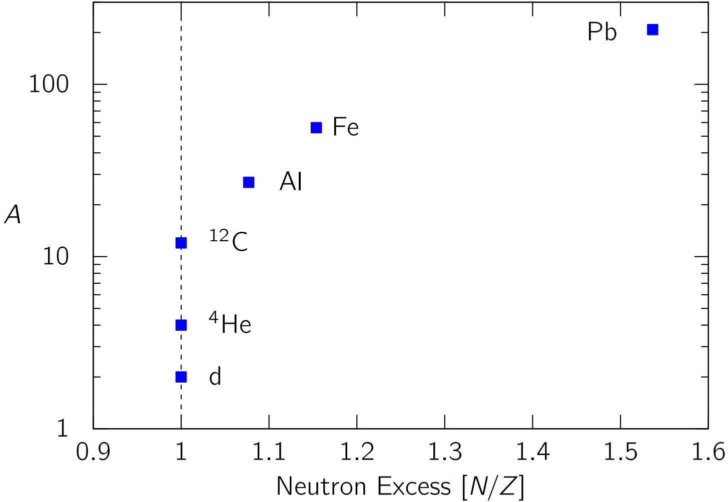
All of these high-impact results have come from very litle data.

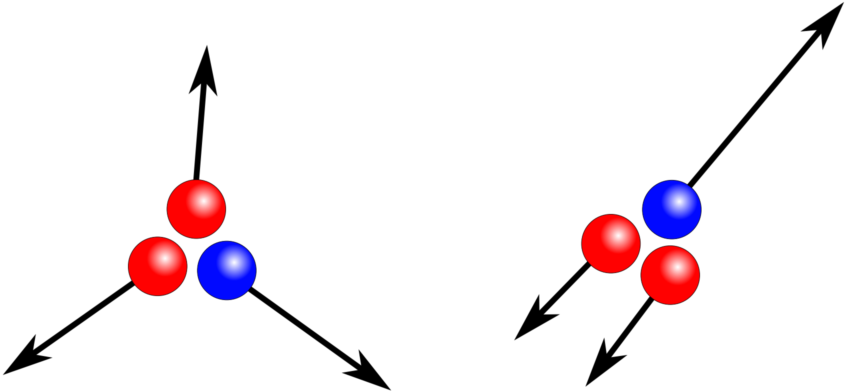
Experiment	*pp* Events	*pn* Events
EVA/BNL (C)	–	18
Hall A (C)	263	179
Hall A (^{4}He)	50	223
CLAS (C, Al, Fe, Pb)	425	150

Current data can't disentangle size from nuclear asymmetry.



We have no data on *nn* pairs.

Three-nucleon correlations?



Fomin, Higinbotham, Sargsian, Solvignon, Ann.Rev.Nucl.Part.Sci. 67 129 (2017)

Day, Frankfurt, Sargsian, Strikman, arXiv:1803.07629 (2018)

Three-nucleon correlations?

PRL **96,** 082501 (2006) PHYSICAL REVIEW LETTERS week ending 3 MARCH 2006

$\boxed{\text{Measurement}}$ of Two- and Three-Nucleon Short-Range Correlation Probabilities in Nuclei

K. S. Egiyan,[1,34] N. B. Dashyan,[1] M. M. Sargsian,[10] M. I. Strikman,[28] L. B. Weinstein,[27] G. Adams,[30] P. Ambrozewicz,[10]

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PRL 114, 169201 (2015) PHYSICAL REV

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PHYSICAL REVIEW C **97**, 065204 (2018)

Search for three-nucleon short-range correlations in light nuclei

Z. Ye,[1,2,3] P. Solvignon,[4,5,*] D. Nguyen,[2] P. Aguilera,[6] Z. Ahmed,[7] H. Albataineh,[8] K. Allada,[5] B. Anderson,[9] D. Anez,[10]

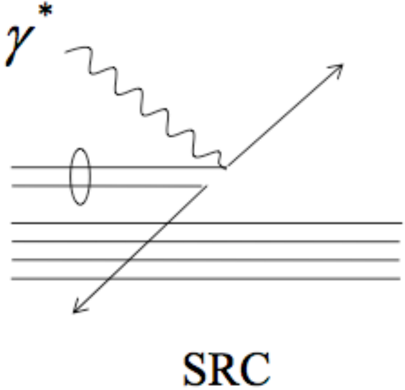
arXiv:1803.07629v1

Towards observation of three-nucleon short-range correlations in high Q^2 $A(e,e')X$ reactions

Donal B. Day[1], Leonid L. Frankfurt[2], Misak M. Sargsian[3] and Mark I. Strikman[4]

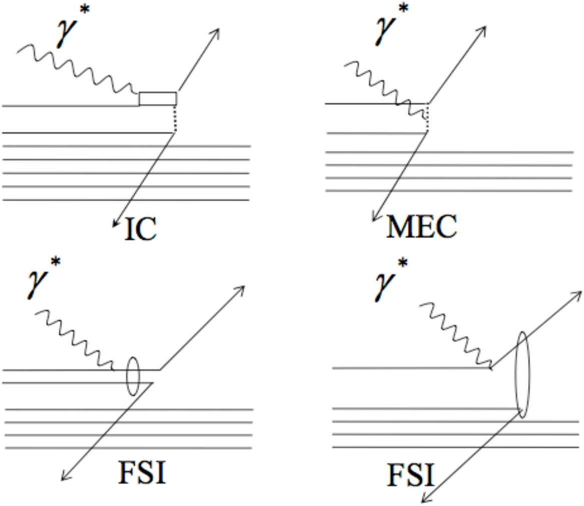
Interlude: Reaction Mechanisms

What we want:



Interlude: Reaction Mechanisms

What we (might) get:



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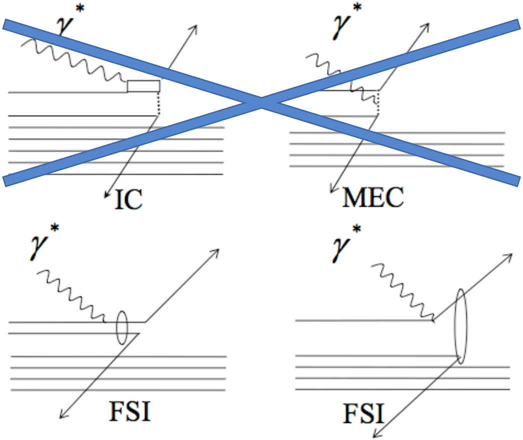

MEC suppressed @ **high-Q^2**,
IC suppressed at **$x_B > 1$.**

Frankfurt, Sargsian, and Strikman PRC **56**, 1124 (1997).
Colle, Cosyn, and Ryckebusch, PRC **93**, 034608 (2016).

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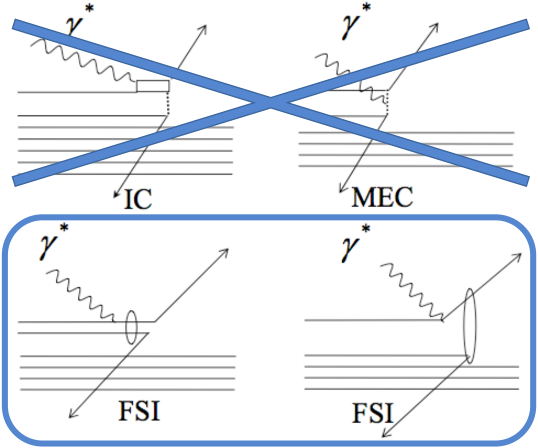
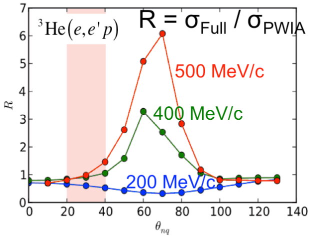


MEC suppressed @ **high-Q^2**,
IC suppressed at **$x_B > 1$.**

FSI suppressed in **anti-parallel** kinematics. Treated using **Glauber** approximation.



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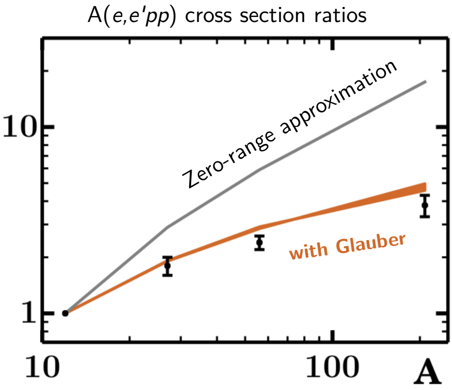
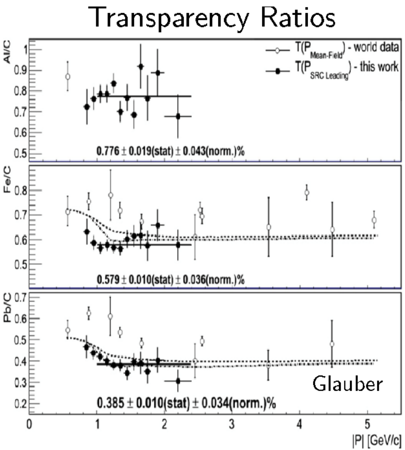
Glauber agrees with data.



Colle and Hen et al., PRC 722, 63 (2013)



Hen et al., PLB 722, 63 (2013)

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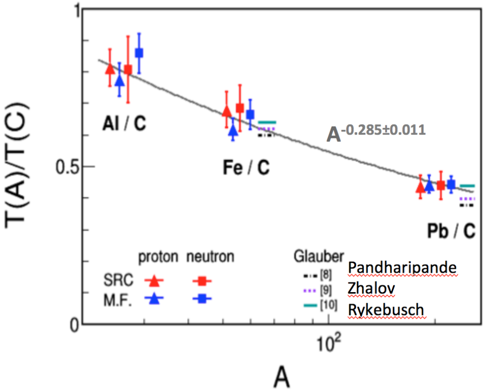
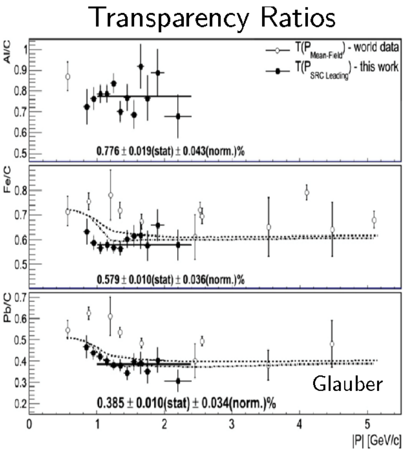
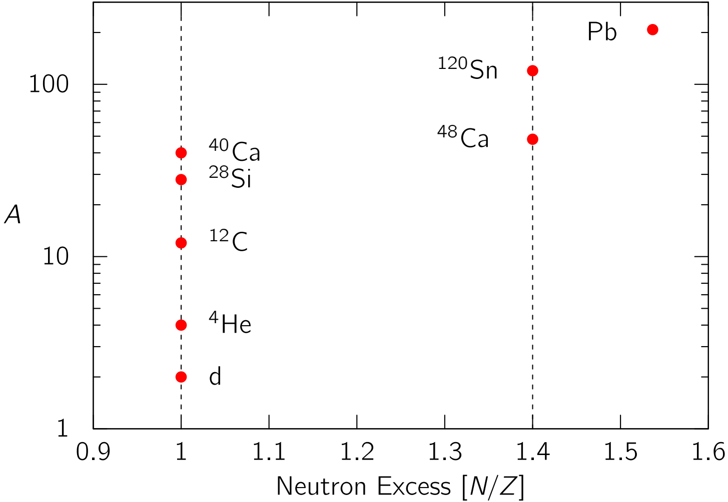


M. Duer et al., in review



Hen et al., PLB 722, 63 (2013)

We propose to measure several new important targets.

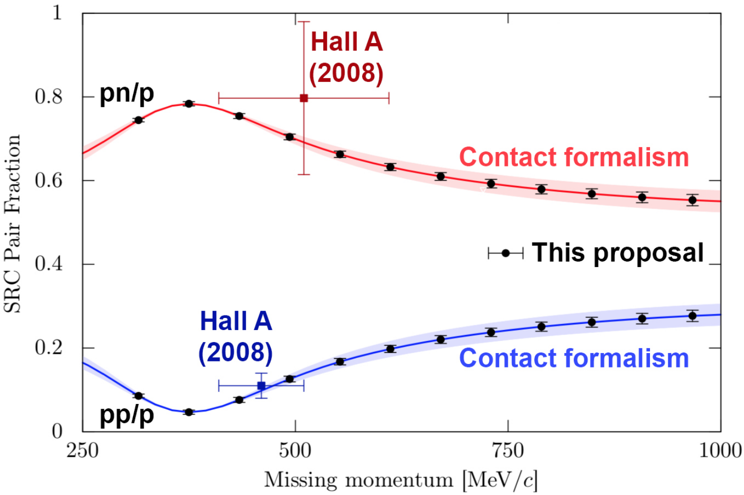


The CLAS-12 detector will give us better rates, acceptance, neutron capabilities.

Reaction	*pp*	*pn*	*np*	*nn*
Counts per target	13,000	13,000	8,500	250

Pb will have $\approx 1/2$ the statistics.

An increase in statistics will allow quantitative determinations.



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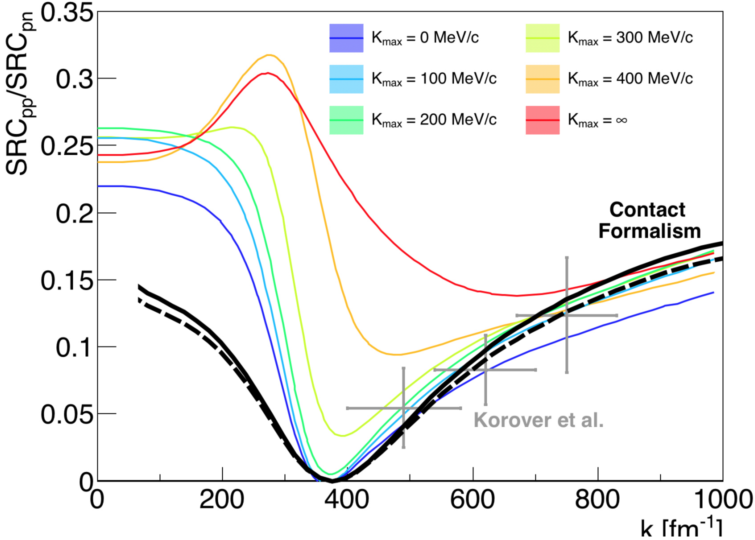

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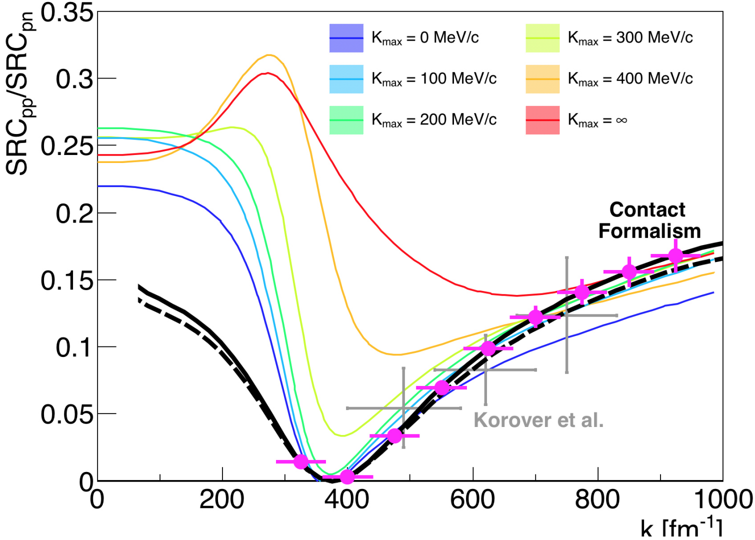

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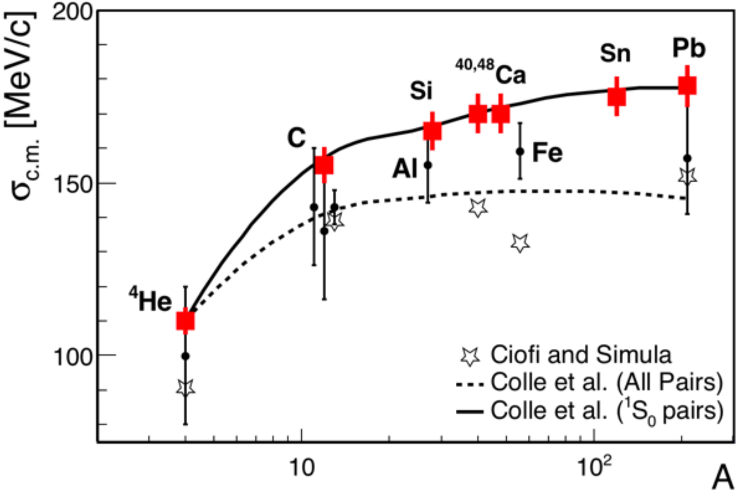
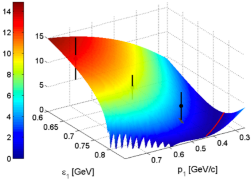
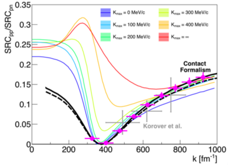


Future Directions in SRC research

NN Int. & nuclear wave-function

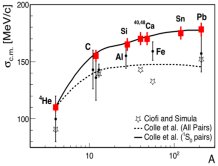
[^{2}H & ^{4}He]





Many-Body systems & nuclear asymmetry

[^{48}Ca, ^{120}Sn, ^{208}Pb]

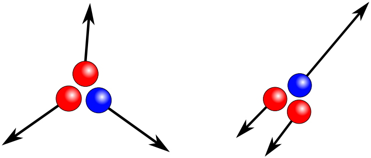


- Decoupling N/Z & A
- nn vs. pp

3N-SRC

[^{4}He, ^{12}C, ^{40}Ca]

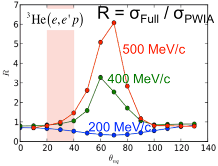
1st Observation & A-dependence



Reaction Mechanisms

[^{4}He, ^{12}C, ^{28}Si, ^{40}Ca, ^{120}Sn ^{208}Pb]

- A-dependence vs. Glauber
- Q^2 independence



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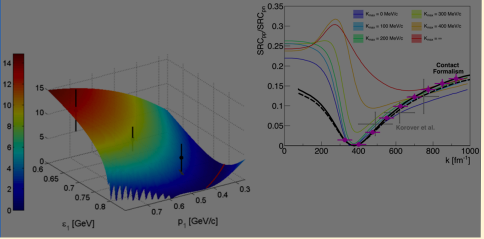

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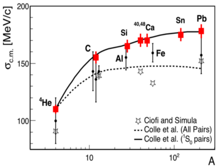

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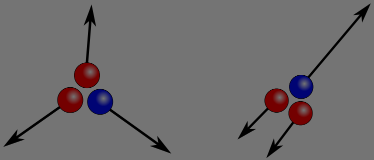

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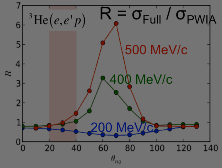
- Q^2 independence
- A-dependence
- vs. Glauber



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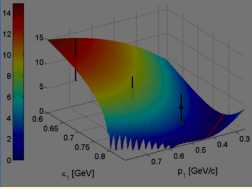

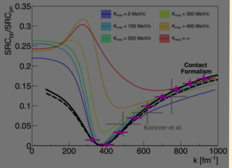

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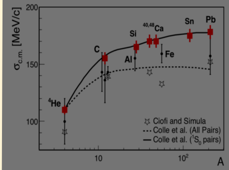

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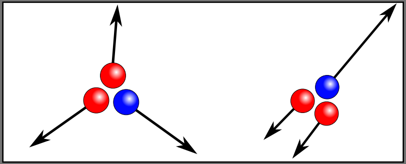

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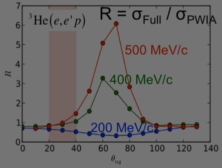

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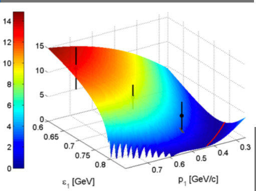

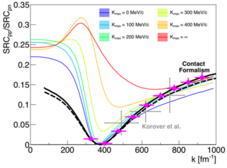

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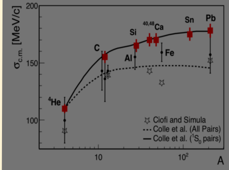

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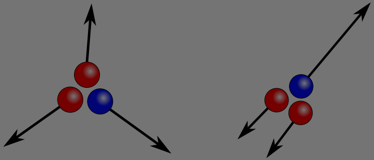
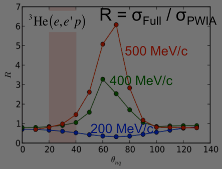


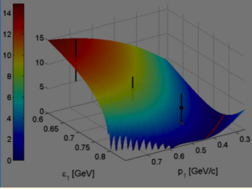
Reaction Mechanisms
[^{4}He, ^{12}C, ^{28}Si, ^{40}Ca, ^{120}Sn ^{208}Pb]

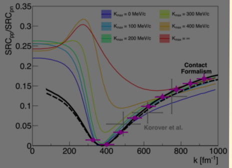
- Q^2 independence
- A-dependence
- vs. Glauber



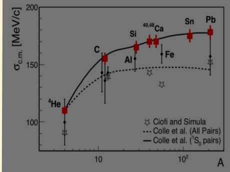
Future Directions in SRC research

NN Int. & nuclear wave-function
[^{2}H & ^{4}He]





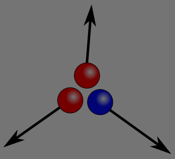
Many-Body systems & nuclear asymmetry
[^{48}Ca, ^{120}Sn, ^{208}Pb]

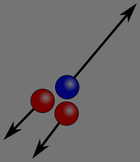


- Decoupling N/Z & A
- nn vs. pp

3N-SRC
[^{4}He, ^{12}C, ^{40}Ca]

1st Observation & A-dependence





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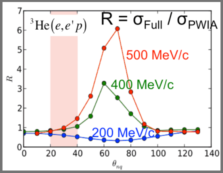

Future Directions in SRC research

NN Int. & nuclear wave-function
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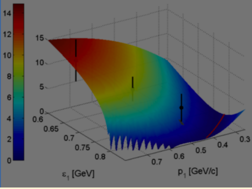

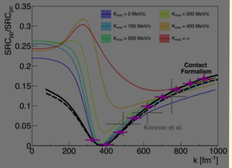

Many-Body systems & nuclear asymmetry
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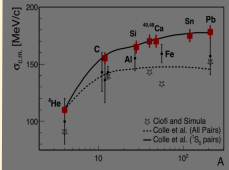

- Decoupling N/Z & A
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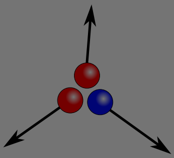
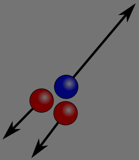
3N-SRC
[^{4}He, ^{12}C, ^{40}Ca]

1st Observation & A-dependence





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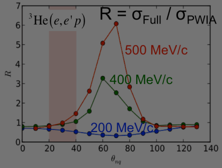
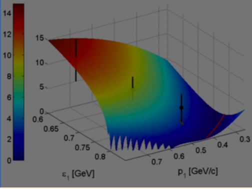
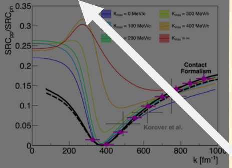


Future Directions in SRC research

NN Int. & nuclear wave-function

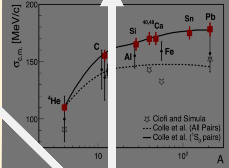
[^{2}H & ^{4}He]





Many-Body systems & nuclear asymmetry

[^{48}Ca, ^{120}Sn, ^{208}Pb]

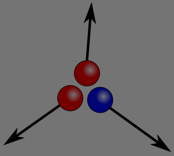


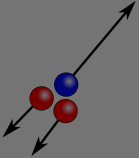
- Decoupling N/Z & A
- nn vs. pp

3N-SRC

[^{4}He, ^{12}C, ^{40}Ca]

1st Observation & A-dependence





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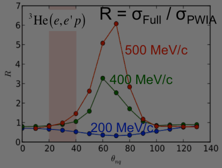
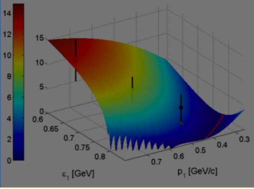
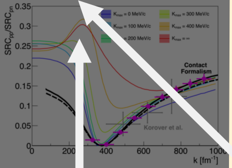


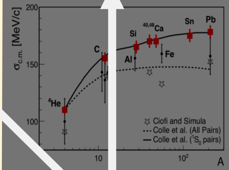
Future Directions in SRC research

NN Int. & nuclear wave-function
[^{2}H & ^{4}He]





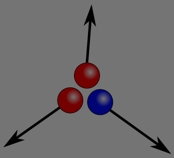
Many-Body systems & nuclear asymmetry
[^{48}Ca, ^{120}Sn, ^{208}Pb]

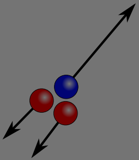


- Decoupling N/Z & A
- nn vs. pp

3N-SRC
[^{4}He, ^{12}C, ^{40}Ca]

1^{st} Observation & A-dependence





Reaction Mechanisms
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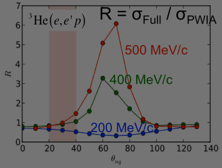
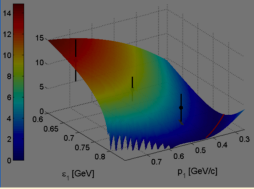
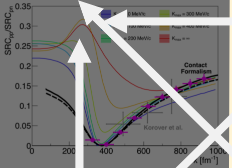
- Q^{2} independence
- A-dependence
-     vs. Glauber



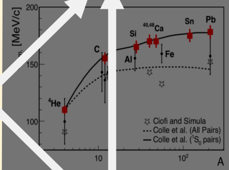
Future Directions in SRC research

NN Int. & nuclear wave-function
[^2H & ^4He]





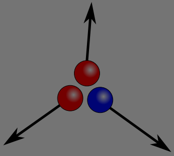
Many-Body systems & nuclear asymmetry
[^{48}Ca, ^{120}Sn, ^{208}Pb]

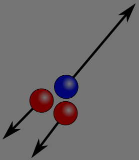


- Decoupling N/Z & A
- nn vs. pp

3N-SRC
[^4He, ^{12}C, ^{40}Ca]

1st Observation & A-dependence





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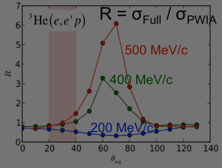
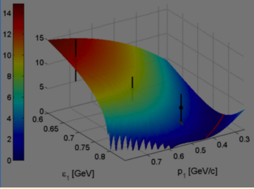
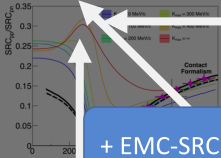


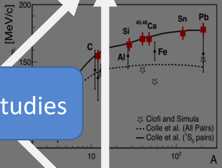
Future Directions in SRC research

NN Int. & nuclear wave-function
[^{2}H & ^{4}He]





Many-Body systems & nuclear asymmetry
[^{48}Ca, ^{120}Sn, ^{208}Pb]

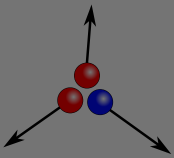


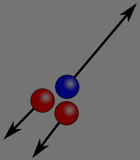
- Decoupling N/Z & A
- nn vs. pp

+ EMC-SRC Studies

3N-SRC
[^{4}He, ^{12}C, ^{40}Ca]

1st Observation & A-dependence





Reaction Mechanisms
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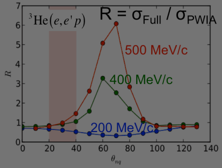
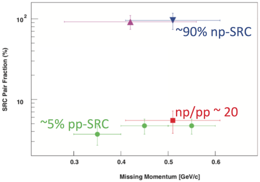


Multiple Proposals $\longrightarrow$ One program

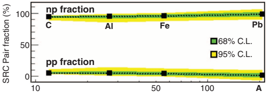
We choose to follow the PAC guidance and present the full program all at once.

"An issue was raised regarding our approval of long beam time allocations for CLAS12, without scrutinizing the precise relationship between beam time and physics goals. Indeed, such scrutiny would be very difficult for a PAC, especially in cases where the precision on a final result requires extensive analysis. Furthermore, this would end up crossing the line to acting as a scheduling group, rather than a PAC. However, we want to make the point that long beam time allocations for run groups, must be seen as flexible in their scheduling."
—J. Napolitano, PAC44 summary letter

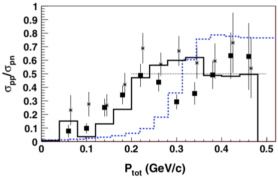
To recap:



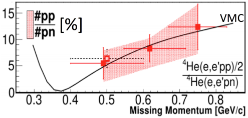
~90% np-SRC
np/pp ~ 20
~5% pp-SRC
SRC Pair Fraction (%)
Missing Momentum [GeV/c]



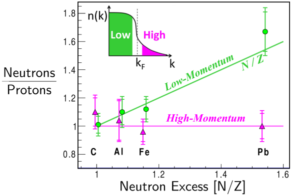
np fraction
pp fraction
C
Al
Fe
Pb
68% C.L.
95% C.L.
SRC Pair fraction (%)
A



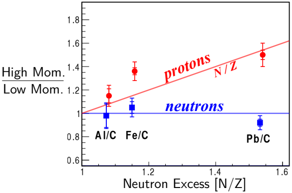
σ_{pp}/σ_{pn}
P_{tot} (GeV/c)



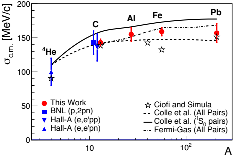
#pp
#pn
[%]
VMC
^{4}He(e,e'pp)/2
^{4}He(e,e'pn)
Missing Momentum [GeV/c]



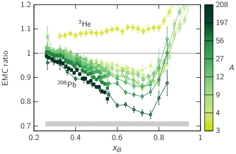
Neutrons
Protons
n(k)
Low
High
k_F
k
Low-Momentum
N / Z
High-Momentum
C
Al
Fe
Pb
Neutron Excess [N/Z]



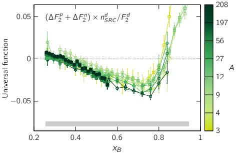
High Mom.
Low Mom.
protons
N / Z
neutrons
Al/C
Fe/C
Pb/C
Neutron Excess [N/Z]



$\sigma_{c.m.}$ [MeV/c]
^{4}He
C
Al
Fe
Pb
This Work
BNL (p,2pn)
Hall-A (e,e'pp)
Hall-A (e,e'pn)
Ciofi and Simula
Colle et al. (All Pairs)
Colle et al. ($^1S_0$ pairs)
Fermi-Gas (All Pairs)
A

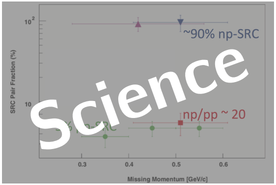


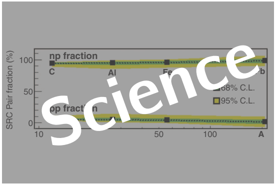
^{3}He
^{208}Pb
EMC ratio
x_B
A

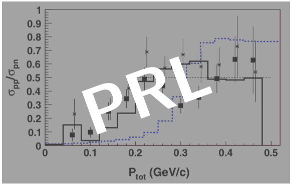


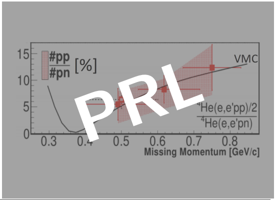
$(\Delta F_2^p + \Delta F_2^n) \times n_{SRC}^d / F_2^d$
Universal function
x_B
A

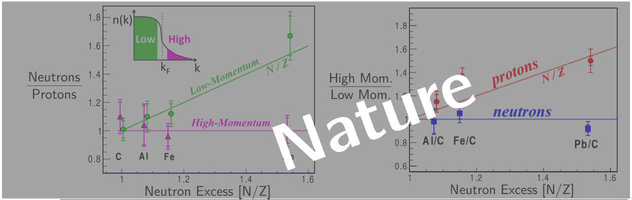
To recap:

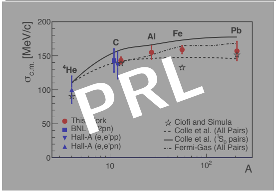


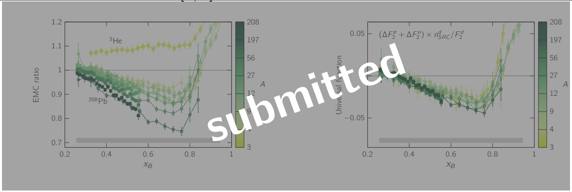




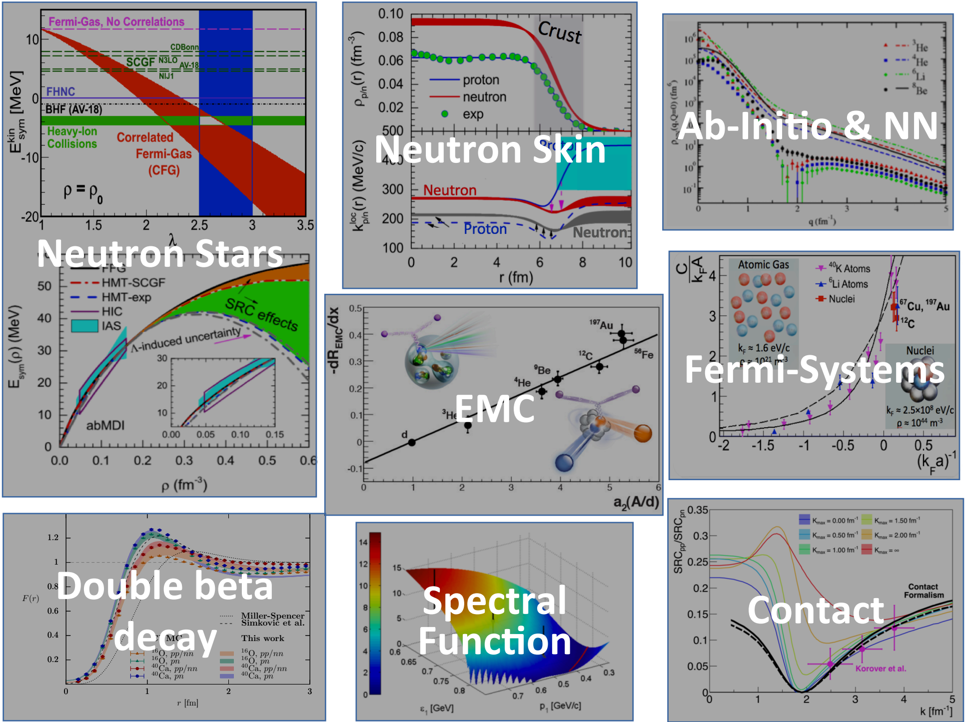






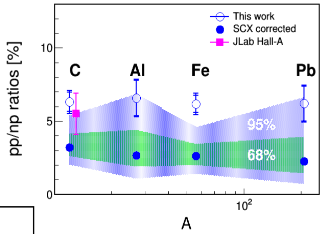


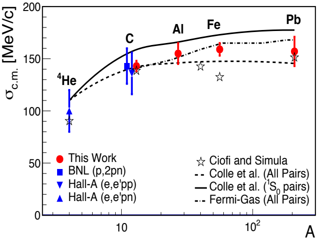
+ other PRL; PLB; PRC; ...

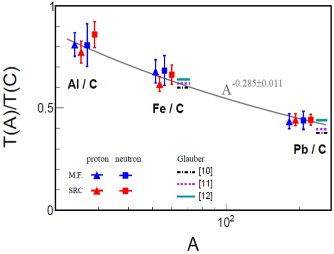

Neutron Stars
Neutron Skin
Ab-Initio & NN
EMC
Fermi-Systems
Double beta decay
Spectral Function
Contact

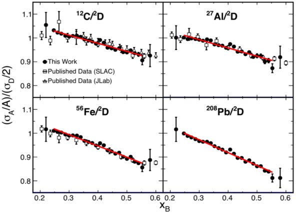
2018 Data

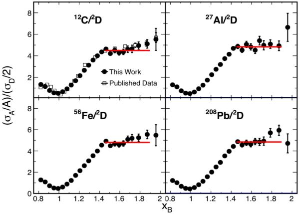
NEW!

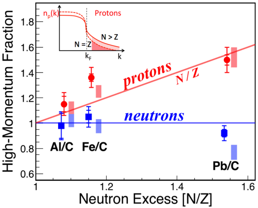


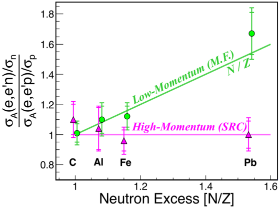


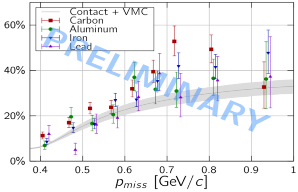






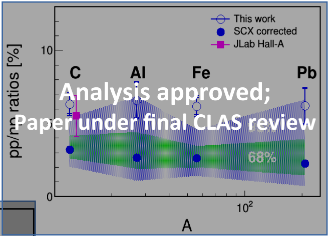


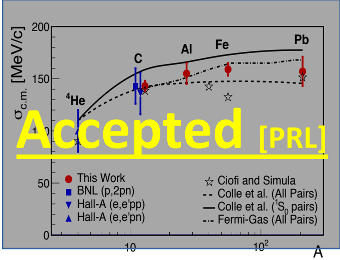


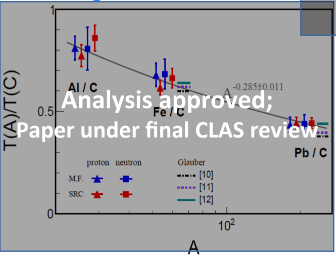


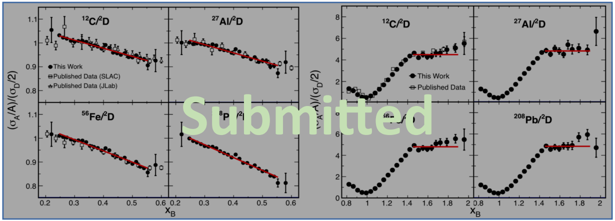
2018 Data

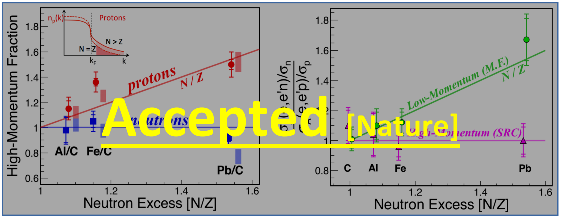

NEW!

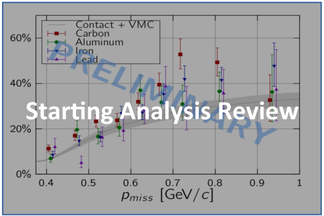

Analysis approved;
Paper under final CLAS review
This work
SCX corrected
JLab Hall-A
C
Al
Fe
Pb
pp/np ratios [%]
68%
A


Accepted [PRL]
$\sigma_{c.m.}$ [MeV/c]
^{4}He
C
Al
Fe
Pb
This Work
BNL (p,2pn)
Hall-A (e,e'pp)
Hall-A (e,e'pn)
Ciofi and Simula
Colle et al. (All Pairs)
Colle et al. ($^1S_0$ pairs)
Fermi-Gas (All Pairs)
A


Analysis approved;
Paper under final CLAS review
T(A)/T(C)
Al / C
Fe / C
Pb / C
-0.285±0.011
proton neutron
M.F.
SRC
Glauber
[10]
[11]
[12]
A


Submitted
^{12}C/^{2}D
^{27}Al/^{2}D
^{56}Fe/^{2}D
^{208}Pb/^{2}D
This Work
Published Data (SLAC)
Published Data (JLab)
Published Data
$(\sigma_A/A)/(\sigma_D/2)$
x_B


Accepted [Nature]
High-Momentum Fraction
Protons
N > Z
N = Z
protons
N / Z
neutrons
Al/C
Fe/C
Pb/C
Neutron Excess [N/Z]
Low-Momentum (M.F.)
N / Z
High-Momentum (SRC)
C
Al
Fe
Pb
Neutron Excess [N/Z]


Starting Analysis Review
PRELIMINARY
Contact + VMC
Carbon
Aluminum
Iron
Lead
p_{miss} [GeV/c]

Beam-time request

Target:	**d**	**^{4}He**	**^{12}C**	**^{28}Si**	**^{40}Ca**	**^{48}Ca**	**^{120}Sn**	**^{208}Pb**	**Total**
Days (6.6 GeV)	5	3	2	2	3	3	4	5	**27**
Calibration									**1**
Target Changes									**2**
								Total at 6.6 GeV:	**30**
Days (4.4 GeV)	2	1	1	0	0	0	1	1	**6**
Calibration									**1**
Target Changes									**1**
								Total at 4.4 GeV:	**8**

Beam-time request

Target:	d	^{4}He	^{12}C	^{28}Si	^{40}Ca	^{48}Ca	^{120}Sn	^{208}Pb	Total
Days (6.6 GeV)	5	3	2	2	3	3	4	5	**27**
Calibration									**1**
Target Changes									**2**
								Total at 6.6 GeV:	**30**
Days (4.4 GeV)	2	1	1	0	0	0	1	1	**6**
Calibration									**1**
Target Changes									**1**
								Total at 4.4 GeV:	**8**

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Target:	d	^{4}He	^{12}C	^{28}Si	^{40}Ca	^{48}Ca	^{120}Sn	^{208}Pb	Total
Days (6.6 GeV)	5	3	2	2	3	3	4	5	**27**
Calibration									**1**
Target Changes									**2**
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Target Changes									**1**
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Days (6.6 GeV)	5	3	2	2	3	3	4	5	**27**
Calibration									**1**
Target Changes									**2**
								Total at 6.6 GeV:	**30**
Days (4.4 GeV)	2	1	1	0	0	0	1	1	**6**
Calibration									**1**
Target Changes									**1**
								Total at 4.4 GeV:	**8**

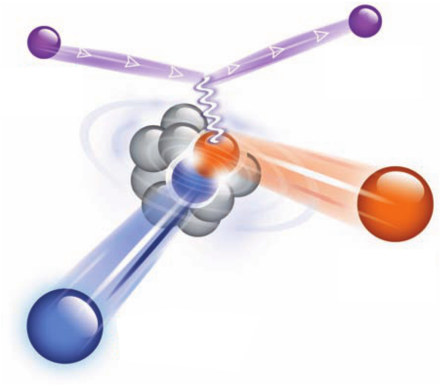
Beam-time request

Target:	d	^{4}He	^{12}C	^{28}Si	^{40}Ca	^{48}Ca	^{120}Sn	^{208}Pb	Total
Days (6.6 GeV)	5	3	2	2	3	3	4	5	**27**
Calibration									**1**
Target Changes									**2**
								Total at 6.6 GeV:	**30**
Days (4.4 GeV)	2	1	1	0	0	0	1	1	**6**
Calibration									**1**
Target Changes									**1**
								Total at 4.4 GeV:	**8**

Complements approved Hall C (*e,e'*) EMC-SRC program:

- 67 PAC days, 15 different targets

Back-up slides



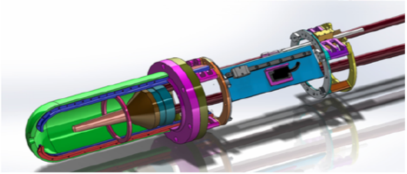
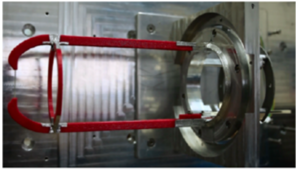
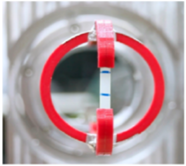
Overlap with $e4\nu$

Energy	^{4}He	^{12}C	^{120}Sn	Total
4.4 GeV	1	1	1	3
6.6 GeV	2	2	2	6

- 9 beam days of overlap
- Shared calibrations
- Optimized setting changes

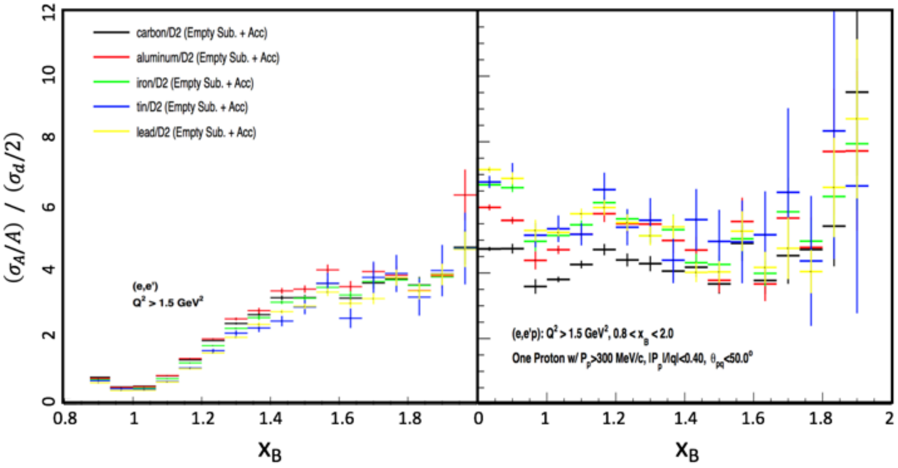
New CLAS-12 multi-target system

Developed by collaborators at UTSFM, Valparaiso, Chile

See me for video of prototype.

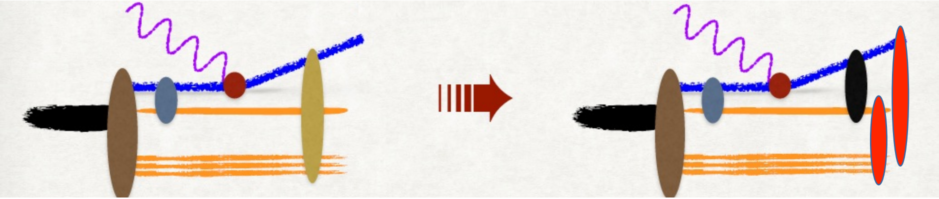
Recoil-tagging may give us a new handle.



Schmookler et al., in preparation

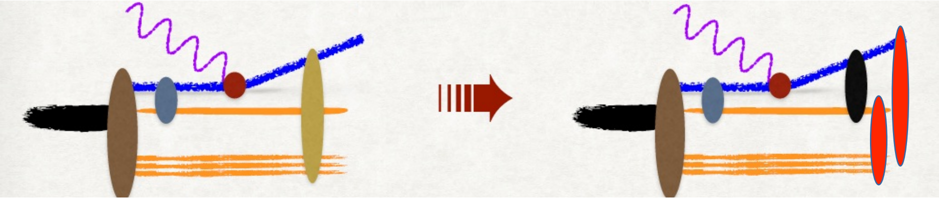
FSI: Theory Guidance

For large Q^2, x>1



FSI: Theory Guidance

For large Q^2, x>1



$$r_{FSI} \sim \frac{1}{\Delta E v} \lesssim 1 \text{ fm}$$

[PRC 56 1124-1137 (1997), arXiv: 0806.4412]

$$\Delta E = -q_0 - M_A + \sqrt{m^2 + (p_i + q)^2} + \sqrt{M_{A-1}^2 + p_i^2}$$

Can be approximated by Glauber (transparency)

Large but confined within the SRC pair

Rescattering do not produce 2N–SRC candidates due to high p_t

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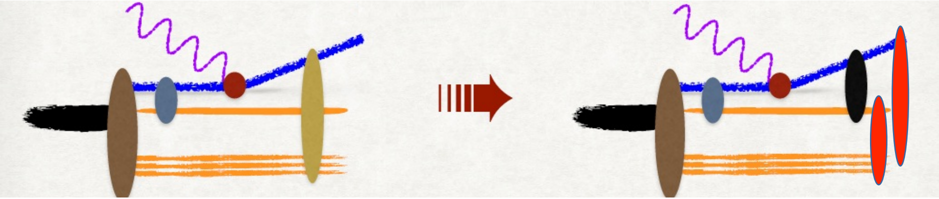

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 Can be approximated by Glauber (transparency)

 Large but confined within the SRC pair

- **Choose kinematics to min FSI**
- **Choose observables not sensitive to** 

Rescattering do not produce 2N–SRC candidates due to high p_t

Nuclear contact in EFT and the EMC effect

Chen, Detmold, Lynn, Schwenk, PRL 119, 262502 (2017)

$$\frac{F_2^A(x, Q^2)}{A} \simeq F_2^N(x, Q^2) + g_2(A, \Lambda) f_2(x, Q^2, \Lambda)$$

$$g_2(A, \Lambda) = \frac{1}{2A} \left\langle A \right| : \left(N^\dagger N\right)^2 : \left| A \right\rangle_\Lambda$$

g_2 **IS** the nuclear contact!

We tried to model the modification of a single *np*-SRC pair.

Work in collaboration with Barak Schmookler

We tried to model the modification of a single *np*-SRC pair.

$$F_2^A = (Z - n_{\mathrm{SRC}}^A)F_2^p + (N - n_{\mathrm{SRC}}^A)F_2^n + n_{\mathrm{SRC}}^A(F_2^{p*} + F_2^{n*})$$

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$$F_2^A = (Z - n_{\mathrm{SRC}}^A)F_2^p + (N - n_{\mathrm{SRC}}^A)F_2^n + n_{\mathrm{SRC}}^A(F_2^{p*} + F_2^{n*})$$

$$F_2^A = ZF_2^p + NF_2^n + n_{\mathrm{SRC}}^A(\Delta F_2^p + \Delta F_2^n)$$

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$$F_2^A = ZF_2^p + NF_2^n + n_{\mathrm{SRC}}^A(\Delta F_2^p + \Delta F_2^n)$$

$$F_2^d = F_2^p + F_2^n + n_{\mathrm{SRC}}^d(\Delta F_2^p + \Delta F_2^n)$$

We tried to model the modification of a single *np*-SRC pair.

$$\frac{n^d_{\text{SRC}}}{F^d_2}(\Delta F^p_2 + \Delta F^n_2) = \frac{\frac{F^A_2}{F^d_2} - (Z - N)\frac{F^p_2}{F^d_2} - N}{\frac{n^A_{\text{SRC}}}{n^d_{\text{SRC}}} - N}$$

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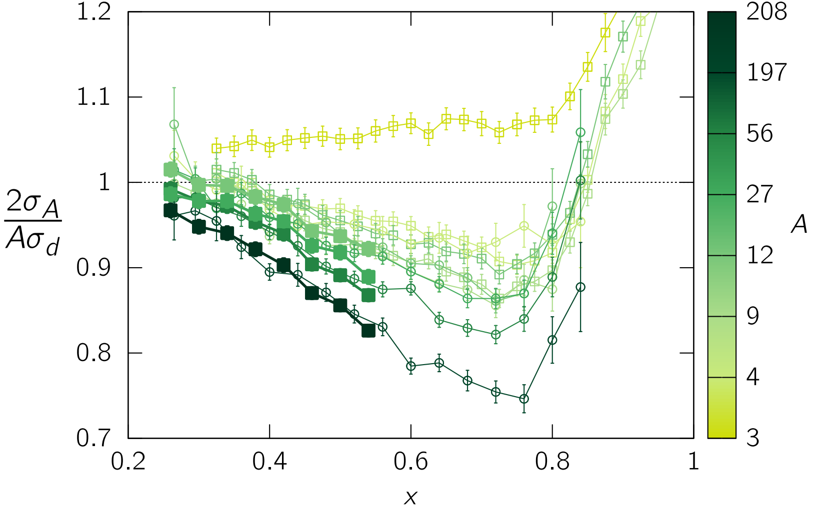
$$\frac{n^d_{\text{SRC}}}{F^d_2}(\Delta F^p_2 + \Delta F^n_2) = \frac{\frac{F^A_2}{F^d_2} - (Z-N)\frac{F^p_2}{F^d_2} - N}{\frac{n^A_{\text{SRC}}}{n^d_{\text{SRC}}} - N}$$

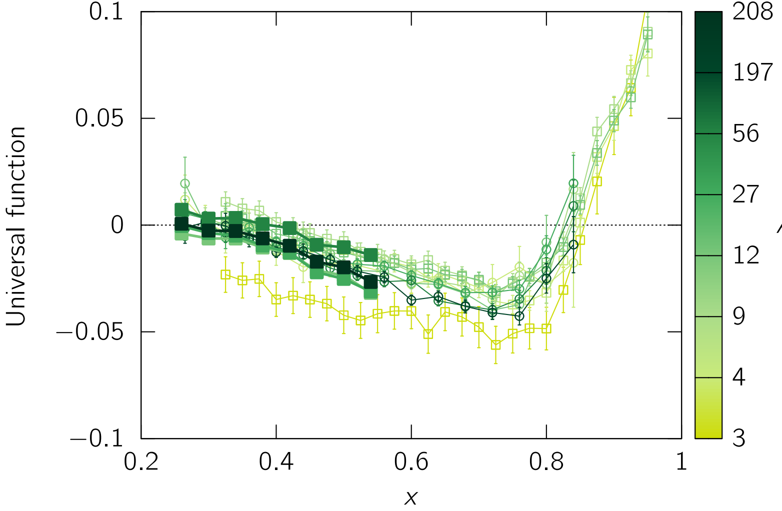
Universal function   Nucleus-dependent

EMC data vary significantly by nucleus.



Submitted for publication

The SRC-modification function seems universal.



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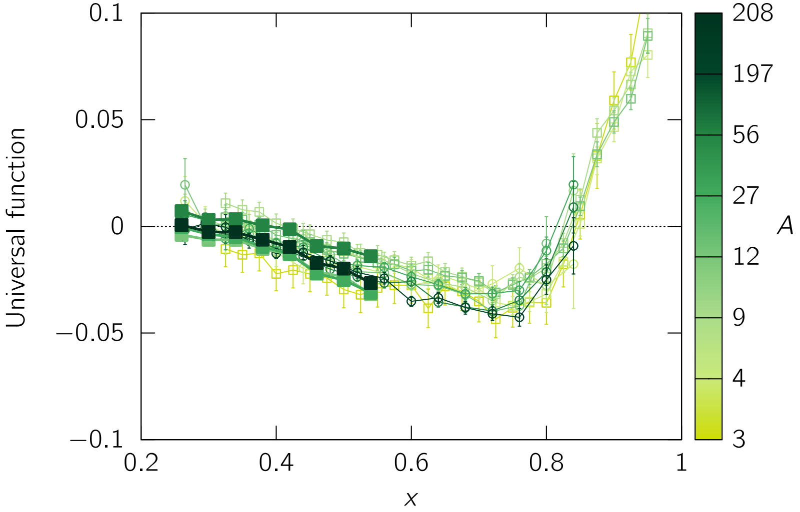

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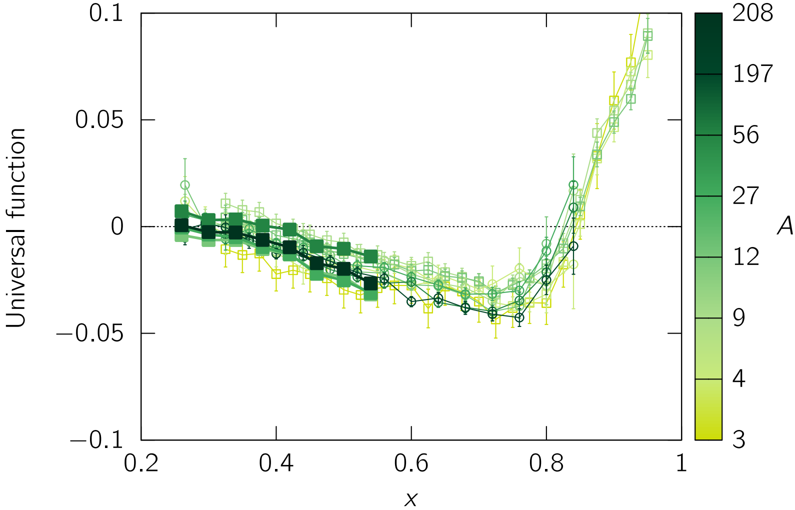
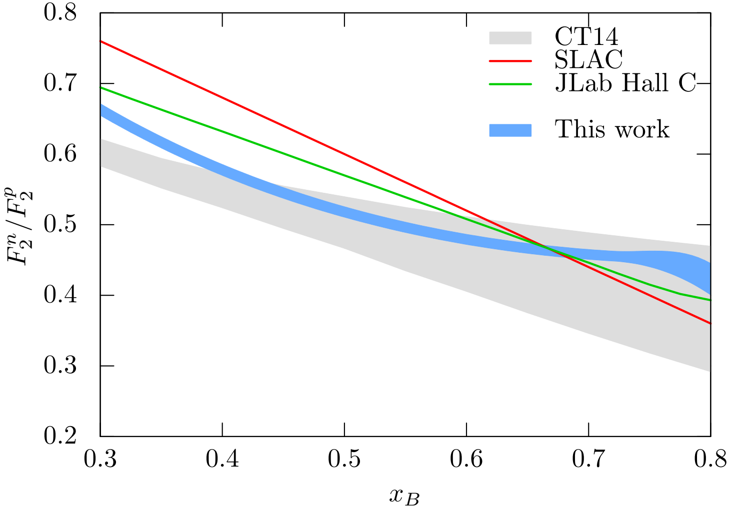
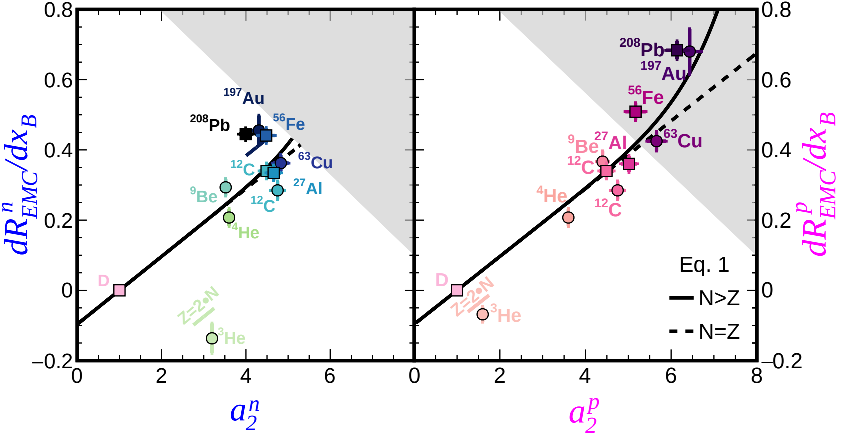


See Kulagin and Petti, PRC 82 054614 (2010)

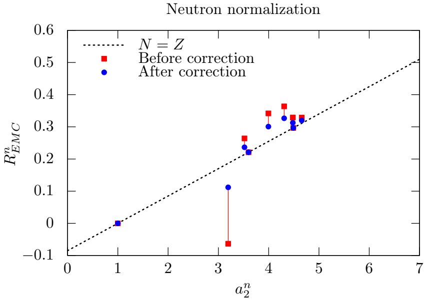
Free neutron F_2 extraction

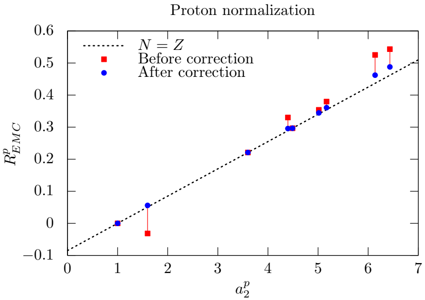


Predicting the EMC-SRC correlation



Self-consistent isoscalar corrections





Neutrinos: C12-17-006 (23 PAC days)

Energy	^{4}He	^{12}C	^{16}O	^{40}Ar	^{120}Sn	Total
1.1	0.5	0.5	0.5	0.5	0.5	2.5
2.2	1	1	1	1	1	5
4.4	1	1	X	1	1	4
6.6	2	2	X	2	2	8
Total	4.5	4.5	1.5	4.5	4.5	**19.5+3.5***

*Plus 3.5 PAC days overhead is for beam energy and target changes (2.5 days) and calibrations (1 day).

SRC: PR12-18-003 (37 PAC days)

Energy	d	^{4}He	^{12}C	^{28}Si	^{40}Ca	^{48}Ca	^{120}Sn	^{208}Pb	Total
4.4	2	1	1	X	X	X	1	1	6
6.6	5	3	2	2	3	3	4	5	27
Total	7	4	3	2	3	3	5	6	**33+4***

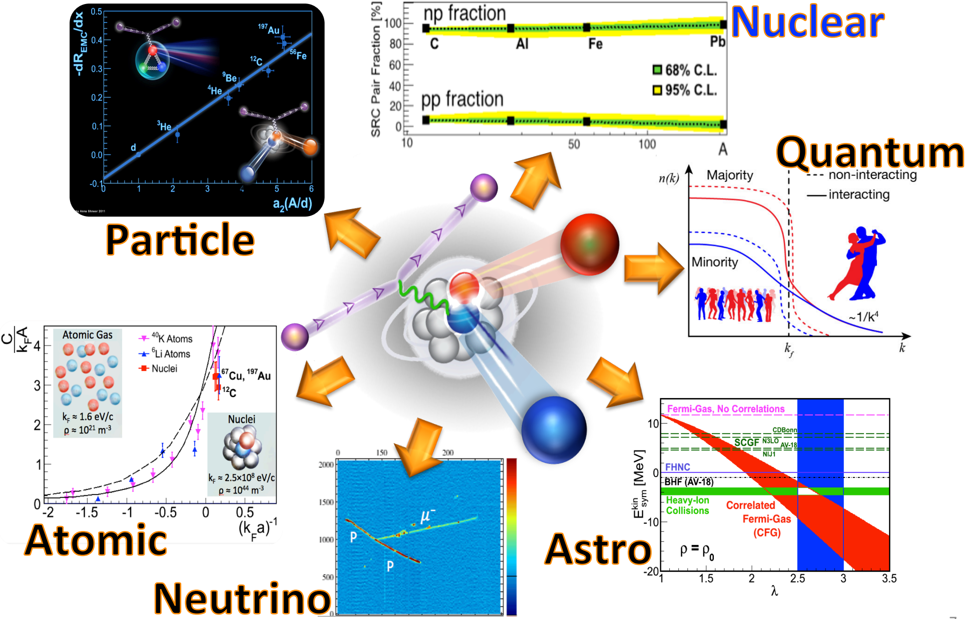
*Plus 4 PAC days overhead for target and beam energy and changes (2 days) and calibrations (2 days).

Combined experiment beam time request (49.5 PAC days):

Energy	d	^{4}He	^{12}C	^{16}O	^{28}Si	^{40}Ar	^{40}Ca	^{48}Ca	^{120}Sn	^{208}Pb	Total
1.1	X	0.5	0.5	0.5	X	0.5	X	X	0.5	X	2.5
2.2	X	1	1	1	X	1	X	X	1	X	5
4.4	2	1	1	X	X	1	X	X	1	1	7
6.6	5	3	2	X	2	2	3	3	4	5	29
Total	7	5.5	4.5	1.5	2	4.5	3	3	6.5	6	**43.5+6***

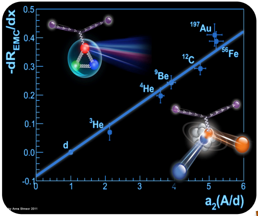
*Plus 6 PAC days for beam energy and target changes (4 days) and calibrations (2 days).

Important to Physics! ☺

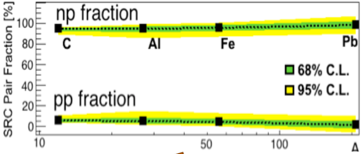


Important to Physics! ☺

Particle



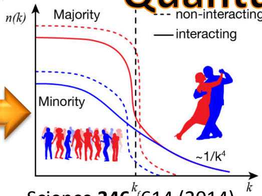
PRL **106**, 052301 (2011),
PRD **84**, 117501(2011),
PRC **85**, 047301(2012),
IJMPE **22**, 1330017 (2013),
arXiv 1607.03065 (2016).



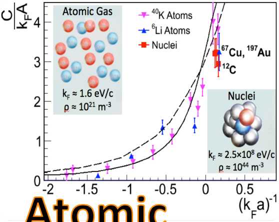
Nuclear

Science **320**, 1476 (2008),
PRL **108**, 092502 (2012),
PLB 772, **63** (2013),
PRL **113**, 022501 (2014),
PRC **92**, 024604 (2015).

Quantum

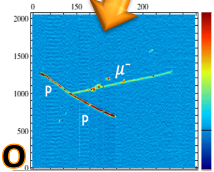


Science **346**, 614 (2014).



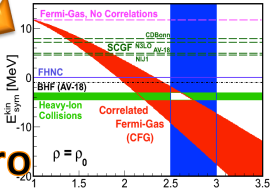
Atomic

PRC **92**, 045205 (2015).



Neutrino

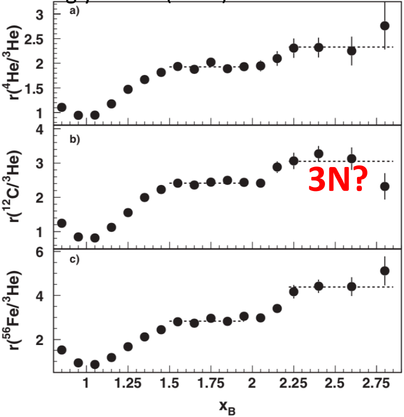
PRD **90**, 012008 (2014); arXiv 1604.02482 (2016)

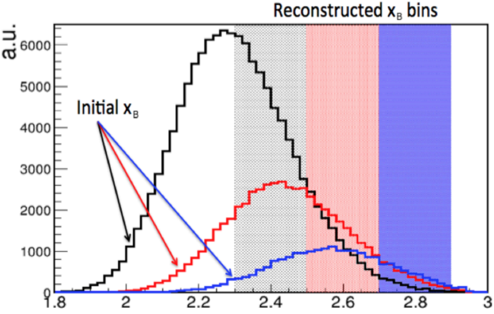


Astro

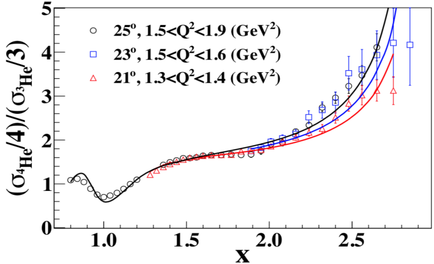
PRC **91**, 025803 (2015), PRC **93**, 044610 (2016),
PRC **91**, 044601 (2015), PRC **93**, 014619 (2016),
PRC **92**, 011601 (2015), PLB **759**, 79 (2016),
Hen and Steiner et al., In Preparation.

Egiyan PRL (2006)





Higinbotham & Hen PRL (2015)



Ye PRC (2018)

Bound nucleons in EFT and QCD

1. EFT: $F_2^A(x,Q^2) = F_2^N(x,Q^2) + g_2(A,\Lambda)\cdot f_2(x,Q^2,\Lambda)$

Bound = Free + Factorized Modification

2. QCD: $|N\rangle_{bound} = |N\rangle + (\varepsilon_{bound} - \varepsilon)|N^*\rangle$

Hen, Miller, Piasetzky and Weinstein,
Reviews of Modern Physics (2017).

Chen, Detmold, Lynnm, and
Schwenk, PRL (2018).

SRC and the Symmetry Energy

<u>Tensor Correlations:</u>

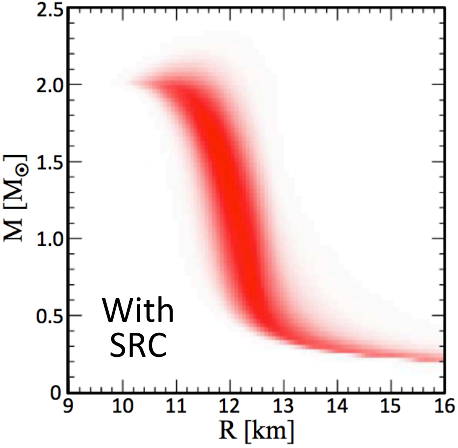
- Break the Fermi-Gas picture
- Reduce the kinetic symmetry energy (at ρ_0)
- Enhance the potential symmetry energy (at ρ_0)
- Softens the potential symmetry density dependence

But.... Still consistent with constrains from neutron stars observations!

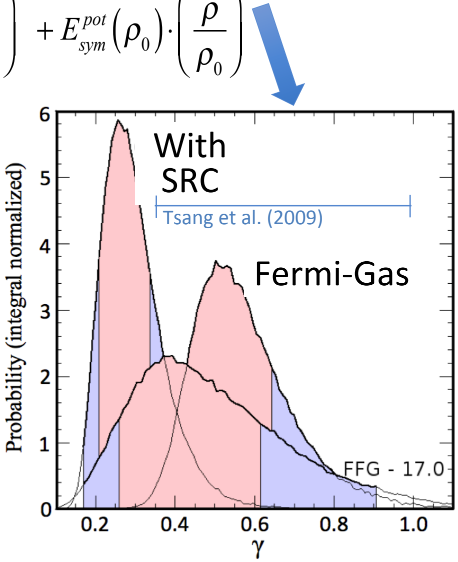
O. Hen and A. Steiner et al. (on arXiv soon) O. Hen et al., PRC 91, 025803 (2015)

SRC and the Symmetry Energy

$$E_{sym}(\rho) = E_{sym}^{kin}(\rho_0) \cdot \left(\frac{\rho}{\rho_0}\right)^{\alpha} + E_{sym}^{pot}(\rho_0) \cdot \left(\frac{\rho}{\rho_0}\right)^{\gamma_i}$$

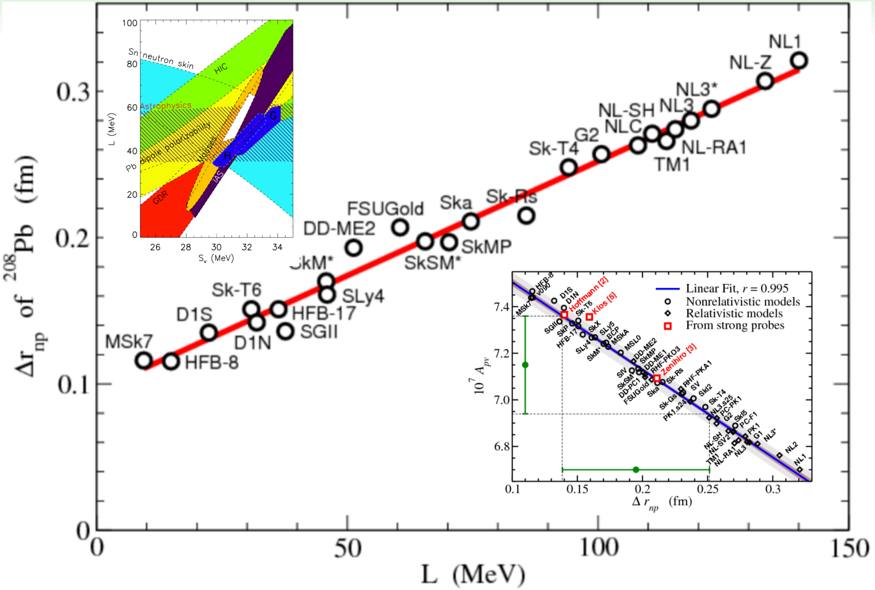


O. Hen and A. Steiner et al. (on arXiv soon)



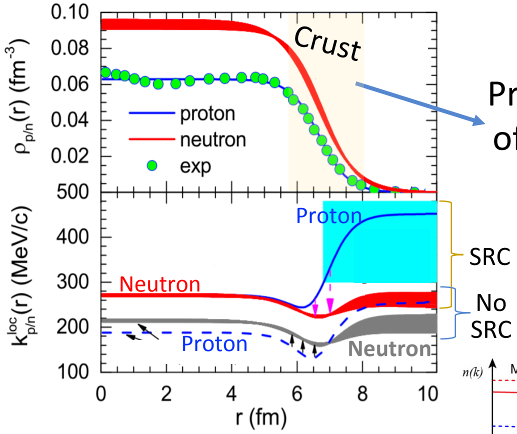
O. Hen et al., PRC 91, 025803 (2015)

Skin Width and Symmetry Energy

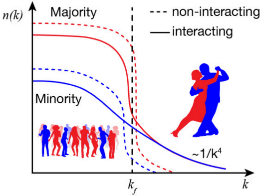


Pairing and…. Neutron Skins

Protons move faster in the neutron skin



Protons in the **crust** ‘feel’ one of the largest neutron excess reachable by terrestrial experiments



B.J. Cai et al., arXiv: 1606.08045 (2016).

Pairing and…. Neutron Skins

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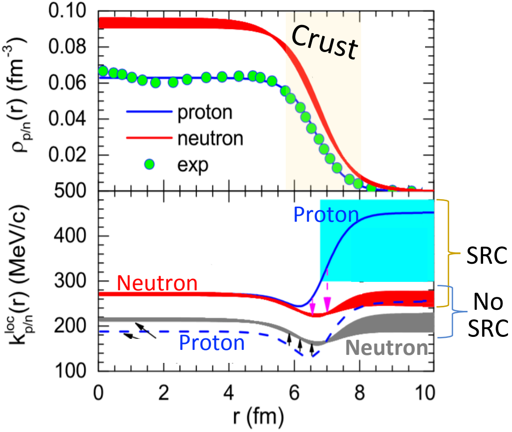
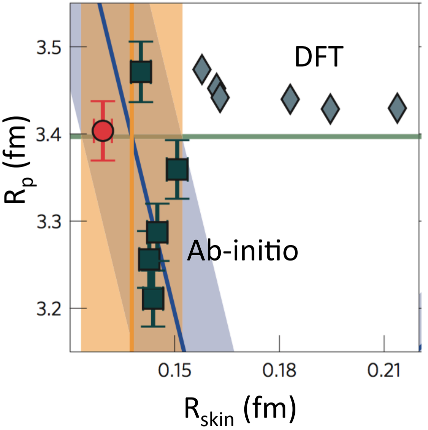


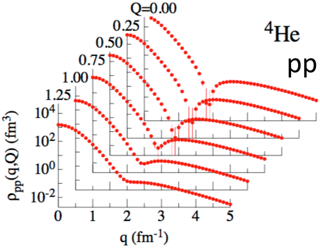
B.J. Cai et al., arXiv: 1606.08045 (2016).

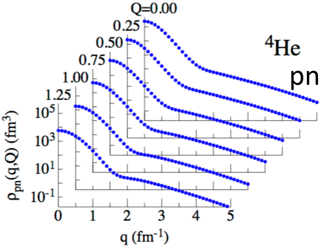
Do SRC change the neutron skin?



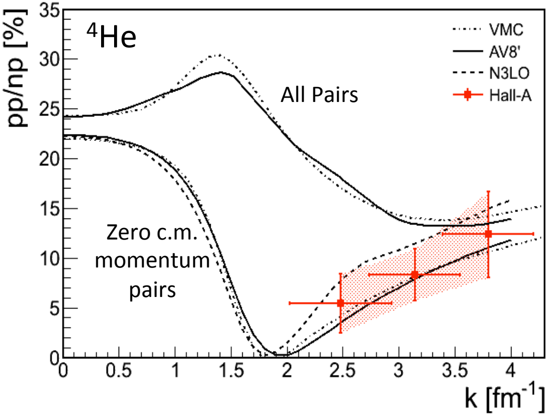
G. Hagen et al., Nature Physics 12, 186 (2016)

Pairing Calculations – Light Nuclei





Two Body momentum distributions



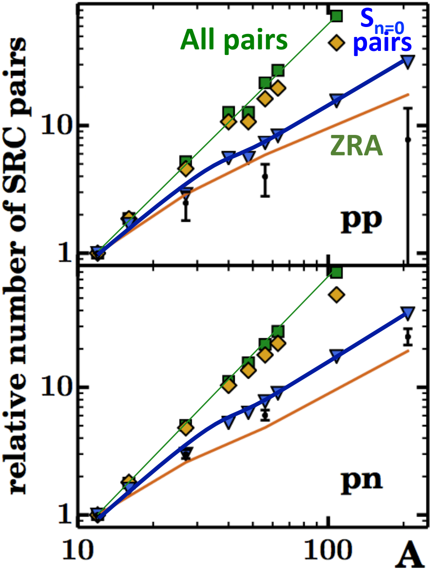
SRC pairs are consistent only with zero c.m. momentum pairs!

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).

Pairing Calculations – Heavy Nuclei

<u>Mean-Field approach:</u>
Shift the complexity from the wave function to the operators!

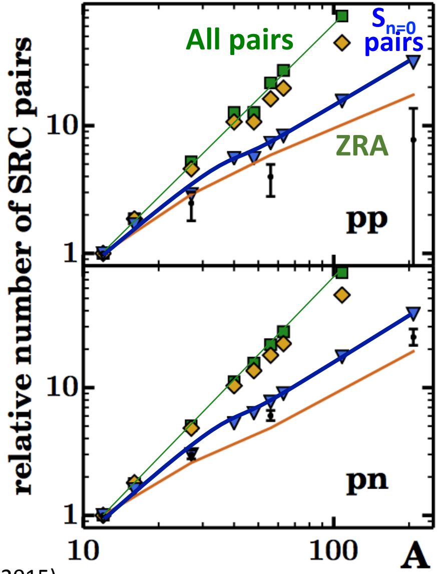
- Start from a mean-field staler determinant.
- Introduce SRC using *tensor* correlation operators that act on close proximity nucleons (specifically ${}_1S_0$ and ${}^3S_0$).
- The action of the correlation operators change the quantum numbers to produce deuteron-like SRC pairs!



C. Colle and O. Hen et al., Phys. Rev. C **92**, 024604 (2015)

Pairing Calculations – Heavy Nuclei

- Extract from data the number of pp (np) SRC pairs in nuclei relative to ^{12}C.
- Observe that the pair number increases very slowly with A
- consistent with $^1S_0$ ($^3S_0$) pairs creating SRCs.



C. Colle and O. Hen et al., Phys. Rev. C **92**, 024604 (2015)

Pairing Calculations – Heavy Nuclei

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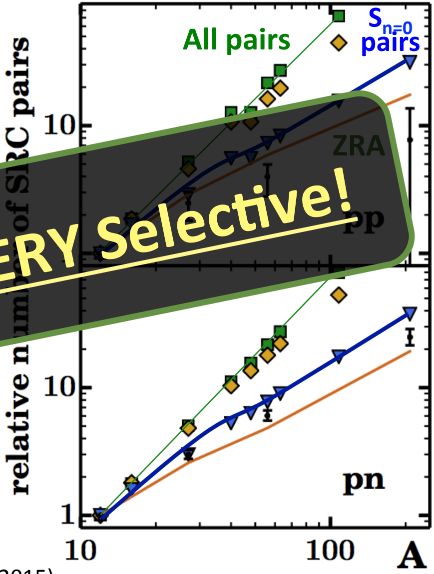
SRC Pairs are VERY Selective!



C. Colle and O. Hen et al., Phys. Rev. C **92**, 024604 (2015)

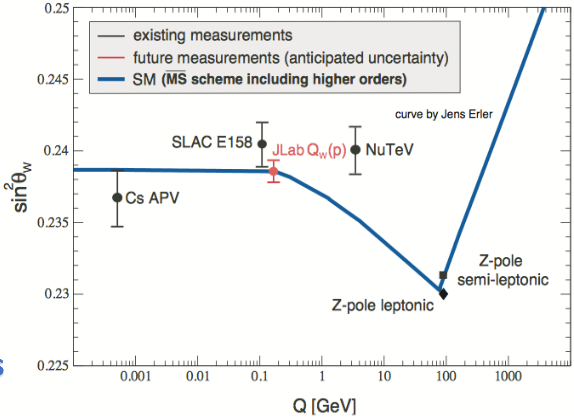
Pairing and…. the EMC Effect

IsoSpin dependent EMC effect (*u* quark distribution more modified than *d*) can explain the NuTeV anomaly.

1. Mean-Field models
   (Cloet, Benz, Thomas)

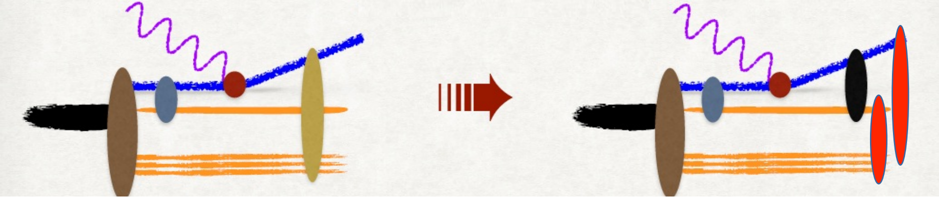
2. EMC-SRC models
   (Miller, Frankfurt, Strikman, degli Atti, Kulagin, Petti)

If $\langle T_p \rangle > \langle T_n \rangle$:
➔protons more-modified than neutrons
➔ u modification > d



FSI: Theory Guidance

For large Q^2, x>1



FSI: Theory Guidance

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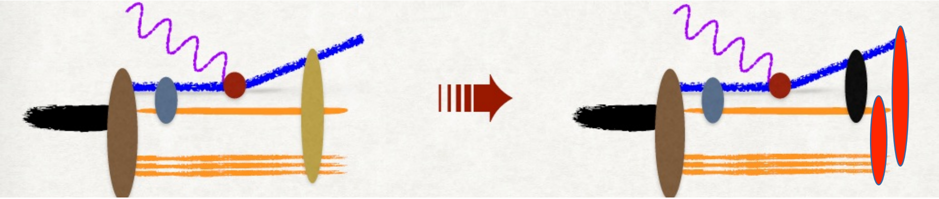

$$r_{FSI} \sim \frac{1}{\Delta E v} \lesssim 1 \text{ fm}$$

[PRC 56 1124-1137 (1997), arXiv: 0806.4412]

$$\Delta E = -q_0 - M_A + \sqrt{m^2 + (p_i + q)^2} + \sqrt{M_{A-1}^2 + p_i^2}$$

Can be approximated by Glauber (<u>transparency</u>)

Large but confined within the SRC pair

Rescattering do not produce 2N–SRC candidates due to high p_t

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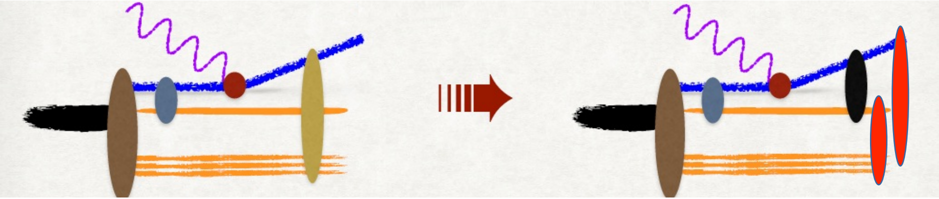

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- **Choose kinematics to min FSI**
- **Choose observables not sensitive to** 

 Can be approximated by Glauber (transparency)

 Large but confined within the SRC pair

Rescattering do not produce 2N–SRC candidates due to high p_t

Unitary Interlude

- "high momentum" interpretation relies on *single nucleon* interaction operators.
  - Compatible \w calculation using hard potentials (e.g., AV18).
  - Difficult to go much beyond than C / Ca.

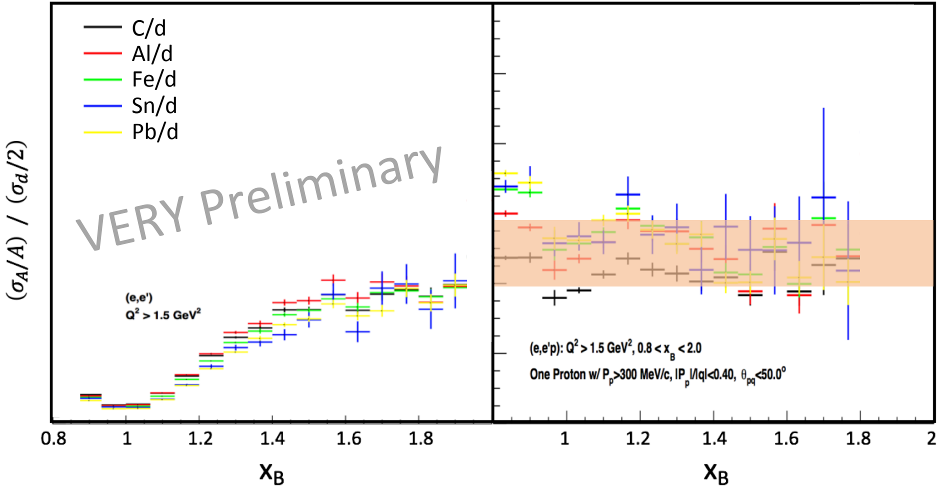
- Unitary transforms simplifies calculations of heavy nuclei at the expense of forming many-body operators.

  $\langle \Psi | O | \Psi \rangle = \langle \Psi U^{\dagger} | U O U^{\dagger} | U \Psi \rangle$

  - Transforms "high momentum" to "short range"
    <u>Win:</u> Simpler wave functions
    <u>Lose:</u> Complicated interaction operators
    <u>Trick:</u> Transform wave-function but not the operators 😬😬
  - No calculations for e-scattering off heavier nuclei, yet.

- Complete physical equivalent.
  - Same cross sections
  - Different interpretations

SRC Spectator Tagging



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

Short-Distance Factorization

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

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

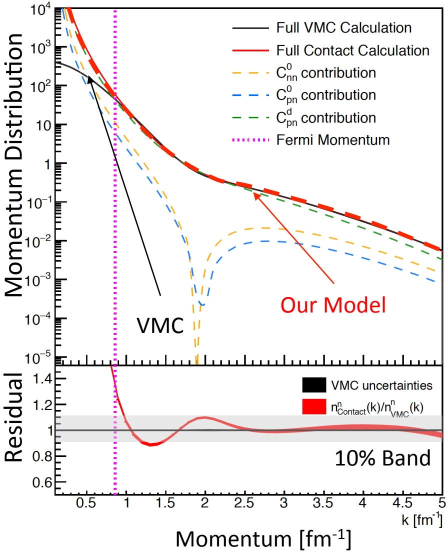
- Universal function of the NN interaction.
- Taken as the zero energy solution to the 2 body problem

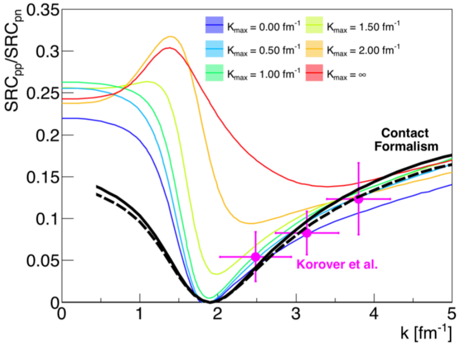
- Nucleus (/ system) specific function
- Depends on all nucleons except the SRC pair (primarily mean-field)

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

Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, Phys. Lett. B **780**, 211 (2018)

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





Nuclear contacts can also be extracted from experiment!

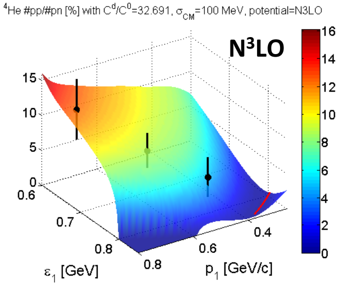
Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, Phys. Lett. B **780**, 211 (2018)

Spectral Function

Define pair spectral function as:

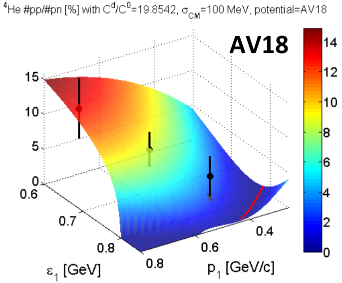
$$S^{\alpha}_{ab} = \frac{1}{4\pi}\int \frac{d\boldsymbol{p}_2}{(2\pi)^3}\delta(f(p_2))\,|\tilde{\varphi}^{\alpha}_{ab}(|(\boldsymbol{p}_1-\boldsymbol{p}_2)/2|)|^2\, n^{\alpha}_{ab}(\boldsymbol{p}_1+\boldsymbol{p}_2)$$

$$f(p_2) = \epsilon_1+\epsilon_2-2m+(B^A_i-\bar{B}^{A-2}_f)+\frac{(\boldsymbol{p}_1+\boldsymbol{p}_2)^2}{2m(A-2)}$$



Factorize the continuum states of the spectral function:

$$S^p(p_1,\epsilon_1) = C^1_{pn}S^1_{pn}(p_1,\epsilon_1)+C^0_{pn}S^0_{pn}(p_1,\epsilon_1) + 2C^0_{pp}S^0_{pp}(p_1,\epsilon_1).$$



Compare with (e,e'pN) data!

First studies of combined missing energy and momentum!

Weiss, Korover, Piasetzky, Hen, and Barnea, arXiv: 1806.10217 (2018)

Consistent k- & r-Space Contacts

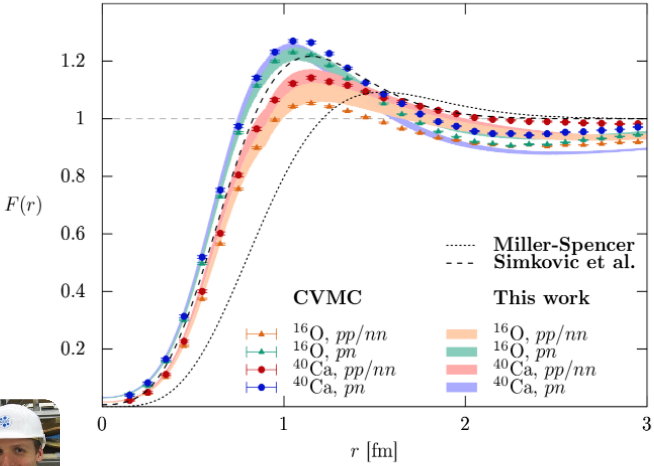
<table>
<tr><th rowspan="2">A</th><th colspan="4">k-space</th><th colspan="4">r-space</th></tr>
<tr><th>$C_{pn}^{s=1}$</th><th>$C_{pn}^{s=0}$</th><th>$C_{nn}^{s=0}$</th><th>$C_{pp}^{s=0}$</th><th>$C_{pn}^{s=1}$</th><th>$C_{pn}^{s=0}$</th><th>$C_{nn}^{s=0}$</th><th>$C_{pp}^{s=0}$</th></tr>
<tr><td rowspan="2">^{4}He</td><td>12.3 ± 0.1</td><td>0.69 ± 0.03</td><td colspan="2">0.65 ± 0.03</td><td rowspan="2">11.61 ± 0.03</td><td colspan="3" rowspan="2">0.567 ± 0.004</td></tr>
<tr><td>14.9 ± 0.7 (exp)</td><td colspan="3">0.8 ± 0.2 (exp)</td></tr>
<tr><td>^{6}Li</td><td>10.5 ± 0.1</td><td>0.53 ± 0.05</td><td colspan="2">0.49 ± 0.03</td><td>10.14 ± 0.04</td><td colspan="3">0.415 ± 0.004</td></tr>
<tr><td>^{7}Li</td><td>10.6 ± 0.1</td><td>0.71 ± 0.06</td><td>0.78 ± 0.04</td><td>0.44 ± 0.03</td><td>9.0 ± 2.0</td><td>0.6 ± 0.4</td><td>0.647 ± 0.004</td><td>0.350 ± 0.004</td></tr>
<tr><td>^{8}Be</td><td>13.2 ± 0.2</td><td>0.86 ± 0.09</td><td colspan="2">0.79 ± 0.07</td><td>12.0 ± 0.1</td><td colspan="3">0.603 ± 0.003</td></tr>
<tr><td>^{9}Be</td><td>12.3 ± 0.2</td><td>0.90 ± 0.10</td><td>0.84 ± 0.07</td><td>0.69 ± 0.06</td><td>10.0 ± 3.0</td><td>0.7 ± 0.7</td><td>0.65 ± 0.02</td><td>0.524 ± 0.005</td></tr>
<tr><td>^{10}B</td><td>11.7 ± 0.2</td><td>0.89 ± 0.09</td><td colspan="2">0.79 ± 0.06</td><td>10.7 ± 0.2</td><td colspan="3">0.57 ± 0.02</td></tr>
<tr><td rowspan="2">^{12}C</td><td>16.8 ± 0.8</td><td>1.4 ± 0.2</td><td colspan="2">1.3 ± 0.2</td><td rowspan="2">14.9 ± 0.1</td><td colspan="3" rowspan="2">0.83 ± 0.01</td></tr>
<tr><td>18 ± 2 (exp)</td><td colspan="3">1.5 ± 0.5 (exp)</td></tr>
</table>

Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, Phys. Lett. B **780**, 211 (2018)

Correlation Function

Derive Correlation function:

$$F_{NN,s}(r) \equiv \frac{\rho_{NN,s}(r)}{\rho_{NN}^{\text{uncorr.}}(r)}$$ +Pauli Exchange



Cruz-Torres and Schmidt et al., arXiv: 1710.07966 (2018)