Probing nuclear short-range correlations with protons and electrons – forging links between data and models

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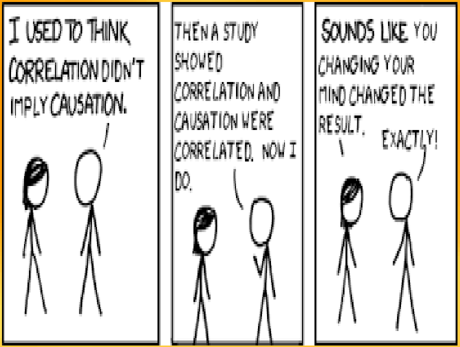
Weizmann Institute of Science, March 2017

Talking about nuclear correlations



- **Whole is different from the sum of the "parts"**
- **"Parts" can be effective degrees of freedom**
- **In nuclei: "Parts" are quasi-nucleons moving in a mean-field potential (SCHEME DEPENDENCE)**

- **Comprehensive picture of nuclear SRC (A and isospin dependence)?**
- **How to forge links between nuclear-strucure theory (models) and observables sensitive to nuclear SRC?**

STRATEGY (and OUTLINE of this presentation)

1. Develop an appropriate expansion for transition matrix element between short-range correlated wave functions (Low-order correlation operator approximation (LCA))
2. Apply it to the computation of nuclear momentum distributions and find the driving physical mechanisms (Compare results to those of "ab-initio" approaches)
3. Compute aggegrated effect of SRC as a function of A (a_2 data from $A(e,e')$)
4. Compute isospin dependence of SRC ($A(e,e'pp)/A(e,e'pn)$ data)
5. Develop a proper reaction theory for SRC-sensitive two-nucleon knockout
   - proper factorization properties of cross sections (data for c.m. distributions of SRC pairs)
   - FSI corrections (elastic and charge-exchange)
   - $A(e,e'NN)$ for $N \gtrsim Z$ and $p(A, pNNA-2)$ for $N > Z$

Nuclear transition matrix elements with SRC (I)

- Shift complexity from wave functions to operators

$$\mid \Psi \rangle = \frac{1}{\sqrt{\mathcal{N}}} \widehat{\mathcal{G}} \mid \Phi \rangle \qquad \text{with,} \qquad \mathcal{N} \equiv \langle \Phi \mid \widehat{\mathcal{G}}^{\dagger} \widehat{\mathcal{G}} \mid \Phi \rangle$$

$\mid \Phi \rangle$ is an IPM single Slater determinant

- Nuclear SRC correlation operator $\widehat{\mathcal{G}}$

$$\widehat{\mathcal{G}} \approx \widehat{\mathcal{S}} \left(\prod_{i<j=1}^{A} \left[1 + \hat{l}(i,j) \right] \right) ,$$

- Major source of correlations: central (Jastrow), tensor and spin-isospin (universal dependent on r_{ij})

$$\hat{l}(i,j) = -g_c(r_{ij}) + f_{t\tau}(r_{ij}) \widehat{S}_{ij} \vec{\tau}_i \cdot \vec{\tau}_j \, . + f_{\sigma\tau}(r_{ij}) \vec{\sigma}_i \cdot \vec{\sigma}_j \vec{\tau}_i \cdot \vec{\tau}_j$$

Nuclear transition matrix elements with SRC (II)

- Turn expectation values between correlated states Ψ into expectation values between uncorrelated states Φ

$$\langle \Psi \mid \widehat{\Omega} \mid \Psi \rangle = \frac{1}{\mathcal{N}} \langle \Phi \mid \widehat{\Omega}^{\text{eff}} \mid \Phi \rangle$$

- "Conservation Law of Misery": $\widehat{\Omega}^{\text{eff}}$ is an A-body operator

$$\widehat{\Omega}^{\text{eff}} = \widehat{\mathcal{G}}^{\dagger} \, \widehat{\Omega} \, \widehat{\mathcal{G}} = \left(\sum_{i<j=1}^{A} \left[1 - \hat{l}(i,j) \right] \right)^{\dagger} \widehat{\Omega} \left(\sum_{k<l=1}^{A} \left[1 - \hat{l}(k,l) \right] \right)$$

- Truncation procedure for short-distance phenomena

K. Wilson's OPE: $\Psi^{\dagger}(\vec{R} - \frac{\vec{r}}{2}) \Psi(\vec{R} + \frac{\vec{r}}{2}) \approx \sum_{n} c_n(\vec{r}) O_n(\vec{R}) \quad (\mid \vec{r} \mid \approx 0)$

Low-order correlation operator approximation (LCA)

- LCA: N-body operators receive SRC-induced $(N+1)$-body corrections

Norm $\mathcal{N} \equiv \langle \Phi \mid \widehat{\mathcal{G}}^{\dagger}\widehat{\mathcal{G}} \mid \Phi \rangle$: aggregated SRC effect

- LCA expansion of the norm $\mathcal{N}$

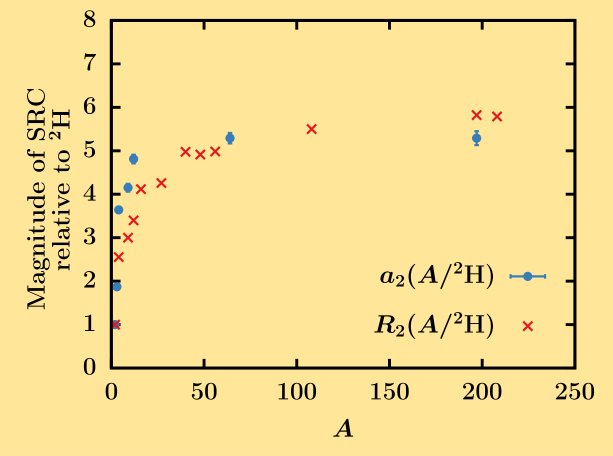
$$\mathcal{N} = 1 + \frac{2}{A} \sum_{\alpha<\beta} {}_{\text{nas}}\langle \alpha\beta \mid \hat{l}^{\dagger}(1,2) + \hat{l}^{\dagger}(1,2)\hat{l}(1,2) + \hat{l}(1,2) \mid \alpha\beta \rangle_{\text{nas}}.$$

  1. $\mid \alpha\beta \rangle_{\text{nas}}$: normalized and anti-symmetrized two-nucleon IPM-state
  2. $\sum_{\alpha<\beta}$ extends over all IPM states $\mid \alpha \rangle \equiv \mid n_\alpha l_\alpha j_\alpha m_{j_\alpha} t_\alpha \rangle$,
- $(\mathcal{N} - 1)$: measure for aggregated effect of SRC in g.s. of A
- Aggregated quantitative effect of SRC in A relative to ^{2}H

$$R_2(A/^2\text{H}) = \frac{\mathcal{N}(A) - 1}{\mathcal{N}(^2\text{H}) - 1} = \frac{\text{measure for SRC effect in } A}{\text{measure for SRC effect in } ^2\text{H}}.$$

- Input to the calculations for $R_2(A/^2\text{H})$
  1. HO IPM states with $\hbar\omega = 45A^{-1/3} - 25A^{-2/3}$
  2. A-independent universal correlation functions $[g_c(r), f_{t\tau}(r), f_{\sigma\tau}(r)]$

$a_2(A/^2\text{H})$ from $A(e,e')$ at $x_B \gtrsim 1.5$ and $R_2(A/^2\text{H})$



1. $A \lesssim 40$: strong mass dependence in SRC effect
2. $A > 40$: soft mass dependence
3. SRC effect saturates for A large *(for large A aggregated SRC effect per nucleon is about $5\times$ larger than in ^2H)*

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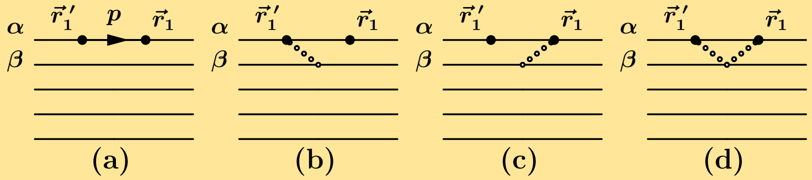
Single-nucleon momentum distribution $n^{[1]}(p)$

- Probability to find a nucleon with momentum p

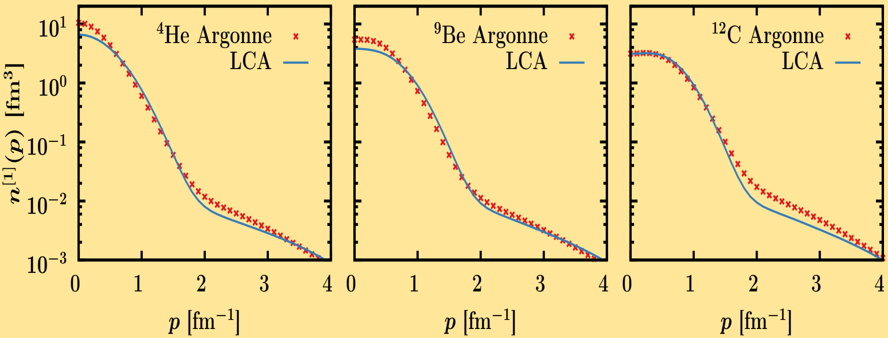
$$n^{[1]}(p) = \int \frac{d^2\Omega_p}{(2\pi)^3} \int d^3\vec{r}_1 \; d^3\vec{r}_1{}' \; d^{3(A-1)}\{\vec{r}_{2-A}\} e^{-i\vec{p}\cdot(\vec{r}_1{}' - \vec{r}_1)} \times \Psi^*(\vec{r}_1, \vec{r}_{2-A}) \Psi(\vec{r}_1{}', \vec{r}_{2-A}).$$

- SRC-induced corrections to IPM $n^{[1]}(p)$ are of two-body type
- Normalization property $\int dp\, p^2 n^{[1]}(p) = 1$ can be preserved



(a): IPM contribution **(b)-(d): SRC contributions in LCA**

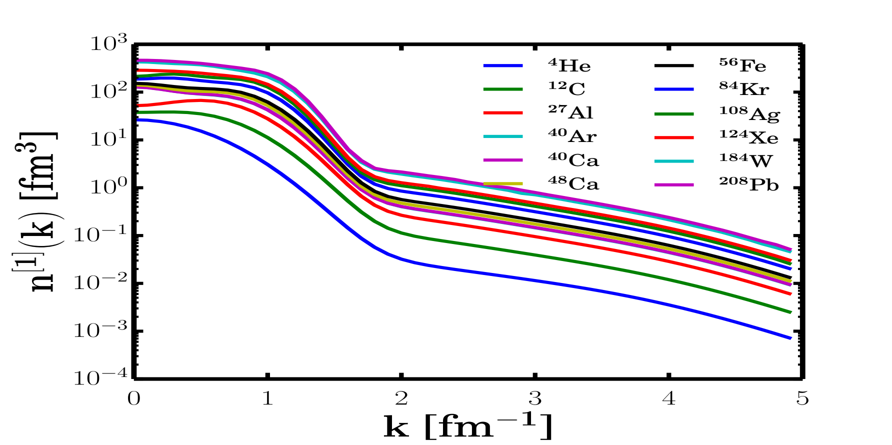
$n^{[1]}(p)$ for $A \leq 12$: LCA (Ghent) vs QMC (Argonne)



QMC: PRC89(2014)024305 LCA: JPG42(2015)055104

1. $p \lesssim p_F = 1.25\ \mathrm{fm}^{-1}$: $n^{[1]}(p)$ is "Gaussian" (IPM PART)
2. $p \gtrsim p_F$: $n^{[1]}(p)$ has an "exponential" fat tail (CORRELATED PART)
3. fat tail of $n^{[1]}(p)$ in QMC and LCA are comparable

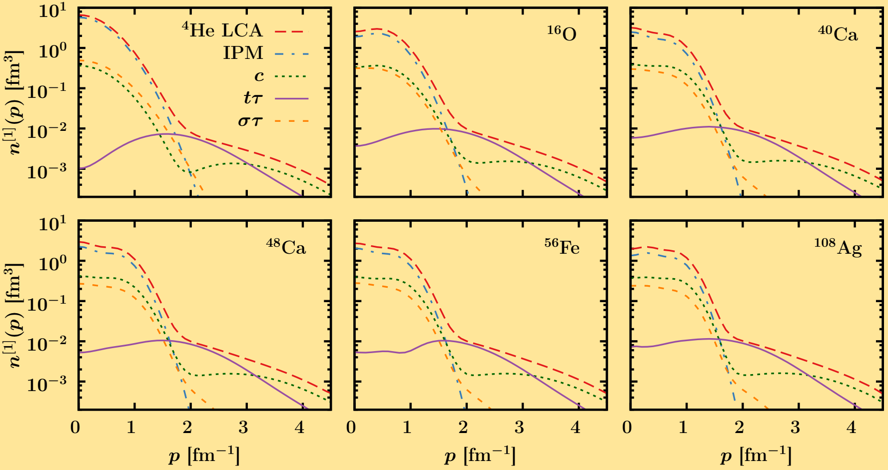
$n^{[1]}(k)$ in LCA: from light to heavy



LCA: JPG42(2015)055104

1. p dependence of the fat tail of $n^{[1]}(k)$, $k \gtrsim 2$ fm^{-1} is "universal" (induced by SRC 2N correlations)

Major source of correlated strength in $n^{[1]}(p)$?



1. $1.5 \lesssim p \lesssim 3$ fm^{-1} is dominated by tensor correlations
2. central correlations substantial at $p \gtrsim 3.5$ fm^{-1}

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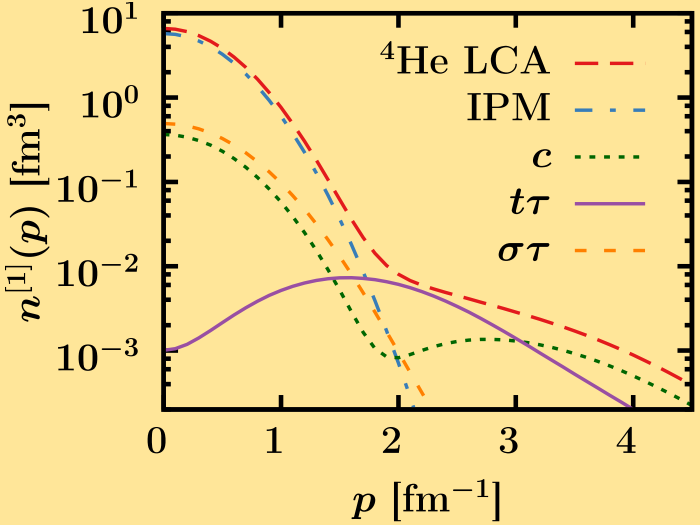

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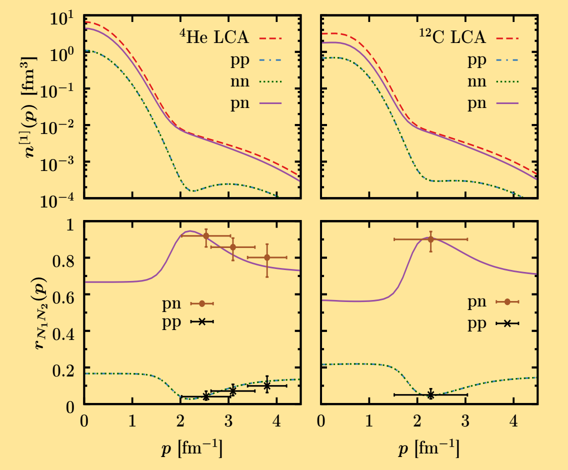
Isospin dependence of SRC: pp, nn and pn

$r_{N_1N_2}(p)$: relative contribution of (N_1N_2) pairs to $n^{[1]}(p)$



- Naive IPM:

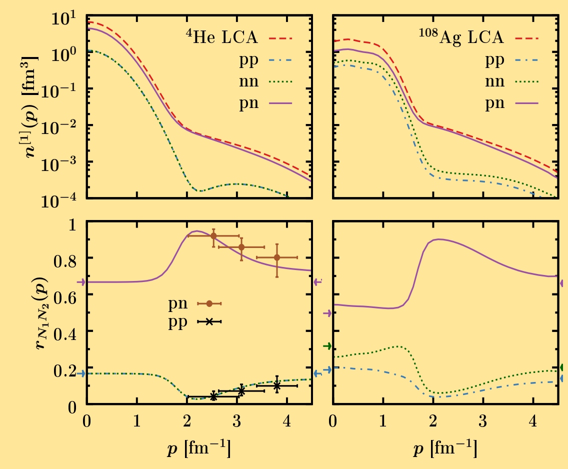
$$r_{pp} = \frac{Z(Z-1)}{A(A-1)},$$
$$r_{nn} = \frac{N(N-1)}{A(A-1)},$$
$$r_{pn} = \frac{2NZ}{A(A-1)}.$$

- Data extracted from ^{4}He$(e,e'pp)/(e,e'pn)$ (PRL 113, 022501) and $\frac{^{12}\text{C}(p,ppn)}{^{12}\text{C}(p,pp)}$ (Science 320, 1476) assuming that $r_{pp} \approx r_{nn}$

The fat tail is dominated by "pn" (momentum dependent)

Isospin dependence of SRC: pp, nn and pn

$r_{N_1N_2}(p)$: relative contribution of (N_1N_2) pairs to $n^{[1]}(p)$



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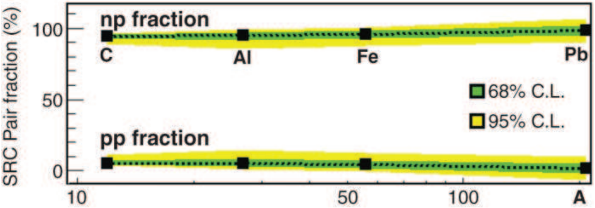
The fat tail is dominated by "pn" (momentum dependent)

Imbalanced strongly interacting Fermi systems

Sciencexpress

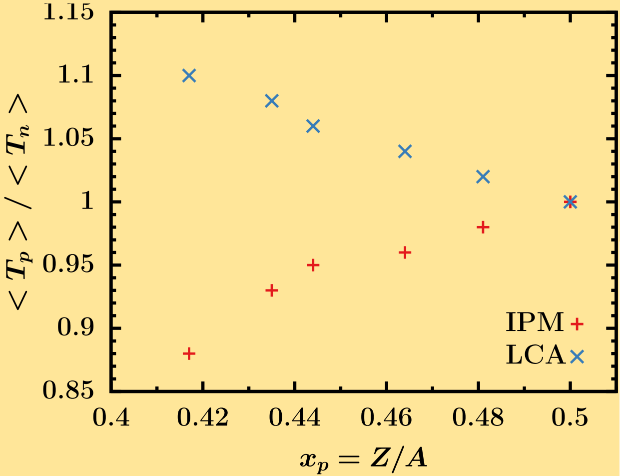
Momentum sharing in imbalanced Fermi systems

O. Hen,[1*] M. Sargsian,[2] L. B. Weinstein,[3] E. Piasetzky,[1] H. Hakobyan,[4,5] D. W. Higinbotham,[6] M

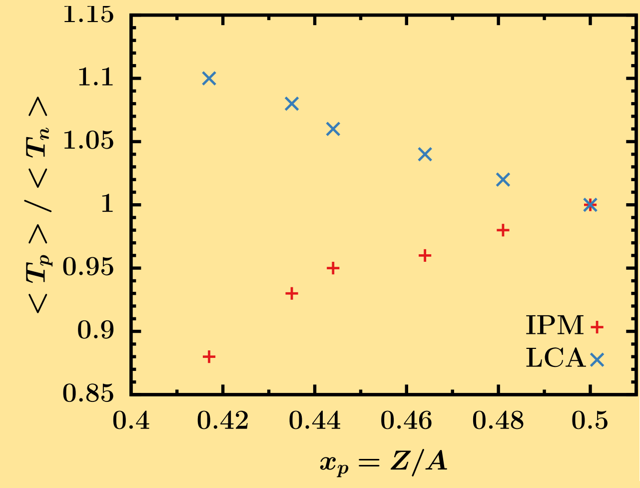


LCA predicts that $\approx$90% of correlated pairs is "pn", and $\approx$5% is "pp" (UNIVERSAL: A independent)

Predictions for $\langle T_p \rangle$ / $\langle T_n \rangle$ ratio



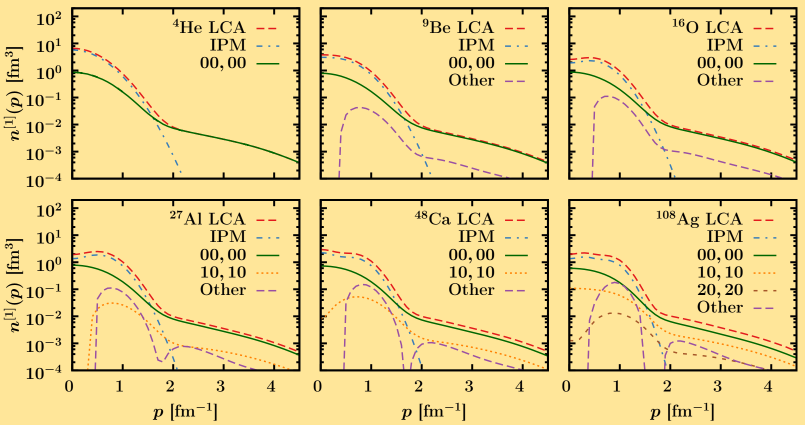
Predictions for $\langle T_p \rangle \,/\, \langle T_n \rangle$ ratio



SRC turn the IPM predictions upside down (minority component has largest kinetic energy ; dependent on $x_p = Z/A$

Quantum numbers of SRC-susceptible IPM pairs?

$n^{[1],\mathrm{corr}}$ stems from correlation operators acting on IPM pairs. What are relative quantum numbers (nl) of those IPM pairs?



$$\sum_{nl}\sum_{n'l'} n^{[1],\mathrm{corr}}_{nl,n'l'}(p) = n^{[1],\mathrm{corr}}(p)$$

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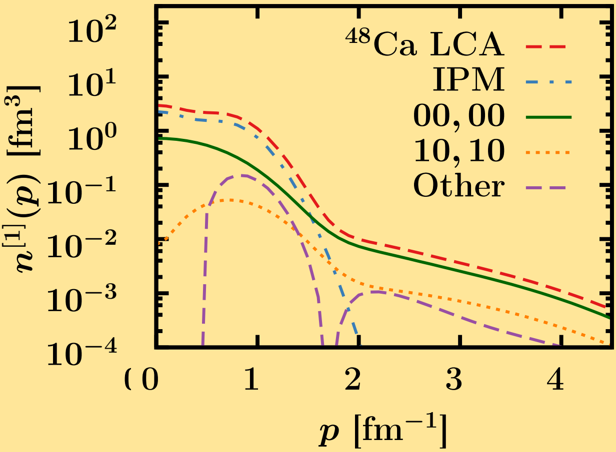
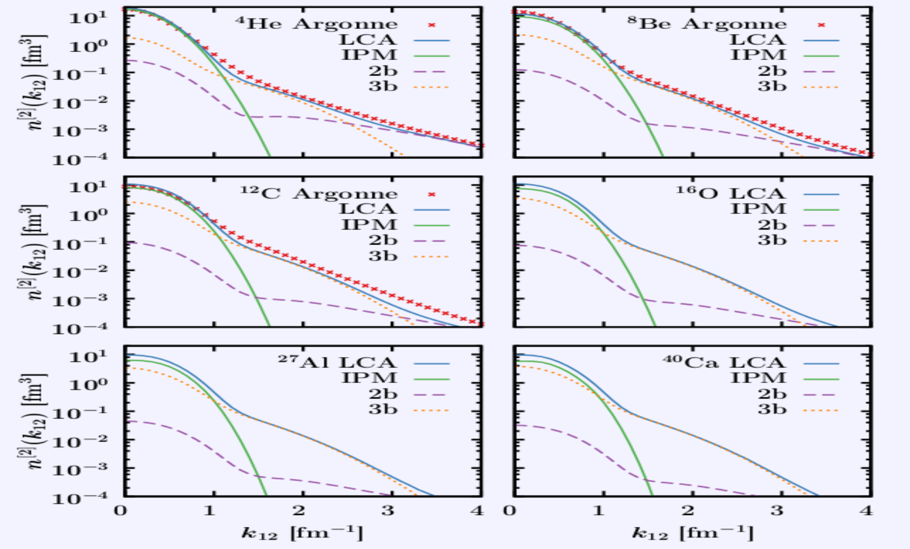


Major source of SRC: correlations acting on ($n = 0$ $l = 0$) IPM pairs

Relative two-nucleon momentum distribution in LCA: tail is dominated by "3-body" SRC effects



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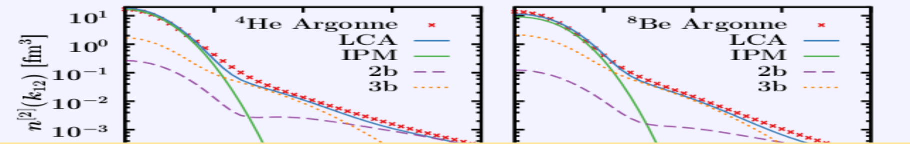
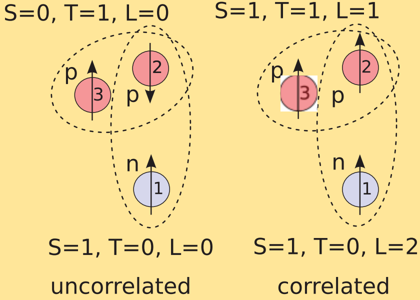


Correlations through the mediation of a third particle:



Feldmeier *et al.*, PRC 84 (2011), 054003

Nucleon knockout data and nuclear models (I)

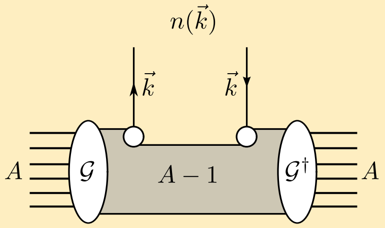
The quasi-free one-nucleon knockout case

- Link between $A(e,e'N)$ cross section and single-nucleon spectral function can be derived

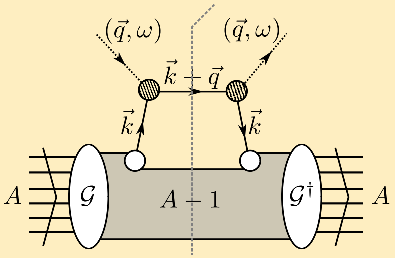
$$\frac{d^5\sigma}{d\epsilon' d\Omega_{\epsilon'} d\Omega_N dE_N}(e,e'N) = K\sigma_{eN} S(E_m, p_m)$$

- Factorization is approximate: relativity, final state interactions, spin effects, ...

NUCLEAR STRUCTURE



$A(e,e'p)$ OBSERVABLES

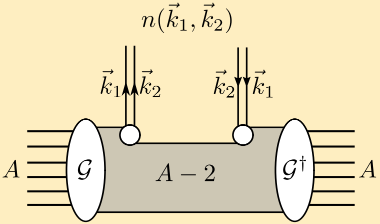


Nucleon knockout data and nuclear models (II)

The quasi-free two-nucleon knockout case

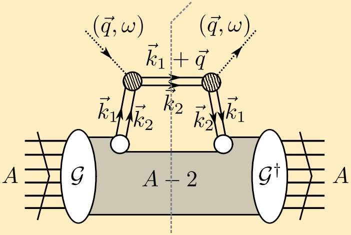
- Connection between SRC driven $A(e, e'NN)$ observables and high-momentum part of two-nucleon momentum distribution?

NUCLEAR STRUCTURE



Two-nucleon momentum distribution

$A(e, e'NN)$ OBSERVABLES

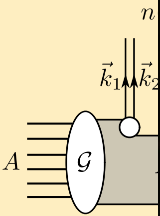


Measurements with specific kinematic cuts

The quasi-free two-nucleon knockout case

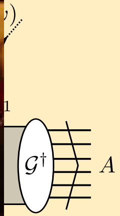
- Connection between SRC driven *A*(*e*, *e*′*NN*) observables and high-momentum part of two-nucleon momentum distribution?

NUCLEAR STRUCTURE



Two-nucleo distribution

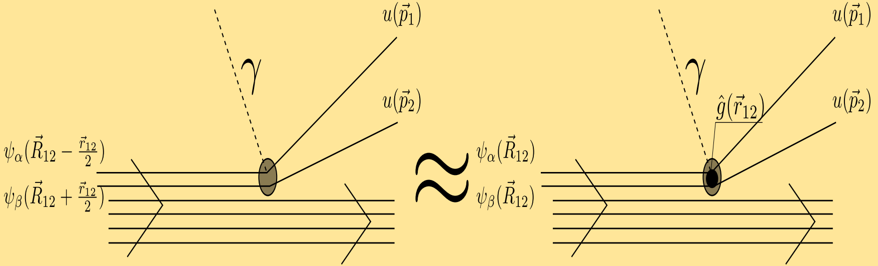
A(*e*, *e*′*NN*) OBSERVABLES



th specific

Exclusive SRC-driven $A(e, e'NN)$ (I)

- SRC-prone IPM pairs: close-proximity $(n_{12} = 0, l_{12} = 0)$ state
- The EXCLUSIVE $A(e, e'NN)$ cross sections can be factorized [PLB383,1 ; PRC89,024603 ; PRC96,034608]



ZRA: Zero-range approximation

Exclusive SRC-driven $A(e,e'NN)$ (II)

1. **$A(e,e'NN)$ cross section factorizes according to**

$$\frac{d^8\sigma}{d\epsilon' d\Omega_{\epsilon'} d\Omega_1 d\Omega_2 dT_{p_2}}(e,e'NN) = K\sigma_{eNN}(k_+,k_-,q)F^{(D)}(P)$$

$F^{(D)}(P)$: FSI corrected conditional probability to find a dinucleon with c.m. momentum P in a relative $(n_{12}=0, l_{12}=0)$ state

2. ***A* dependence of the $A(e,e'pp)$ cross sections is soft**

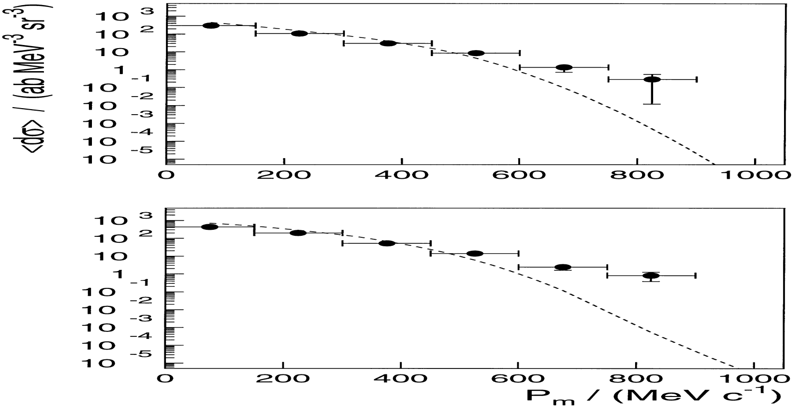
(much softer than predicted by naive $Z(Z-1)$ counting)

$$\frac{A(e,e'pp)}{{}^{12}\mathrm{C}(e,e'pp)} \approx \frac{N_{pp}(A)}{N_{pp}\left({}^{12}\mathrm{C}\right)} \times \left(\frac{T_A(e,e'p)}{T_{{}^{12}\mathrm{C}}(e,e'p)}\right)^{1-2}$$

3. **C.m. width of SRC susceptible pairs is “large” (in p-space)**

Factorization of the $A(e, e'pp)$ cross sections

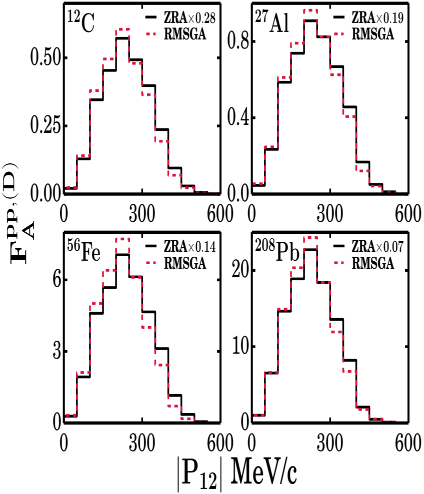
$^{12}C(e, e'pp)$ @ MAMI (Mainz) (Physics Letters B **421** (1998) 71.)

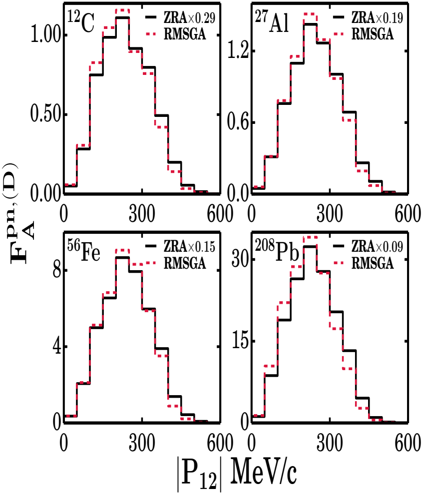


For P $\lesssim$ 0.5 GeV c.m. motion of correlated pairs in ^{12}C is mean-field like $\left(\exp \frac{-P^2}{2\sigma^2_{c.m}}\right)$! Data prove the proposed factorization in terms of $F^{(D)}(P)$.

Effect of FSI on factorization of $A(e,e'pN)$ c.s.?

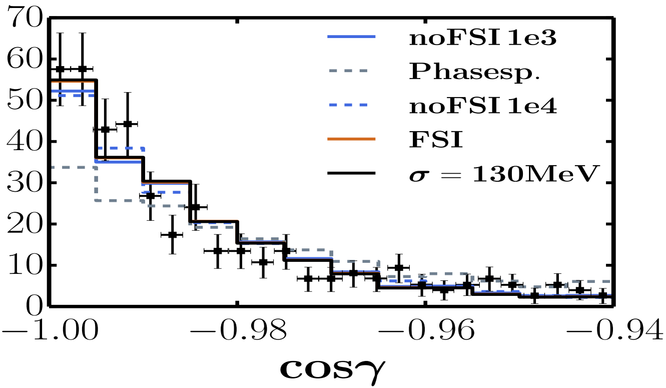
A(e, e′pp) **A(e, e′pn)**





$A(e, e'NN)$: Effect of the final-state interactions?

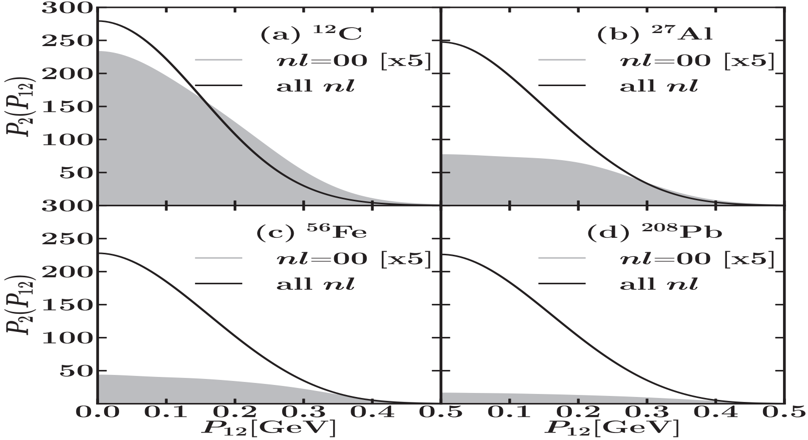
Opening-angle distribution of ^{4}He$(e, e'pp)$



1. FSI (eikonal model) reduces the cross sections
2. FSI marginally affects the angular distributions
   (FSI preserves factorization properties)

C.m. motion of correlated pp pairs

PHYSICAL REVIEW C **89**, 024603 (2014)



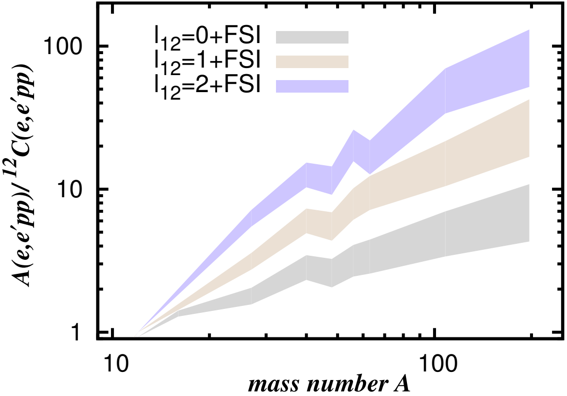
Width of c.m. distribution is a lever to discriminate between SRC-prone and other IPM pairs (Erez Cohen's talk)

Mass dependence of the $A(e,e'pp)$ cross sections

PREDICTION: A dependence of $A(e,e'pp)$ c.s. is soft

(much softer than predicted by naive $Z(Z-1)$ counting)

$$\frac{A(e,e'pp)}{{}^{12}\mathrm{C}(e,e'pp)} \approx \frac{N_{pp}(A)}{N_{pp}\left({}^{12}\mathrm{C}\right)} \times \left(\frac{T_A(e,e'p)}{T_{{}^{12}\mathrm{C}}(e,e'p)}\right)^{1-2}$$



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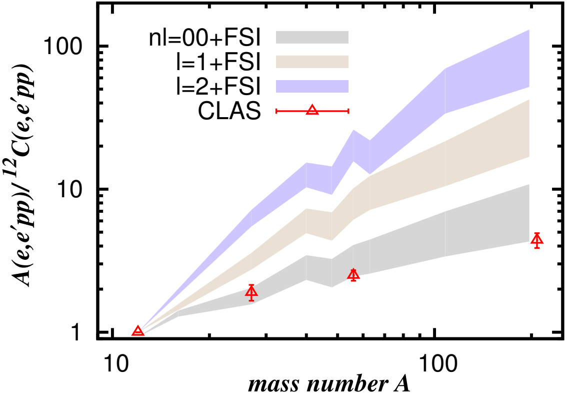
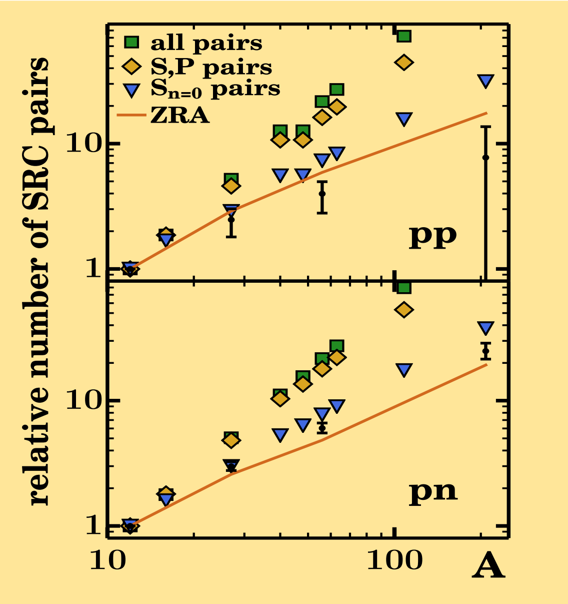


Data compatible with absorption on SRC-prone ($n_{12} = 0, l_{12} = 0$) IPM pairs

PRC92, 024604 (2015)

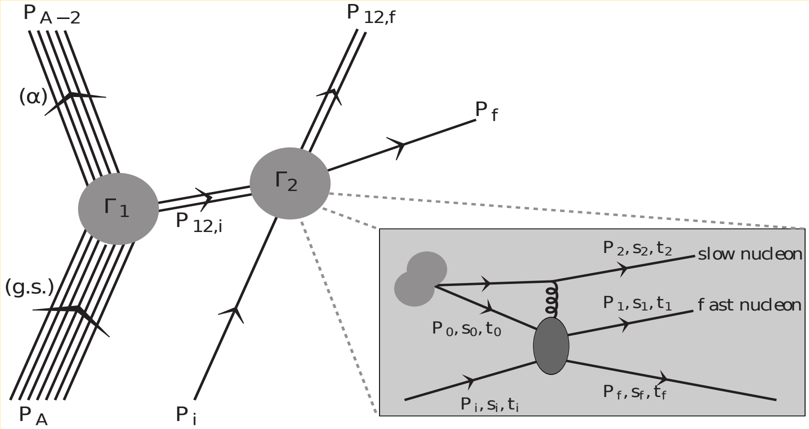
A dependence of number of pp and pn SRC pairs



- Analysis of $A(e,e'pp)$ and $A(e,e'p)$ (A=^{12}C, ^{27}Al, ^{56}Fe, ^{208}Pb) in “SRC” kinematics (Data Mining Collaboration @JLAB)
- FSI corrections applied to the data
- Reaction-model calculations in the large phase space: importance sampling
- Relative number of SRC pp-pairs and pn-pairs

$p(A, pNN\ A-2)$ with radioactive beams

SRC in neutron-rich matter? Success of program hinges on existence of a proper factorization expression for cross section.



Thomas Aumann's talk

CONCLUSIONS (I)

- **Nuclear SRC can be captured by general and rather robust principles applicable to NMDs (models) and to 2N knockout**
- **LCA: efficient and realistic way of computing the SRC contributions to NMDs**
  1. **Magnitude of EMC effect and $A(e,e')/D(e,e')$ scaling factor ($x_B \gtrsim 1.5$) can be predicted in LCA**
  2. $A \leq 12$: **LCA predictions for fat tails are in line with those of QMC**
  3. **LCA predictions for $\langle T_N \rangle$ and radii are "realistic" (consistency checks)**
  4. **Natural explanation for the universal behavior of the NMD tails**
- **MAJOR contribution to SRC strength: correlation operators acting on IPM pairs in a nodeless relative S state**

CONCLUSIONS (II)

- Insights from study of SRC contribution to NMD has implications for SRC-driven $A(e, e'NN)A-2$ and $p(A, pNN\ A-2)$
  1. Scaling behavior of cross section ($\sim F(P)$) **(CONFIRMED!)**
  2. Very soft mass dependence of cross section **(CONFIRMED!)**
  3. Peculiar c.m. width of the SRC-susceptible pairs **(CONFIRMED!)**
- Generally applicable techniques for quantifying SRC: two-body effects in neutrino reactions, role of SRC in exotic forms of hadronic matter, ...
- **SRC induced spatio-temporal fluctuations are measurable, are significant and are quantifiable**


THANK YOU!

Selected publications

- C. Colle, W. Cosyn, J. Ryckebusch
  "Final-state interactions in two-nucleon knockout reactions"
  arXiv:1512.07841 and PRC **93** (2016) 034608.
- J. Ryckebusch, M. Vanhalst, W. Cosyn
  "Stylized features of single-nucleon momentum distributions"
  arXiv:1405.3814 and Journal of Physics G **42** (2015) 055104.
- C. Colle, O. Hen, W. Cosyn, I. Korover, E. Piasetzky, J. Ryckebusch, L.B. Weinstein
  "Extracting the Mass Dependence and Quantum Numbers of Short-Range Correlated Pairs from $A(e,e'p)$ and $A(e,e'pp)$ Scattering" arXiv:1503.06050 and PRC **92** (2015), 024604.
- C. Colle, W. Cosyn, J. Ryckebusch, M. Vanhalst
  "Factorization of electroinduced two-nucleon knockout reactions"
  arXiv:1311.1980 and PRC **89** (2014), 024603.
- Maarten Vanhalst, Jan Ryckebusch, Wim Cosyn
  "Quantifying short-range correlations in nuclei"
  arXiv:1206.5151 and PRC **86** (2012), 044619.