Beyond quasi-elastic: $A(e,e')$, $A(e,e'p)$, $A(e,e'pN)$ and $A\nu$ experiments – role of Short-Range Correlations

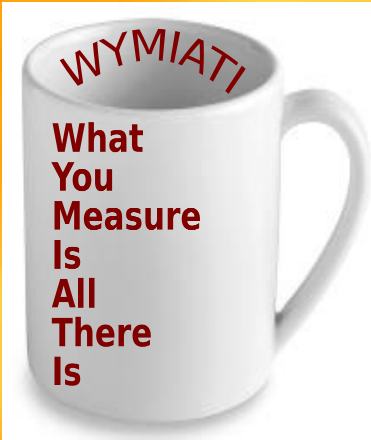
Jan Ryckebusch, Wim Cosyn

NuSTEC Workshop, March 2022

PLB792 (2019) 21 & PRC100 (2019) 054620 & PLB820 (2021) 136526

Central research questions of this presentation

- **Is there a comprehensive picture of nuclear SRC? *(Quest to learn about stylized facts of SRC)***
  1. Variation with mass A
  2. Isospin (flavor) composition of SRC (pp&nn&pn)
  3. Neutron-to-proton asymmetry (N/Z) dependence of SRC
- **How to forge links between nuclear models dealing with SRC and observables? Recent data from electron-nucleus scattering ($A(e,e'), A(e,e'N), A(e,e'pX)$)**
- **Model for appearance of SRC in $\vec{r}$ and $\vec{p}$ space? Nuclear Wigner distributions that include SRC?**

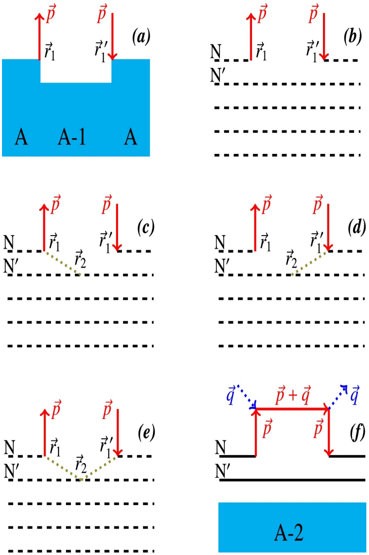


After WYSIATI ("What You See Is All There Is") D. Kahneman, *"Thinking, Fast and Slow"* (2012).

OUTLINE

1. Low-order correlation operator approximation (LCA) to compute effect of SRC (nuclear structure & nuclear reactions)
2. Apply LCA to the computation of nuclear momentum distributions (NMDs) for 15 $A(N,Z): 4 \leq A \leq 208\ ;\ 1 \leq \frac{N}{Z} \leq 1.54$
   CHECK: Compare LCA results to ab-initio ones
3. Aggegrated effect of SRC and its evolution with A and N/Z
   CHECK: a_2 data from $A(e,e')$
4. Isospin composition of SRC (pp&nn&pn)
   CHECK: $A(e,e'pp), A(e,e'pn), A(e,e'p)$ data for ^{12}C, ^{27}Al, ^{56}Fe, ^{208}Pb in "SRC" kinematics
5. N/Z asymmetry dependence of SRC
   CHECK: $A(e,e'pp), A(e,e'pn), A(e,e'p), A(e,e'n)$ data for ^{12}C, ^{27}Al, ^{56}Fe, ^{208}Pb in "SRC" kinematics
6. Nuclear Wigner distributions including SRC

Single-nucleon momentum distributions in LCA



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

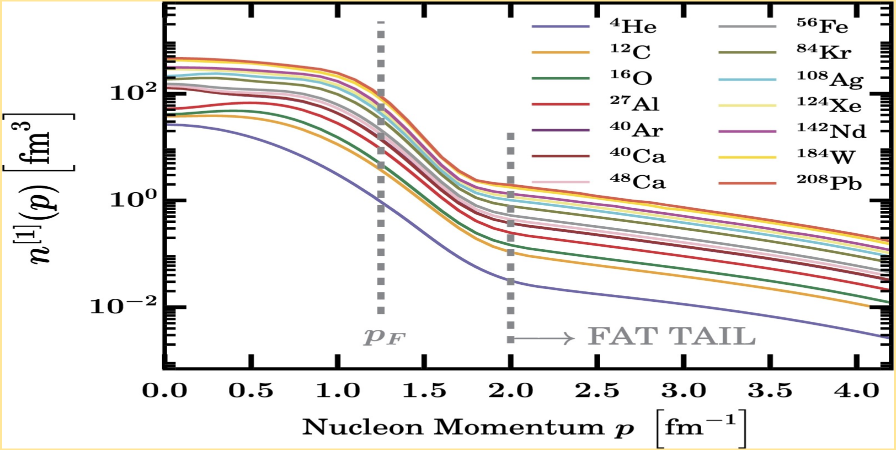
$$n^{[1]}(p) = \frac{A}{(2\pi)^3} \int d^2\Omega_p \int d^3\vec{r}_1 \; d^3\vec{r}_1{}' \; d^{3(A-1)}\{\vec{r}_{2-A}\} \times e^{-i\vec{p}\cdot(\vec{r}_1{}'-\vec{r}_1)} \; \Psi^*(\vec{r}_1, \vec{r}_{2-A})\Psi(\vec{r}_1{}', \vec{r}_{2-A})$$

- Universal correlation operators

$$|\Psi\rangle = \widehat{\mathcal{G}}\,|\Phi\rangle \,/ \sqrt{\langle\Phi|\,\widehat{\mathcal{G}}^\dagger\widehat{\mathcal{G}}\,|\Phi\rangle}\;,$$

- $\mathcal{G}$: Central $g_C(r)$, spin-isospin $f_{\sigma\tau}(r)$, tensor $f_{t\tau}(r)$ correlations
- Truncation at $\mathcal{O}\left(\mathcal{G}^2\right)$: SRC part of $n^{[1]}(p)$ = 2-body contributions
- Quantify the *pp*, *nn*, *pn* and *np* contribution to $n^{[1]}(p)$

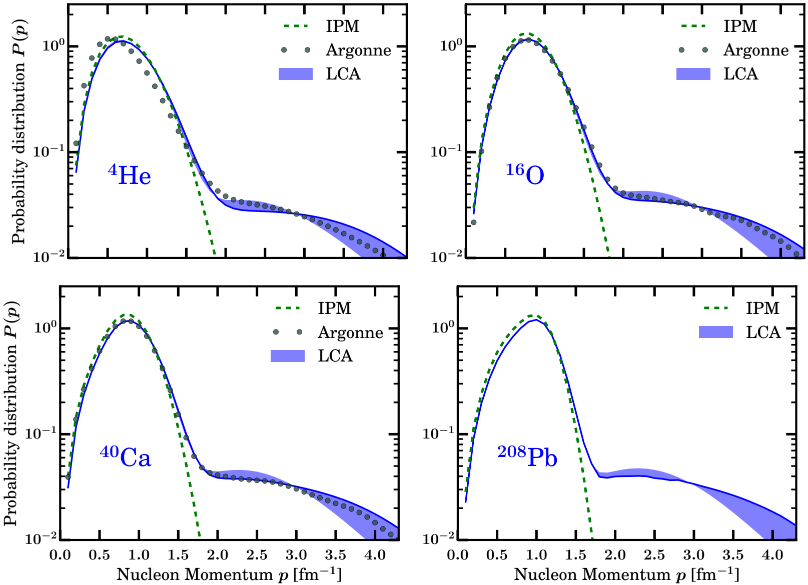
$n^{[1]}(p)$ in LCA: from light to heavy nuclei



LCA: JPG42('15)055104 & PLB792('19)21 & PRC100 ('19)054620

1. Two distinct momentum regimes ("IPM" and "SRC")
2. Momentum dependence of fat tail of $n^{[1]}$ is "universal"

Probability distribution $P(p) \sim p^2 n^{[1]}(p)$



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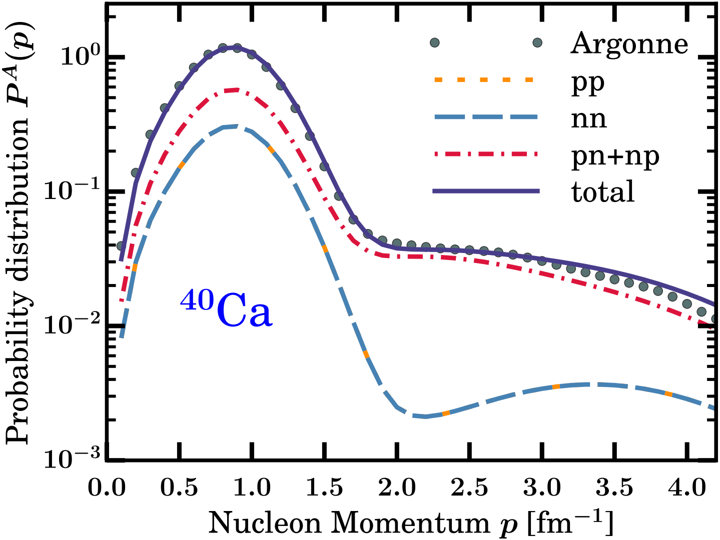

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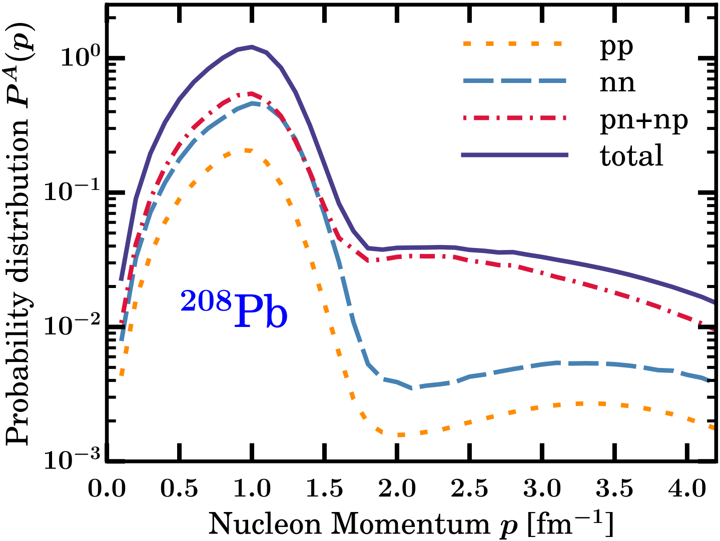
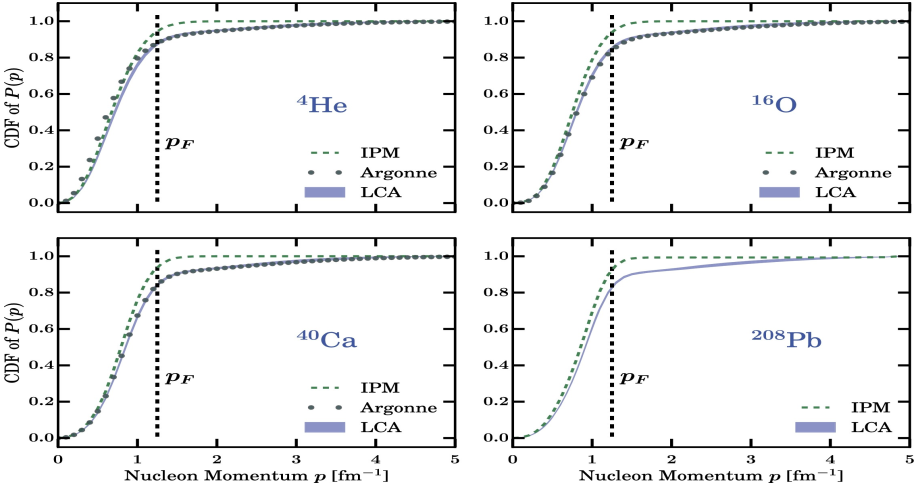


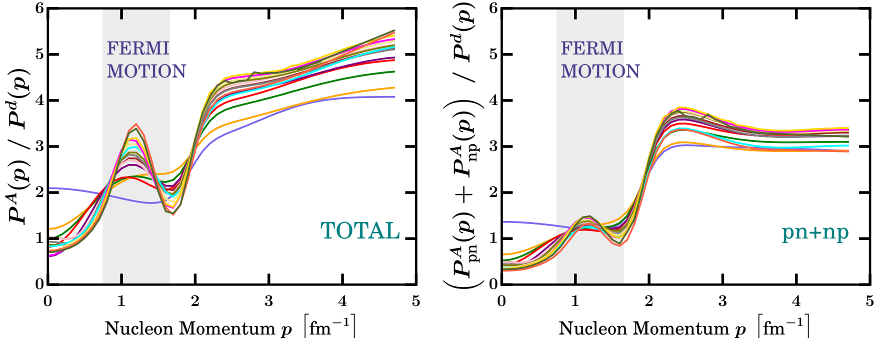
Cumulative momentum distributions



1. Reduction of quasi-elastic $(e, e'N)$ at low (E_m, p_m)
2. Background of $(e, e'NN)$ events at high (E_m, p_m)

Ratios of probability distributions: $P^A(p)/P^d(p)$

$$P^A(p) = \underbrace{P^A_{\mathrm{pp}}(p) + P^A_{\mathrm{pn}}(p)}_{P^A_{\mathrm{p}}(p)\ \text{(proton part)}} + \underbrace{P^A_{\mathrm{nn}}(p) + P^A_{\mathrm{np}}(p)}_{P^A_{\mathrm{n}}(p)\ \text{(neutron part)}} \ .$$



N=Z: ^{4}He, ^{12}C, ^{16}O, ^{40}Ca

N≠Z: ^{9}Be, ^{27}Al, ^{40}Ar, ^{48}Ca, ^{56}Fe, ^{63}Cu, ^{84}Kr, ^{108}Ag, ^{124}Xe, ^{197}Au, ^{208}Pb

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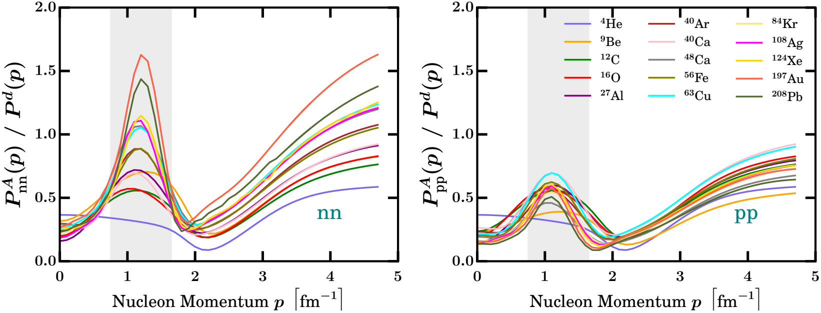
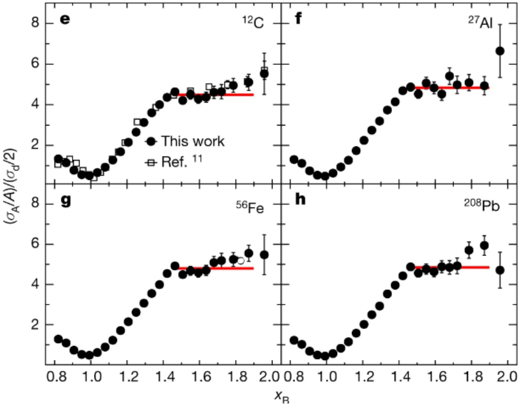


N=Z: ^{4}He, ^{12}C, ^{16}O, ^{40}Ca

N$\neq$Z: ^{9}Be, ^{27}Al, ^{40}Ar, ^{48}Ca, ^{56}Fe, ^{63}Cu, ^{84}Kr, ^{108}Ag, ^{124}Xe, ^{197}Au, ^{208}Pb

Measurable signal of the *A*-to-*d* scaling of the momentum distributions?



In selected kinematics the A-to-d (e, e') cross sections approximately scale!

SRC SCALING FACTORS

THEORY:

$$a_2(A) = \frac{\int_{p>2\ \mathrm{fm}^{-1}} dp P^A(p)}{\int_{p>2\ \mathrm{fm}^{-1}} dp P^d(p)}$$

EXPERIMENT:

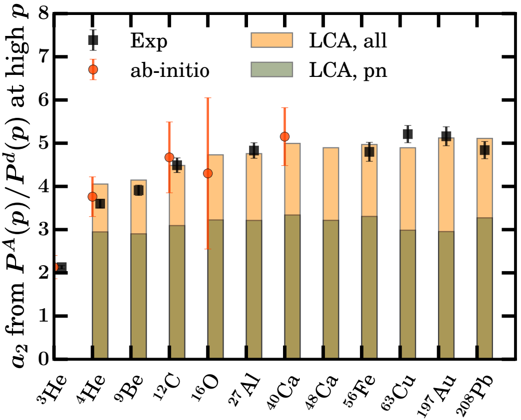
$$a_2^{exp}(A) = \frac{2}{A} \frac{\sigma^A(e,e')}{\sigma^d(e,e')}$$

$$\left(1.5 \lesssim x \lesssim 1.9\ ;\ Q^2 \approx 2\ \mathrm{GeV}^2\right)$$

Aggregated impact of SRC on a nucleon in $A(N,Z)$ relative to the deuteron!

Aggregated quantitative effect of SRC in A relative to d

$$a_2(A) = \frac{\int_{p>2\ \mathrm{fm}^{-1}} dp P^A(p)}{\int_{p>2\ \mathrm{fm}^{-1}} dp P^d(p)} \; ; \; a_2^{exp}(A) = \frac{2}{A}\frac{\sigma^A(e,e')}{\sigma^d(e,e')} \quad \left(1.5 \lesssim x \lesssim 1.9 \; ; \; Q^2 \approx 2\ \mathrm{GeV}^2\right)$$

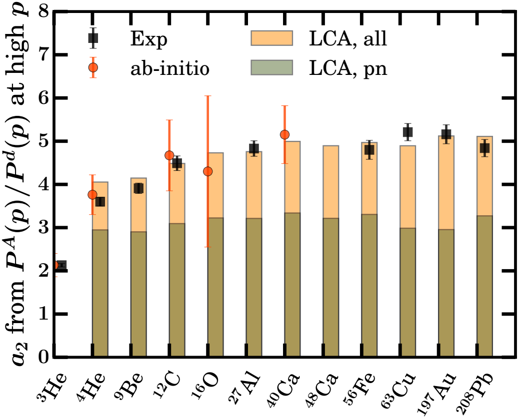


DATA: N. Fomin *et al.*, PRL108(2012) ; B. Schmookler *et al.*, Nature566(2019) ; J.E. Lynn *et al.*, JPG47 (2020)

1. $A \lesssim 27$: soft A dependence
2. $A \gtrsim 27$: SATURATION
3. $a_2\left({}^{40}\mathrm{Ca}\right) = 4.99$; $a_2\left({}^{48}\mathrm{Ca}\right) = 4.89$
   ratio$\left({}^{48}\mathrm{Ca}/{}^{40}\mathrm{Ca}\right)$:
   - LCA: 0.98
   - Expt: 0.971 ± 0.012
   (D. Nguyen *et al.*, PRC102(2020))

Aggregated quantitative effect of SRC in A relative to d

$$a_2(A) = \frac{\int_{p>2\ \mathrm{fm}^{-1}} dp P^A(p)}{\int_{p>2\ \mathrm{fm}^{-1}} dp P^d(p)} \; ; \; a_2^{exp}(A) = \frac{2}{A}\frac{\sigma^A(e,e')}{\sigma^d(e,e')} \qquad \left(1.5 \lesssim x \lesssim 1.9\, ;\; Q^2 \approx 2\ \mathrm{GeV}^2\right)$$



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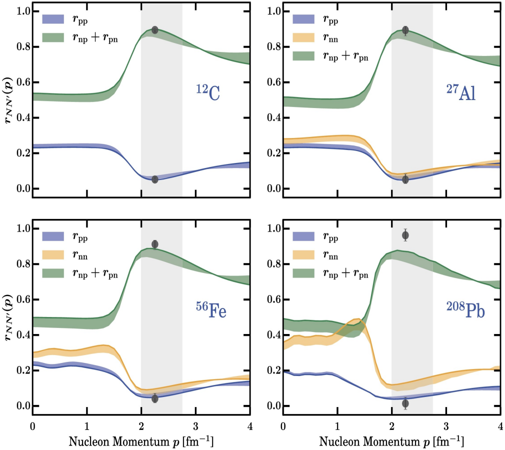
Nuclear momentum distribution: pair composition

Pair composition: $n^{[1]}(p) \equiv \underbrace{n^{[1]}_{pp}(p) + n^{[1]}_{pn}(p)}_{n^{[1]}_{p}(p) \text{ (proton part)}} + \underbrace{n^{[1]}_{nn}(p) + n^{[1]}_{np}(p)}_{n^{[1]}_{n}(p) \text{ (neutron part)}}$



DATA: O. Hen *et al.*, Science346(2014)

-SRC pair fractions

$$r_{pp}(p) = \frac{n^{[1]}_{pp}(p)}{n^{[1]}(p)}$$

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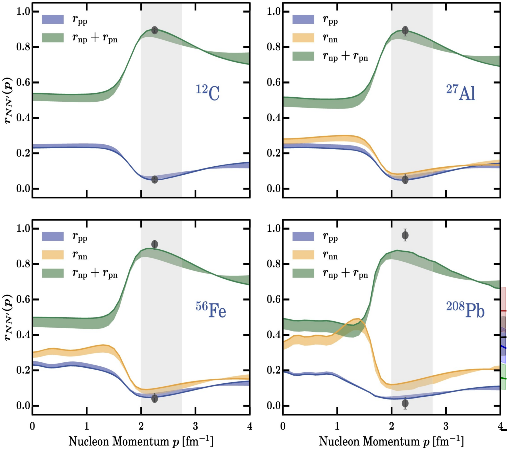

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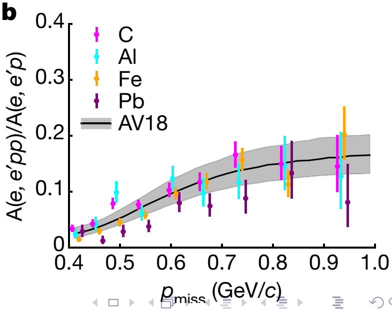
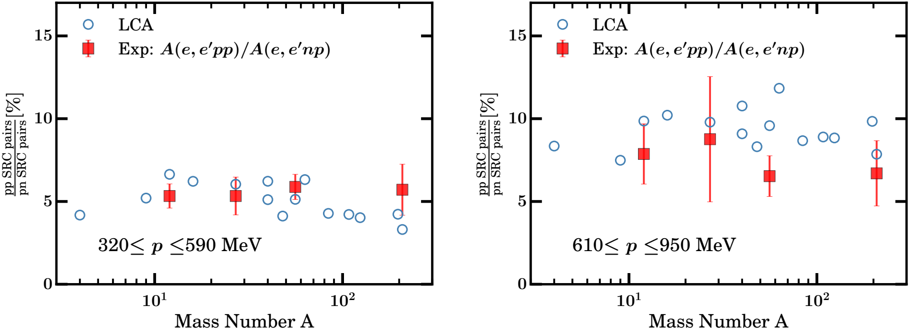


DATA: O. Hen *et al.*, Science346(2014) ; A. Schmidt *et al.*, Nature (2020)

Pair composition of SRC: LCA versus experiment



LCA: Ratios from computed $n^{[1]}(p)$ for 15 nuclei

$$\frac{\int_{p_l}^{p_h} dp\, p^2\, n^{[1]}_{\text{pp}}(p)}{\int_{p_l}^{p_h} dp\, p^2 \left[n^{[1]}_{\text{pn}}(p) + n^{[1]}_{\text{np}}(p) \right]}$$

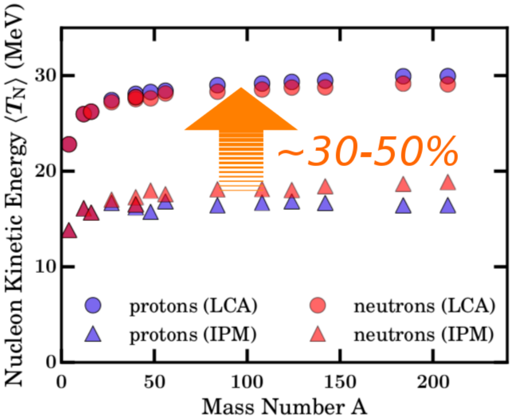
M. Duer *et al.*, PRL122(2019): Ratios from measured

$$\left. \frac{\sigma_{en}}{2\sigma_{ep}} \frac{A(e,e'pp)}{A(e,e'pn)} \right|_{p_l \leq p_m \leq p_h}$$

for A= ^{12}C, ^{27}Al, ^{56}Fe, ^{208}Pb

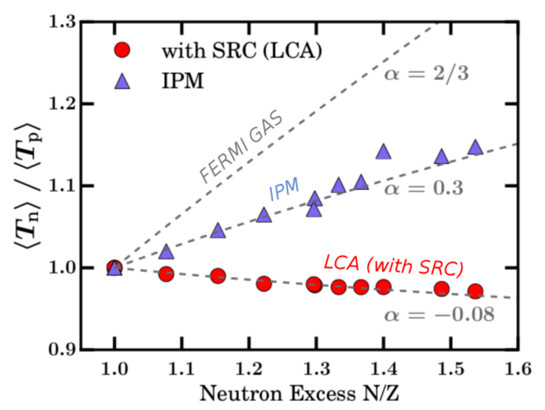
Fourth moment of $n^{[1]}(p)$ from LCA

Fourth moment of $n^{[1]}(p)$: $\langle T_{\rm p} \rangle = \frac{1}{2M_p} \frac{\int_0^\Lambda dp\, p^4 \left[n_{\rm pp}^{[1]}(p) + n_{\rm pn}^{[1]}(p) \right]}{\int_0^\Lambda dp\, p^2 \left[n_{\rm pp}^{[1]}(p) + n_{\rm pn}^{[1]}(p) \right]}$



SRC induce inversion of kinetic energy sharing in neutron-rich nuclei

Ratio $\langle T_n = p_n^2/(2M_n)\rangle \,/\, \langle T_p = p_p^2/(2M_p)\rangle$ from computed $n^{[1]}(p)$



After correcting for SRC in LCA, minority component has largest kinetic energy (strongly depends on **N**/**Z**)

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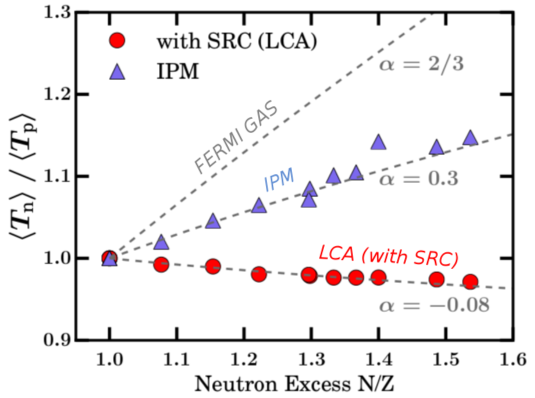
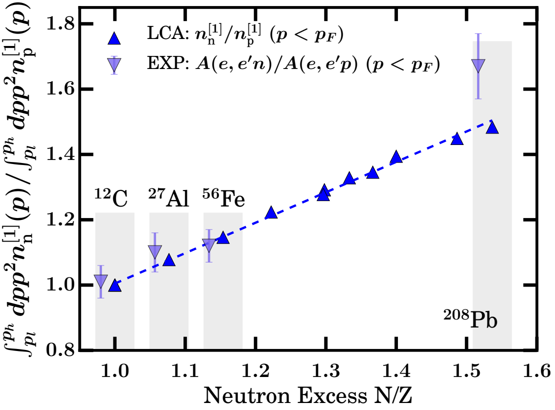


After correcting for SRC in LCA, minority component has largest kinetic energy (strongly depends on **N**/**Z**)

Weight of neutrons relative to protons in $n^{[1]}(p)$

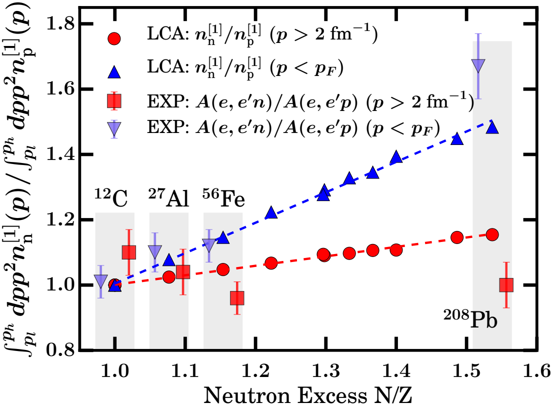
$$\text{IPM:} \frac{\int_0^{p_F} dp p^2 n_{\mathrm{n}}^{[1]}(p)}{\int_0^{p_F} dp p^2 n_{\mathrm{p}}^{[1]}(p)} .$$



- DATA: M. Duer *et al.*, Nature 560 (2018) 617
-

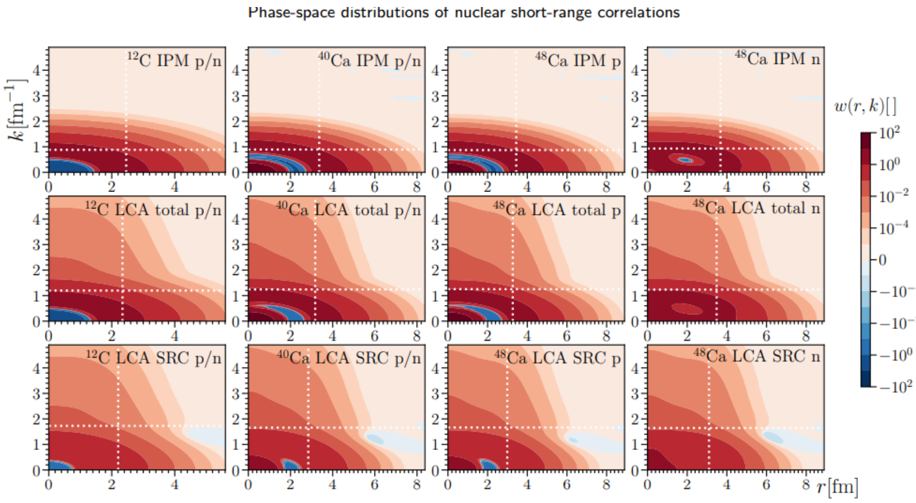
Weight of neutrons relative to protons in $n^{[1]}(p)$

$$\text{IPM:}\ \frac{\int_0^{p_F} dp p^2 n^{[1]}_{\text{n}}(p)}{\int_0^{p_F} dp p^2 n^{[1]}_{\text{p}}(p)}\,. \qquad \text{SRC}:\ \frac{\int_{0.4\text{ GeV}}^{1\text{ GeV}} dp p^2 n^{[1]}_{\text{n}}(p)}{\int_{0.4\text{ GeV}}^{1\text{ GeV}} dp p^2 n^{[1]}_{\text{p}}(p)}\,.$$



- DATA: M. Duer *et al.*, Nature 560 (2018) 617
- Relative weight of the protons and neutrons is very different in "IPM" and "SRC" regions!
  1. IPM: $0.93\frac{N}{Z} + 0.07$
  2. SRC: $0.29\frac{N}{Z} + 0.71$

Nuclear Wigner distributions $W(r, k)$ including SRC



SRCs reduce the neutron skin in $N \neq Z$ nuclei by about 5-10%

SUMMARY

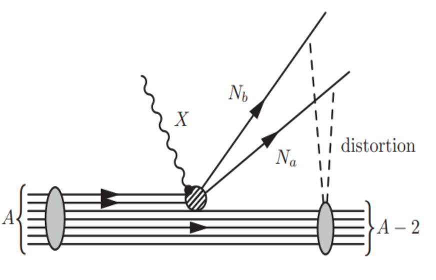
- **SRC induced spatio-temporal fluctuations in nuclei are measurable, are significant and are quantifiable**
- **LCA: suited for systematic studies of SRC contributions to $n^{[1]}(p)$ and SRC-sensitive reactions**
  1. **Reasonable predictions for a_2 factors**
  2. $A \leq 40$: **LCA predictions for fat tails in line with QMC ones**
  3. **Natural explanation for the "universal" behavior of the fat tails of NMD**
- **Distinct isospin and N/Z SRC effects: in line with $A(e, e'pN)$ findings**
- **LCA: put the nuclear structure and nuclear reaction theory on the same footing (absolute cross sections)**

LCA for modeling two-nucleon knockout

PHYSICAL REVIEW C **94**, 024611 (2016)

Influence of short-range correlations in neutrino-nucleus scattering

T. Van Cuyck,[1,*] N. Jachowicz,[1,†] R. González-Jiménez,[1] M. Martini,[1,2] V. Pandey,[1] J. Ryckebusch,[1] and N. Van Dessel[1]
[1]*Department of Physics and Astronomy, Ghent University, Proeftuinstraat 86, B-9000 Gent, Belgium*
[2]*ESNT, CEA-Saclay, IRFU, Service de Physique Nucléaire, F-91191 Gif-sur-Yvette Cedex, France*
(Received 1 June 2016; published 15 August 2016)



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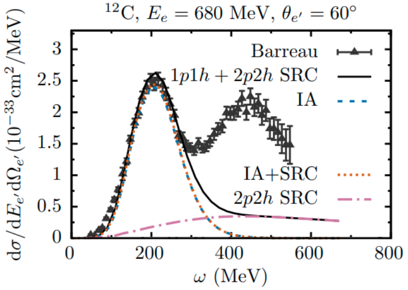


THANK YOU!

Selected publications

- JR, W. Cosyn, T. Vieijra, C. Casert *"Isospin composition of the high-momentum fluctuations in nuclei from asymptotic momentum distributions"* arXiv:1907.07259 and PRC **100** (2019), 054620.
- JR, W. Cosyn, S. Stevens, C. Casert, J. Nys *"The isospin and neutron-to-proton excess dependence of short-range correlations"* arXiv:1808.09859 and PLB **B792** (2019), 21.
- S. Stevens, JR, W. Cosyn, A. Waets *"Probing short-range correlations in asymmetric nuclei with quasi-free pair knockout reactions"* arXiv:1707.05542 and PLB **B777** (2018), 374.
- C. Colle, W. Cosyn, JR *"Final-state interactions in two-nucleon knockout reactions"* arXiv:1512.07841 and PRC **93** (2016) 034608.
- JR, M. Vanhalst, W. Cosyn *"Stylized features of single-nucleon momentum distributions"* arXiv:1405.3814 and JPG **42** (2015) 055104.
- C. Colle, O. Hen, W. Cosyn, I. Korover, E. Piasetzky, JR, 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.