Quantifying the nuclear high-momentum fluctuations in symmetric and asymmetric nuclei

Jan Ryckebusch, Wim Cosyn

3rd SRC-EMC Workshop, March 2021

PLB792 (2019) 21 & PRC100 (2019) 054620

Central research questions of this presentation

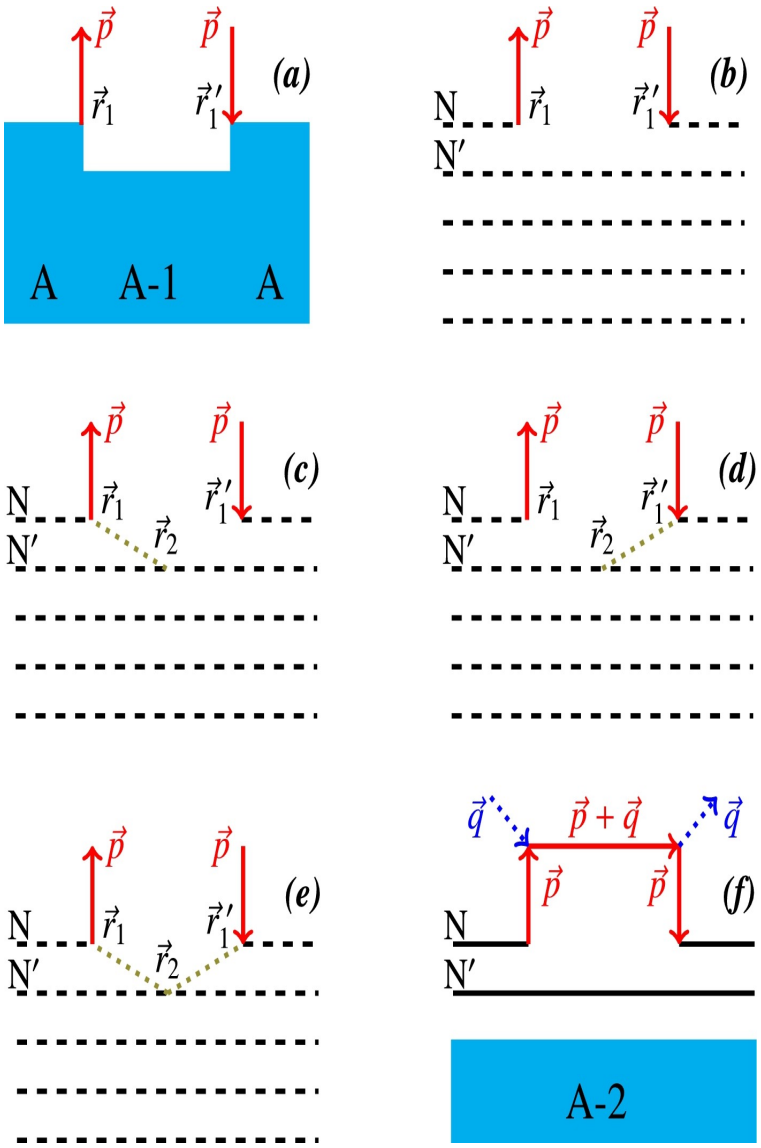
- **Is there a comprehensive picture of nuclear SRC? *(Quest to learn about stylized facts of SRC)***
  1. Variation with mass A
  2. Isospin (flavor) composition of SRC (pp&nn&pn)
  3. Neutron-to-proton asymmetry (N/Z) dependence of SRC
- **How to forge links between nuclear models dealing with SRC and observables? Recent data from electron-nucleus scattering ($A(e, e')$, $A(e, e'N)$, $A(e, e'pX)$)**
- **Are there connections between nucleon and quark medium modifications?**

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. Size and generative mechanisms of the EMC effect

Single-nucleon momentum distributions in LCA



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

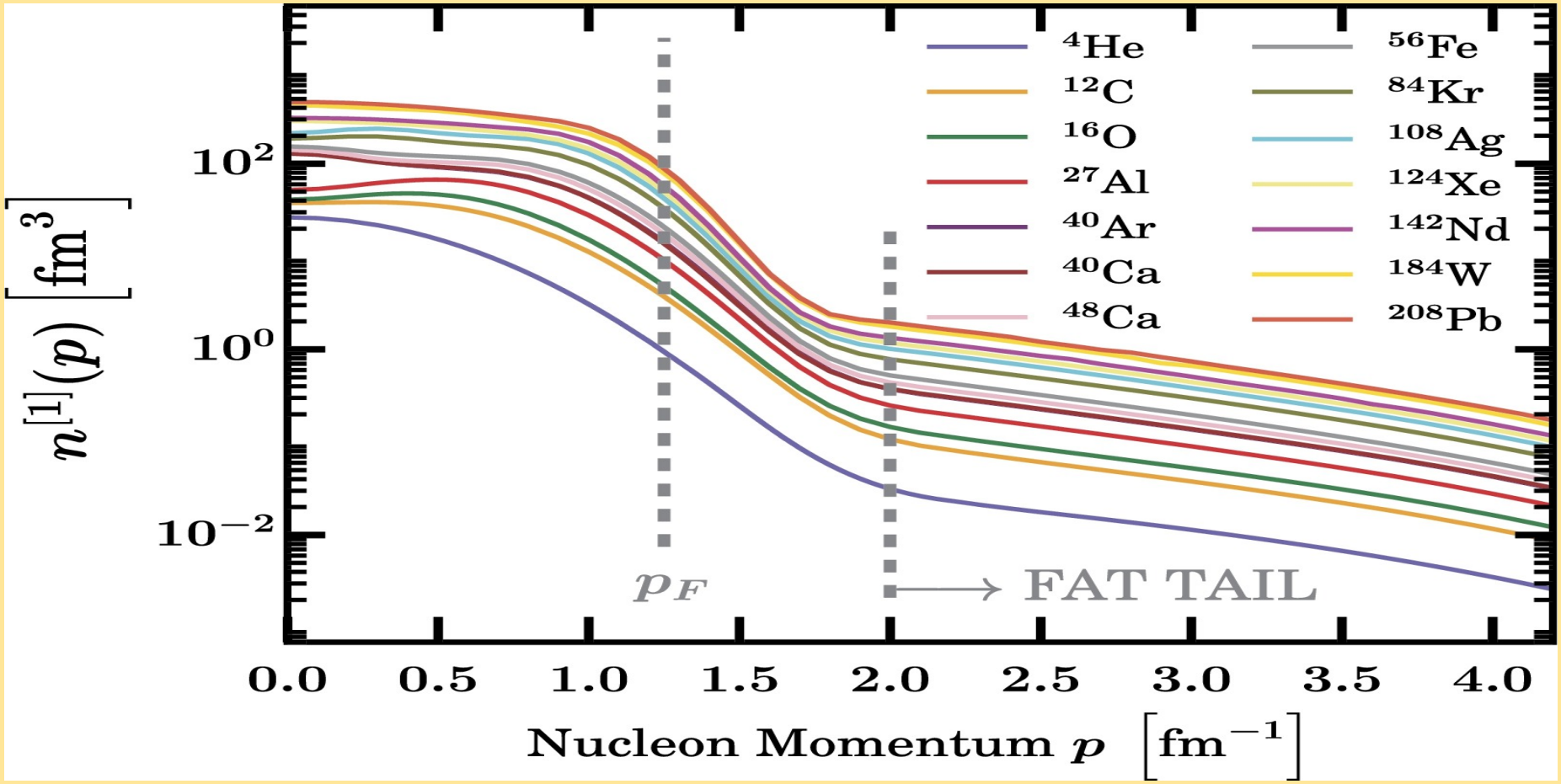
$$n^{[1]}(p) = \frac{A}{(2\pi)^3} \int d^2\Omega_p \int d^3\vec{r}_1 \; d^3\vec{r}_1{}' \; d^{3(A-1)}\{\vec{r}_{2-A}\} \times e^{-i\vec{p}\cdot(\vec{r}_1{}'-\vec{r}_1)} \; \Psi^*(\vec{r}_1, \vec{r}_{2-A})\Psi(\vec{r}_1{}', \vec{r}_{2-A})$$

- 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 $n^{[1]}(p)$

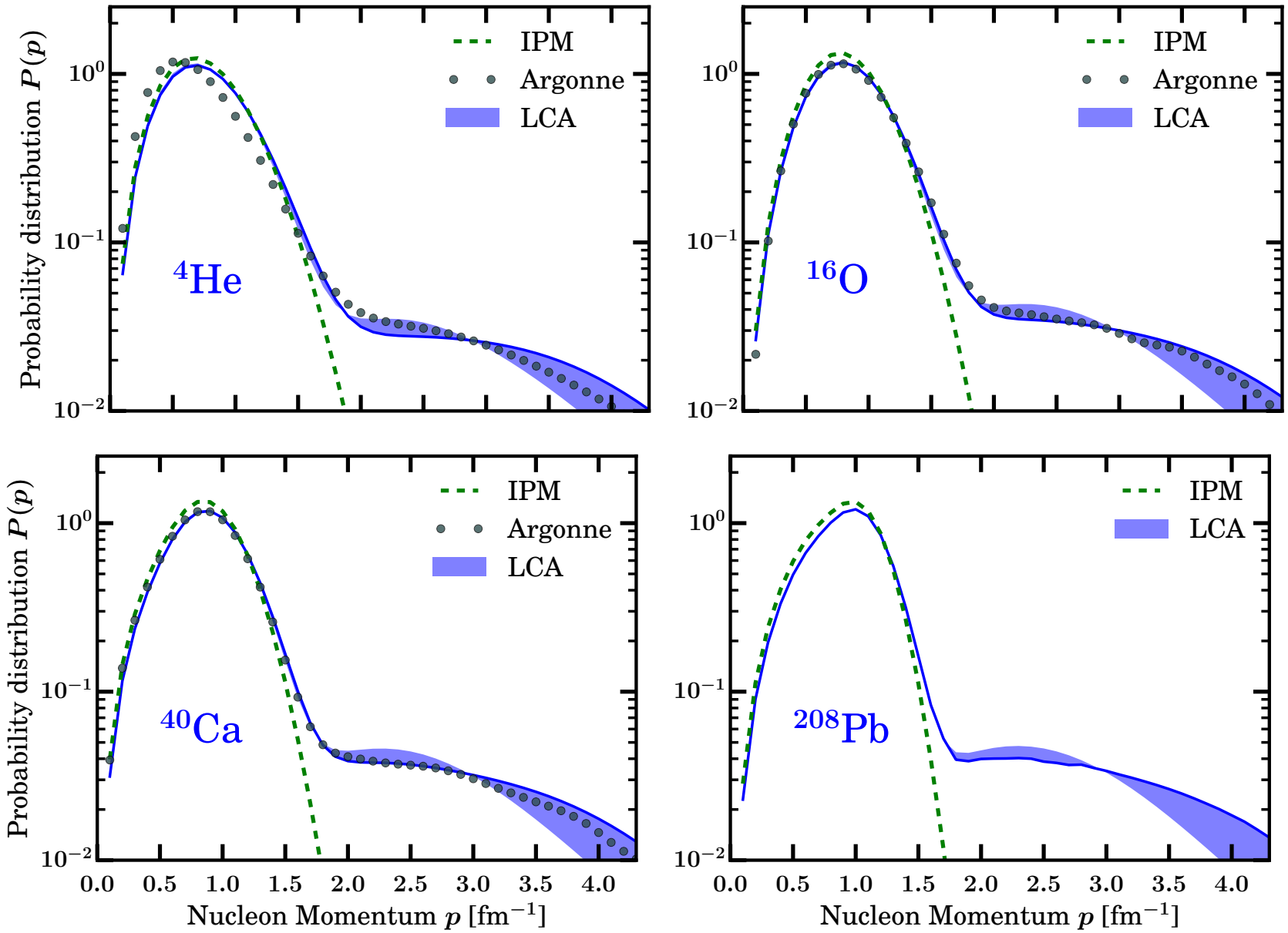
$n^{[1]}(p)$ in LCA: from light to heavy nuclei



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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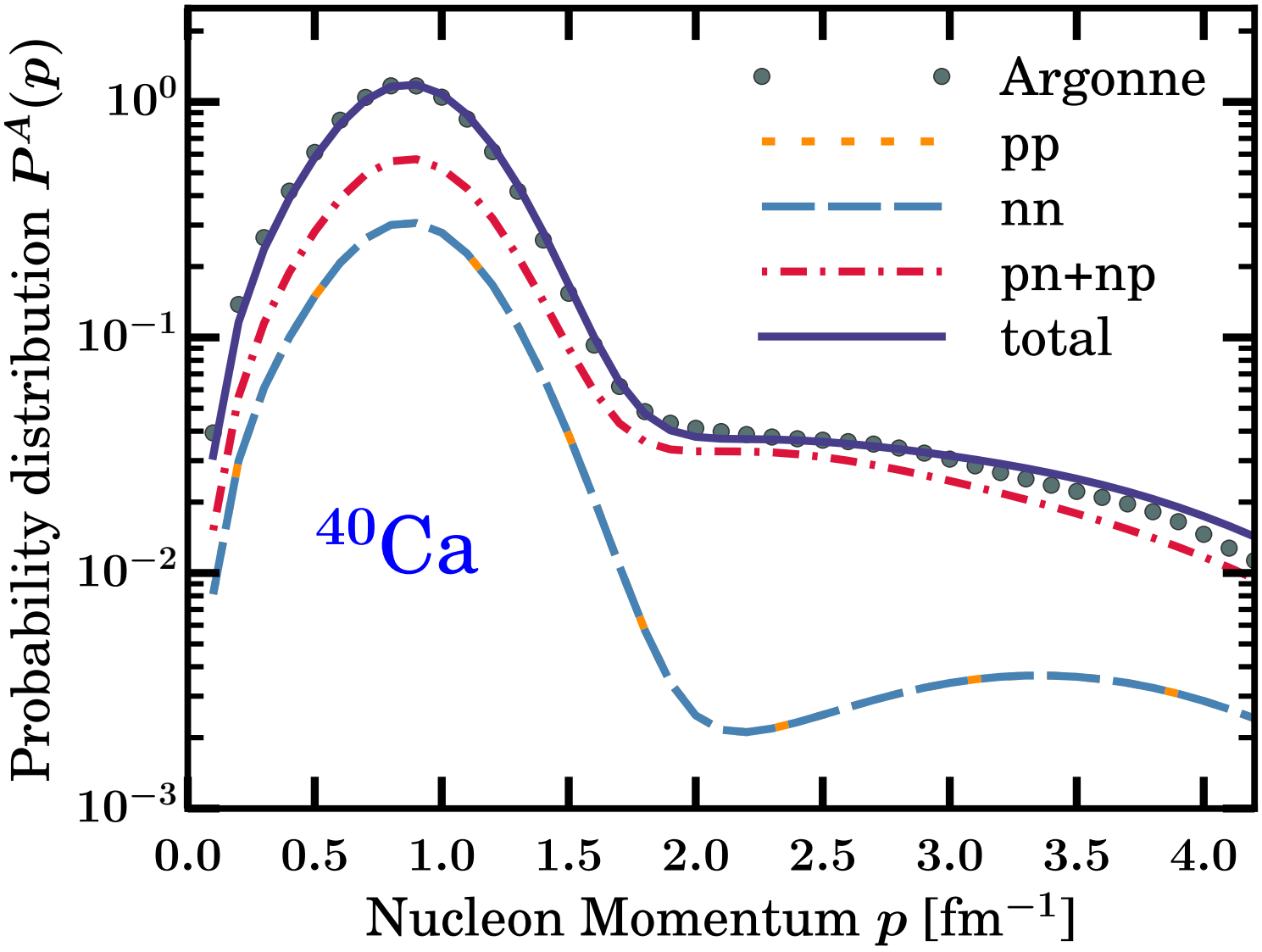

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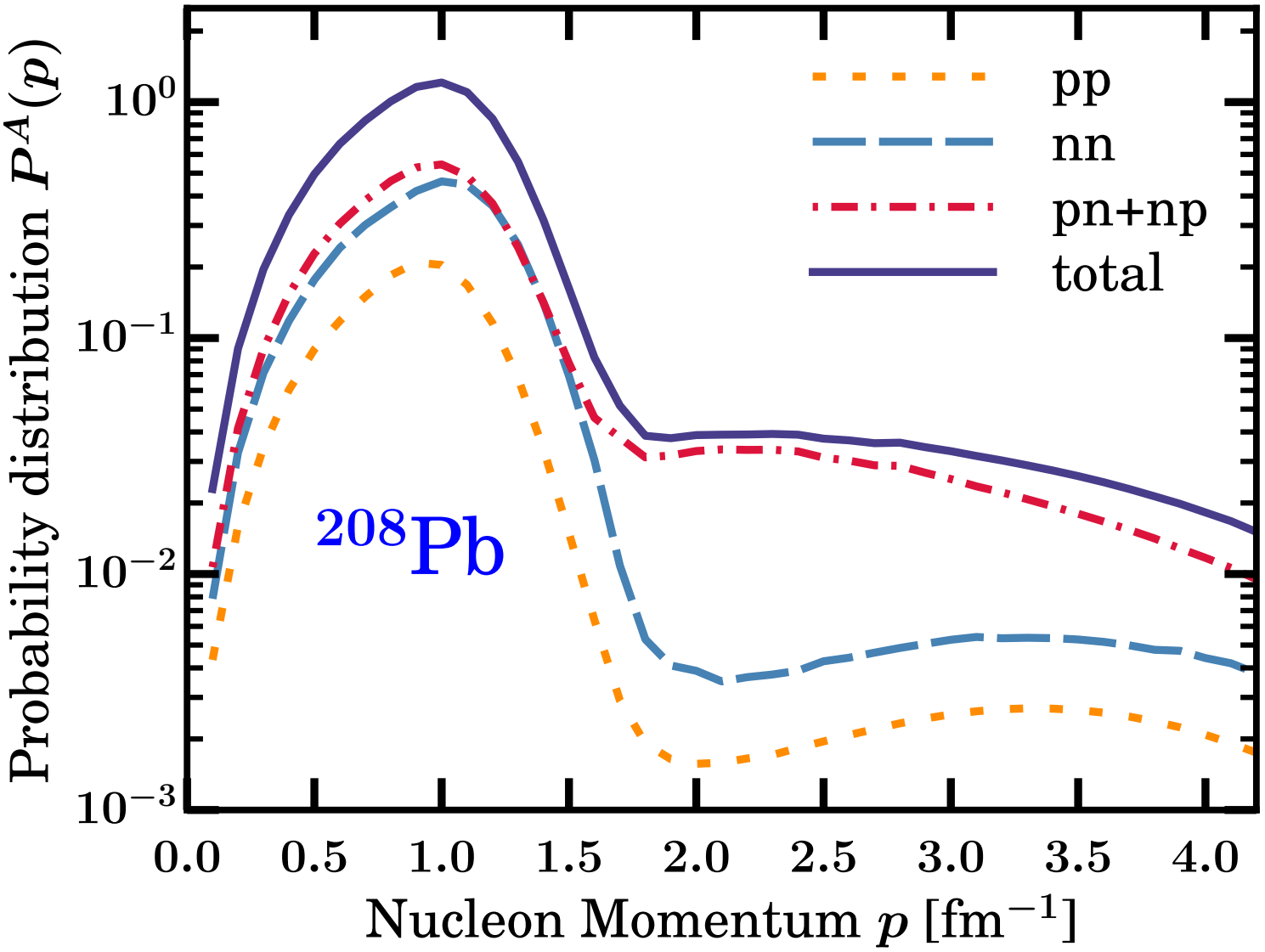
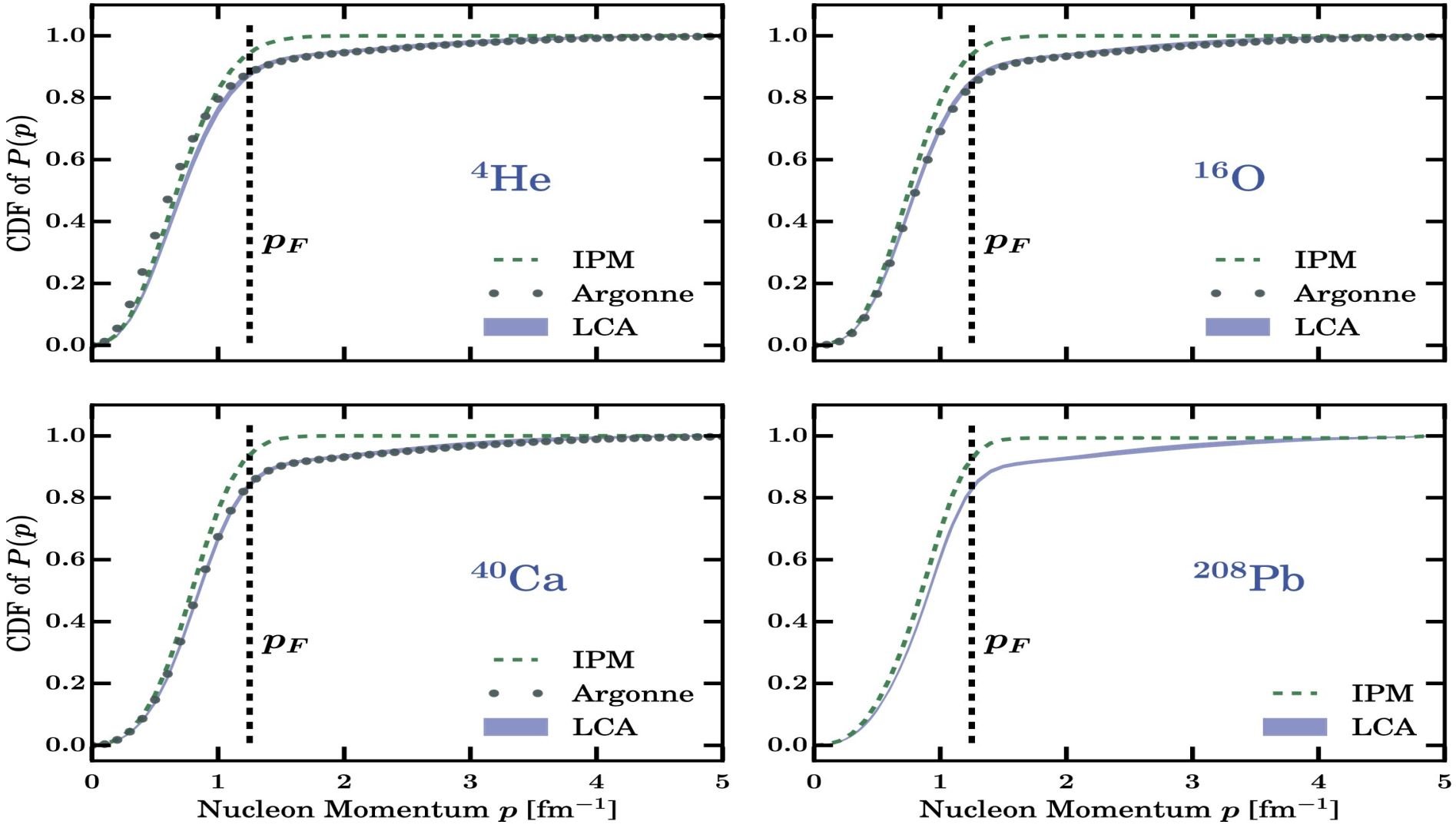
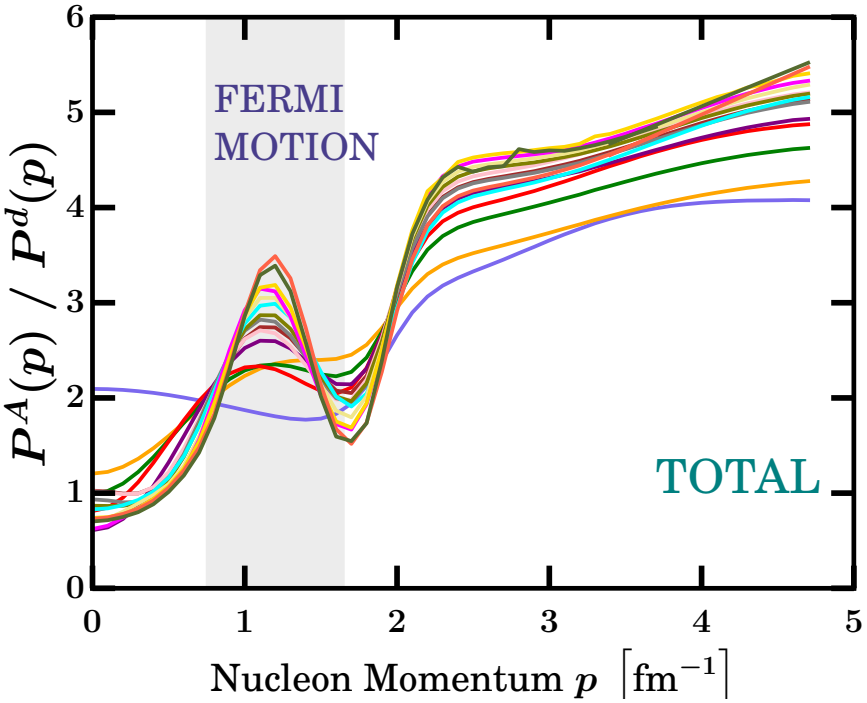


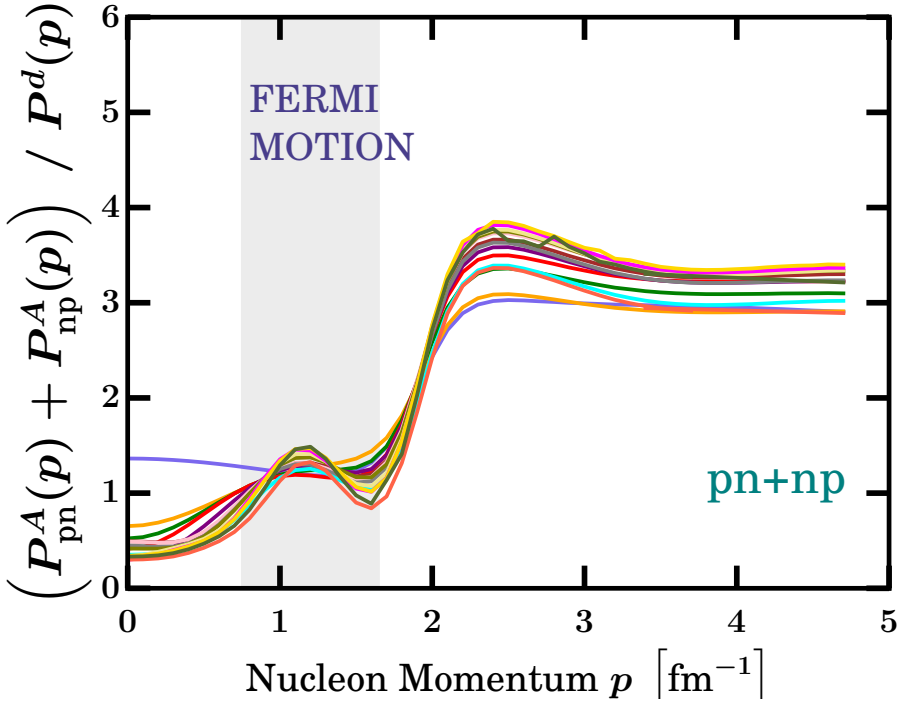
Cumulative momentum distributions



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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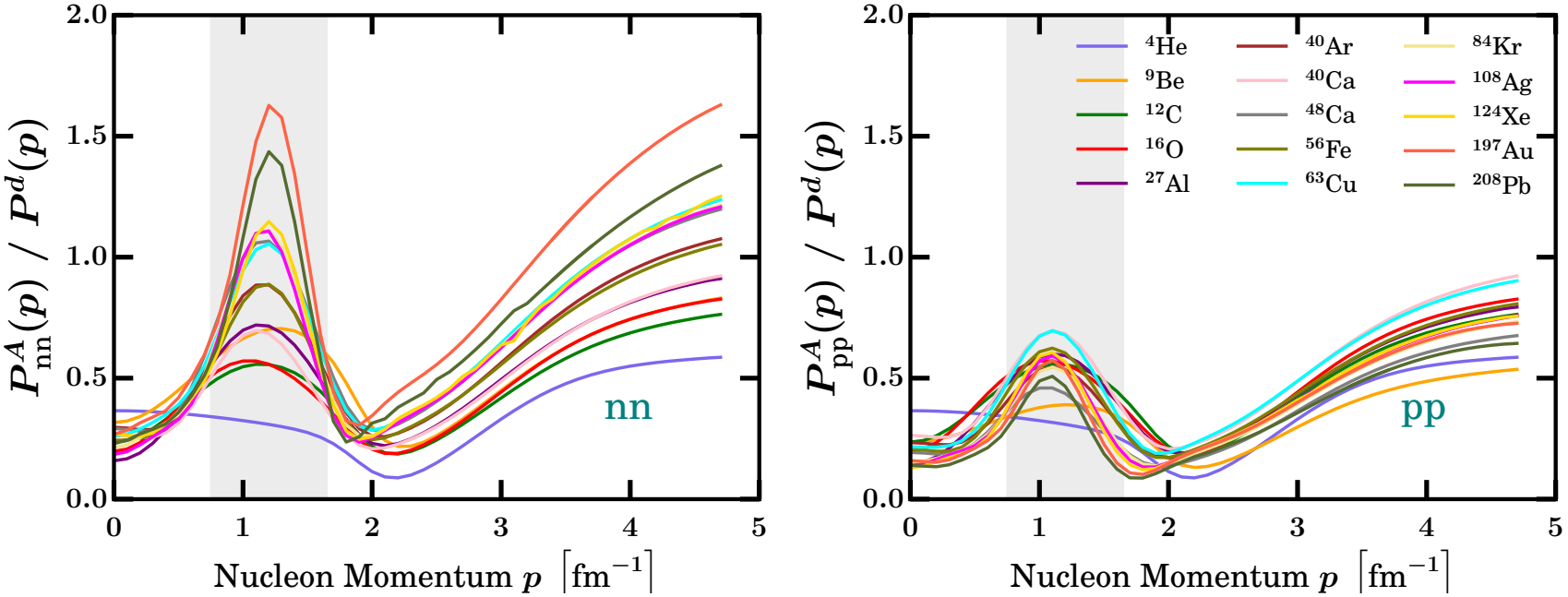

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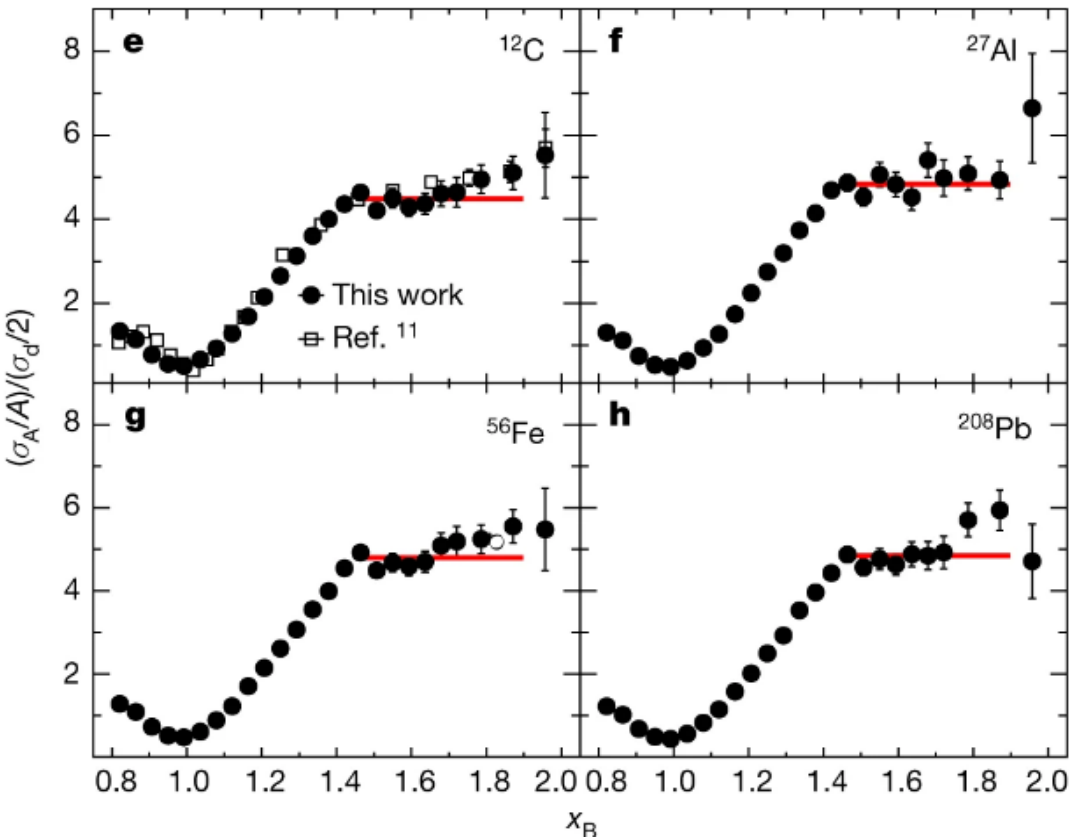
Measurable signal of the *A*-to-*d* scaling of the momentum distributions?



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:

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

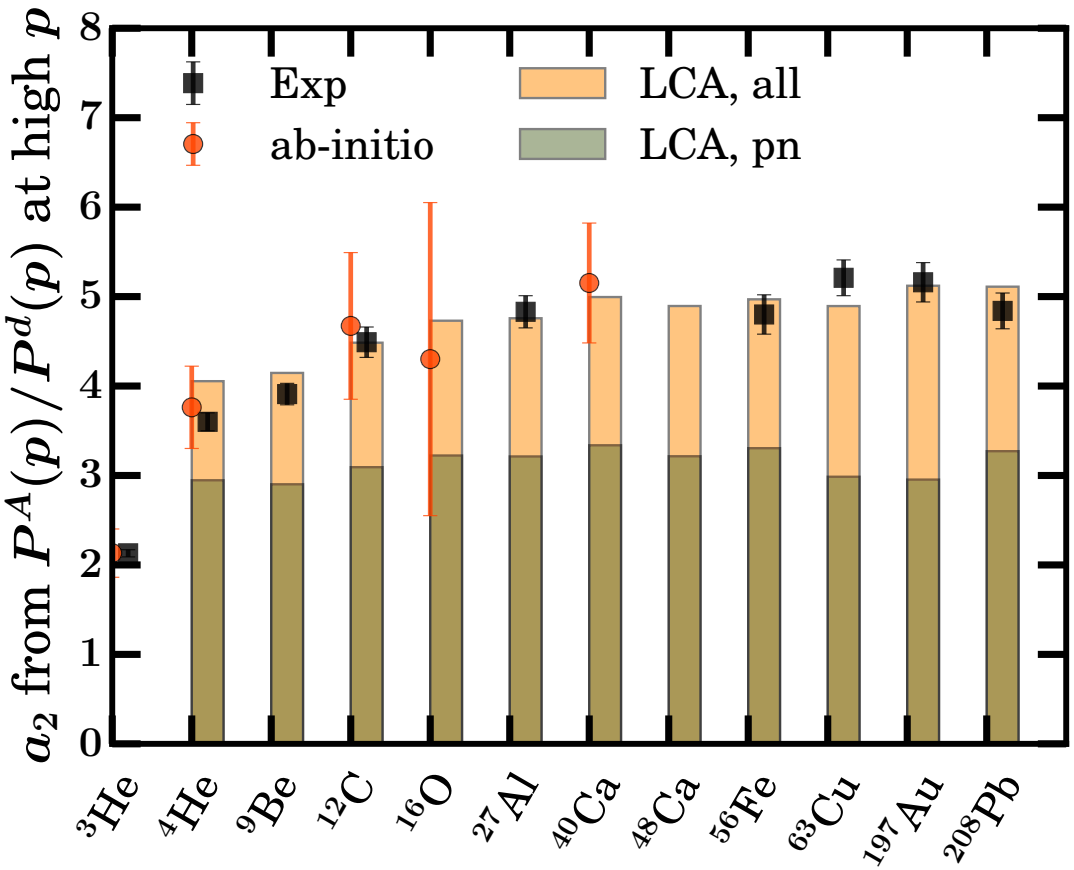
$$\left(1.5 \lesssim x \lesssim 1.9\ ;\ Q^2 \approx 2\ \mathrm{GeV}^2\right)$$

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

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

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))

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

Aggregated quantitative effect of SRC in A relative to d

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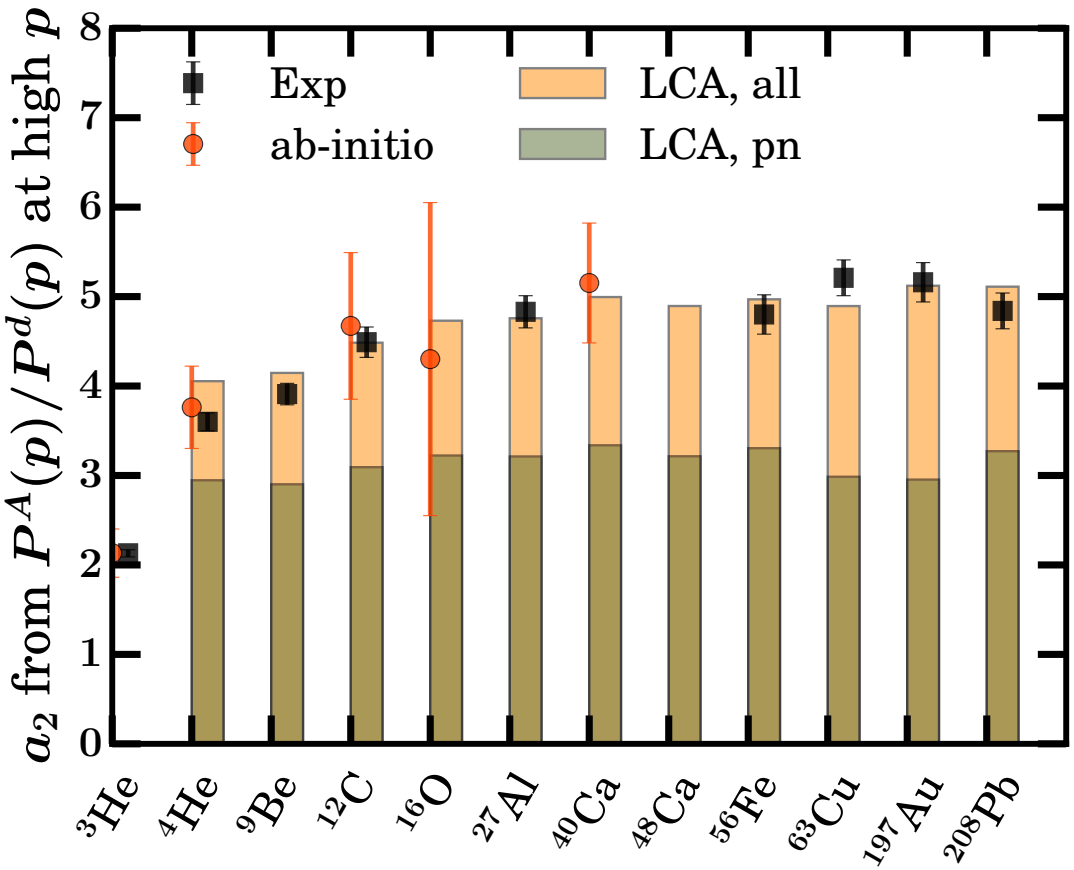

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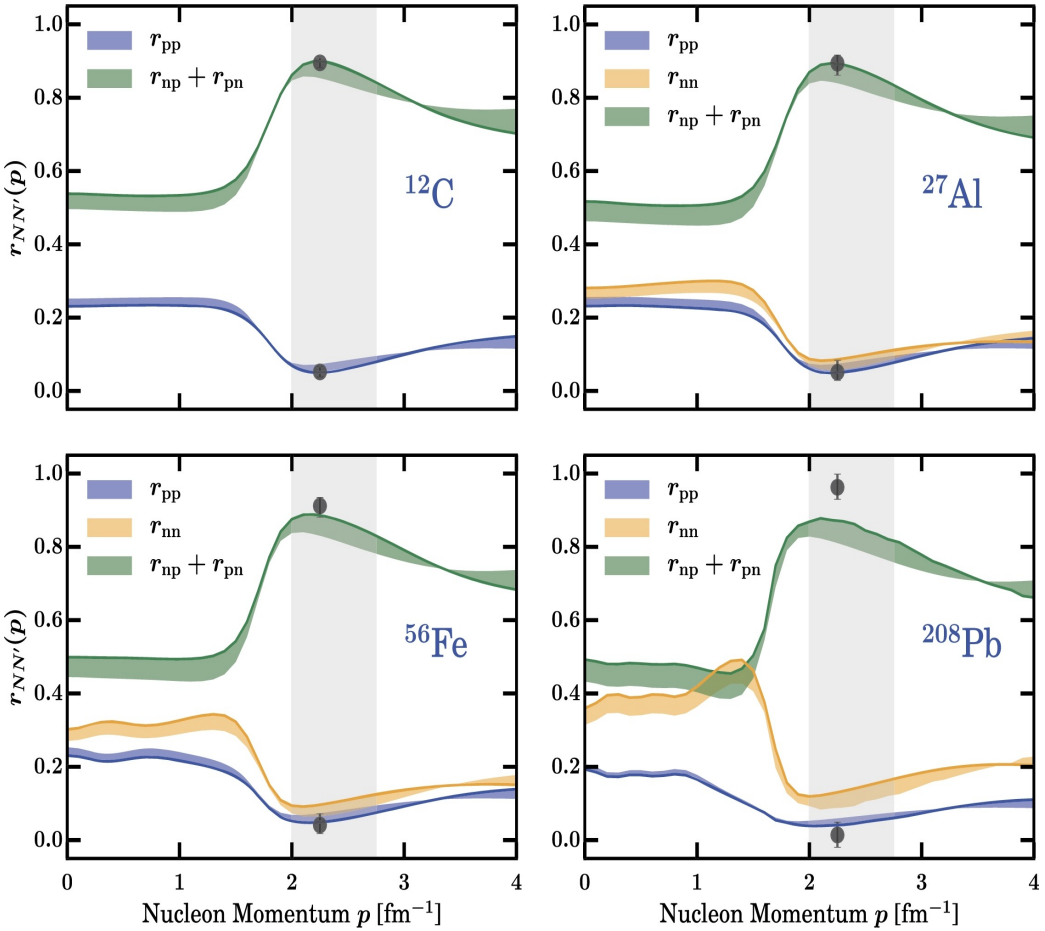
Nuclear momentum distribution: pair composition

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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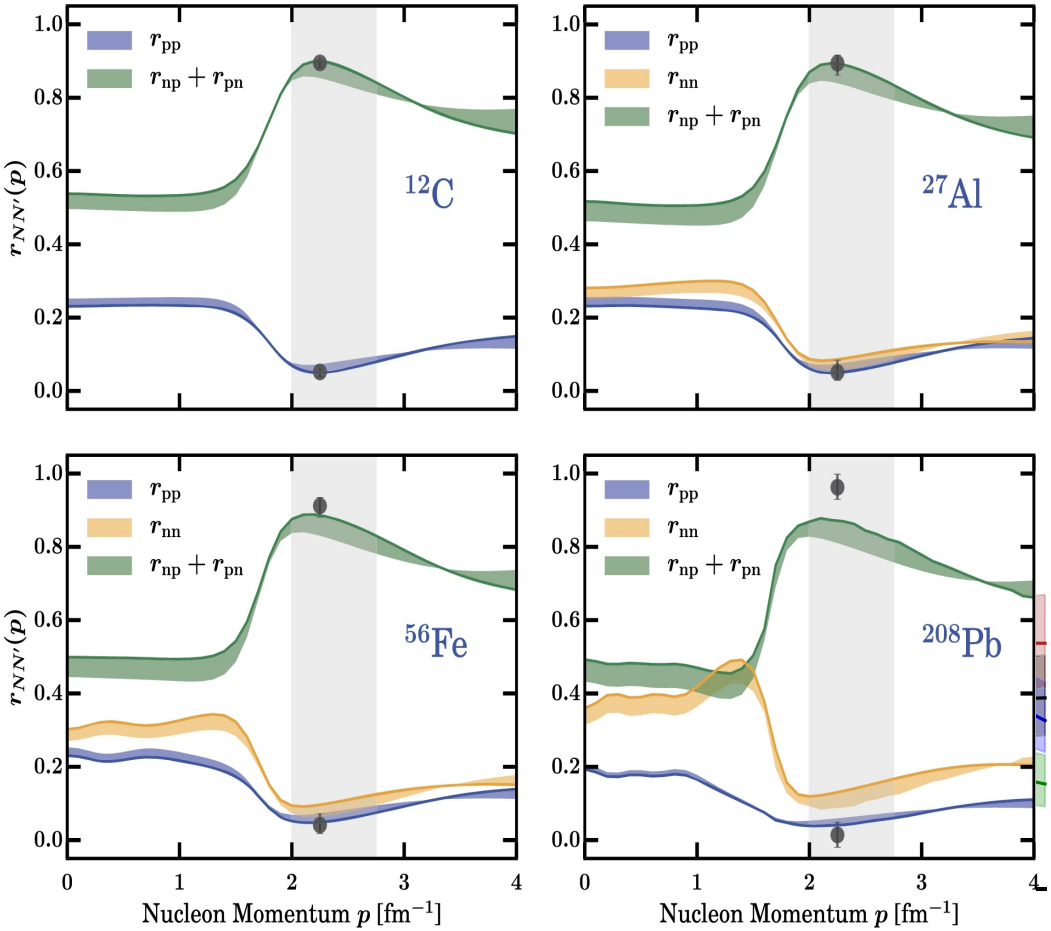

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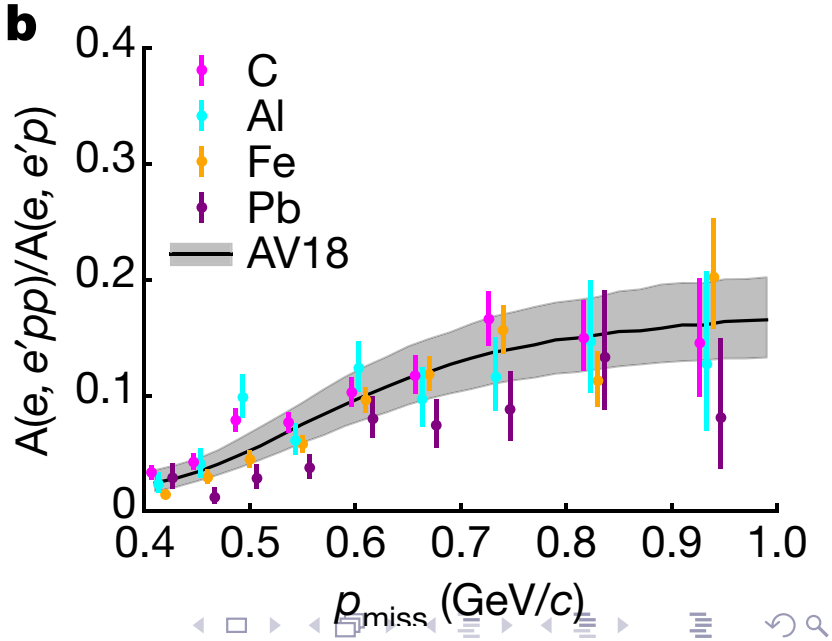
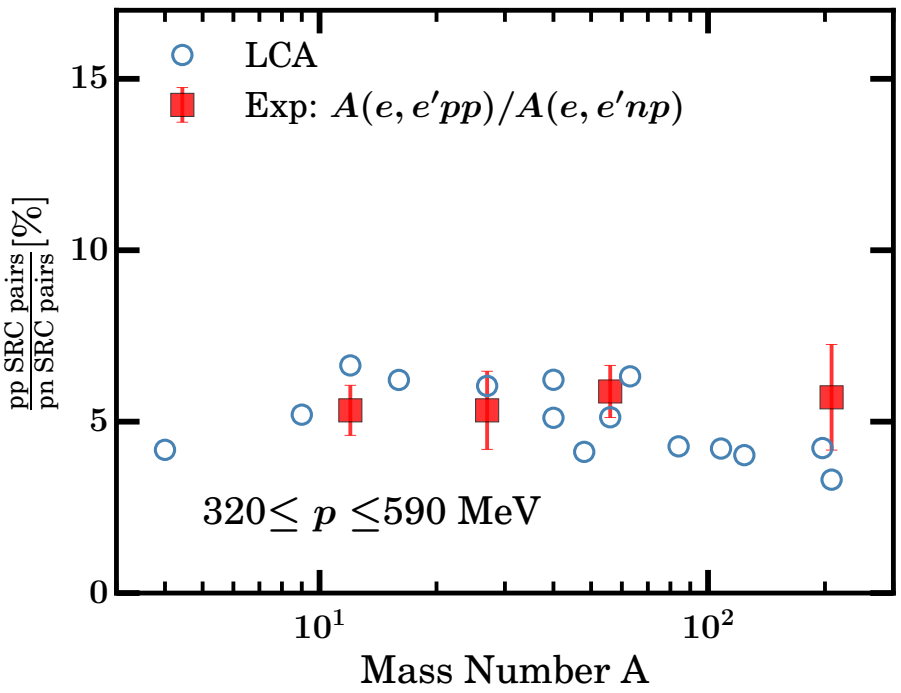
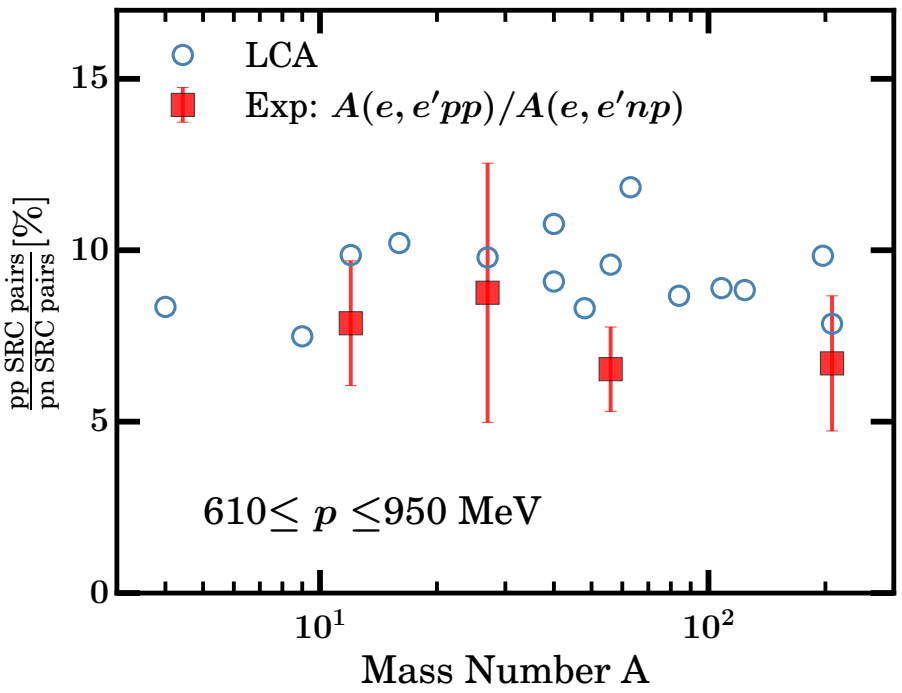


Pair composition of SRC: LCA versus experiment





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

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

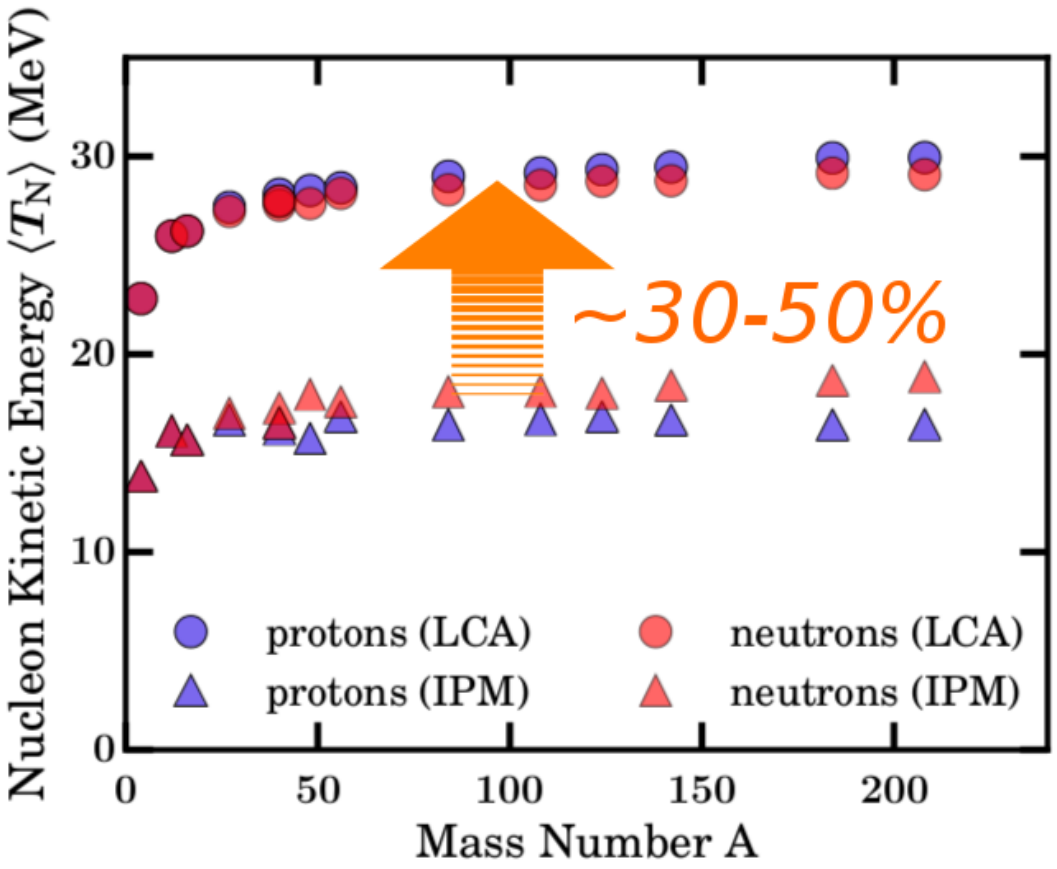
M. Duer *et al.*, PRL122(2019): Ratios from measured

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

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

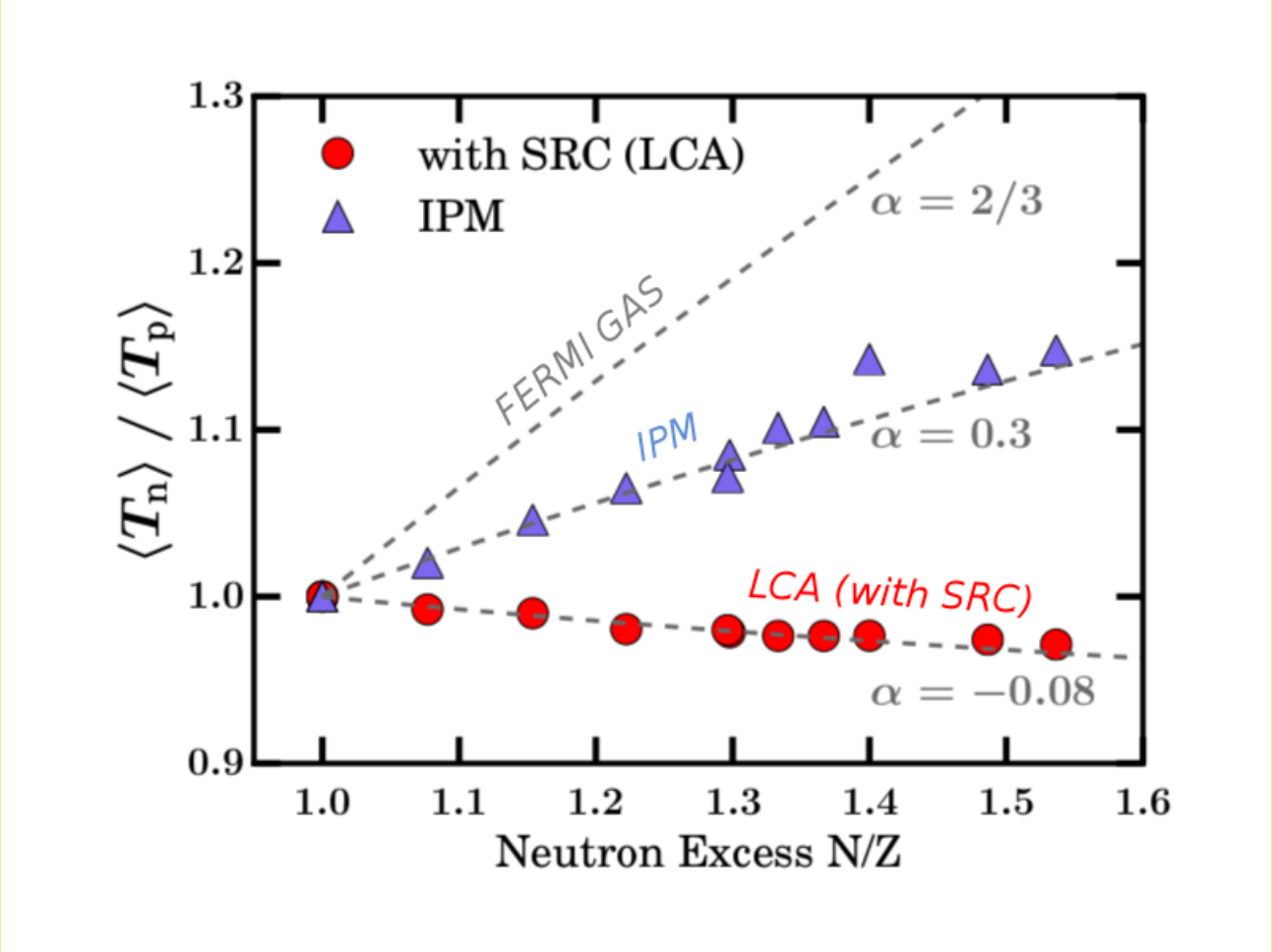
Fourth moment of $n^{[1]}(p)$ from LCA

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



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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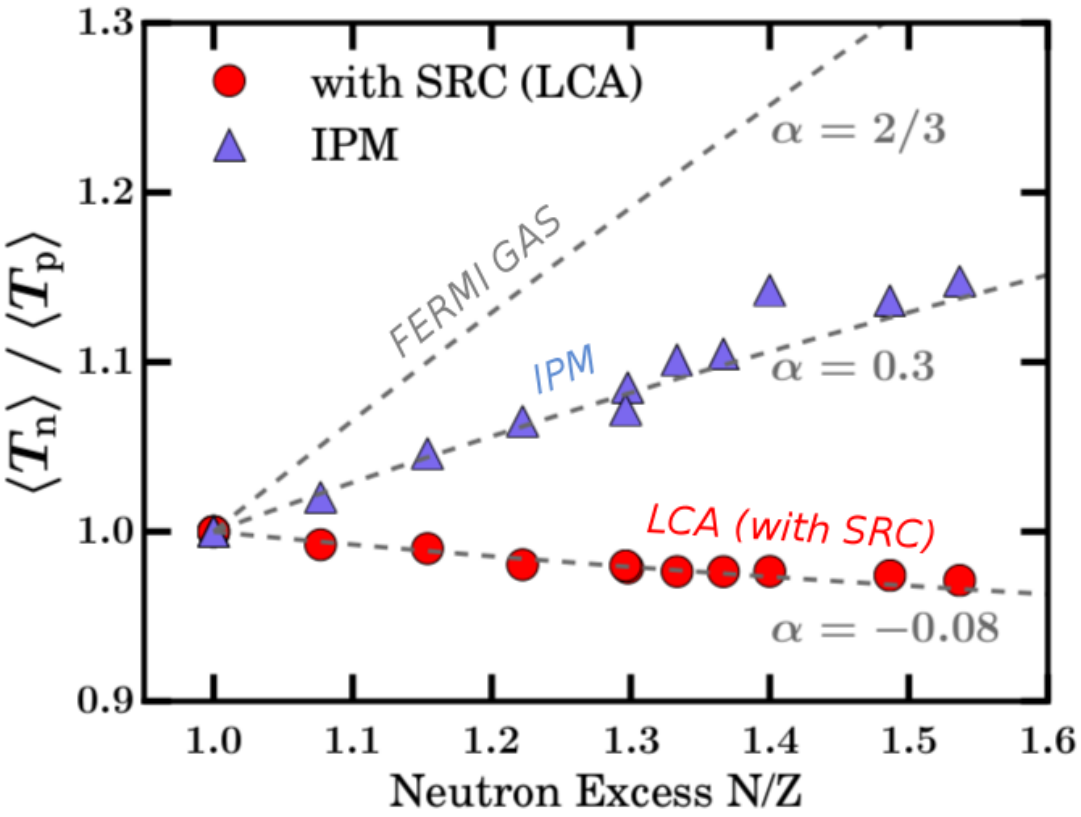
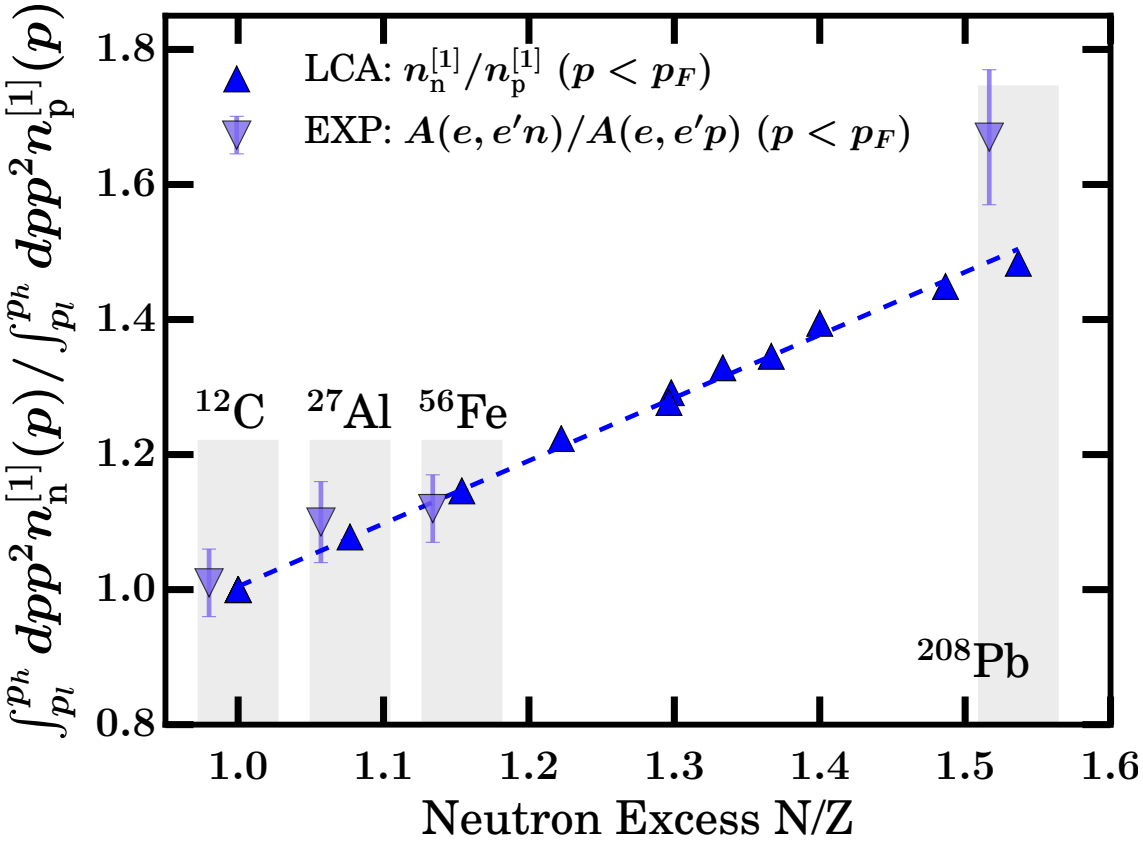


After correcting for SRC in LCA, minority component has largest kinetic energy (strongly depends on **N**/**Z**)

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

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



- DATA: M. Duer *et al.*, Nature 560 (2018) 617
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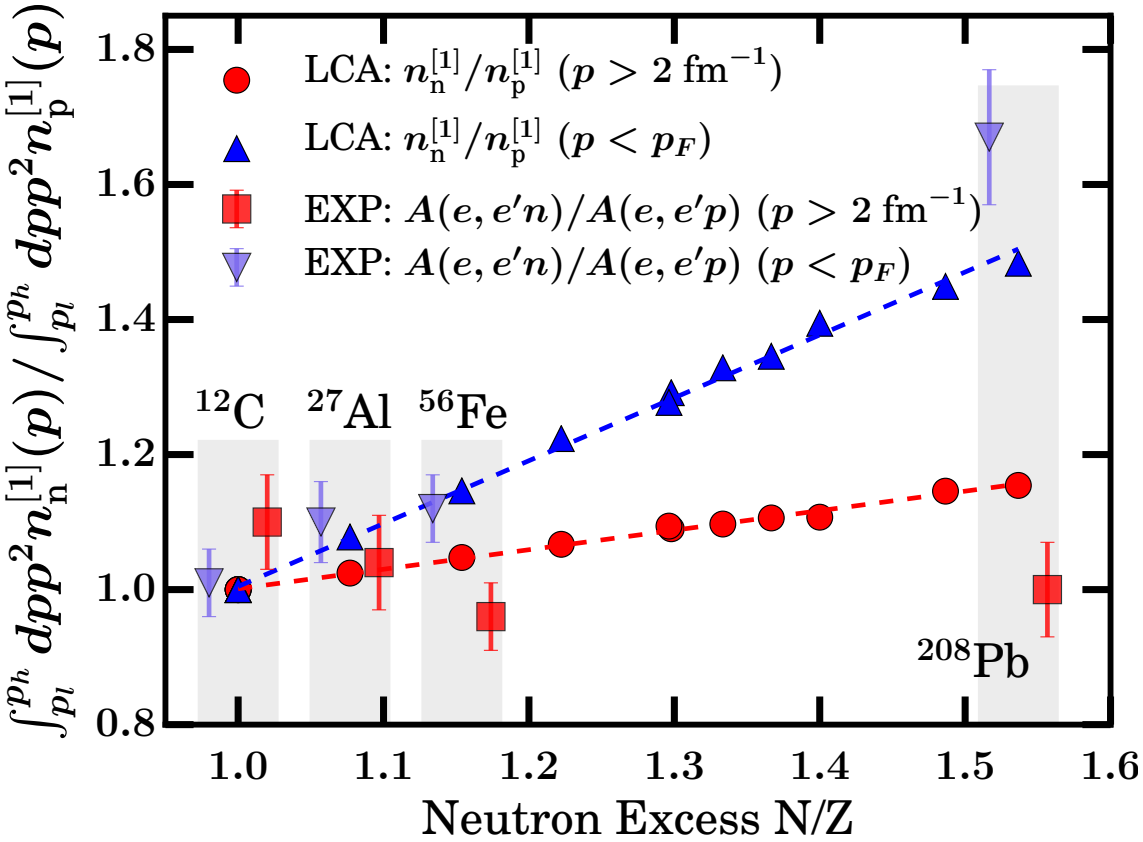
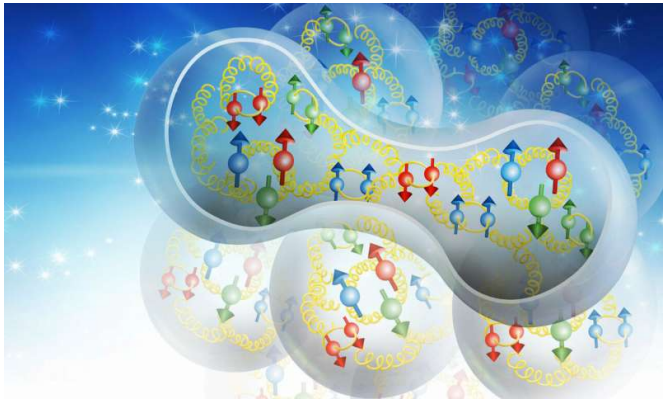
$$\text{IPM:}\ \frac{\int_0^{p_F} dp p^2 n^{[1]}_{\text{n}}(p)}{\int_0^{p_F} dp p^2 n^{[1]}_{\text{p}}(p)}\ . \qquad \text{SRC}:\ \frac{\int_{0.4\ \text{GeV}}^{1\ \text{GeV}} dp p^2 n^{[1]}_{\text{n}}(p)}{\int_{0.4\ \text{GeV}}^{1\ \text{GeV}} dp p^2 n^{[1]}_{\text{p}}(p)}\ .$$



- 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: $0.29\frac{N}{Z} + 0.71$

Quark modification & nucleon pairs

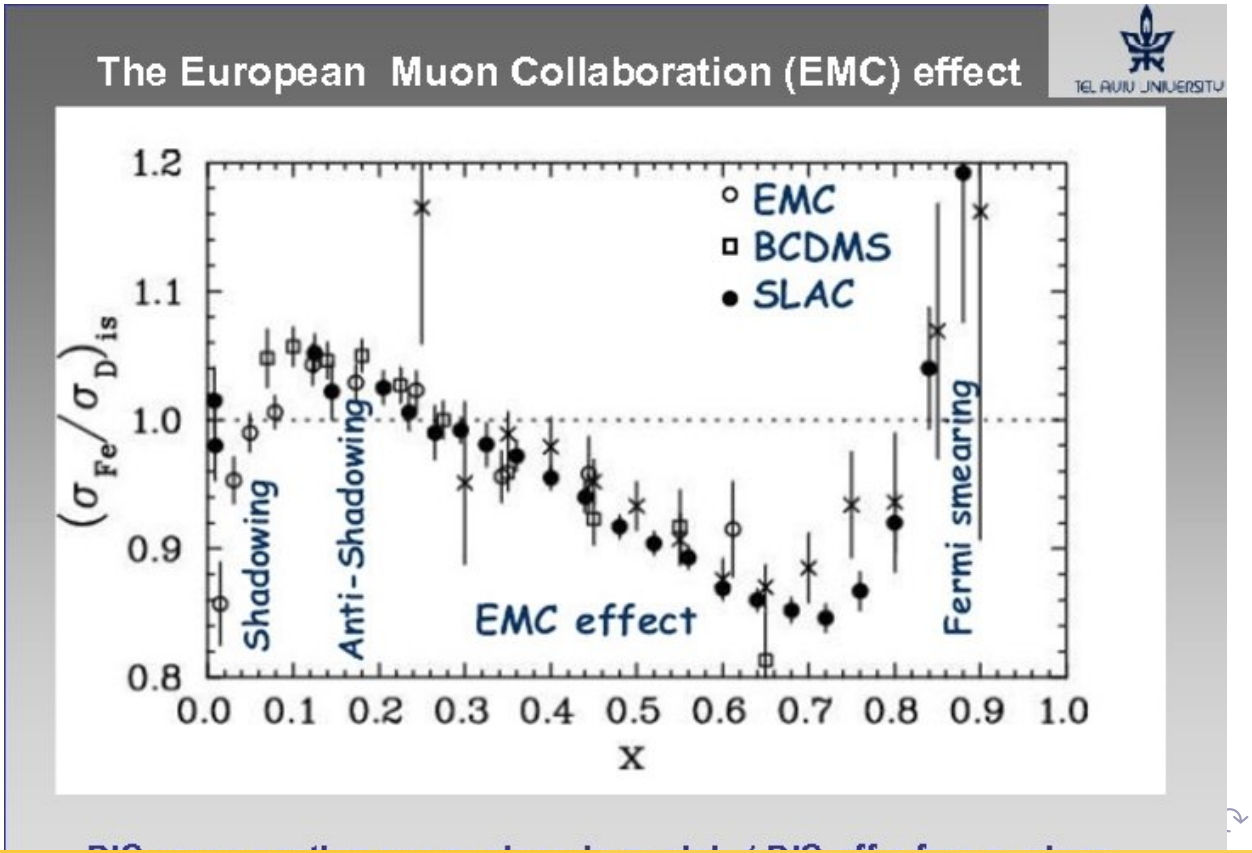


DIS $A(e,e')$ & $d(e,e')$ at $0.2 \lesssim x \lesssim 0.7$

$$-\frac{dR_{EMC}(A,x)}{dx} = -\frac{d\left(\frac{2F_2^A(x,Q^2)}{AF_2^d(x,Q^2)}\right)}{dx}$$

Short-distance neutron-proton pairs may be responsible for the bulk of the EMC effect

Alternate views: PRL **123**, 042501 (2019)



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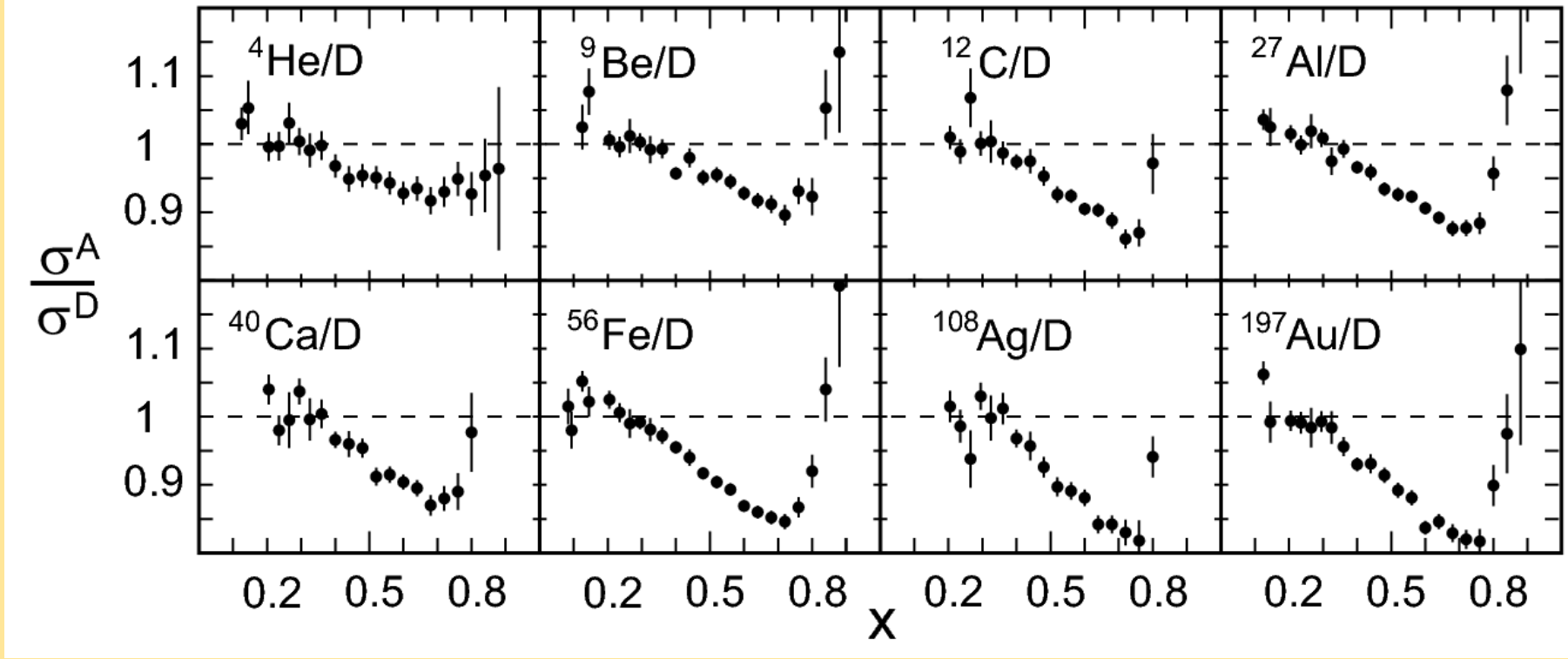


Size of EMC effect depends on A(N, Z)

Isospin dependence of EMC effect?

Predict size of EMC effect and learn about generative mechanisms

- Per-proton probability to find a high-momentum proton in $A(N,Z)$ relative to D: A-to-D medium modifications

$$a_2^p(A) = \lim_{\text{high } p} \frac{A\, P_p^A(p)}{Z\, P_p^D(p)}$$

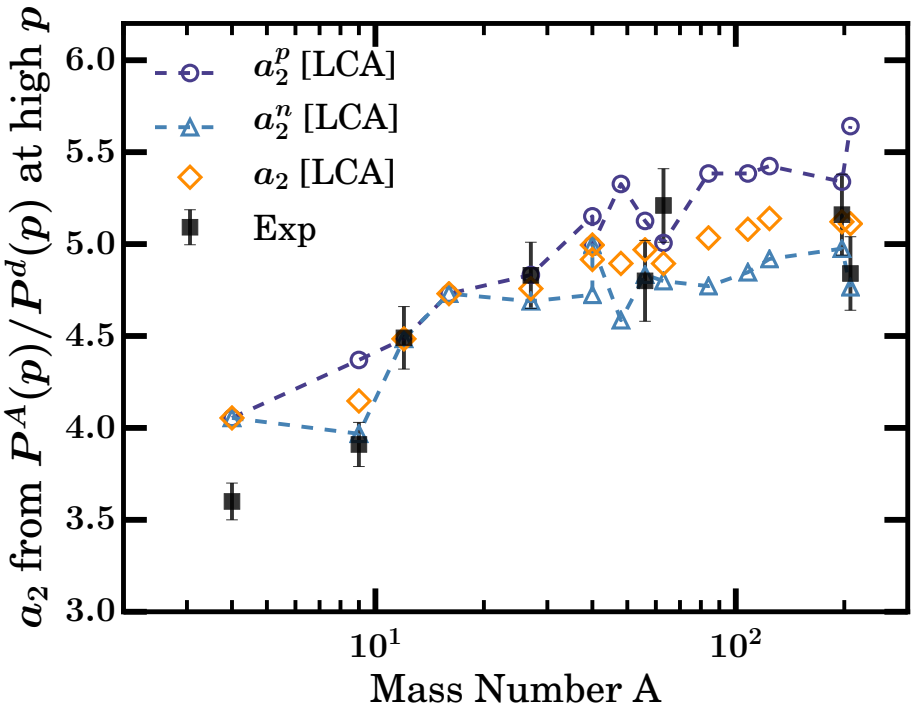
  Can be computed in LCA!
- Size of EMC effect is connected to "SRC" nucleons

$$\frac{dR_{EMC}(A,x)}{dx} = m_1 \left(\underbrace{\frac{Z a_2^p(A) + N a_2^n(A)}{A}}_{\text{ISOSCALAR}} - 1 \right) + m_2 \left(\underbrace{\frac{Z a_2^p(A) - N a_2^n(A)}{A}}_{\text{ISOVECTOR}} \right)$$

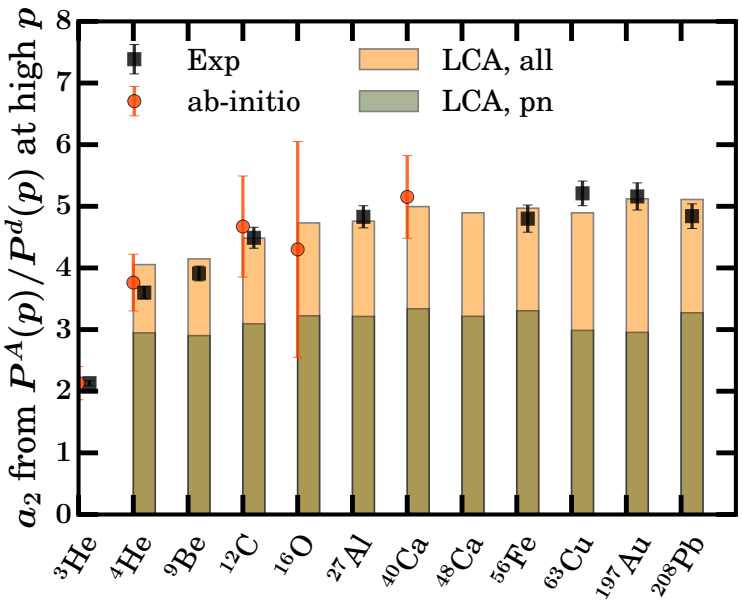
  Connects measured size of EMC effect to computed SRC scaling factors!

Proton and neutron modifications in nuclei

Proton & neutron SRC scaling factors



- Per-proton dynamical modification is larger than the per-neutron one for $N > Z$
- SRC scaling factor $a_2(A)$: $(Za_2^p(A) + Na_2^n(A))/A$

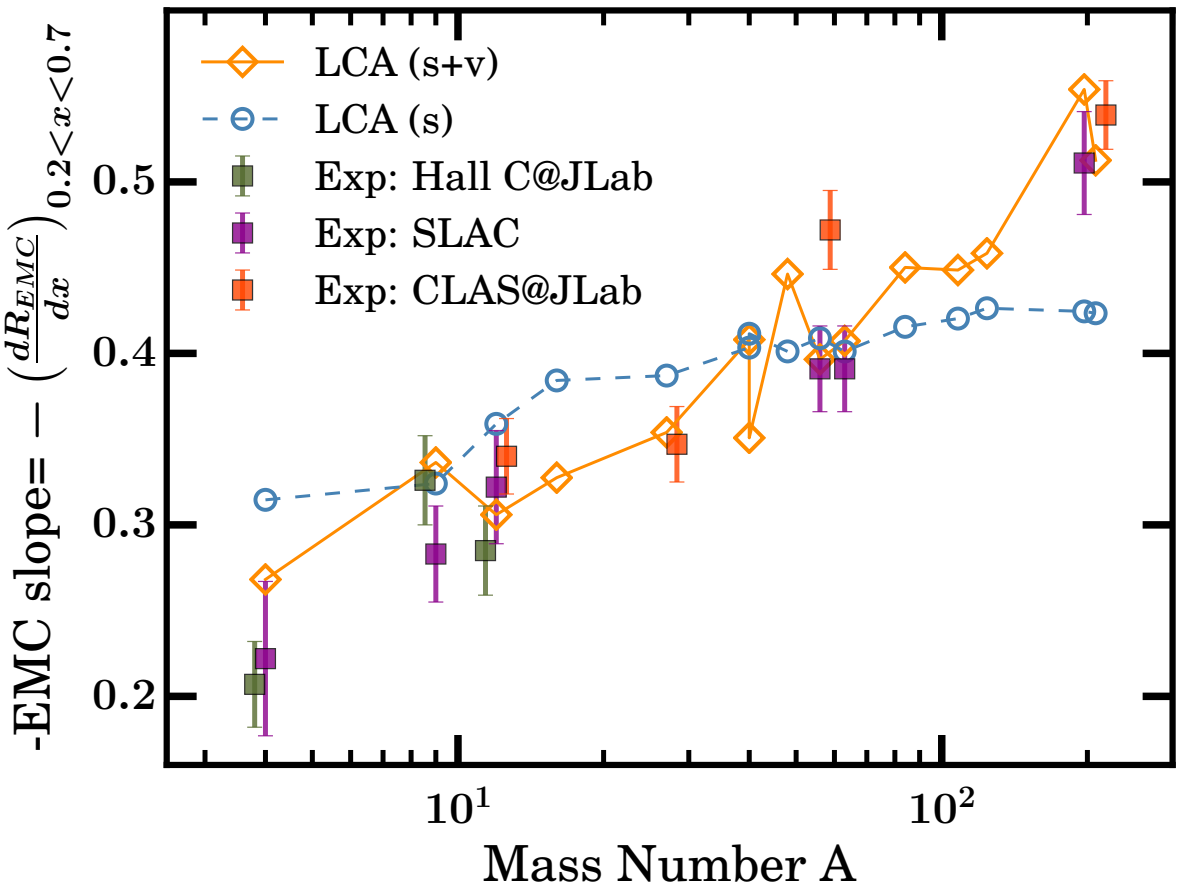


Measured SRC scaling factors from:

$$a_2^{exp}(A) = \frac{2}{A}\frac{\sigma^A(e,e')}{\sigma^d(e,e')}(1.5 \lesssim x \lesssim 1.9)$$

for $Q^2 \approx 2$ GeV^2

Size of the EMC effect



Meausured size of the EMC effect displays stronger variations across $A(N,Z)$ than SRC scaling factors a_2

- LCA (s): isospin blind generative mechanisms
- LCA (s+v): also isospin-dependent generative mechanisms
- our analysis corroborates the suggestion that flavor dependent nuclear effects influence the size of the EMC effect

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)

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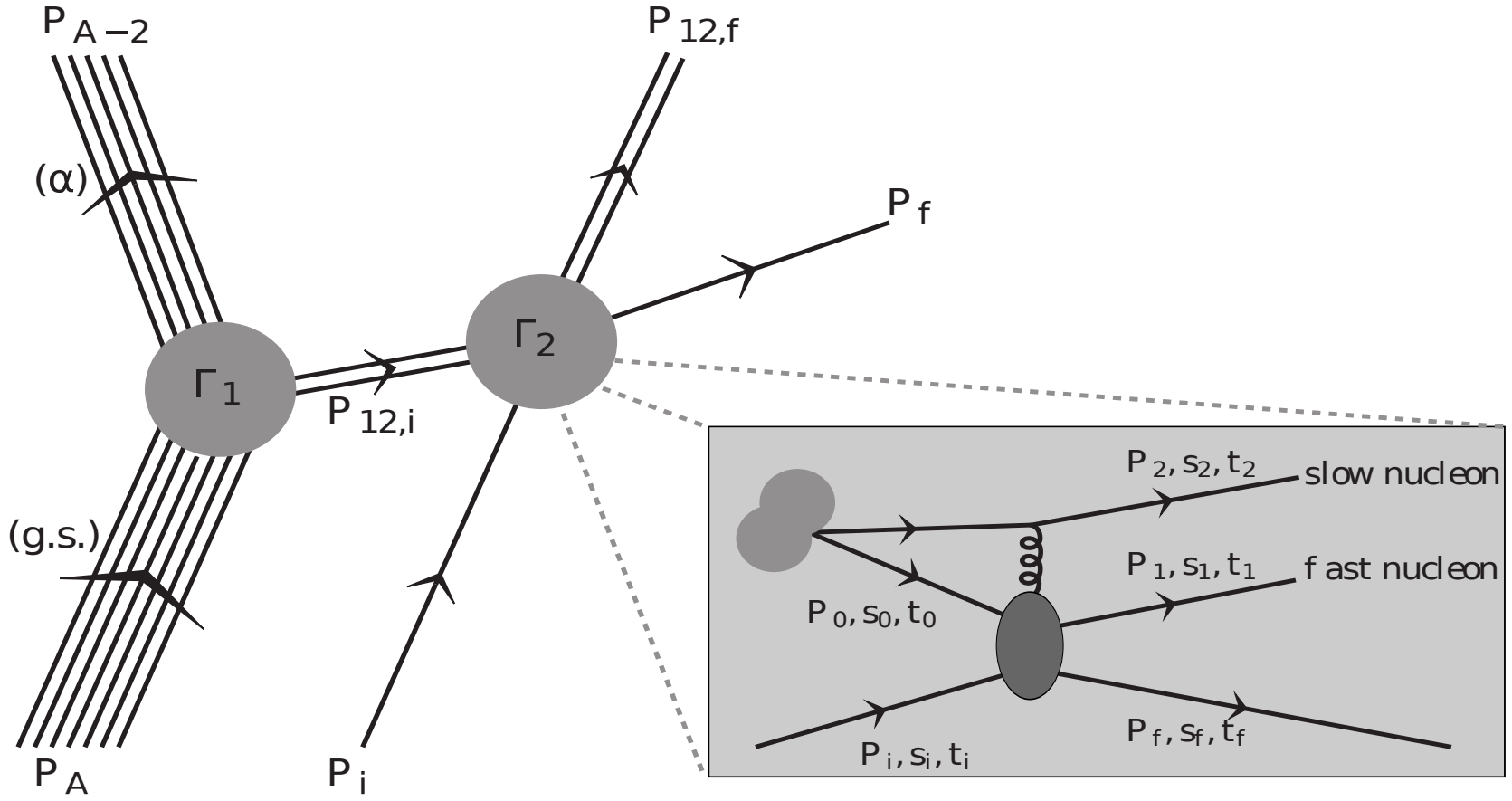
$p(A, pNN\ A-2)$ with radioactive beams

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



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

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

$$\frac{\mathrm{d}\sigma^{(pN_1N_2)}}{\mathrm{d}\Omega_f\,\mathrm{d}E_1\,\mathrm{d}\Omega_1\,\mathrm{d}E_2\,\mathrm{d}\Omega_2} = 2^{2|M_T|-1}\,\mathcal{S}(J_A,\beta\gamma)\,\mathcal{K}\,\frac{\mathrm{d}\sigma^{pN_1}}{\mathrm{d}t}\left\{\frac{E_2}{E_m+m_{N_1}}\sum_J\frac{1}{2J+1}\sum_M\sum_T\frac{1}{2T+1}F^{\beta\gamma}_{JM,T}(\vec{P},\vec{k})\right\}_{\mathrm{PF}}, \tag{11}$$

with $\mathcal{K}$ a kinematic factor

$$\mathcal{K} = \frac{1}{(2\pi)^8}\,\frac{(P_f\cdot P_1)^2-m_p^2m_{N_1}^2}{\sqrt{(P_i\cdot P_A)^2-m_p^2m_A^2}}\,m_Am_R^*\,\frac{p_fp_1p_2}{E_R}\left|1-\frac{E_f}{E_R}\frac{\vec{p}_R\cdot\vec{p}_f}{p_f^2}\right|^{-1} \tag{12}$$

$$F^{\beta\gamma}_{JM,T}(\vec{P},\vec{k}) = \sum_{\mu=T-1}^{1-T}\Bigg|\mathcal{F}^{(0)}_\nu[f_c-3f_{\sigma\tau}](k)\,\mathcal{P}^{\varepsilon\beta\gamma}_{JMT\mu}(\vec{P}) - \delta_{T,0}\,12\sqrt{2\pi}\,\mathcal{F}^{(2)}_\nu[f_{t\tau}](k)\sum_{m_l=-2}^{2}\langle 2m_l1\mu|1(m_l+\mu)\rangle\,\mathcal{P}^{\varepsilon\beta\gamma}_{JMT(m_l+\mu)}(\vec{P})\,Y_{2,m_l}(\Omega_k)\Bigg|^2.$$

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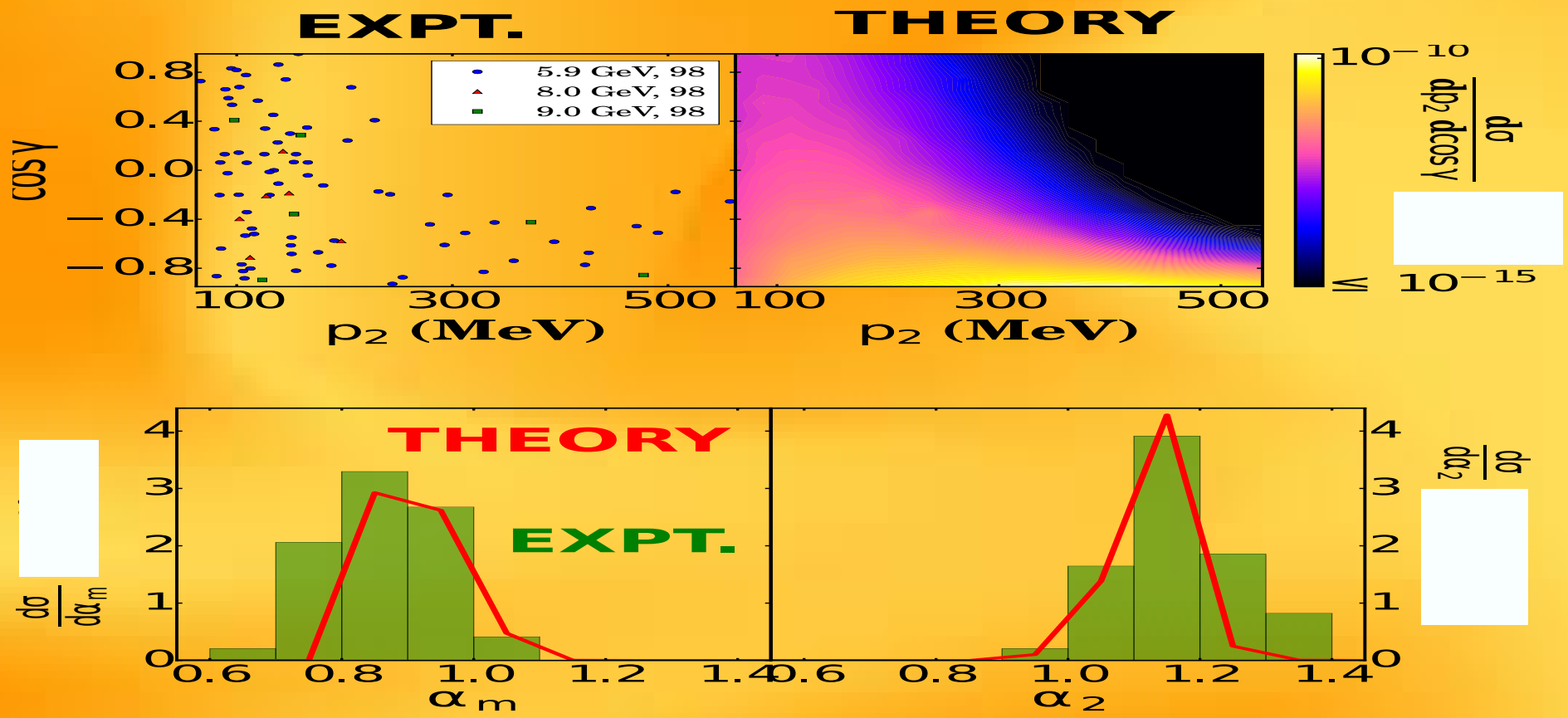
Postdictions for $^{12}C(p, ppn)$ from BNL



- DATA: A. Tang *et al.*, Phys. Rev. Lett. **90**, 042301 (2003)
- Calculations based on a factorized form of the cross section

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$p(A, pNN\ A-2)$ with radioactive beams: asymmetry dependence of nuclear SRC

Ratios of SRC pp to pn pairs for various carbon isotopes