Mass dependence and scaling properties of nuclear short- range correlations

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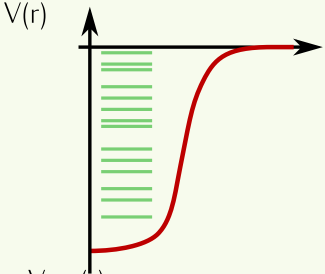
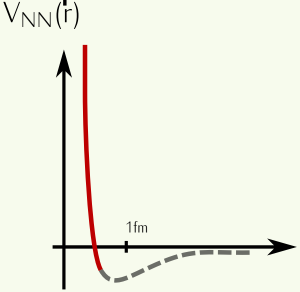
Outline

1. Introduction
2. Our model
3. Inclusive measurements
4. Exclusive reactions
5. EMC vs SRC

`M.V., W.C., J.R., PRC84 031302(R) ('11),PRC86 044619 ('12), arXiv:1210.6175`

Introduction





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  - baryons (p, n,..) and mesons (π, ρ,..)
  - nuclear shell model: protons and neutrons in a average mean-field potential
- 1960s–70s: discovery of quantum chromo-dynamics (QCD) with **partonic** d.o.f.
- Mean-field approach has limitations

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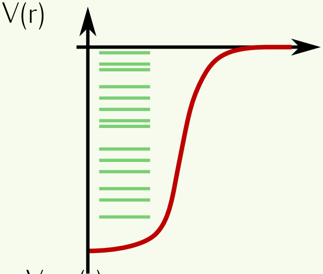

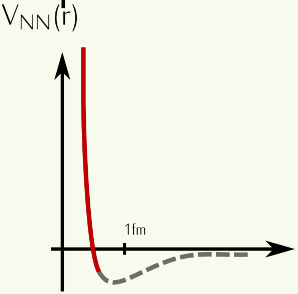

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  - How do colourless hadrons, nuclei emerge from QCD?
  - Partonic properties of hadrons change in a dense medium (EMC effect)
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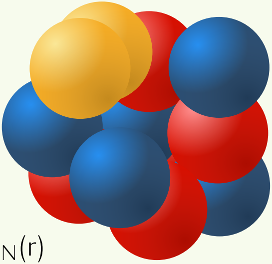

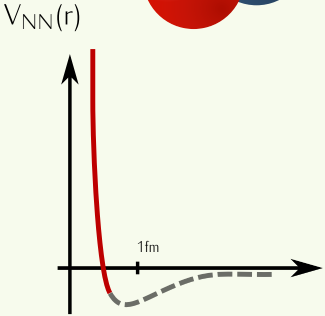

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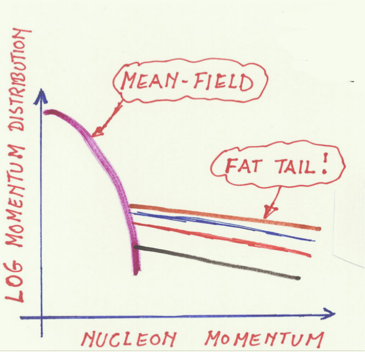
- Mean-field approach has limitations
  - Nucleus is more than sum of nucleons.
  - hard core of the NN-potential induces **short-range correlations** (SRC)
  - induce high density & high momentum fluctuations in the nucleus, deplete shell model levels.

Momentum distributions



- Hard core of the NN potential induces SRC → **high-momentum tails**
- Lots of nuclear structure activity in computing one- and two-body momentum distributions using ab initio methods
- In experiments, one-body and two-body momentum distributions are **not directly observable** and the obtained information on SRC is indirect
- f.i. $A(e, e'p)$ cross section only **factorizes** in non-relativistic approximation

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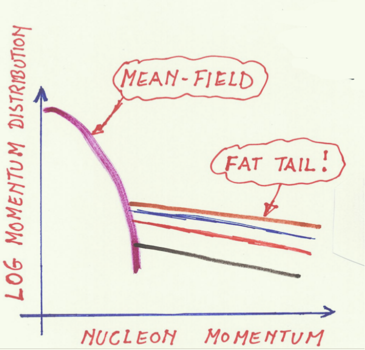

$$d\sigma_A^{(e,e'p)} = K\sigma^{ep}\rho^D(\vec{p}_m)$$

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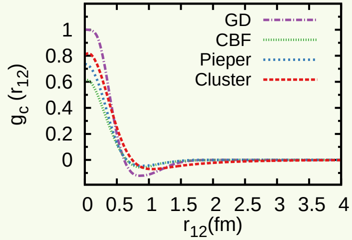
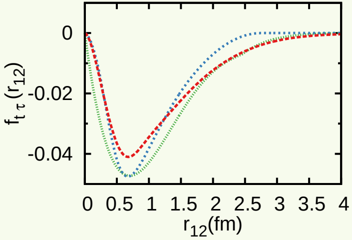
Short-range correlations in nuclei





- Time-honoured method is the use of correlation functions

$$| \overline{\Psi} \rangle = \frac{1}{\sqrt{\langle \Psi_{MF} | \widehat{\mathcal{G}}^{\dagger} \widehat{\mathcal{G}} | \Psi_{MF} \rangle}} \widehat{\mathcal{G}} | \Psi_{MF} \rangle$$

- Dominated by central and tensor correlations: highly **local** → **universal character**
- In practice: perturbative (cluster, virial) expansions are required to compute correlated part of momentum distribution
- Local character of SRC truncates expansion (2N SRC ≫ 3N SRC)
- Ab initio calculations get very complicated for medium and heavy nuclei

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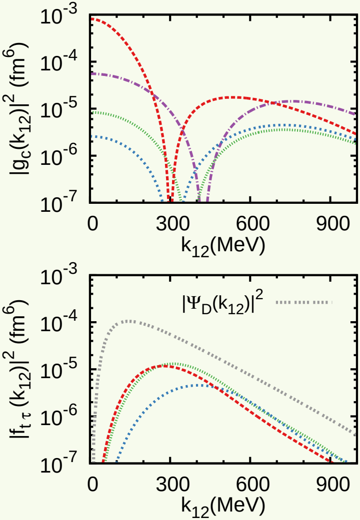

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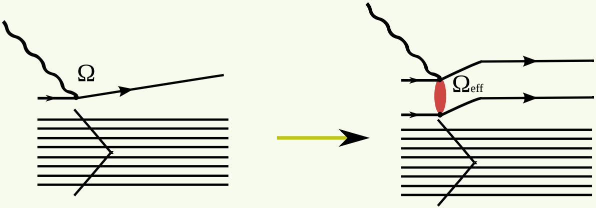
Response to EW interaction

- One-body operator matrix element $\langle\overline{\Psi}|\widehat{\Omega}|\overline{\Psi}\rangle = \langle\Psi_{\mathrm{MF}}|\,\widehat{\mathcal{G}}^{\dagger}\widehat{\Omega}\widehat{\mathcal{G}}\,|\Psi_{\mathrm{MF}}\rangle$
- Effective one-body operator receives **two-body** etc. contributions through the correlation operators.

$$\widehat{\mathcal{G}}^{\dagger}\ \widehat{\Omega}\ \widehat{\mathcal{G}} \approx \widehat{\Omega} + \sum_{i<j=1}^{A}\left(\left[\widehat{\Omega}^{[1]}(i) + \widehat{\Omega}^{[1]}(j)\right]\left[-g_c\left(r_{ij}\right) + \widehat{t}\left(i,j\right)\right] + h.c.\right)\ .$$



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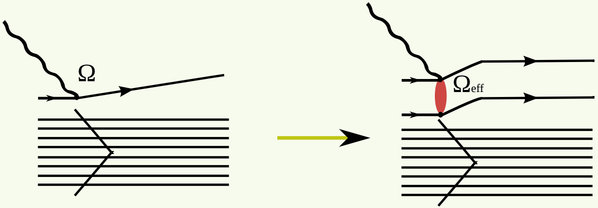

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Our Model

Quantify the amount of correlated pairs

Approximate method that covers the whole A-range

- Correlation functions require strength at $r_{12} \approx 0$
- Harmonic oscillator basis: coordinate transformation

$$\begin{pmatrix} \vec{r}_1 \\ \vec{r}_2 \end{pmatrix} \longrightarrow \begin{pmatrix} \vec{R} \\ \vec{r}_{12} \end{pmatrix}$$

- Analytical basis transformation through Standard Moshinsky Brackets

$$\begin{pmatrix} \phi_{n_1 l_1}(\vec{r}_1) \\ \phi_{n_2 l_2}(\vec{r}_2) \end{pmatrix} \xrightarrow{\langle n_1 l_1 n_2 l_2 | N L n \mathcal{L} \rangle_{SMB}} \begin{pmatrix} \phi_{NL}(\vec{R}) \\ \phi_{n\mathcal{L}}(\vec{r}_{12}) \end{pmatrix}$$

- $\phi_{nl}(\vec{r}) \sim r^l \rightarrow$ Only $\mathcal{L} = 0$ (relative S-wave) has strength at $r_{12} \approx 0$

Identify $n = 0, \mathcal{L} = 0$ pairs in the mean-field wf as prone to SRC !!

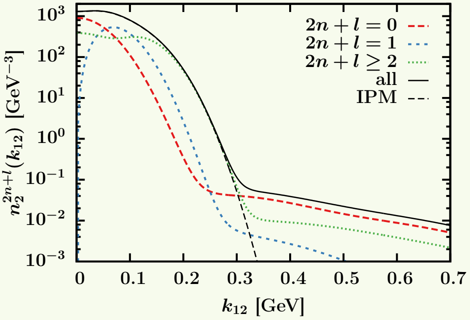
In formulas

- $$|\alpha_1\alpha_2;JM\rangle_{na} = \sum_{\substack{n_{12}l_{12}N_{12}\Lambda_{12}\\ LM_LSM_S TM_T}} \frac{\hat{j_1}\hat{j_2}\hat{L}\hat{S}}{\sqrt{2(1+\delta_{\alpha_1\alpha_2})}}\left[1-(-1)^{l_{12}+S+T}\right]$$
$$\times\langle n_{12}l_{12}N_{12}\Lambda_{12}(L)\mid n_1l_1n_2l_2(L)\rangle_{\mathrm{SMB}}\begin{Bmatrix} l_1 & l_2 & L\\ \frac{1}{2} & \frac{1}{2} & S\\ j_1 & j_2 & J\end{Bmatrix}\langle LM_LSM_S\mid JM\rangle$$
$$\times\langle\tfrac{1}{2}t_1\tfrac{1}{2}t_2\mid TM_T\rangle\left|\left[n_{12}l_{12}(\vec{r}_{12}),N_{12}\Lambda_{12}\left(\vec{R}_{12}\right)\right]LM_L,SM_S,TM_T\right\rangle$$
- Normalization: $\frac{A(A-1)}{2} = \sum_{\substack{JM\\ \alpha_1\alpha_2}} {}_{na}\langle\alpha_1\alpha_2;JM\,|\alpha_1\alpha_2;JM\rangle_{na}$
- Suggestion: number of correlated pairs

$$N(A,Z) = \sum_{\substack{JM\\ \alpha_1\alpha_2}} {}_{na}\left\langle\alpha_1\alpha_2;JM\left|\mathcal{P}_{\vec{r}_{12}}^{n=0,l_{12}=0}\right|\alpha_1\alpha_2;JM\right\rangle_{na}$$

Dominance of $n = 0, \mathcal{L} = 0$ pairs

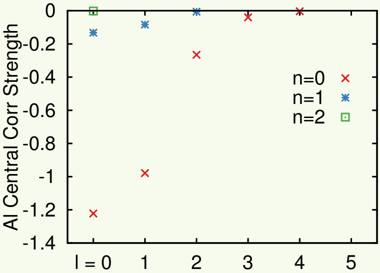
^{56}Fe two-body relative momentum distribution

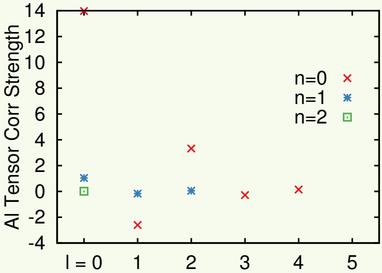


- First order cluster expansion
- Contribution of different relative quantum numbers
- Clear dominance of IPM $n = 0, l = 0$ above the Fermi momentum
- Correlation operators can change the quantum numbers of course

Strength of correlation functions

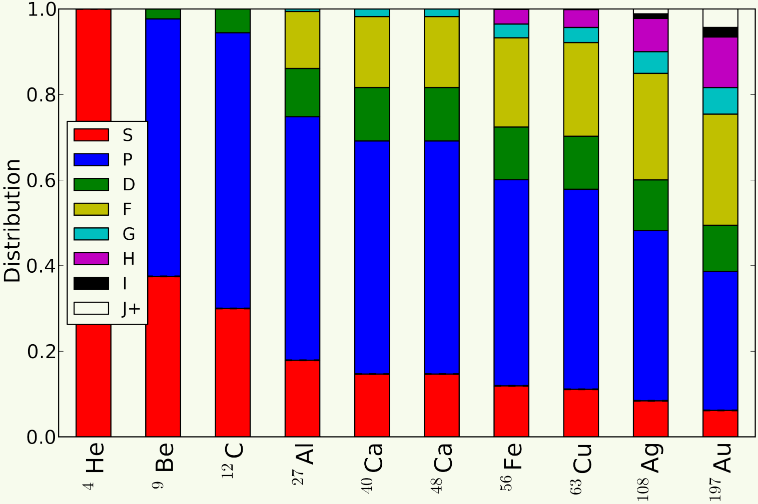
Overlap of correlation function with different contributions





- Integrated effect of the tensor correlations is larger by a factor of ≈ 10 compared to central correlations
- $n = 0, \mathcal{L} = 0$ contributions dominate

Distribution of the relative quantum numbers $\mathcal{L} = S, P, D, F, G, H, I, \geq J$ for pp pairs



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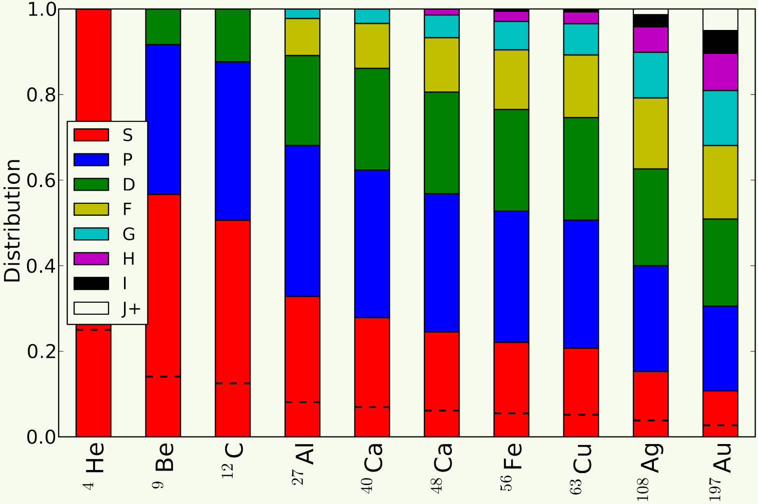

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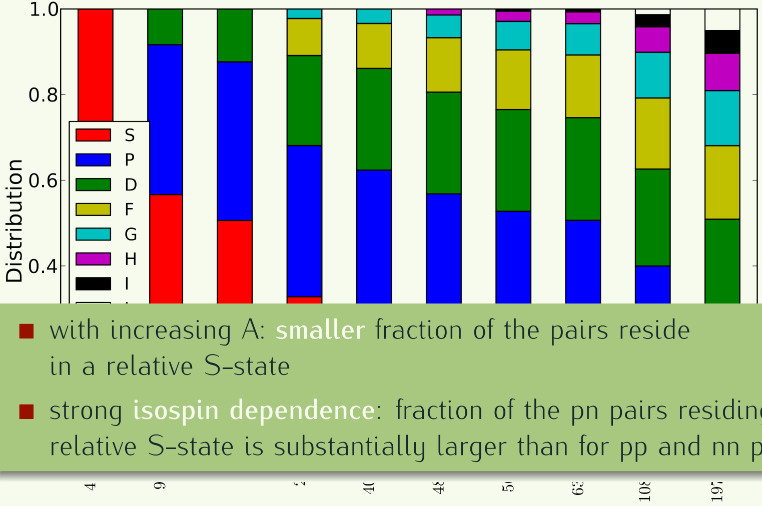
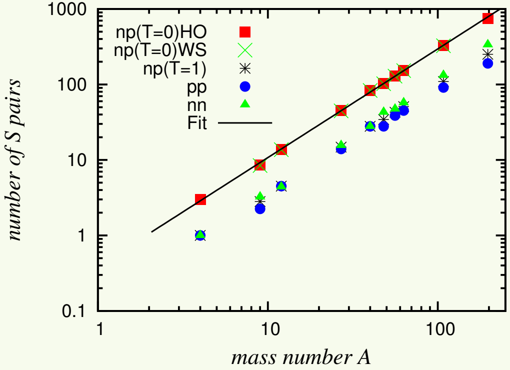


- with increasing A: **smaller** fraction of the pairs reside in a relative S-state
- strong **isospin dependence**: fraction of the pn pairs residing in a relative S-state is substantially larger than for pp and nn pairs.

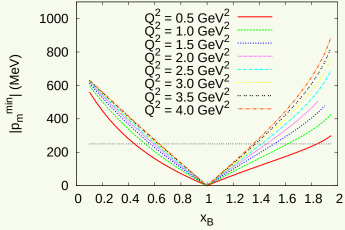
Number of pp, nn and pn pairs with $\mathcal{L} = 0$

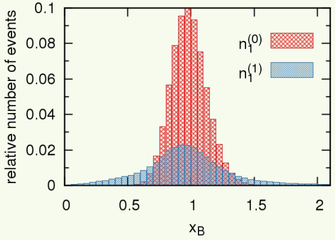


power law $\sim A^{1.44 \pm 0.01}$

- Very soft A-dependence (naive A^2)
- Power law is robust
- Isospin dependence

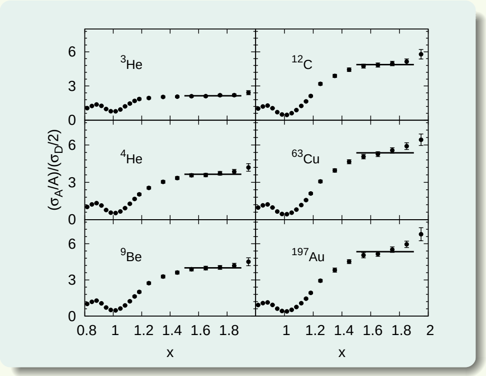
Inclusive electron scattering measurements





- Inclusive A(e,e') scattering at Bjorken $x > 1.4$ and high Q^2
- SRC universality: Cross section ratios to the deuteron show scaling $\sigma^A = a_2 \frac{A}{2} \sigma^D \rightarrow a_2$ is measure for the amount of correlated pairs
- Compared to deuteron correlated pair in nucleus A also has
  - Binding energy
  - Center of mass motion
  - FSI with nuclear medium

A-dependence of SRC: experiment



data: Fomin et al. (JLab Hall C), PRL108 092502

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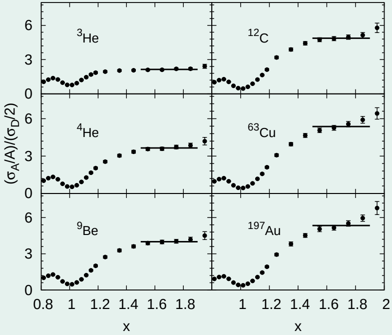

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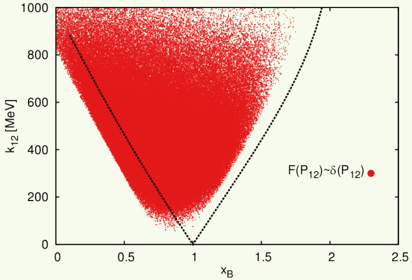
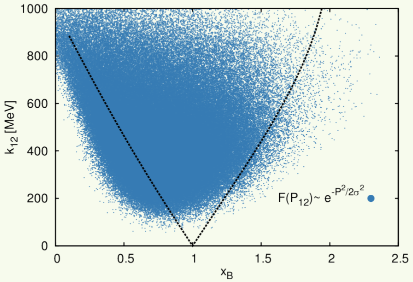
Nuclear corrections for a_2

Effect of $A-2$ excitation energy



MC simulations of breakup of 2N correlated pairs in ^{12}C for $\epsilon = 5.766$ GeV and $\langle Q^2 \rangle$=2.7 GeV^2

Effect of c.m. motion of pn pairs



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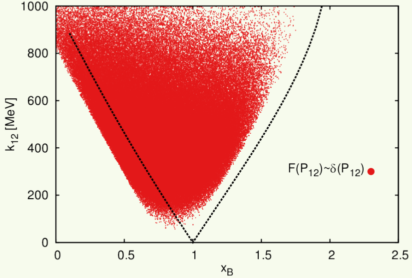

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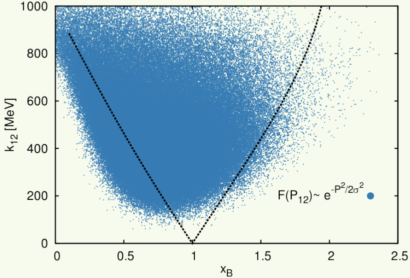
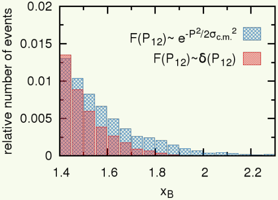
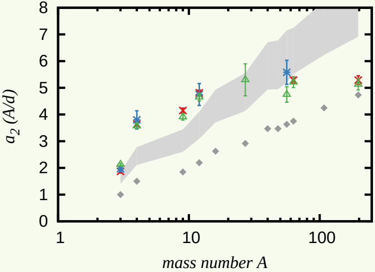






Data: K. Egiyan et al. (CLAS), PRL96 082501 ('06), N. Fomin et al. (JLab Hall C), PRL108 092502 ('12)

L. Frankfurt et al. (SLAC), PRC48 2451 ('93)

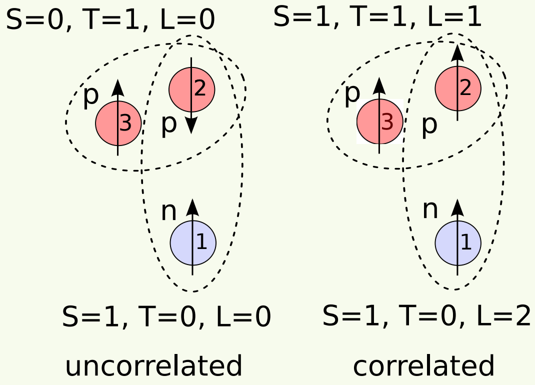
- Assumed dominance of np pairs with relative $n = 0, l = 0 (S = 1)$
- $a_2 \approx \frac{2}{A} N_{pn(S=1)}(A, Z) \int_{PS} d\vec{P}_{12} F^{pn}(P_{12})$

- Corrections of the c.m. motion and binding applied
- FSI being worked on...
- Prediction: $a_2(^{40}\mathrm{Ca}) \approx a_2(^{48}\mathrm{Ca})$ [preliminary Hall A E08014 data seems to agree]
- Missing strength at low A due to clustering?
- Overestimation at high A.
- Mass dependence much softer than NZ.

Can one quantify the number of $3N$ correlations?

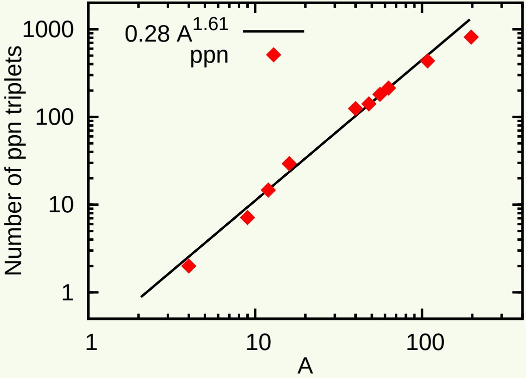
Three-body correlations induced by tensor correlations

$$\left(f_{t\tau}(r_{12})\widehat{S_{12}}\right)\left[f_{LS}(r_{23})\vec{L}_{23}\cdot\vec{S}_{23}\right]$$



Feldmeier, Horiuchi, Neff, Suzuki: PRC84 054003

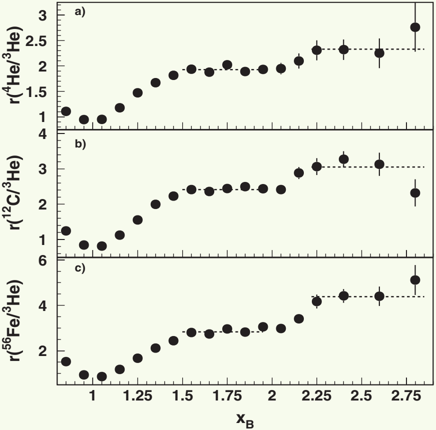
Mass dependence of number of ppn triples with $\left(l_{12} = 0, l_{(12)3} = 0\right)$



- Number of ppn triples prone to SRC effects $(l_{12} = 0, l_{(12)3} = 0)$: $N_{ppn}(A) = 0.28A^{1.61}$
- Again very soft A-dependence

$A(e,e')$ for $2.2 \lesssim x_B$ and 3N SRCs

Scaling of the $A(e,e')$ response to the ^{3}He one



JLab Hall-B, PRL96, 082501

- Quantify scaling behavior:

$$a_3\left(A/^3He\right) \equiv \frac{3}{A}\frac{\sigma^A\left(x_B,Q^2\right)}{\sigma^{^3He}\left(x_B,Q^2\right)},$$

- Assume that signal is dominated by the ppn correlations!
- Assume that $\sigma_{eppn}(Q^2,x_B) \approx \sigma_{e^3He}(Q^2,x_B)$
- Very naive counting (all ppn triples contribute): $a_3 \sim A^2$
- Suggestion: $a_3(A/^3He) \sim \frac{3}{A}N_{ppn}(A)$ (number of ppn triples with $l_{12}=0, l_{(12)3}=0$)

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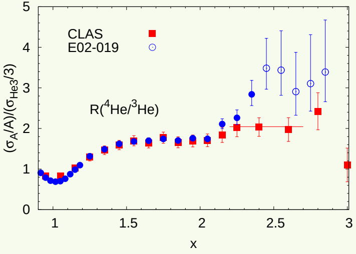

JLab Hall-C, PRL108, 092502

Discrepancy in the data (see also prelim. Hall A E08014 results)

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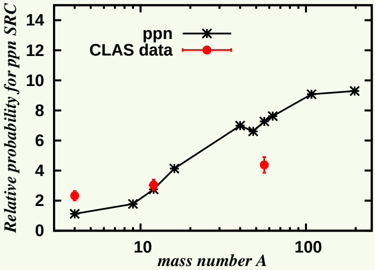

$a_3(A/^3He)$ as a measure of the per-nucleon probability of ppn SRC relative to ^{3}He (calculations are NOT corrected for c.m. motion, FSI, ...)

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- Assume that signal is dominated by the ppn correlations!
- Assume that $\sigma_{eppn}(Q^2,x_B) \approx \sigma_{e^3He}(Q^2,x_B)$
- Very naive counting (all ppn triples contribute): $a_3 \sim A^2$
- Suggestion: $a_3(A/^3He) \sim \frac{3}{A}N_{ppn}(A)$ (number of ppn triples with $l_{12}=0, l_{(12)3}=0$)

Exclusive $A(e, e'NN)$ scattering measurements

Exclusive $A(e,e'pp)$ reactions

Probe the content of nuclear SRC? $\rightarrow$ exclusive 2N knockout!!

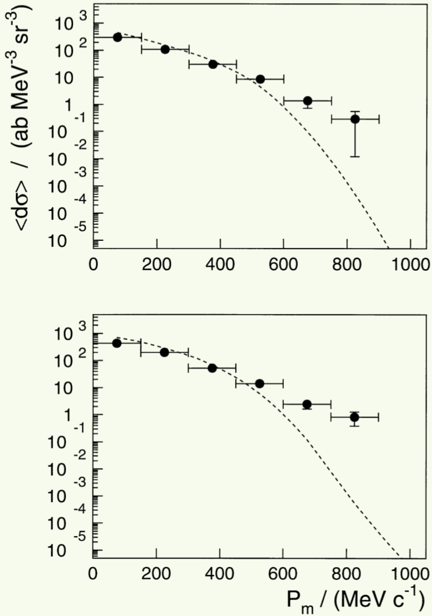
The fact that SRC-prone proton-proton pairs are mostly in a state with relative orbital momentum $l_{12}=0$ has important consequences for the EXCLUSIVE $A(e,e'pp)$ cross sections (J.R. PLB 383,1 ('96))!!

- The $A(e,e'pp)$ cross sections factorizes according to

$$\frac{d^8\sigma}{d\epsilon' d\Omega_{\epsilon'} d\Omega_1 d\Omega_2 dT_{p_2}}(e,e'pp) \approx K\sigma_{eN_1N_2}(k_+,k_-,q)F^D(P)$$

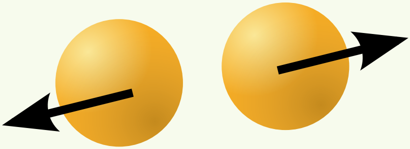
- $F(P)$: probability to find a diproton with c.m. momentum P and relative orbital momentum $l_{12}=0$!

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



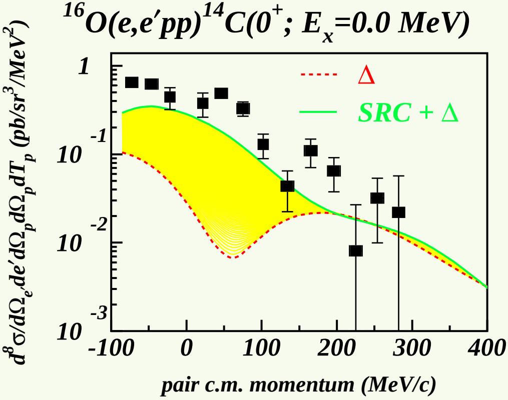
$^{12}C(e, e'pp)$ @ MAMI (Mainz)
(PLB **421** (1998) 71.)

- Up to $\mathbf{P} = \mathbf{0.5}$ **GeV** c.o.m. motion in ^{12}C is mean-field (Gaussian) like
- Data agree with the factorization in terms of $F(P)$!
- Largest at $P_m = 0 \rightarrow$ back-to-back



What do experiments say (2)

Triple coincidence measurements $A(e,e'pp)$ at low Q^2 determined the quantum number of the correlated pairs!

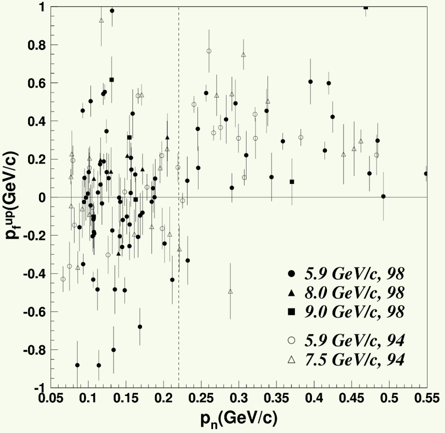


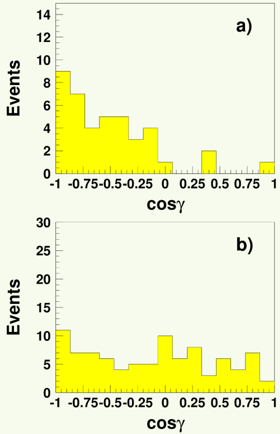
Unfactorized theory (MEC, IC, central + tensor correlations)
EPJA 20 (2004) 435

- High resolution $^{16}O(e,e'pp)$ studies (MAMI, NIKHEF)
- Ground-state transition: $^{16}O\ (0^+) \rightarrow {}^{14}C\ (0^+)$
- Quantum numbers of the active diproton [relative (c.m.)]: $^1S_0(\Lambda=0)$ (lower P) and $^3P_1(\Lambda=1)$ (higher P)
- only $^1S_0(\Lambda=0)$ diprotons are subject to SRC

What do experiments say (3)

2N correlations in $^{12}\mathrm{C}(p, 2p + n)$ at BNL

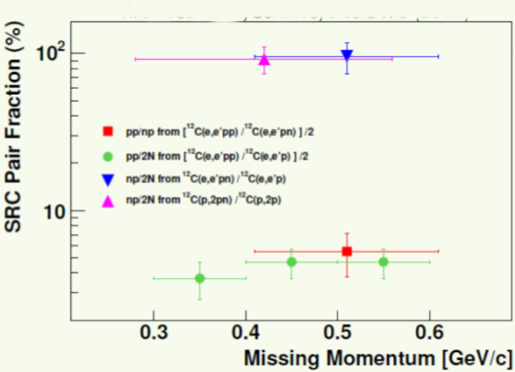




Tang et al., PRL90, 042301 ('03)

What do experiment say (4)

2N correlations in $^{12}\mathrm{C}(e,e'pp)$ / $^{12}\mathrm{C}(e,e'p)$ JLAB Hall A

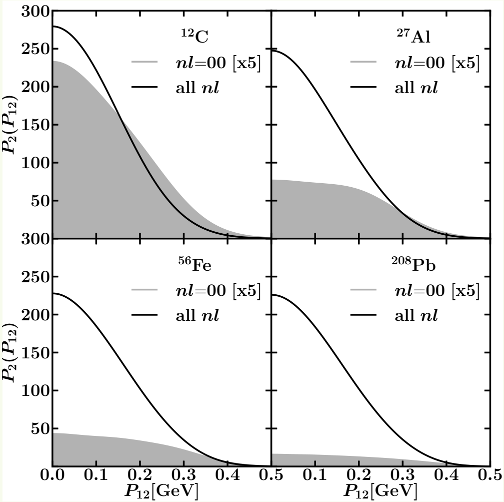


- 20% of the nucleons are in a SRC pair
- 90% of the correlated pairs are *np* pairs → tensor force dominance

R. Subedi et al., Science 320, 1476 ('08)
R. Shneor et al., PRL99, 072501 ('07)

The pp c.m. momentum distribution

$$d\sigma(e,e'pp) \approx K\sigma_{eN_1N_2}(k_+,k_-,q)F(P)$$

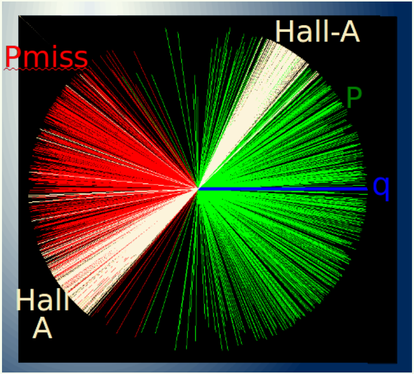


- $F(P)$: probability to find a diproton with c.m. momentum P and relative orbital momentum $l_{12} = 0$!

Widths of c.m. momentum distributions carry information about the quantum numbers of the pairs

- Strength has very soft A-dependence

$A(e, e'pp)$ data from Hall B



$x_B > 1.2$, $\theta_{pq} < 25°$,
$0.62 < p/q < 0.96$, $p_m > 300\text{MeV}$
`Fig. from Or Hen`

- CLAS data mining effort (L. Weinstein et al.)
- Study the influence of experimental cuts on $F(P)$ in a MC
- Check: nice agreement with opening angle distribution from Hall A $A(e, e'pp)$ data
- Widths a little bit ($\sim$ 10 MeV) narrower after the MC
- Influence of FSI checked in our RMSGA model (relativistic Glauber), widths again narrow by about 10 MeV

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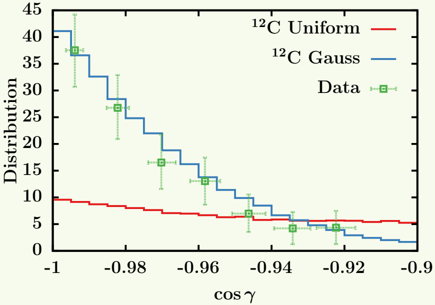

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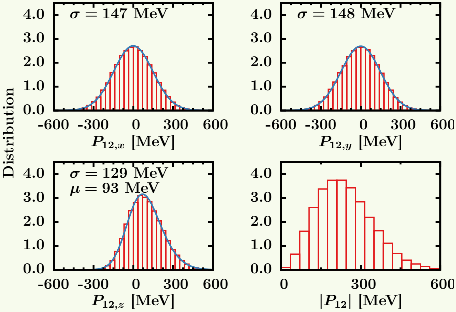

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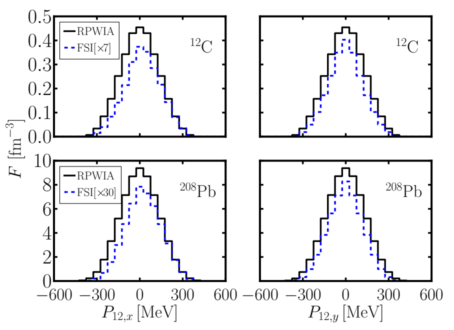

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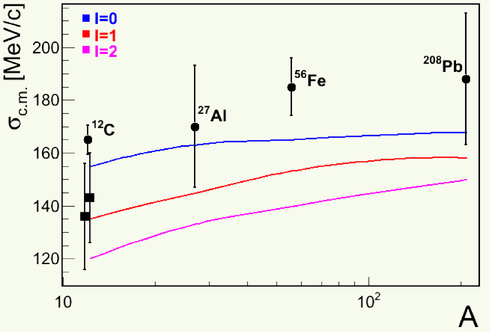
Center of mass motion of correlated pp pairs



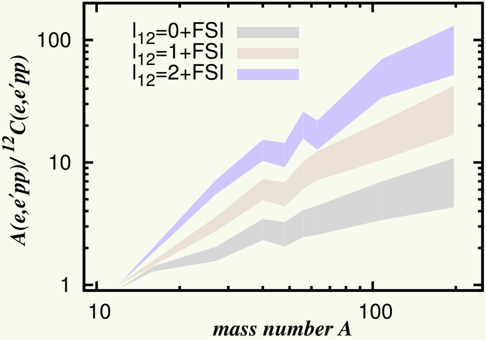
DATA IS **PRELIMINARY**! COURTESY OF CLAS DATA MINING (O. HEN AND E. PIASETZKY)

- Analysis of exclusive $A(e,e'pp)$ for ^{12}C, ^{27}Al, ^{56}Fe, ^{208}Pb
- Distribution of events against P is fairly Gaussian
- $\sigma_{c.m.}$: Gaussian widths from a fit to measured c.m. distributions
- Theory lines: Gaussian fits to computed c.m. distributions for $I = 0, 1, 2$

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

Prediction: A dependence of $A(e, e'pp)$ cross section 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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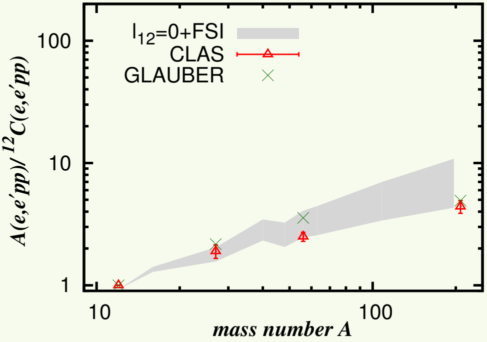
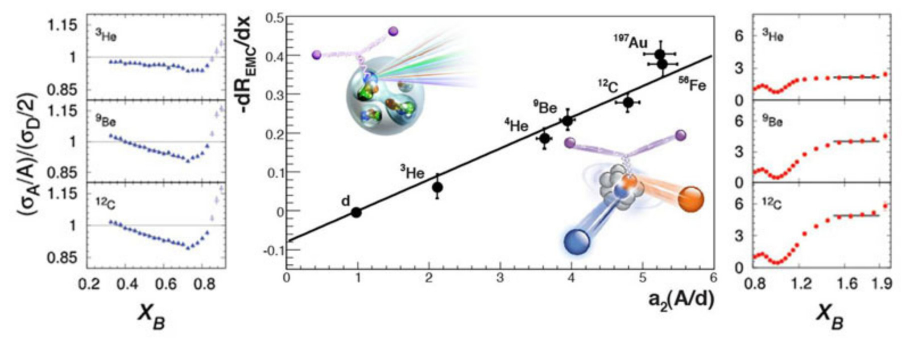


- PRELIMINARY DATA (COURTESY OF O. HEN AND E. PIASETZKY) COMPATIBLE WITH ABSORPTION ON $l_{12} = 0$ PAIRS!
- Relativized Glauber calculation in zero range approximation (relative S $\rightarrow \delta(r_{12})$) agrees as well
- Last time: very soft A-dependence

EMC vs SRC

Experimental Observation: EMC vs SRC



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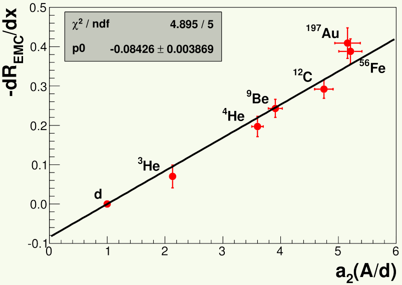

L.B. Weinstein et al. PRL106 052301 ('11)
O. Hen et al. PRC85 047301 ('12)

- EMC effect quantified by slope of ratio F_{2A}/F_{2N}.
- Recent observation that $a_2(A)$ and EMC slope show a linear correlation.
- Suggests that both phenomena might be driven by **local density** and/or **high virtuality** fluctuations.
- Several experiments planned for JLAB12 (deuteron EMC, isospin dependence, more a_2, EMC measurements,...)

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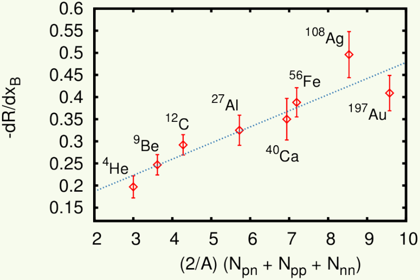

- Number of relative S-pairs per nucleon shows linear correlation with EMC slopes.

- EMC effect quantified by slope of ratio F_{2A}/F_{2N}.
- Recent observation that $a_2(A)$ and EMC slope show a linear correlation.
- Suggests that both phenomena might be driven by **local density** and/or **high virtuality** fluctuations.
- Several experiments planned for JLAB12 (deuteron EMC, isospin dependence, more a_2, EMC measurements,...)

Conclusions

- The number of SRC-prone pairs in a nucleus $A(N, Z)$ is proportional with the number of IPM pairs in a **relative** S state ($n = 0, \mathcal{L} = 0$) or *close* together
- The number of SRC-prone pairs follows a robust power law for pp,pn,nn: $\sim A^{1.44 \pm 0.01}$
- Inclusive $A(e, e')$ at $1.5 \lesssim x_B$ (2N): The $a_2\,(A/D)$ can be predicted and these predictions are not inconsistent with trends and magnitude of the data (corrections for c.m. motion)
- Inclusive $A(e, e')$ at $2.2 \lesssim x_B$ (3N): Fair prediction for the $a_3\left(A/^3\mathrm{He}\right)$
- Exclusive $A(e, e'pp)$:
  - scaling behavior of cross section with c.o.m. momentum $\sim F(P)$: Confirmed!
  - very soft mass dependence of cross section: Confirmed!
- Magnitude of the EMC effect $\frac{-dR_{EMC}}{dx_B}$ is proportional with the predicted number of SRC-prone pairs