# Detailed study of EMC, SRC effects and their correlations

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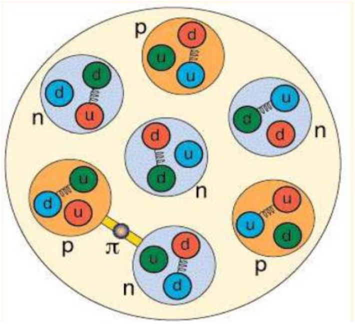
( in collaboration with J. Arrington, D. Day, N. Fomin, D. Gaskell, P. Solvignon)

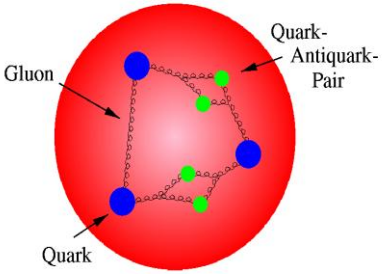
Jefferson Lab Hall C summer workshop, June 22, 2012

# Context and questions

- **Nuclei = protons + neutrons**
  **( Traditional nuclear physics )**



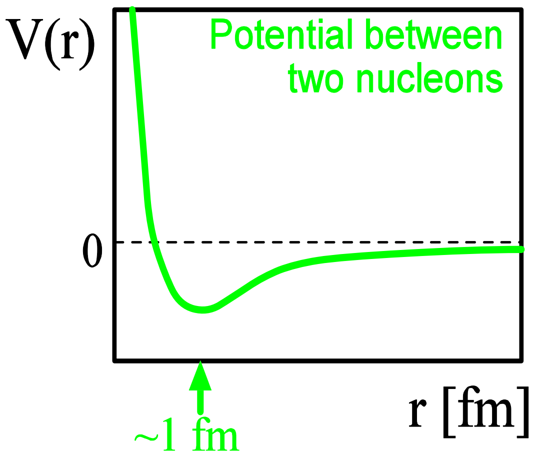

- **Nucleons= q + qbar +gluons**
  **( Quantum Chromo Dynamics )**




- **How protons and neutrons are built from quarks and gluons?**

- **How protons and neutrons interact to form the nucleus?**

# Context and questions

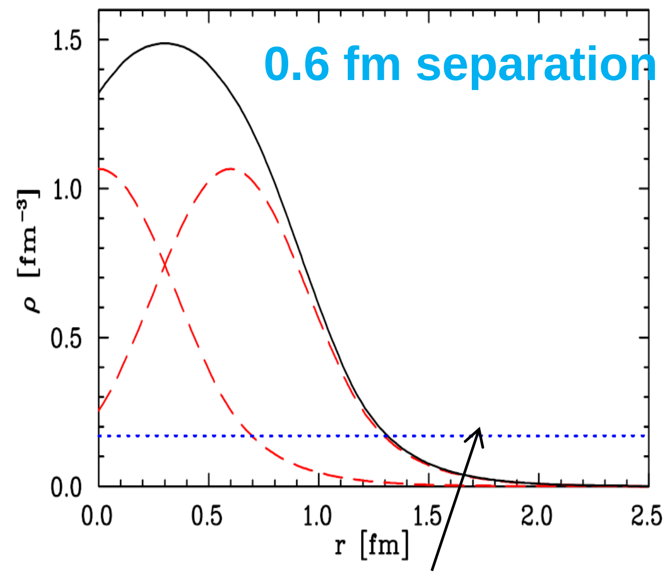



- Nucleons are tightly packed in nuclei; nucleon separation is only limited by the short range repulsive core.

- Even for a 1 fm separation, the central densities can increase by a factor of ~4 (neutron star density!).

- Are this high density local fluctuations high enough to modify nucleon structure?

- Are the quark momentum distributions modified by these transient density fluctuations?




Average nuclear density

Need to get a handle on these medium modifications for a QCD based understanding of nuclei.

# Outline

- EMC effect
- Short range correlations
- Connection between EMC effect and short-range correlations
- Future experimental investigations
- Summary

# The EMC effect

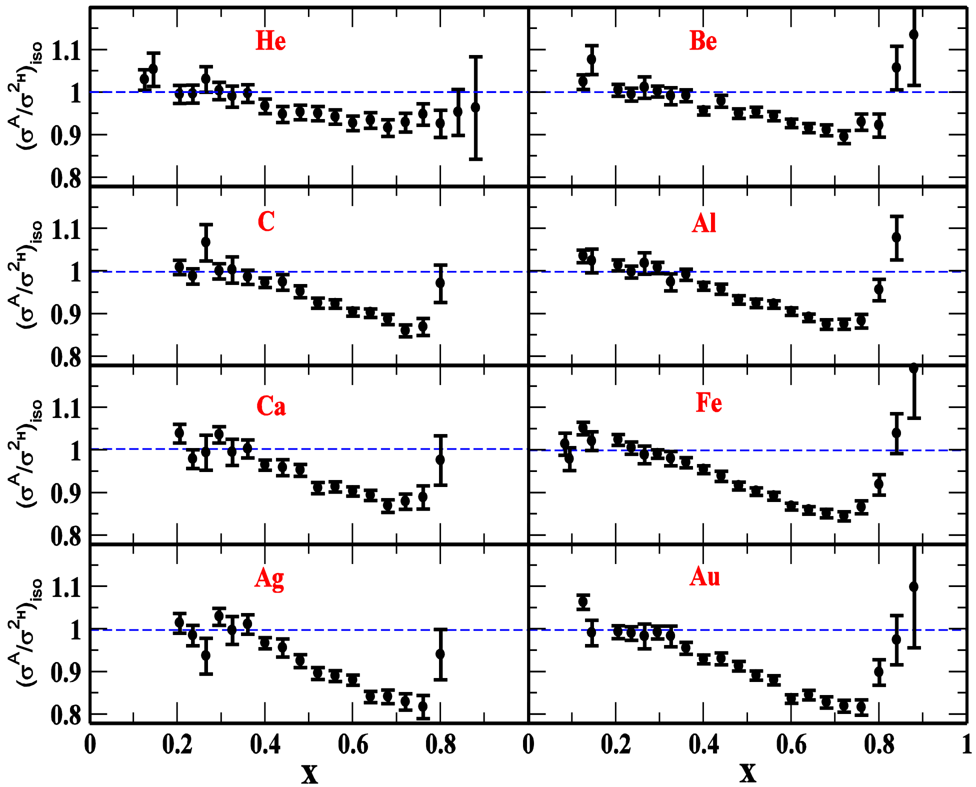
# The EMC effect

**EMC effect indicates that quark distributions are modified inside nuclei.**

Aubert et al., Phys. Lett. B123, 275 (1983)

**Extensive measurements on heavy targets (SLAC, NMC, BCDMS,..)**

- **SLAC E139**
  - **Most precise large-x data (before E03103)**
  - **Nuclei from A=4 to 197**
- **Conclusions from SLAC E139**
  - **$Q^2$-independent**
  - **Universal x-dependence (same shape) for all A**
  - **Magnitude varies with A**
    - **Scales with A**
    - **Also scales with *"average"* nuclear density**




**SLAC E139**

*Gomez et al., Phys. Rev. D49, 4348 (1994).*

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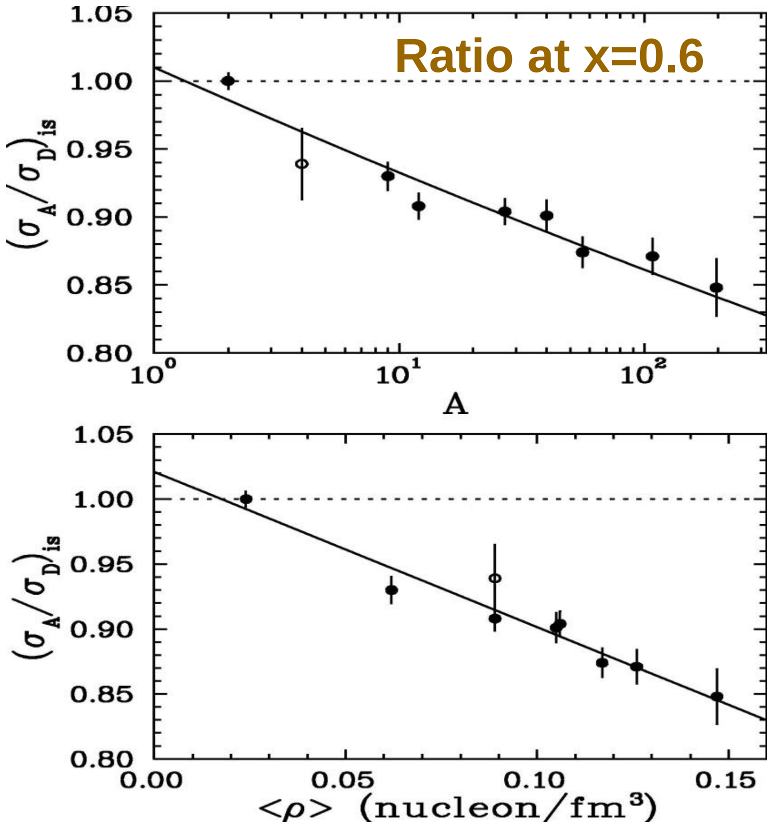


**SLAC E139**

*Gomez et al., Phys. Rev. D49, 4348 (1994).*

## The EMC effect: Jlab E03103 collaboration

# Main goals of E03-103 in Hall C at JLab

- First measurement of EMC effect on $^3$He for x > 0.4
- Precision of $^4$He ratios.
- Precision data at large x for heavy nuclei.

- Ran during summer and fall of 2004 with 5.77 GeV.

  (spokespersons: J. Arrington, D. Gaskell)

- Cryo targets: $^1$H, $^2$H, $^3$He, $^4$He
- Solid targets: Be, C, Al, Cu, Au
- Additional data at 5 GeV on carbon and deuterium to investigate detailed $Q^2$ dependence of the EMC ratios.
- Concurrent with E02019 (inclusive cross sections at x>1, F(y) scaling, short range correlations, ...)

# The EMC effect: E03103 results

**Light nuclei results published in J.Seely, et al., PRL103, 202301 (2009)**

- E03103 results are consistent with previous world data
- First measurement of EMC effect on $^3$He for $x > 0.4$
- Provided high precision data for $^4$He
- Cross section ratios appears to scale (independent of $Q^2$) to very large x.

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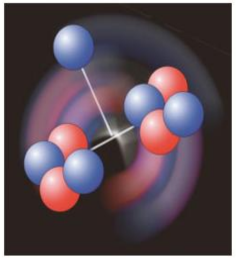
Phys. Rev. Lett. **103**, 202301
(issue of 13 November 2009)
Title and Authors

**20 November 2009**

## Quarks Influenced by Their Neighborhood

The internal structure of a proton or neutron is not completely fixed--experiments going back decades suggest that the particles are slightly different when inside a nucleus. Now results in the 13 November *Physical Review Letters* show that the effect is not dependent on the mass or on the density of the entire nucleus, as some theories have predicted. Instead, neutrons and protons appear to change according to their immediate neighborhood within the nucleus.



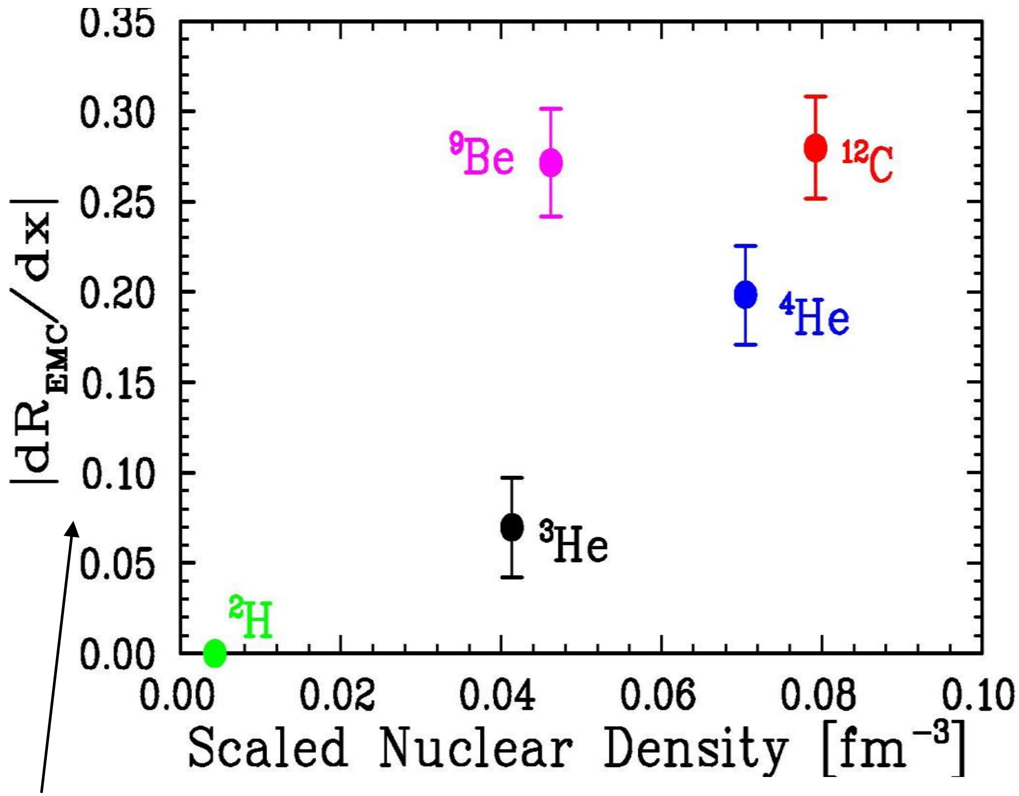
P. Mueller/Argonne National Lab

**Long paper with results including heavy nuclei soon (A. Daniel et al., in preparation)**

# E03-103 results

J.Seely, et al., PRL103, 202301 (2009)

- **Large difference in the magnitude of the EMC effect in $^3$He and $^4$He doesn't support previous mass dependent fits.**
- **Both A- and ρ-dependent fits fail to describe these light nuclei.**
- **Data show smooth behavior as density increases except for $^9$Be.**
- **One possible explanation is that the effect depends on nucleon's local environment.**




❑*Size of the effect given by a fit to the cross section ratios between x= 0.35 and x= 0.7*
❑*Nuclear densities scaled by (A-1)/A to avoid contribution from struck nucleon*
❑*Average density calculated using ab-initio GFMC calculation*

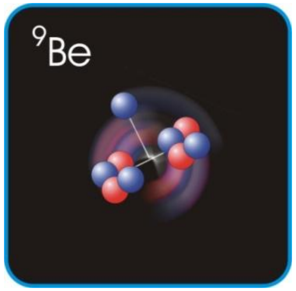
(S.C. Pieper and R.B. Wiringa, Ann. Rev. Nucl. Part. Sci 51, 53 (2001))

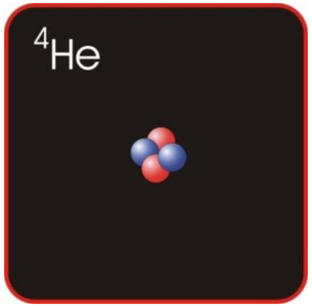
# E03-103 results

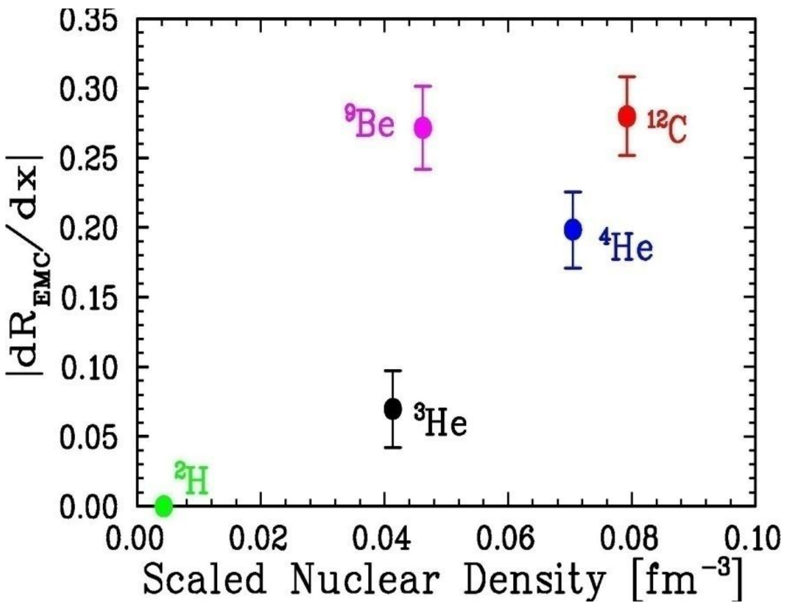
J.Seely, et al., PRL103, 202301 (2009)

- **Though $^9$Be has low average density; large component of the structure is $2\alpha+n$ , all protons are in $\alpha$ like clusters**

  ***(K. Arai, et al., PRC54, 132 (1996))***



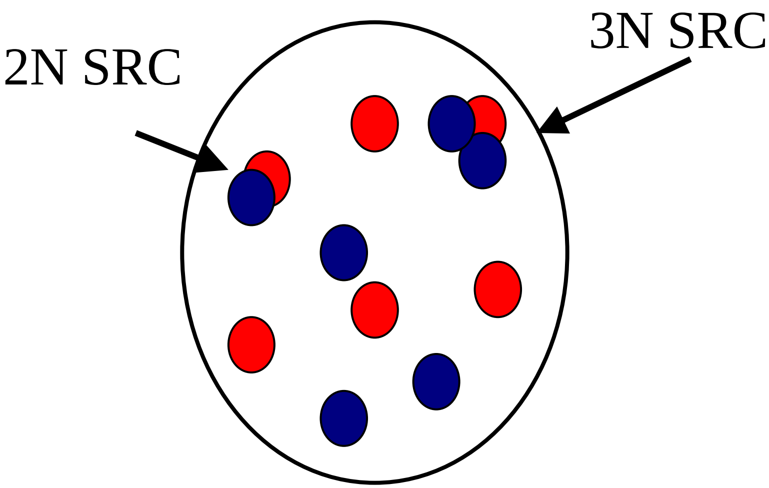



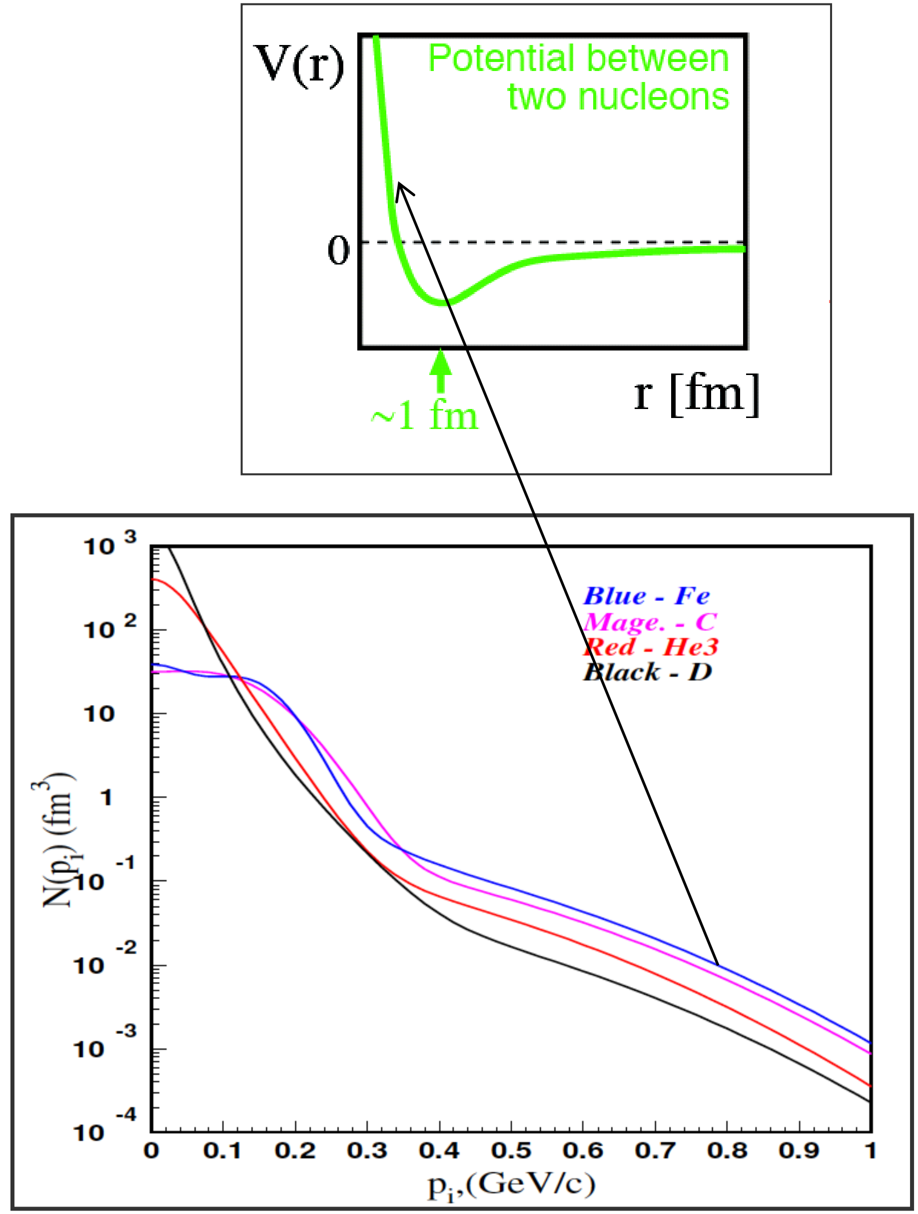

- **Higher density regions contribute to larger nuclear modifications than expected from simple shell model calculations**
- **High dense regions could alter the nucleon (and quark) momentum distributions or even internal structure of nucleon itself**

**EMC effect is a local effect; not a bulk property of nuclear medium**

# Short-range Correlations

# Short-range correlations




- ❑Short-range NN interaction generates high momenta ($k>k_{Fermi}$)
- ❑Universal mechanism for all nuclei
- ❑Similar shape for $k>k_{Fermi}$
- ❑ Momentum of fast nucleons is balanced by the correlated nucleon(s), not the rest of the nucleus

C. Ciofi degli Atti and S. Simula, Phys. Rev. C **53** (1996) 1689.

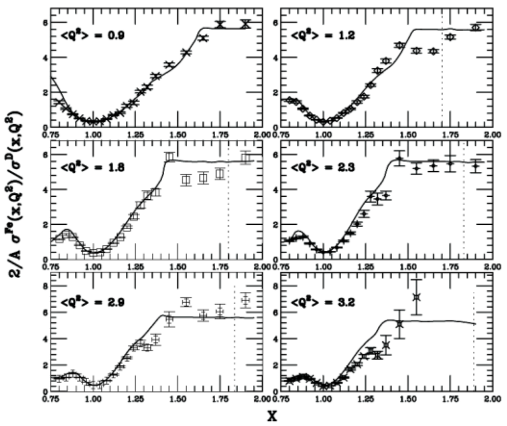
# Short-range correlations

## *A(e,e') at x>1*

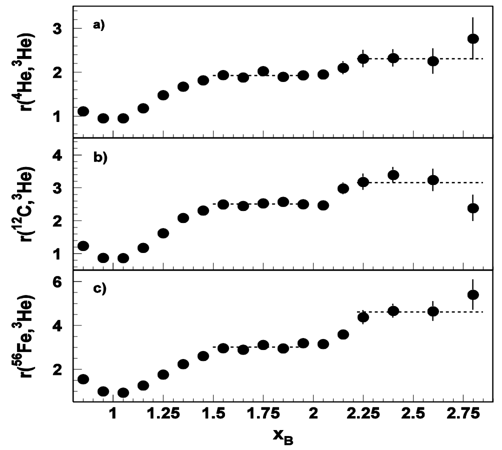
***For momentum sufficiently above $k_F$, mean field contributions small; dominated by 2N-SRCs***

- **SRC results in universal shape of the nuclear wave function for all nuclei at $K>K_F$; then $n_A(k)= a_2(A)\ n_D(k)$**
- **To measure the probability of finding a correlation, ratios of heavy to light nuclei are taken**
- **Observed scaling (flat ratios) suggests that the electron is probing the high momentum nucleon.**

D. Day et al PRL 59, 427 (1987)



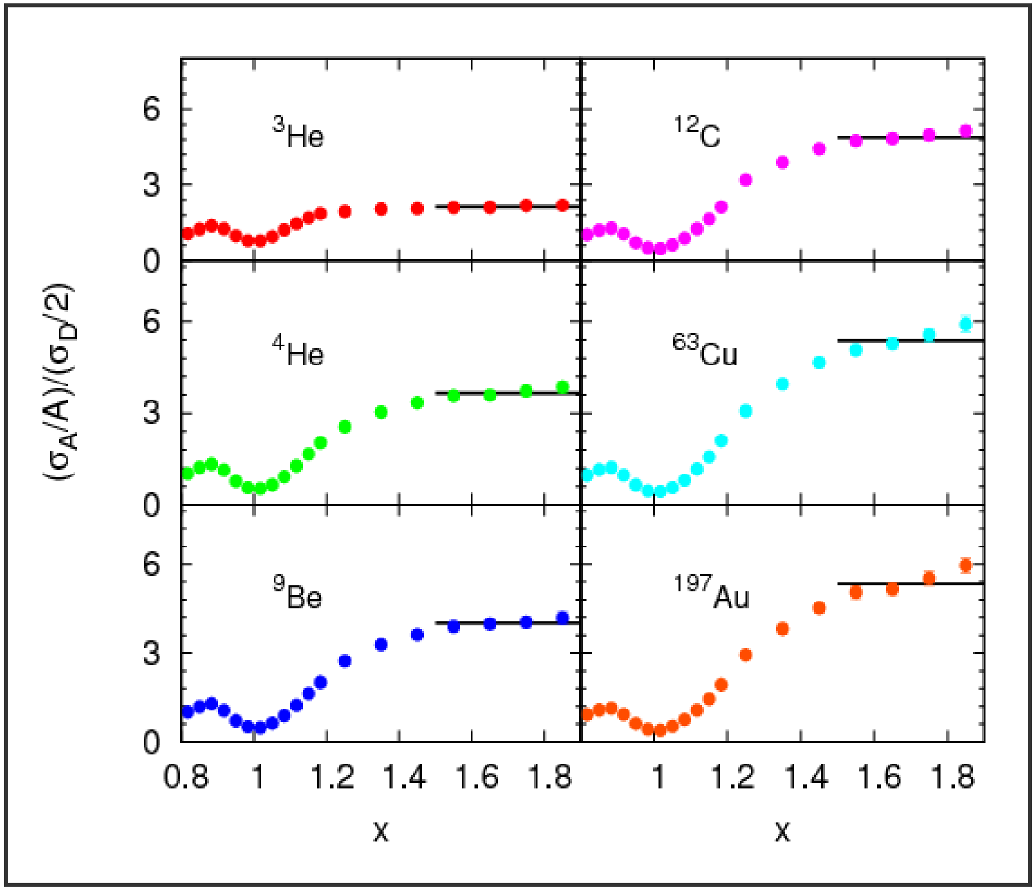

Frankfurt, Strikman, Day, Sargsyan PRC48, 2451 (1993)




CLAS data, Egiyan et al. PRL. 96, 082501 (2006)

# Short-range correlations: new Hall C data

- More recently new data from E02-019 (spokespersons J. Arrington, D. Day, B. Filippone, A. Lung)
- Ran in Hall C (concurrent with E03103 )
- 2N correlations in “direct ‘’ A/D ratios (no interpolation)
- Ratios in plateau, proportional to number of 2N SRCs



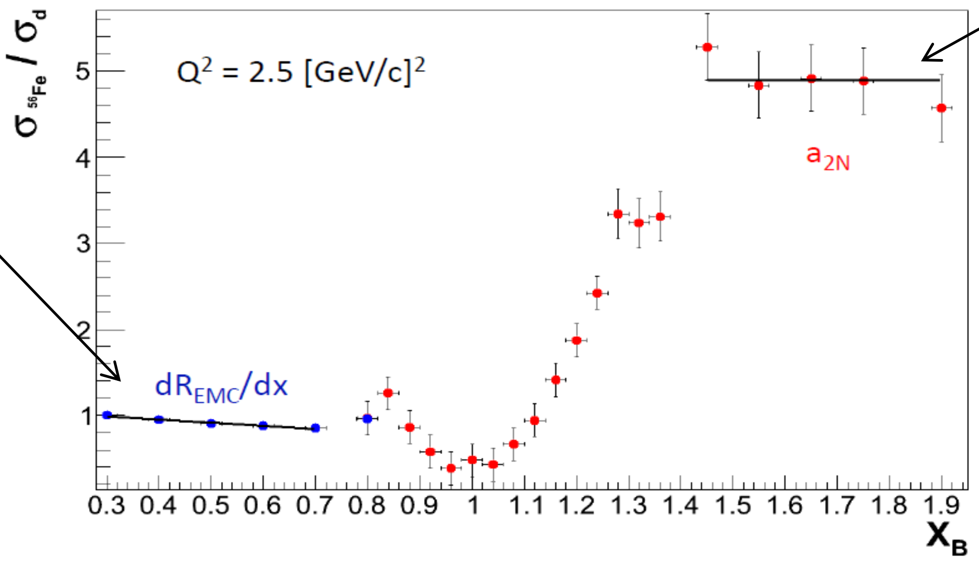

Fomin et al., PRL108, 092502 (2012)

# EMC-SRC Connection

# Cross section ratios from inclusive scattering at x>1 and x<1

**DIS probes partonic (quark) structure of hadrons**

**Inclusive scattering at x>1 probes partonic (nucleon) structure of nuclei.**




D. Higinbotham et al., arXiv: 1003.4497

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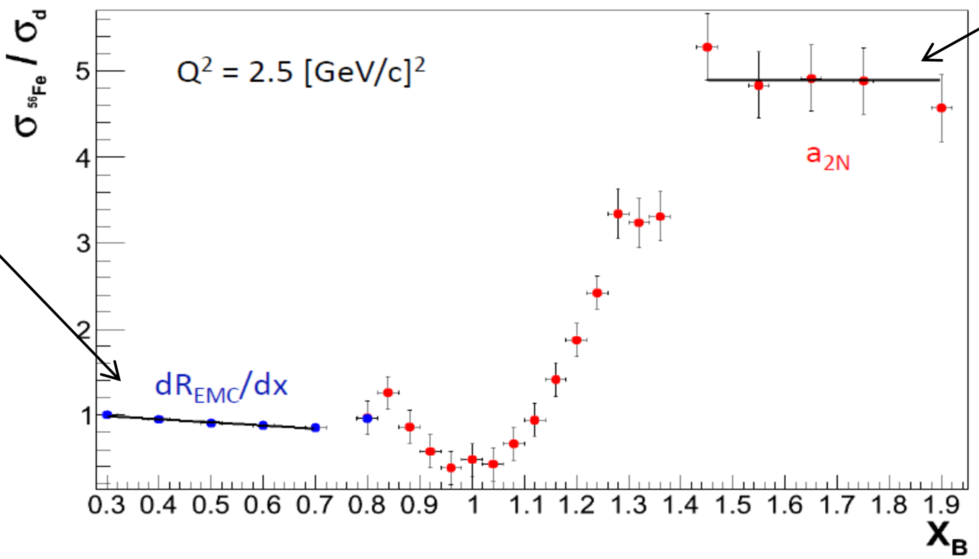



D. Higinbotham et al., arXiv: 1003.4497

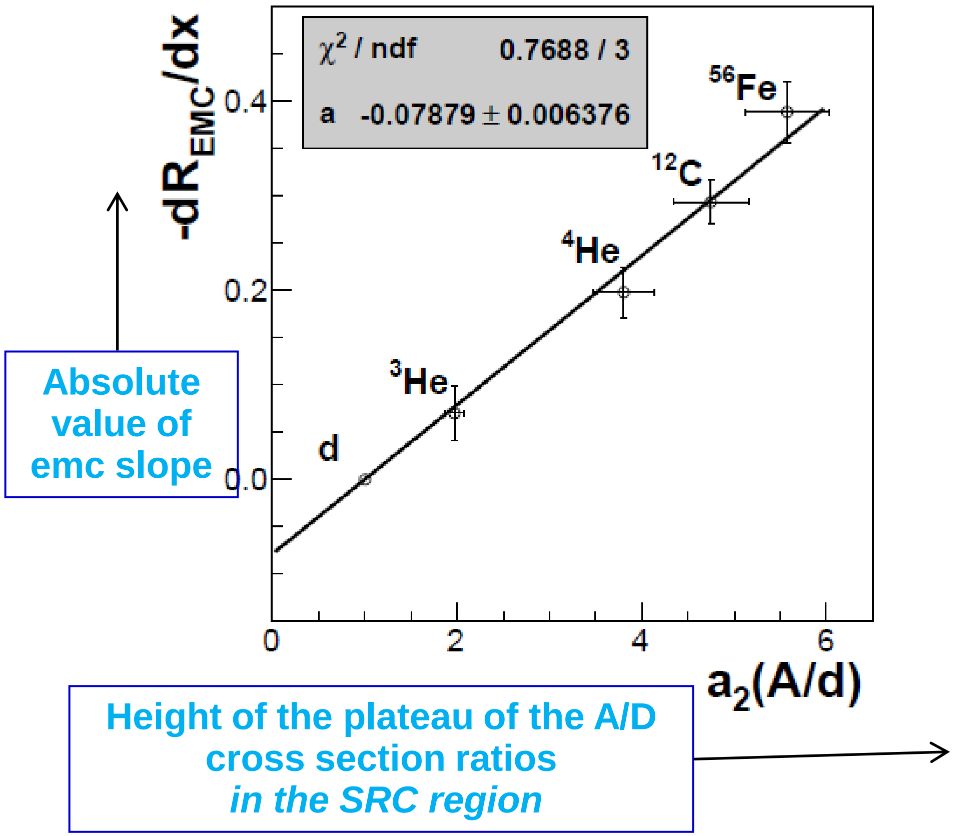
**Two processes share the same initial state; however different mechanisms (QES vs DIS)**

**Is there a connection between EMC slopes and SRC scaling plateaus?**

**How are they connected?**

**What is the underlying cause?**

# SRC vs EMC




*L. B. Weinstein, E. Piasetzky, D.W. Higinbotham, J. Gomez, O. Hen, R. Schneor PRL 106:052301,2011*

- **Observed a linear relationship between magnitude of EMC effect and SRC scaling factor.**
- **Suggests both effects could be sensitive to a similar quantity; one explanation is nucleons at high momentum (virtuality)**

**Both effects probes what happens when nucleons come close together, is one sensitive to some dynamics that drive the other?**

**Let's look at these processes in some detail**

# SRC vs EMC: some analysis details

## Data sets used

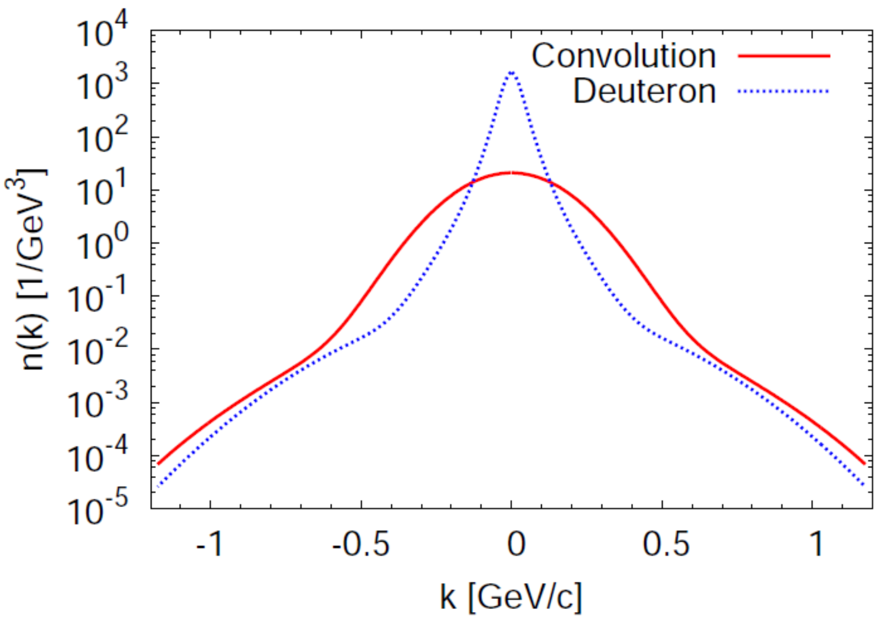
- ❑For EMC: SLAC E139, Jlab Hall C E03103
- ❑For SRC: SLAC, Jlab Hall B (CLAS), Jlab Hall C E02019

# SRC vs EMC: some analysis details

**Data sets used**

- ❑**For EMC: SLAC E139, Jlab Hall C E03103**
- ❑**For SRC: SLAC, Jlab Hall B (CLAS), Jlab Hall C E02019**

- ❑ **In PWIA, the number of SRC pair $a_2=n_A(k)/n_2(k)$ (assumes SRCs are at rest)**
- ❑**However, for A>2, the SRC pair moves in mean field created by rest of the nucleons**
- ❑**Non zero CM momentum will flatten QE peak, lower the low momentum part and enhance the high momentum tail**
- ❑**This is an A-dependent correction (estimated to be ~20% for heavy nuclei)**

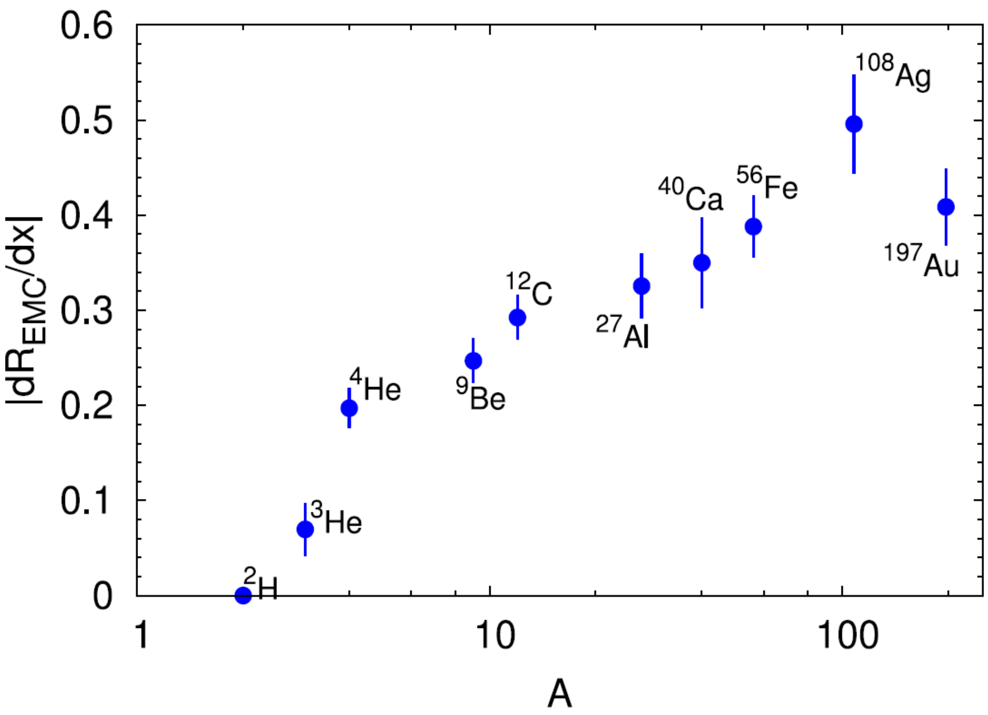



n(k) in deuterium and n(k) in deuterium convoluted with CM motion of corelated pairs in Fe (prescription from C. D. Atti, Simula PRC53, 1689 (1993))

**$a_2=\sigma_A/\sigma_D$ =relative measure of high momentum nucleons**
**$R_{2N}$=relative number of at-rest SRCs in nucleus (= $a_2$ with CM corr.)**

# EMC vs SRC : A-dependence

- ❑ SLAC E139 analysis found reasonable agreement to ln(A) dependence (at fixed x)
- ❑ Present analysis with "slope" definition yields different trend (large A region vs small A region)



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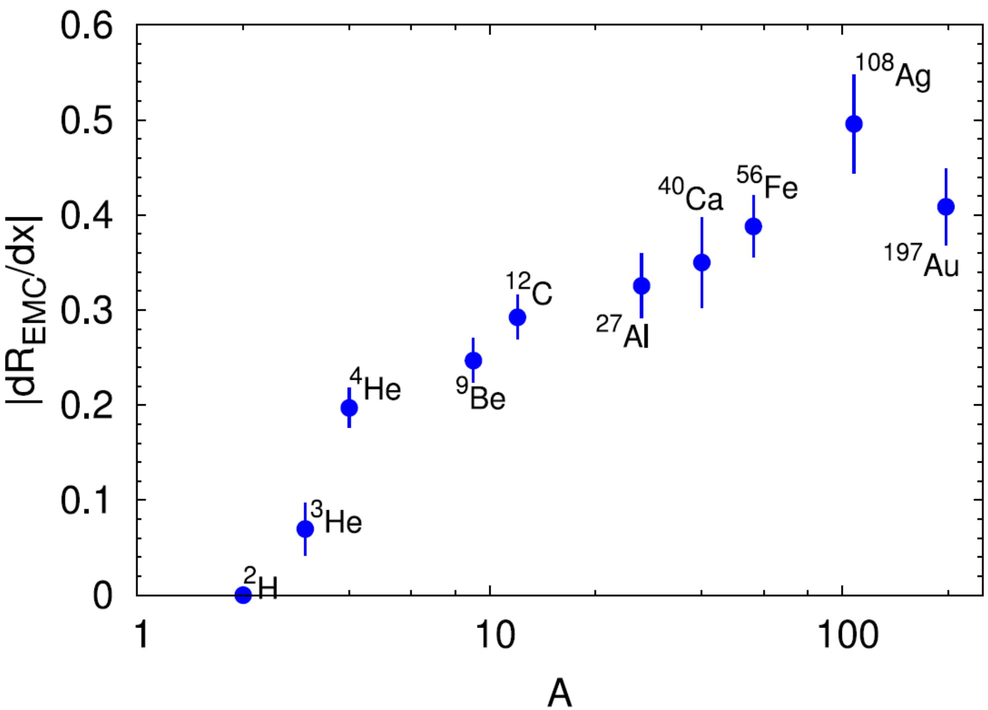
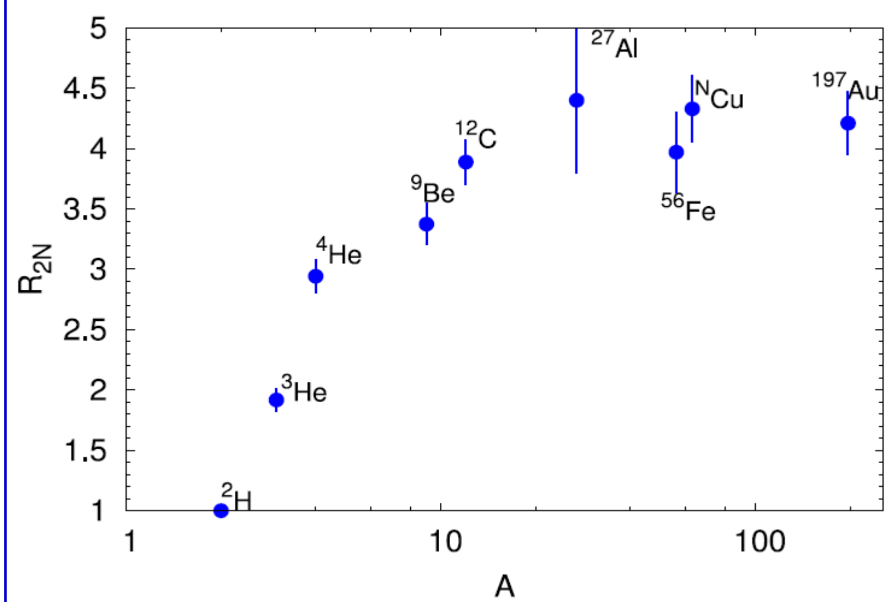


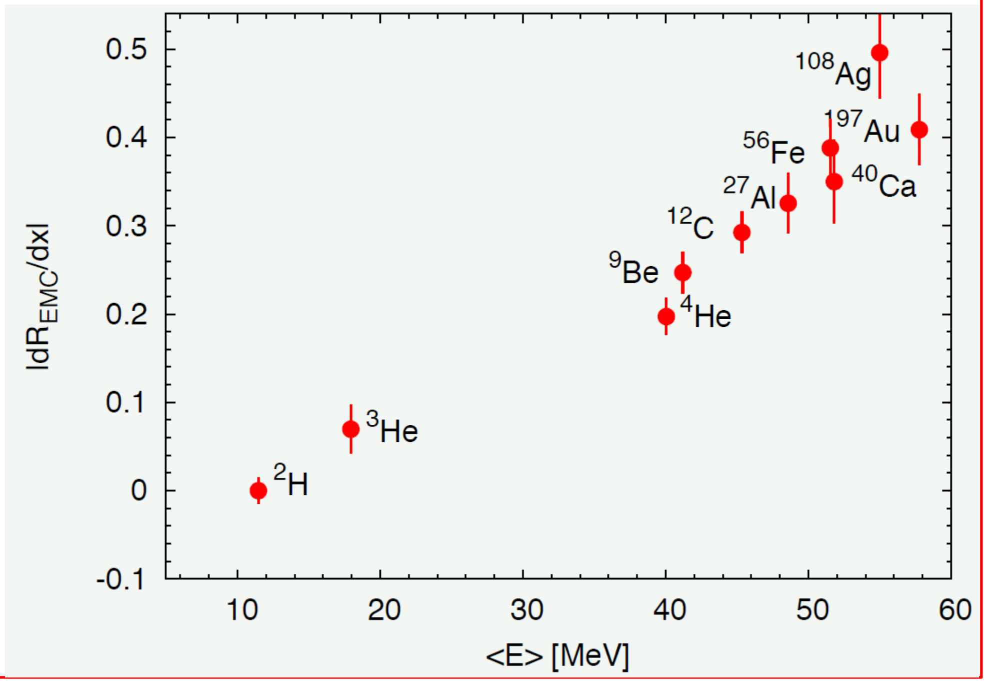

❑ SRC data also implies there is not a simple linear relationship in ln(A)

❑Appears to saturate above A>12



# EMC vs SRC: Mean separation energies

- ❑ Binding models assumes no modification to nucleon structure; then EMC effect is due to a simple rescaling of x (by ~ <E>/$M_N$ )
- ❑ Our analysis shows qualitatively EMC effect correlates well with <E>



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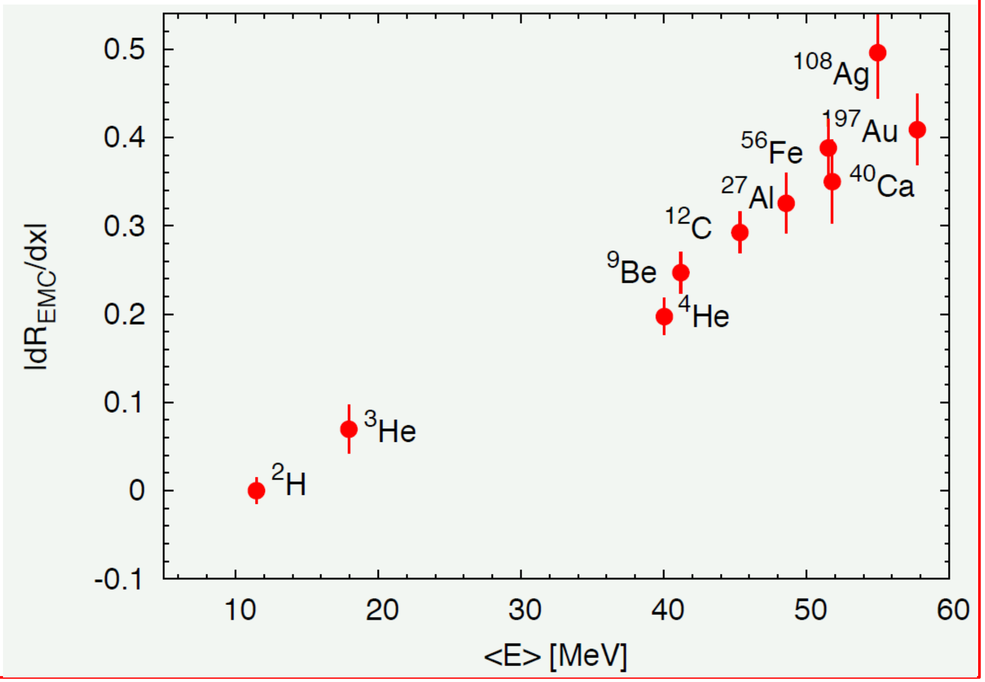
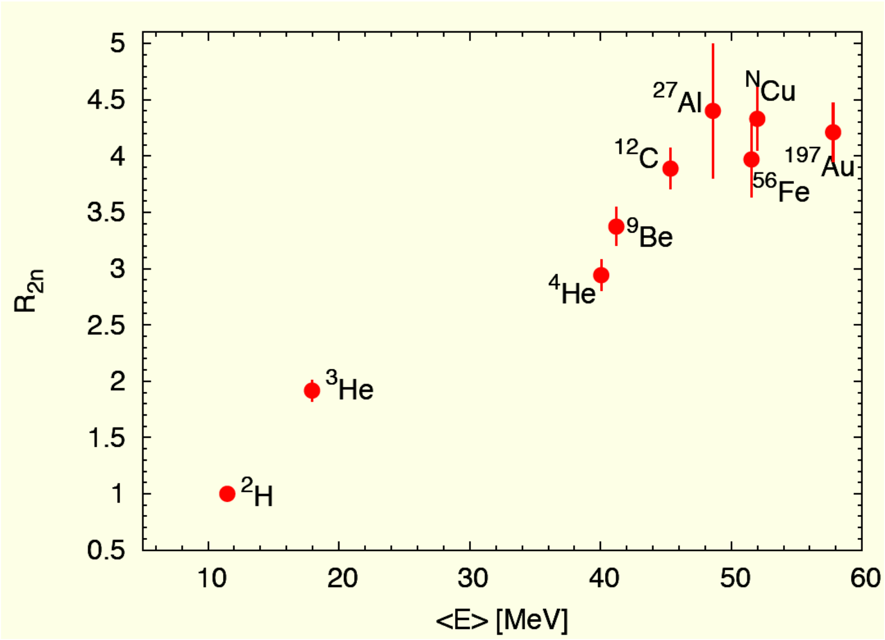



❑Similar trend in SRC data




*Separation energies from Kulagin (based on PRC 82, 054614 (2010), NPA 765, 126 (2006))*

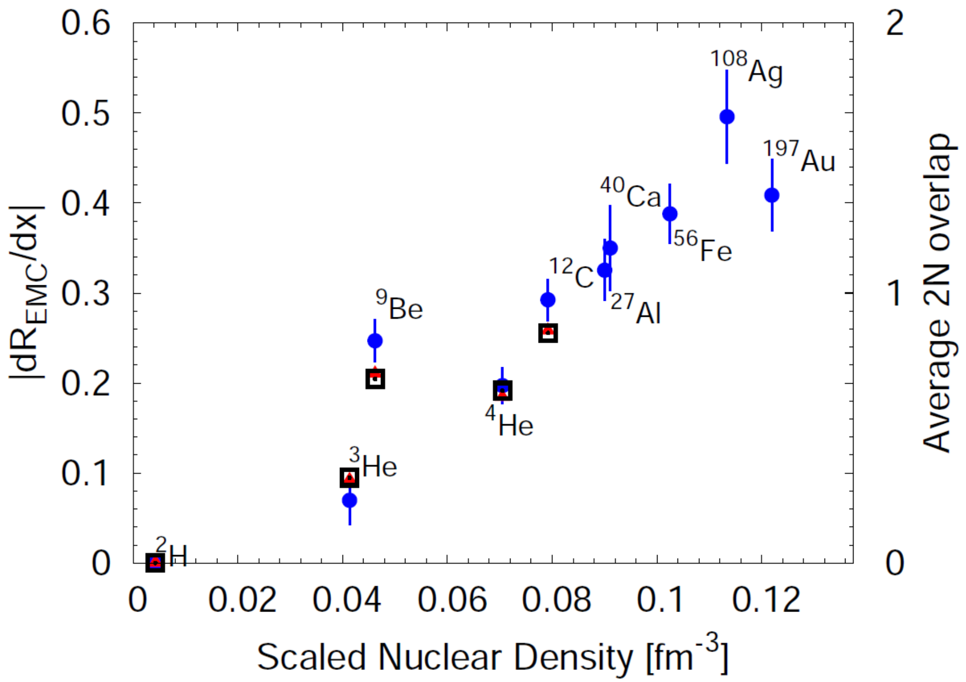
# EMC vs SRC:  average density vs NN overlap

- **E03103 data suggested EMC effect might be  due to *local density*.**
- **Nucleons can have significant overlap in the nucleus before they respond to the repulsive core**
- **Use this NN overlap as a measure of local density that a given nucleon experiences.**

$$O_{NN} = \int_0^\infty W(r)\rho_2^{NN}(r)d^3r$$

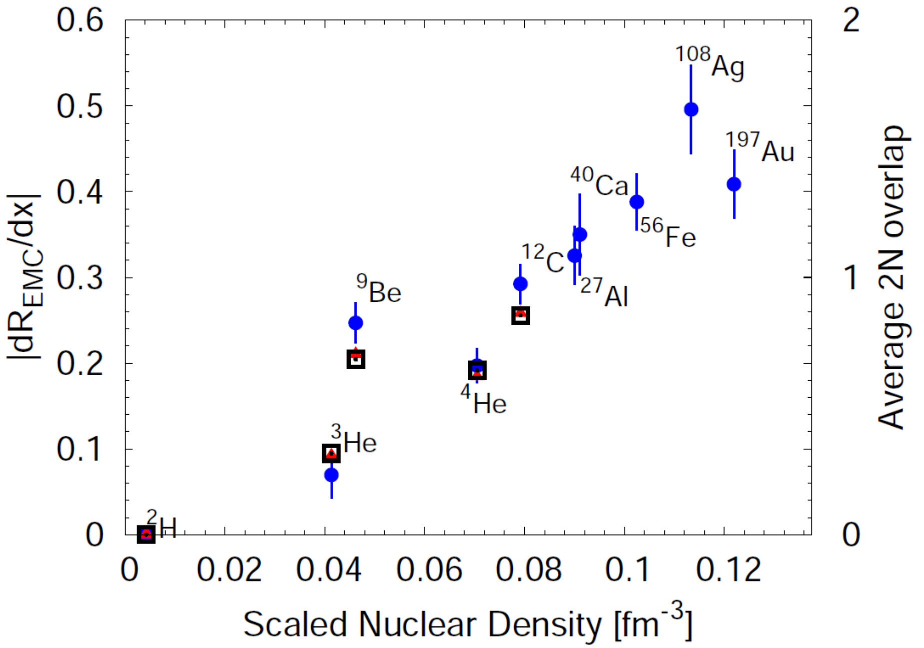
**Cutoff function to  evaluate the contribution at short distances**

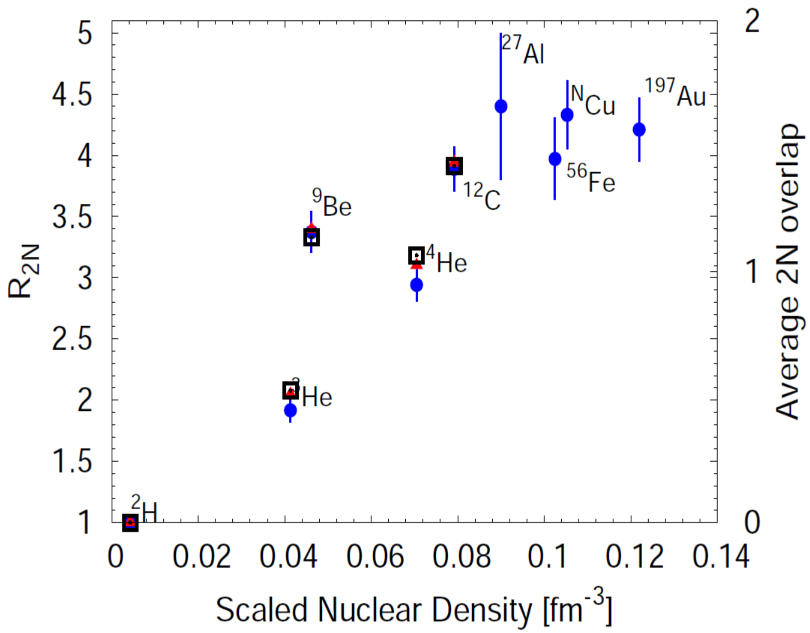
**2-body density distributions from GFMC**



# EMC vs SRC: average density vs NN overlap

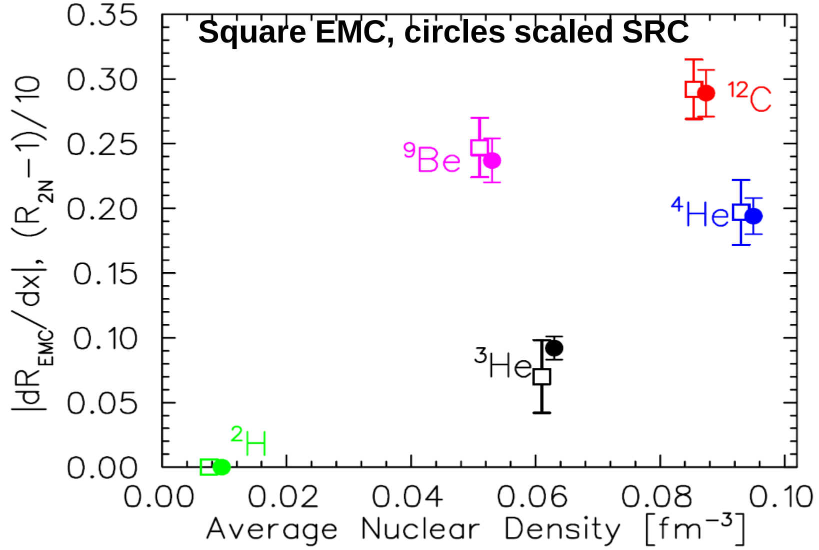
- NN overlap exhibits same density dependence
- SRC data also shows similar trend
- Good qualitative reproduction of the behavior for light nuclei (GFMC calculations available only up to A=12)
- More definitive test of this "local density" will be done after 12 GeV upgrade (with addition of light nuclei)



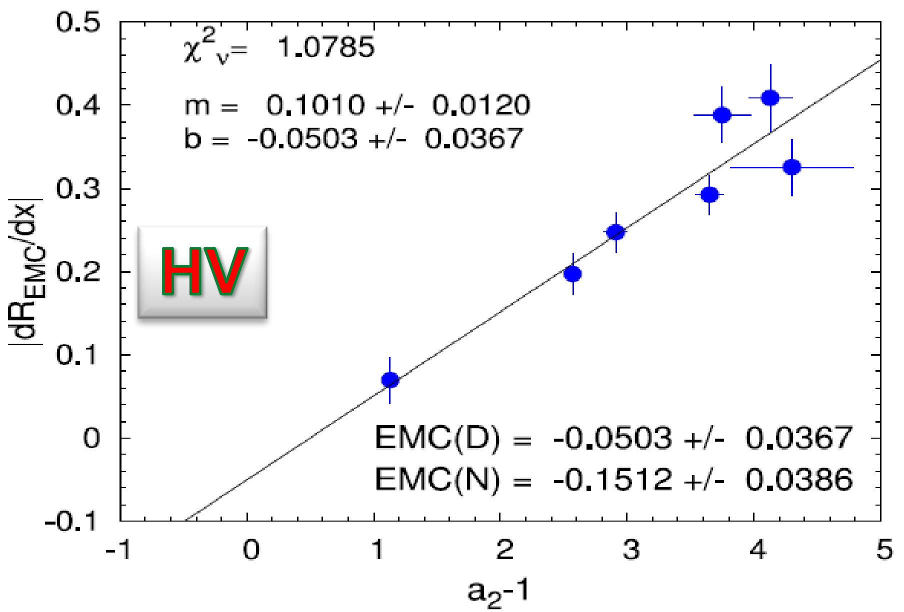
# EMC vs SRC: why the unexpected similar behavior?

**Both the SRC and EMC show nearly identical dependence on average nuclear density**




| **Could be due to highly virtual nucleons (HV effect); then** | **Could be due to local density effects (LD effect); then** |
|---|---|
| In this picture, since $a_2$ measures the relative high momentum tail it is the relevant qty to compare with EMC effect. | 1. Compare EMC effect to $R_{2N}$ (measure of correlated pairs relative to deuteron)<br>2. Only n-p pairs generate high momentum nucleons but all NN pairs contribute to high local density.<br>3. To study the nuclear dependence, rescale one observable by possible np to NN pairs. |

# EMC vs SRC: (2 param, no constraints)



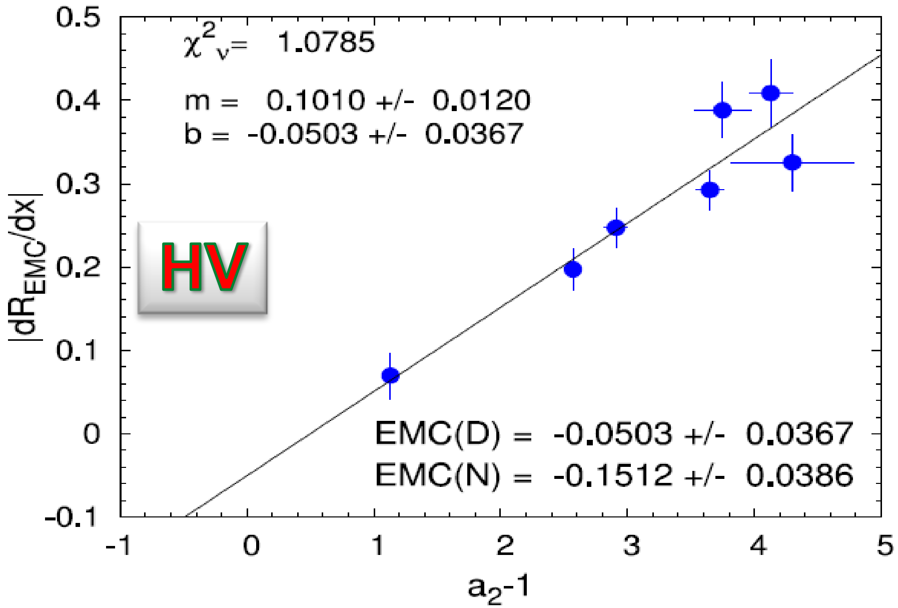

**Using the correlation one can extract IMC ("In medium correction" )by extrapolating $a_2$=0**

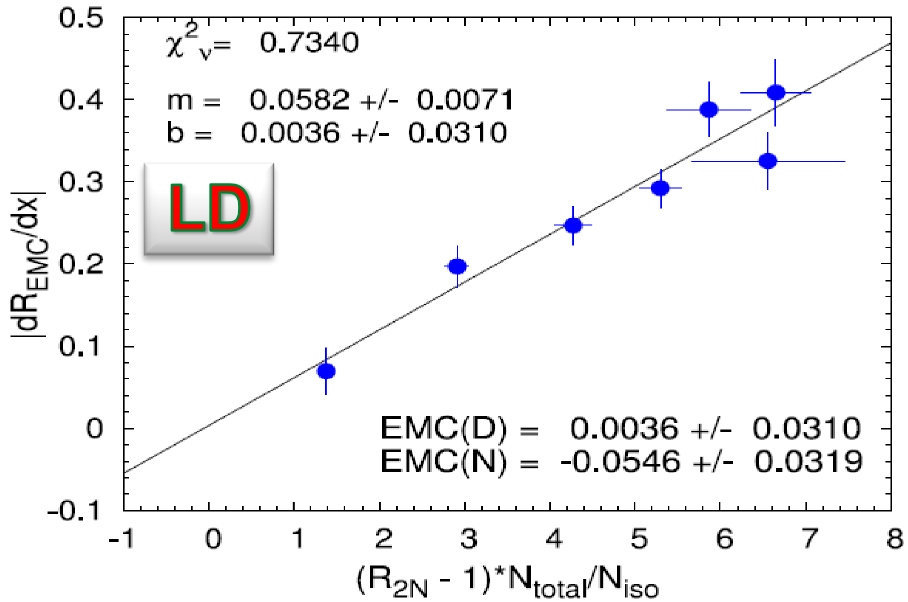
IMC(D) = EMC(N) - EMC(D)

**Weinstein et al, PRL 106, 052301 (2011),**
**O. Hen et al, PRC85, 047301 (2012)**

# EMC vs SRC: (2 param, no constraints)

| Hypothesis | $\chi^2_\nu$ | EMC(D) | IMC(D) |
|---|---|---|---|
| High virtuality | 1.08 | -0.0503±0.037 | 0.1010±0.037 |
| Local density | 0.73 (0.88) | 0.0036±0.031 | 0.0582±0.031 |

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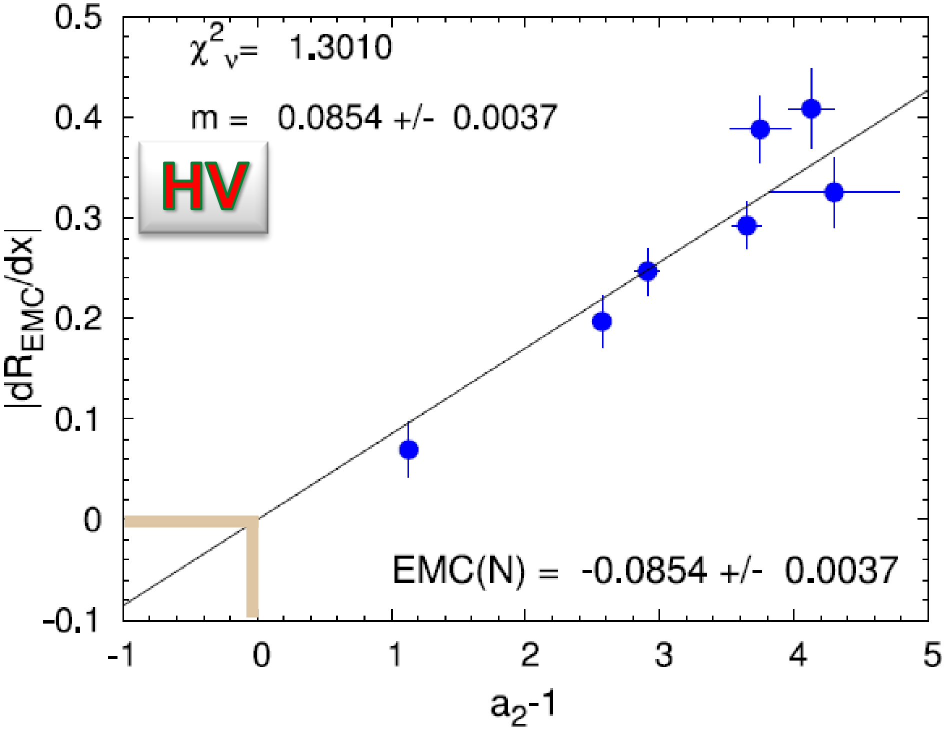
IMC(D) = EMC(N) - EMC(D)

**Weinstein et al, PRL 106, 052301 (2011),**
**O. Hen et al, PRC85, 047301 (2012)**

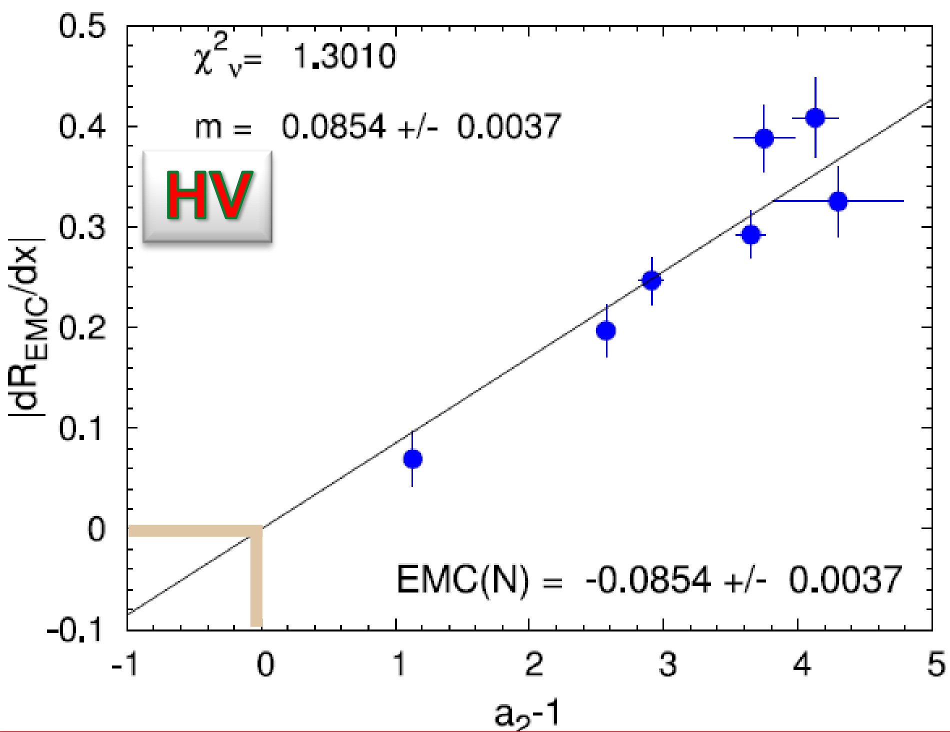
- LD hypothesis yield smaller $\chi^2_\nu$
- Horizontal error bars larger (compared to HV) because of theoretical uncertainty in CM correction
- Reducing this error to $a_2$ changes $\chi^2_\nu$ from 0.73 to 0.88

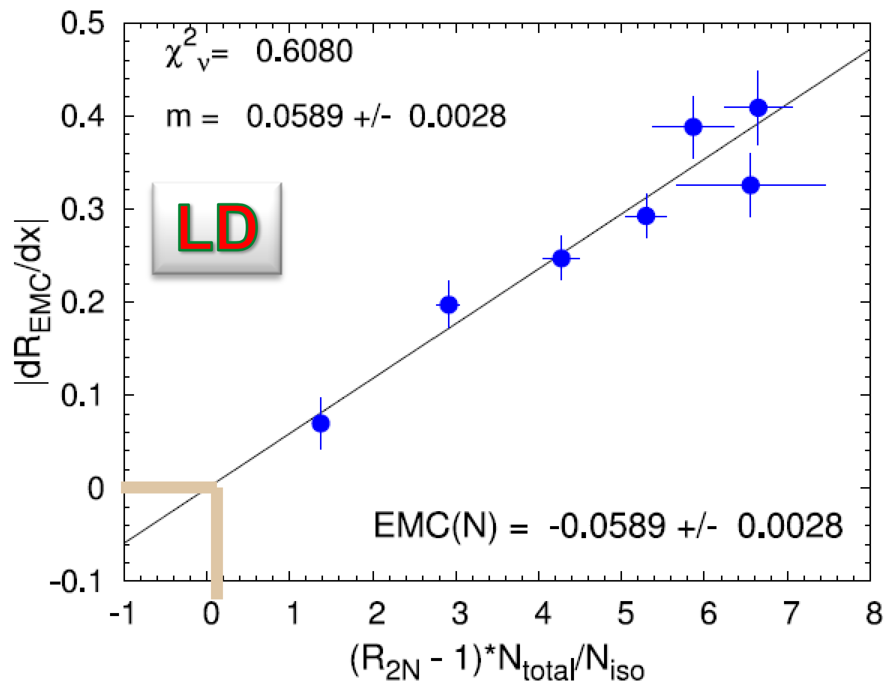
# EMC vs SRC: (1 parameter fit)



# EMC vs SRC: (1 parameter fit)

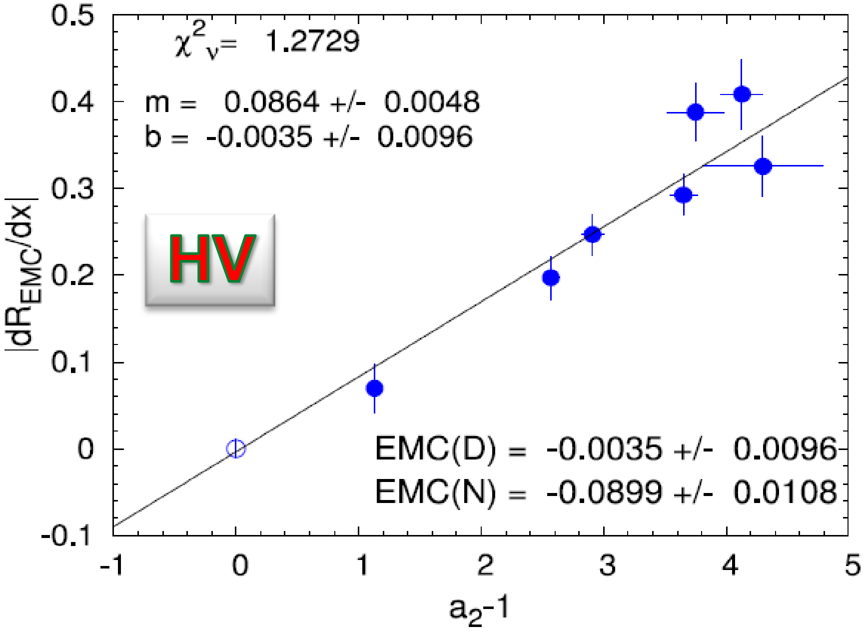
| Hypothesis | $\chi^2_\nu$ | EMC(D) | IMC(D) |
|---|---|---|---|
| High virtuality | 1.30 | - | 0.0854±0.004 |
| Local density | 0.61 (0.73) | - | 0.0589±0.003 |




- ❑ Here a single parameter (slope) is used and the fit is forced to go through zero for EMC slope at $a_2$-1=0
- ❑However, the resulting fit will have unrealistically small uncertainties for points close to deuteron (smaller than any measurement for light nuclei)

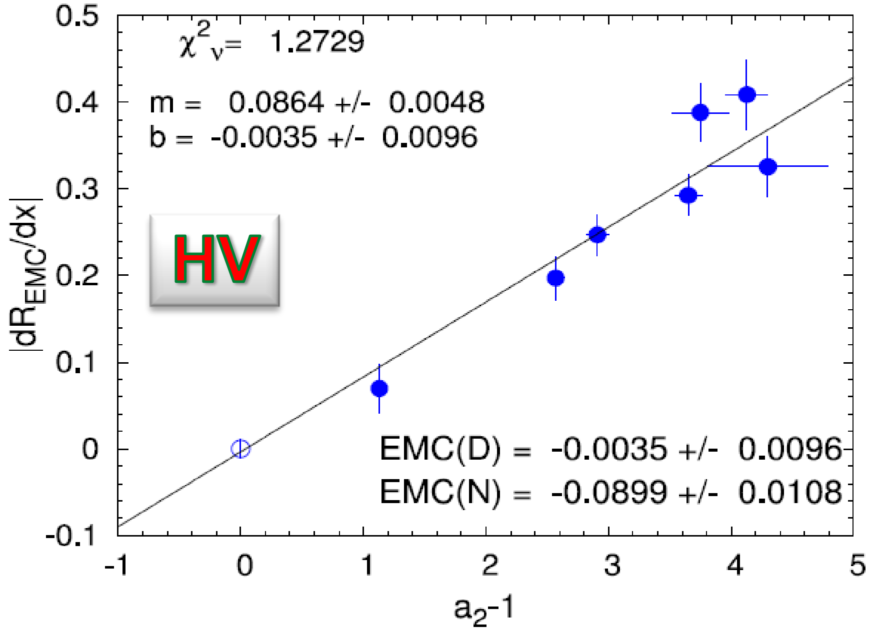
# EMC vs SRC: 2 param fit (non zero unc. for D2 point)

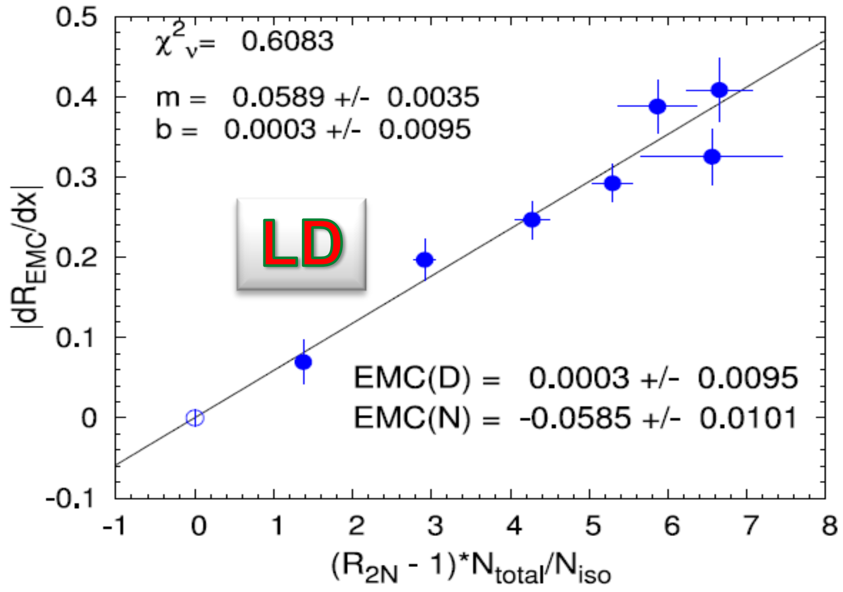



❑ Let's redo the previous fits (but with reasonable estimate of uncertainties; 0+-0.01 for EMC, 1+-0.015 for $a_2$ and $R_{2N}$ ; estimated from cross section measurements of E03103 from E02019 )

# EMC vs SRC: 2 param fit (non zero unc. for D2 point)

| Hypothesis | $\chi^2_\nu$ | EMC(D) | IMC(D) |
|---|---|---|---|
| High virtuality | 1.27 | -0.0035±0.010 | 0.0864±0.010 |
| Local density | 0.61 (0.73) | 0.0003±0.010 | 0.0589±0.010 |




❑ Let's redo the previous fits (but with reasonable estimate of uncertainties; 0+-0.01 for EMC, 1+-0.015 for $a_2$ and $R_{2N}$ ; estimated from cross section measurements of E03103 from E02019 )

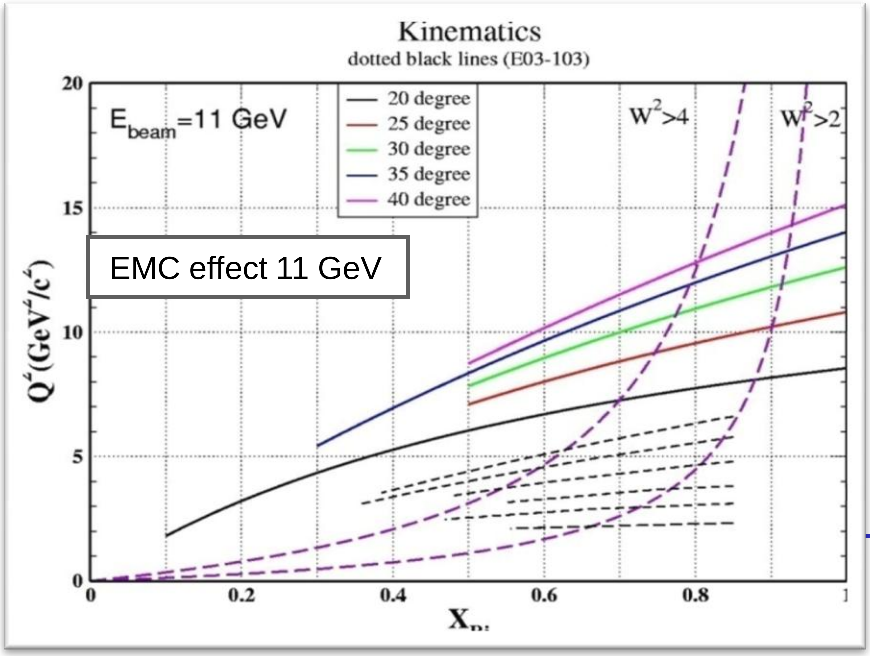
# EMC vs SRC: summary of fits

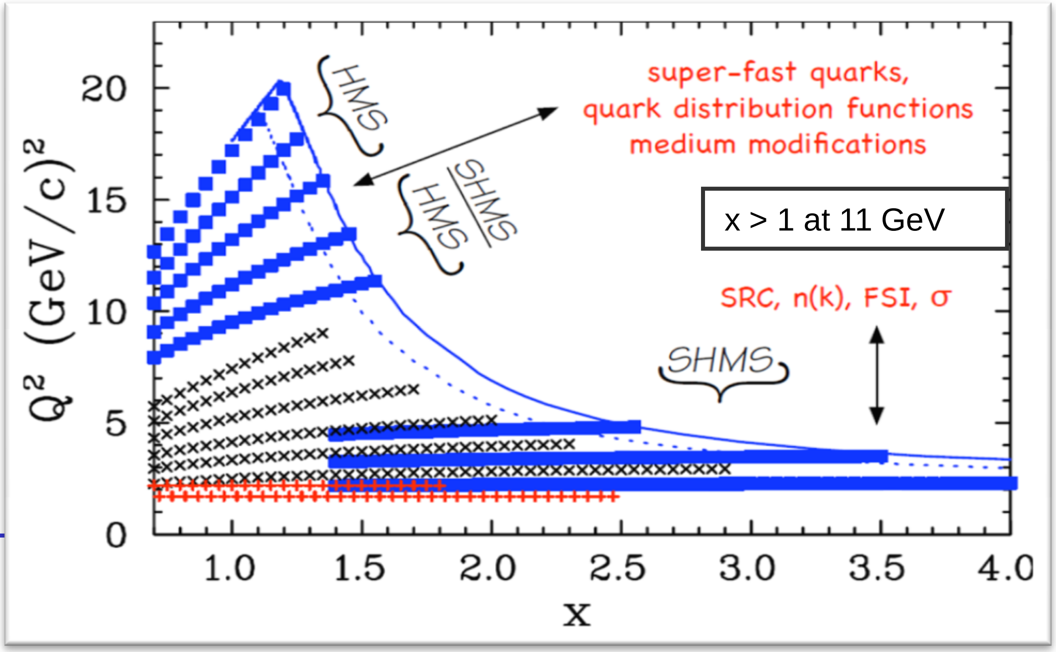
| Hypothesis | Fit type | $\chi^2_\nu$ | EMC(D) | IMC(D) |
|---|---|---|---|---|
| High virtuality | 2-param, no constraint | 1.08 | -0.0503±0.037 | 0.1010±0.037 |
| Local density | 2-param, no constraint | 0.73 (0.88) | 0.0036±0.031 | 0.0582±0.031 |
| High virtuality | 1-param | 1.30 | - | 0.0854±0.004 |
| Local density | 1-param | 0.61 (0.73) | - | 0.0589±0.003 |
| High virtuality | 2-param, non zero uncertainties for D2 point | 1.27 | -0.0035±0.010 | 0.0864±0.010 |
| Local density | 2-param, non zero uncertainties for D2 point | 0.61 (0.73) | 0.0003±0.010 | 0.0589±0.010 |

- **Local density hypothesis yields better $\chi^2_\nu$, but high virtuality not ruled out.**
- **Range of IMC values can be extracted under different assumptions with varying uncertainties; this may have some impact on free nucleon extrapolations especially at large x values (Fermi motion effects start to become important for x>0.6 ).**
- **Note that we have investigated the impact of different prescriptions of isoscalar corrections, Coulomb corrections,…the numerical values of the results changes while the overall trend do not change.**

# Future: inclusive 11 GeV experiments in Hall C

- **Approved E10-008 and (x<1, spokespersons J. Arrington, A. Daniel, D. Gaskell ) and E06-105 ( x>1; spokespersons and J. Arrington and D. Day) experiments will provide more data at *x>1 and x<1 regions*.**



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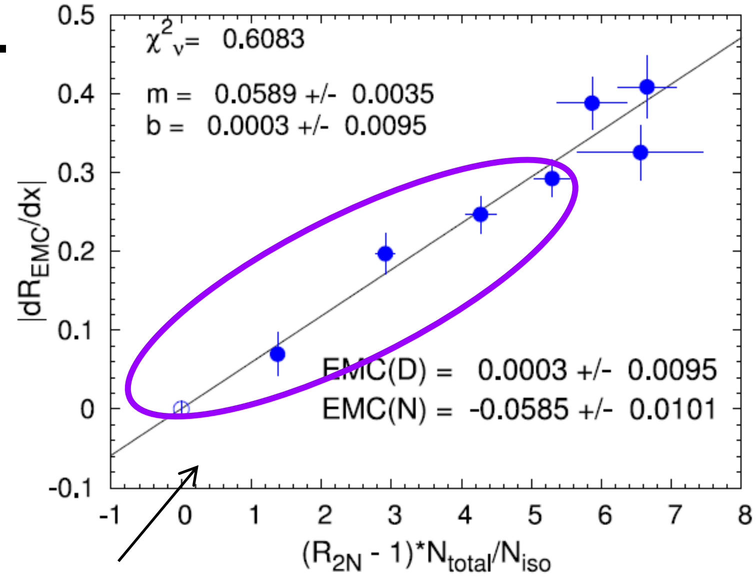
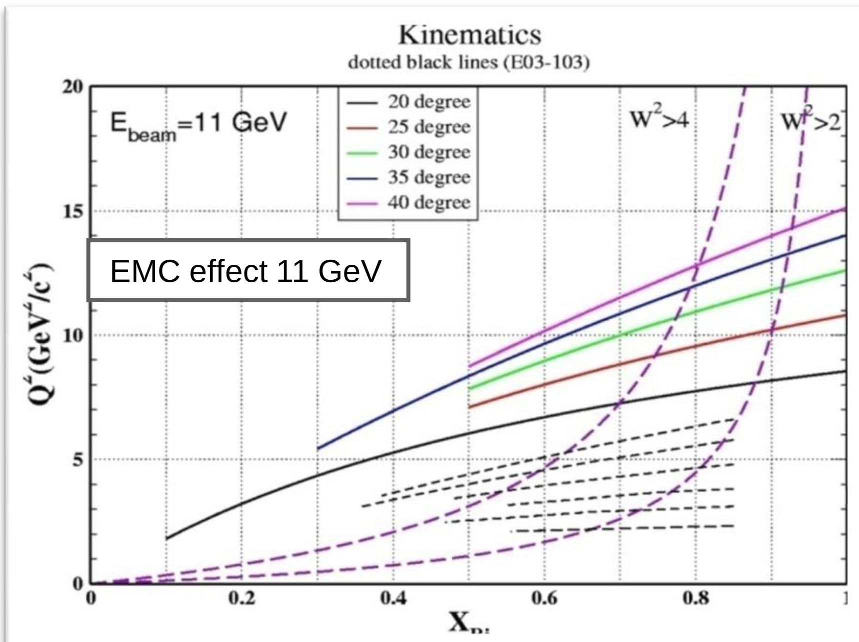
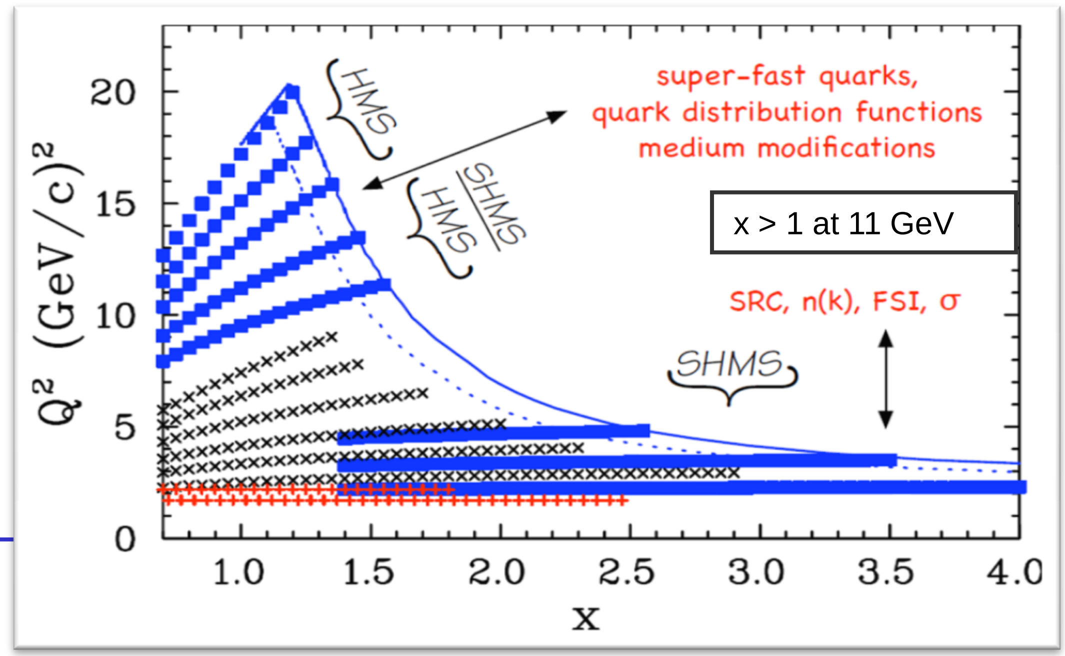
- **Among other things, these experiments will investigate the proposed explanations with a whole series of light nuclei with significant *cluster structure*.**




**$^6$Li, $^7$Li, $^{10}$B, $^{11}$B, $^{40}$Ca, $^{48}$Ca will be added to this**



# Summary

- ❑Our investigations of EMC and SRC effects shows that traditional models of simple density or A-dependence fails to explain the new data on light nuclei.

- ❑Both observables show similar behavior; however, specific origin of the observed modification is not clearly identified. Data favors local density picture; but high virtuality explanation is also plausible

- ❑Approved 11GeV experiments in Hall C will provide more information on these correlations, adding several light nuclei with significant cluster structure.

# Acknowledgments


***Nadia Fomin (several figures)***

***Sergey Kulagin (separation energies)***

***E03103, E02019, Hall C collaborations***