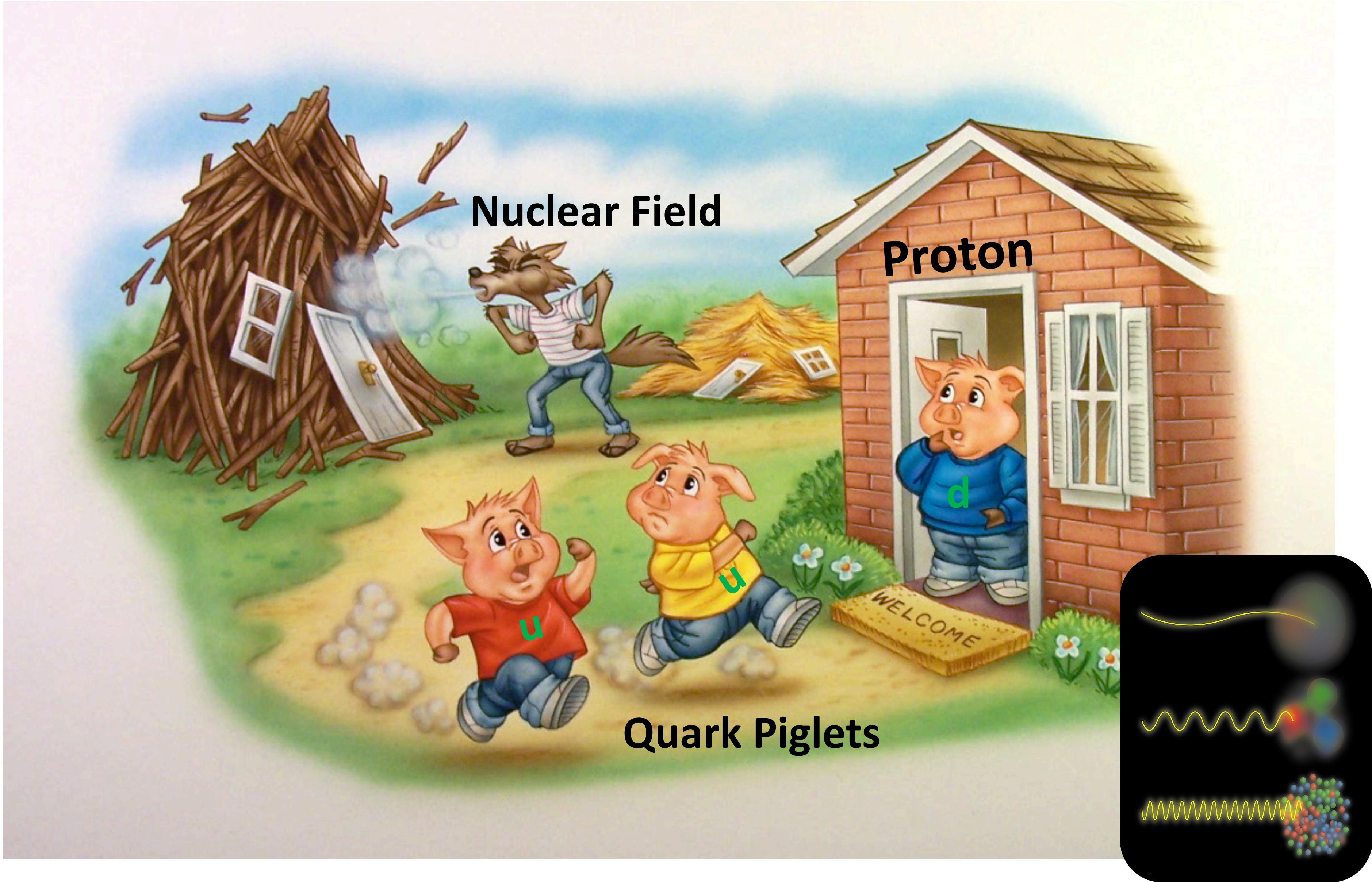
QCD in Nuclei: Bound Nucleon Structure and Short-Range Correlations

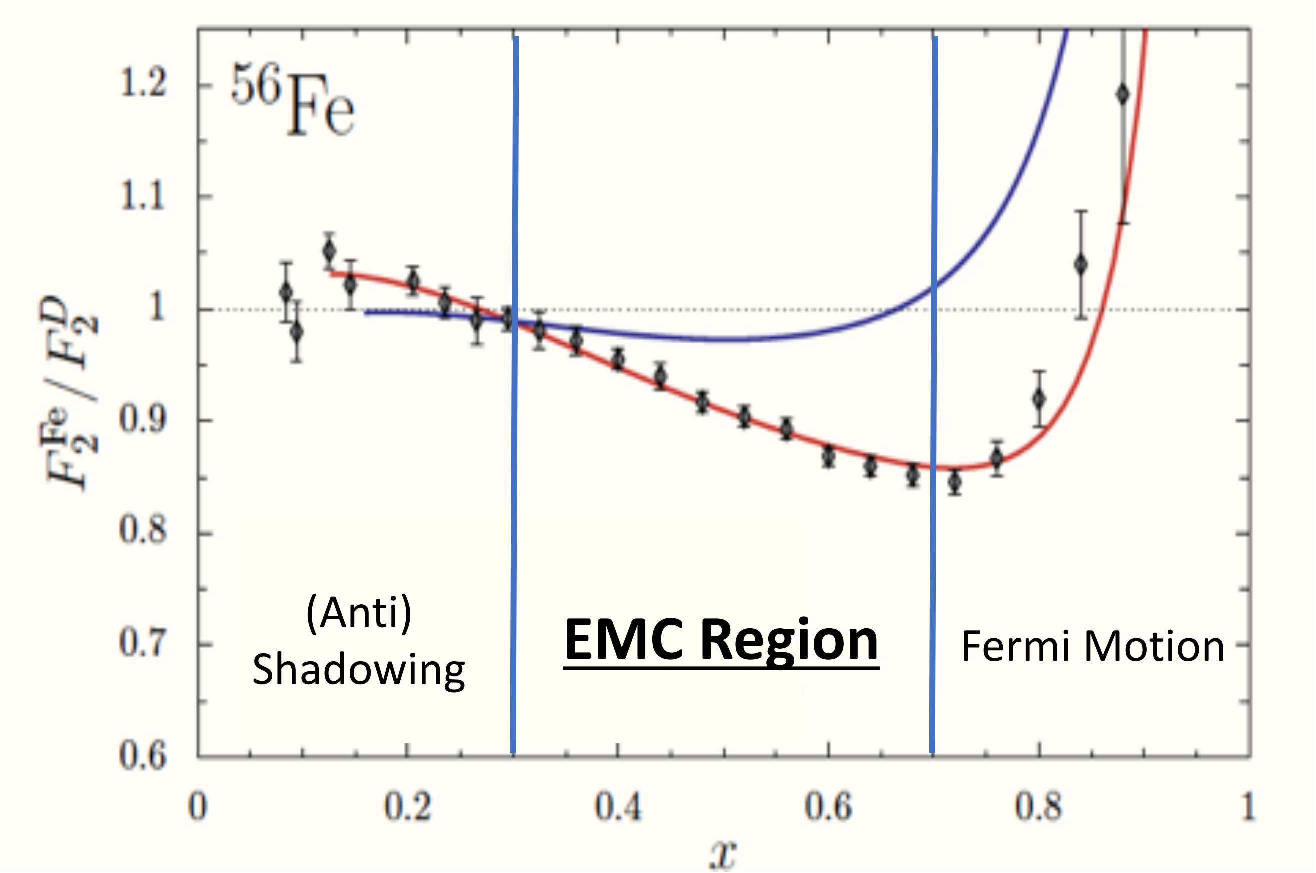
Or Hen - MIT

APS Division of Particles and Fields (DPF)
Summer Meeting, August 2nd 2017, Fermilab.

Nuclear / Partonic Scale Separation



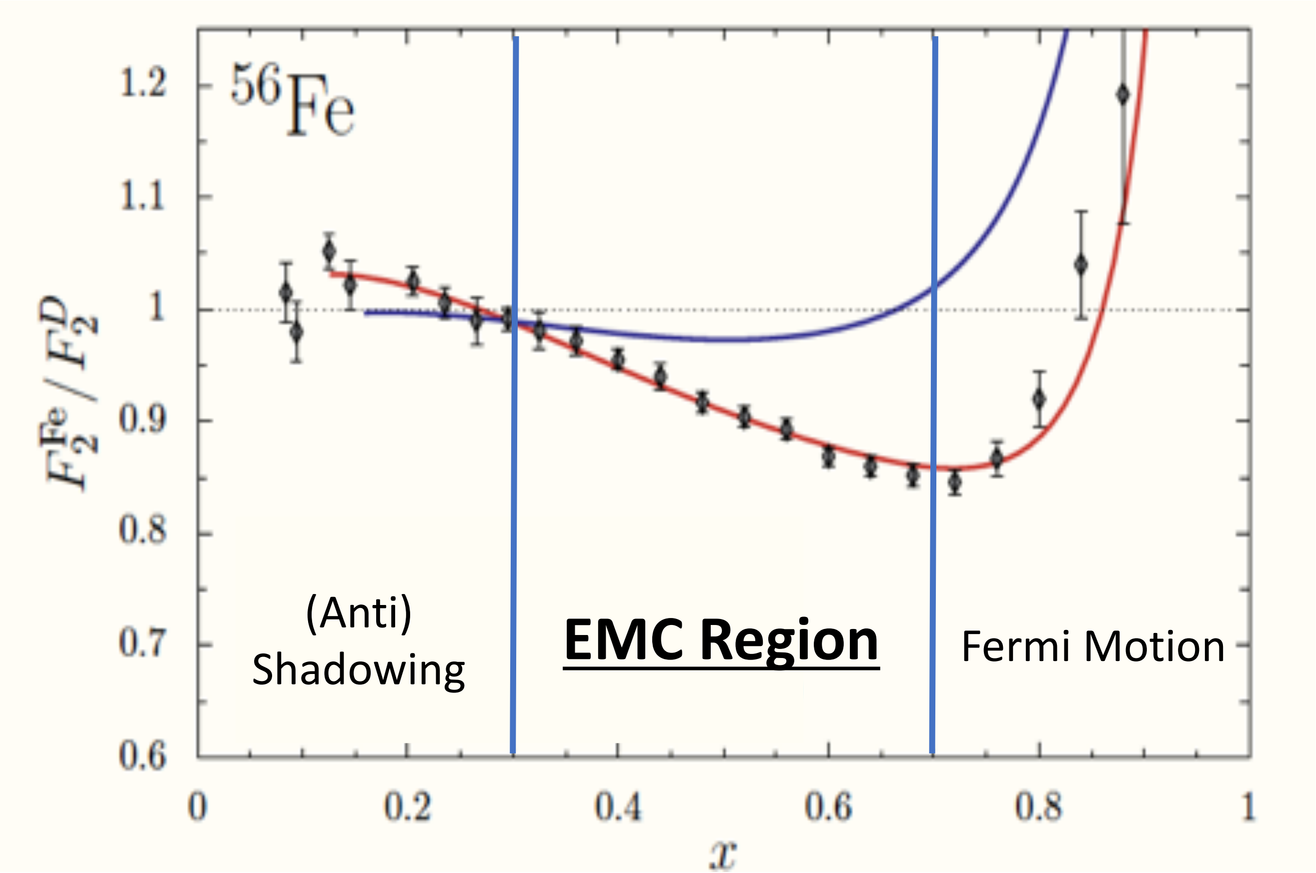
EMC: Bound Nucleons ≠ Free Nucleons



$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_A = \frac{4\alpha^2 E'^2}{Q^4}\left[2\frac{F_1}{M}\sin^2\left(\frac{\theta}{2}\right) + \frac{F_2}{\nu}\cos^2\left(\frac{\theta}{2}\right)\right]$$

$$F_2\left(x,Q^2\right) = \sum_i e_i^2 \cdot x \cdot f_i(x)$$

EMC: No Scale Separation ???



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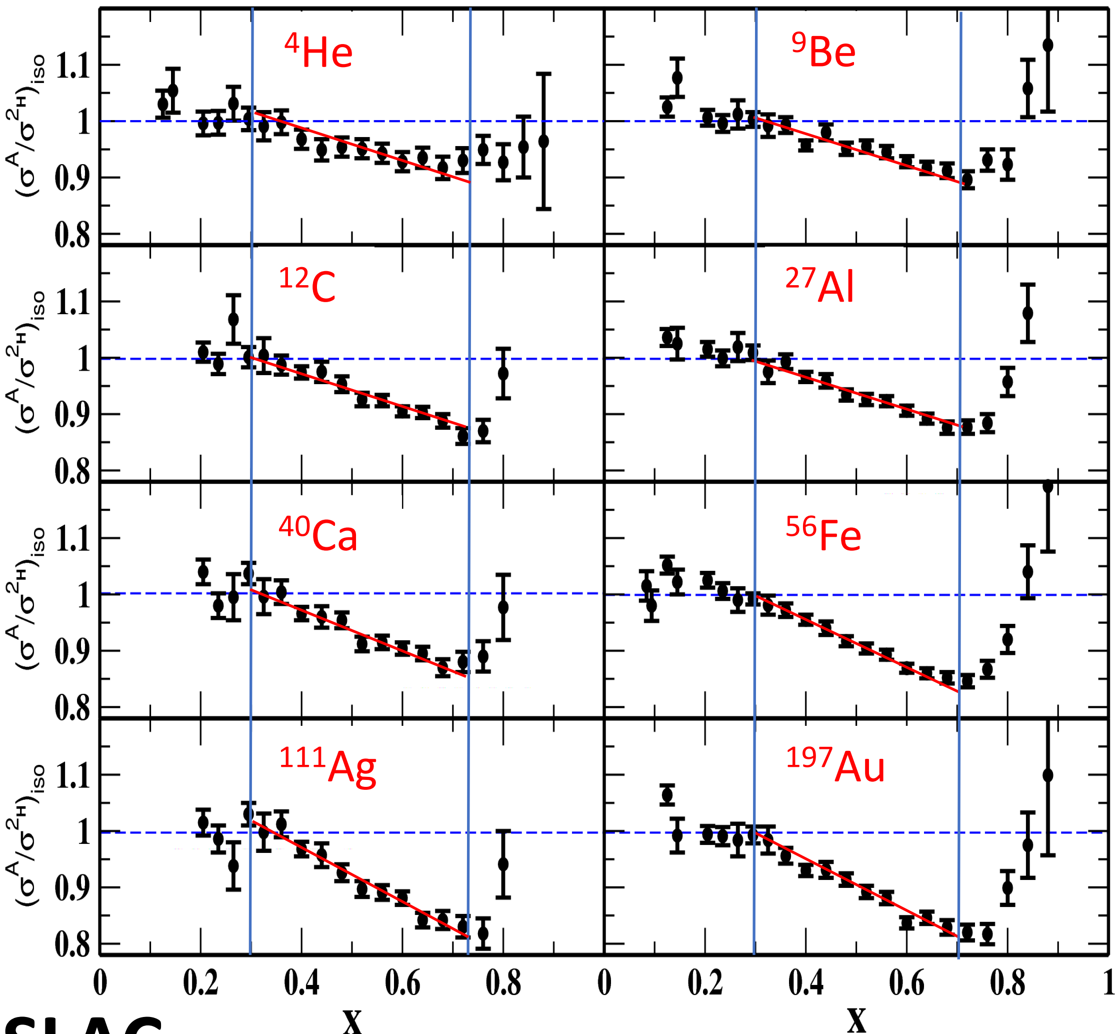
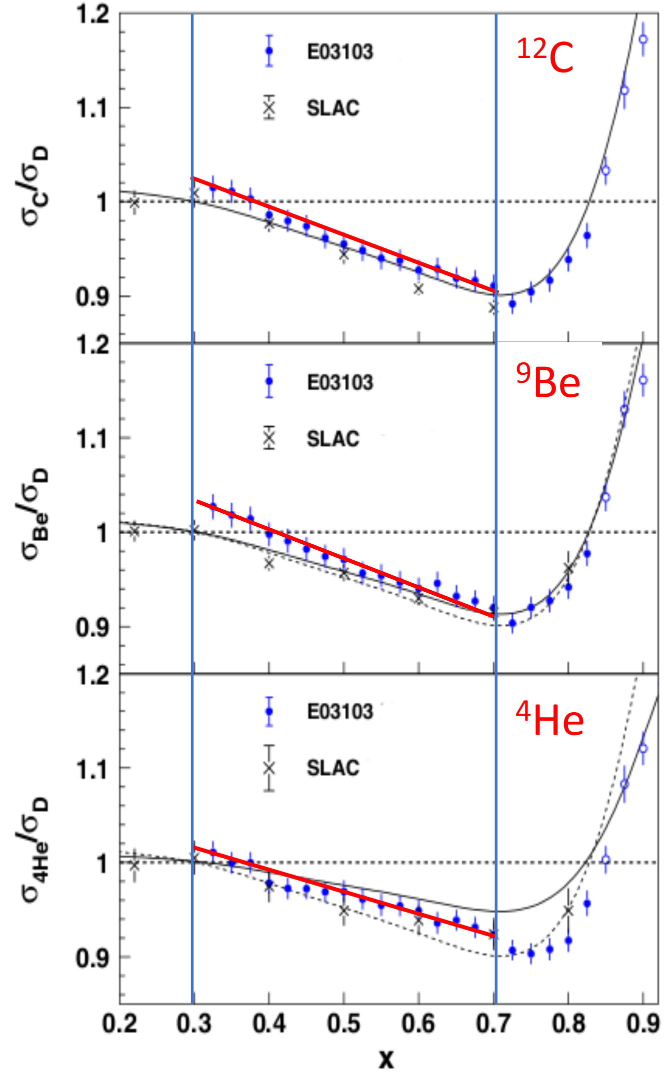
EMC: Nuclear Effect!



SLAC

J. Gomez et al., Phys. Rev. D **49**, 4348 (1994).

JLab



J. Seely et al., Phys. Rev. Lett. **103**, 202301 (2009).

Theory: 1000 papers, 3 Ideas

1. Proper treatment of 'known' nuclear effects
   [explain some of the effect, up to $x \approx 0.5$]
   - Nuclear Binding and Fermi motion, Pions, Coulomb Field.
   - **No modification of bound nucleon structure.**

2. Bound Nucleons are 'larger' than free nucleons.
   - Larger confinement volume => slower quarks.
   - Mean-Field effect.
   - Momentum Independent.
   - **Static.**

3. Short-Range Correlations
   - Beyond the mean-field.
   - Momentum dependent.
   - **Dynamical!**

EMC – Everyone's Model is Cool (G. A. Miller)

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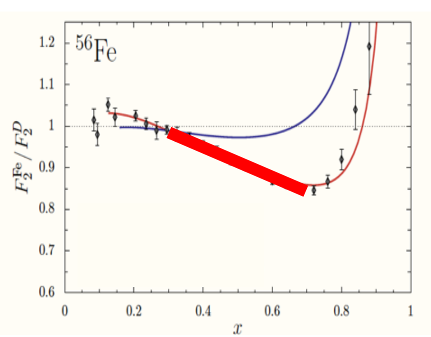
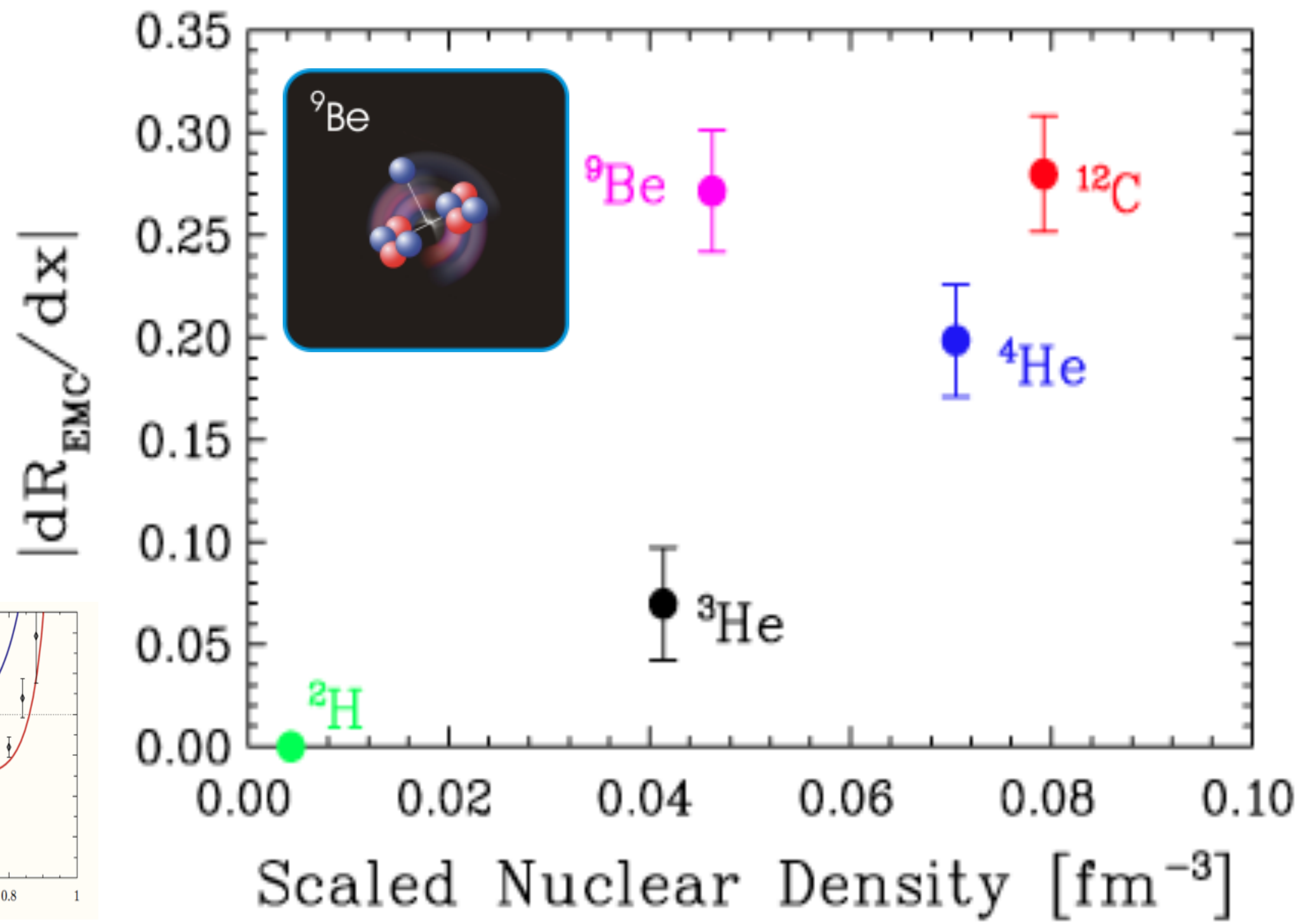
EMC: (non-trivial) Nuclear Effect!





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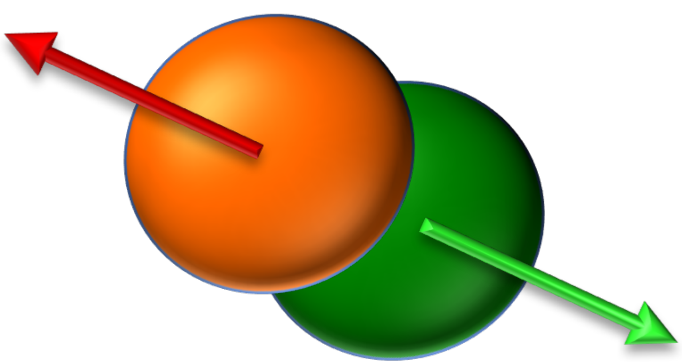
Beyond the Mean-Field: Short-Range Correlations

Temporal fluctuations of Nucleon that are close together in the nucleus (wave functions overlap)

=> Momentum space: pairs with *high relative momentum* and *low c.m. momentum* compared to the Fermi momentum (k_F)



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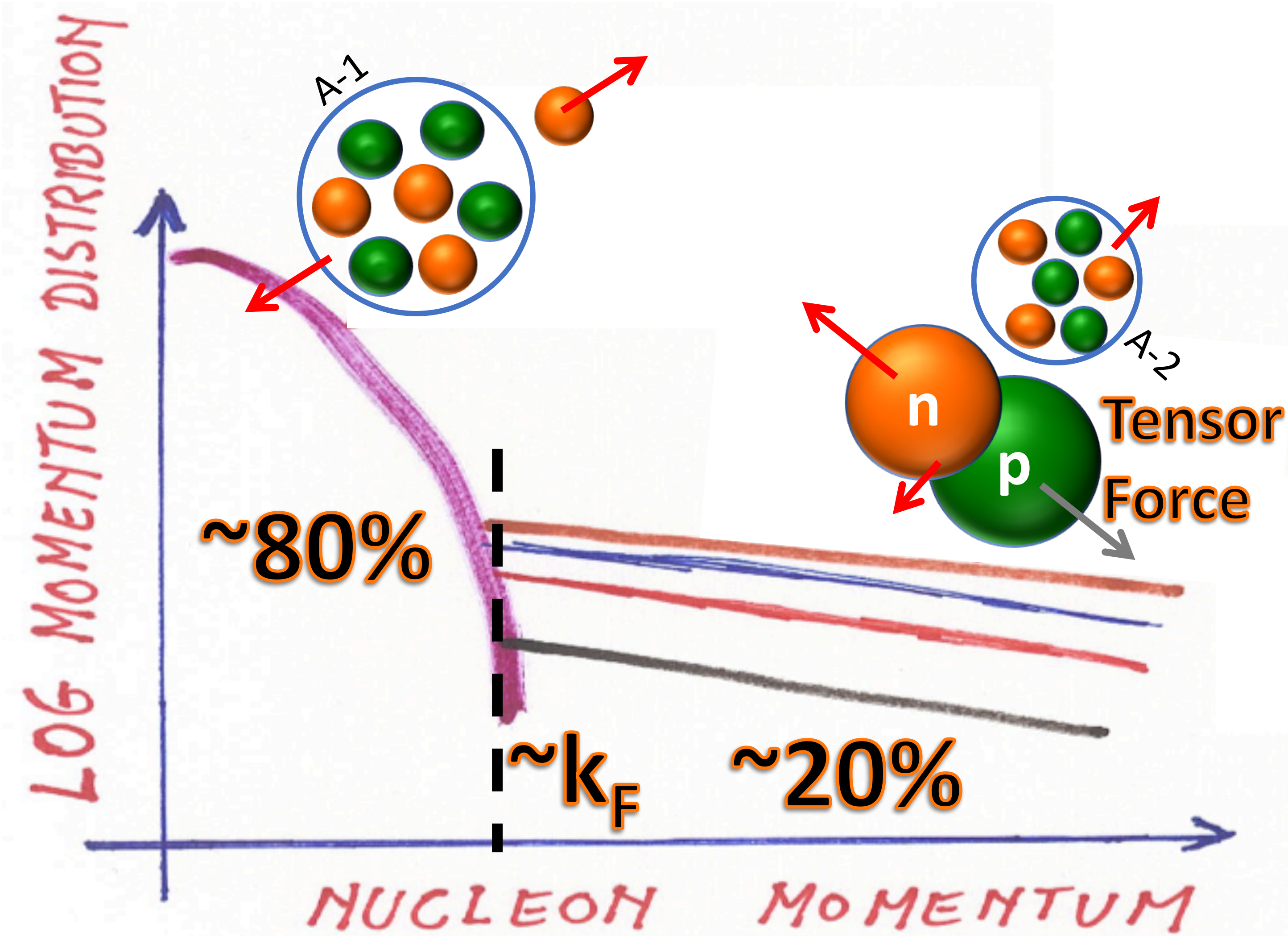
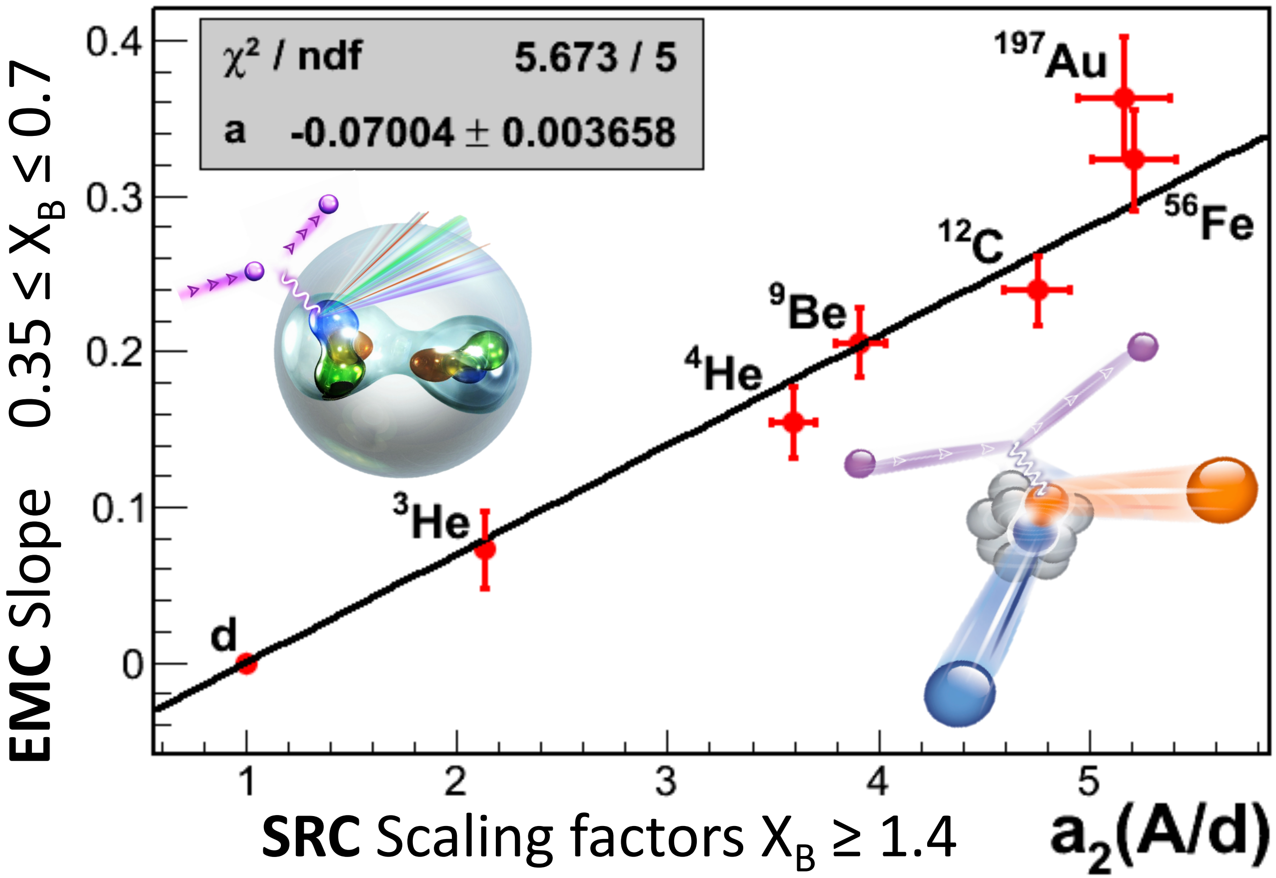
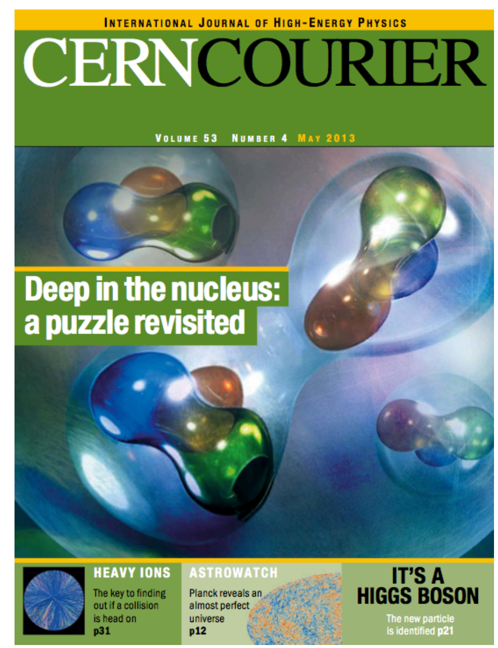


EMC and SRC are Correlated!





O. Hen et al., Int. J. Mod. Phys. E. **22**, 1330017 (2013).
O. Hen et al., Phys. Rev. C **85** (2012) 047301.
L. B. Weinstein, E. Piasetzky, D. W. Higinbotham, J. Gomez, O. Hen, R. Shneor, Phys. Rev. Lett. **106** (2011) 052301.

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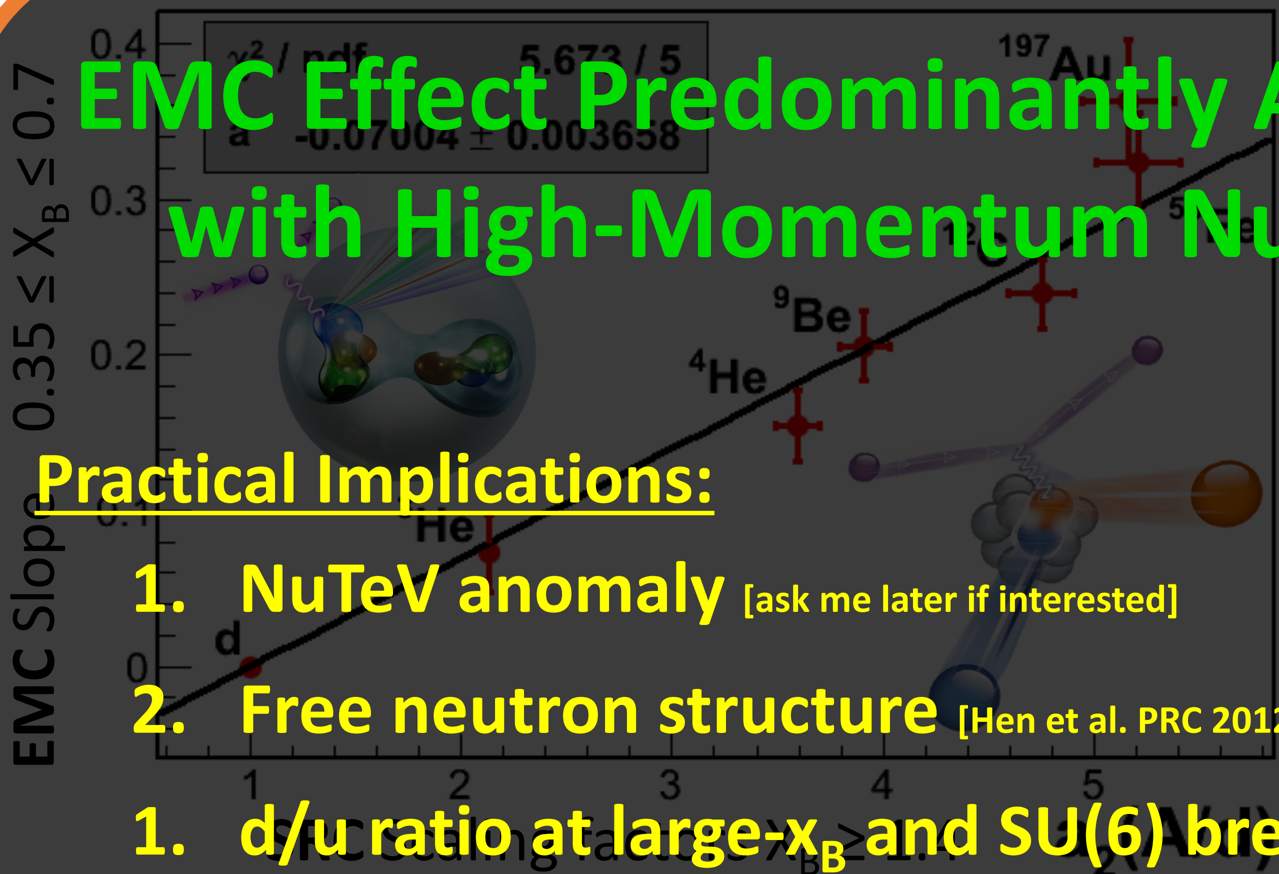

EMC Effect Predominantly Associated with High-Momentum Nucleons?

Practical Implications:

1. **NuTeV anomaly** [ask me later if interested]
2. **Free neutron structure** [Hen et al. PRC 2012]
1. **d/u ratio at large-x_B and SU(6) breaking** [Hen et al. PRD 2011]

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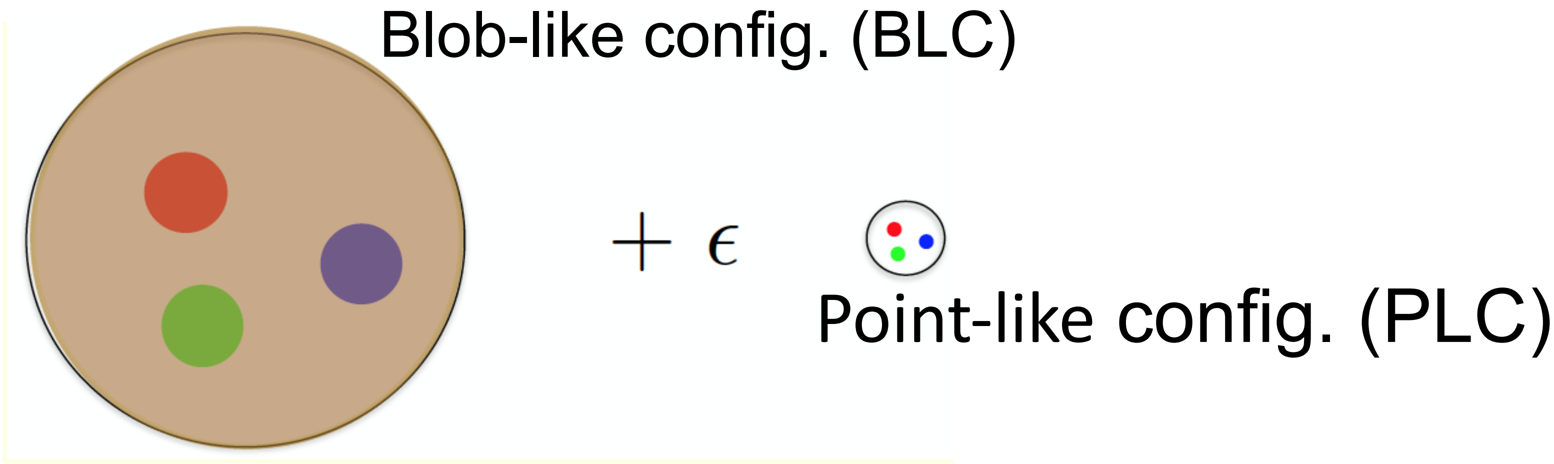
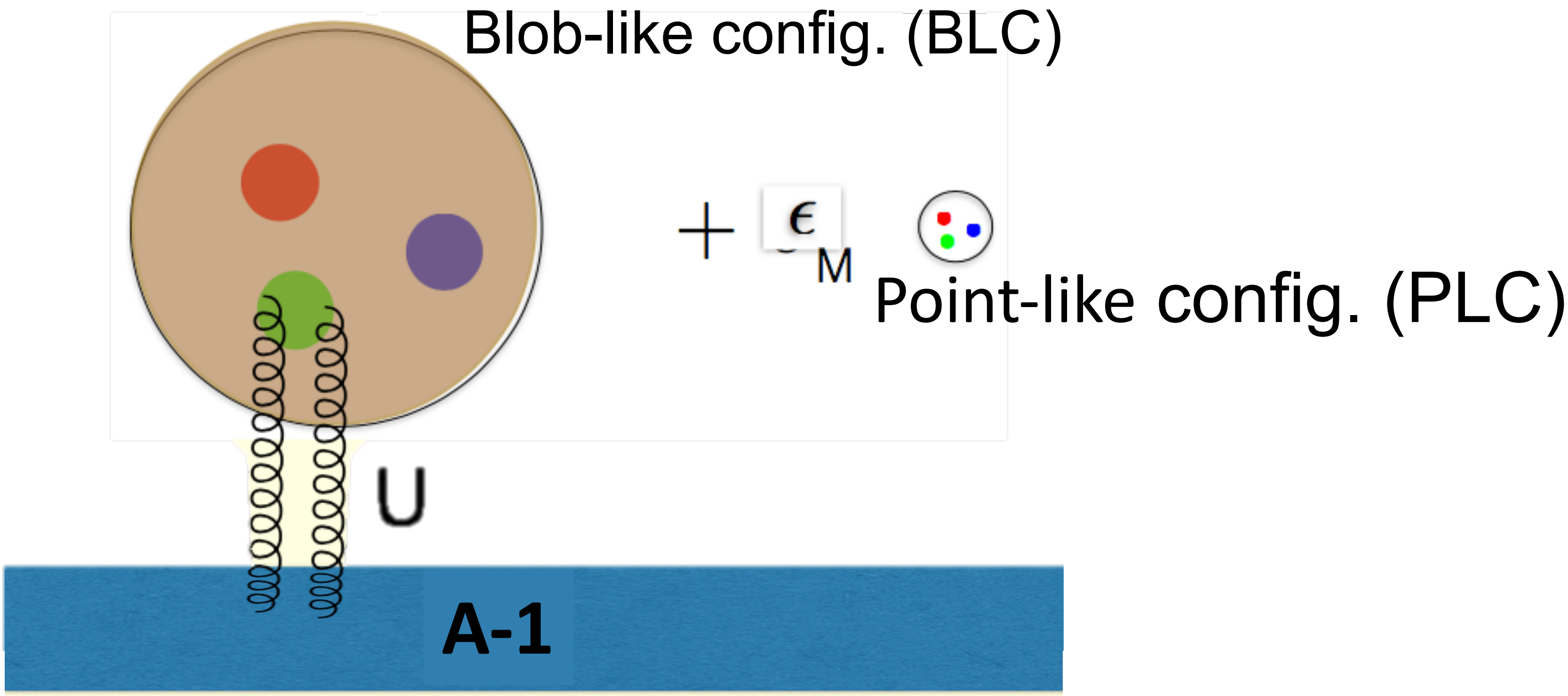
Nucleon: Simple 2-State Model



PLC are smaller => Dominate high-x F_2

Nucleon: Simple 2-State Model



Medium interacts with BLC, energy denominator increases, PLC Suppressed:

$$|\epsilon_M| < |\epsilon|$$

PLC Suppression Dominated by SRC!

$$\text{Free nucleon} : H_0 = \begin{bmatrix} E_B & V \\ V & E_P \end{bmatrix}, V > 0$$

$$|N\rangle \quad = |B\rangle + \epsilon|P\rangle,\ \epsilon = \frac{V}{E_B - E_P} < 0$$

$$\text{In nucleus (M)} : H = \begin{bmatrix} E_B - |U| & V \\ V & E_P \end{bmatrix}$$

$|N\rangle_M = |B\rangle + \epsilon_M|P\rangle$, $|\epsilon_M| < |\epsilon|$, PLC suppressed, $\epsilon_M - \epsilon > 0$ amplitude effect!

$|N\rangle_M - |N\rangle \propto (\epsilon_M - \epsilon) \propto U = \frac{p^2 - m^2}{2M}$ Shroedinger eq.

$q_M(x) = q(x) + (\epsilon_M - \epsilon) f(x)\, q(x)$, $\frac{df}{dx} < 0$, $x \geq 0.3$ PLC suppression

$R = \frac{q_M}{q}$; $\frac{dR}{dx} = (\epsilon_M - \epsilon)\frac{df}{dx} < 0$ Reproduces EMC effect - like every model

Why this model??? Large effect if $v = p^2 - m^2$ is large, it is

Effect is in the amplitude, not probability

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Small Amplitude => Large Probability!

The two state model has a ground state $|N\rangle$ and an excited state $|N^*\rangle$

$$|N\rangle_M = |N\rangle + (\epsilon_M - \epsilon)|N^*\rangle$$

The nucleus contains excited states of the nucleon

These configurations are the origin of high x EMC ratios

Estimate

$$\frac{\Delta q}{q}(x) = 2(\epsilon_M - \epsilon)\frac{\langle N^*|\mathcal{O}(x)|N\rangle}{\langle N|\mathcal{O}(x)|N\rangle} \approx 0.15$$

$$2(\epsilon_M - \epsilon) \sim 0.15$$

$$P_{N^*} = (\epsilon_M - \epsilon)^2 \sim 6 \times 10^{-3}$$

Previously missing in models of the EMC effect- same model predicts some other effect

Short Range Correlations and the EMC Effect in Effective Field Theory

Jiunn-Wei Chen,[1,2,*] William Detmold,[2,†] Joel E. Lynn,[3,4,‡] and Achim Schwenk[3,4,5,§]
[1] Department of Physics, CTS and LeCosPA, National Taiwan University, Taipei 10617, Taiwan
[2] Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[3] Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany
[4] ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany
[5] Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

arXiv: 1607.03065 (2016)

EFT description of bound nucleon structure:

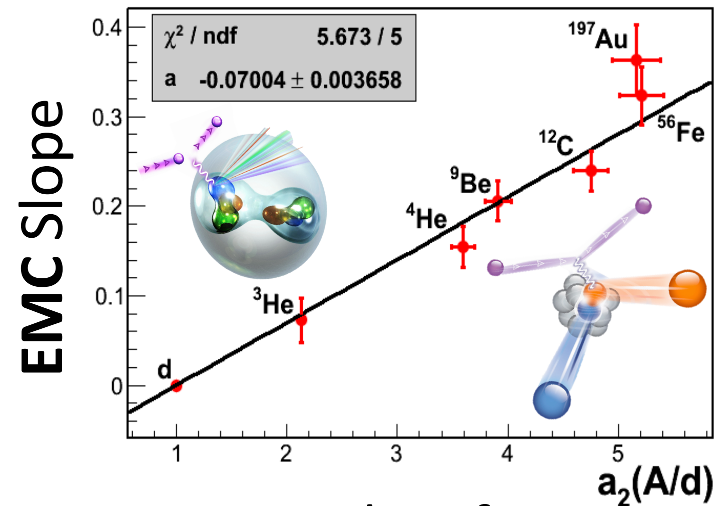
$$F_2^A(x,Q^2)/A = F_2^N(x,Q^2) + g_2(A,\Lambda) f_2(x,Q^2,\Lambda).$$

$$g_2(A,\Lambda) = \underbrace{\frac{1}{A}\langle A|\left(N^\dagger N\right)^2|A\rangle_\Lambda}_{\text{SRC contact}}$$

SRC contact

$$a_2(A, x>1) = \frac{g_2(A,\Lambda)}{g_2(2,\Lambda)}$$

[SRC Scaling Factor]



SRC Scaling factors

Bound nucleons in EFT and QCD

1. EFT: $F_2^A(x,Q^2) = F_2^N(x,Q^2) \; + \; g_2(A,\Lambda) \; \cdot \; f_2(x,Q^2,\Lambda)$

2. QCD: $|N\rangle_{bound} \; = \; |N\rangle \; + \; (\varepsilon_{bound} - \varepsilon) \cdot \; |N^*\rangle$

Hen et al., Reviews of Modern Physics, In-Print (2017)

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"Free" "Modification"

Hen et al., Reviews of Modern Physics, In-Print (2017)

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"Nuclear" "Partonic"

Hen et al., Reviews of Modern Physics, In-Print (2017)

Bound nucleons in EFT and QCD

SRC contact

$$\propto \langle A|\left(N^\dagger N\right)^2|A\rangle_\Lambda$$

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2. QCD: $|N\rangle_{bound} = |N\rangle + (\varepsilon_{bound} - \varepsilon) \cdot |N^*\rangle$

$$\propto \frac{p^2 - m^2}{2M}$$

SRC dominated

Hen et al., Reviews of Modern Physics, In-Print (2017)

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Bound nucleons in EFT and QCD

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<u>2. QCD:</u> $|N\rangle_{bound} = |N\rangle + (\varepsilon_{bound} - \varepsilon) \cdot |N^*\rangle$

"SRC" "Partonic"

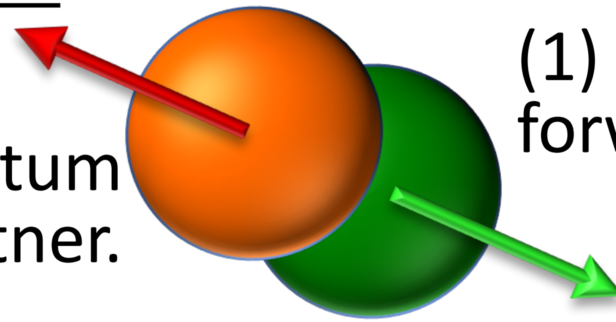
Need to probe and constrain both SRC and the partonic modification! [In comes JLab6 - JLab12 - EIC]

Hen et al., Reviews of Modern Physics, In-Print (2017)

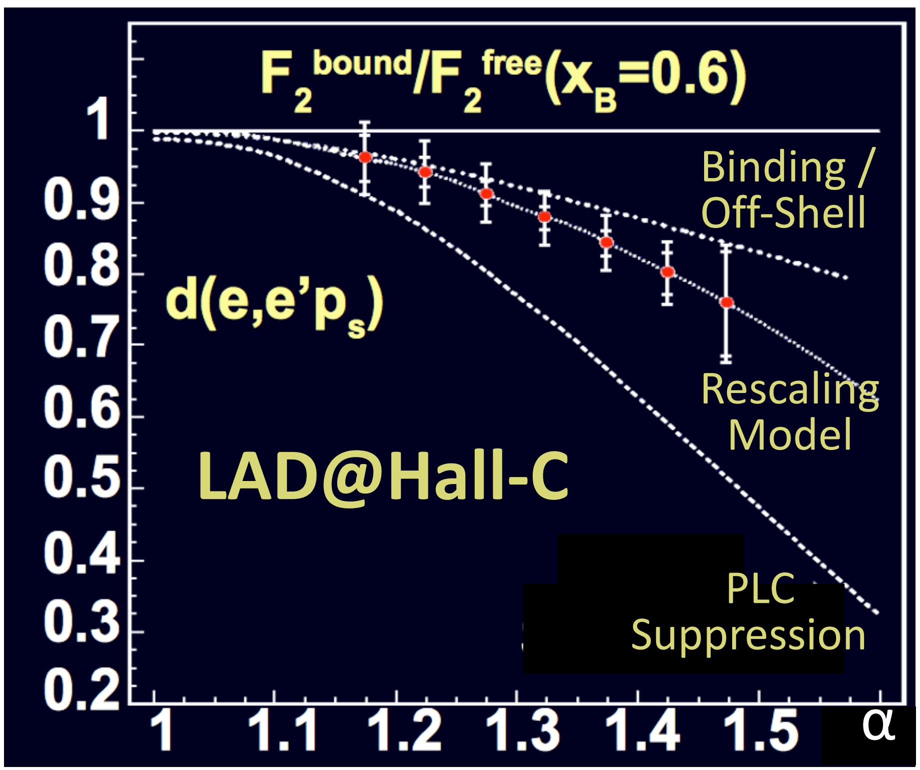
Test of Bound Nucleon Modification?

Focus on the deuteron:

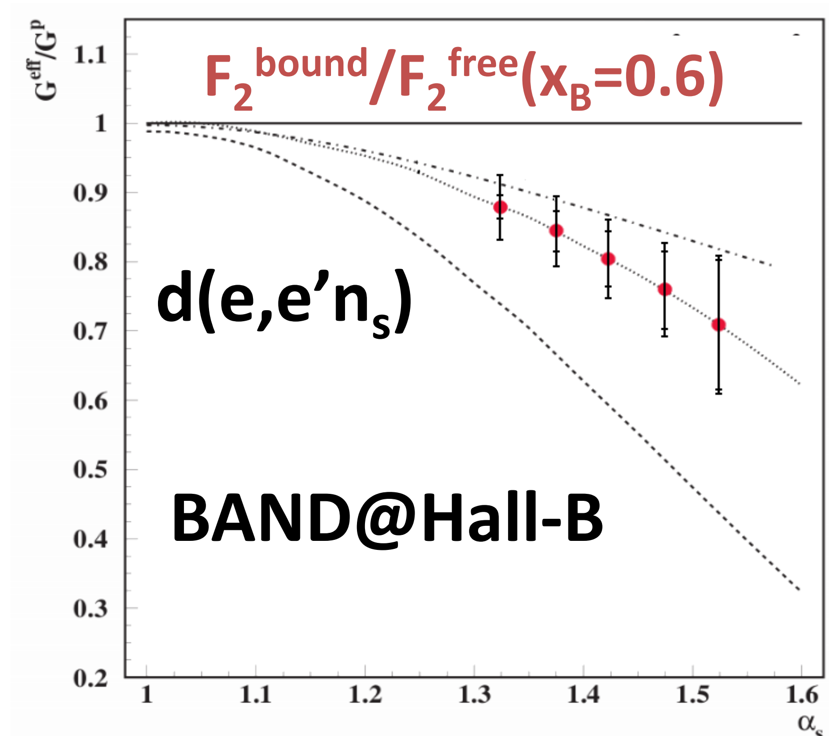
(2) Infer its momentum from the recoil partner.



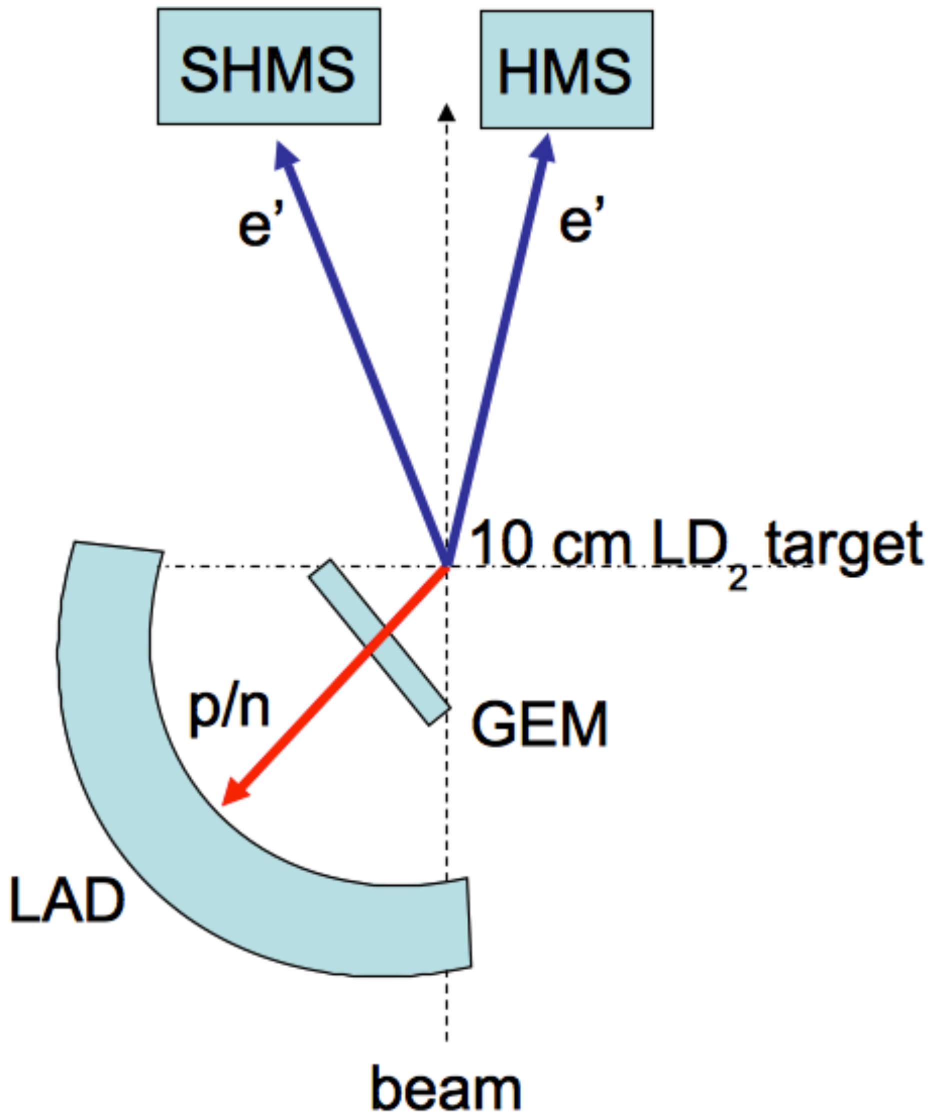
(1) Perform DIS off forward going nucleon.



Melnitchouk et al., Z. Phys. A **359**, 99-109 (1997)

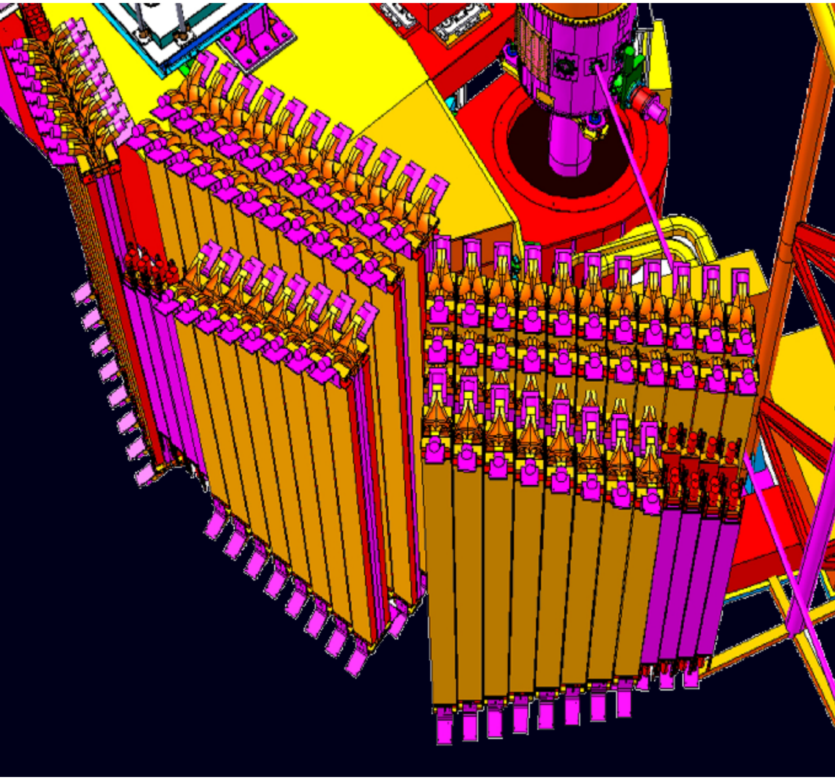


Tagging Concept $d(e,e'N_{recoil})$

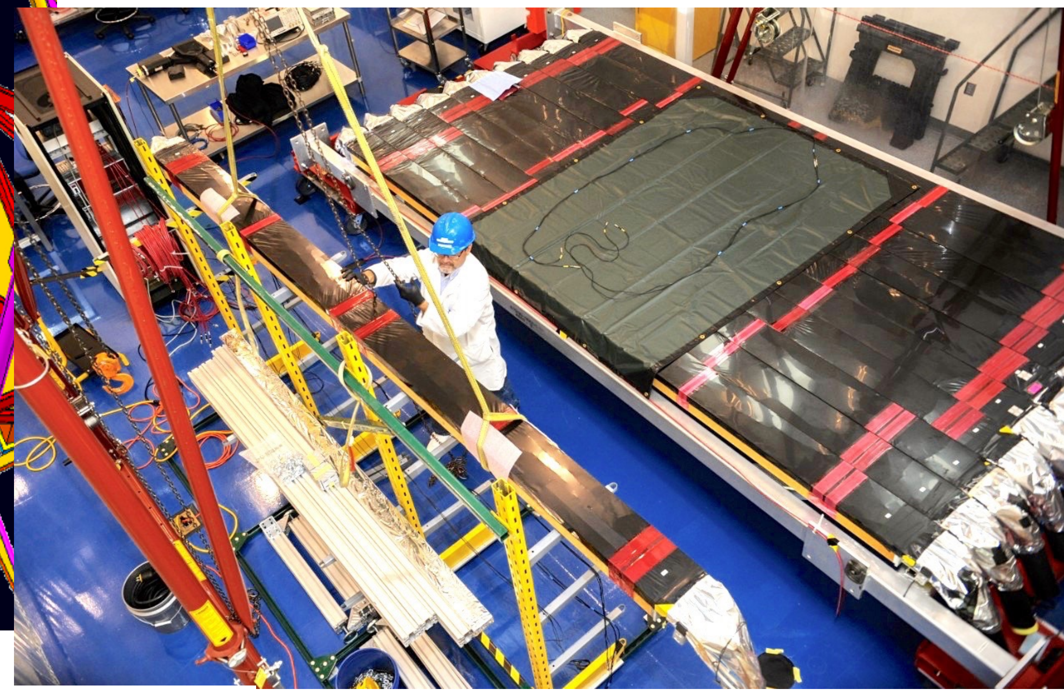


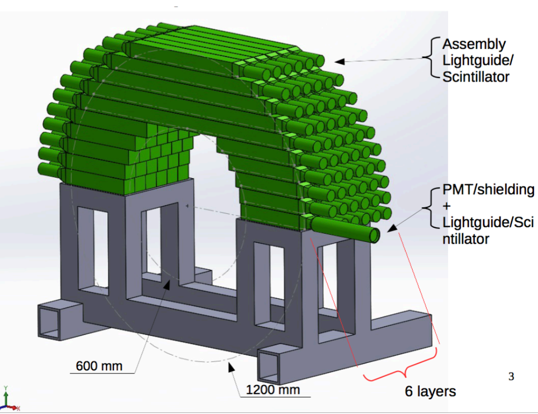
- High resolution spectrometers for (e,e') measurement in DIS kinematics
- Large acceptance recoil proton \ neutron detector
- Long target + GEM detector – reduce random coincidence

Building Large-Acceptance Detectors

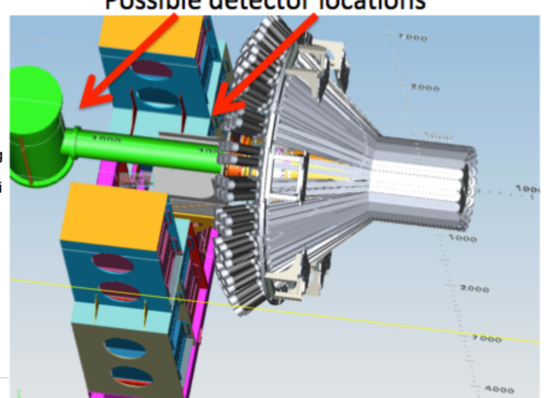


Large Acceptance Detector (LAD@Hall-C)





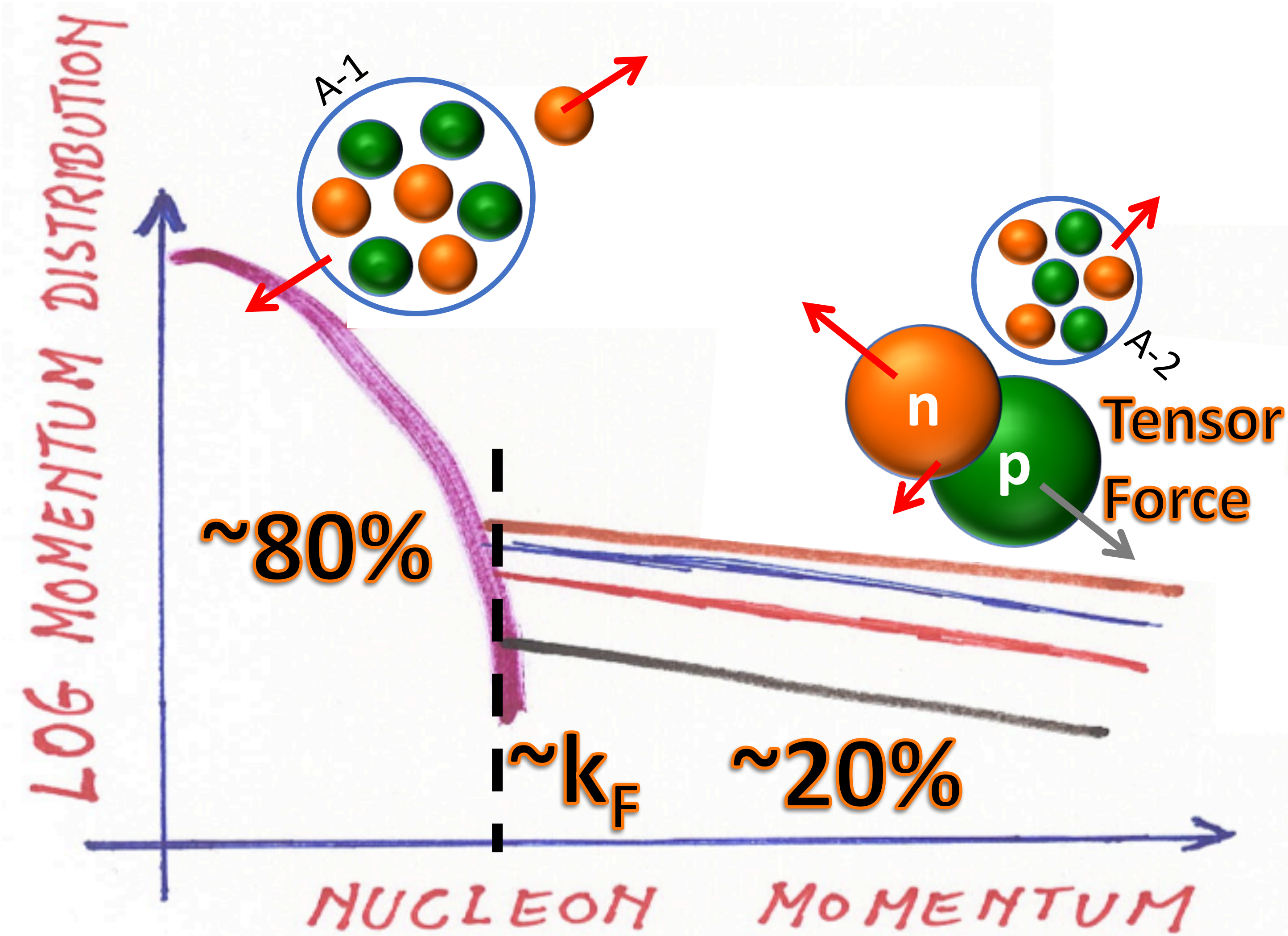
Possible detector locations



Backward Angle Neutron Detector (BAND@Hall-B)

R&D @ MIT / UTSM / TAU
Construction @ BATES

Beyond the Mean-Field: Short-Range Correlations

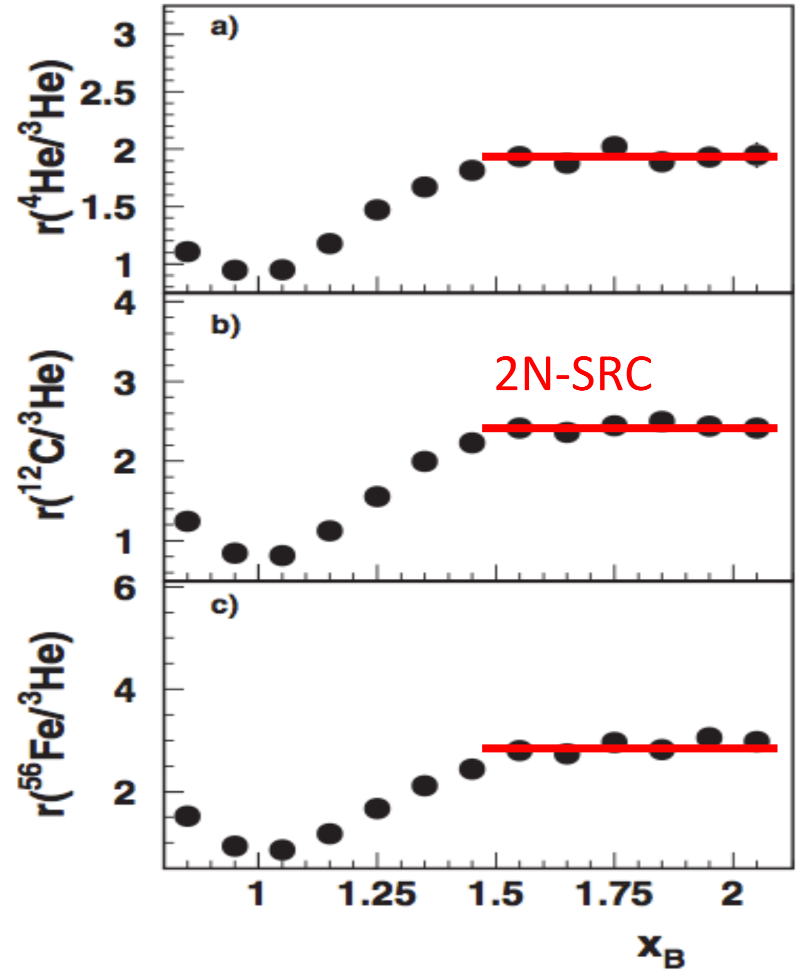


High-Momentum Scaling

- A/d (e,e') cross section ratios sensitive to $n_A(k)/n_d(k)$

- Observed scaling for $x_B \geq 1.5$.

$\Rightarrow n_A(k>k_F) = a_2(A) \times n_d(k)$



K. Egiyan et al., PRL **96**, 082501(2006).

L. Frankfurt et al. , Phys. Rev. C **48**, 2451 (1993).
K. Egiyan et al., Phys. Rev. C **68**, 014313 (2003). N. Fomin et al., Phys. Rev. Lett. **108**, 092502 (2012).

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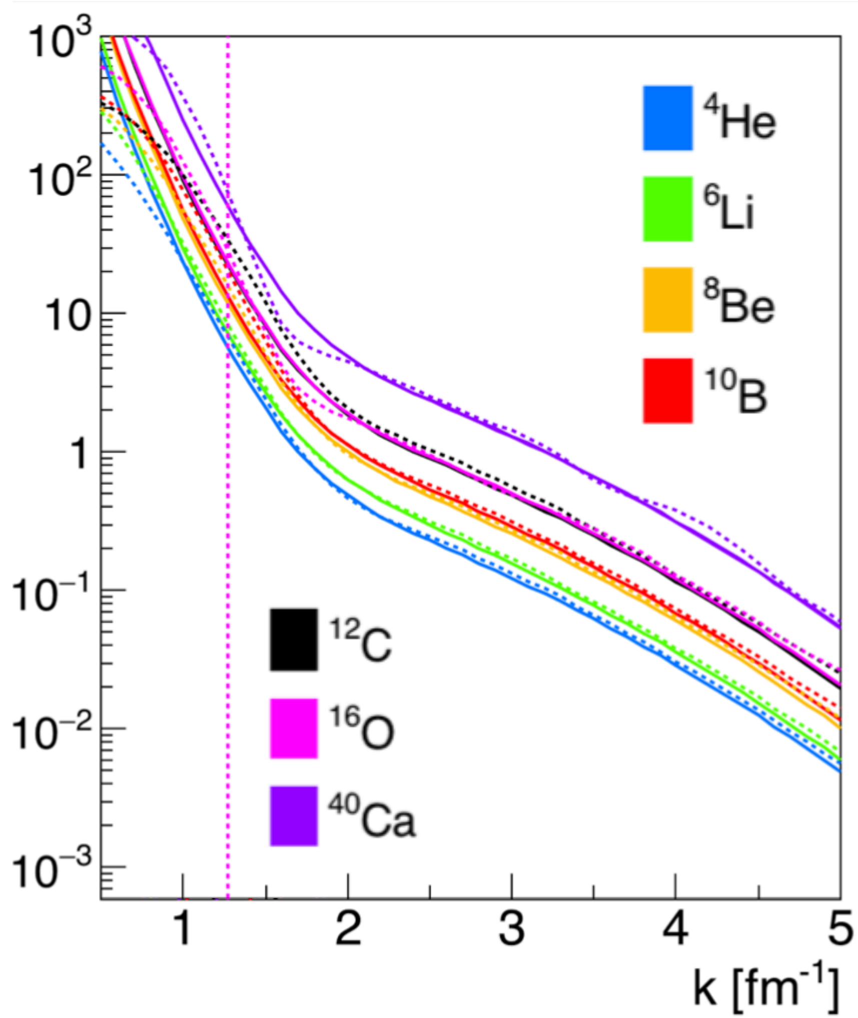
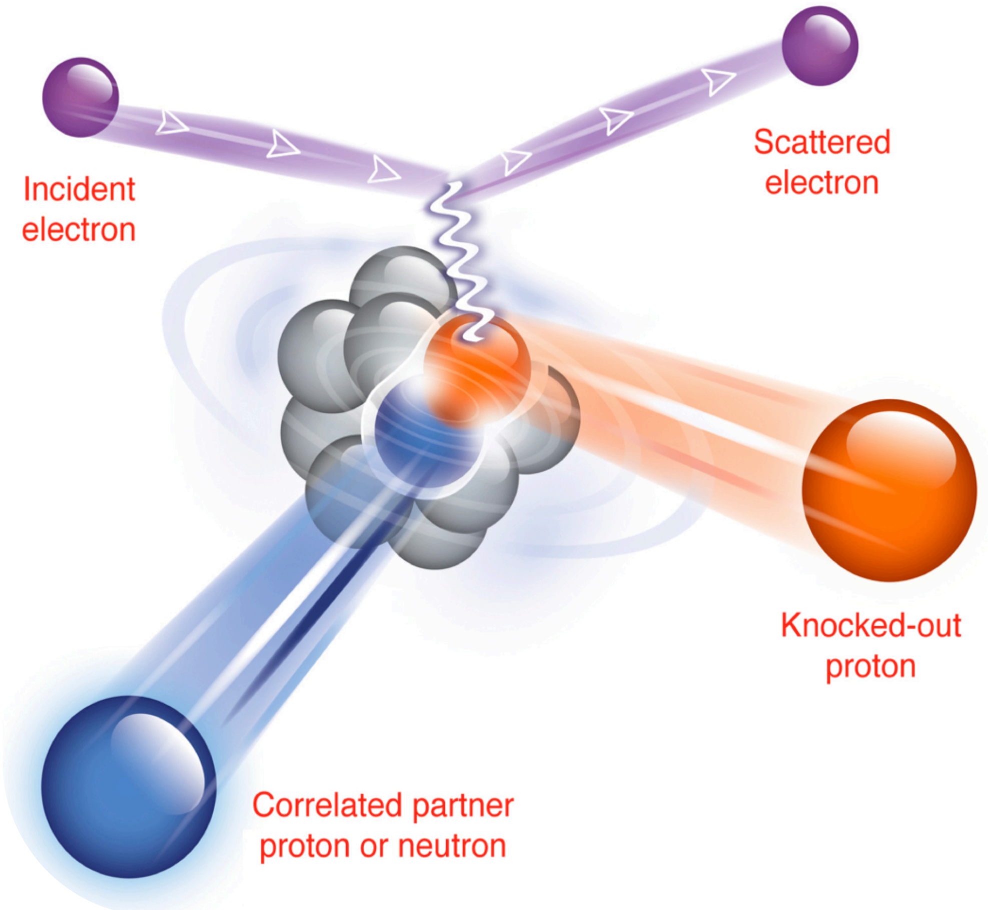


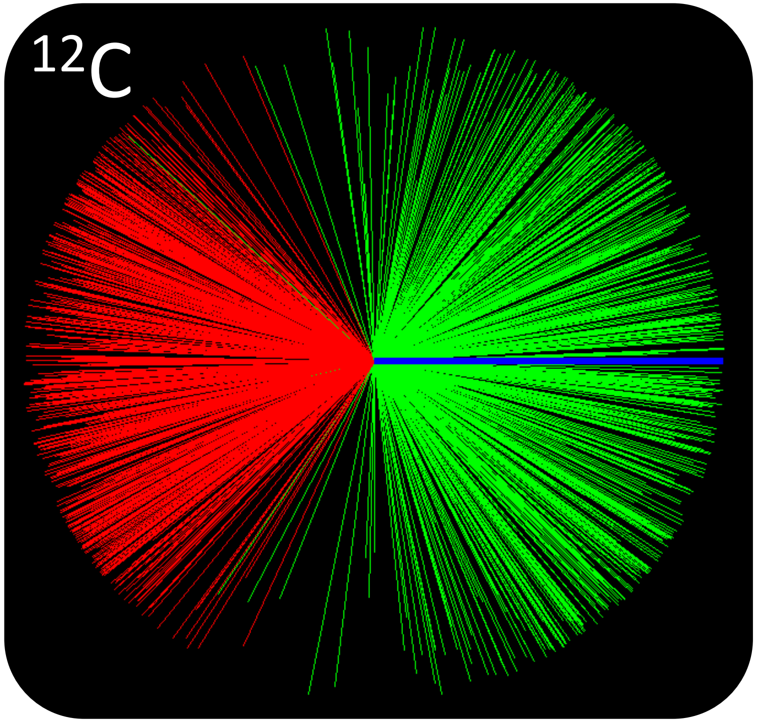
K. Egiyan et al., Phys. Rev. C **68**, 014313 (2003).

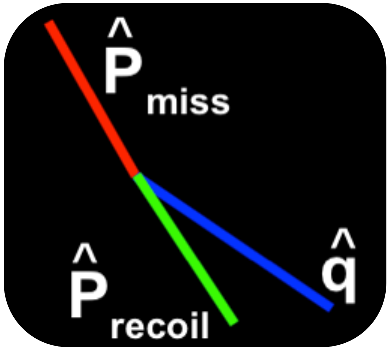
SRC Probes: Exclusive (e,e'pN) Scattering

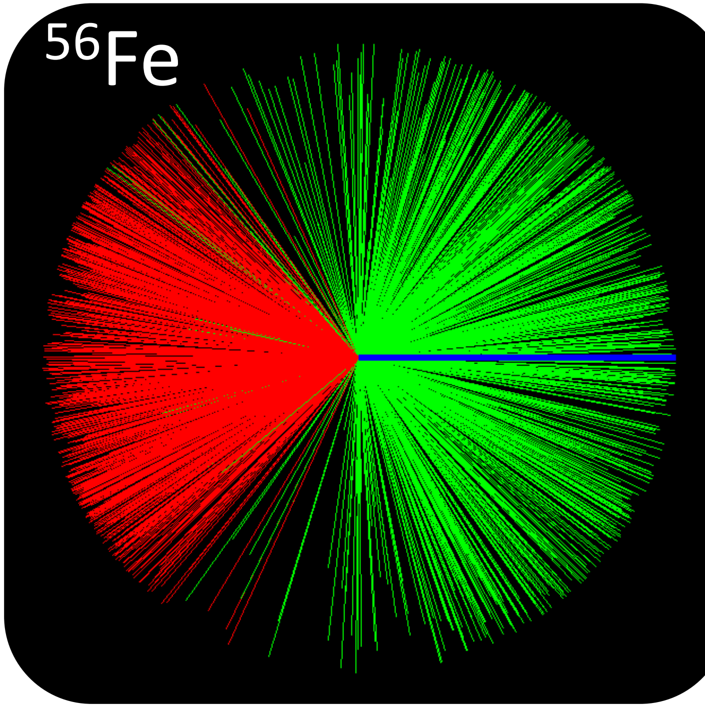
Breakup the pair =>
Detect ***both*** nucleons =>
Reconstruct 'initial' state

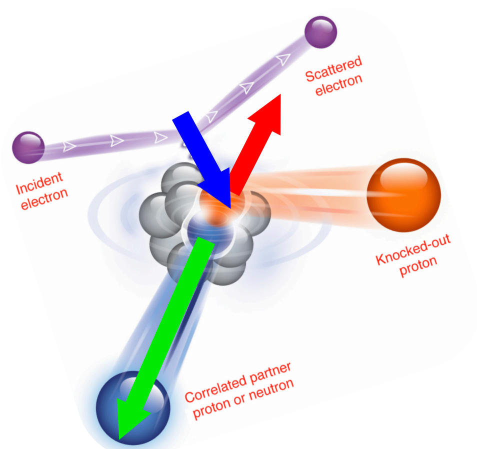


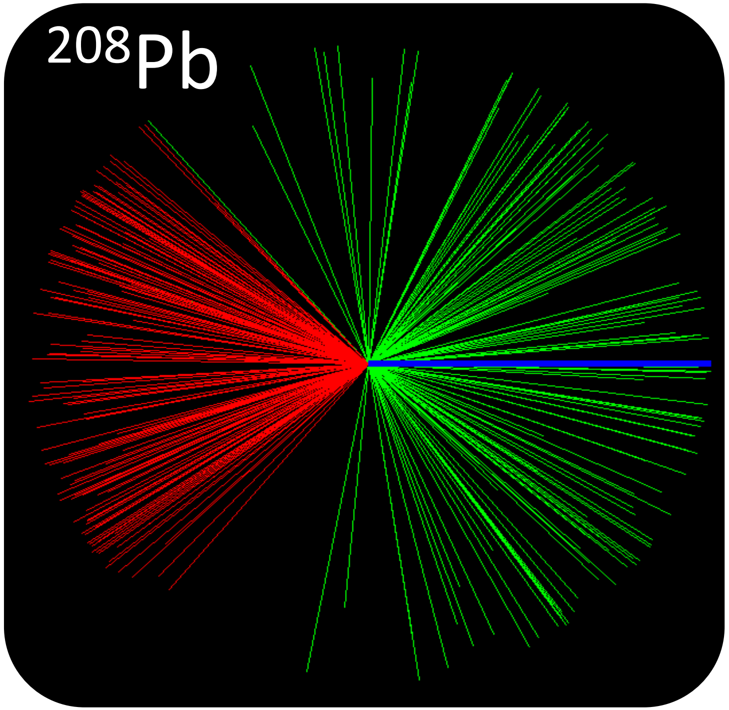
3D Reconstruction

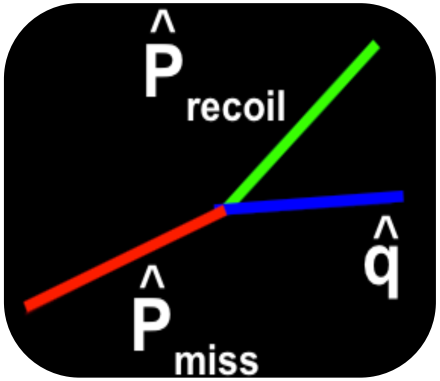






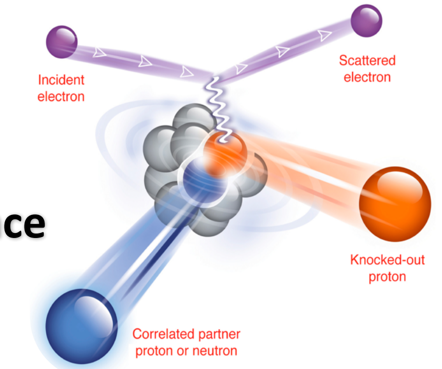


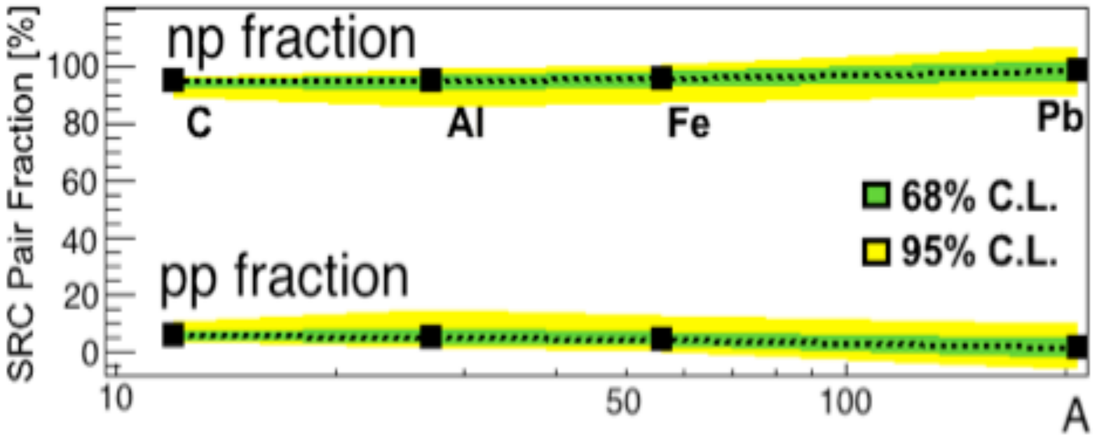




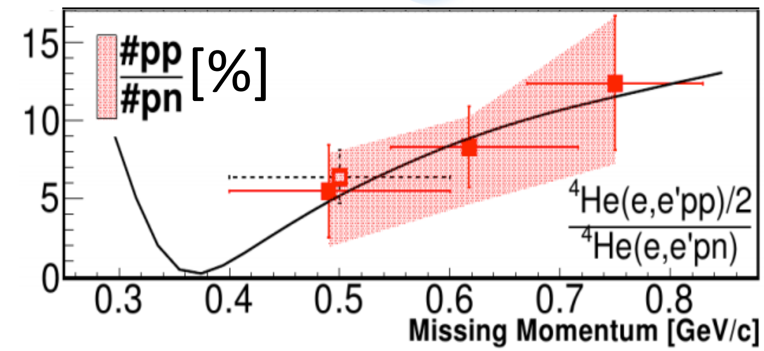
Back-to-back =
SRC pairs!

np dominance results



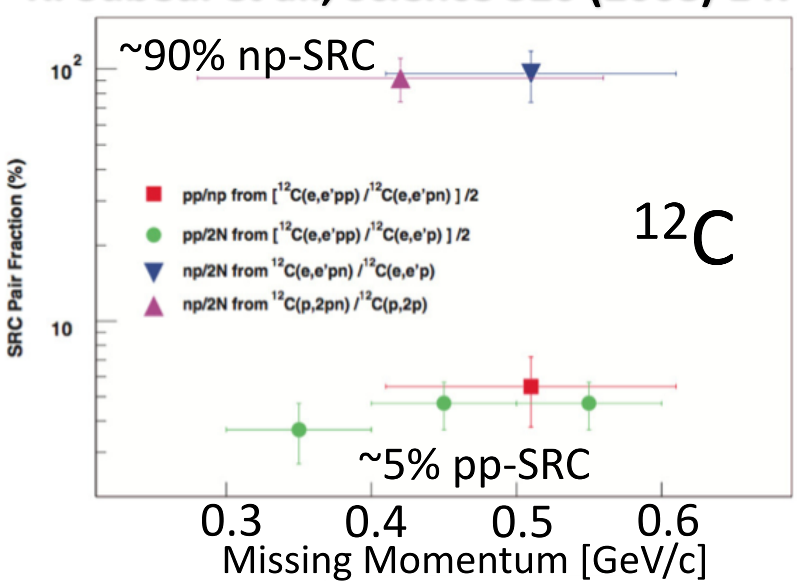


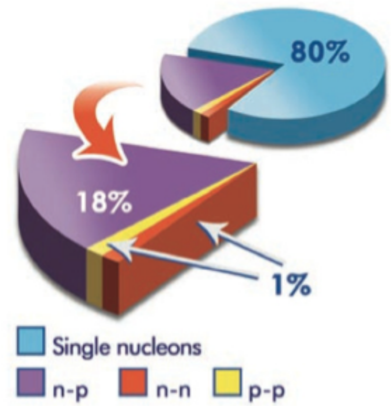
O. Hen et al., Science 364 (2014) 614

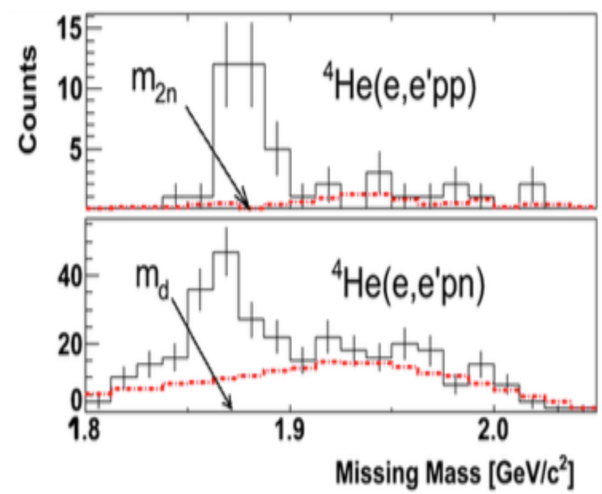


R. Subedi et al., Science 320 (2008) 1476

I. Korover et al., PRL 113 (2014) 022501



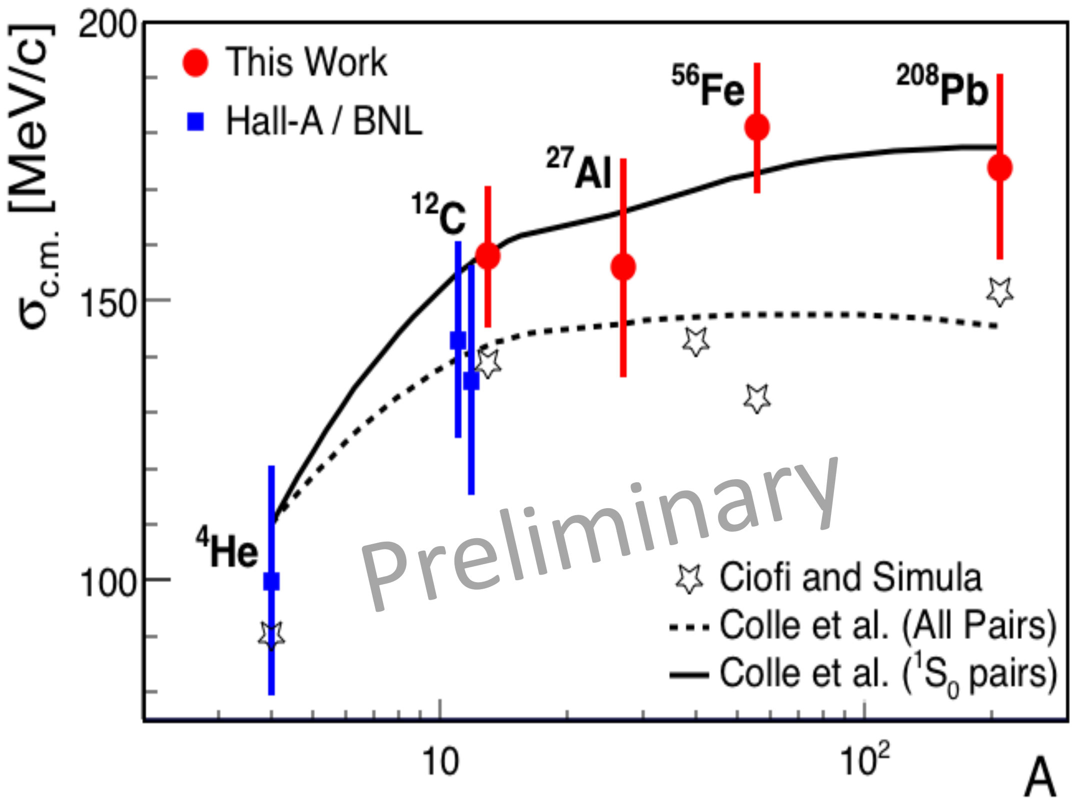


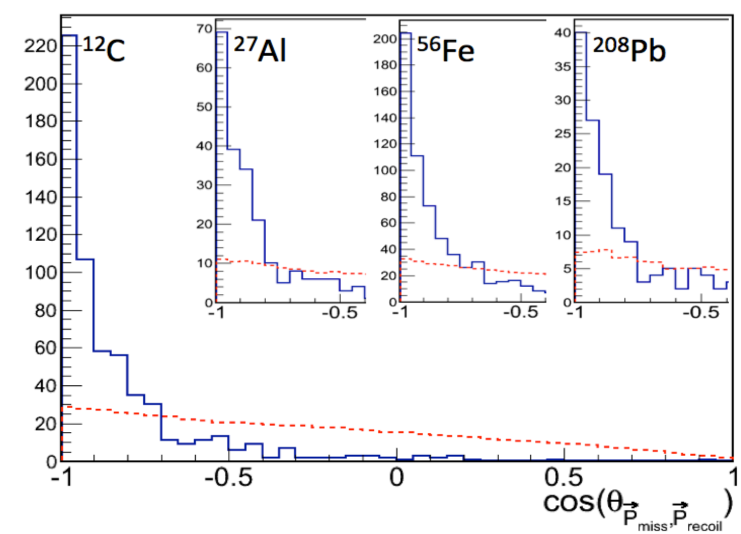


A. Tang et al., PRL (2003); E. Piasetzky et al., PRL (2006); R. Shneor et al., PRL (2007)

C.M. Motion and Pairing Mechanisms

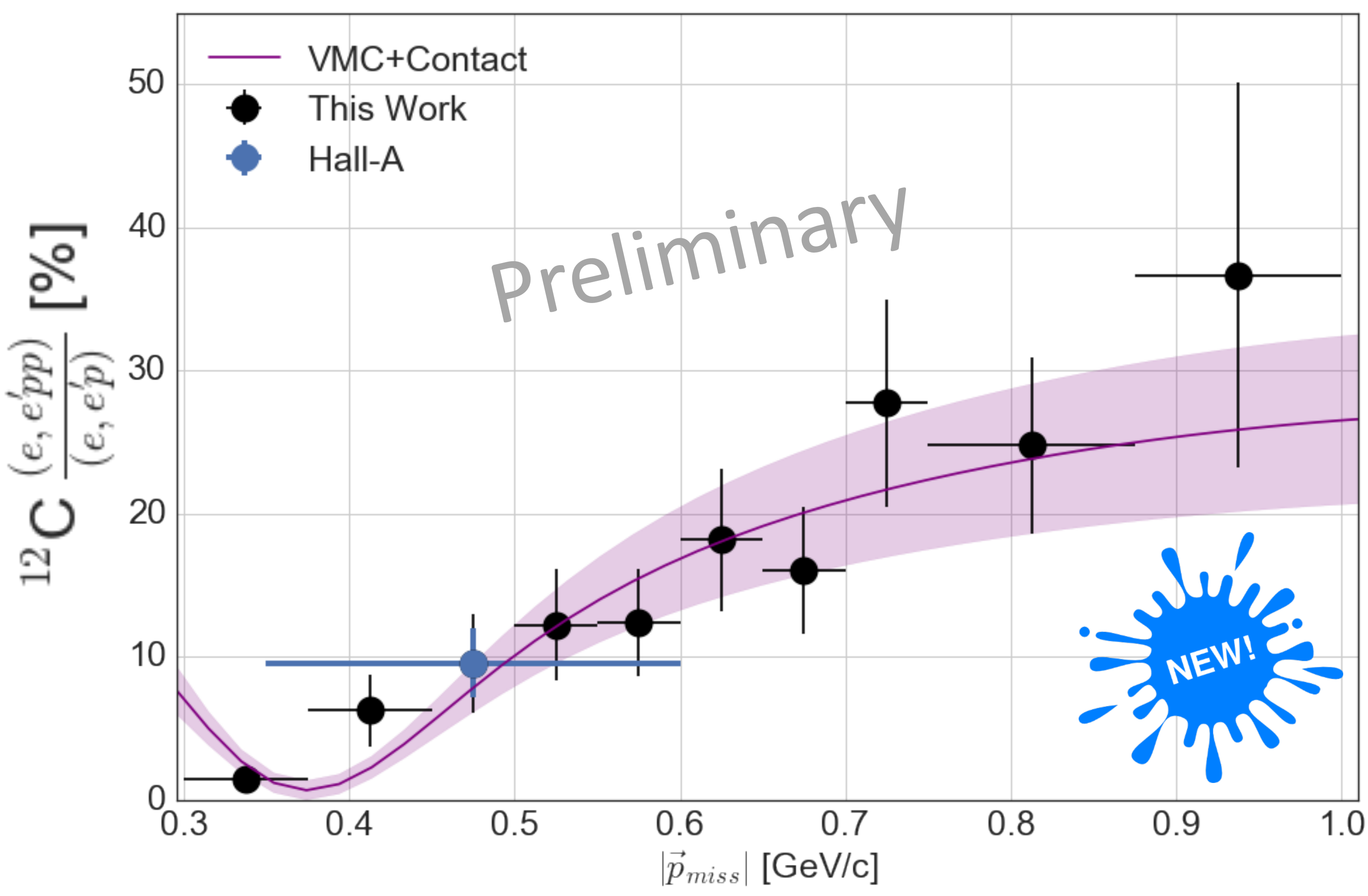
"… *high relative momentum* and ***low c.m. momentum*** compared to the Fermi momentum (k_F)"





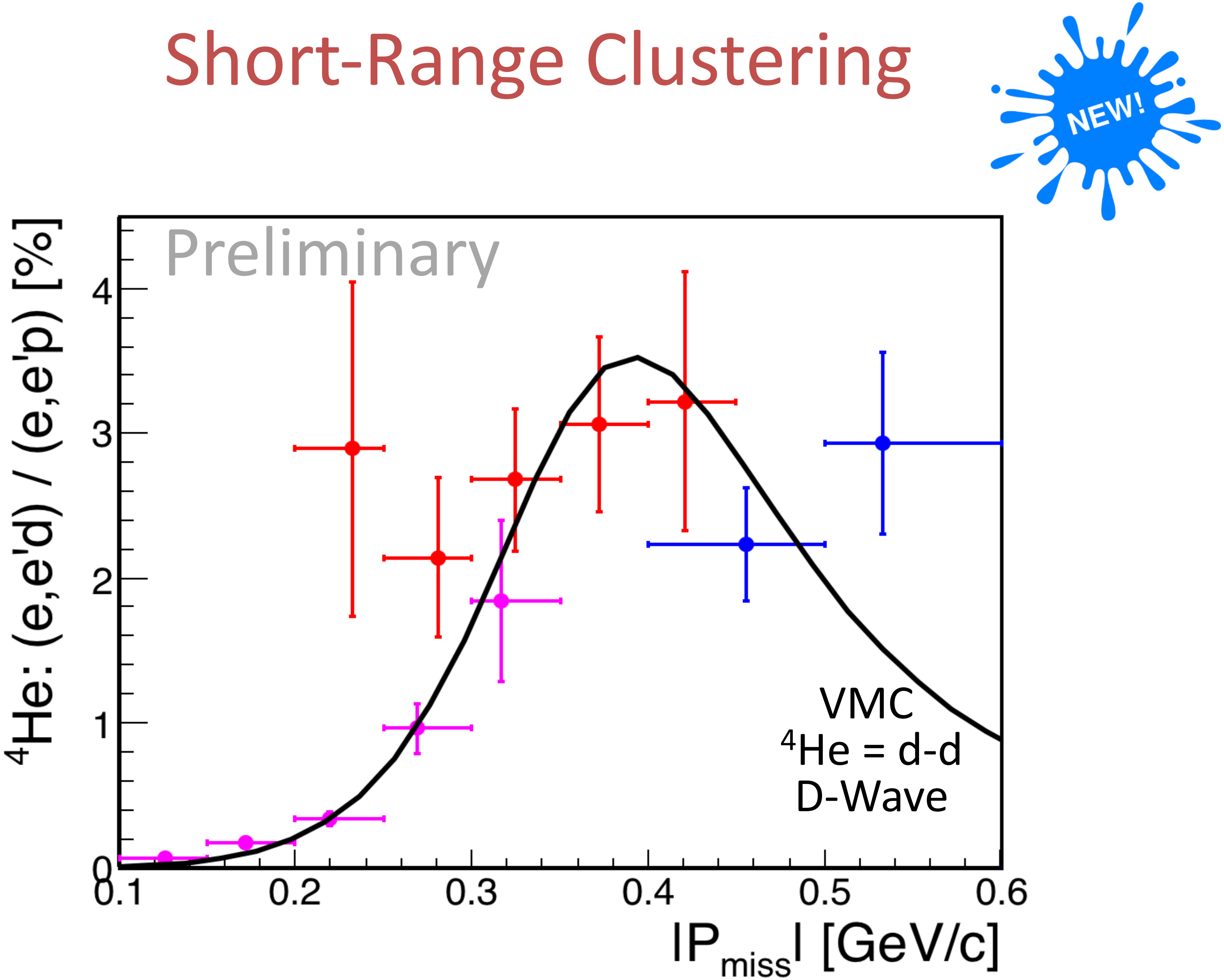
E. Cohen et al. (CLAS Collaboration), In-Preparation (2017)

NN interaction at Short Distances



(CLAS Collaboration), In-Preparation (2017)

Short-Range Clustering

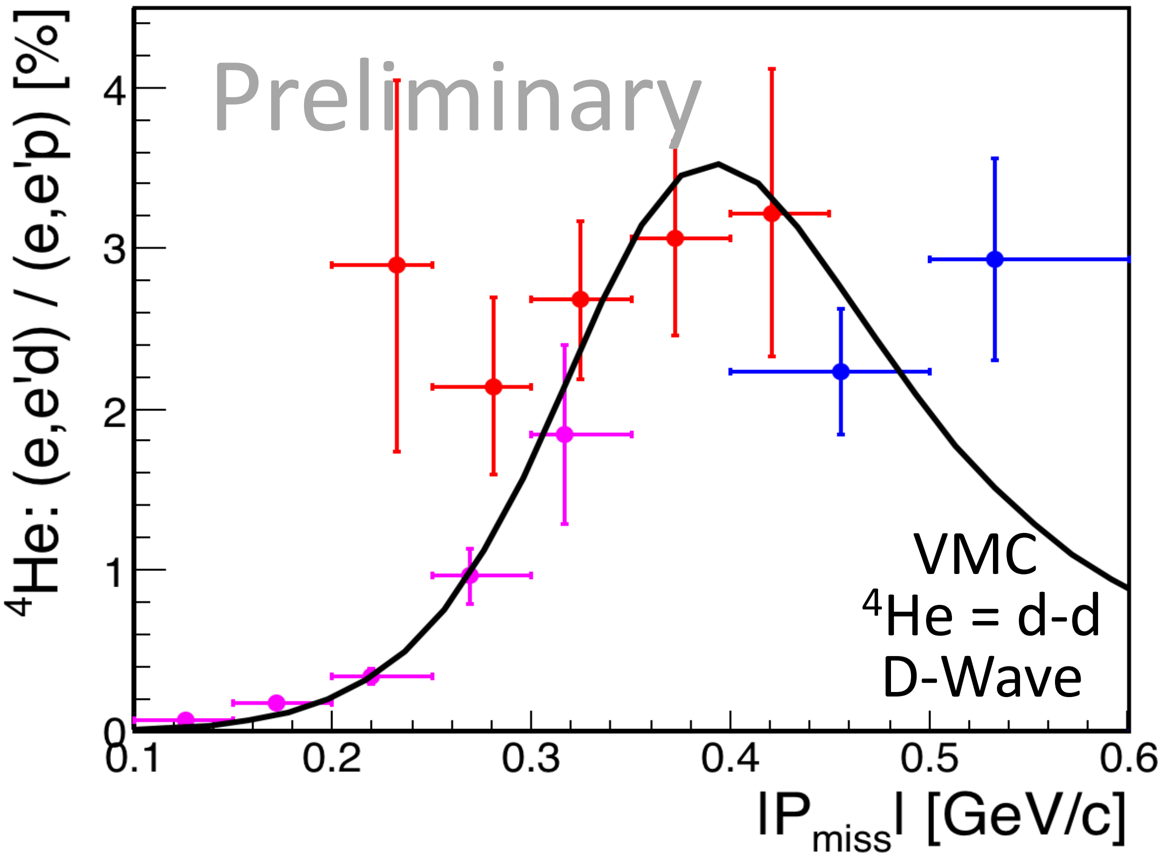


I. Korover et al. (Hall-A Collaboration), In-Preparation (2017)

Short-Range Clustering

First (?) **observation of 4-nucleon correlation**?

First (?) **confirmation of ab-initio calculations in extreme conditions**

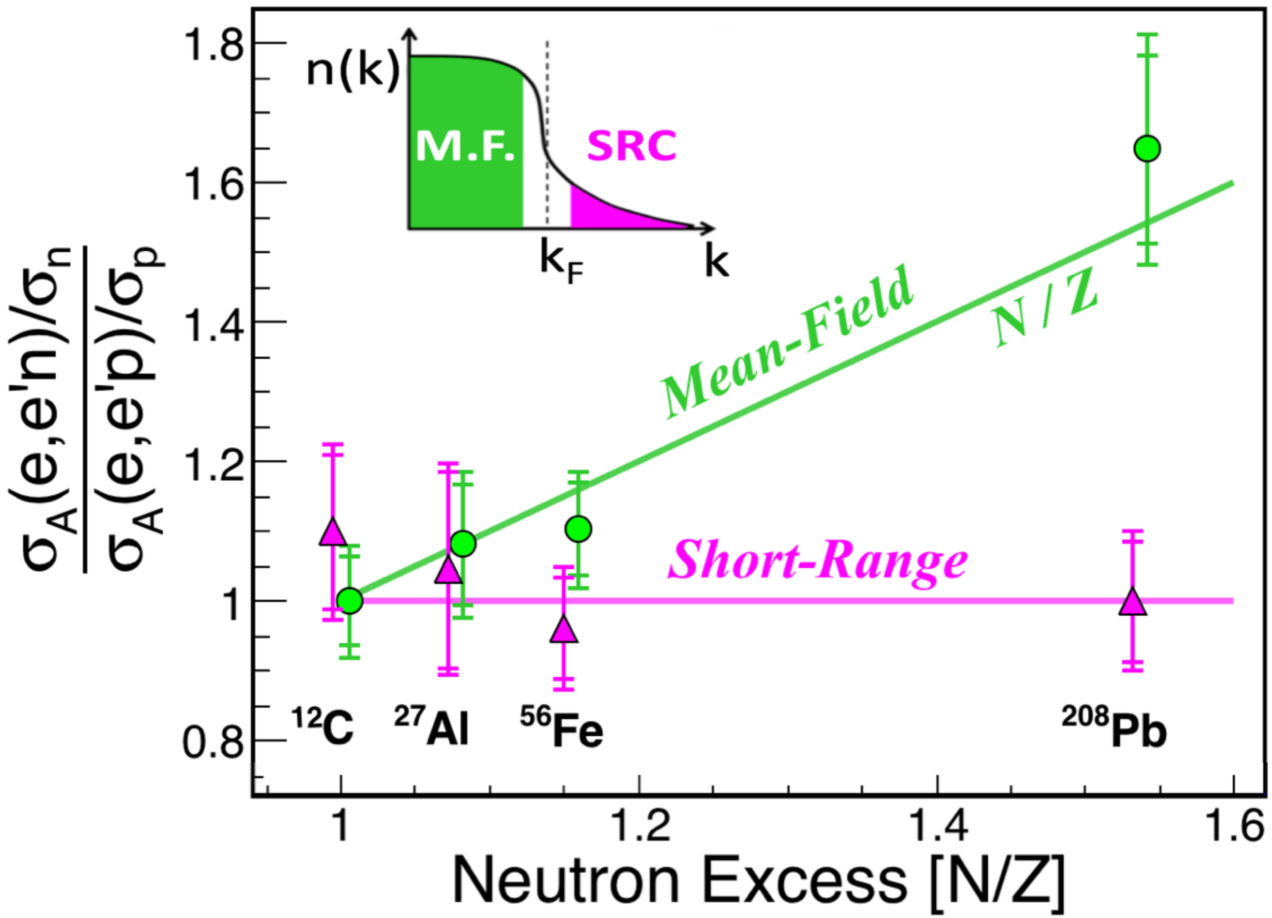


$<x_B> \sim 1.2$, $<Q^2> \sim 2.0$
$E_{miss} < 150$ MeV
Anti-Parallel kin.

I. Korover et al. (Hall-A Collaboration), In-Preparation (2017)

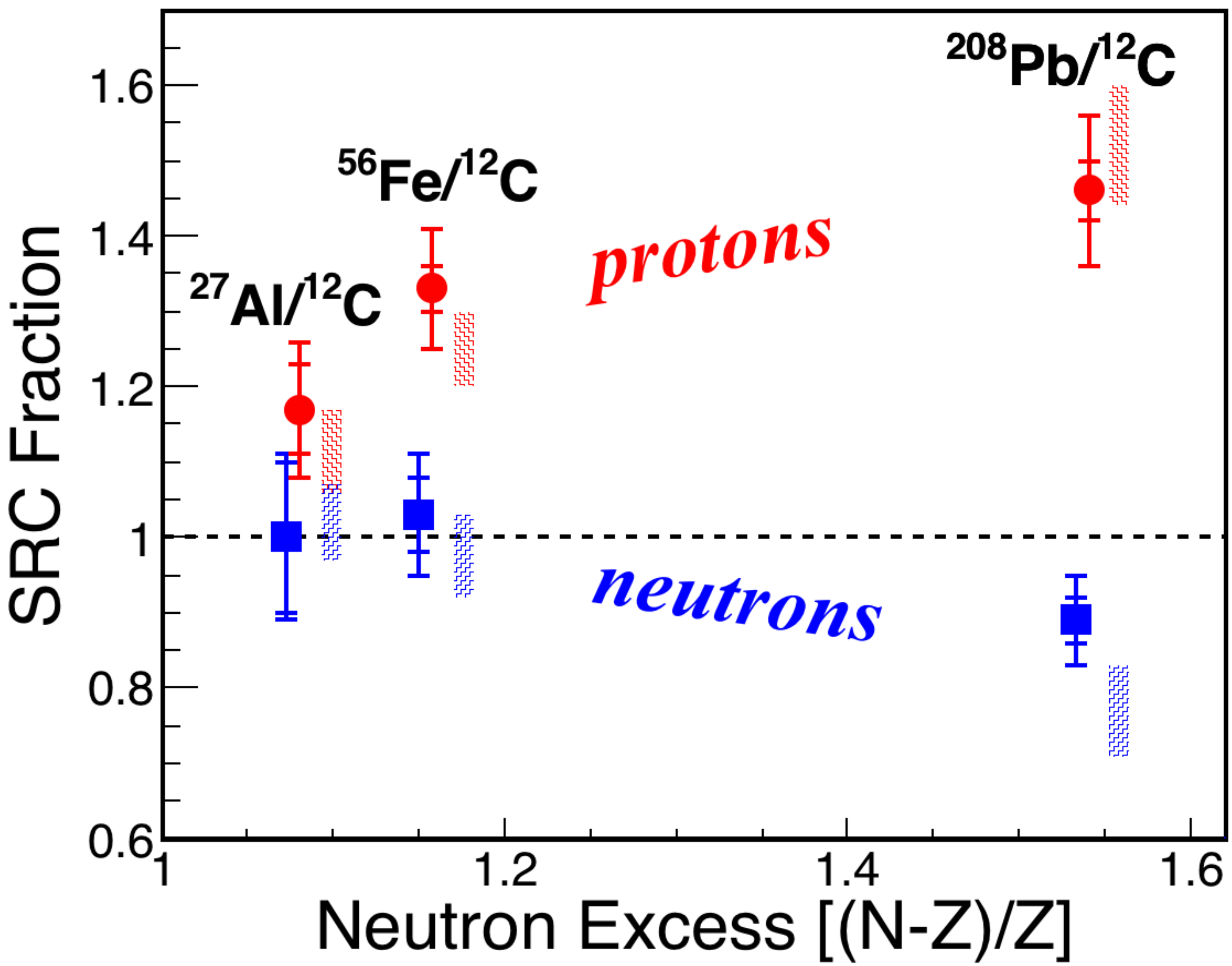
Equal Number of Correlated Protons and Neutrons!

NEW!



M. Duer et al. (CLAS Collaboration), In-Preparation (2017)

Neutron Rich Nuclei: Larger Fraction of Correlated Protons



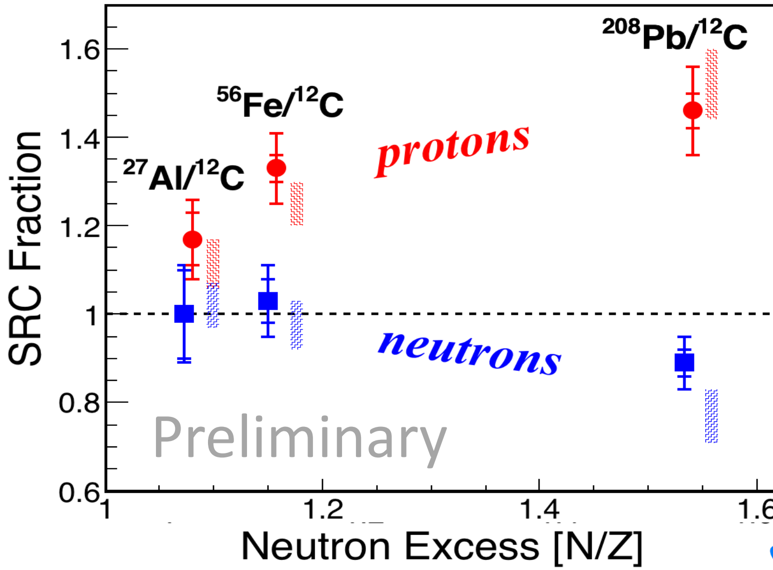
M. Duer et al. (CLAS Collaboration), In-Preparation (2017)

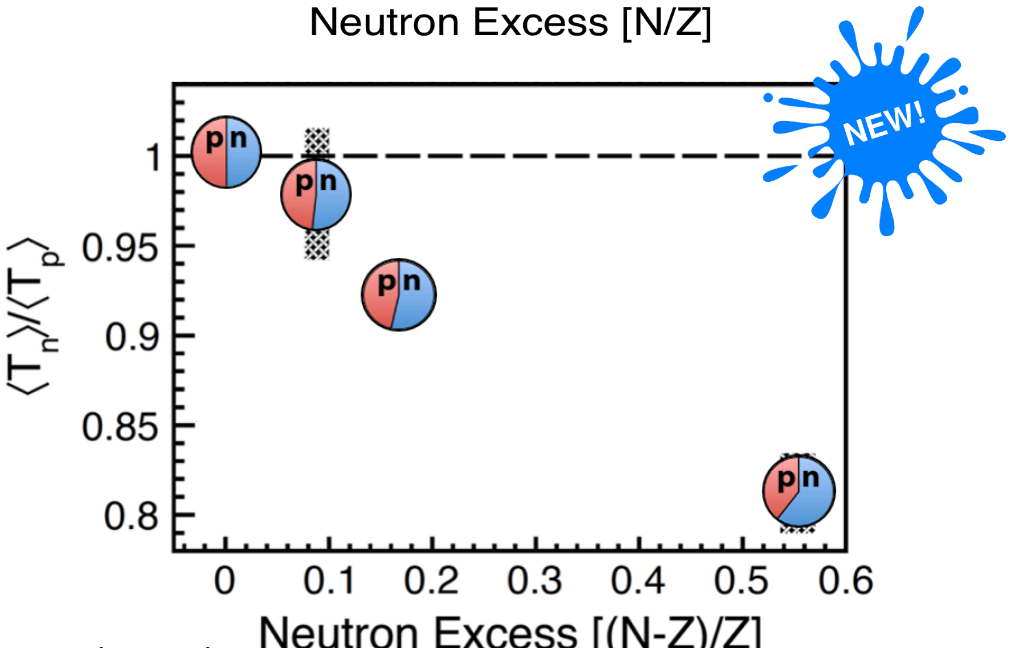
Protons Move Faster In Neutron Rich Nuclei

Theory model: depleted mean-field + scaled deuteron tail.

Simplistic, but works!

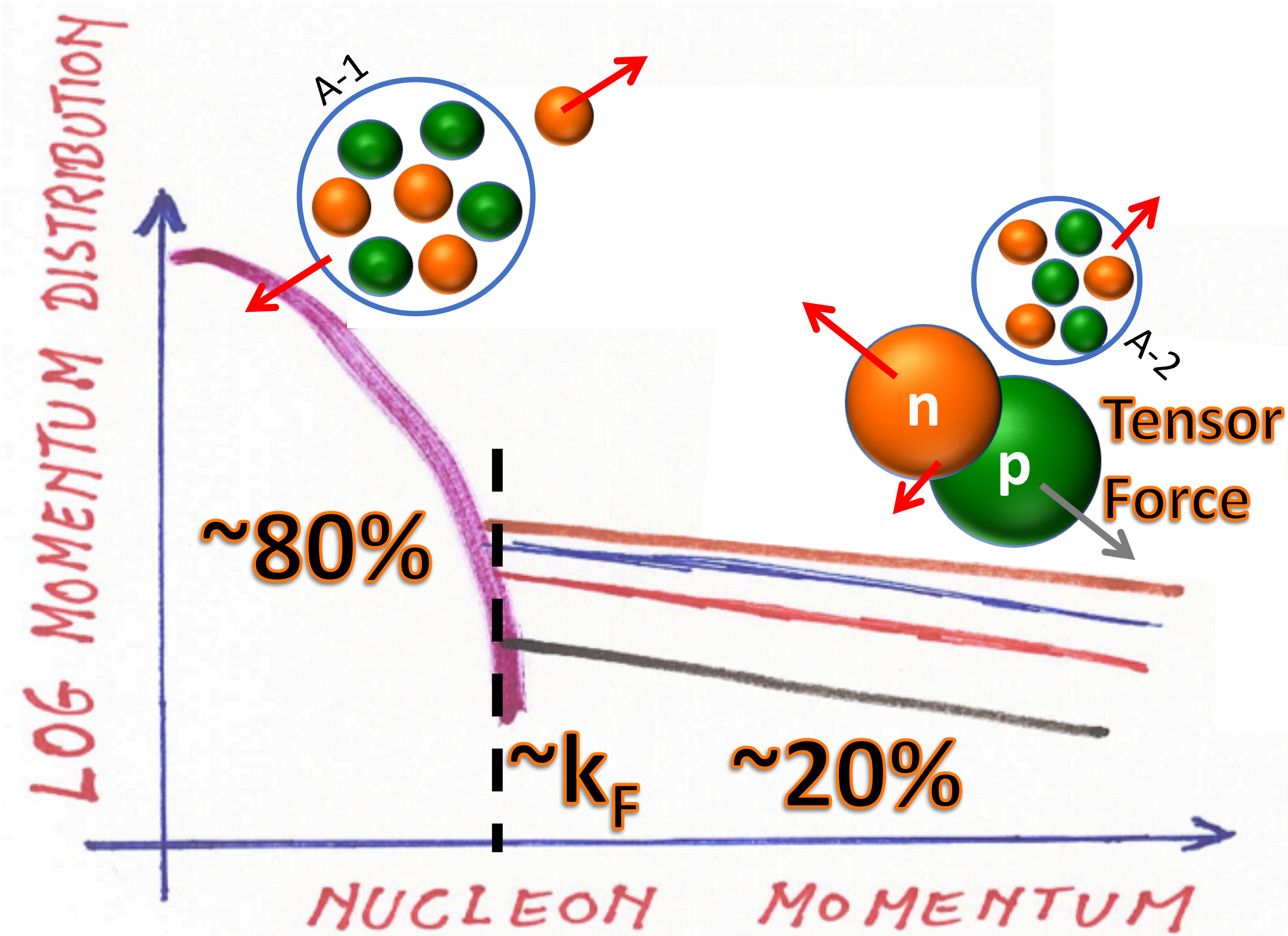
Indicates protons move faster than neutrons!





M. Duer et al. (CLAS Collaboration), In-Preparation (2017)

Beyond the Mean-Field: Short-Range Correlations



RMP Review

Nucleon-Nucleon Correlations, Short-lived Excitations, and the Quarks Within

Or Hen

Massachusetts Institute of Technology, Cambridge, MA 02139

Gerald A. Miller

Department of Physics, University of Washington, Seattle, WA 98195

Eli Piasetzky

School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel

Lawrence B. Weinstein

Department of Physics, Old Dominion University, Norfolk, VA 23529

arXiv: 1611.09748 (2017)

Conclusions

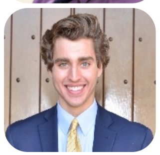
- EMC is a nuclear effect.
  - Can not be explained without bound nucleon structure modification.
- SRC lead to high virtuality nucleons.
  - Should contain a non-nucleonic component
- EMC and SRC are connected by phenomenology and via several theoretical models due to their high virtuality.
  - Only (?) models that can self consistently explain all available data.
  - Effect is in the amplitude – 15% modification can come from 1% probability!
- JLab12 experiments planned to test and constrain theory!
  - SRC pair counting => number of modified nucleons.
  - Tagged EMC => Modification level of correlated nucleons.

The Correlations group

- **MIT (Or Hen):**


Barak Schmookler


Reynier Torres


Efrain Segarra


Afroditi Papadopoulou


Axel Schmidt


George Laskaris


Maria Patsyuk


Adi Ashkenazy

- **TAU (Eli Piasetzky):**


Erez Cohen


Meytal Duer


Igor Korover

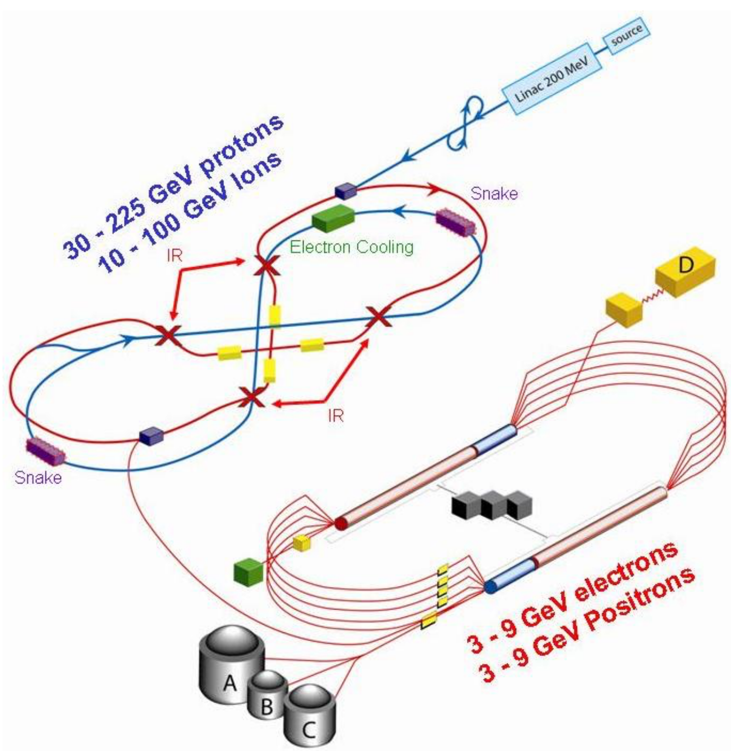
- **ODU (Larry Weinstein):**

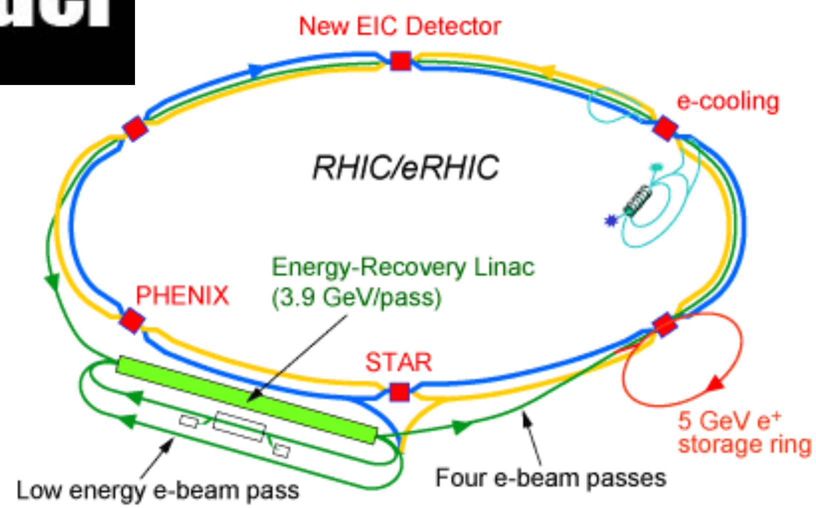

Mariana Khachatryan


Florian Hauenstein

- **Theory Collaborators (lots!)**

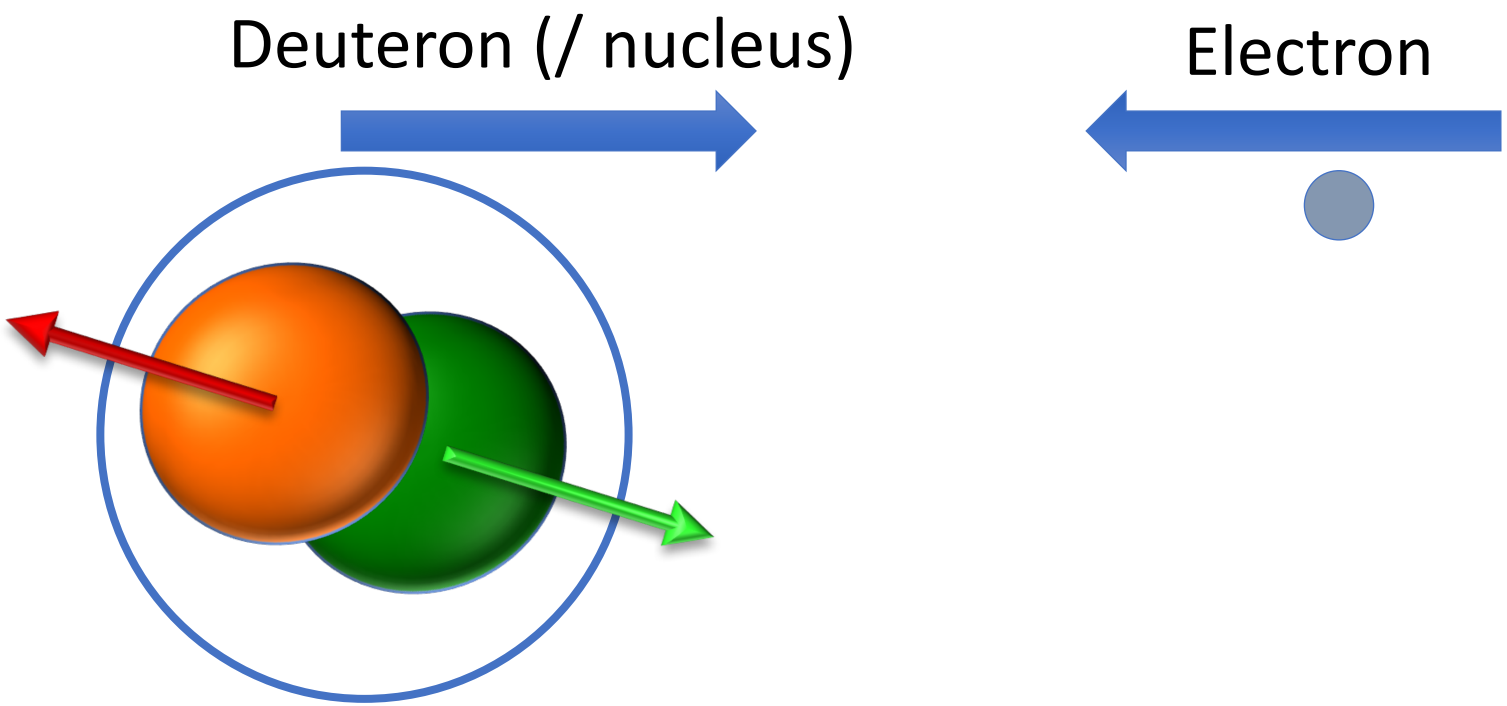
Beyond JLab12: EIC



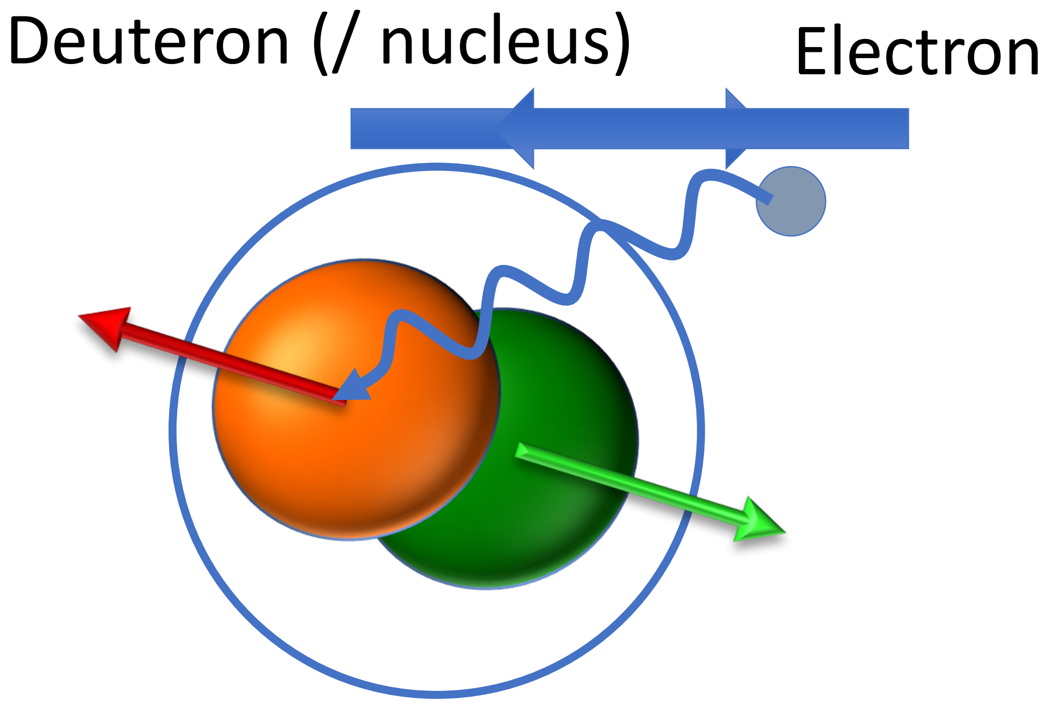


** Your Design Here? **

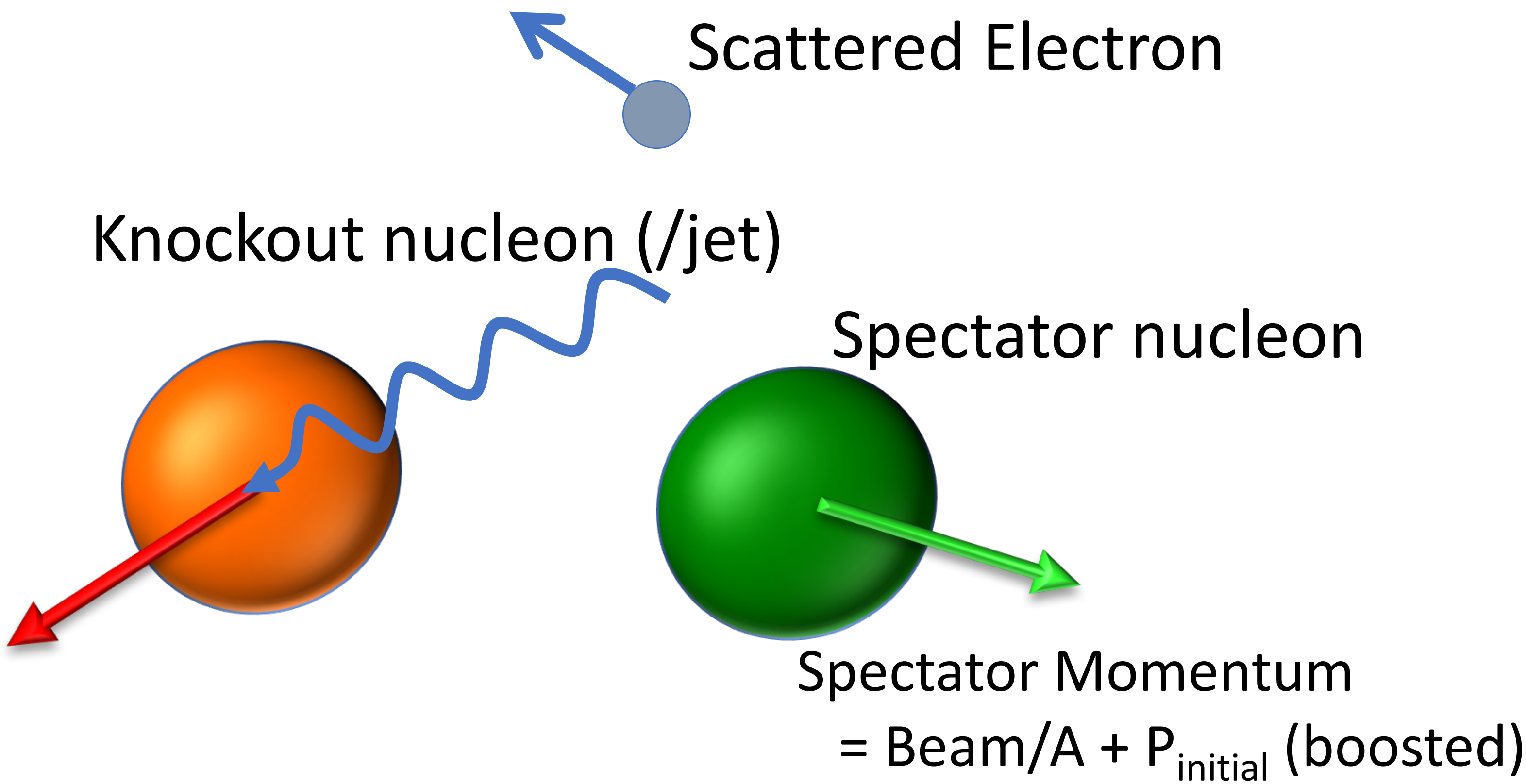
Collider Concept



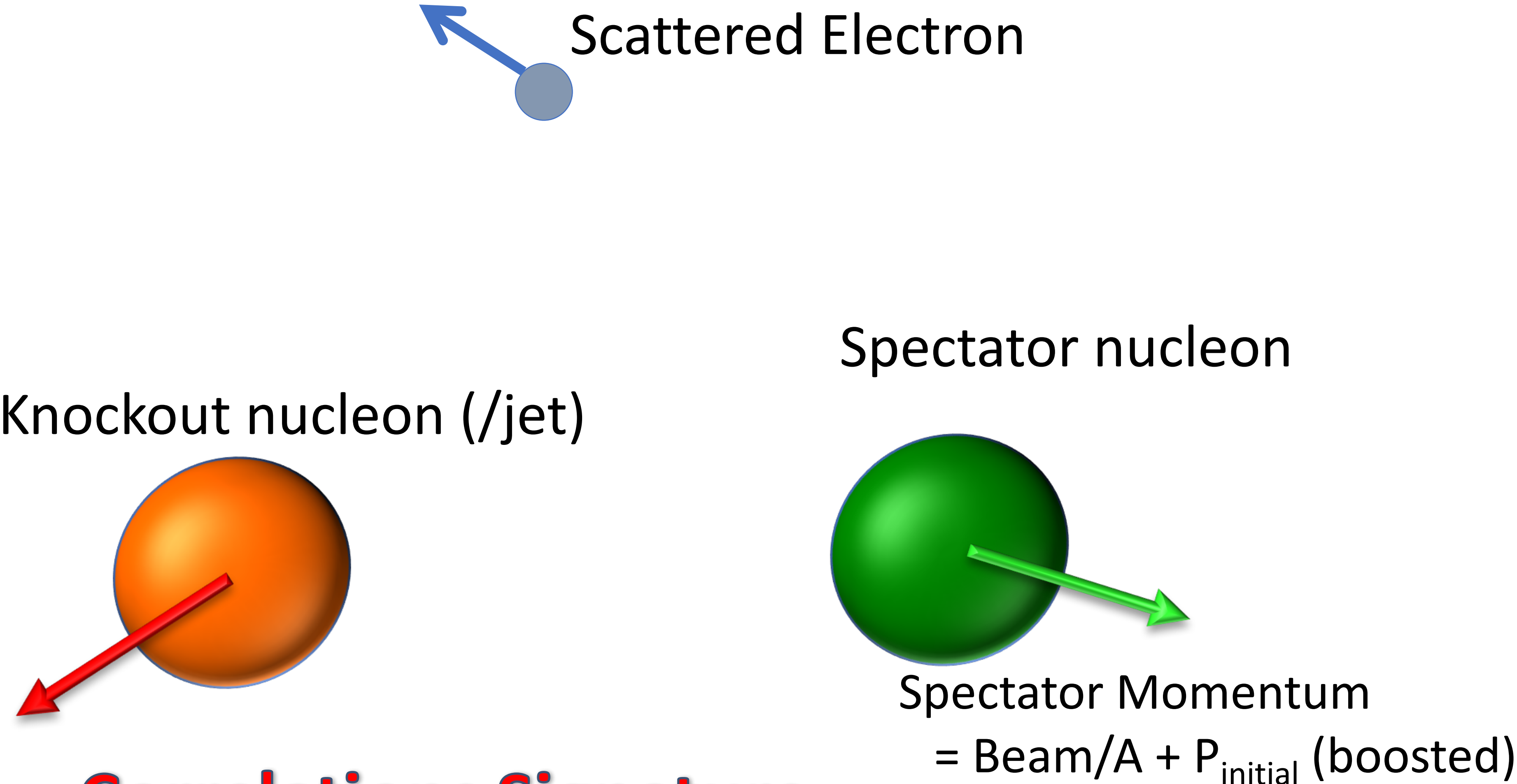
Collider Concept



Collider Concept



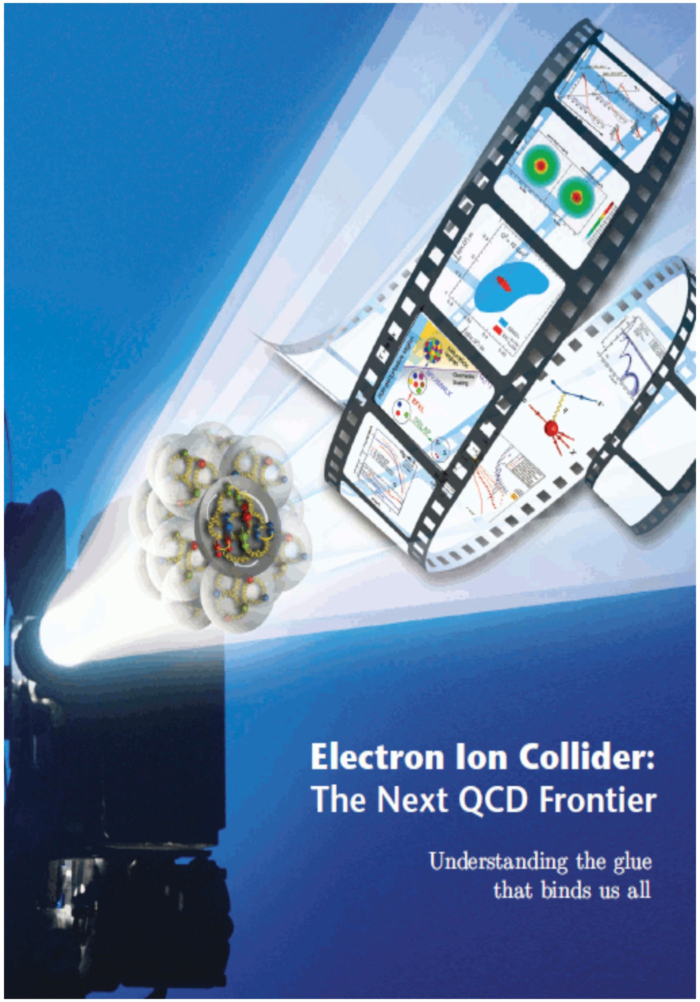
Collider Concept



Correlations Signature:

Large Spectator momentum

Collider Kinematics



Spectator Momentum

100 GeV d: $\gamma = 50$

Center of Mass		Lab	
P_z (CM) GeV/c	P_{perp} (CM) GeV/c	P_z (Lab) GeV/c	θ_p (Lab)
0	0	50	0
0.2	0	41	0
0.4	0	34	0
0.6	0	28	0
0.6	0.2	29	0.007
0.6	0.6	36	0.02