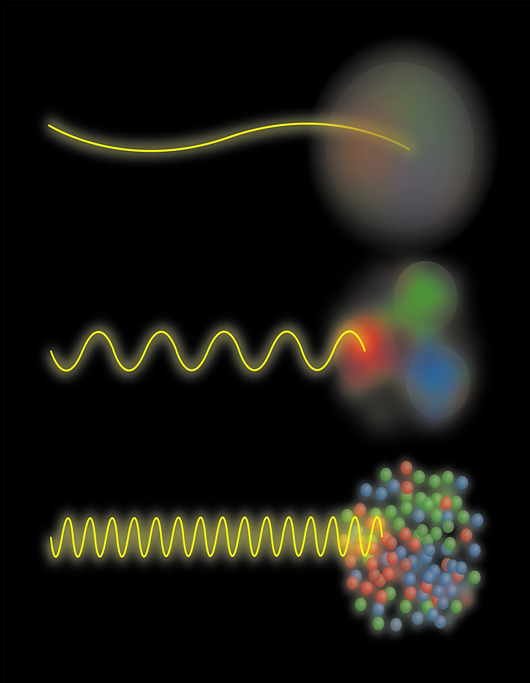
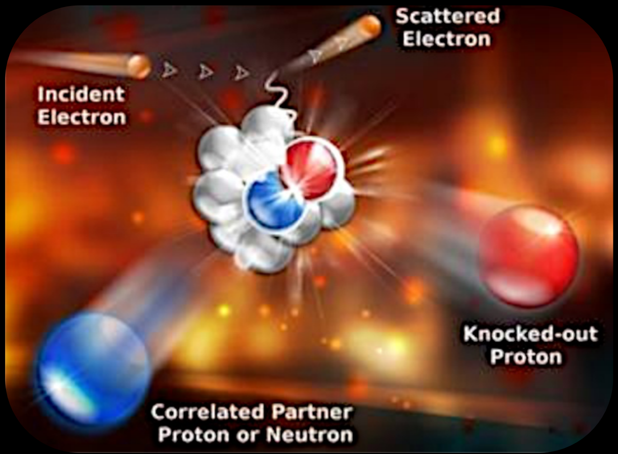
Disentangling the EMC Effect



Or Hen

MIT



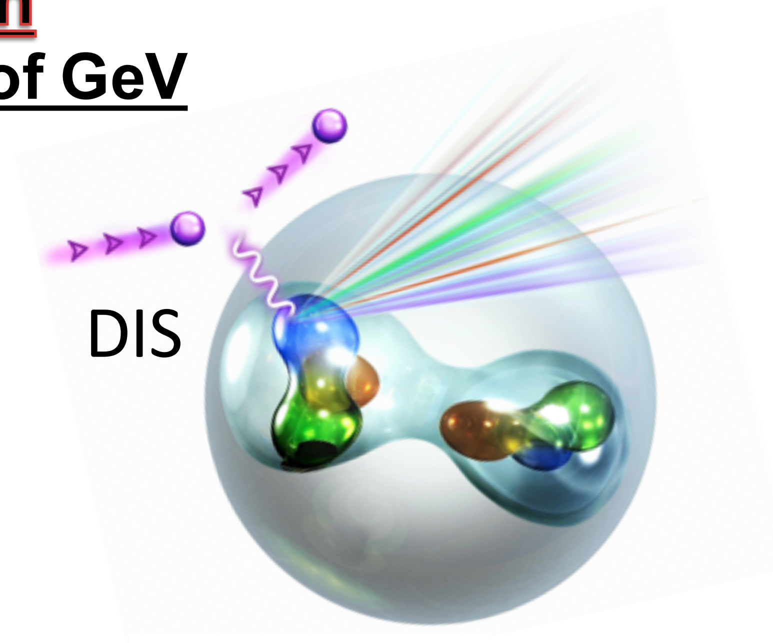
DIS 2016
DESY, HAMBURG 11-15 APRIL 2016

DIS-2016, April 14th, 2016, Hamburg, Germany.

QE vs. DIS

DIS: Study of the partonic structure of the nucleon

DIS scale: several tens of GeV



$0<x_B<1$: equals the fraction of nucleon momentum carried by the struck parton (in the infinite momentum frame).

$$x_B = \frac{Q^2}{2m\omega}$$

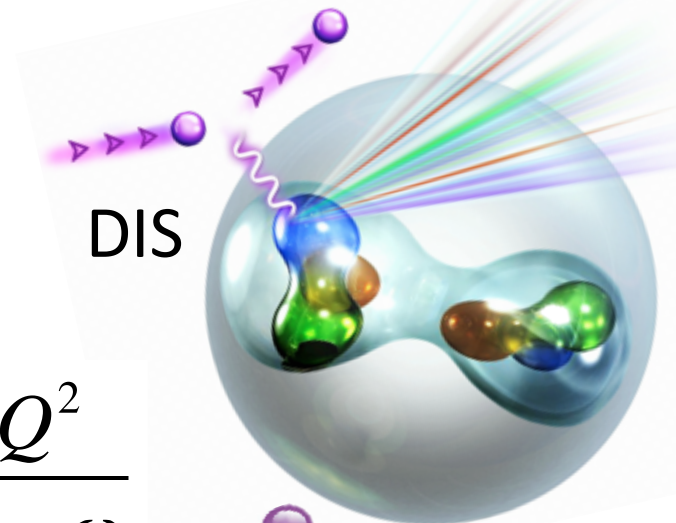
$$Q^2 = -q_\mu q^\mu$$

QE vs. DIS

DIS: Study of the <u>partonic</u> structure of the <u>nucleon</u>

DIS scale: <u>several tens of GeV</u>

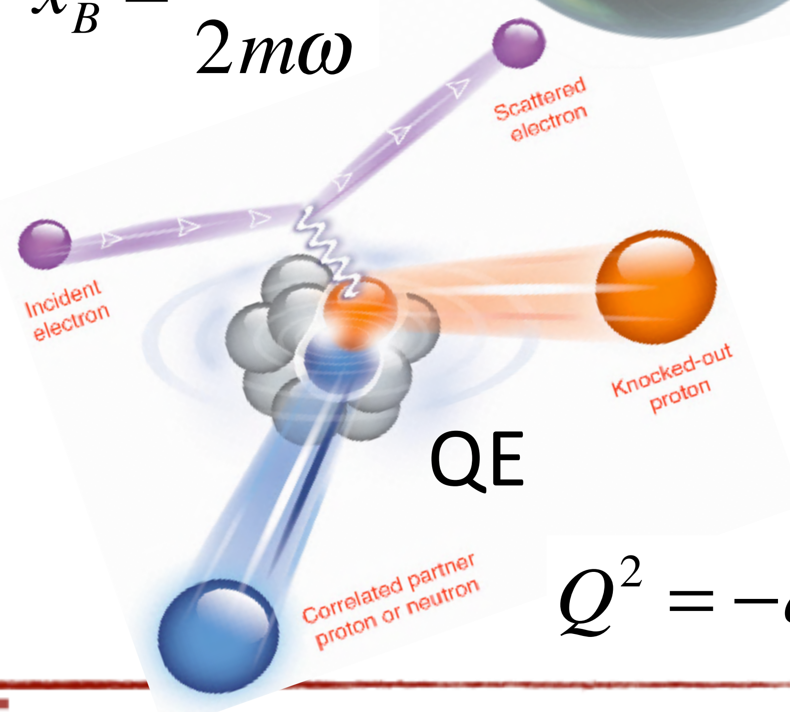
DIS



$$x_B = \frac{Q^2}{2m\omega}$$

QE: Study of the <u>nucleonic</u> structure of the <u>nucleus</u>

QE scale: <u>several GeV</u>



QE

$$Q^2 = -q_\mu q^\mu$$

QE vs. DIS

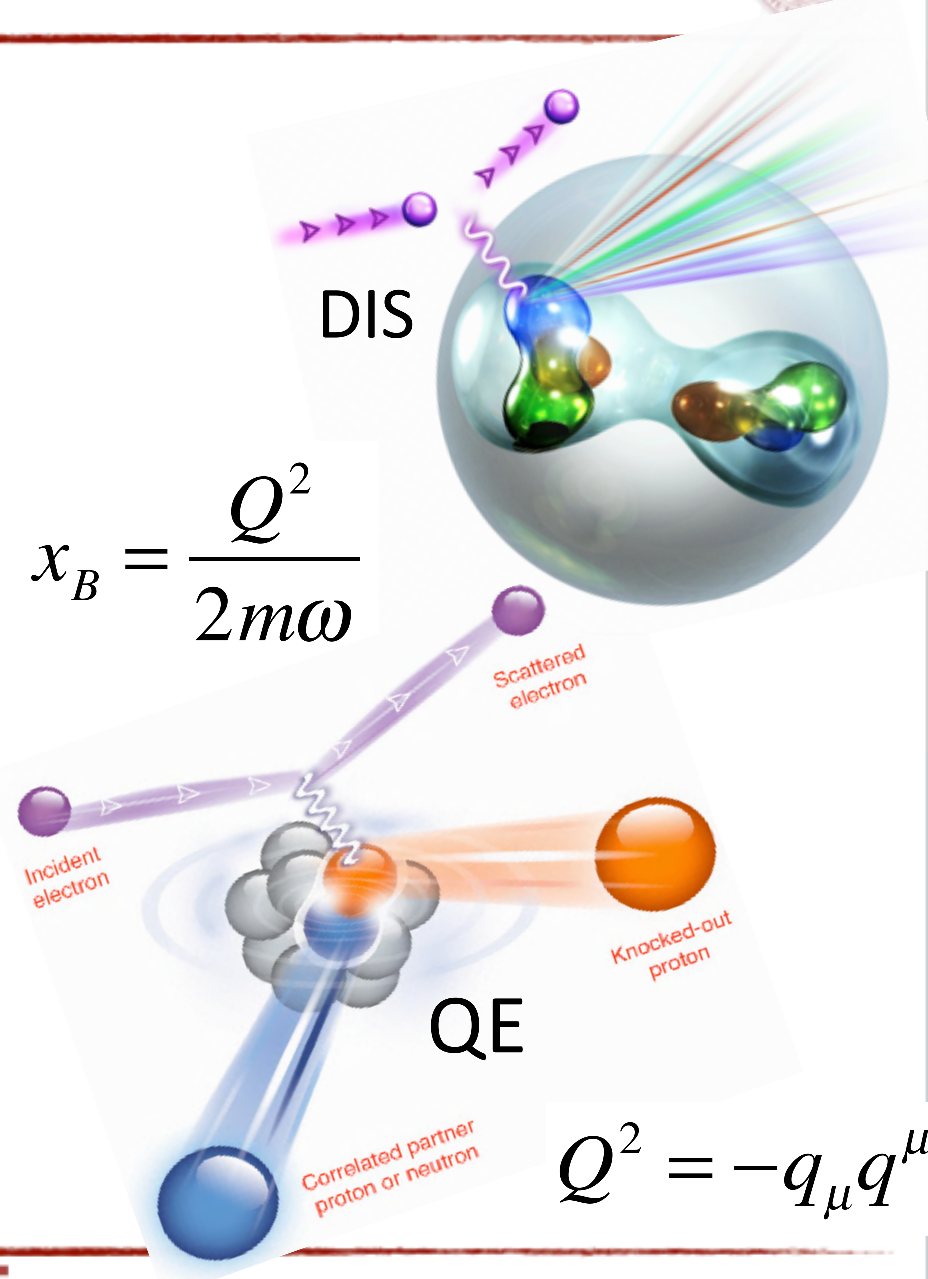
DIS: Study of the <u>partonic</u> structure of the <u>nucleon</u>

$0<x_B<1$: equals the fraction of nucleon momentum carried by the struck parton (in the infinite momentum frame).

QE: Study of the <u>nucleonic</u> structure of the <u>nucleus</u>

$0<x_B<A$:

- Counts the <u>*number of nucleons involved*</u> in the reaction.
- Determines the <u>*minimal initial momentum*</u> of the scattered nucleon.



$$x_B = \frac{Q^2}{2m\omega}$$

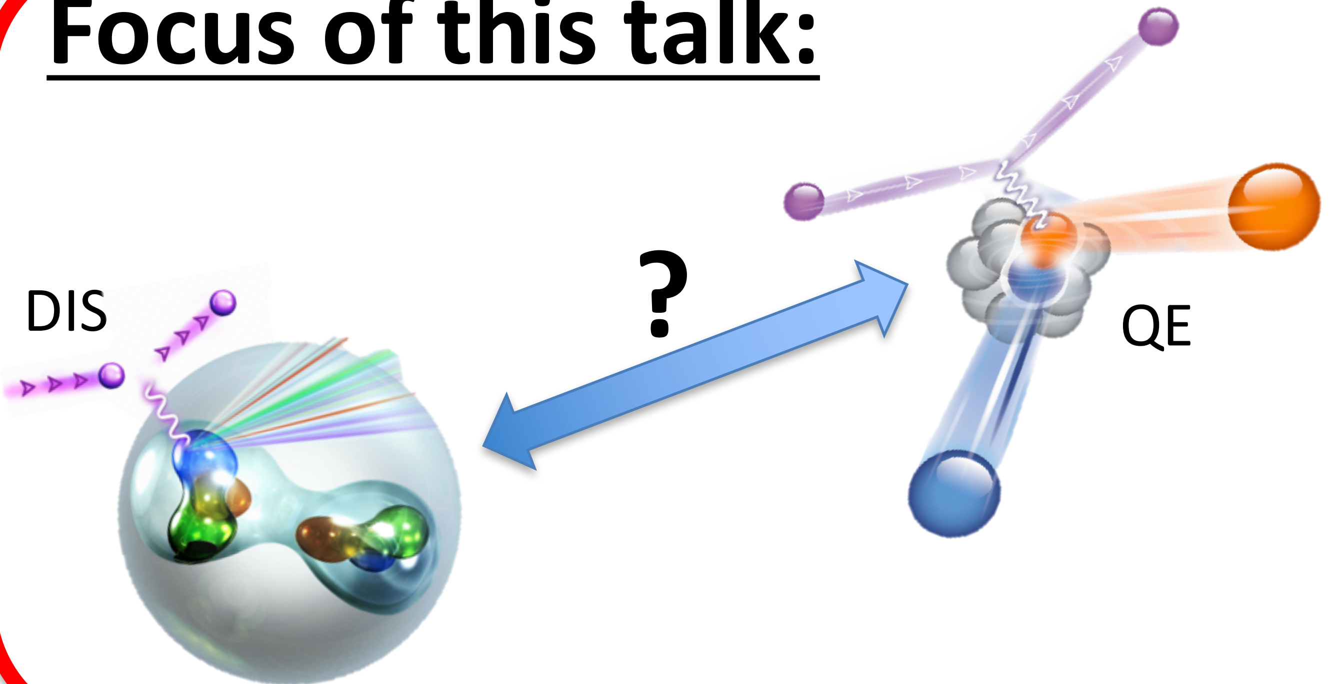
$$Q^2 = -q_\mu q^\mu$$

QE vs. DIS

DIS: Study of the partonic structure of the nucleon

$0<x_B<1$:
nucleon
the stru
moment

Focus of this talk:

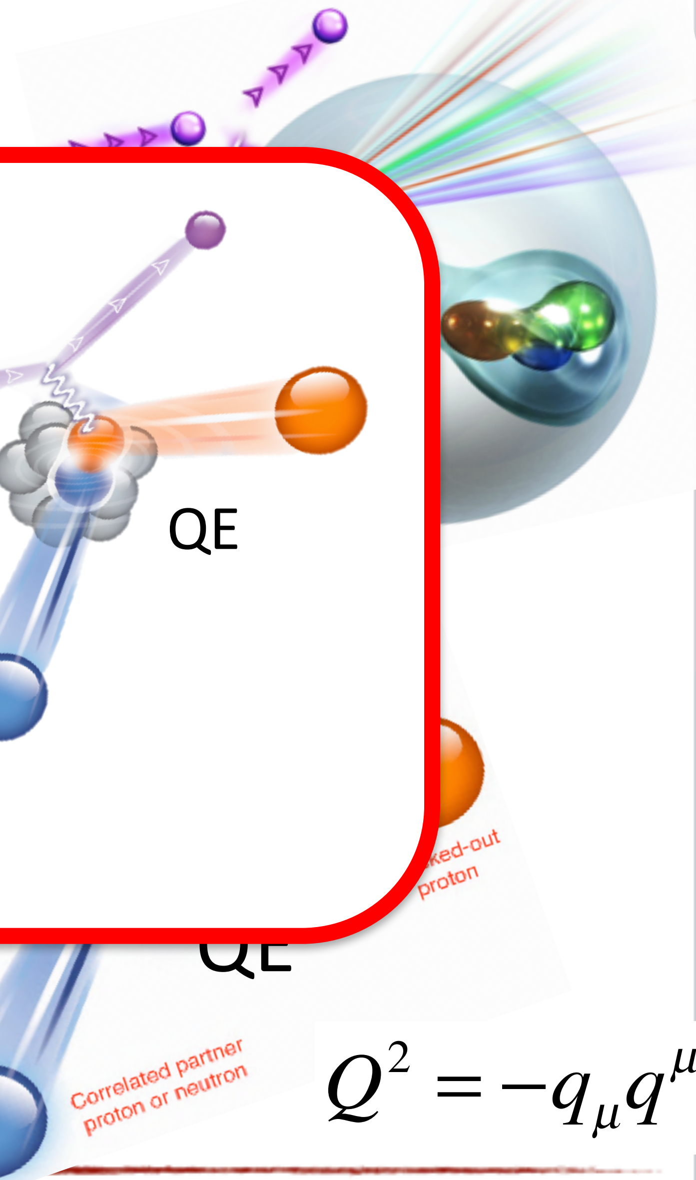


QE: St
str

$0<x_B<A$:

• Counts
involved

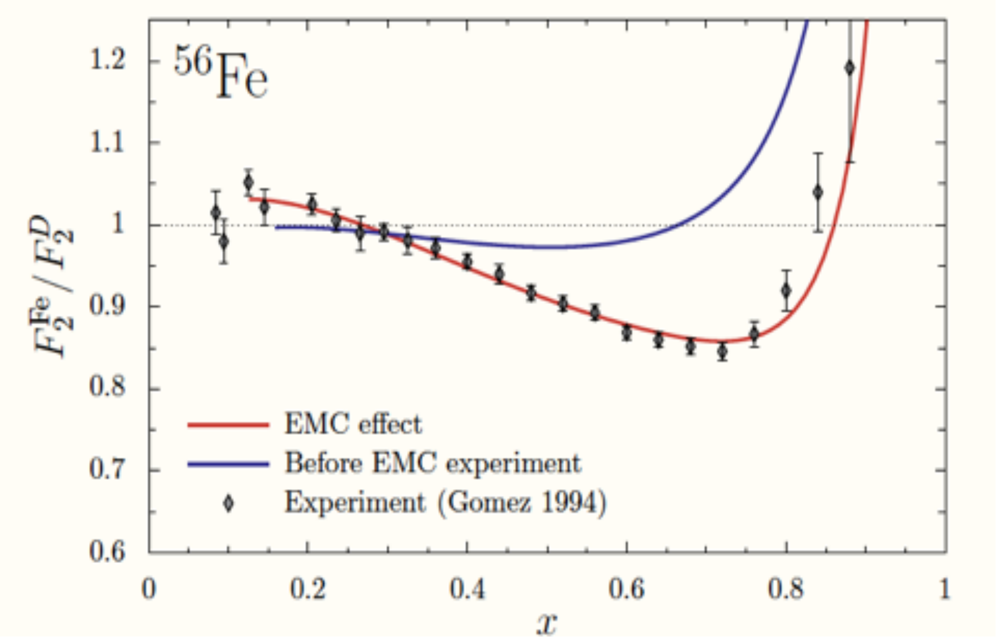
• Determines the *minimal initial momentum* of the scattered nucleon.



$$Q^2 = -q_\mu q^\mu$$

EMC Effect

- Deviation of the per-nucleon DIS cross section ratio of nuclei relative to deuterium from unity.
- Universal shape for 0.3<x<0.7 and 3<A<197.
- ~Independent of Q^2.
- Overall increasing as a function of A.
- No fully accepted theoretical explanation.



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

EMC Effect

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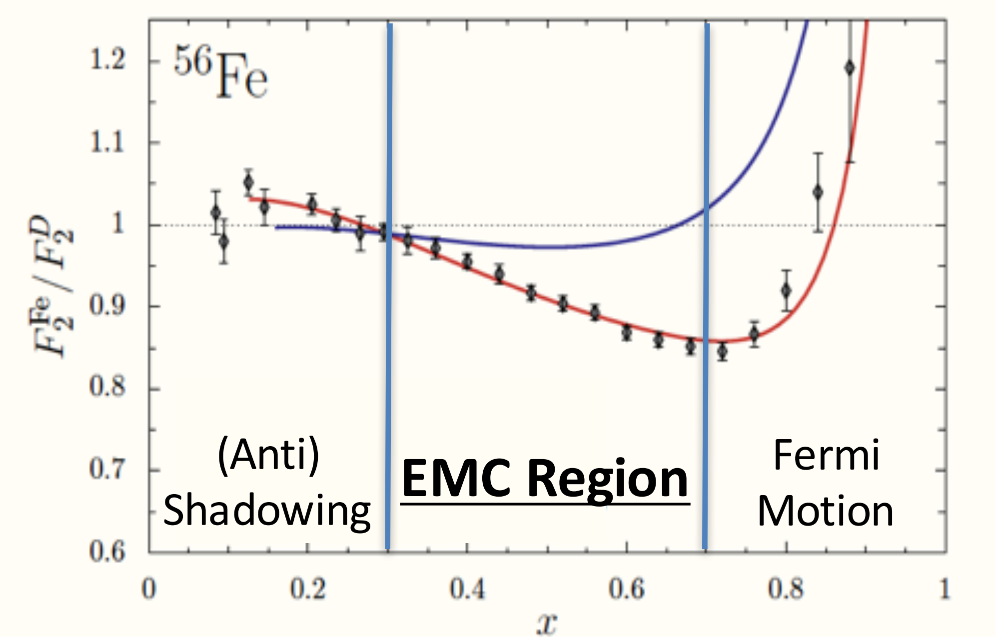

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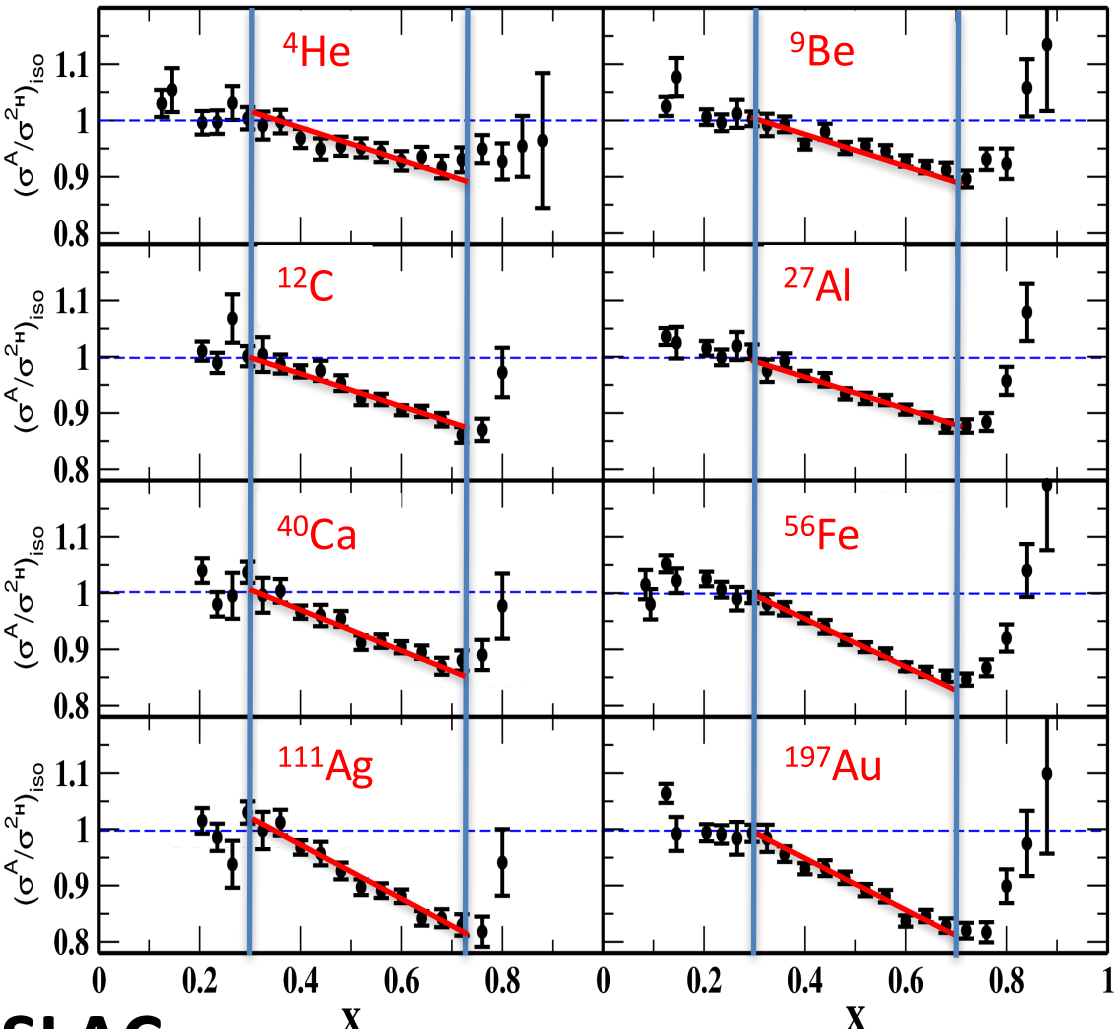
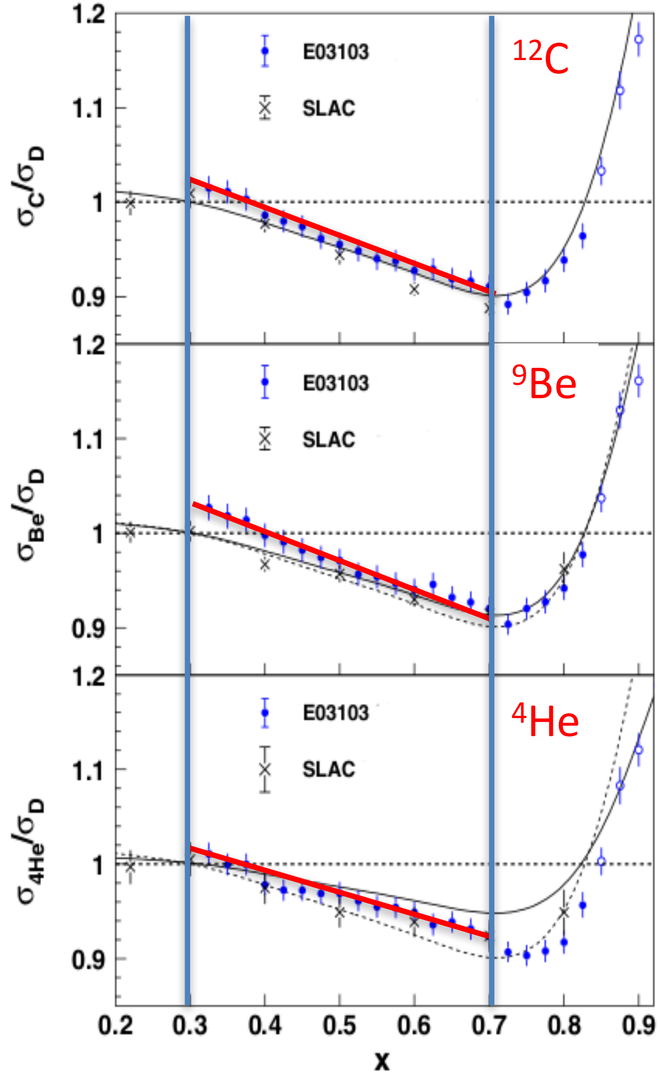
Universality of the EMC Effect



SLAC

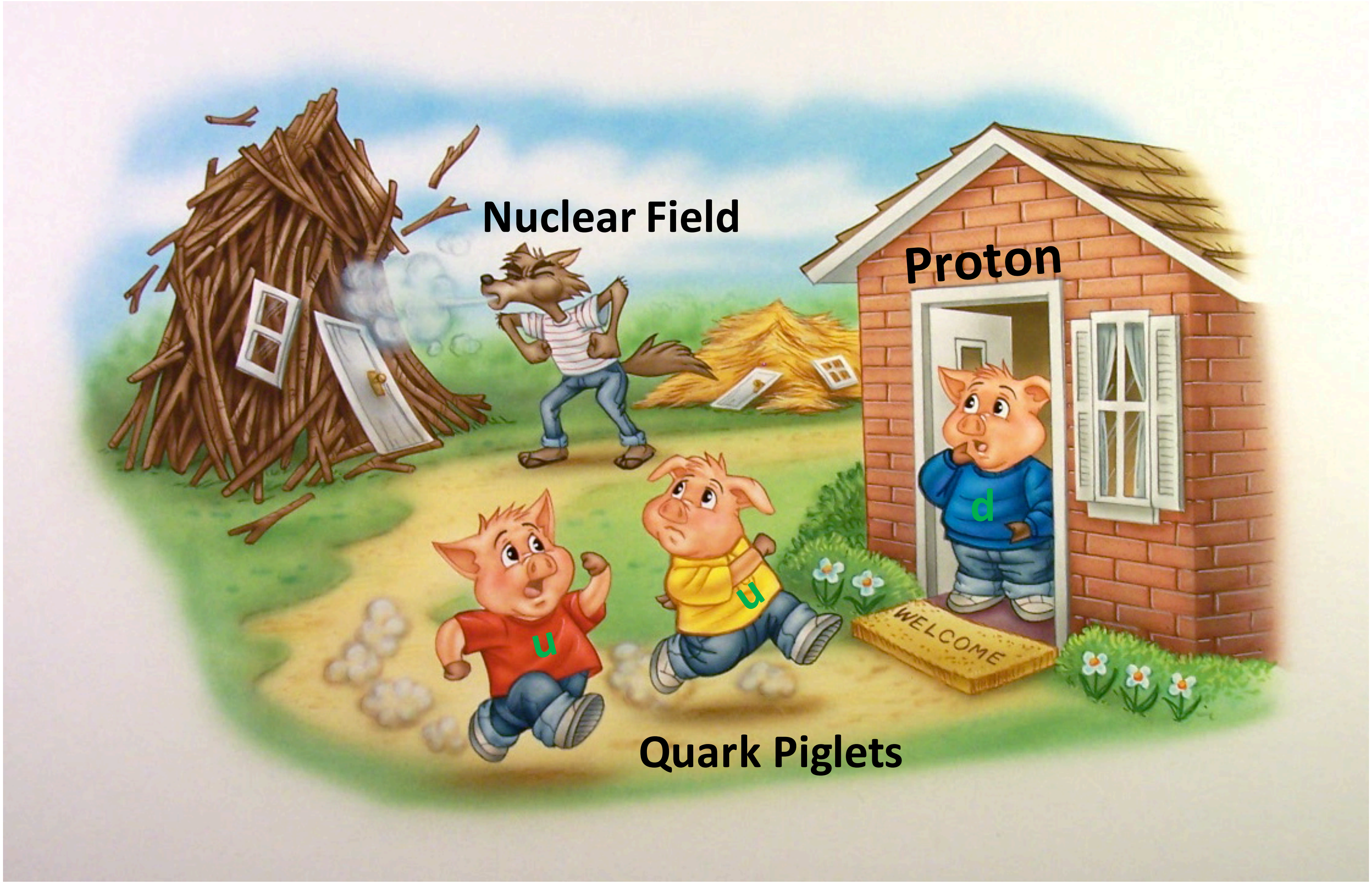
J. Gomez et al., Phys. Rev. D **49**, 4348 (1994).

JLab



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

EMC Challenge: Scales in Physics



EMC Theory

- Standard nuclear effects that contribute:
  [explain some of the effect, up to x≈0.5]
  - Nuclear Binding and Fermi motion
  - Coulomb Field
- Various theoretical models:
  [Most incorporate modification of the bound nucleon structure]
  - Dynamical rescaling
  - Point-like configuration suppression
  - Structure function modification in the nuclear mean-field
  - 6 quark clusters
  - More....

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

EMC Theory

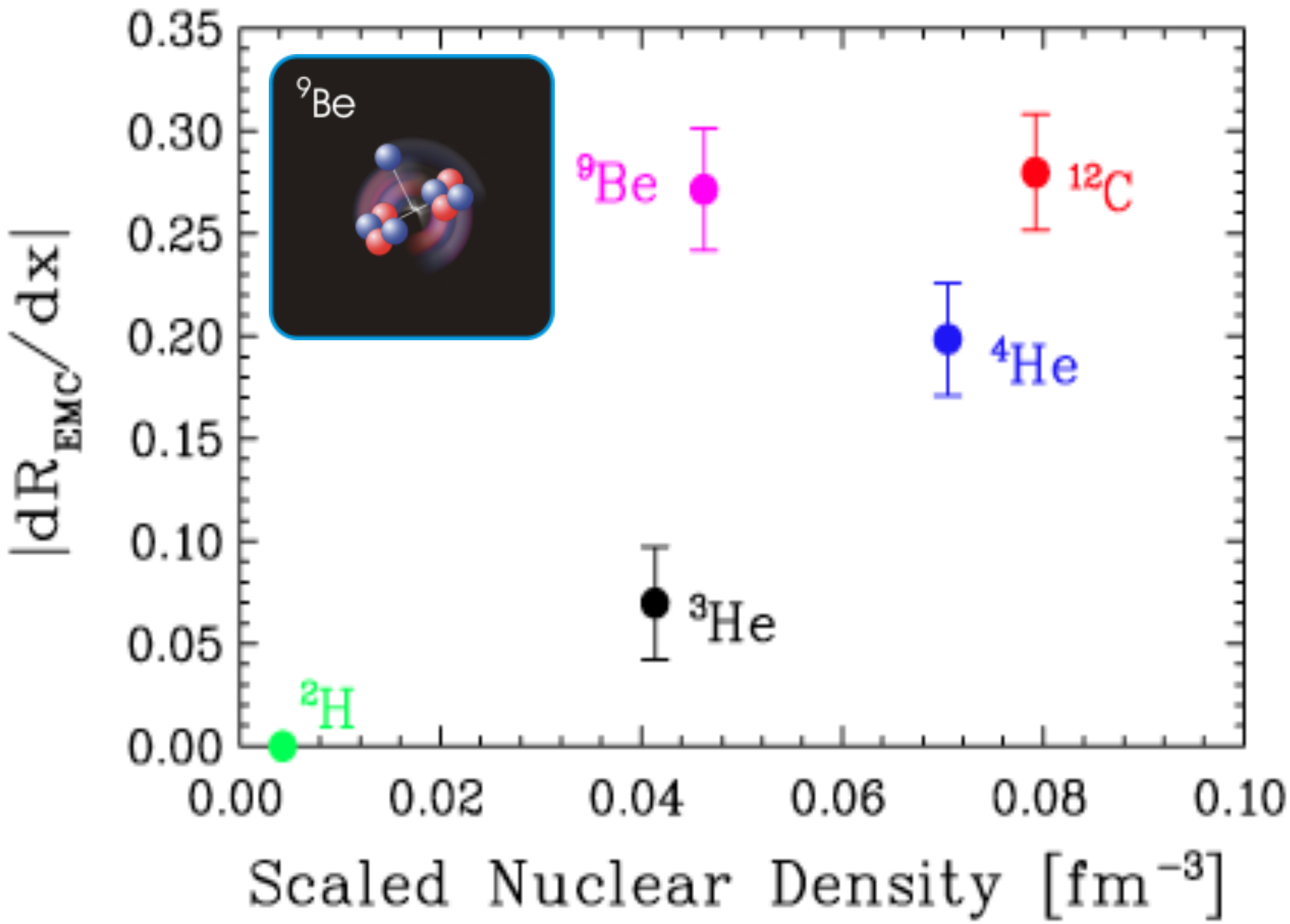
- Standard nuclear effects that contribute:
  [explain some of the effect, up to x≈0.5]
  - Nuclear Binding and Fermi motion
  - Coulomb Field
- V

(1) One Model Isn't Cool: "No Bound-Nucleon Structure Modification"

  - …unction modification in the nuclear mean-field
  - 6 quark clusters
  - More….

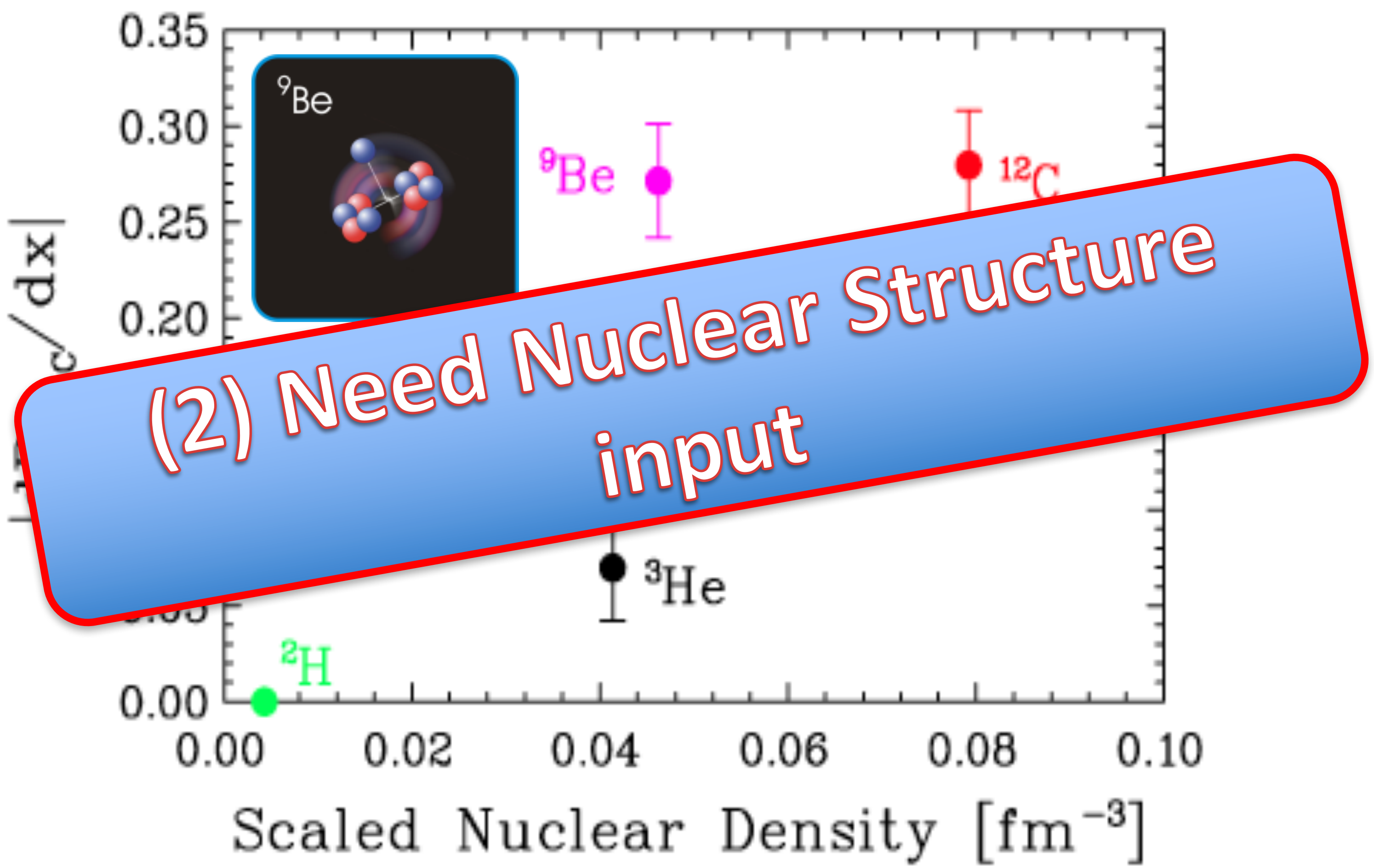
EMC – Everyone's Model is Cool (G. A. Miller)

Non Trivial Nuclear Dymanics



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

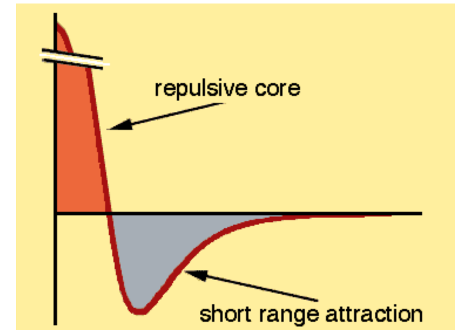
Non Trivial Nuclear Dymanics



Nuclear Shell Model

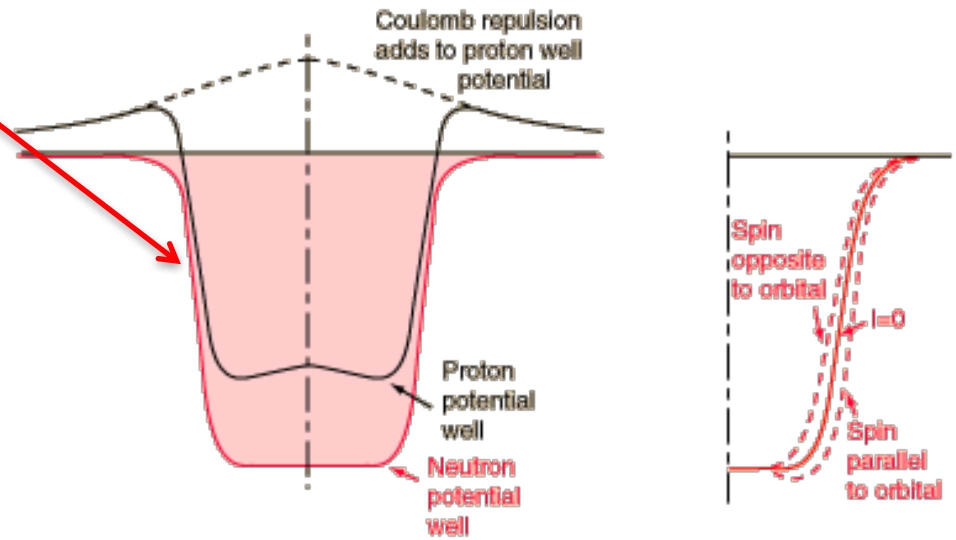
- Many-Body Hamiltonian:

$$H = \sum_{i=1}^{A} \frac{p^2}{2m_N} + \sum_{i<j=1}^{A} v_{2body}(i,j) + \cancel{\sum_{i<j<k=1}^{A} v_{3body}(i,j,k)} + \ldots$$



- Mean-Field Approximation:

$$H = \sum_{i=1}^{A} \frac{p^2}{2m_N} + \sum_{i=1}^{A} V(i)$$



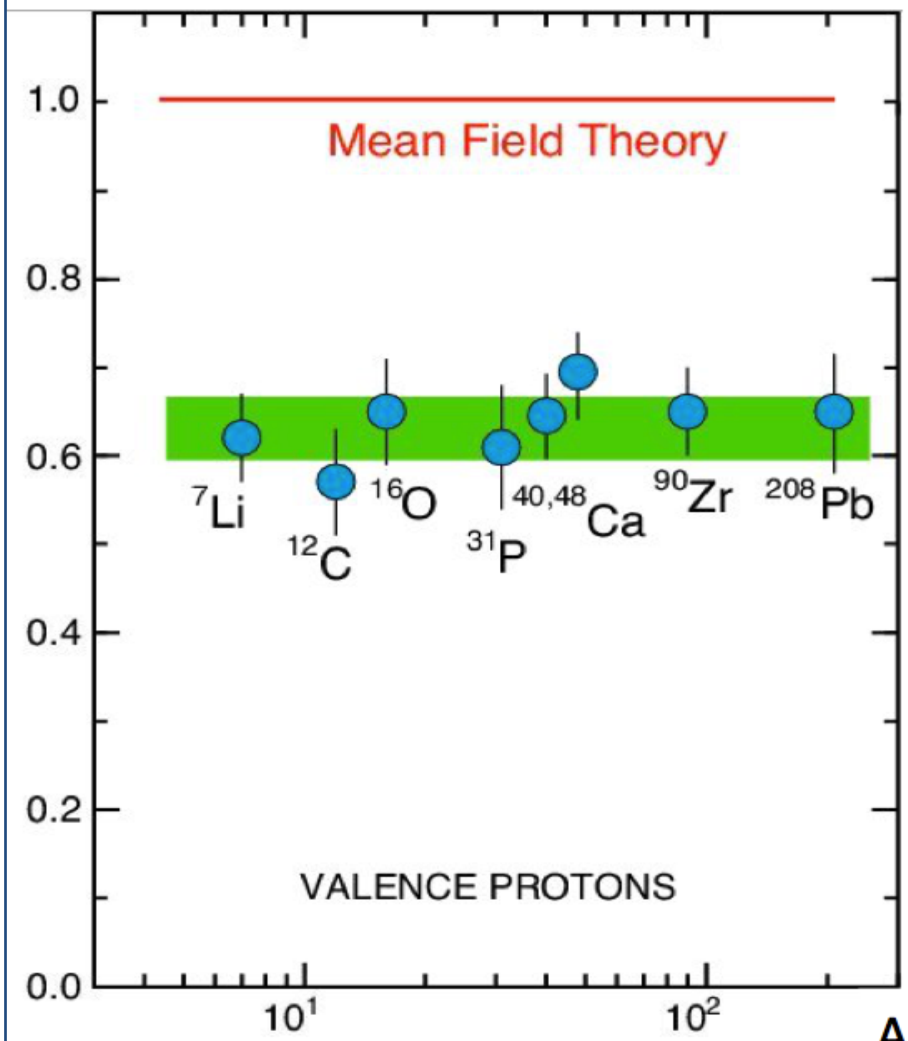
Results in an “atom-like” shell model:

- Ground state energies
- Excitation Spectrum
- Spins
- Parities
- …

E. Wigner, M. Mayer, and J. Jenson, 1963 Nobel Prize

Beyond the Shell-Model: NN Correlations

- Spectroscopic factors extracted from A(e,e'p) measurements yield only 60-70% of the expected single-particle strength



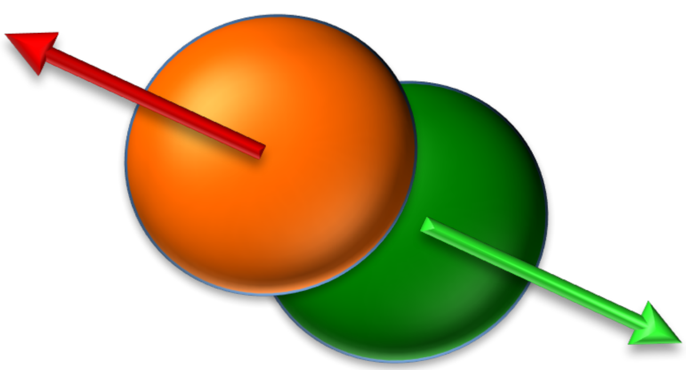
L. Lapikas, Nucl. Phys. A **553** (1993) 297.

- **Missing:**
  - ~20%: Long-Range Correlations
  - **~20%: Short-Range Correlations (SRC)**

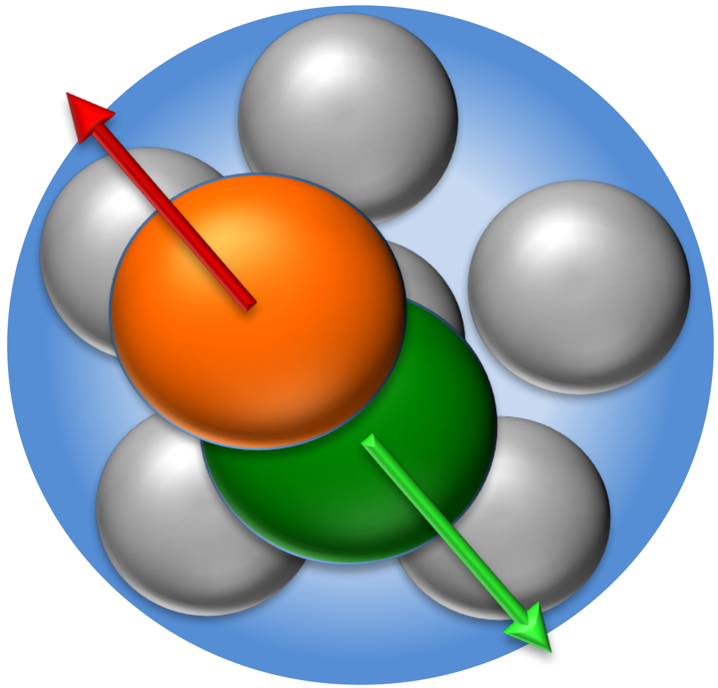
Short-Range Correlation (SRC)

Nucleon pairs 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)



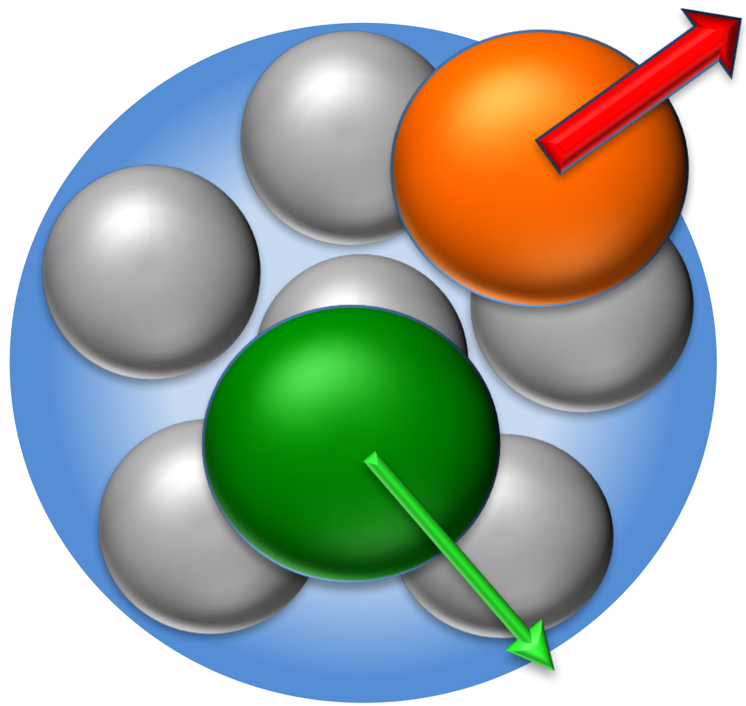
Exclusive 2N-SRC Studies



Exclusive 2N-SRC Studies

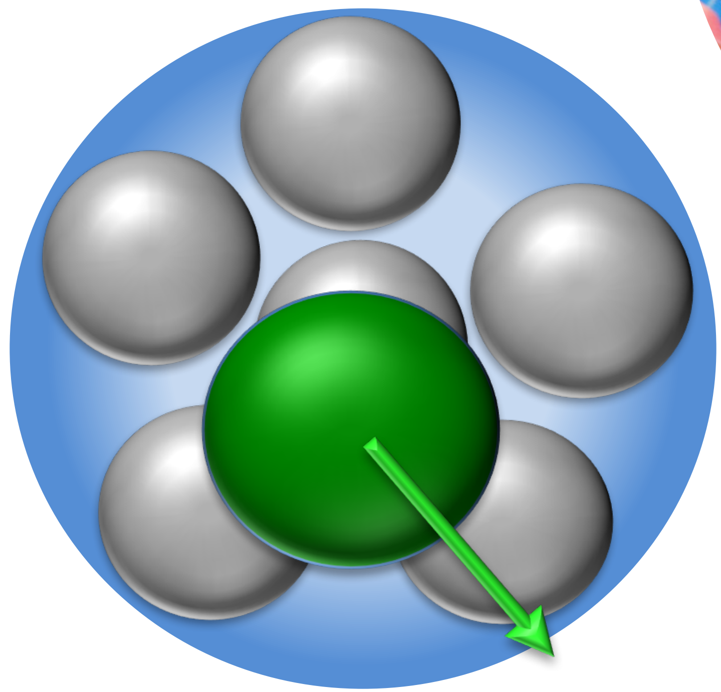
FIFA WORLD CUP Brasil

Exclusive 2N-SRC Studies



FIFA WORLD CUP
Brasil

Exclusive 2N-SRC Studies



FIFA WORLD CUP
Brasil

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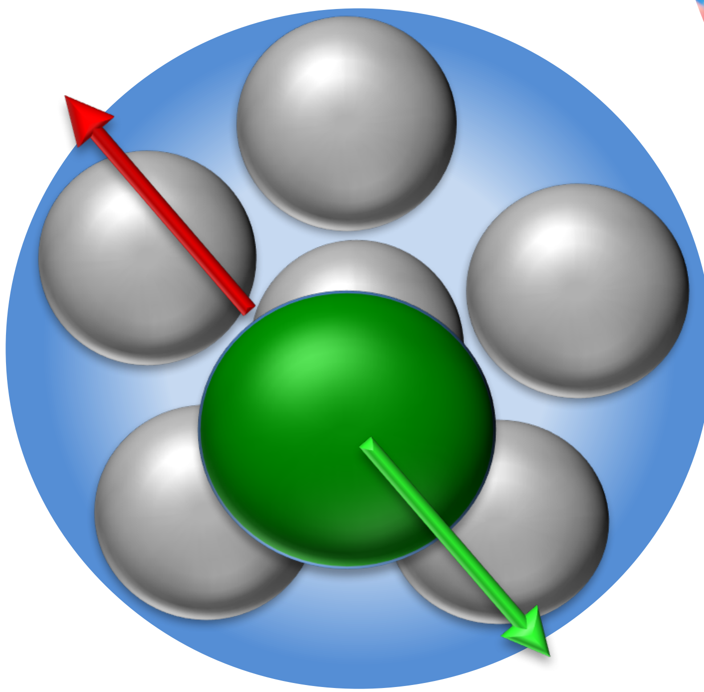

FIFA WORLD CUP
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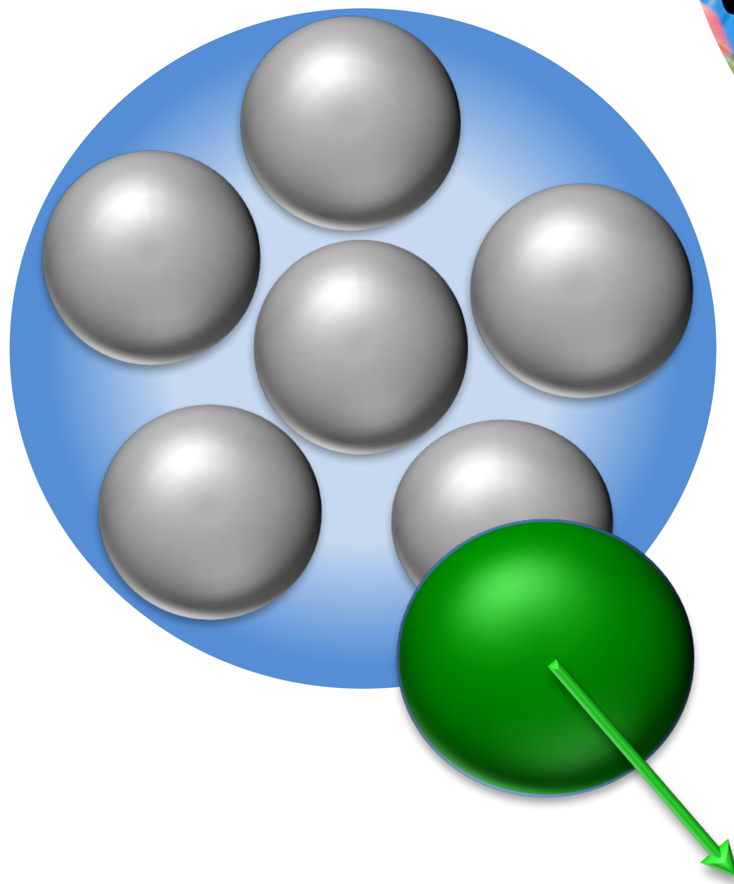
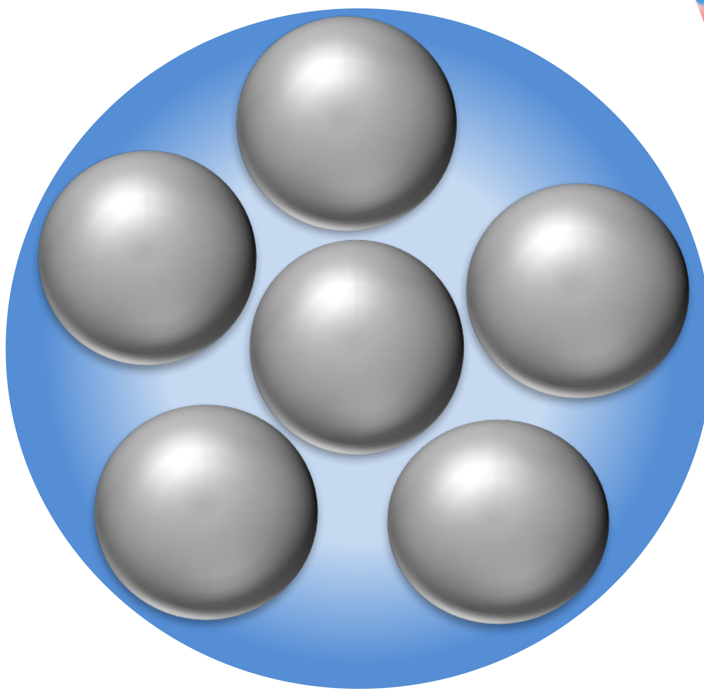
Exclusive 2N-SRC Studies



2014
FIFA WORLD CUP
Brasil

Exclusive 2N-SRC Studies



FIFA WORLD CUP
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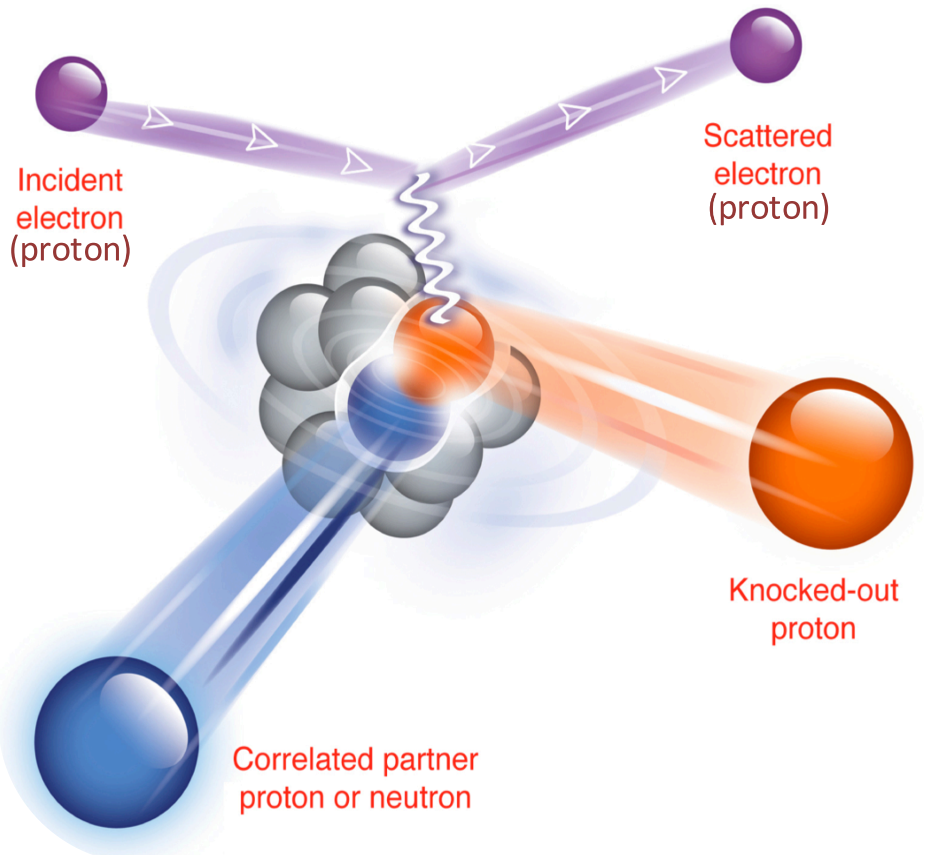
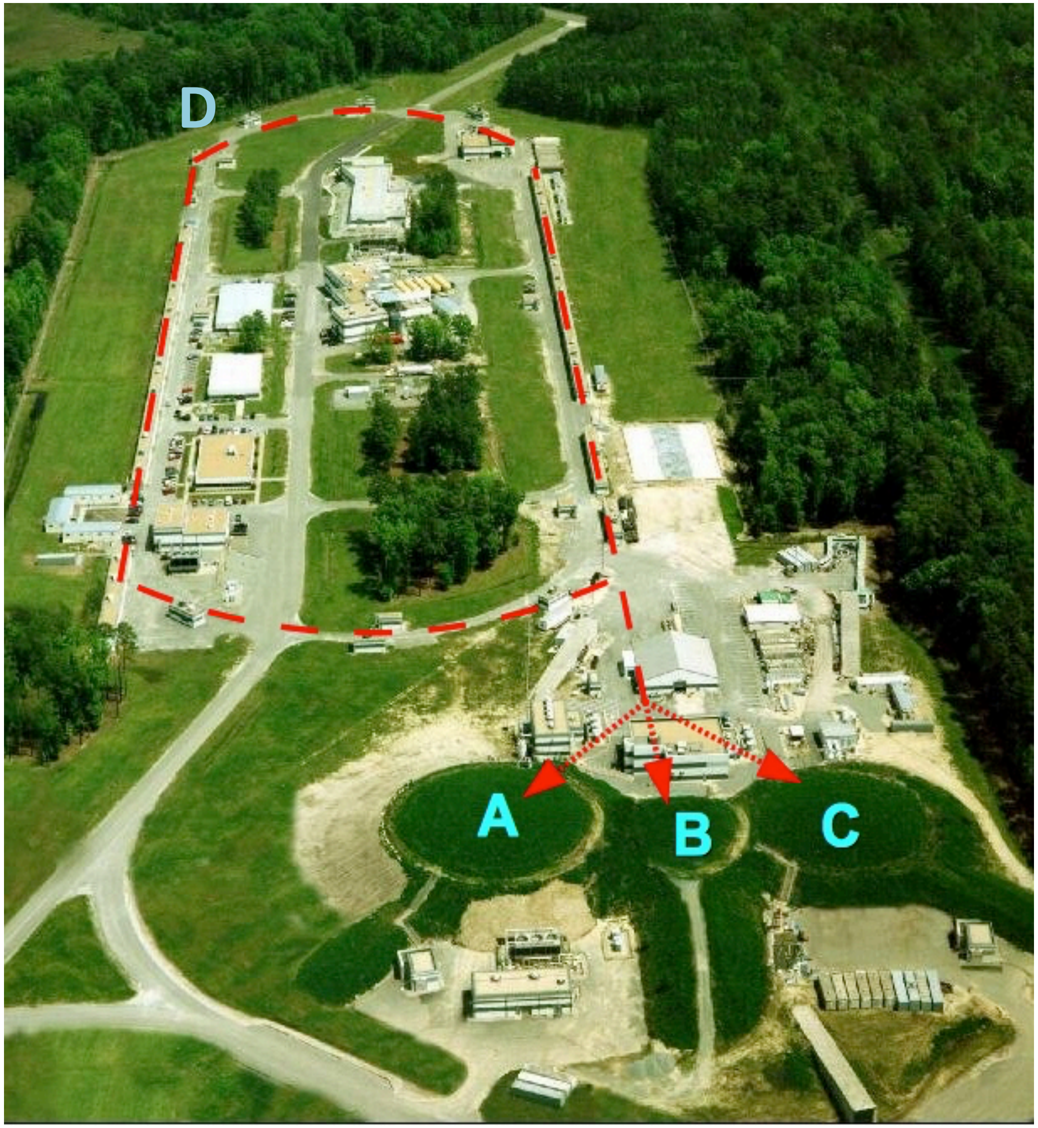
Exclusive 2N-SRC Studies

Breakup the pair =>
Detect both nucleons =>
Reconstruct ‘initial’ state

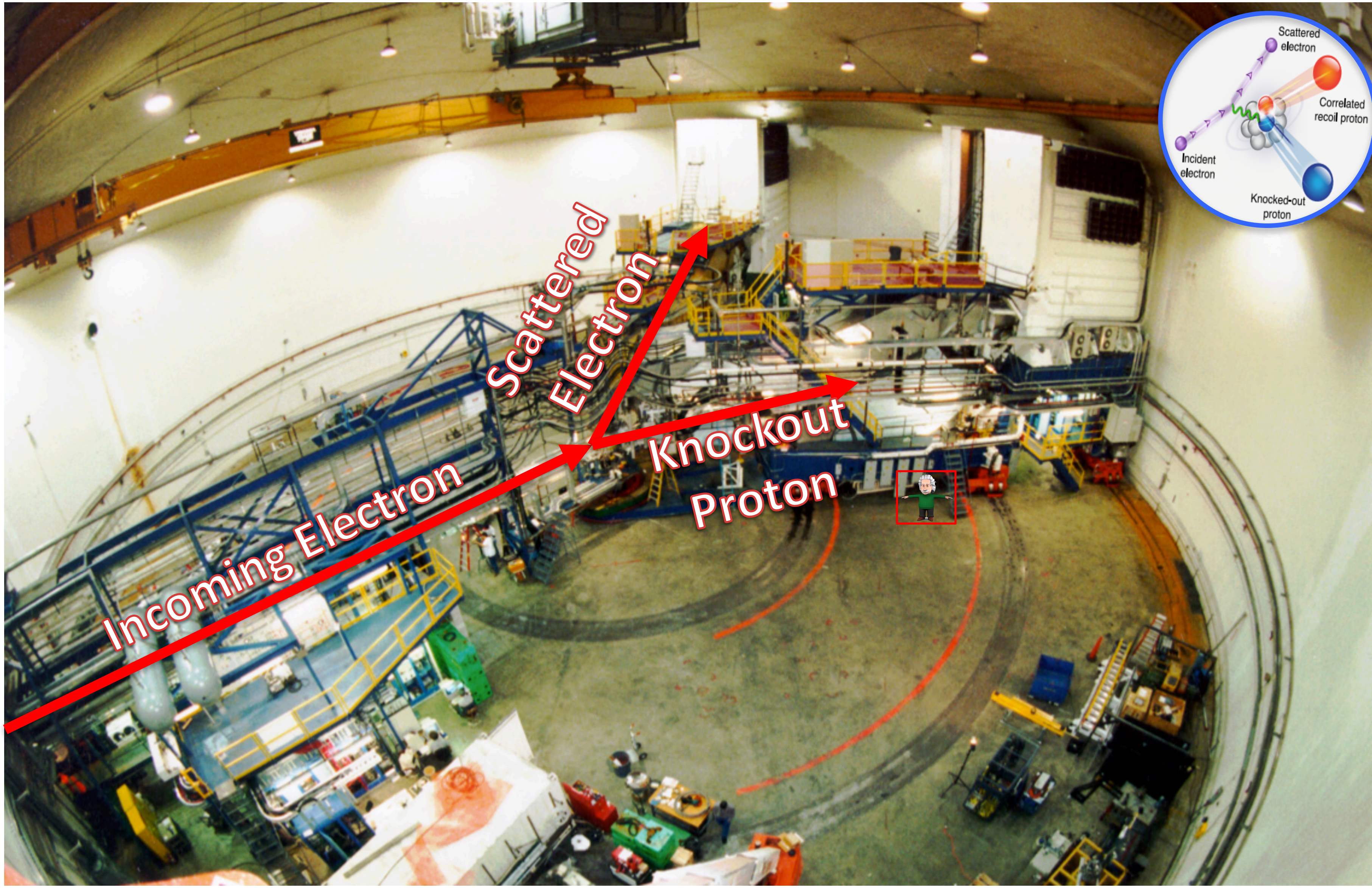


Next Gen. @ Jefferson Lab (JLab)

- High intensity polarized electron beam.
  - 1994 – 2012: 6 GeV
  - 2015: upgraded to 12 GeV
- 3 (now 4) experimental halls.
- 7 years of 12 GeV program already approved.



Hall-A: High-Resolution Spectrometers



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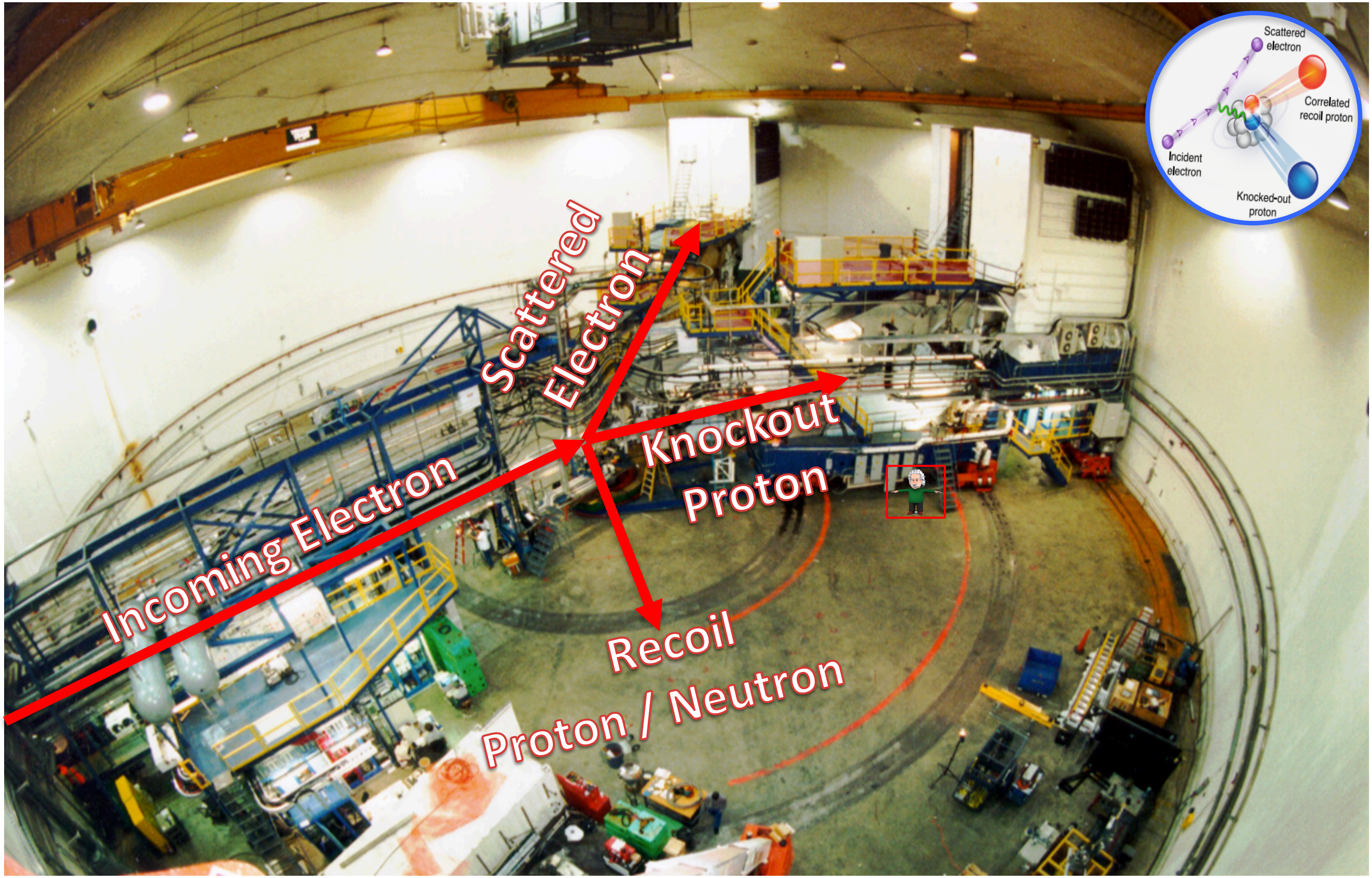

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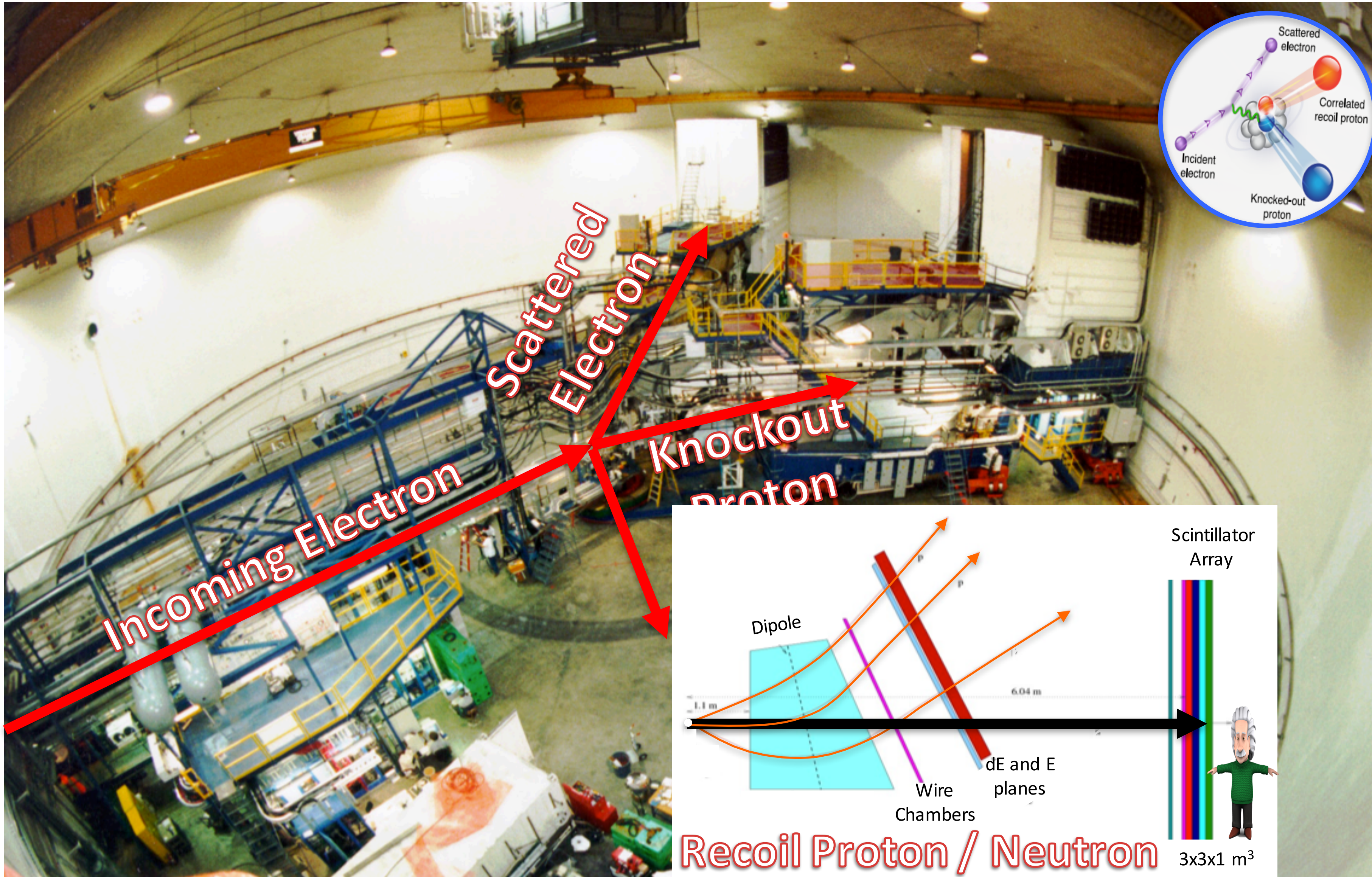
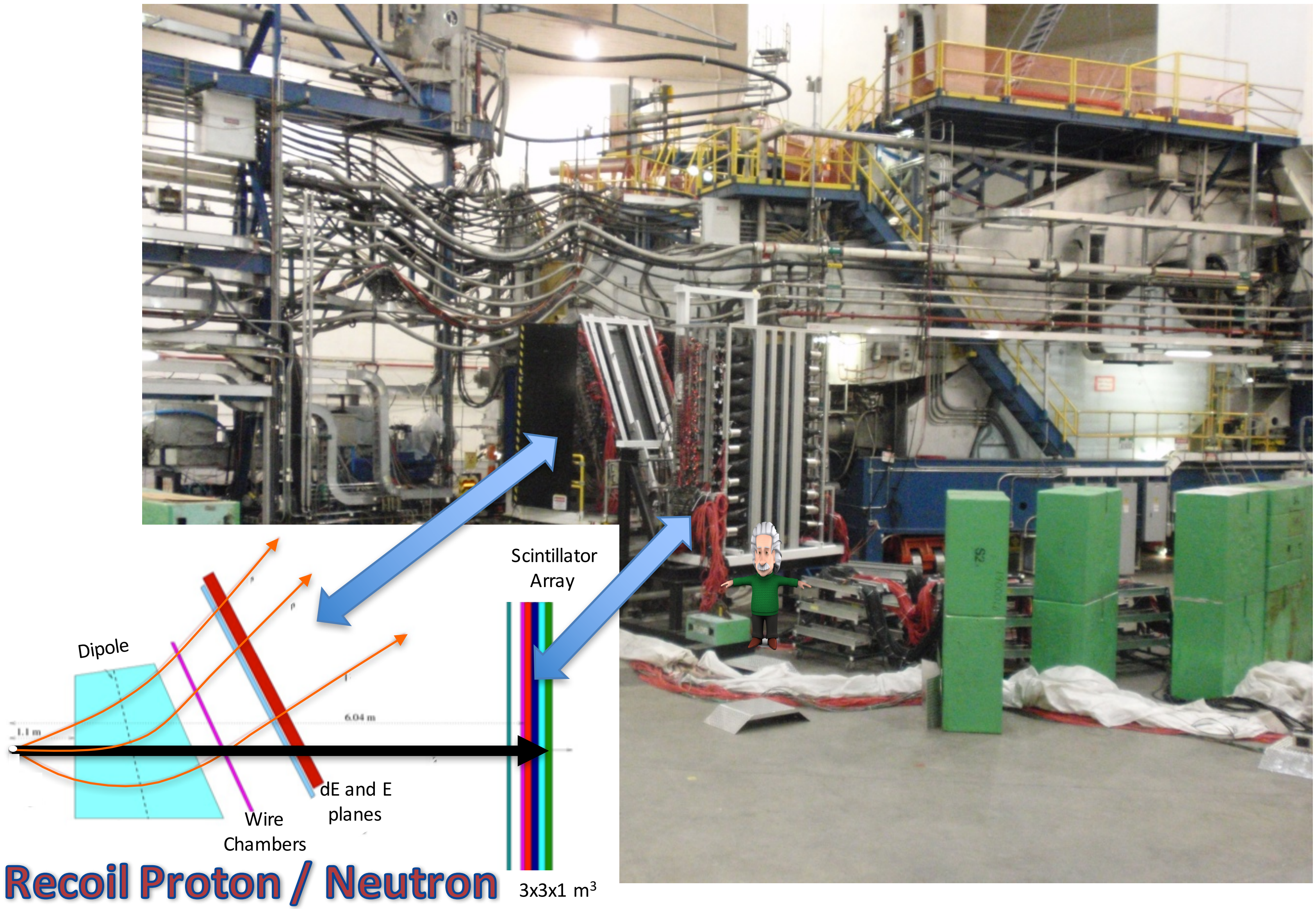


Building BigBite and HAND

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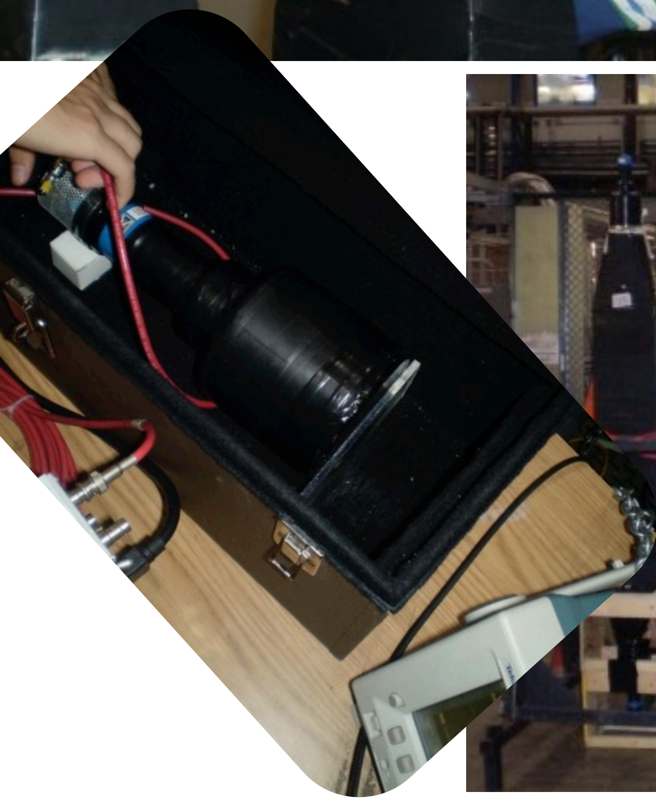
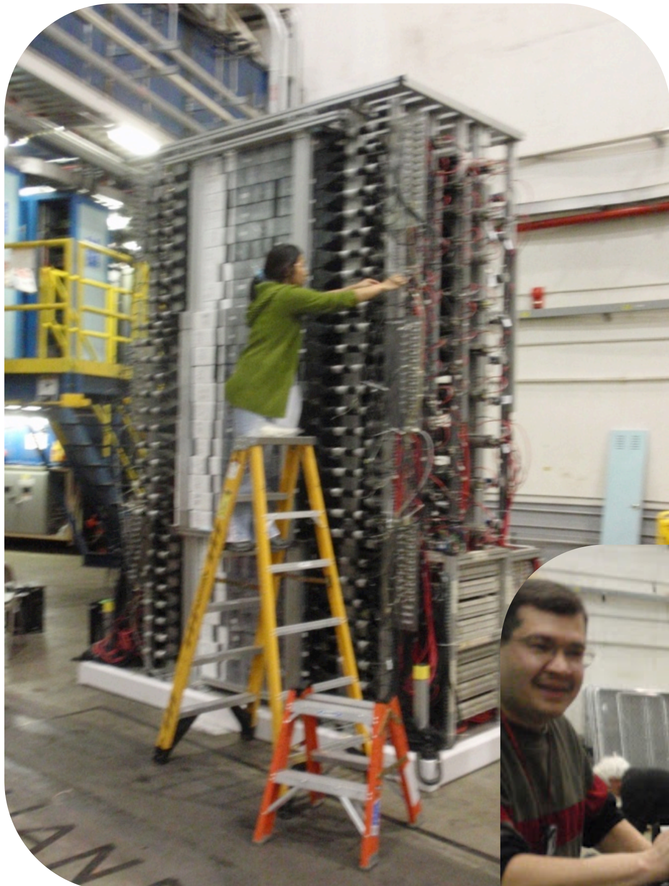



HYSTER

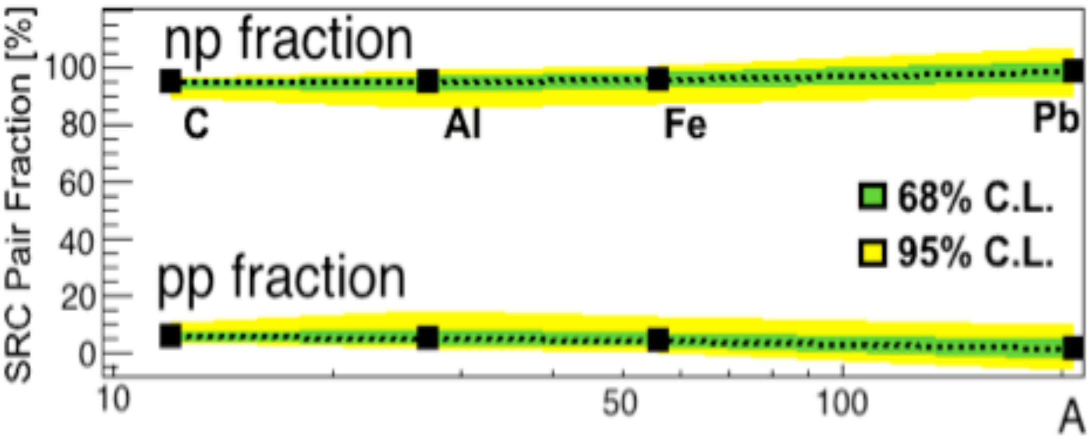




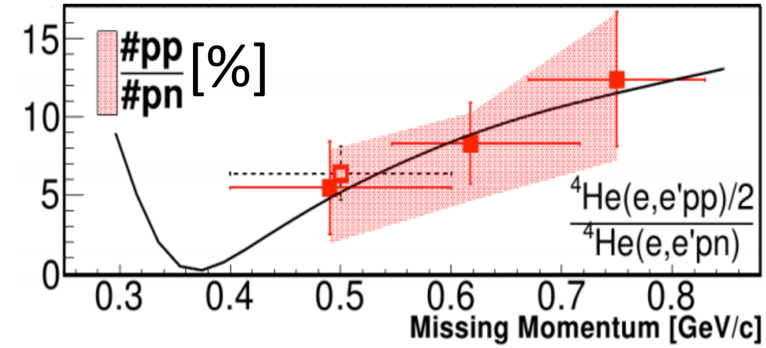




Results I: Isospin Structure

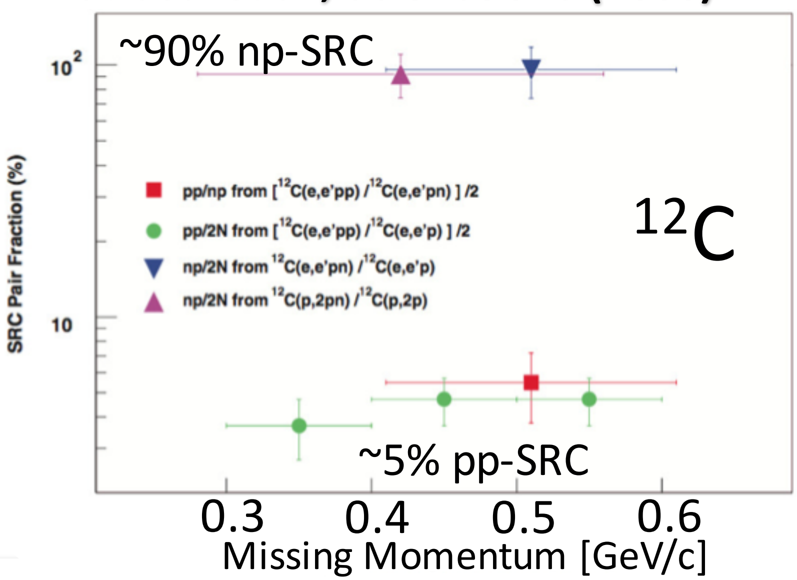


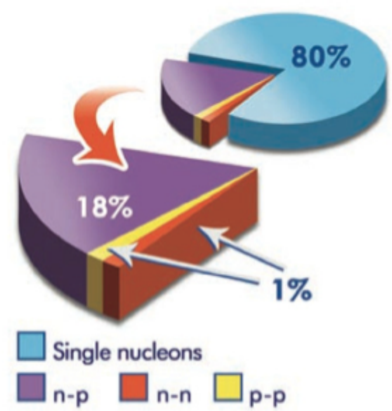
O. Hen et al., Science 364 (2014) 614

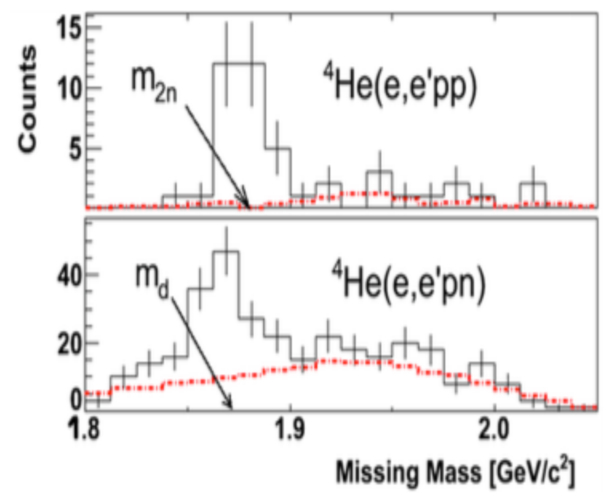


R. Subedi et al., Science 320 (2008) 1476

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)

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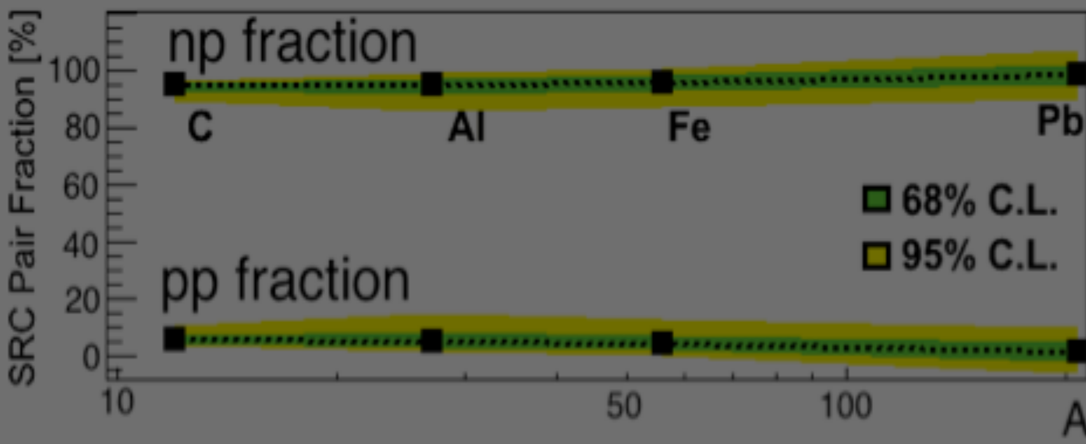
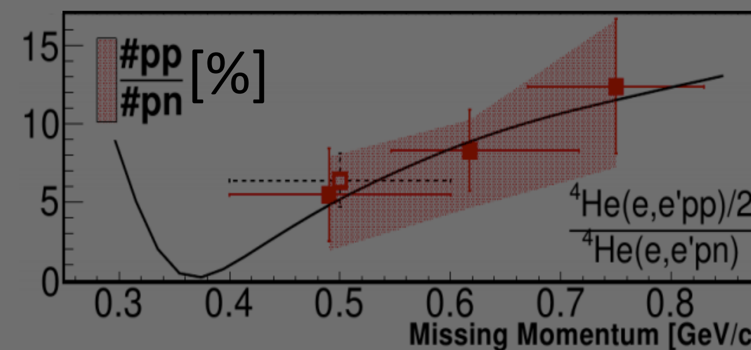


O. Hen et al., Science 364 (2014) 614



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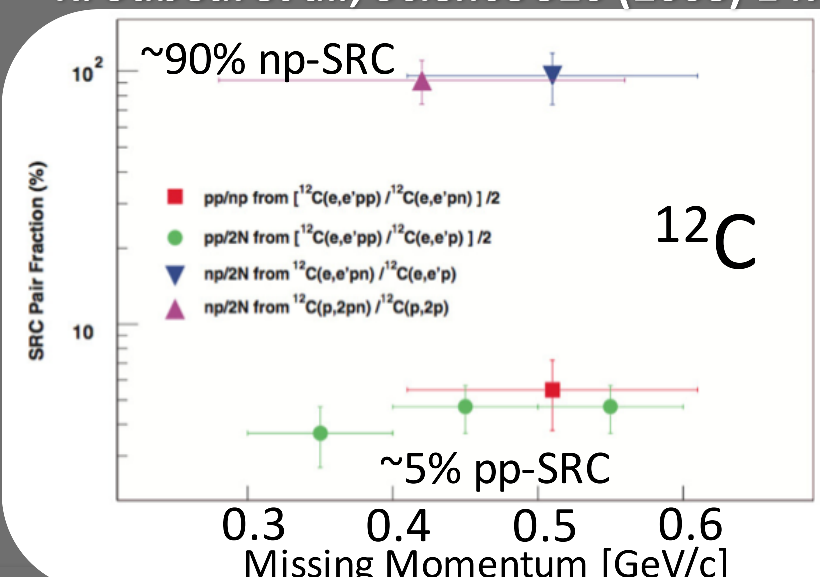
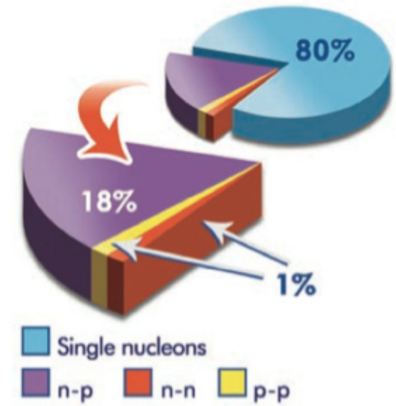
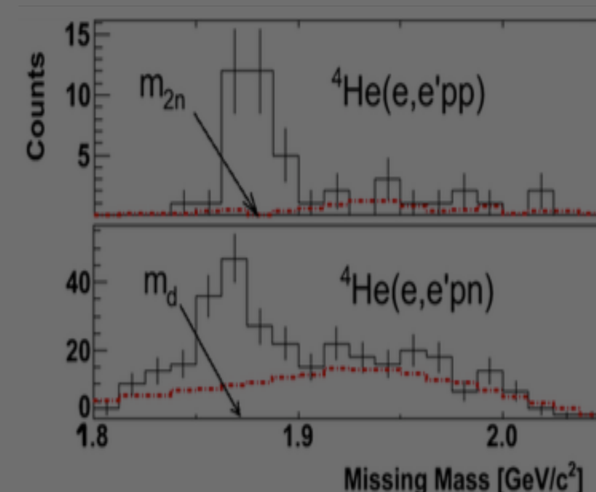
I. Korover et al., PRL 113 (2014) 022501







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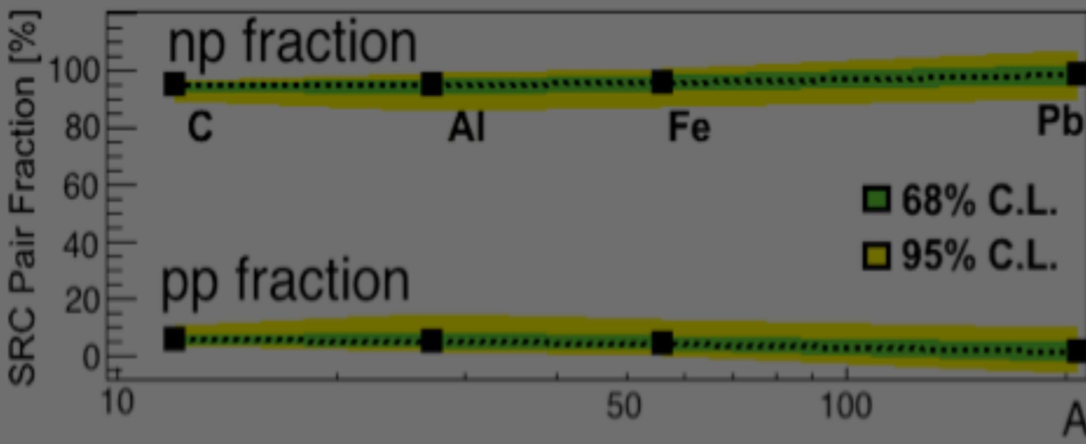

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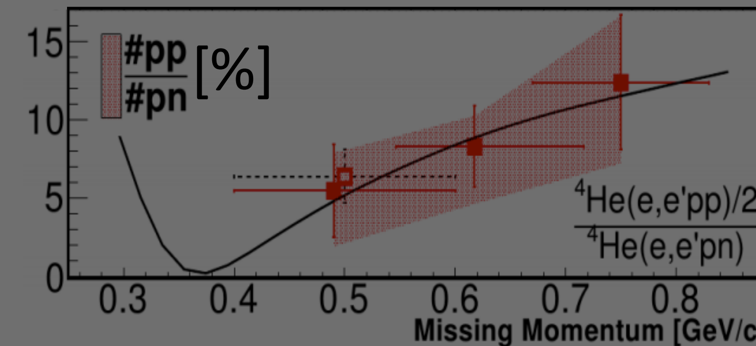

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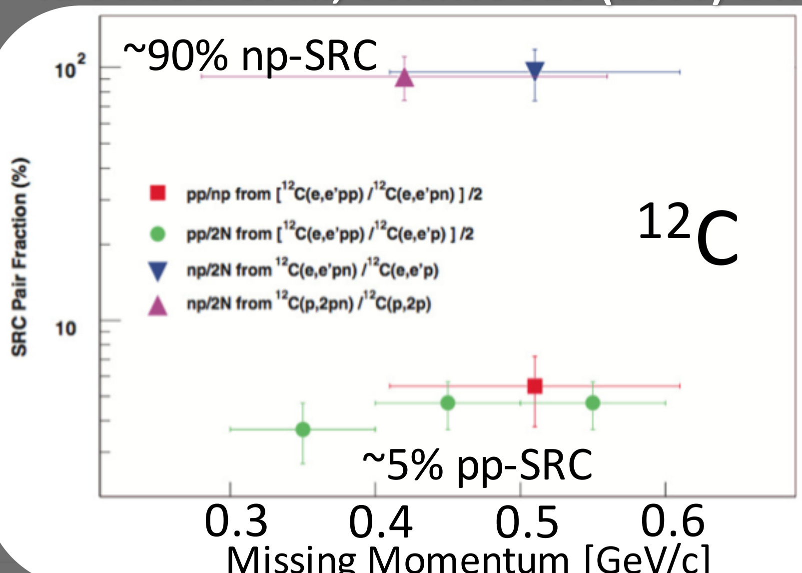
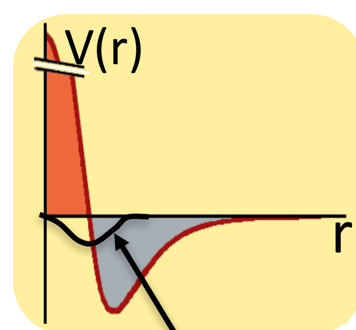
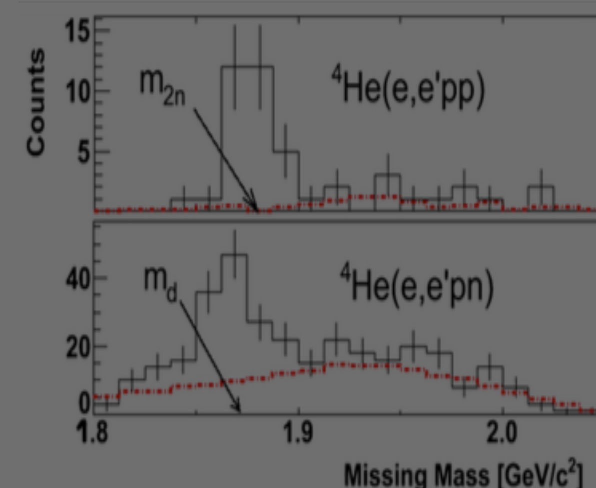




Short-Range Tensor Attraction!



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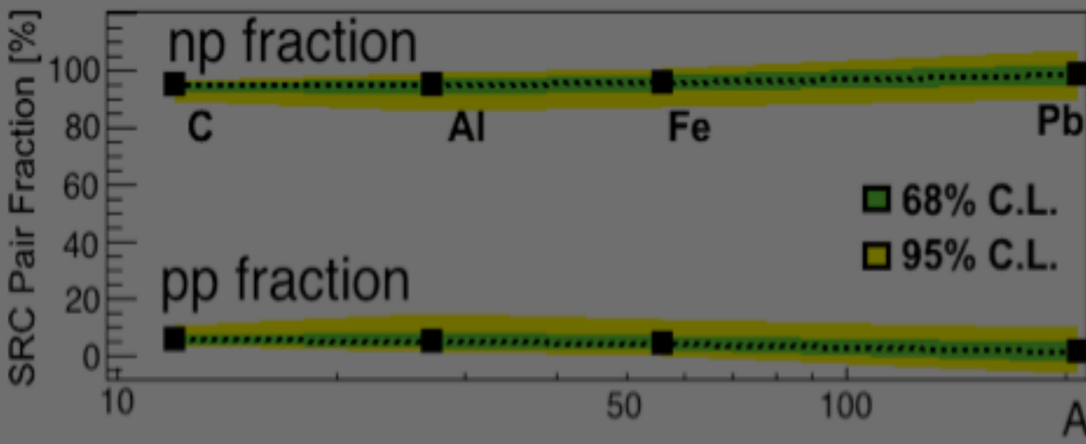
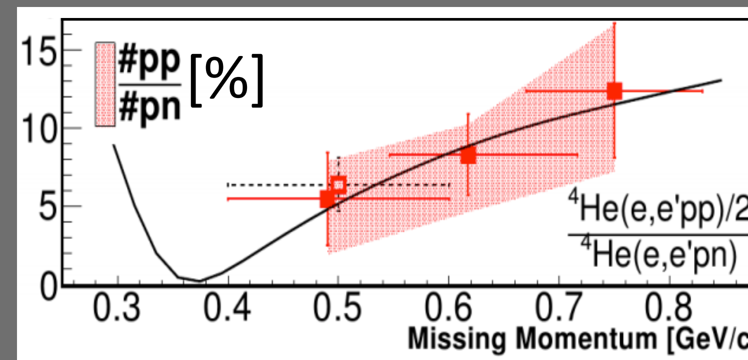


O. Hen et al., Science 364 (2014) 614



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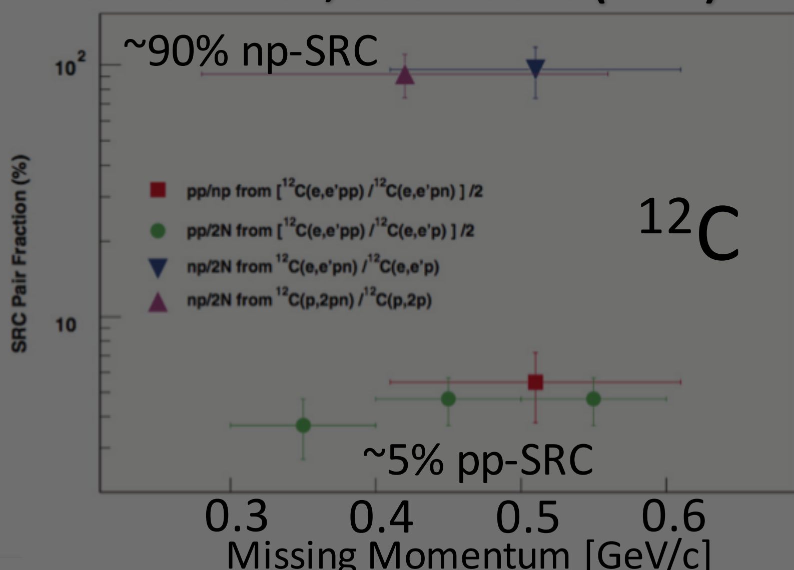

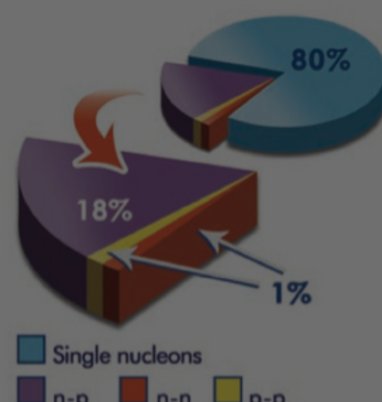

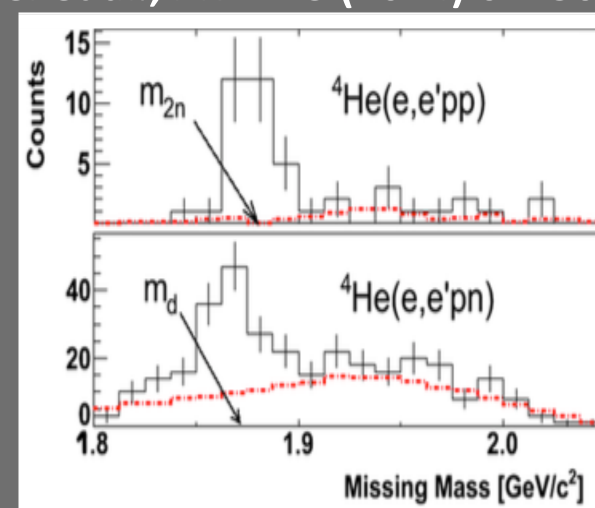

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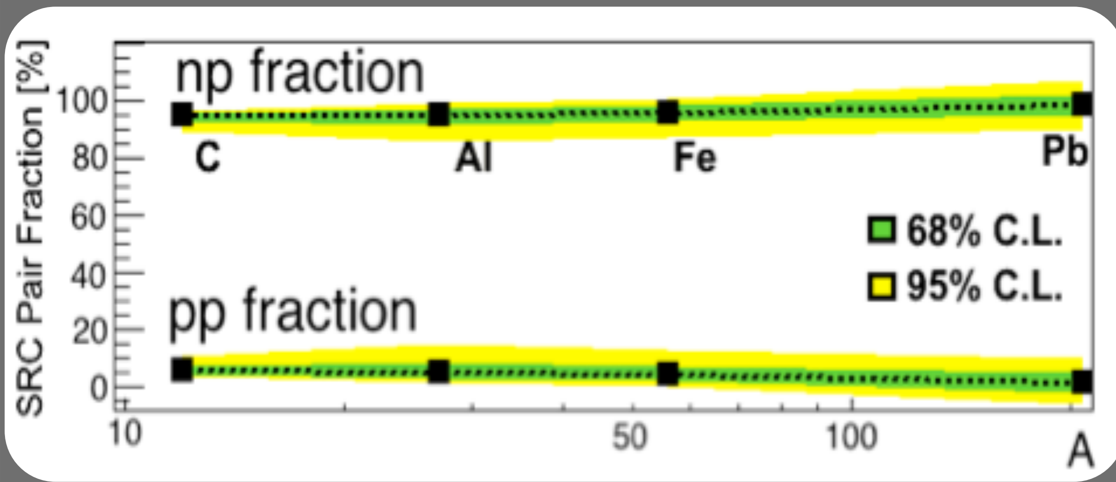
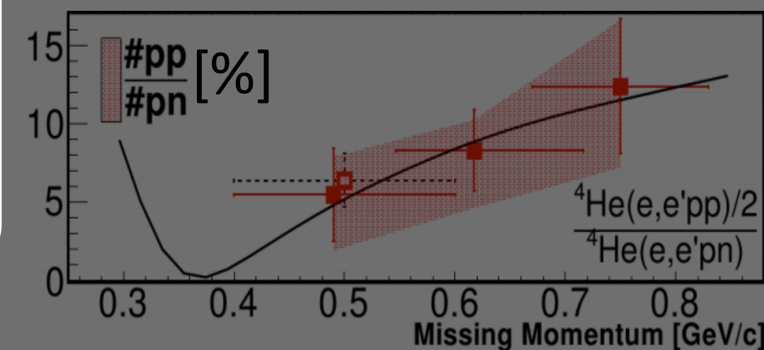
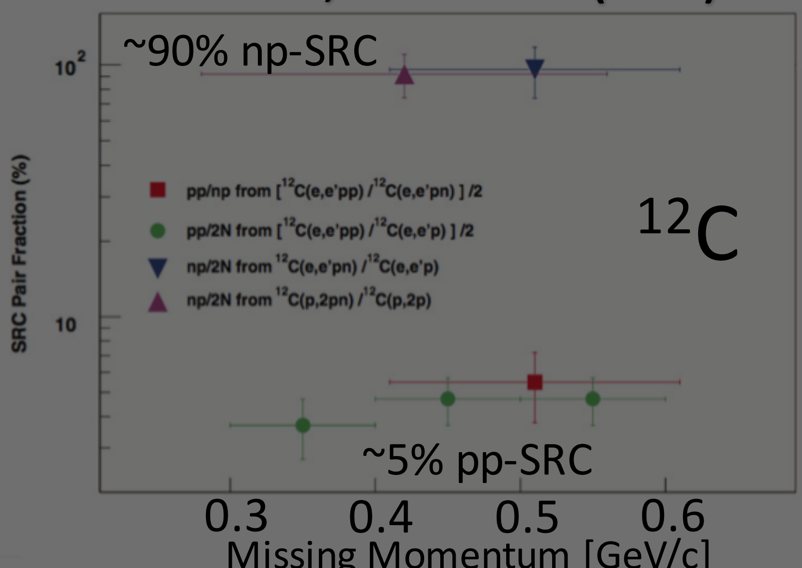


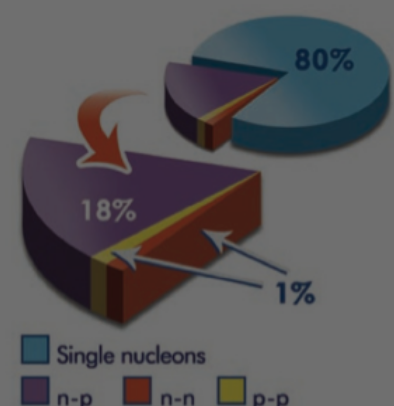
O. Hen et al., Science 364 (2014) 614

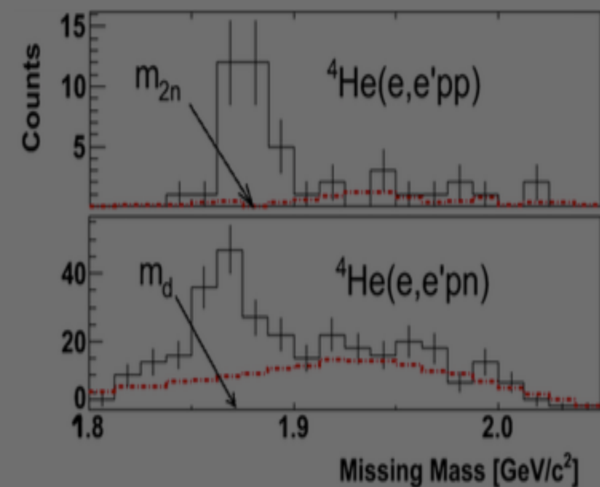


I. Korover et al., PRL 113 (2014) 022501

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

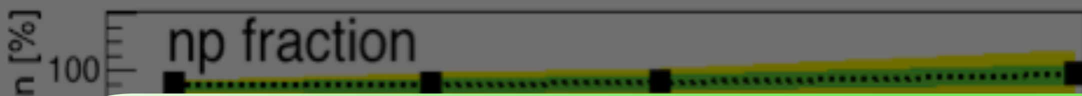






A. Tang et al., PRL (2003); E. Piasetzky et al., PRL (2006); R. Shneor et al., PRL (2007)

Results I: Isospin Structure



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

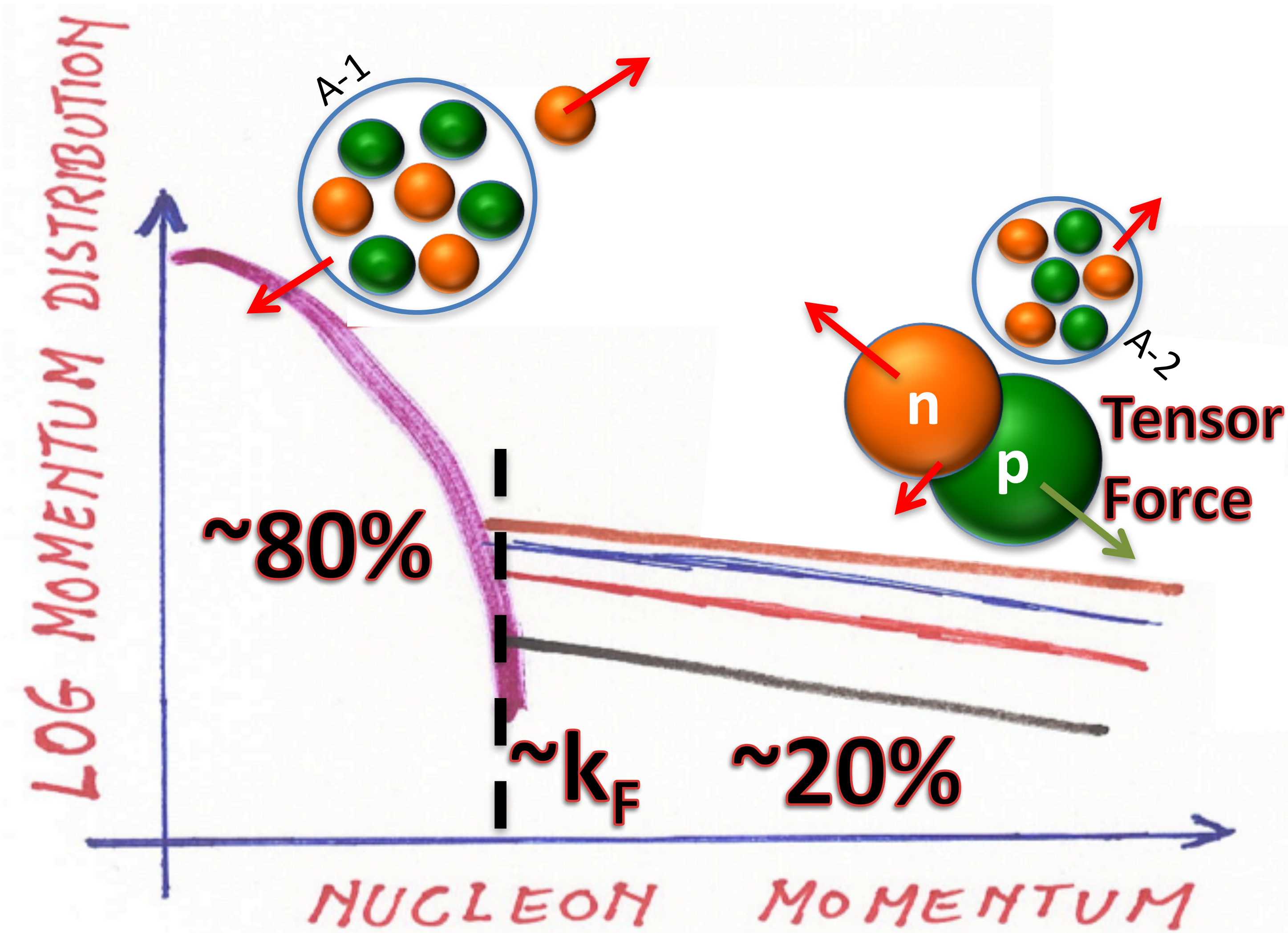
Bottom Line:

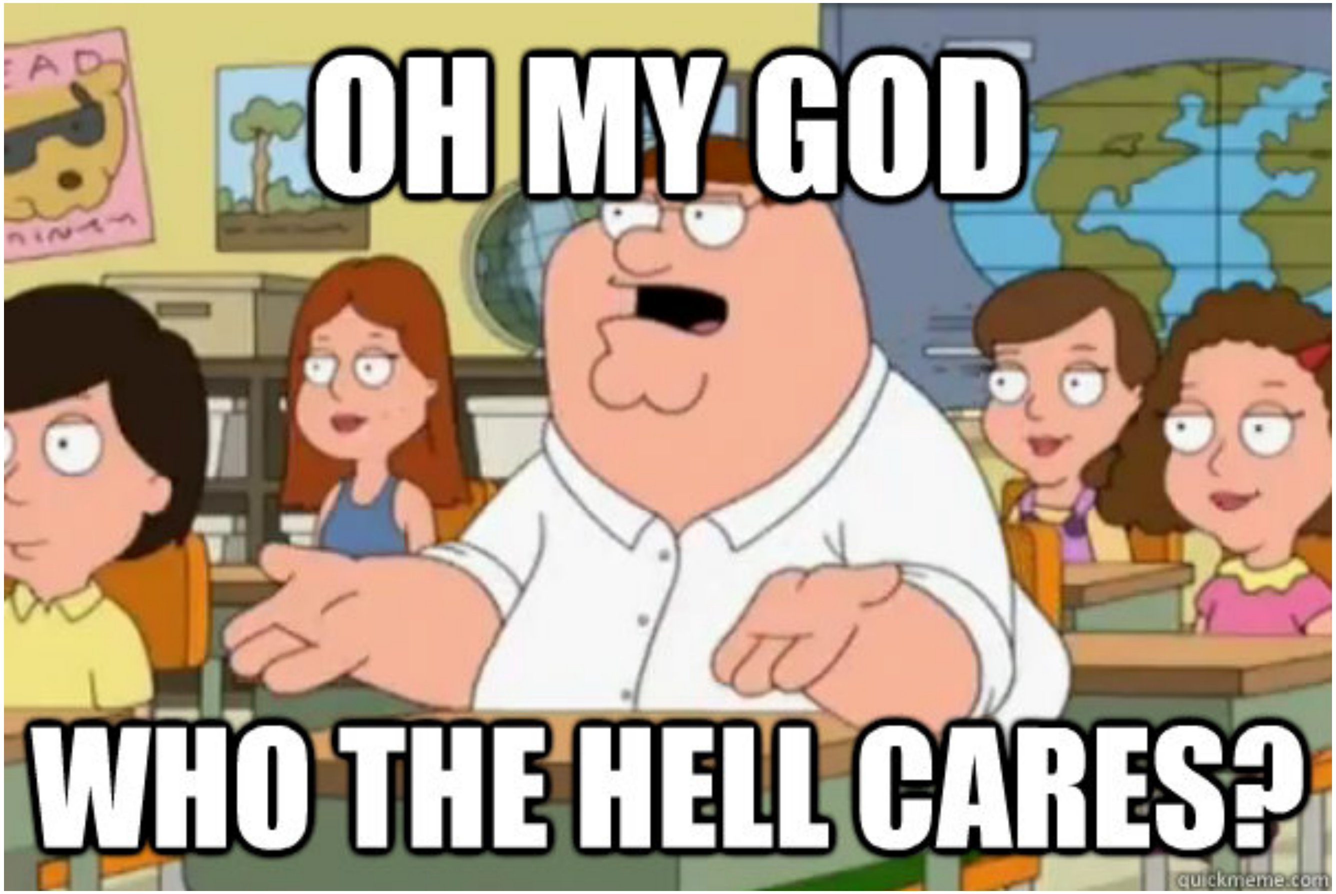
- 'Density Fluctuations' predominantly due to np-SRC.
- Universal character observed in A = 4 – 208 nuclei.
- Strong indication for Tensor force dominance at short distance

0.3 0.4 0.5 0.6
Missing Momentum [GeV/c]

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

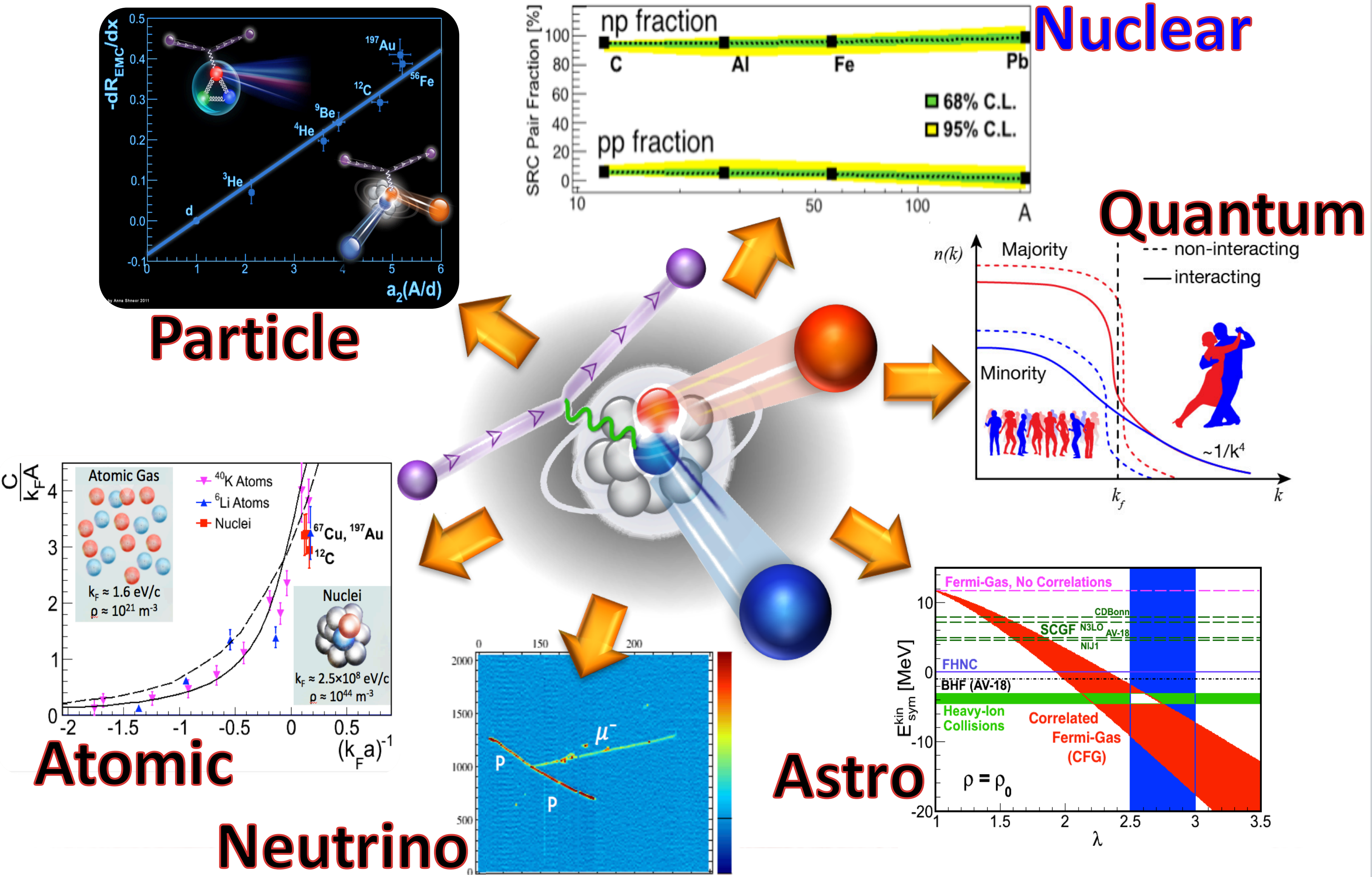
Intermediate summary: Universal structure of nuclei



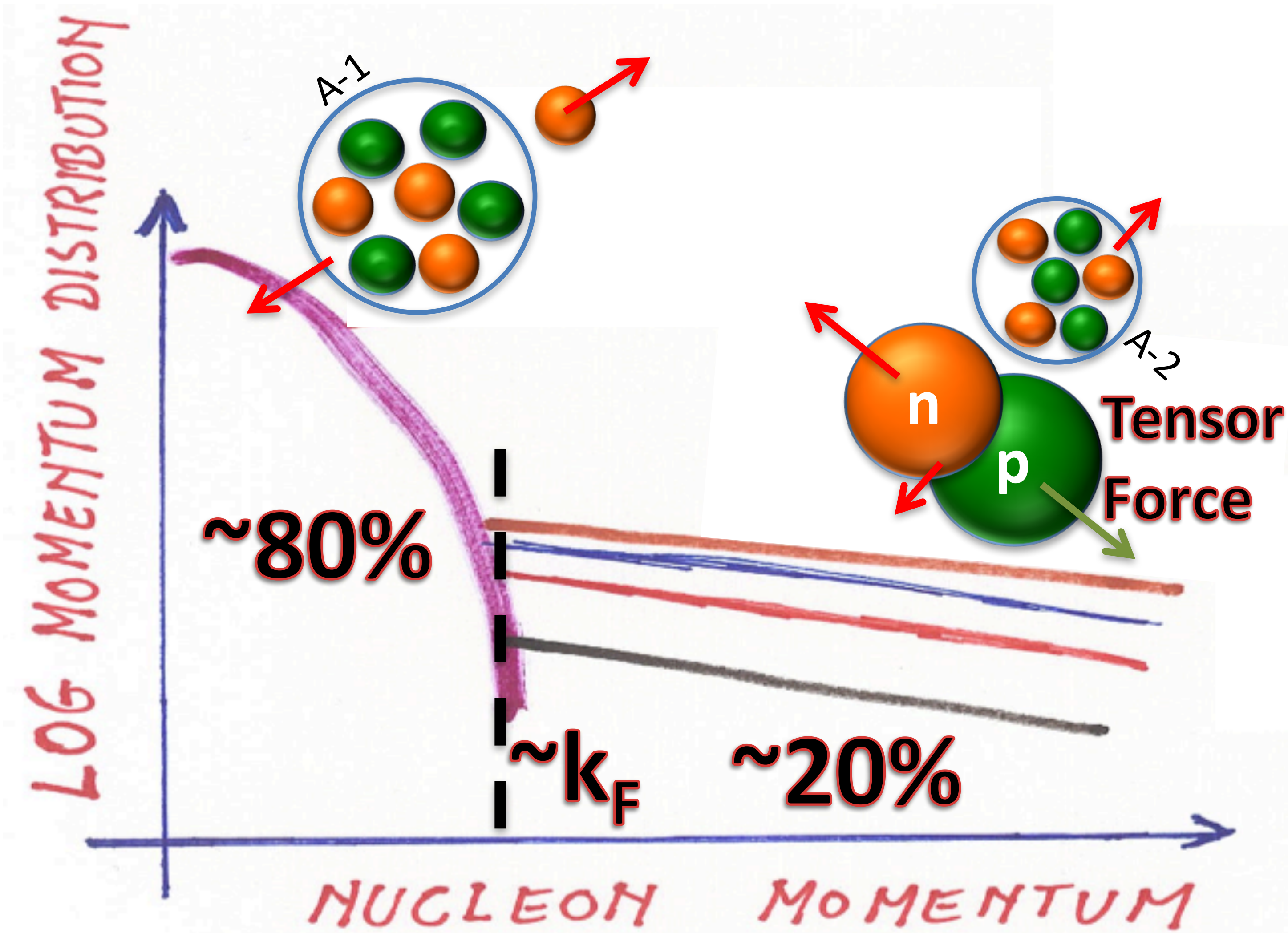


*Me at this point of the talk

You Should Care!



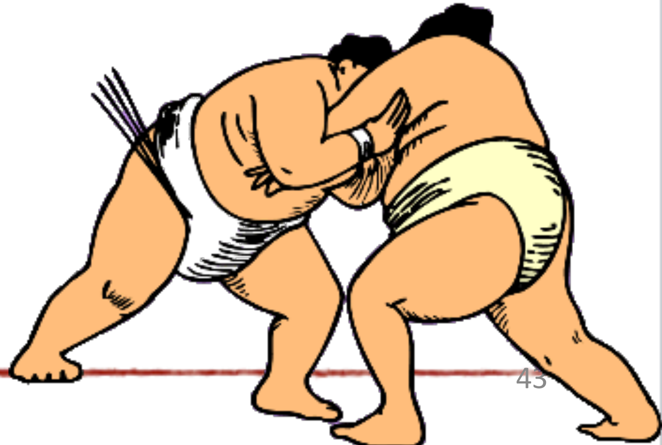
Intermediate summary: Universal structure of nuclei



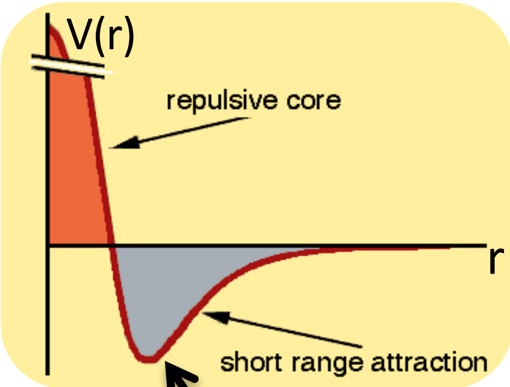
Two Leading 'EMC Models Families'

- Mean-Field Models
  - All nucleons are modified due to the influence of the nuclear medium.
- Virtuality Dependent Models
  - Nucleons have a different modification that related to their virtuality.

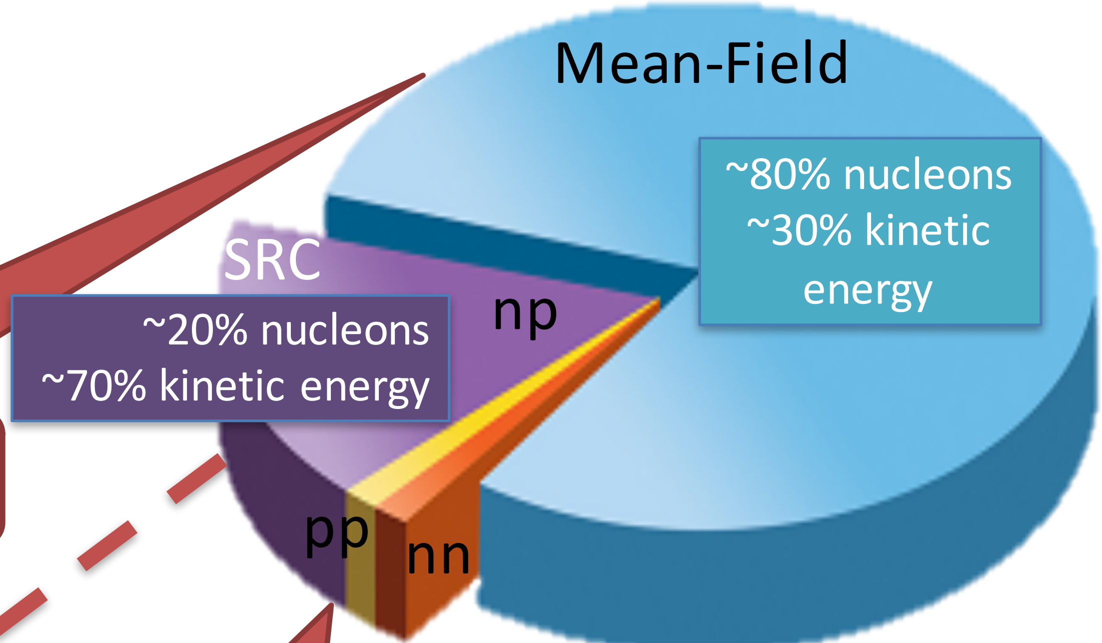
- BOTH MODELS CONSISTENT WITH DATA!



Where is the EMC Effect?

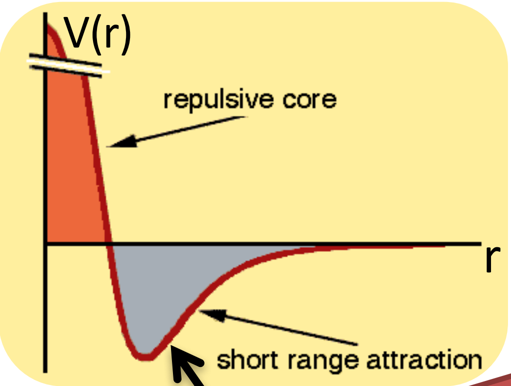


Largest attractive force

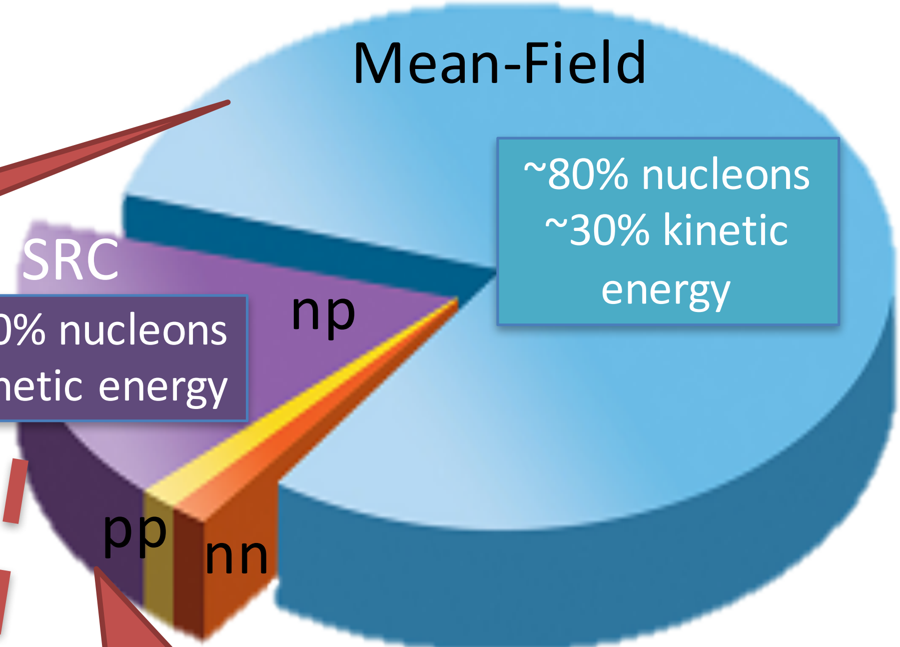


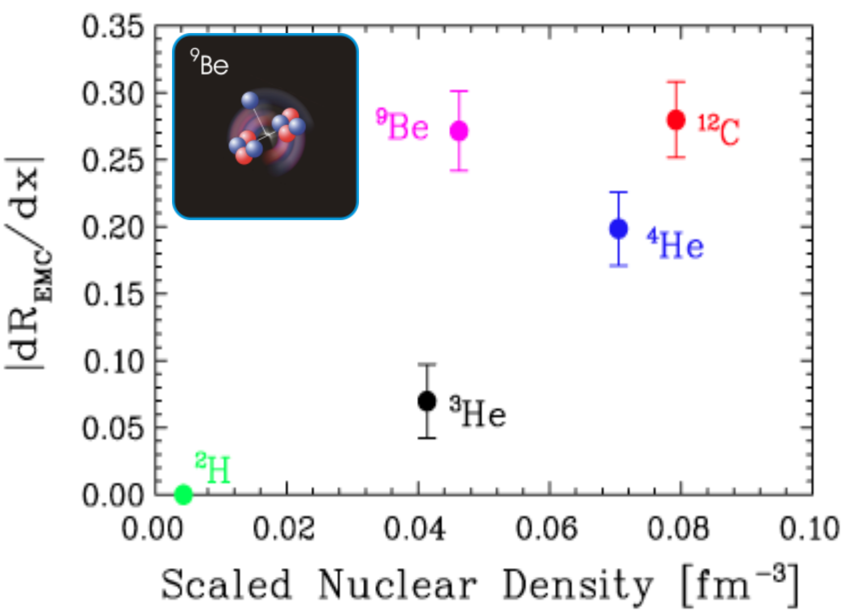
High local nuclear matter density, large momentum, large off shell, large virtuality ($v = p^{\mu 2} - m^2$)

Where is the EMC Effect?



Largest attractive force

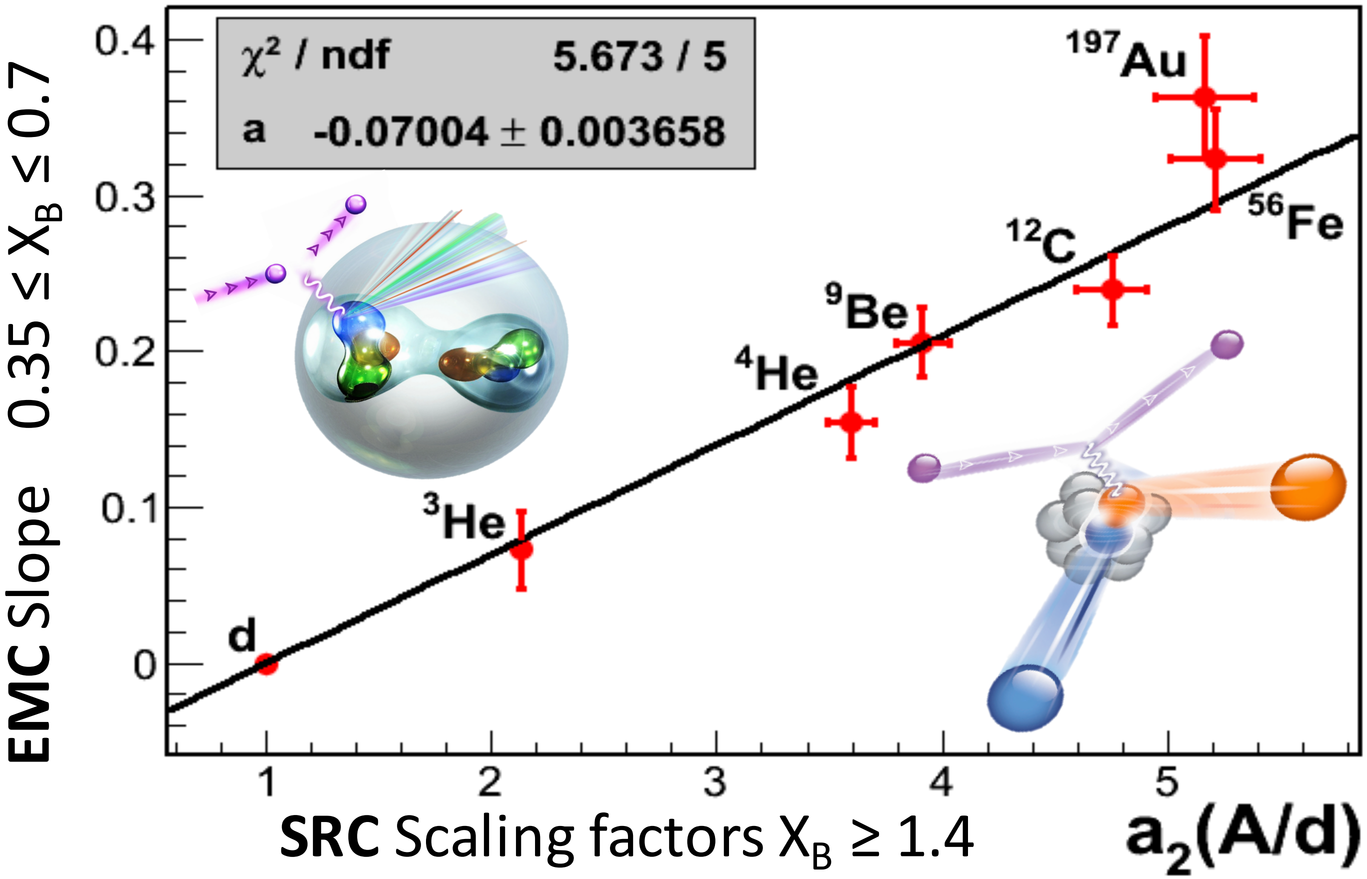




J. Seely et al., Phys. Rev. Lett. **103**, 202301 (2009).

High local nuclear matter density, large momentum, large off shell, large virtuality ($v = p^{\mu 2} - m^2$)

Results IV: EMC-SRC Correlation

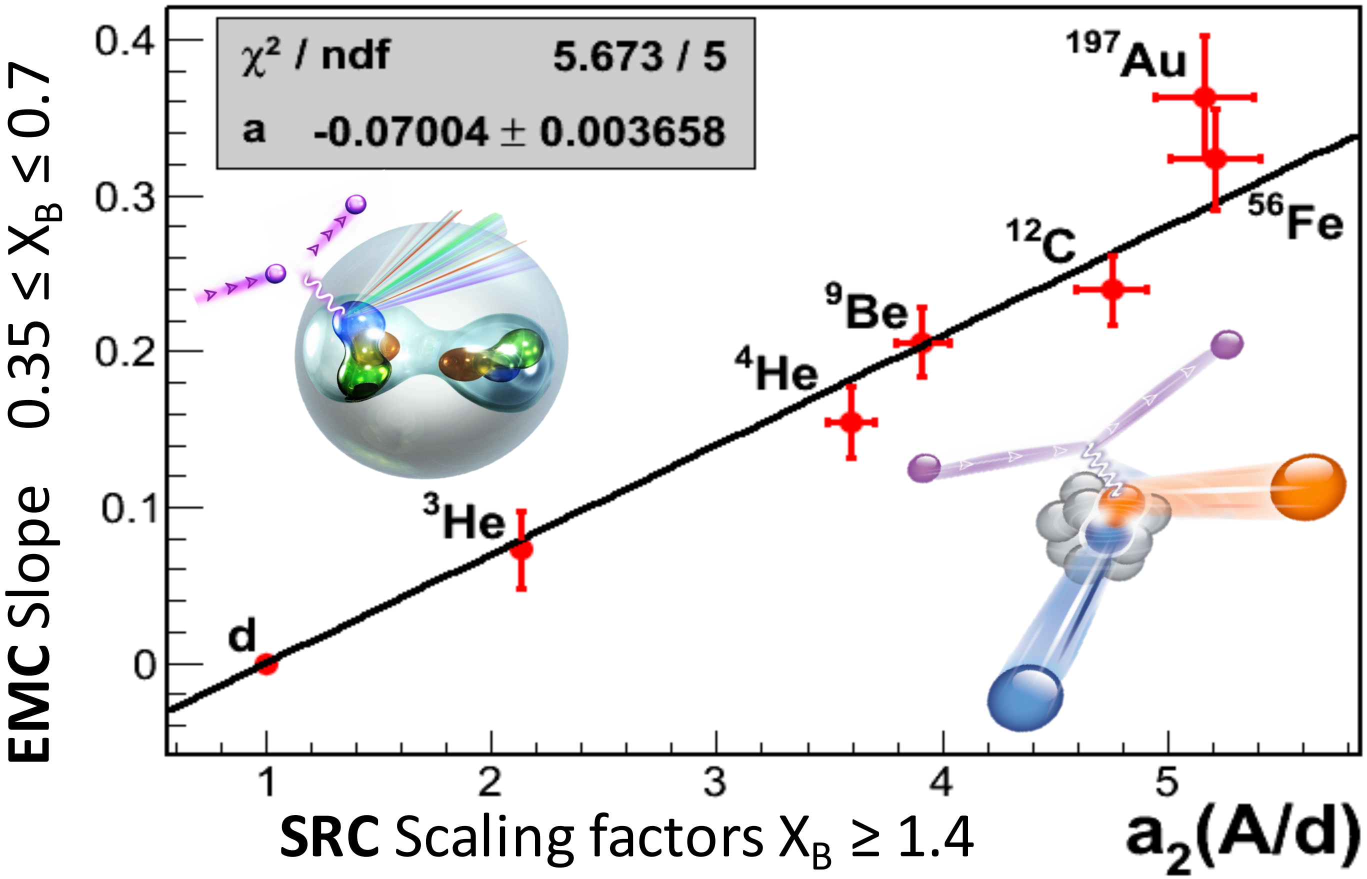


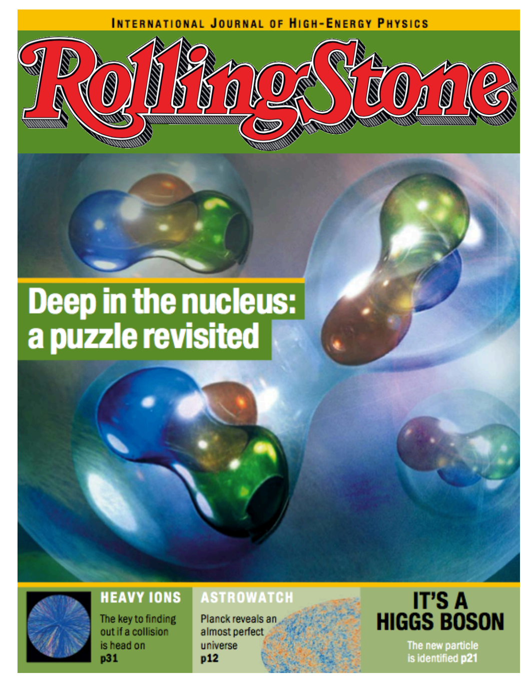
O. Hen et al., Int. J. Mod. Phys. E. **22**, 1330017 (2013).

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.

Results IV: EMC-SRC Correlation





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Results IV: EMC-SRC Correlation

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]

O. Hen et al., Int. J. Mod. Phys. E. **22**, 1330017 (2013).
O. Hen et al., Phys. Rev. C **85** (2012) 047301.
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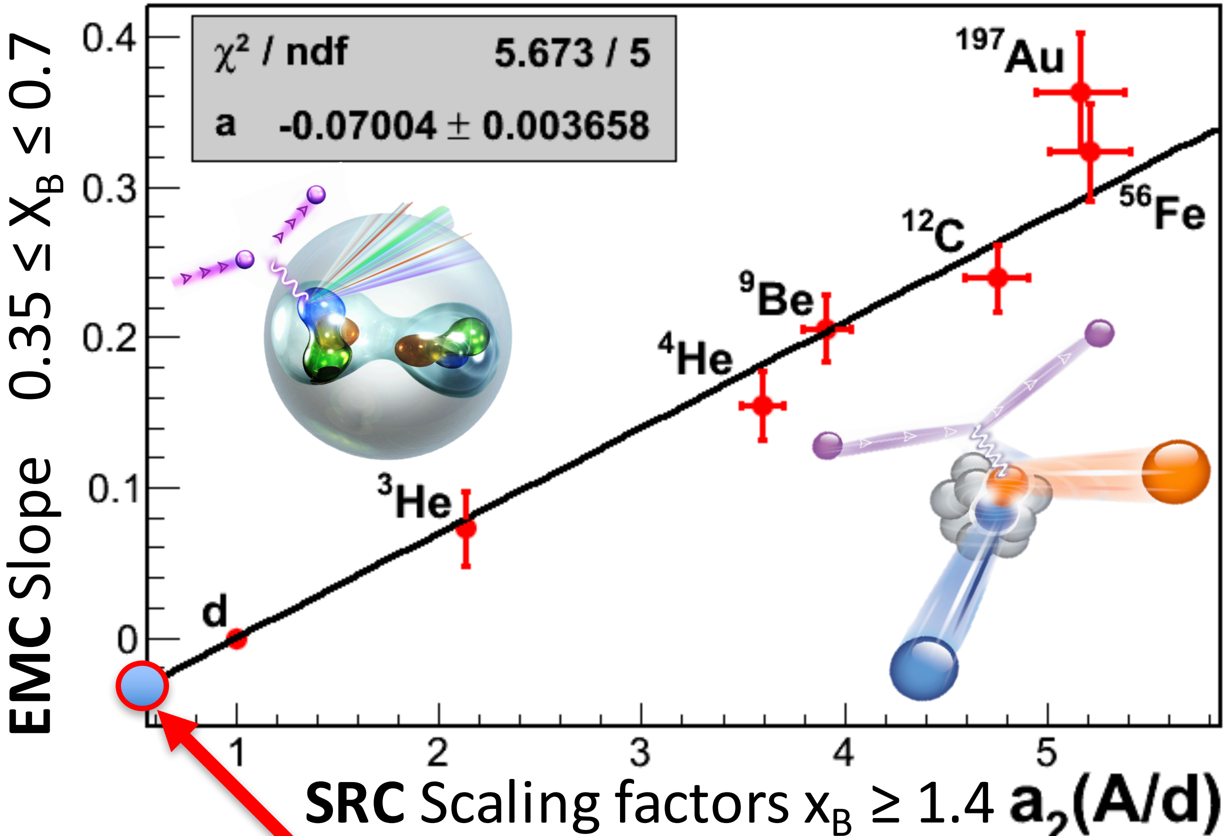
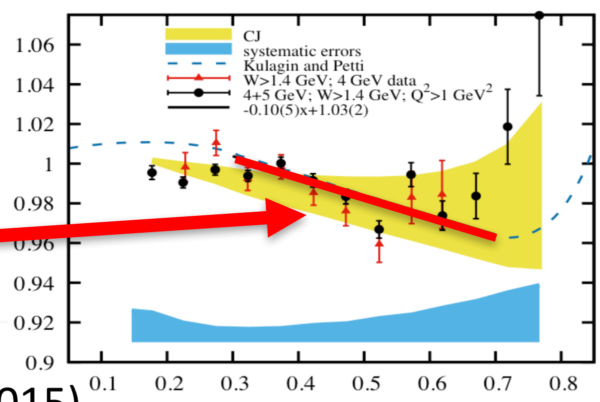


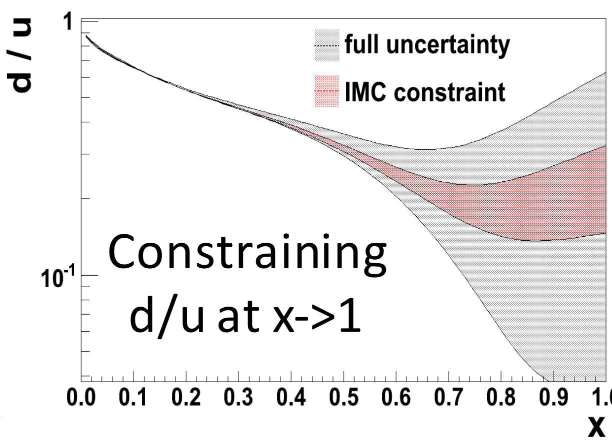
IMC Effect Slope:

EMC/SRC (2011) -0.09(1)

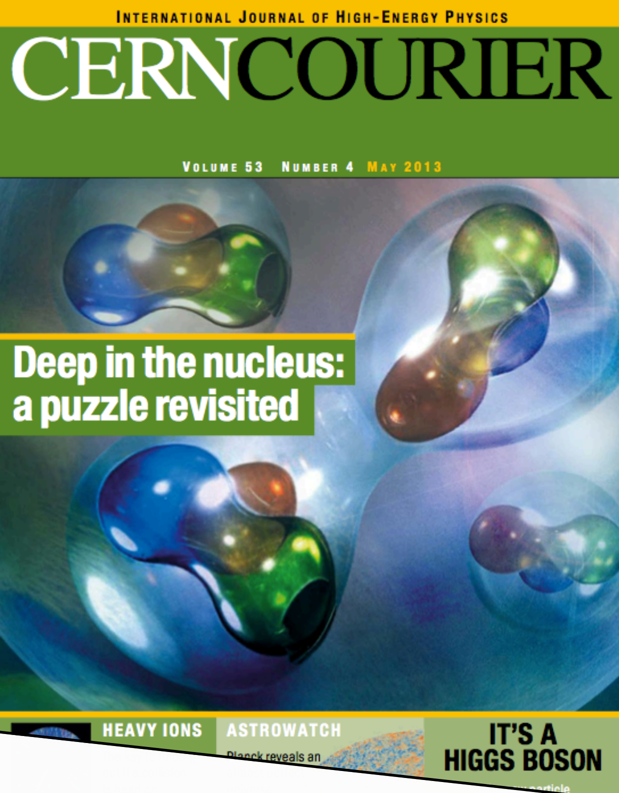
BONUS (2015) -0.10(5)



K. Griffioen et al., PRC (2015)



O. Hen et al., PRD (2011)



52301 (2011) PHYSICAL REVIEW LETTERS week of 4 FEBRUA

Short Range Correlations and the EMC Effect

L. B. Weinstein,[1,*] E. Piasetzky,[2] D. W. Higinbotham,[3] J. Gomez,[3] O. Hen,[2] and R. Shneor[2]

PHYSICAL REVIEW C **85**, 047301 (2012)

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O. Hen,[1] E. Piasetzky,[1] and L. B. Weinstein[2]

Short range correlations and the EMC effect

E. Piasetzky[a], L.B. Weinstein[b], D.W. Higinbotham[c], J. Gomez[c], O. Hen[a], R. Shneor[a]

NUCLEAR PHYSICS A

PHYSICAL REVIEW D **84**, 117501 (2011)

Constraints on the large-x d/u ratio from electron-nucleus scattering at $x > 1$

O. Hen,[1] A. Accardi,[2,3] W. Melnitchouk,[3] and E. Piasetzky[1]

International Journal of Modern Physics E
Vol. 22, No. 7 (2013) 1330017 (30 pages)

THE EMC EFFECT AND HIGH MOMENTUM NUCLEONS IN NUCLEI

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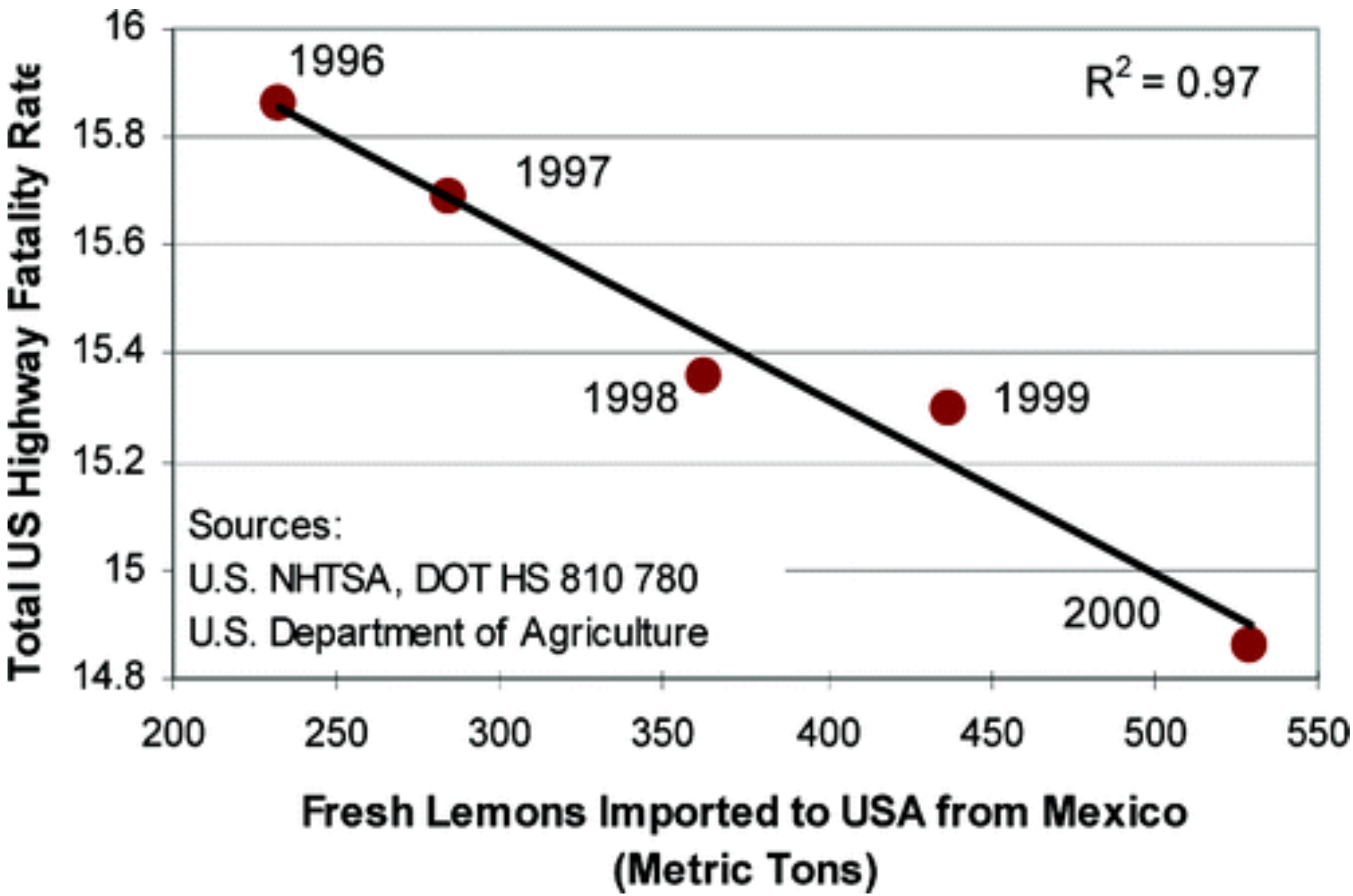
THE EMC EFFECT AND HIGH MOMENTUM NUCLEONS IN NUCLEI

Other Correlations…



Other Correlations

Mexican Lemonade Saves Lives!

Physics Behind the Correlation?

- The EMC-SRC Correlation is robust.
  - Independent of different experimental and theoretical corrections applied to the SRC scaling data
- Models suggested that the EMC effect depends on the average kinetic energy, <T>, carried by nucleons in the nucleus
  - <T> is dominated by 2N-SRC

O. Hen et al., Phys. Rev. C 85 (2012) 047301   J. Arrington et al., Phys.Rev. C 86 (2012) 065204

Experimental Tests ?

- Goal: measure the virtuality (nuclear density) dependence of the structure function
- (our) Method: tagged DIS using d(e,e'N_{recoil}) reactions

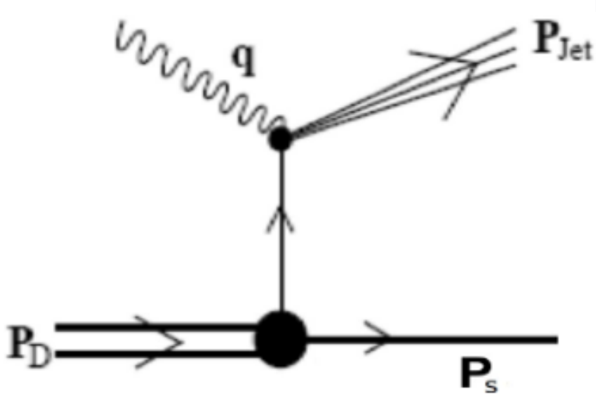
Deuterium is the only system in which the momentum of the struck nucleon equals that of the recoil (Assuming no FSI)

In Medium Nucleon Structure Functions, SRC, and the EMC effect

Study the role played by high-momentum nucleons in nuclei

A proposal to Jefferson Lab PAC 38, Aug. 2011

O. Hen (contact person), E. Piasetzky, I. Korover, J. Lichtenstadt, I. Pomerantz, I. Yaron, and R. Shneor
Tel Aviv University, Tel Aviv, Israel

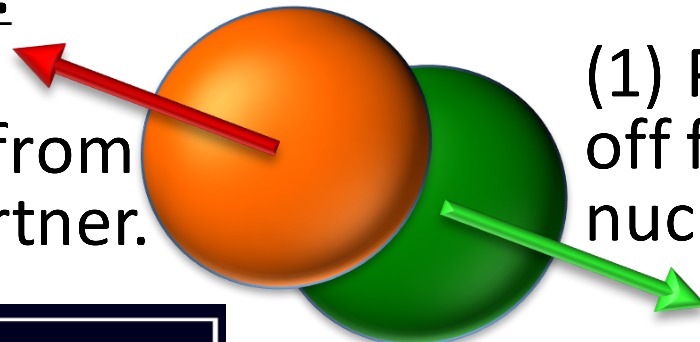


Tagged Structure Functions (JLab12)

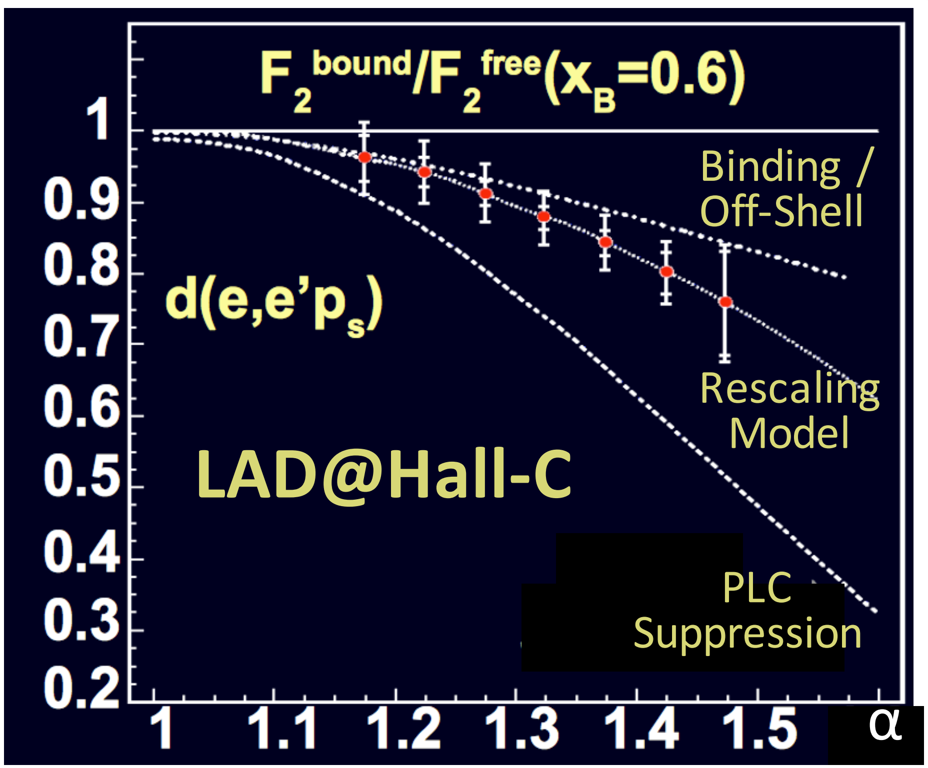
Internal structure of SRC nucleons?

Focus on the deuteron:

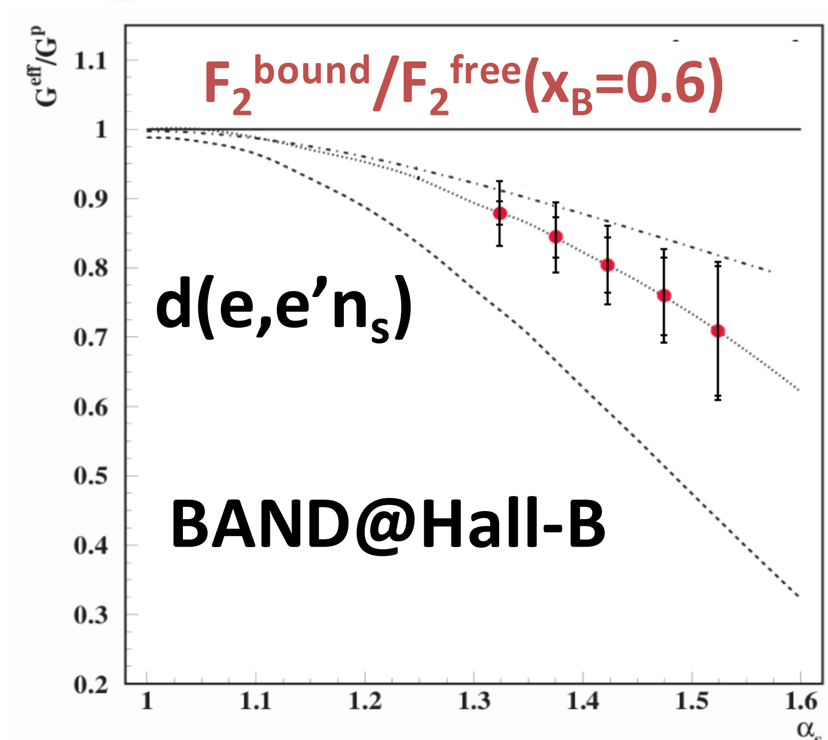
(2) Infer its momentum from the recoil partner.



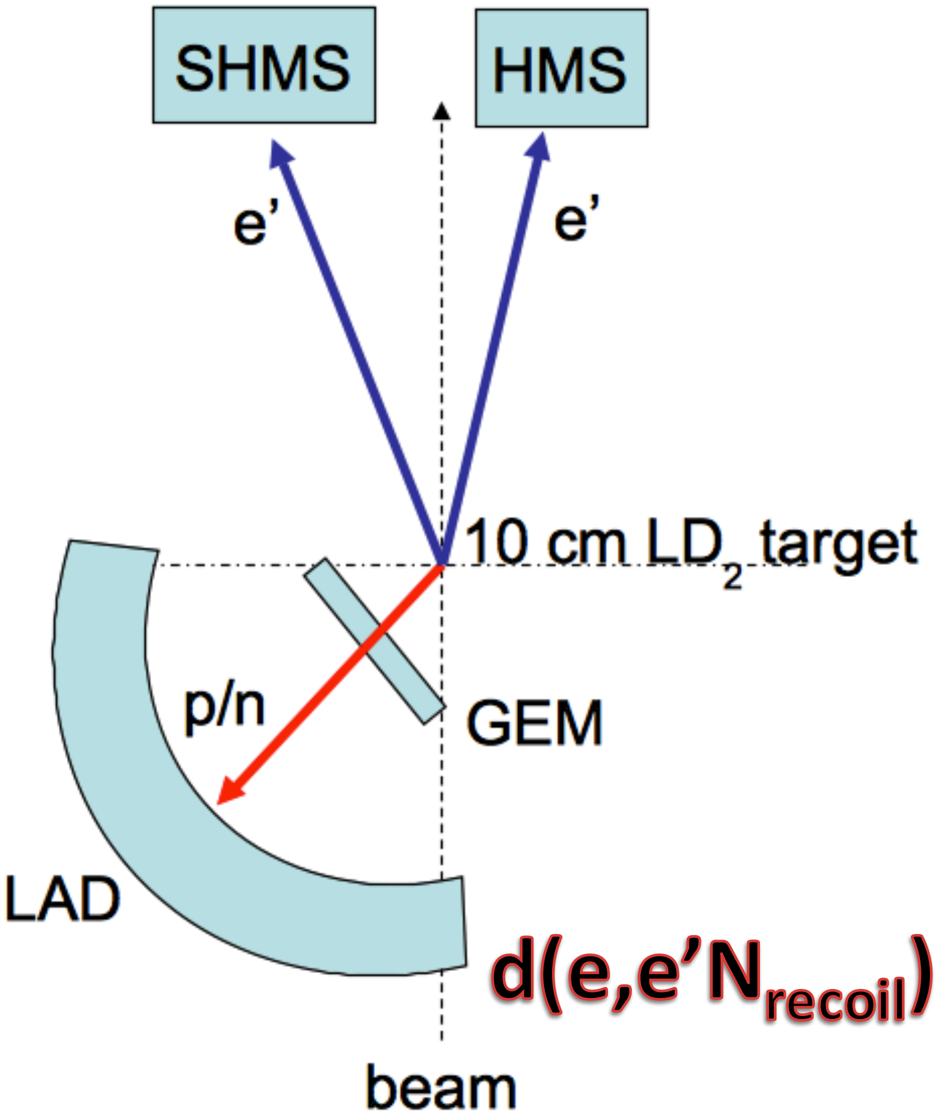
(1) Perform DIS off forward going nucleon.



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

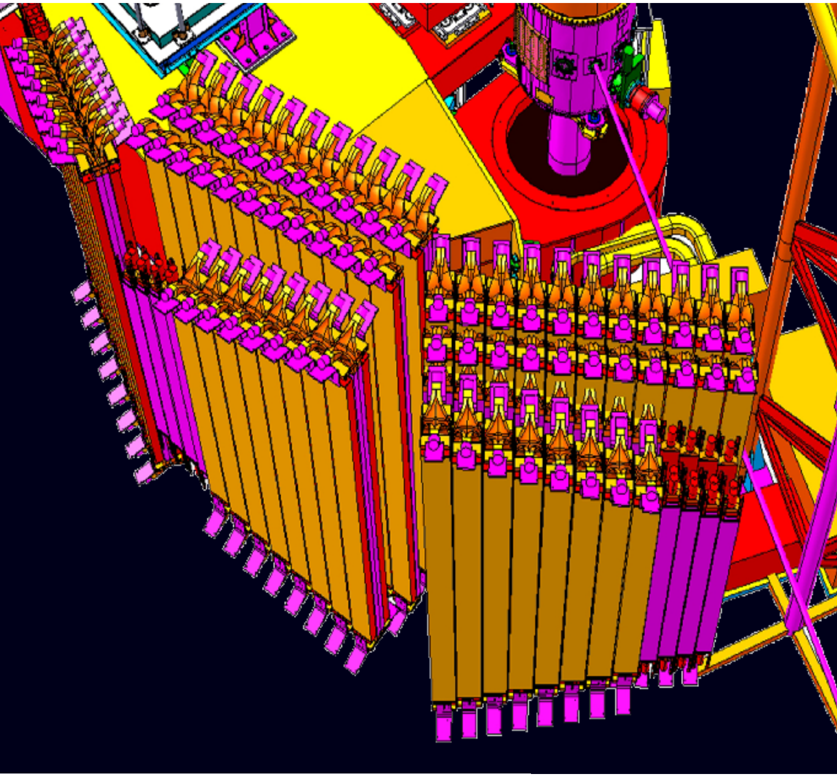


Tagging Concept…

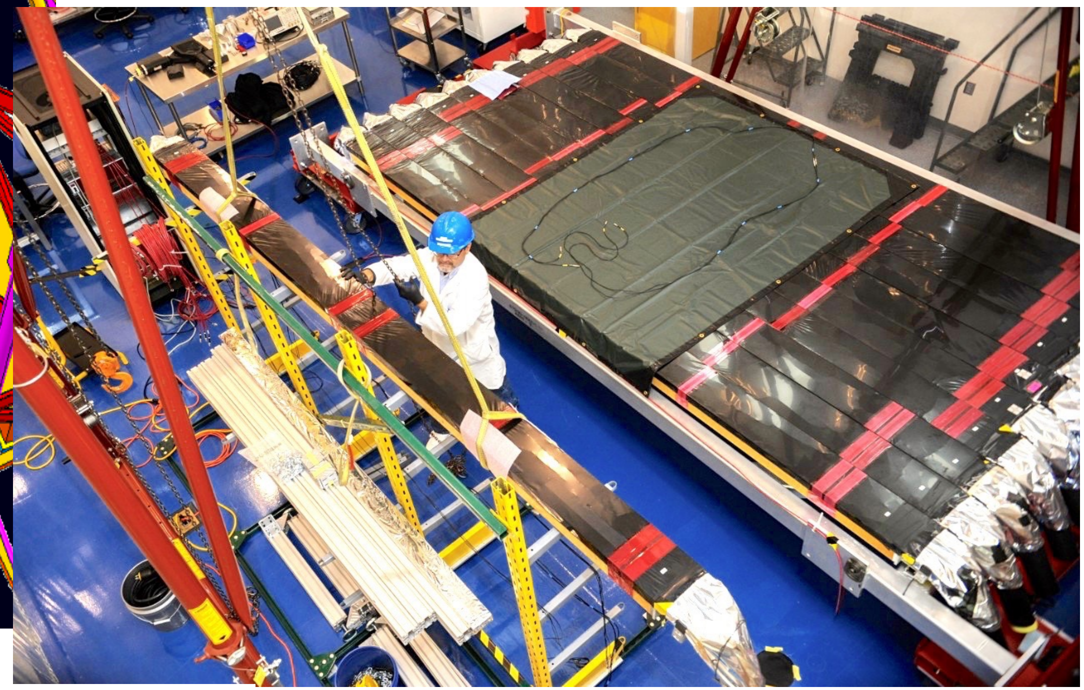


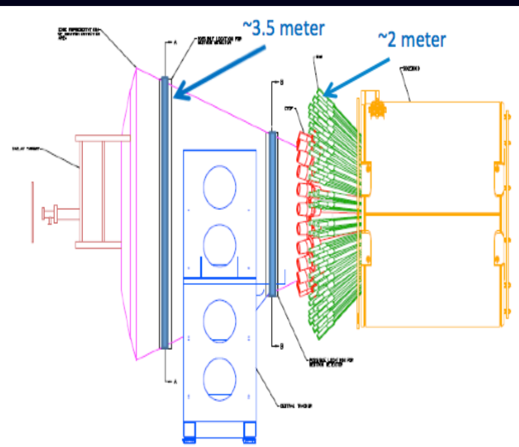
- High resolution spectrometers for (e,e') measurement in DIS kinematics
- Large acceptance recoil proton \ neutron detector
- Long target + GEM detector – reduce random coincidence

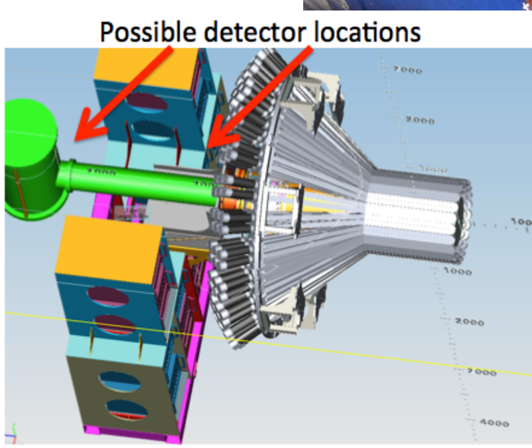
Building Large-Acceptance Detectors



Large Acceptance Detector (LAD@Hall-C)



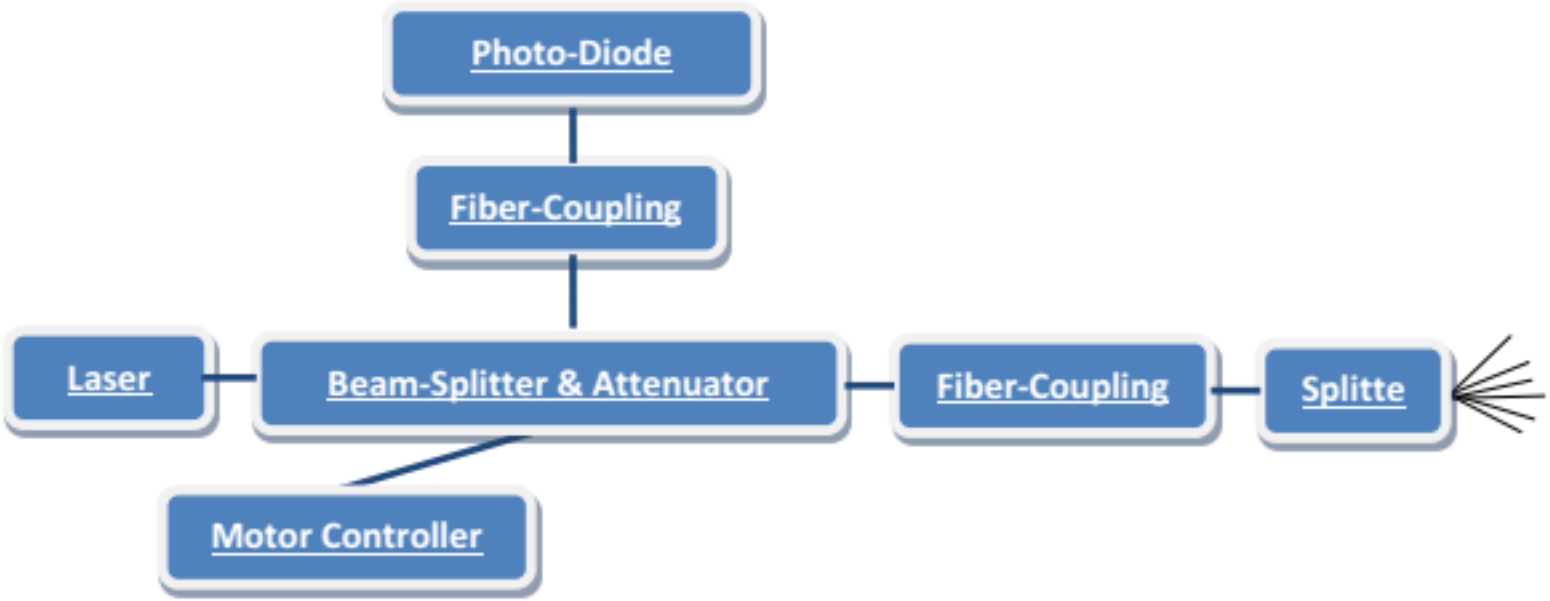


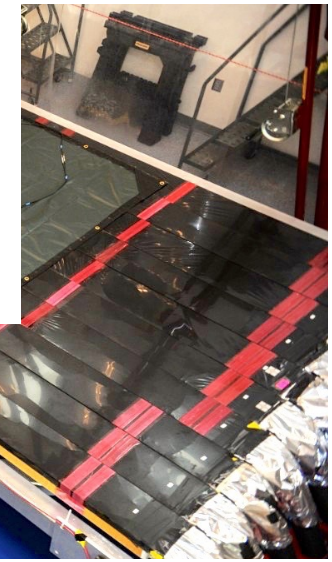


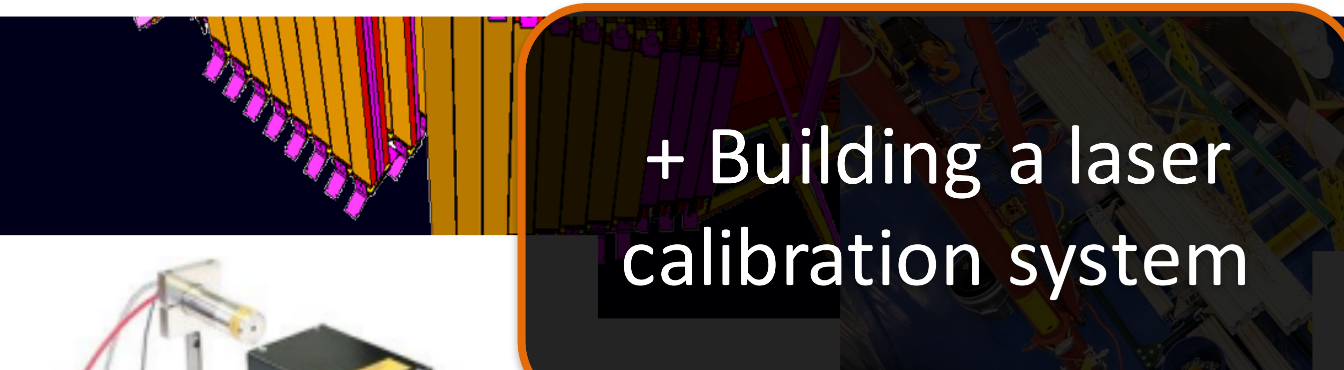
Backward Angle Neutron Detector (BAND@Hall-B)

R&D @ MIT / Construction @ BATES

ors



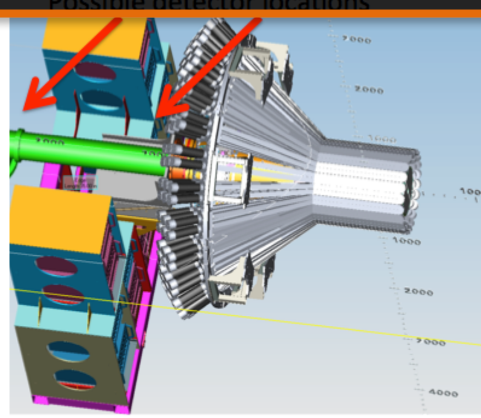




+ Building a laser calibration system

Fig 2: Standa STA-01-TH Laser

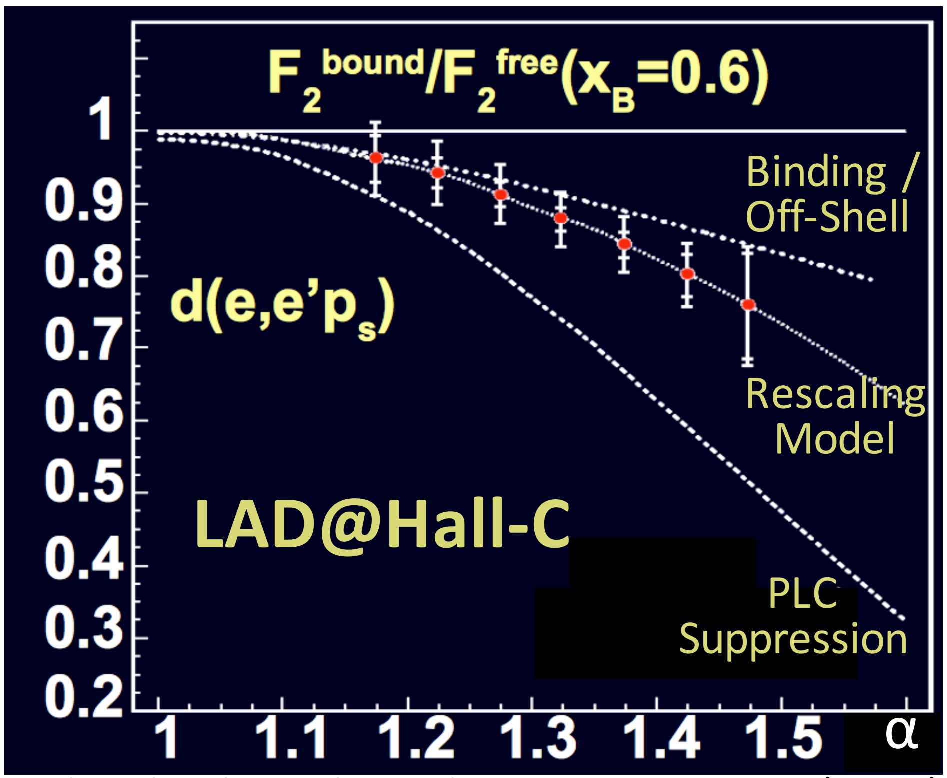
Possible detector locations



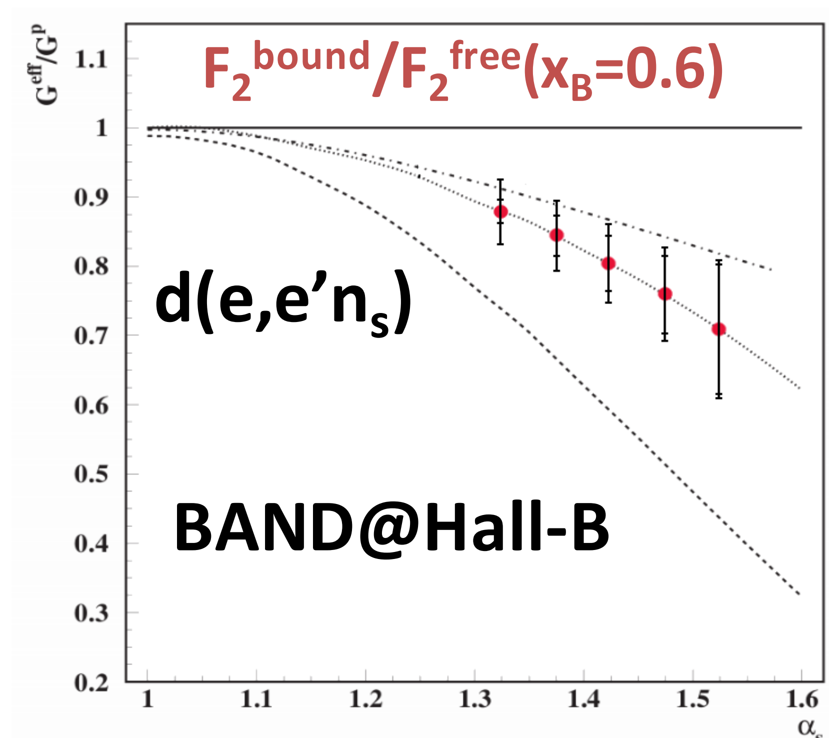
Backwa
Detecto
F
Const

Kinematics and Uncertainties

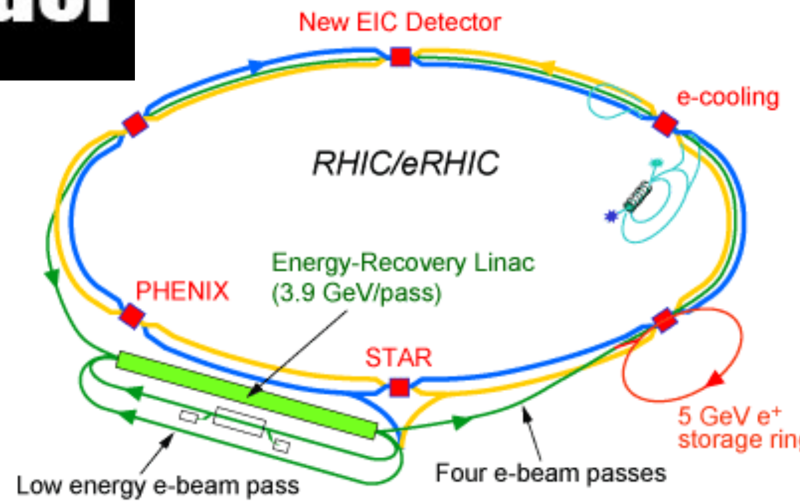
- Tagging allows to extract the structure function in the nucleon reference frame: $x' = \dfrac{Q^2}{2(\bar{q}\cdot\bar{p})}$
- Expected coverage: x’ ~ 0.3 & 0.45(0.5) < x’ < 0.55(0.7) @ $W^2 > 4\ [\mathrm{GeV/c}]^2$

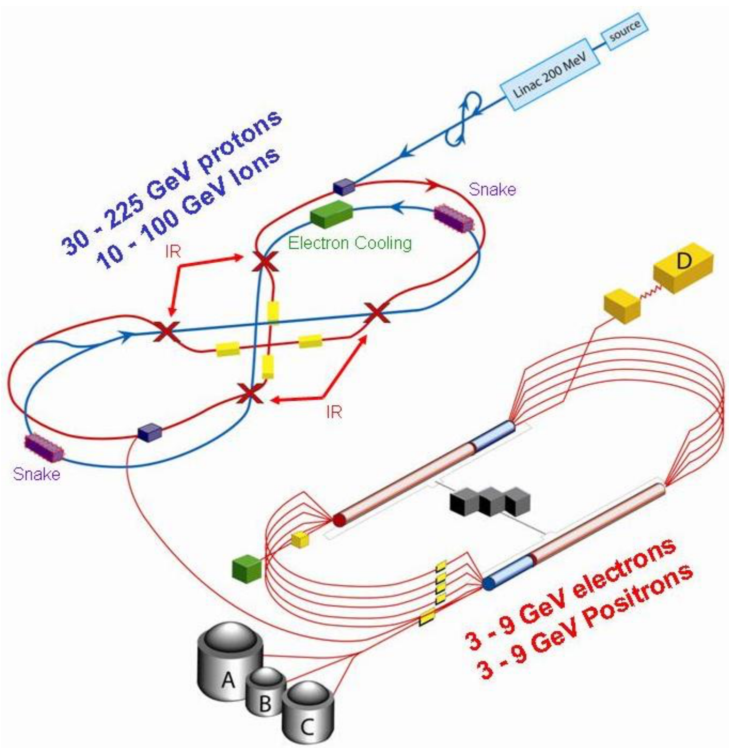


Melnitchouk et al., Z. Phys. A **359**, 99-109 (1997)



Prospects beyond JLab 12 GeV?



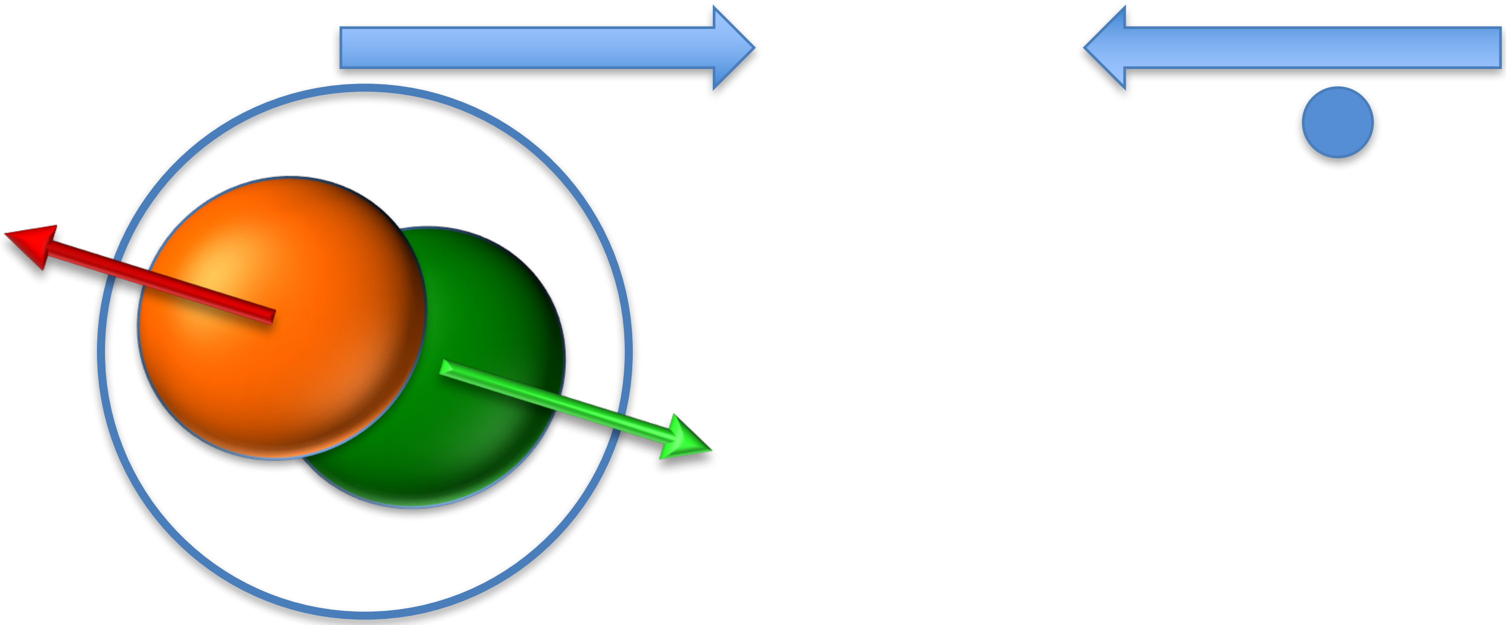


** Your Design Here? **

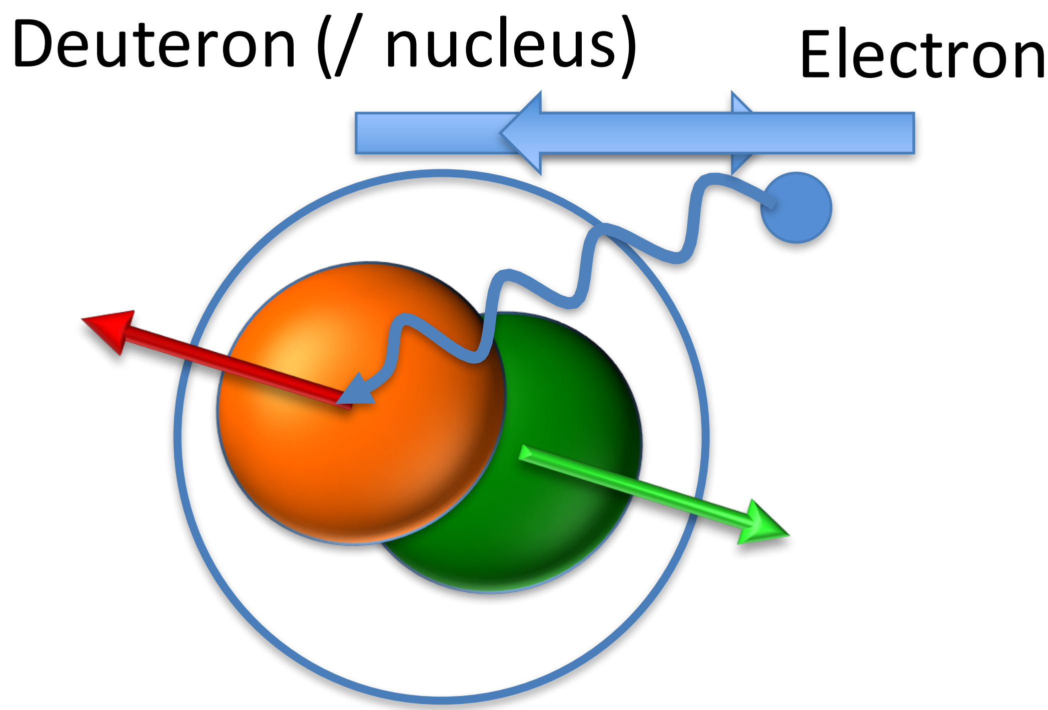
Collider Concept…

Deuteron (/ nucleus)

Electron



Collider Concept…



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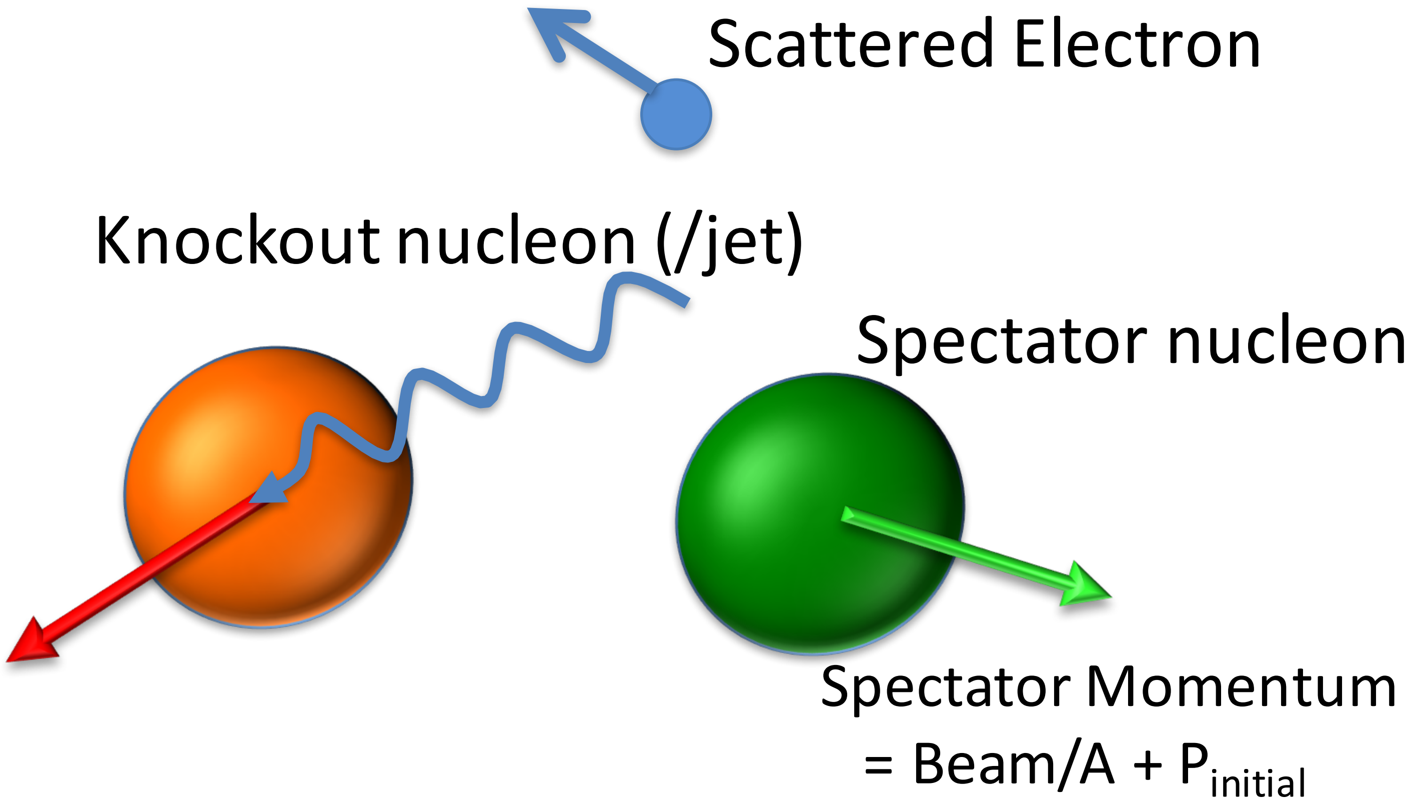
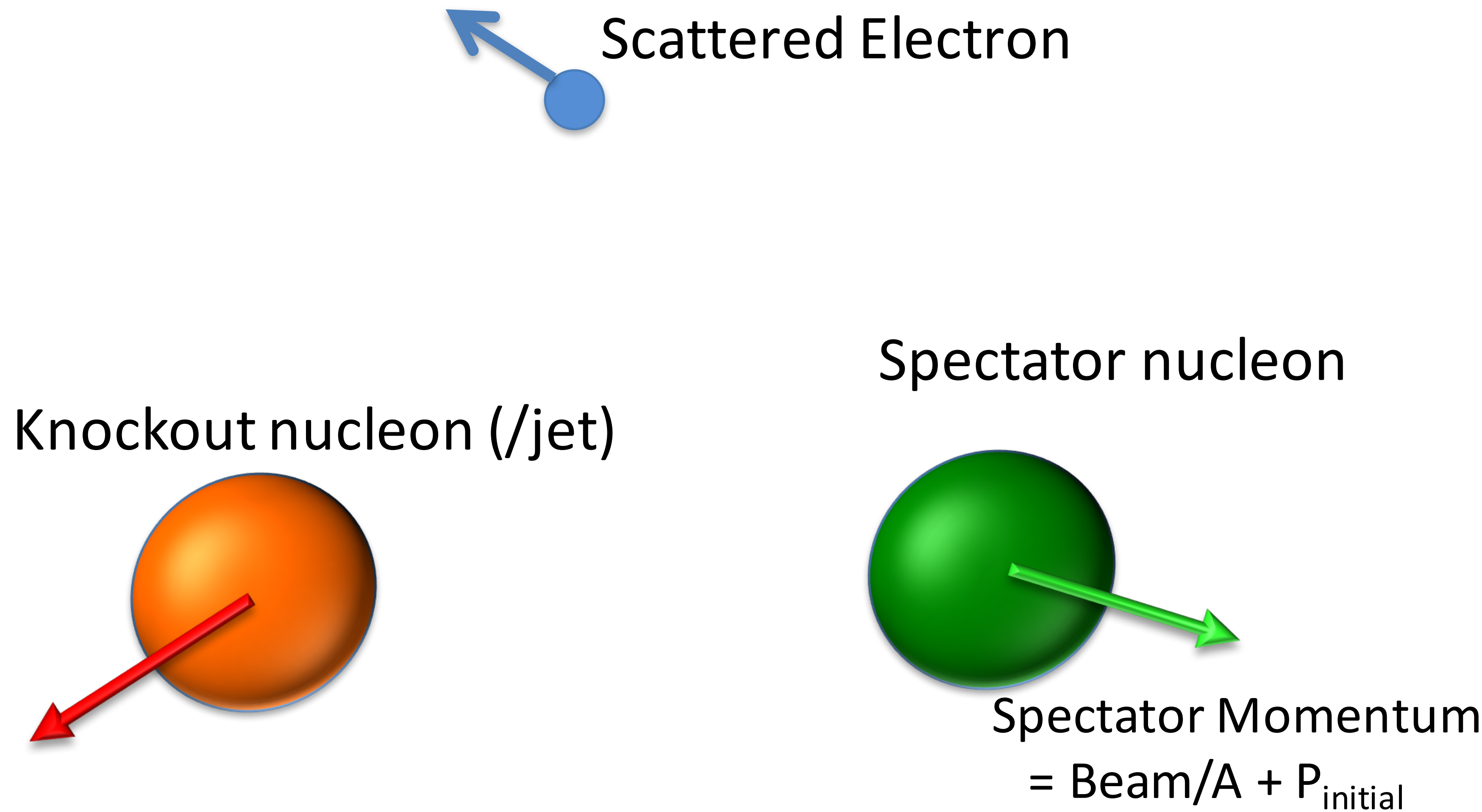


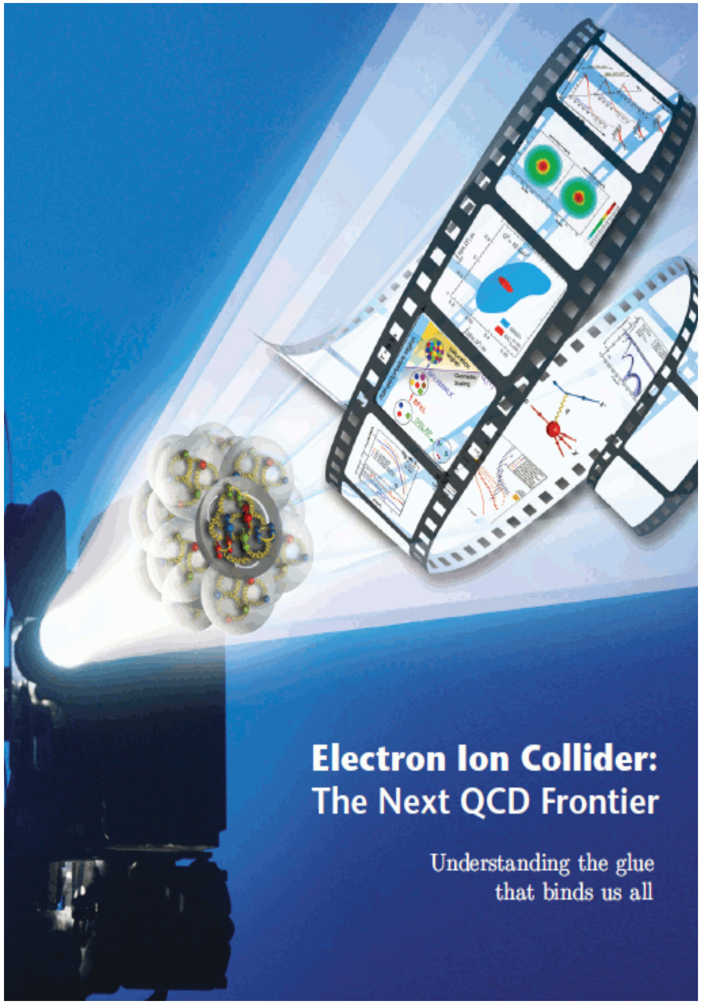
Collider Concept…



Signature of Correlations:

Spectator momentum > beam momentum

Collider Tagging Kinematics



Spectator Momentum

100 GeV d: $\gamma = 50$

Center of Mass: P_z (CM) GeV/c	Center of Mass: P_{perp} (CM) GeV/c	Lab: P_z (Lab) GeV/c	Lab: 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

The group

- MIT:


Barak Schmookler


Navaphon (Tai) Muangma


Reynier Torres

  – Or Hen
  – Shalev Gilad

- ODU:


Mariana Khachatryan

  – Larry Weinstein

- Tel-Aviv:


Erez Cohen


Meytal Duer

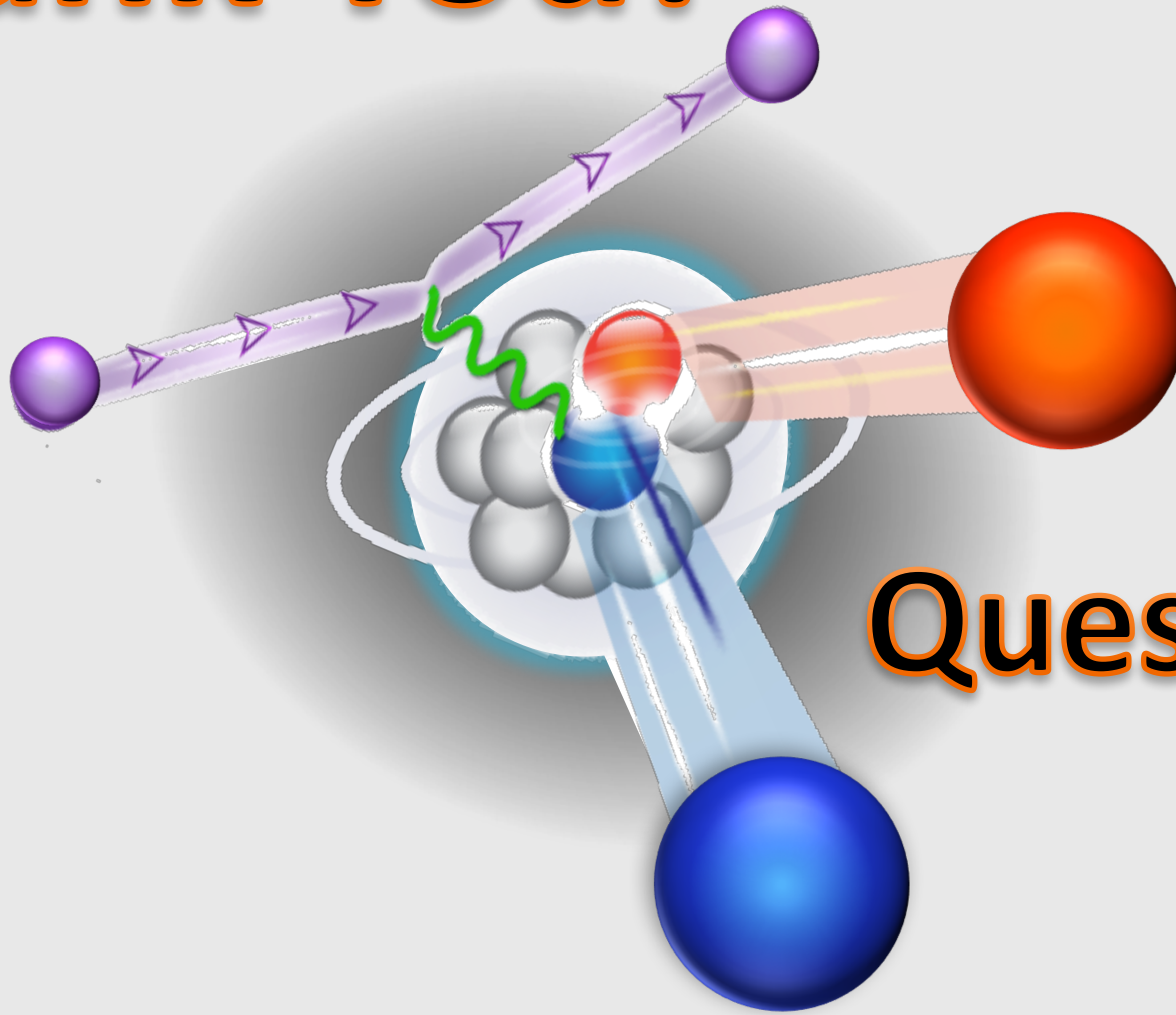

Igor Korover

  – Eli Piasetzky

- Many theory friends ☺

New collaborators are always welcome!

Thank You!



Questions?