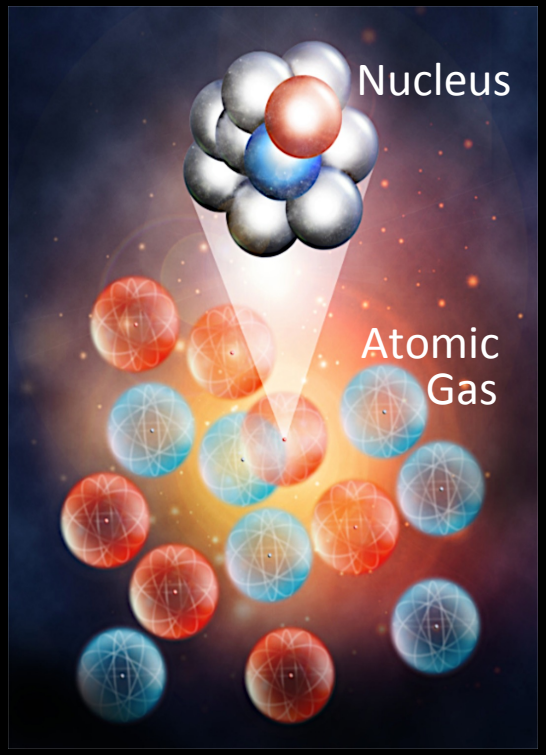
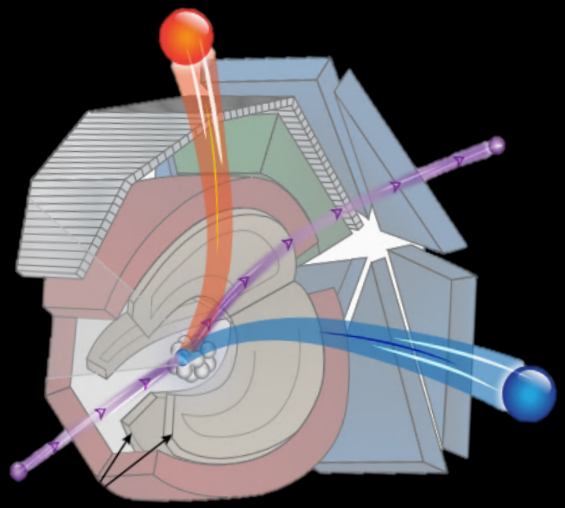
# Energy Sharing in Imbalanced Fermi systems
## [CLAS6 results + future CLAS12 experiments]

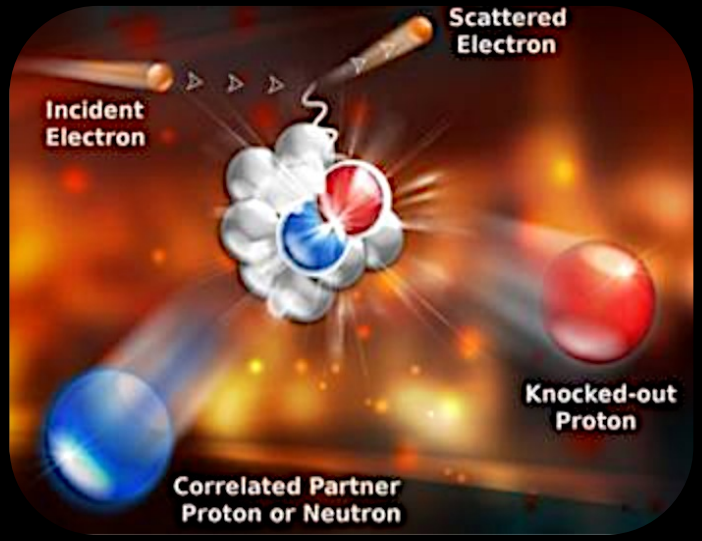


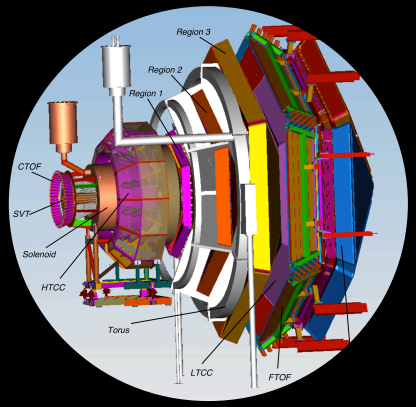


Or Hen

Tel-Aviv University




CLAS2015
INFN – Laboratori Nazionali del Sud
and Sezione di Catania – Catania, Italy

CLAS12 4th European Workshop, February 20th 2015, Catania, Italy.

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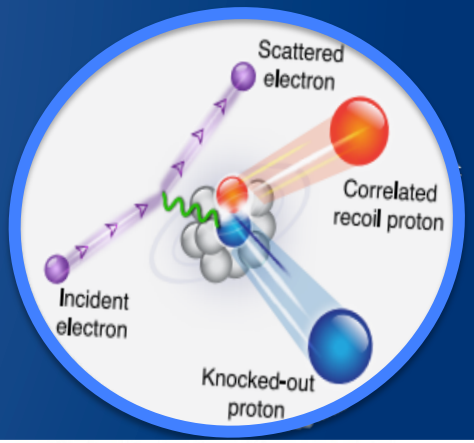
# Two-Nucleon Short-Range Correlations (2N-SRC) are pairs of nucleons that:

- Are close together (overlap) in the nucleus
- Have *high relative momentum* and *low c.m. momentum*, where high and low are compared to the Fermi momentum ($k_F$) of the nucleus

# Why Study High-Momentum Nucleons in Nuclei?

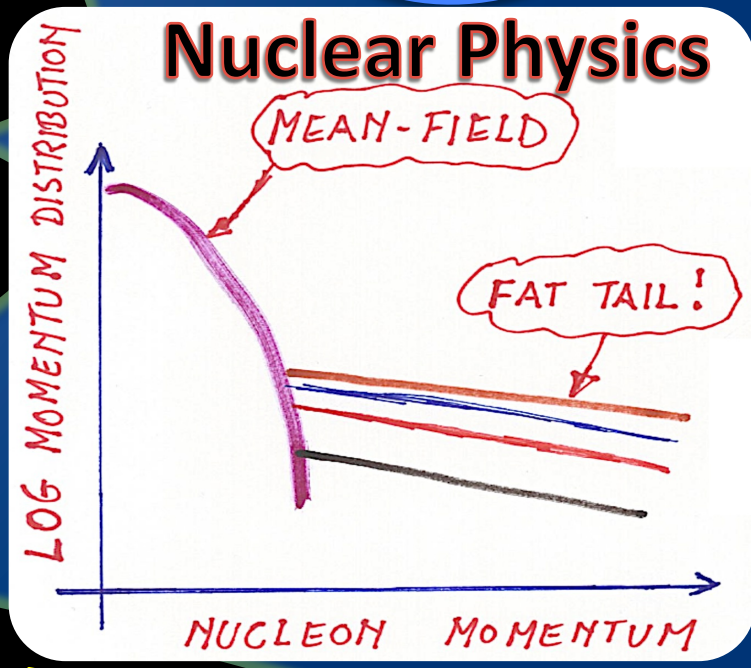
**Particle Physics**

The EMC Effect.
Neutrino-Nucleus Scattering.
The NuTeV Anomaly.




**Astrophysics**

Neutron Stars.
Nuclear Symmetry Energy.




**Quantum / Atomic Physics**

Energy Sharing in Imbalanced Fermi Systems.
Contact Interaction in Universal Fermi Systems.

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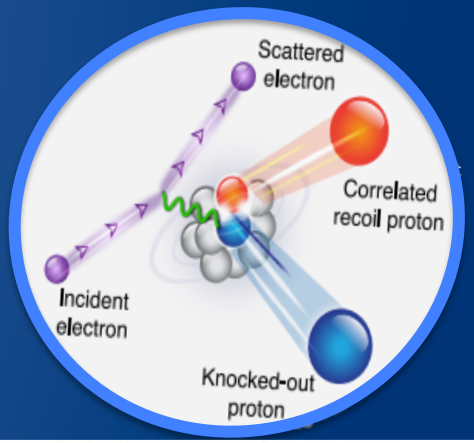


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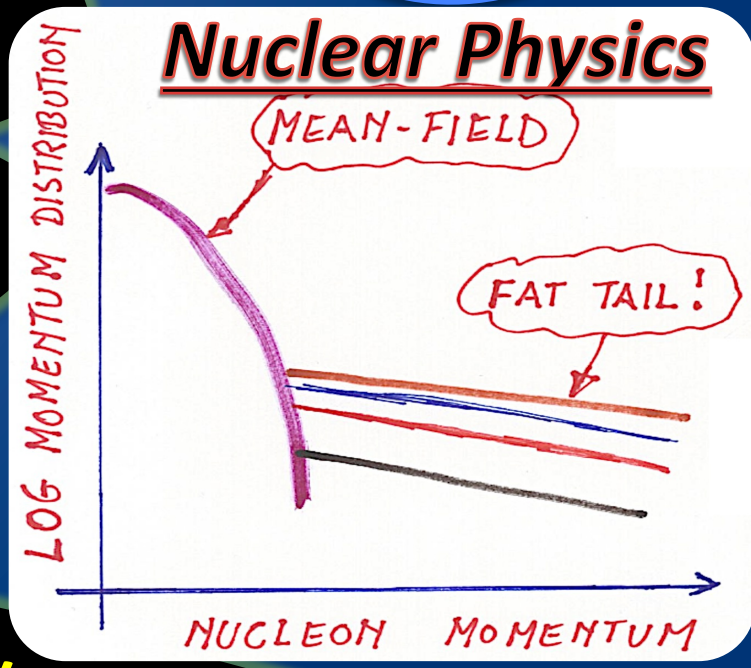


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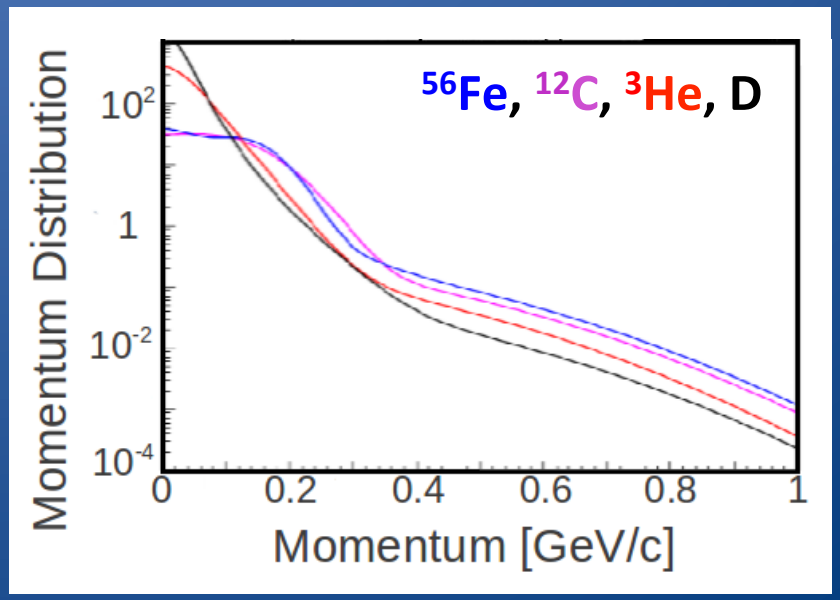
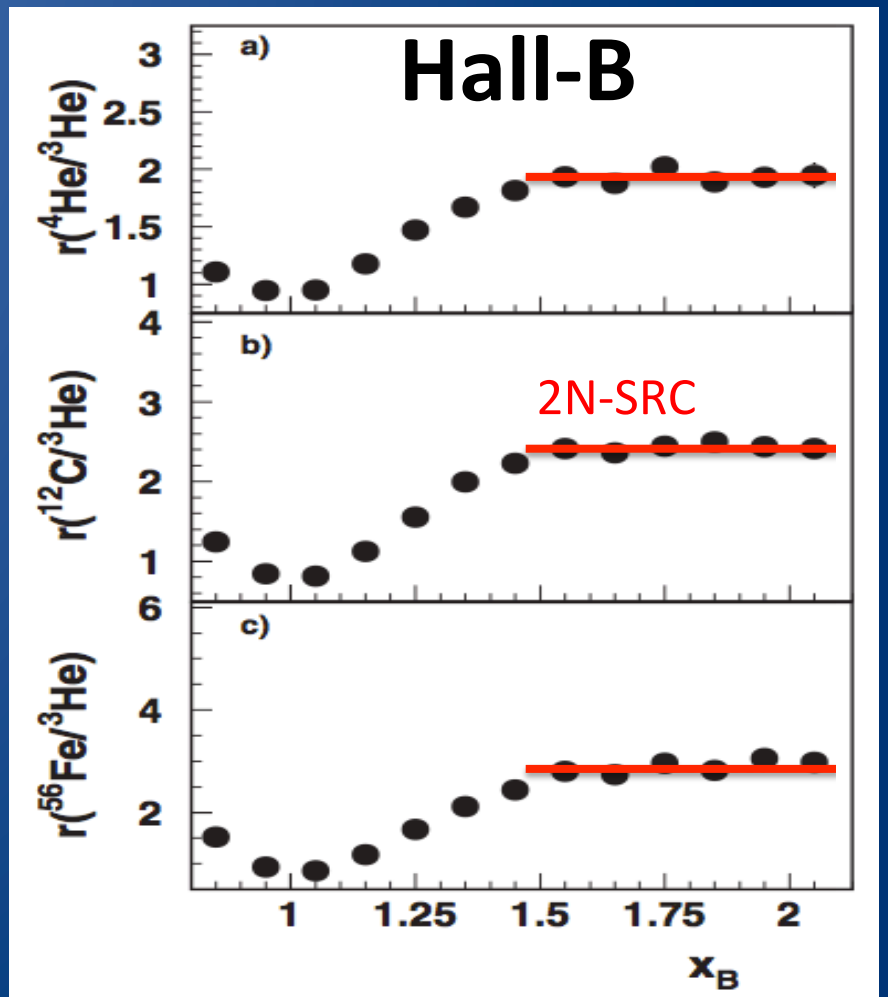
Contact Interaction in Universal Fermi Systems.

# High-Momentum Scaling

- A(e,e') cross section ratios are sensitive to $n_A(k)/n_d(k)$.
- Observed scaling in $\sigma_A/\sigma_d$ for $x_B \geq 1.5$ implies that:

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




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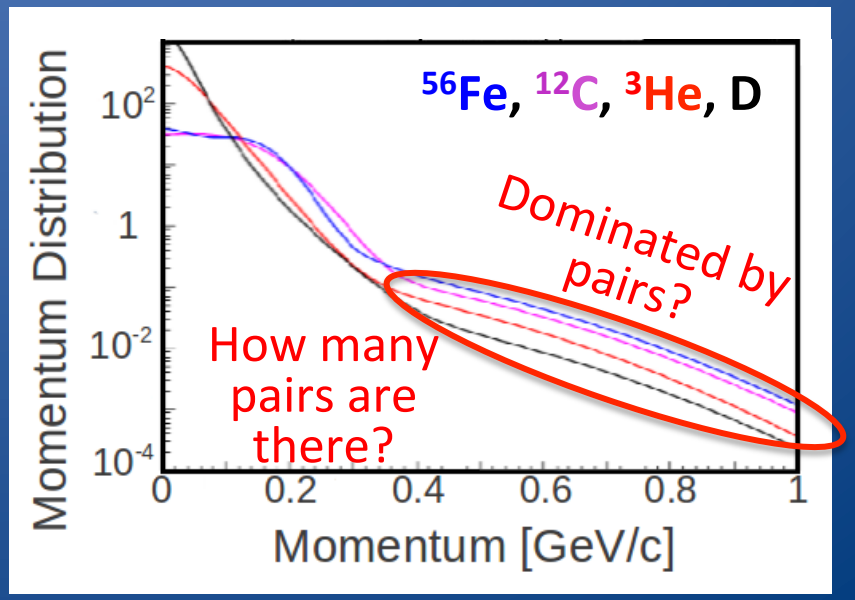


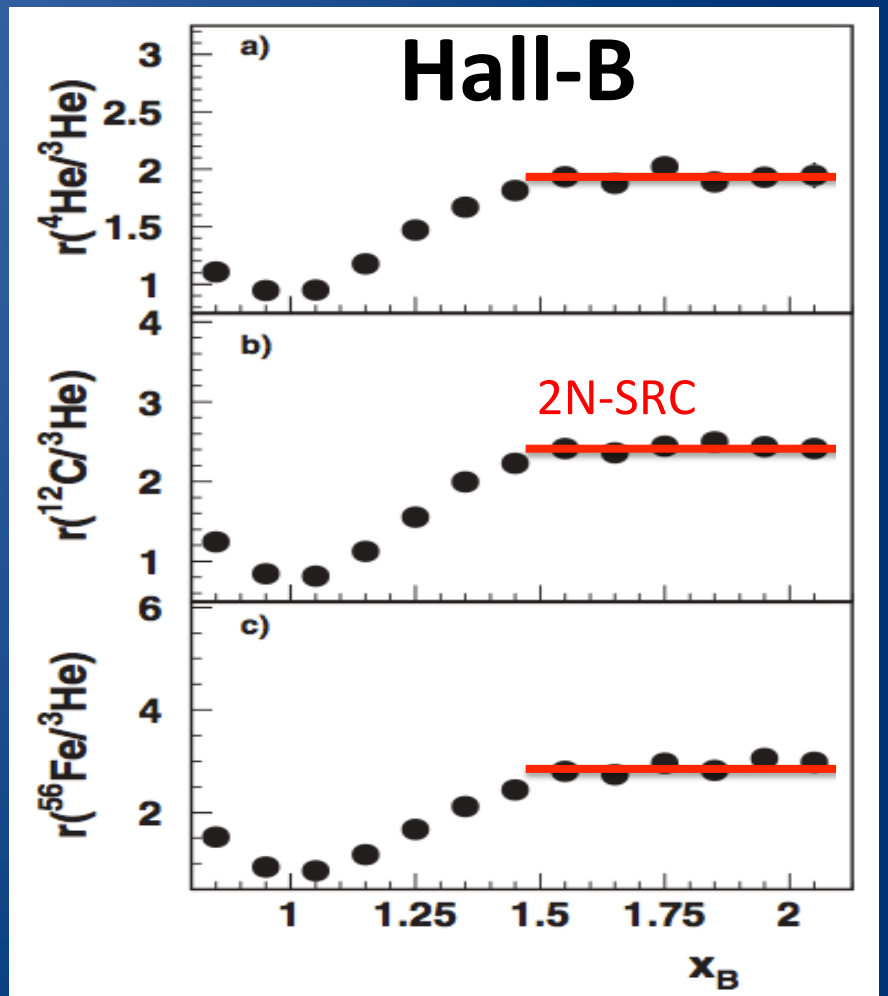


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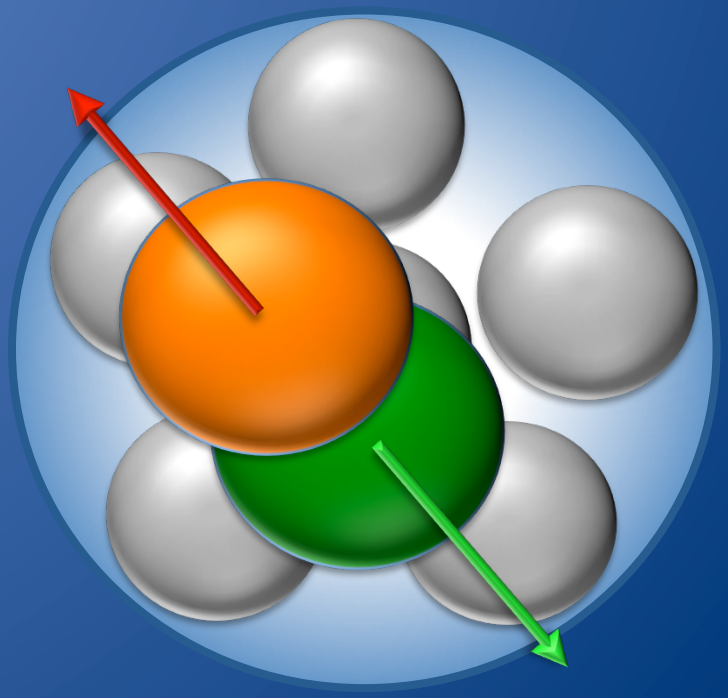
# Exclusive 2N-SRC Studies



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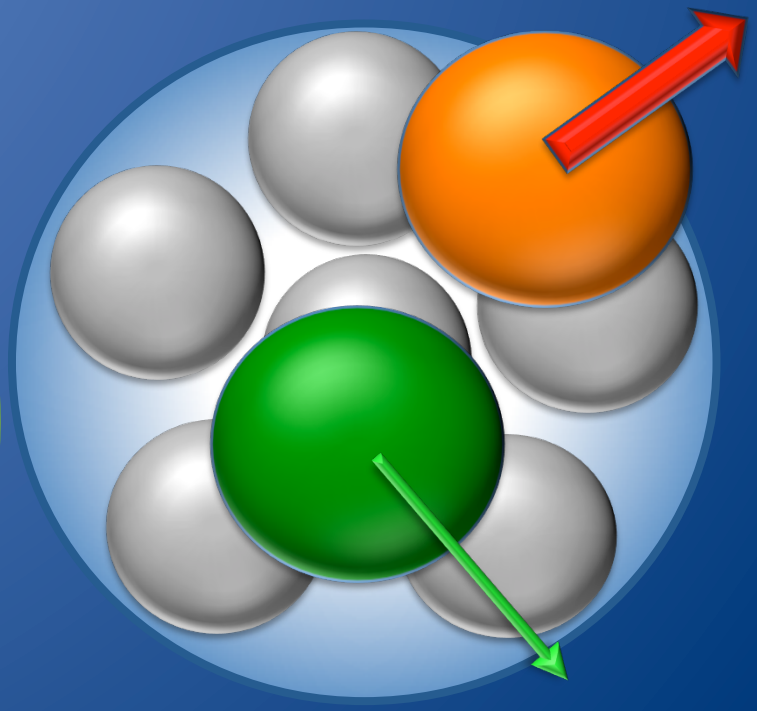

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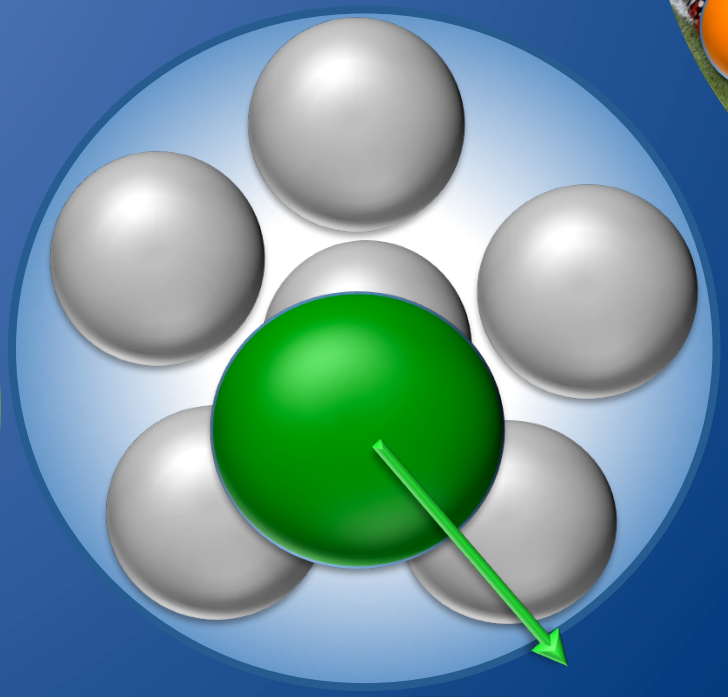

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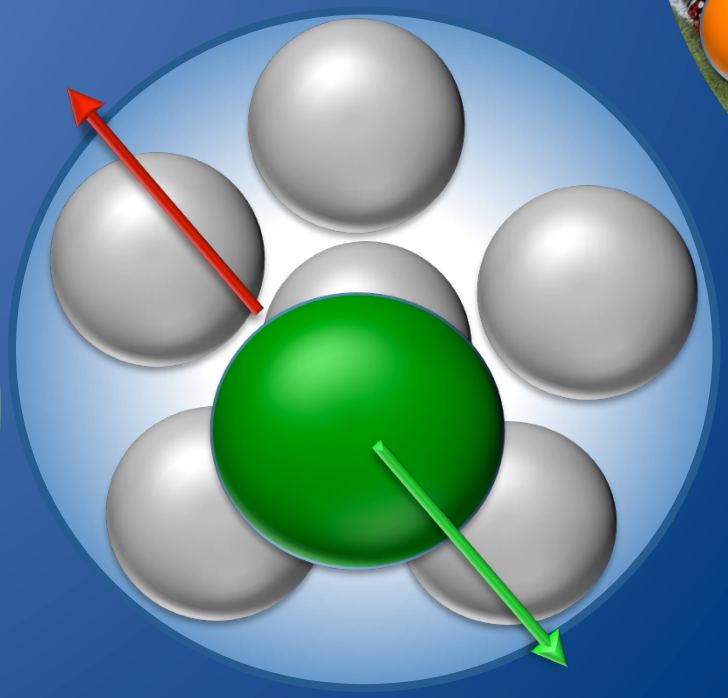

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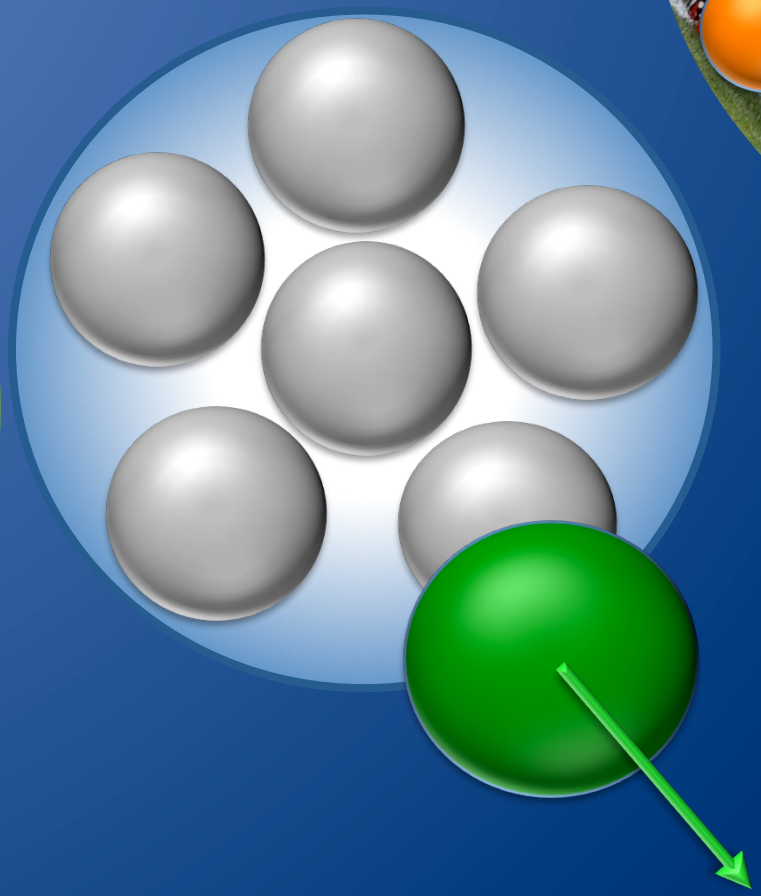

# Exclusive 2N-SRC Studies

FIFA WORLD CUP
Brasil

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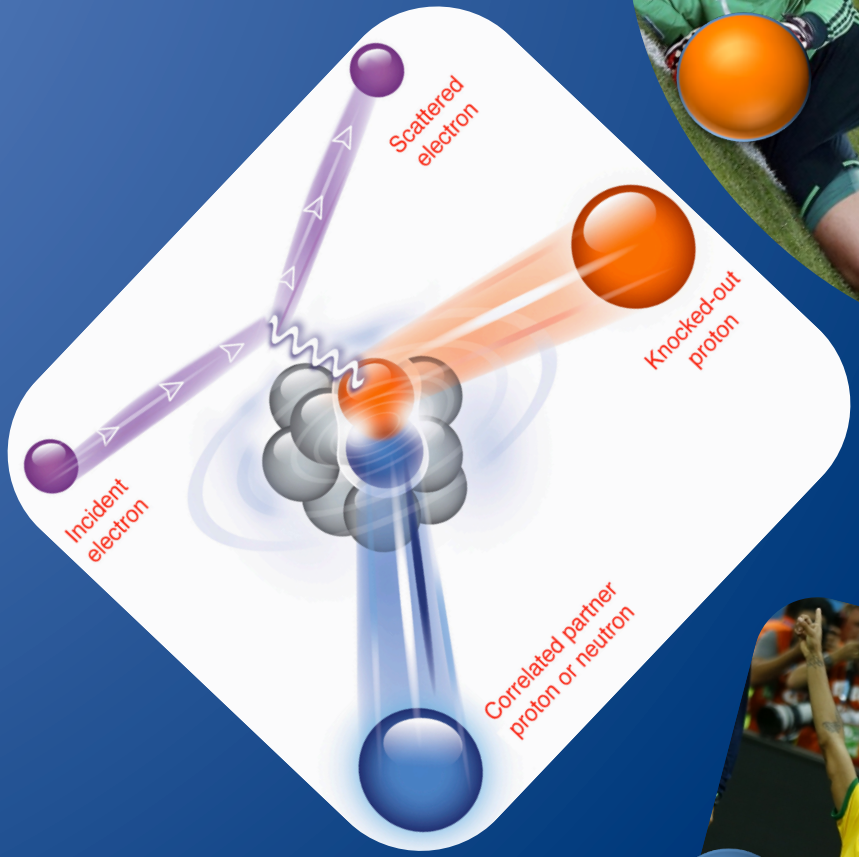
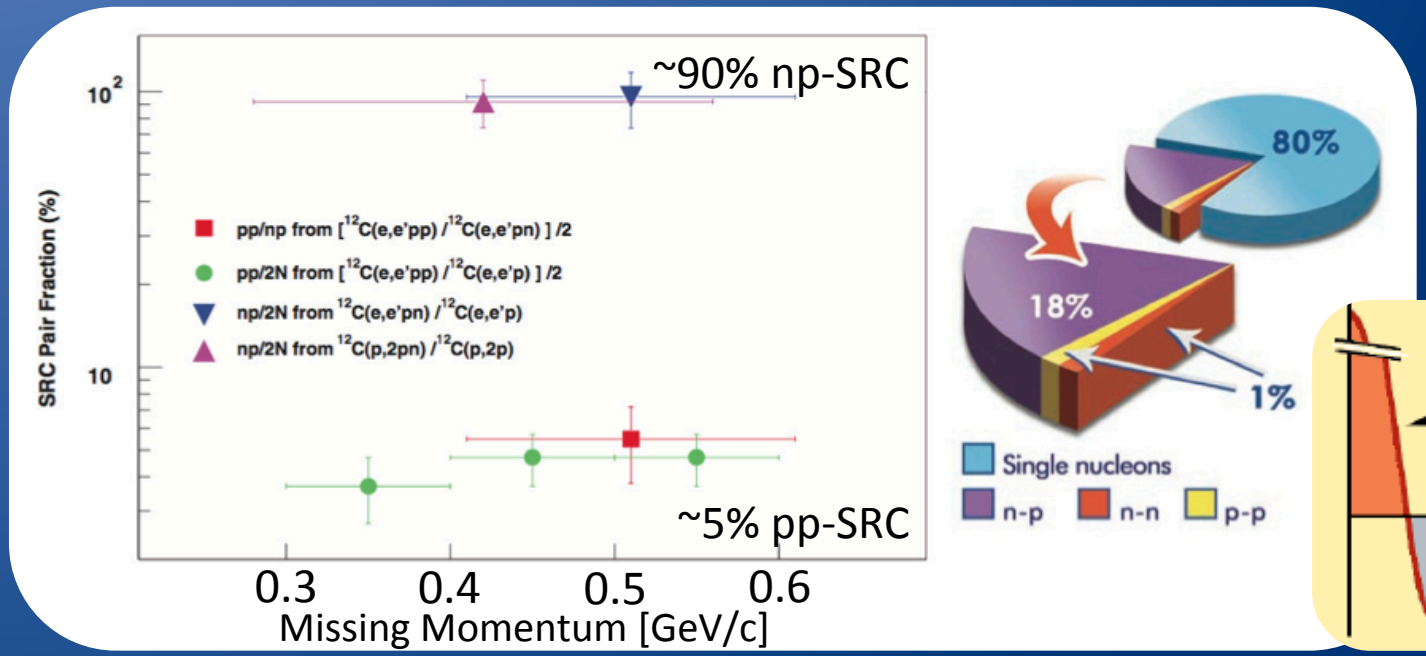



FIFA WORLD CUP Brasil

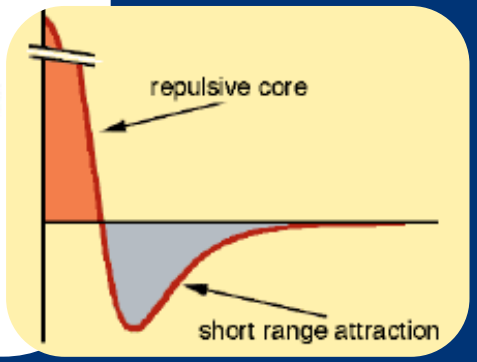
# $^{12}C(e,e'pN)$ Results

- Knockout high-initial-momentum proton, look for correlated nucleon partner.
- For $300 < P_{miss} < 600$ MeV/c all nucleons are part of 2N-SRC pairs: 90% np, 5% pp (nn).










A. Tang et al., Phys. Rev. Lett. 90 (2003) 042301
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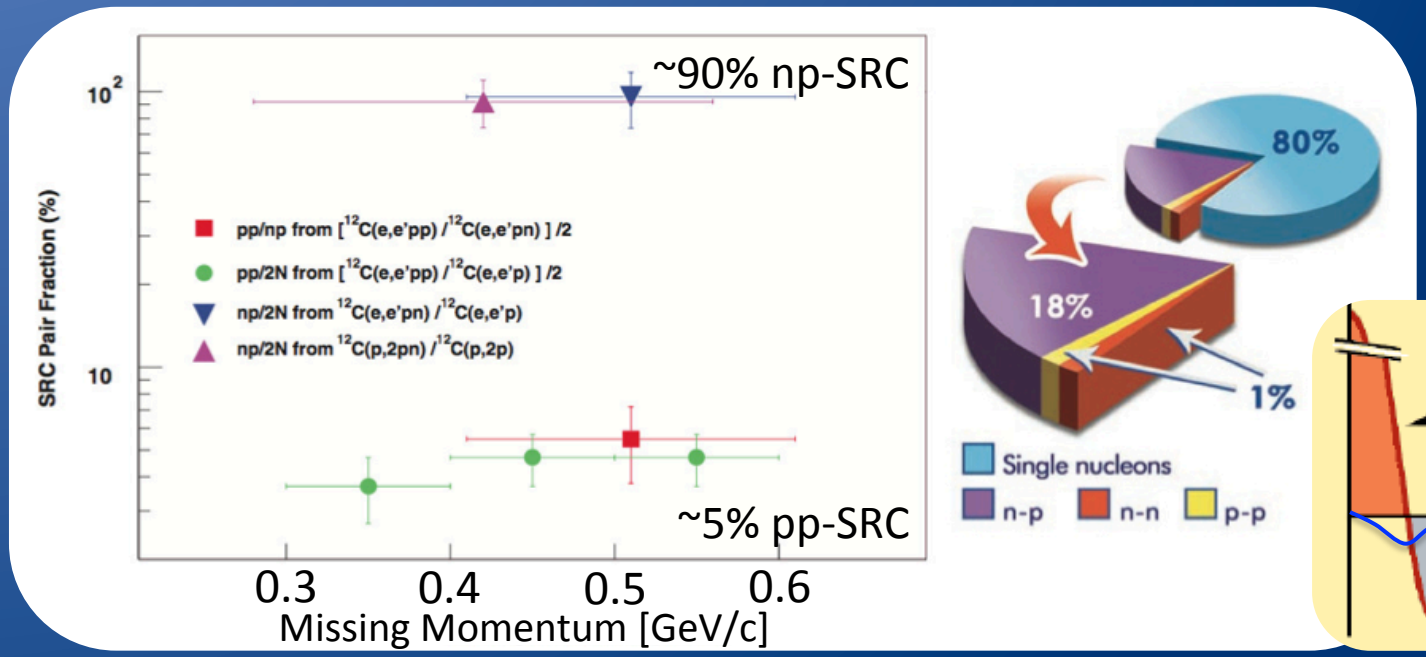





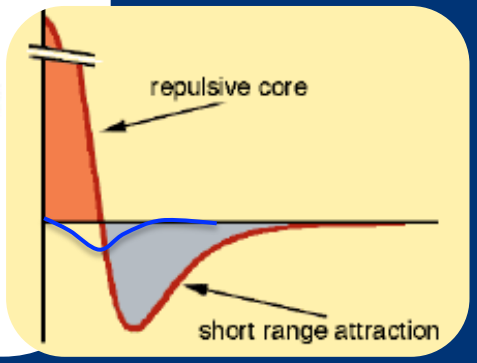


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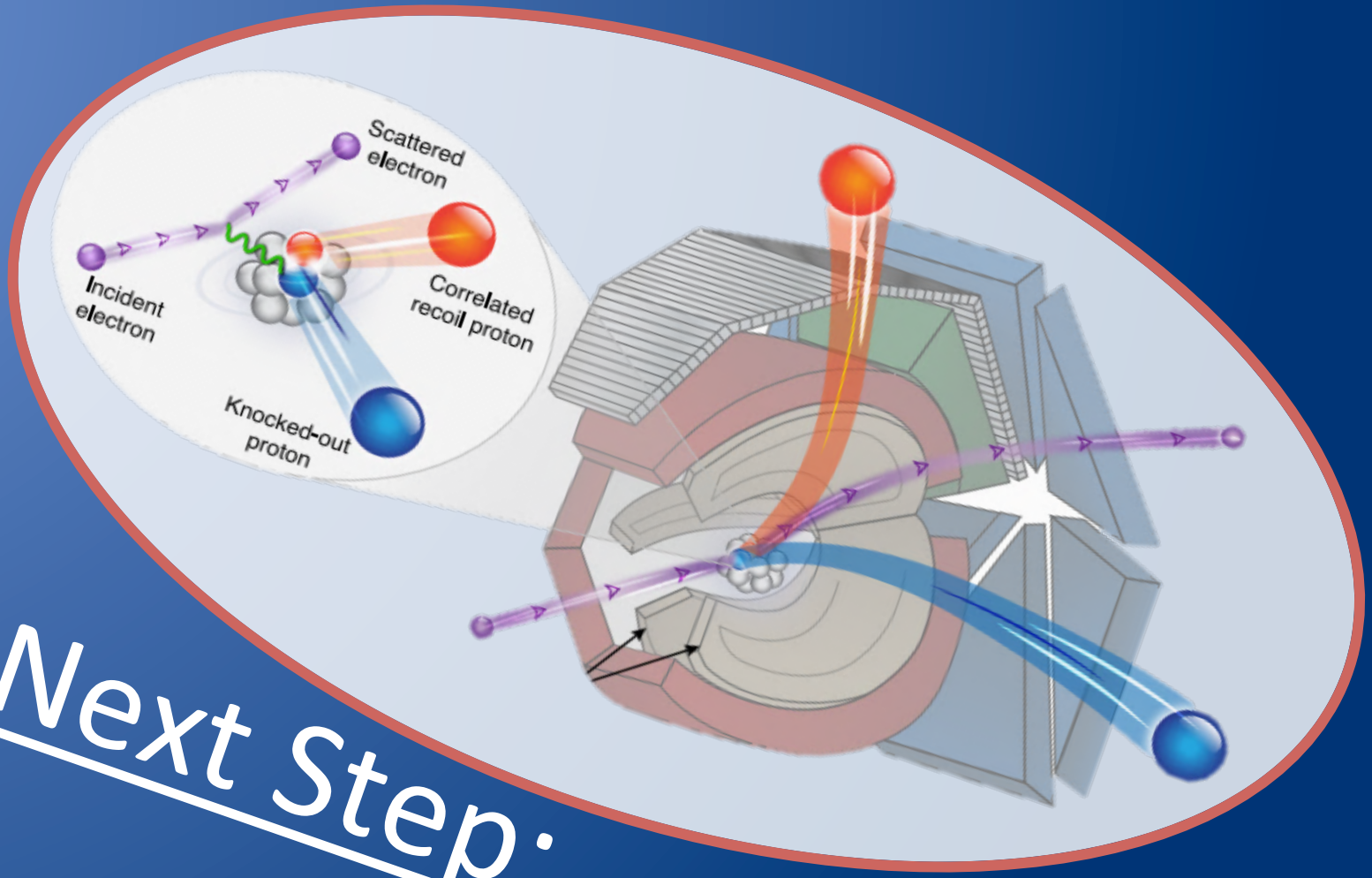
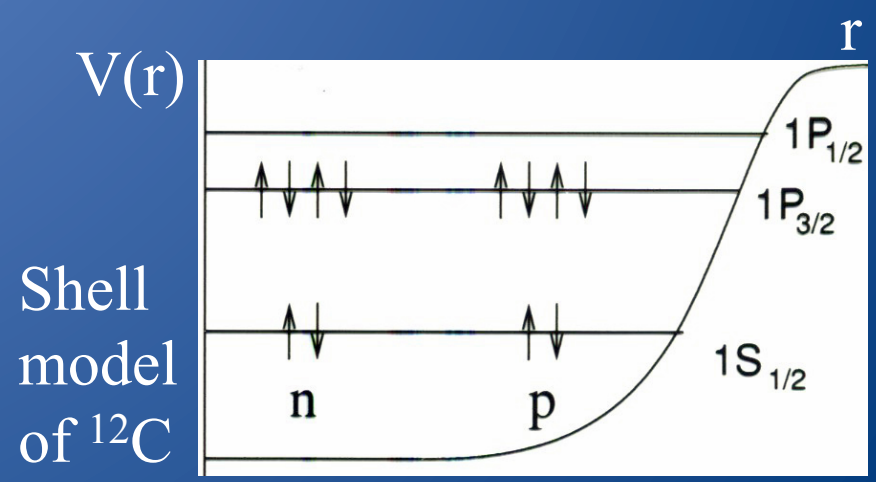



# The Next Step:

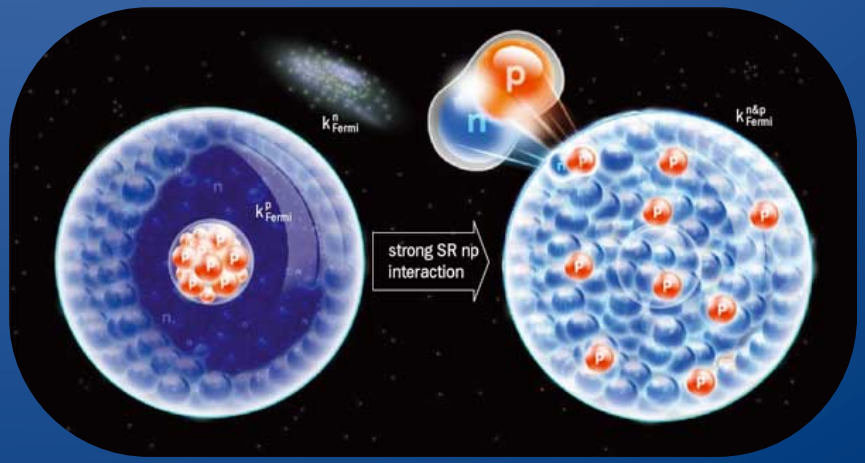
# Heavy Nuclei

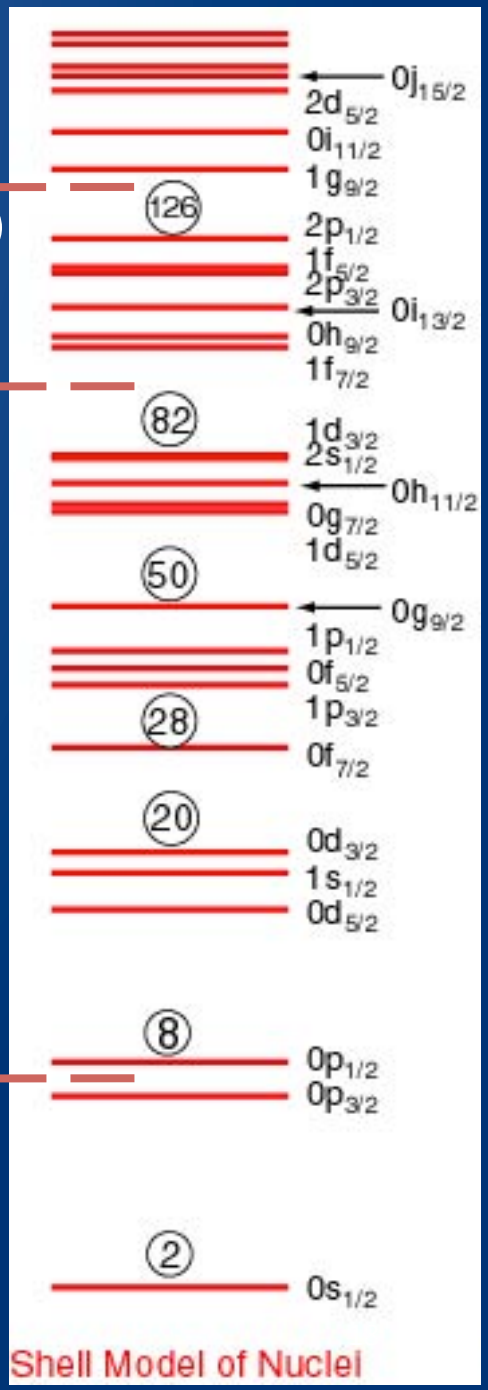
# Correlations in Heavy Nuclei

- Bridging the gap between light nuclei and neutron stars?
- General properties of Fermionic systems?

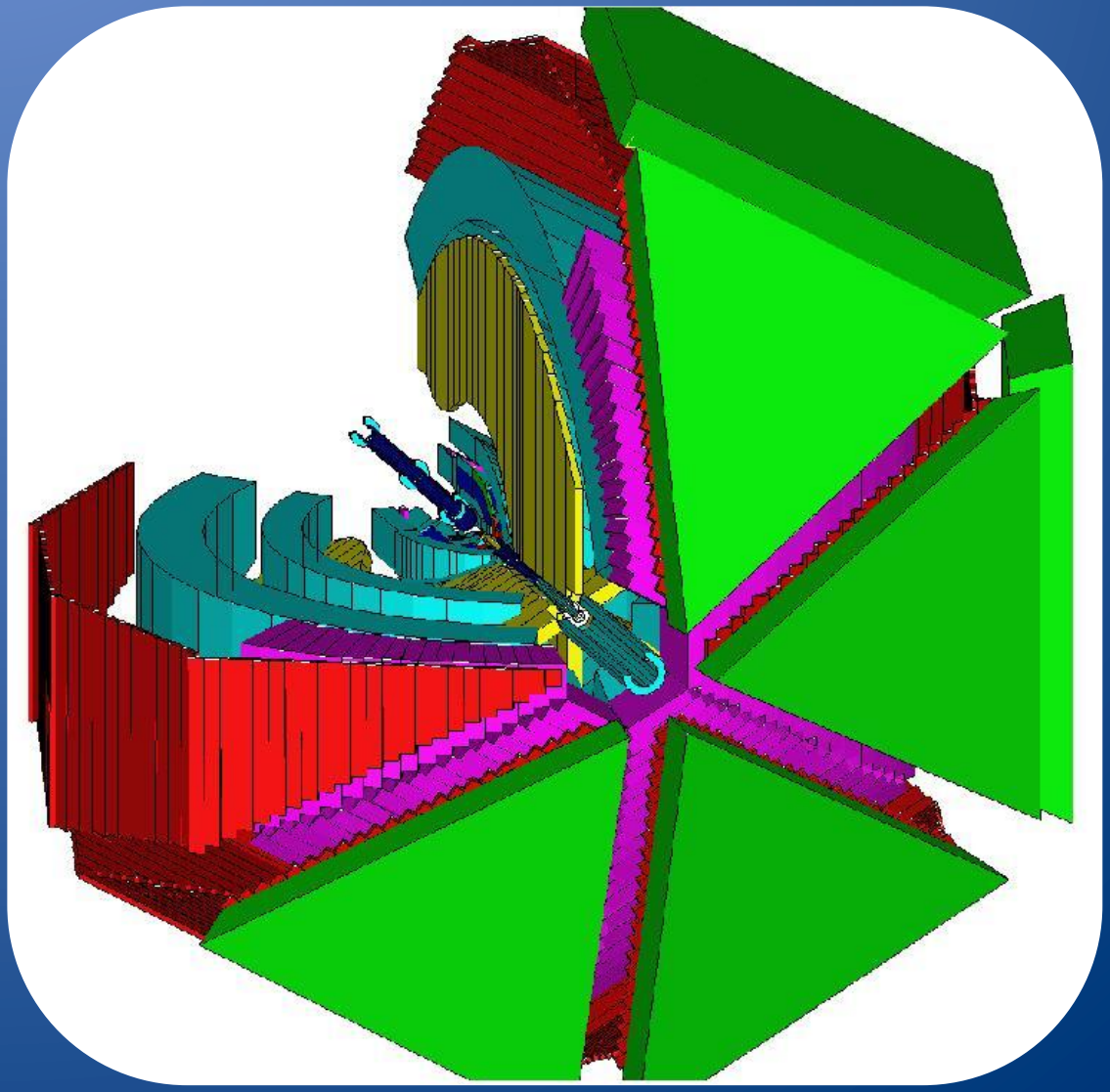



Shell model of $^{12}C$



# CEBAF Large Acceptance Spectrometer *[CLAS]*



Hall B Large Acceptance Spectrometer

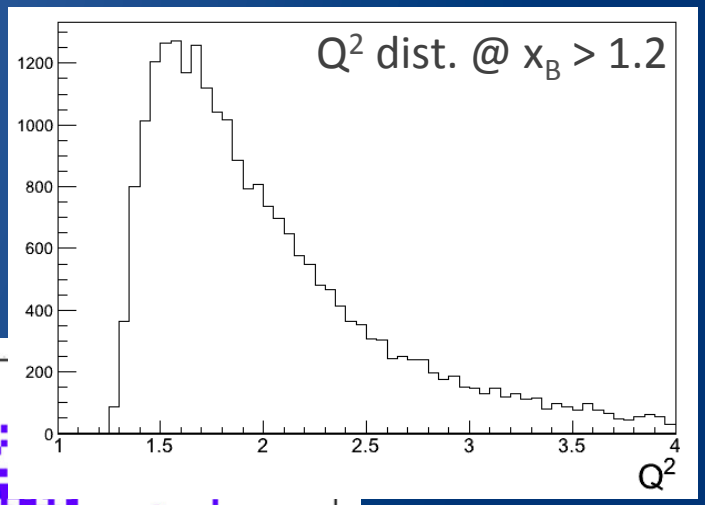
Open (e,e’) trigger, Large-Acceptance, Low luminosity (~$10^{34}$ $cm^{-2}$ $sec^{-1}$)

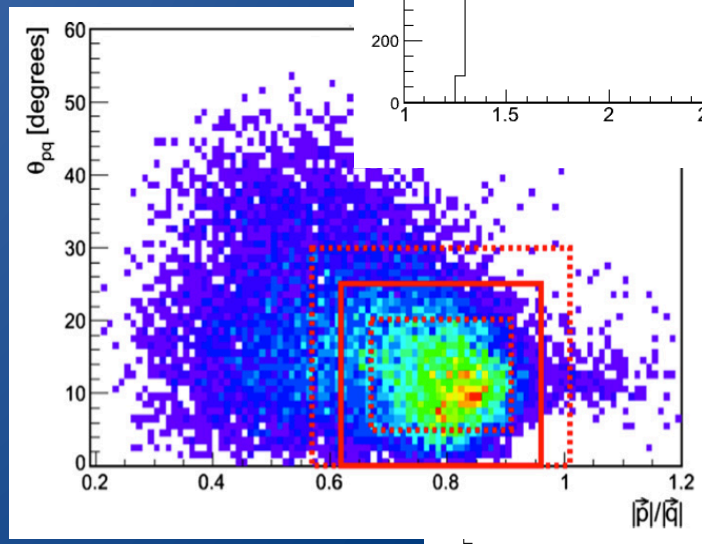
# Mining CLAS Data for SRCs

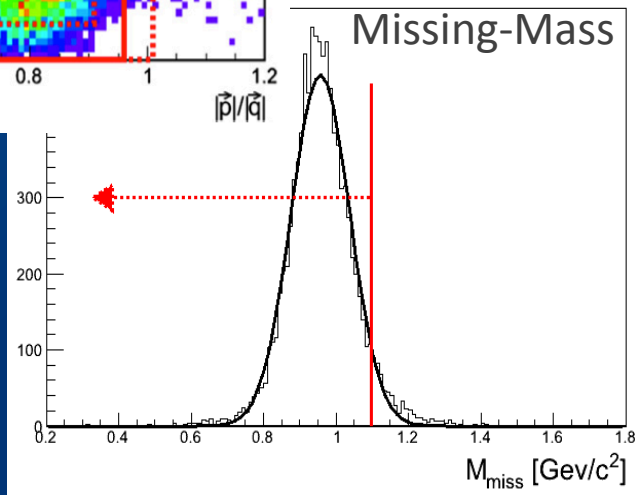
## Reanalyzed existing CLAS data via a data-mining initiative

5 GeV electrons on $^{12}C$, $^{27}Al$, $^{56}Fe$, and $^{208}Pb$:

1. Cut (e,e'p) kinematics to simulate previous measurements*.
2. Look for a correlated recoil proton.



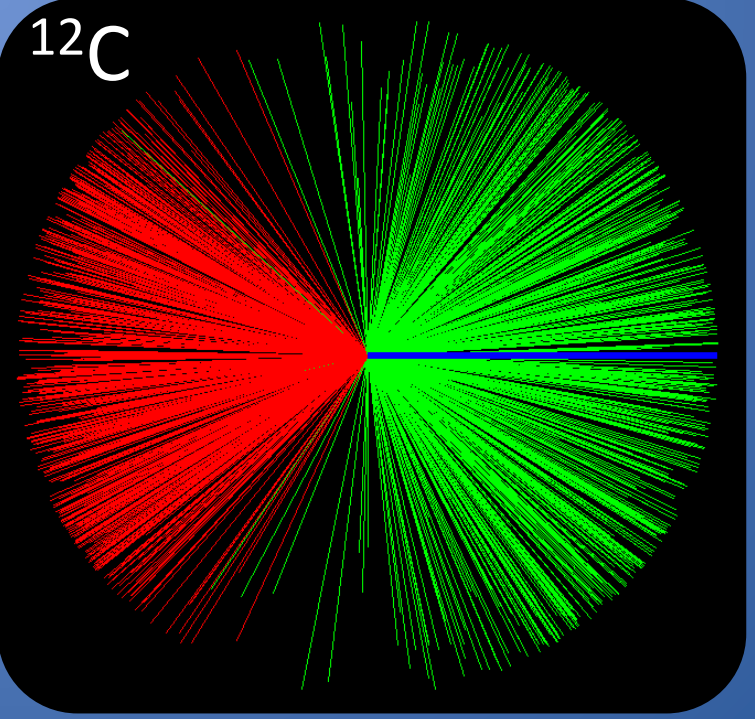



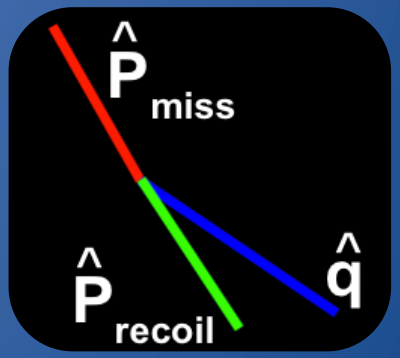



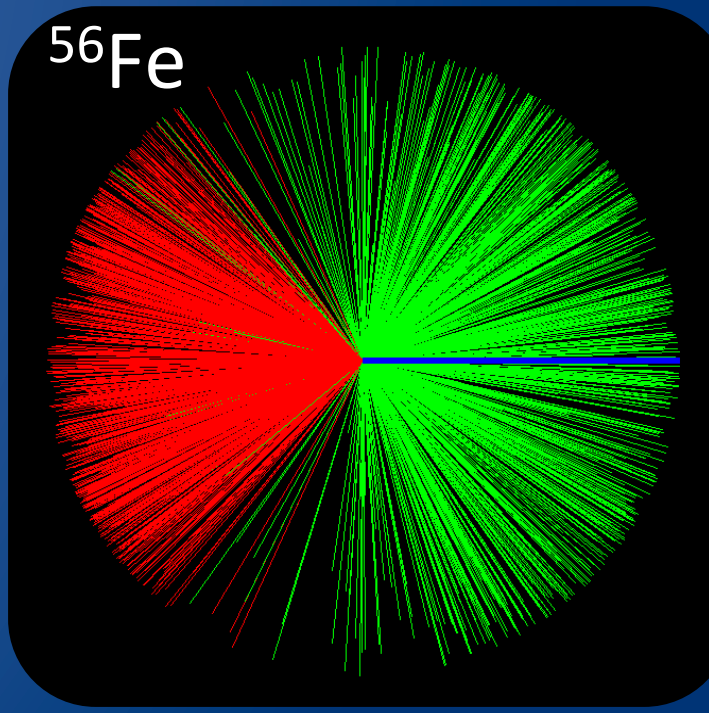

O. Hen et al. (CLAS Collaboration), Phys. Lett. B **772**, 63 (2013)

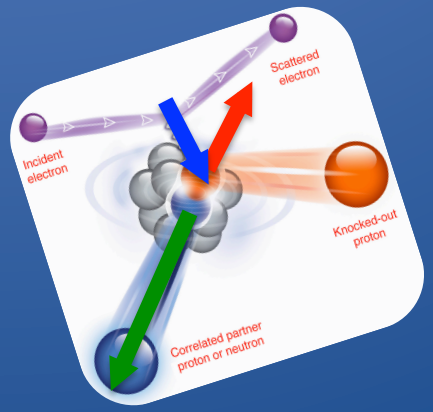
*Quasielstic knockout of high-initial-momentum protons

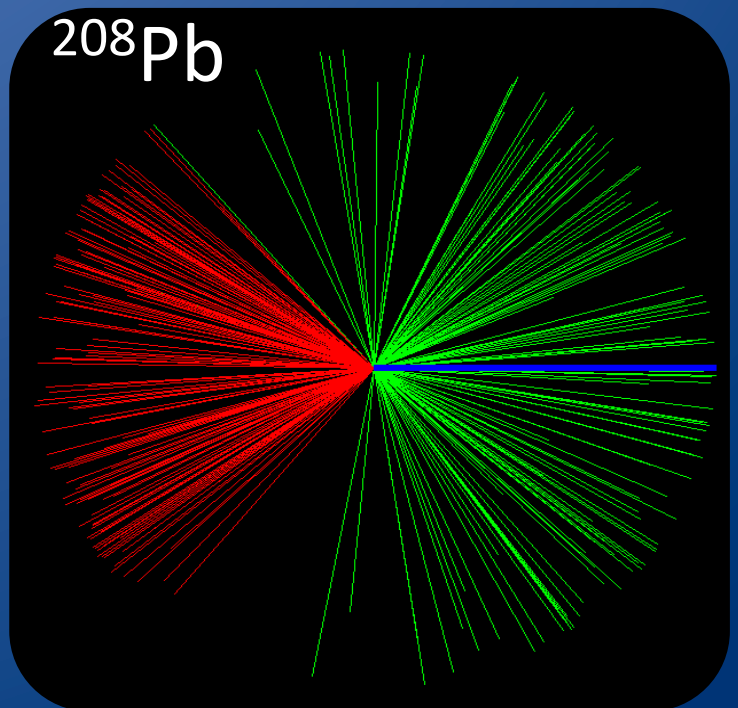
# 3D Reconstruction

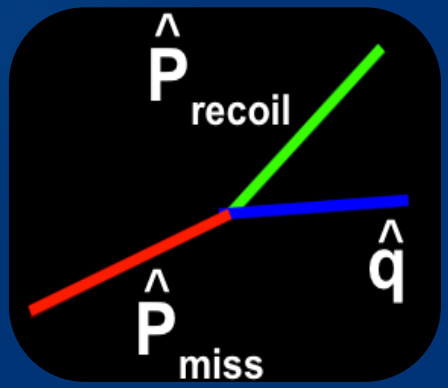


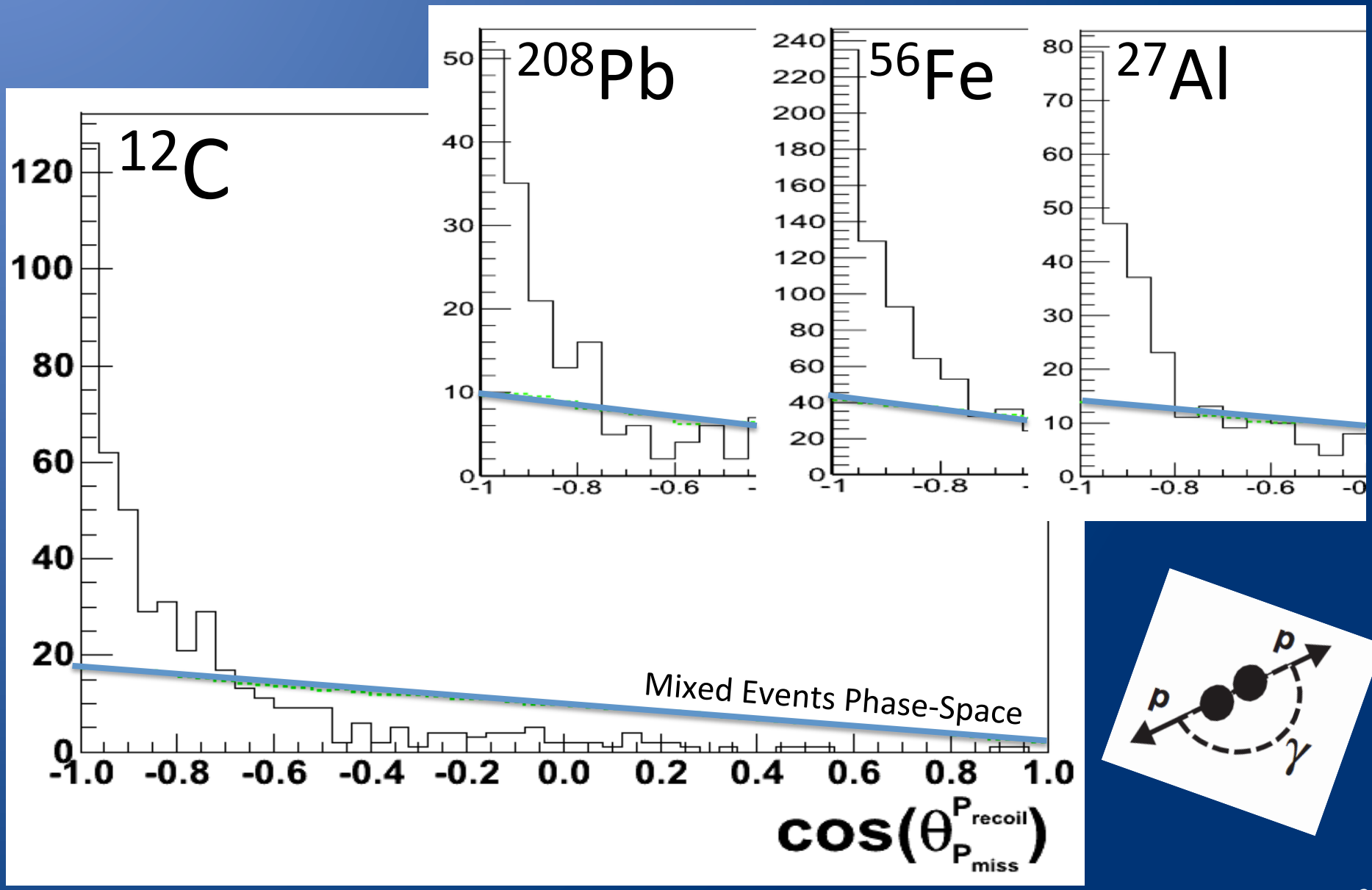




Back-to-back

= pairs!

# Opening angle



# Sensitivity to SRCs

Assuming scattering off 2N-SRC pairs:

- (e,e'p) is sensitive to *np* and *pp* pairs
- (e,e'pp) is sensitive to *pp* pairs alone

=> (e,e'pp)/(e,e'p) ratio is sensitive to the *np*/*pp* ratio

$$A(e,e'pp) \propto \# pp_A \cdot 2\sigma_p$$

$$A(e,e'p) \propto \# pp_A \cdot 2\sigma_p + \# pn_A \cdot \sigma_p$$

$$= \# pp_A \cdot 2\sigma_p \left[ 1 + \frac{1}{2} \frac{\# pn_A}{\# pp_A} \right]$$

$$\Rightarrow \frac{\# np_A}{\# pp_A} = 2 \cdot \left[ \frac{A(e,e'p)}{A(e,e'pp)} - 1 \right]$$

Assuming No FSI

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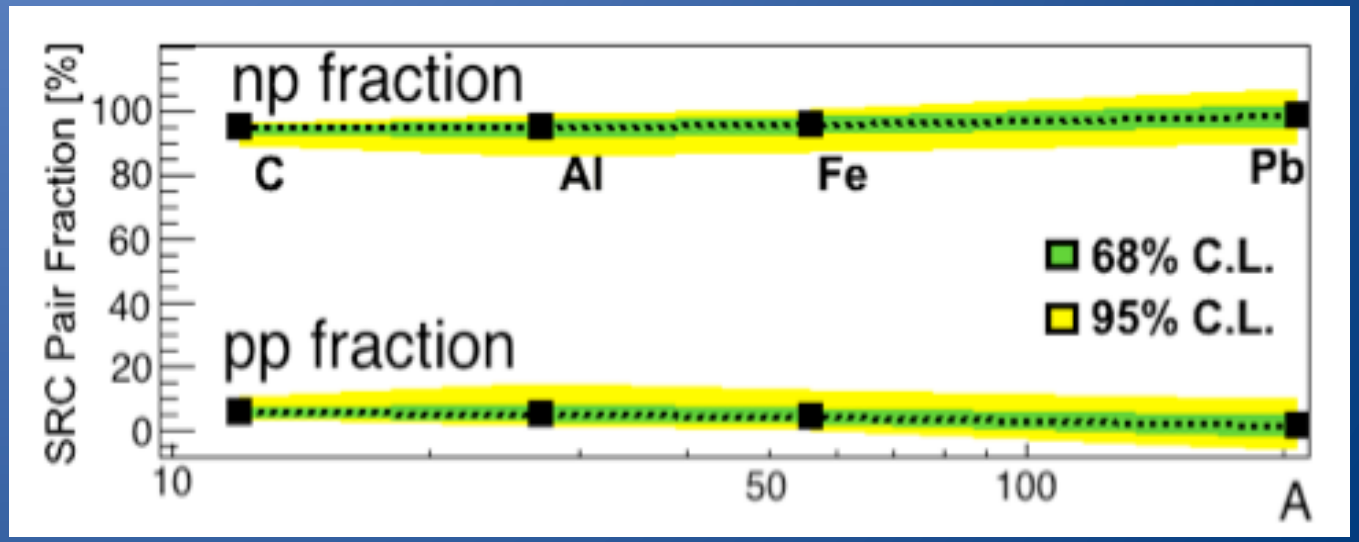
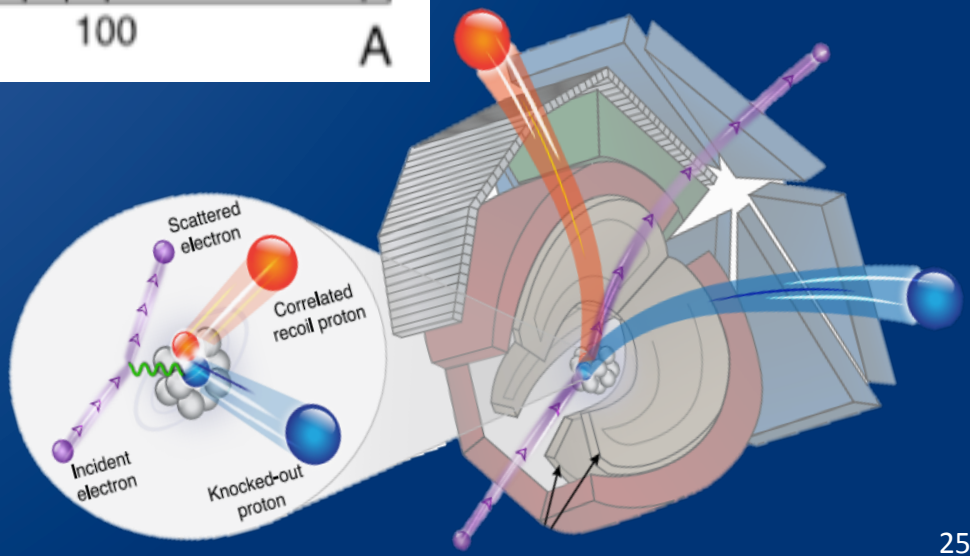
Corrected for Final-State Interactions (FSI) on the outgoing nucleon

(Attenuation and Single-Charge Exchange.)

O. Hen et al. (CLAS Collaboration), Phys. Lett. B **772**, 63 (2013)

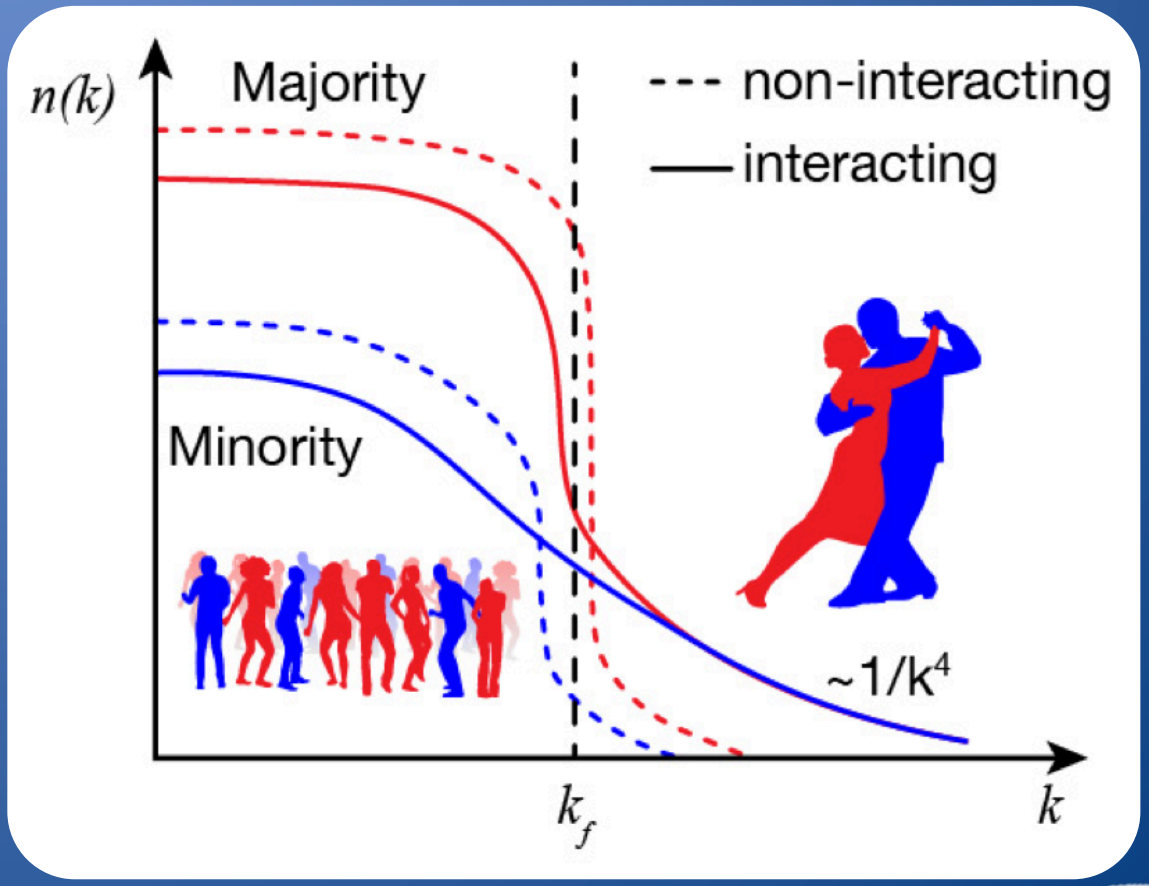
# np-pairs also dominate SRC in *heavy asymmetric* nuclei



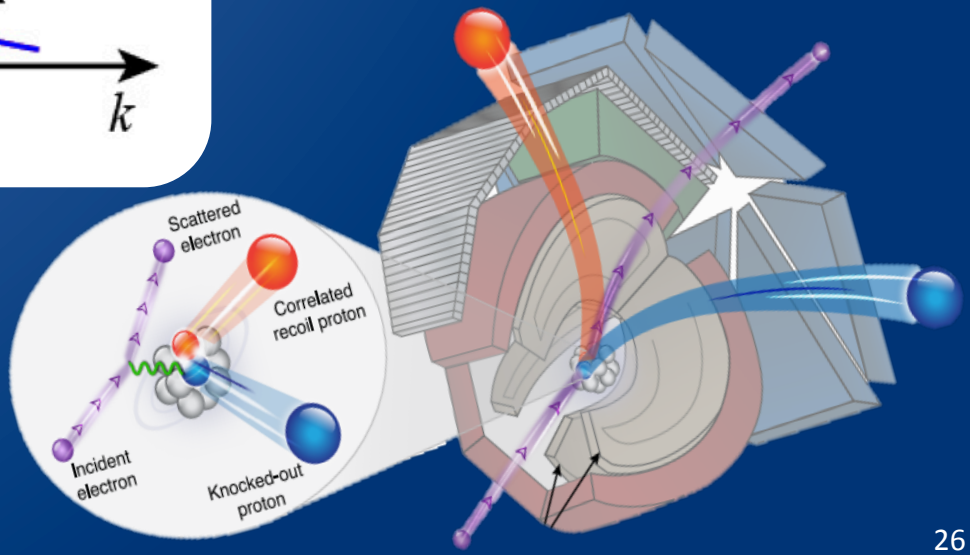




O. Hen et al. (CLAS Collaboration), Science 346, 614 (2014)

# Kinetic Energy Sharing in Asymmetric Nuclei




**Momentum distribution of imbalanced two-component Fermi system**




O. Hen et al. (CLAS Collaboration), Science 346, 614 (2014)

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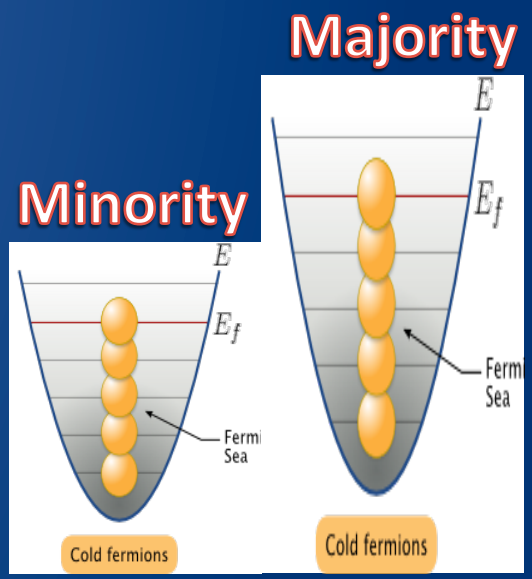
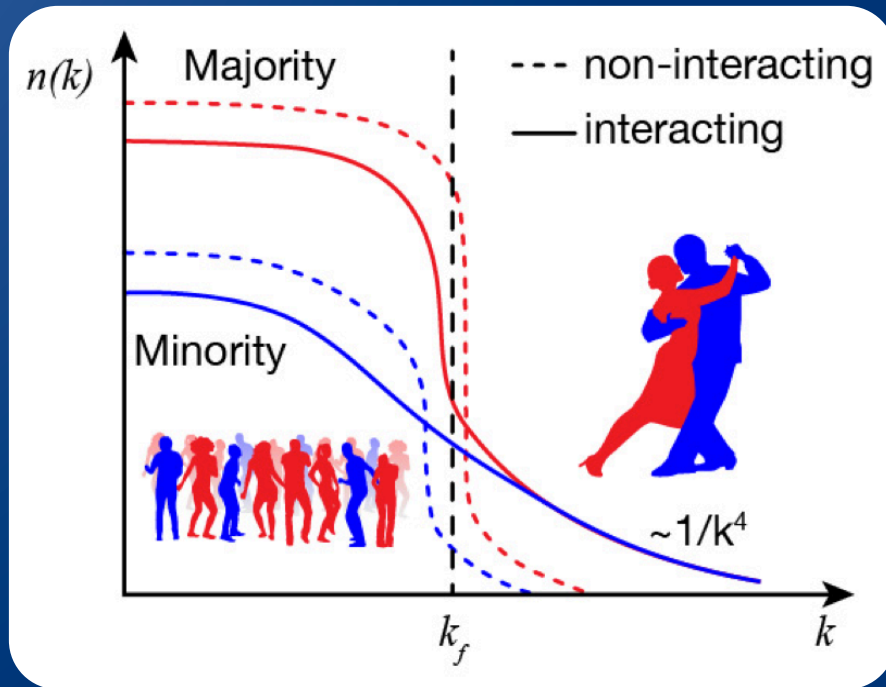
Pauli Principle:

***Majority (neutrons)*** fermions move faster (higher Fermi momentum)

np correlations:

***Minority (protons)*** fermions move faster (greater pairing probability)



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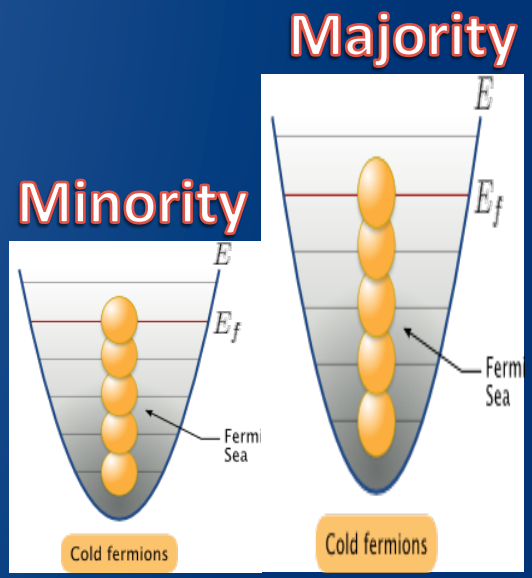
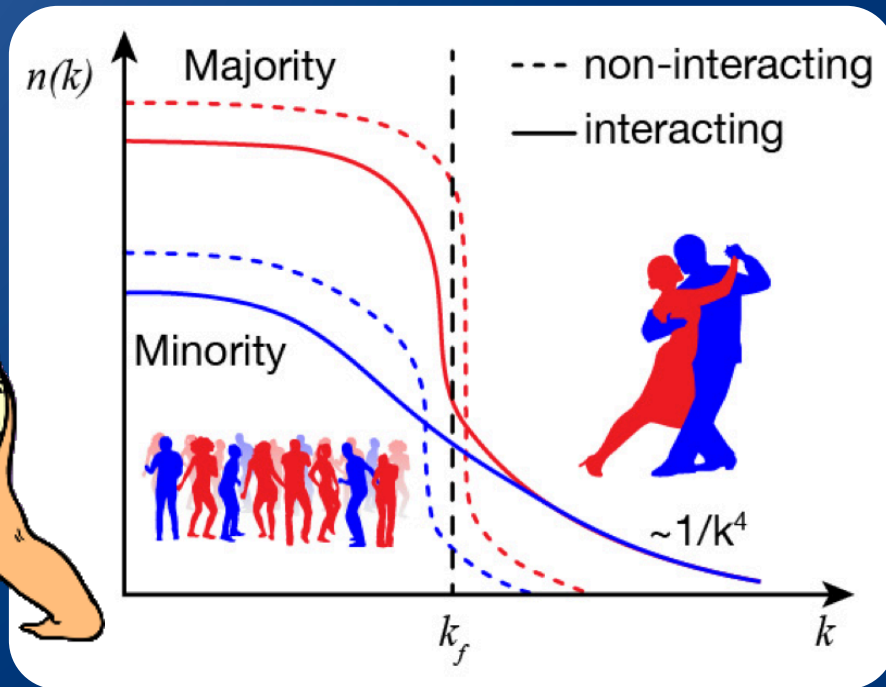
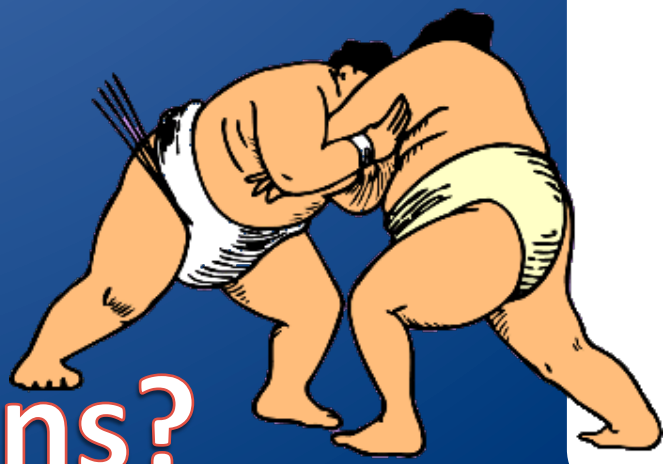


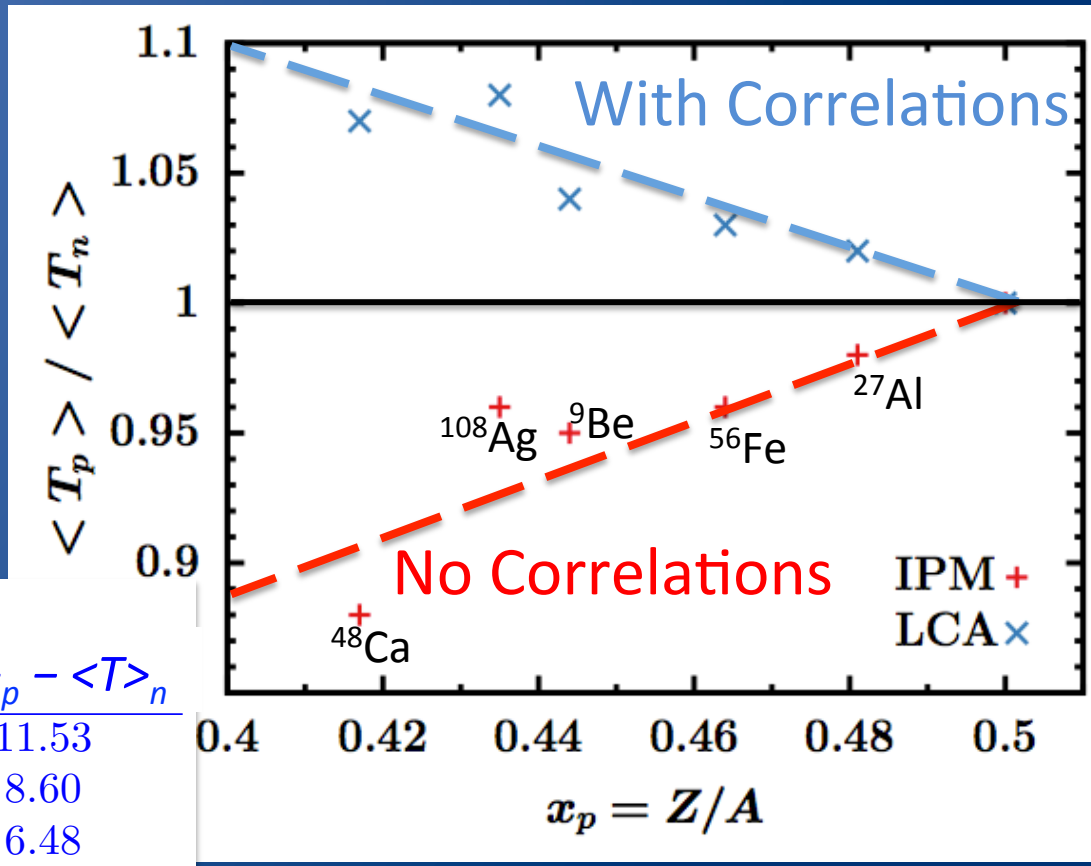



# Who wins?

# Calculations *Predict* Correlations Wins

$\langle T \rangle_{Minority} \geq \langle T \rangle_{Majority}$



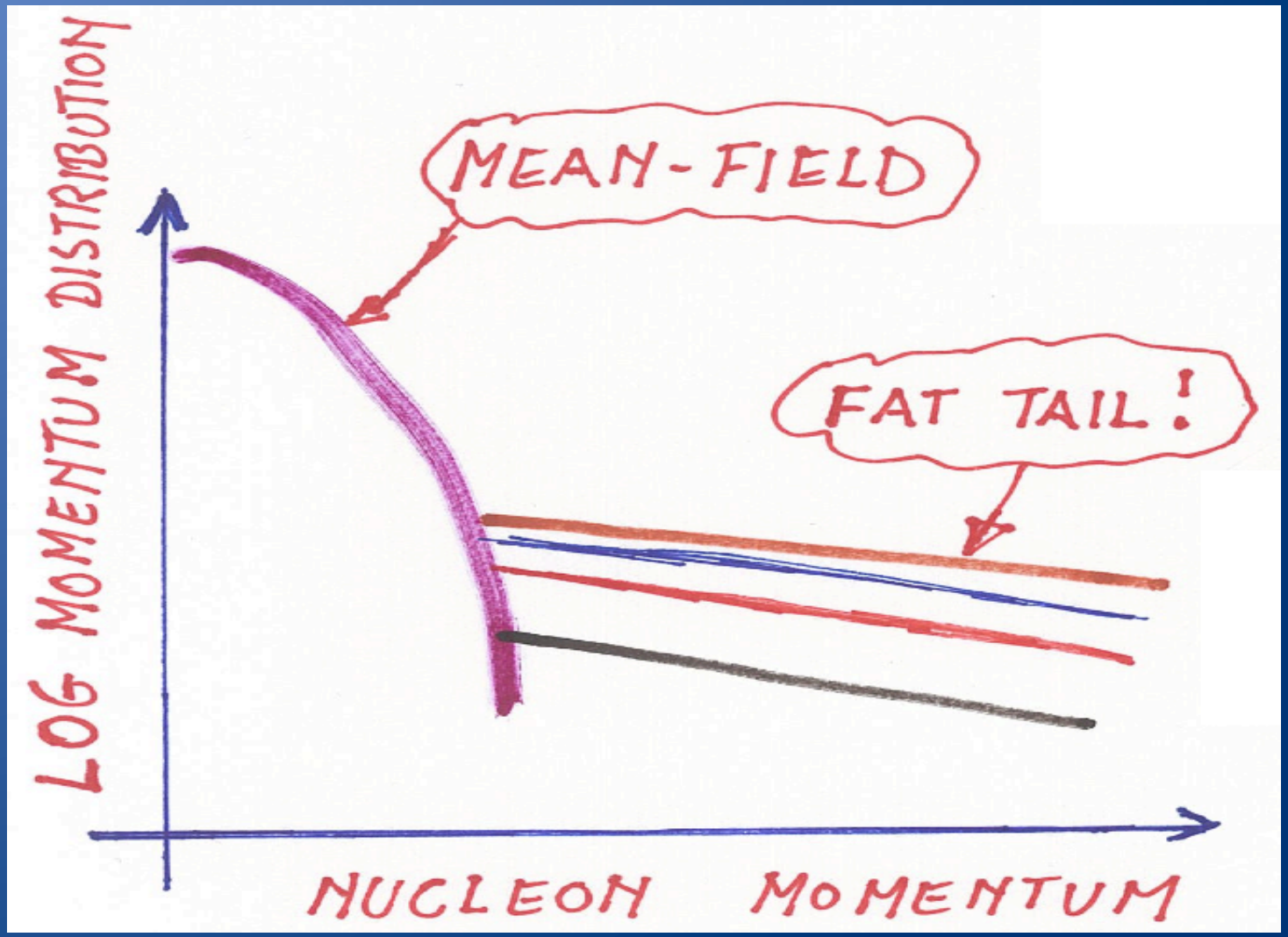

Light Nuclei (A<12)

| | $\frac{\lvert N-Z \rvert}{A}$ | $\langle T \rangle_p$ | $\langle T \rangle_n$ | $\langle T \rangle_p - \langle T \rangle_n$ |
|---|---|---|---|---|
| $^{8}$He | 0.50 | 30.13 | 18.60 | 11.53 |
| $^{6}$He | 0.33 | 27.66 | 19.06 | 8.60 |
| $^{9}$Li | 0.33 | 31.39 | 24.91 | 6.48 |
| $^{3}$He | 0.33 | 14.71 | 19.35 | -4.64 |
| $^{3}$H | 0.33 | 19.61 | 14.96 | 4.65 |
| $^{8}$Li | 0.25 | 28.95 | 23.98 | 4.97 |
| $^{10}$Be | 0.2 | 30.20 | 25.95 | 4.25 |
| $^{7}$Li | 0.14 | 26.88 | 24.54 | 2.34 |
| $^{9}$Be | 0.11 | 29.82 | 27.09 | 2.73 |
| $^{11}$B | 0.09 | 33.40 | 31.75 | 1.65 |

Heavy Nuclei (27<A<108):
M. Vanhalst, W. Cosyn, and J. Ryckebusch, arXiv: 1405.3814.

VMC Calculations: R. Wiringa et al., Phys. Rev. C **89**, 024305 (2013)

# Intermediate summary: Universal structure of nuclei



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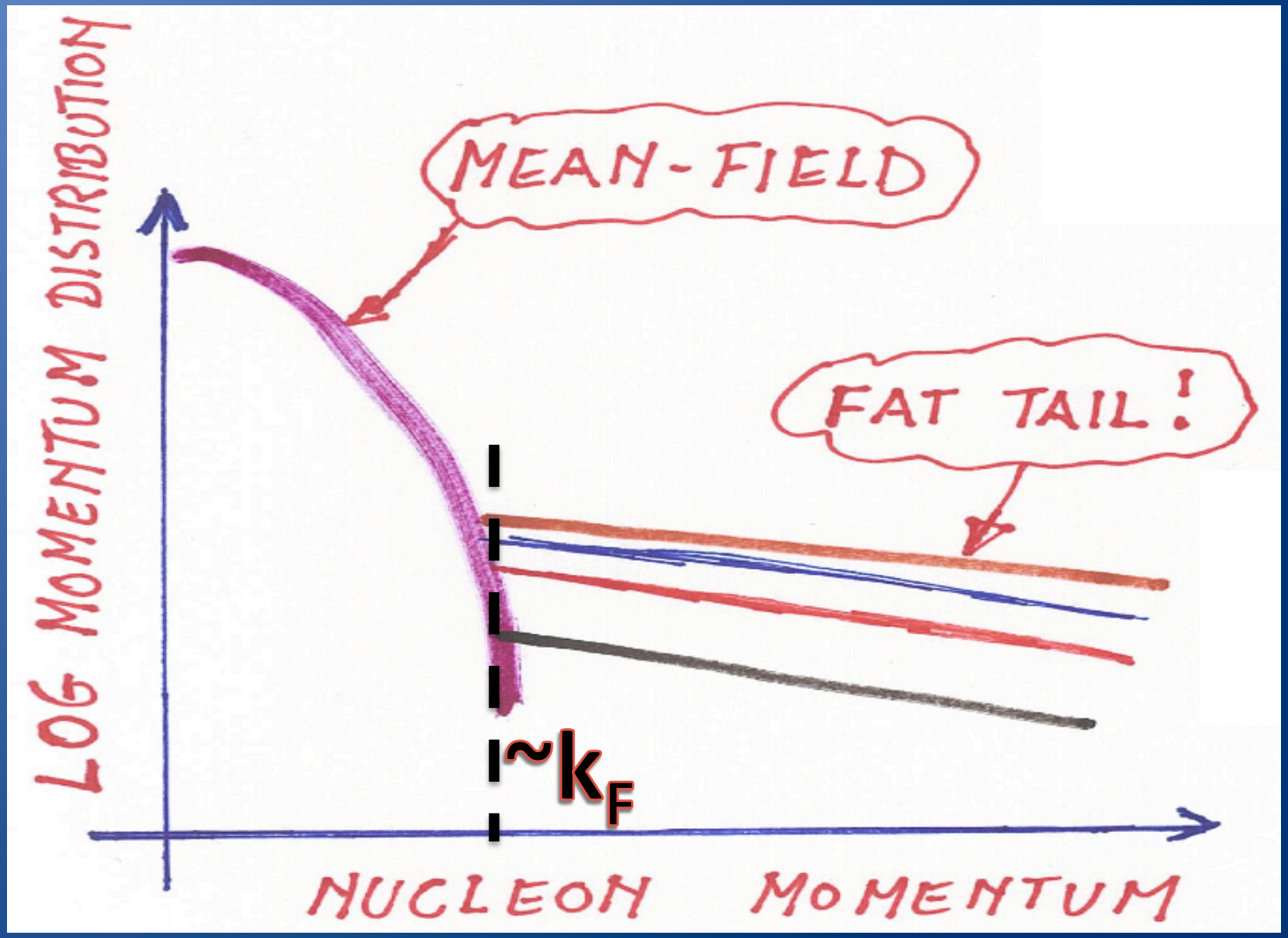

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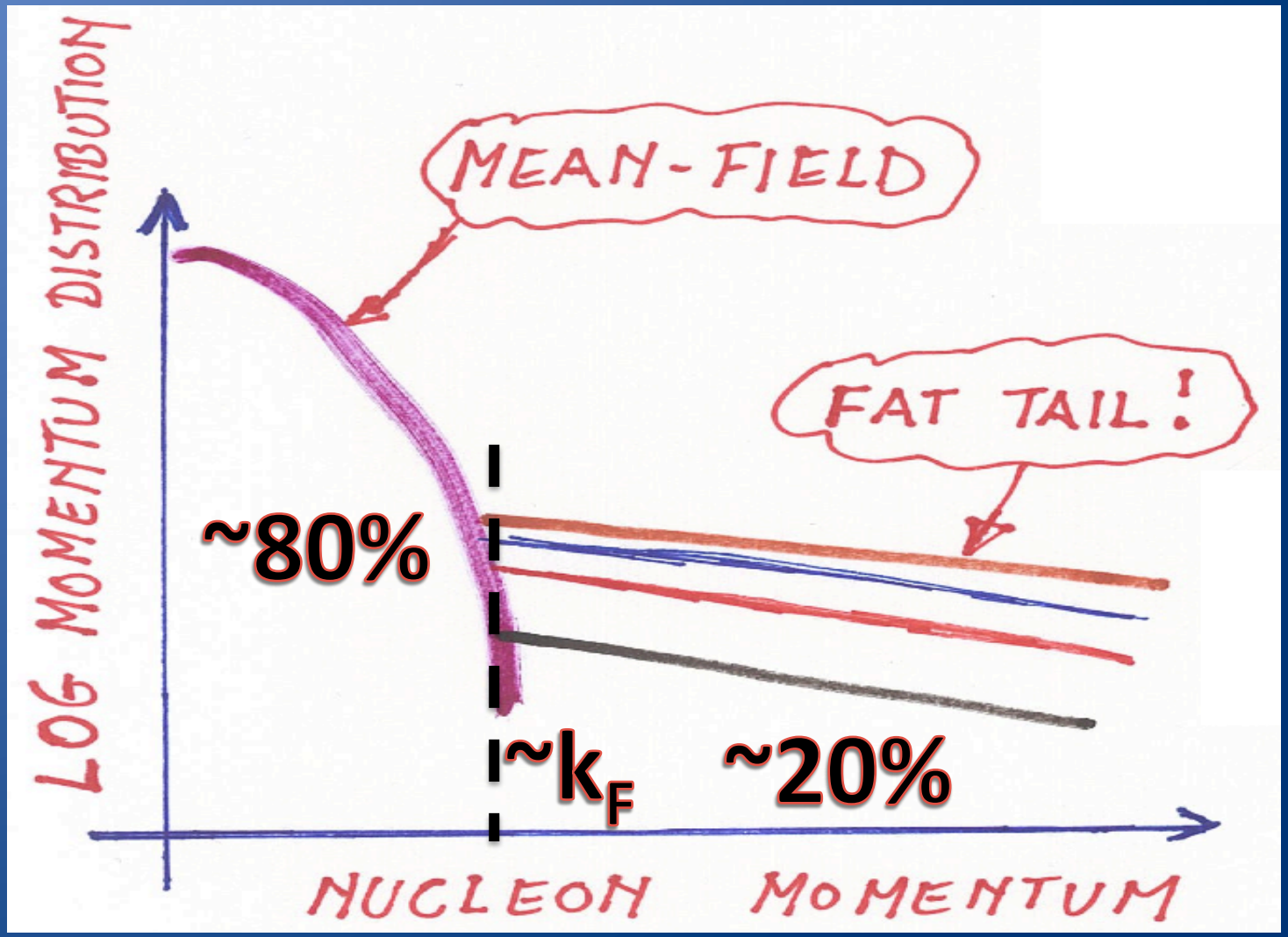
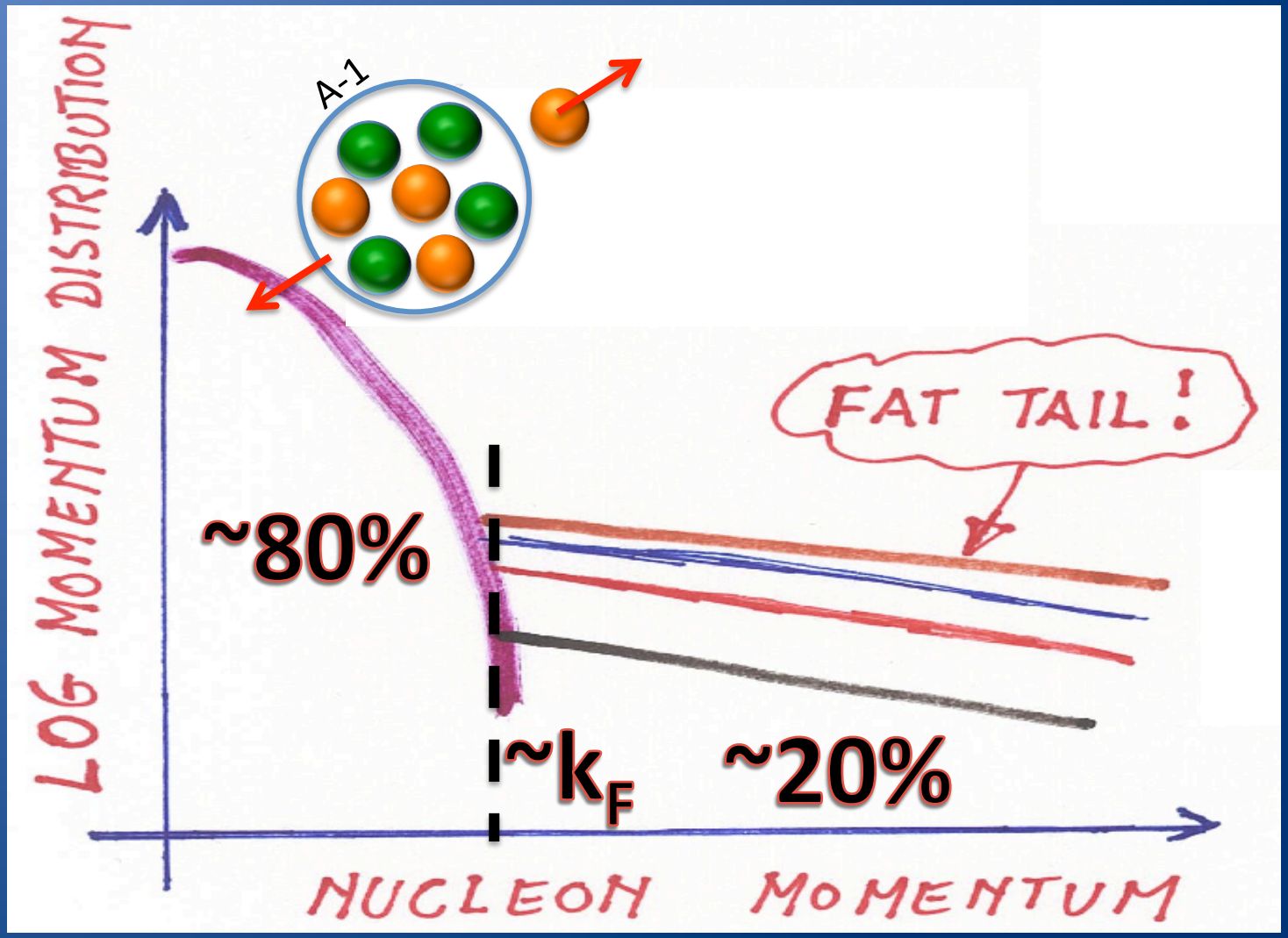


# Intermediate summary: Universal structure of nuclei



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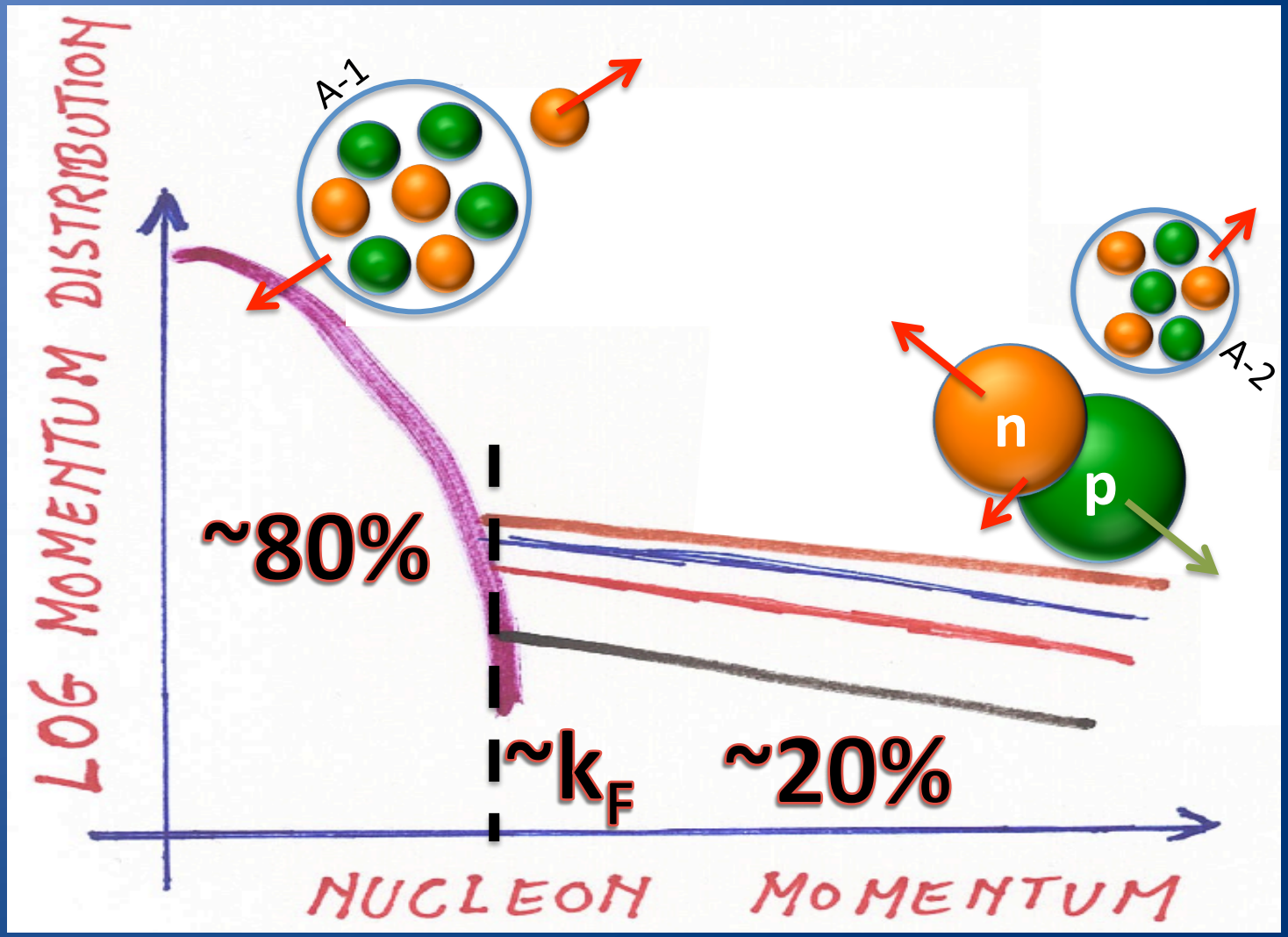

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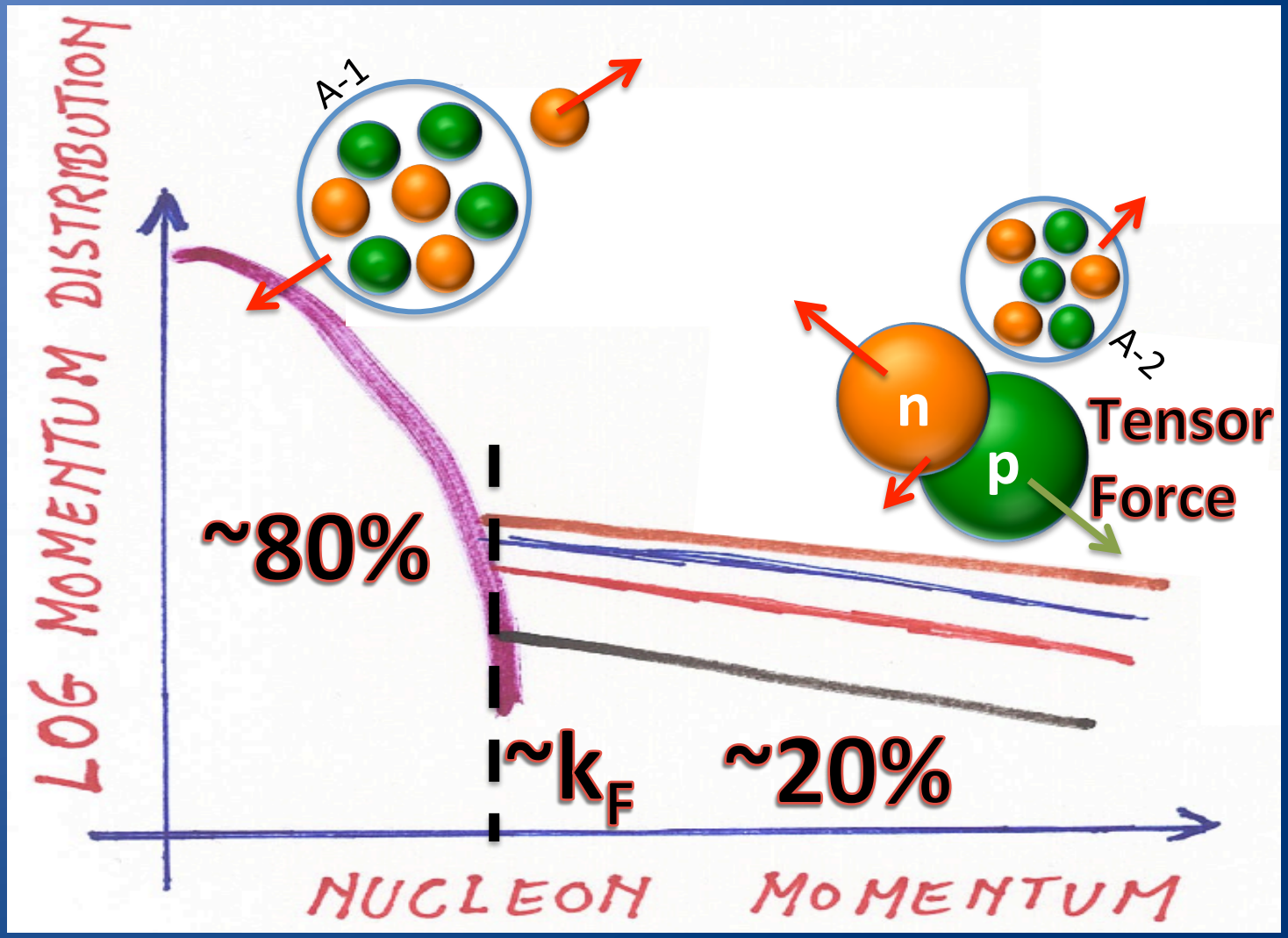

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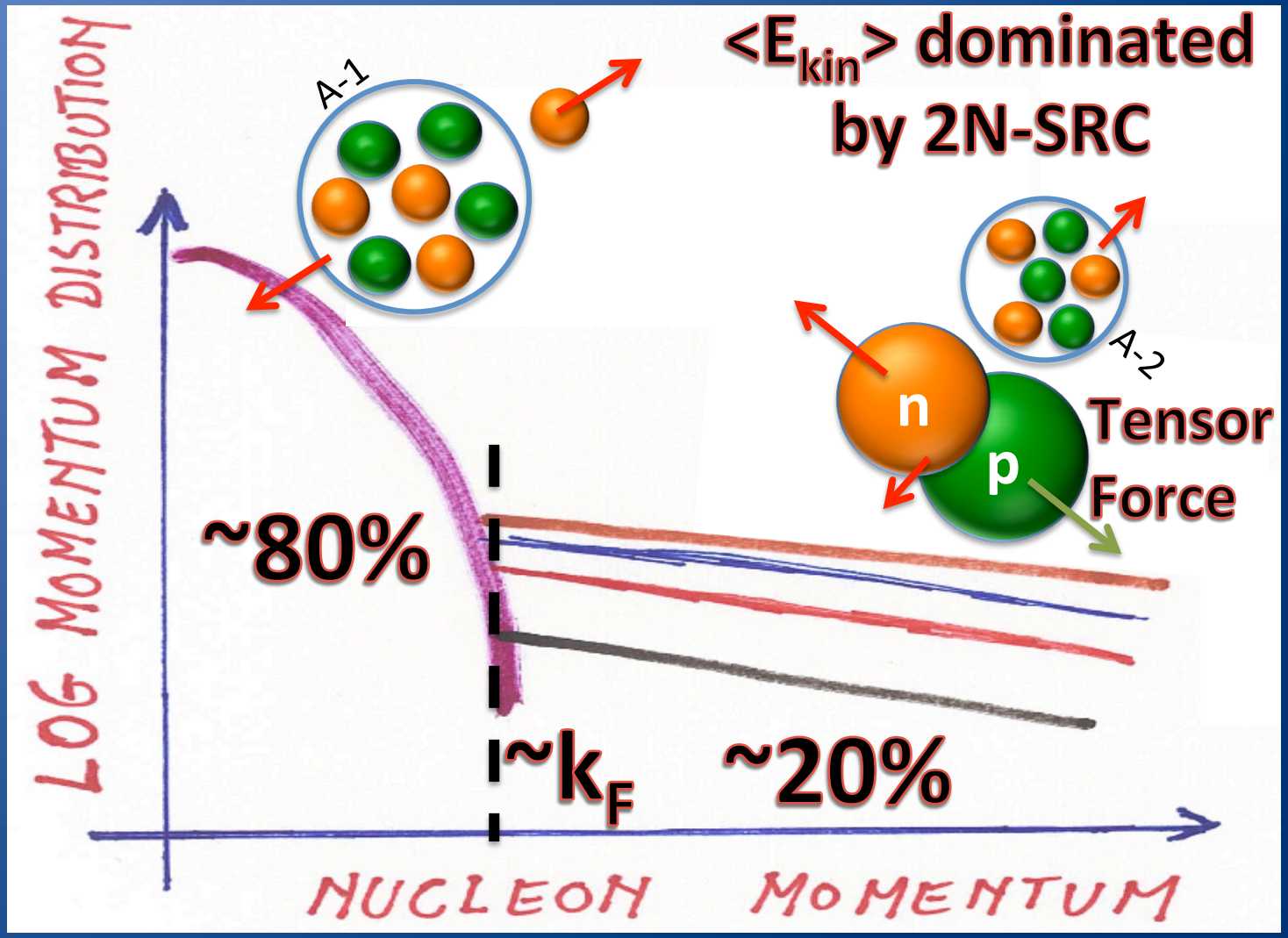
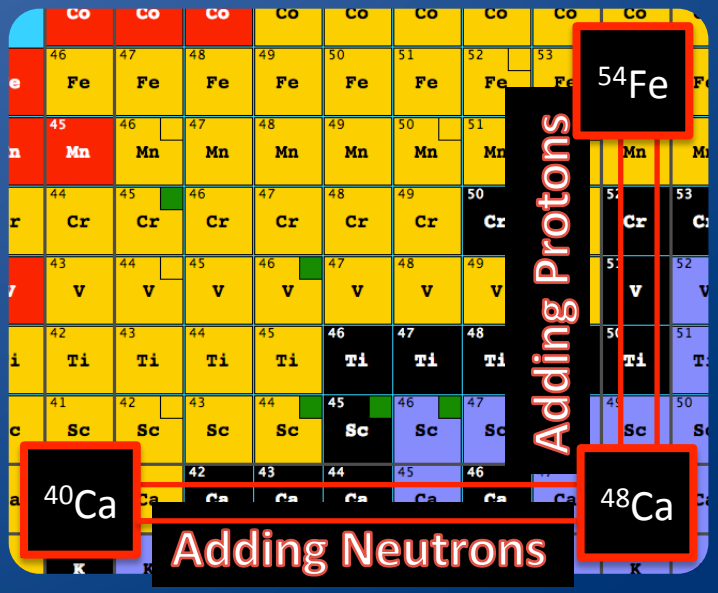
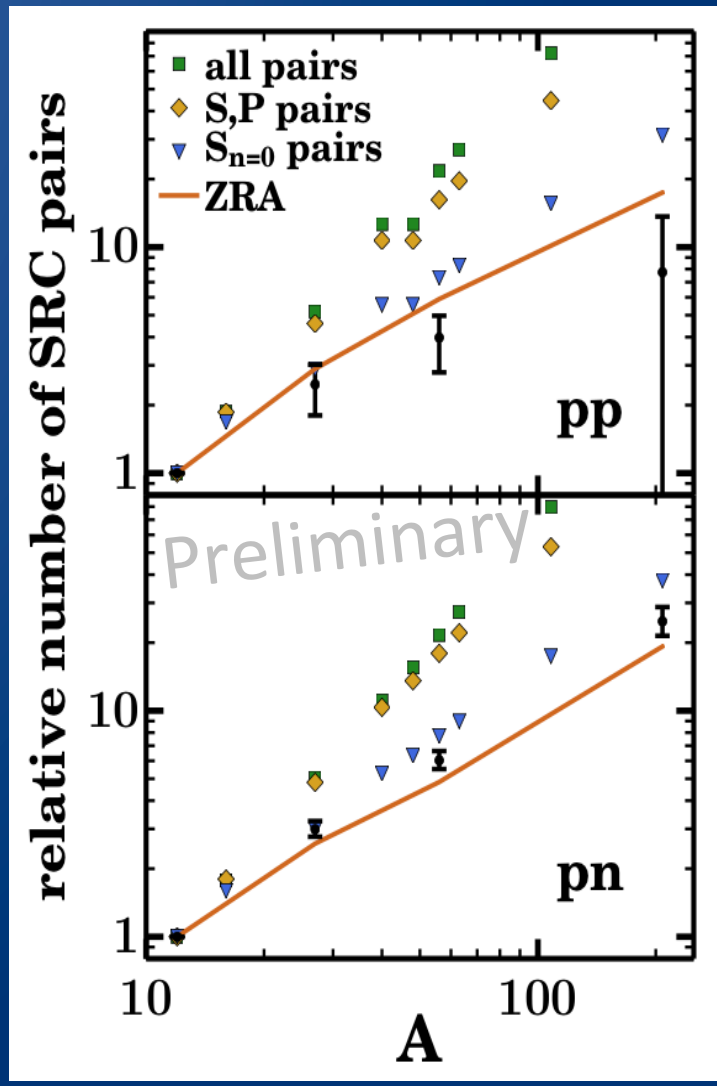


# Questions for Next Generation

- Mean-Field to SRC Transition (Migdal Jump).
- Quantum numbers of SRC pairs.
- Motion of SRC pairs.
- Dynamics of Pairing in Imbalanced systems
- Tensor vs. Scalar Correlations
- 3N-SRCs (?)

<u>+ High-$Q^2$ kinematics:</u>
Reduced reaction mechanism effects



# CLAS12 Rate Estimations (50 days)

| | $x_B$ | $Q^2$ | E' | $\theta_e$ | q | $\theta_p$ | #events/target |
|---|---|---|---|---|---|---|---|
| EG2 (6 GeV) | 1.2 | 1.7 | 4.2 | 16.2° | 1.5 | 55° | ~500 |
| Proposed (12 GeV) | 1.2 | 3.5 | 9.5 | 10.5° | 2.4 | 45° | ~5,000 |

*Assuming a 10% neutron detection efficiency we expect equal amount of A(e,e'pp) and A(e,e'pn) events.

Better to put target up stream and out bend electrons

Targets: $^{12}C$, $^{40}Ca$, $^{48}Ca$, $^{54}Fe$, $^{208}Pb$.

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## CLAS12 vs. CLAS6 Rates:

x10 – Overall luminosity.

x2 – Nuclear target luminosity (no deuterium target).

x1 – Beam time.

x1 – Mott Cross-section.

x0.5 – Acceptance (from simulations).

Total Rate (12 GeV / 6 GeV): x10

Targets: $^{12}C$, $^{40}Ca$, $^{48}Ca$, $^{54}Fe$, $^{208}Pb$.

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*Assuming a 10% neutron detection efficiency we expect equal amount of A(e,e'pn) and A(e,e'pn) events.

Better to put target up stream

**Current Status:**

Finalizing Acceptance simulations (with H. Hakobayn group) and optimizing target location towards a full proposal in the summer.

**CLAS12 vs. CLAS6 Rates:**

x10 – Overall luminosity.

x2 – Nuclear target luminosity (no deuterium target).

x1 – Beam time.

x1 – Mott Cross-section.

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**Total Rate (12 GeV / 6 GeV): x10**

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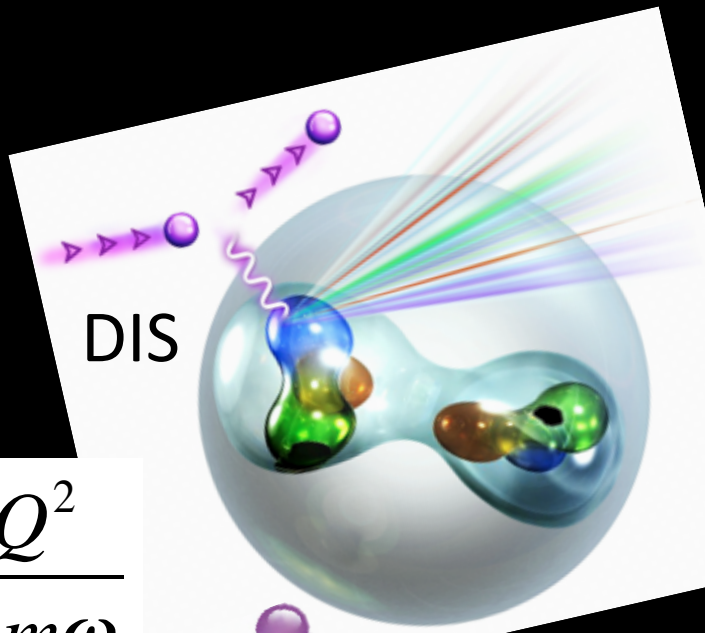
# Quasi-Elastic vs. Deep Inelastic Scattering

TEL AVIV UNIVERSITY

**DIS:** Study of the partonic structure of the nucleon

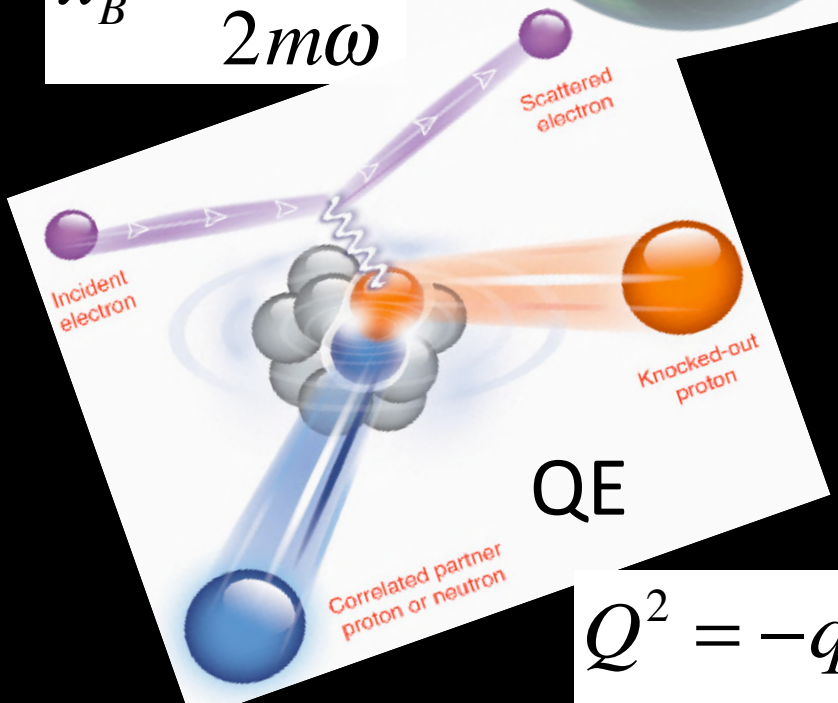
DIS scale: several tens of GeV




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

**QE:** Study of the nucleonic structure of the nucleus

QE scale: several GeV




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

# Quasi-Elastic vs. Deep Inelastic Scattering

TEL AVIV UNIVERSITY

DIS: Stu
st
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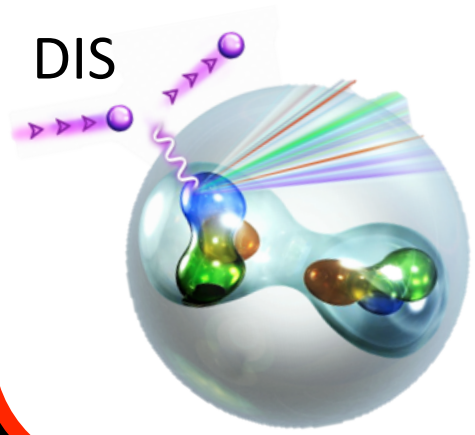
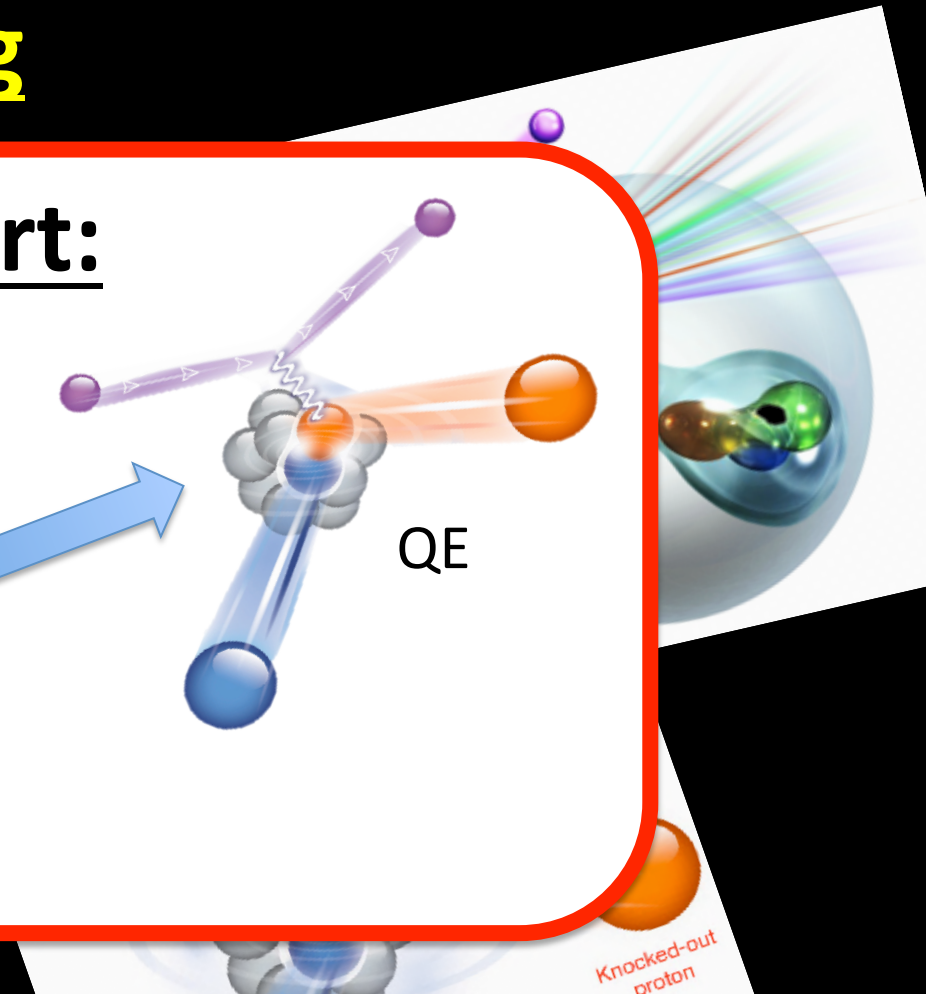
QE: St
str
QE s

## Focus of this part:




?



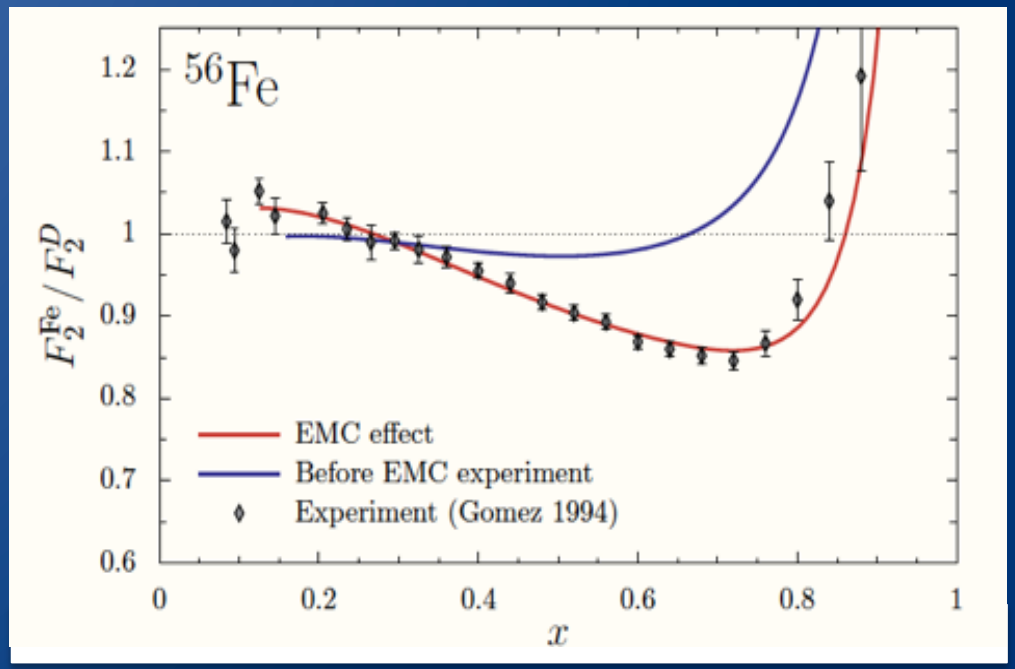

**General Naive Expectation :**

**DIS off nucleons in *nuclei***

**= DIS off free nucleons**

# 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.




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

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

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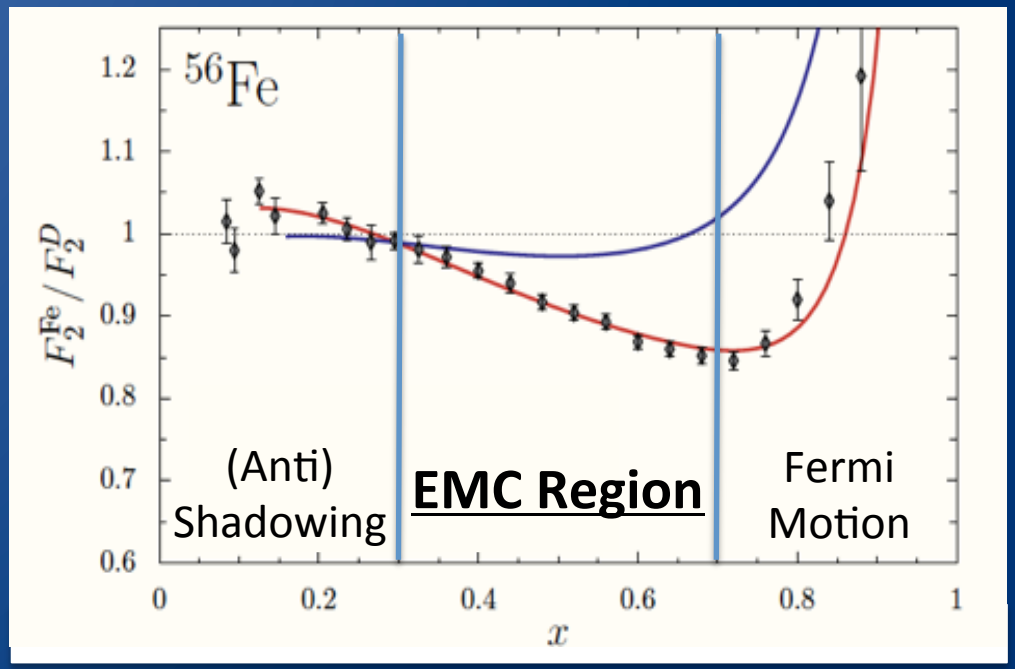


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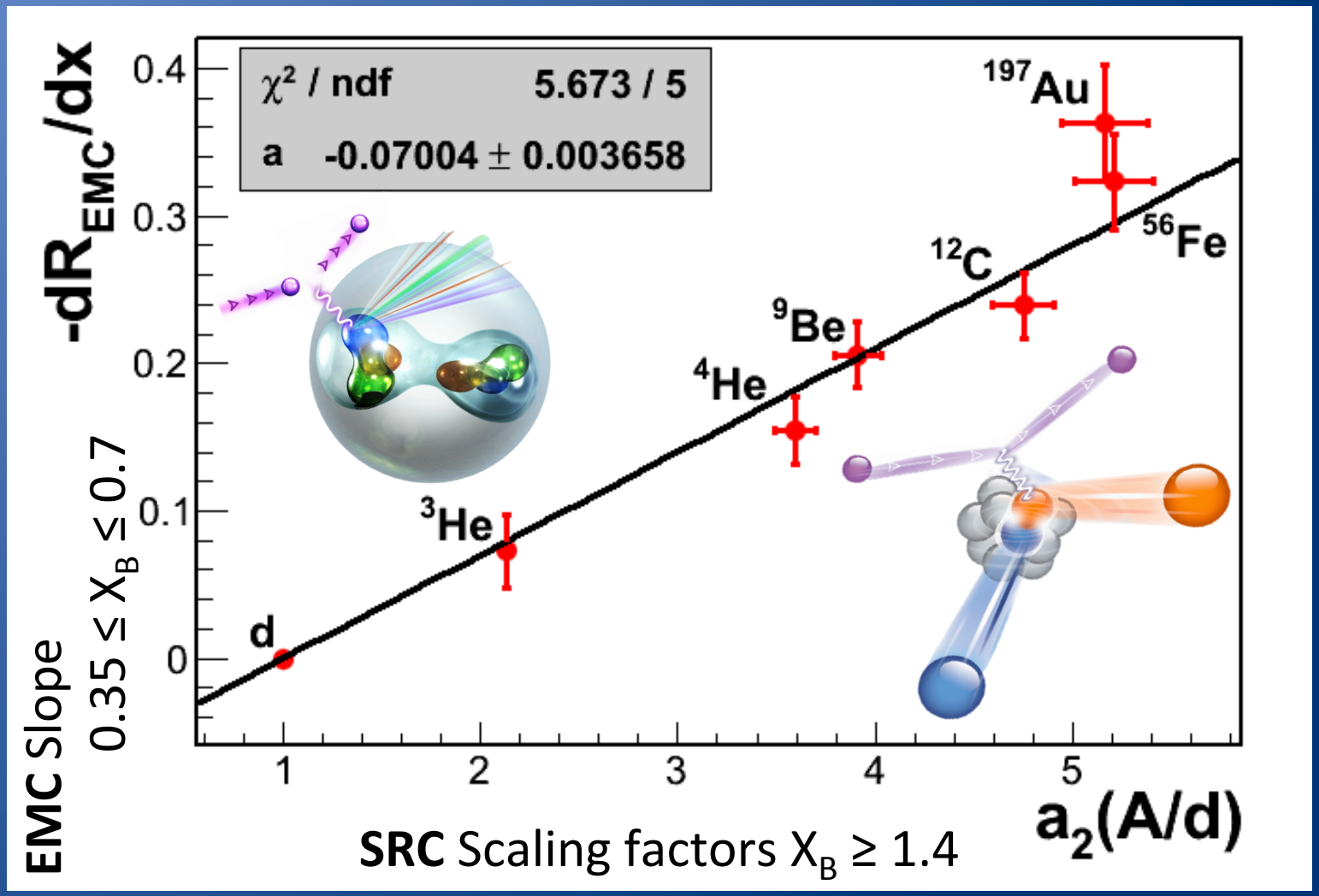
# EMC-SRC Correlation





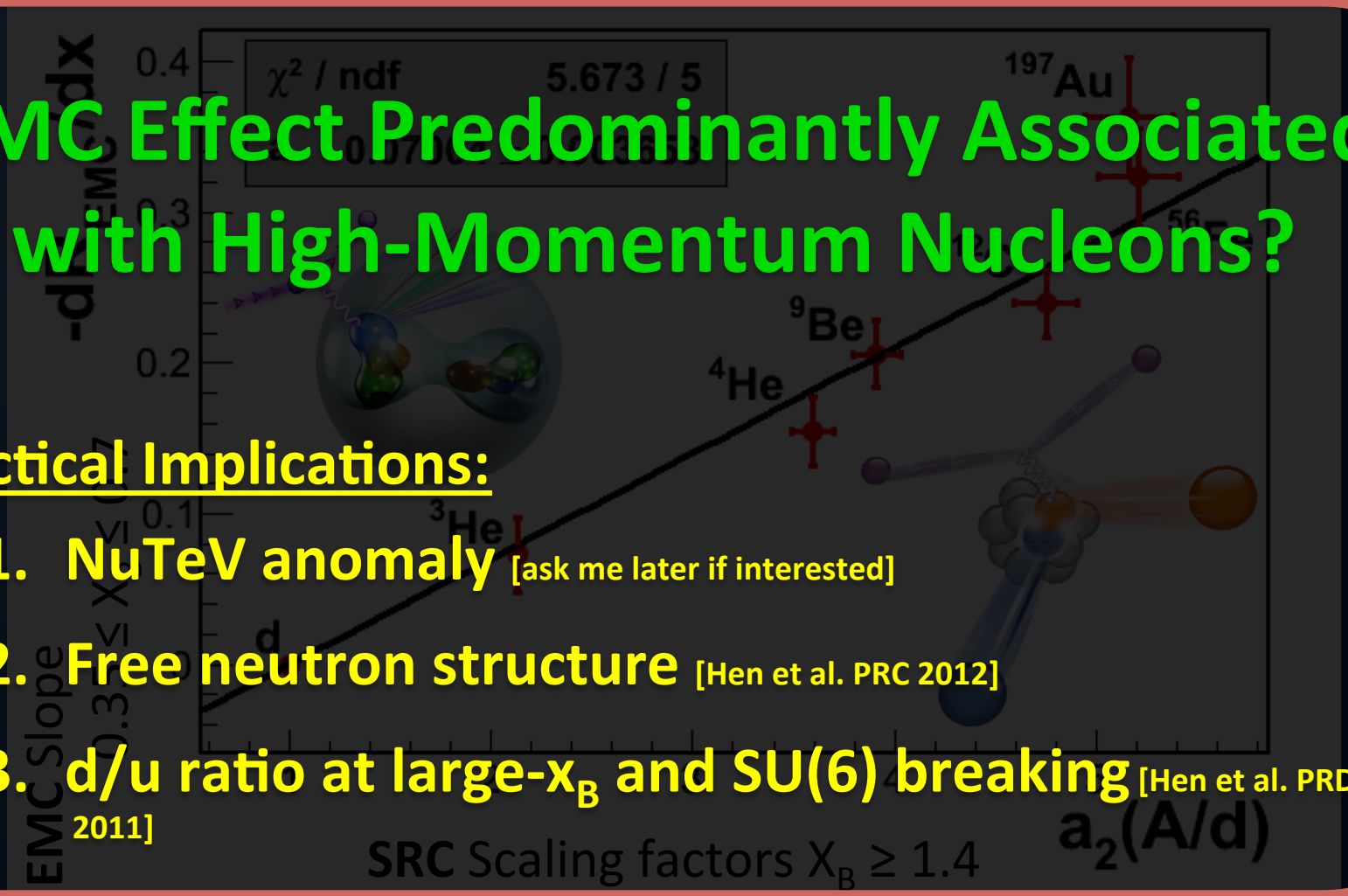
O. Hen et al., Int. J. Mod. Phys. E. **22**, 1330017 (2013).

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.

# 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]
3. **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.

L. B. Weinstein, E. Piasetzky, D. W. Higinbotham, J. Gomez, O. Hen, R. Shneor, Phys. Rev. Lett. **106** (2011) 052301.

# Experimental Tests ?

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

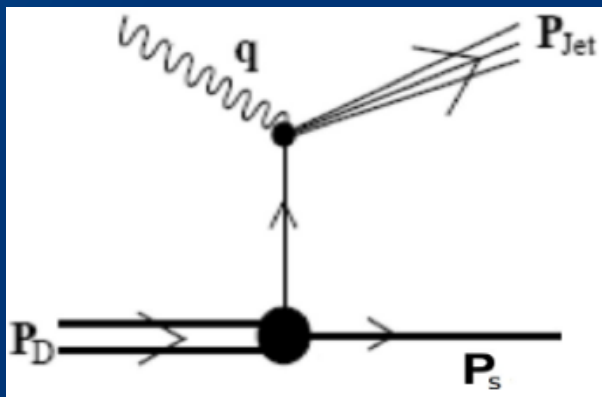
Deuterium is the only system in which the momentum of the struck nucleon equals that of the recoil (Assuming no FSI)

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

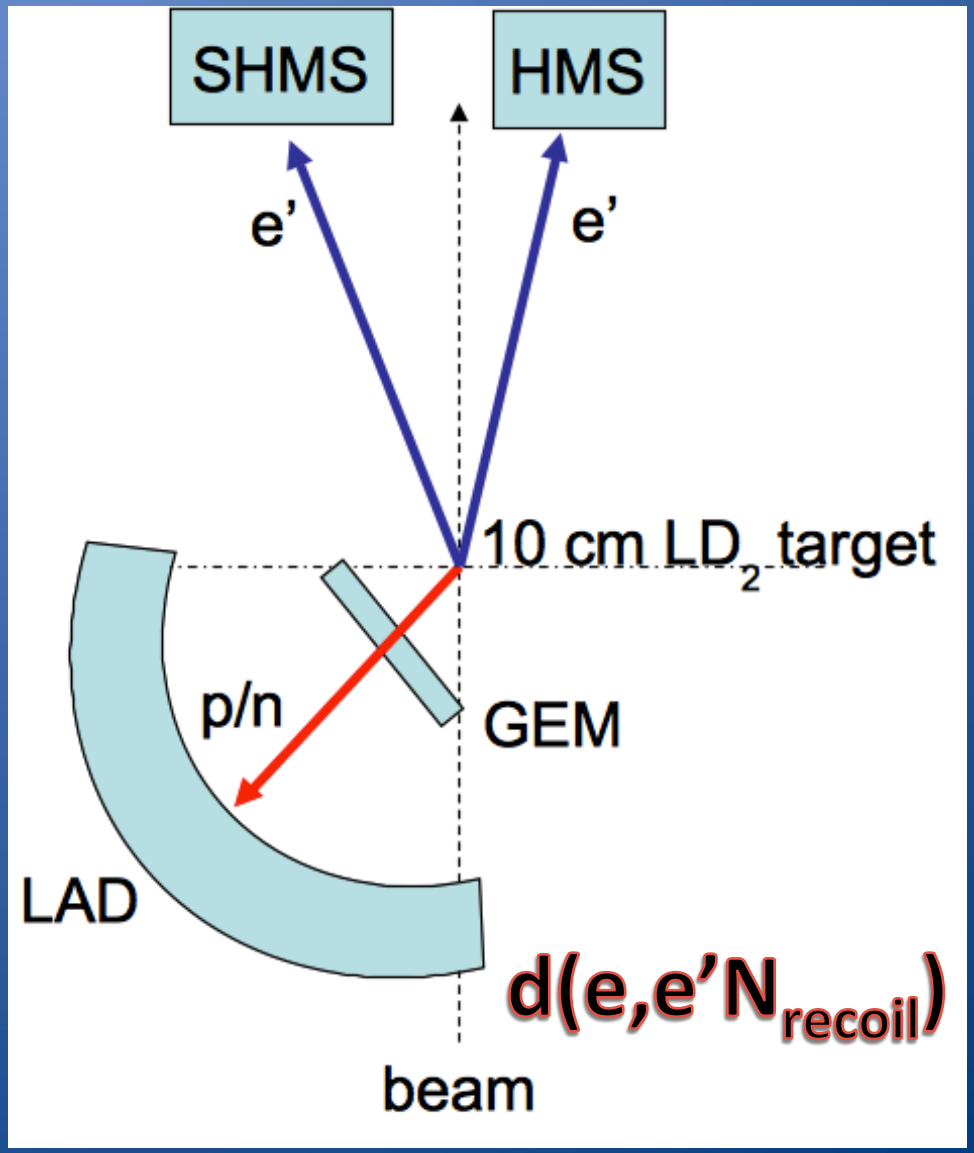
Study the role played by high-momentum nucleons in nuclei

**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



# Our Concept…

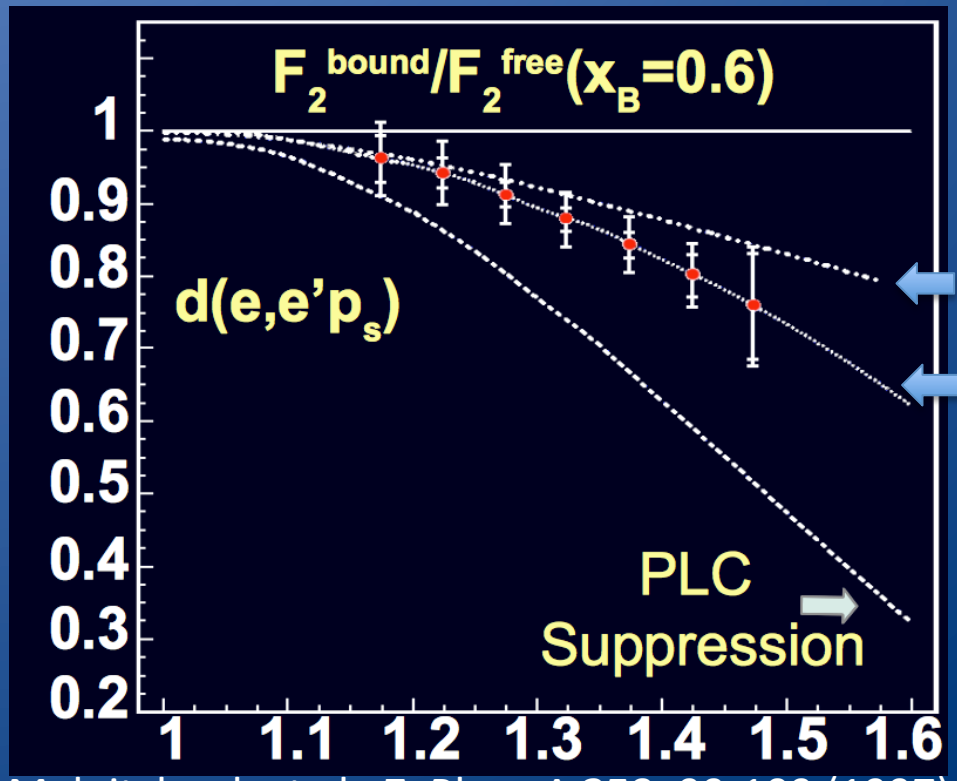



- High resolution spectrometers for (e,e') measurement in DIS kinematics
- Large acceptance recoil proton \ neutron detector
- Long target + GEM detector – reduce random coincidence

JLab Experiment E11-107,
Spokespersons: O. Hen (TAU), L. B. Wienstain (ODU), S. Gilad (MIT), S. A. Wood (JLab).

# Kinematics and Uncertainties

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




Binding / Off-Shell

Rescaling Model

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

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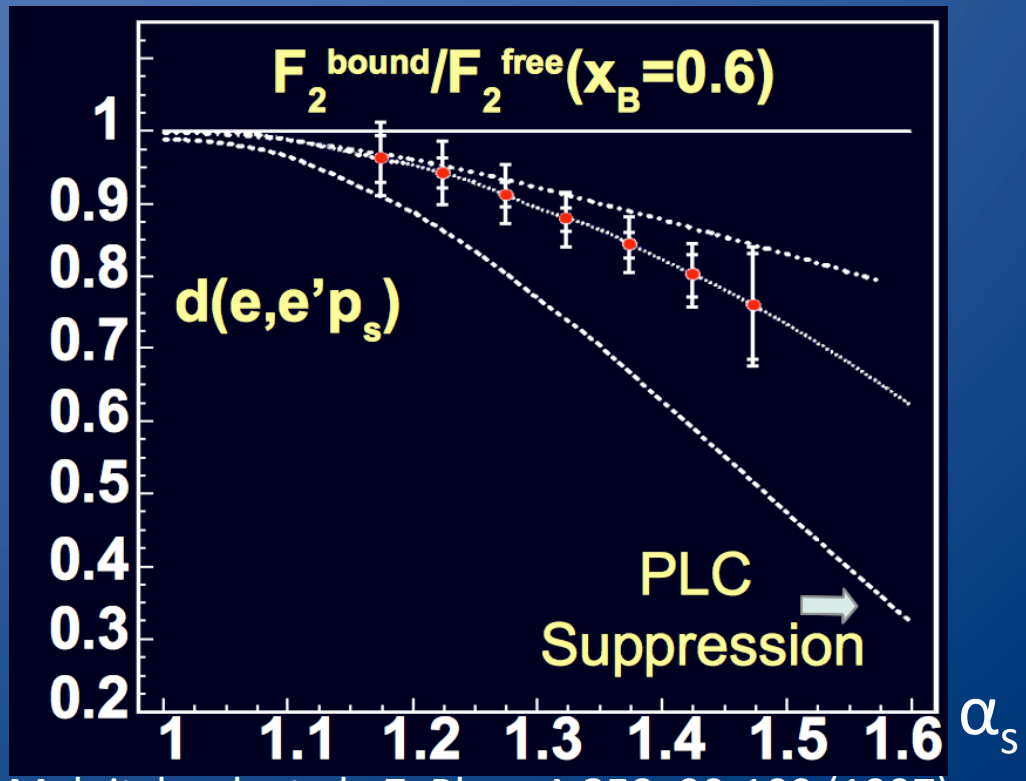
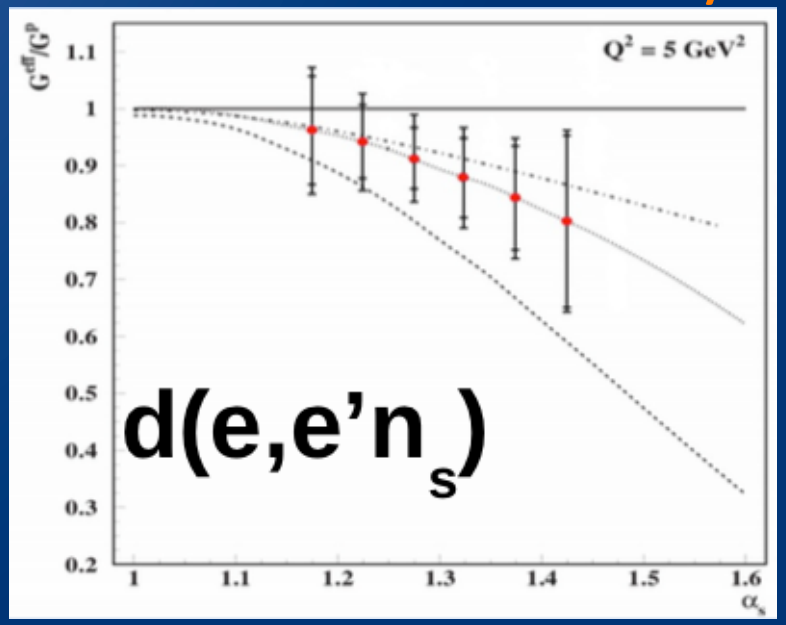


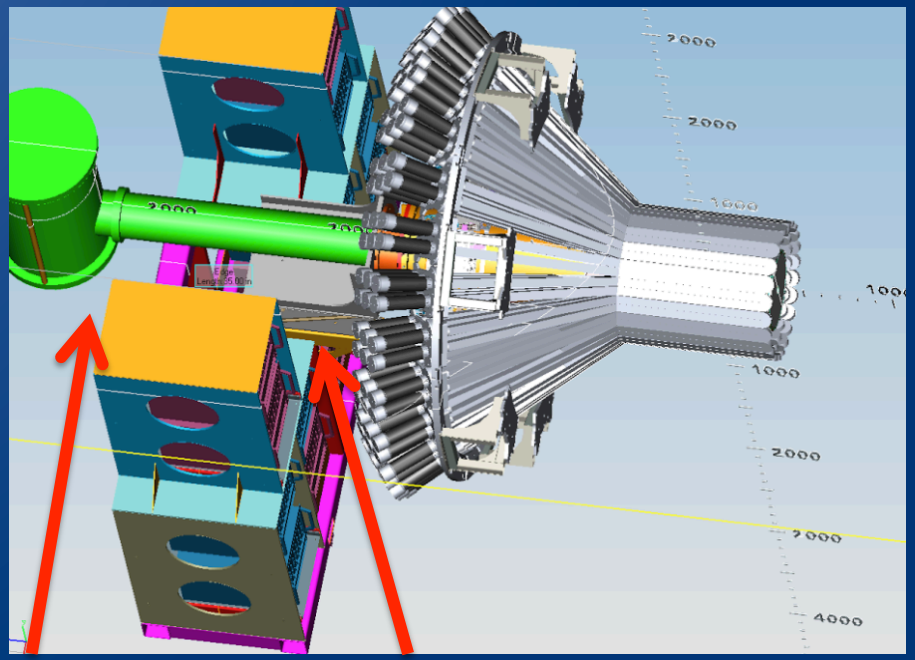

Melnitchouk et al., Z. Phys. A **359**, 99-109 (1997)

Low Neutron Sensitivity…



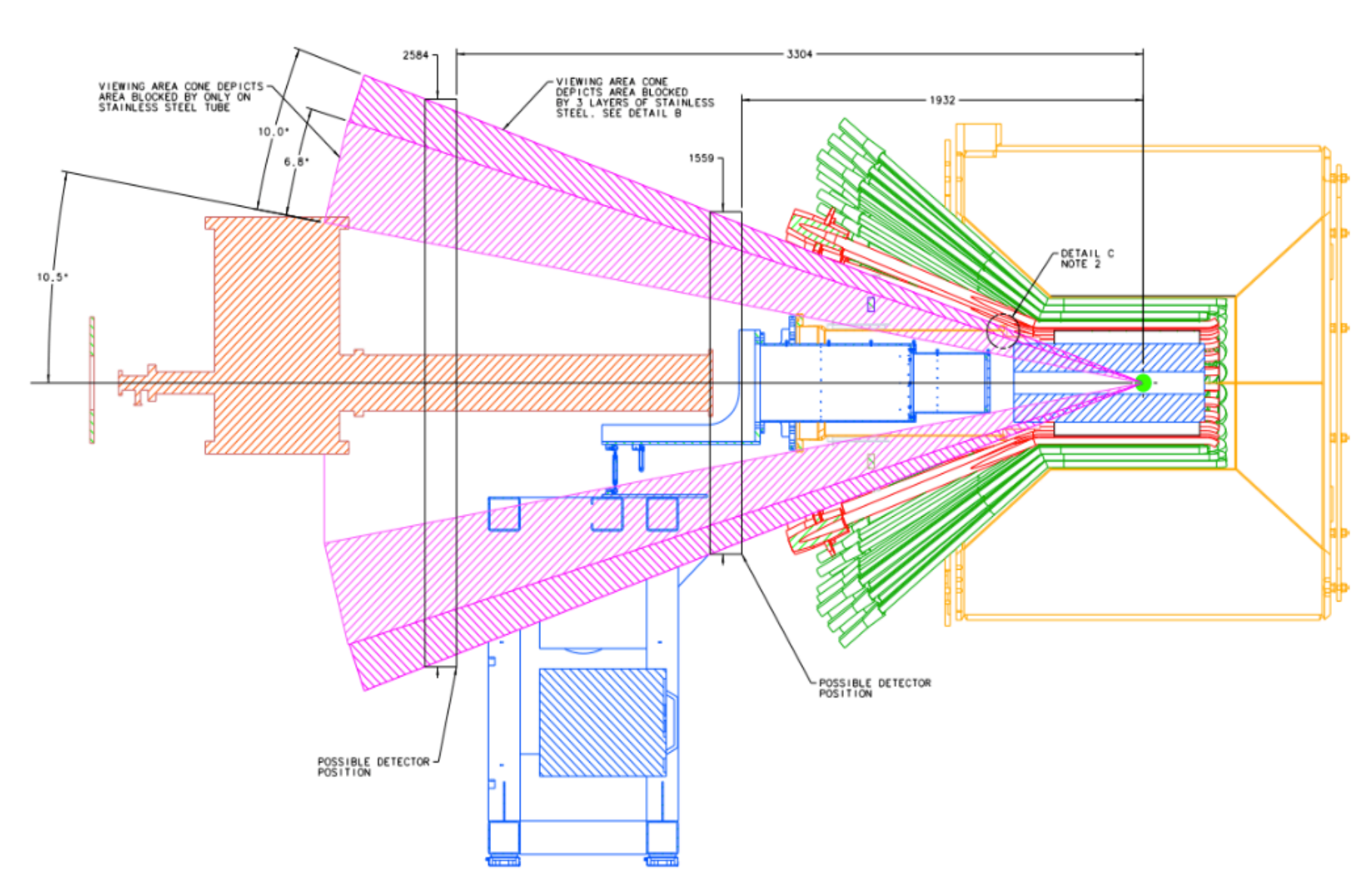
# Recoil neutron tagging in CLAS12 ?

- <u>Concept:</u> Adding a backward (>140$^{o}$) recoil neutron detector to the approved CLAS12 deuteron running.
- <u>Advantages (compared to Hall-C):</u>
  - Reduced luminosity = Low random coincidence background.
  - Large electron acceptance.
  - 90 days already approved for deuteron running.
  - Continues x' coverage.




Possible detector locations

# Good Coverage for 160º – 170º



# Rate Estimation (relative to Hall-C)

x2.5 – Beam time (90 days vs. 35 days).

x13 – Electron acceptance @ 17$^{o}$.

x0.1 – Luminosity.

x3 – e-p vs. e-n DIS cross-section

x0.2 – Recoil n. acceptance (160$^{o}$-170$^{o}$ vs. >120$^{o}$).

X2 – Recoil n. detection efficiency (40% vs. 20%).

**<u>Total Relative rate: x3.</u>** [+ reduced random coincidence and continuous x' coverage]

# Rate Estimation (relative to Hall-C)

x2.5 – Beam time (90 days vs. 35 days).

x0.3 – Electron acceptance @ 17°.

x0.1 – Luminosity.

x3 – n vs. e n DIS cross section.

x0.2 – Recoil n. acceptance (160°-170° vs. >120°).

X2 – Recoil n. detection efficiency (40% vs. 20%).

**Total Relative Rate: x3** [accounted random coincidence and continuous x' coverage]

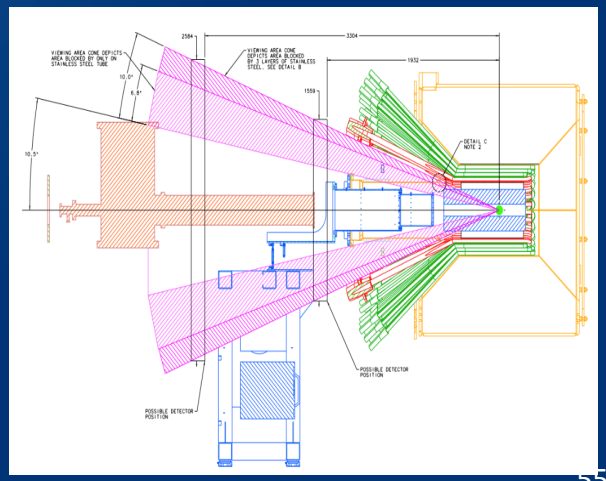
**Current Status:**

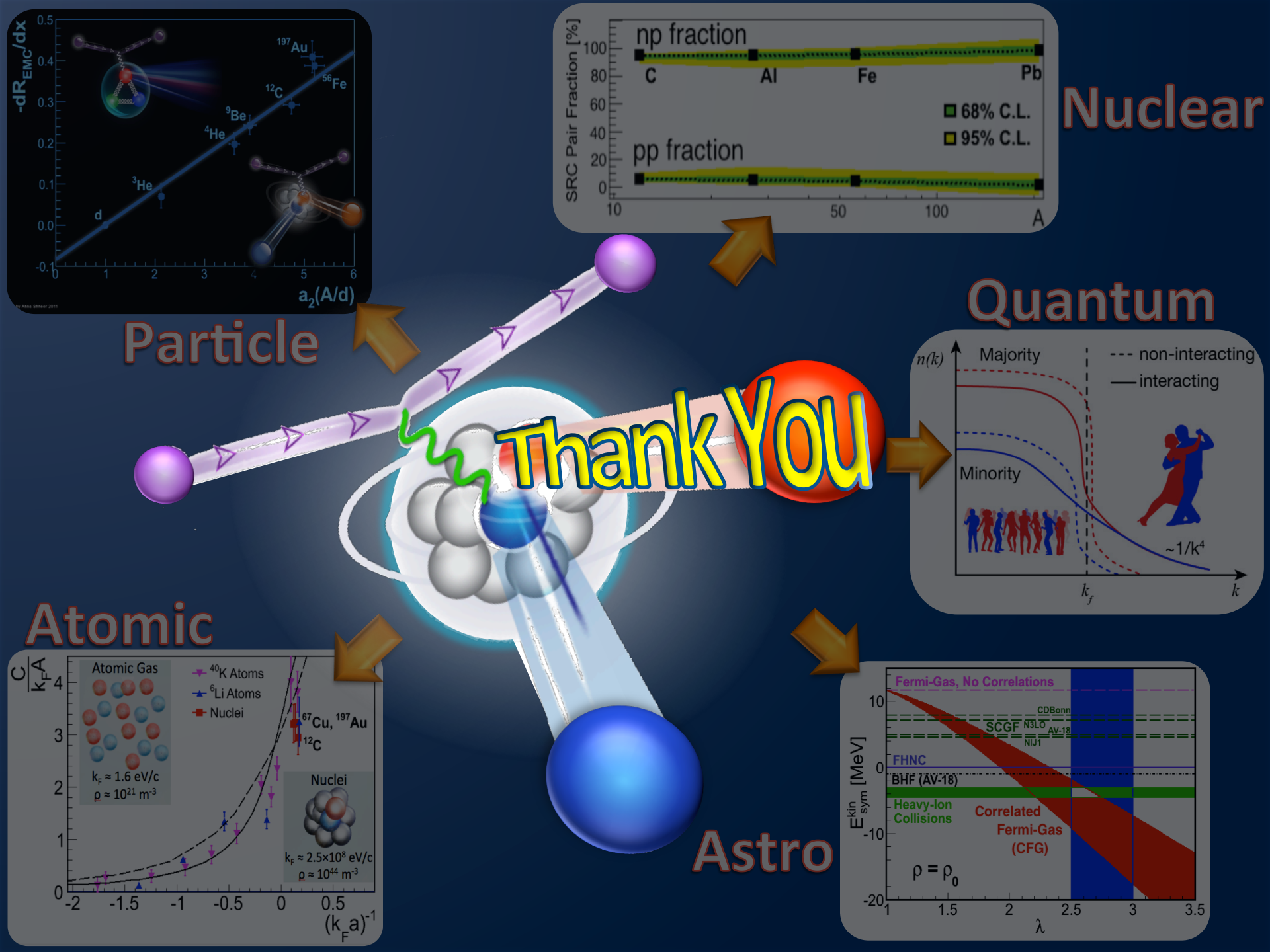
- Simulating neutron detection efficiency and optimizing detector design.
- Apply for CLAS collaboration approval in the summer.

# Summery

- Data-Mining analysis yield valuable information on:
  1. 2N-SRC pairs in heavy asymmetric nuclei.
  2. Energy sharing in imbalanced Fermi systems.
  3. Contact interactions in universal Fermi gases.
  4. Nuclear symmetry energy.
  5. Isospin dependent EMC effect and the NuTeV anomaly.

- CLAS12 can be used study:
  - Correlations in heavy nuclei.
  - Structure function of SRC protons by recoil neutron tagging.




Thank You
Particle
$-dR_{EMC}/dx$
$a_2(A/d)$
d
$^3$He
$^4$He
$^9$Be
$^{12}$C
$^{56}$Fe
$^{197}$Au
Nuclear
SRC Pair Fraction [%]
np fraction
pp fraction
C
Al
Fe
Pb
68% C.L.
95% C.L.
A
Quantum
n(k)
Majority
Minority
non-interacting
interacting
~1/k$^4$
$k_f$
k
Atomic
Atomic Gas
$^{40}$K Atoms
$^6$Li Atoms
Nuclei
$^{67}$Cu, $^{197}$Au
$^{12}$C
$k_F \approx 1.6$ eV/c
$\rho \approx 10^{21}$ m$^{-3}$
$k_F \approx 2.5\times10^8$ eV/c
$\rho \approx 10^{44}$ m$^{-3}$
$\frac{C}{k_F A}$
$(k_F a)^{-1}$
Astro
Fermi-Gas, No Correlations
SCGF
CDBonn
N3LO
AV-18
NIJ1
FHNC
BHF (AV-18)
Heavy-Ion Collisions
Correlated Fermi-Gas (CFG)
$\rho = \rho_0$
$E^{kin}_{sym}$ [MeV]
λ