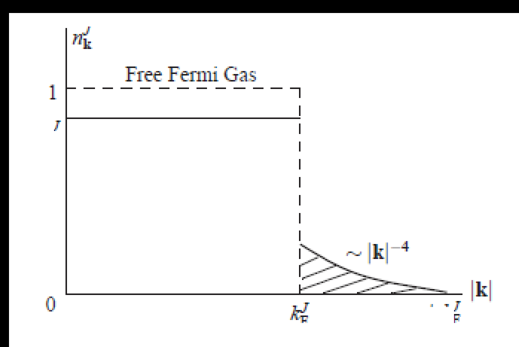
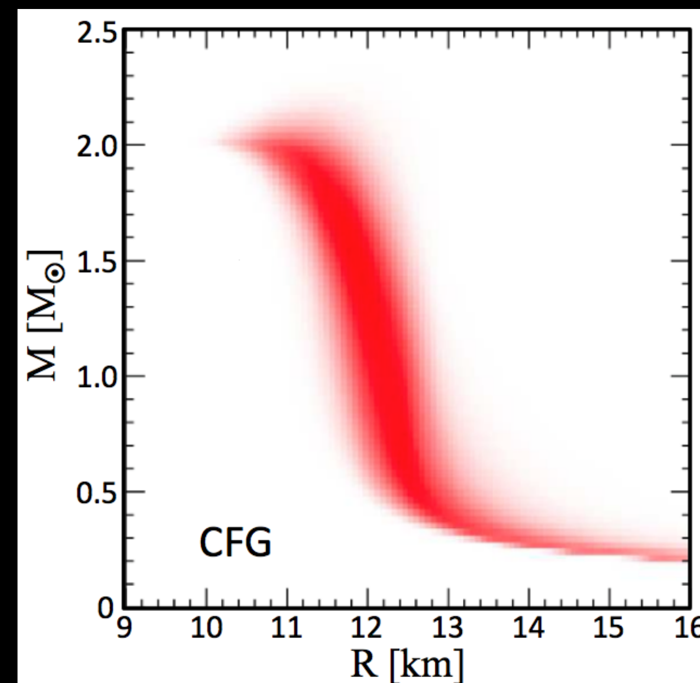
6th International Symposium on Nuclear Symmetry Energy (NuSYM16)
June 13- June 17, 2016, Tsinghua University, Beijing, China

Analysis of Neutron Stars Observations Using a Correlated Fermi Gas Model

O. Hen, A.W. Steiner, E. Piasetzky,
and L.B. Weinstein





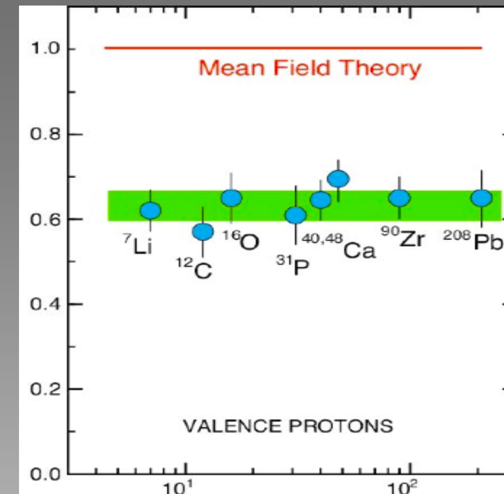
Eli Piasetzky Tel Aviv University ISRAEL

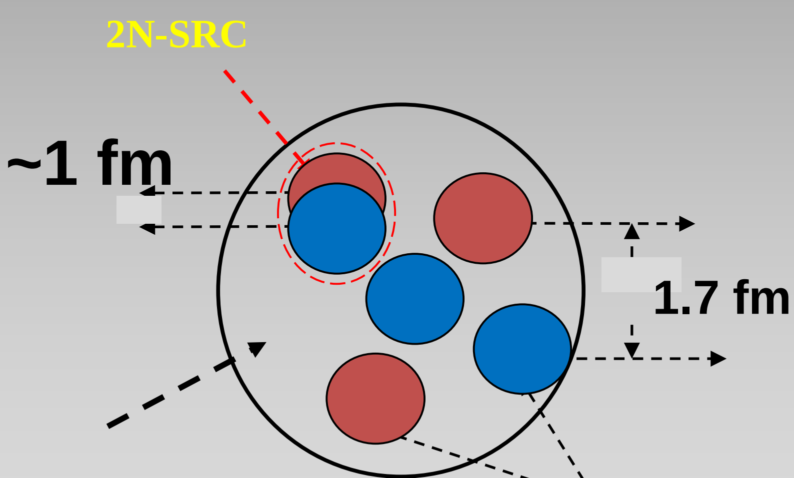
Short Range (tensor) Correlations in nuclei

Hard Semi inclusive scattering
A(e, e'p)

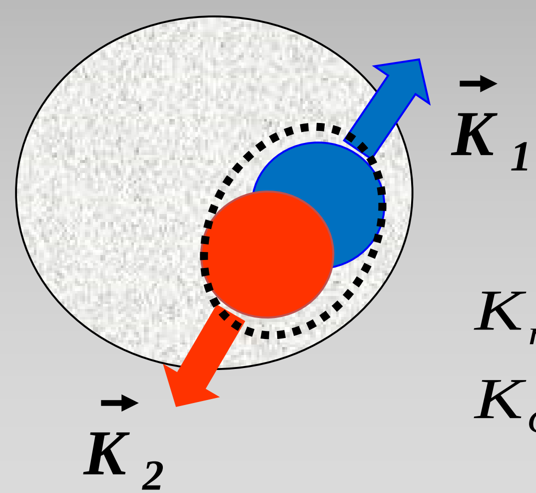
Only 60-70% of the expected single-particle strength.

SRC and LRC





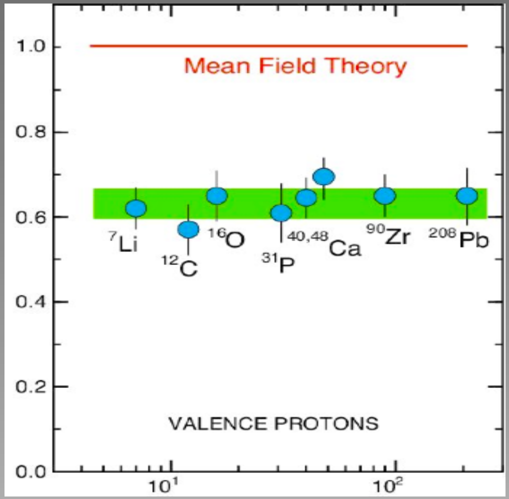
ρ_o = 0.16 GeV/fm^3



$$K_{rel} > K_F$$
$$K_{CM} < K_F$$

Short Range (tensor) Correlations in nuclei

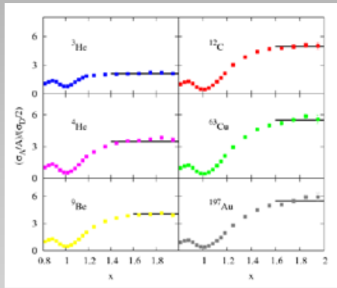
Hard Semi inclusive scattering
A(e, e'p)

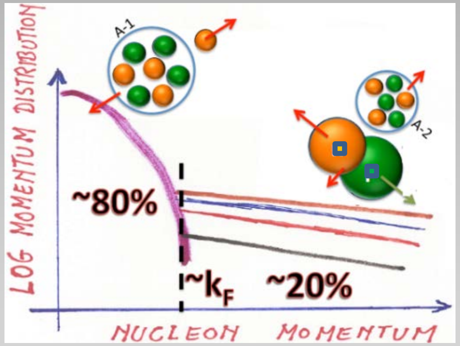


Only 60-70% of the expected single-particle strength.

SRC and LRC

Hard inclusive scattering
A(e, e')

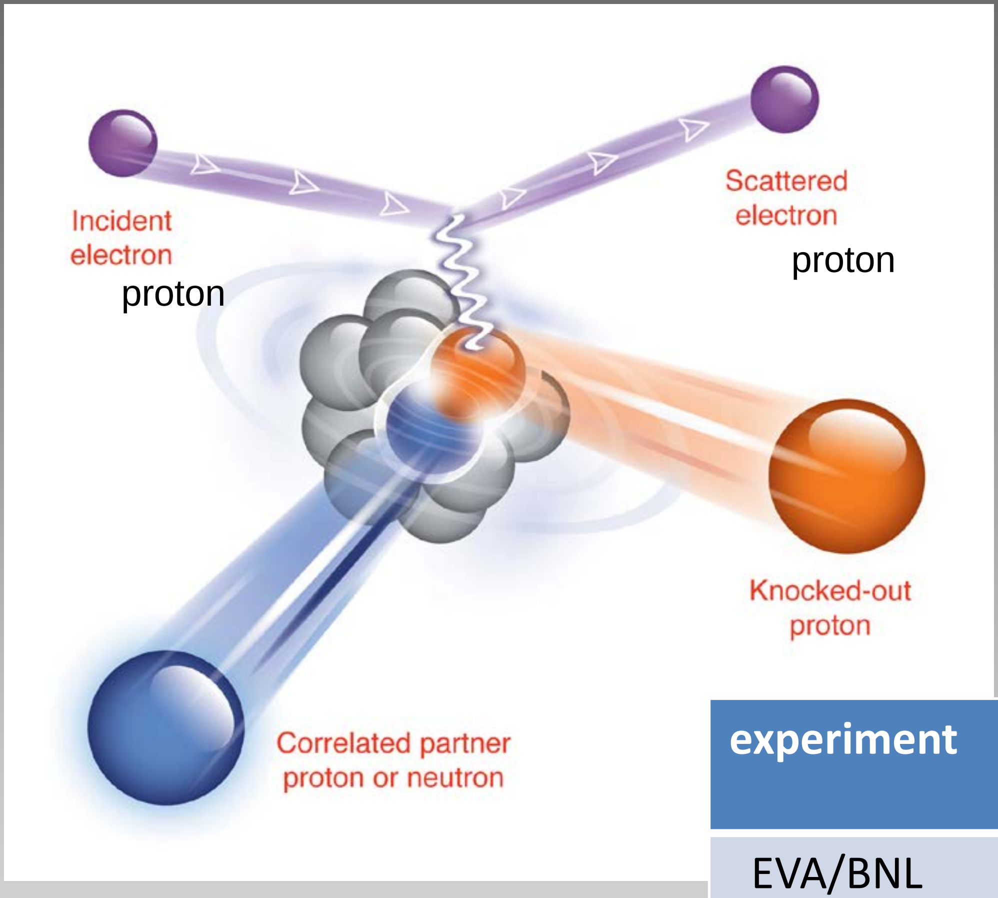




This 20-25 % includes all three isotopic compositions (pn, pp, or nn) for the 2N-SRC phase in ^{12}C.

Hard exclusive scattering
A(e, e'pp) and A(e, e'pn)

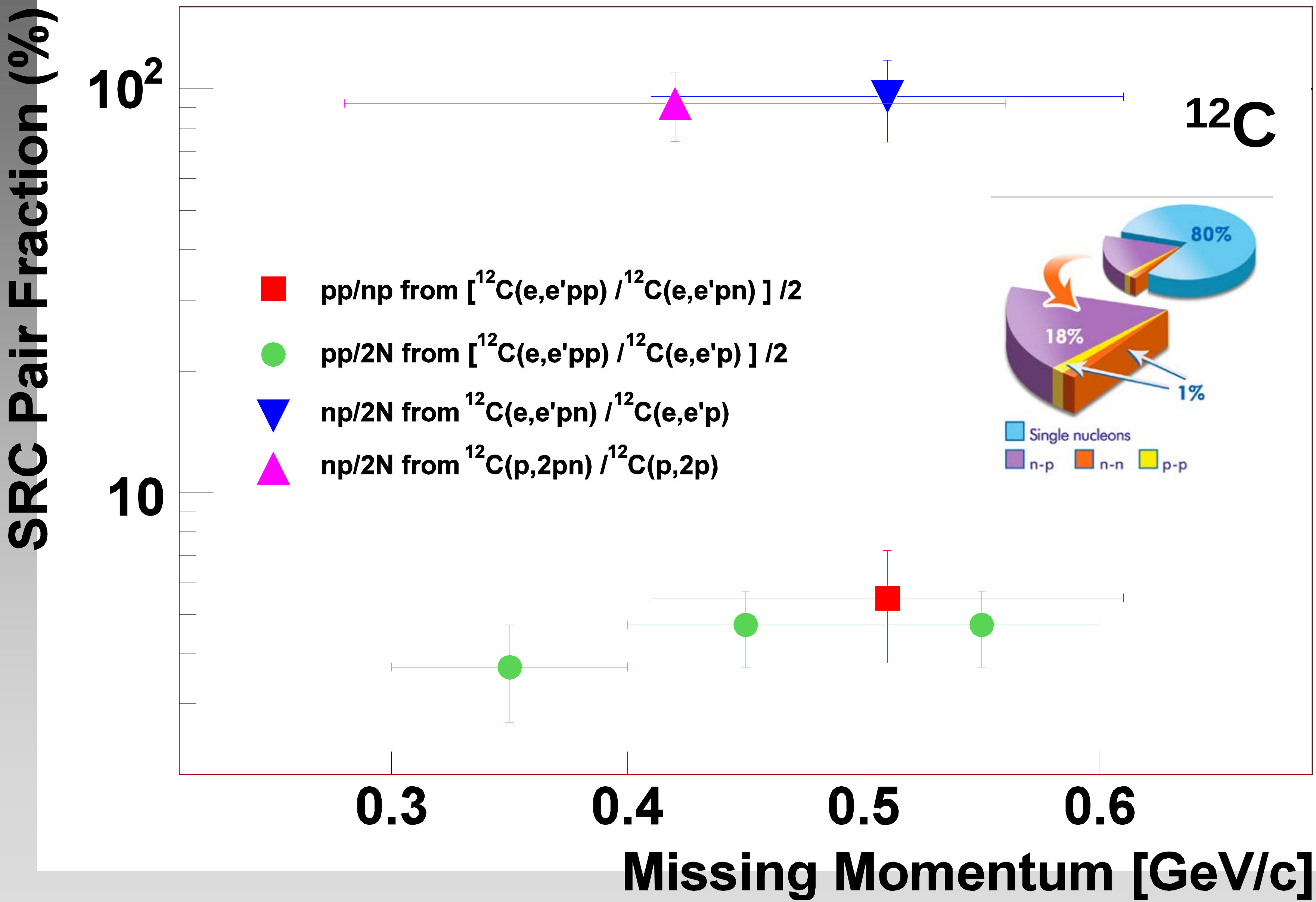
Quasi-Free scattering off a nucleon in a short range correlated pair



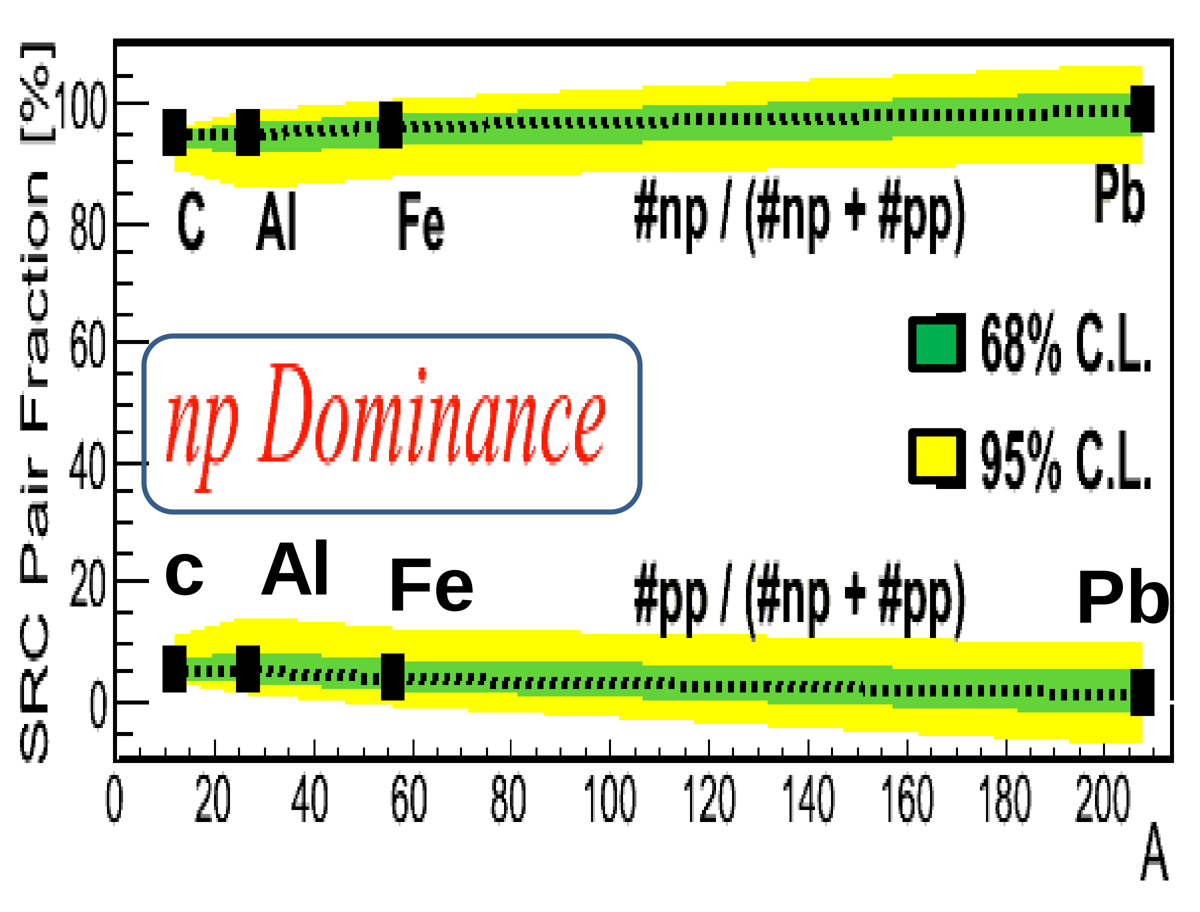
Hard exclusive triple – coincidence measurements

experiment	nuclei	pairs	Pmiss [MeV/c]
EVA/BNL	^{12}C	pp only	300-600
E01-015/ Jlab	^{12}C	pp and np	300-600
E07-006/ JLab	^{4}He	pp and np	400-850
CLAS/JLab	C, Al, Fe, Pb	pp only	300-700

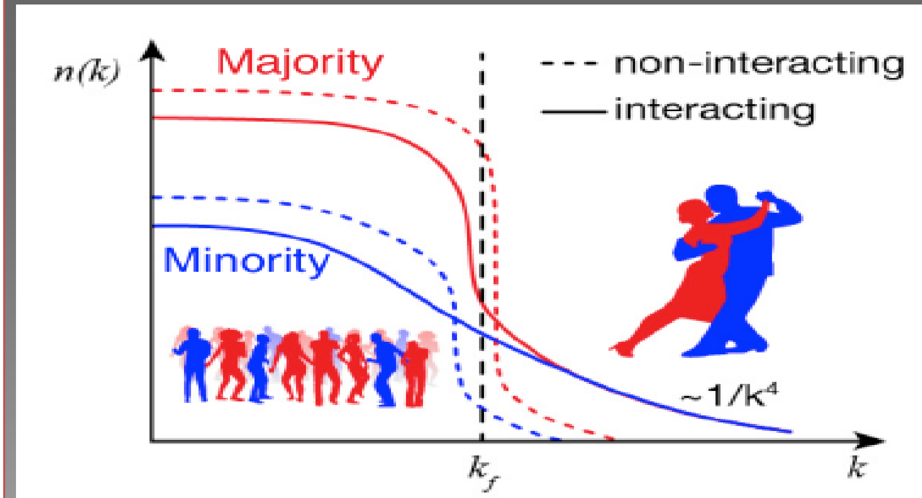
R. Subedi et al., Science 320, 1476 (2008).



np / pp SRC pairs ratio



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



Neutron-skin in coordinate and proton-skin in momentum in heavy nuclei:

What we can learn from their correlation in an Extended+ Thomas-Fermi Approximation

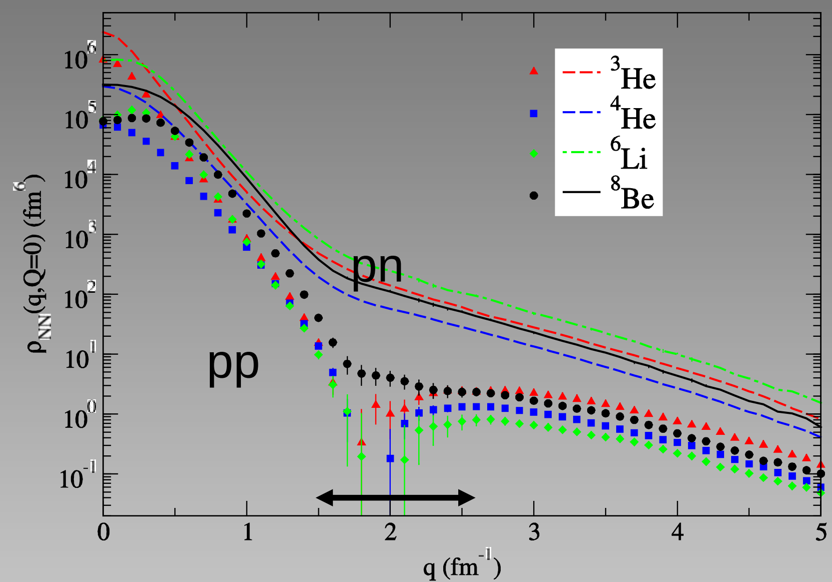
Bao-An Li

a LOT more n than p in the skin.

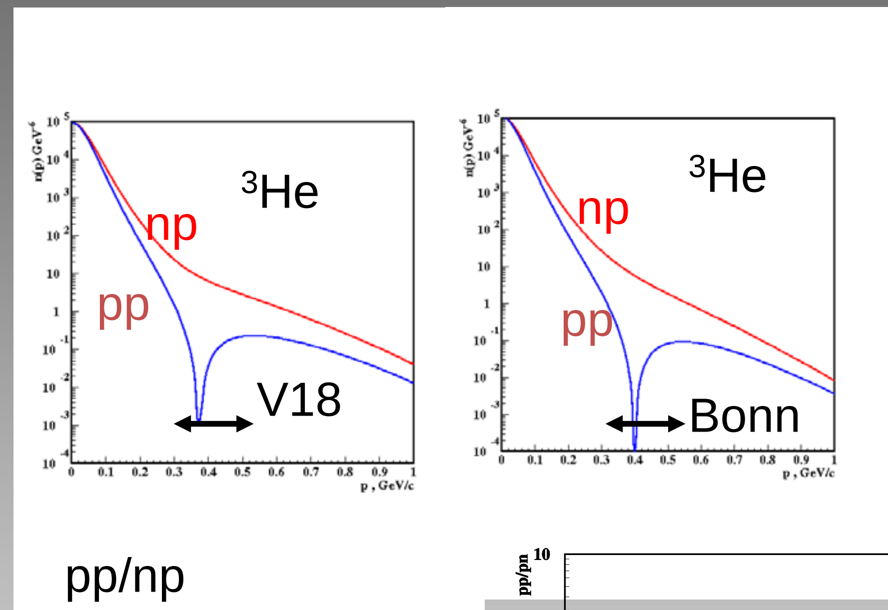
protons in the skin move faster than neutrons.

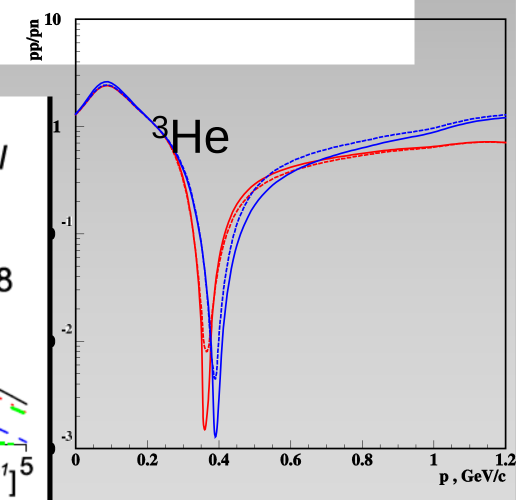
The fraction of high-momentum protons is larger in the skin then in the core.

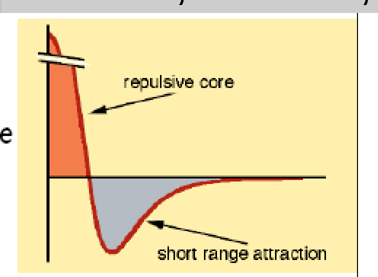
At 300-600 MeV/c there is an excess strength in the np momentum distribution due to the strong correlations induced by the tensor NN potential.



Schiavilla, Wiringa, Pieper, Carson, PRL 98,132501 (2007).

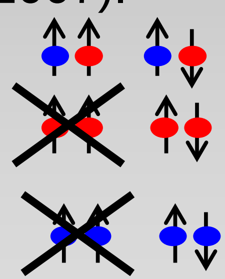


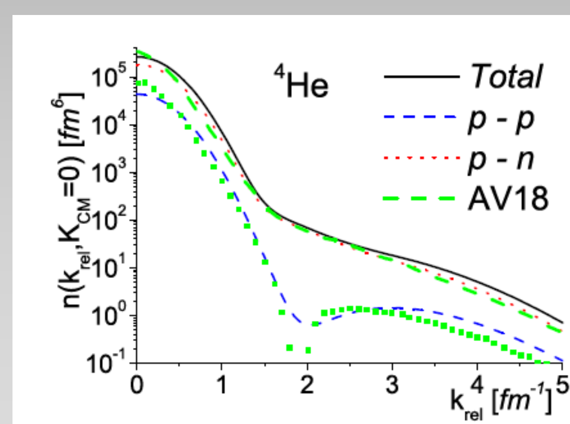




SRC

L = 0, 2





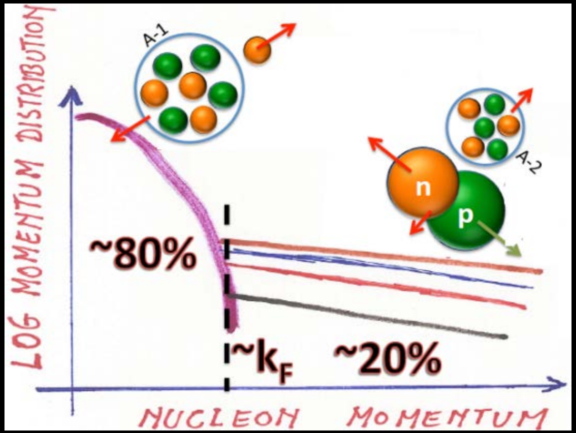
Ciofi and Alvioli PRL 100, 162503 (2008).

Sargsian, Abrahamyan, Strikman, Frankfurt PR C71 044615 (2005

Nuclei:

Identified triple coincidence SRC pairs in: (^{3}He,) ^{4}He, ^{12}C, ^{27}Al, ^{56}Fe, and ^{208}Pb

High momentum tail In nuclei dominated by SRC pairs



np-SRC dominance

Short Range (tensor) Correlations
are need to describe :

the short distance structure of nuclei

Momentum and energy distributions
of nucleons in nuclei

Free Fermi Gas (FFG)
is WRONG !

Symmetry energy ?

Symmetry Energy

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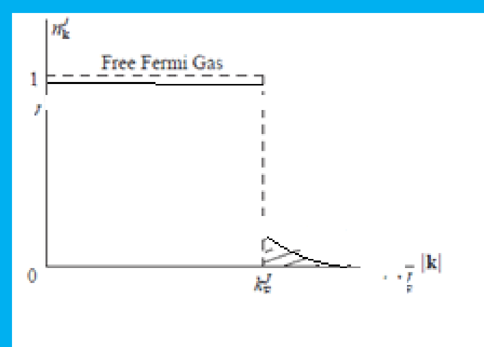
$$E(\rho_n, \rho_p) = E_0(\rho_n = \rho_p) + E_{sym}(\rho)\left(\frac{\rho_n - \rho_p}{\rho}\right)^2 + O(\delta^4)$$

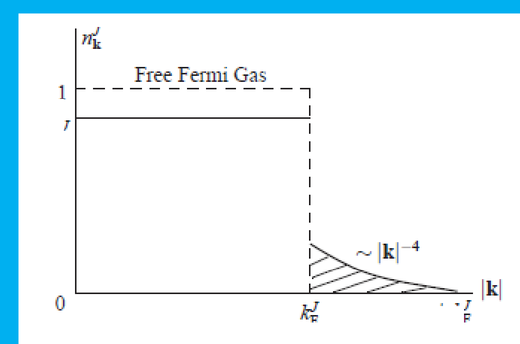
symmetry energy

$$E_{sym}(\rho) \approx E(\rho)_{\mathrm{PNM}} - E(\rho)_{\mathrm{SNM}}$$

(Pure Neutron Matter) (Symmetric Nuclear Matter)

$$E_{sym}(\rho) = E_{sym}^{kin}(\rho) + E_{sym}^{pot}(\rho)$$

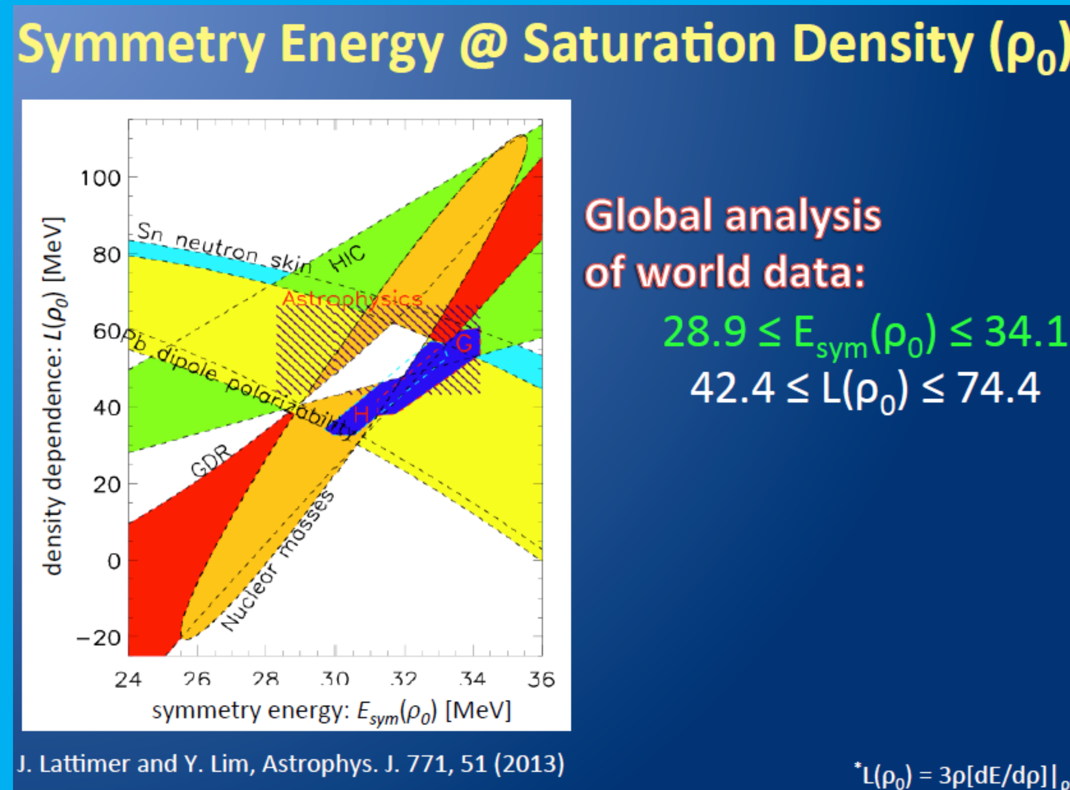




$$E_{sym}^{kin}(with\,\mathrm{SRC}) < E_{sym}^{kin}(no\,\mathrm{SRC})$$

If the potential part is extracted by:

$$E_{sym}^{pot}(\rho_0) = E_{sym}(\rho_0) - E_{sym}^{kin}(\rho_0)$$



SRC

np-SRC dominance

$$\Rightarrow \quad E_{sym}^{kin}(with\,\mathrm{SRC}) < E_{sym}^{kin}(no\,\mathrm{SRC})$$

$$E_{sym}^{pot}(with\,\mathrm{SRC}) > E_{sym}^{pot}(no\,\mathrm{SRC})$$

Density dependence of Symmetry Energy

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$$E_{sym}(\rho) = E_{sym}^{kin}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\alpha} + E_{sym}^{pot}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

FG: $E_{sym}^{kin}(\rho_0) = 12.5\ \mathrm{MeV}$ $\alpha = 2/3$

with Tensor Correlations (CFG):

$$E_{sym}^{kin}(\rho) = E_{sym}^{kin}(\rho)|_{\mathrm{FG}} - \Delta E_{sym}^{kin}(\rho)$$

where the SRC correction term is:

$$\Delta E_{sym}^{kin} \equiv \frac{E_F^0}{\pi^2} c_0 \left[\lambda\left(\frac{\rho}{\rho_0}\right)^{1/3} - \frac{8}{5}\left(\frac{\rho}{\rho_0}\right)^{2/3} + \frac{3}{5}\frac{1}{\lambda}\left(\frac{\rho}{\rho_0}\right)\right]$$

Lower γ

Tensor correlations:

Breaks the Fermi Gas picture

Reduce the kinetic symmetry Energy (at ρ_0)

Enhance the potential symmetry Energy (at ρ_0)

Soften the potential symmetry density dependence

Impact on Compact Astronomical Systems ?

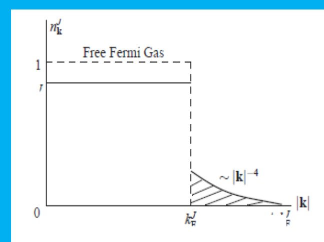
How large is the effect ?

Free Fermi Gas (FFG)

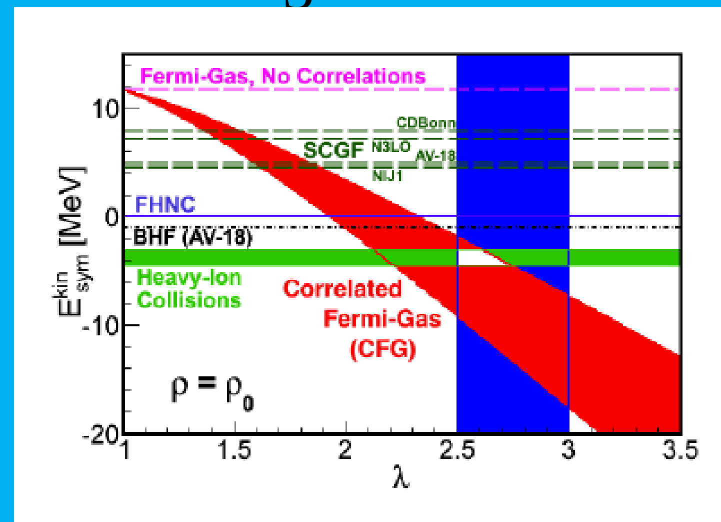
$$n(k) = \begin{cases} A & k < k_F \\ 0 & k > k_F \end{cases}$$

$$E_{sym}^{kin} = (2^{2/3} - 1) \cdot \frac{3}{5} \cdot E_F(\rho_0) \approx 12.5\,\text{MeV}$$

With correlations (CFG)



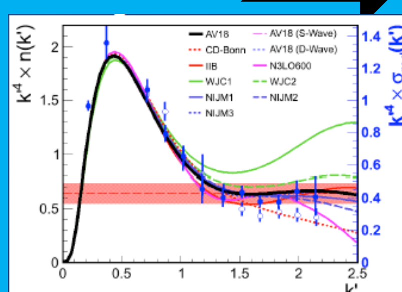
$$n(k) = \begin{cases} A_0 & k < k_F \\ C_0 / k^4 & k_F < k < \lambda k_F \\ 0 & k > \lambda k_F \end{cases}$$



	$E_{\rm sym}^{\rm kin}(\rho_0)$ [MeV]	γ $\pm 1\sigma(2\sigma)$
CFG	-10 ± 3	0.25 ± 0.05
FG	-10 ± 3	0.58 ± 0.05
	0	0.55 ± 0.06
	12.5	0.48 ± 0.10
	17	0.41 ± 0.13
Tsang *et al.* [6]	12.5	$0.7^{+0.1(0.35)}_{-0.2(0.3)}$

$c_0 = 4.16 \pm 0.95,$

$\lambda \approx 2.75 \pm 0.25$



O. Hen et al., Phys. Rev. C 91, 025803 (2015).

Can the drastically reduced γ be consistent with n - starts data ?

Analysis of Neutron Stars Observations Using a Correlated Fermi Gas Model

O. Hen,[1] A.W. Steiner,[2,3,4] E. Piasetzky,[1] and L.B. Weinstein[5]

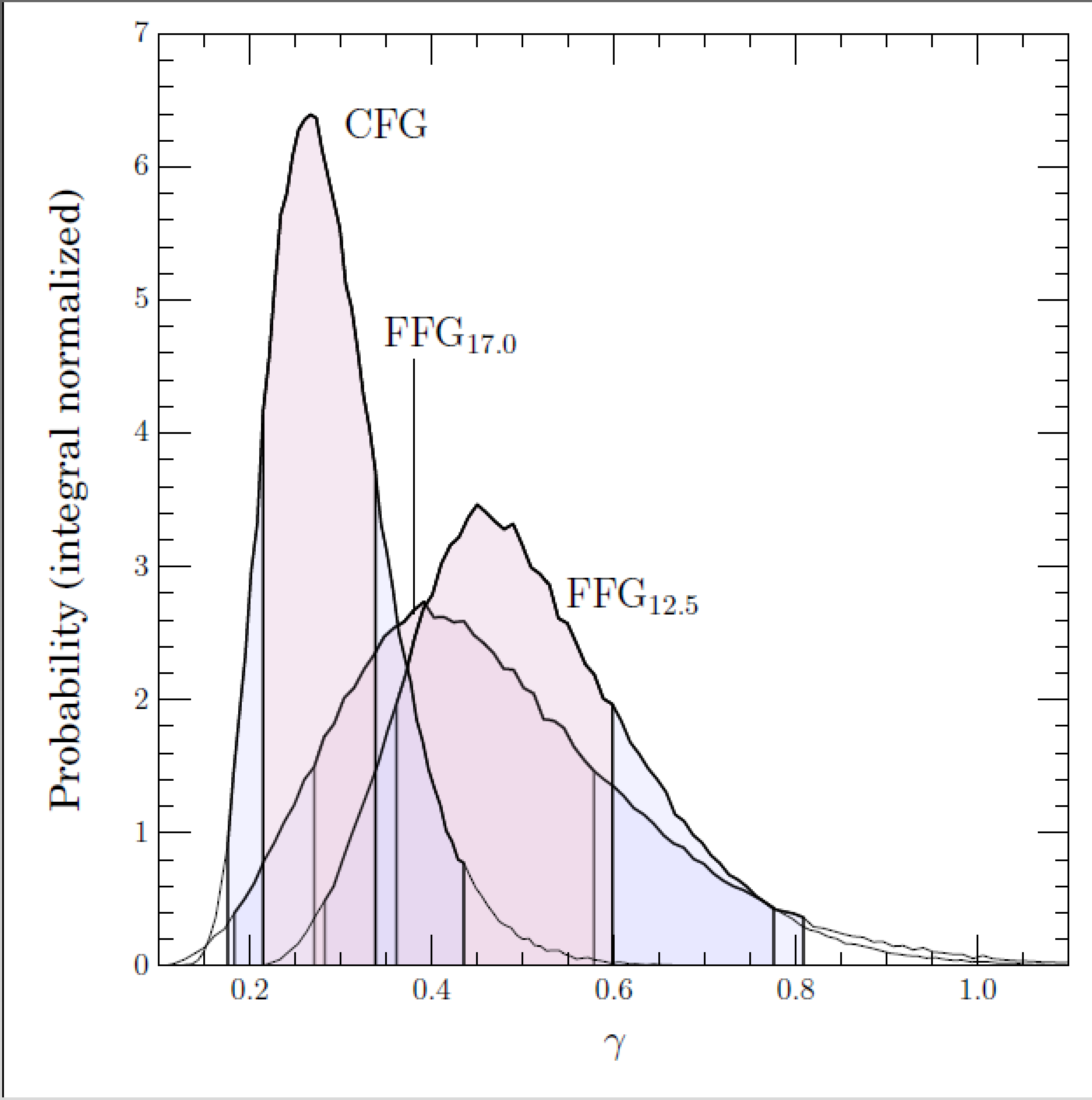
Global fit of NS EOS to NS mass/radius data taking into account:
terrestrial constrains and physical limitations (causality and hydro dynamical stability)

EOS: 3 energy – density regions
low (<15 MeV/fm^3), medium (15-350 MeV/fm^3), high (>350 MeV/fm^3)

A. W. Steiner, J. M. Lattimer, and E. F. Brown, Astrophys. J. **722**, 33 (2010), 1005.0811.

Data : The NS observations used in the analysis presented here include high precision mass extractions from Pulsar-timing measurements, simultaneous mass-radius extractions from photospheric radius expansion (PRE) X-ray burst measurements, and thermal spectra measurement of low-mass X-ray Binaries (LMXB)

Bayesian analysis using FFG and CFG ,models



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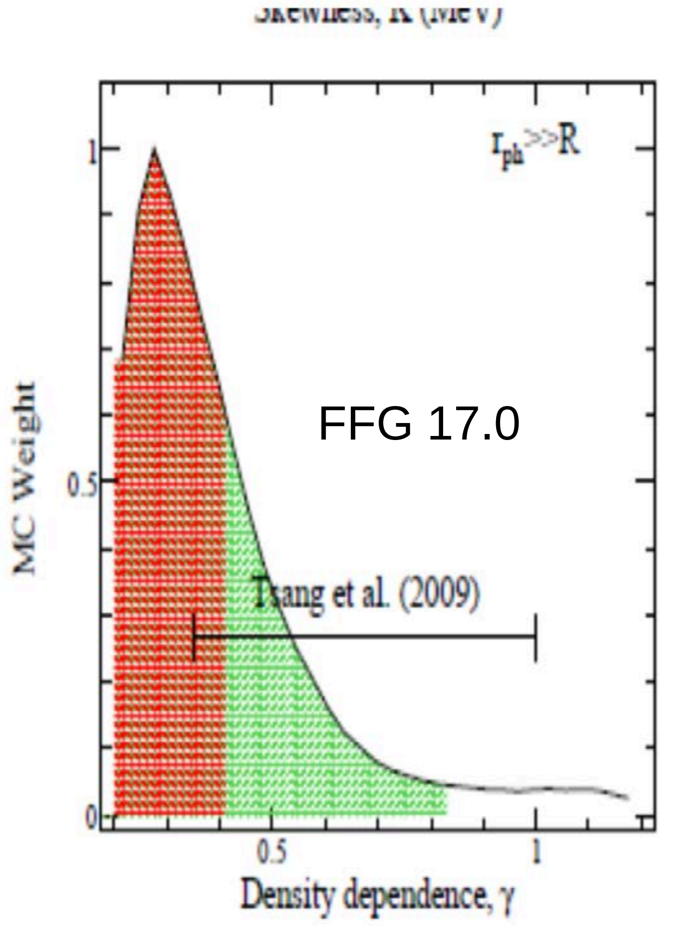
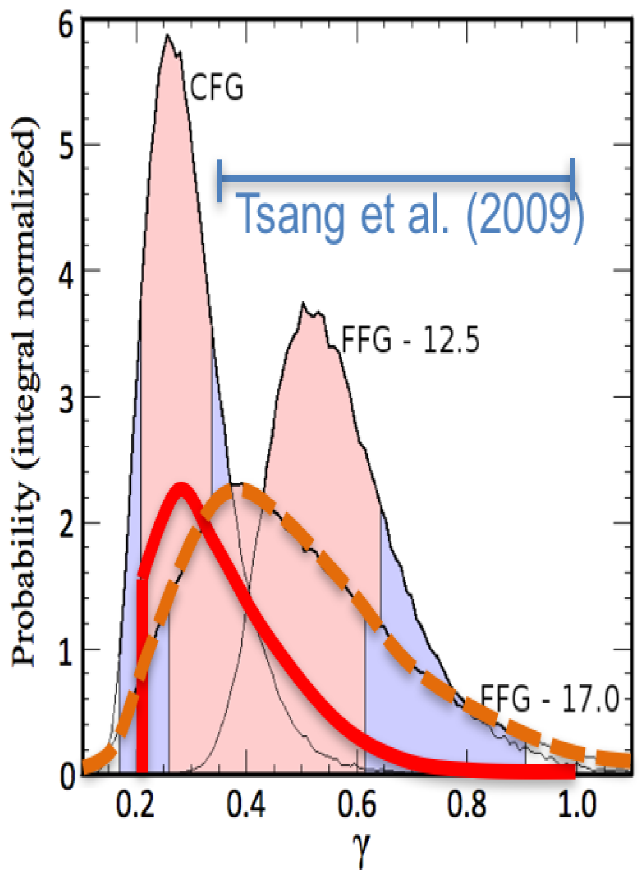
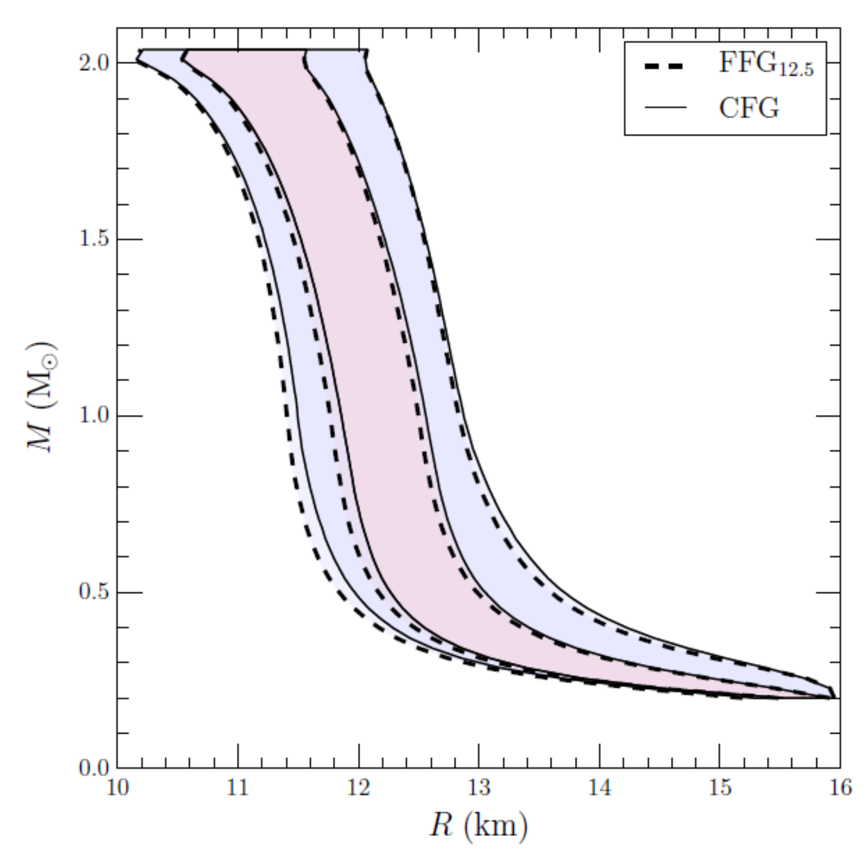
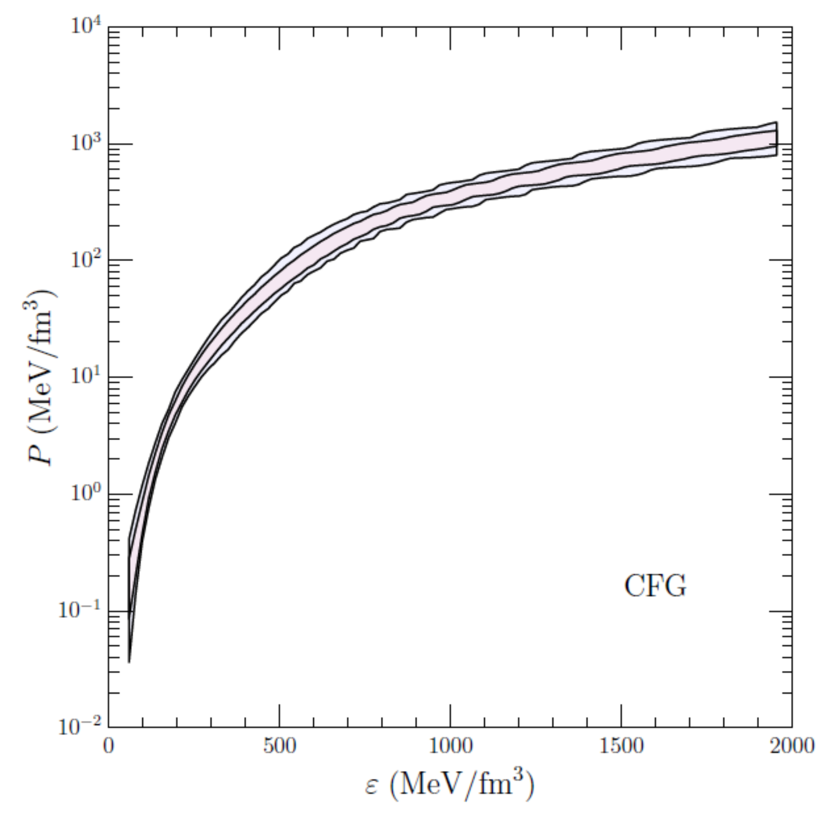
SLB astro phys J 722, 33 (2010)









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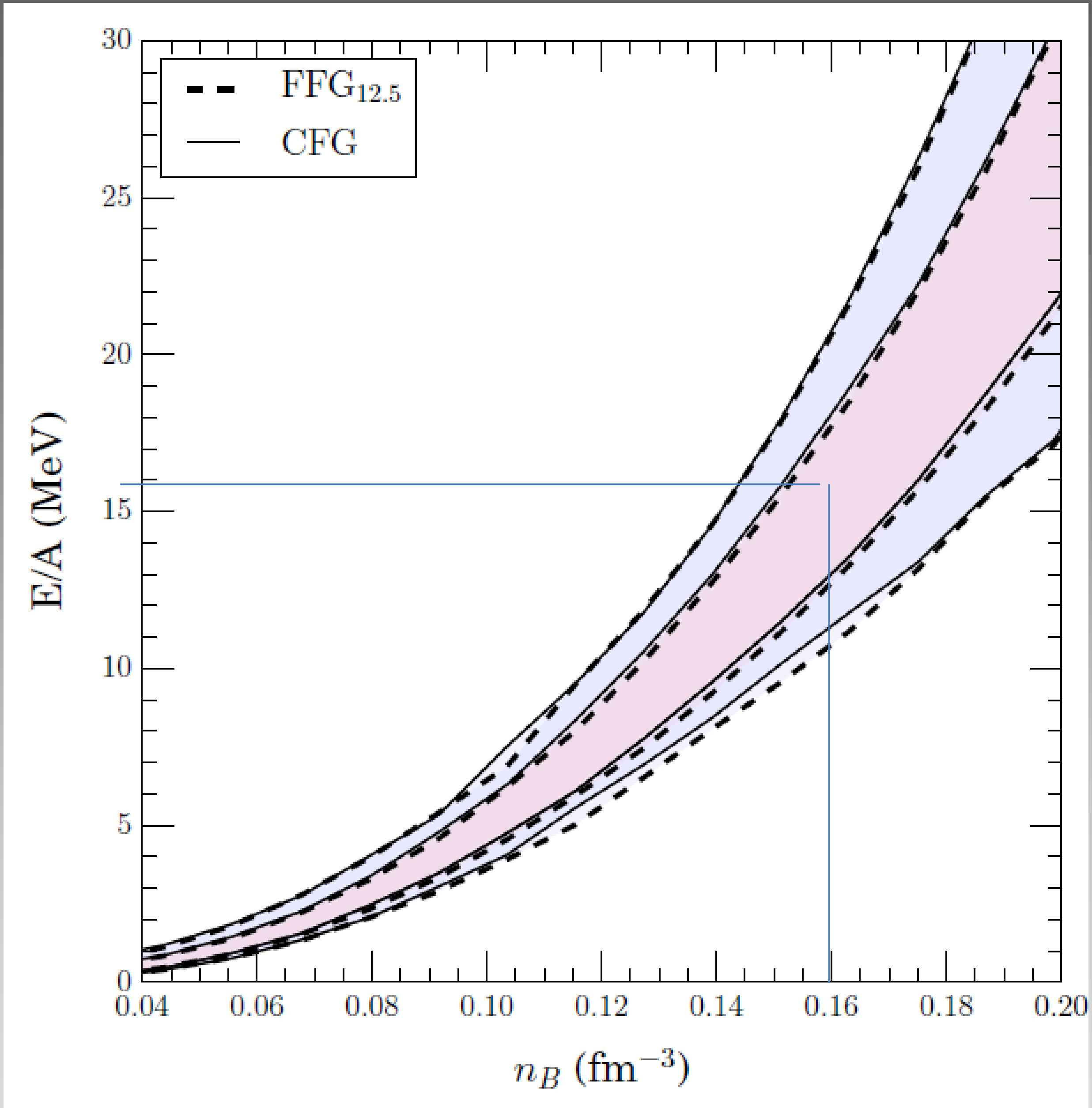

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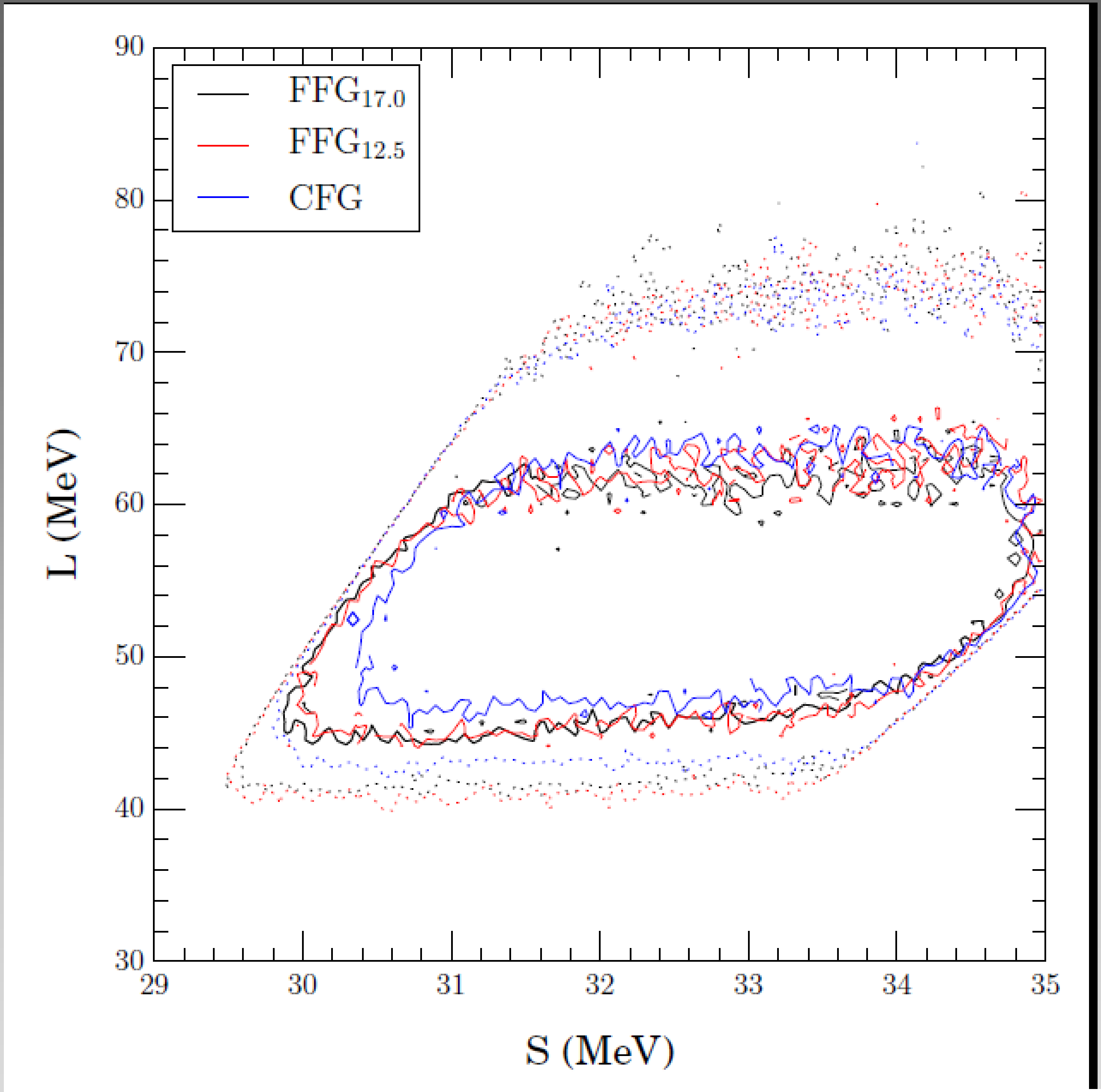

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Analysis of Neutron Stars Observations Using a Correlated Fermi Gas Model

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EOS global fits to Neutron Star Observations

Incorporating CFG model into global fits to neutron stars observables

- Data can be fit using both FFG and CFG models
- Most observables are insensitive to the use of FFG / CFG
- Resulting γ is very different:
  - CFG: 0.21 – 0.34
  - FFG (12.5): 0.42 – 0.64

Let me speculate:

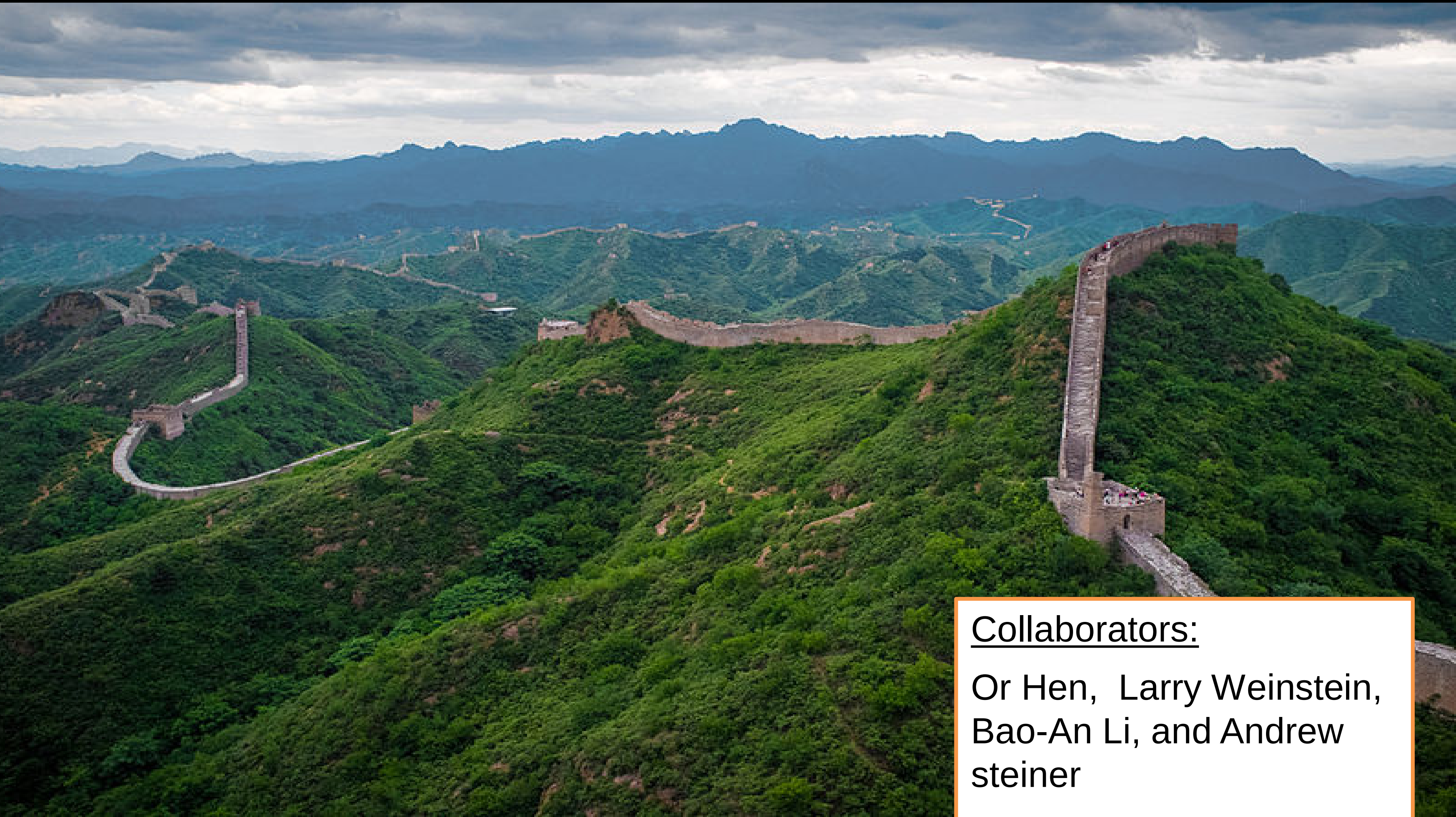
If calculations of heavy-ions collisions will be done with realistic momentum distribution (i.e. not ignoring SRC) the resulted density dependent of the potential symmetry (γ) energy will also be found to be soft.

See talk by

Or Hen Next generation studies of short-range correlations using electron, proton and gamma

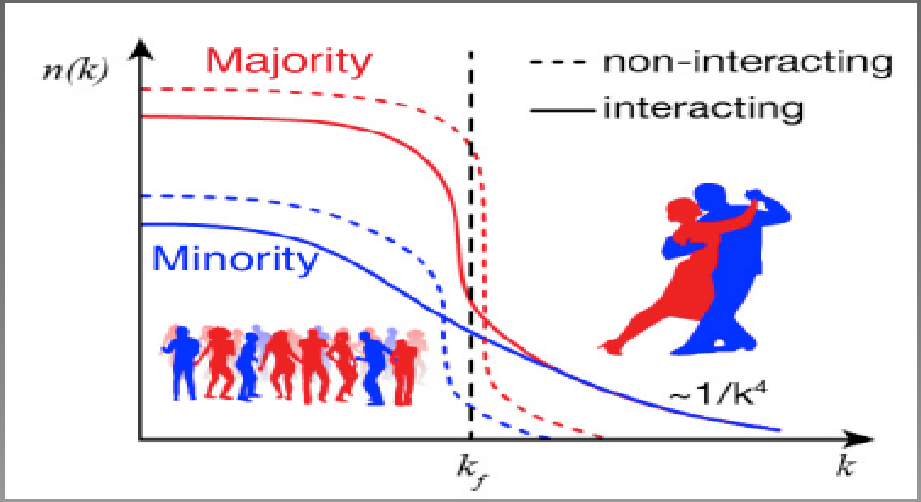
Acknowledgment

I would like to thank the organizers for the invitation.



<u>Collaborators:</u>

Or Hen, Larry Weinstein, Bao-An Li, and Andrew steiner



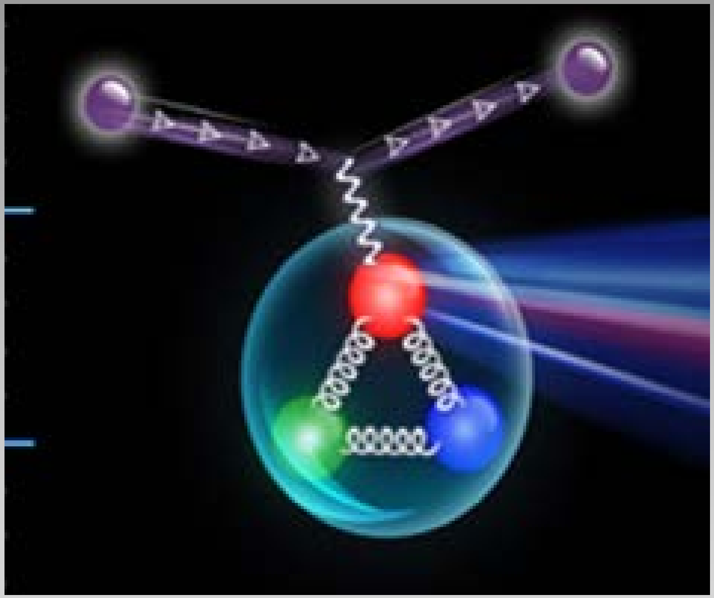
Neutron-skin in coordinate and proton-skin in momentum in heavy nuclei:

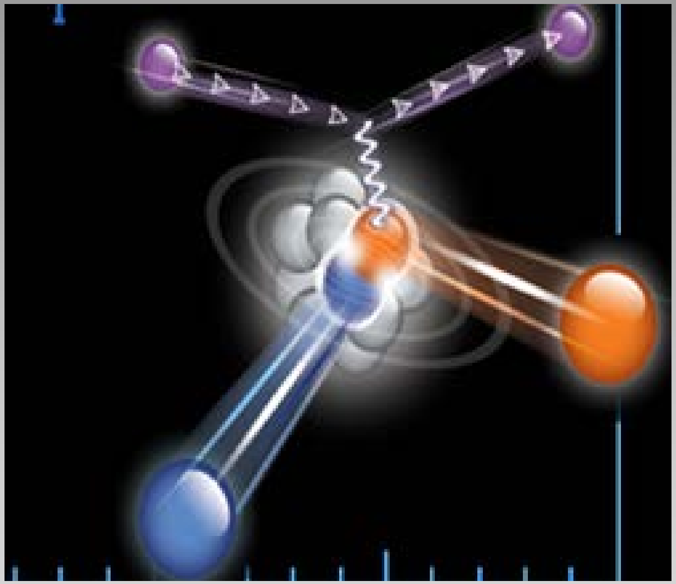
What we can learn from their correlation in an Extended+ Thomas-Fermi Approximation

Bao-An Li

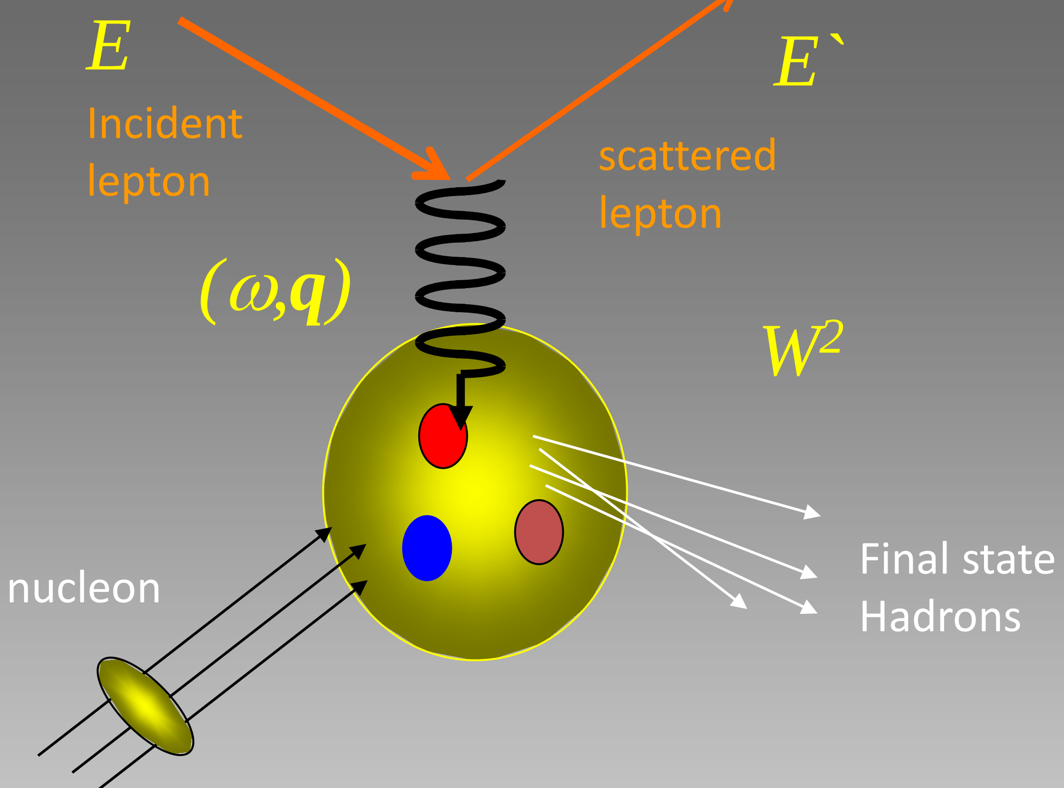
The fraction of high-momentum protons is larger in the skin then in the core.

The EMC effect and Short Range Correlation in nuclei





Deep Inelastic Scattering (DIS)



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

$$\omega = E' - E$$

$$x_B = \frac{Q^2}{2m\omega} \quad \left(= \frac{Q^2}{2(q \cdot p_T)}\right)$$

$$0 \le x_B \le 1$$

Electrons, muons, neutrinos

SLAC, CERN, HERA, FNAL, JLAB

E, E' 5-500 GeV

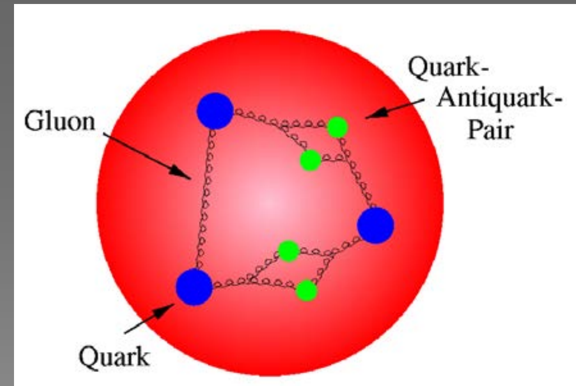
Q^2 5-50 GeV^2

w^2 >4 GeV^2

$0 \le X_B \le 1$

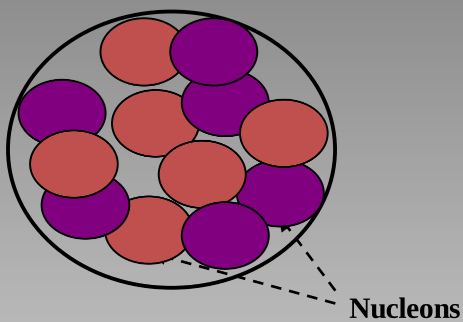
X_B gives the fraction of nucleon momentum carried by the struck parton

Information about nucleon vertex is contained in $F_1(x,Q^2)$ and $F_2(x,Q^2)$, the unpolarized structure functions



DIS scale: several tens of GeV

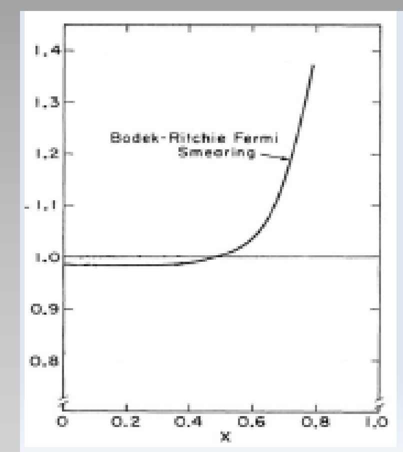
Nucleon in nuclei are bound by ~MeV

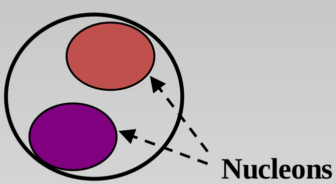


(My) Naive expectations :

DIS off a bound nucleon = DIS off a free nucleon

(Except for small Fermi momentum corrections)



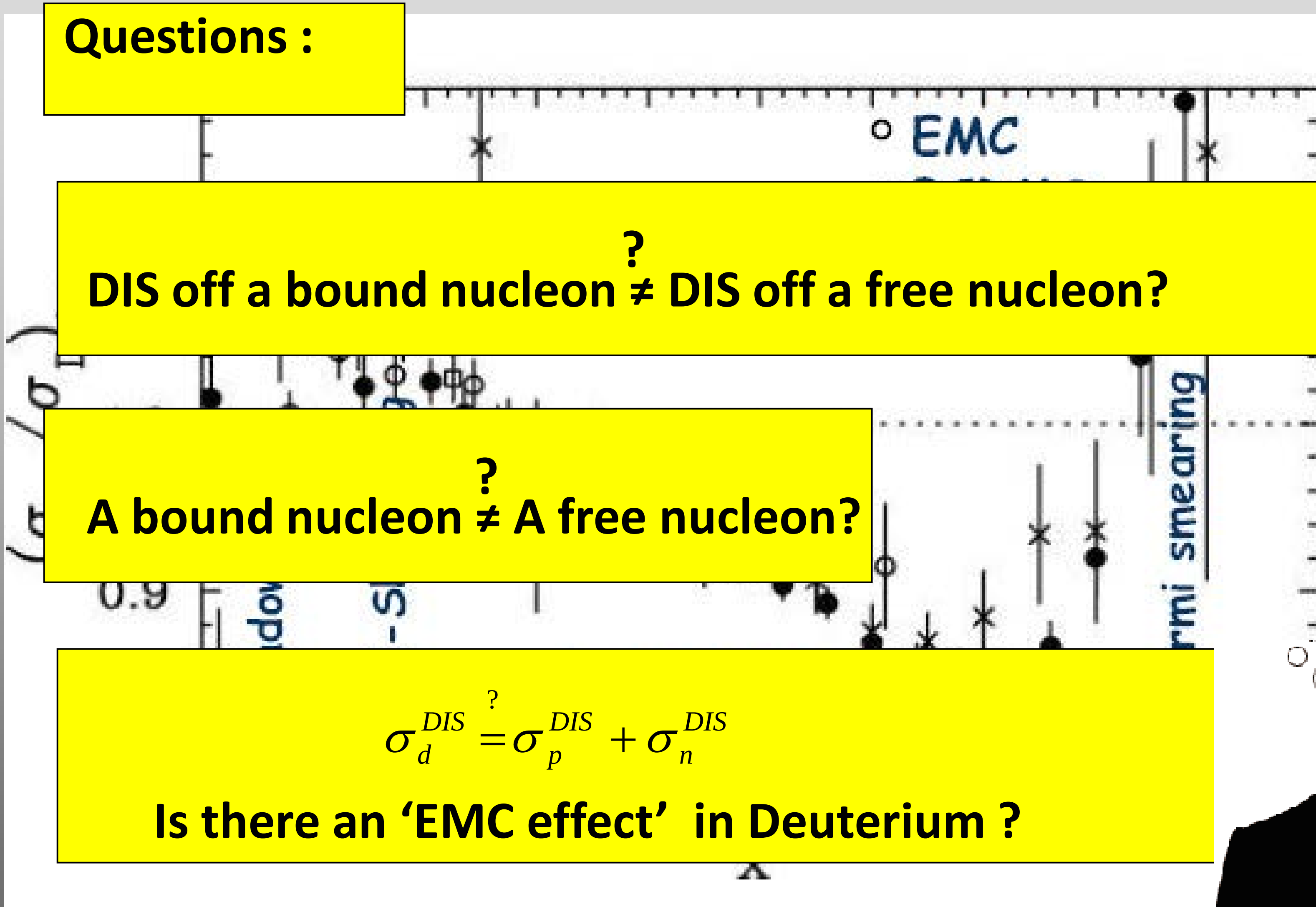


Deuteron: binding energy ~2 MeV

Average nucleons separation ~2 fm

DIS off a deuteron = DIS off a free proton neutron pair

The European Muon Collaboration (EMC) effect



Questions :

DIS off a bound nucleon $\stackrel{?}{\neq}$ DIS off a free nucleon?

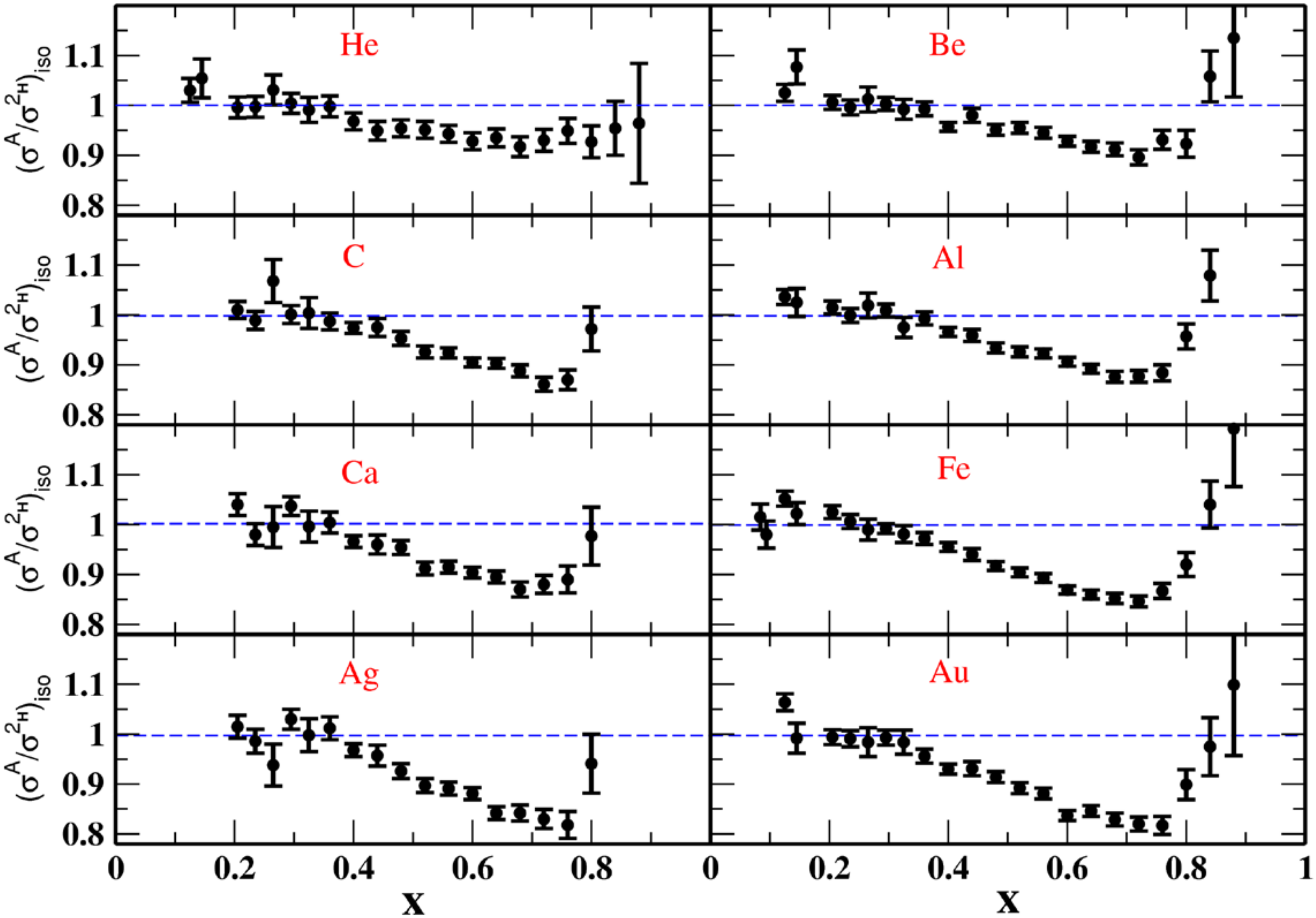
A bound nucleon $\stackrel{?}{\neq}$ A free nucleon?

$$\sigma_d^{DIS} \stackrel{?}{=} \sigma_p^{DIS} + \sigma_n^{DIS}$$

Is there an 'EMC effect' in Deuterium ?

σ^{DIS} per nucleon in nuclei $\neq$ σ^{DIS} per nucleon in deuteron

SLAC E139

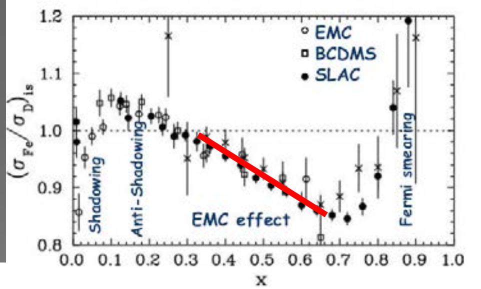


Data from CERN SLAC JLab 1983- 2009

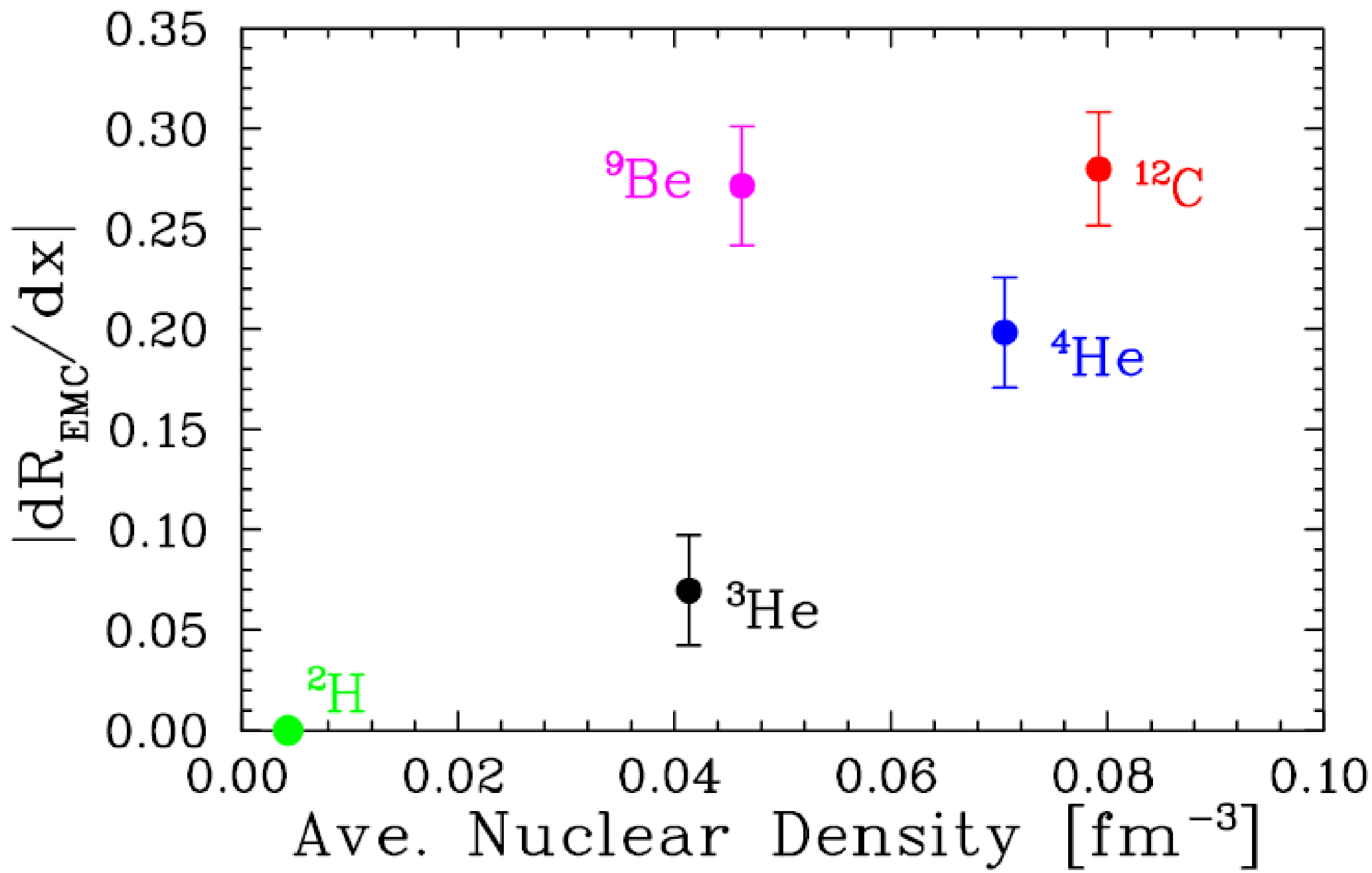
EMC collaboration, Aubert et al. PL B 123,275 (1983)

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

A review of data collected during first decade, Arneodo, Phys. Rep. 240,301(1994)



EMC is a not a bulk property of nuclear medium



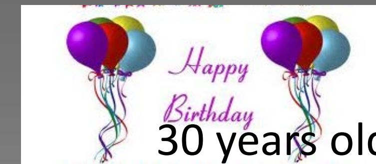
JLab / Hall C

. Seely et al. PRL 103, 202301 (2009)

Scaled nuclear density = *(A-1)/A <ρ>*
→ remove contribution from struck nucleon

<ρ> from ab initio few-body calculations
→ *[**S.C. Pieper and R.B. Wiringa,** Ann. Rev. Nucl. Part. Sci 51, 53 (2001)]*

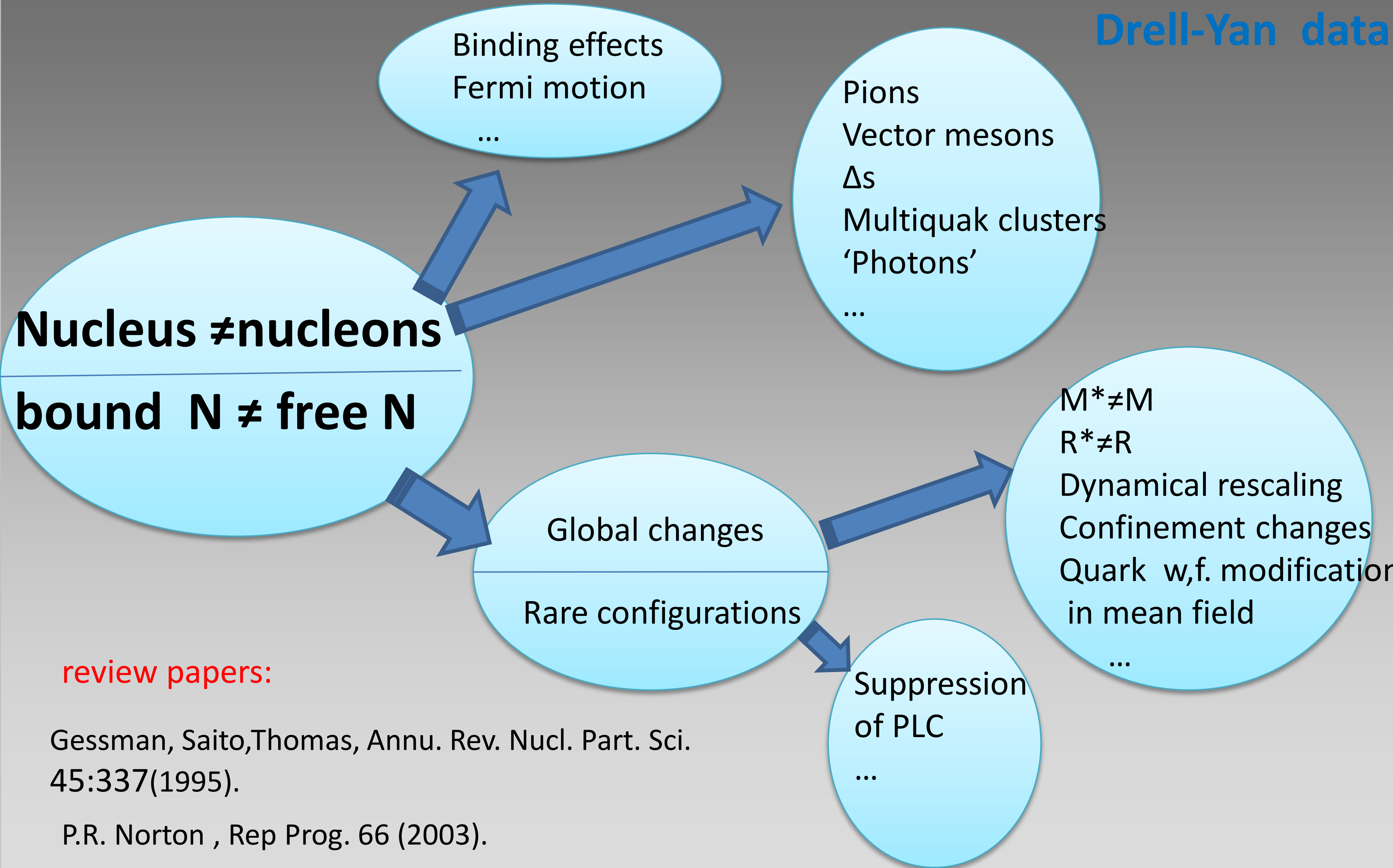
The European Muon Collaboration (EMC) effect



Well established measured effect with no consensus as to its origin

Models of the EMC effect

Drell-Yan data



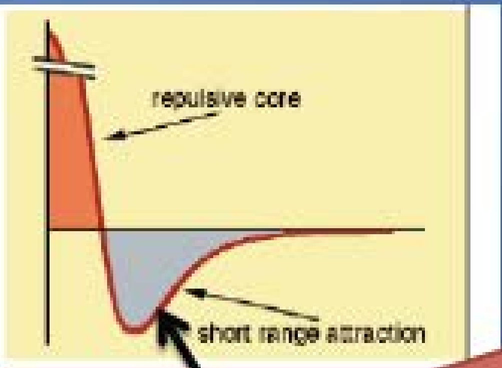
review papers:

Gessman, Saito,Thomas, Annu. Rev. Nucl. Part. Sci. 45:337(1995).

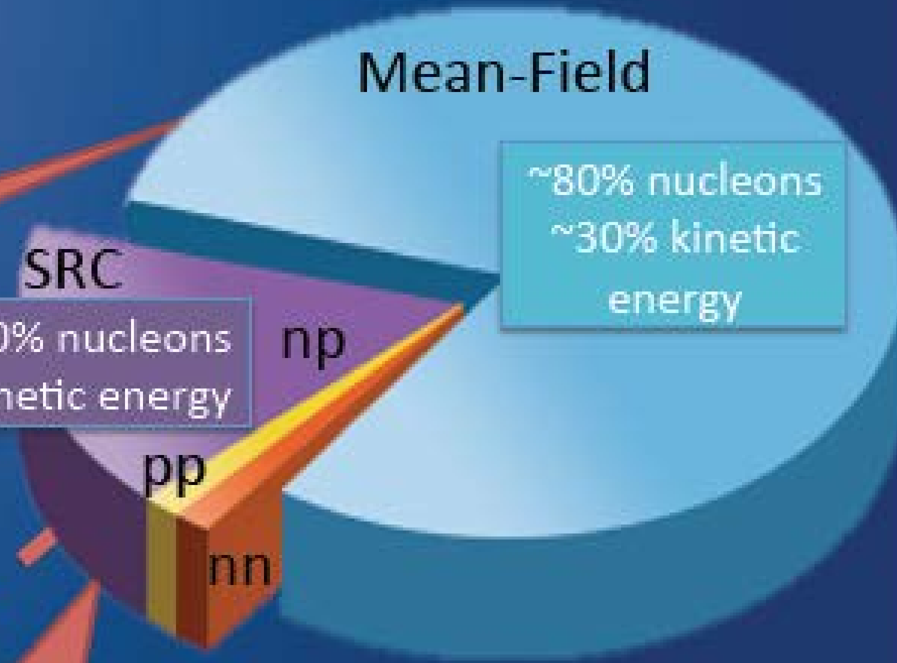
P.R. Norton , Rep Prog. 66 (2003).

Frankfurt and Strikman (2012)

Where is the EMC Effect?



Largest attractive force



Mean-Field

SRC

High local nuclear matter density, large momentum, large off shell, large virtuality

$$\upsilon = p^2 - m^2$$

Inclusive electron scattering A(e,e')

Deep Inelastic Scattering

→ Partonic (quark) Structure of **Hadrons**

Inclusive Scattering at $X_B>1$ A(e,e')

→ Partonic (nucleon) Structure of **Nucleus**

Comparing magnitude of EMC effect and SRC scaling factors

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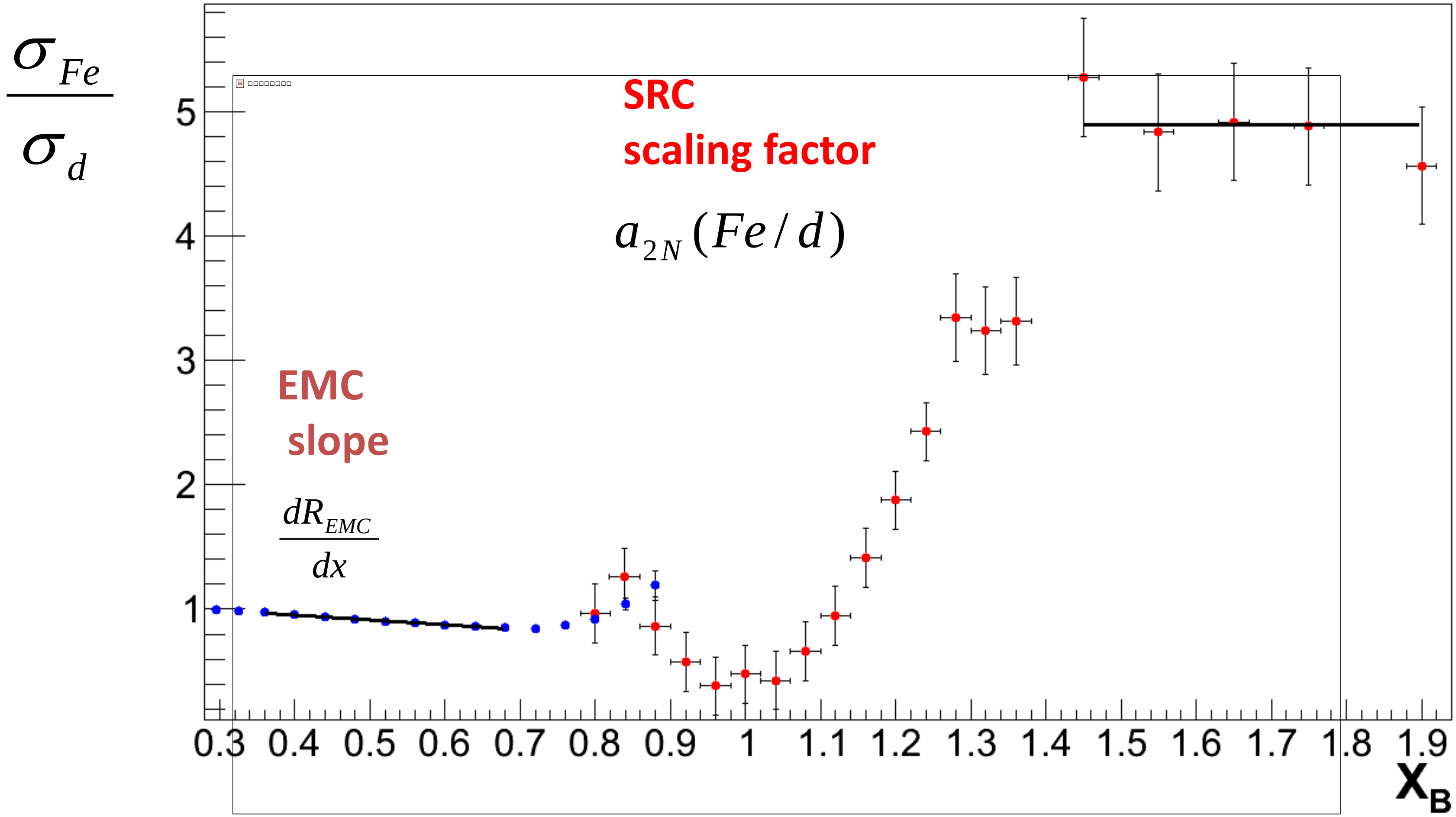


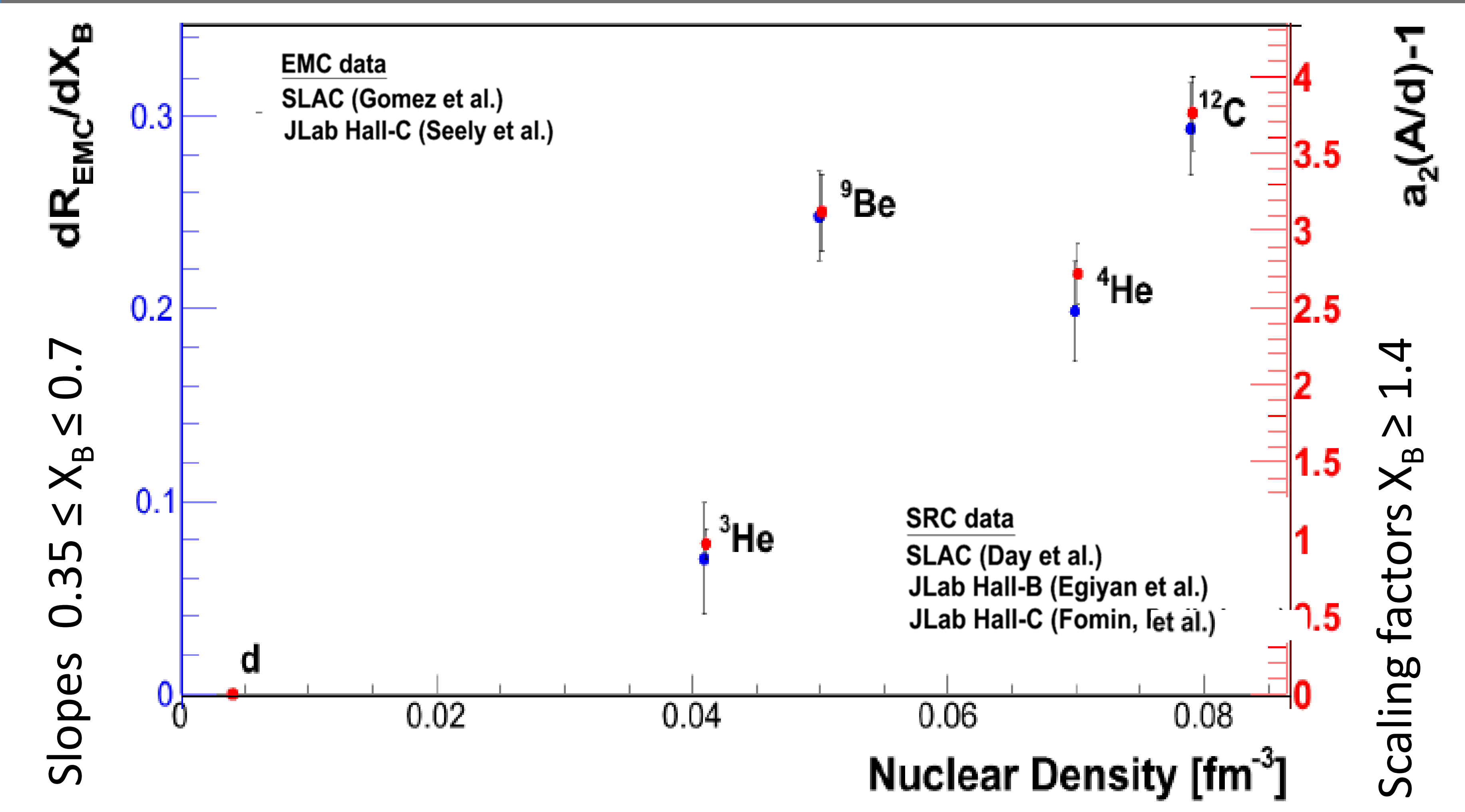
SLAC data:

Gomez et al., Phys. Rev. D49, 4348 (1983).

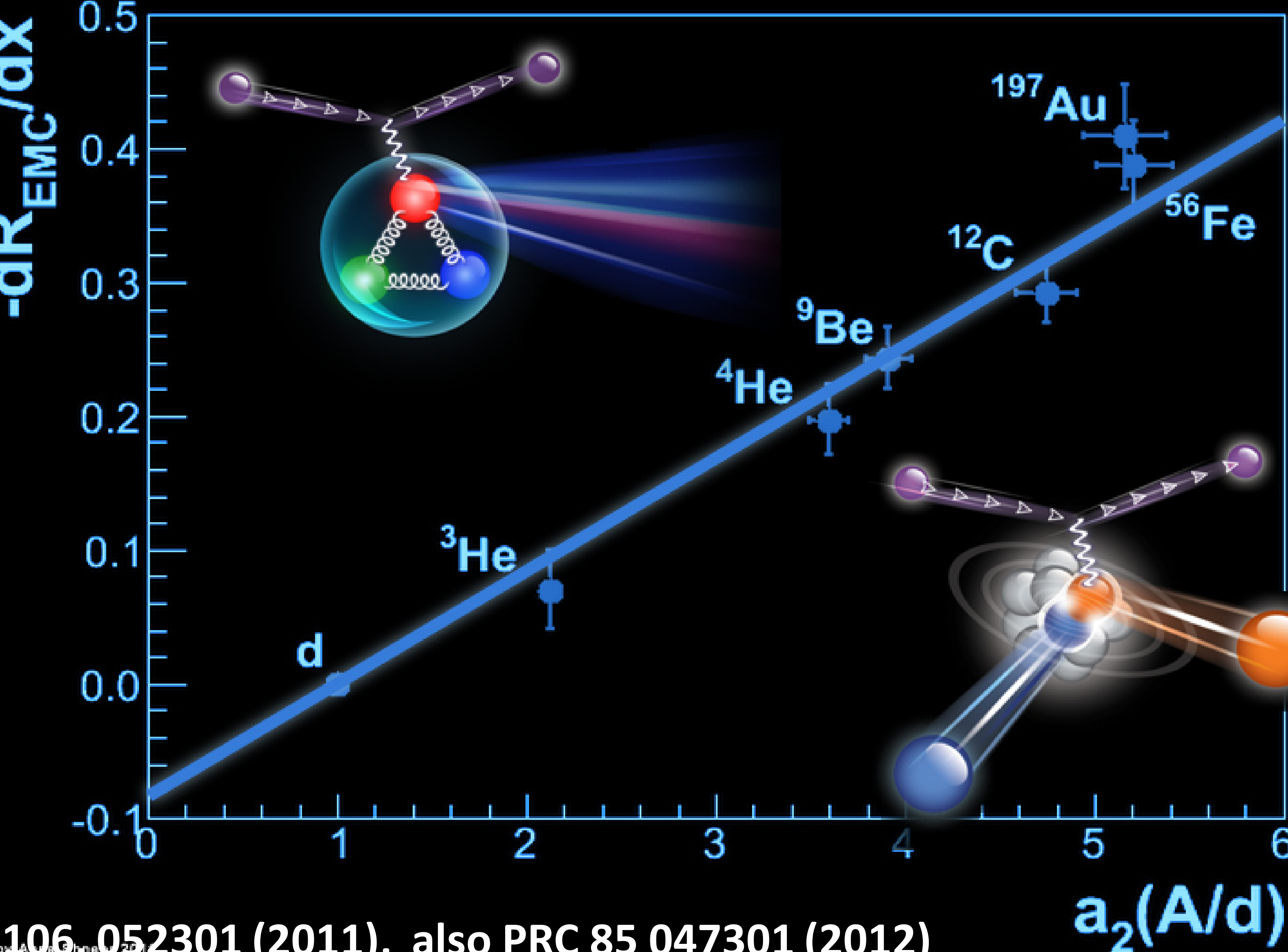
Q^2=2, 5, 10, 15 GeV/c^2 (averaged)

Frankfurt, Strikman, Day, Sargsyan, Phys. Rev. C48 (1993) 2451.

Q^2=2.3 GeV/c^2



EMC data
SLAC (Gomez et al.)
JLab Hall-C (Seely et al.)
SRC data
SLAC (Day et al.)
JLab Hall-B (Egiyan et al.)
JLab Hall-C (Fomin, et al.)
d
3He
9Be
4He
12C
Nuclear Density [fm-3]
dREMC/dXB
Slopes 0.35 ≤ XB ≤ 0.7
a2(A/d)-1
Scaling factors XB ≥ 1.4



EMC

SRC

PRL 106, 052301 (2011), also PRC 85 047301 (2012)

Deuteron is not a free np pair

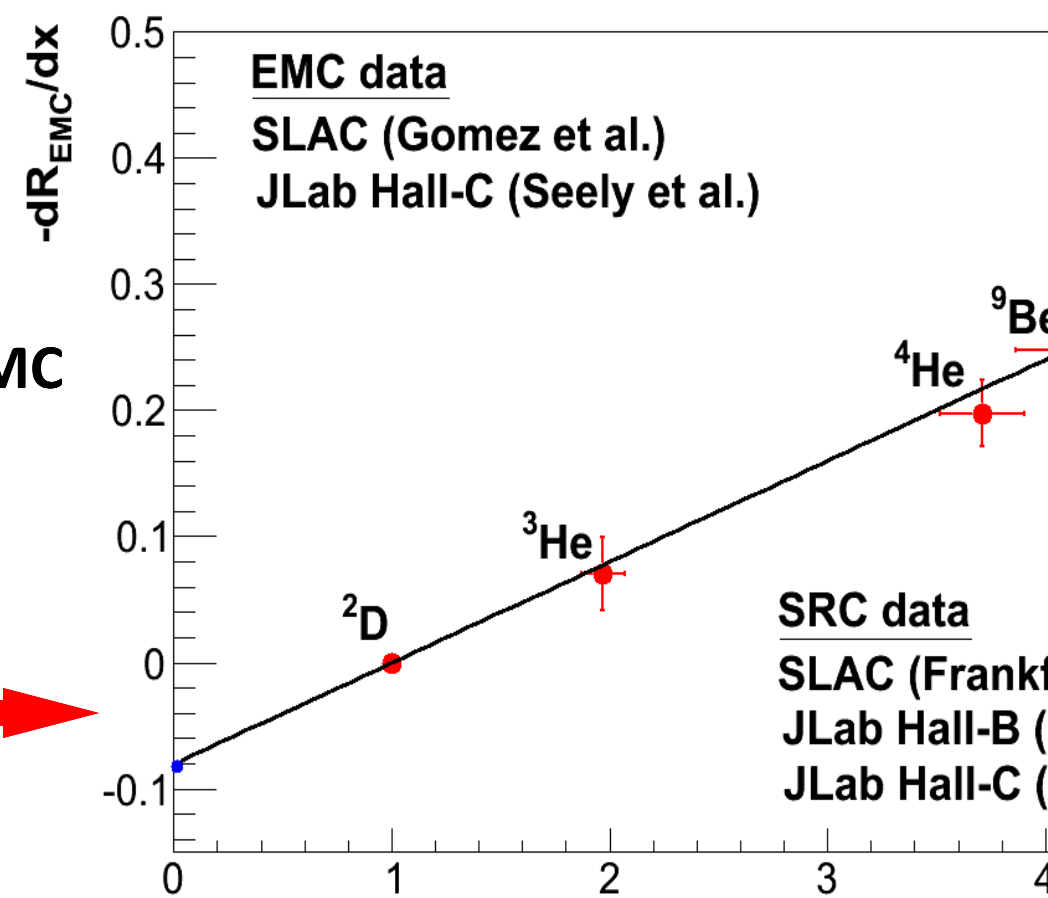
$$\sigma_d \neq \sigma_p + \sigma_n$$

$$\sigma_d \Big/ \sigma_p + \sigma_n \approx \sigma_{^3He} \Big/ \sigma_d$$

EMC

The slopes for
$0.35 \le X_B \le 0.7$

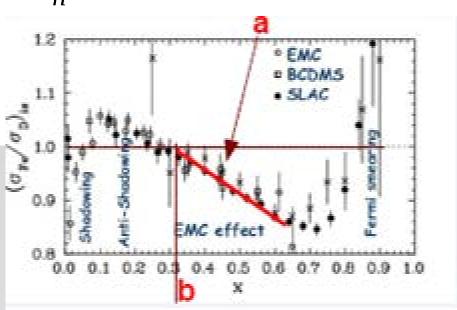
0.09±0.01



SRC

$a_{2N}(A/d)$

$$\frac{\sigma_d}{\sigma_p + \sigma_n}(x = 0.6) \approx \mathbf{0.98}$$



SRC=0 free nucleons

EMC/SRC prediction Agrees with BONUS

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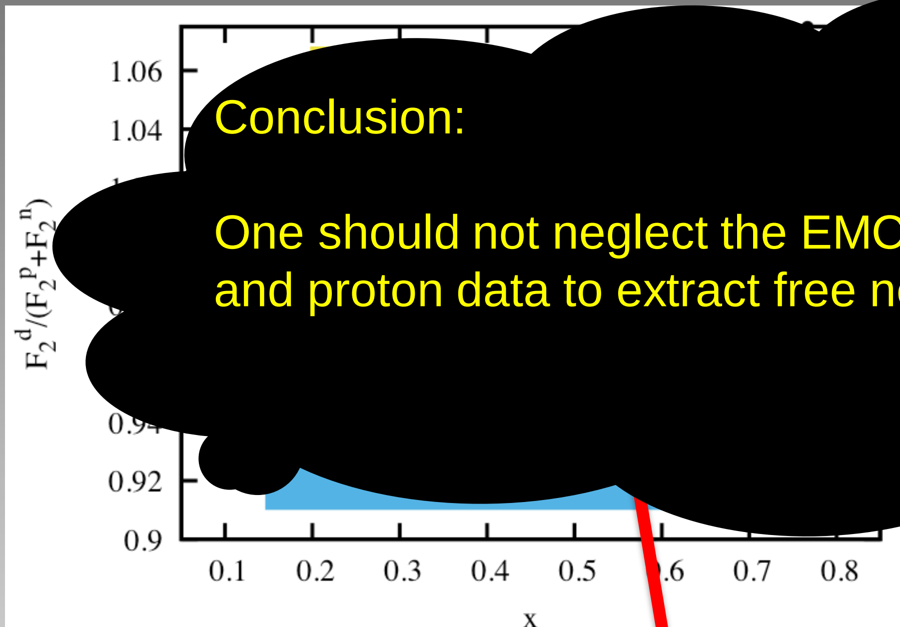
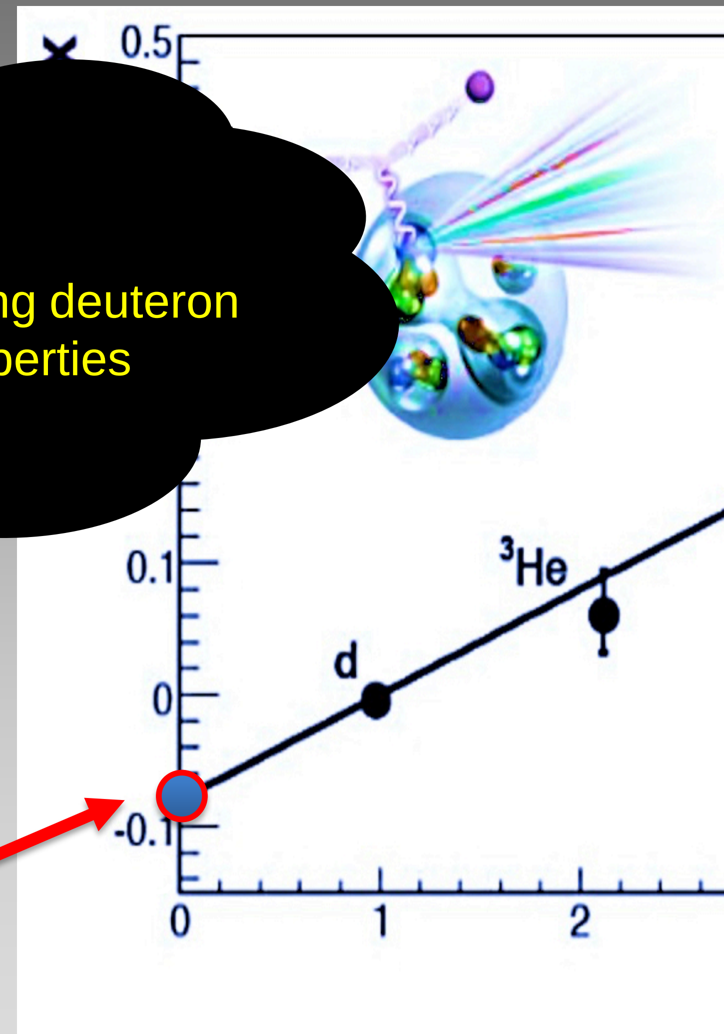
EMC effect in the Deuteron

K. Griffioen *et al.* [BONUS collaboration] preliminary result.



Conclusion:

One should not neglect the EMC effect using deuteron and proton data to extract free neutron properties



Slope:

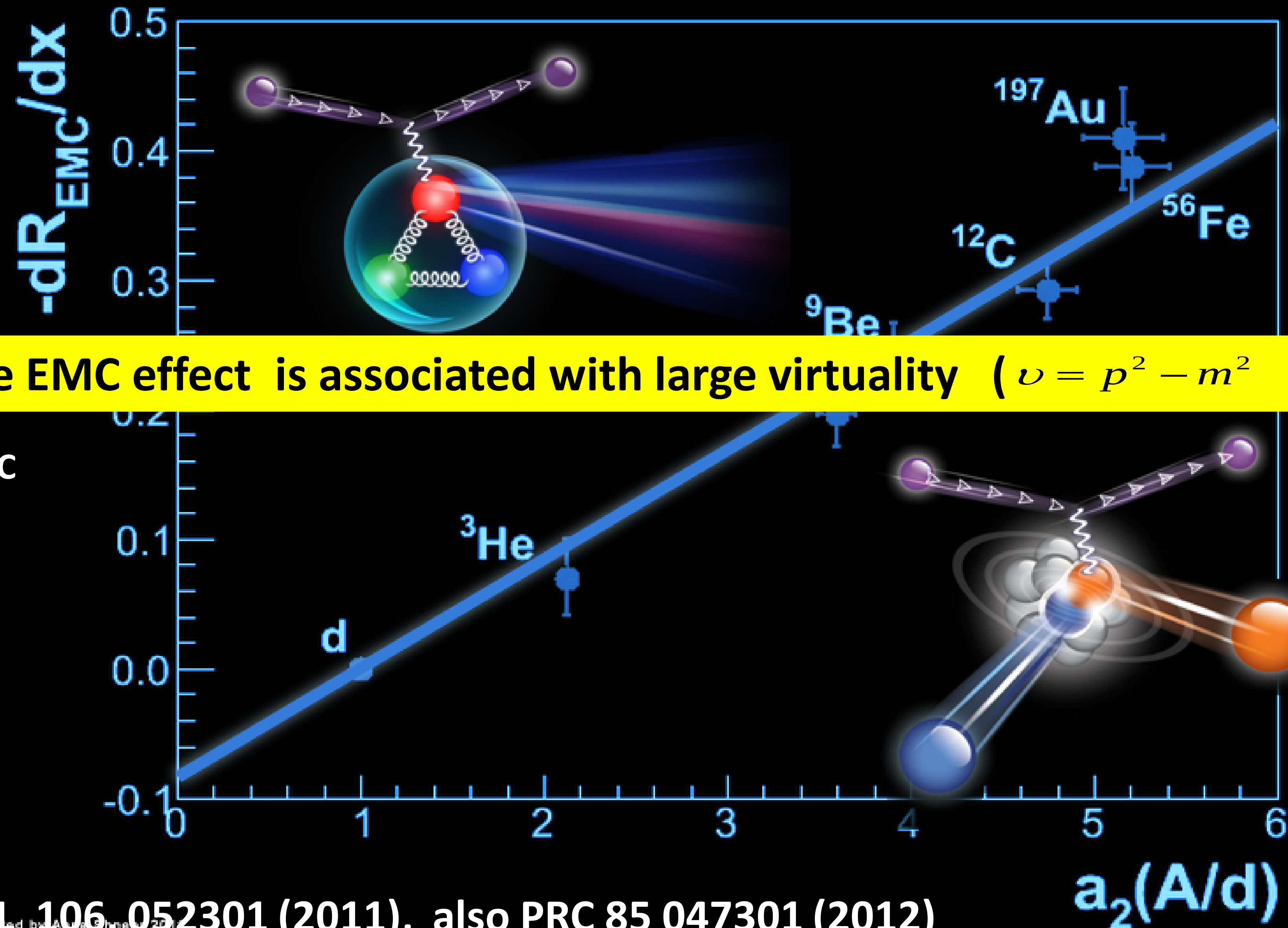
BONUS: -0.10(5)

EMC/SRC: -0.09(1)

arXiv:1506.0087

Weinstein et al. PRL 106, 052301 (2011)

O. Hen et al., Phys. Rev. C 85, 047301 (2012);



the EMC effect is associated with large virtuality ($\upsilon = p^2 - m^2$)

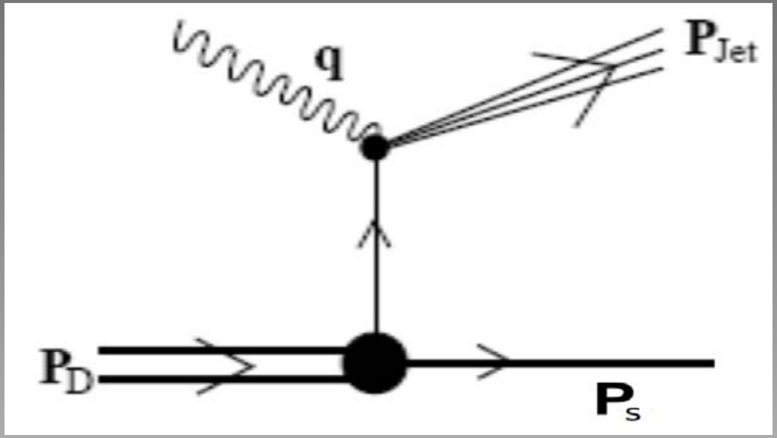
EMC

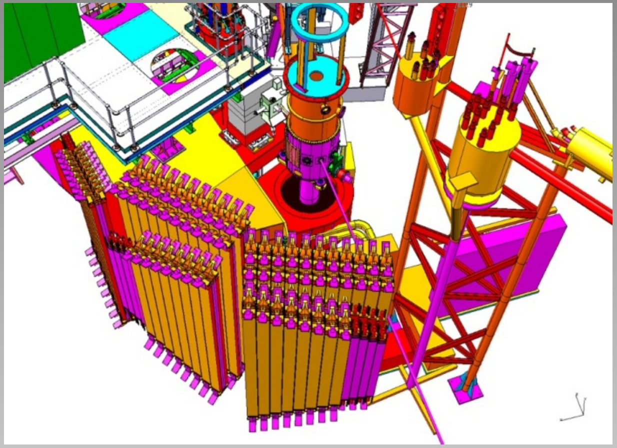
SRC

PRL 106, 052301 (2011), also PRC 85 047301 (2012)

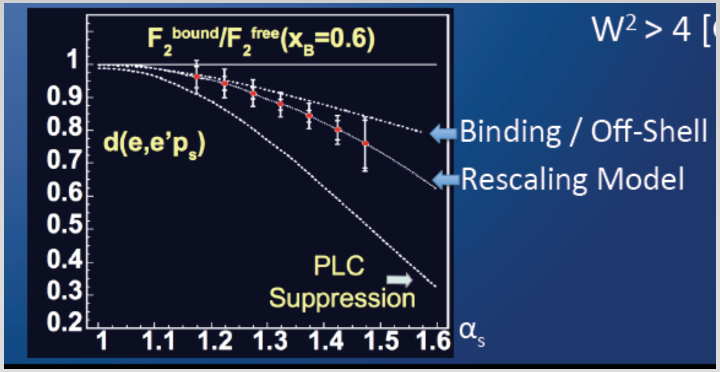
Hypothesis can be checked by measuring DIS off Deuteron tagged with high momentum recoil nucleon

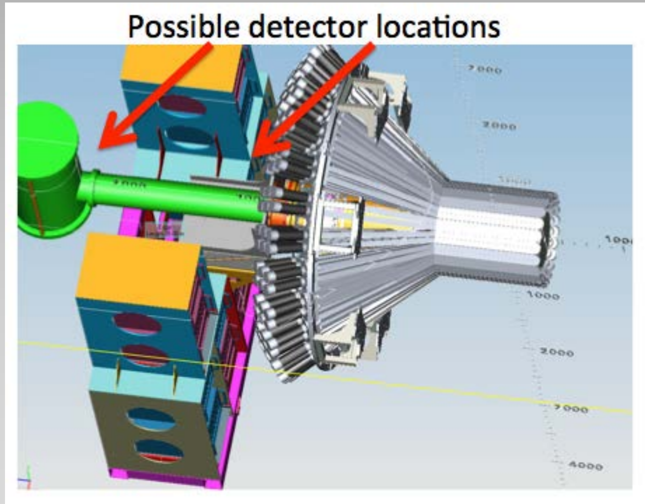
spectator tagging ⇒ large effect





12 GeV JLab approved experiment E 12-11-107





12 GeV approved experiment CLAS E12-11-003a

Short distance structure of nuclei

1 The probability for a nucleon to have momentum ≥ 300 MeV / c in medium nuclei is ~25%

2 More than ~90% of all nucleons with momentum ≥ 300 MeV / c belong to 2N-SRC.

1 2 → Most of kinetic energy of nucleon in nuclei is carried by nucleons in 2N-SRC.

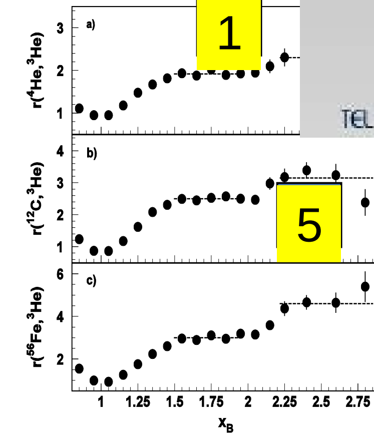
3 Probability for a nucleon with momentum 300-600 MeV / c to belong to np-SRC is ~18 times larger than to belong to pp-SRC.

1 2 3 → In light asymmetric nuclei :

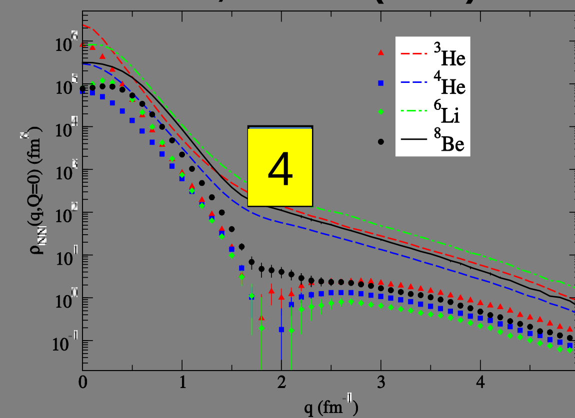
$$\left\langle k_{minority} \right\rangle > \left\langle k_{majority} \right\rangle$$

In heavy asymmetric nuclei ?

CLAS / HALL B

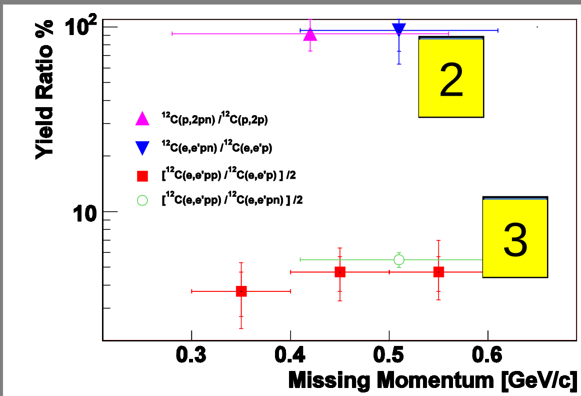


. PRL. 96, 082501 (2006)



PRL 98,132501 (2007).

EVA / BNL and Jlab / HALL A

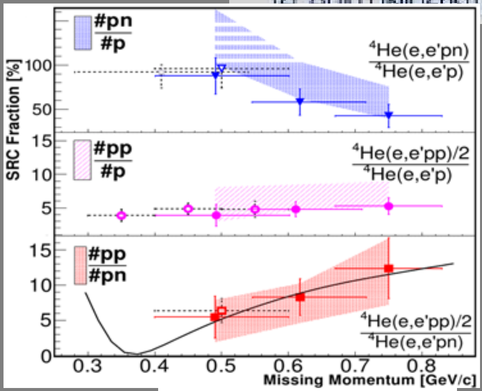


PRL 162504(2006); Science 320, 1476 (2008).

Short distance structure of nuclei

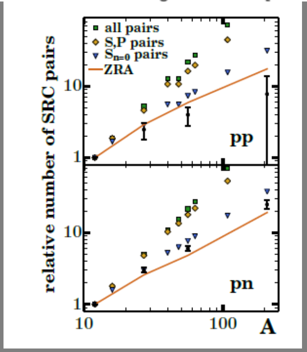
4

Dominant NN force in the 2N-SRC is tensor force.



The high momentum tail (300-600 MeV/c) is dominated by
L=0,2 S=1 np –SRC pairs.

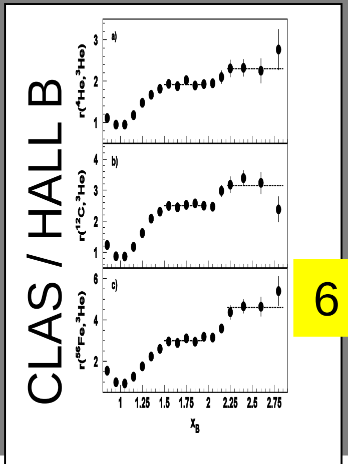
4



These pairs are produced from Sn=0 IPM pairs

6

Three nucleon SRC are present in nuclei. They contribute about an order of magnitude less than the 2N_SRC



6

Isospin structure ? Geometry ? Abundance ?

Summary – relevant of Correlations

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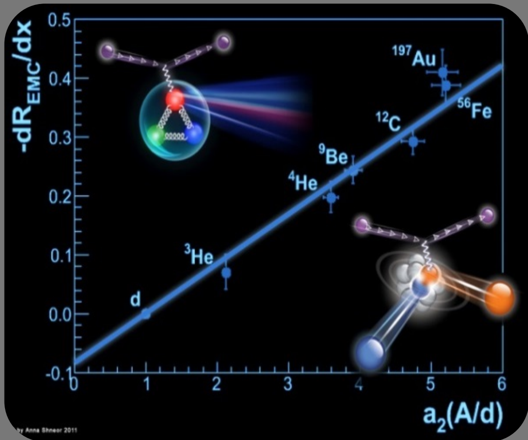
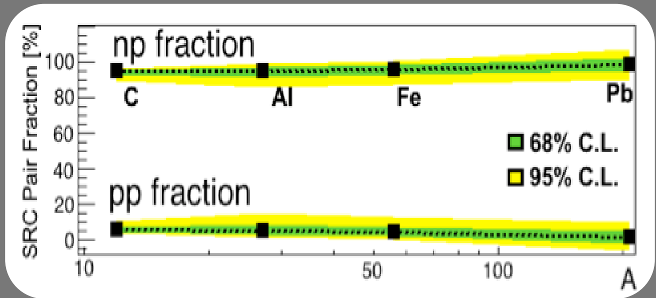
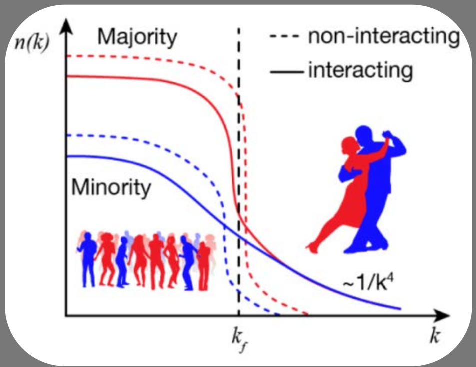
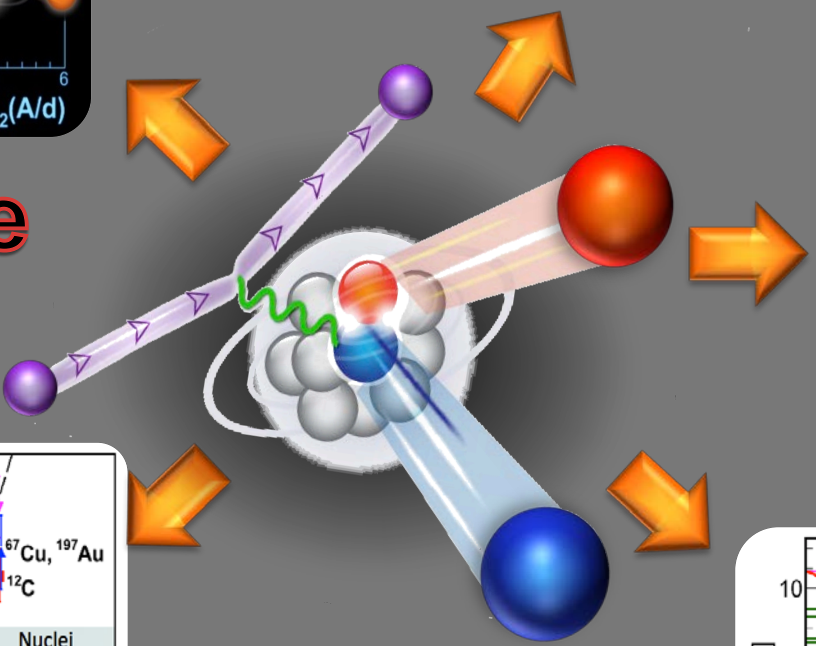




Nuclear

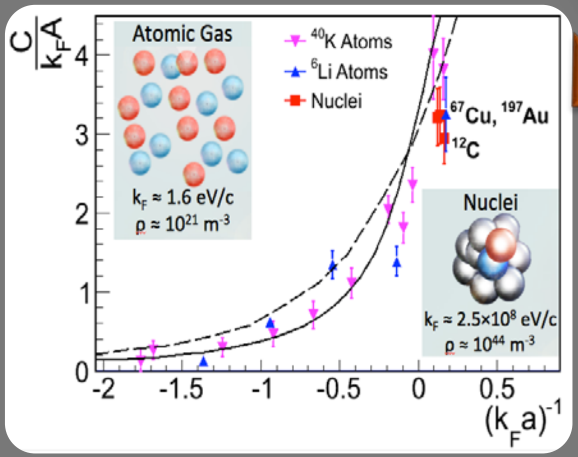


Particle



3N-SRC

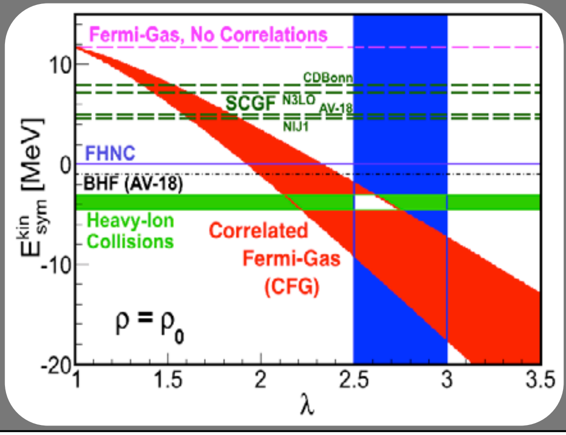
Atomic



Contact term

Astro

Symmetry energy



Summary – proposed experiments

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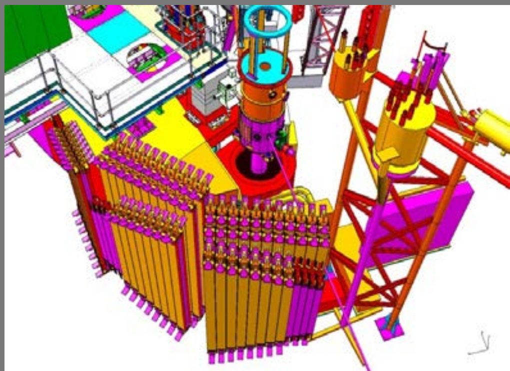
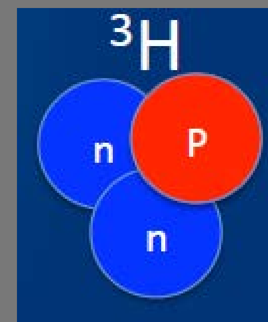
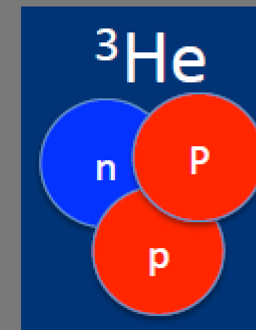
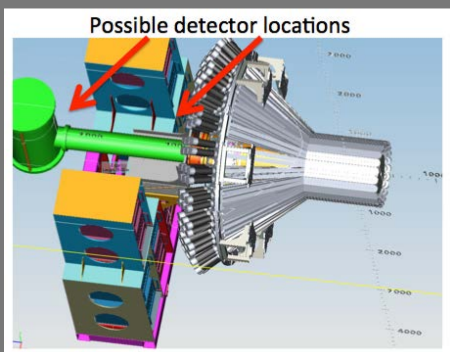


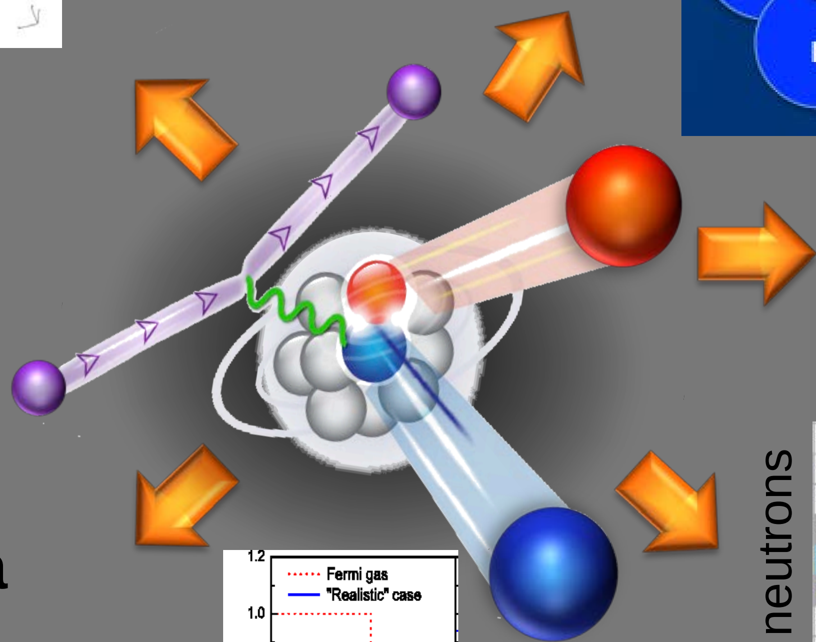
JLab Hall C:
E12-11-107

JLab









JLab Hall A:
E12-14-011

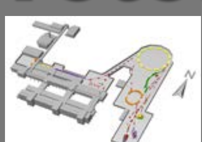
JLab Hall B:
E12-11-003a

^{32}Cl	^{33}Ar		Ca							
^{33}Cl	^{34}Ar	^{35}K		21					Z	
^{34}Cl	^{35}Ar	^{36}K	^{37}Ca	Sc	22					
^{35}Cl	^{36}Ar	^{37}K	^{38}Ca		Ti	23				
^{36}Cl	^{37}Ar	^{38}K	^{39}Ca	^{40}Sc	^{41}Ti	V	24			
^{37}Cl	^{38}Ar	^{39}K	^{40}Ca	^{41}Sc	^{42}Ti		Cr	25		N
^{38}Cl	^{39}Ar	^{40}K	^{41}Ca	^{42}Sc	^{43}Ti	^{44}V	^{45}Cr	Mn	26	
^{39}Cl	^{40}Ar	^{41}K	^{42}Ca	^{43}Sc	^{44}Ti	^{45}V	^{46}Cr		Fe	27
^{40}Cl	^{41}Ar	^{42}K	^{43}Ca	^{44}Sc	^{45}Ti	^{46}V	^{47}Cr	^{48}Mn	^{49}Fe	Co
^{41}Cl	^{42}Ar	^{43}K	^{44}Ca	^{45}Sc	^{46}Ti	^{47}V	^{48}Cr	^{49}Mn	^{50}Fe	^{51}Co
^{42}Cl	^{43}Ar	^{44}K	^{45}Ca	^{46}Sc	^{47}Ti	^{48}V	^{49}Cr	^{50}Mn	^{51}Fe	^{52}Co
^{43}Cl	^{44}Ar	^{45}K	^{46}Ca	^{47}Sc	^{48}Ti	^{49}V	^{50}Cr	^{51}Mn	^{52}Fe	^{53}Co
^{44}Cl	^{45}Ar	^{46}K	^{47}Ca	^{48}Sc	^{49}Ti	^{50}V	^{51}Cr	^{52}Mn	^{53}Fe	^{54}Co
28	^{46}Ar	^{47}K	^{48}Ca	^{49}Sc	^{50}Ti	^{51}V	^{52}Cr	^{53}Mn	^{54}Fe	^{55}Co
	29	^{48}K	^{49}Ca	^{50}Sc	^{51}Ti	^{52}V	^{53}Cr	^{54}Mn	^{55}Fe	^{56}Co

Add 8 f7/2 neutrons

Add 8 protons

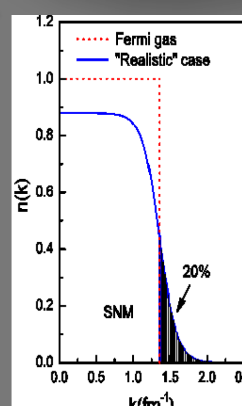
Proton facility



GSI / FAIR

Dubna

Nuclotron



Migdal jump

Acknowledgment

I would like to thank the organizers for the invitation.

Collaborators:

Or Hen, Larry Weinstein, Shalev Gilad, Doug Higinbothan, Steve Wood, John Watson

Misak Sargsian, Mark Strikman, Leonid Frankfurt, Gerald Miller

Some do not like them

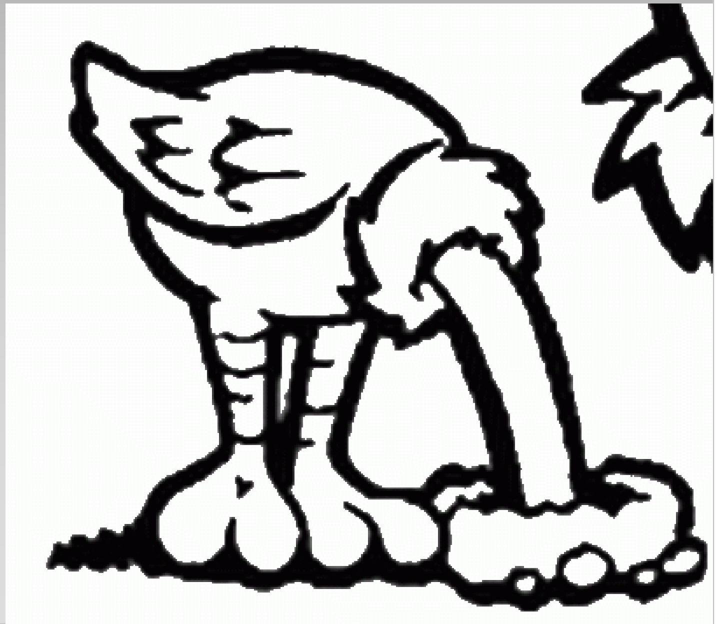
From the perspective of nuclear many-body calculations short-range correlations are not a desired feature but pose a severe problem.

Short-range correlations in nuclei with similarity renormalization group transformations

T. Neff,[1,*] H. Feldmeier,[1,2] and W. Horiuchi[3]

arXiv:1506.02237v1 [nucl-th] 7 Jun 2015

Some theoreticians denied their existence

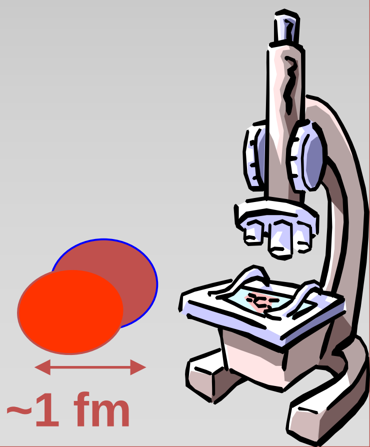


Short range correlations

“The structure of correlated many-body systems, particularly at distance scales small compared to the radius of the constituent nucleons, presents a formidable challenge to both experiment and theory”

(Nuclear Science: A Long Range Plan, The DOE/NSF Nuclear Science Advisory Committee, Feb. 1996 [1].)

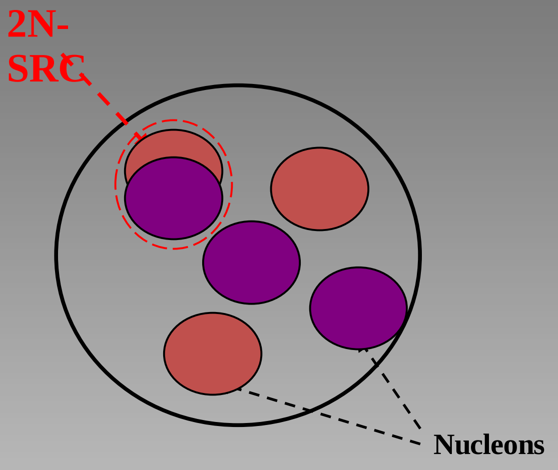
This long standing challenge for nuclear physics can experimentally be effectively addressed thanks to high intensity and high momentum transfer reached by present facilities.



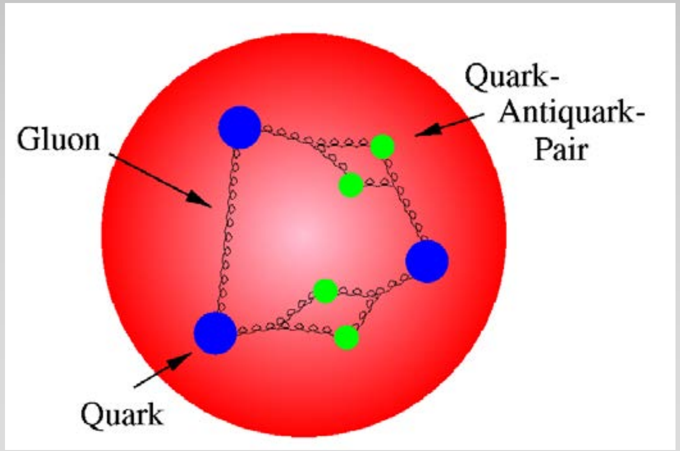
Hard scattering is of particular interest because it has the resolving power required to probe the internal (partonic) structure of a complex target

Hard nuclear reactions

hadronic structure of nuclei



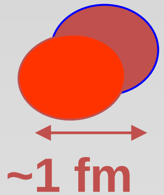
Scale:
several GeV

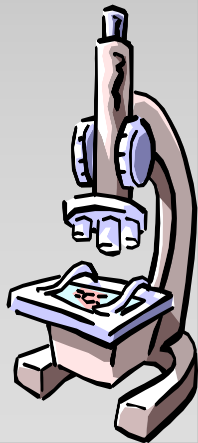


DIS

Scale:
several tens of GeV

partonic structure of hadrons





SRC Outreach

Particle Physics

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

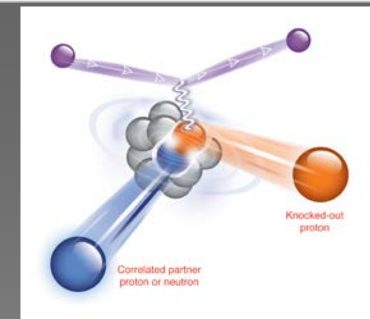
Astrophysics

Neutron Stars.
Nuclear Symmetry Energy.

Quantum \ Atomic Physics

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

Number of hard triple coincidence events (World data)



experiment	pp pairs	np pairs	nn pairs
EVA/BNL	-	18	-
E01-015/JLab	263	179	-
E07-006/JLab	50	223	-
CLAS/JLab	1533	-	-
Total	<2000	<450	0

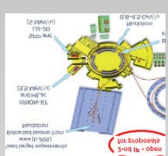
$^{12}C(p,2pn)$

$^{12}C(e,e'pn)$ $^{12}C(e,e'pp)$

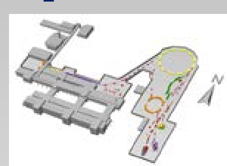
$^{4}He(e,e'pn)$ $^{4}He(e,e'pp)$

$\mathrm{C, Al, Fe, Pb}\,(e,e'pp)$

5 GeV/c 10^9 protons/sec fixed target



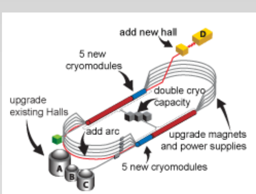
Nuclotron



J-PARC Japan Proton Acce

➔ >10k events/100 Hr

12 GeV electrons at JLab fixed target



X5-10 Mott cross section

X10 Luminosity in CLAS12

Why several GeV and up protons are good probes of SRC ?

- They have Small deBroglie wavelength:

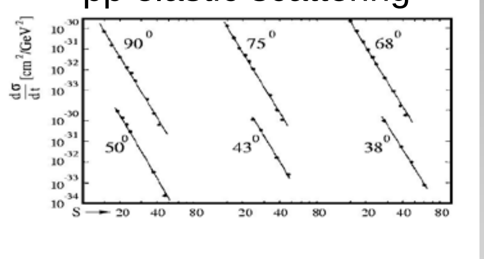
λ = h/p = hc/pc = 2$\pi \bullet$ 0.197 GeV-fm/(6 GeV) $\approx$ 0.2 fm.

- Large momentum transfer is possible

  With wide angle scattering

- The s^{-10} dependence of the p-p elastic scattering preferentially selects high momentum nuclear protons.

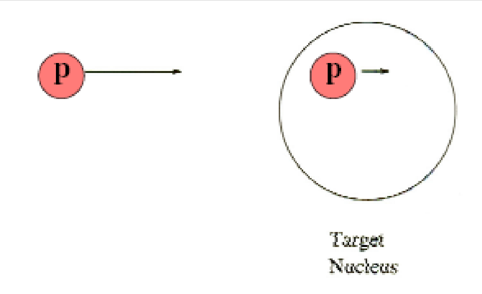
pp elastic scattering



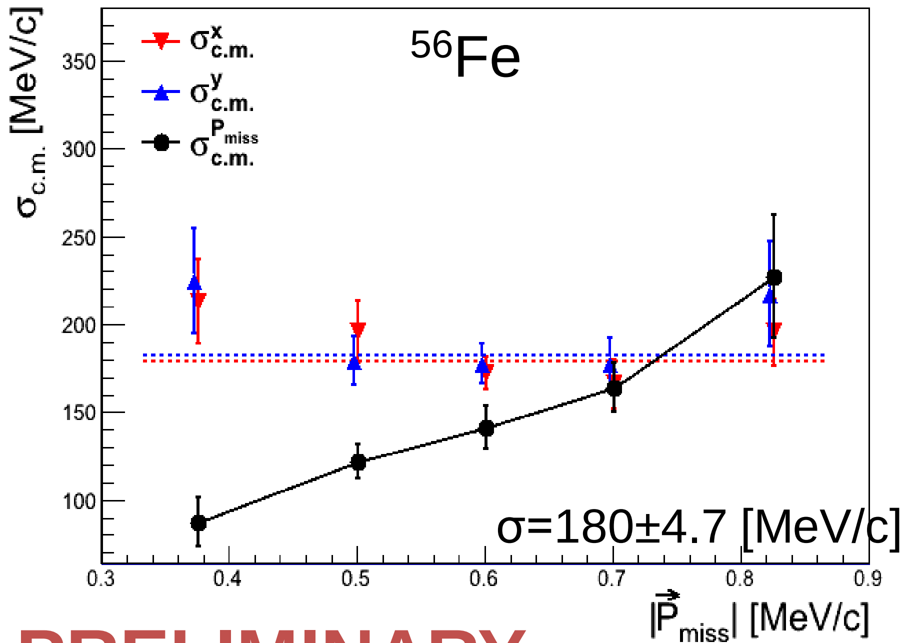
For pp elastic scattering near 90^0 cm

$$\frac{d\sigma}{dt} \propto s^{-10}$$

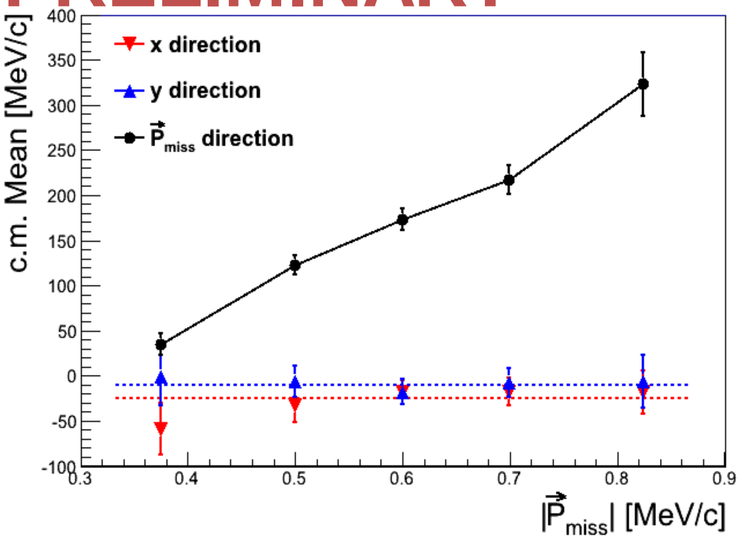
QE pp scattering near 90^0 have a very strong preference for reacting with forward going high momentum nuclear protons

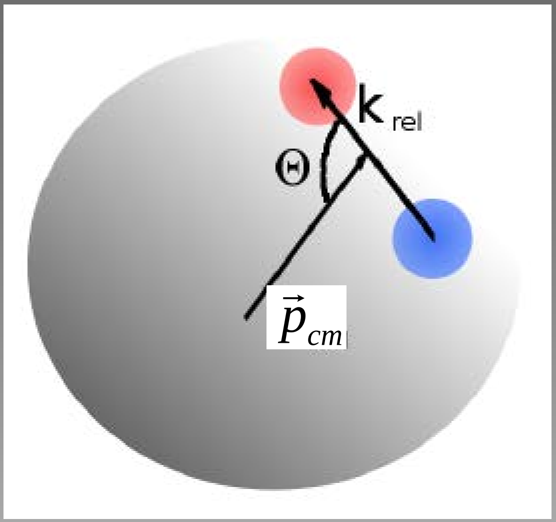


C.M. motion of the pair



PRELIMINARY





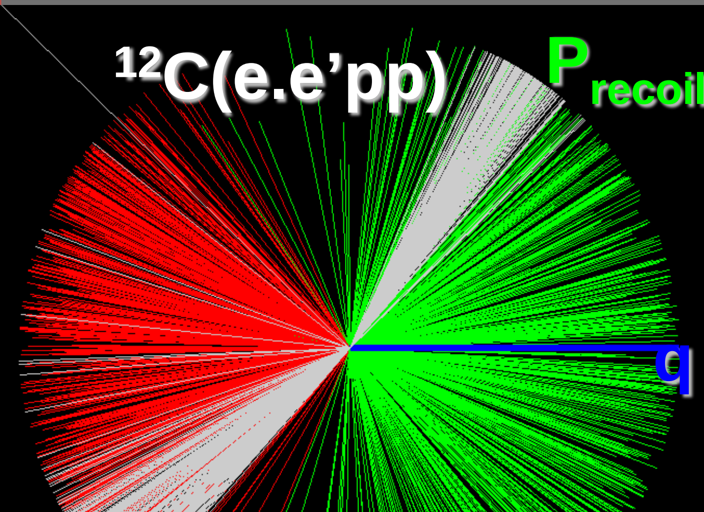
$$\vec{p}_{cm} = \vec{p}_{miss} + \vec{p}_{recoil}$$

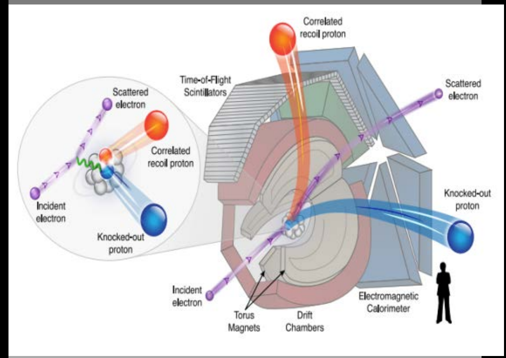
	σ_x	σ_y
^{12}C	169±7	164±6
^{27}Al	162±10	180±13
^{56}Fe	179±6	182±7
^{208}Pb	208±18	186±16

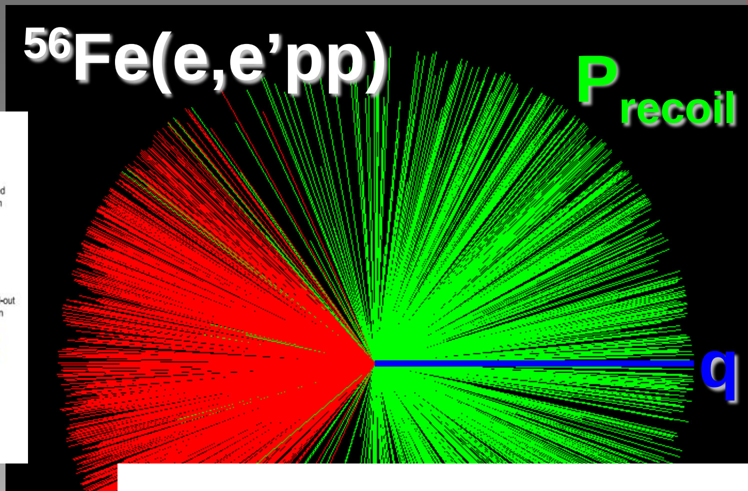
O. Hen E. Cohen et al., in preparation

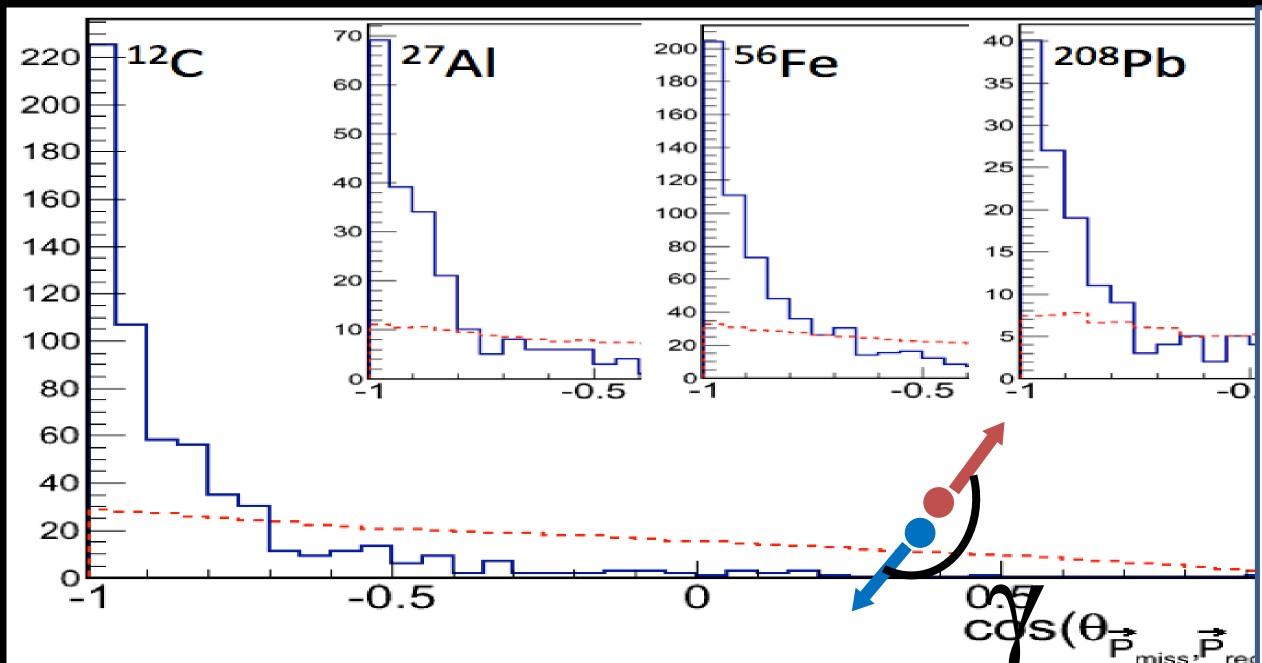
JLab / CLAS, Data Mining, EG2 data set

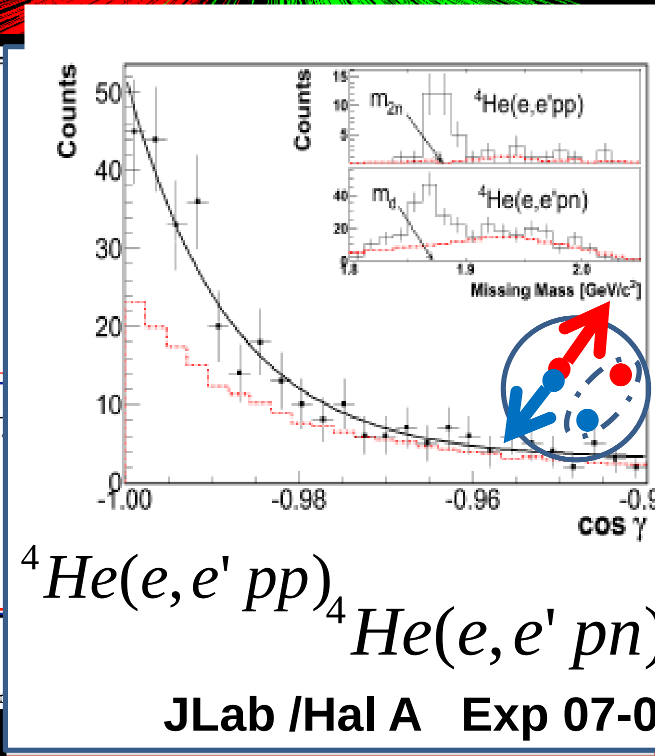
TEL AVIV UNIVERSITY





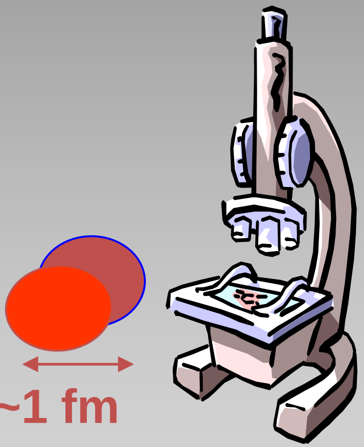






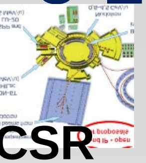
"The structure of correlated many-body systems, particularly at distance scales small compared to the radius of the constituent nucleons, presents a formidable challenge to both experiment and theory"

(Nuclear Science: A Long Range Plan, The DOE/NSF Nuclear Science Advisory Committee, Feb. 1996 [1].)



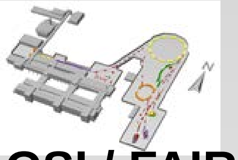
This long standing challenge for nuclear physics can experimentally be effectively addressed thanks to <u>high intensity and high momentum transfer</u> reached by present facilities.

5-10 GeV/c 10^9 protons/sec fixed target



CSR Lanzhou

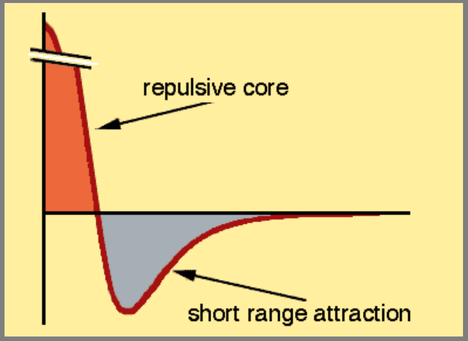
Dubna



GSI / FAIR

→ >10k events/100 Hr

Nuclear Physics 101

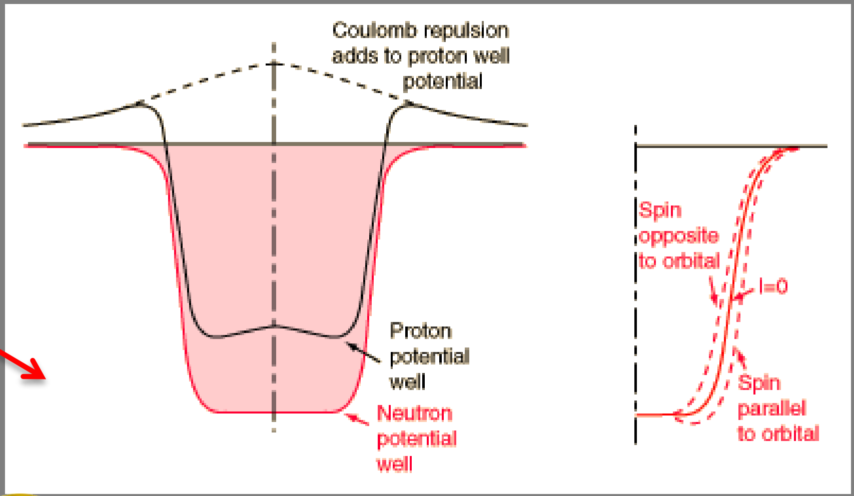


- Many-Body Hamiltonian:

$$H = \sum_{i=1}^{A} \frac{p_i^2}{2m_N} + \sum_{i<j=1}^{A} V_{2N}(i,j) + \sum_{i<j<k=1}^{A} V_{3N}(i,j,k) +$$

- Mean-Field Approximation:

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



Results in an "atom-like" shell model:

- Ground state energies
- Excitation Spectrum
- …

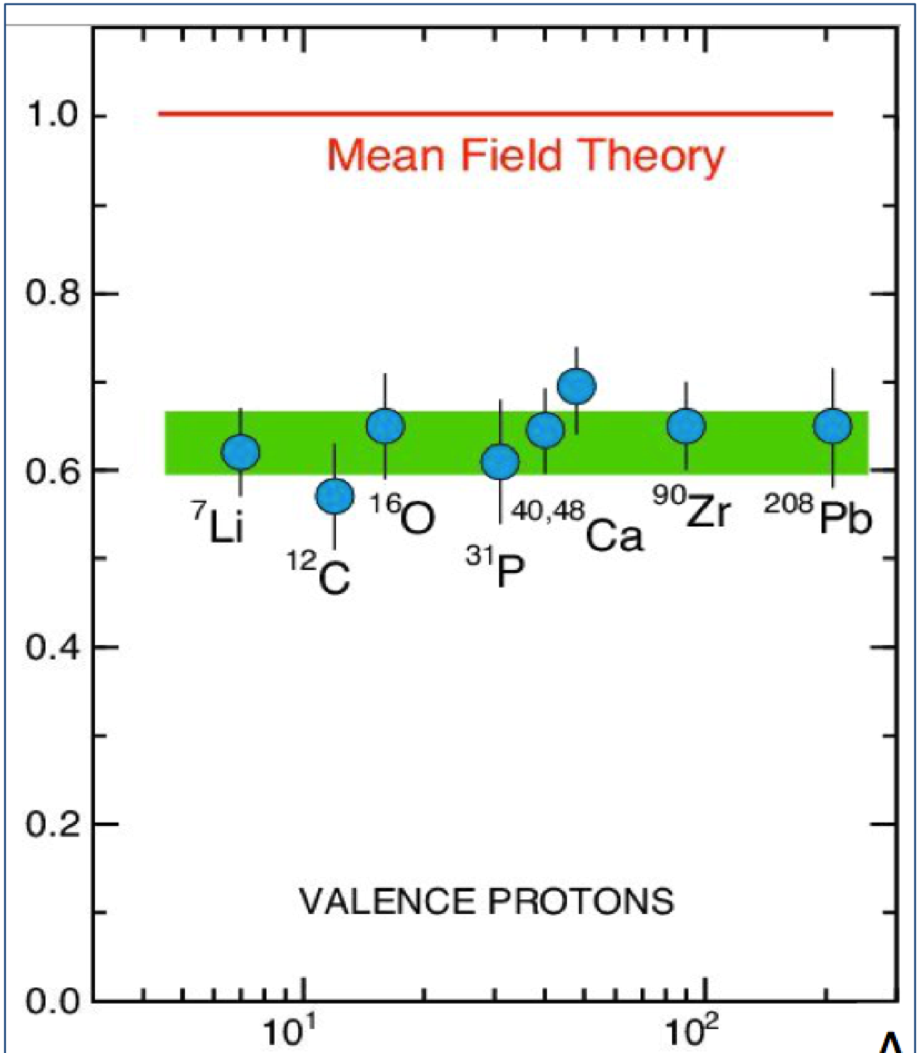
E. Wigner, M. Mayer, and J. Jensor
1963 Nobel Prize

Beyond the Shell-Model: NN Correlations

Beyond the Shell-Model: NN Correlations

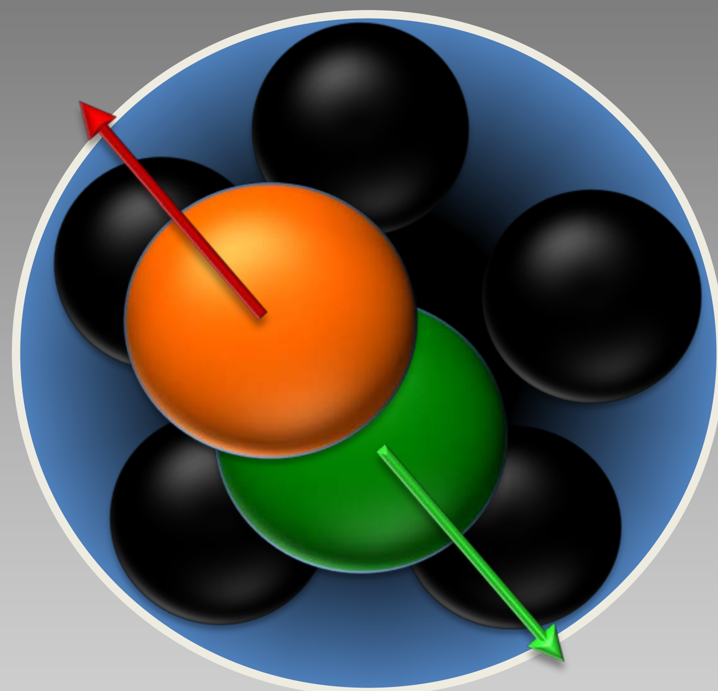
- Spectroscopic factors extracted from A(e,e'p) measurements yield only 60-70% of the expected single-particle strength

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



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

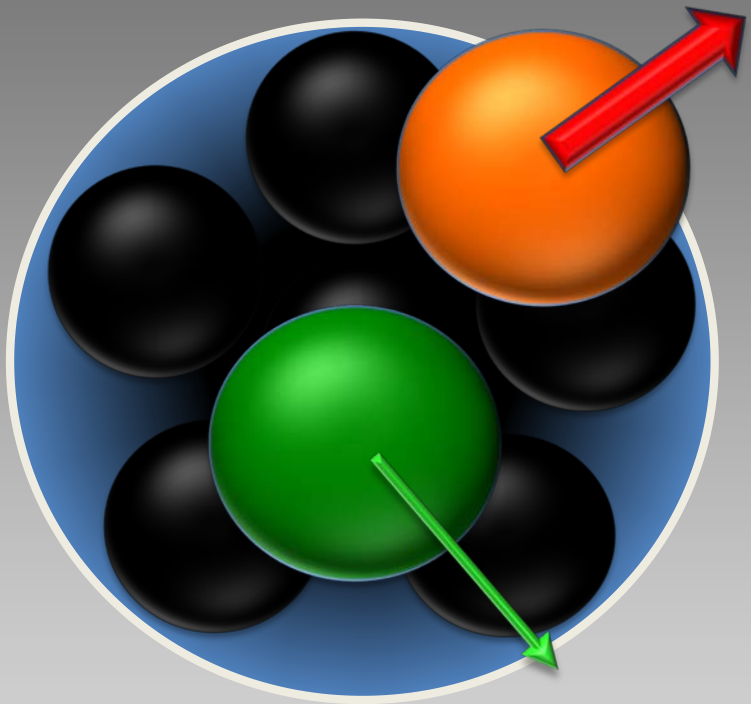
Hard exclusive triple – coincidence measurements



Quasi-Free scattering off a nucleon in a short range correlated pair

triple – coincidence measurements

triple – coincidence measurements



triple – coincidence measurements

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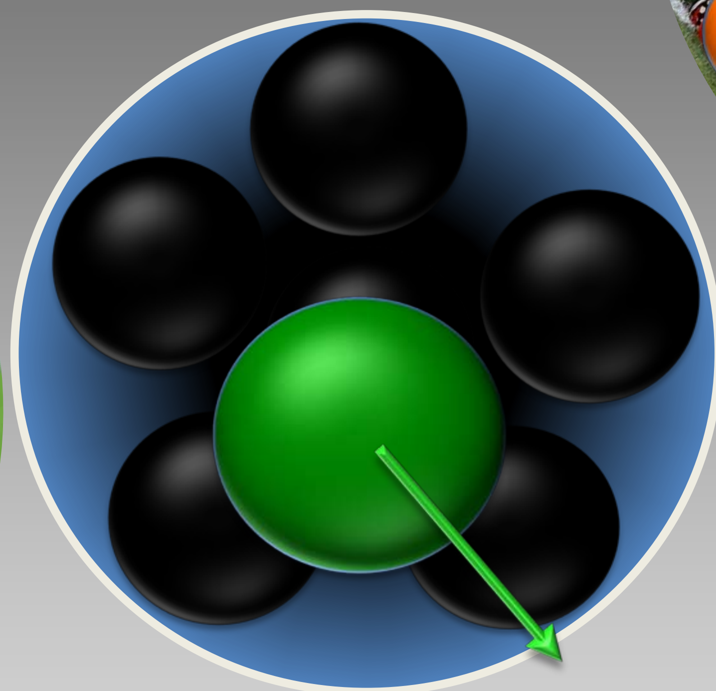

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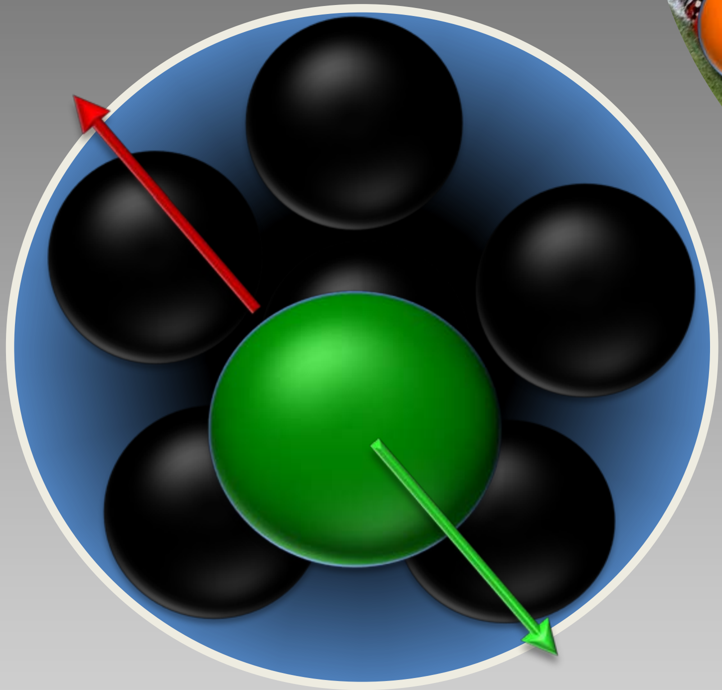

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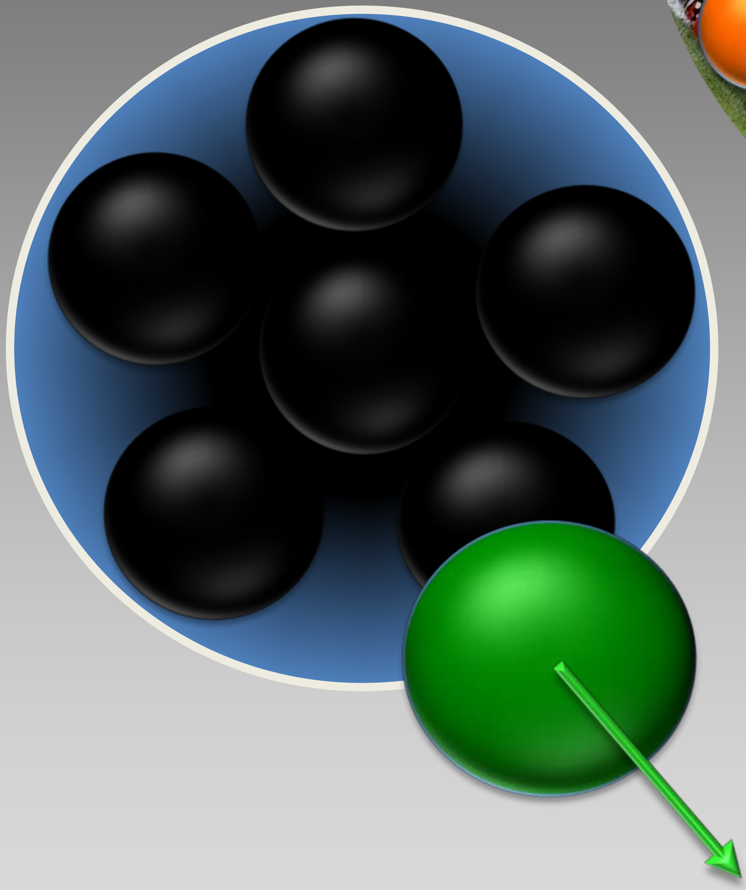

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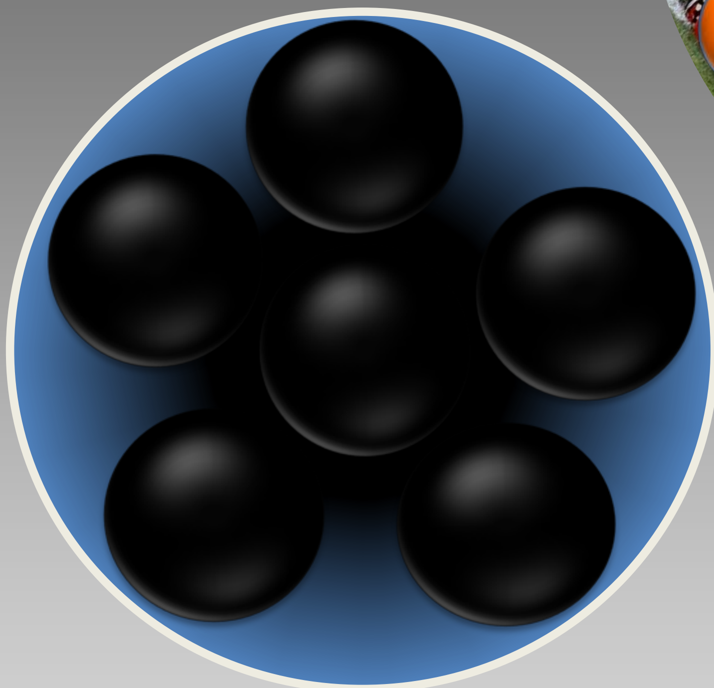
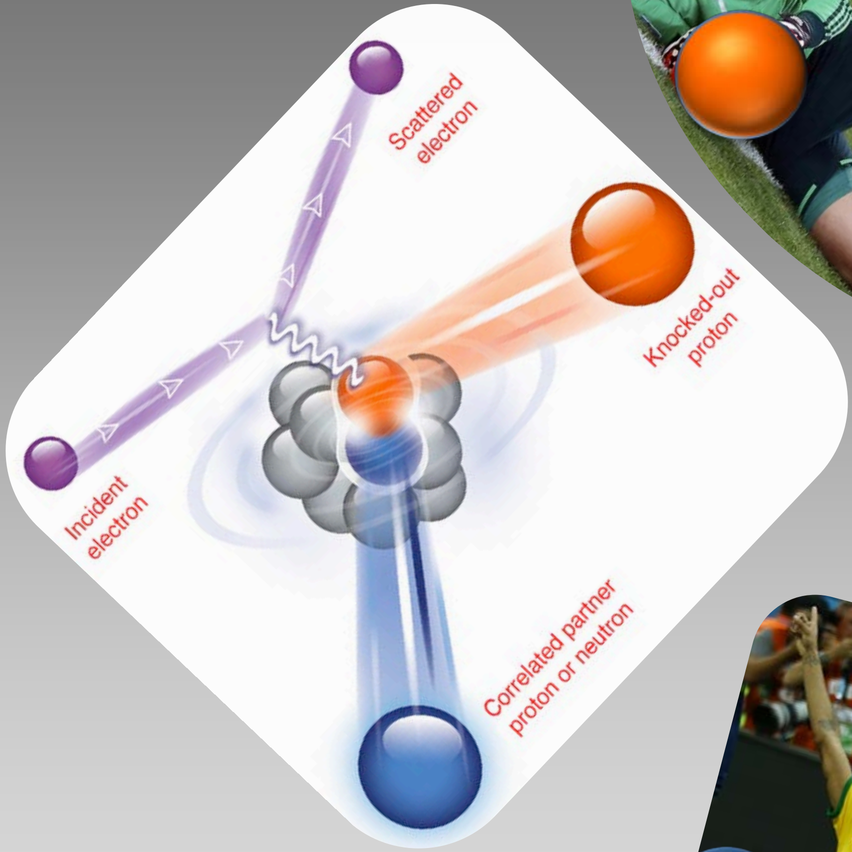
triple – coincidence measurements

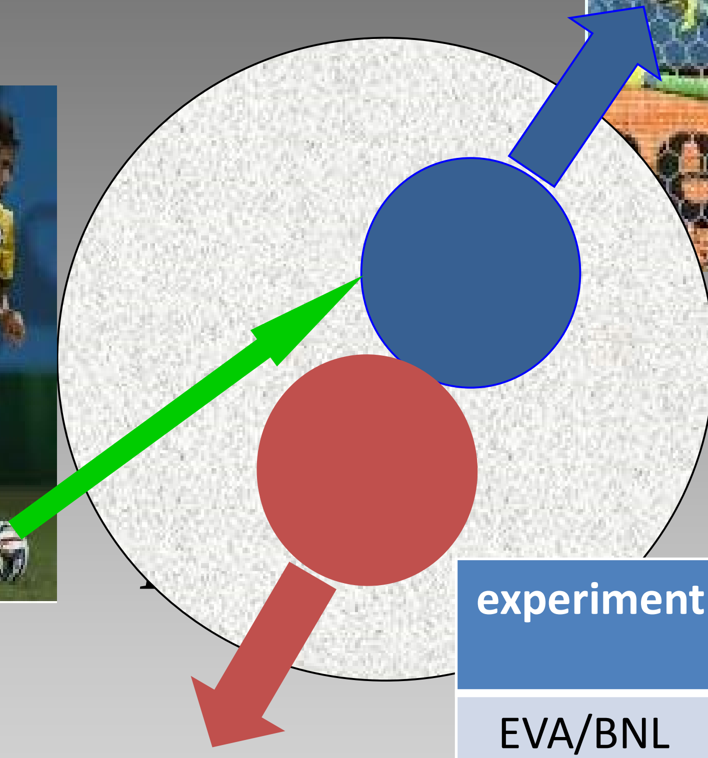


triple – coincidence measurements

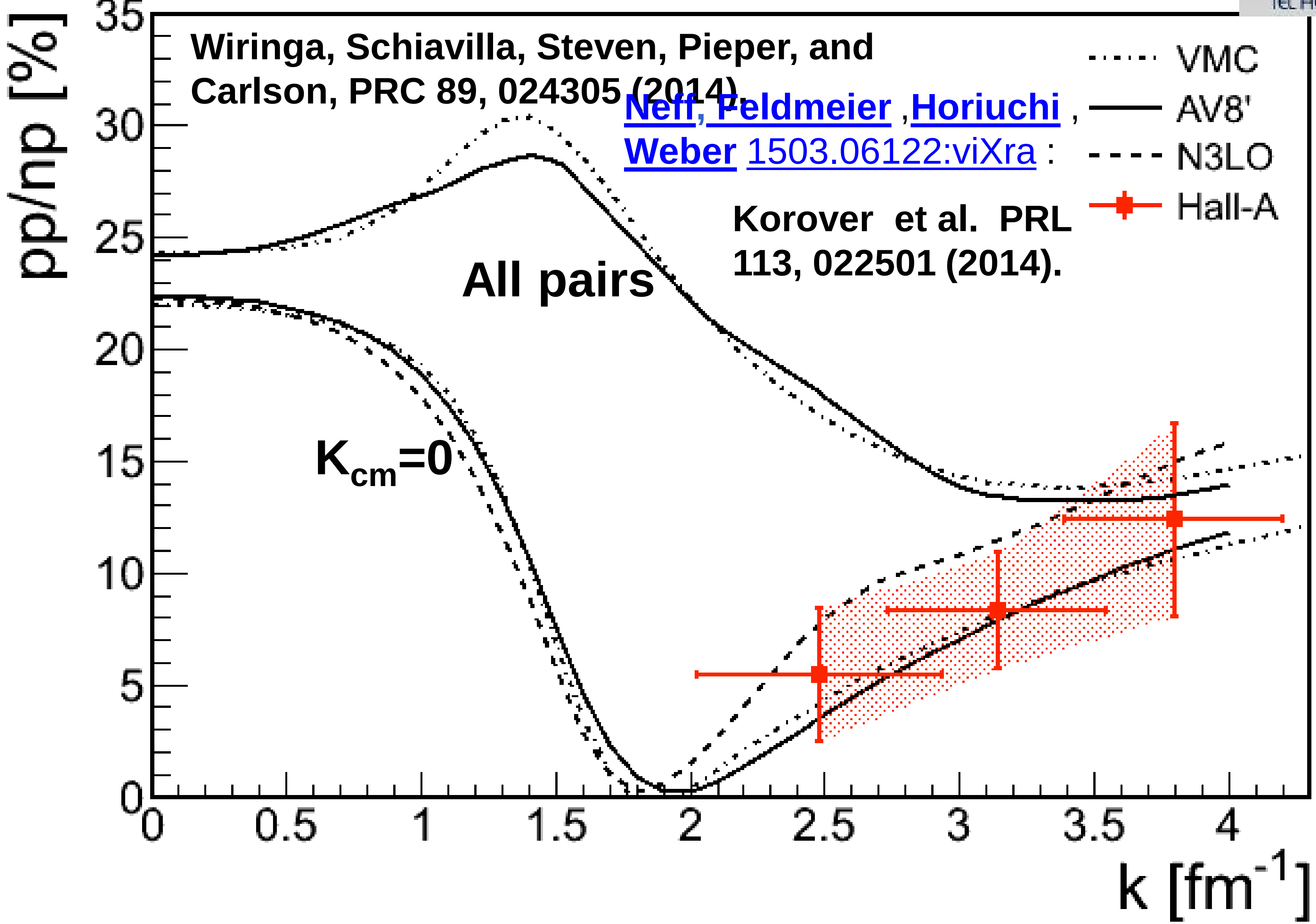


Quasi-Free scattering off a nucleon in a short range correlated pair

Hard exclusive triple – coincidence measurements

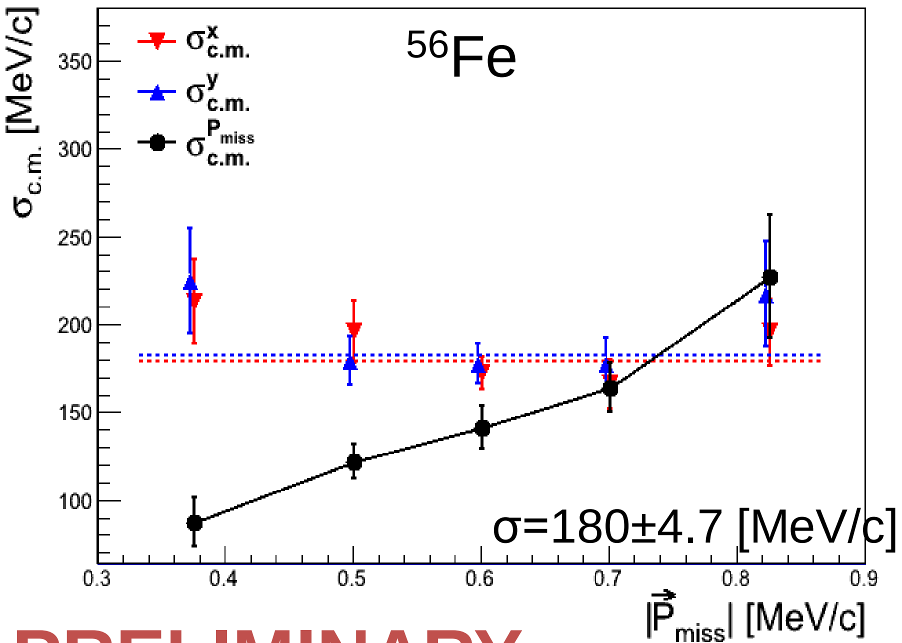


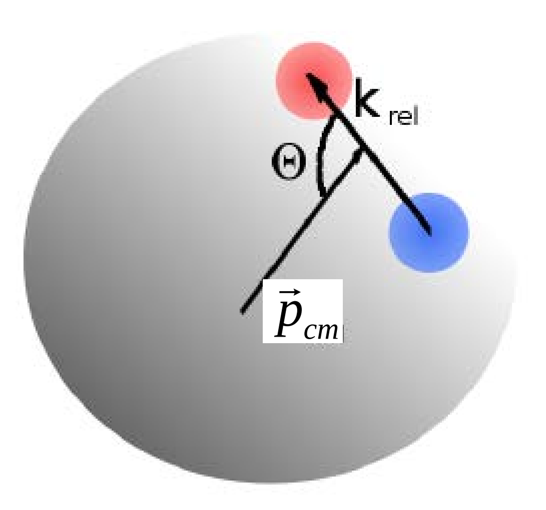
experiment	nuclei	pairs	Pmiss [MeV/c]
EVA/BNL	^{12}C	pp only	300-600
E01-015/ Jlab	^{12}C	pp and np	300-600
E07-006/ JLab	^{4}He	pp and np	400-850
CLAS/JLab	C, Al, Fe, Pb	pp only	300-700



pp/np [%]
35
30
25
20
15
10
5
0
0
0.5
1
1.5
2
2.5
3
3.5
4
k [fm-1]
Wiringa, Schiavilla, Steven, Pieper, and Carlson, PRC 89, 024305 (2014).
Neff, Feldmeier, Horiuchi, Weber 1503.06122:viXra :
Korover et al. PRL 113, 022501 (2014).
All pairs
Kcm=0
VMC
AV8'
N3LO
Hall-A

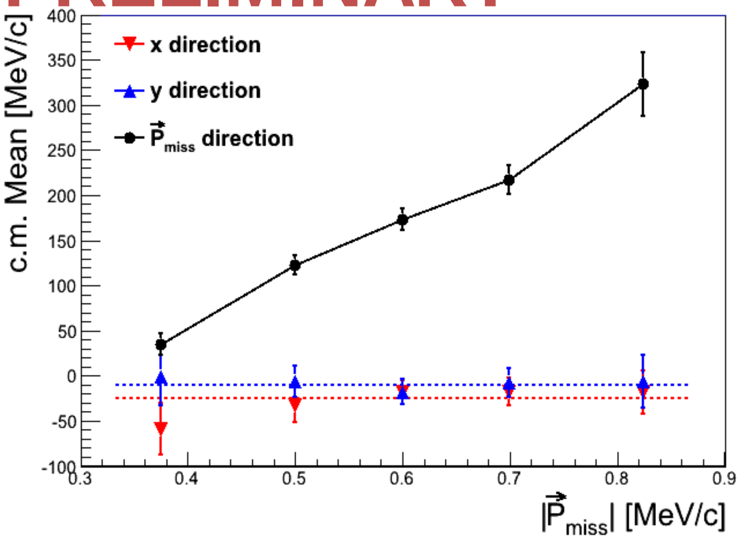
C.M. motion of the pair





$$\vec{p}_{cm} = \vec{p}_{miss} + \vec{p}_{recoil}$$

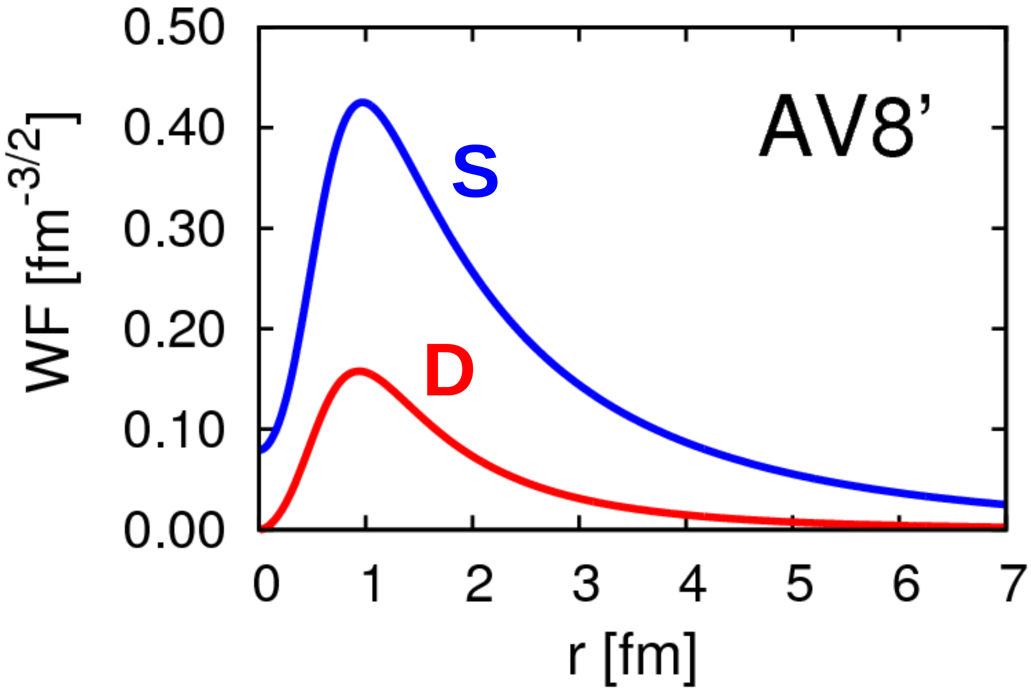
PRELIMINARY



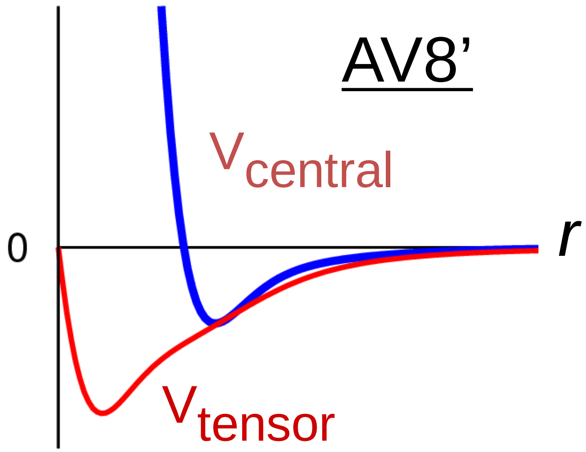
	σ_x	σ_y
^{12}C	169±7	164±6
^{27}Al	162±10	180±13
^{56}Fe	179±6	182±7
^{208}Pb	208±18	186±16

O. Hen E. Cohen et al., in preparation

Deuteron properties & tensor force



Energy	-2.24 MeV
Kinetic	19.88
Central	-4.46
Tensor	**-16.64**
LS	-1.02
P(L=2)	5.77%
Radius	1.96 fm



$R_m(s)$=2.00 fm

$R_m(d)$=1.22 fm

d-wave is
"**spatially compact**"
(high momentum)

E01-015: A customized Experiment to study 2N-SRC

$Q^2 = 2$ GeV/c , $x_B \sim 1.2$, P_m=300-600 MeV/c, E_{2m}<140 MeV

Luminosity ~ 10^{37-38} $cm^{-2}s^{-1}$

Kinematics optimized to minimize the competing processes

High energy, Large Q^2

The large Q^2 is required to probe the small size SRC configuration.

MEC are reduced as $1/Q^2$.

Large Q^2 is required to probe high P_{miss} with x_B>1.

FSI can treated in Glauber approximation.

x_B>1

Reduced contribution from isobar currents.

Large p_{miss}, and $E_{miss} \sim p^2_{miss}/2M$

Large P_{miss_z}

Kinematics optimized to minimize the competing processes

FSI

FSI with the A-2 system:

★ Small (10-20%) .

- Kinematics with a large component of p_{miss} in the virtual photon direction.
- Pauli blocking for the recoil particle.
- Geometry, (e, e'p) selects the surface.

★ Can be treated in Glauber approximation.

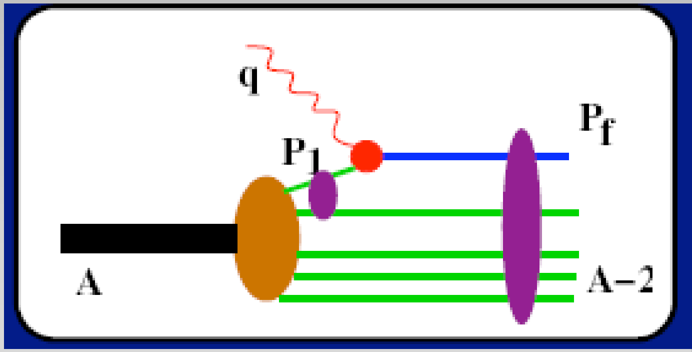
★ Canceled in some of the measured ratios.

FSI in the SRC pair:

These are not necessarily small, BUT:

★ Conserve the isospin structure of the pair .

★ Conserve the CM momentum of the pair.

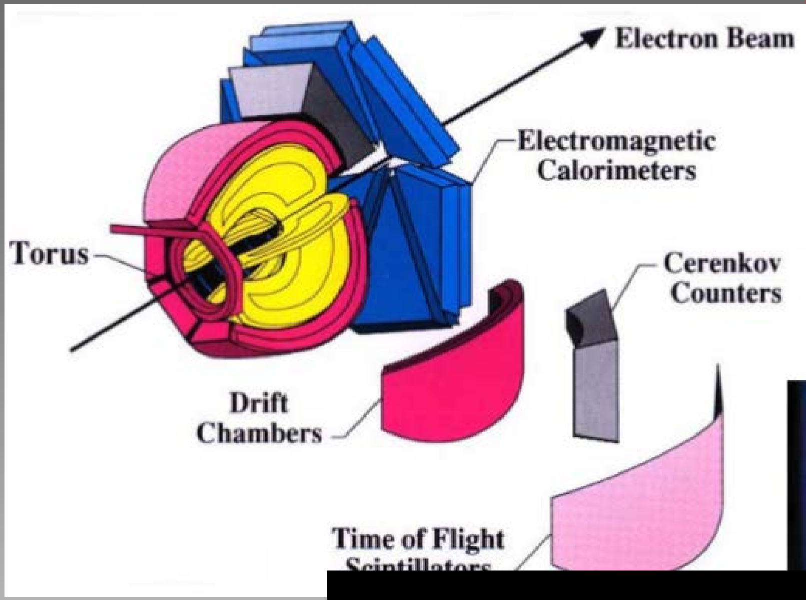


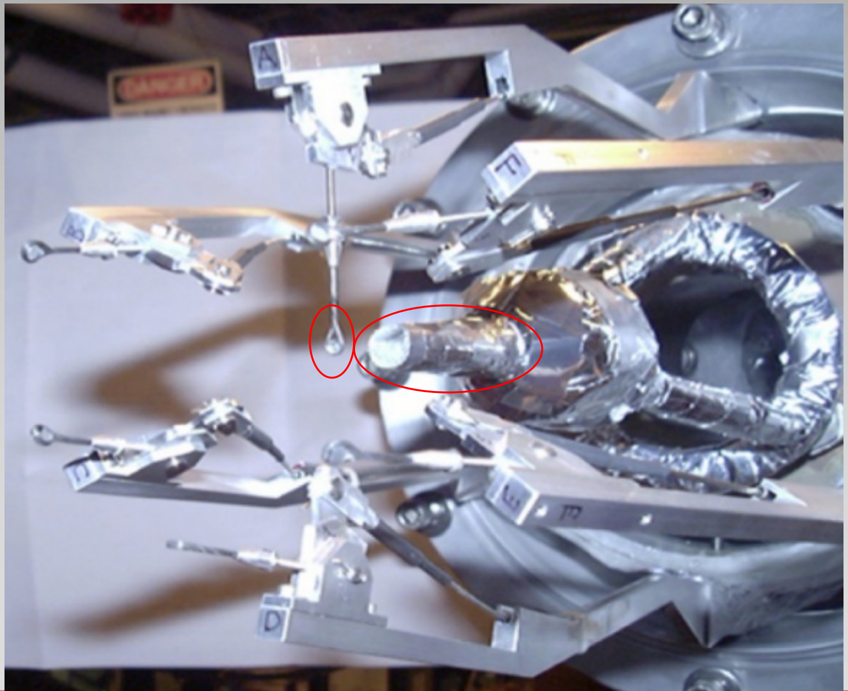
JLab / CLAS Data Mining

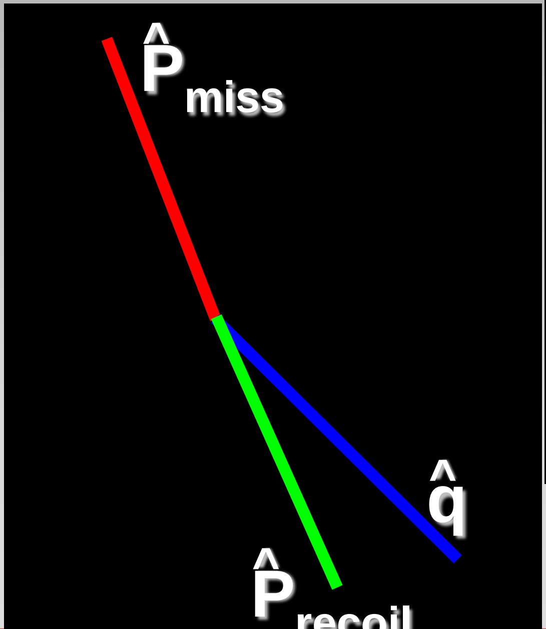
EG2 data set

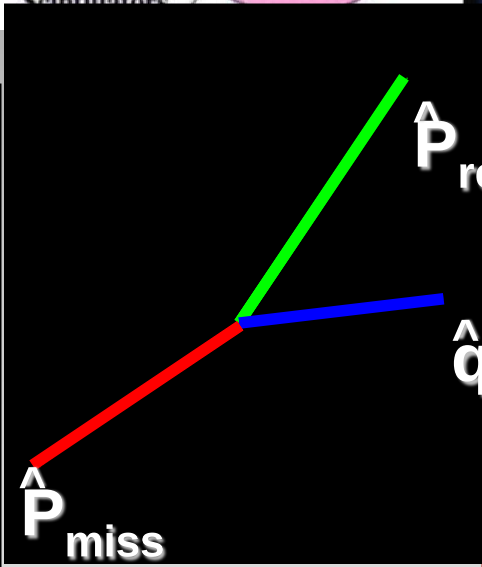
- Run at 2004 in Hall-B of Jefferson Lab
- 5 GeV electron beam
- Deuterium + Solid target simultaneously

^{12}C / ^{56}Fe / ^{208}Pb

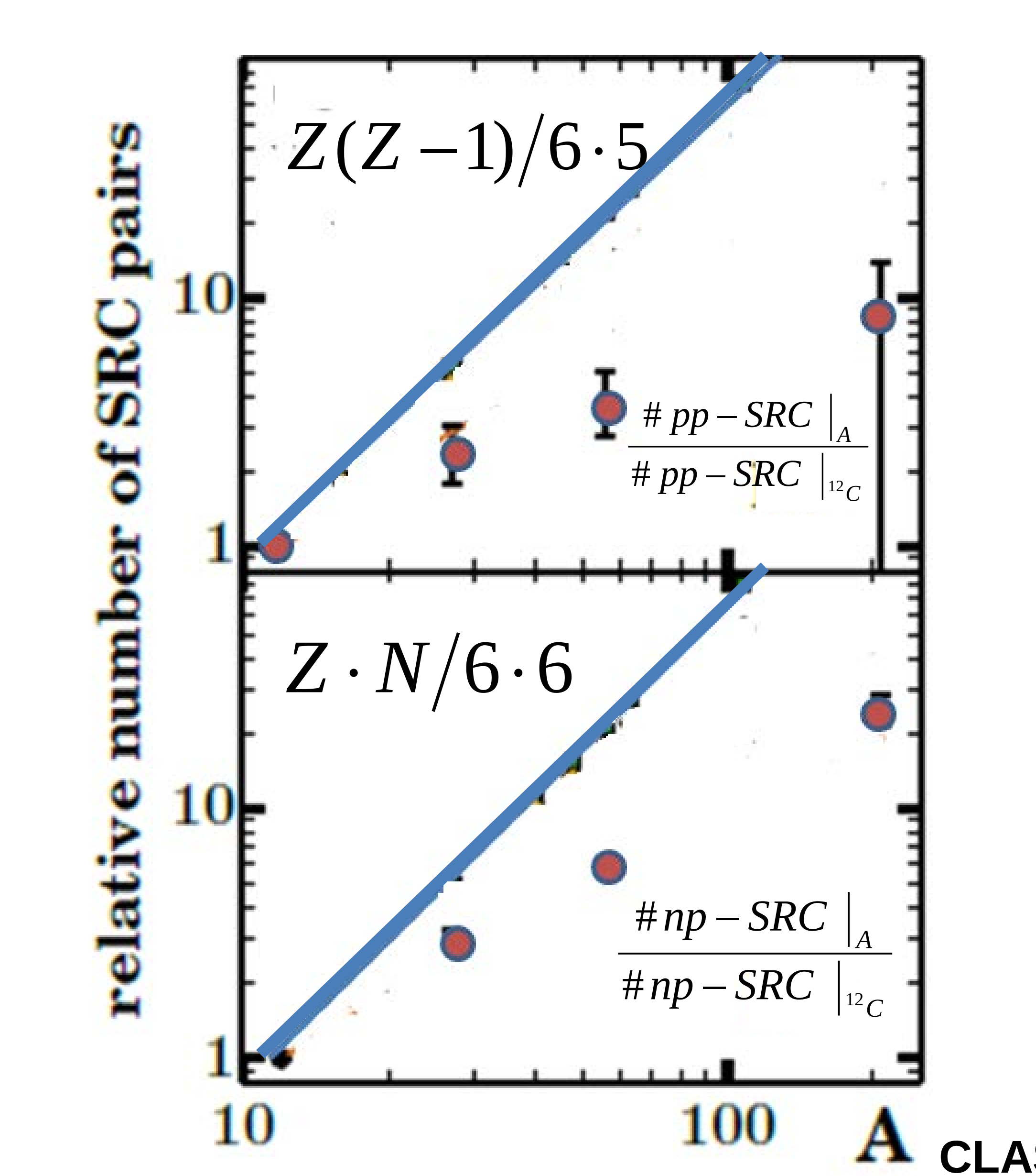






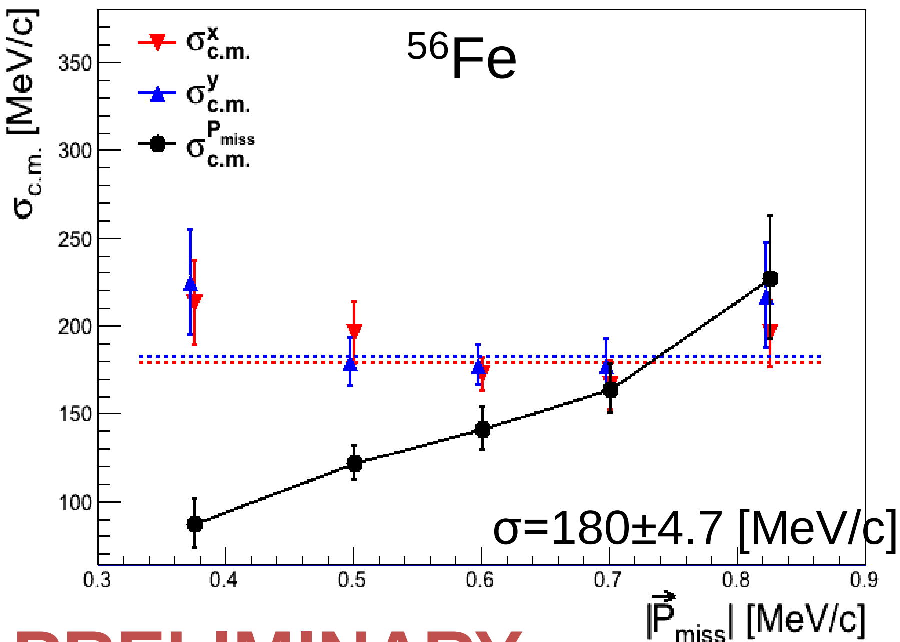


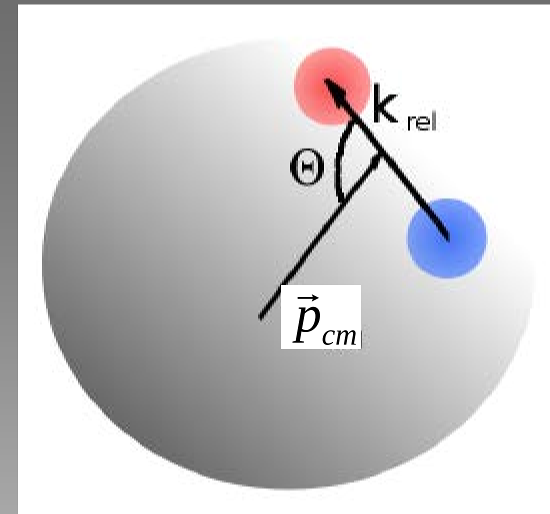
The mass dependence of the SRC pairs



CLAS JLab data see C. Colle et al.
http://arxiv.org/abs/arXiv:1503.06050

C.M. motion of the pair





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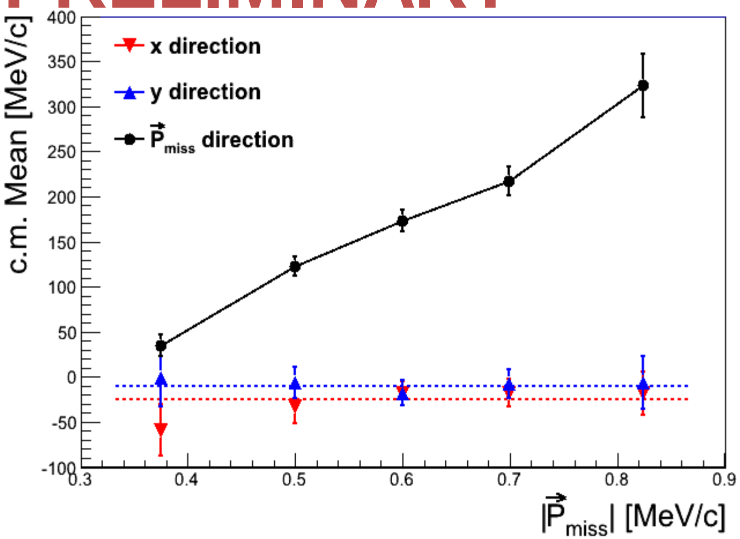
PRELIMINARY



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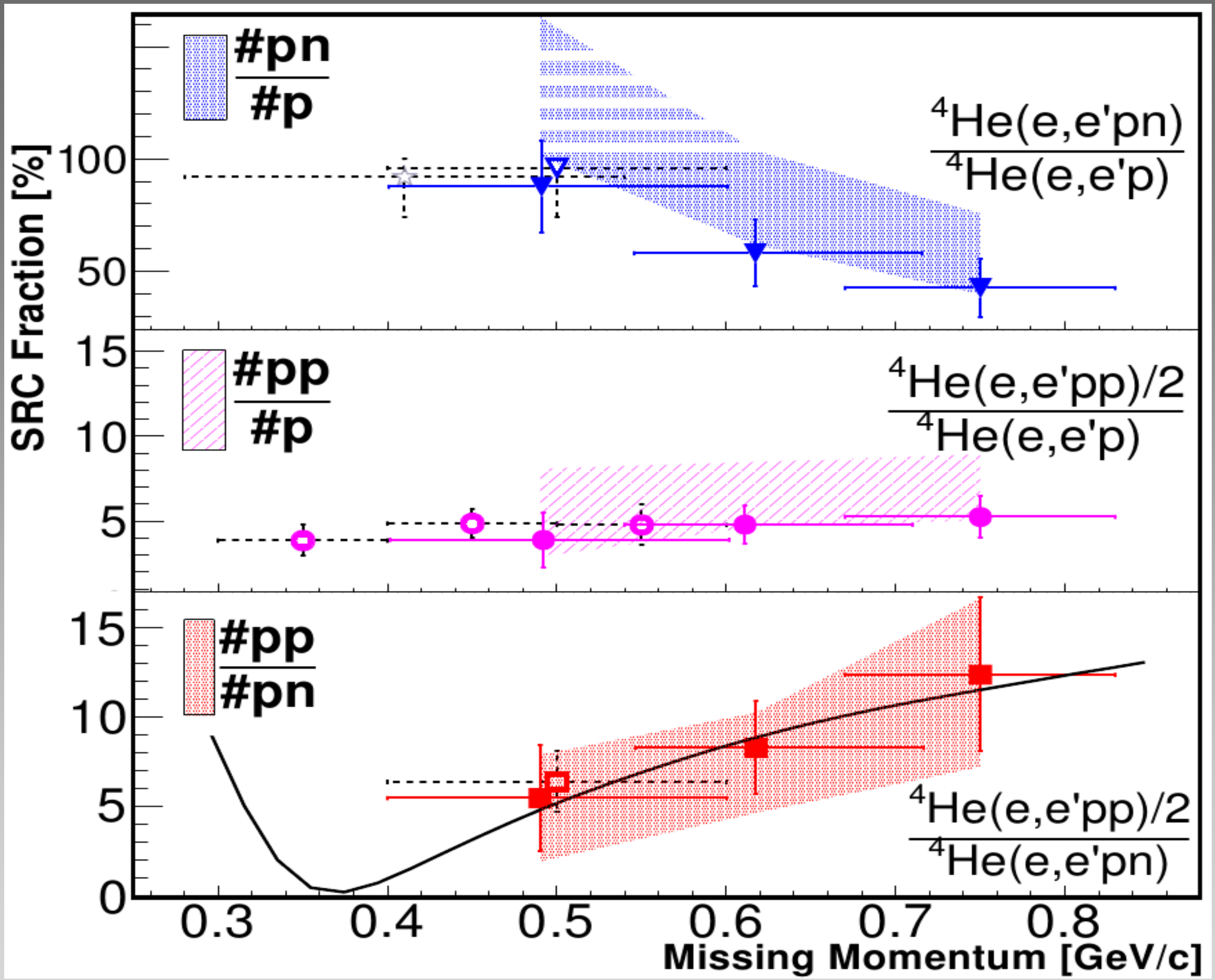
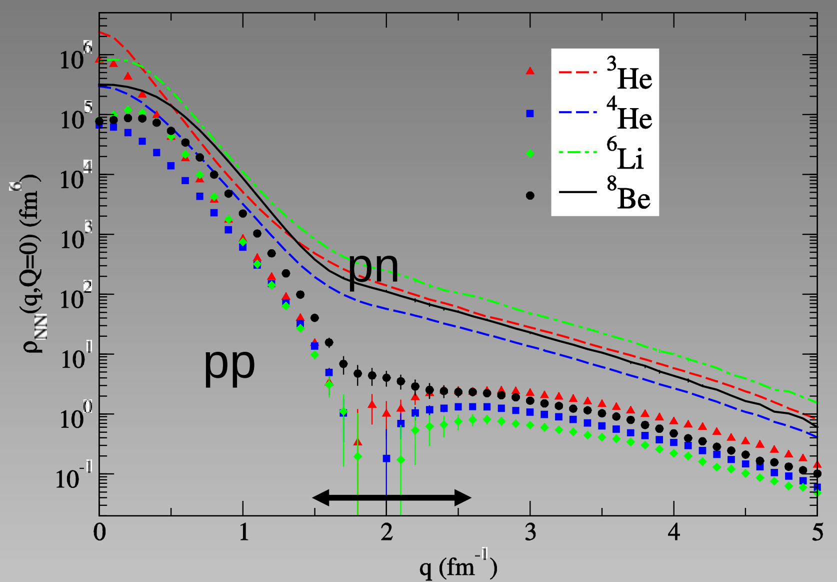
O. Hen E. Cohen et al., in preparation

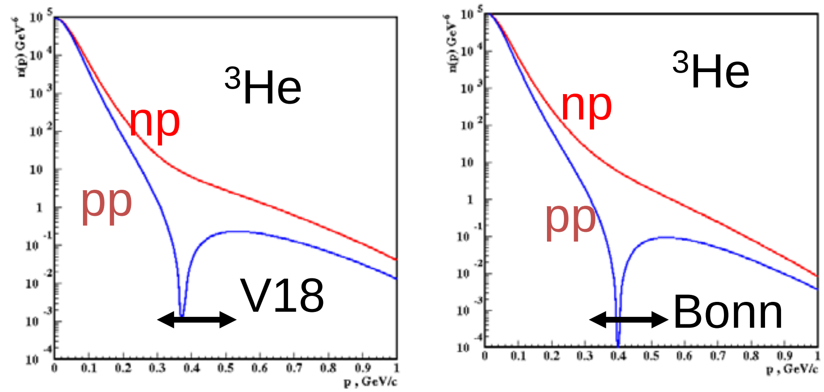
E07-006 (2011) ^{4}He



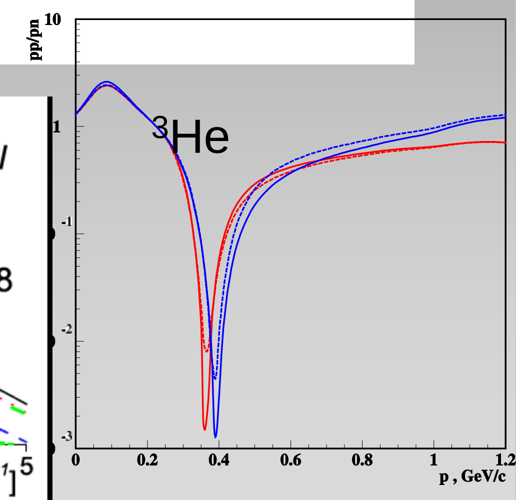
I. Korover et al. Phys. Rev. Let. 113, 022501 (201

At 300-600 MeV/c there is an excess strength in the np momentum distribution due to the strong correlations induced by the tensor NN potential.

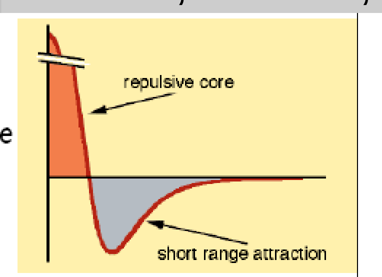




pp/np

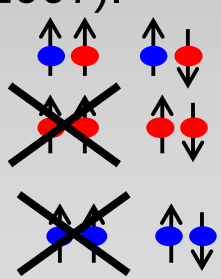


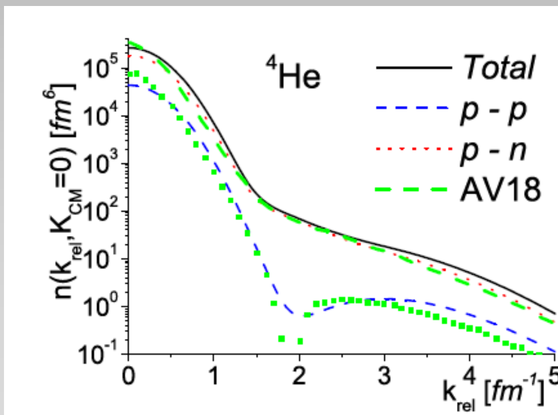
Schiavilla, Wiringa, Pieper, Carson, PRL 98,132501 (2007).



SRC

L = 0, 2

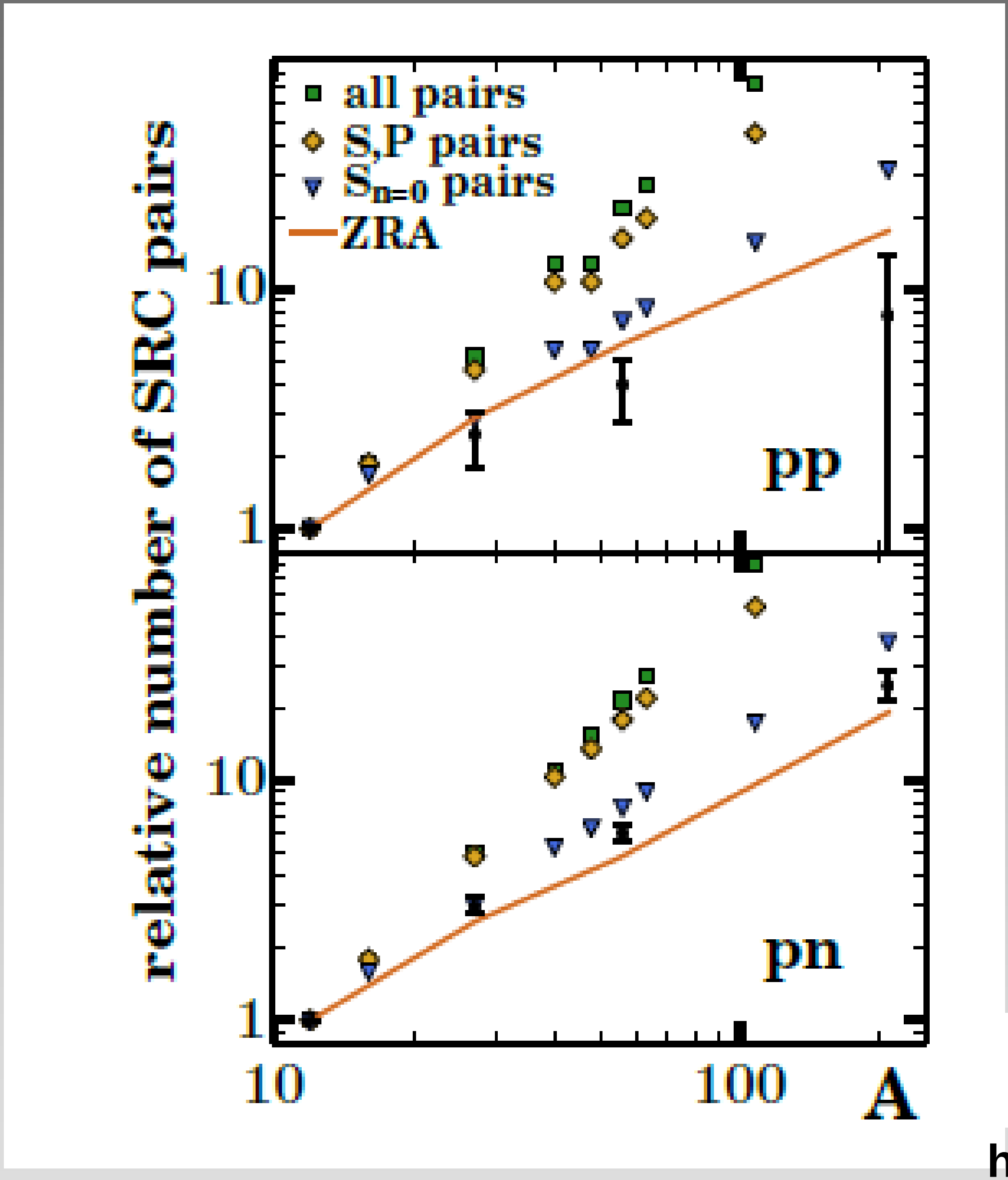




Ciofi and Alvioli PRL 100, 162503 (2008).

Sargsian, Abrahamyan, Strikman, Frankfurt PR C71 044615 (2005

The mass dependence of the SRC pairs



N=0 (nodeless) L=o IPM pairs

Predominantly:

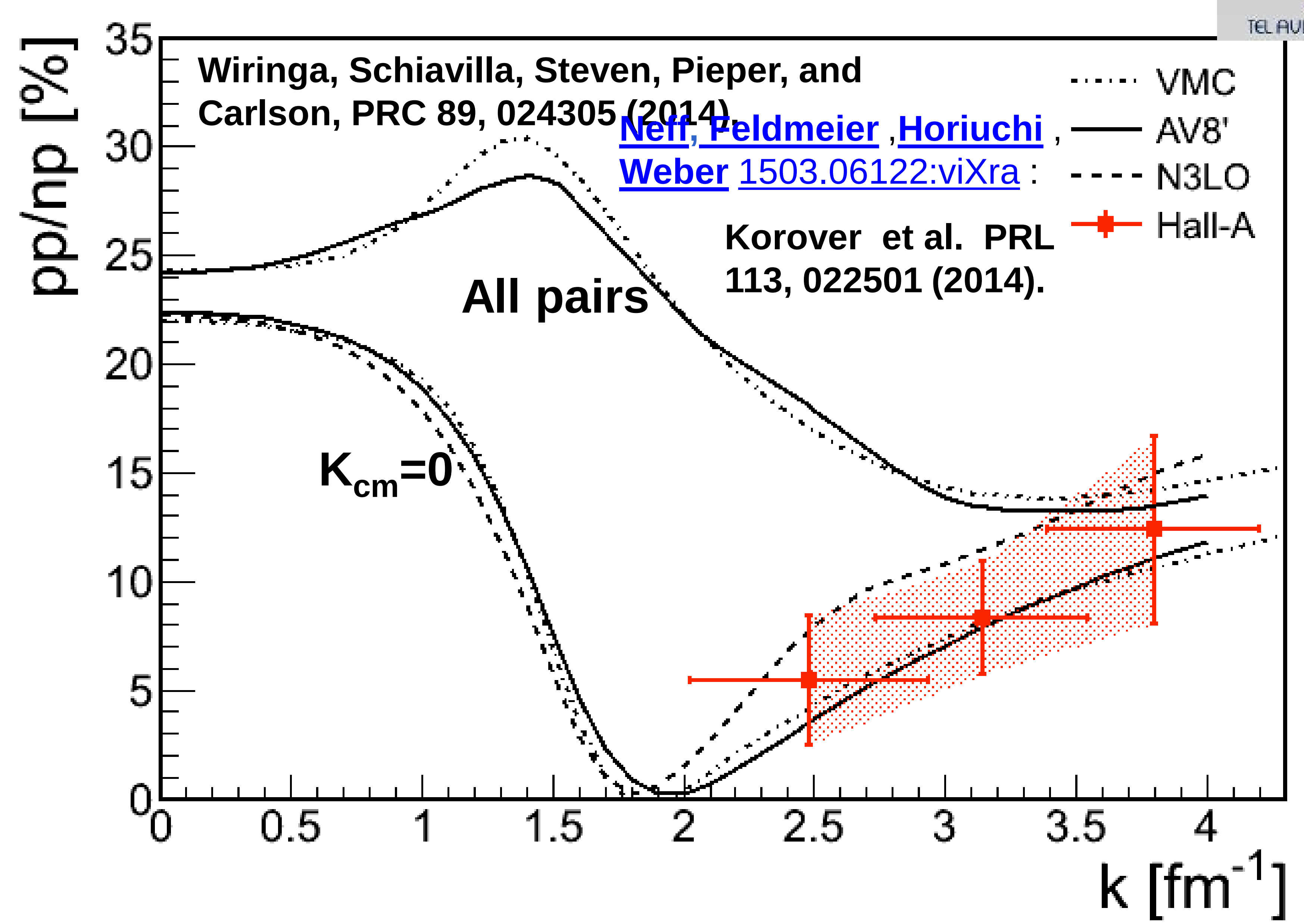
L=0,2 T=0 S=1

(deuteron like) **pairs**

Extracting the Mass Dependence and Quantum Numbers of Short-Range Correlated Pairs from A(e,e'p) and A(e,e'pp) Scattering

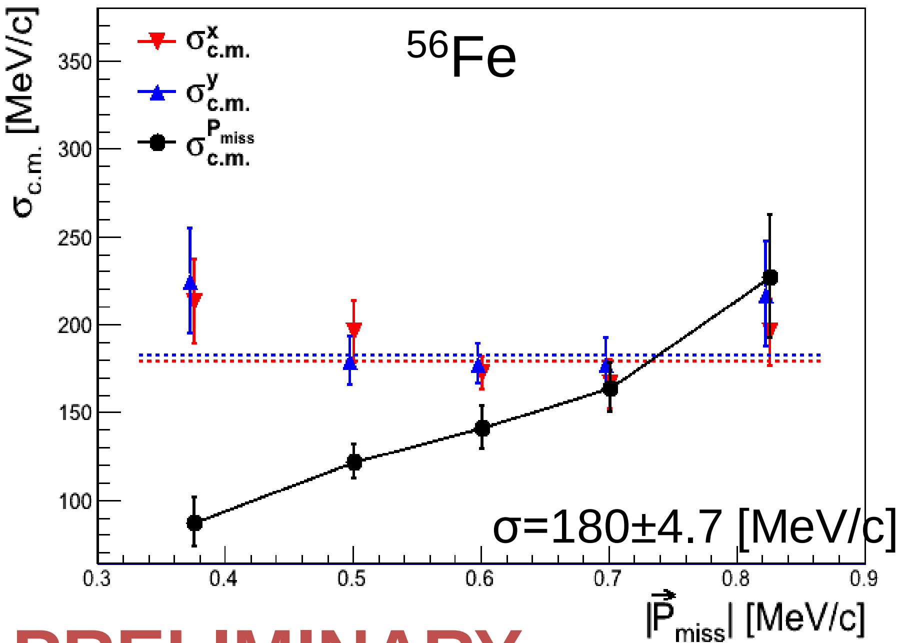
C. Colle,[1] O. Hen,[2] W. Cosyn,[3] I. Korover,[3] E. Piasetzky,[3] J. Ryckebusch,[3] and L.B. Weinstein[3]

http://arxiv.org/abs/arXiv:1503.06050

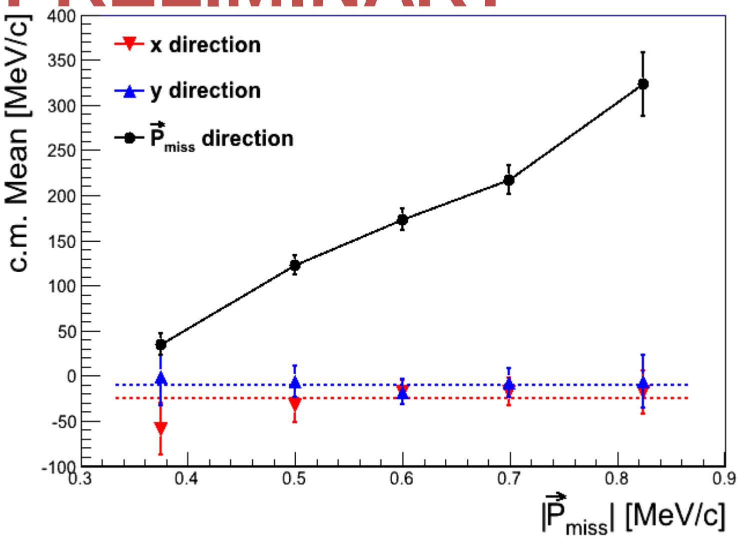


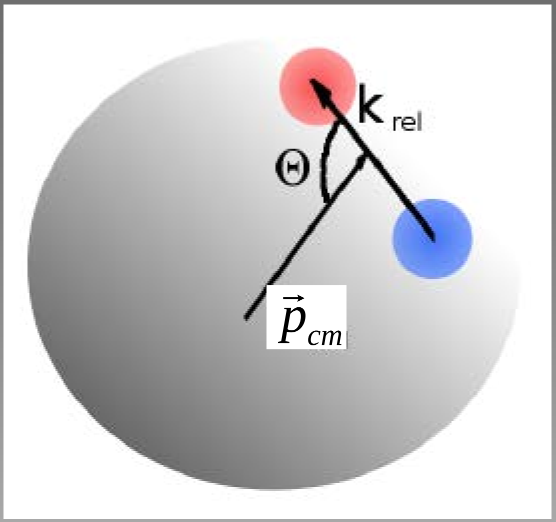
Wiringa, Schiavilla, Steven, Pieper, and Carlson, PRC 89, 024305 (2014).
Neff, Feldmeier, Horiuchi, Weber 1503.06122:viXra :
Korover et al. PRL 113, 022501 (2014).
VMC
AV8'
N3LO
Hall-A
All pairs
Kcm=0
pp/np [%]
k [fm-1]
0
5
10
15
20
25
30
35
0
0.5
1
1.5
2
2.5
3
3.5
4

C.M. motion of the pair



PRELIMINARY





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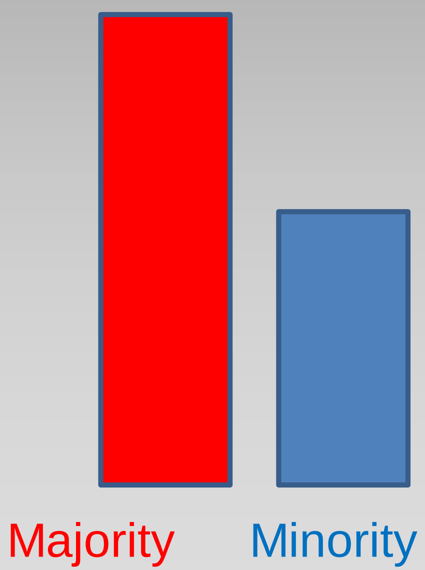
O. Hen E. Cohen et al., in preparation

Momentum sharing in Asymmetric (imbalanced) two components Fermi systems

non interacting Fermions

Pauli exclusion principle →

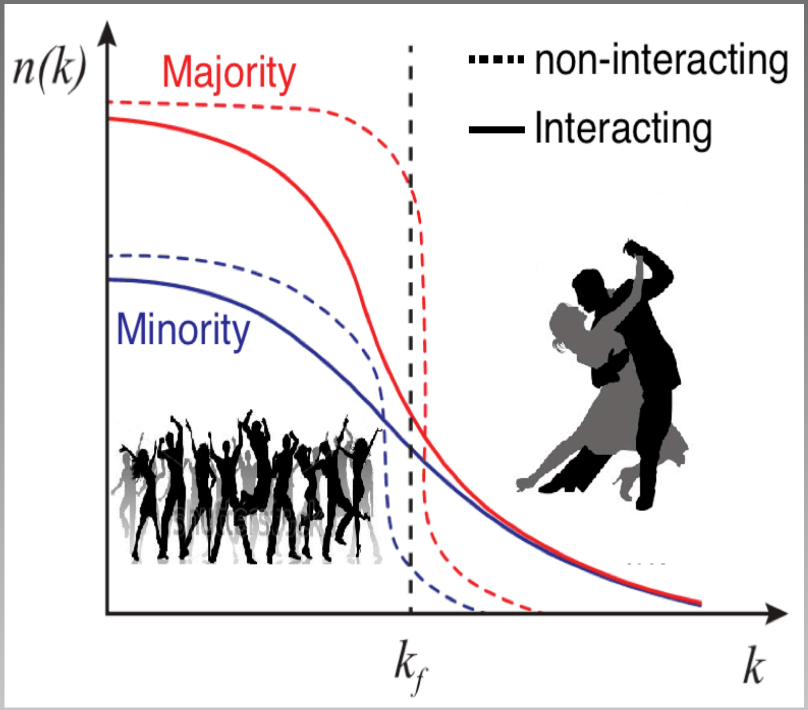


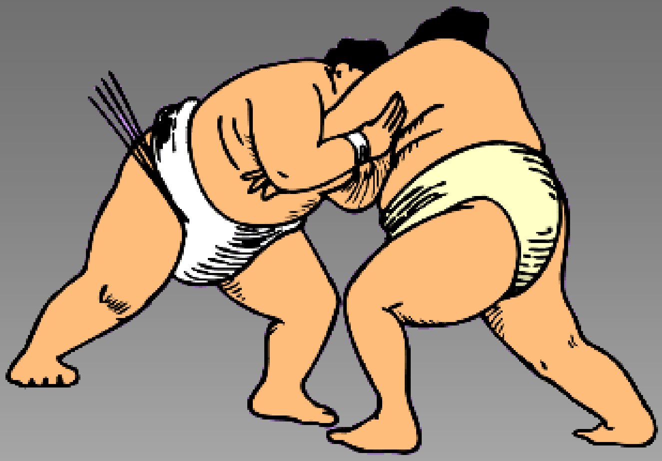
$$k_F^{Majority} > k_F^{Minority}$$

$$\langle T_{Majotiry} \rangle > \langle T_{Minority} \rangle$$

$$\langle k_{Majotiry} \rangle > \langle k_{Minority} \rangle$$

with short-range interaction : strong between unlike fermions, weak between same kind.





Who wins?

Universal property

A minority fermion have a greater probability than a majority fermion to be above the Fermi sea $k > k_F$

Possible inversion of the momentum sharing :

$$\langle k_{minority} \rangle > \langle k_{majority} \rangle$$

Protons move faster than neutrons in N>Z nuclei

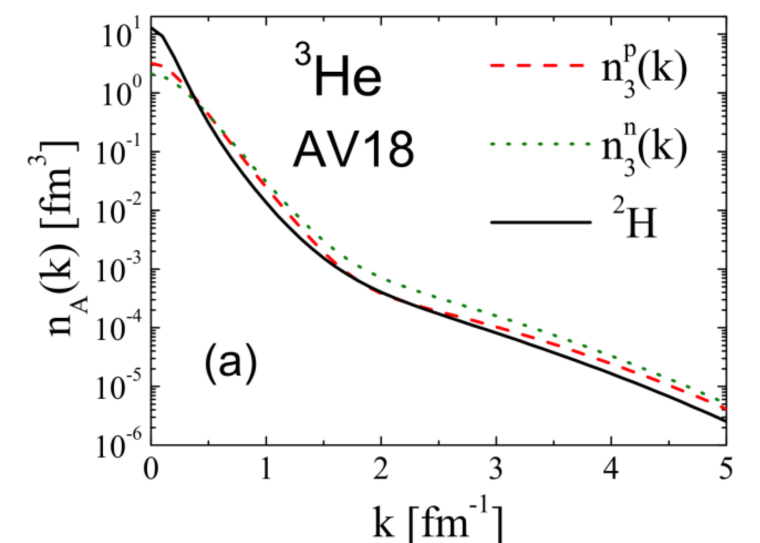
(protons move faster than neutrons in N>Z nuclei)

Light nuclei *A*<11

Variational Monte Carlo calculations by the Argonne group

Wiringa et al.
phys. Rev. C89, 034305 (2014).

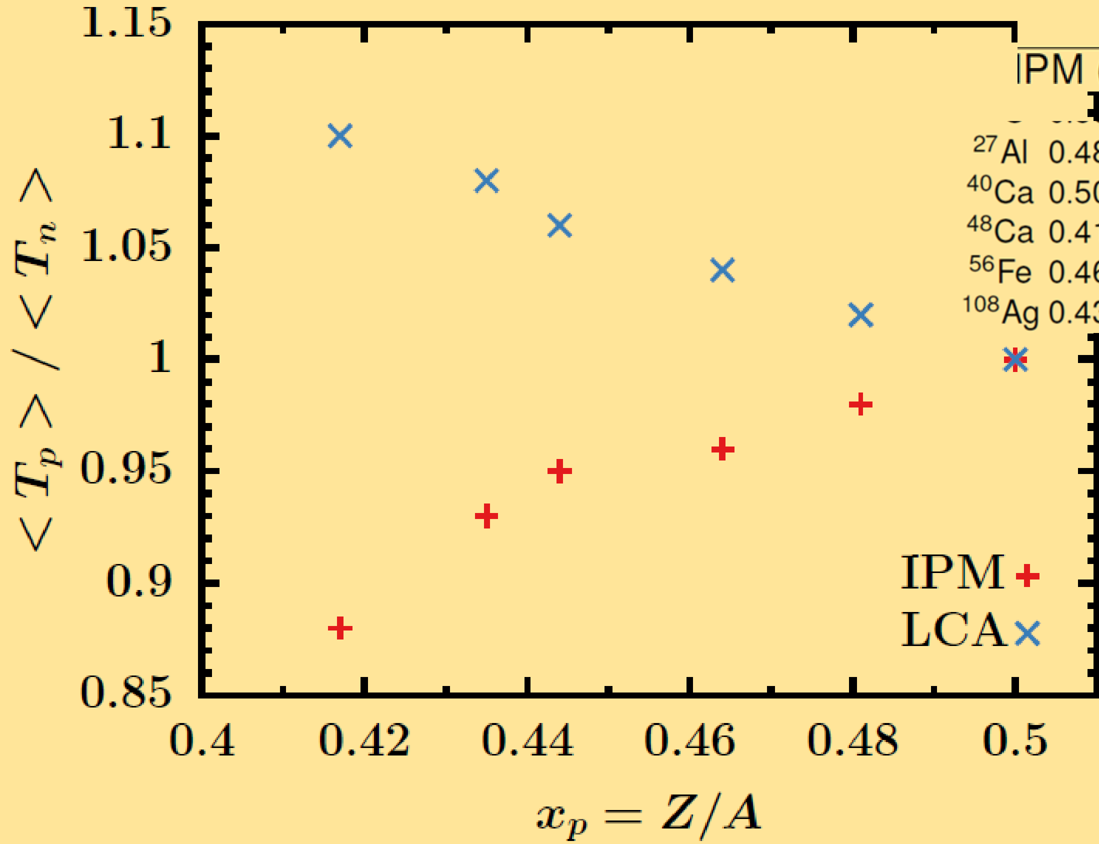
	$\frac{\lvert N-Z \rvert}{A}$	<KE> *p*	<KE> *n*	<KE> *p* − *n*
^{8}He	0.50	30.13	18.60	11.53
^{6}He	0.33	27.66	19.06	8.60
^{9}Li	0.33	31.39	24.91	6.48
^{3}He	0.33	14.71	19.35	-4.64
^{3}H	0.33	19.61	14.96	4.65
^{8}Li	0.25	28.95	23.98	4.97
^{10}Be	0.2	30.20	25.95	4.25
^{7}Li	0.14	26.88	24.54	2.34
^{9}Be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



$$\frac{n_n(k>1)}{n_n(k<1)} > \frac{n_p(k>1)}{n_p(k<1)}$$

Predictions for $\langle T_p \rangle / \langle T_n \rangle$ ratio

Average kinetic energy per nucleon

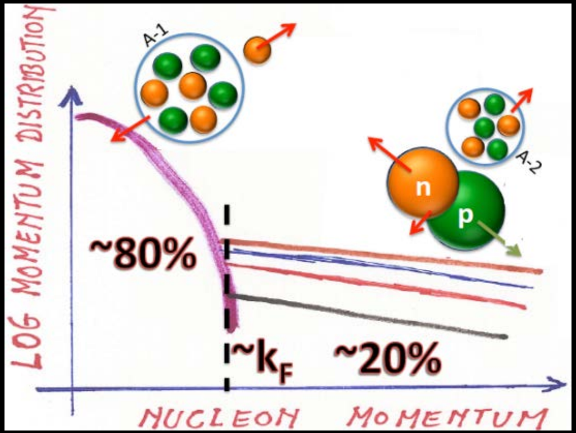


		$\langle T_N \rangle$ (MeV)			
		IPM (p)	IPM (n)	LCA (p)	LCA(n)
^{27}Al	0.481	16.61	16.92	30.93	30.26
^{40}Ca	0.500	16.44	16.42	31.23	31.18
^{48}Ca	0.417	15.64	17.84	33.04	30.06
^{56}Fe	0.464	16.71	17.45	32.33	31.13
^{108}Ag	0.435	16.48	17.81	33.55	31.16

Nuclei:

Identified triple coincidence SRC pairs in: (^{3}He,) ^{4}He, ^{12}C, ^{27}Al, ^{56}Fe, and ^{208}Pb

High momentum tail In nuclei dominated by SRC pairs



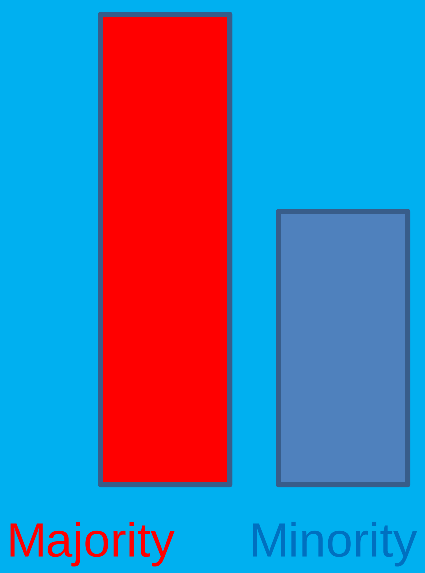
np-SRC dominance

Compact Astronomical Systems ?

Momentum sharing in Asymmetric (imbalanced) two components Fermi systems

non interacting Fermions

Pauli exclusion principle ➔



$$k_F^{Majority} > k_F^{Minority}$$

$$\langle T_{Majotiry} \rangle > \langle T_{Minority} \rangle$$

$$\langle k_{Majotiry} \rangle > \langle k_{Minority} \rangle$$

with short-range interaction : strong between unlike fermions, weak between same kind.

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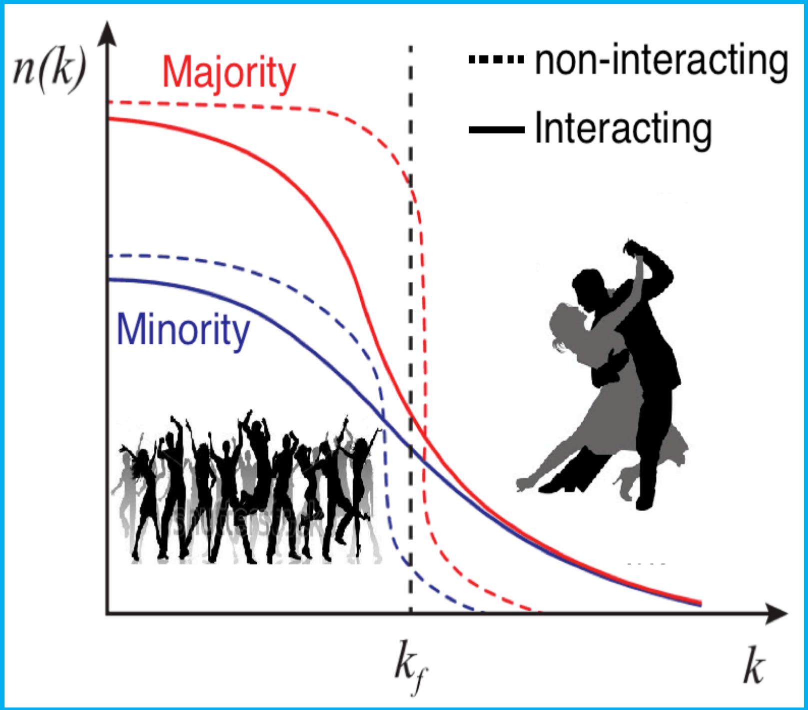
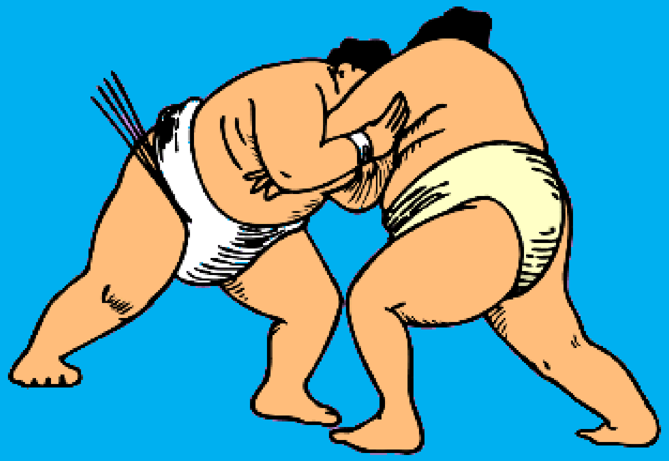




Who wins?

Universal property

A minority fermion have a greater probability than a majority fermion to be above the Fermi sea $k > k_F$

Possible inversion of the momentum sharing :

$$\langle k_{\min ority} \rangle > \langle k_{majority} \rangle$$

Protons move faster than neutrons in N>Z nuclei

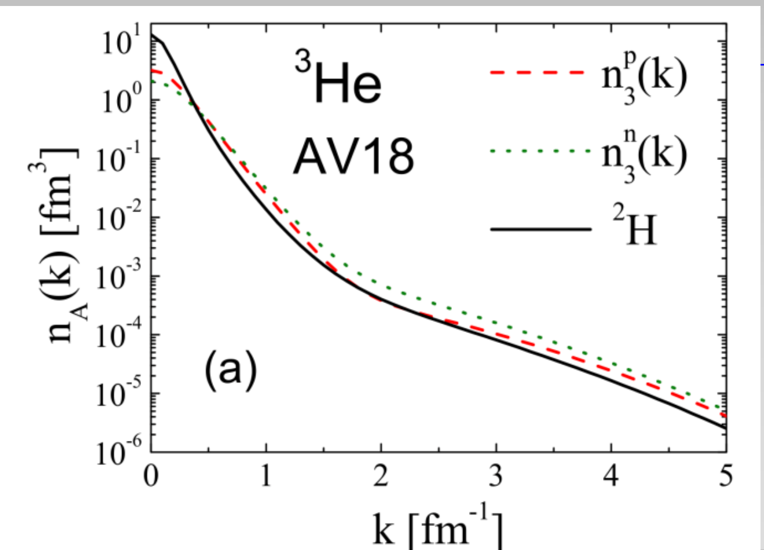
(protons move faster than neutrons in N>Z nuclei)

Light nuclei *A*<11

Variational Monte Carlo calculations by the Argonne group

Wiringa et al.
phys. Rev. C89, 034305 (2014).

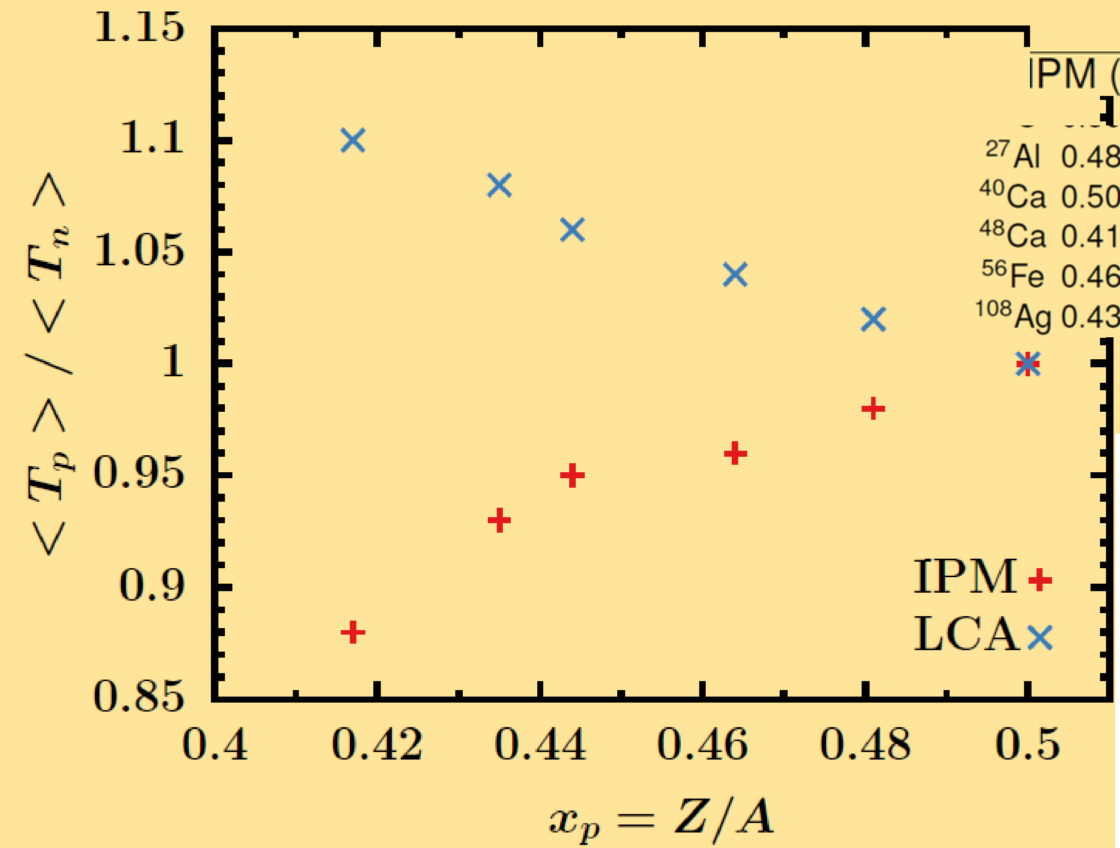
	$\frac{\lvert N-Z \rvert}{A}$	<KE> p	<KE> n	<KE> $p-n$
^{8}He	0.50	30.13	18.60	11.53
^{6}He	0.33	27.66	19.06	8.60
^{9}Li	0.33	31.39	24.91	6.48
^{3}He	0.33	14.71	19.35	-4.64
^{3}H	0.33	19.61	14.96	4.65
^{8}Li	0.25	28.95	23.98	4.97
^{10}Be	0.2	30.20	25.95	4.25
^{7}Li	0.14	26.88	24.54	2.34
^{9}Be	0.11	29.82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



$$\frac{n_n(k>1)}{n_n(k<1)} > \frac{n_p(k>1)}{n_p(k<1)}$$

Predictions for $\langle T_p \rangle / \langle T_n \rangle$ ratio

Average kinetic energy per nucleon



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Implications for Neutron Stars

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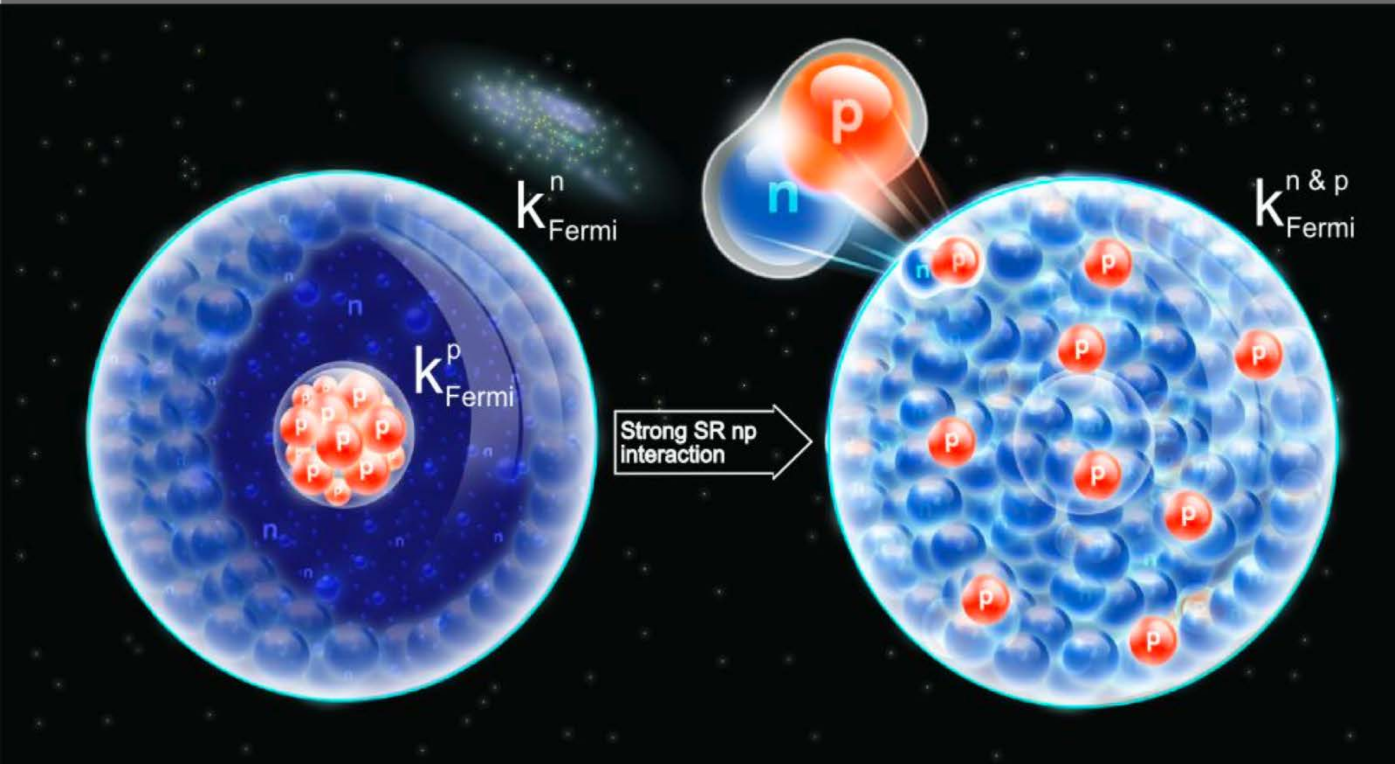


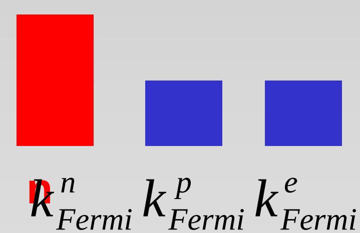
Adapted from: D.Higinbotham, E. Piasetzky, M. Strikman CERN Courier 49N1 (2009) 22

- **At the core of neutron stars, most accepted models assume :**

  ~95% neutrons, ~5% protons and ~5% electrons (β-stability).

- **Neglecting the np-SRC interactions, one can assume three separate Fermi gases (n p and e).**

- **strong np interaction** → **the n-gas heats the p-gas.**



See estimates in Frankfurt and Strikman **: Int.J.Mod.Phys.A23:2991-3055,2008.**

SRC in nuclei: implication for neutron stars

- **At the core of neutron stars, most accepted models assume :**

~95% neutrons, ~5% protons and ~5% electrons (β-stability).

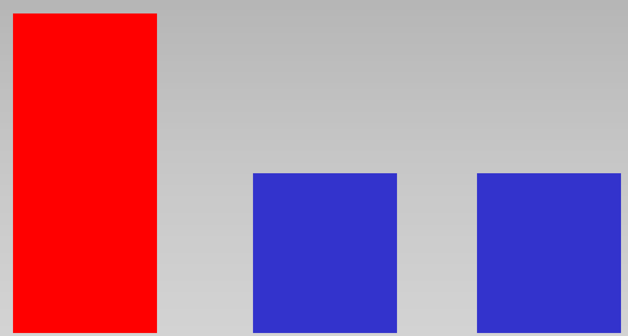
- **Neglecting the np-SRC interactions, one can assume three separate Fermi gases (n p and e).**

At T=0 $$k^n_{Fermi} = k^p_{Fermi} + k^e_{Fermi}$$ $$k^p_{Fermi} = k^e_{Fermi} = (\frac{N_p}{N_n})^{1/3} k^n_{Fermi}$$

For $$\rho = 5\rho_{0,} \; k^n_{Fermi} \approx 500 \text{ MeV/c}, \; k^p_{Fermi} = k^e_{Fermi} \approx 250 \text{ MeV/c}$$

Pauli blocking prevent direct n decay

$$n \rightarrow p + e + \overline{\nu}_e$$



k^n_{Fermi} k^p_{Fermi} k^e_{Fermi}

Strong SR np interaction

SRC in nuclei: implication for neutron stars

Strong SR np interaction

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At T=0

Holes in the n p e Fermi seas

Create (n-p-e) neutral SRC

Remove Pauli Blocking of the direct n decay

Cause instability of the neutron star

At T≠0

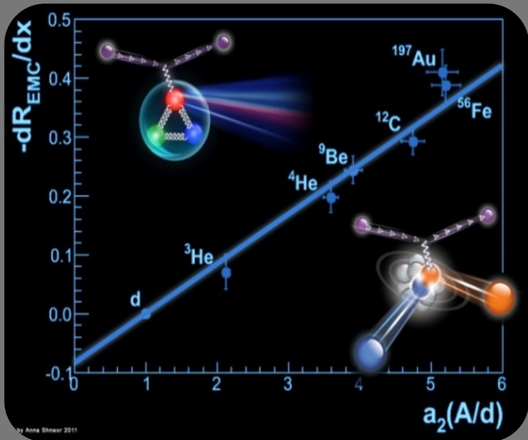
Faster neutrino cooling

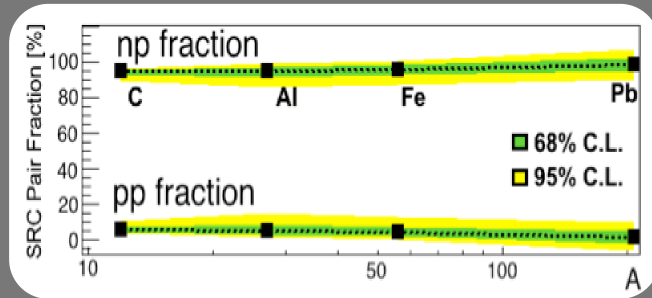
Short life time of hyperon stars

See estimates in Frankfurt and Strikman rXiv:0806.0997

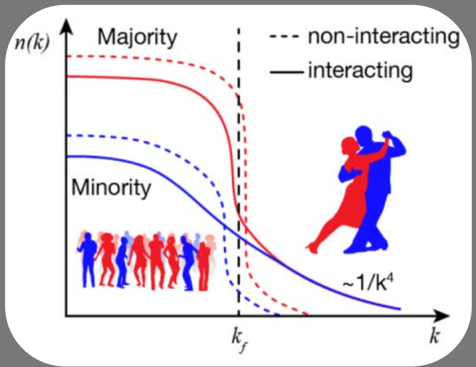
Also: Int.J.Mod.Phys.A23:2991-3055,2008. **arXiv:0806.4412**

Summary – relevant of Correlations

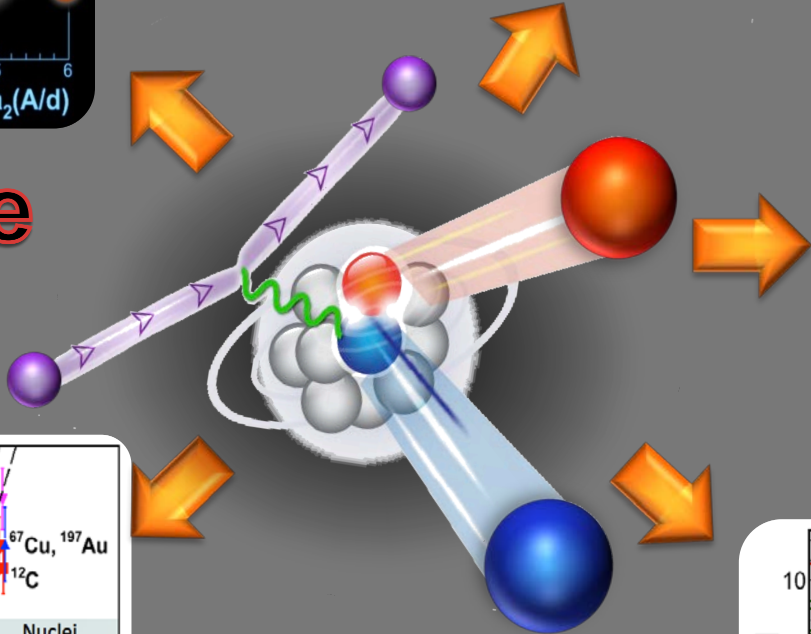




Nuclear

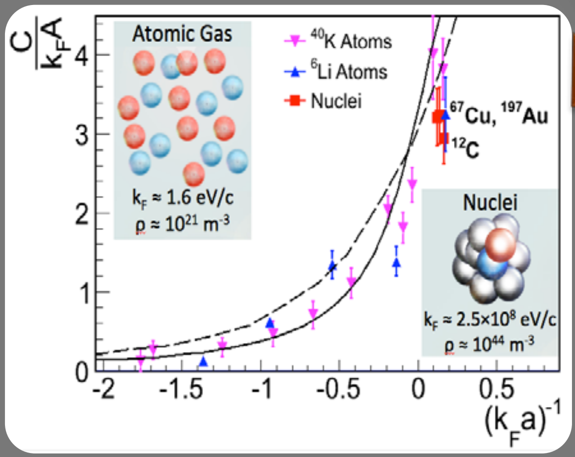


Particle



3N-SRC

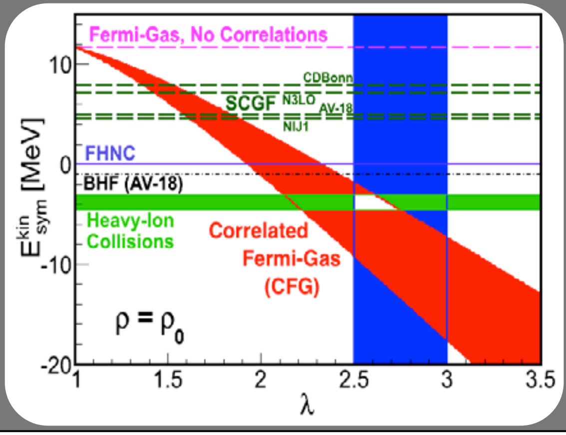
Atomic



Contact term

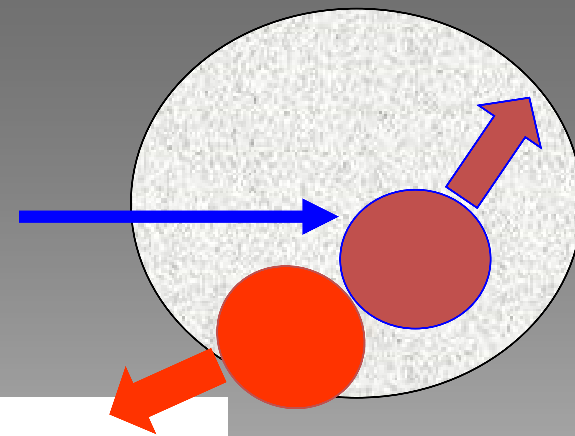
Astro

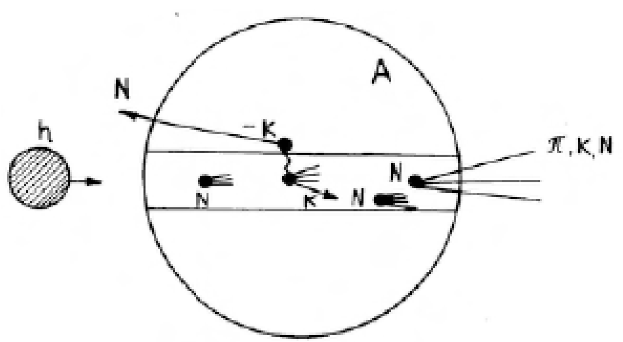
Symmetry energy



The story of studying SRC in nuclei using high energy probes started here with the measurements of Fast Backward Production at ITEP Moscow (p,π) and YerPhi (real and virtual photons) .

The universality of the fast backward emitted spectrum led Strikman Frankfurt to postulate that it is due to SRC





Production of a fast backward nucleon in the hadron - nucleus scattering

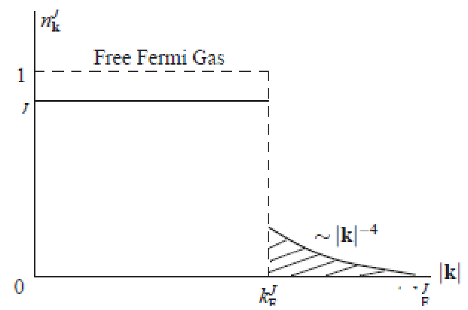
16

Published: *Physics of Atomic Nuclei, Vol. 61, No. 2, 1998, pp. 207–213.*

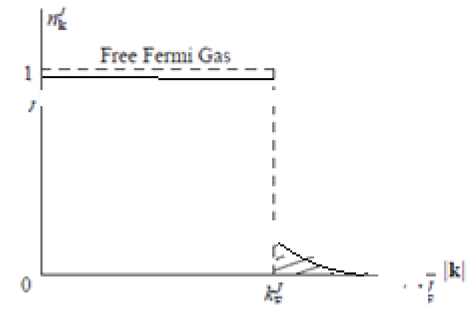
Emission of Cumulative Protons in the Reaction $^{12}C(e, e'p)$

K. V. Alanakyan, M. J. Amaryan, G. A. Asryan, R. A. Demirchyan, K. Sh. Egiyan, M. S. Ohanjanyan, M. M. Sargsyan, S. G. Stepanyan, and Yu. G. Sharabyan

Yerevan Physics Institute, ul. Brat'ev Alikhanian 2, Yerevan, 375036 Armenia

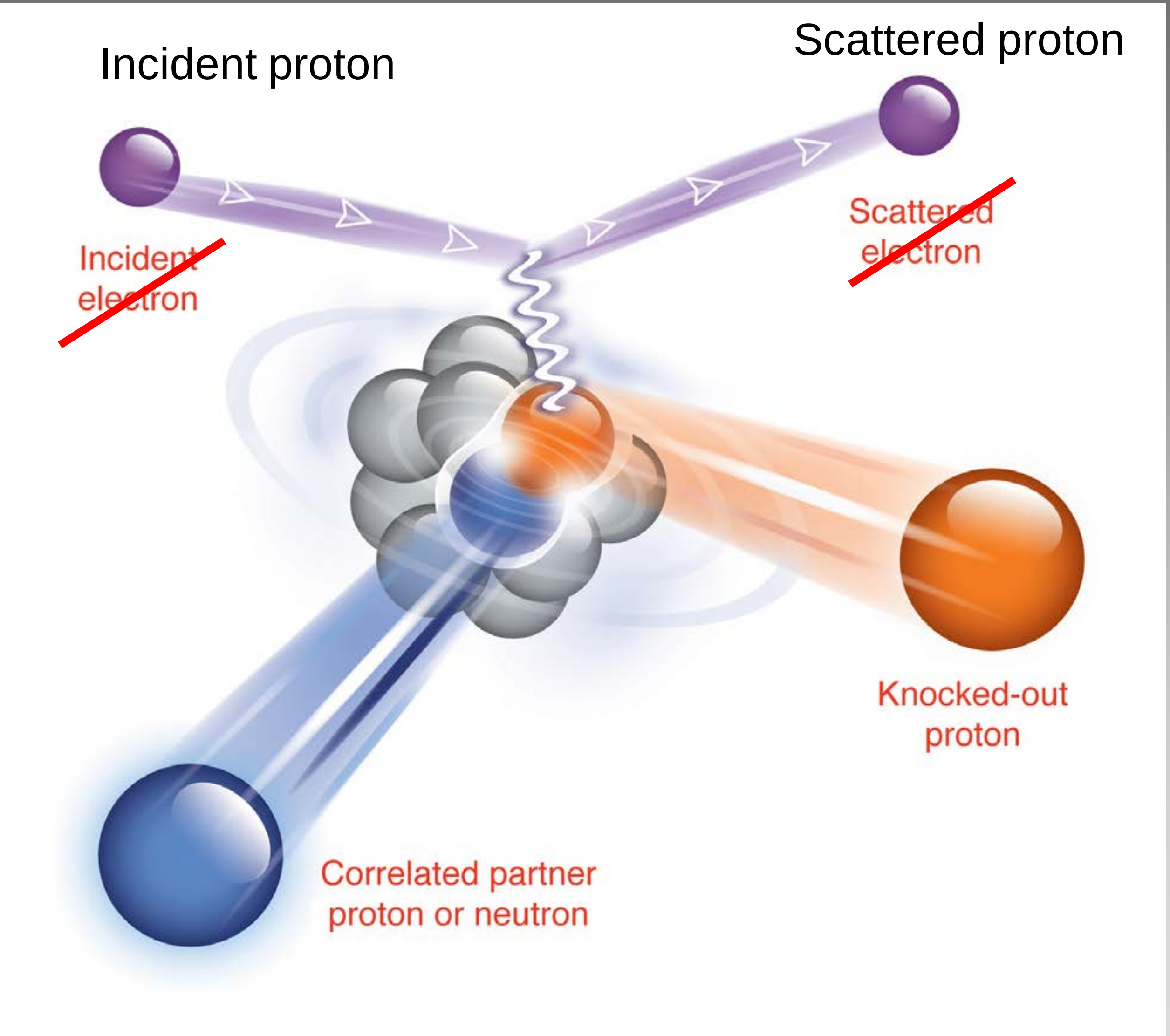


$n'_{\mathbf{k}}$
Free Fermi Gas
1
0
$\sim |\mathbf{k}|^{-4}$
$|\mathbf{k}|$



$n'_{\mathbf{k}}$
Free Fermi Gas
1
0
$|\mathbf{k}|$

First Triple coincidence ^{12}C (p, p p n) measurements at EVA / BNL



Complementary to JLab study with electrons