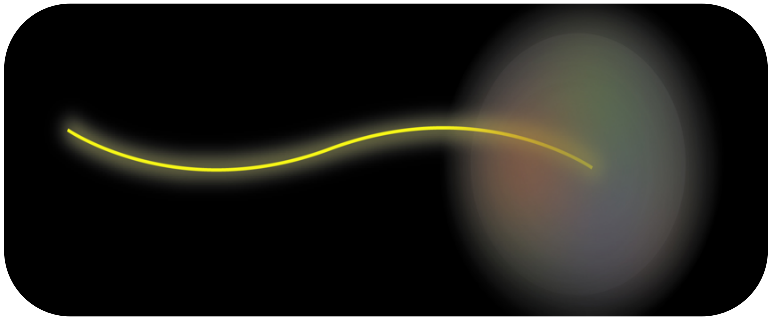
The Fluctuating Nucleus

Or Hen – MIT

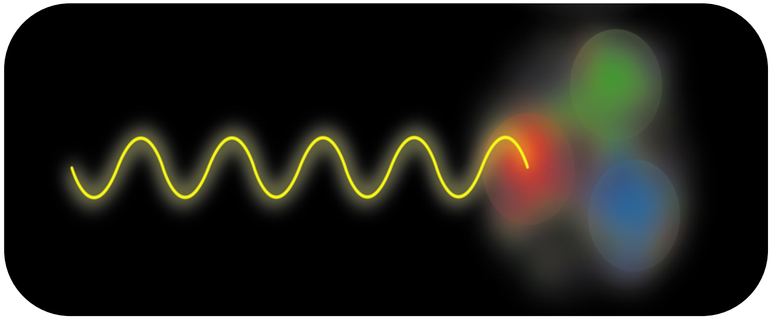
CBM-STAR Joint Workshop,
March 18th 2017, TU Darmstadt, Germany.

Physicists view nuclei in different ways



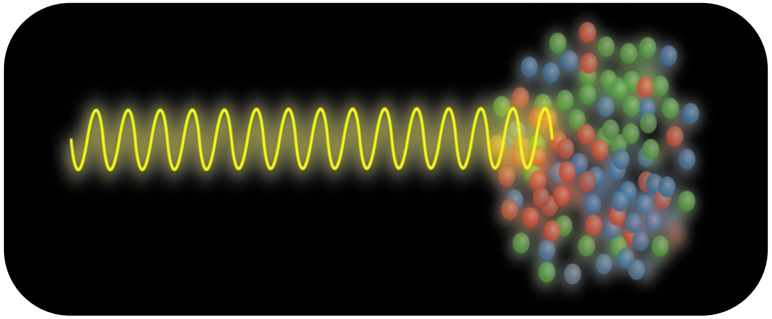
Atomic / Solid-state:

Heavy, charged, blob



Nuclear:

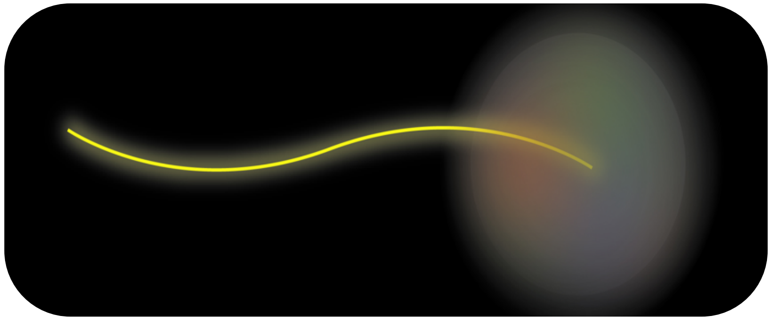
The world!



Particle:

Bag of partons

Physicists view nuclei in different ways



Atomic / Solid-state:

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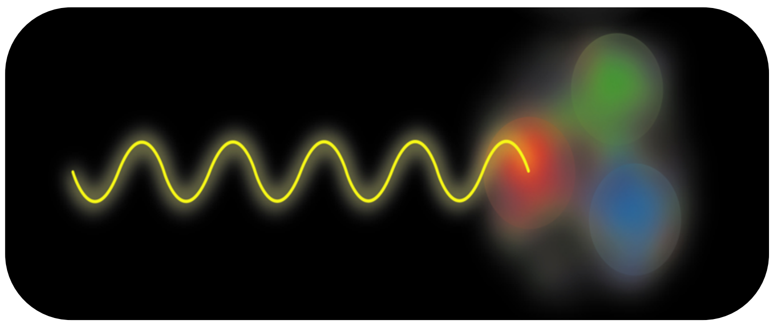
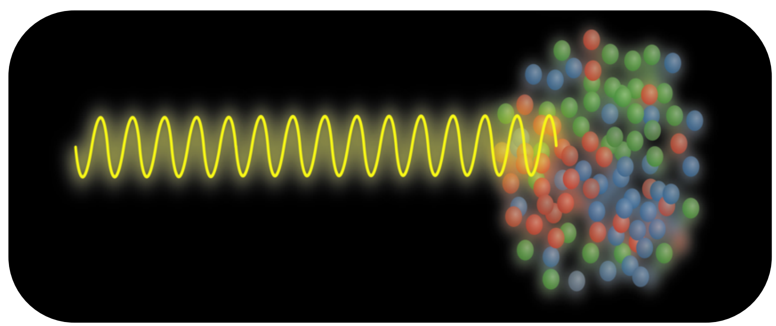


Nuclear:

The world!

(Heavy Ion)

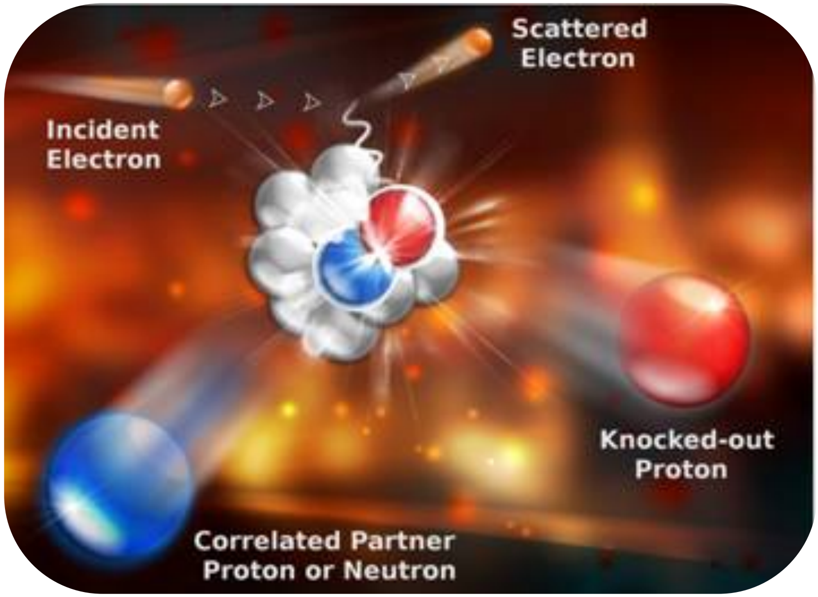


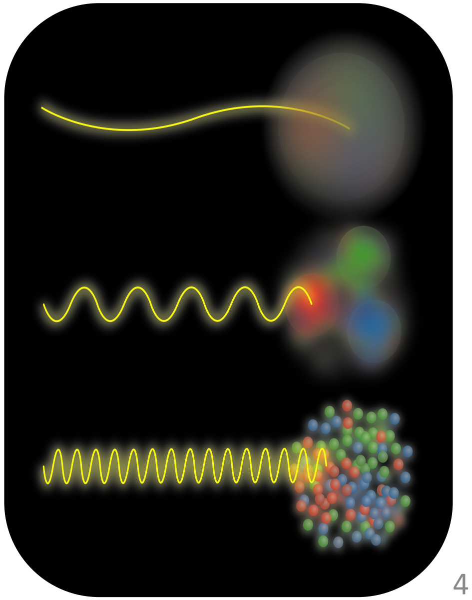
Particle:

Bag of partons

My goal for today:

Convince you that you should care about (some) aspects of nuclear structure! Specifically, **short-range fluctuations.**





Outline

1. Introduction to Short-Range Correlations
2. Universal description of fluctuations of strongly interactive Fermi systems.
3. Implications to nuclear PDFs (EMC effect)
4. Why you should care?!

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1. **Introduction to Short-Range Correlations**

2. Universal description of fluctuations of strongly interactive Fermi systems.

3. Implications to nuclear PDFs (EMC effect)

4. Why you should care?!

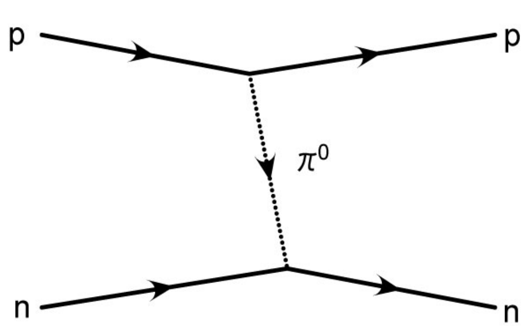
The Nuclear Many-Body Challenge

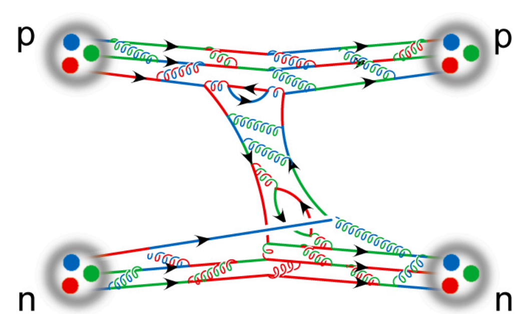
Many-body Schrödinger Equation

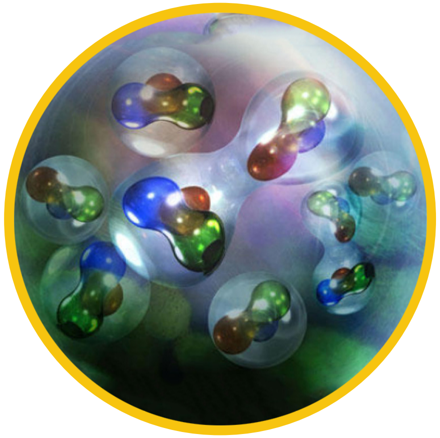
$$\sum_i \left\{-\frac{\hbar^2}{2m_i}\nabla_i^2\Psi(\vec{r}_1,\dots,\vec{r}_N,t)\right\} + U(\vec{r}_1,\dots,\vec{r}_N)\Psi(\vec{r}_1,\dots,\vec{r}_N,t) = i\hbar\frac{\partial}{\partial t}\Psi(\vec{r}_1,\dots,\vec{r}_N,t)$$

Main Challenges:

1. **No 'fundamental' Interaction** => residual interaction between quarks that makeup the nucleons.
2. Phenomenological **parametrizations are complex**! (over 18 operators)

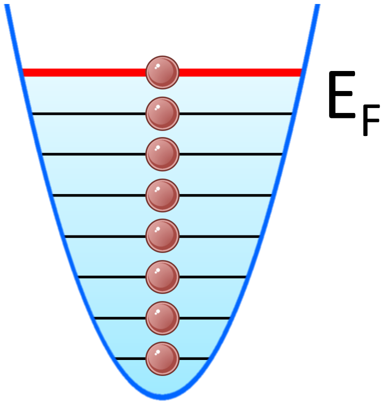






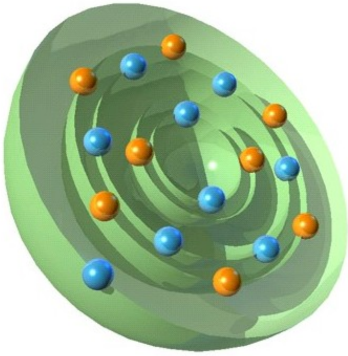
Solution: Effective Theories

Fermi Gas Model

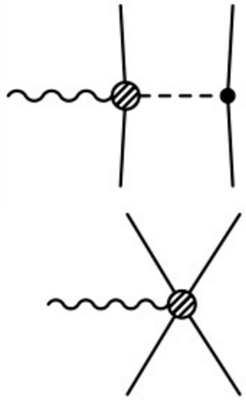


Liquid Drop Model

Shell Model

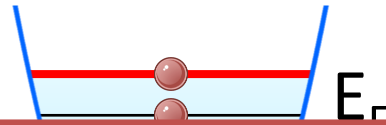


Chiral Perturbation Theory



Solution: Effective Theories

Fermi

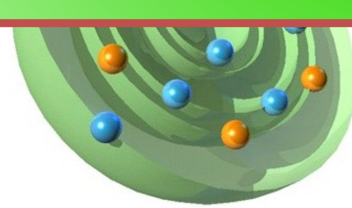


Liquid

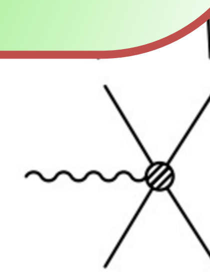
All effective theories relay on the same common idea:

Scale separation of long and short range dynamics in nuclei

Model



Perturbation Theory



Challenge of Correlations

Whole is different from the sum of parts!

$$n_{2N}(k_1, k_2) \neq n_N(k_1) \cdot n_N(k_2)$$
$$\rho_{2N}(\vec{r}_1, \vec{r}_2) \neq \rho_N(\vec{r}_1) \cdot \rho_N(\vec{r}_2)$$

Specifically, in coordinate space:

SRC: $\rho_{2N}(\vec{r}_1, \vec{r}_2) \neq 0$ for $|\vec{\boldsymbol{r}}_1 - \vec{\boldsymbol{r}}_2| \approx \boldsymbol{R_N}$

LRC: $\rho_{2N}(\vec{r}_1, \vec{r}_2) \neq 0$ for $|\vec{r}_1 - \vec{r}_2| \approx R_A$

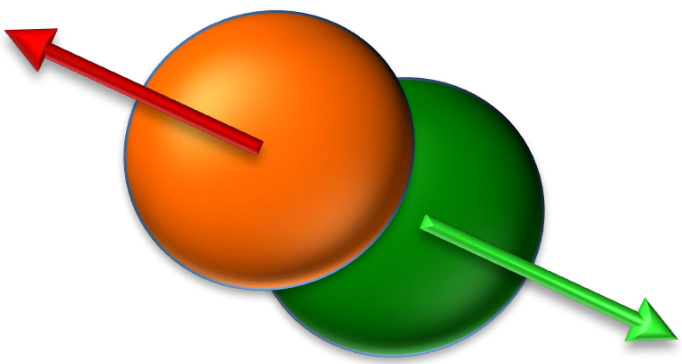
<u>(Some) Interesting questions:</u>

Is there a way to factorize the two-body density? Can we separate the 'mean-field' and 'SRC' effects? Are the SRC effects universal?

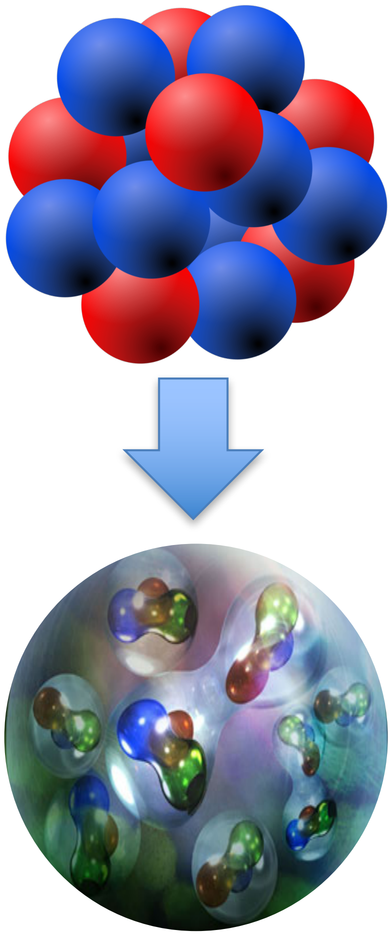
SRC 101

SRC are pairs of nucleon that are close together in the nucleus (wave functions overlap)

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



Nuclear Density Scales



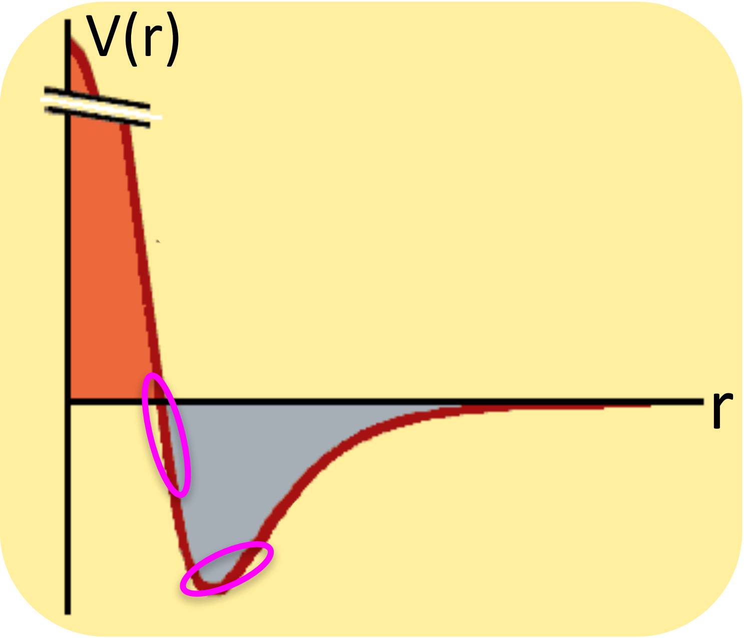
- Nuclear: 0.16 nucleons/fm^3
- Nucleon: 0.36 nucleons/fm^3
- SRC pair: ~ 0.55 nucleons/fm^3

SRC pairs have ~ **x3.5 larger density** compared to saturation nuclear density!

Why SRC?

Nuclear Physics

Better understanding of the *nucleon-nucleon interaction* and the nuclear momentum distribution



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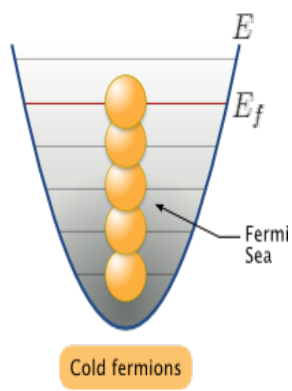

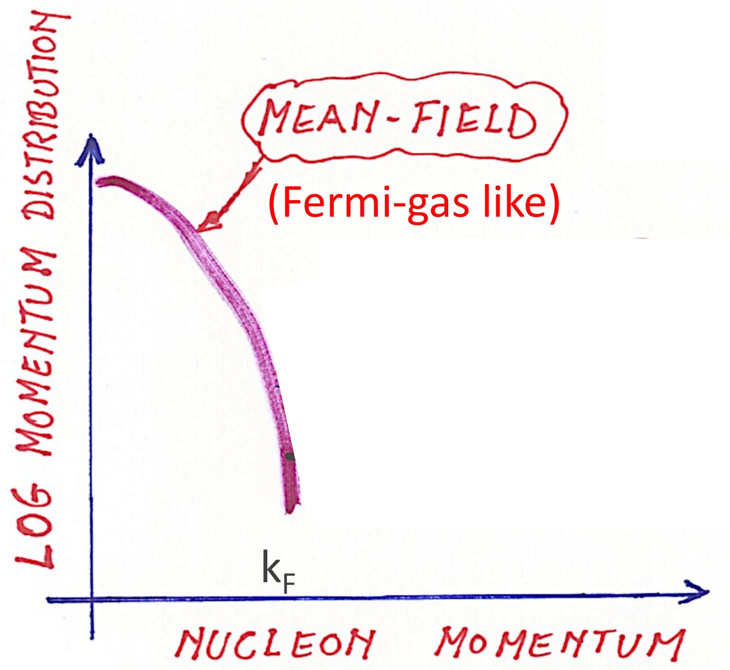

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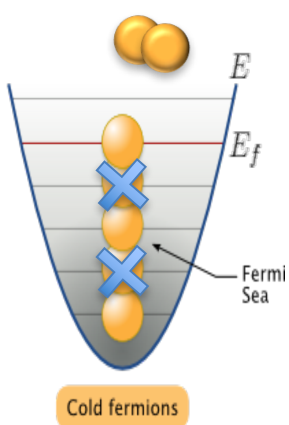
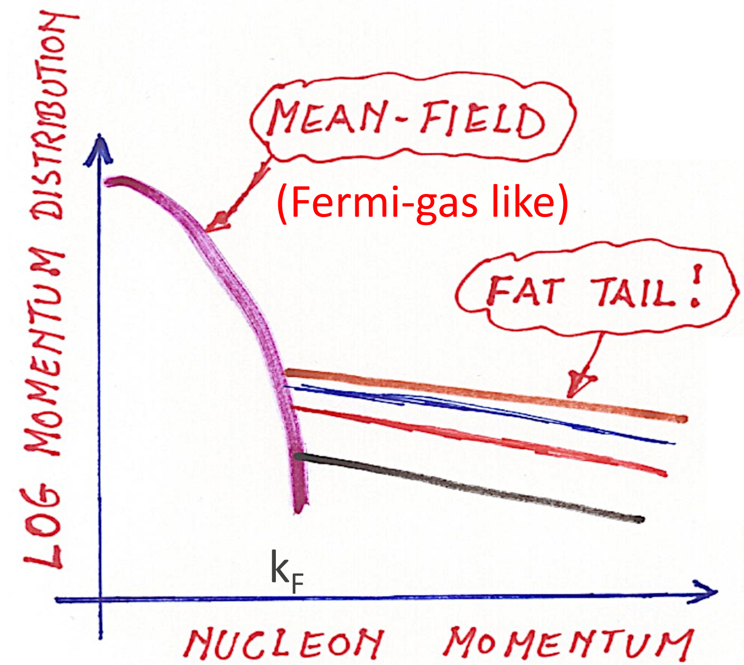
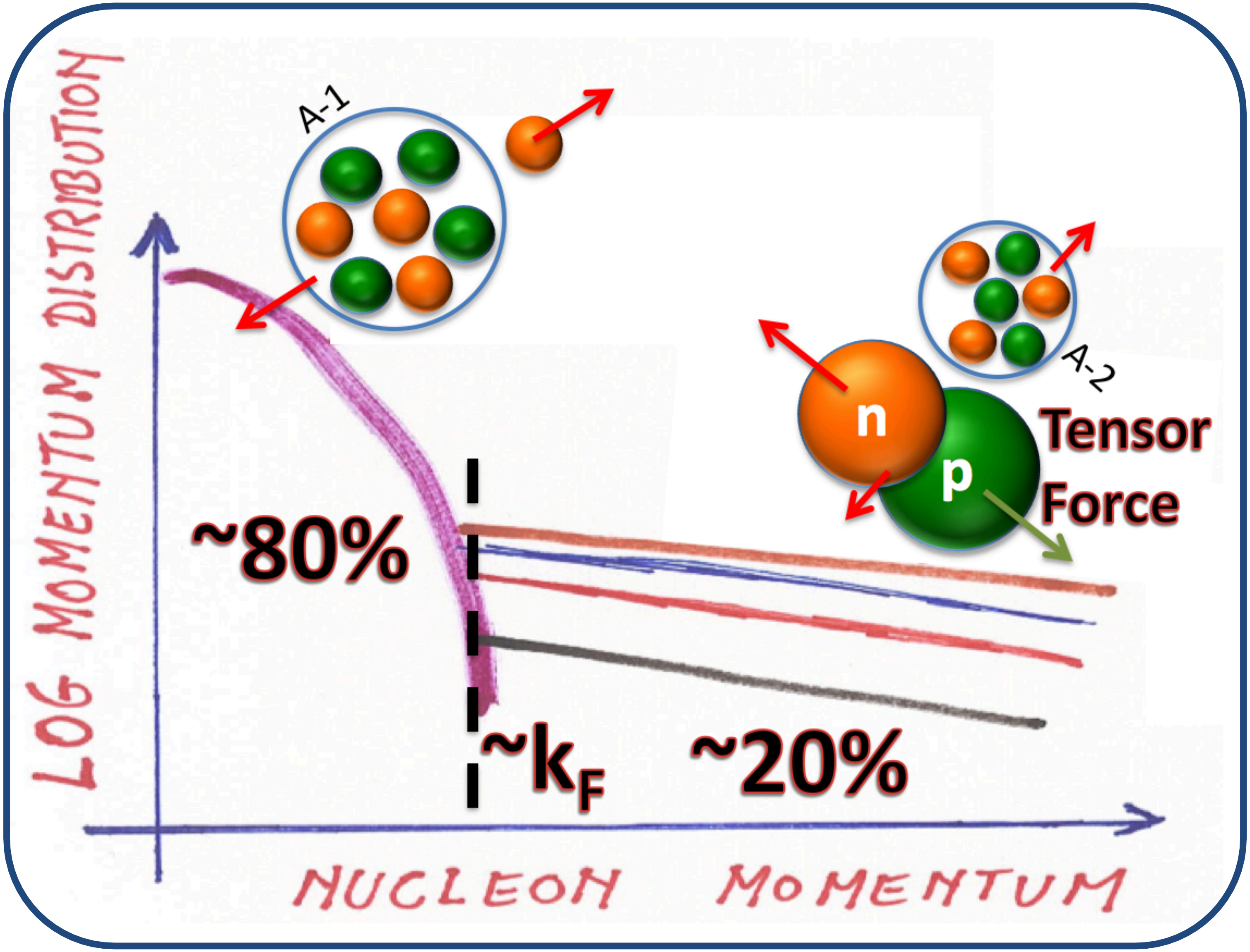
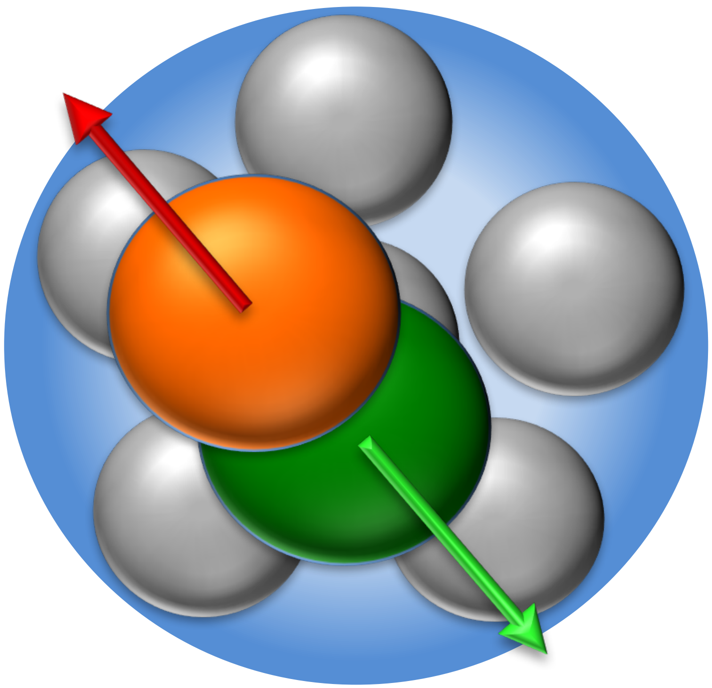




Universal structure of nuclear momentum distributions



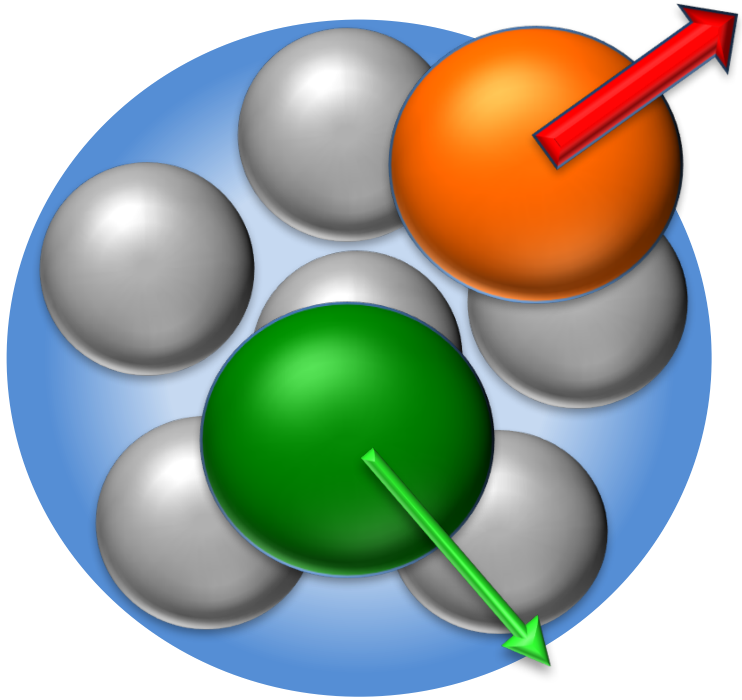
Exclusive 2N-SRC Studies



Exclusive 2N-SRC Studies

FIFA WORLD CUP
Brasil

Exclusive 2N-SRC Studies



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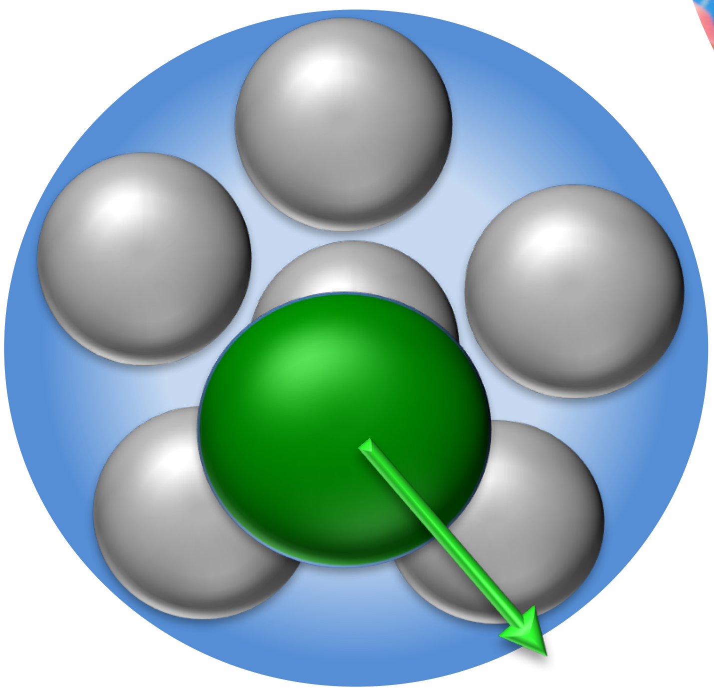

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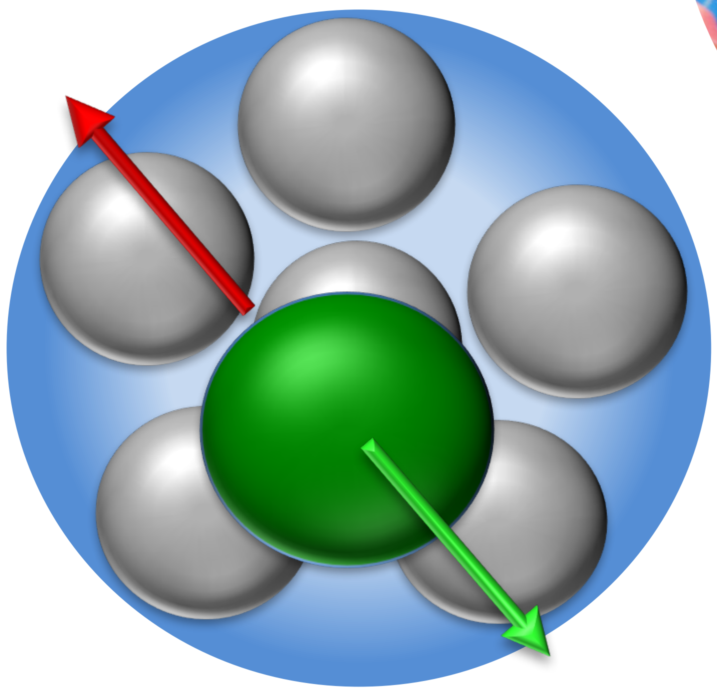

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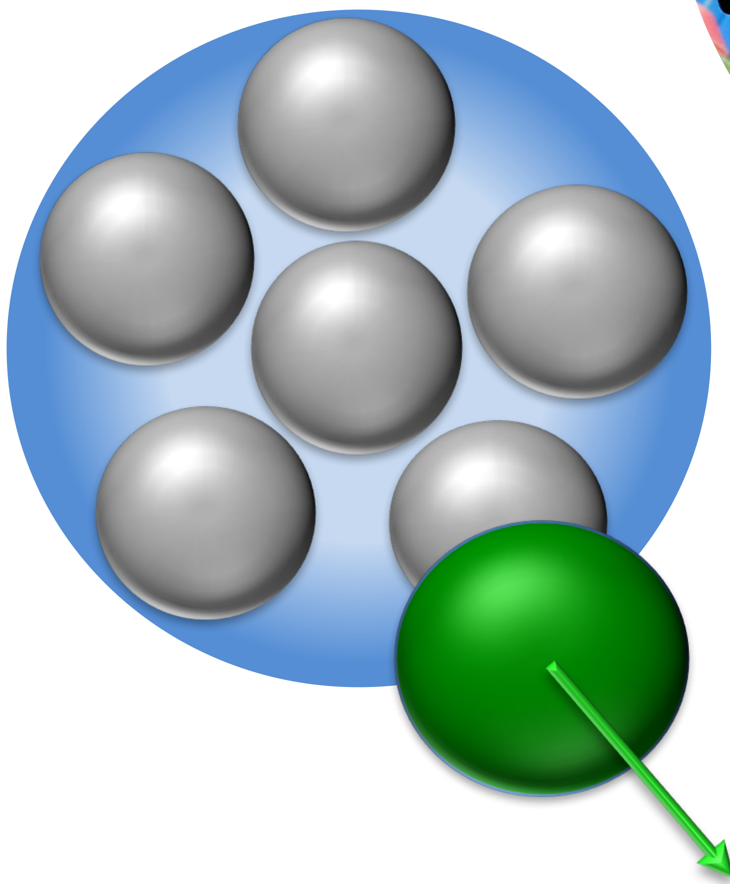

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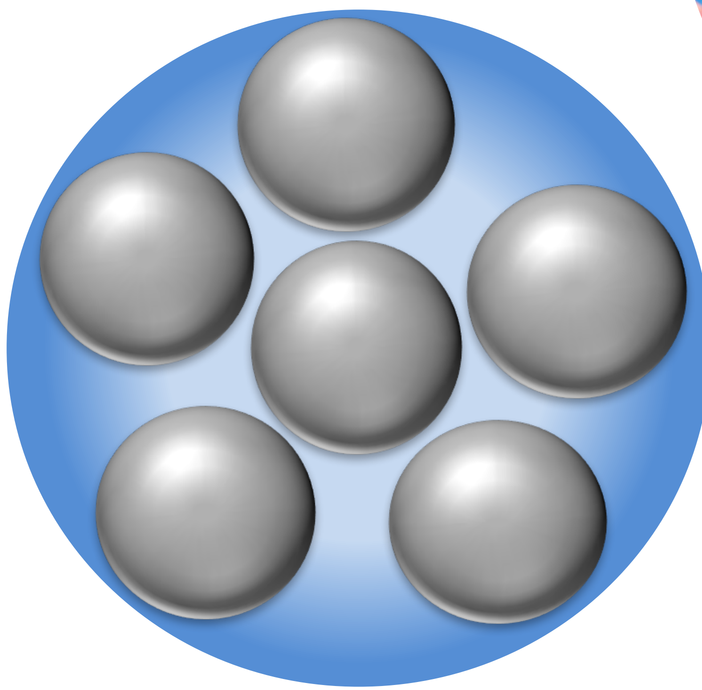

FIFA WORLD CUP
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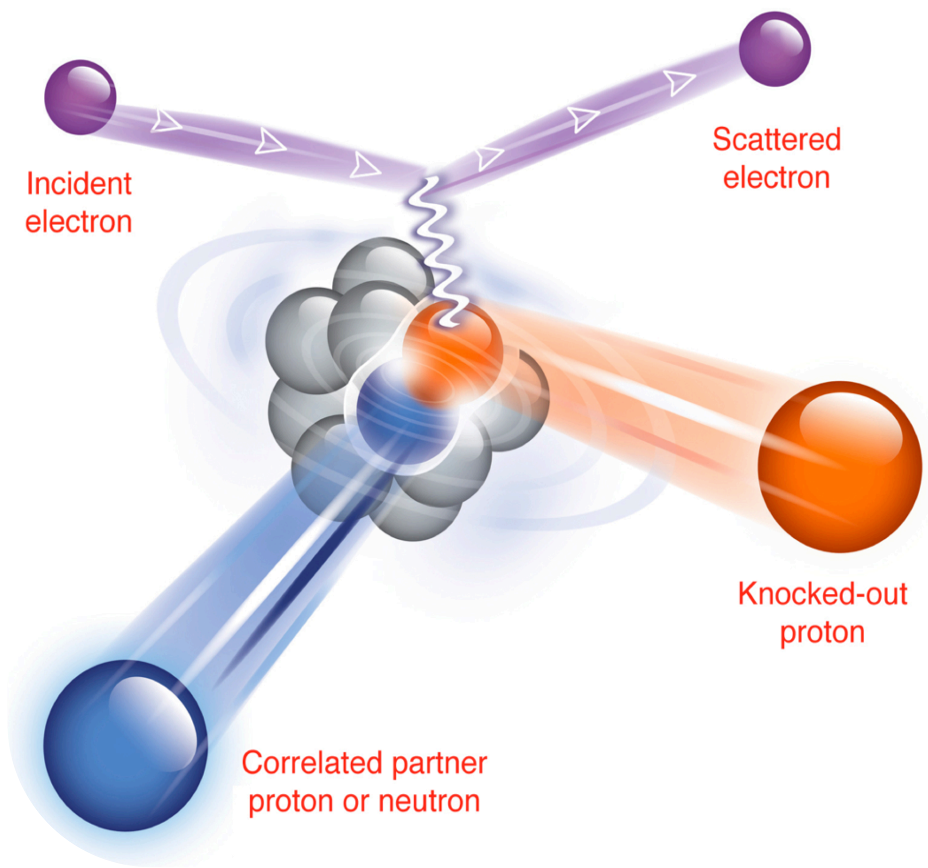
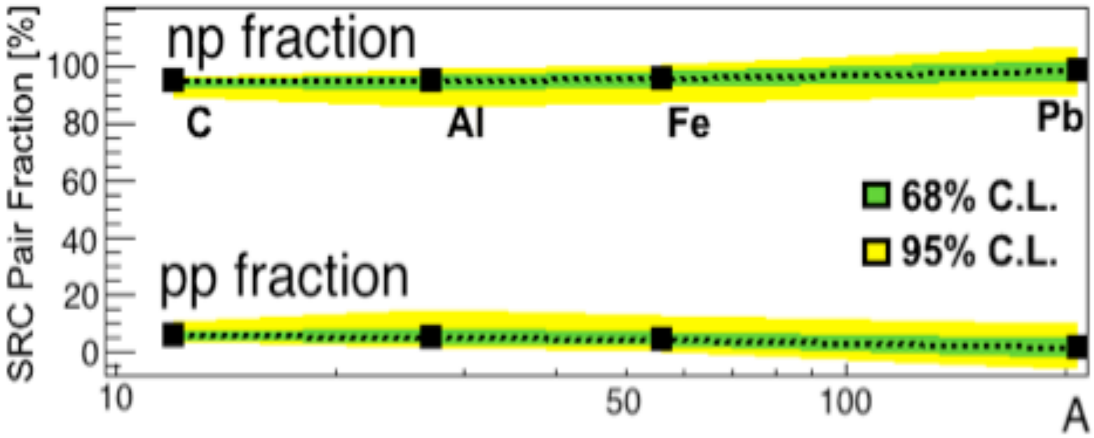
Exclusive 2N-SRC Studies

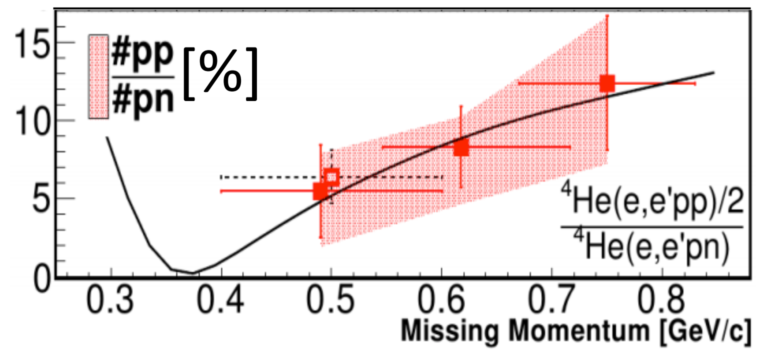
Breakup the pair =>
Detect both nucleons =>
Reconstruct 'initial' state



Proton-Neutron Dominance

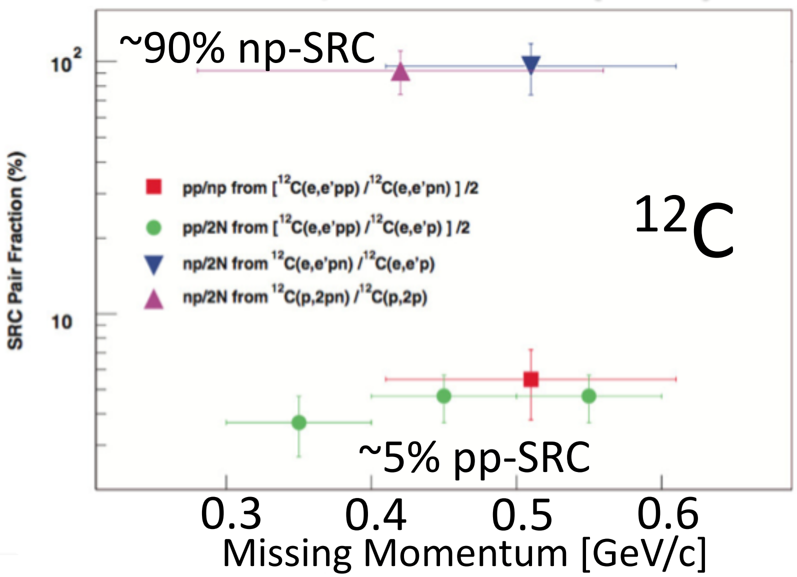


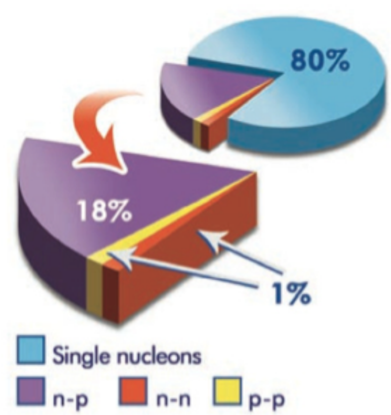
O. Hen et al., Science 364 (2014) 614

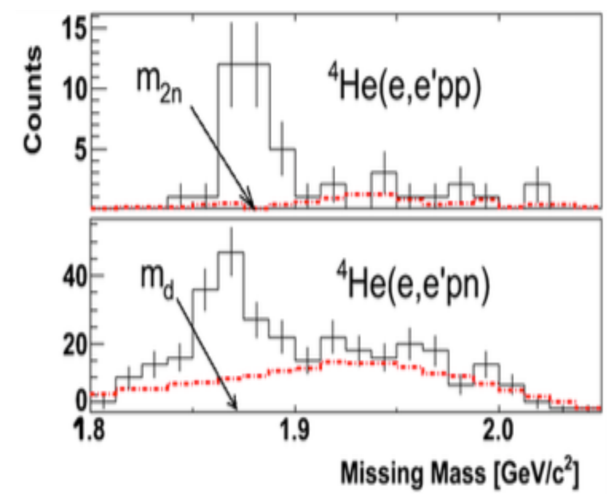


I. Korover et al., PRL 113 (2014) 022501

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



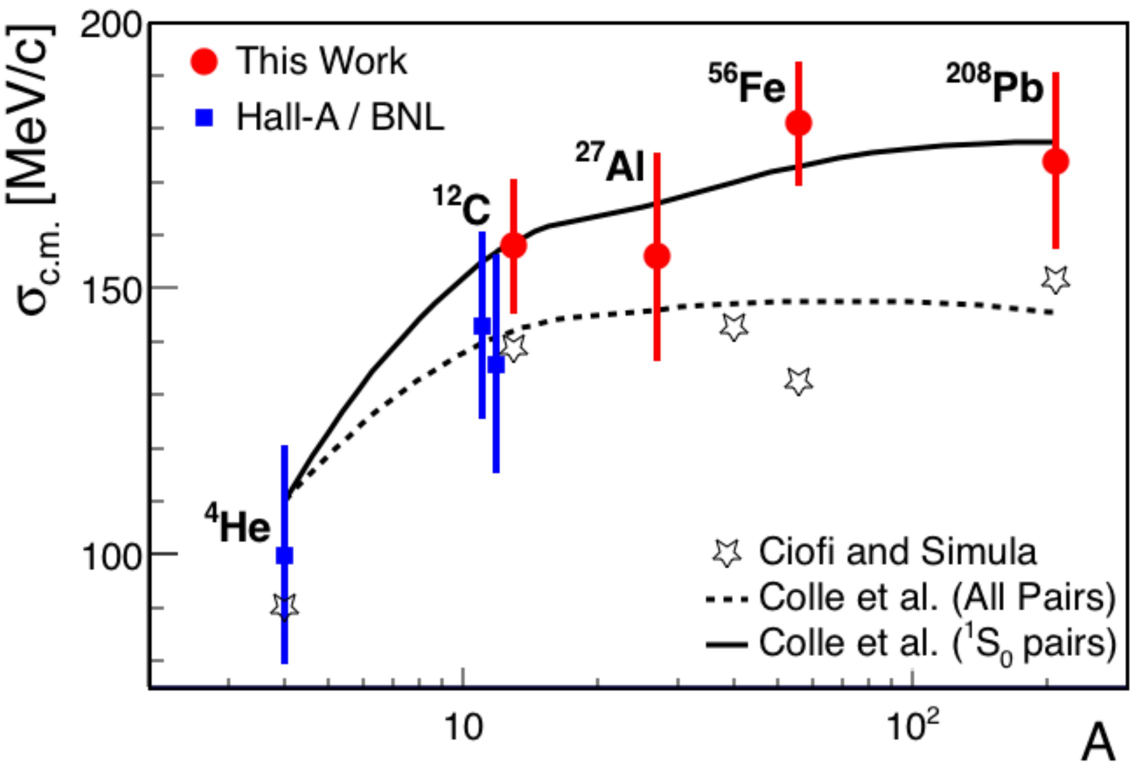


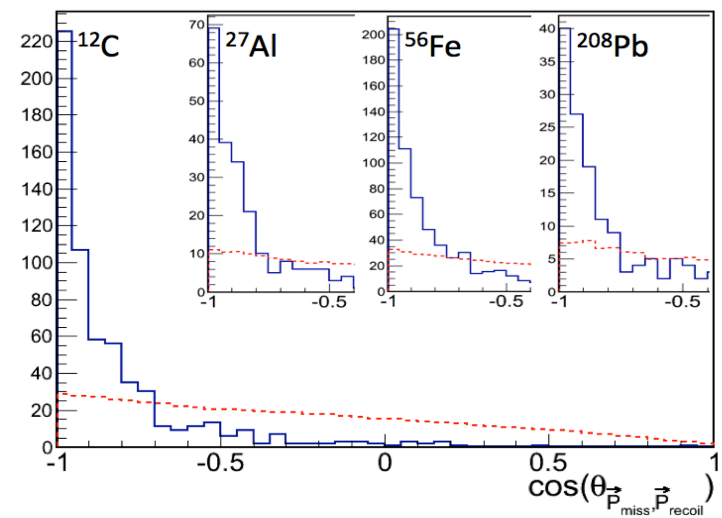


A. Tang et al., PRL (2003); E. Piasetzky et al., PRL (2006); R. Shneor et al., PRL (2007)

NEW DATA – c.m. Motion

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

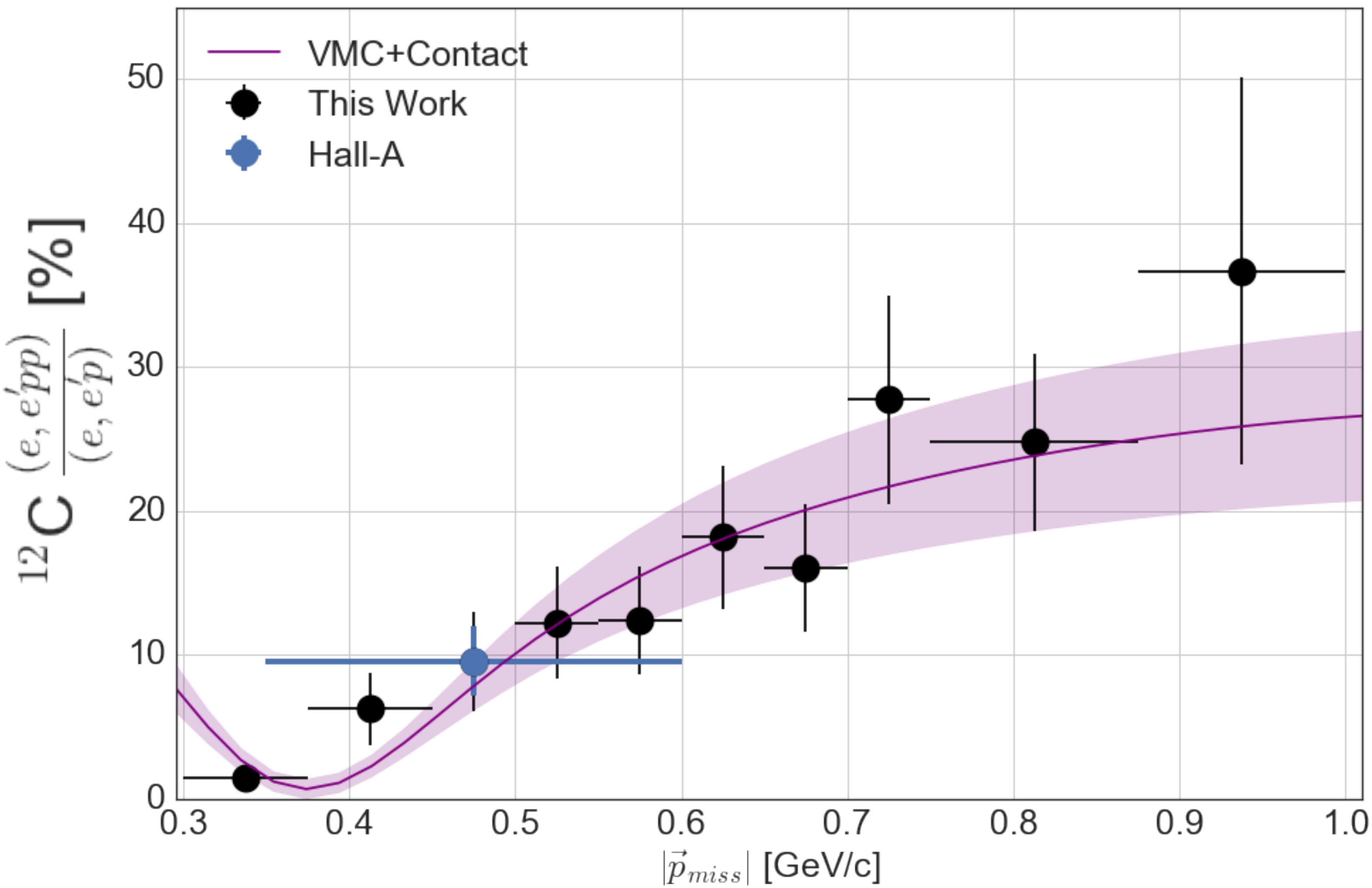




E. Cohen et al. (CLAS Collaboration)

NEW DATA – Repulsive Core (?)

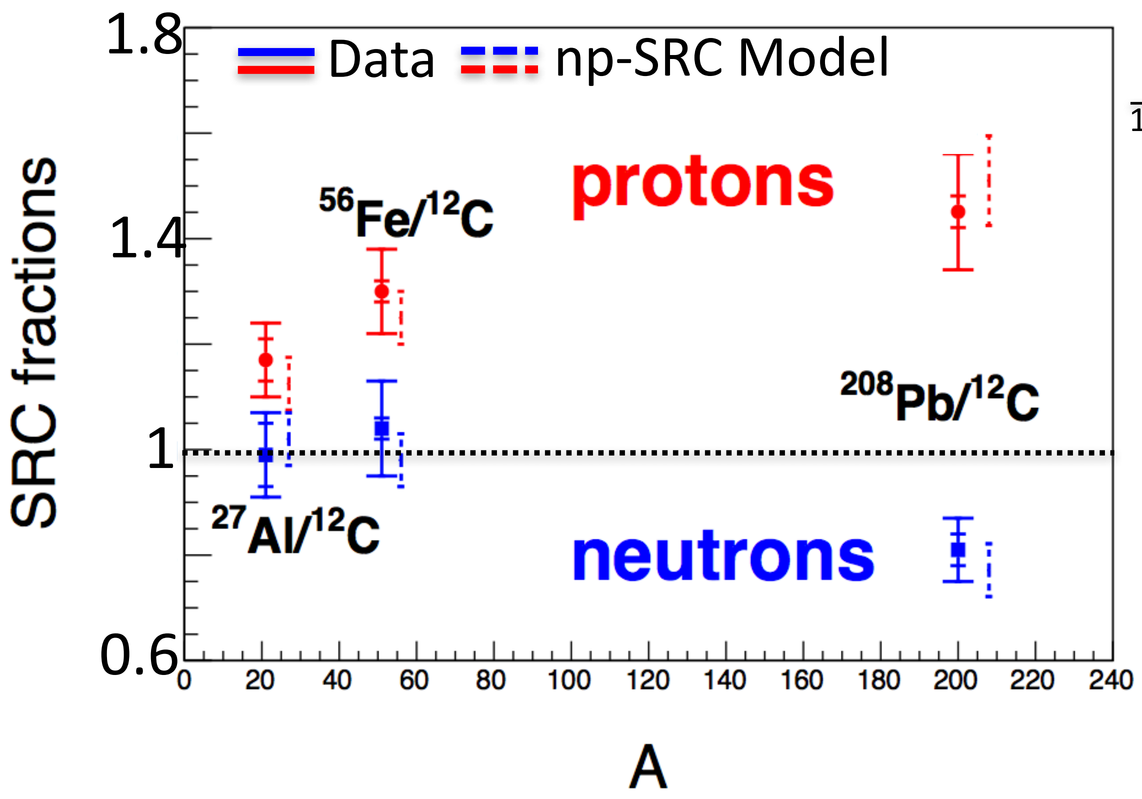
Pushing the nuclear wave function to the limit…



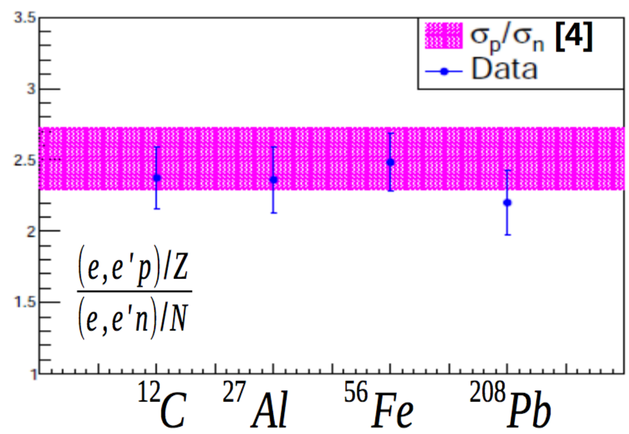
E. Cohen et al. (CLAS Collaboration)

NEW DATA – Asymmetric Nuclei

Protons are more correlated in neutron rich nuclei

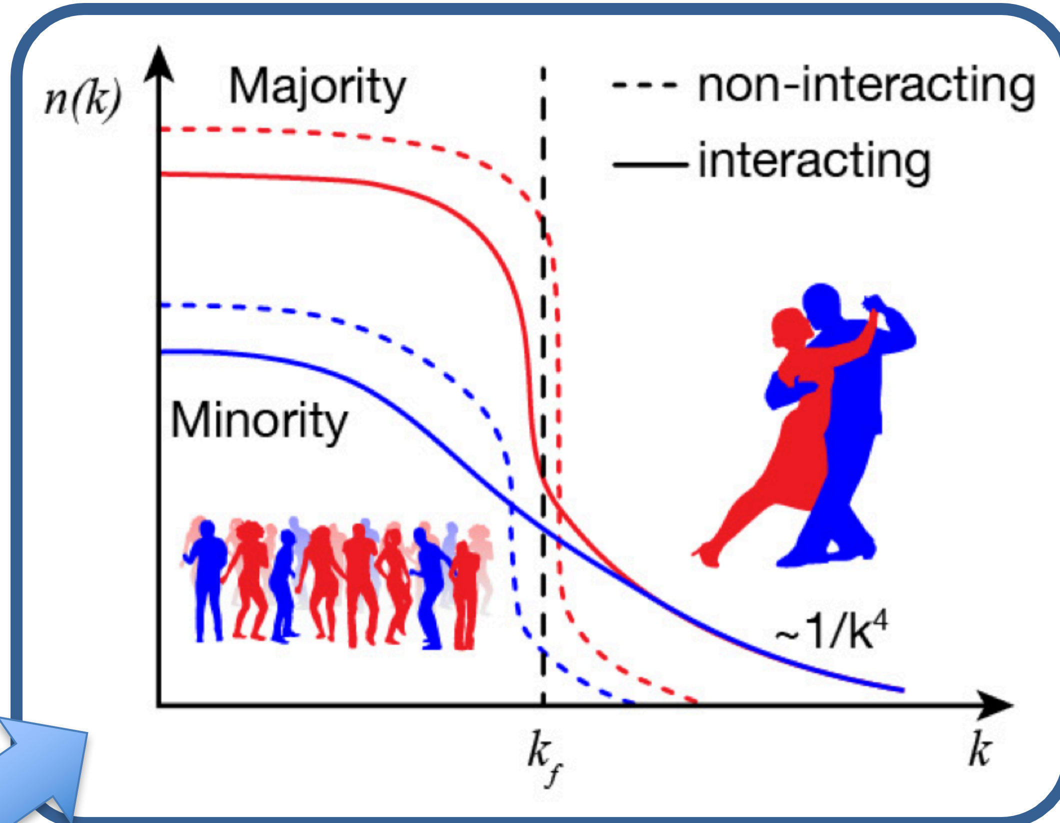


$$\frac{A\,(e,e'N)\,[\text{high-}P_m / \text{low-}P_m]}{^{12}C(e,e'N)\,[\text{high-}P_m / \text{low-}P_m]}$$

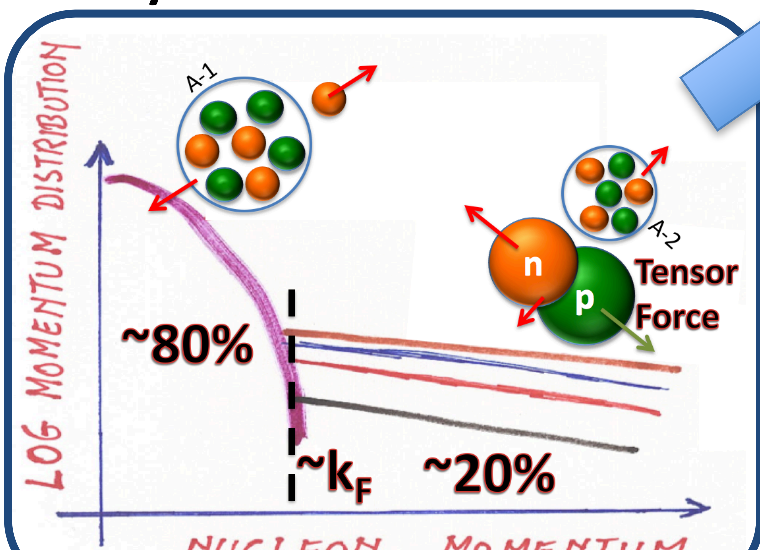


M. Duer et al. (CLAS Collaboration)

Asymmetric Nuclei



Symmetric Nuclei



SRC 101

Consistent set of (e,e'), (e,e'p), (e,e'pN) and (p,2pn) measurements, on a variety of nuclei, allow quantifying SRCs with unprecedented accuracy!

1. SRC Exist in Nuclei (!) and account for:
   - ~ 20% of the nucleons in nuclei.
   - ~100% of the high-p ($k>k_F$) nucleons in nuclei.
2. Have large relative momentum and low c.m. momentum.
3. Predominantly due to np-SRC.
4. Universal for A = 4 – 208 nuclei.
5. np-SRC create a larger fraction of high-momentum protons in neutron rich nuclei!
6. **Tensor force** dominance at short distance.

Outline

✓ Introduction to Short-Range Correlations

2. Universal description of fluctuations of strongly interactive Fermi systems.

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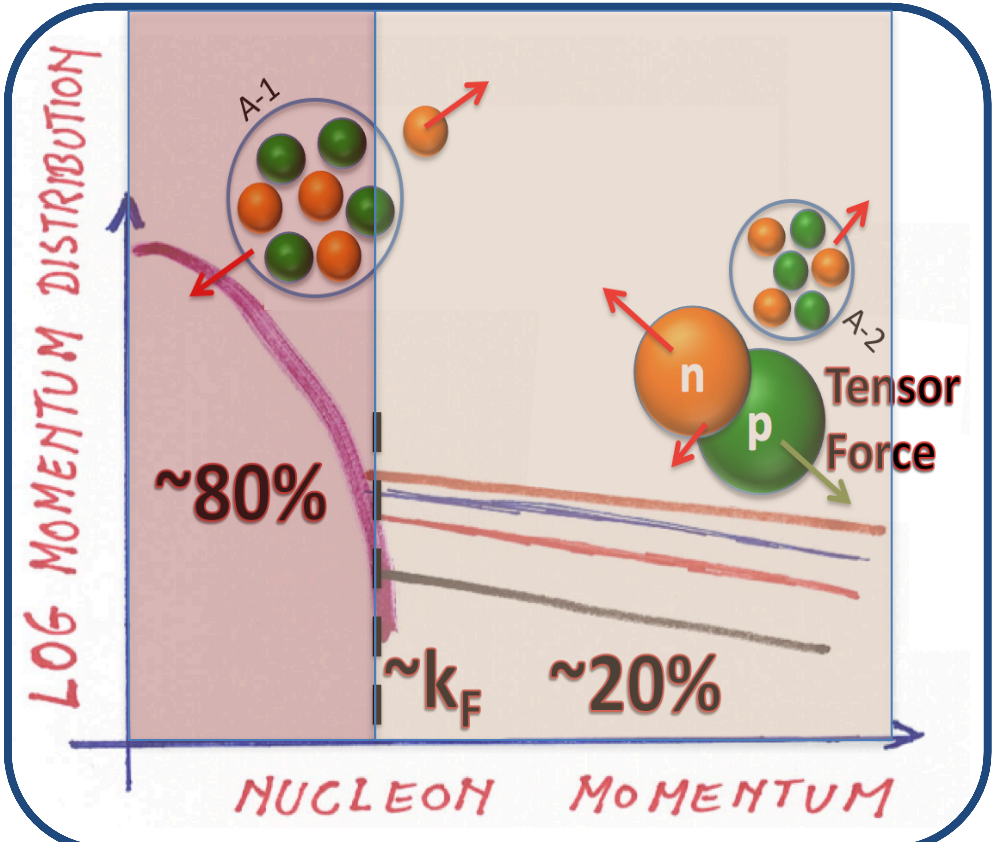
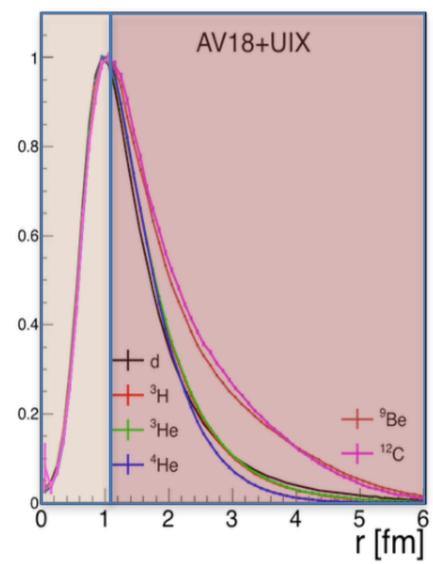
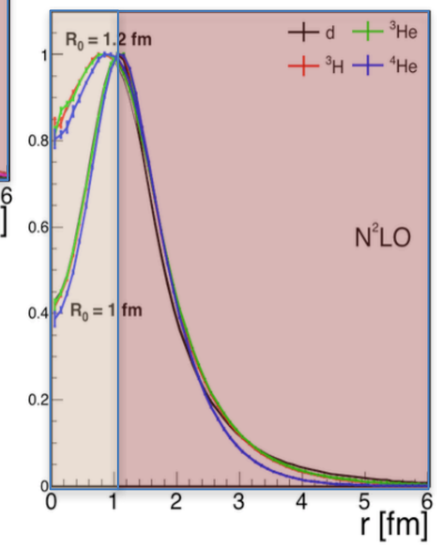
Universal Nuclear Structure

Can one formulate a *universal* effective description of SRC in coordinate and momentum space? (YES!)



Momentum Space





Coordinate Space

Factorization in Nuclei

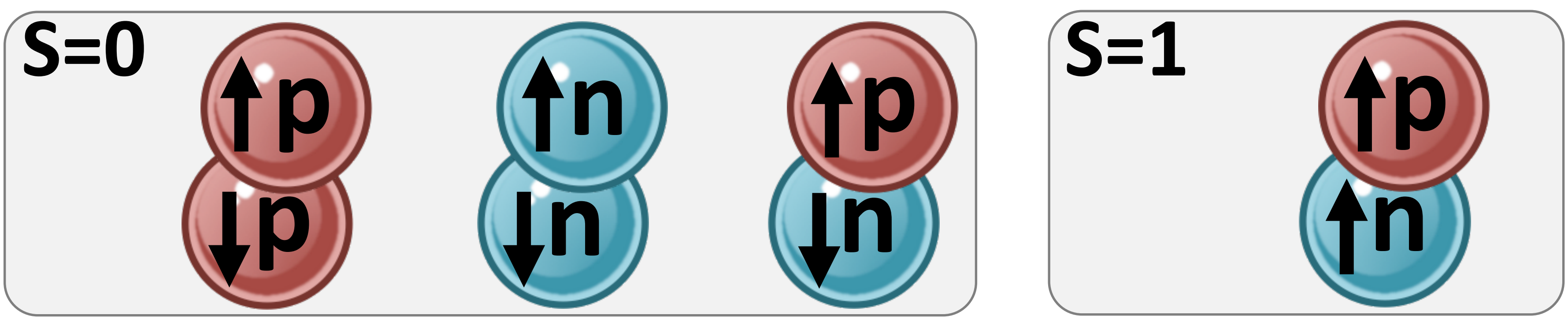
Consider a factorized wave function:

$$\Psi \xrightarrow[r_{ij}\to 0]{} \sum_{\alpha} \varphi_{\alpha}(\boldsymbol{r}_{ij}) A_{ij}^{\alpha}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j})$$

(known) Solution for the two-body problem

Many body, mean-field, function (a number!)

4 wave functions and contacts for L=0



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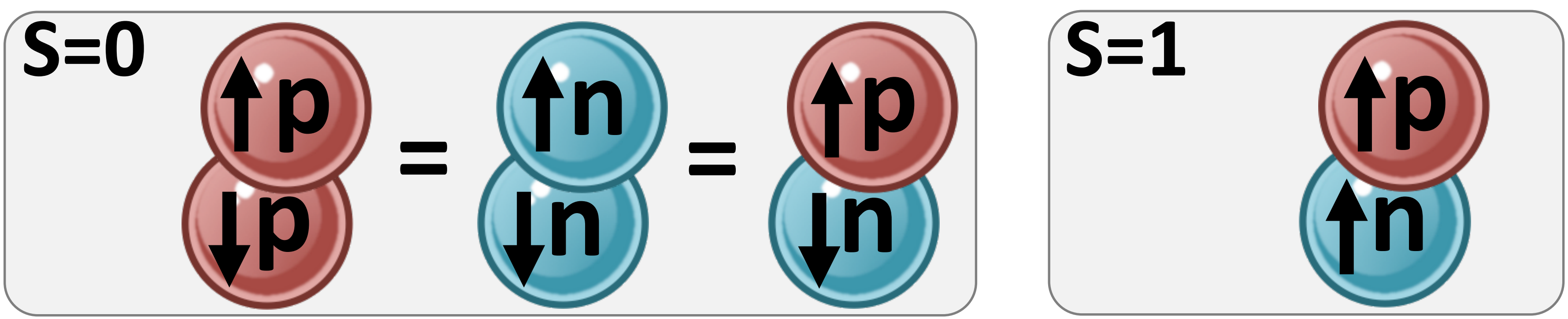
(known) Solution for the two-body problem

Many body, mean-field, function (a number!)

Reduced to 2 contacts from symmetry considerations



Relating to Momentum Space

$$\Psi \xrightarrow[r_{ij}\to 0]{} \sum_{\alpha} \varphi_{\alpha}(\boldsymbol{r}_{ij}) A_{ij}^{\alpha}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j})$$

One Body:

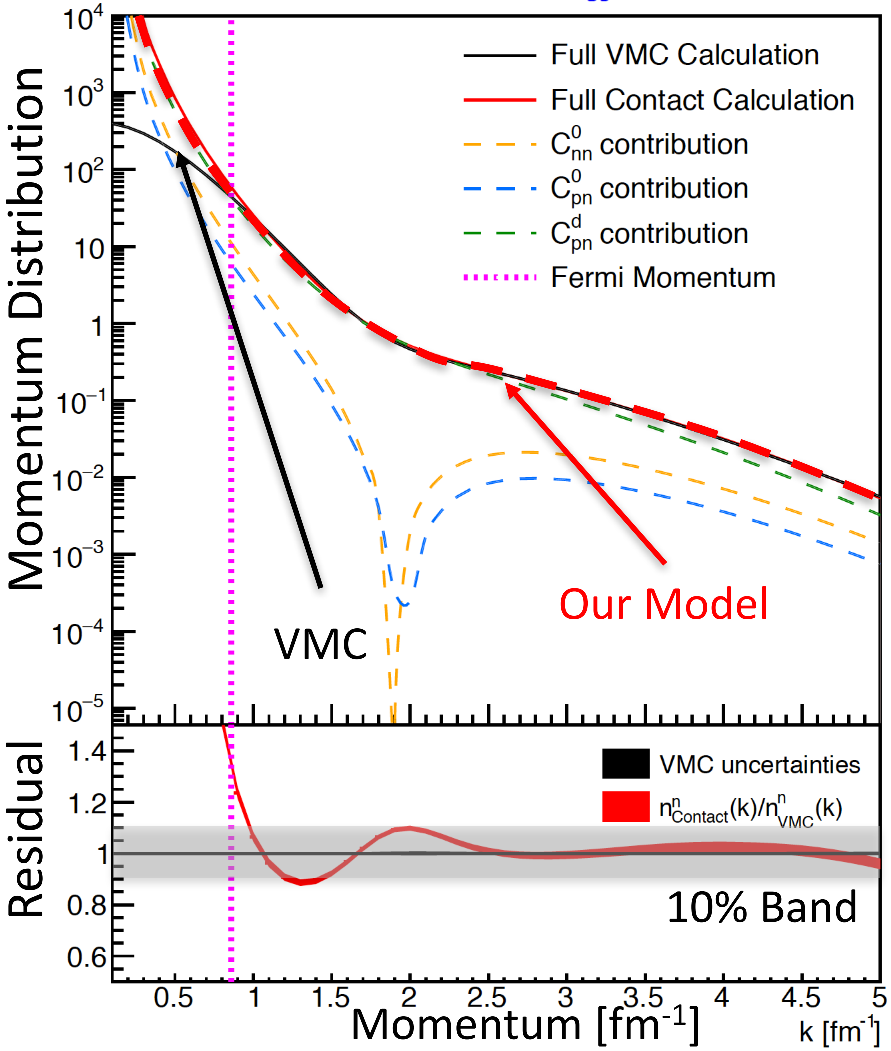
$$\boldsymbol{n_p(k)} = \sum_{\alpha} \left|\tilde{\varphi}_{pp}^{\alpha}(\boldsymbol{k})\right|^2 2C_{pp}^{\alpha} + \sum_{\alpha} \left|\tilde{\varphi}_{pn}^{\alpha}(\boldsymbol{k})\right|^2 C_{pn}^{\alpha}$$

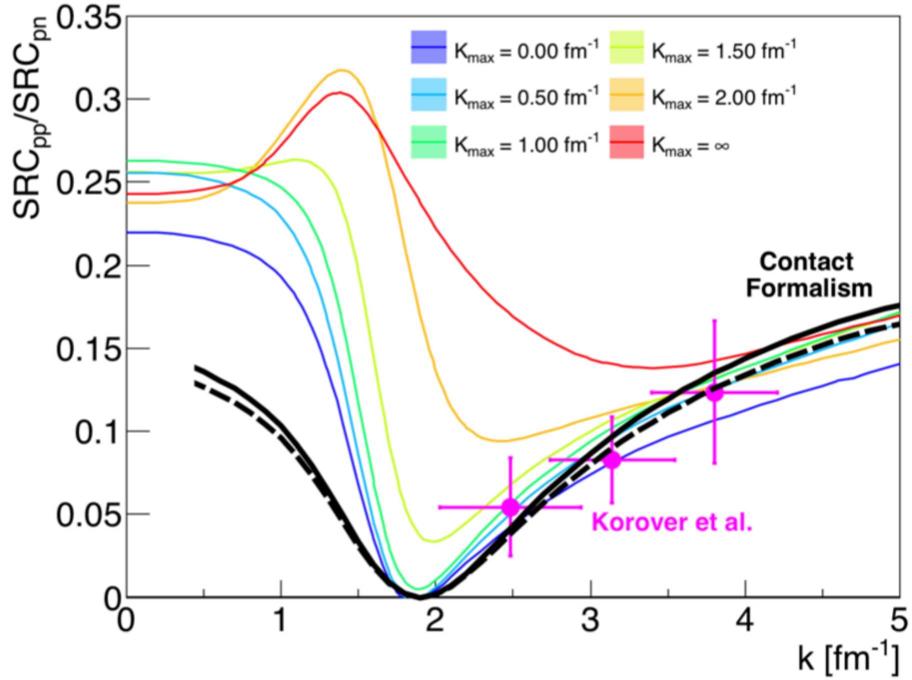
Two body:

$$\boldsymbol{F_{ij}(k)} = \sum_{\alpha} \left|\tilde{\varphi}_{ij}^{\alpha}(\boldsymbol{k})\right|^2 C_{ij}^{\alpha}$$

Universal Nuclear Structure

$$n_p(k) = \sum_\alpha \left|\tilde{\varphi}^\alpha_{pp}(k)\right|^2 2C^\alpha_{pp} + \sum_\alpha \left|\tilde{\varphi}^\alpha_{pn}(k)\right|^2 C^\alpha_{pn}$$





Excellent reproduction of ab-initio calculations!

Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, arXiv 1612.00923 (2016)

Consistent Nuclear Contacts!

Consistent contacts extracted from:

(1) Experimental data,

(2) many-body *momentum* space calculations,

(3) many-body *coordinate* space calculations.

A	k-space				r-space			
	$C_{pn}^{s=1}$	$C_{pn}^{s=0}$	$C_{nn}^{s=0}$	$C_{pp}^{s=0}$	$C_{pn}^{s=1}$	$C_{pn}^{s=0}$	$C_{nn}^{s=0}$	$C_{pp}^{s=0}$
^{4}**He**	12.3±0.1	0.69±0.03	0.65±0.03		11.61±0.03	0.567±0.004		
	14.9±0.7 (exp)	0.8±0.2 (exp)						
^{6}**Li**	10.5±0.1	0.53±0.05	0.49±0.03		10.14±0.04	0.415±0.004		
^{7}**Li**	10.6 ± 0.1	0.71 ± 0.06	0.78 ± 0.04	0.44 ± 0.03	9.0 ± 2.0	0.6 ± 0.4	0.647 ± 0.004	0.350 ± 0.004
^{8}**Be**	13.2±0.2	0.86±0.09	0.79±0.07		12.0±0.1	0.603±0.003		
^{9}**Be**	12.3±0.2	0.90±0.10	0.84±0.07	0.69±0.06	10.0±3.0	0.7±0.7	0.65±0.02	0.524±0.005
^{10}**B**	11.7±0.2	0.89±0.09	0.79±0.06		10.7±0.2	0.57±0.02		
^{12}**C**	16.8±0.8	1.4±0.2	1.3±0.2		14.9±0.1	0.83±0.01		
	18±2 (exp)	1.5±0.5 (exp)						

Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, arXiv 1612.00923 (2016)

Consistent Nuclear Contacts!

Consistent contacts extracted from:

(1) Experimental data,
(2) many-body *momentum* space calculations,
(3) many-body *coordinate* space calculations.

A	k-space				r-space			
	$C_{pn}^{s=1}$	$C_{pn}^{s=0}$	$C_{nn}^{s=0}$	$C_{pp}^{s=0}$	$C_{pn}^{s=1}$	$C_{pn}^{s=0}$	$C_{nn}^{s=0}$	$C_{pp}^{s=0}$
^{4}He	12.3±0.1	0.69±0.03	0.65±0.03		11.61±0.03	0.567±0.004		
	14.9±0.7 (exp)	0.8±0.2 (exp)						
^{6}Li	10.5±0.1	0.53±0.05	0.49±0.03		10.14±0.04	0.415±0.004		
^{7}Li	10.6 ± 0.1	0.71 ± 0.06	0.78 ± 0.04	0.44 ± 0.03	9.0 ± 2.0	0.6 ± 0.4	0.647 ± 0.004	0.350 ± 0.004
^{8}Be	13.2±0.2	0.86±0.09	0.79±0.07		12.0±0.1	0.603±0.003		
^{9}Be	12.3±0.2	0.90±0.10	0.84±0.07	0.69±0.06	10.0±3.0	0.7±0.7	0.65±0.02	0.524±0.005
^{10}B	11.7±0.2	0.89±0.09	0.79±0.06		10.7±0.2	0.57±0.02		
^{12}C	16.8±0.8	1.4±0.2	1.3±0.2		14.9±0.1	0.83±0.01		
	18±2 (exp)	1.5±0.5 (exp)						

Relation to the EMC effect, Coulomb sum rule, reaction cross-sections, correlation functions and more….

Outline

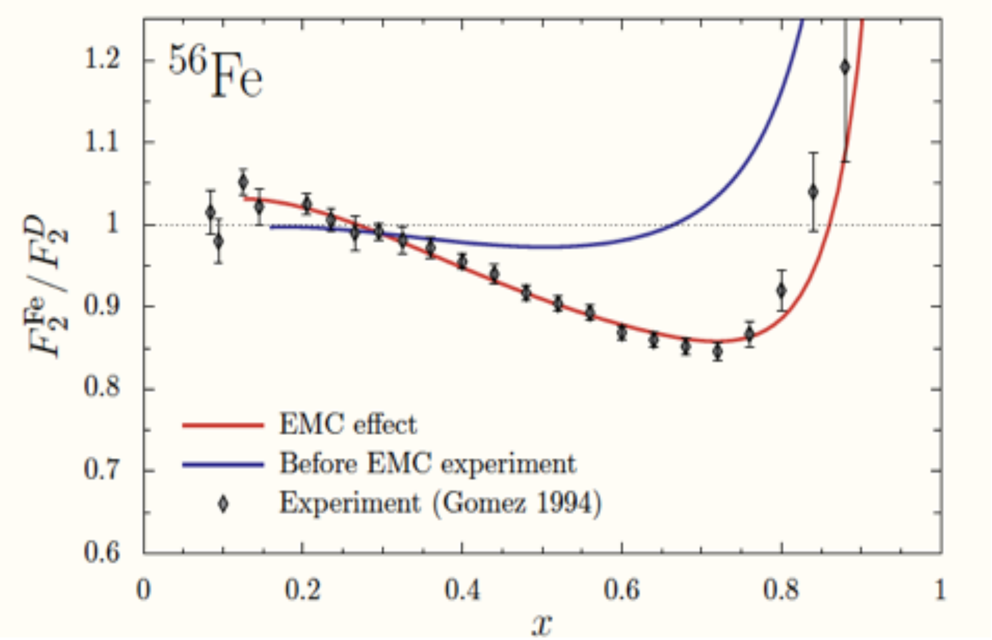
- ✓ Introduction to Short-Range Correlations
- ✓ Universal description of fluctuations of strongly interactive Fermi systems.

3. Implications to nuclear PDFs (EMC effect)

4. Why you should care!

EMC Effect

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



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

EMC Effect

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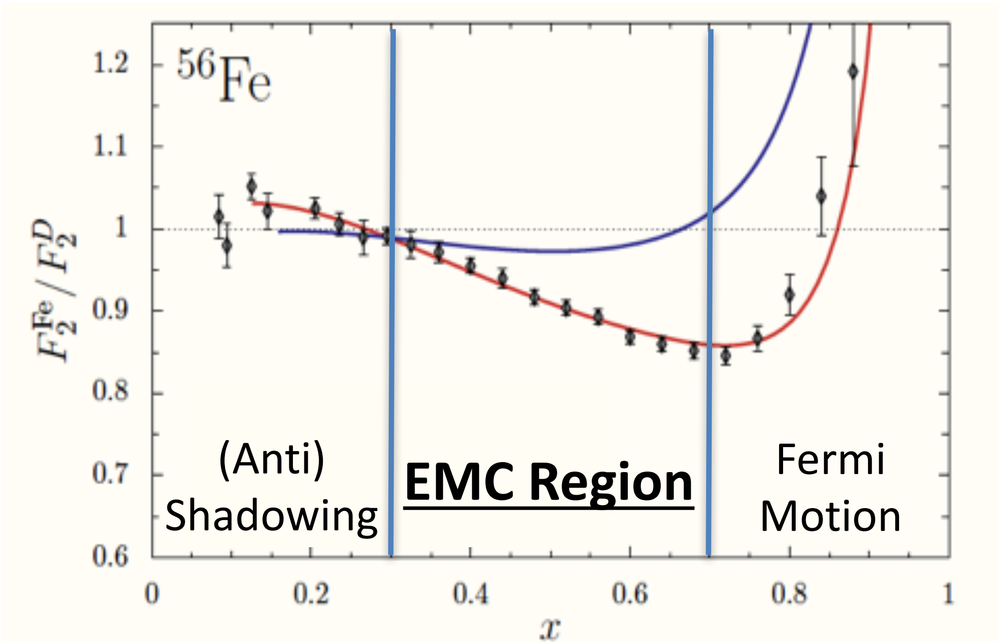

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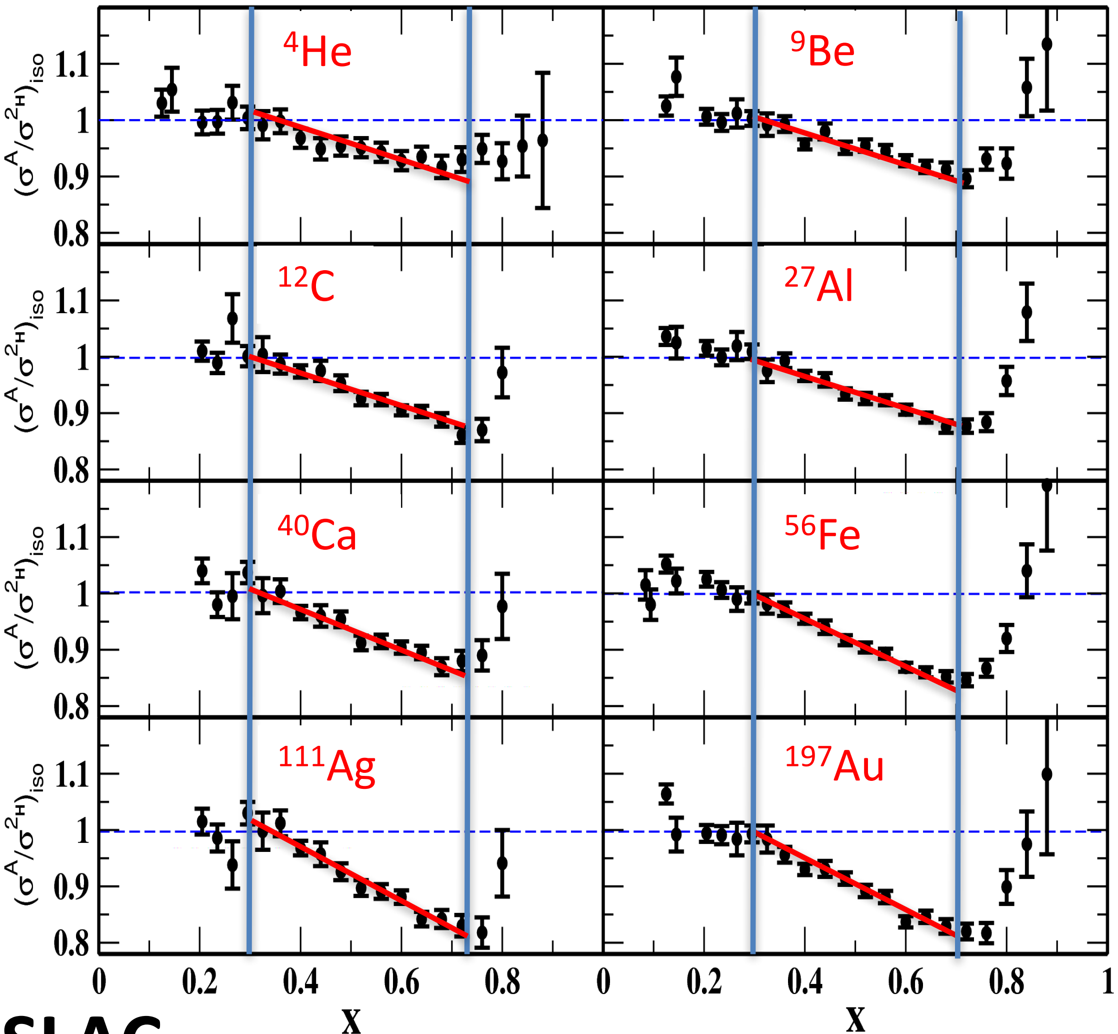
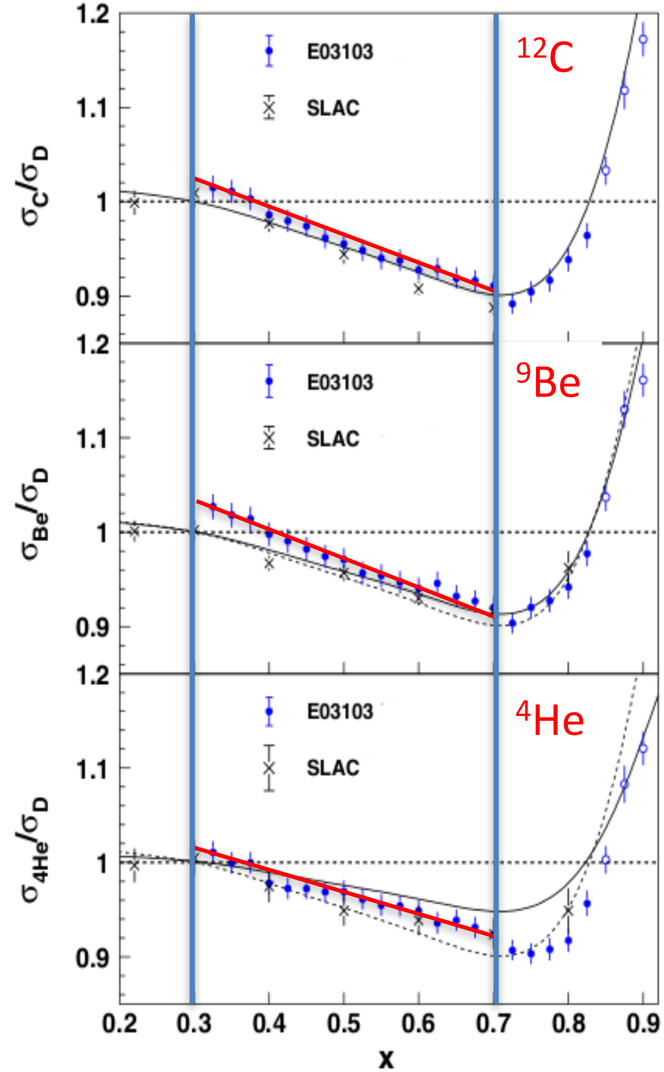
Universality of the EMC Effect



SLAC

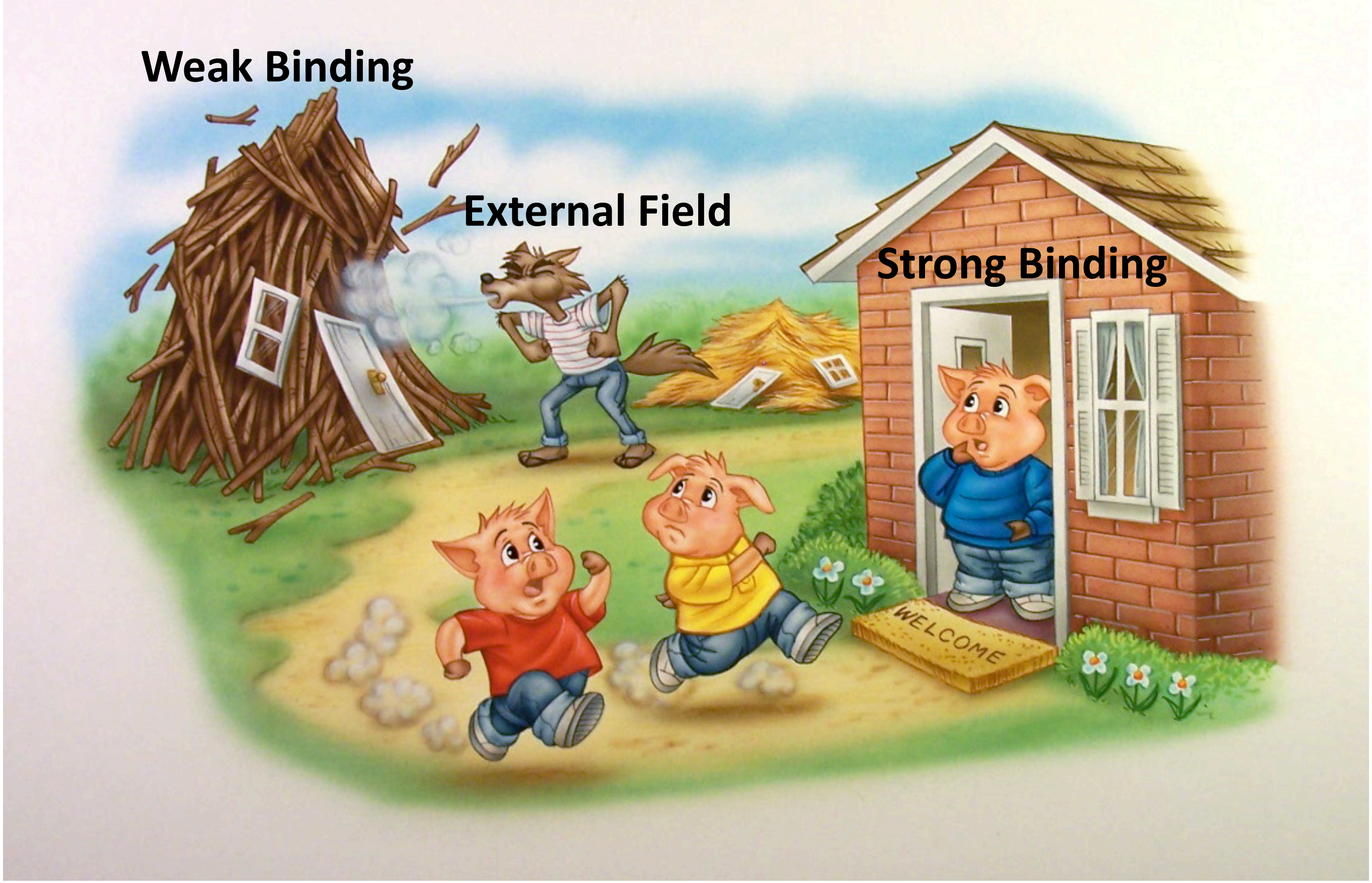
J. Gomez et al., Phys. Rev. D **49**, 4348 (1994).

JLab

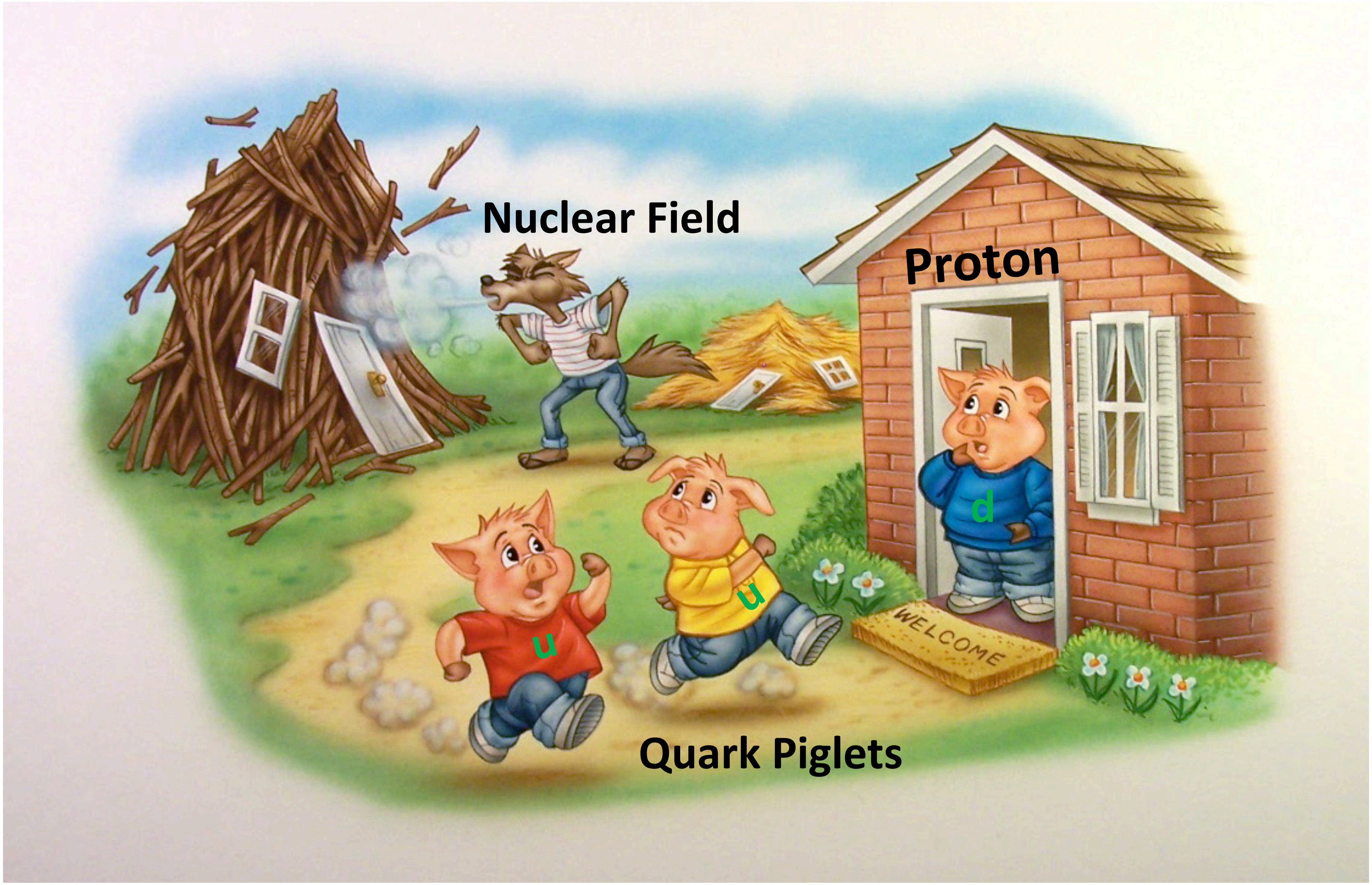


J. Seely et al., Phys. Rev. Lett. **103**, 202301 (2009).

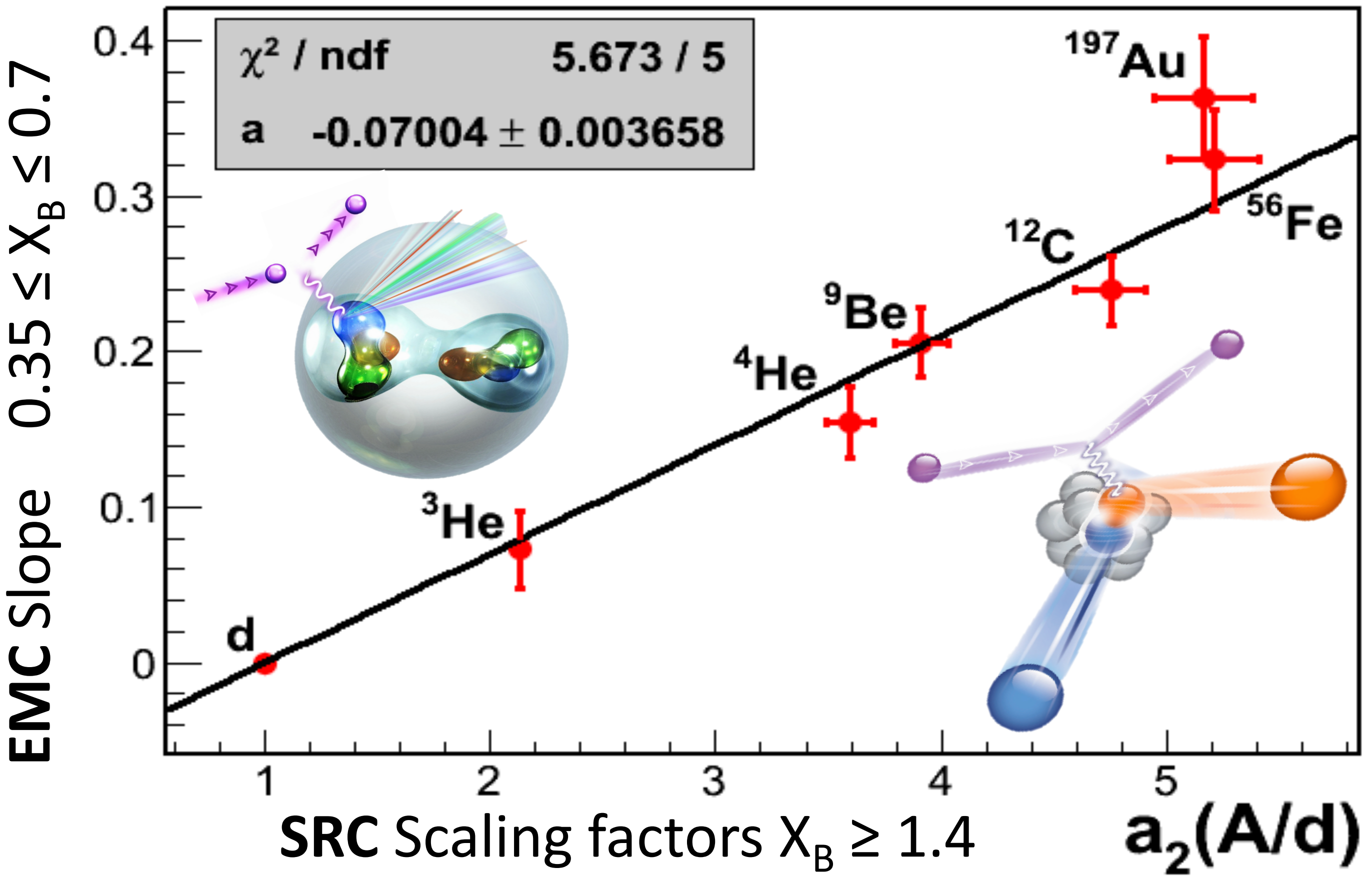
EMC Challenge: 'Strength 'Scales



EMC Challenge: 'Strength 'Scales

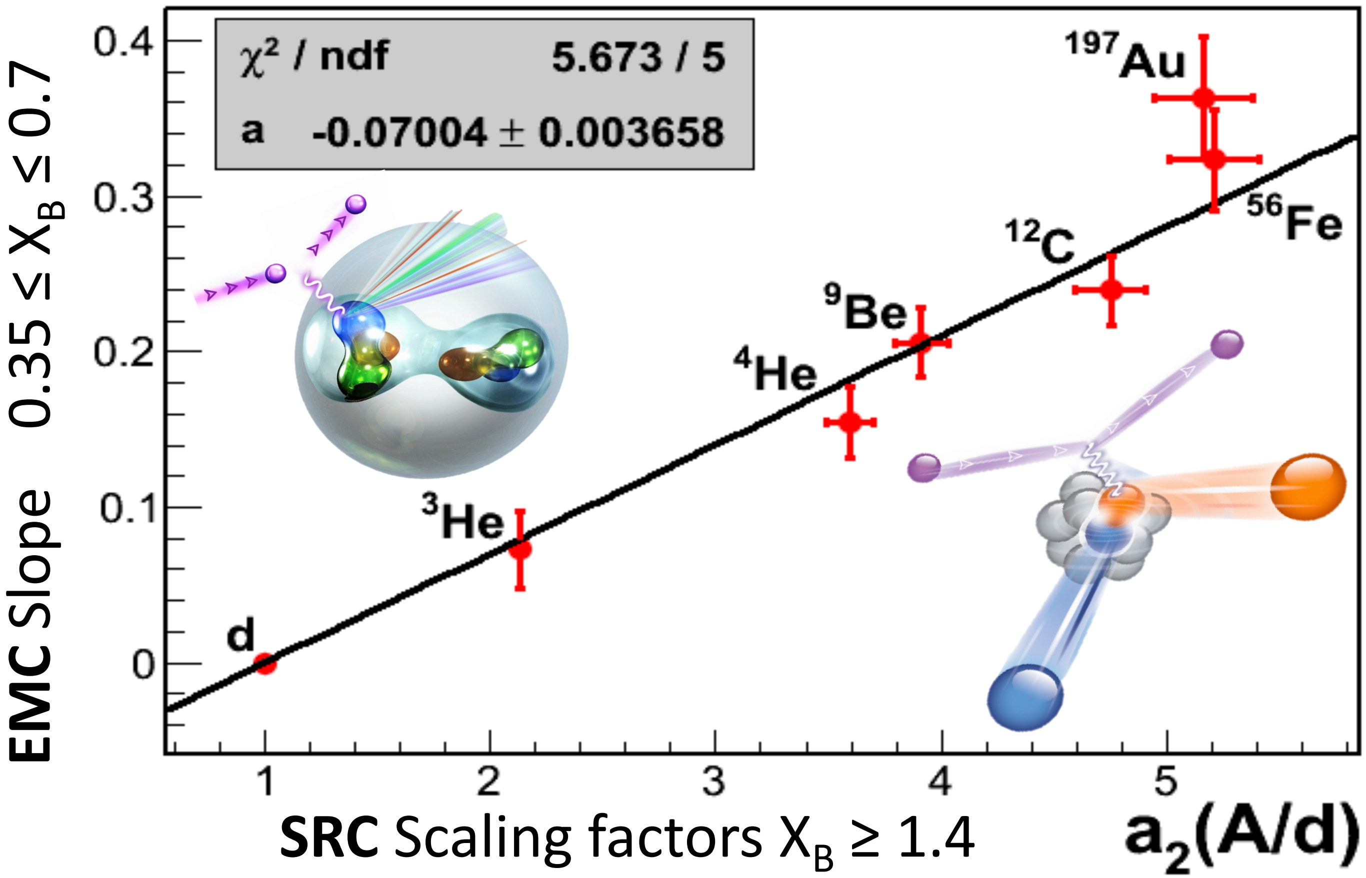


EMC-SRC Correlation



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



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

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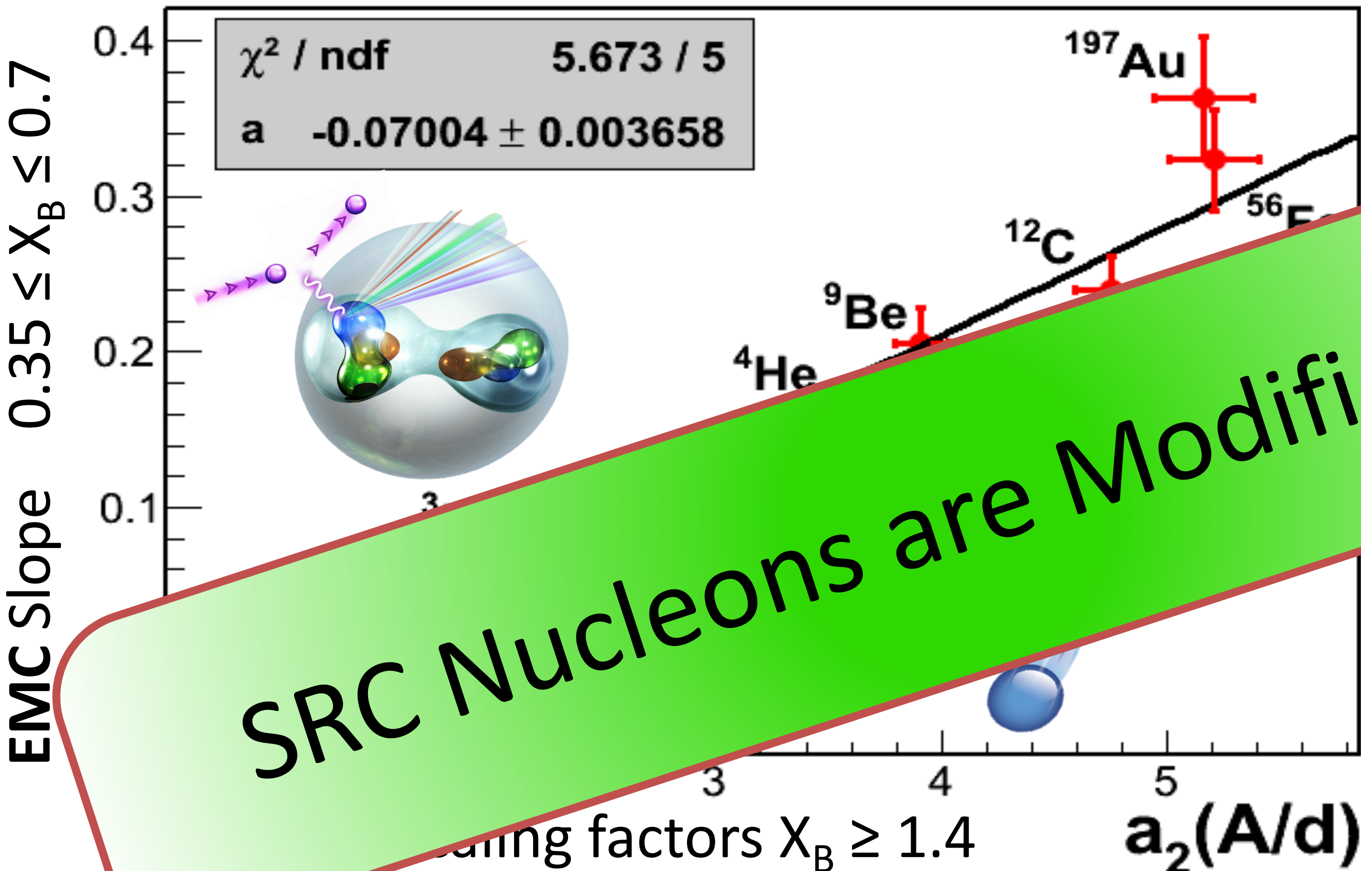
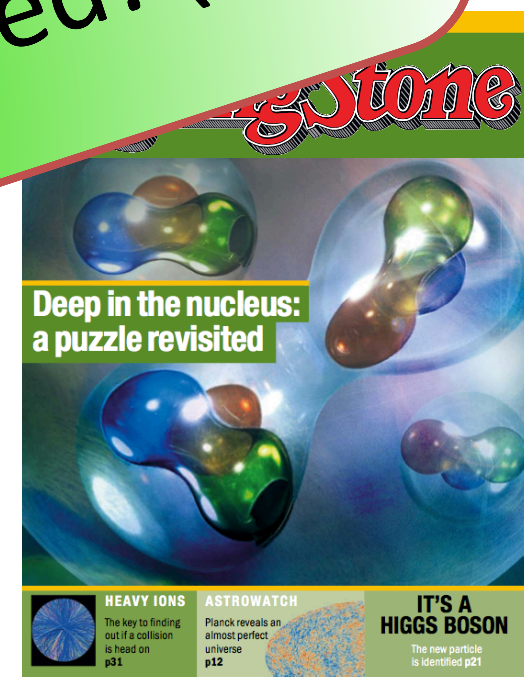
EMC-SRC Correlation



SRC Nucleons are Modified! (?)

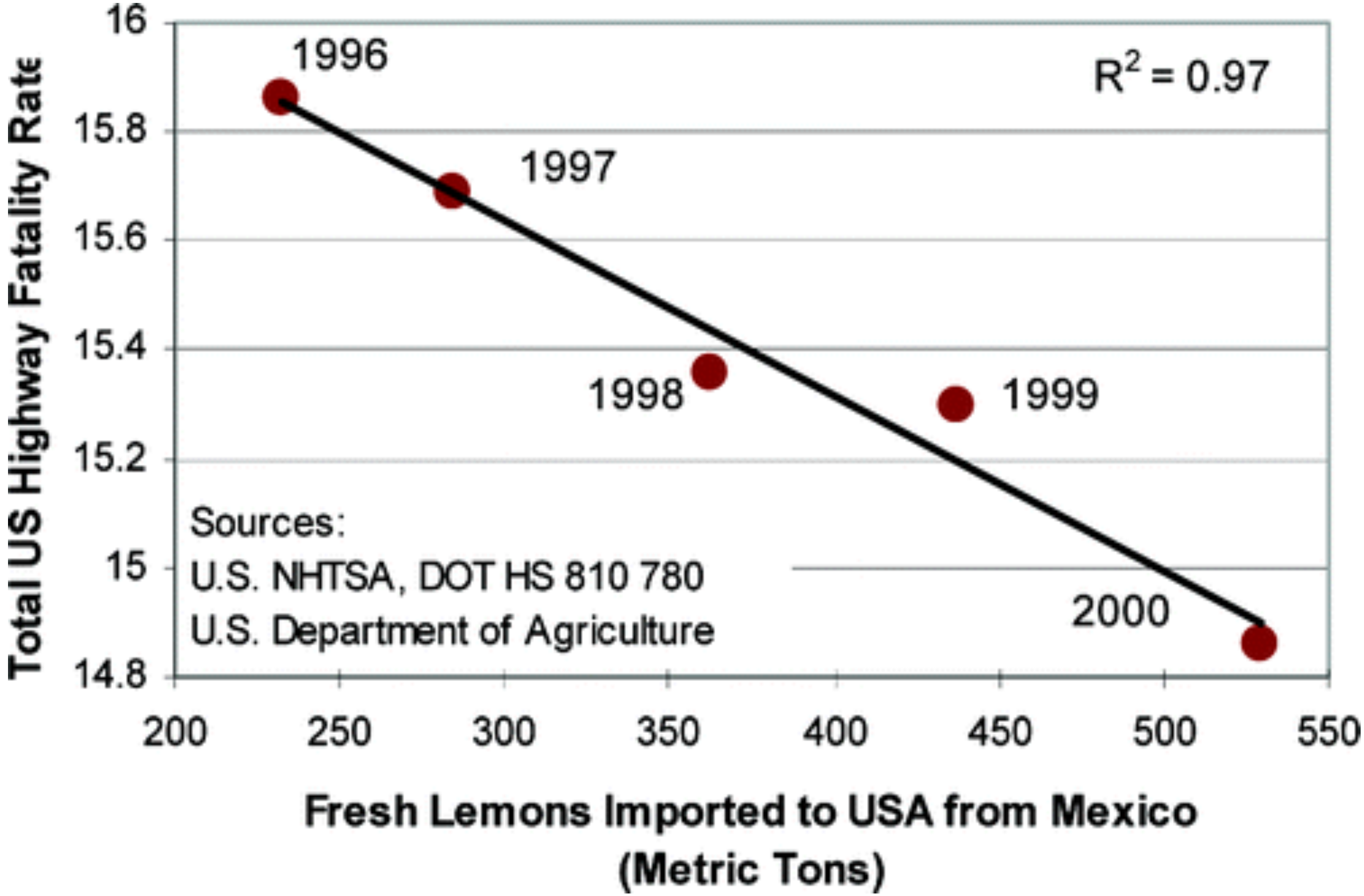


O. Hen et al., Int. J. Mod. Phys. E. **22**, 1330017 (2013).

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.

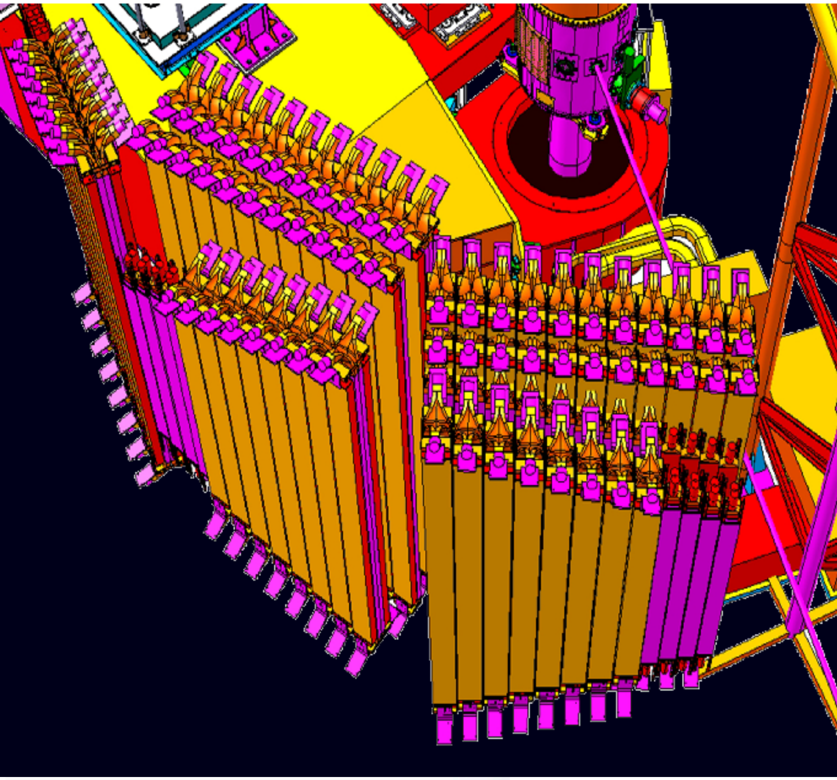
Other Correlations…



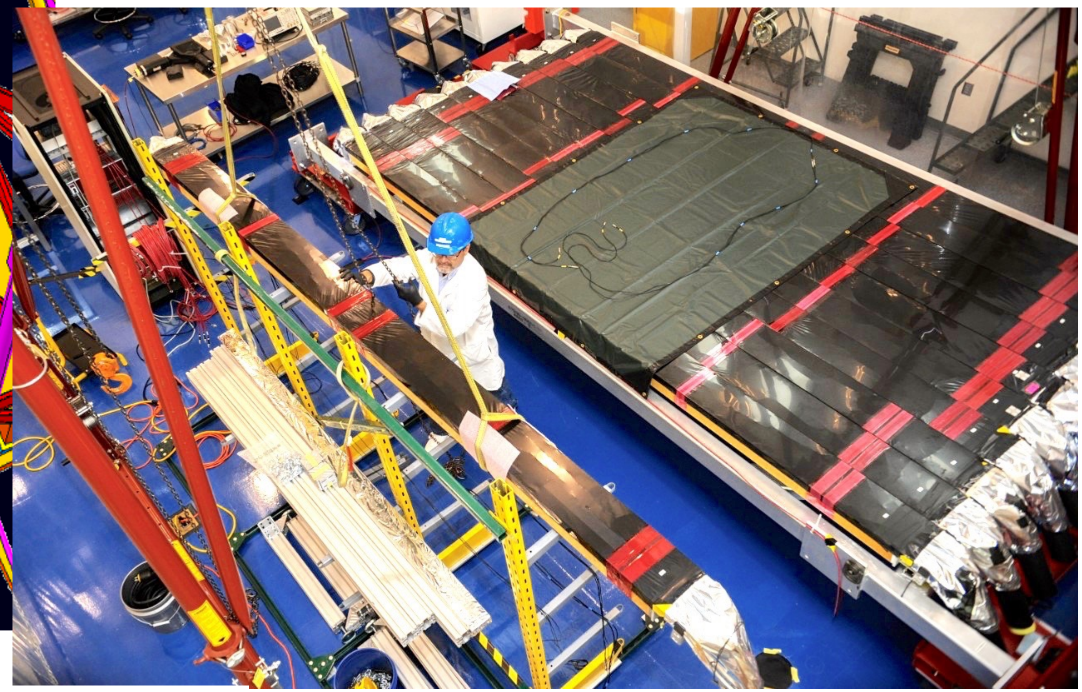
Other Correlations

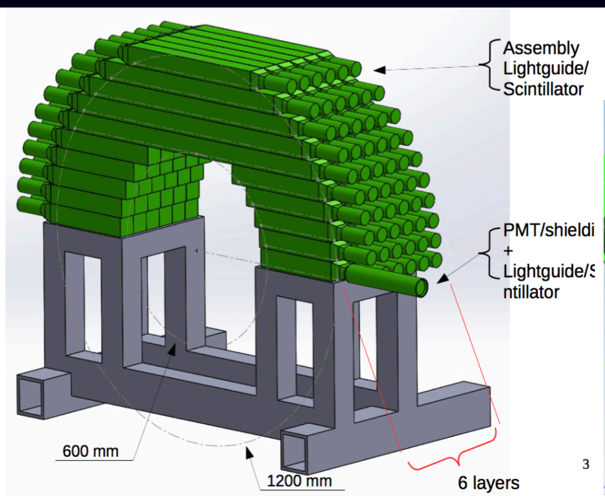
Mexican Lemonade Saves Lives!

Next Generation Experiments

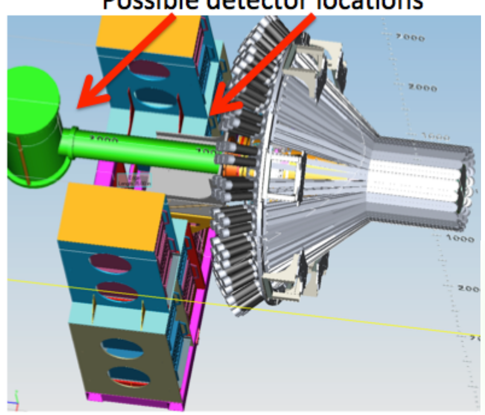


Large Acceptance Detector (LAD@Hall-C)





Possible detector locations



Backward Angle Neutron Detector (BAND@Hall-B)

R&D @ MIT / Construction @ BATES

Forthcoming RMP Review

Nucleon-Nucleon Correlations and the Quarks Within

Or Hen

Massachusetts Institute of Technology, Cambridge, MA 02139

Gerald A. Miller

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

Eli Piasetzky

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

Lawrence B. Weinstein

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

(Dated: November 2, 2016)

- conventional (non-quark) nuclear physics cannot account for the EMC effect
- models need to include nucleon modification to account for the EMC effect. These models can modify the structure of either:
  - mean field nucleons, or
  - nucleons belonging to SRC pairs.
- there is a phenomenological connection between the strength of the EMC effect and the probability that a nucleon belongs to a two-nucleon SRC pair ($a_2(A)$), see Fig. 33.
- the influence of SRC pairs can account for the EMC-SRC correlation because both effects are driven by high virtuality nucleons with $p^2 \neq M^2$,
- the connection between the EMC effect and the coefficients $a_2(A)$ has been derived using two completely different theories, so that this connection is no accident
- nuclei must contain a small percentage of baryons that are not nucleons. Such baryons exist in the short-ranged correlations and are the source of the EMC effect.

Hen, Miller, Piasetzky and Weinstein, to appear in RMP (2016)

Short Range Correlations and the EMC Effect in Effective Field Theory

Jiunn-Wei Chen,[1,2,*] William Detmold,[2,†] Joel E. Lynn,[3,4,‡] and Achim Schwenk[3,4,5,§]

[1] *Department of Physics, CTS and LeCosPA, National Taiwan University, Taipei 10617, Taiwan*
[2] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[3] *Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany*
[4] *ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*
[5] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*

arXiv: 1607.03065 (2016)

Gerald A. Miller

EFT description of bound nucleon structure:

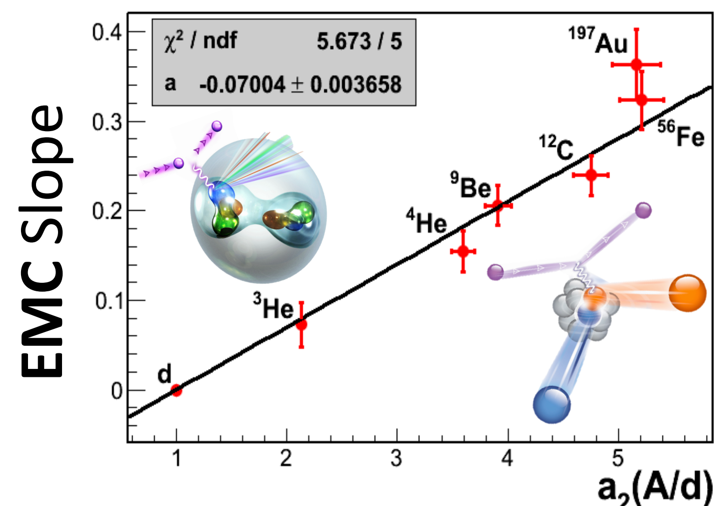
$$F_2^A(x,Q^2)/A = F_2^N(x,Q^2) + g_2(A,\Lambda) f_2(x,Q^2,\Lambda).$$

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

The contact…

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

[SRC Scaling Factor]



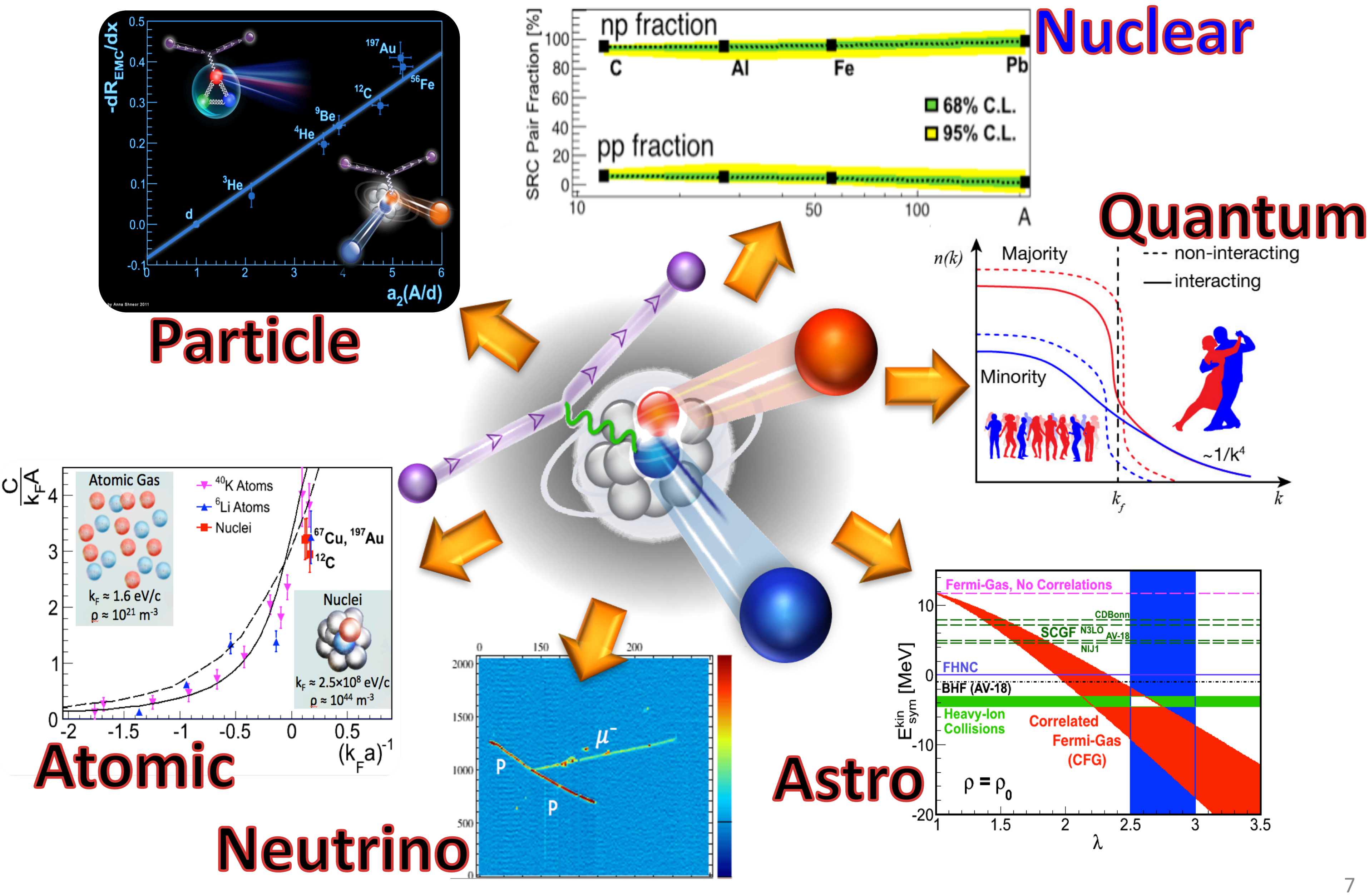
SRC Scaling factors

Outline

- ✓ Introduction to Short-Range Correlations
- ✓ Universal description of fluctuations of strongly interactive Fermi systems.
- ✓ Implications to nuclear PDFs (EMC effect)

4. Why you should care?!

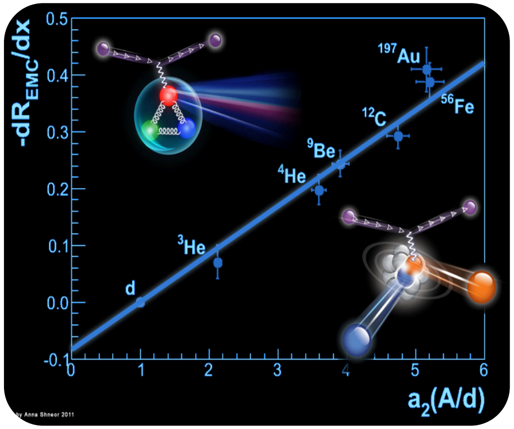
Why SRC?



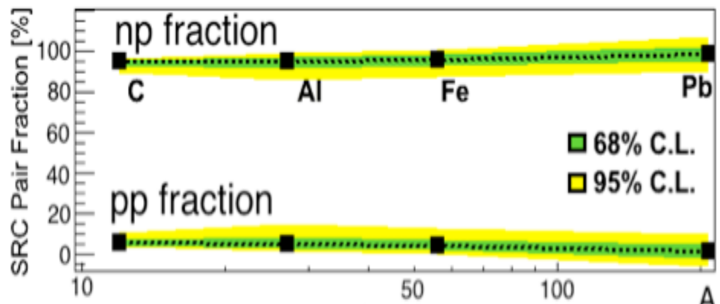
Nuclear
np fraction
pp fraction
C
Al
Fe
Pb
68% C.L.
95% C.L.
SRC Pair Fraction [%]
A
Particle
$-dR_{EMC}/dx$
$a_2(A/d)$
d
^{3}He
^{4}He
^{9}Be
^{12}C
^{56}Fe
^{197}Au
Quantum
n(k)
Majority
Minority
non-interacting
interacting
~1/k^4
k_f
k
Atomic
Atomic Gas
$k_F \approx 1.6$ eV/c
$\rho \approx 10^{21}$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

Why SRC?

Particle



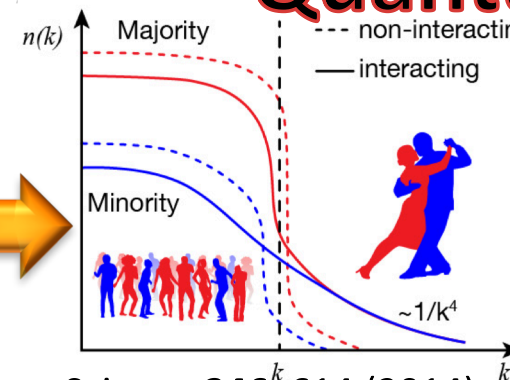
PRL **106**, 052301 (2011),
PRD **84**, 117501(2011),
PRC **85**, 047301(2012),
IJMPE **22**, 1330017 (2013),
arXiv 1607.03065 (2016),
arXiv 1611.09748 (2016).



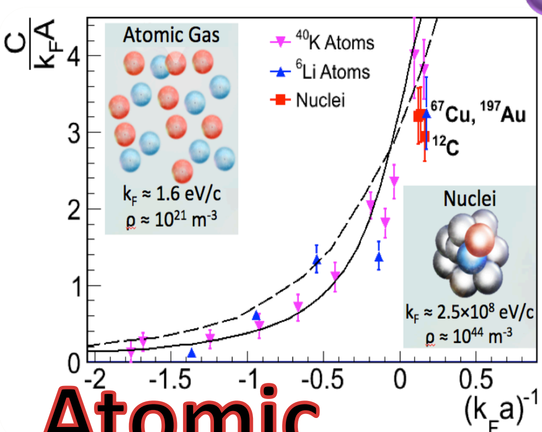
Nuclear

Science **320**, 1476 (2008),
PRL **108**, 092502 (2012),
PLB 772, **63** (2013),
PRL **113**, 022501 (2014),
PRC **92**, 024604 (2015).

Quantum

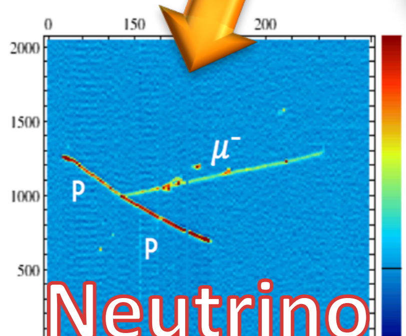


Science **346**, 614 (2014).



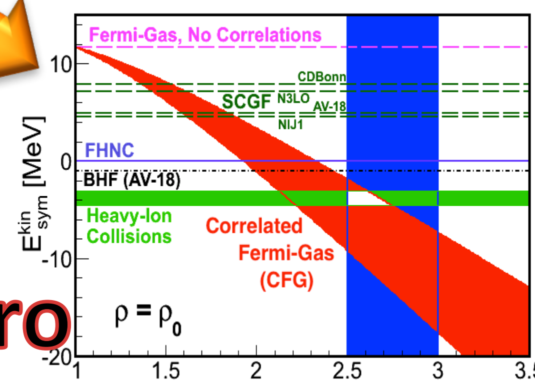
Atomic

PRC **92**, 045205 (2015).
arXiv 1612.00923 (2016).



Neutrino

PRD **90**, 012008 (2014); PRC **94**, 045501 (2016)



Astro

PRC **91**, 025803 (2015), PRC **93**, 044610 (2016),
PRC **91**, 044601 (2015), PRC **93**, 014619 (2016),
PRC **92**, 011601 (2015), PLB **759**, 79 (2016),
arXiv: 1608.00487 (2016); 1606.08045 (2016)

Why SRC?

You can't do nuclei at high energies without correlations!

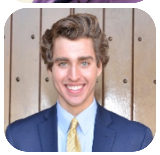
- At any given moment 20% of the nucleons fluctuate into a temporal high density proton-neutron pair.
- The structure of these nucleons is thought to be modified and IS the cause of nuclear PDFs.
- Vary hard to calculate from first principle.
- Not that hard to model using universality

The Correlations group

- **MIT (Or Hen):**


Barak Schmookler


Reynier Torres


Efrain Segarra


Afroditi Papadopoulou

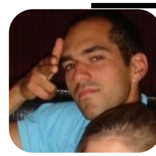

Axel Schmidt


George Laskaris

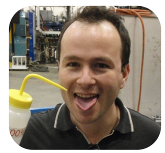

Maria Patsyuk


Taofeng Wang (*visiting scientist)

- **TAU (Eli Piasetzky):**


Erez Cohen


Meytal Duer


Igor Korover


Adi Ashkenazy

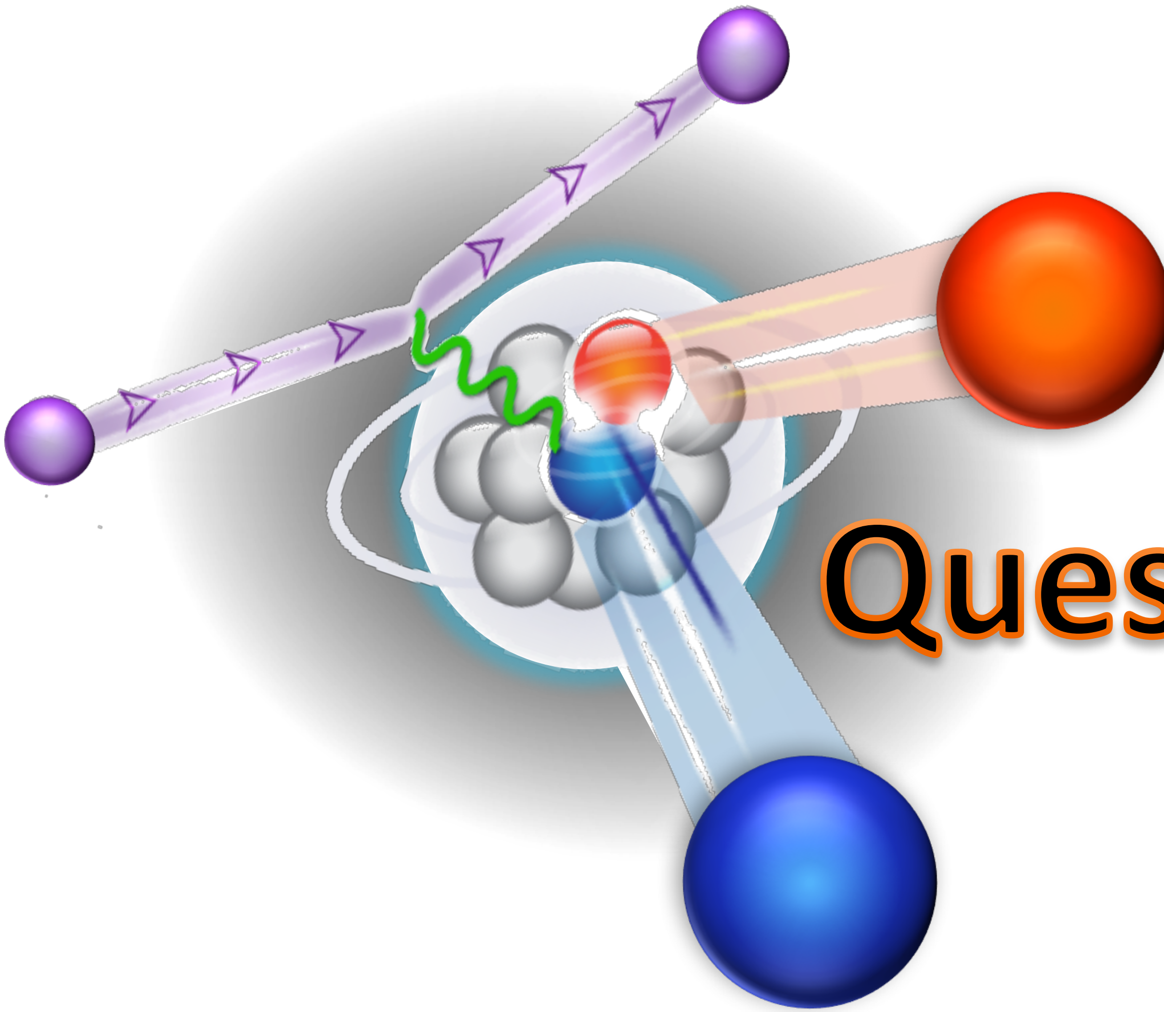
- **ODU (Larry Weinstein):**


Mariana Khachatryan


Florian Hauenstein

- **Theory Collaborators (lots!)**

Thank You!



Questions?