*Claudio Ciofi degli Atti*

# UNIVERSALITY OF SHORT RANGE CORRELATIONS:
## *theoretical predictions*

WORKSHOP

on

Hadron physics with high-momentum hadron beams at J-PARC

January 15 - 18, 2013 KEK, Tsukuba, Japan

# OUTLINE

1. Introduction: why Short Range Correlations?

2. Ab initio solutions of the non relativistic many-body problem and theoretical predictions of SRC.

3. Experimental observations of SRC.

4. Impact of SRC on various fields of physics.

5. Conclusions.

# 1 INTRODUCTION: WHY SHORT RANGE CORRELATIONS (SRC)?

- Many properties of nuclei measured at low $Q^2$ and generated by the average and collective motions of point-like nucleons can be successfully described in terms of the nuclear Mean Field (Shell Model).
- Nowadays it is possible to investigate nuclei at high $Q^2$, probing distances of the order of the nucleon radius ($\simeq 1fm$), and the following longstanding questions arise:

1. *Do nucleon and meson d.o.f. play still a role at short distance, or quark and gluon d.o.f. are the relevant ones?*
2. *Is the two-nucleon short-range behavior strongly affected by the surrounding nucleons?*
3. *Does the short-range behavior of nuclei affect cold matter at high densities, e.g. neutron stars?*
4. *Does the short-range structure of nuclei affect high energy scattering, e.g. hA and AA?*

Answering these questions implies the study of Short-Range Correlations (SRC). To this end, one needs dedicated experiments and a well-defined theoretical framework to interpret them.

## 2 *AB INITIO SOLUTIONS OF THE NUCLEAR MANY-BODY PROBLEM AND THEORETICAL PREDICTIONS OF SRC*

## THE STANDARD MODEL OF NUCLEI

QCD $\Longrightarrow$ Nuclei- non perturbative regime $\Longrightarrow$ too difficult
Many-body systems $\Longrightarrow$ single out the leading effective d.o.f.
Effective d.o.f. in Nuclei $\Longrightarrow$ nucleons and gauge bosons.
Reduction of a field theoretical description to an instantaneous potential description (Schroedinger equation ) $\Longrightarrow$ two-body, three-body,........,A-body potentials are generated.

Primakoff,Holstein 1944

$$\text{(m-body potential)} \simeq \left(\frac{v_N}{c}\right)^{\text{(m-2)}} \times \text{(two-body potential)}$$

$$\left[-\frac{\hbar^2}{2\,m_N}\sum_i \hat{\nabla}_i^2 + \sum_{i<j}\hat{v}_2(i,j) + \sum_{i<j<k}\hat{v}_3(i,j,k)\right]\Psi_o(1\ldots A) = E_o\,\Psi_0$$

$$\Psi_o \equiv \Psi_o(1\ldots A) \qquad i \equiv \mathbf{x}_i \equiv \{\sigma_i, \tau_i, \mathbf{r}_i\} \qquad \sum_{i=1}^{A}\boldsymbol{r}_i = 0$$

Theoretical framework: Solve *ab initio* the standard model with realistic interactions $\Longrightarrow$ compare with experimental data (energy, form factors, transition matrix elements, etc); if agreement $\Longrightarrow$ OK; if not $\Longrightarrow$ look for new d.o.f.

Modern bare two-nucleon interactions ($\simeq$ *2000 phase shifts*)

$$\hat{v}_2(x_i, x_j) = \sum_{n=1}^{18} v^{(n)}(r_{ij})\hat{\mathcal{O}}_{ij}^{(n)} \qquad r_{ij} \equiv |\mathbf{r}_i - \mathbf{r}_j|$$

$$\mathcal{O}_{ij}^{(1)} = 1, \qquad \mathcal{O}_{ij}^{(2)} = \sigma_i \cdot \sigma_j, \quad \mathcal{O}_{ij}^{(3)} = \tau_i \cdot \tau_j$$

$$\mathcal{O}_{ij}^{(4)} = (\sigma_i \cdot \sigma_j)(\tau_i \cdot \tau_j), \quad \mathcal{O}_{ij}^{(5)} = \hat{S}_{ij}, \quad \mathcal{O}_{ij}^{(6)} = \hat{S}_{ij}\tau_i \cdot \tau_j,$$

$$\hat{S}_{ij} = 3(\hat{r}_{ij} \cdot \sigma_i)(\hat{r}_{ij} \cdot \sigma_j) - \sigma_i \cdot \sigma_j$$

- short-range repulsion (common to many systems)
- intermediate- to long-range tensor character(unique to nuclei)

# THE MEAN FIELD APPROXIMATION

$$\sum_{i<j} \hat{v}_2(i,j) + \sum_{i<j<k} \hat{v}_3(i,j,k) \Longrightarrow \sum_i V_i(i).$$

$$\Downarrow$$

$$\left[-\frac{\hbar^2}{2\,m_N}\sum_i \hat{\nabla}_i^2 + \sum_i V(r_i)\right]\Phi_o(1,\ldots,A) = \epsilon_o\,\Phi_o(1,\ldots,A)$$

**Mean-field (shell model) wave function**

$$\Phi_0(1,2,\ldots,A) = \hat{\mathcal{A}}\prod_i^A \phi_{\alpha_i}(x_i) \equiv \Phi_{0p0h} \quad \alpha_i > \alpha_F, \phi_{\alpha_i} = 0$$

**Exact correlated wave function**

$$\Psi_0(1,2,\ldots,A) = C_{0p0h}\,\phi_{0p0h} + C_{1p1h}\,\Phi_{1p1h} + C_{2p2h}\,\Phi_{2p2h} + \ldots$$

$$SRC \longrightarrow \sum_{n=1}^{\infty} C_{np\,nh}\Phi_{np\,nh}$$

# VARIOUS *ab initio* THEORETICAL METHODS

- Direct solution for few-body systems (Faddeev, Fadeev-Yakubowsky): Gloeckle & co.
- Expansion in complete set of basis functions: Suzuki & co.
- Introduction of correlations into the mean field wave function by proper correlation operators: Feldmeier & co.
- Correlated basis functions with Green Function Monte Carlo: Pandharipande, Schiavilla & co..
- Correlated basis functions and cluster expansion: Pisa & Perugia Groups

$$\Psi_o = \hat{\mathbf{F}}\,\Phi_o$$

$$\hat{\mathbf{F}} = \hat{\mathcal{S}} \prod_{i<j} \hat{f}_{ij} = \hat{\mathcal{S}} \prod_{i<j} \left[ \sum_n f^{(n)}(r_{ij})\, \hat{\mathcal{O}}_{ij}^{(n)} \right]$$

# THE RELEVANT QUANTITY: DENSITY MATRICES

Diagonal one-body density matrix (***1BDM***)(***matter distribution***):

$$\rho_{(1)}(\boldsymbol{r}_1) = \int |\Psi_0(\boldsymbol{r}_1, \boldsymbol{r}_2 \ldots, \boldsymbol{r}_A)|^2 \prod_{i=2}^{A} d\boldsymbol{r}_i$$

Non diagonal (***1BDM***) (***One-body density fluctuations***):

$$\rho_{(1)}(\boldsymbol{r}_1, \boldsymbol{r}'_1) = \int \Psi_0^*(\boldsymbol{r}_1, \boldsymbol{r}_2 \ldots, \boldsymbol{r}_A)\, \Psi_0(\boldsymbol{r}'_1, \boldsymbol{r}_2 \ldots, \boldsymbol{r}_A) \prod_{i=2}^{A} d\boldsymbol{r}_i$$

Non diagonal 2-body density matrix (***2BDM***)(two body density fluctuations):

$$\rho_{(2)}(\boldsymbol{r}_1, \boldsymbol{r}_2; \boldsymbol{r}'_1, \boldsymbol{r}'_2) = \int \Psi_0^*(\boldsymbol{r}_1, \boldsymbol{r}_2 \ldots, \boldsymbol{r}_A)\, \Psi_0(\boldsymbol{r}'_1, \boldsymbol{r}'_2 \ldots, \boldsymbol{r}_A) \prod_{i=3}^{A} d\boldsymbol{r}_i$$

Diagonal 2BDM:

$$\rho_{(2)}(\boldsymbol{r}_1, \boldsymbol{r}_2) = \int |\Psi_0(\boldsymbol{r}_1, \boldsymbol{r}_2 \ldots, \boldsymbol{r}_A)|^2 \prod_{i=3}^{A} d\boldsymbol{r}_i$$

# The relative (rel ) and center-of-mass (CM ) density matrices

$$\boldsymbol{r} = \boldsymbol{r}_1 - \boldsymbol{r}_2 \qquad \boldsymbol{R} = (\boldsymbol{r}_1 + \boldsymbol{r}_2)/2$$

$$\rho_{(2)}(\boldsymbol{r}, \boldsymbol{R}) = \int |\Psi_0(\boldsymbol{R} + \frac{\boldsymbol{r}}{2}, \boldsymbol{R} - \frac{\boldsymbol{r}}{2}, \boldsymbol{r}_3 \ldots, \boldsymbol{r}_A)|^2 \prod_{i=3}^{A} d\boldsymbol{r}_i$$

$$\rho_{CM}(\boldsymbol{R}) = \int \rho_{(2)}(\boldsymbol{r}, \boldsymbol{R}) d\boldsymbol{r}$$

$$\rho_{rel}(\boldsymbol{r}) = \int \rho_{(2)}(\boldsymbol{r}, \boldsymbol{R}) d\boldsymbol{R}$$

The relative 2BDM has been calculated by different groups within different many-body approaches and realistic *b*are NN interactions.

# The RELATIVE 2BDM and the CORRELATION HOLE in FEW-NUCLEON SYSTEMS

Schiavilla *et al*, Nucl. Phys. A267 (1987) 267

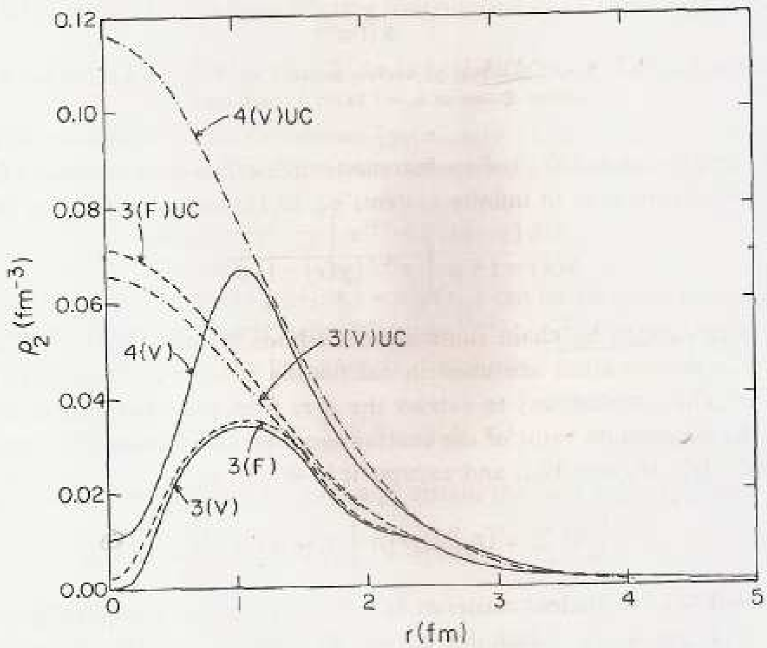



Fig. 2. $\rho_2(r)$ (full lines) and $\rho_{2,uc}(r)$ (dash-dot) for $A=3$ and 4 nuclei. The results obtained with Faddeev wave function are shown by dashed curves.

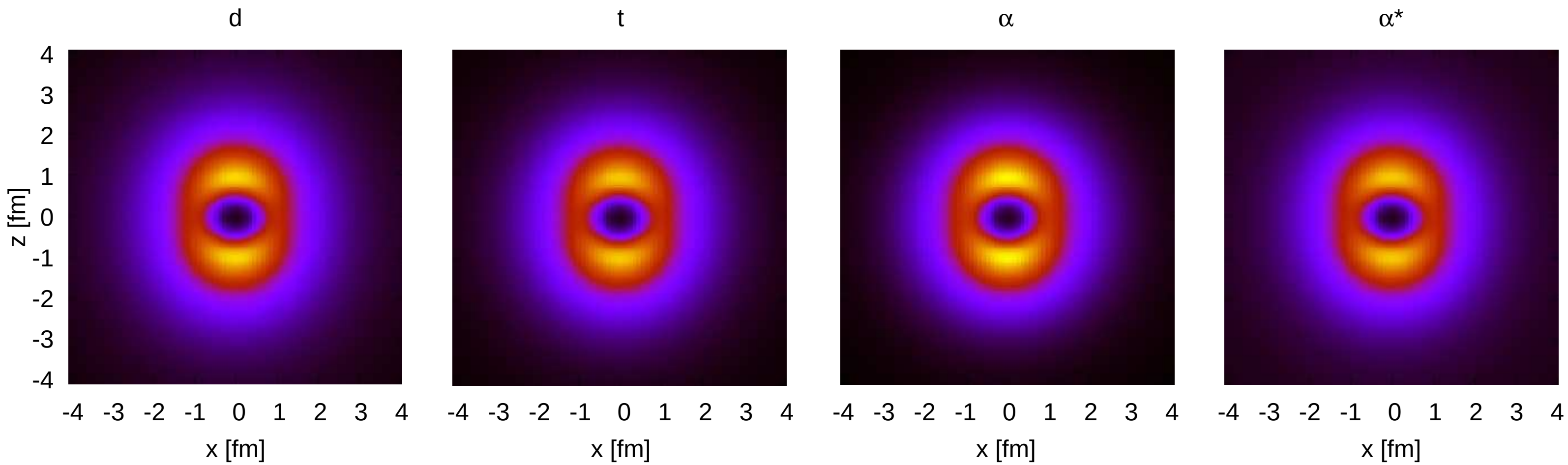
Figure 1: The two-body relative distribution in $^3He$ and $^4He$ (After Ref. [?])

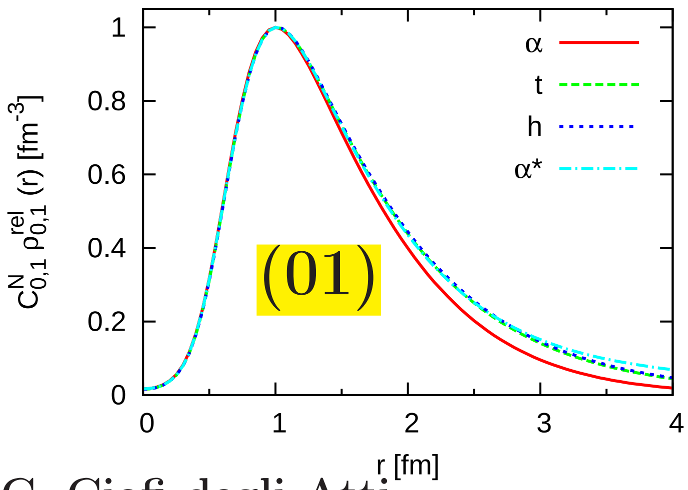
# The 2BDM $\rho_{(2)}$ in few-nucleon systems in (ST)=(10) and (01) states

Suzuki, Horiuchi, Nucl. Phys. A818, 188 (2009)

Feldmaier, Horiuchi, Neff, Suzuki, Phys. Rev. C84,054013(2011)

(10)




At $r < 1.5 fm$ the 2BDM exhibits A-independence

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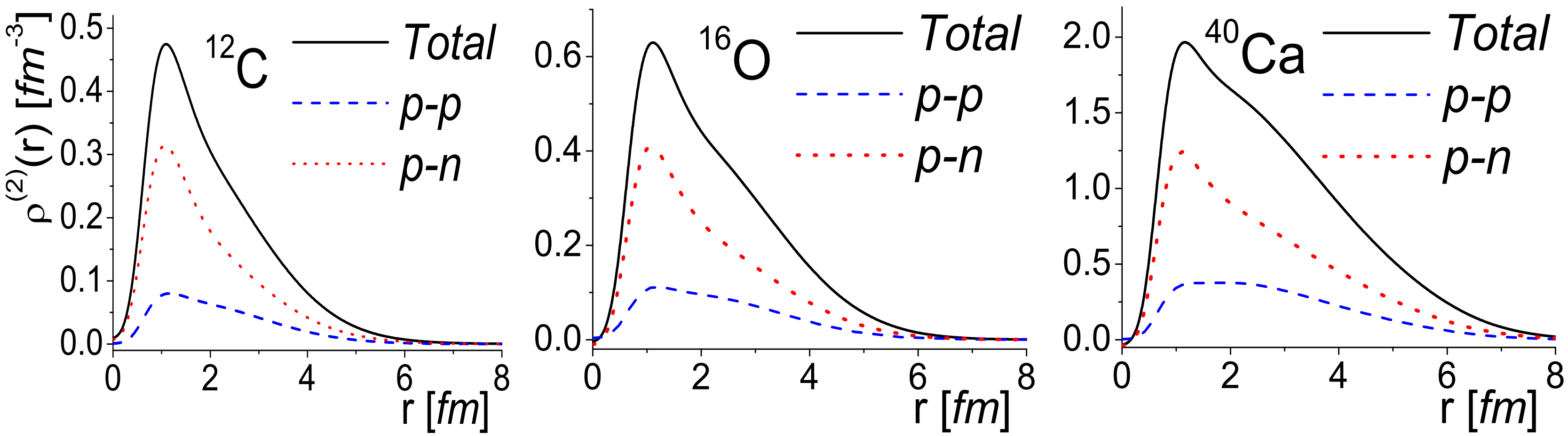
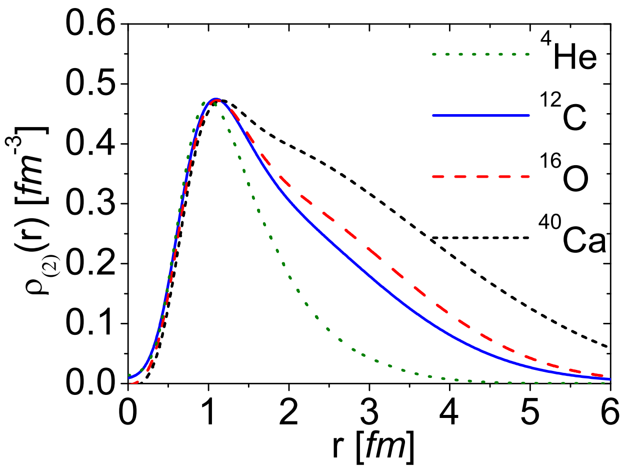
# The 2BDM $\rho_{(2)}(r)$ in COMPLEX NUCLEI

Alvioli, CdA, Morita, ArXiv: 0709:3989 (2007)




At $r < 1.5 fm$ the 2BDM exhibits A-independence in complex nuclei as well

$\Downarrow$

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# The Correlated 2BDM versus the Mean-Field 2BDM

Pieper, Wiringa, Pandharipande, Phys. Rev. C46 1741 (2000)

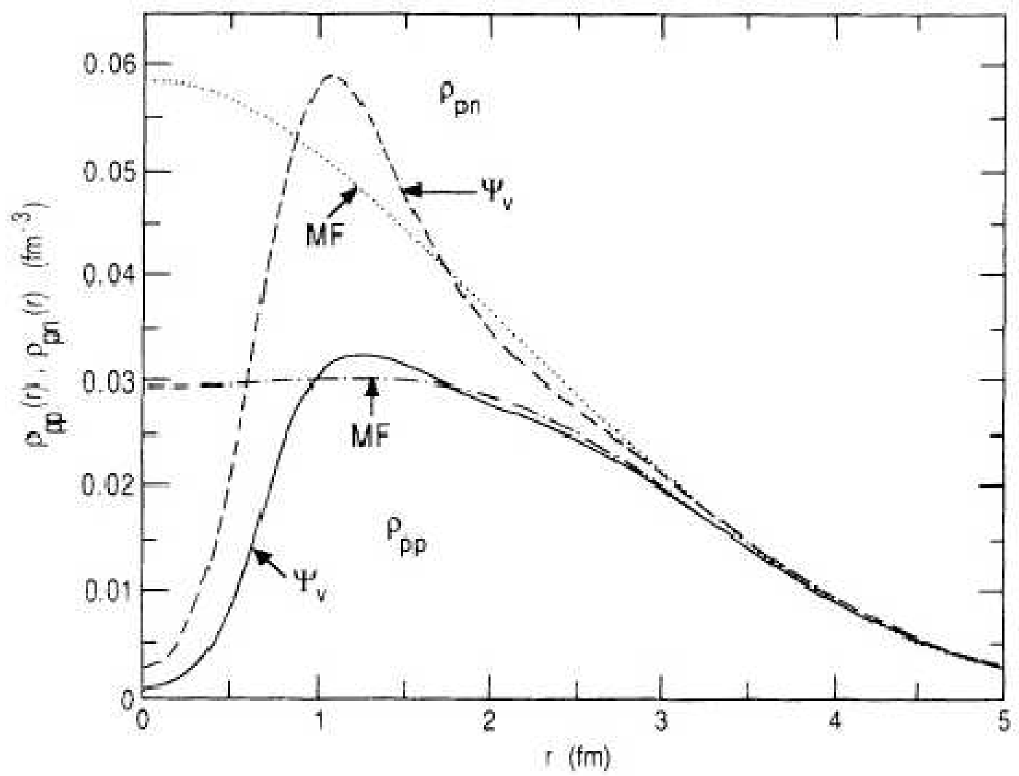



Figure 2: The two body density distribution within realistic and mean-field approaches for $^{16}O$

## SRC in configuration space: summary

- SRC are characterized by the *correlation hole,* generated by the cooperation of the *short-range repulsive interaction* and the *intermediate-range tensor attraction* . The basic features of the correlation hole are independent of the mass $A$ $\Longrightarrow$ universality of SRC.

- SRC in configuration space can be defined as follows: *"They represent the deviation of realistic many-body* $\rho_{(2)}(r)$ *from the mean-field* $\rho_{(2)}(r)$ *at* $r \leq 1.5 - 2 fm^{-1}$*."*

- How can we investigate the existence and the properties of the correlation hole ? To this end we have to shift to momentum space. What do we expect? We expect: (i) an increase of nucleon high momentum components, and (ii) peculiar momentum configurations in the nuclear wave function..

(i) *increase of the high momentum content of the wave function*

## Mean-field (shell model) wave function

$$\Phi_0(1,2,\ldots,A) = \hat{\mathcal{A}}\prod_i^A \phi_{\alpha_i}(x_i) \equiv \Phi_{0p0h} \quad \alpha_i > \alpha_F, \phi_{\alpha_i} = 0$$

## Correlated wave function

$$\Psi_0(1,2,\ldots,A) = C_{0p0h}\,\phi_{0p0h} + C_{1p1h}\,\Phi_{1p1h} + C_{2p2h}\,\Phi_{2p2h} + \ldots$$

$$SRC \Longrightarrow \sum_{n=1}^{\infty} C_{npnh}\Phi_{npnh}$$

**Thus :**

SRC populate states (n particle-n hole) with momentum much higher than the Fermi momentum $k_F \simeq 1.4 fm^{-1}$!!!

## (ii) *SRC generate peculiar wave function configurations*

Momentum conservation

$$\sum_{1}^{A} \vec{k}_i = 0$$

Consider a nucleon with high momentum $\vec{k}_1$

In a mean-field configuration

$$\vec{k}_1 \simeq -\sum_{2}^{A} \vec{k}_i \quad \vec{k}_i \simeq \frac{\vec{k}_1}{A-1}$$

In a two-nucleon correlation configuration

$$\vec{k}_1 \simeq -\vec{k}_2 \quad \vec{K}_{A-2} = \sum_{3}^{A} \vec{k}_i \simeq 0 \quad \vec{k}_{rel} \simeq \vec{k}_1 \quad \vec{K}_{CM} = -\vec{K}_{A-2} \simeq 0$$

SRC :HIGH relative and LOW CM momenta of a pair.

Frankfurt, Strikman, Phys. Rep. 1988

# THE HIGH MOMENTUM COMPONENTS IN THE ONE-BODY MOMENTUM DISTRIBUTION

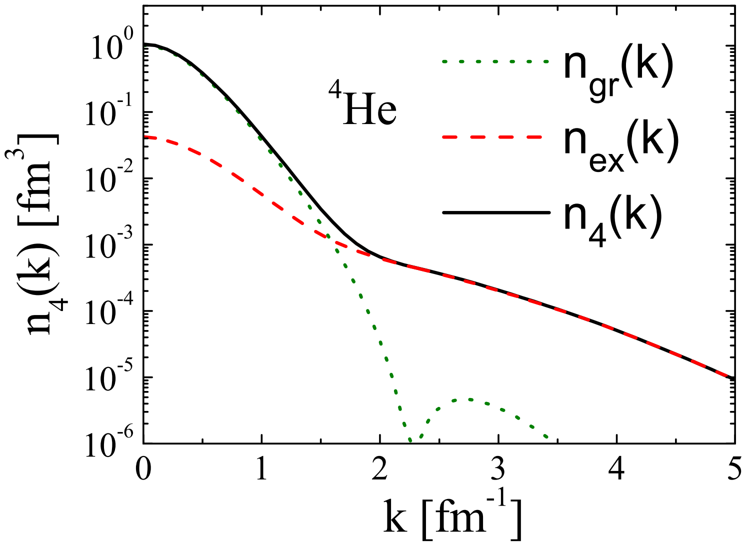
$$\rho(\boldsymbol{r}_1, \boldsymbol{r}'_1) = \int \Psi_0^*(\boldsymbol{r}_1, \boldsymbol{r}_2 \ldots, \boldsymbol{r}_A)\, \Psi_0(\boldsymbol{r}'_1, \boldsymbol{r}_2 \ldots, \boldsymbol{r}_A) \prod_{i=2}^{A} d\boldsymbol{r}_i$$

$$n(\boldsymbol{k}) = \int e^{-i\,\boldsymbol{k}\cdot(\boldsymbol{r}_1 - \boldsymbol{r}'_1)} \rho(\boldsymbol{r}_1, \boldsymbol{r}'_1) d\boldsymbol{r}_1 d\boldsymbol{r}'_1$$

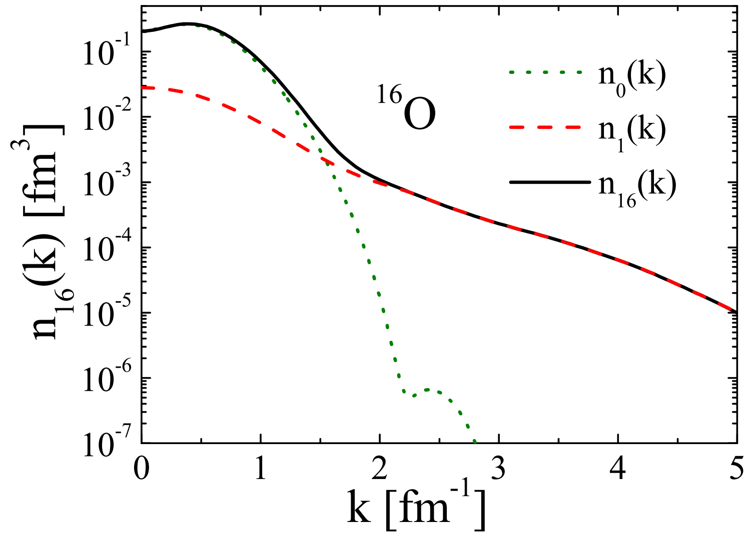
$$n_A(\boldsymbol{k}_1) = \sum_{ST} n_A^{(ST)}(\boldsymbol{k}_1) =$$

$$= \int d\boldsymbol{r}_1\, d\boldsymbol{r}'_1 e^{i\,\boldsymbol{k}_1\cdot(\boldsymbol{r}_1 - \boldsymbol{r}'_1)} \sum_{ST} \int d\boldsymbol{r}_2 \rho_{ST}^{N_1 N_2}(\boldsymbol{r}_1, \boldsymbol{r}'_1; \boldsymbol{r}_2)$$

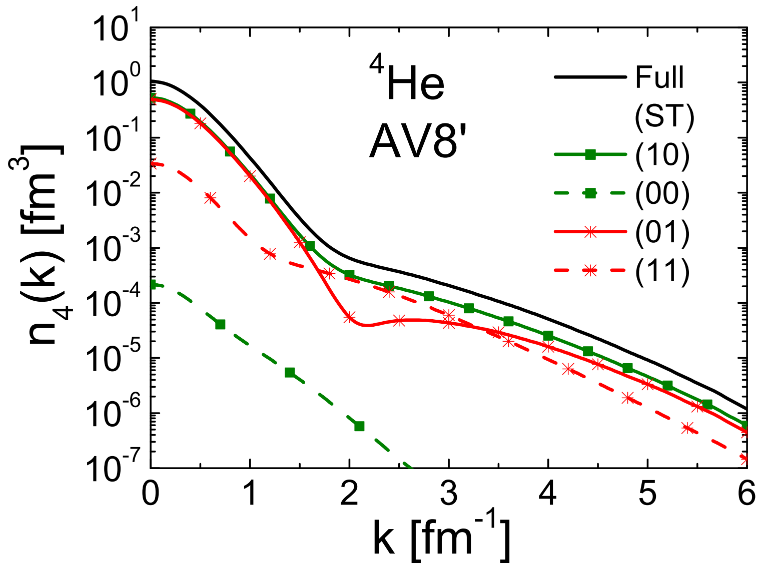
Alvioli, CdA, Kaptari, Mezzetti, Morita,
arXiv:1211.0134v1[nucl-th] to appear in Phys. Rev.



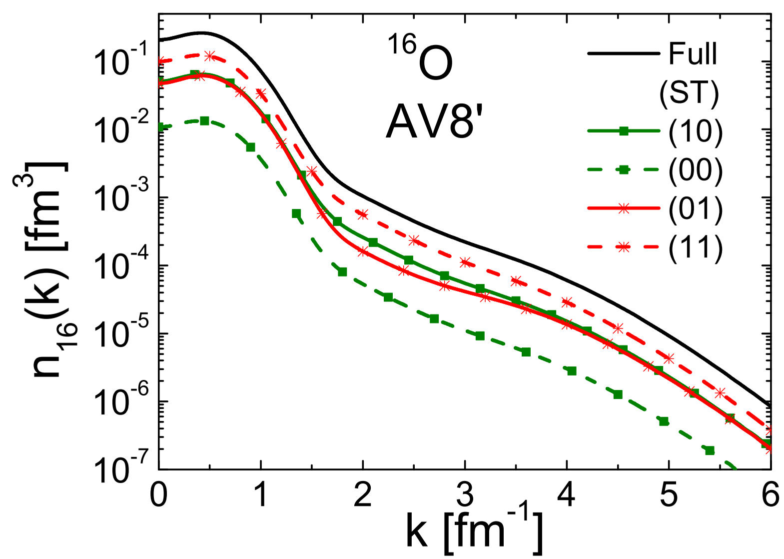
$^4$He
$n_{gr}(k)$
$n_{ex}(k)$
$n_4(k)$
$n_4(k)$ [fm$^3$]
k [fm$^{-1}$]

$^{16}$O
$n_0(k)$
$n_1(k)$
$n_{16}(k)$
$n_{16}(k)$ [fm$^3$]
k [fm$^{-1}$]

$^4$He
AV8'
Full
(ST)
(10)
(00)
(01)
(11)
$n_4(k)$ [fm$^3$]
k [fm$^{-1}$]

$^{16}$O
AV8'
Full
(ST)
(10)
(00)
(01)
(11)
$n_{16}(k)$ [fm$^3$]
k [fm$^{-1}$]

# TWO-BODY MOMENTUM DISTRIBUTIONS

$$\boldsymbol{k}_{rel} \equiv \boldsymbol{k} = \frac{1}{2}(\boldsymbol{k}_1 - \boldsymbol{k}_2) \qquad \boldsymbol{K}_{CM} \equiv \boldsymbol{K} = \boldsymbol{k}_1 + \boldsymbol{k}_2$$

**1.** $n(\boldsymbol{k}_1, \boldsymbol{k}_2) = n(\boldsymbol{k}_{rel}, \boldsymbol{K}_{CM}) = n(k_{rel}, K_{CM}, \theta) =$

$$= \frac{1}{(2\pi)^6} \int d\boldsymbol{r}\, d\boldsymbol{r}'\, d\boldsymbol{R}\, d\boldsymbol{R}'\, e^{-i\,\boldsymbol{K}\cdot(\boldsymbol{R}-\boldsymbol{R}')}\, e^{-i\,\boldsymbol{k}\cdot(\boldsymbol{r}-\boldsymbol{r}')} \rho^{(2)}(\boldsymbol{r}, \boldsymbol{r}'; \boldsymbol{R}, \boldsymbol{R}')$$

**2.** $n(k_{rel}, K_{CM} = 0)$

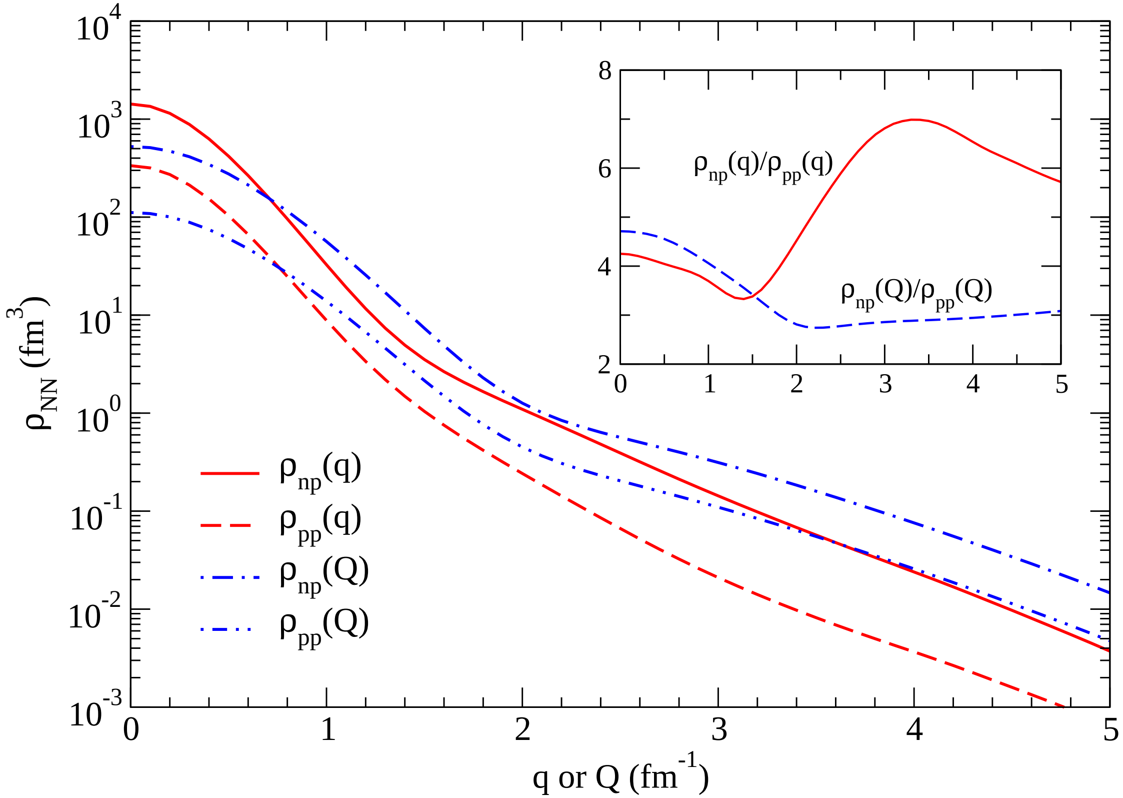
$$K_{CM} = 0 \quad \Longrightarrow \quad \boldsymbol{k}_2 = -\boldsymbol{k}_1,$$

***back-to-back nucleons, like in the deuteron***

**3.** $n_{rel}(k) = \frac{1}{(2\pi)^3} \int n(\boldsymbol{k}, \boldsymbol{K})\, d\boldsymbol{K}$ **4.** $n_{CM}(K) = \frac{1}{(2\pi)^3} \int n(\boldsymbol{k}, \boldsymbol{K})\, d\boldsymbol{k}$

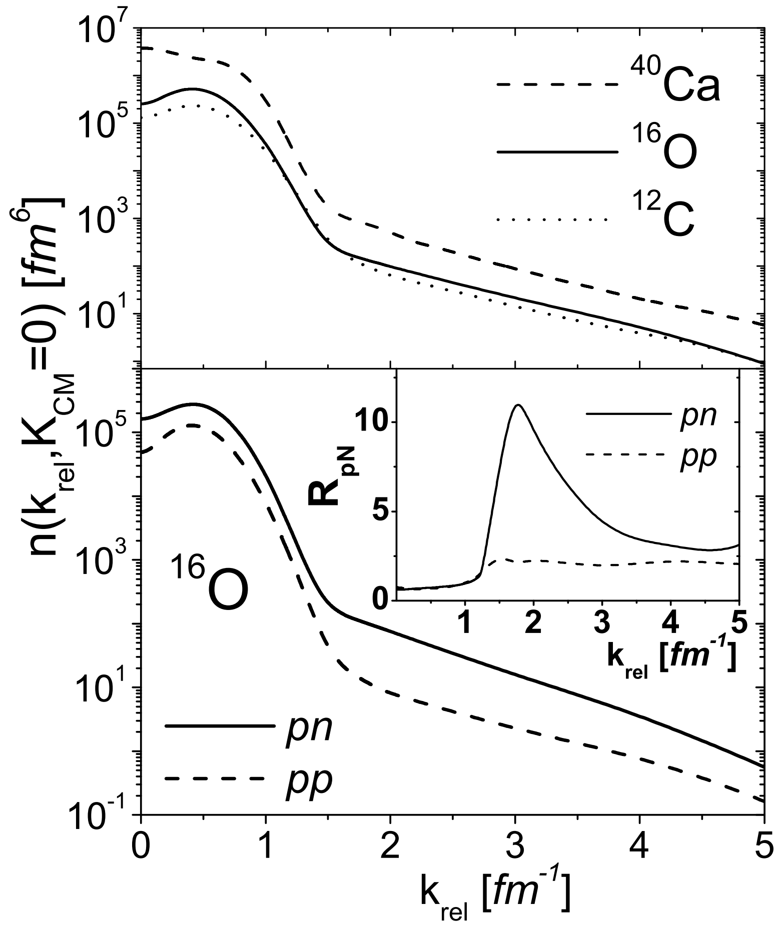
# $n(k_{rel}), n(K_{CM})$ in FEW-NUCLEON SYSTEMS

Schiavilla et al Phys. Rev. Lett. 98(2007)132501 $\quad q \equiv \mathbf{k}_{rel} \quad Q \equiv \mathrm{K}_{CM}$




## TENSOR DOMINANCE

# $n(k_{rel}, K_{CM} = 0)$ in COMPLEX NUCLEI

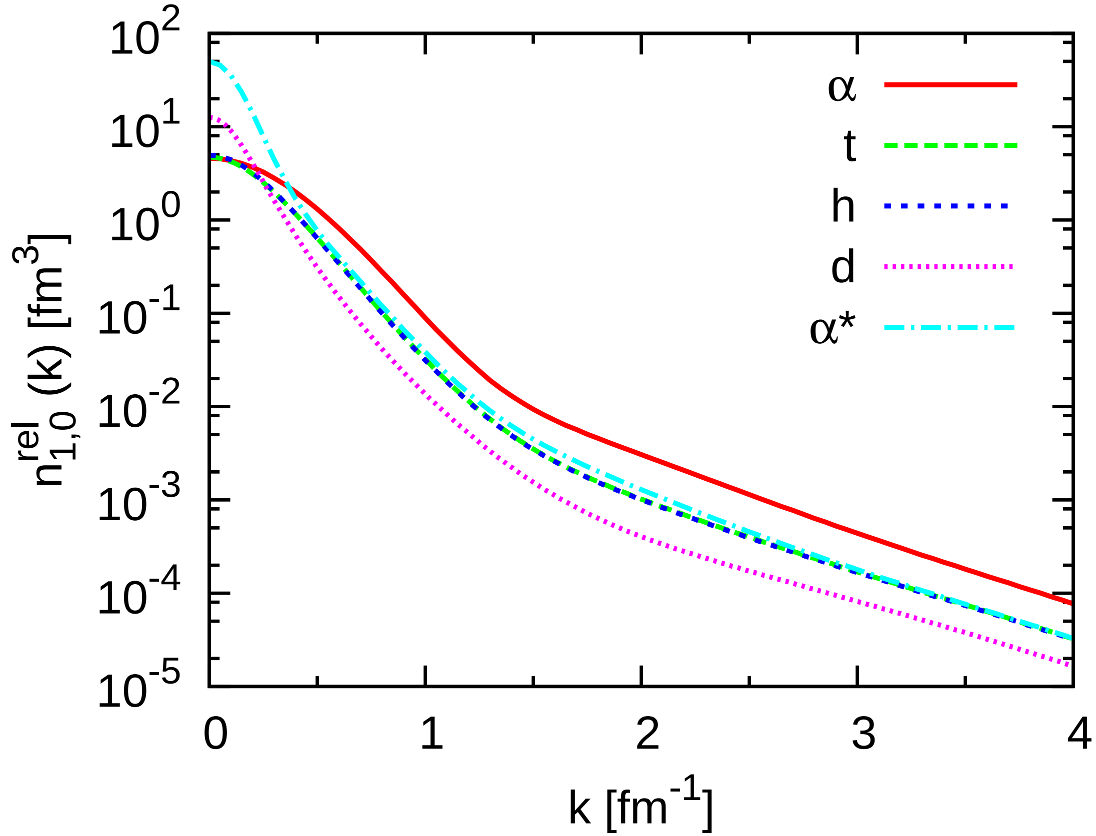



Alvioli, CdA, Morita Phys. Rev. Lett. 100 (2008)162503

Tensor dominance and $n_A(k_{rel}) \simeq n_D(k)$

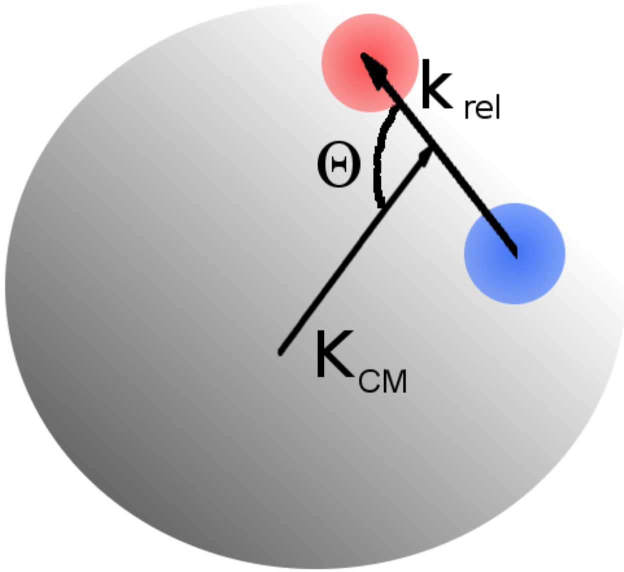
# SPIN-ISOSPIN DEPENDENCE of $n_{rel}(k_{rel})$ in FEW-NUCLEON SYSTEMS

H. Feldmaier, W. Horiuchi, T. Neff, Y. Suzuki, Phys. Rev. (2011)




UNIVERSALITY: $n^A_{rel}(k_{rel}) \simeq C_A n_D(k)$ in (10) state

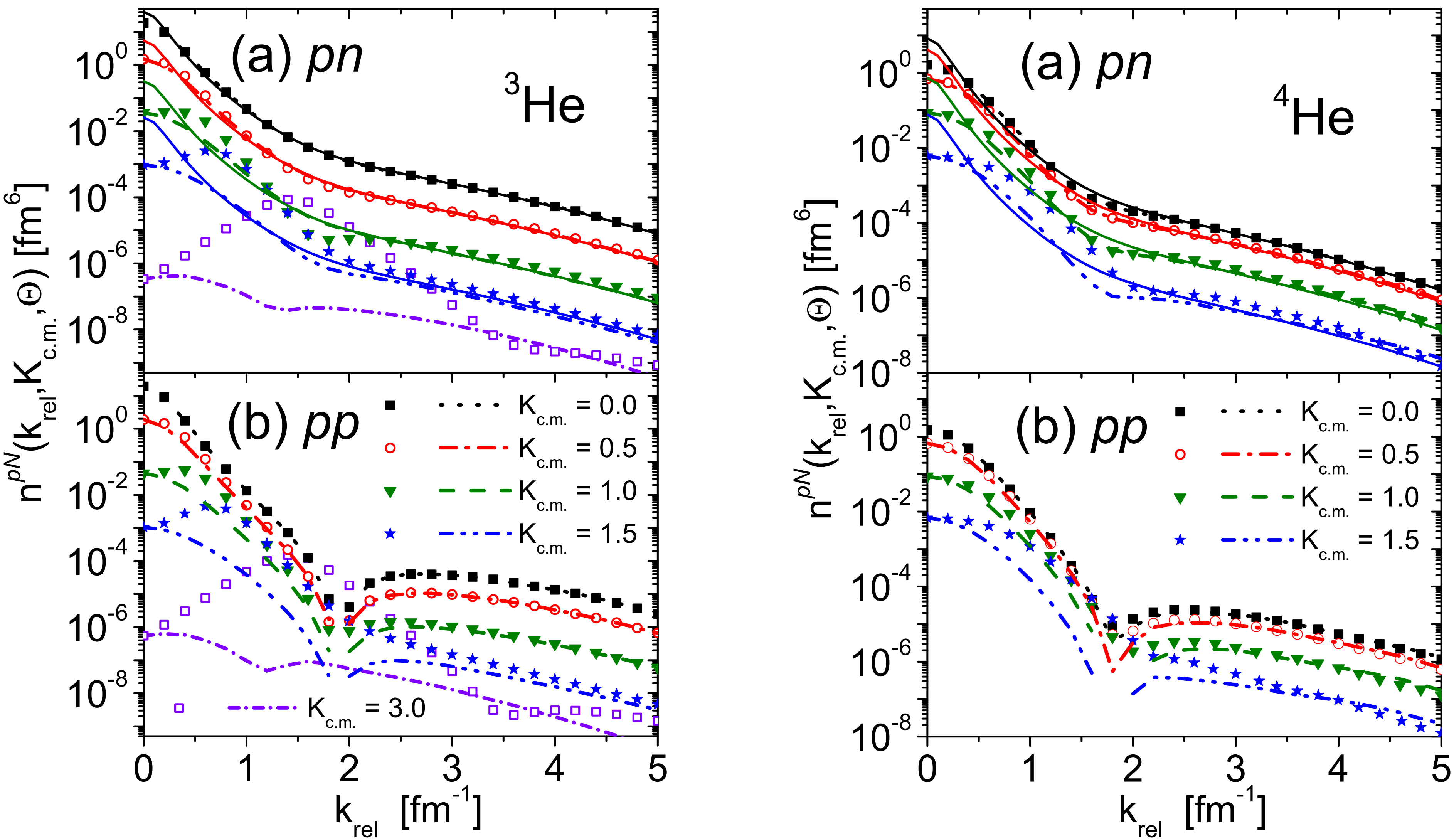
# THE 3D PICTURE OF $n(\boldsymbol{k}_{rel}, \boldsymbol{K}_{CM}) = n(k_{rel}, K_{CM}, \Theta)$



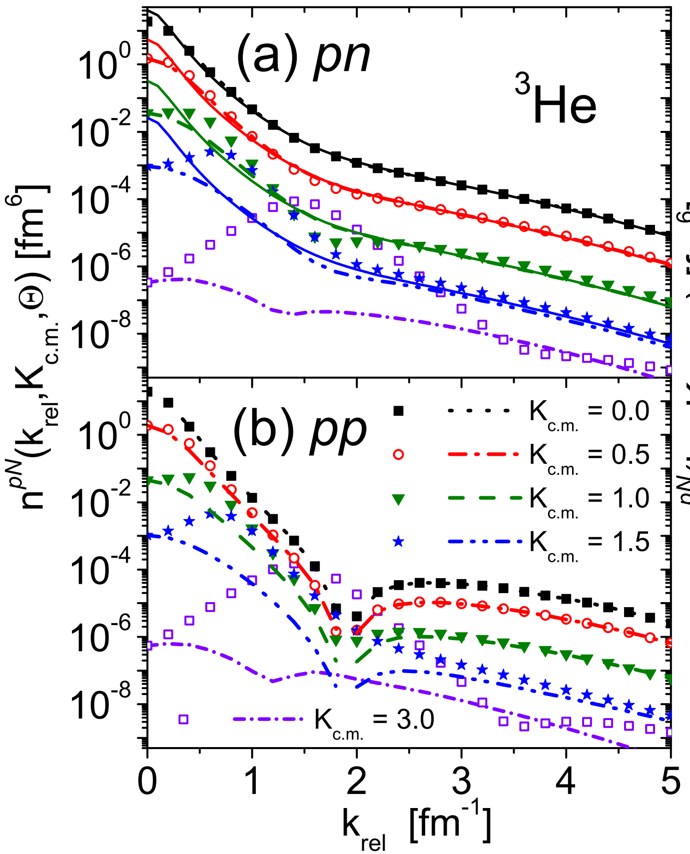

## ! VERY IMPORTANT !

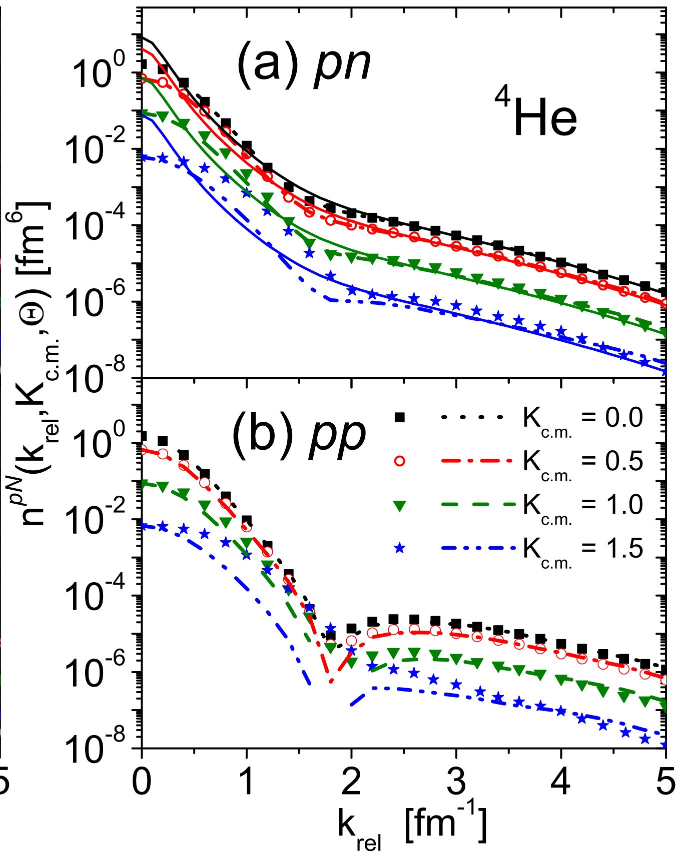
- If $n(k_{rel}, K_{CM}, \Theta)$ is $\theta$ independent, it means that $n(\boldsymbol{k}_{rel}, \boldsymbol{K}_{CM}) = n(k_{rel})\, n(K_{CM})$ i.e. the relative and CM motions factorize.

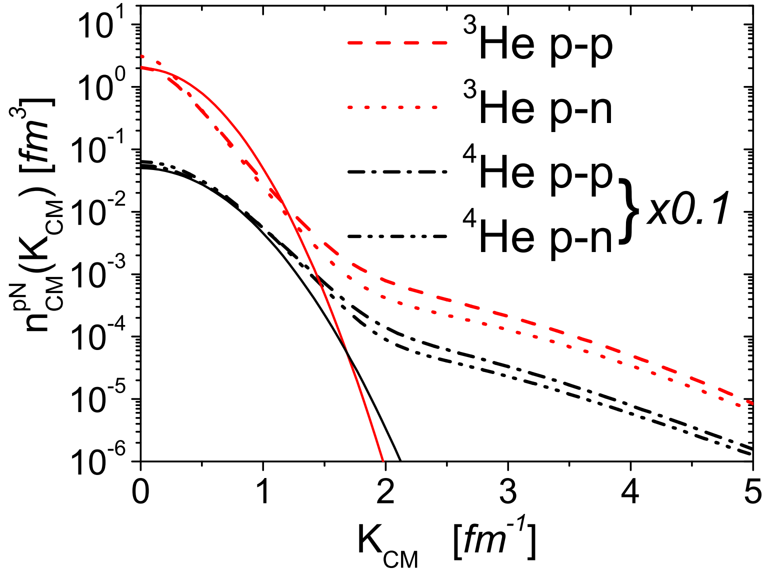
$n(k_{rel}, K_{CM}, \theta)$ **symbols-**$\Theta = 90^o$**, dashes-**$\Theta = 180^o$**, full-**$^2H$**.**




Alvioli, CdA, Kaptari, Mezzetti, Morita, Scopetta, Phys. Rev. C85(2012)




**at large values of $k_{rel}$ and small values of $K_{CM}$ we have :**

$$n^{pn}(\boldsymbol{k}_{rel}, \boldsymbol{K}_{CM}) \Longrightarrow n^{pn}(k_{rel}, K_{CM}) \simeq n^D(k_{rel}) n_{CM}(K_{CM})$$

**Factorization is proved by a rigorous many-body calculation**

We demonstrated that in the region $\mathrm{k_{rel}} \geq \mathrm{k^{-}_{rel}}(\mathrm{K_{CM}}))$ factorization occurs.

$$\mathbf{k_1} + \mathbf{k_2} - \mathbf{K_{CM}} = \mathbf{0}, \quad \mathbf{k_{rel}} = (\mathbf{k_1} - \mathbf{k_2})/\mathbf{2}, \quad \mathbf{k_2} = -\mathbf{k_1} + \mathbf{K_{CM}})$$

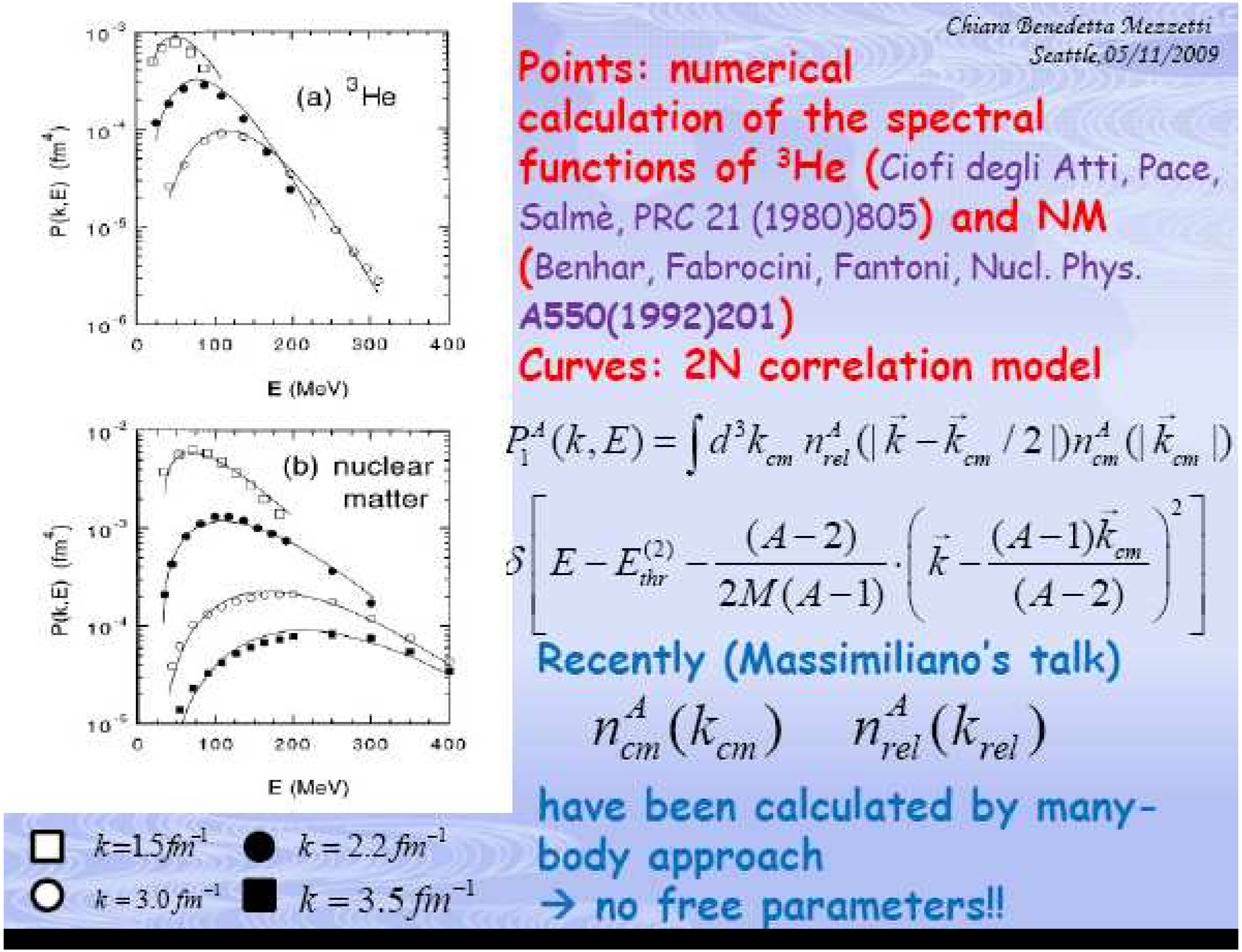
$$n_{pn}(k_{rel}, K_{CM}) \simeq n_D(k_{rel}) n_{CM}(K_{CM}) = n_D(|\boldsymbol{k}_1 - \frac{\boldsymbol{K}_{CM}}{2}|) n_{CM}(K_{CM})$$

which means

$$\begin{aligned} n^N(k_1) &\simeq \int n_D(|\boldsymbol{k}_1 - \frac{\boldsymbol{K}_{CM}}{2}|) n^N_{CM}(K_{CM})\, d\,\boldsymbol{K}_{CM} = \\ &= \int P^N(k_1, E^*_{A-1})\, d\,E^*_{A-1} \end{aligned}$$

where $P^N(k_1, E^*_{A-1})$ is the NUCLEON SPECTRAL FUNCTION

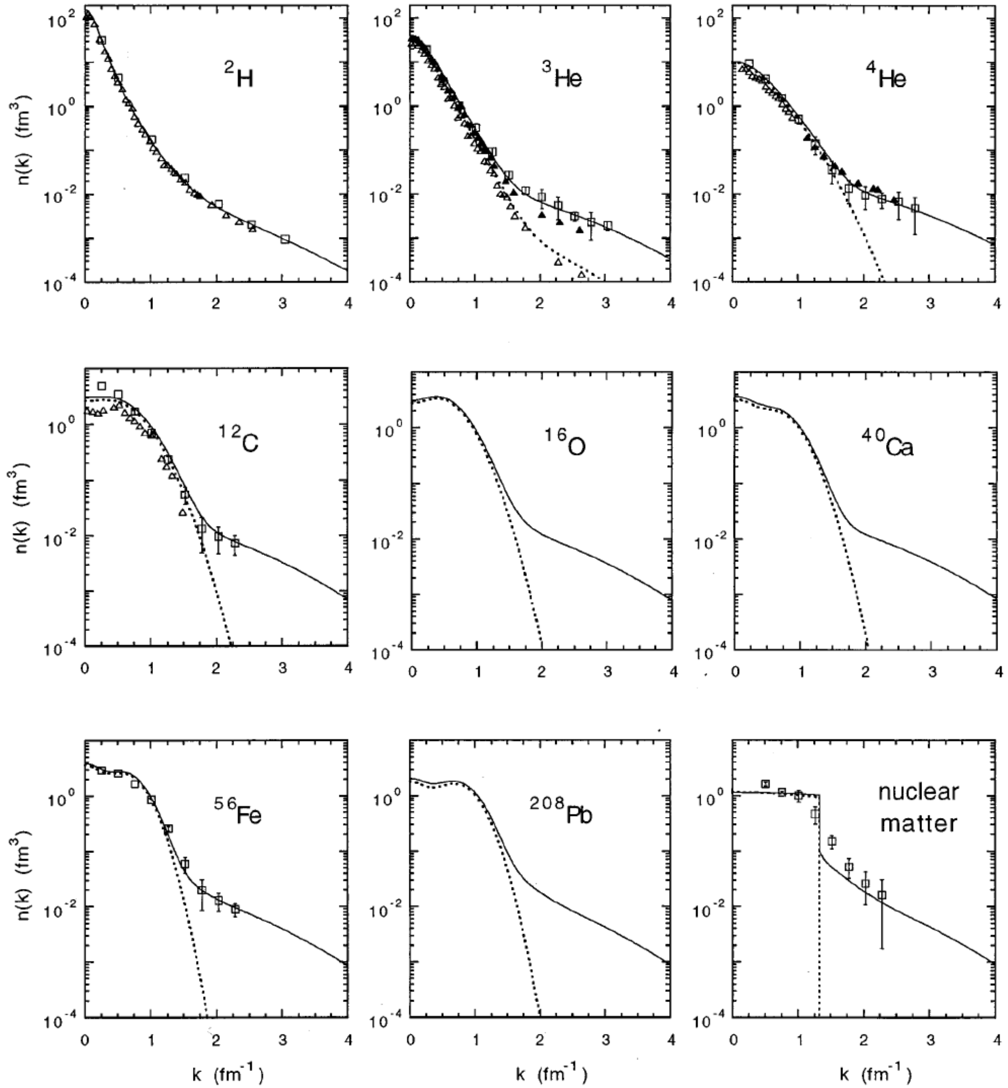
$$\begin{aligned} P^N(k_1, E^*_{A-1}) &= \int n_D(|\boldsymbol{k}_1 - \frac{\boldsymbol{K}^N_{CM}}{2}|) n^N_{CM}(K_{CM}) d\,\boldsymbol{K}_{CM} \times \\ &\times \delta\left(E^*_{A-1} - \frac{A-2}{2m_N(A-1)}\left[\boldsymbol{k}_1 - \frac{A-1}{A-2}\boldsymbol{K}_{CM}\right]^2\right) \end{aligned}$$




CdA, Simula, Frankfurt, Strikman, 1991 CdA, Simula 1996

# 3 EXPERIMENTAL EVIDENCE OF SRC

# 3.1 The momentum distributions from inclusive $A(e,e')X$ processes




- Errors very large
- At high $k$ errors much less than the difference between Mean-Field and correlated distributions
- Experimental data exist only for a limited range of $A$ and low values of momenta.

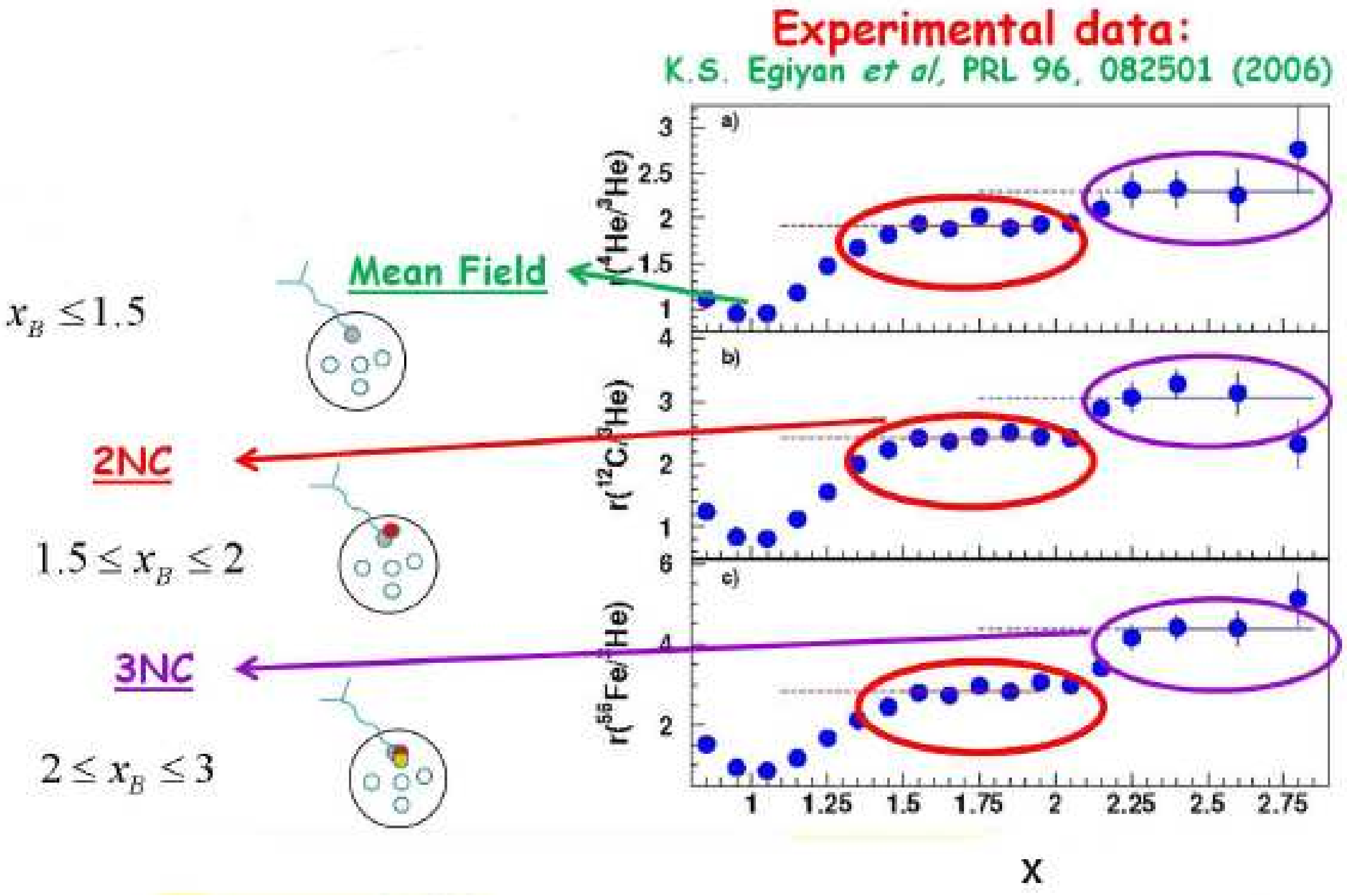
CdA, Pace, Salmè, Phys. Rev. C43 1141(1991)

See also a recent review: Arrington et al, Progr. Part. Nucl. Phys. 2012

# 3.2 The inclusive cross section ratio (a very useful quantity)

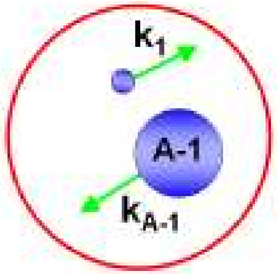
Original idea (Frankfurt, Strikman, Phys. Rep. 5 (1988) 235)

$$\sigma_A(x_B, Q^2) =\simeq \frac{A}{2} a_2(A)\sigma_2(1.5 < x_B < 2, Q^2) + \frac{A}{3} a_3(A)\sigma_3(2 < x_B < 3, Q^2) + \ldots$$



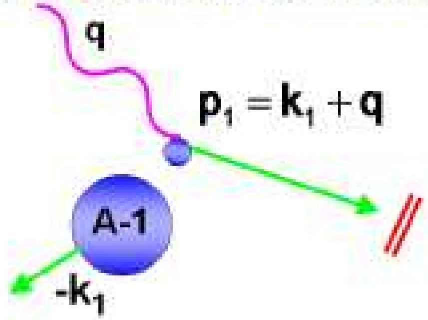
# 3.3 Exclusive one-body knock-out reactions A(a,a'N)X a=(e,N)

## The (e,e'p) process on mean field and correlated nucleons.




Mean Field:

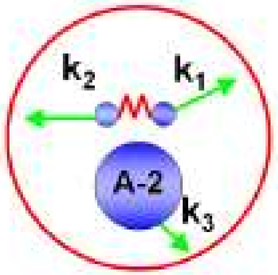
$$k_1 + k_{A-1} = 0$$



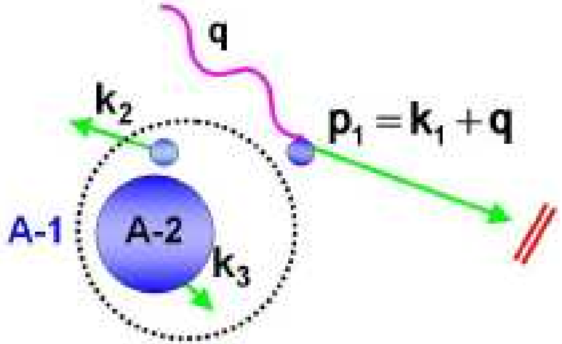

Correlations:

$$k_1 + k_2 + k_3 = 0$$

Simple model:




$$\begin{cases} k_2 \simeq -k_1 \quad k_3 \simeq 0 \quad E^*_{A-2} = 0 \\ E^*_{A-1} \simeq \frac{A-2}{A-1} \frac{k_1^2}{2\, m_N} \end{cases}$$



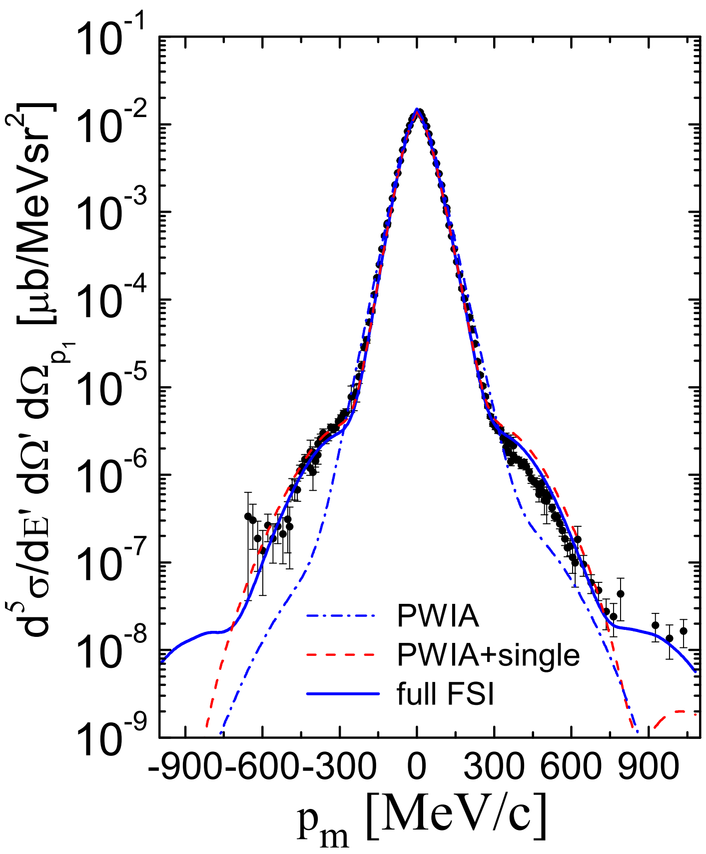

Realistic model:

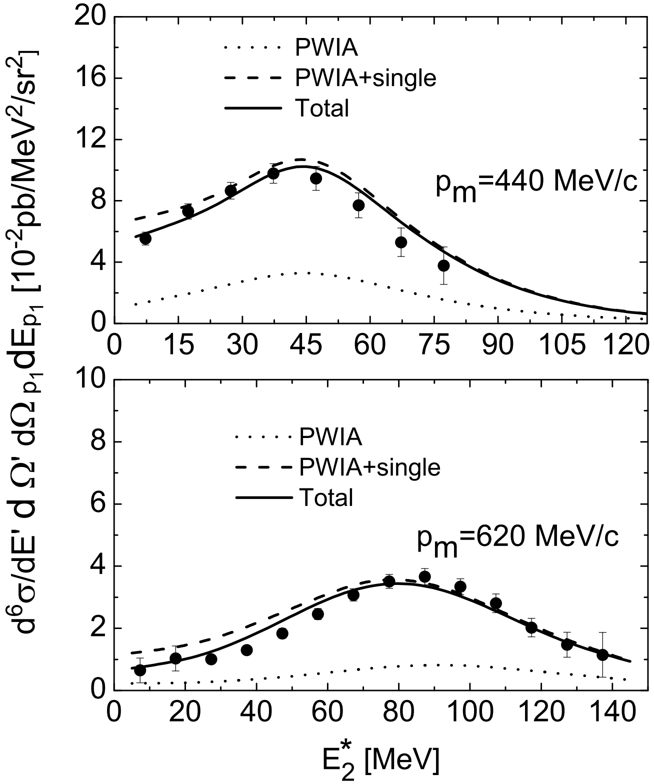
$$\begin{cases} k_3 \neq 0 \qquad E^*_{A-2} \neq 0 \\ E^*_{A-1} = \frac{A-2}{2m_N(A-1)} \left[ k_1 + \frac{A-1}{A-2} k_3 \right]^2 + \bar{E}_{A-2} \end{cases}$$

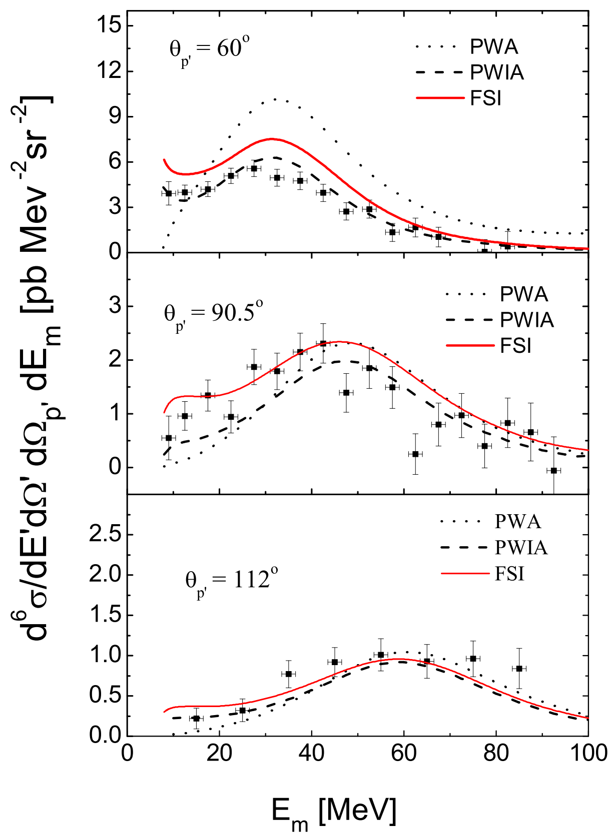
C. Ciofi degli Atti 18 Valparaiso, February 2009

# JLAB (SACLAY ) Experiments Phys. Rev. Lett. (2005)(1988 )

$e +^3 He \rightarrow e' + p +^2 H$ $\qquad$ $e +^3 He \rightarrow e' + p + (pn)$



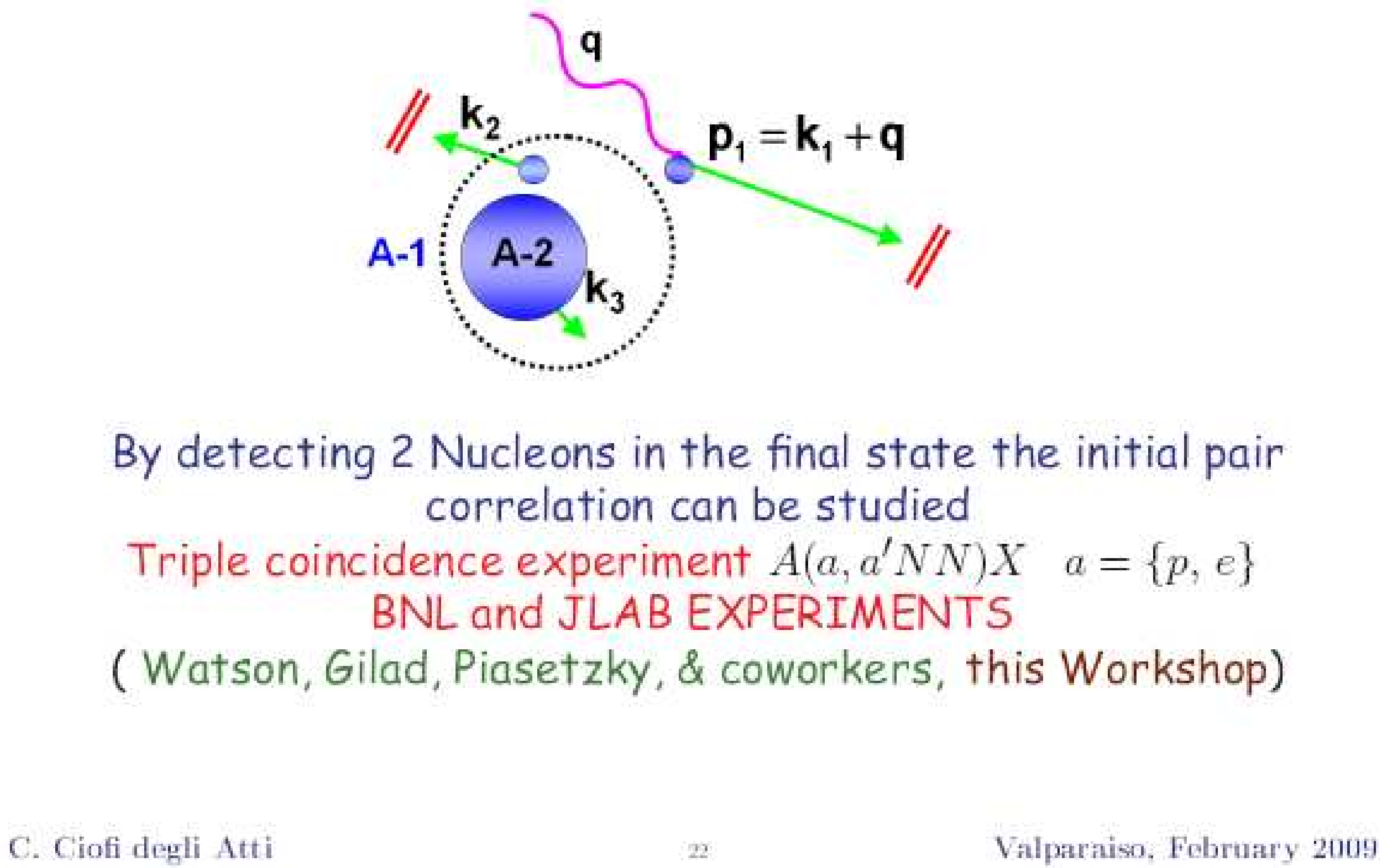



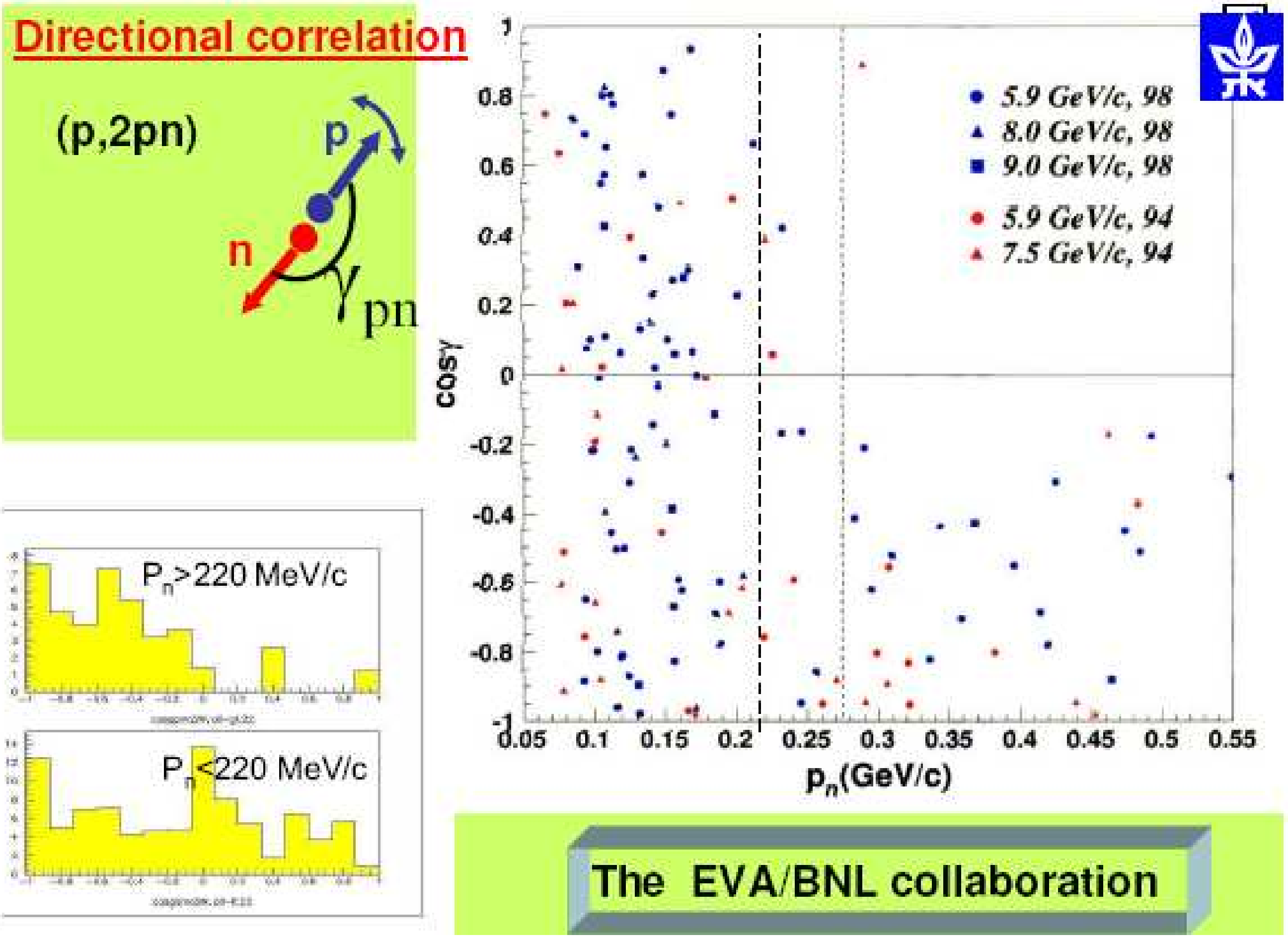

CdA, L.P. Kaptari, Phys. Rev. Lett. 95(2005); 100 (2008)

FSI under control. SRC peak observed. Agreement with other groups.

## 3.4 Exclusive two-body knock-out reactions A(a,a'2N)X a=(e,N) ⇒ *two-body nucleon spectral function.*



# $^{12}C(p, p'pN)X$ AGK BNL (2003); Piasetzky talk




Experiment

Tang et al PRL 04231 (2003)

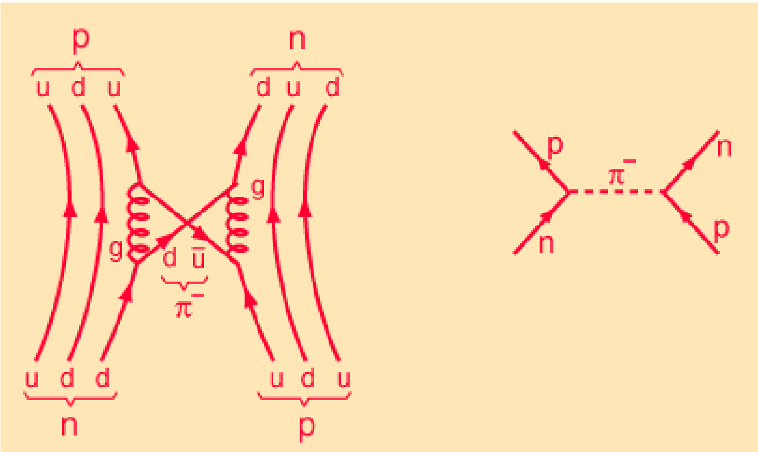
Analysis

Piasetzky, Sargsian, Frankfurt, Strikman, Watson

PRL 162504 (2006)

# 4 IMPACT OF SRC ON VARIOUS FIELDS OF PHYSICS

# 3.1.Transition from hadron to quark gluon descriptions of nuclei



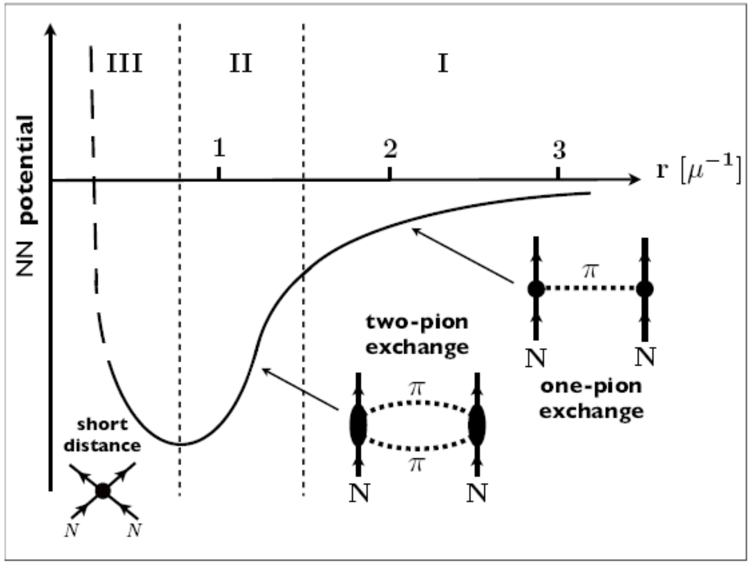



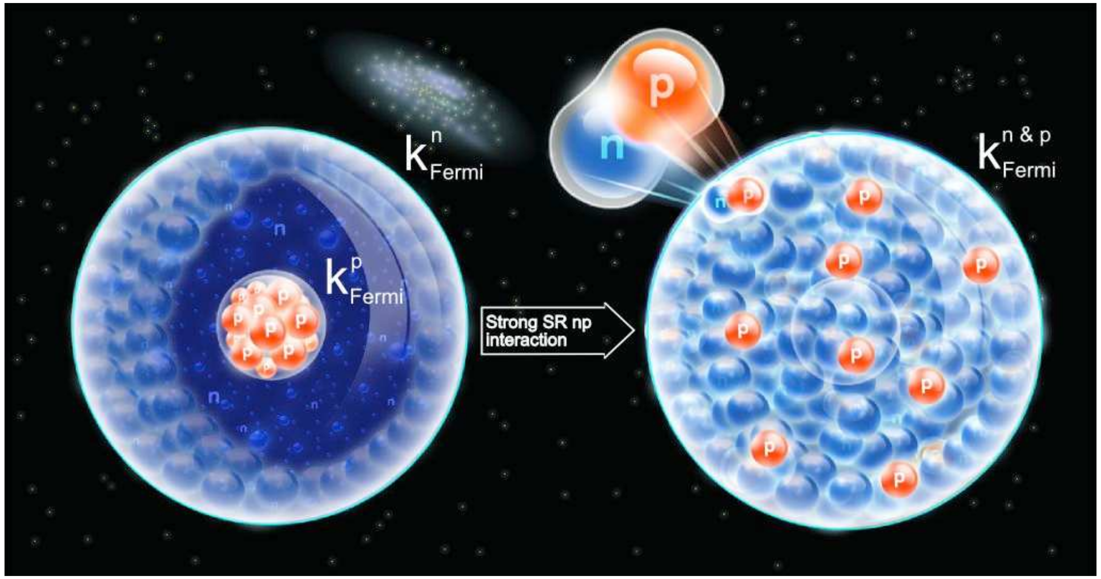

Fig. 2. Hierarchy of scales governing the nucleon-nucleon interaction (adapted from Taketani [5]). The distance $r$ is given in units of the pion Compton wavelength, $\mu^{-1} \simeq 1.4$ fm.

Nucleon radius $< r^2 >^{1/2} \simeq 0.8 fm^{-1}$ $\Rightarrow$ Nucleon overlap.

Adapted from: W. Weise, Nucl. Phys. A 805(2008)145c

# 3.2 Formation of cold dense nuclear matter in the laboratory and the structure of neutron stars

## Implications for Neutron Stars




- At the core of neutron stars, most accepted models assume :~95% neutrons, ~5% protons
- Neglecting the np-SRC interactions, one can assume two separate Fermi gases
- Since np interaction is large compared to nn, n gas heats the p gas
- This could effect the upper limit on mass of neutron and allow the neutrons in the star decay

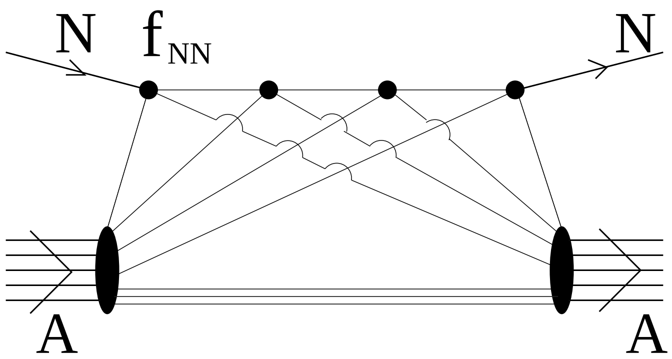
Sixth International Conference on Perspectives in Hadronic Physics    Jefferson Lab

See e.g. Frankfurt, Sargsian, Strikman Int. Jour. Mod. Phys.A (2008)

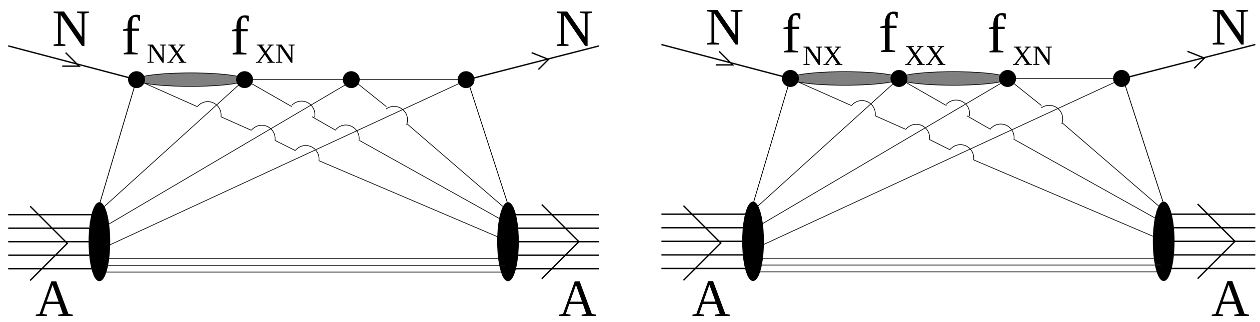
## 3.3 High energy hadron-Nucleus and Nucleus-Nucleus scattering

C.d.A, B. Kopeliovich *et al* Phys. Rev.(2009, 2010,2011,2012)

**Glauber + Gribov Inelastic shadowing + SRC**




(Glauber)




(Inelastic Shadowing)

The exact expansion of $|\Psi_0|^2$ (Glauber, Foldy & Walecka ):

$$|\Psi_0(\boldsymbol{r}_1, ..., \boldsymbol{r}_A)|^2 = \prod_{j=1}^{A} \rho(\boldsymbol{r}_j) + \sum_{i<j=1}^{A} \boldsymbol{\Delta}(\boldsymbol{r}_\mathrm{i}, \boldsymbol{r}_\mathrm{j}) \prod_{k\neq(il)}^{A} \rho(\boldsymbol{r}_k) + \dots$$

Another recent calculation of the effects of SRC in high energy scattering processes:

"A Monte Carlo generator of nucleon configurations in complex nuclei including Nucleon-Nucleon correlations"

M. Alvioli, H.J. Drescher and M. Strikman,

Phys. Lett. (2009)

# 4. CONCLUSIONS

- NN SRC can be calculated *ab initio* with realistic NN interactions. They exhibit several universal (*independent of A*) features.

- NN SRC have been unambiguously experimentally observed in few-nucleon systems and $^{12}C$.

- NN SRC can provide basic information on the nature of the NN force. The experimental information so far obtained is in agreement with the current picture of phenomenological realistic NN interactions.

- SRC can have relevant effects on the structure of cold dense hadronic matter and high energy $h - A$ and $A - A$ scattering processes.

- The successful experimental study of NN SRC is a relatively new field of research that has to be continued, extending it to an increasing number of nuclei and to the investigation of the 3D structure of SRC (JLab, JPARC(?)).