C. CIOFI degli ATTI

Nucleon-Nucleon Correlations and Gribov Inelastic Shadowing in Nuclear Collisions

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OUTLINE

1. Short Range Correlations (SRC) in nuclei: recent theoretical and experimental advances.

2. Beyond the Glauber approximation: effects of SRC and Gribov inelastic shadowing by the light cone dipole approach.

3. Results of calculations I:
(The total hadron-Nucleus cross sections at HERA B, RHIC and LHC energies).

4. Results of calculations II:
(The number of inelastic collisions in hadron-Nucleus and Nucleus-Nucleus scattering).

5. Conclusions

Collaboration Perugia-UTFSM, Valparaiso
Boris Kopeliovich, Irina Potashnikova, Ivan Schmidt

1. SHORT RANGE CORRELATIONS IN NUCLEI: RECENT THEORETICAL AND EXPERIMENTAL ADVANCES

THE STANDARD MODEL OF NUCLEI

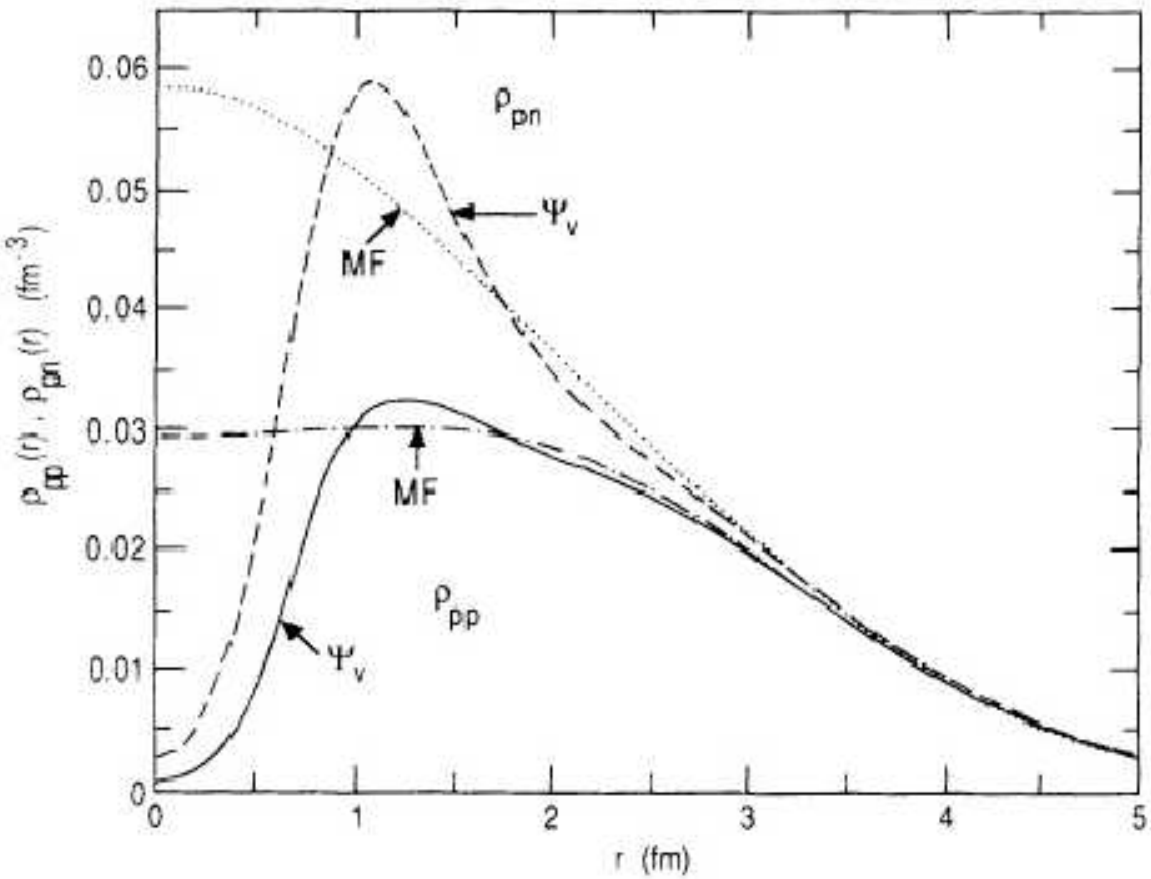
$$\left[-\frac{\hbar^2}{2\,m}\sum_i \hat{\nabla}_i^2 + \sum_{i<j}\hat{v}(i,j) + \sum_{i<j<k}\hat{v}(i,j,k) + \ldots\right]\Psi_o = E_o\,\Psi_0$$

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

$$\hat{\mathcal{O}}_{ij}^{(n)} = \left[1\,,\,\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j\,,\,\hat{S}_{ij}\,,\,(\boldsymbol{L}\cdot\boldsymbol{S})_{ij}\,,\,\ldots\right]\otimes\left[1\,,\,\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j\right]\,.$$

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

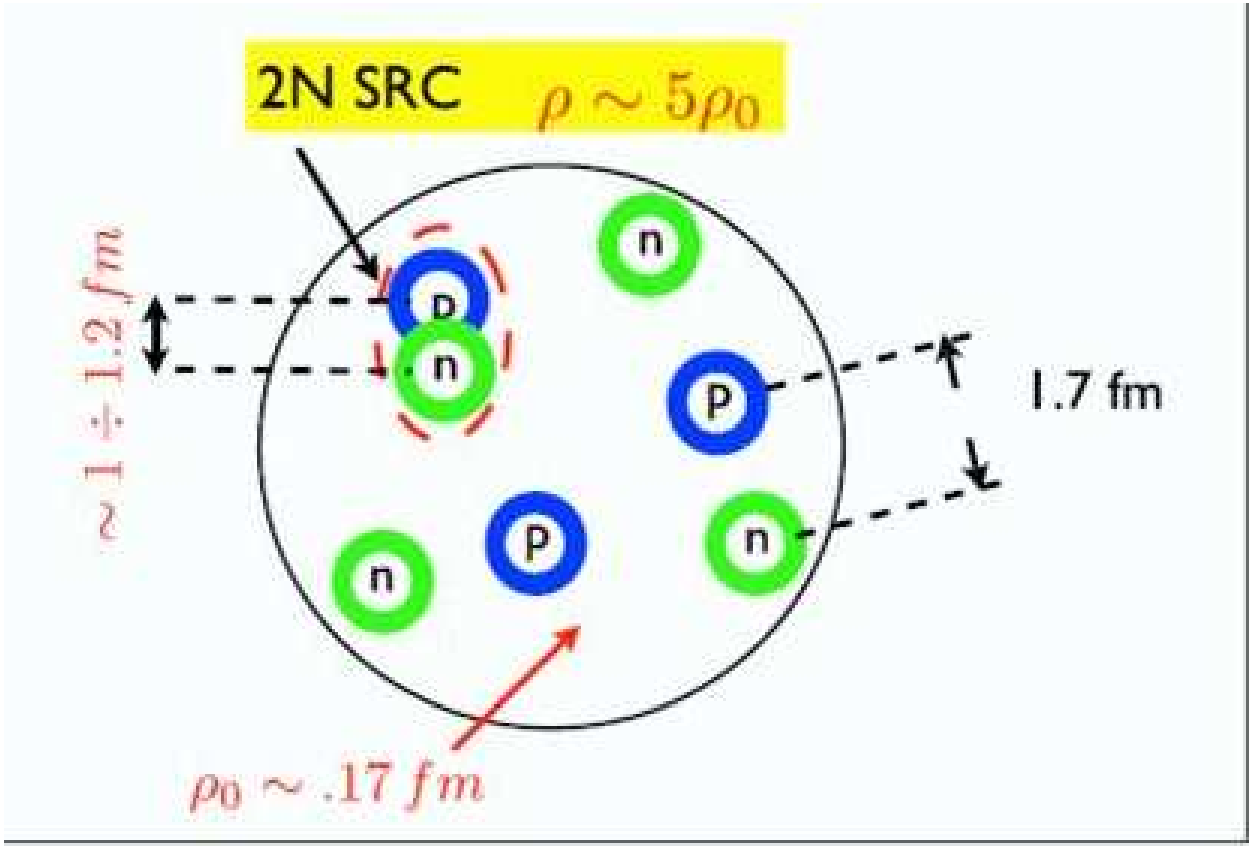
Very difficult many-body problem but recent theoretical developments lead to accurate solutions with a full treatment of NN correlations.



Short Range Correlations (SRC): the strong modification of the Mean Field two-nucleon density distribution in the region $r \leq 1.2\,fm$ due the interpaly between the core repulsion and the tensor attraction .

Different many-body approaches and interactions, lead to the same structure of $\rho_{NN}(r)$. No model dependence.
Urbana-Argonne Group Phys. Rev. Lett. 98 (2007) 132501.
Perugia Group Phys. Rev. Lett. 100 (2008) 162503; Phys. Rev. Lett. 100 (2008) 122301.

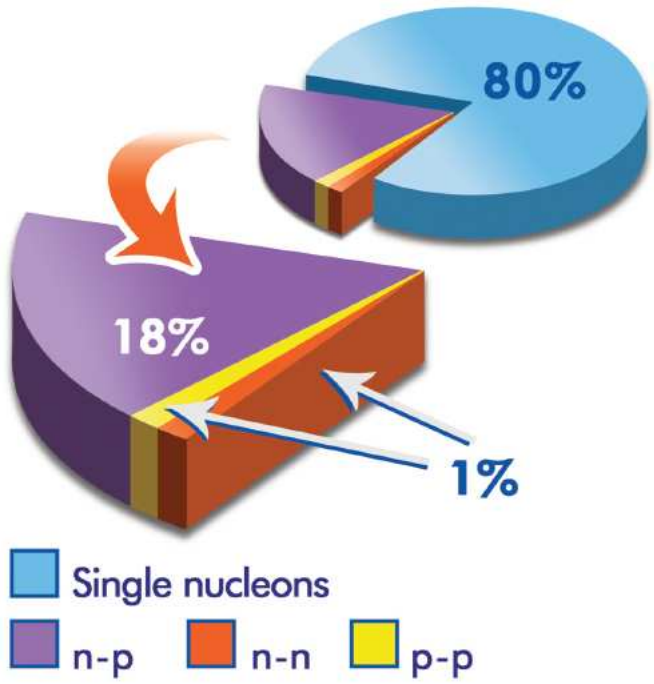
THE NOVEL VIEW OF THE ATOMIC NUCLEUS



Nuclei consist also of drops of cold high density matter whose predicted percentage is $\sim 10 - 20\%$.
Can such a percentage be measured? Yes

A(p,p'pN)X AGK BNL (2003); A(e,e'p)X, A(e,e'pn)X JLab (2006-2008); 12 GeV Jlab

The correlation pizza in ^{12}C



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

2 BEYOND THE GLAUBER APPROXIMATION: SRC AND GRIBOV INELASTIC SHADOWING BY THE LIGHT CONE DIPOLES APPROACH

2.1 SRC correlations

The $h - A$ elastic amplitude

$$\Gamma^{hA}(\boldsymbol{b}) = 1 - \left[1 - \int |\Psi_0(\boldsymbol{r}_1 \ldots \boldsymbol{r}_A)|^2 \prod_{j=1}^{A} \Gamma_j^{hN}(\boldsymbol{b} - \boldsymbol{s}_j) d^3 r_j\right]$$

Evaluation of $\Gamma^{hA}(\mathbf{b}) \Rightarrow (3A-3)$-fold integration. For complex nuclei impracticable, unless MC integration

$$\Downarrow$$

EXPANSION OF $|\Psi_0(\boldsymbol{r}_1 \ldots \boldsymbol{r}_A)|^2$

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

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

$$+ \sum_{(i<j)\neq(k<l)} \boldsymbol{\Delta}(\boldsymbol{r}_\mathbf{i}, \boldsymbol{r}_\mathbf{j})\, \boldsymbol{\Delta}(\boldsymbol{r}_\mathbf{k}, \boldsymbol{r}_\mathbf{l}) \prod_{m\neq(i,j,k,l)}^{A-4} \rho_1(\boldsymbol{r}_m) + \ldots$$

$$\boldsymbol{\Delta}(\boldsymbol{r}_\mathbf{i}, \boldsymbol{r}_\mathbf{j}) = \rho^{(2)}(\boldsymbol{r}_i, \boldsymbol{r}_j) - \rho^{(1)}(\boldsymbol{r}_i)\, \rho^{(1)}(\boldsymbol{r}_j)\,;$$

$$\rho^{(1)}(\mathbf{r}_1) = \int |\Psi_0(\boldsymbol{r}_1, ..., \boldsymbol{r}_A)|^2 \prod_{i=2}^{A} d\mathbf{r}_i\,;\ \rho^{(2)}(\mathbf{r}_1, \mathbf{r}_2) = \int |\Psi_0(\boldsymbol{r}_1, ..., \boldsymbol{r}_A)|^2 \prod_{i=3}^{A} d\mathbf{r}_i$$

$$\int d\mathbf{r}_j\, \rho^{(2)}(\mathbf{r}_i, \mathbf{r}_j) = \rho^{(1)}(\mathbf{r}_i)\,;\ \int d\mathbf{r}_j \boldsymbol{\Delta}(\mathbf{r}_i, \mathbf{r}_j) = 0$$

$$\rho^{(1)}(\mathbf{r}) \equiv \rho(\mathbf{r})$$

1. "GLAUBER APPROXIMATION"

Single density approximation: usual approximation in Glauber-type calculations

$$|\Psi(\boldsymbol{r}_1, ..., \boldsymbol{r}_A)|^2 \simeq \prod_{j=1}^{A} \rho(\boldsymbol{r}_j)$$

2. BEYOND THE GLAUBER APPROXIMATION

All terms of the expansion containing ALL possible products of UNLINKED two-body contractions $\Delta's$, e.g. $\Delta(i,j)\Delta(k,l)\Delta(m,n)\ldots$ $(i,j) \neq (k,l) \neq (m,n)\ldots$ are exactly summed up so that two nucleon correlations are taken exactly into account. The summation yields :

$$\int |\Psi_0(1,2,\ldots,A)|^2 \prod_{i=1}^{A}[1-\Gamma(\boldsymbol{b}-\boldsymbol{b}_i)] \prod_{j=1}^{A} dj \;=$$

$$= \left[1-\int \rho(1)\Gamma(\boldsymbol{b}-1)d1\right]^A \sum_{m=0}^{\frac{A}{2}} \left[\frac{\frac{1}{2}\int \Delta(12)\Gamma(\boldsymbol{b}-1)\Gamma(\boldsymbol{b}-2)d1d2}{\left(1-\int \rho(1)\Gamma(\boldsymbol{b}-1)d1\right)^2}\right]^m$$

Linked products of $\Delta's$ represents higher order correlations, e.g. $\Delta(i,j)\Delta(j,k)$ represents 3-nucleon correlations and will be coupled to the product of three $\Gamma(\boldsymbol{b}-i)$, and so on.

In the optical $(A >> 1)$ limit one obtains:

Glauber approximation

$$\sigma_{tot} = 2 \text{ Re} \int d^2b \left\{ 1 - e^{-\frac{1}{2}\sigma_{NN}^{tot} T_A^h(\boldsymbol{b})} \right\}$$

Beyond Glauber

$$\sigma_{tot} = 2 \text{ Re} \int d^2b \left\{ 1 - e^{-\frac{1}{2}\sigma_{NN}^{tot} \widetilde{T}_A^h(\boldsymbol{b})} \right\}$$

$$T_A^h(b) \Rightarrow \widetilde{T}_A^h(b) = T_A^h(b) - \Delta T_A^h(b)$$

$$\Delta T_A^h(\boldsymbol{b}) = \\ = \frac{1}{\sigma_{NN}^{tot}} \int d^2s_1\, d^2s_2\, \Gamma(\boldsymbol{s}_1)\Gamma(\boldsymbol{s}_2) \int_{-\infty}^{\infty} d\, z_1 d\, z_2\, A^2\, \Delta(\boldsymbol{b} - \boldsymbol{s}_1, z_1; \boldsymbol{b} - \boldsymbol{s}_2, z_2)$$

Glauber in 1971 made an estimate of the effects of correlations on the thickness function. His formula :

$$T_A^h(b) \Rightarrow \widetilde{T}_A^h(b) = T_A^h(b) - \Delta T_A^{Gl}(b)$$

$$\Delta T_A^{Gl}(\boldsymbol{b}) = \left(\frac{2\pi A f(0)}{k}\right) l_c \int_{-\infty}^{+\infty} \rho^2(\mathbf{b}, z) d\, z$$

l_c "correlation length"

Basic approximation:

$$\frac{\text{Range of NN force } \mathbf{a}}{\text{Range of correlations } l_c} << 1 \qquad (1)$$

R. J. Glauber, *High Energy Collision Theory, 1971*

"Various types of correlations in positions and spin may exist between nucleons of an actual nucleus ... If the system being considered is spatially uniform an idea of the magnitude and nature of the effects due to pair correlations may be obtained by assuming that the range of NN force a is smaller than the range of correlations l_c and the nuclear radius R

$$l_c \gg a \text{ and } R \gg a$$

Because R is not vastly larger than a, and the correlation length l_c is not too different in magnitude from the force range, the approximations that follow from these conditions should only be used for rough estimates".

2.2 Gribov corrections by the light cone dipole approach

(Zamolodchikov, Kopeliovich, Lapidus, JEPT Lett. 33 (1981) 612)

Key ingredients:

the universal dipole nucleon cross section

$$\sigma_{\bar{q}q}(r_T, s) = \sigma_0(s) \left[1 - exp\left(-\frac{r_T^2}{R_0^2(s)} \right) \right]$$

the light cone wave function of the projectile

q-2q model: $|\Psi_N(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3)|^2 = \frac{2}{\pi\, R_p^2}\, exp\left(-\frac{2r_T^2}{R_p^2} \right)$

$$\sigma_{tot}^{pA} = 2 \int d^2b \left[1 - \langle e^{-\frac{1}{2}\sigma_{\bar{q}q}(r_T,s)\, T_A^{\bar{q}q}(b,r_T,\alpha)} \rangle \right] \qquad (2)$$

$$\langle \ldots \rangle = \int_0^1 d\alpha \int d^2 r_T \ldots$$

GL plus IS BY LIGHT CONE DIPOLES

(Kopeliovich, Potashnikova, Schmidt, Phys. Rev. C73 (2006) 034901):

$$T_A^{\bar{q}q}(b, r_T, \alpha) = \frac{2}{\sigma_{\bar{q}q}(r_T)} \int d^2s \; Re\, \Gamma^{\bar{q}qN}(\mathbf{s}, \mathbf{r}_T, \alpha)\, T_A(\mathbf{b} - \mathbf{s})$$

GL plus SRC plus IS BY LIGHT CONE DIPOLES

(Alvioli, CdA, Kopeliovich, Potashnikova, Schmidt, Phys. Rev. C81 (2010) 025204):

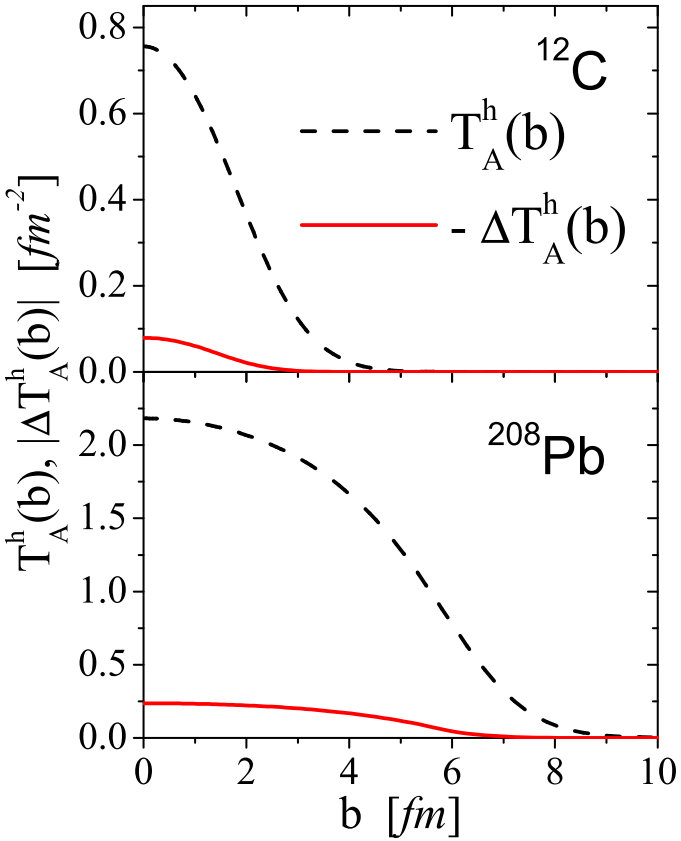
$$\Delta T_A^{\bar{q}q}(b, r_T, \alpha) =$$
$$\frac{1}{\sigma_{\bar{q}q}(r_T)} \int d^2s_1 d^2s_2 \Delta_A^{\perp}(\mathbf{s}_1, \mathbf{s}_2) \times Re\Gamma^{\bar{q}q,N}(\mathbf{b}-\mathbf{s}_1, r_T, \alpha) Re\Gamma^{\bar{q}q,N}(\mathbf{b}-\mathbf{s}_2, r_T, \alpha)$$

3. RESULTS of CALCULATIONS-I

($\sigma_{tot}, \sigma_{el}, \sigma_{qe}, \sigma_{sd}, \sigma_{dd}$ hadronic cross sections at HERA B, RHIC and LHC energies)

The inclusion of NN correlations leads to a modification of the nuclear thickness function

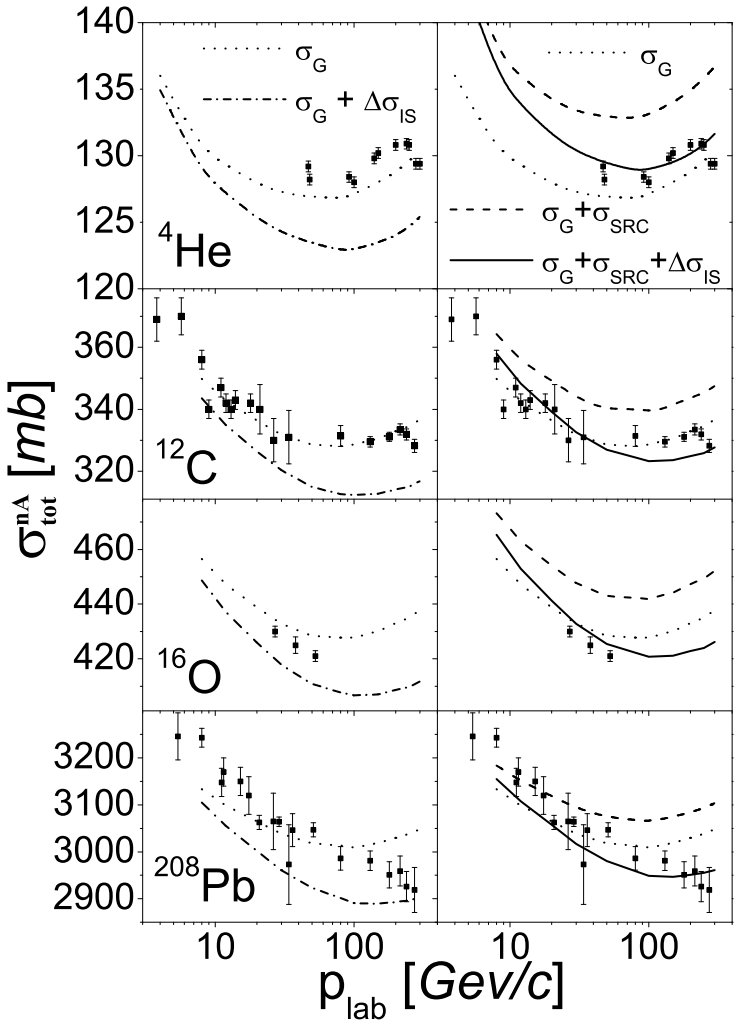
$$T_A^h(b) \Rightarrow T_A^h(b) - \Delta T_A^h(b)$$



Nuclear thickness function $T_A^h(b)$ and the correction due to the NN correlations $\Delta T_A^h(b)$ calculated at HERA energies for ^{12}C and ^{208}P respectively.

The total neutron − Nucleus cross section at high energies:

(M. Alvioli, C.d.A, et al Phys. Rev. C78(R),031601(2008))



- No free parameters!!
- Full SRC.
- Gribov inelastic shadowing at lowest order.
- Main result: SRC increase the opacity, Gribov IS decreases it, the two effects being of about the same order in this energy range.
- What about higher order Gribov corrections?.

CALCULATION of σ_{tot}, σ_{el}, σ_{qe}, σ_{sd}, σ_{dd}...

(Alvioli, CdA, Kopeliovich, Potashnikova, Schmidt, Phys. Rev. C81 (2010) 025204)

Full SRC and Gribov inelastic shadowing to all orders by the light cone dipole approach.

RHIC

^{12}C	*GL*	*+ SRC*	*q-2q*	*+ SRC*	*3q*	*+ SRC*
σ_{tot}	**413.71**	**425.73**	391.12	406.90	**394.96**	**410.20**
σ_{el}	112.13	119.68	97.94	109.16	100.34	111.29
σ_{qe}	30.14	28.14		26.13		26.72
^{208}Pb	*GL*	*+ SRC*	*q-2q*	*SRC*	*3q*	*+ SRC*
σ_{tot}	**3297.56**	**3337.57**	3155.29	3228.11	**3208.92**	**3262.58**
σ_{el}	1368.36	1398.08	1246.73	1314.04	1293.75	1343.76
σ_{qe}	80.42	74.36		71.99		73.92

4. RESULTS OF (PRELIMINARY) CALCULATIONS II : THE EFFECTS OF SRC AND IS ON THE NUMBER OF INELASTIC COLLISIONS IN $h - A$ AND $A - A$ SCATTERING

(CdA, Mezzetti, Kopeliovich, Potashnikova, Schmidt, To appear)

4.1 The number of inelastic collisions in hA scattering

In order to know the absolute value of a hard nuclear cross section, the measured fraction of the total number of inelastic events $N^{hA}_{hard}/N^{hA}_{in}$ is normalized as follows

$$R^{hard}_{A/N} = \frac{\sigma^{hA}_{in}\, N^{hA}_{hard}}{A\,\sigma^{hN}_{in}\, N^{hN}_{hard}} = \frac{1}{N_{coll}}\,\frac{N^{hA}_{hard}}{N^{hN}_{hard}}\,, \quad N_{coll} = A\,\frac{\sigma^{hN}_{in}}{\sigma^{hA}_{in}}$$

The number of hard collisions at a given impact parameter should be defined as follows

$$R^{hard}_{A/N}(b) = \frac{N^{hA}_{hard}(b)}{n_{coll}(b)\, N^{hN}_{hard}} \qquad n_{coll}(b) = \frac{\sigma^{hN}_{in}\, T_A(b)}{P_{in}(b)}$$

and $P_{in}(b)$ is the probability for an inelastic interaction to occur at impact parameter b; it is affected by both SRC and IS through $T^h_A(b)$:

The following quantities have been considered

$$n_{coll}^{Gl}(b) = \frac{\sigma_{in}^{hN}\, T_A(b)}{1 - e^{-\sigma_{in}^{hN}\, T_A^h(b)}}$$

$$n_{coll}^{Gl+SRC}(b) = \frac{\sigma_{in}^{hN}\, T_A(b)}{1 - e^{-\sigma_{in}^{hN}\, \widetilde{T}_A^h(b)}}$$

$$n_{coll}^{Gl+SRC+IS}(b) = \frac{\sigma_{in}^{hN}\, T_A(b)}{P_{in}(b)}$$

where

$$P_{in}(b) = \frac{d\sigma_{tot}}{d^2b} - \frac{d\sigma_{el}}{d^2b} - \frac{d\sigma_{diff}}{d^2b} - \frac{d\sigma_{qel}}{d^2b} - \frac{d\sigma_{qsd}}{d^2b},$$

with

$$\frac{1}{2}\frac{d\sigma_{tot}}{d^2b} = 1 - e^{\frac{1}{2}I_A(b)} \left\langle e^{-\frac{1}{2}\sigma_{dip}T_A^h(b)} \right\rangle$$

$p - ^{208}Pb$

GLAUBER

	σ_{in}^{NN} $[mb]$	σ_{tot}^{NA} $[mb]$	σ_{el}^{NA} $[mb]$	σ_{qel}^{NA} $[mb]$	σ_{in}^{NA} $[mb]$	N_{coll}
RHIC	42.1	3297.6	1368.4	66.0	1863.2	**4.70**
LHC	68.3	3850.6	1664.8	121.0	2064.8	**6.88**

GLAUBER+SRC

	σ_{in}^{NN} $[mb]$	σ_{tot}^{NA} $[mb]$	σ_{el}^{NA} $[mb]$	σ_{qel}^{NA} $[mb]$	σ_{in}^{NA} $[mb]$	N_{coll}
RHIC	42.1	3337.6	1398.1	58.5	1881.0	**4.65**
LHC	68.3	3885.8	1690.5	112.6	2082.7	**6.82**

GLAUBER+SRC+GRIBOV IS $(q - 2q)$

	σ_{in}^{NN} $[mb]$	σ_{tot}^{NA} $[mb]$	σ_{el}^{NA} $[mb]$	σ_{qel}^{NA} $[mb]$	σ_{in}^{NA} $[mb]$	N_{coll}
RHIC	42.1	3228.1	1314.0	71.99	1842.1	**4.75**
LHC	68.3	3833.3	1655.7	113.4	2064.2	**6.88**

Gribov IS increase N_{coll}, SRC decreases it to the Glauber value the effects are of the order of few percent in agreement with the results of deuteron-Gold calculations (Kopeliovich, Phys. Rev. C68 (2003) 025204)

4.2 The number of inelastic collisions in $A-A$ scattering

Collision of two heavy nuclei A and B with nucleon numbers A_A and A_B respectively.

5.2.1 Glauber approximation:

$$T^h_{AB}(\vec{b}) = \int d^2b_A\, T_A(\vec{b}_A)\, T^h_B(\vec{b}-\vec{b}_A)$$
$$= \frac{2}{\sigma^{NN}_{tot}} A_A A_B \int d^2b_A d^2b_B \rho^A_1(\vec{b}_A) Re\Gamma^{NN}(\vec{b}-\vec{b}_A+\vec{b}_B)\rho^B_1(\vec{b}_B)$$

5.2.2 Beyond the Glauber approximation:

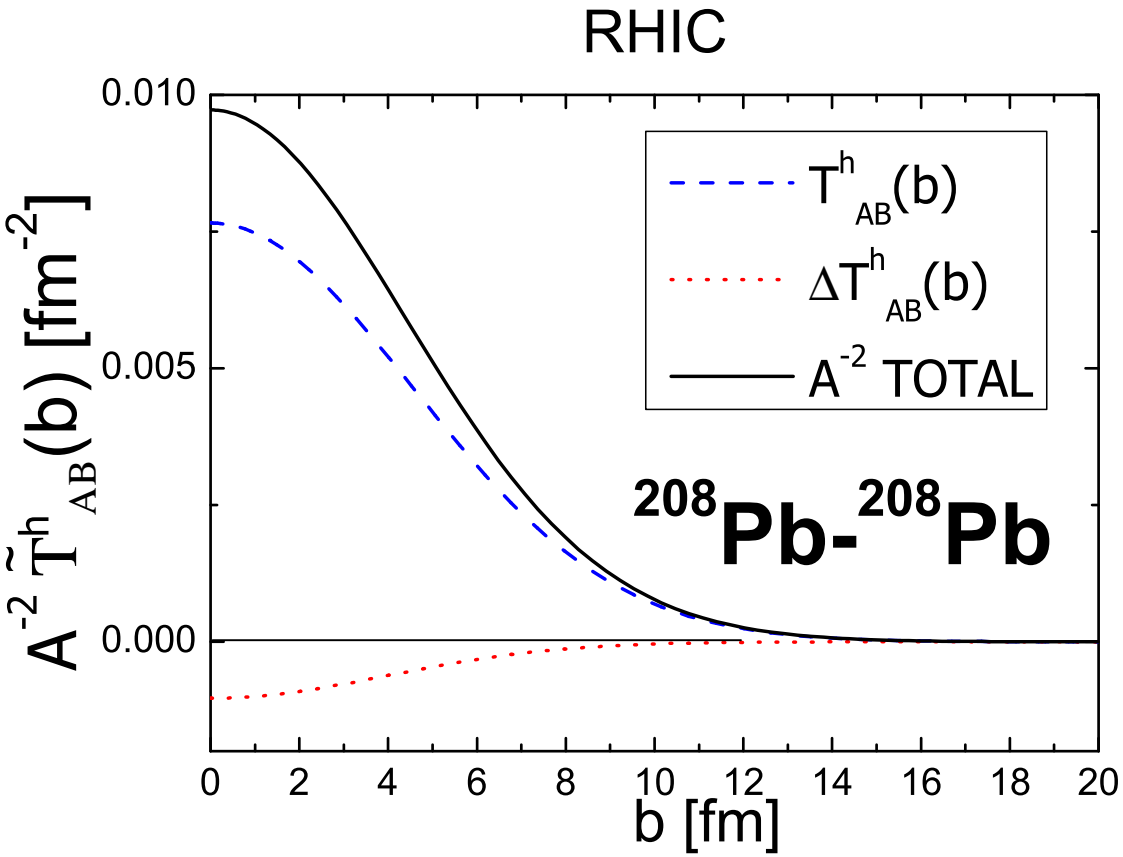
$$T^h_B(\vec{b}-\vec{b}_A) \to \widetilde{T}^h_B(\vec{b}-\vec{b}_A) = T^h_B(\vec{b}-\vec{b}_A) - \Delta T^h_B(\vec{b}-\vec{b}_A)$$

The final Nucleus-Nucleus thickness function is thus

$$\widetilde{T}^h_{AB}(\vec{b}) = T^h_{AB}(\vec{b}) - \Delta T^h_{AB}(\vec{b})$$

the correlation contribution being

$$\Delta T^h_{AB}(\vec{b}) = \frac{1}{\sigma^{NN}_{tot}} A_A A^2_B \int d^2 b_A \rho_A(\vec{b}_A)$$
$$\times \int d^2 b_{B1} d^2 b_{B2} \Delta^{\perp}_B(\vec{b}_{B1}, \vec{b}_{B2}) \Gamma^{NN}(\vec{b} - \vec{b}_A + \vec{b}_{B1}) \Gamma^{NN}(\vec{b} - \vec{b}_A + \vec{b}_{B2}) +$$
$$+ \{A \longleftrightarrow B\}$$



Large effects on the thickness function but what about N_{coll}^{AB} ?

The number of collisions at impact parameter b is

$$n_{coll}^{AB}(b) = \frac{\sigma_{in}^{hN} T_{AB}(b)}{P_{in}^{AB}(b)}$$

- $\sigma_{in}^{hN} T_{AB}(b)$ is affected neither by SRC nor by IS.
- how to calculate $P_{in}^{AB}(b)$? The usual formula

$$P_{in}^{AB}(b) = 1 - \exp[-\sigma_{in}^{NN} T_{AB}^{h}(b)]$$

misses many terms of the Glauber theory. However the probability of no interaction $\exp[-\sigma_{in}^{NN} T_{AB}^{h}(b)]$ is expected to be very small with or without the missed terms, the Gribov IS corrections and the effects of NN correlations. Except the very peripheral collisions $P_{in}^{AB}(b) \simeq 1$ and it seems therefore that n_{coll}^{AB} is practically not affected by NN correlations and IS .

4. CONCLUSIONS

- Advanced solutions of the nuclear many-body problem lead to nuclear wave functions exhibiting a rich correlation structure which has experimentally been observed: the Nucleus is neither a Fermi gas nor a system of independent particles but rather a self-bound saturated liquid which nowadays can theoretically be described with high degree of confidence.
- A reliable theoretical approach has been developed to treat simultaneously NN correlations and Gribov inelastic shadowing in high energy nuclear collisions.
- In the considered processes the effects from NN correlations are not exceptionally large, but still of the same order of other effects that are commonly being considered in high energy nuclear interactions.