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An improved Glauber-Gribov Approach to Diffractive Hadron-Nucleus Scattering

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AIM and MOTIVATIONS

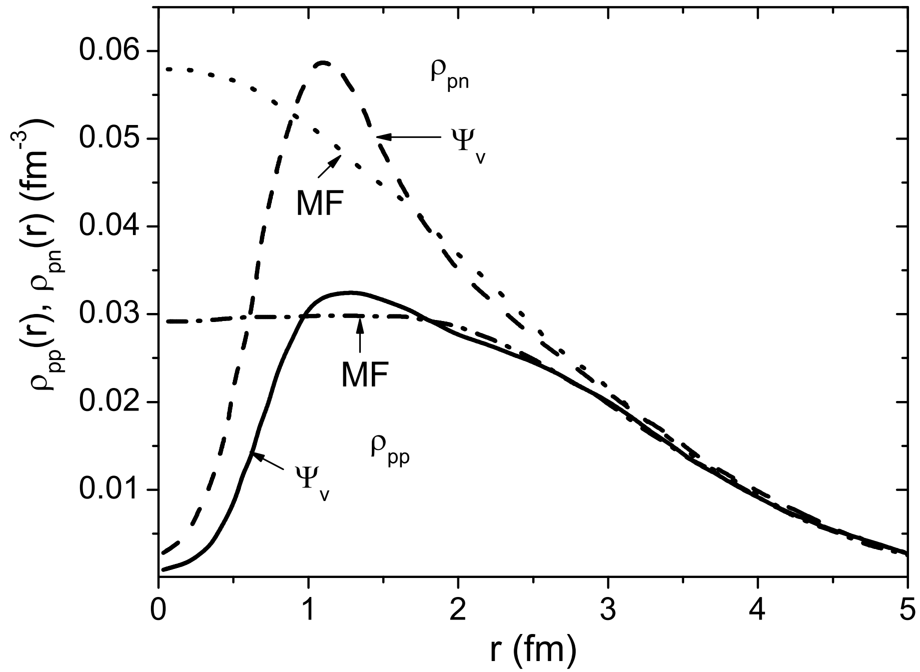
Most theoretical approaches to describe the scattering of a multi GeV particle impinging on a nucleus are based upon Glauber multiple scattering theory and the independent-particle model in spite of the fact that atomic nuclei are self bound saturated liquid where nuclear constituents spend part of their time in strongly correlated configurations.

A consistent approach to treat NN correlations and Gribov inelastic Shadowing has been developed by a Collaboration between:

UTFSM, Chile (B. Kopeliovich, I. Potashnikova, I. Schmidt)
and
INFN Perugia, Italy (M. Alvioli, CdA, C. Mezzetti)

1. SHORT RANGE CORRELATIONS IN HADRONIC MATTER

The two-body density distributions of ^{16}O



Short Range Correlations (SRC): the strong modification of the Mean Field two-nucleon density distribution in the region $r \leq 1.5\,fm$ due the interplay between the core repulsion and the tensor attraction. At $r \geq 1.5\,fm$ mean field (independent particle) motion is OK.

Universal feature A- NN- and -Many-Body-Approach independent.

Urbana-Argonne Group Phys. Rev. Lett. 98 (2007) 132501.

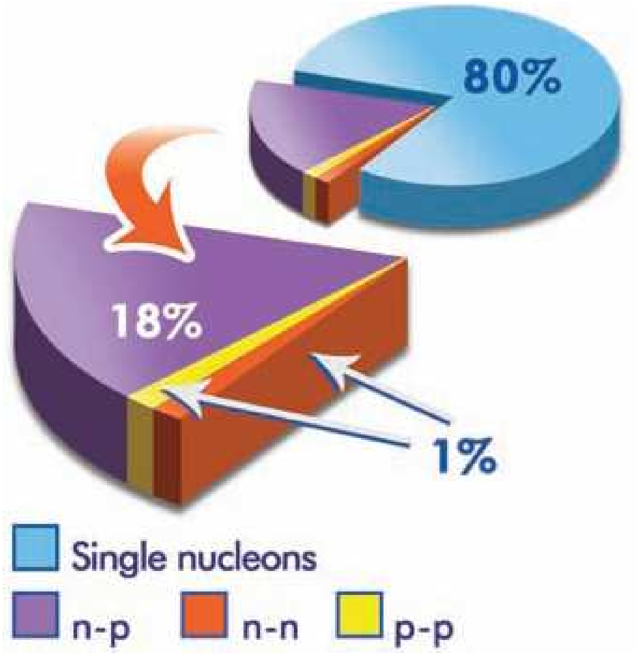
Perugia Group Phys. Rev. Lett. 100 (2008) 162503; 122301.

ROCK SOLID!

RECENT EXPERIMENTAL EVIDENCE

SCIENCE 320, 1476 (2008)

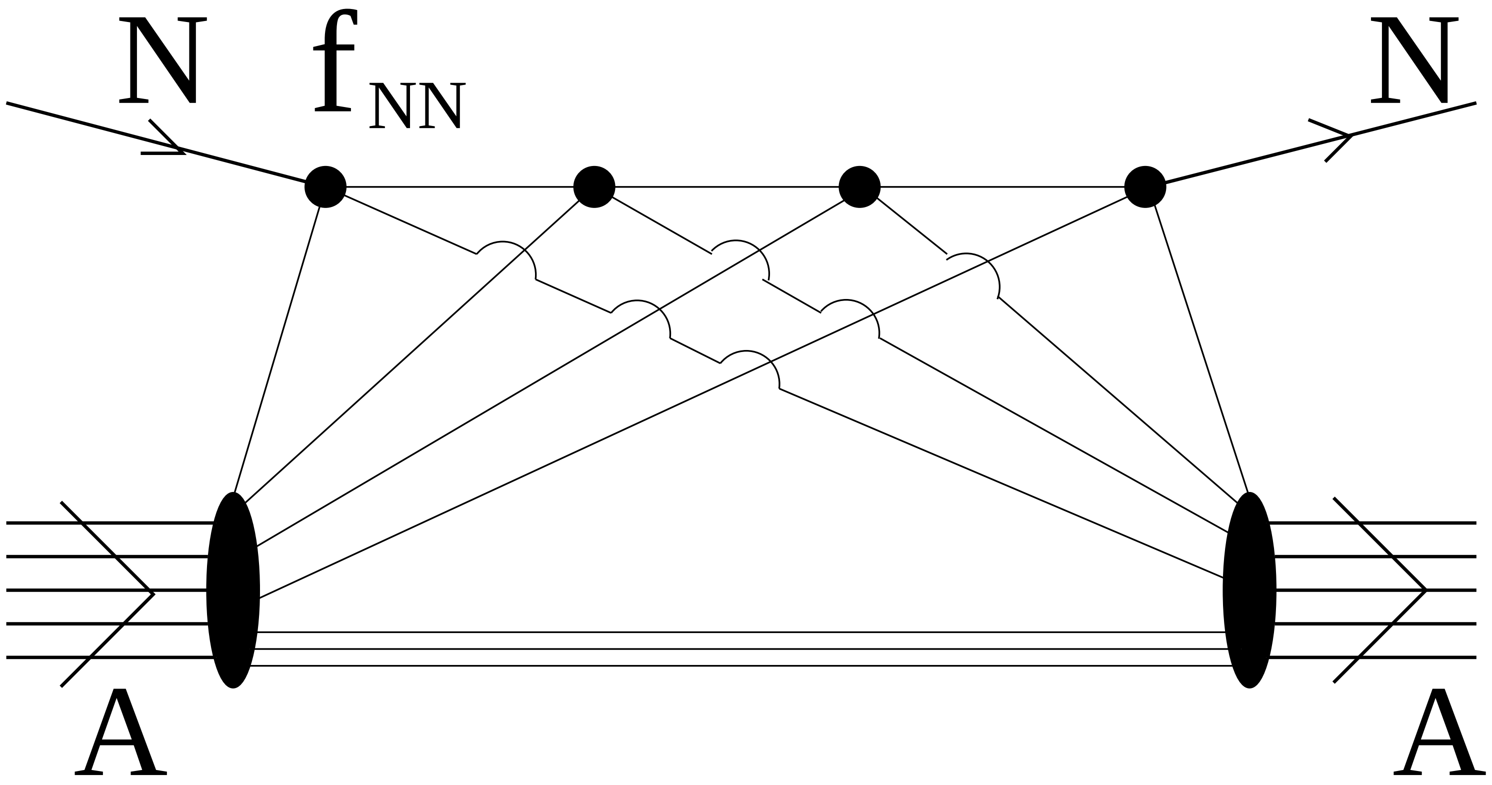
R. SUBEDI et al Probing Cold Dense Nuclear Matter



"The protons and neutrons in a nucleus can form strongly correlated nucleon pairs. Scattering experiments, show that .... the neutron-proton pairs are nearly 20 times as prevalent as proton-proton pairs.... . This is due to the nature of the strong force ."

2 BEYOND THE GLAUBER APPROXIMATION :THE EFFECTS OF SHORT RANGE CORRELATIONS AND GRIBOV INELASTIC SHADOWING

Glauber Multiple Scattering in Diagrams



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

$$\boldsymbol{r}_i \equiv \{\boldsymbol{s}_i, z_i\}$$

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

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

The single particle ("Glauber") approximation

$$|\Psi_0(\boldsymbol{r}_1, ..., \boldsymbol{r}_A)|^2 \simeq \prod_{j=1}^{A} \rho(\boldsymbol{r}_j)$$

$$G^{hA}(\boldsymbol{b}) = 1 - \left[1 - \int \rho(\boldsymbol{r}_1)\Gamma^{hN}(\boldsymbol{b} - \boldsymbol{s}_1) d\boldsymbol{r}_1\right]^A$$

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:

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

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".

After 50 years from Glauber's statement SRC are still either totally ignored or they are treated within the "rough approach".

It's time to do better.

2.2 Effects of SRC (all terms of the expansion are considered)

$$G^{hA}(\boldsymbol{b}) = 1 - \left[1 - \int \rho(\boldsymbol{r}_1)\Gamma^{hN}(\boldsymbol{b}-\boldsymbol{s}_1)d\boldsymbol{r}_1\right]^A \times$$

$$\times \sum_{m=0}^{\frac{A}{2}} \left[\frac{\frac{1}{2}\int \Delta(\boldsymbol{r}_1,\boldsymbol{r}_2)\Gamma^{hN}(\boldsymbol{b}-\boldsymbol{s}_1)\Gamma^{hN}(\boldsymbol{b}-\boldsymbol{s}_2)d\boldsymbol{r}_1 d\boldsymbol{r}_2}{\left(1-\int \rho(\boldsymbol{r}_1)\Gamma^{hN}(\boldsymbol{b}-\boldsymbol{r}_1)d\boldsymbol{r}_1\right)^2}\right]^m \Rightarrow \left[A >> 1\right]$$

$$\Rightarrow 1 - \exp\left[-T_{Gl}^{hN}(\boldsymbol{b}) + T_{SRC}^{hN}(\boldsymbol{b})\right]$$

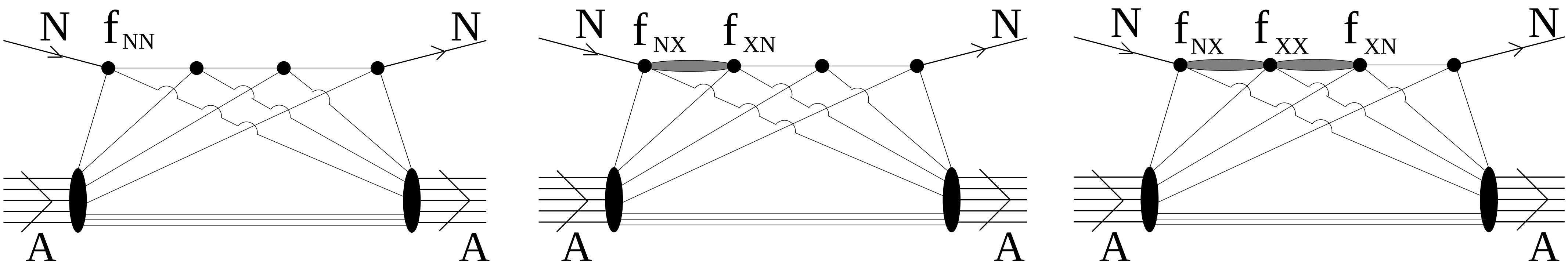
$$T_{Gl}^{hN}(\mathbf{b}) = \frac{2}{\sigma_{tot}^{NN}} \int d^2s\, \Gamma^{hN}(\boldsymbol{s})\, T_A(\boldsymbol{b}-\boldsymbol{s}) \qquad T_A(\boldsymbol{b}) = \int_{-\infty}^{\infty} d\,z\, \rho(\boldsymbol{b}, z)$$

$$T_{SRC}^{hN}(\boldsymbol{b}) =$$

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

2.3 Glauber plus Gribov Inelastic Shadowing (IS) (lowest and higher orders)

V. N. Gribov, Sov. JETP 29 (1969) 483;
J. Pumplin, M. Ross, Phys. Rev. Lett. 21(1968)1778;
V.A.Karmanov,L.A.Kondratyuk, JETP Lett. 18 (1973) 451;
B. Z. Kopeliovich, I. K. Potashnikova, I. Schmidt, Phys. Rev. C73 (2006)034901



Glauber   Inelastic Shadowing

(Diffractive excitation of the projectile)

Gribov inelastic shadowing by the light-cone dipole approach

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

Gribov corrections can be summed to all orders by switching to the interaction eigenstates of the propagating hadron; these were identified as color dipoles in agreement with the 2-gluon exchange interaction in hadron-Nucleon scattering. A certain degree of model dependence is introduced, which is reflected in the key ingredients:

the universal dipole nucleon cross section, e.g.

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

the light cone wave function of the projectile, e.g.:

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

GL plus SRC plus IS BY LIGHT CONE DIPOLES

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

$$T^{\bar{q}q}_{Gl+SRC}(b, r_T, \alpha) = \frac{1}{\sigma_{\bar{q}q}(r_T)} \times$$

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

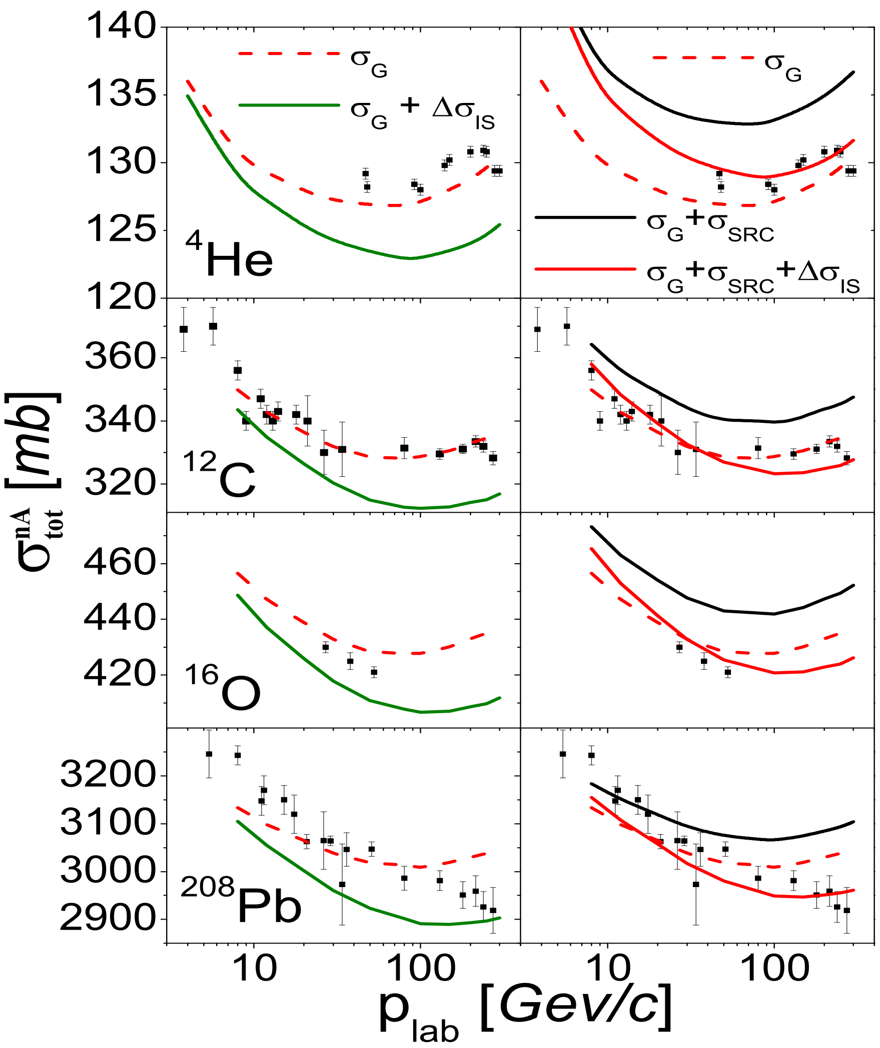
$$\sigma^{pA}_{tot} = 2 \int d^2 b \left(1 - \langle \exp\left[-\frac{1}{2}\sigma_{\bar{q}q}(r_T, s)\, T^{\bar{q}q}_{A}(b, r_T, \alpha)\right]\rangle\right)$$

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

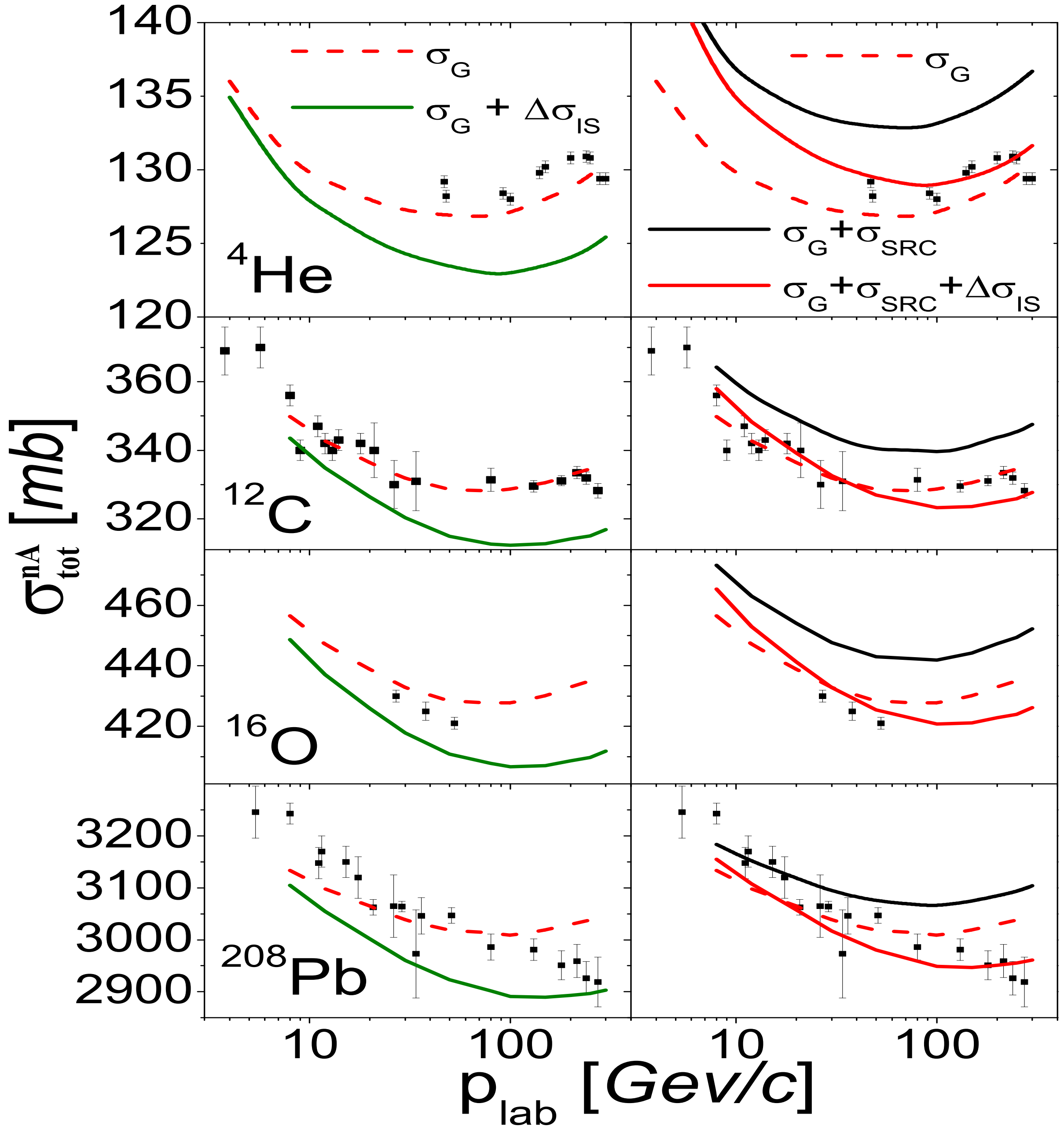
3. RESULTS of CALCULATIONS-I

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 and depends upon energy, the two effects being of about the same order in this energy range.
- What about higher order Gribov corrections?



σ_G
$\sigma_G + \Delta\sigma_{IS}$
$\sigma_G+\sigma_{SRC}$
$\sigma_G+\sigma_{SRC}+\Delta\sigma_{IS}$
^{4}He
^{12}C
^{16}O
^{208}Pb
σ^{nA}_{tot} [mb]
p_{lab} [Gev/c]

SRC plus HIGHER ORDER IS CALCULATIONS of $(\sigma^{hA}_{tot}, \sigma^{hA}_{el}, \sigma^{hA}_{qe}, \sigma^{hA}_{sd}, \sigma^{hA}_{dd}, \ldots$ at HERA B, RHIC and LHC energies)

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

LHC

^{208}Pb	Glauber	Glauber +SRC	q-2q model +SRC	3q model +SRC
$\sigma_{tot}(mb)$	**3850.63**	**3885.77**	3833.26	**3839.26**
$\sigma_{el}(mb)$	1664.76	1690.48	1655.70	1660.67
$\sigma_{qe}(mb)$	120.92	112.65	113.37	113.88

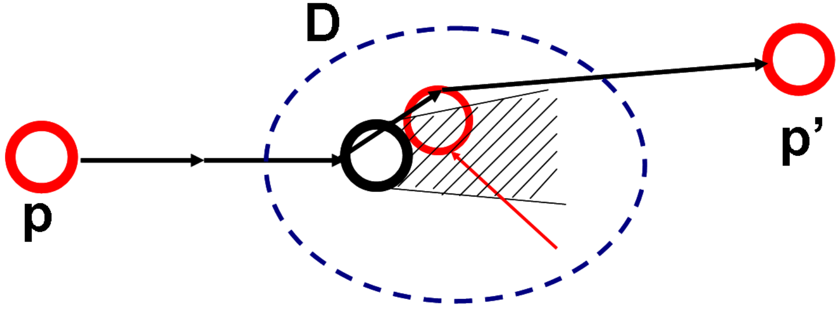
RHIC

^{208}Pb	GL	$+\ SRC$	$q\text{-}2q$	SRC	$3q$	$+\ SRC$
$\sigma_{tot}(mb)$	**3297.56**	**3337.57**	3155.29	3228.11	**3208.92**	**3262.58**
$\sigma_{el}(mb)$	1368.36	1398.08	1246.73	1314.04	1293.75	1343.76
$\sigma_{qe}(mb)$	80.42	74.36		71.99		73.92

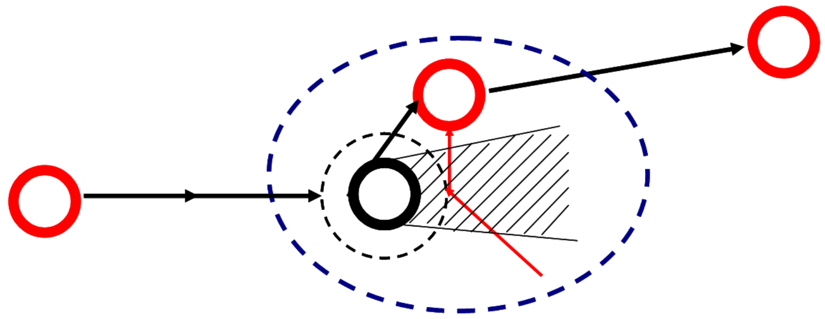
A cartoon showing the effect of SRC on the nuclear transparency in Glauber scattering

Consider the total $p - D$ cross section

$$\sigma^{\mathbf{pD}}_{\mathbf{tot}} = \sigma^{\mathbf{pp}}_{\mathbf{tot}} + \sigma^{\mathbf{pn}}_{\mathbf{tot}} - \boldsymbol{\Delta}\sigma_{\mathbf{shad}}$$



Double Scattering – Glauber Shadowing



Double Scattering – Glauber Shadowing + SRC

SRC reduce Glauber shadowing, increase the total cross section i. e. make the nucleus more opaque. This is a general phenomenon independent of A .

4. RESULTS OF 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, Phys. Rev. C84 (2011) 025205)

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 $P_{in}(b) = 1 - exp[-\sigma^{NN}_{in} T^h_A b]$ is the probability for an inelastic interaction to occur at impact parameter b; it is affected by both SRC and IS through $T^h_A(b)$:

$p -^{208} Pb$

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.

4.2 The effects of SRC in $A-A$ scattering

Collision of two heavy nuclei A and B with nucleon numbers A_A and A_B respectively. Only $\Gamma' s$ having no indexes in common were considered. Each nucleon in A interacts with correlated nucleons in B and viceversa

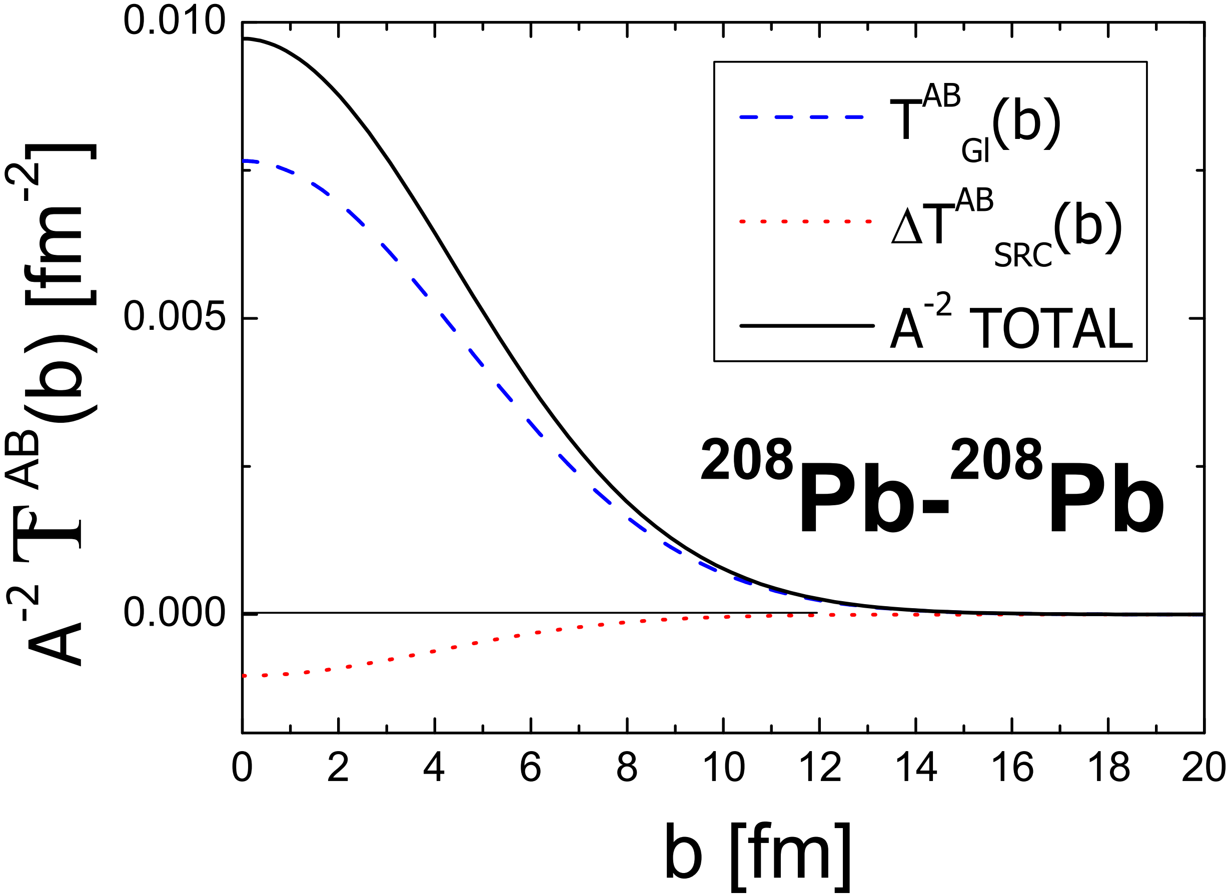
$$
\begin{aligned}
T^{AB}_{Gl}(\boldsymbol{b}) &= \int d^2b_A\, T_A(\boldsymbol{b}_A)\, T^h_B(\boldsymbol{b}-\boldsymbol{b}_A) \\
&= \frac{2}{\sigma^{NN}_{tot}} A_A A_B \int d^2b_A d^2b_B \rho^A(\boldsymbol{b}_A) Re\Gamma^{NN}(\boldsymbol{b}-\boldsymbol{b}_A+\boldsymbol{b}_B)\rho^B(\boldsymbol{b}_B)
\end{aligned}
$$

$$
\Delta T^{AB}_{SRC}(\boldsymbol{b}) = \frac{1}{\sigma^{NN}_{tot}} A_A\, A^2_B \int d^2\, b_A \rho_A(\boldsymbol{b}_A)
$$

$$
\times \int d^2b_{B1} d^2b_{B2} \Delta^{\perp}_B(\boldsymbol{b}_{B1},\boldsymbol{b}_{B2})\Gamma^{NN}(\boldsymbol{b}-\boldsymbol{b}_A+\boldsymbol{b}_{B1})\Gamma^{NN}(\boldsymbol{b}-\boldsymbol{b}_A+\boldsymbol{b}_{B2}) +
$$

$$
+\{A \longleftrightarrow B\}
$$

$$T_{AB}(\boldsymbol{b}) = T_{Gl}^{AB}(\boldsymbol{b}) - 2\Delta T_{SRC}^{AB}(\boldsymbol{b})$$



Large effects on the thickness function

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, for large values of A_A and A_B 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 .

5. CONCLUSIONS

- *A Reliable theoretical approach has been developed to treat simultaneously SRC NN correlations and Gribov inelastic shadowing in high energy nuclear collisions.*

- *In the considered processes the effects from NN correlations are of the same order of the effects of Gribov inelastic shadowing, the two effects acting in the opposite directions.*

- *Several calculations of various processes (N, π and ρ color transparency, coherent and incoherent photoproduction, density fluctuation effects in relativistic heavy ion scattering, and several others), have been produced by the "rough approach". State-of-the-art calculations are called for.*