Medium Modifications from Generalized Parton Distributions

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Motivation

To understand transverse motion in hadrons and its relation to Final State Interactions (problem first studied within QCD, perhaps, by Ellis, Furmanski, and Petronzio, '80s)

$\Rightarrow$ Need to explore the connection between:

k_T $\Rightarrow$ observable through azimuthal asymmetries involving transverse polarization

b $\Rightarrow$ observable through DVCS and related processes.

$\Rightarrow$ Need a consistent treatment of a number of reactions: SIDIS, DVCS, hadroproduction (DY, Λ, ...)

Main idea: Use nuclei as laboratories to "trigger" modifications of transverse d.o.f.

What is the physical origin of the transverse degrees of freedom investigated through either GPDs or TMDs?

$\longrightarrow$ Initial/Final State Interactions?

$\longrightarrow$ Confinement/Hadronization?

$\longrightarrow$ Or else ... ?

Two basic messages:

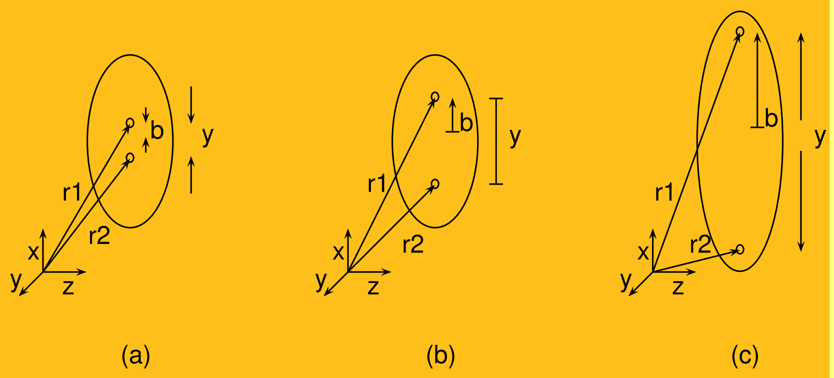
1) Mainly to experimentalists: **YES** to nuclear targets in studies of GPDs!

2) More speculative: we can also learn about *"in medium" properties*, and *quark structure of nuclei* using GPDs.

Brief summary ...

⇒ **Quarks' Transverse Location**

Soper (1977), Burkardt (2000), Diehl (2003)



$\mathbf{b}$ measured with respect to "longitudinal center of momentum": $\mathbf{R} = \sum_i x_i \mathbf{r}_i$

$$q(x, \mathbf{b}) = \int \frac{d^2\boldsymbol{\Delta}}{(2\pi)^2} \, e^{-i\mathbf{b}\cdot\boldsymbol{\Delta}} H_q(x, 0, -\boldsymbol{\Delta}^2) \;\longrightarrow\; \langle \mathbf{b}^2(x) \rangle = \mathcal{N}_b \int d^2\mathbf{b} \, q(x, \mathbf{b}) \, \mathbf{b}^2$$

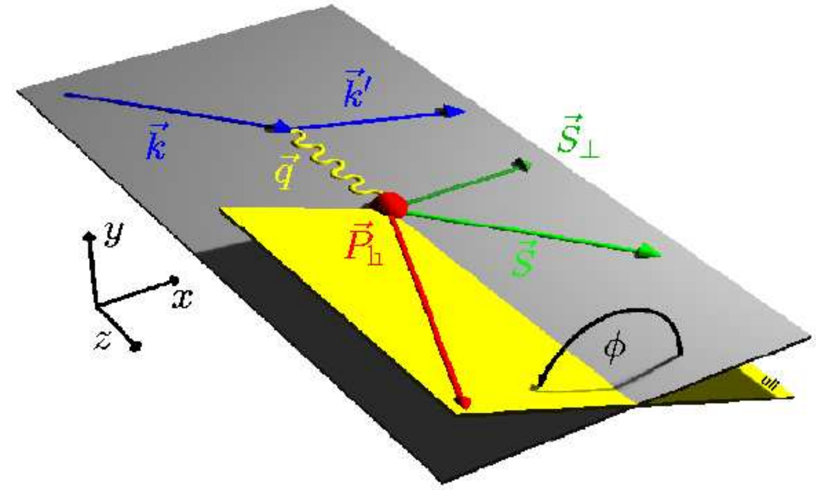
Brief summary ...

⇒ Form factors from GPDs

- $$F_1^q(t) = \int_0^1 dx\, H_q(x, \xi, t \equiv -\boldsymbol{\Delta}^2) \quad q = u, d, s, \ldots$$
- $$F_2^q(t) = \int_0^1 dx\, E_q(x, \xi, t \equiv -\boldsymbol{\Delta}^2) \quad q = u, d, s, \ldots$$

$$F^p_{1(2)}(t) = \frac{2}{3} F^u_{1(2)}(t) - \frac{1}{3} F^d_{1(2)}(t) - \frac{1}{3} F^s_{1(2)}(t)$$

Brief summary ...



⇒ **Quarks' Transverse Momentum**

Cahn ('78), Sivers ('90s), Boer, Mulders ('90s)
Brodsky, Hwang, Ji, Collins (2002)

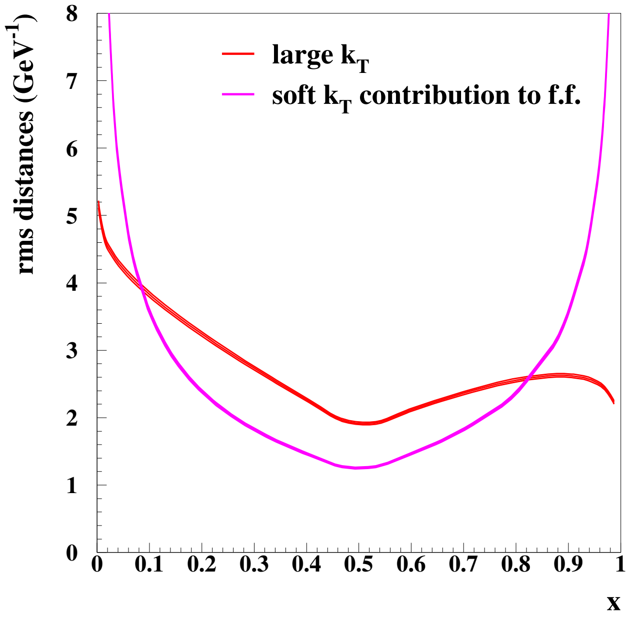
8 TMDs of which:

$$f_1(x, \mathbf{k}), h_1^\perp(x, \mathbf{k}) \quad unpolarized!!$$

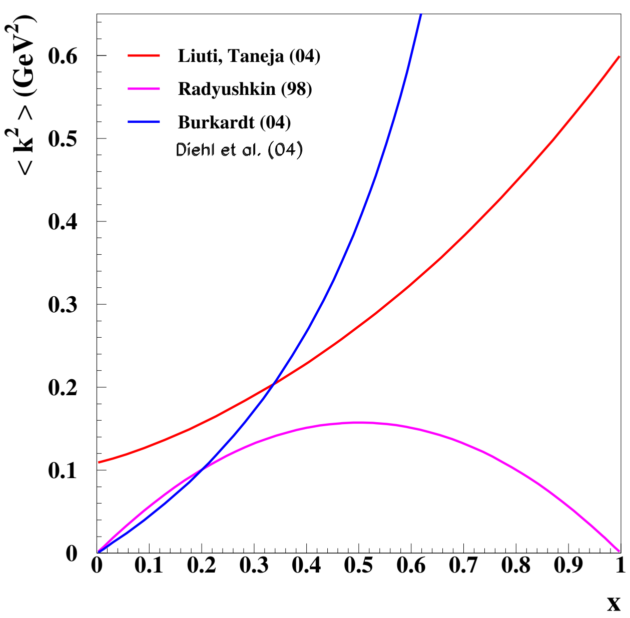
$$\int d^2\mathbf{k}\, f_1(x, \mathbf{k}) = f(x) \equiv \quad PDF$$

Constraints from the Nucleon Form Factor

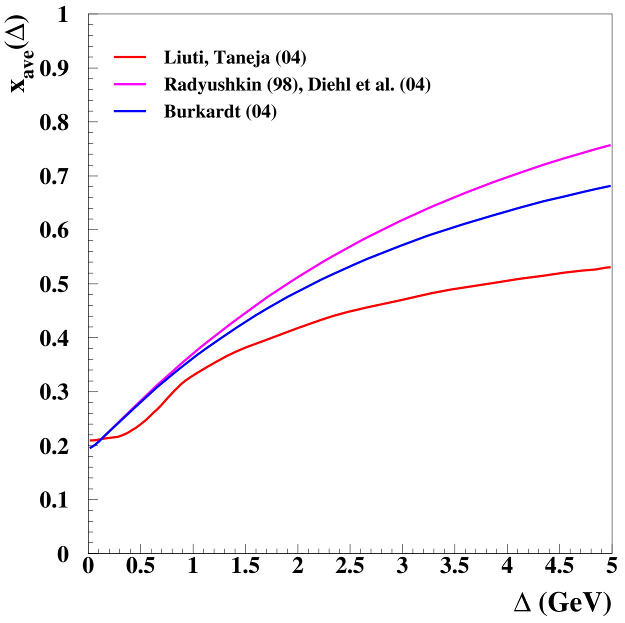
$\langle b^2(x) \rangle^{1/2}$



$\langle k_T^2(x) \rangle^{1/2}$



$\langle x(\Delta) \rangle$



S.L., S.K. Taneja, Phys. Rev. **D70**, 074019, (2004)

$\langle b^2(x) \rangle$ analysis extended and confirmed in Diehl et al., EPJ **C39**, (2005)

Role of nuclei as “laboratories”

- Coordinate Space:

  1) GPDs from Color Transparency

  2) Calculating “from scratch” Overlapping Volumes in DIS

- Momentum Space:

  1) Off-forward EMC Effect

  2) In Medium Form Factors

Understanding Nuclear Medium Modifications: Off-forward EMC Effect

S.L., S.K. Taneja, hep-ph/0504027; hep-ph/0505123

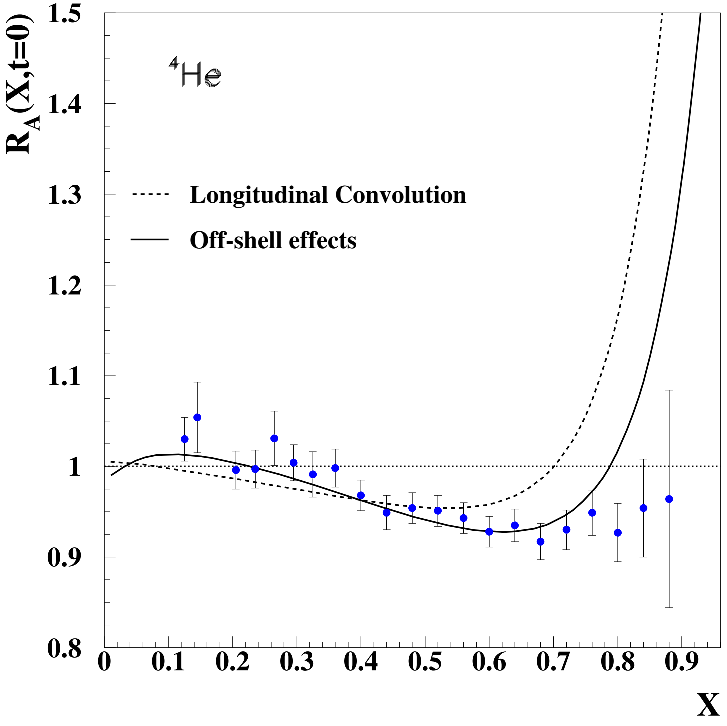
- Nuclear Shadowing and Antishadowing are a consequence of (k_T and/or k_μ^2 dependent!) parton reinteractions (S.Brodsky, A. Muller, N.Nikolaev)

  $\Rightarrow$ study of transversity in nuclei can shed light on role of ISI/FSI and rotational symmetry breaking

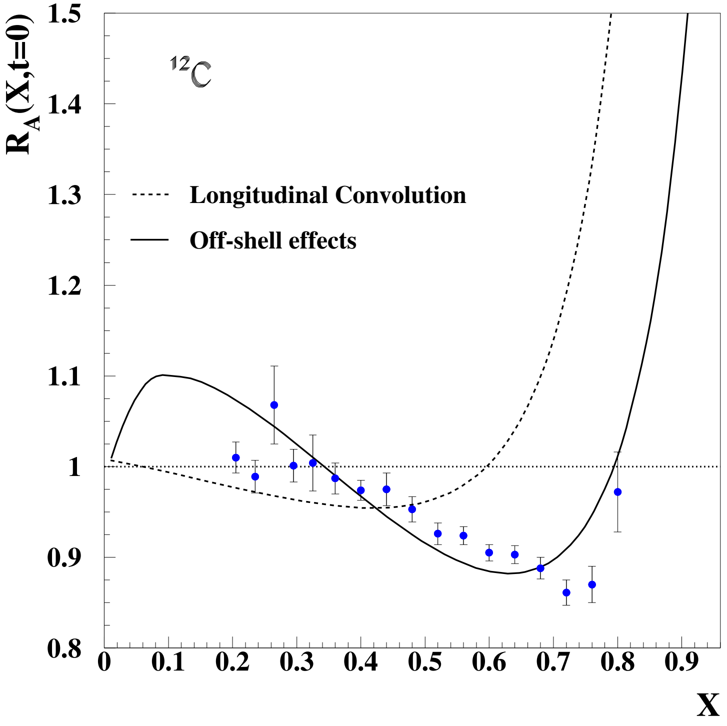
Brodsky, Schmidt, Yang, PRD (2003)

- With GPDs intrinsic momentum and size dependences can be disentangled.

Forward EMC effect: The Signal of Medium Effects in DIS

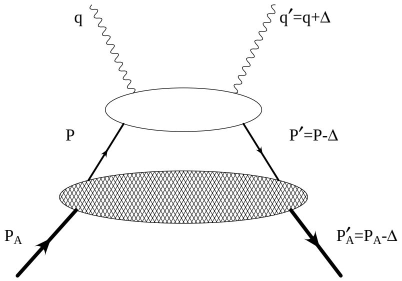


$$R_A = \frac{F_2^A(x,Q^2)}{F_2^N(x,Q^2)}$$



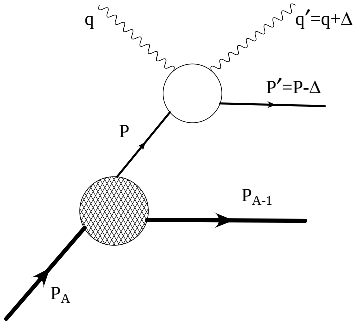
Coherent DVCS $\longrightarrow$ Off-forward EMC Effect

Coherent-DVCS



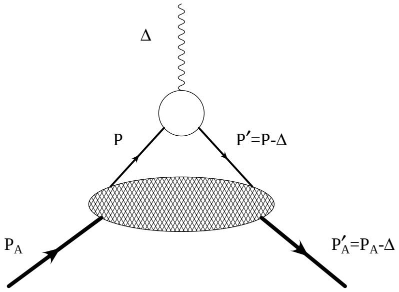
(a)

Incoherent-DVCS



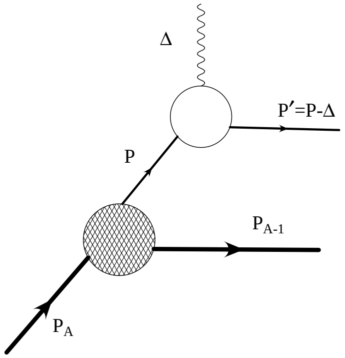
(b)

Coherent-BH



(c)

Incoherent-BH



(d)

Coherent DVCS $\rightarrow$ Off-forward EMC Effect

$$T^A_{\mu\nu}(P_A, \Delta) = \int \frac{d^4 P}{(2\pi)^4} T^N_{\mu\nu}(k, P, \Delta)\, \mathcal{M}^A(P, P_A, \Delta),$$

$$\mathcal{M}^A_{ij}(P, P_A, \Delta) = \int d^4 y\, e^{iP\cdot y} \langle P'_A | \overline{\Psi}_{A,j}(-y/2) \Psi_{A,i}(y/2) | P_A \rangle.$$

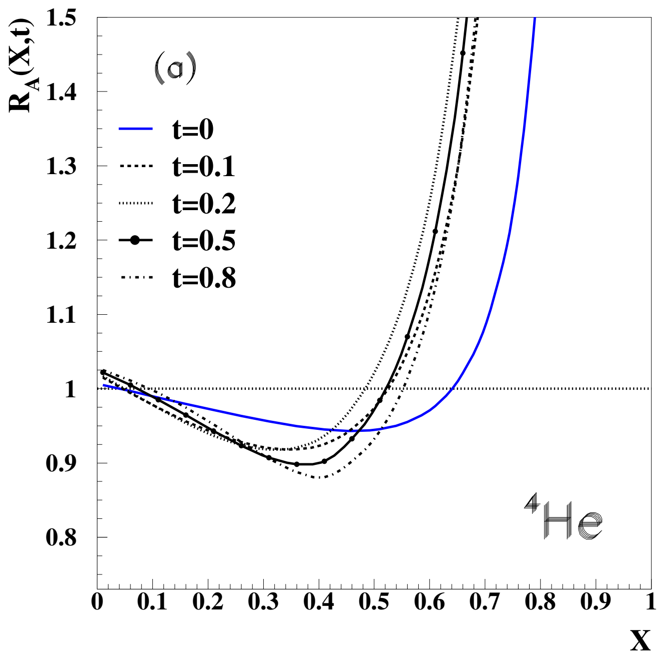
Nuclear medium modified GPD: beyond longitudinal convolution

$$
\begin{aligned}
H^A(X,\zeta,t) &= \int \frac{dP^2 dY}{2(2\pi)^3}\,\rho_A\left(P^2,(P+\Delta)^2\right) \\
&\times \sqrt{\frac{Y-\zeta}{Y}}\left[H^N_{OFF}\left(\frac{X}{Y},\frac{\zeta}{Y},t;P^2\right) - \frac{1}{4}\frac{(\zeta/Y)^2}{1-\zeta/Y}\,E^N_{OFF}\left(\frac{X}{Y},\frac{\zeta}{Y},t;P^2\right)\right]
\end{aligned}
$$

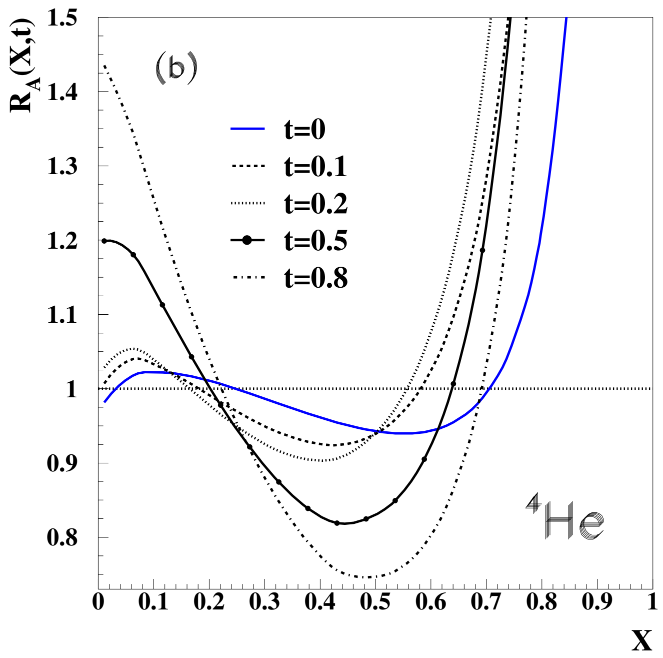
Accounting for off-shell effects...

$$
\sqrt{1-\zeta_N}\,H^N_{OFF}(X_N,\zeta_N,t;P^2) = \frac{X_N}{1-X_N}\sqrt{\frac{X_N-\zeta_N}{X_N}}\int \frac{dk^2}{2\pi}\,\widetilde{\rho}_N\left[k^2(P^2),k'^2(P^2)\right],
$$

Off-forward: X & t-dependences



On-shell nucleons



Off-shell nucleons

$$R_A = [H_A(X,t)/F_A(t)]/[H_N(X,t)/F_N(t)]$$

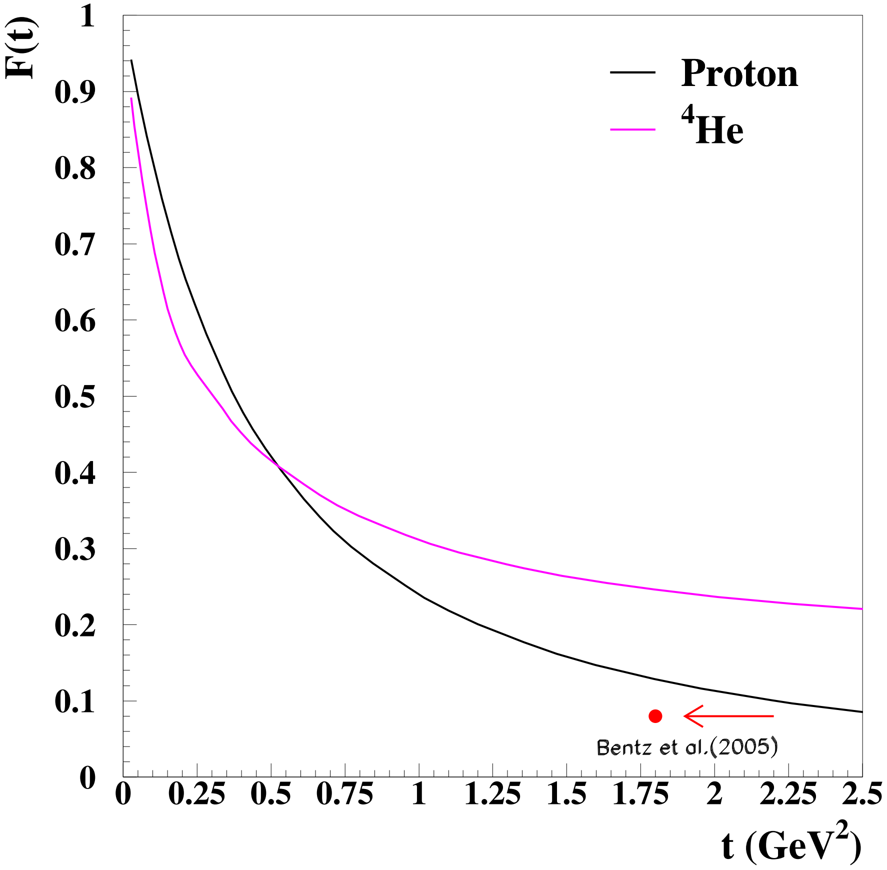
Form Factor in Nuclei

$$\boxed{F_A(t) = \int_0^A dx H_A(x,t)}$$

$$F_A(t) = F_A^{point}(t) F_N(t) \qquad \Rightarrow \text{Longitudinal Convolution}$$

$$F_A(t) = \int_X^A dY \int dP^2 \rho_A(Y,t;P^2) H_N\left(\frac{X}{Y}, t; P^2\right) \qquad \Rightarrow \text{Off} - \text{shell Particles}$$

Form Factor in Nuclei



There is more: GPDs provide model independent insight!

Example: Color Transparency

S.L., S.K. Taneja, Phys. Rev. **D70**, 074019, (2004)

$$T_A(\Delta^2) = \frac{\left[\int_0^1 dx H_A(x,\Delta)\right]^2}{\left[\int_0^1 dx H(x,\Delta)\right]^2}$$

$$H_A(x,\Delta) = \int_0^{b_{max}(A)} db\, b\, q(x,b) J_0(b\Delta)$$

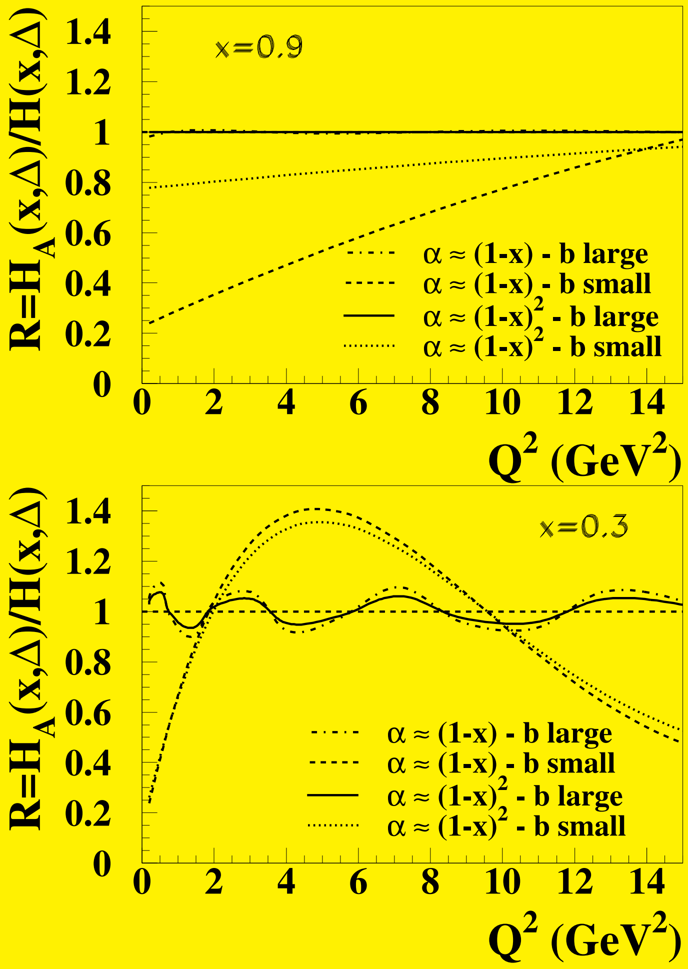
$b_{max}(A)$ = size of the filter given by a square function

$\Rightarrow$ By assuming: $q(x,b) = A(x)\exp(-\alpha(x)\, b)$

i) $\alpha \propto (1-x)/x \Rightarrow$ soft in $k_\perp$

ii) $\alpha \propto (1-x)^2/x \Rightarrow$ hard in $k_\perp$

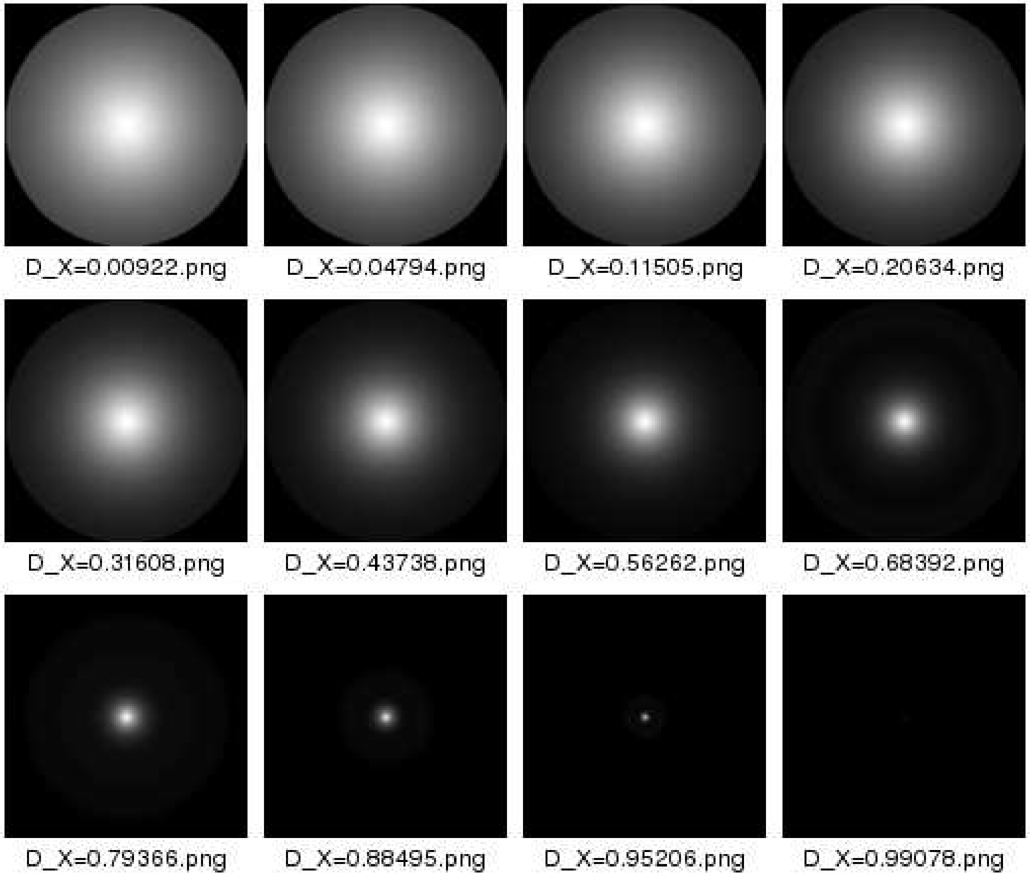
predict both damping and oscillations of the transparency ratio



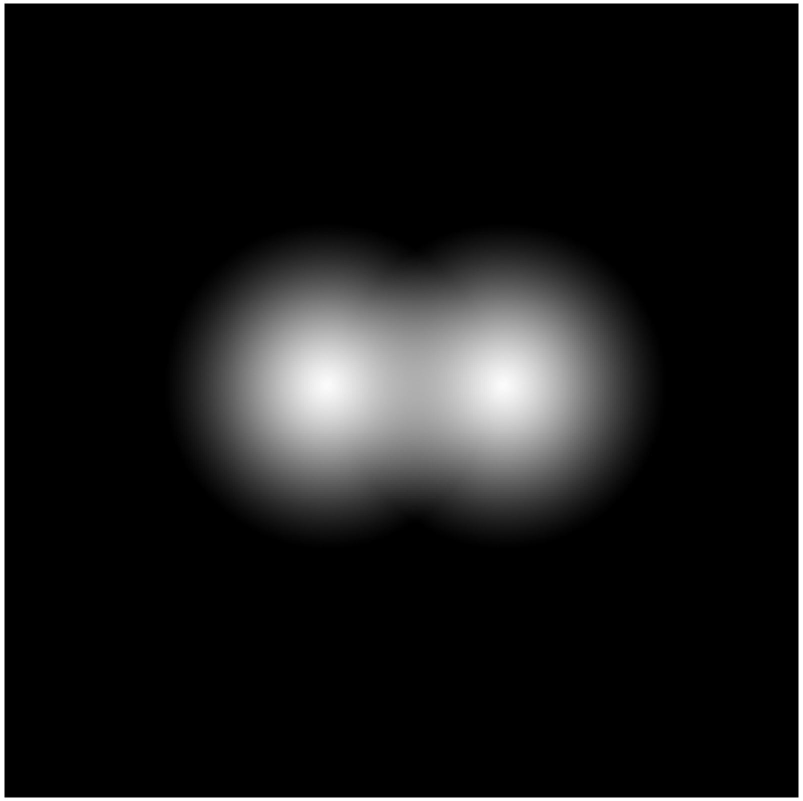
$$
\begin{aligned}
R &= 1 - \exp(-\alpha\, b_{max})\,[\alpha\, b_{max} J_0(\Delta b_{max}) \\
&+ \cos(\Delta b_{max})]
\end{aligned}
$$

Quantitative analysis on its way (with H. Gao)

Spatial dependence in nuclei: overlapping volumes

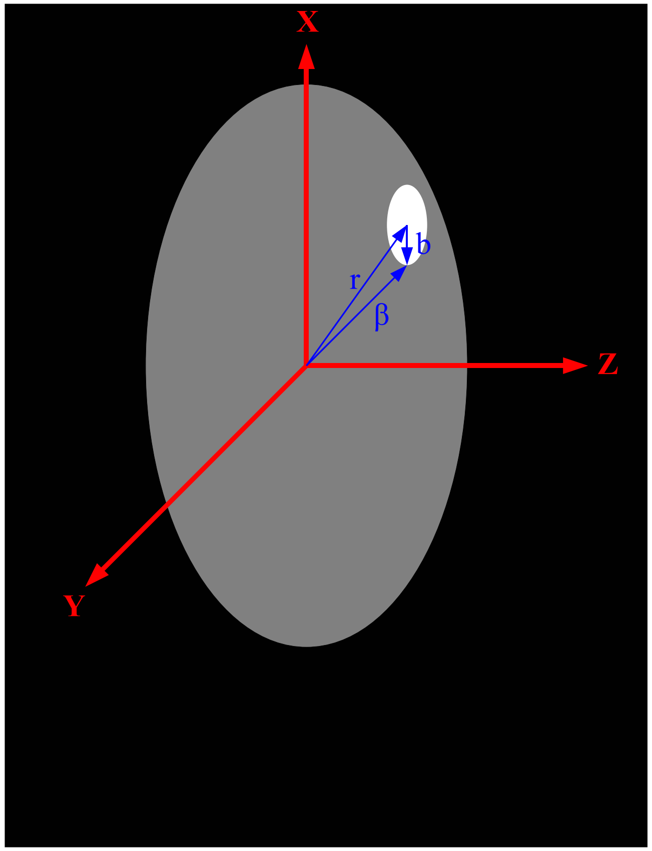


Single Nucleon



... in a nucleus

Impact Parameter Dependent Nuclear Parton Distributions



$$q_A(X,\mathbf{r}) = \int_X^A dY \int d^2\mathbf{b}\, \widetilde{\rho}_A(Y,\mathbf{r}-\mathbf{b})\, q_N(X/Y,\mathbf{b})$$

$$\begin{aligned} X &= k^+/P^+ \\ Y &= P^+/P_A^+ \\ \beta &= \mathbf{r} - \mathbf{b} \end{aligned}$$

$$q_N(X/Y, \mathbf{b}) \quad \text{“in medium}'' \text{ nuclear GPD}$$

$$\widetilde{\rho}_A(Y, \beta) = \frac{2}{\pi B^2} f_A(Y) h_A(Y, \beta/B)$$

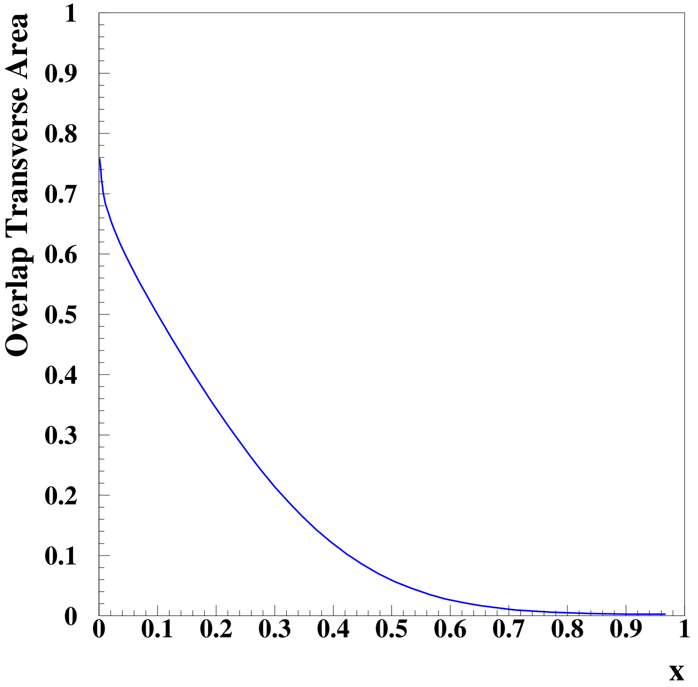
Transverse "Area Overlap" for a hard nuclear process

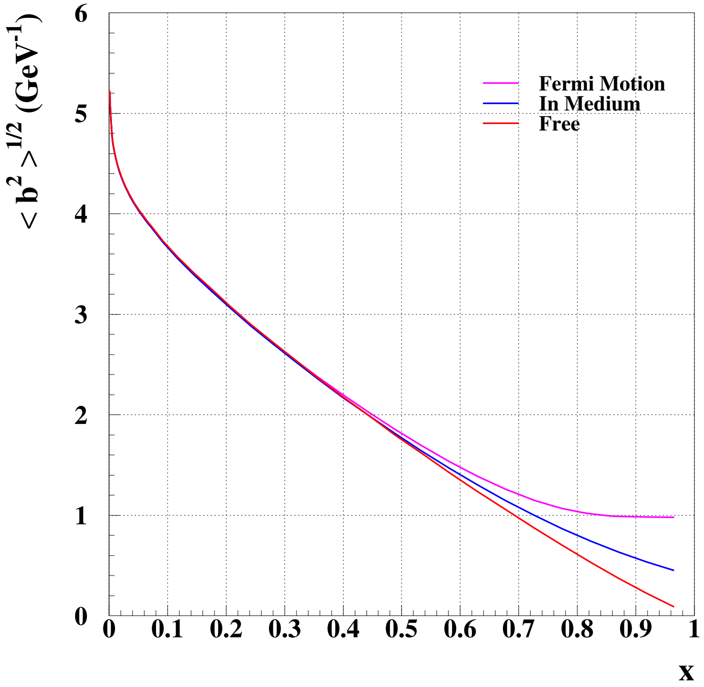
$$\langle b_A^2(X)\rangle = \frac{1}{q_A(X)}\left[\int_X^A dY\,\langle b_N^2(X/Y)\rangle q_N(X/Y) f_A(Y) + \int_X^A dY\,\langle \beta^2(Y)\rangle q_N(X/Y) f_A(Y)\right].$$

$$A_{op} = \frac{\langle b_N^2(X)\rangle}{\langle b_A^2(X)\rangle} = \frac{1}{1+\frac{\langle \beta^2(X)\rangle}{\langle b_N^2(X)\rangle}}$$

Overlap volume previously calculated with "semi-empirical" models!

Preliminary Results





Transverse "Area Overlap"

Impact Parameter for in medium proton

Overall (integral) increase of $\approx 6\%$ with respect to free proton!

Conclusions

• GPDs provide a whole new dimension for studying transverse d.o.f in hadrons through the interplay between k_T and b

• More constraints on GPDs from nuclei ...

• ... and at the same time: New insight on nuclear medium modifications from GPDs

• Our exploratory study includes both k_T and b dependent observables, vast phenomenology!

• Diquark Model + Color Transparency, S.L. and S.K. Taneja, Phys. Rev. **D70**, 074019, (2004); Off-forward EMC Effect, S.L. and S.K. Taneja, hep-ph/0504027, to be published in Phys. Rev. **C**; Coherent vs. Incoherent Scattering, S.L. and S.K. Taneja, hep-ph/0505123.

Outlook

- More systematic studies are needed:

  - Treatment of Longitudinal Distances $\Rightarrow$ modeling dependence on skewedness ζ

  - Q^2 Evolution of $\langle b^2 \rangle$, $\langle k_T \rangle$.

- Extend studies to other GPDS: H_T E_T (connected to transversity) and their "coordinate space" counterparts.

- Extend studies to time-like region.

Interpretations of results

Nuclear functions are peaked around $Y = 1$, and $P^2 = M^2$

$H^A(X,t) \approx A H_N(X/\langle Y_1^A(t)\rangle) < A H_N(X)$

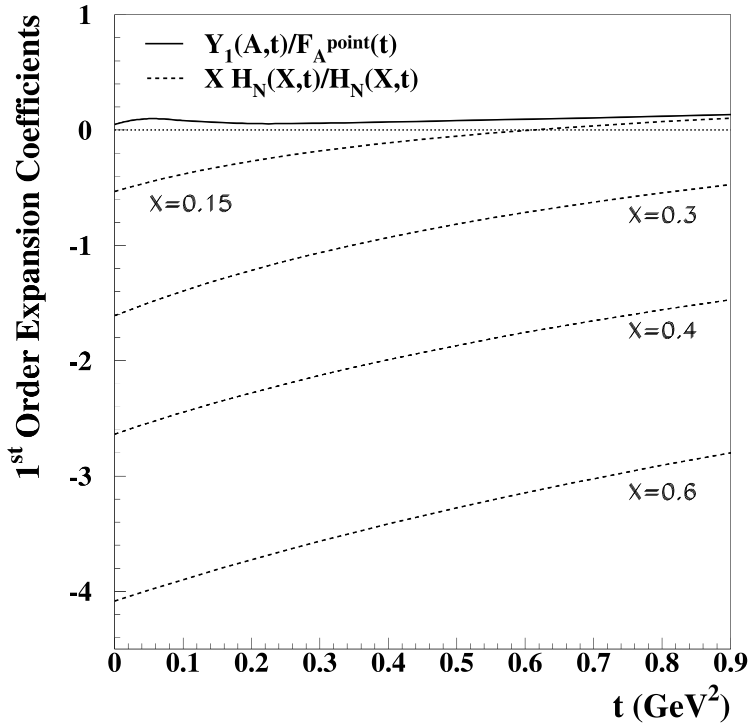
t-dependent "dynamical" X-rescaling

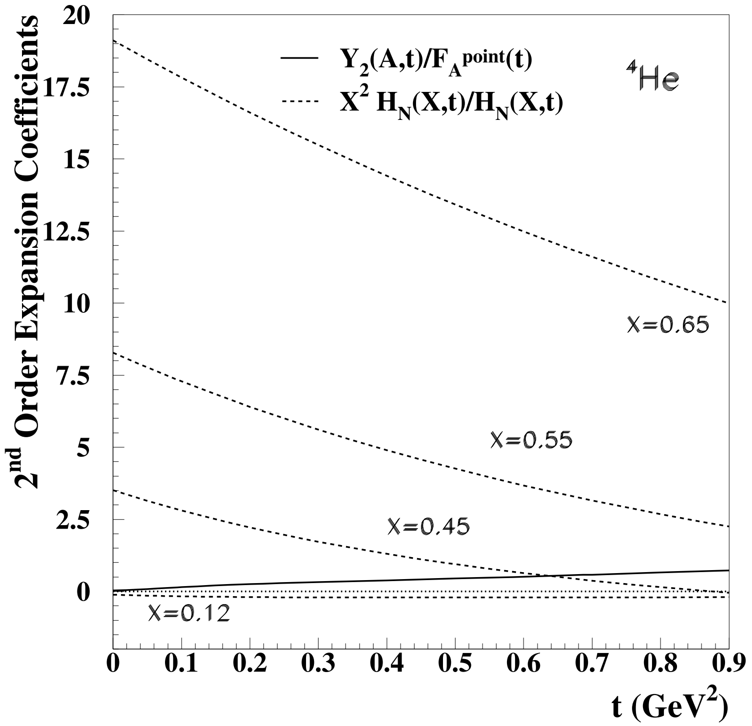
$\langle Y_1^A(t)\rangle = \int_0^A dY \, \rho_A(Y,t)(1-Y) \approx \frac{\langle E(t)\rangle_A/M}{F^{A,point}(t)}$

$\langle E(t)\rangle_A$ is a "t-dependent nuclear binding"

Role of nucleon off-shellness is same as in forward case $\Rightarrow$ it affects the k_T dependence !

$$
\begin{aligned}
F^{A,point}(t) &= \int_0^A dY\, \rho_A(Y,t) \\
\langle Y_1(A,t)\rangle &= \int_0^A dY\, \rho_A(Y,t)(1-Y) \\
\langle Y_2(A,t)\rangle &= \int_0^A dY\, \rho_A(Y,t)(1-Y)^2,
\end{aligned}
$$


1st Order Expansion Coefficients
Y1(A,t)/FApoint(t)
X HN(X,t)/HN(X,t)
X=0.15
X=0.3
X=0.4
X=0.6
t (GeV2)


2nd Order Expansion Coefficients
Y2(A,t)/FApoint(t)
X2 HN(X,t)/HN(X,t)
4He
X=0.65
X=0.55
X=0.45
X=0.12
t (GeV2)