# Parton Distributions in Nuclei

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**Les Rencontres de Physique de la Vallee D'Aoste**

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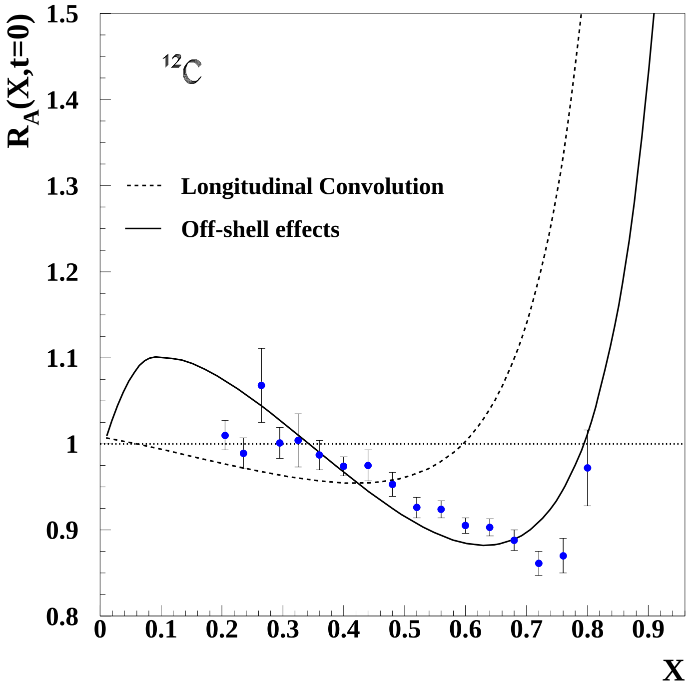
## Motivation

⇒ … "a necessary evil" … (*Jon Pumplin, DIS 2005*)




…encountered *e.g.* in:

- determination of $sin^2\theta_W$ from CCFR data
- quark gluon plasma searches
- …

## What we do know about PDFs in Nuclei

- 1983 – discovery of the EMC effect: $20\%$ deviations of nuclear $F_2^A(x, Q^2)$ from free nucleon one.

- Through 1980's and 90's – measurements of different kinematical regions
  - low Bjorken x: shadowing and anti-shadowing (NMC, BCDMS, E665)
  - A-dependence (SLAC, NMC, E665, BCDMS, HERMES)
  - isospin dependence (NMC)
  - $Q^2$ dependence (HERMES)
  - separation of valence, sea, and gluon distributions (E772,E866)

## Open Questions

- Universality: $F_3^A$ vs. $F_2^A$
- Isospin dependence
- $F_L^A$
- Gluons are poorly known in whole $x$ range
- **Meaning of all this in terms of QCD**

## Relevance for QCD: A Missing Piece of the Spin Puzzle

In order to understand the role of orbital angular momentum in the proton one needs to understand transverse motion in hadrons and its relation to Final State Interactions (problem first studied within QCD, perhaps, by Ellis, Furmanski, Petronzio, Efremov and Radyushkin, '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, hadro-production (DY, $\Lambda$, ...)

**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?

$\rightarrow$ Initial/Final State Interactions?

$\rightarrow$ Confinement/Hadronization?

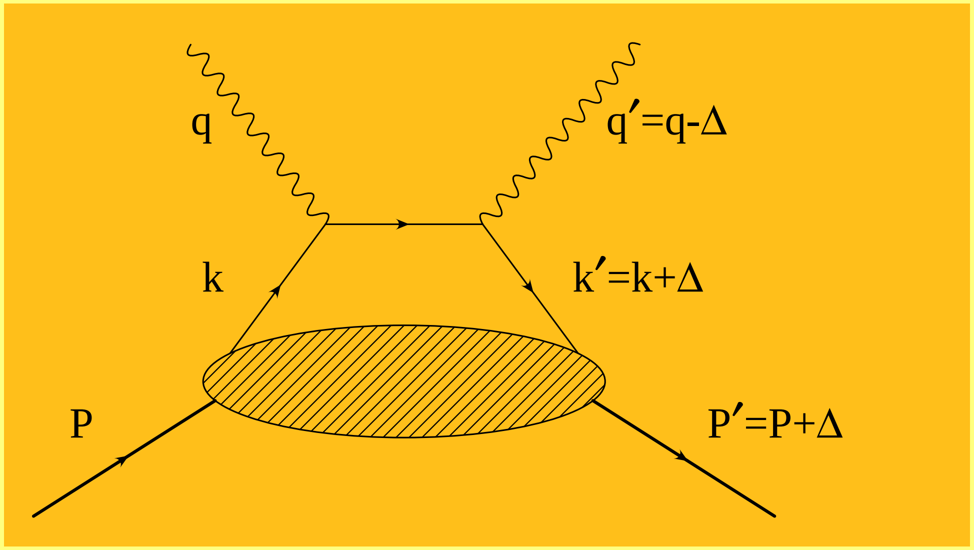
$\rightarrow$ Or else ... ?

Brief summary ...

## ⇒ Phenomenology

**(1)** GPDs are most easily visualized as the soft parts in the amplitude for $e.g.$ DVCS

$$\mathcal{A} \propto \int_{-1}^{1} dx \left[ \frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right] \overline{U}(P') \left\{ H(x, \xi, t)\gamma^{+} + E(x, \xi, t)\frac{-i}{2M}\sigma^{+\rho}\Delta_{\rho} \right\} U(P)$$



Brief summary ...

## ⇒ Form factors from GPDs

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

$$F_{1(2)}^p(t) = \frac{2}{3}F_{1(2)}^u(t) - \frac{1}{3}F_{1(2)}^d(t) - \frac{1}{3}F_{1(2)}^s(t)$$

$$F_{1(2)}^n(t) = -\frac{1}{3}F_{1(2)}^u(t) + \frac{2}{3}F_{1(2)}^d(t) - \frac{1}{3}F_{1(2)}^s(t)$$

Brief summary ...

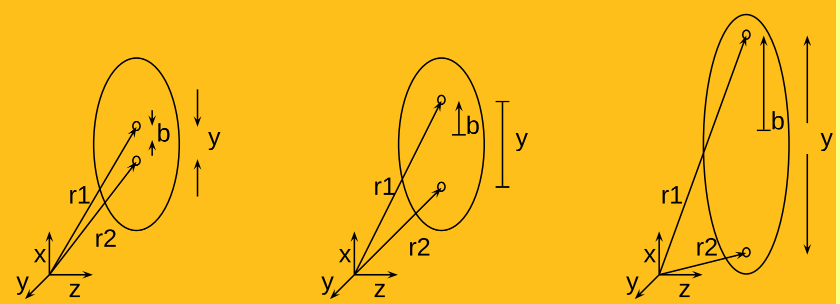
## ⇒ DIS Structure Functions from GPDs

$$q(x) \quad = \quad H_q(x,0,0) \;\; q = u, d, s, \ldots$$

## Brief summary ...

### ⇒ **Quarks' Transverse Location**

Soper (1977), Ralston and Pire (2000),
Burkardt (2000), Diehl (2003)

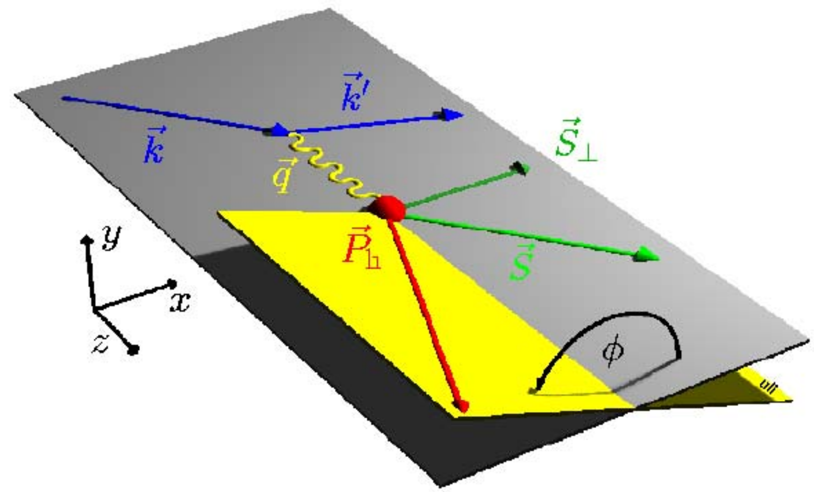


(a) (b) (c)

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

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

Brief summary ...




⇒ **Quarks' Transverse Momentum**

Cahn ('78), Sivers ('90s), Boer, Mulders ('90s)

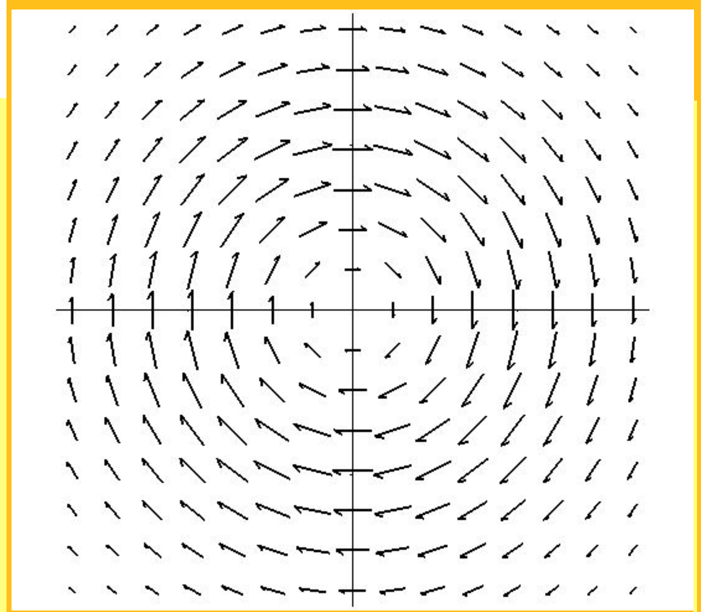
Brodsky, Hwang, Ji, Collins (2002)

8 TMDs of which:

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

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

Brief summary ...



Burkardt, PRD **72**, 094020 (2005)

⇒ **Relation between Quarks' Transverse Momentum and Transverse Location**

Burkardt (2004), Diehl and Hägler (2005), Liuti and Taneja (2004)

$$f(x,\mathbf{k}) = \int d^2\mathbf{b} \int d^2\mathbf{b}'\, e^{i\mathbf{k}\cdot(\mathbf{b}-\mathbf{b}')}\, q(x,\mathbf{b},\mathbf{b}') \;\rightarrow \langle \mathbf{k}^2(x)\rangle = \mathcal{N}_k \int d^2\mathbf{k}\, f(x,\mathbf{k})\, \mathbf{k}^2$$

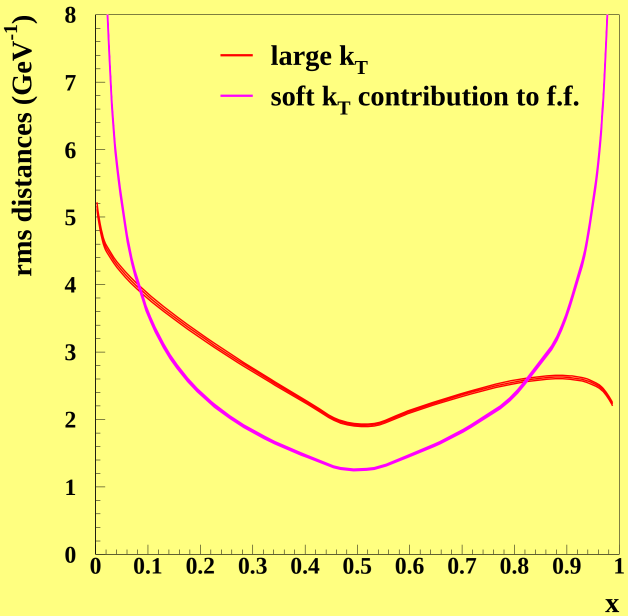
Liuti and Taneja PRD **70** 074019 (2004)

## Brief summary ...

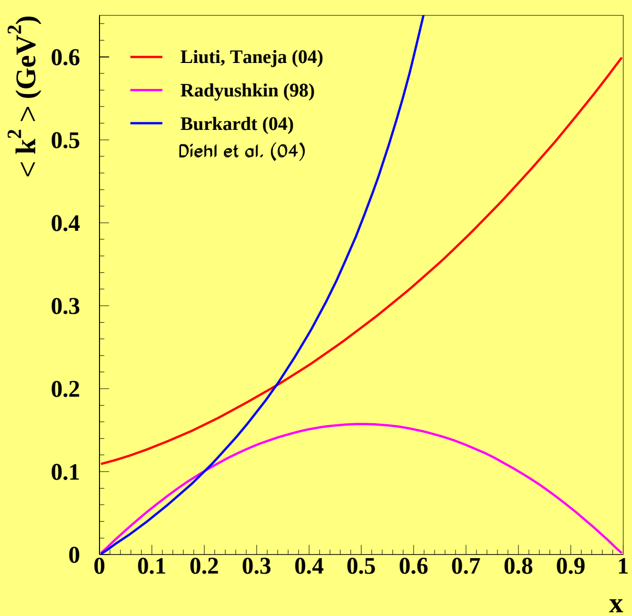
**⇒ Phenomenology**

**(2)** Constraints on $\xi = 0$ GPDs from Nucleon Form Factors and PDFs

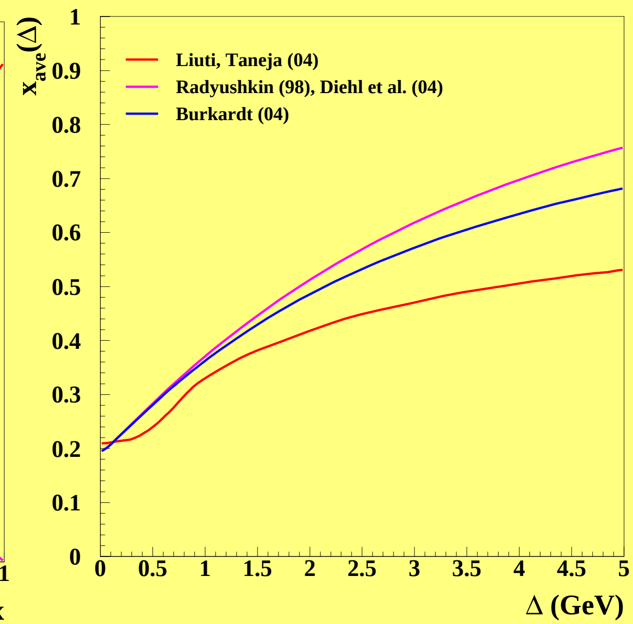
$\langle b^2(x) \rangle^{1/2}$




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




$\langle x(\Delta) \rangle$




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)

## Understanding Nuclear Medium Modifications: Off-forward EMC Effect

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

- Extend logics behind forward EMC effect to the off-forward case ⇒ Few important modifications

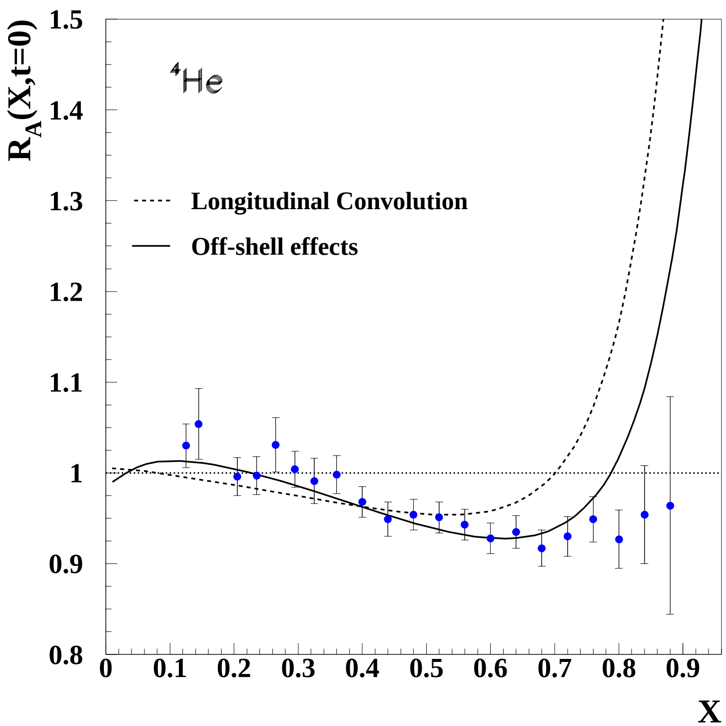
### The forward EMC effect

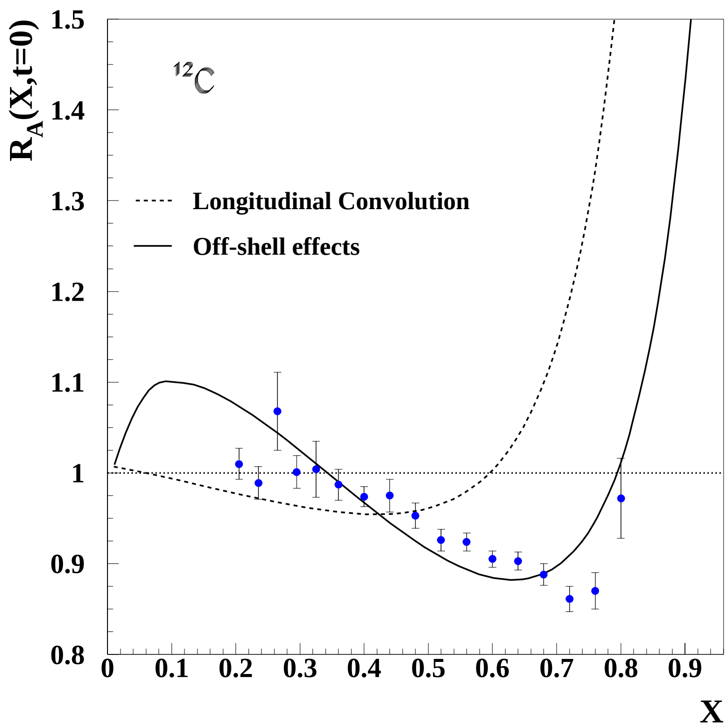
Basic idea: transverse degrees of freedom/particle off-shellness do not decouple naively from LC variables, but play an explicit role in deep inelastic scattering from nuclei, at leading order.

(1) $k_T$ and/or $k_\mu^2$dependent parton reinteractions, involving the exchange of Pomeron, Odderon, and other Reggeon exchanges, generate nuclear shadowing and antishadowing at $x_{Bj} \leq 0.2$ (Brodsky, Schmidt and Yang, Muller, N.Nikolaev)
(⇒ study of transversity in nuclei can shed light on role of ISI/FSI and rotational symmetry breaking)

(2) "Active $k_T$" effects enhance the relatively small binding correction and produce further "kinematical type" $x_{Bj}$-rescaling at $x \geq 0.2$.

## Forward EMC effect: The Signal of Medium Effects in DIS

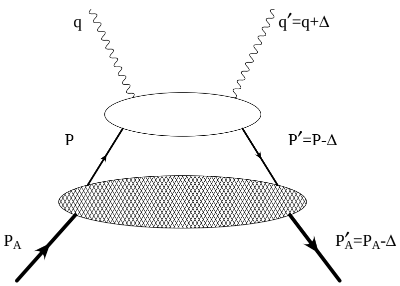



$$R_A = \frac{F_2^A(x,Q^2)}{F_2^N(x,Q^2)}$$

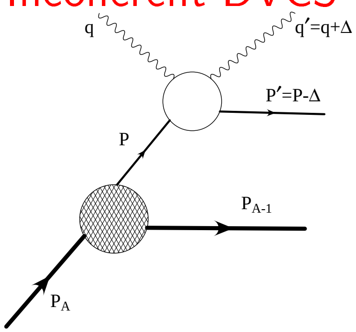
## Off-forward EMC Effect $\rightarrow$ Coherent DVCS

Coherent-DVCS



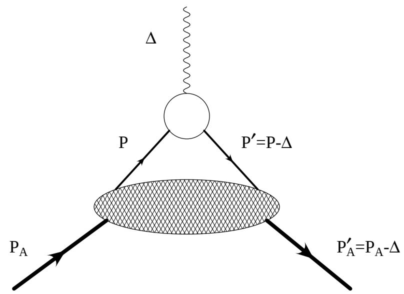

(a)

Incoherent-DVCS



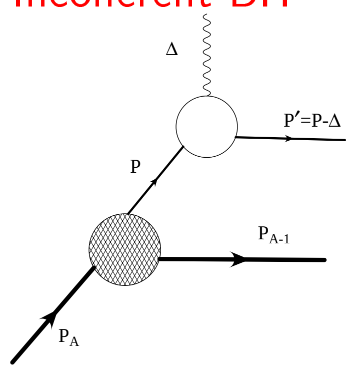

(b)

Coherent-BH




(c)

Incoherent-BH




(d)

## Off-forward EMC Effect $\rightarrow$ Spin 0 Nuclei

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

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

## Modified nucleon GPD: Model

**Large $X$, $k_X^2 \equiv M_X^2$: two component model**

$$\rho_q[k^2(P^2), k'^2(P^2), k_X^2)] \quad \propto \quad \mathrm{Tr}\{\gamma^+ \mathcal{M}\} = \frac{g(k^2)}{D(x,\mathbf{k})} \frac{g(k'^2)}{D(x,\mathbf{k}')}$$

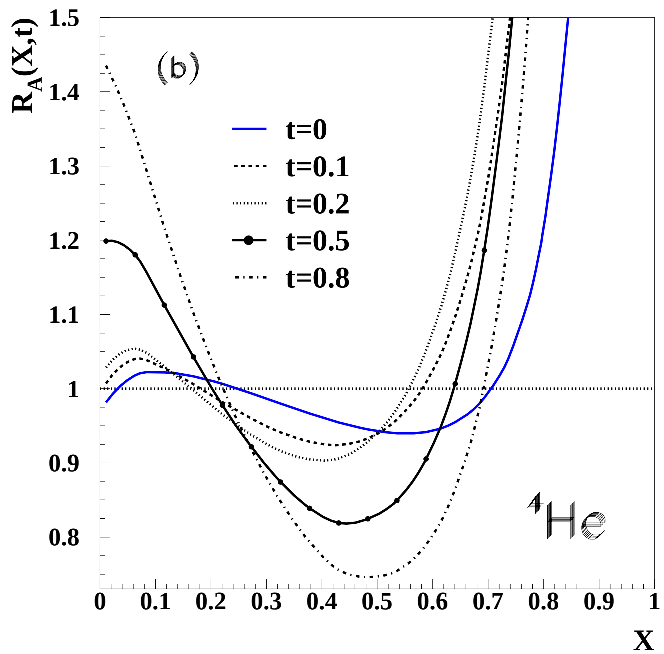
**Low $X$, $k_X^2 \propto 1/X$ : t-channel exchanges**

$$\rho_q[k^2(P^2), k'^2(P^2), k_X^2)] \quad \propto \quad T_{qN}(t \neq 0);$$

- We extend the shadowing/antishadowing model using the analitic properties of $T_{qN}$, to the $t \neq 0$ case. Model valid at $\zeta = 0$.

- $T_{qN}$ is subsequently inserted, as usual, in the Glauber series

# Off-forward: X & t-dependences




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

## Form Factor in Nuclei

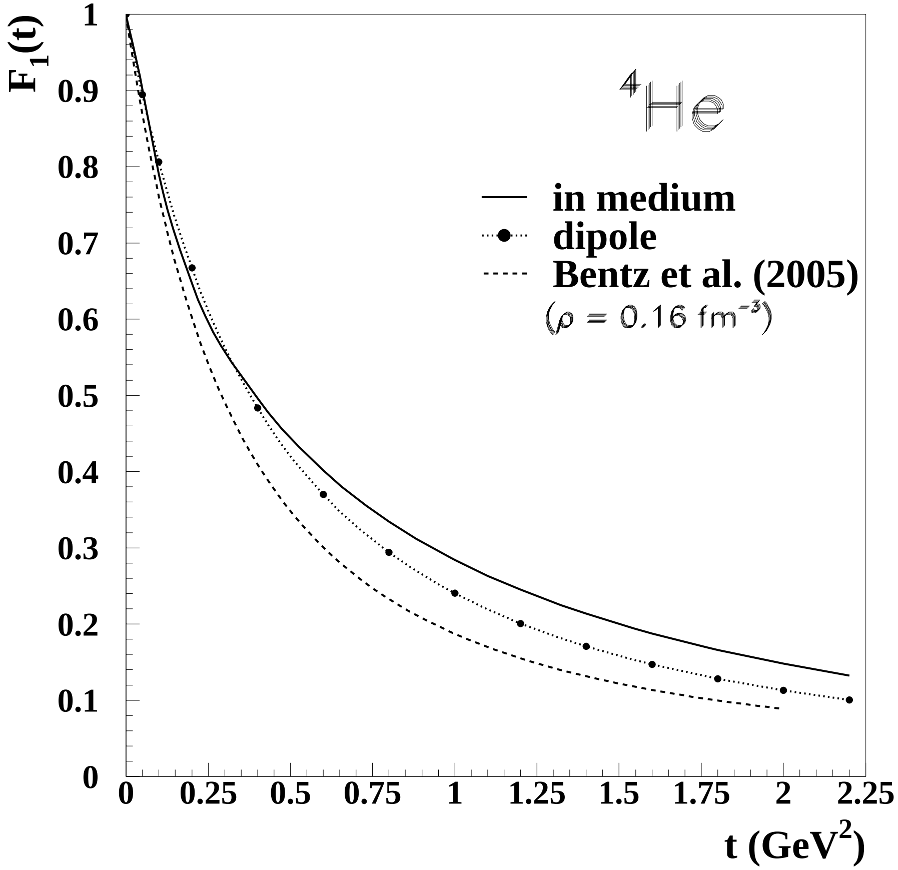
$$F_A(t) = \int_0^A dx H_A(x,t)$$

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

$$F_A(t) = \int_X^A dY \int dP^2 \rho_A(Y,t;P^2) H_N\left(\frac{X}{Y}, t; P^2\right)$$ $\Rightarrow$ Active $k_T$

$$\hat{F}_1^N(t) = \left[\frac{F^A(t)}{F_{LC}^A(t)}\right] F_1^N(t)$$

# 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)

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

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

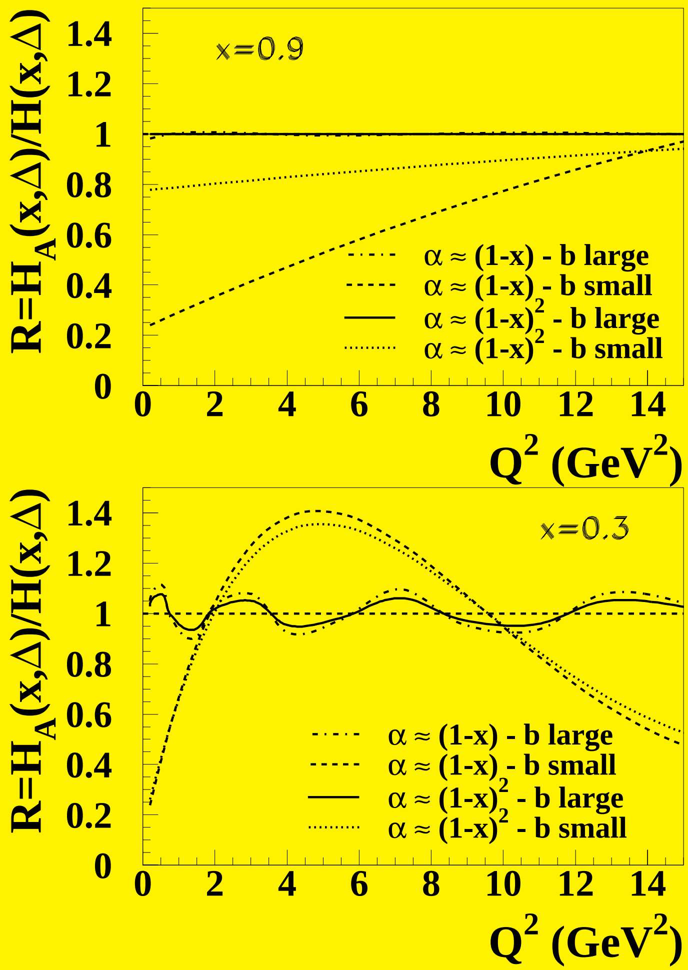
$b_{max}(A)$ = size of the filter given by a square function

$\Rightarrow$ 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 $k_\perp$

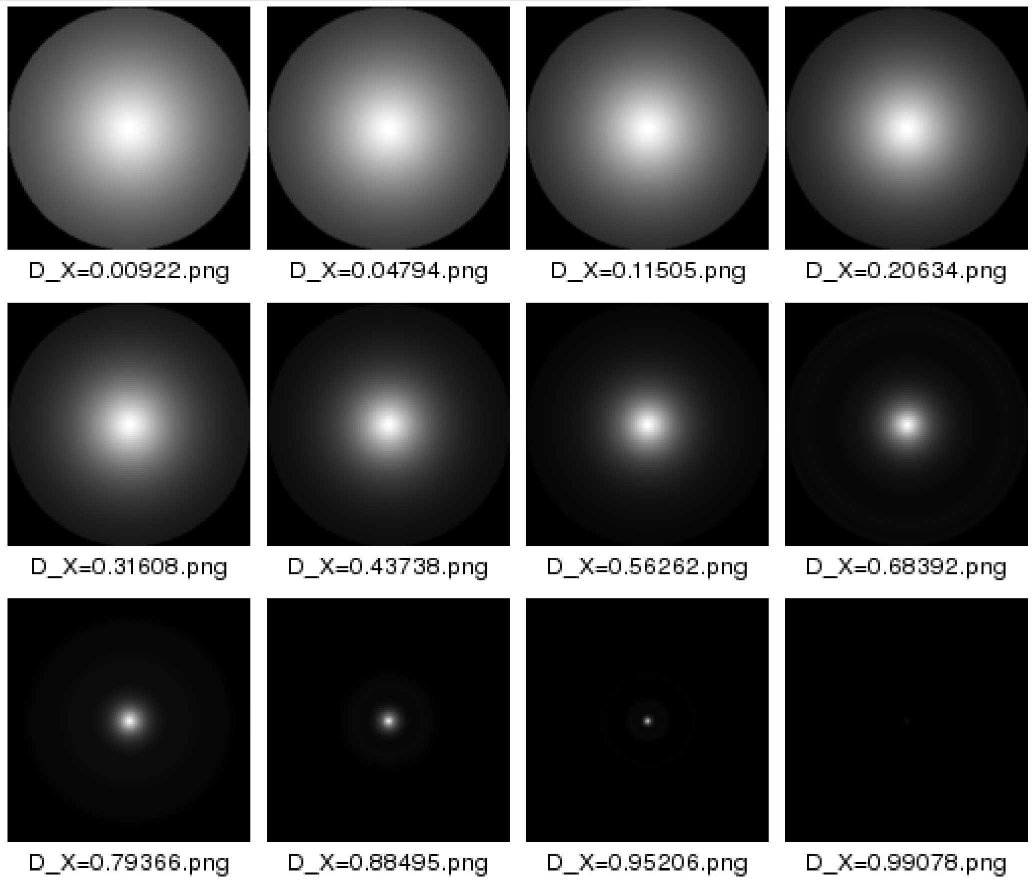
predict both damping and oscillations of the transparency ratio




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

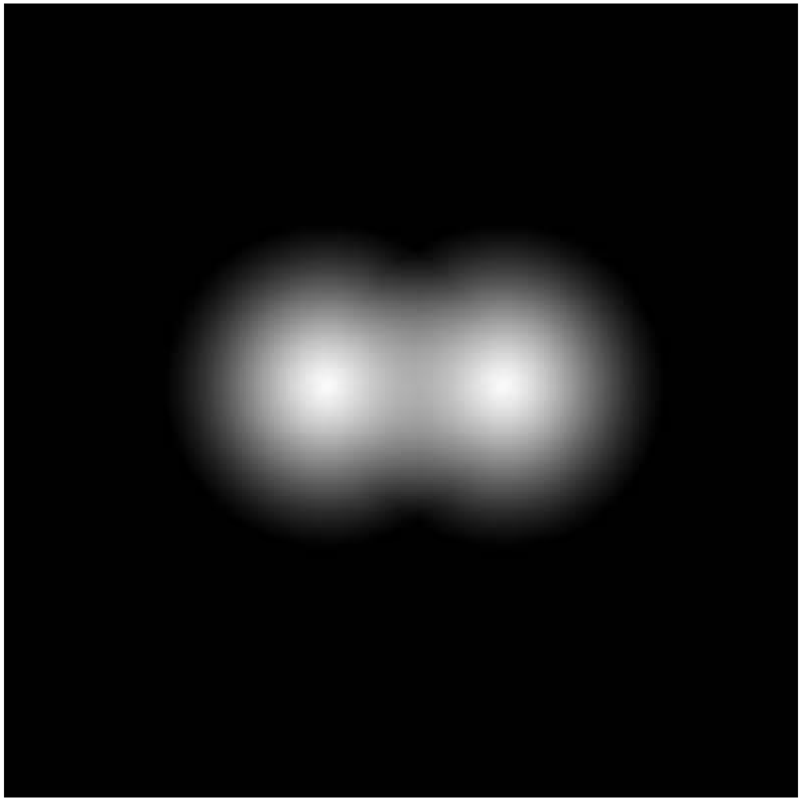
Quantitative analysis on its way
(with D. Dutta & H. Gao)

## Spatial dependence in nuclei: overlapping volumes

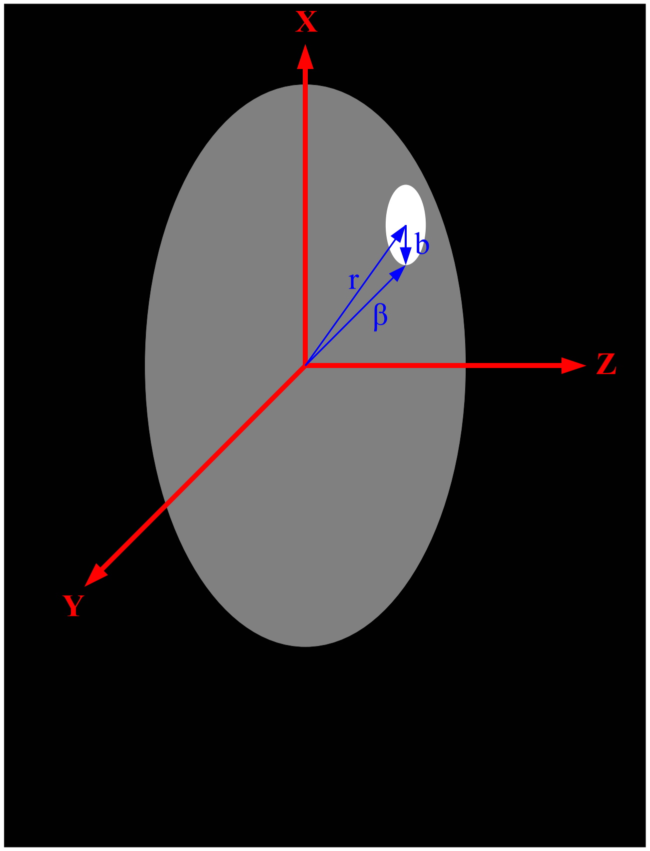



**Single Nucleon**

**... in a nucleus**



# Impact Parameter Dependent Nuclear Parton Distributions




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

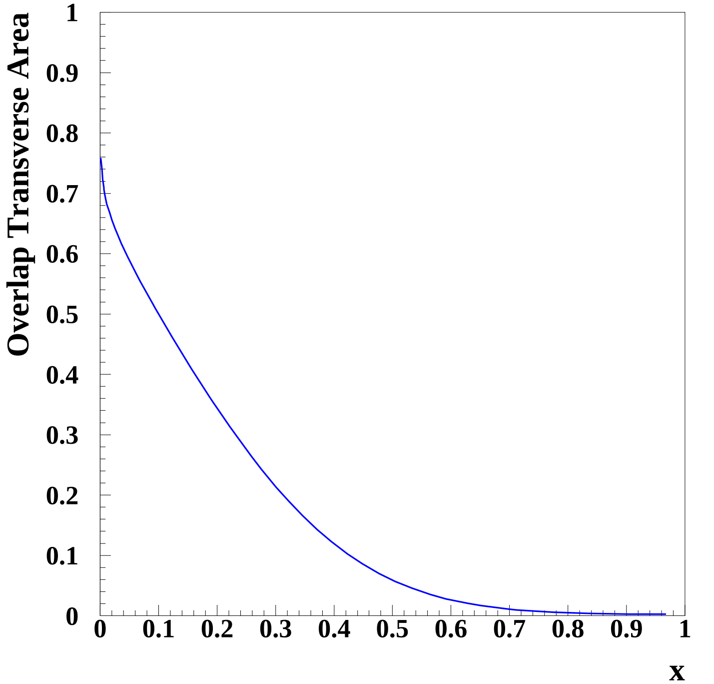
## Transverse "Area Overlap" for a hard nuclear process

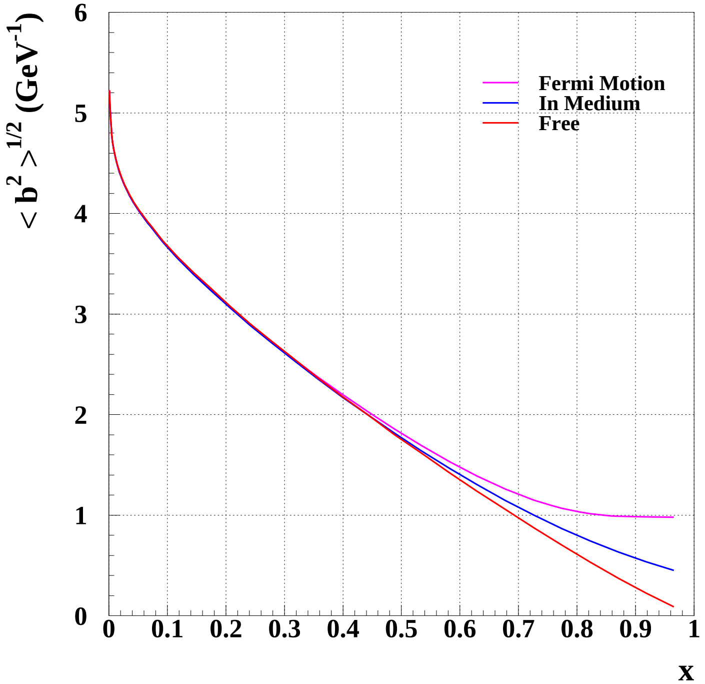
$$\langle b_A^2(X)\rangle = \frac{1}{q_A(X)}\left[\int_X^A dY\,\langle b_N^2(X/Y)\rangle q_N(X/Y) f_A(Y) + \int_X^A dY\,\langle \beta^2(Y)\rangle q_N(X/Y) f_A(Y)\right].$$

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

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

## Preliminary Results



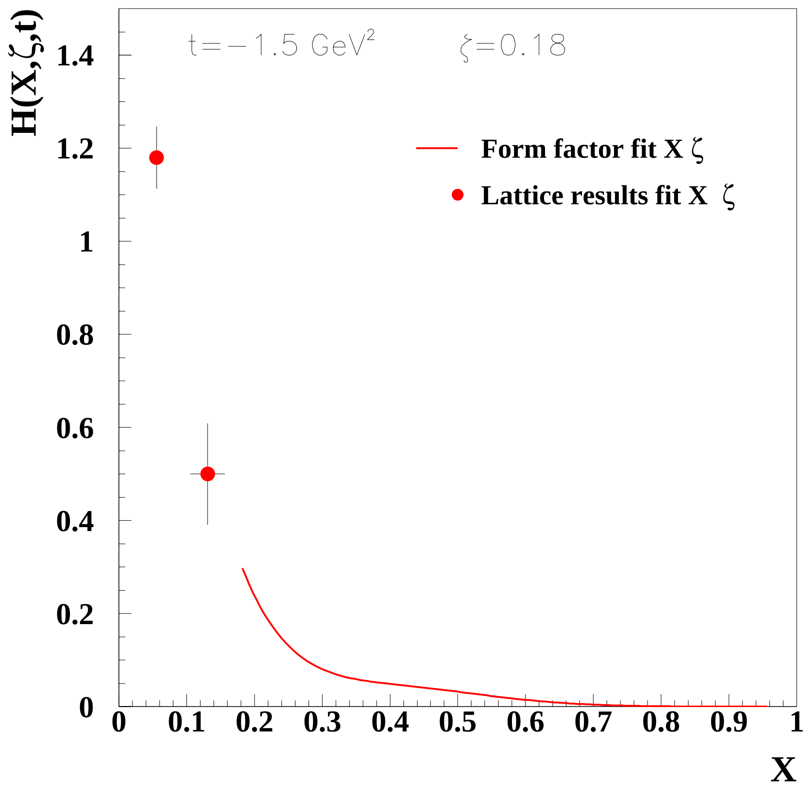




**Transverse "Area Overlap"**

**Impact Parameter for in medium proton**

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

# New Parameterization at $\zeta \neq 0$!



## 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; In medium Form factors, S.L., hep-ph/0601125.

## Outlook

- More systematic studies are needed:

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

  - $Q^2$ 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 $P^2 = M^2$

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

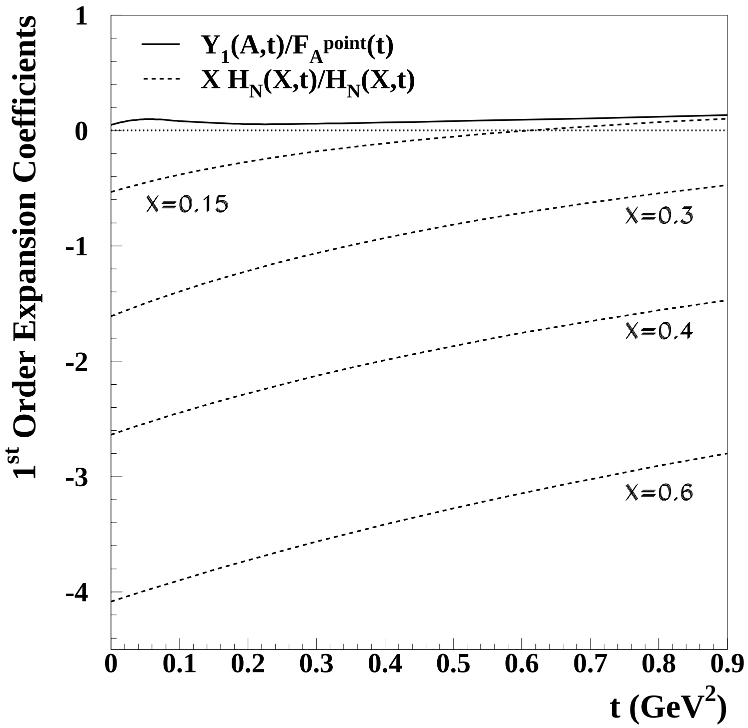
t-dependent "dynamical" X-rescaling

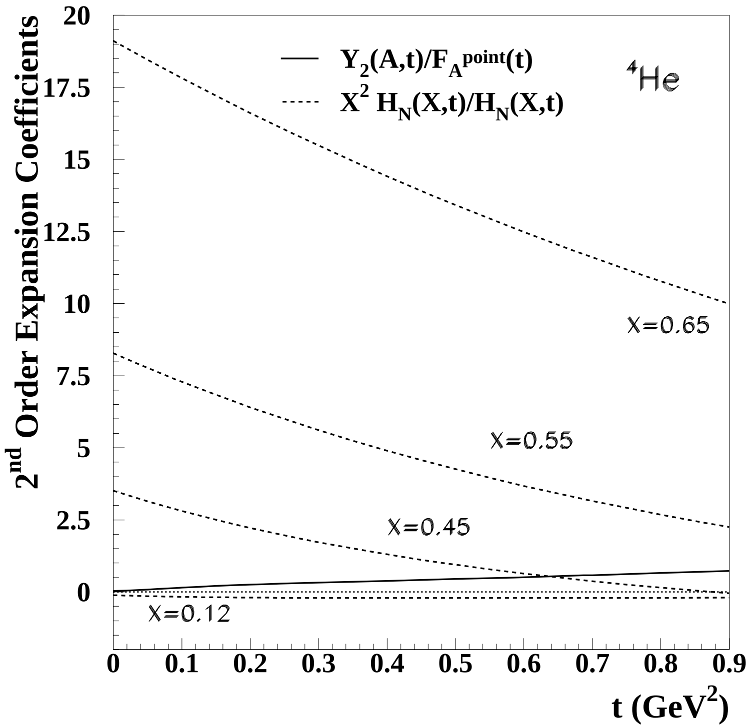
$$\langle Y_1^A(t)\rangle = \int_0^A dY\, \rho_A(Y,t)(1-Y) \approx \frac{\langle E(t)\rangle_A/M}{F^{A,point}(t)}$$

$\langle E(t)\rangle_A$ 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)