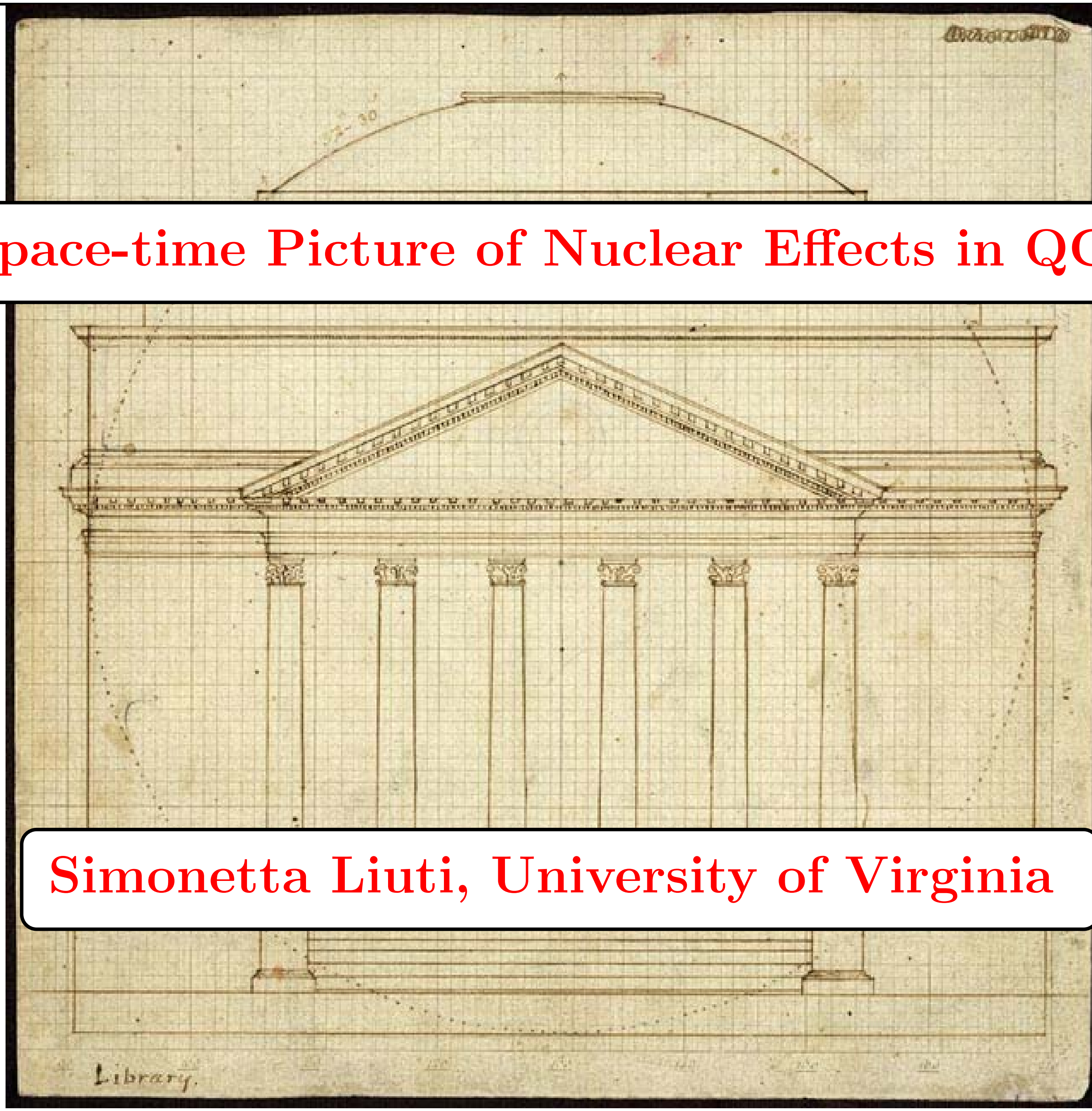
Space-time Picture of Nuclear Effects in QCD



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Motivation: Why Nuclei?

To understand Transverse Motion in hadrons – and its *possible* relation to Confinement and/or Final State Interactions – phenomenology needs to address the connection between:

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

and

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

- **Main effort**: Extract dynamics from SIDIS, hadro-production (DY, Λ, ...), and DVCS
- **Additional trigger**: Nuclear environment provides a laboratory where to switch on modifications of transverse d.o.f.

Specific Aim of Talk

- "Nuclei as laboratories for QCD" proposed at the inception of QCD by Ioffe, Nikolaev, Brodsky, A. Mueller, Ralston, Pire...

$\Rightarrow$ Soon many intricacies appeared $\Leftarrow$

... no clear-cut interpretation of EMC effect, shadowing, CT...

- DVCS type experiments provide a whole new dimension for addressing these problems

We hope to obtain "mutual information":

More constraints from nuclei on transverse behavior ...

... and new insight on nuclear medium modifications from previously inaccessible spatial d.o.f.

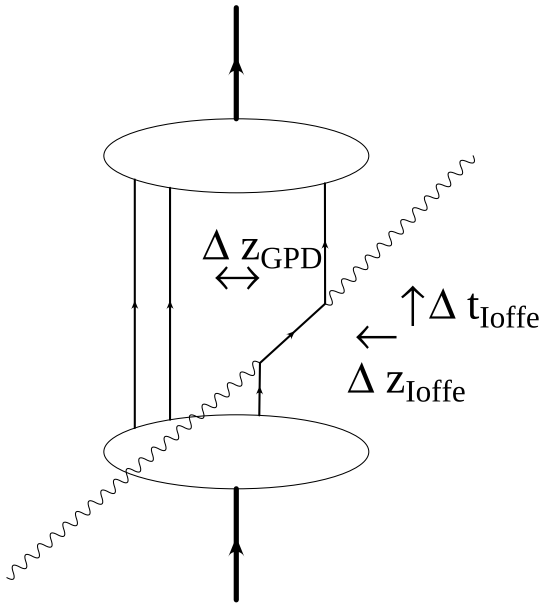
$\Rightarrow$ **At stake is the feasibility of 3D images of hadrons** $\Leftarrow$

Outline

(systematic attack of this vast phenomenology)

- Definition of spatial variables in nuclei
- Example: Off-forward EMC effect
- Parenthesis on how to obtain information from data
- Nuclear exclusive reactions, and a new inclusive-exclusive connection
- Conclusions

Feasibility of 3D scanning of hadrons: definition of sizes



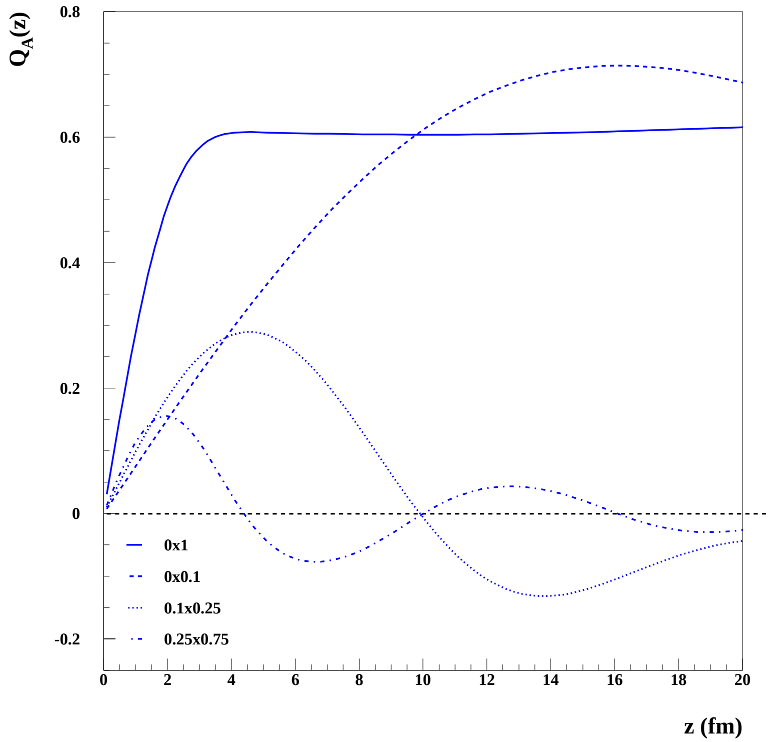
$(\Delta z + \Delta t)_{\rm Ioffe} \equiv \Delta z^+$

quark's *mobility*

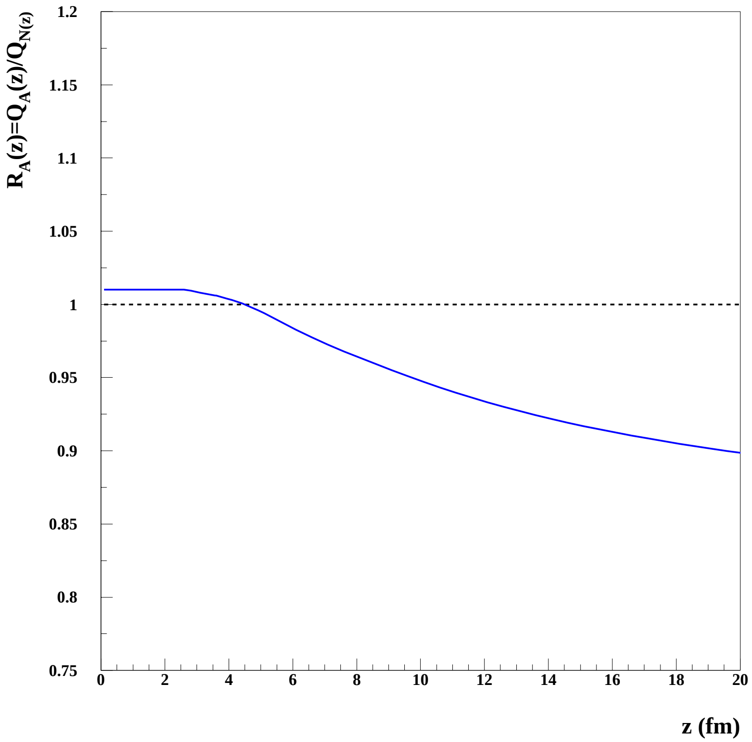
(P. Hoyer, L. Mankiewicz)

$\Rightarrow$ **we "measure" the sensitivity to large Δz^+ by looking at low x DIS in nuclei**

- Similar argument in transverse direction: $\mathbf{b_{PQCD}} \Leftrightarrow \mathbf{b_{GPD}}$
- Study the interplay between these variables in nuclei



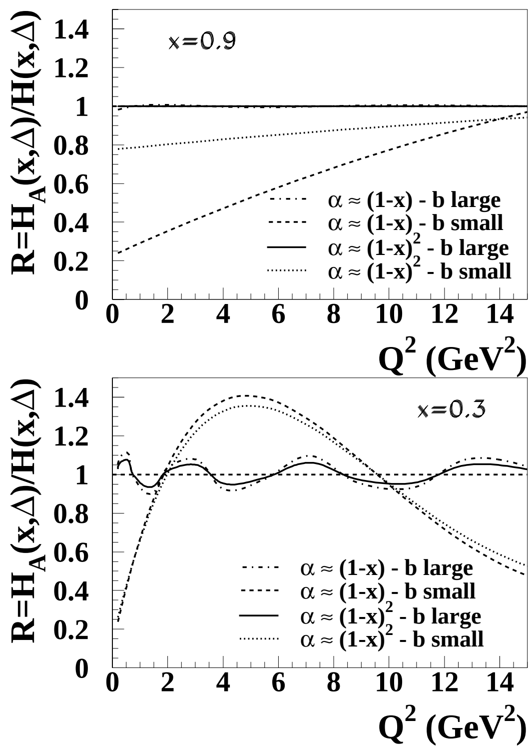
z^+ distribution in ^{12}C



Ratio ^{12}C to D

In transverse direction ⇒ Color Transparency

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



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

Example: Off-forward EMC effect

S.L., S.K. Taneja, PRC **72** *(2005) 034902, PRC* **72** *(2005) 032201*

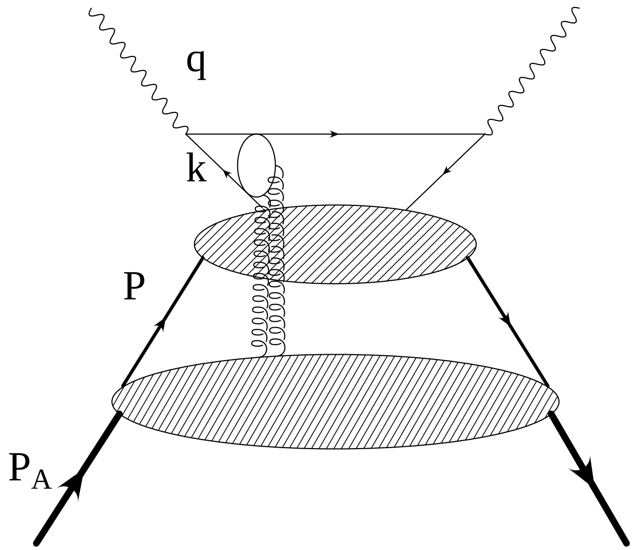
• Extend logics behind forward EMC effect to the off-forward case
⇒ Some important modifications

Basic idea

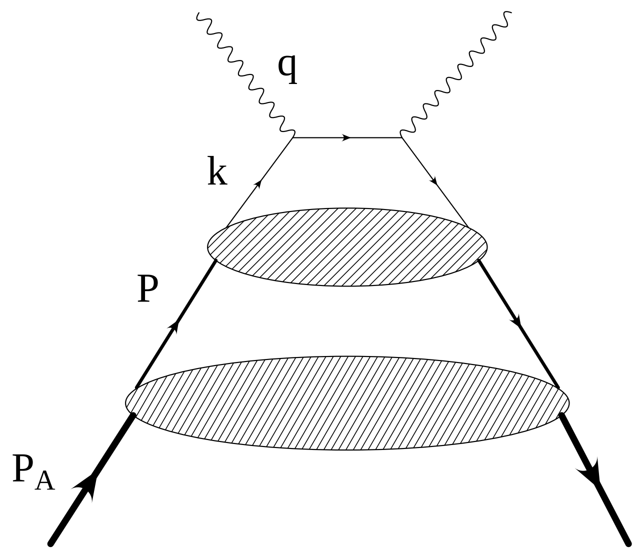
Transverse d.o.f./particle off-shellness do not decouple naively from LC variables, but play an explicit role at leading order

(1) k_T (k_μ^2)-dependent parton reinteractions, involving the exchange of Pomeron, Odderon, and other Reggeon exchanges, generate both nuclear shadowing and antishadowing at $x_{Bj} \leq 0.2$

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



$x_{Bj} \leq 0.2$



$x_{Bj} \geq 0.2$

Forward EMC effect: The Signal of Medium Effects in DIS

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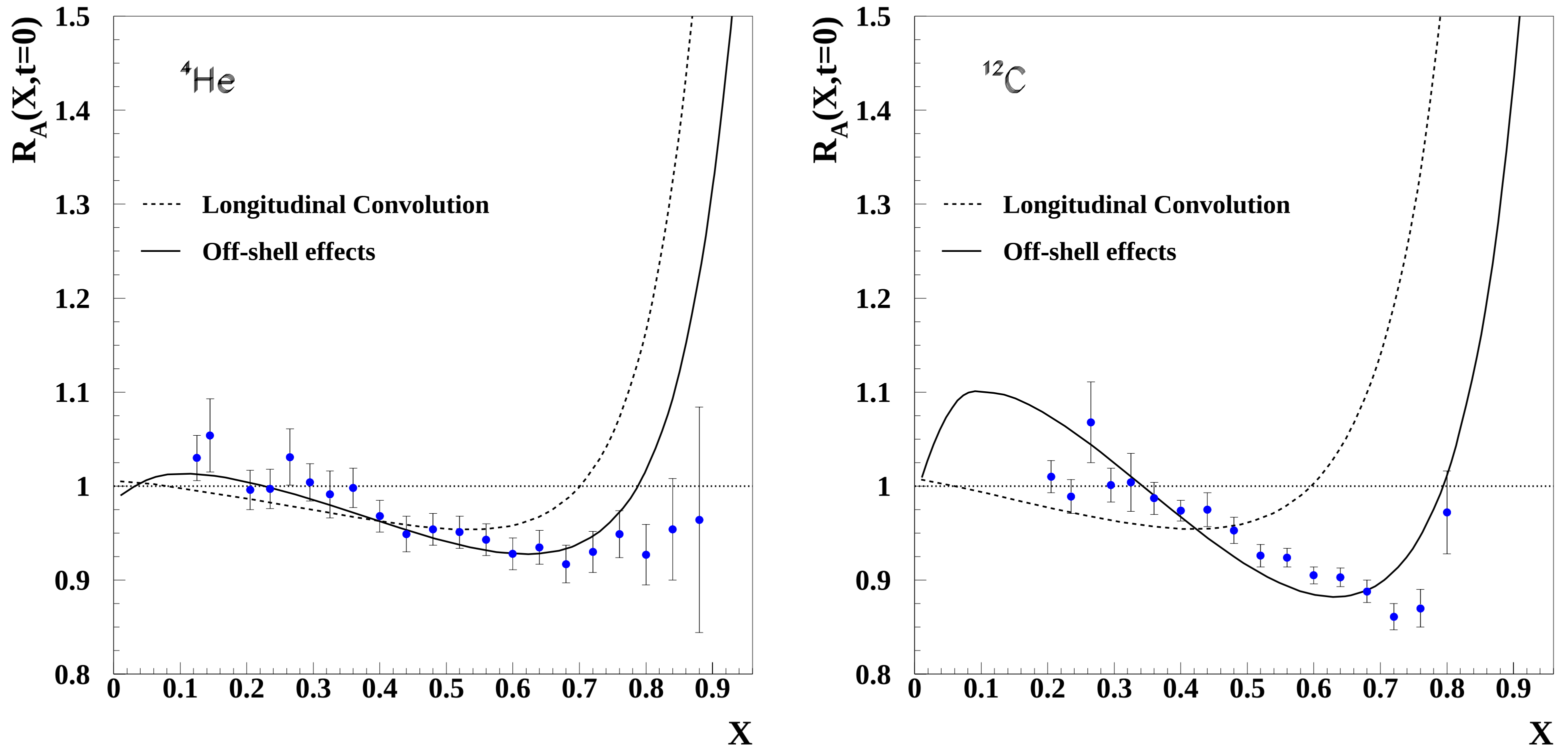


$$R_A = \frac{F_2^A(x,Q^2)}{F_2^N(x,Q^2)}$$

Off-Forward EMC effect → Spin 0 Nuclei

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

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

Nuclear medium modified GPD: beyond LC convolution

$$H^A(X,\zeta,t) \quad = \quad \int \frac{dY\, d^2\,\mathbf{P}_\perp}{2(2\pi)^3} \frac{\mathcal{A}}{(A-Y)} \rho_A \left(Y,\zeta,t,P^2\right) \hat{F}\left(\frac{X}{Y},\frac{\zeta}{Y},t,P^2\right)$$

$$\hat{F} = \sqrt{\frac{Y-\zeta}{Y}} \left[\hat{H}^N \left(\frac{X}{Y},\frac{\zeta}{Y},P^2,t\right) - \frac{1}{4}\frac{(\zeta/Y)^2}{1-\zeta/Y} \hat{E}^N \left(\frac{X}{Y},\frac{\zeta}{Y},P^2,t\right)\right].$$

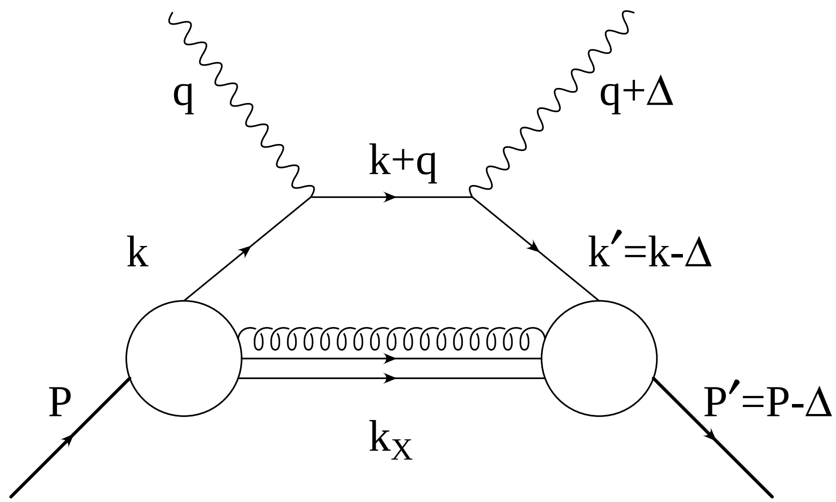
Nuclear medium modified GPD: case $\zeta = 0$

$$\text{Active } k_T \quad H^A(X,t) = \int_X^A dY\, d^2\mathbf{P}_\perp\, \rho_A(Y,t,P^2)\hat{H}^N\left(\frac{X}{Y},t,P^2\right),$$

$$\text{Collinear} \quad H^A_{LC}(X,t) = \int_X^A dY\, f_A(Y,t)H^N\left(\frac{X}{Y},t\right),$$

Spectral Representation of Modified Nucleon GPD

$$\hat{H}_q = \frac{X}{1-X} \int dM_X^2 \int \frac{d^2\mathbf{k}_\perp}{(2\pi)^3}\, \rho_q[k^2(P^2), k'^2(P^2), M_X^2)]$$



Large X, $k_X^2 \equiv M_X^2$: two component (diquark) model

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

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

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

Transverse kinematics

$$k^2 = X_N P^2 - \frac{X_N}{1 - X_N} M_X^2 - \frac{(\mathbf{k}_\perp - X_N \mathbf{P}_\perp)^2}{1 - X_N},$$

$$P^2 = [(Y/A) M_A^2 - (M_{A-1}^2 + \mathbf{P_\perp^2}) Y/(A - Y) - \mathbf{P_\perp^2}]$$

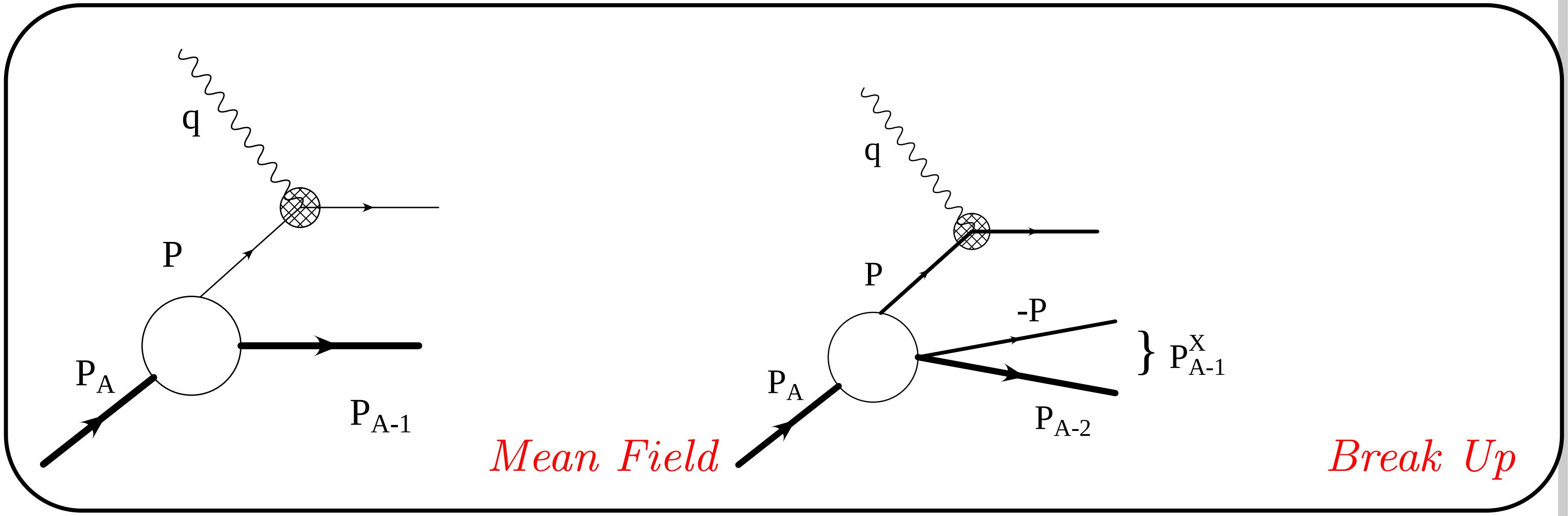
- We extend the shadowing/antishadowing model using the analitic properties of T_{qN}, to the $t \neq 0$ case. Model valid at $\zeta = 0$.
- T_{qN} is subsequently inserted, as usual, in the Glauber series

Spectral Representation of Nucleus

$$\mathcal{M}_{ij}^{A} = \rho_A(P,P') \sum_S U_i(P,S)\overline{U}_j(P',S)$$

$$\rho_A(Y,t,P^2) = \int dM_{A-1}^{X} \int d^3\mathbf{P}\, S_A(\mathbf{P},\mathbf{P'},M_{A-1}^{X})\delta(Y - P^+/M)$$

$$S_A = S^A_{MeanField} + S^A_{BreakUp}$$



Off-forward: X & t-dependences

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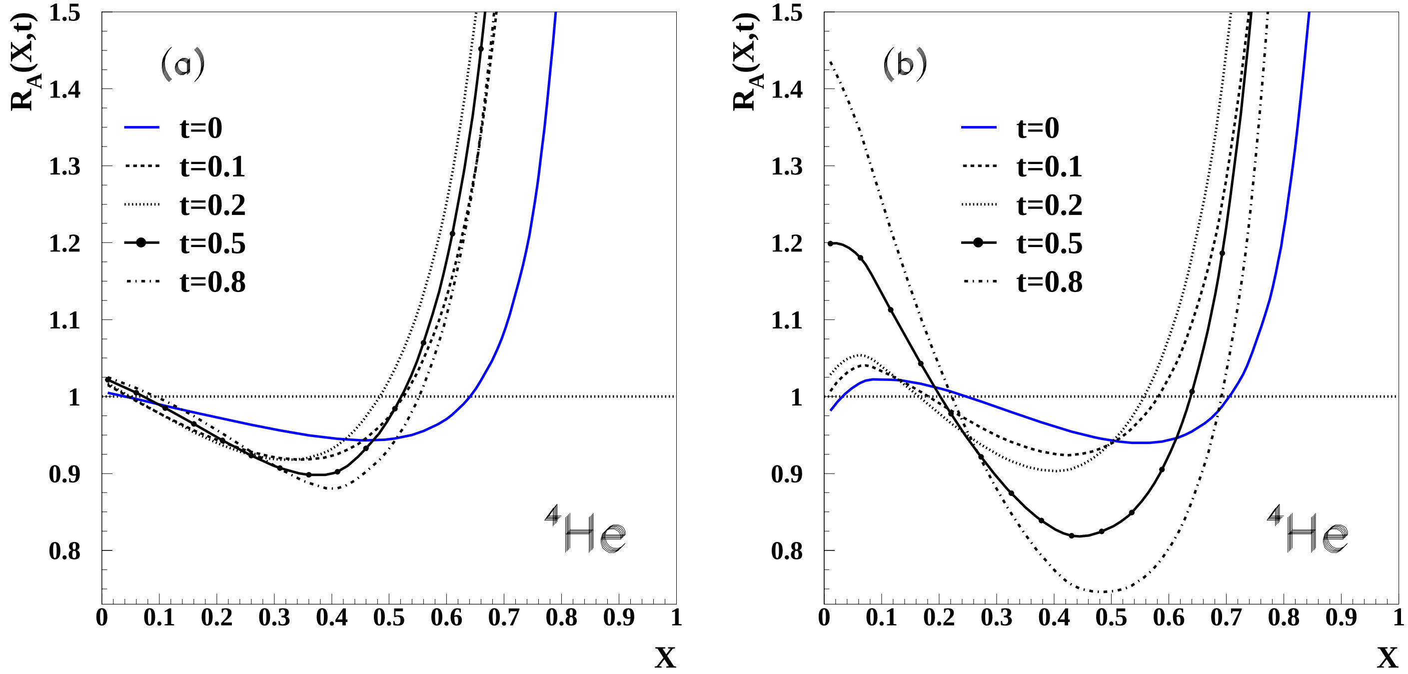


LC Approximation

k_T Effects

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

Explanation of Result

- Why larger dip?

Using LC approx.: $H_A(X,t) \approx H_N(X/(1 - \langle E(t)\rangle/M)$

$\langle E(t)\rangle \approx \langle E(t=0)\rangle \rightarrow$ no sensible difference

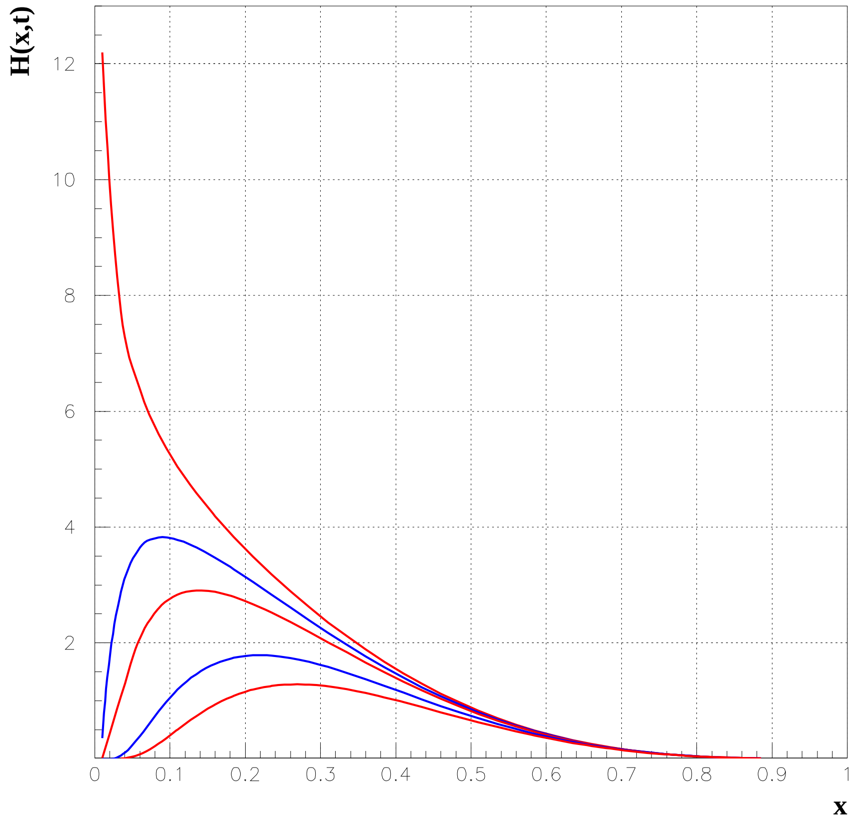
Using Active-$k_\perp$: $H_A(X,t) \approx H_N(X/(\langle Y(P^2,t)\rangle)$

$\langle Y(P^2,t)\rangle \neq \langle Y(P^2,t=0)\rangle$!!

- Similarly for $k_\perp$-dependent mechanism giving anti-shadowing

Effect due to "non-trivial" t dependence of higher moments in nuclei

GPDs trigger on $k_\perp$ dependent effects!!



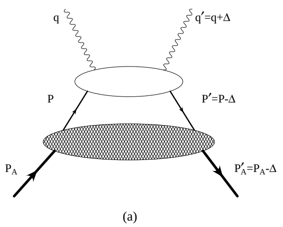
$t \downarrow$

Practical Parenthesis

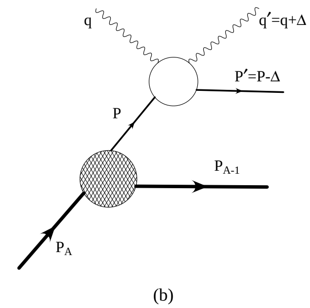
1. DVCS and BH + Coherent and Incoherent Relative Contributions
2. Nucleon Parametrization

DVCS & BH

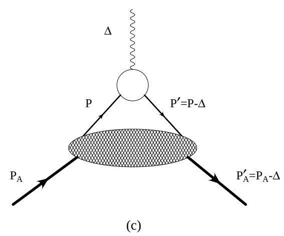
Coherent-DVCS



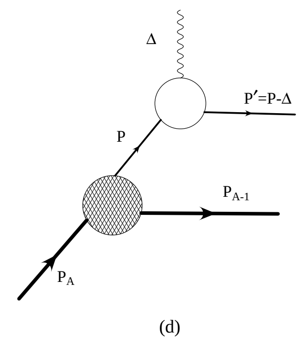
Incoherent-DVCS



Coherent-BH



Incoherent-BH



Beam Spin Asymmetry

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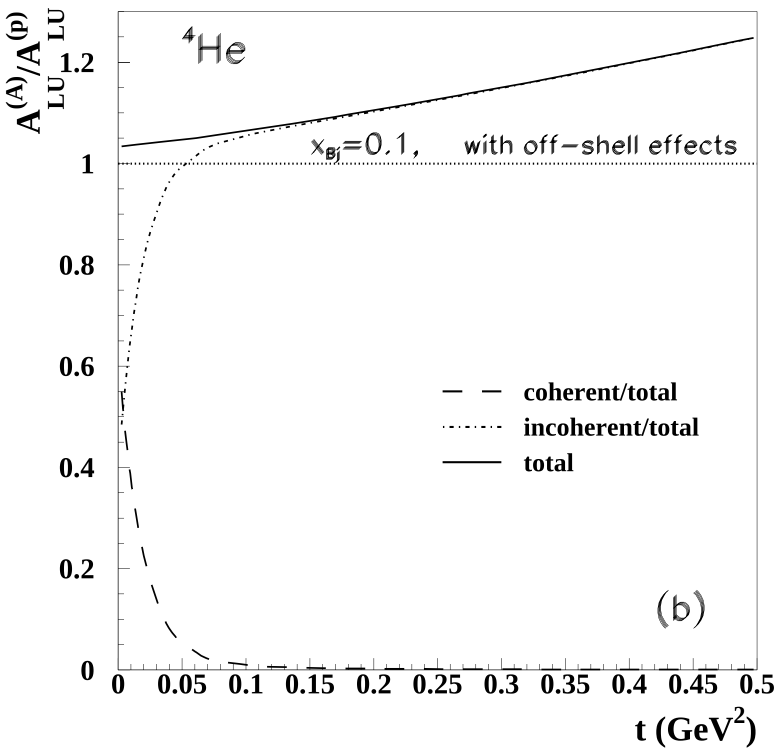


$$R^{(A)}_{LU}(\zeta,t) = A^A_{LU}/A^p_{LU} = \frac{Z^2\mathcal{I}^A_{coh}+Z\mathcal{I}^A_{incoh}}{\mathcal{F}^p_{DVCS}(\zeta,t)F_1(t)} \times \frac{F_1^2(t)}{Z^2F_A^2(t)+ZF_1^2(t)}$$

$$\mathcal{I}^A_{coh} = \mathcal{F}^A_{DVCS}(\zeta,t)F_A(t) \qquad \mathcal{I}^A_{incoh} = \mathcal{F}^A_{DVCS,0}(\zeta,t)F_1(t)$$

GPDs from Form Factors and H.O. Moments at $\zeta = 0$ and $\zeta \neq 0$

$\zeta = 0$

- Two component model:

Jakob, Mulders, Rodrigues, Nucl. Phys. A **626**, *937 (1997)*

$$\mathcal{F}(x, \mathbf{\Delta}) = \int d^2\mathbf{k}\, \phi^*(x, \mathbf{k}) \phi(x, \mathbf{k} + (1-x)\mathbf{\Delta})$$

$$F_2(x) = \int d^2\mathbf{k} \mid \phi(x, \mathbf{k}) \mid^2$$

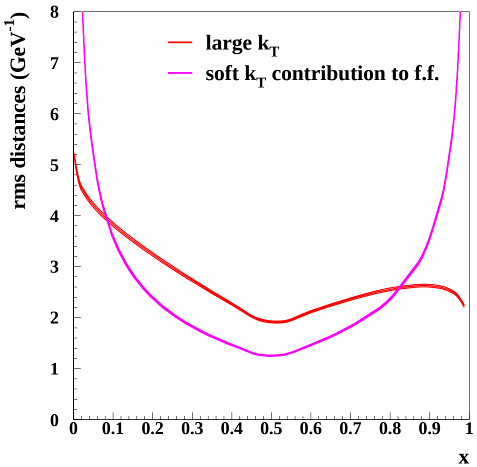
$$F(\mathbf{\Delta}^2) = \int d^2\mathbf{k} \int_0^1 dx\, \phi^*(x, \mathbf{k}) \phi(x, \mathbf{k} + (1-x)\mathbf{\Delta})$$

$$\phi(x, \mathbf{k}) = \frac{g(k^2)}{D(x, \mathbf{k})}.$$

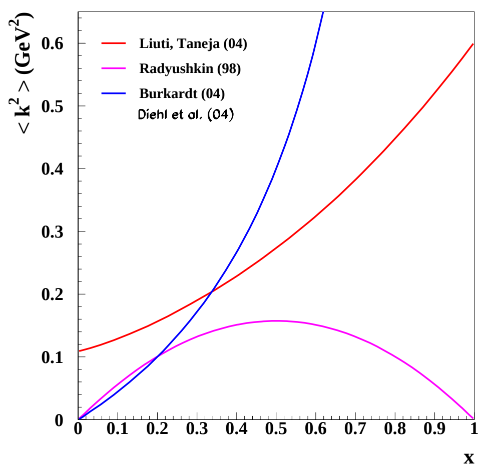
$$D(x, \mathbf{k}) = \mathcal{M}_X^2\, x - \frac{\mathbf{k}^2}{1-x}$$

$$g(k^2) = g\, \frac{k^2 - m^2}{\mid k^2 - \Lambda^2 \mid^2}$$

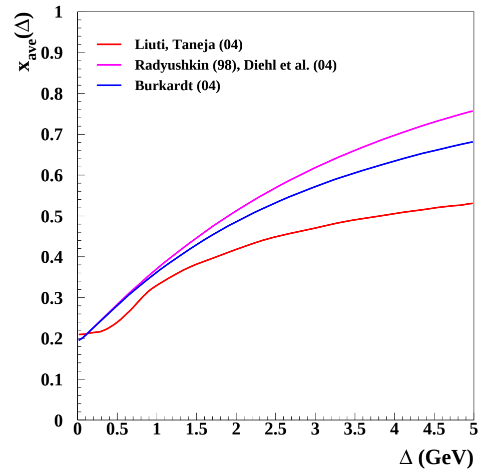
Motivation: a parametrization that satisfies all these constraints



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



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



$$\langle x(\Delta)\rangle$$

Nice connection to long. and transv. polarized distribution and fragmentation functions but....

... low x dependence needs to be reproduced accurately
DFJK05 and *GGRV05*

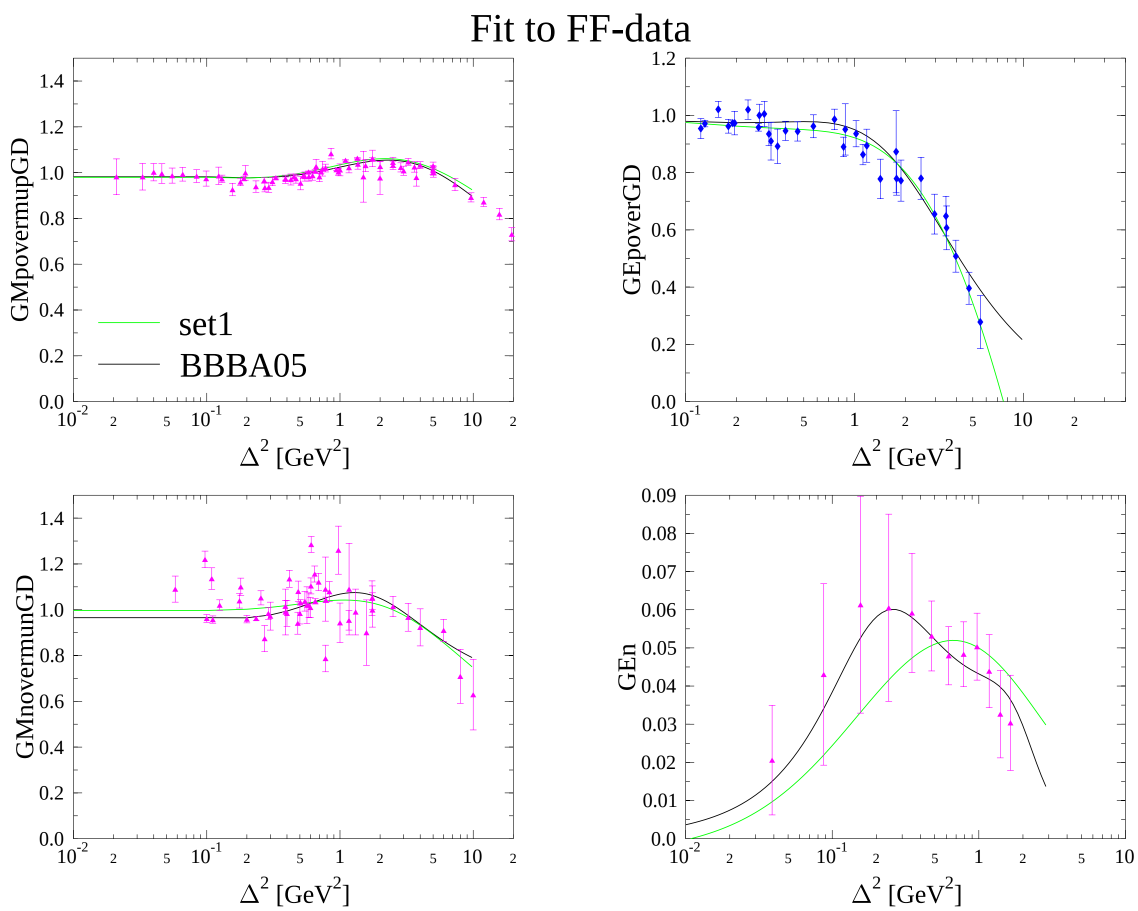
Extra factor: $x^{-\alpha'(1-x)^p-\beta}$

for H

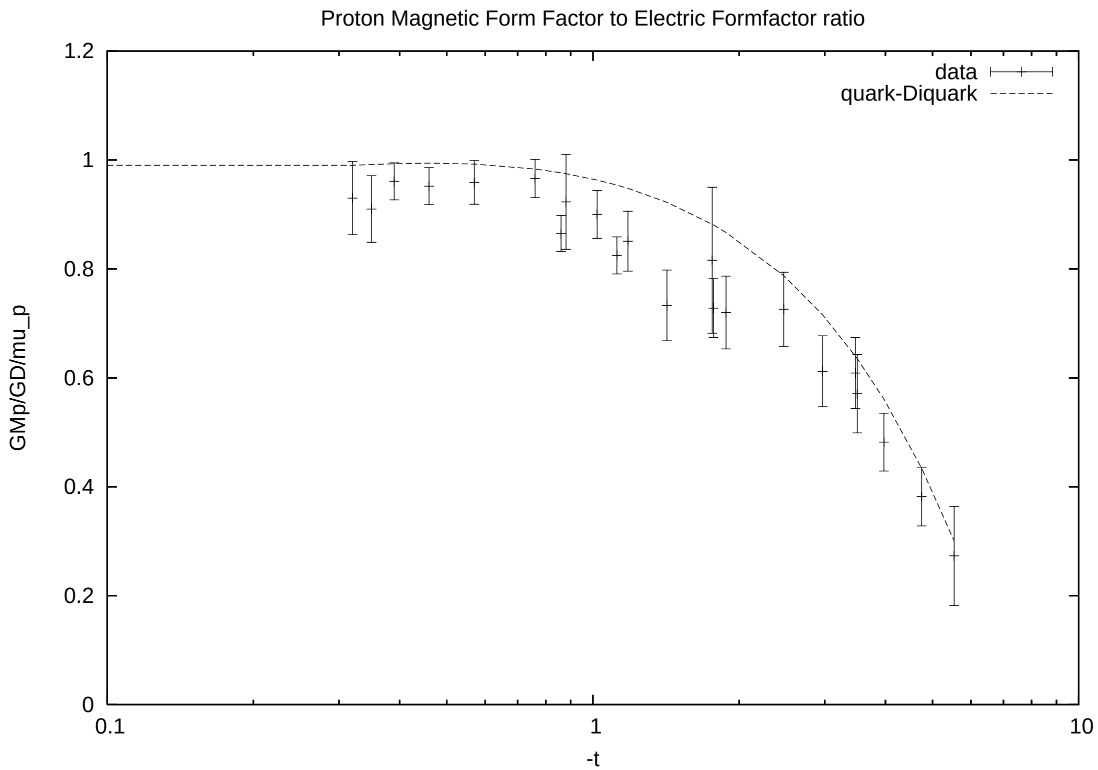
$x^{-\alpha'(1-x)^p-\beta}$ for H, E I

$x^{-\gamma}$ for E II

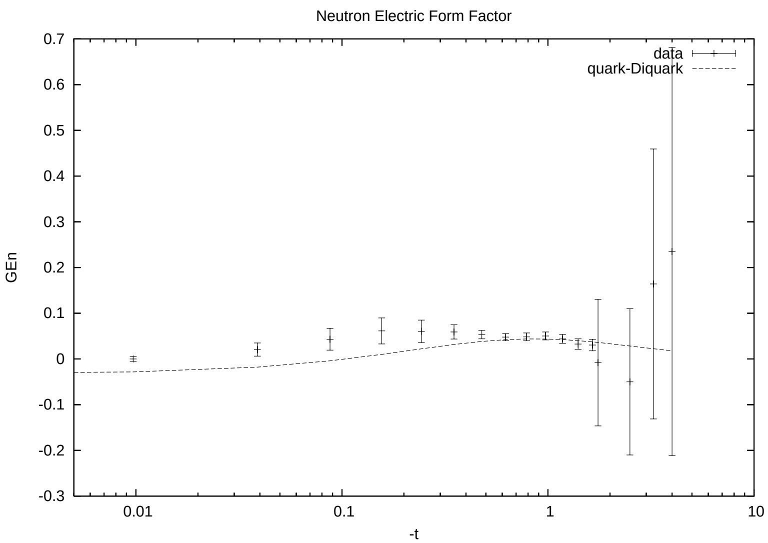
All Form Factors I

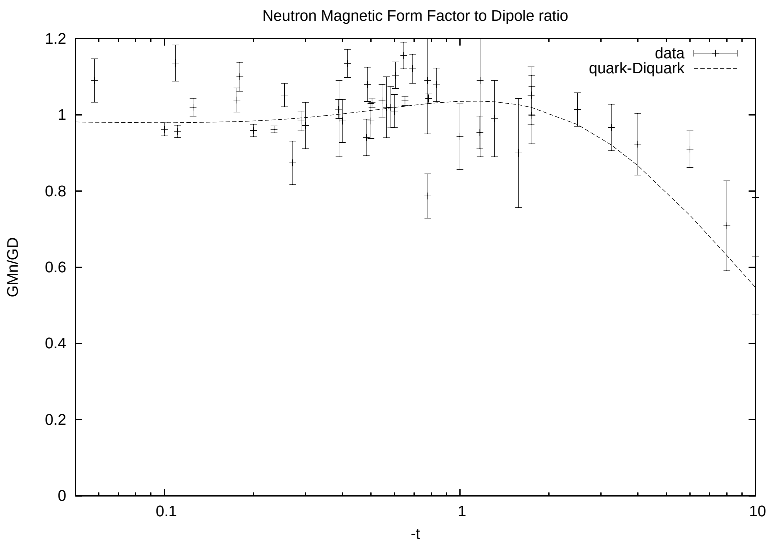


Proton Form Factors II

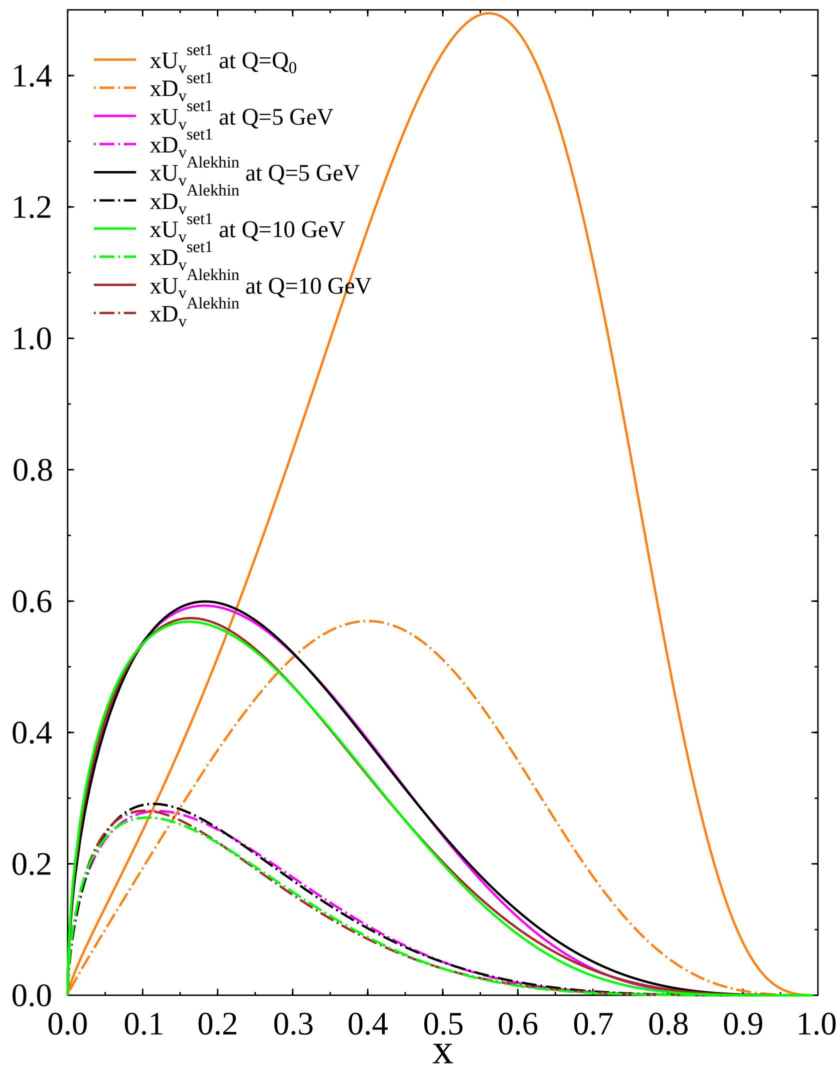


Neutron Form Factors II



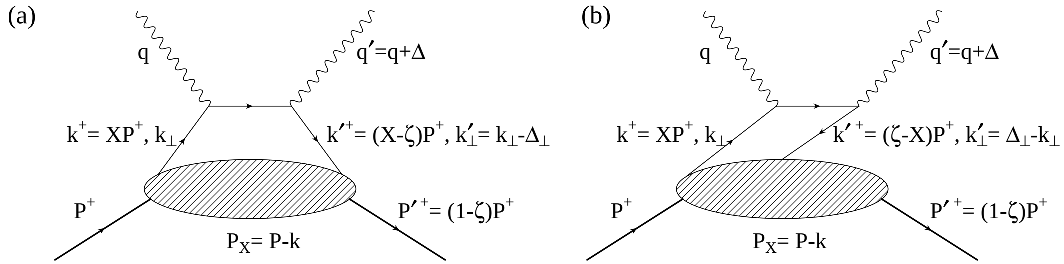


PDFs



xU_v^set1 at Q=Q_0
xD_v^set1
xU_v^set1 at Q=5 GeV
xD_v^set1
xU_v^Alekhin at Q=5 GeV
xD_v^Alekhin
xU_v^set1 at Q=10 GeV
xD_v^set1
xU_v^Alekhin at Q=10 GeV
xD_v^Alekhin
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
x

$\zeta \neq 0$



Strategy:

1. Treat separately the DGLAP ($X > \zeta$) and ERBL ($X < \zeta$) regions
2. Extend constraints obtained from form factors to $X > \zeta$
3. Apply the generalized mean value theorem at $0 < X < \zeta$

$$\int_0^\zeta dX X^{n-1} H^q(X,\zeta,t) = \zeta \left\langle H^q(X,\zeta,t) X^{n-1} \right\rangle$$

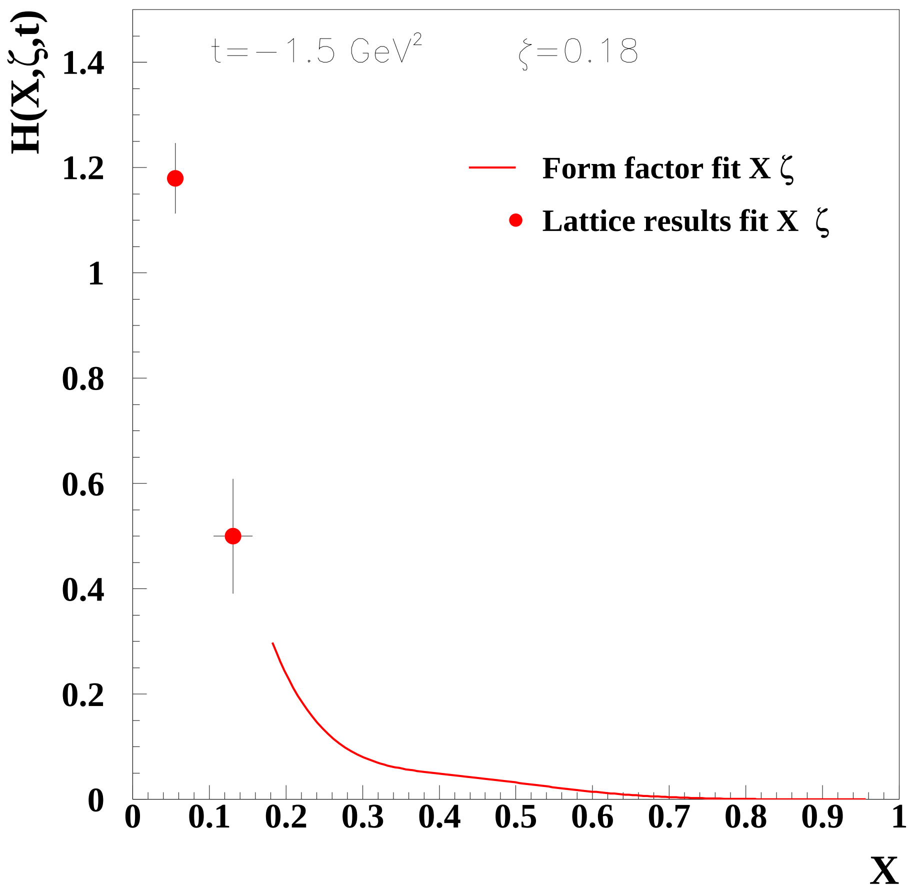
$$\left\langle H^q(X,\zeta,t) X^{n-1} \right\rangle = \frac{1}{\zeta} \left[H_n^q(\zeta,t) \right]_{LAT} - \left[\int_\zeta^1 dX X^{n-1} H_n^q(X,\zeta,t) \right]_{DGLAP}$$

$$\langle X \rangle_n = \frac{\int_0^\zeta dX X^n H^q(X,\zeta,t)}{\int_0^\zeta dX X^{n-1} H^q(X,\zeta,t)}$$

The value of H^q in these points is obtained as:

$$H^q(\langle X \rangle_1, \zeta, t) = \frac{[H_1^q(\zeta,t)]_{0\zeta}}{\zeta} \quad (1)$$

$$H^q(\langle X_2 \rangle_2, \zeta, t) = \left(\frac{[H_2^q(\zeta,t)]_{0\zeta}}{[H_3^q(\zeta,t)]_{0\zeta}} \right) \frac{[H_2^q(\zeta,t)]_{0\zeta}}{\zeta} \quad (2)$$


t=−1.5 GeV^2
ζ=0.18
Form factor fit X ζ
Lattice results fit X ζ
H(X,ζ,t)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
X

Nuclear Exclusive: Form Factor in Nuclei

S.L., hep-ph/0601125

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

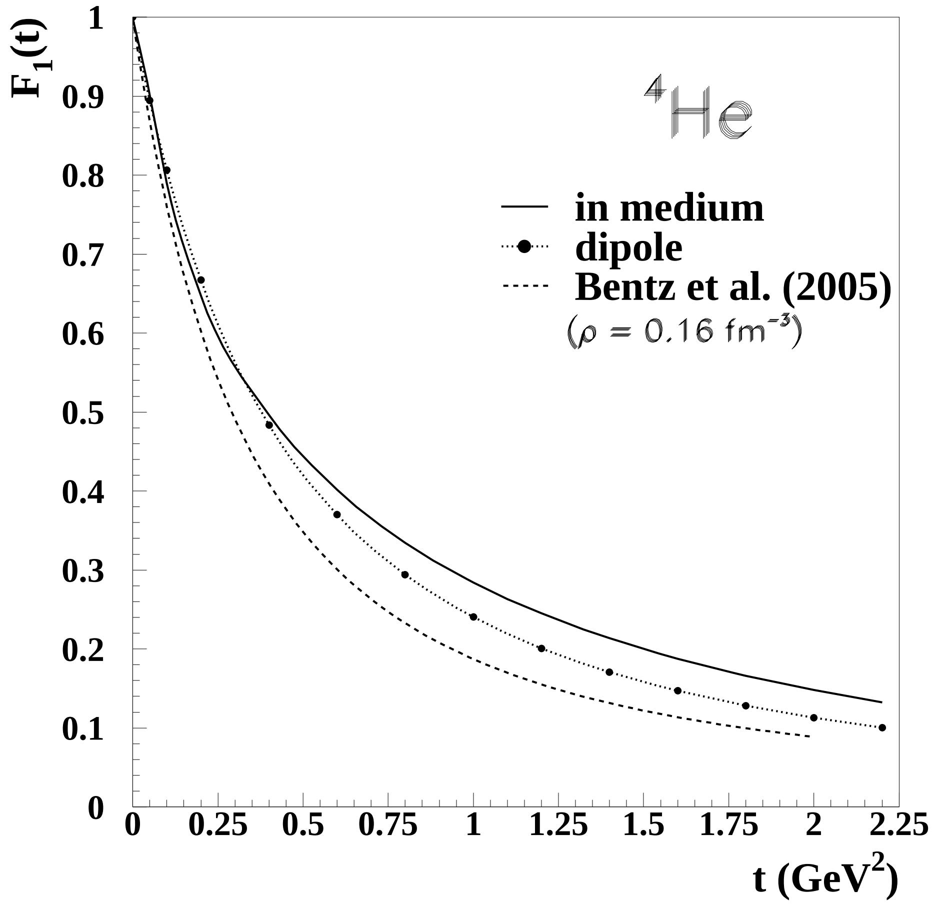
$$F_A^{LC}(t) = F_A^{point}(t) F_N(t)$$

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

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

↑ Medium Modified Form Factor ↑

Form Factor in Nuclei *S.L., hep-ph/0601125*



What about distances...?

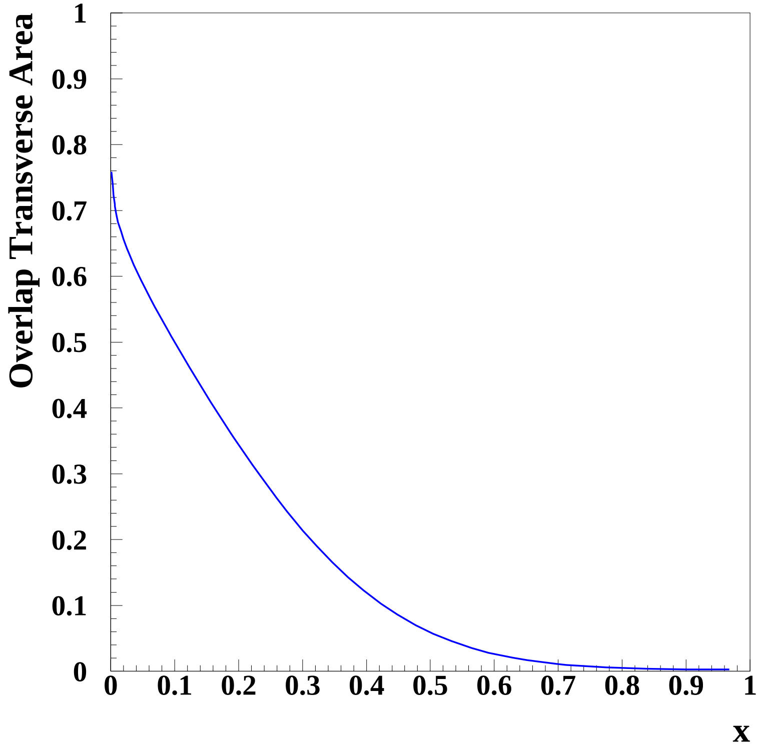
Transverse "Area Overlap" for a hard nuclear process

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

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

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

Transverse “Area Overlap”



Conclusions

- Even more than before, nuclei provide a natural laboratory to study QCD in coordinate space: tip of the ice-berg
- 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.