Overview of Generalized Parton Distributions in Nuclei

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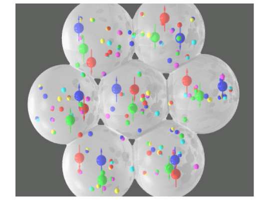
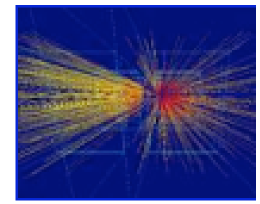
Outline

- ***Introduction: Nuclear Targets at MEIC***
    - *Focus on exclusive experiments, GPDs (today's talk)*
    - *Color Transparency (tomorrow's talk)*
    - *Radius of Quark Distributions in Nuclei*
- ***From JLAB 6-12 GeV to MEIC***
- ***Conclusions/Outlook***

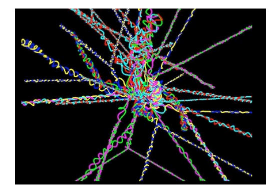
A BRIEF HISTORY…



⇒ The idea of using nuclei as "laboratories for QCD" is introduced in the '80s by Brodsky, Frankfurt, Ioffe, Kopeliovich, Miller, A. Mueller, Nikolaev, Pire, Ralston, Strikman….



⇒ Experiments are performed: EMC, NMC @ CERN, E665 @ Fermilab, DY and J/ψ production @ Fermilab, etc…



⇒ Many intricacies and controversies appear: <u>no clear-cut interpretation</u> of the "EMC-effect", of the onset of shadowing and anti-shadowing (are sum rules satisfied in nuclei? are parton distributions probabilities?), Color Transparency….

⇒ TODAY: Deeply Virtual Exclusive Experiments add a whole new dimension where to explore nuclear medium modifications. One can observe previously inaccessible spatial d.o.f.

Images from L. Frankfurt + G. Miller websites

Recent activity in this field

Theoretical work

Formalism

D.Mueller and Kirchner (2004) .. Some formalism on A-dependence of DVCS
Guzey and Strikman (2004) .. A-dependence in BSA from nuclear DVCS
Liuti and Taneja (2005) .. Nuclear Medium Modifications of GPDs
Berger, Cano, Diehl, Pire (2001) Deuteron/Spin 1

Color Transparency

Liuti and Taneja (2005) .. Color Transparency
Burkardt and Miller (2006) .. Color Transparency

Models

M. Polyakov (2003) Liquid Drop Model
Cano and Pire (2003) Deuteron
Scopetta (2004) .. 3He
Liuti and Taneja (2005) 4He --detailed study of coherent and incoherent cha
Guzey and Siddikov (2006) .. A-dependence @ low x_{Bj}

Experiments

HERMES $\Rightarrow$ initial results (large uncertainties)

Jlab $\Rightarrow$ Deuteron: M. Mazouz et al.,

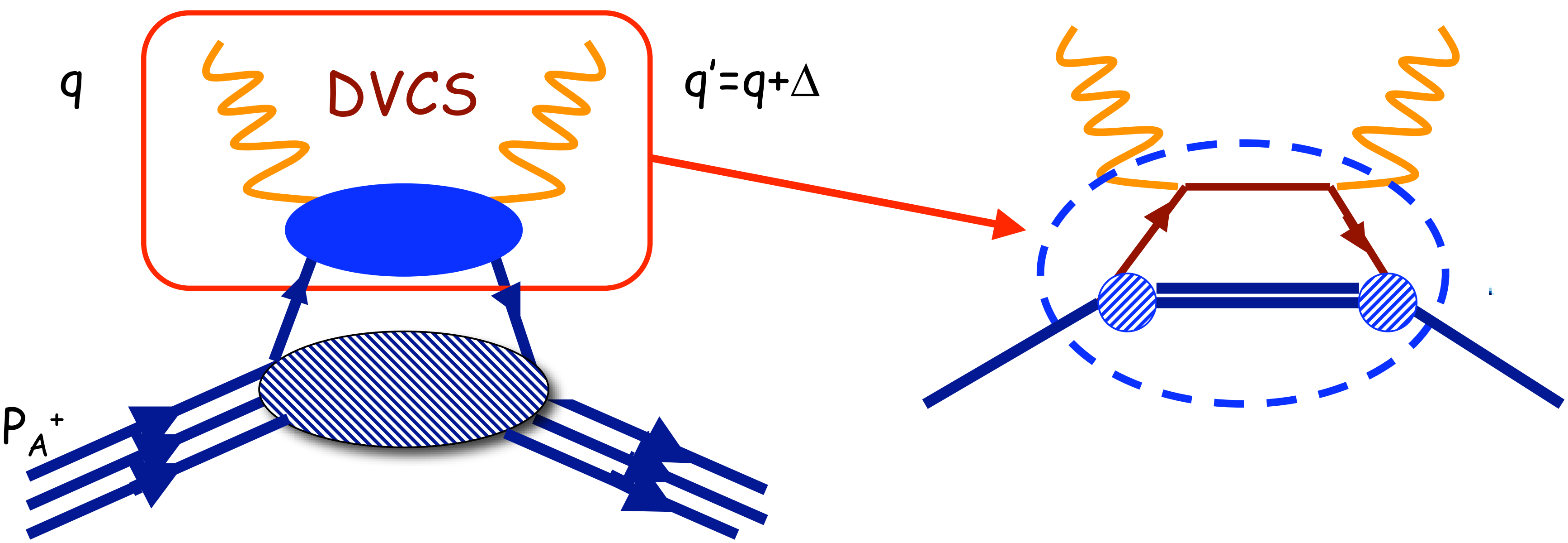
Jlab $\Rightarrow$ ^{4}He: K. Hafidi et al., + LOI for 12 GeV

2. Some Formalism

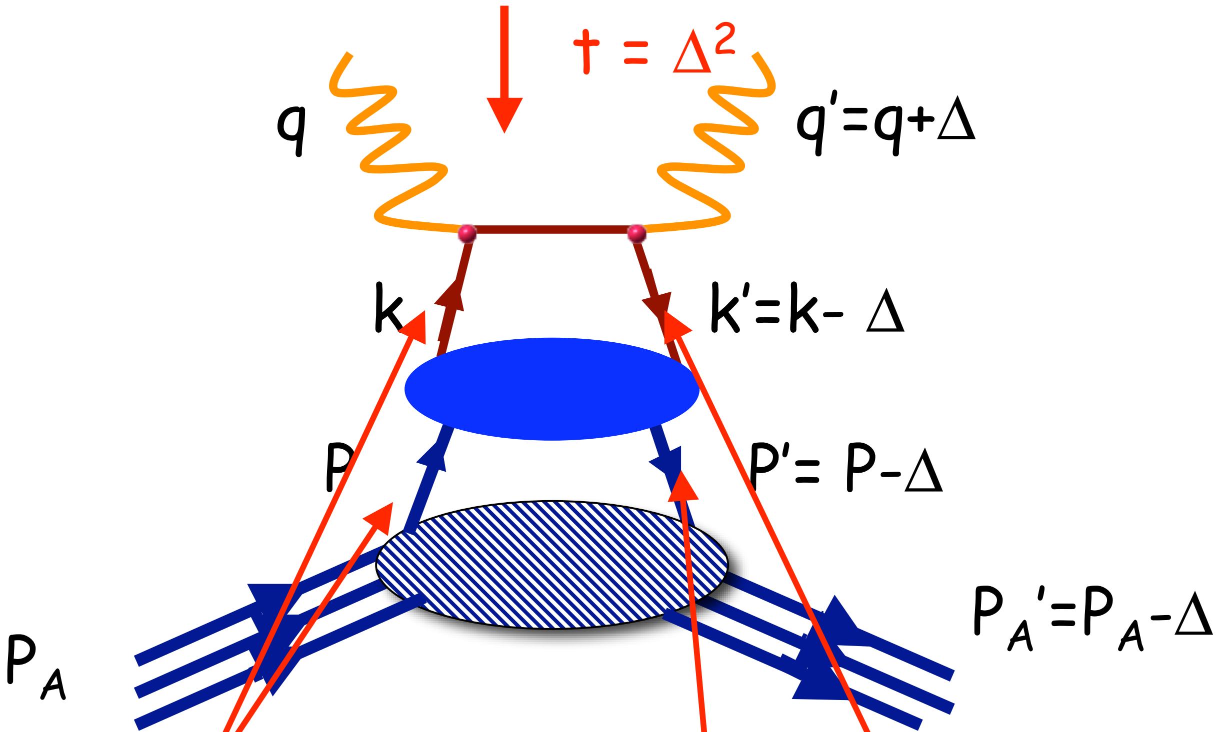
GPDs in Nuclei: Off-forward EMC effect

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

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



Non-forward kinematics



Longitudinal momentum fractions

$Z = A\, P^+/P_A^+$

$X = A\, k^+/P_A^+$

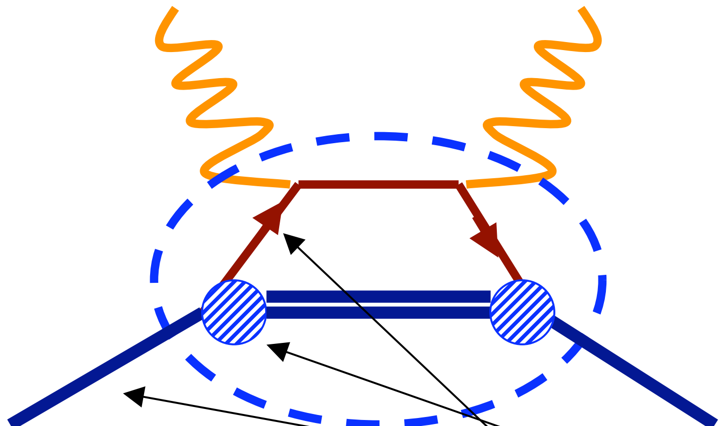
$X/Z = k^+/P^+$

$\zeta = A\, \Delta^+/P_A^+ = \Delta^+/P^+$

$X - \zeta = A\, k'^+/\, P_A^+$

$Z - \zeta = A\, P'^+/\, P_A^+$

Use e.g. a spectator model (with a spin 0 diquark) to take a closer look to the nucleon correlator $\mathcal{M}^N$...



$$\mathcal{M}^N_{ij} = \overline{U}_i(P', S)\overline{\Gamma}_{i\alpha}(k', P)\,\frac{(\not{k}' + m)_{\alpha\beta}}{k'^2 - m^2}\,\frac{(\not{k} + m)_{\beta\gamma}}{k^2 - m^2}\Gamma_{\gamma j}(k, P)U_j(P, S)$$

From $\mathcal{M}^N$ to $\mathcal{M}^A$ (Spin 0)

$$\mathcal{M}^A_{ij} = \overline{U}_{A-1}(P'_A, S)\overline{\Gamma}_A(P', P'_A)\,\frac{(\not{P}' + M)}{P'^2 - M^2}\,\frac{(\not{P} + M)}{P^2 - M^2}\Gamma_A(P, P_A)\,U_{A-1}(P_A, S$$

$U_{A-1} \rightarrow$ spectator $A-1$ nucleons with mass M^*_{A-1}

$\Gamma_A \rightarrow$ nuclear vertex function

$$\mathcal{M}^A_{ij} = \mathcal{N}_A \left(\sum_S U_i(P, S)\overline{U}_j(P', S) \right) \rho_A(P^2, P'^2)$$

Non-forward nuclear spectral function

$$\begin{aligned} \rho_A(P^2, P'^2) &\approx S_A(\mid \mathbf{P} \mid, \mid \mathbf{P}' \mid, E) \\ &= \sum_f \Phi_f(\mid \mathbf{P} \mid)\Phi^*_f(\mid \mathbf{P}' \mid)\delta\left(E - (E^f_{A-1} - E_A)\right) \end{aligned}$$

<u>With LC variables</u>

$\rho_A(Y, \zeta, t, P^2)$

In order to extract GPDs, use helicity amplitudes

Quark-Nuc
Helicity A

For real photon production the amplitude relations are

$$\boxed{f_{\Lambda_\gamma,0;+1,0} = \sum_{\lambda,\lambda'} g_{\Lambda_\gamma,\lambda;+1,\lambda'} C_{0,\lambda';0,\lambda}.}$$

The C amplitudes can be written in terms of the quark-nucleon helicity amplitudes:

Chiral-Even
Quark-Nuc
Helicity Am

$$C_{0,\lambda';0,\lambda} = \sum_{\Lambda_N,\Lambda'_N} \int d^4 P \, B_{0,\Lambda'_N;0,\Lambda_N} A_{\Lambda'_N\lambda';\Lambda_N,\lambda}$$

Nucleon-Nucl
Helicity Amps

Two terms survive for pseudoscalar production:

$$\begin{aligned} T &\Rightarrow \quad g_{1+,0-} \, C_{0-;0+} \\ L &\Rightarrow \quad g_{0+,0-} \, C_{0-;0+} \end{aligned}$$

Both terms contain the same chiral odd C function. The latter is given by:

$$\underline{C_{0,-;0,+}} = \int d^4P \, [B_{0+.0-}A_{+-;-+} + B_{0-;0-}A_{--;-+} + B_{0+;0+}A_{+-;++} + B_{0-;0+}A_{--;++}]$$

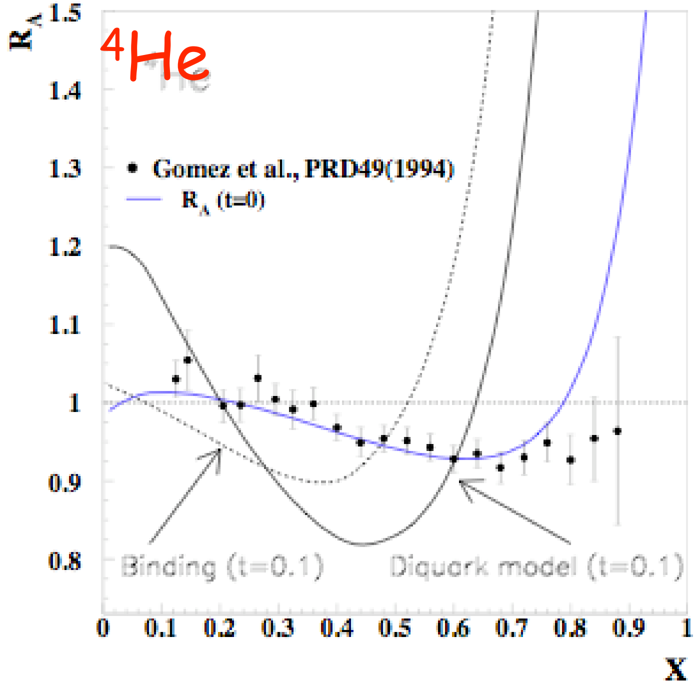
For photon production the leading twist contribution to the hard amplitudes singles out
helicity conserving case for which only

$$T \quad \Rightarrow \quad g_{1+,1+} \, C_{0+;0+}$$

The chiral even C functions are given by:

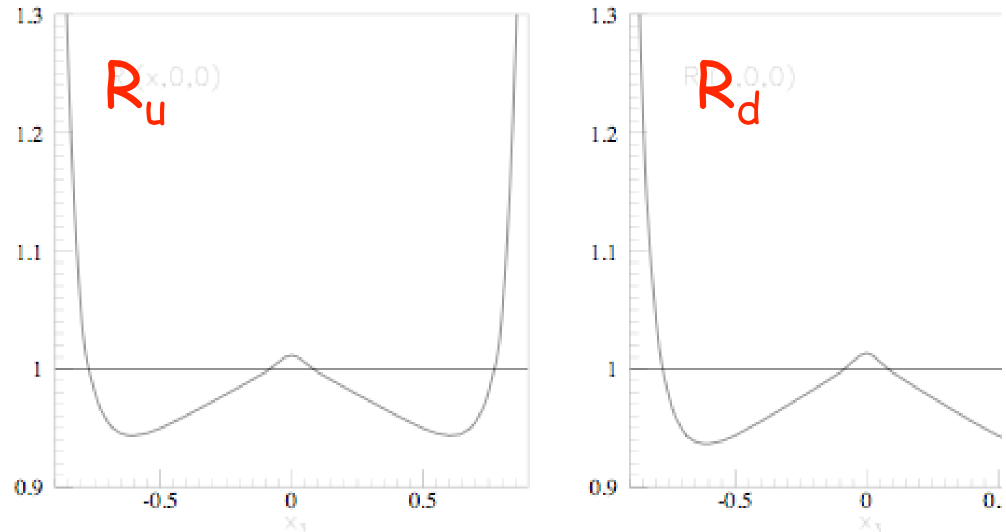
$$\underline{C_{0,+;0,+}} = \int d^4P \, [B_{0+.0-}A_{++;-+} + B_{0-;0-}A_{-+;-+} +$$

$$
\begin{aligned}
H^A(X,\zeta,t) &= \int \frac{d^2P_\perp dY}{2(2\pi)^3}\mathcal{A}\rho_A(Y,P_\perp^2,\zeta,t) \\
&\times \; c_1(\zeta,t)\left[H^N\left(\frac{X}{Y},\frac{\zeta}{Y},P^2,t\right)-\frac{1}{4}\frac{(\zeta/Y)^2}{1-\zeta/Y}E^N\left(\frac{X}{Y},\frac{\zeta}{Y},P^2,t\right)\right] \\
&+ \; c_2(\zeta,t)\sqrt{\frac{t-t_o}{2M}}E^N\left(\frac{X}{Y},\frac{\zeta}{Y},P^2,t\right)
\end{aligned}
$$

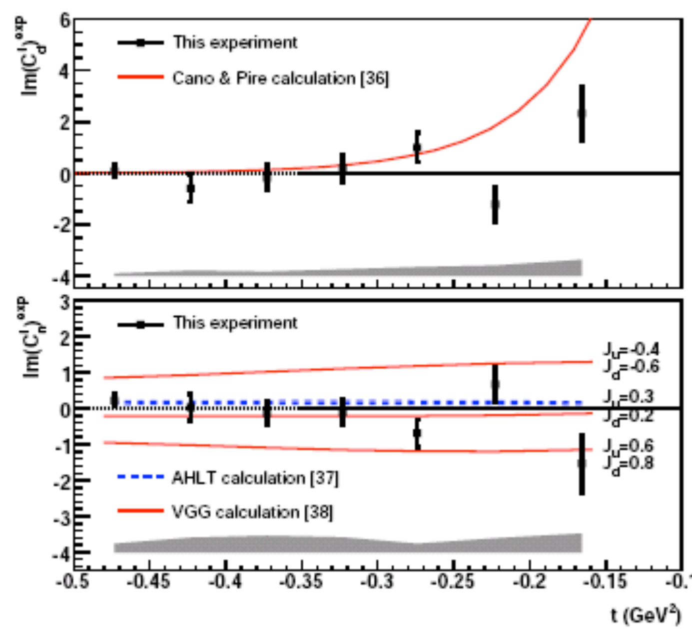


S.L. and S.Taneja

^{3}He



S. Scopetta



F. Cano and B

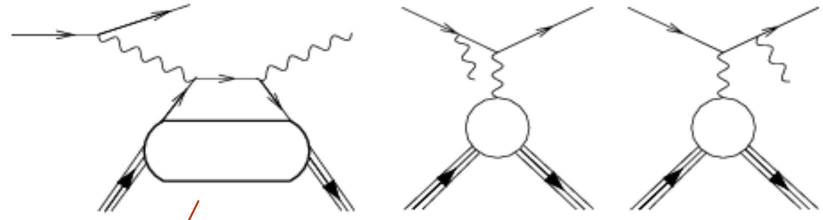
Deuteron

(data from Ha

Mazouz et al.)

Extracting GPDs from Cross Sections and Beam Spin Asymmetries

$(ep \rightarrow e'p'\gamma)$



$$\frac{d^5\sigma(\lambda,\pm e)}{d^5\Phi} = \frac{d\sigma_0}{dQ^2 dx_B}\left|\mathcal{T}^{BH}(\lambda) \pm \mathcal{T}^{DVCS}(\lambda)\right|^2 / |e|^6$$

$$= \frac{d\sigma_0}{dQ^2 dx_B}\left[\left|\mathcal{T}^{BH}(\lambda)\right|^2 + \left|\mathcal{T}^{DVCS}(\lambda)\right|^2 \mp \mathcal{I}(\lambda)\right]\frac{1}{e^6}$$

$$\frac{d^4\Sigma}{dQ^2dx_{Bj}dtd\phi} \equiv \frac{d^4\sigma^+}{dQ^2dx_{Bj}dtd\phi} - \frac{d^4\sigma^-}{dQ^2dx_{Bj}dtd\phi} \qquad \propto \Im m\mathcal{H}$$

$$\frac{d^4\sigma}{dQ^2dx_{Bj}dtd\phi} \equiv \frac{d^4\sigma^+}{dQ^2dx_{Bj}dtd\phi} + \frac{d^4\sigma^-}{dQ^2dx_{Bj}dtd\phi} \qquad \propto \Re e\mathcal{H}$$

$$\mathcal{F}(\zeta,t) = -i\pi\sum_q e_q^2\left[F^q(\zeta,\zeta,t) - F^q(-\zeta,\zeta,t)\right] + \mathcal{P}\int_{1-\zeta}^{1} dX\left(\frac{1}{X-\zeta} + \frac{1}{X}\right)F^q(X,\zeta,t).$$

$F^q \equiv H^q$,

BH, DVCS and Interference contributions azymuthal dependence written explicitely (Belitsky, Muller, Kirchner)

$$\mathcal{T}_{BH}^2 = \frac{e^6(1+\epsilon^2)^{-2}}{x_A^2 y^2 t\, \mathcal{P}_1(\varphi)\mathcal{P}_2(\varphi)} \sum_{n=0}^{n=2} \boxed{c_n^{BH}} \cos(n\varphi),$$

$$|\mathcal{T}_{DVCS}^{\lambda}|^2 = \frac{e^6}{y^2 Q^2} \sum_{n=0}^{n=2} \left\{ \boxed{c_n^{DVCS}} \cos(n\varphi) + \lambda \boxed{s_n^{DVCS}} \sin(n\varphi) \right\},$$

$$\mathcal{I}^{\lambda} = \frac{e^6}{x_A y^3 t\, \mathcal{P}_1(\varphi)\mathcal{P}_2(\varphi)} \sum_{n=0}^{n=3} \left\{ \boxed{c_n^{\mathcal{I}}} \cos(n\varphi) + \boxed{\lambda s_n^{\mathcal{I}}} \sin(n\varphi) \right\}.$$

Coefficients correspond to the L,T,LT,TT,LT', ... terms in the x-sec.

4He: Spin 0

Bethe-Heitler

$$c_0^{BH} = \left[\left\{ (2-y)^2 + y^2(1+\epsilon^2)^2 \right\} \left\{ \frac{\epsilon^2 Q^2}{t} + 4(1-x_A) + (4x_A + \epsilon^2)\frac{t}{Q^2} \right\} \right.$$
$$+ 2\epsilon^2 \left\{ 4(1-y)(3+2\epsilon^2) + y^2(2-\epsilon^4) \right\} - 4x_A^2(2-y)^2(2+\epsilon^2)\frac{t}{Q^2}$$
$$\left. + 8K^2 \frac{\epsilon^2 Q^2}{t} \right] F_A^2, \qquad (24)$$

$$c_1^{BH} = -8(2-y)K \left\{ 2x_A + \epsilon^2 - \frac{\epsilon^2 Q^2}{t} \right\} F_A^2, \qquad (25)$$

$$c_2^{BH} = 8K^2 \frac{\epsilon^2 Q^2}{t} F_A^2, \qquad (26)$$

DVCS

$$c_0^{DVCS} = 2(2-2y+y^2)\, \mathcal{H}_A \mathcal{H}_A^*,$$

Interference

$$c_0^{\mathcal{I}} = -8(2-y)\frac{t}{Q^2} F_A \Re e\{\mathcal{H}_A\}$$
$$\times \left\{ (2-x_A)(1-y) - (1-x_A)(2-y)^2 \left(1 - \frac{t_{min}}{Q^2} \right) \right\},$$
$$c_1^{\mathcal{I}} = 8K(2y-y^2-2) F_A \Re e\{\mathcal{H}_A\},$$
$$s_1^{\mathcal{I}} = 8Ky(2-y) F_A \Im m\{\mathcal{H}_A\}.$$

Interference between BH and DVCS from Nuclear Beam Spin Asymmetry

Nuclear Beam Spin Asymmetry

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

$$A_{LU}^{(A)} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \approx \frac{s_1^{\mathcal{I}}}{c_o^{BH}} \sin\phi$$

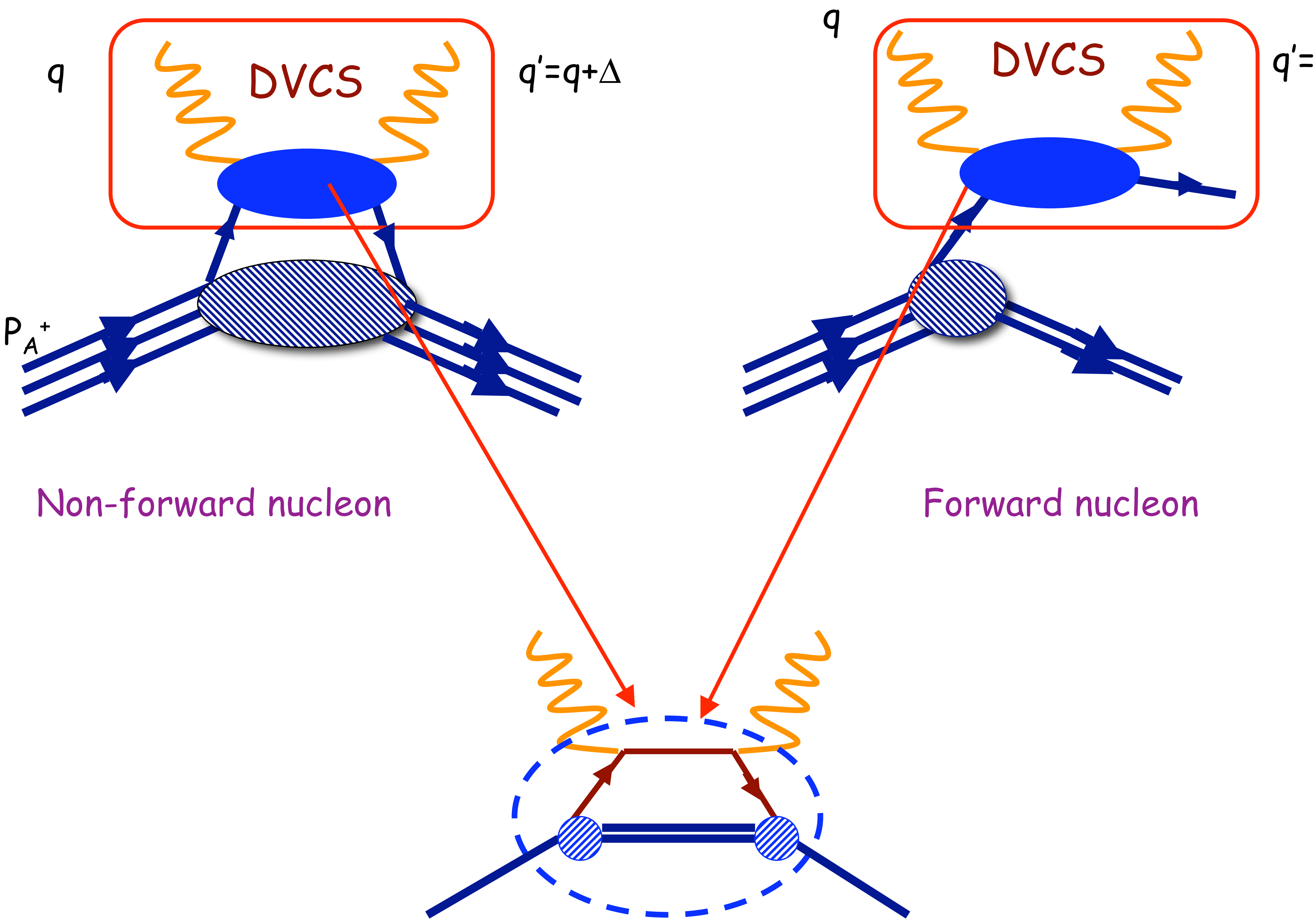
$$\boxed{s_1^{\mathcal{I}} \propto \Im\mathrm{m}\, \mathcal{H}_A \, F_A(t)}$$

$$\boxed{c_o^{BH} \propto [F_A(t)]^2}$$

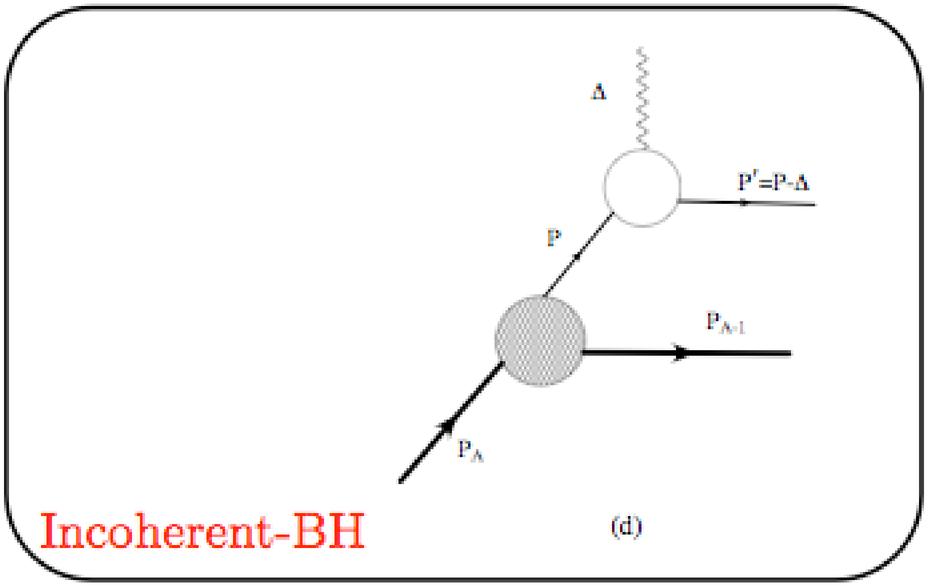
$$\boxed{\Im\mathrm{m}\, \mathcal{H}_A(X, \zeta, t) = -\pi \sum_q e_q^2 \left[H_A^q(\zeta, \zeta, t) + H_A^{\bar{q}}(\zeta, \zeta, t)\right]}$$

(Kirchner and Mueller, 2004)

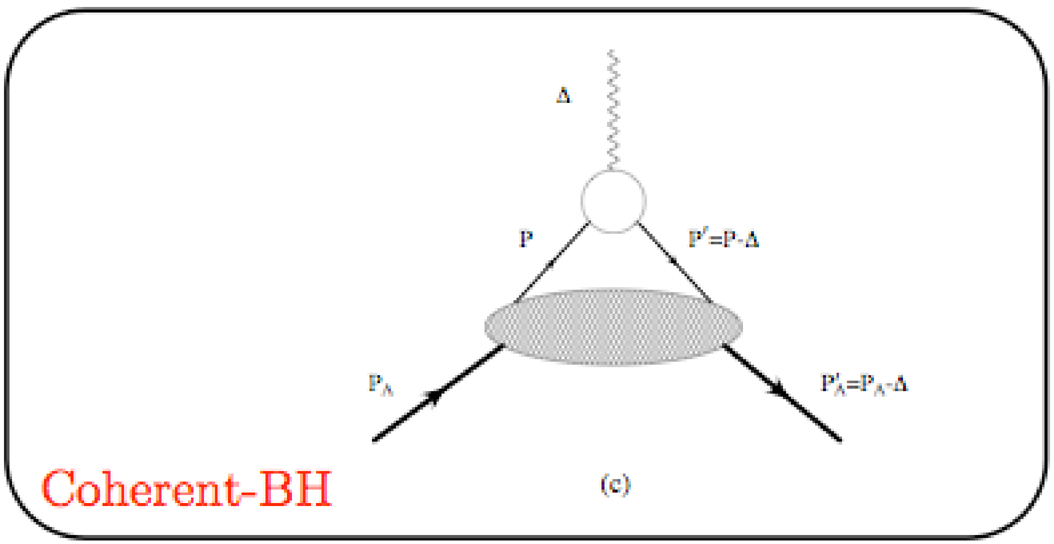
Coherent vs. Incoherent processes



Similarly for Bethe Heitler processes from nuclei



(d)



(c)

$\Rightarrow$ Interference Term for Coeherent DVCS & BH

$$\mathcal{I}_{coh}(\zeta,t) = \mathcal{K}\, H^A(\zeta,t) \times Z^2 F^A(t)$$

Non-forward spectral function

$$\boxed{H^A(\zeta,t) = \int \frac{d^2P_\perp dY}{2(2\pi)^3} \mathcal{N}\, \rho^A(Y,P^2;\zeta,t) H^N\left(\frac{\zeta}{Y},\frac{\zeta}{Y},t;P^2;\right)}$$

$\uparrow$ **off-forward EMC-effect** $\uparrow$

$\Rightarrow$ Interference Term for Incoeherent DVCS & BH

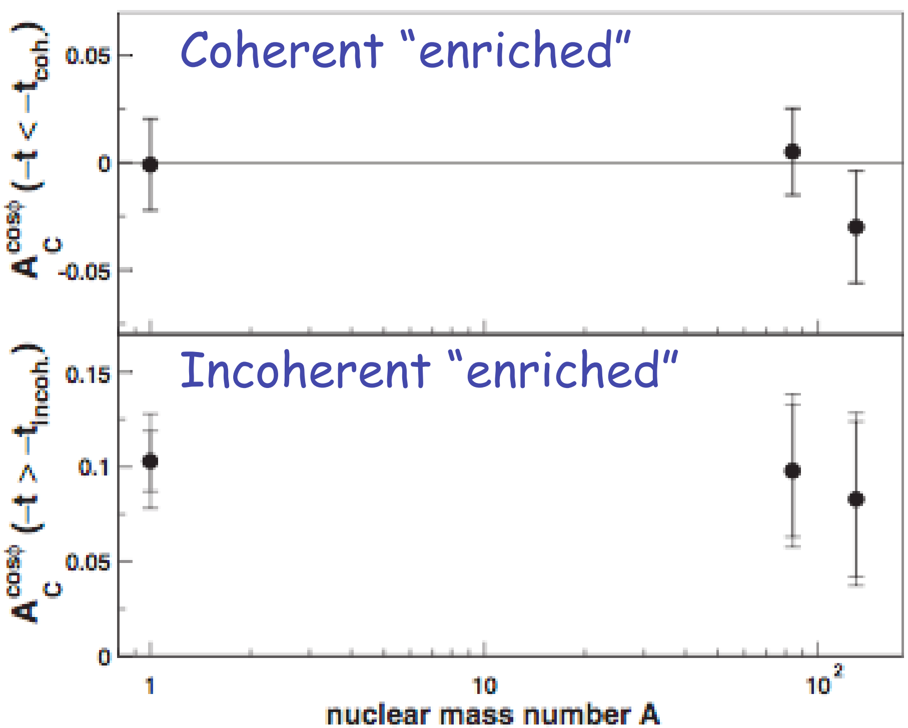
$$\mathcal{I}_{inc}(\zeta,t) = \mathcal{K} H_0^A(\zeta,t) \times Z F_1^N(t)$$

Forward spectral function

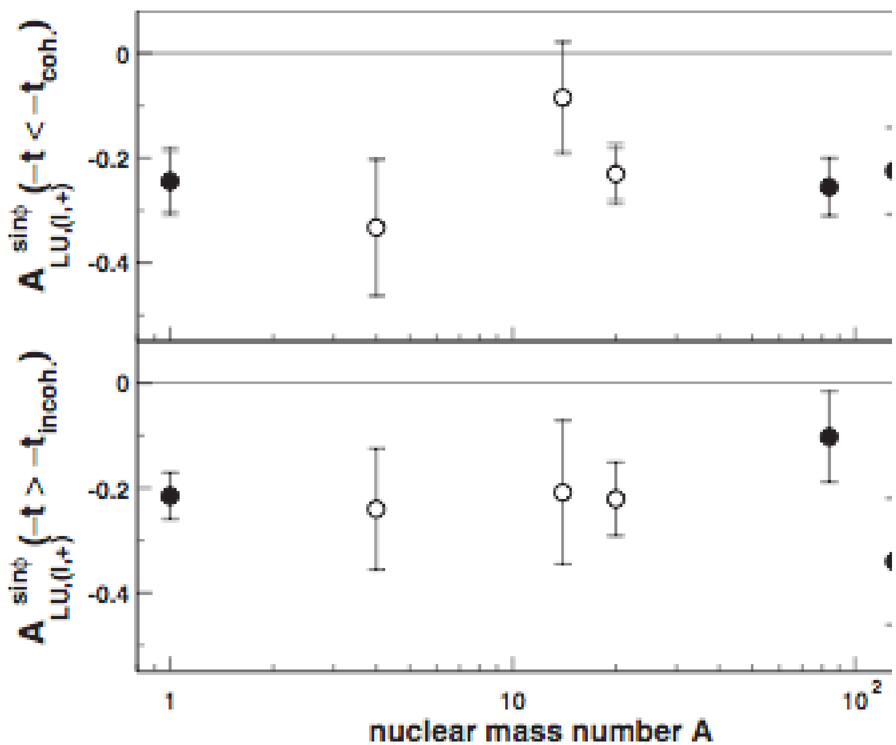
$$\boxed{H_0^A(\zeta,t) = \int \frac{d^2P_\perp dY}{2(2\pi)^3} \mathcal{N}\, \rho_0^A(Y,P^2) H^N\left(\frac{\zeta}{Y},\frac{\zeta}{Y},t;P^2\right)}$$

Hermes ⇒ first data

Phys.Rev.C81 (2010)



Beam Charge Asymmetry

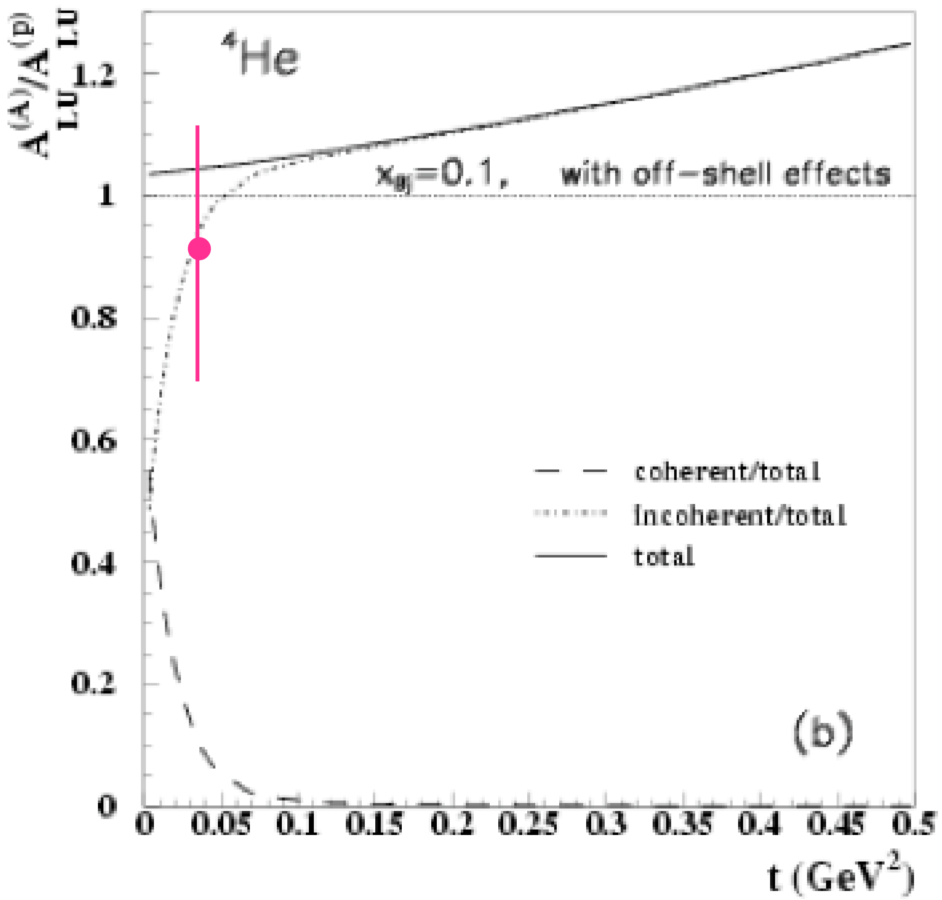


Beam Spin Asymmetry

$R_{LU}^{\sin\phi}(A/p) = 0.91 \pm 0.19$ coherent

$R_{LU}^{\sin\phi}(A/p) = 0.93 \pm 0.23$ incoherent

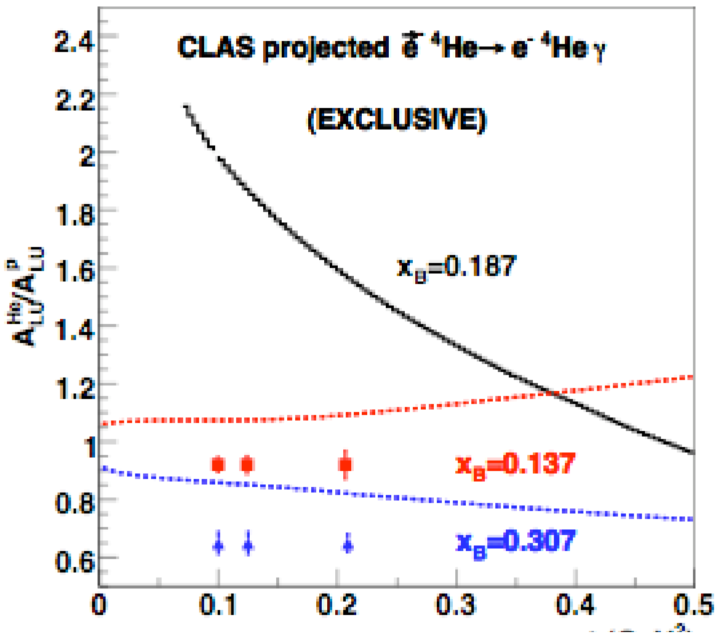
Hermes data

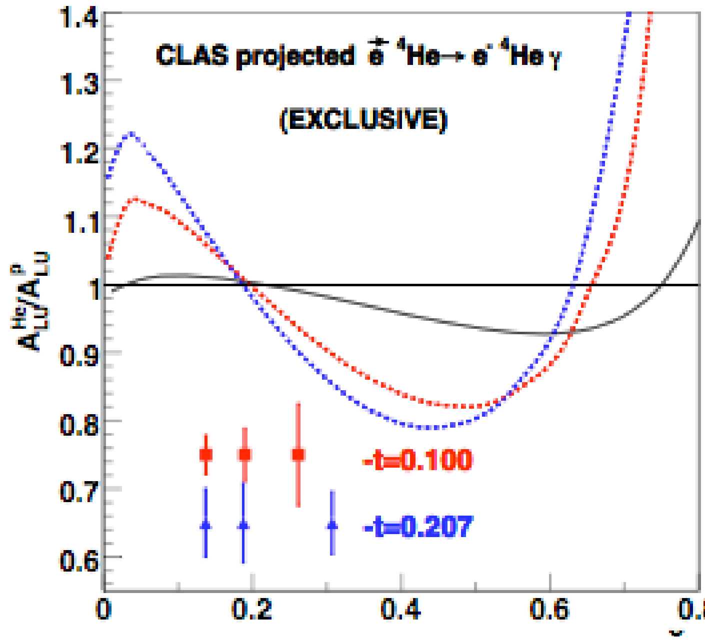


$$\boxed{R_{LU}^{(A)}(\zeta,t) = A_{LU}^{A}/A_{LU}^{p} = \frac{Z^2\mathcal{I}_{coh}^A + Z\mathcal{I}_{incoh}^A}{\mathcal{F}_{DVCS}^p(\zeta,t)F_1(t)} \times \frac{F_1^2(t)}{Z^2F_A^2(t)+ZF_1^2(t)}}$$

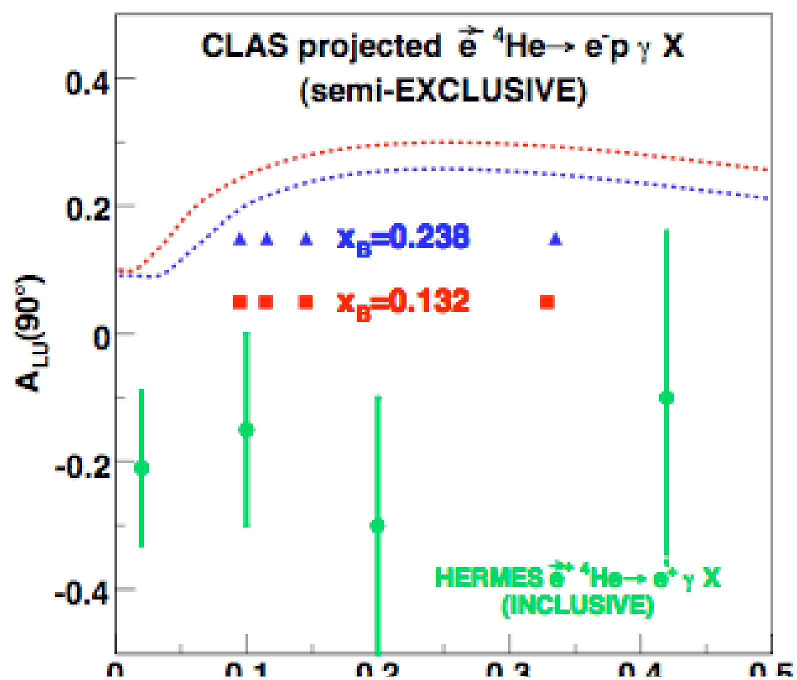
$$\mathcal{I}_{coh}^A = \mathcal{F}_{DVCS}^A(\zeta,t)F_A(t) \qquad \mathcal{I}_{incoh}^A = \mathcal{F}_{DVCS,0}^A(\zeta,t)F_1(t)$$

Jlab/Hall B analysis (K. Hafidi et al.) in progress (talk by H. Egiyan at DIS 2





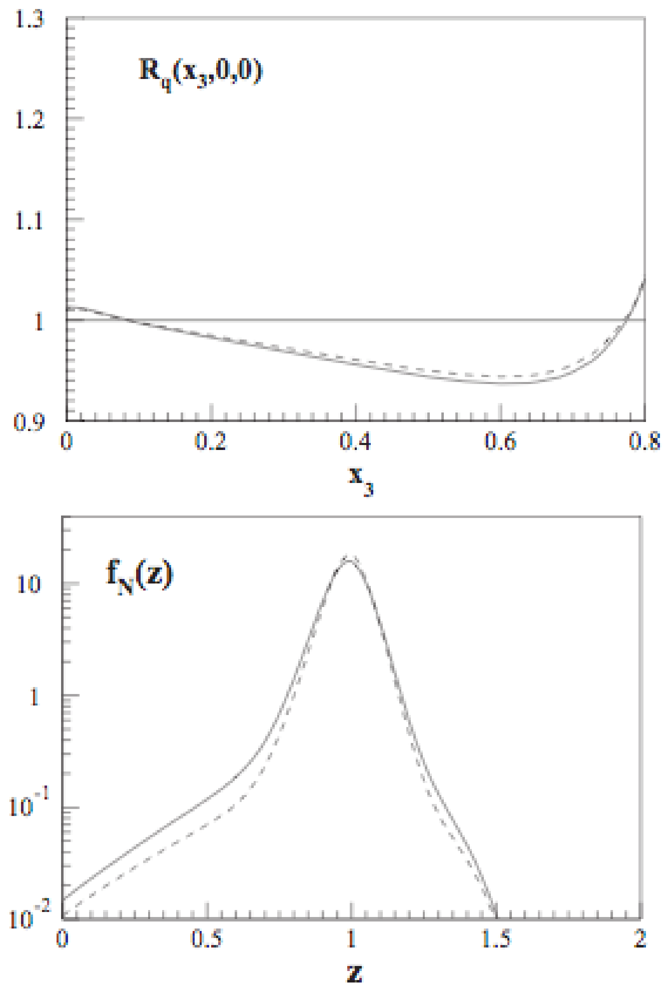
coherent



incoherent

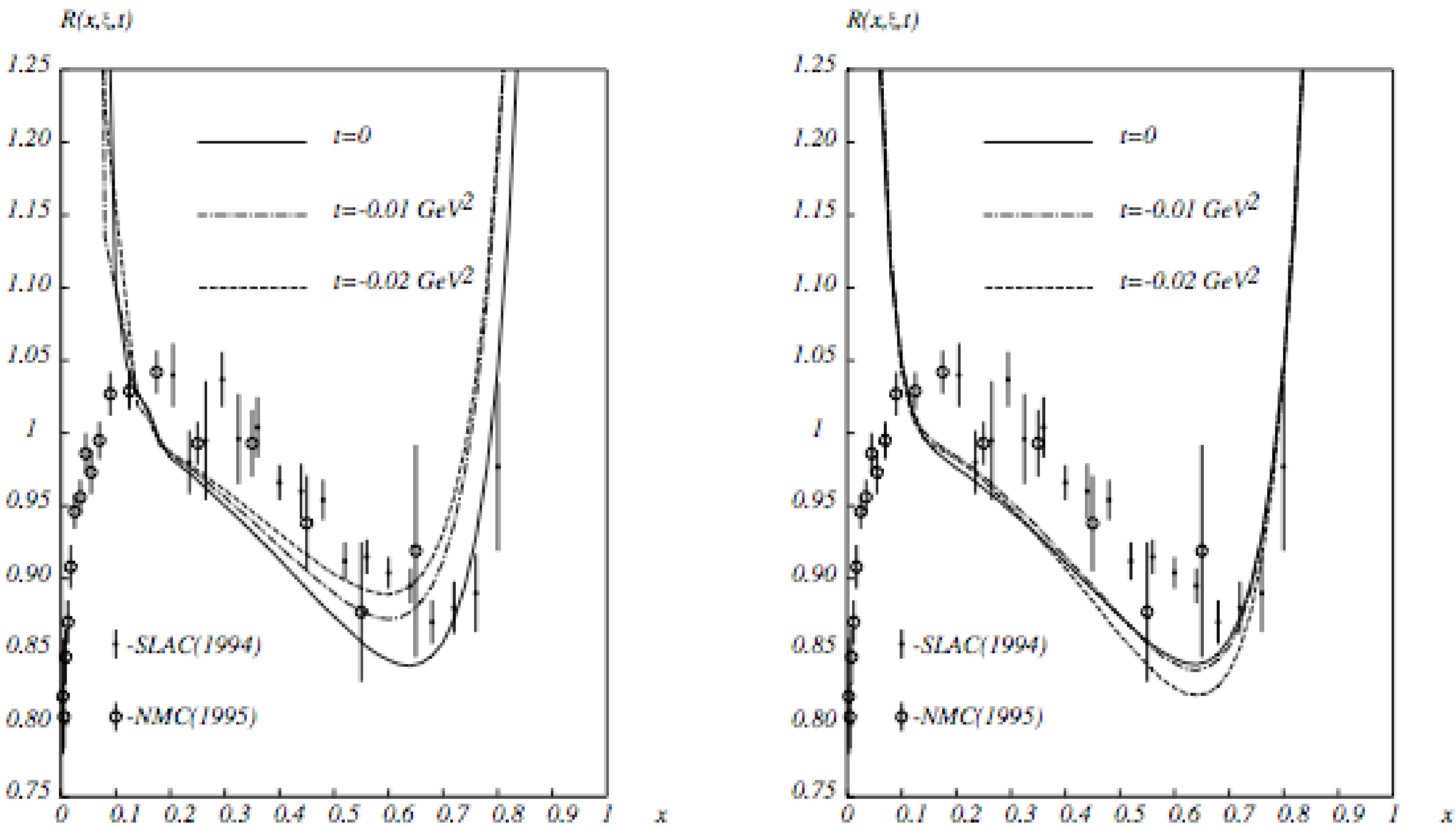
Main issue and Models

S. Scopetta, Phys.Rev.C79 (2009)



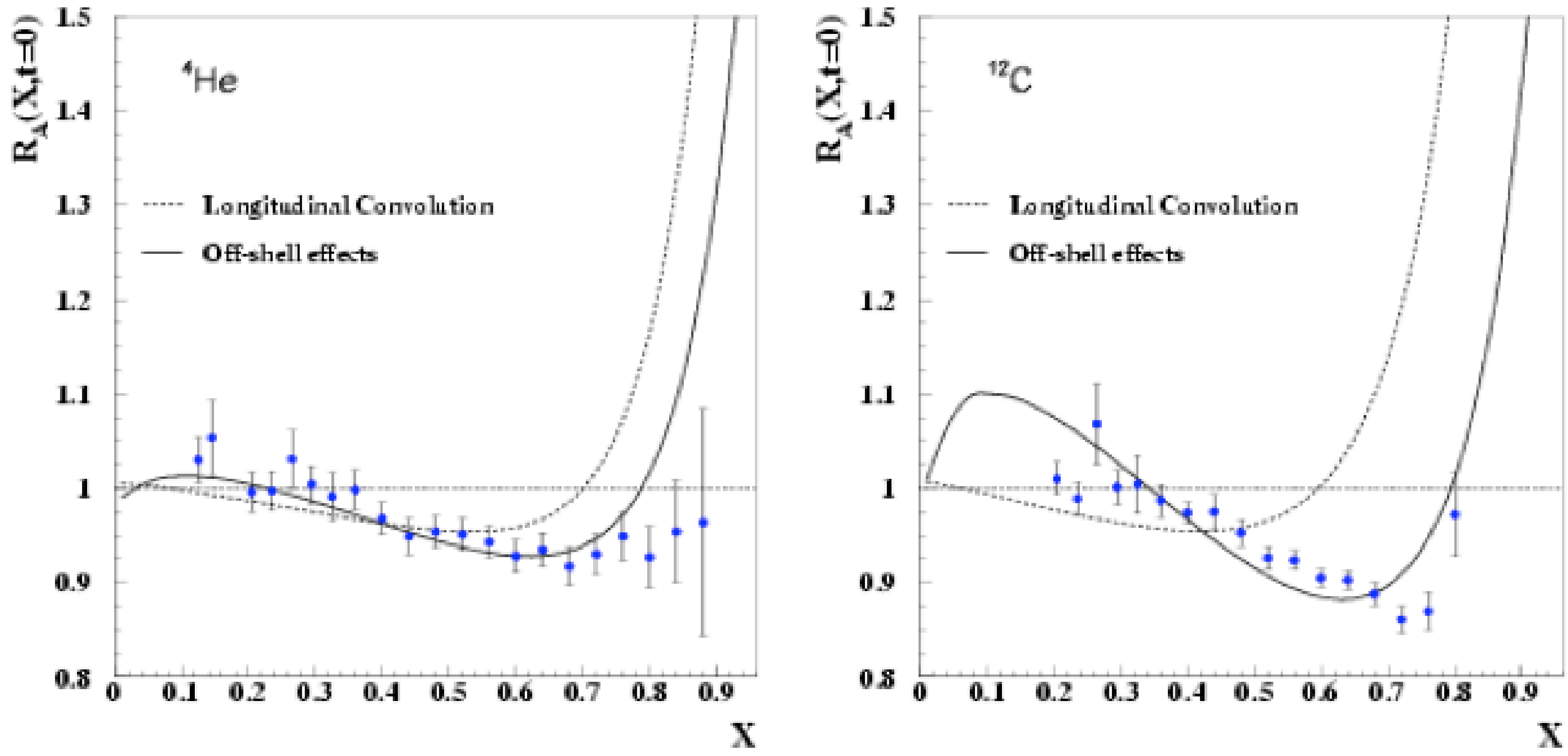
Remark again "conventional" nuclear effects

Guzey and Siddikov (2006)

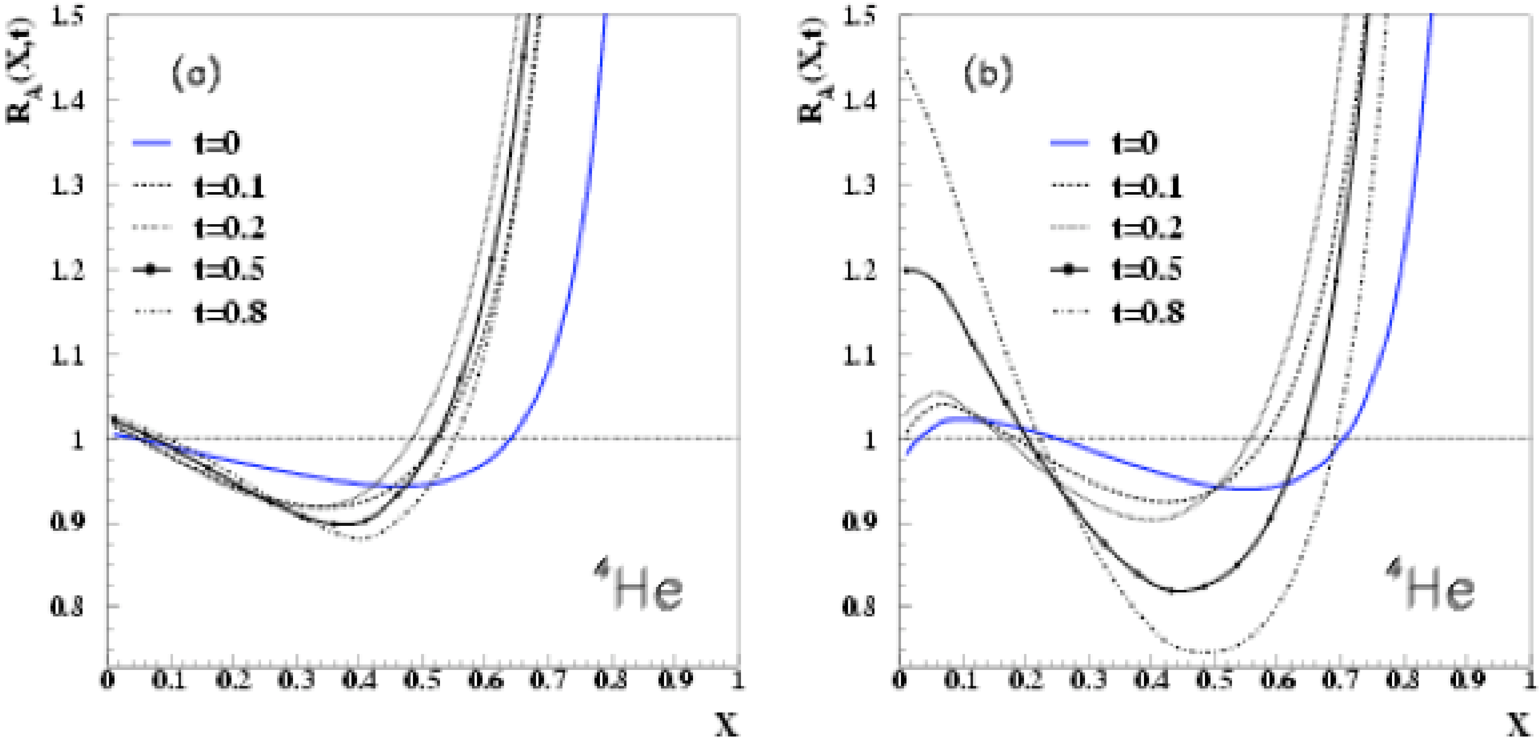


Introduce meson d.o.f. ⇒"pion excess" model

Liuti and Taneja (2005)



Effect is related to <u>transverse motion of quarks</u>



(a)
$R_A(X,t)$
t=0
t=0.1
t=0.2
t=0.5
t=0.8
^{4}He
X
(b)
$R_A(X,t)$
t=0
t=0.1
t=0.2
t=0.5
t=0.8
^{4}He
X

Moral: do exclusive experiments help us understand nuclear medium modifications and/or QCD in nuclei or are we back to square one?

(to the Everyone's Model's Cool effect? G.Miller)

Explanation of Result

- Why larger dip?

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

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

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

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

- 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!!

Brodsky, Yang, Schmidt, PRD (2

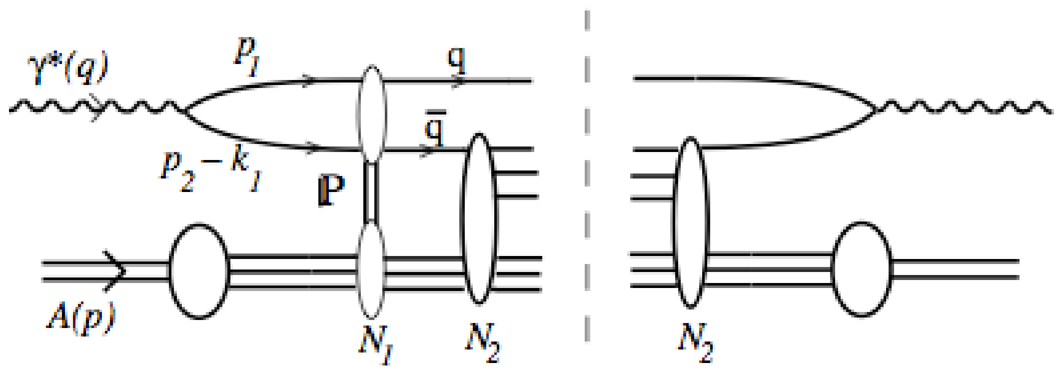


Figure 2: Glauber-Gribov shadowing involves interference between rescattering amplitudes.

Brodsky: the Glauber-Gribov picture involves interference between rescattering amplitudes

S.L. and Taneja: these effects, by "tagging" on transverse components are enhanced in exclusive experiments

Nuclei are a unique handle to test/highlight role of partons multi-correlations, ISI and FSI!

Nuclear Exclusive: Form Factor in Nuclei

S.L., hep-ph/0601125

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

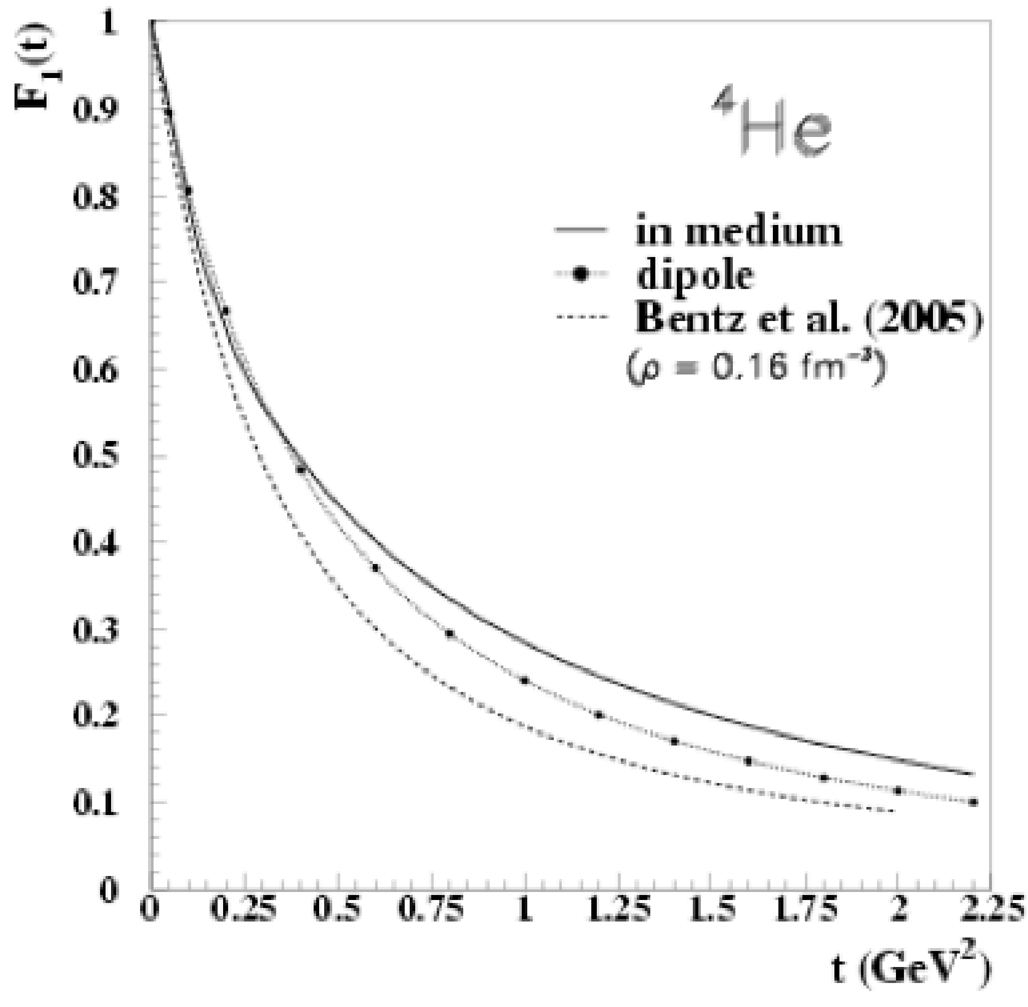
$$F_A^{LC}(t) = F_A^{point}(t) F_N(t)$$

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

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

↑ **Medium Modified Form Factor** ↑

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



Conclusions and Outlook

- In exclusive experiments in the MEIC range nuclei provide an even better laboratory to study QCD in coordinate space: vast phenomenology…
- We have seen more constraints on GPDs from nuclei…
- …and at the same time new insights on nuclear modifications from GPDs
- Re-interactions are important and emphasize transverse d.o.f.: need to explore connections between k_T and b (tomorrow's talk)
- Comparison between GPD models and data is indeed possible…GPD extraction is possible!!!
- "Global Analysis" is an essential step