Theory of the EMC effect and GPDs in Nuclei

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Nuclear Structure and Dynamics at Short Distances

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Challenges from the organizing committee…

- Can the many-body-effects appearing in the interaction current be separated from those appearing in the wave function?
- ✓ Can conventional nuclear theory provide calculations of the observables measured in coincidence experiments?
- What is the relation between two-nucleon correlations and the EMC effect?
- ✓ What is the role of relativistic effects in the present context?
- What experiments can determine the role of three nucleon correlations?
- ✓ What is the role of quark, as opposed to nucleon or meson, effects in understanding the plateau and the EMC effect?
- ✓ Which other reactions can be used to elucidate the effects of short-ranged correlations?
- ✓ How can the EMC effect be studied in semi-inclusive DIS (and exclusive DVCS)?
- How do hadronization effects reveal themselves in semi-inclusive DIS?

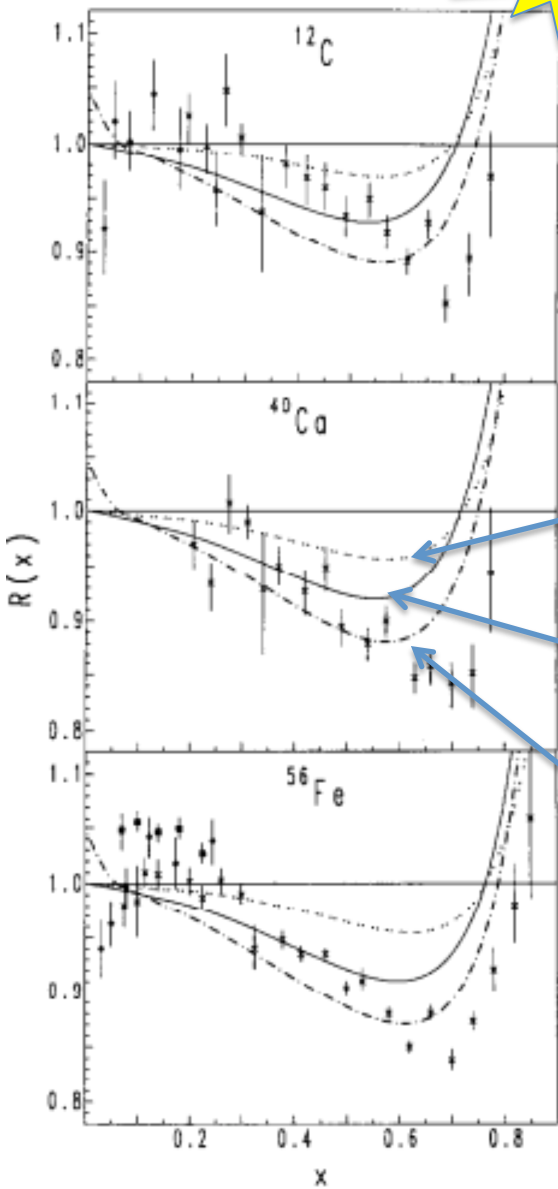
Outline

- ✓ Some theoretical issues on the EMC effect
- ✓ Introduction to Generalized Parton Distributions (GPDs) and Deeply Virtual Compton Scattering (DVCS): Kinematics and Definitions
- ✓ What we can learn from GPDs and DVCS from Nuclei
- ✓ QCD analysis of DVCS from Nuclei

… ab initio….

Ciofi, Liuti, Phys. Lett. B

20 July 1989



Binding: Akulinichev, Kulagin, Vagradov

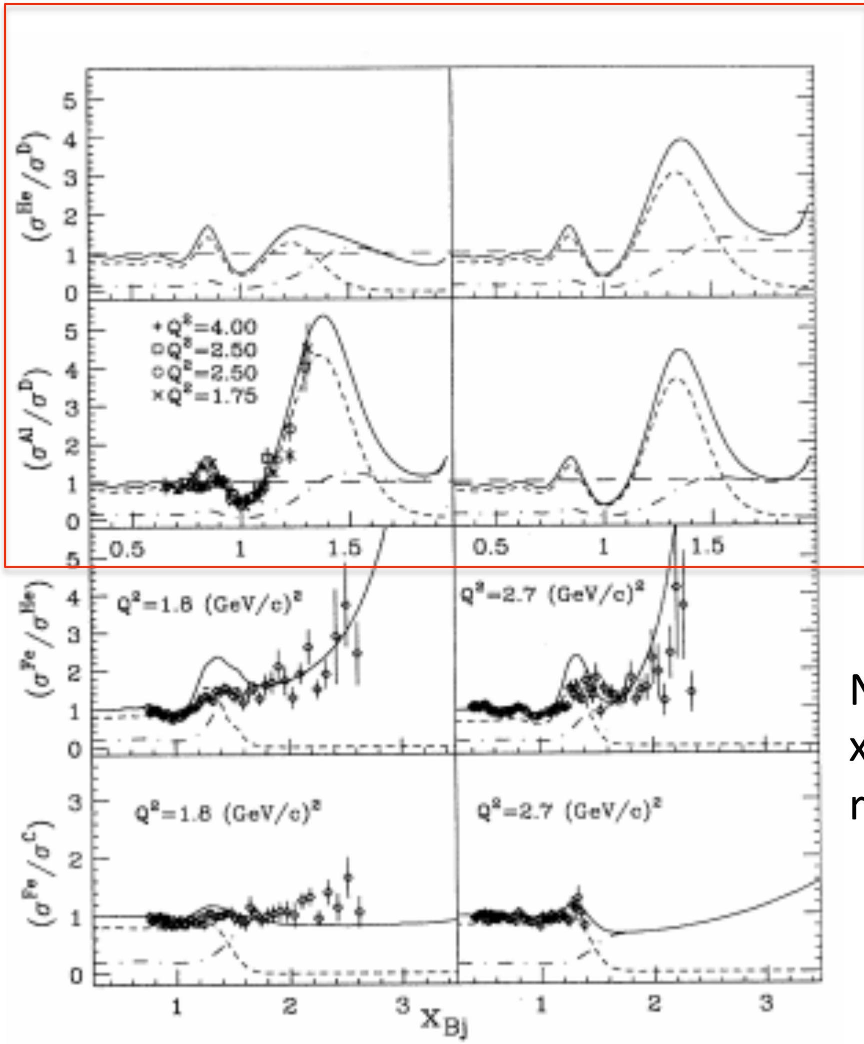
Phys.Lett.B(1985)

SRC

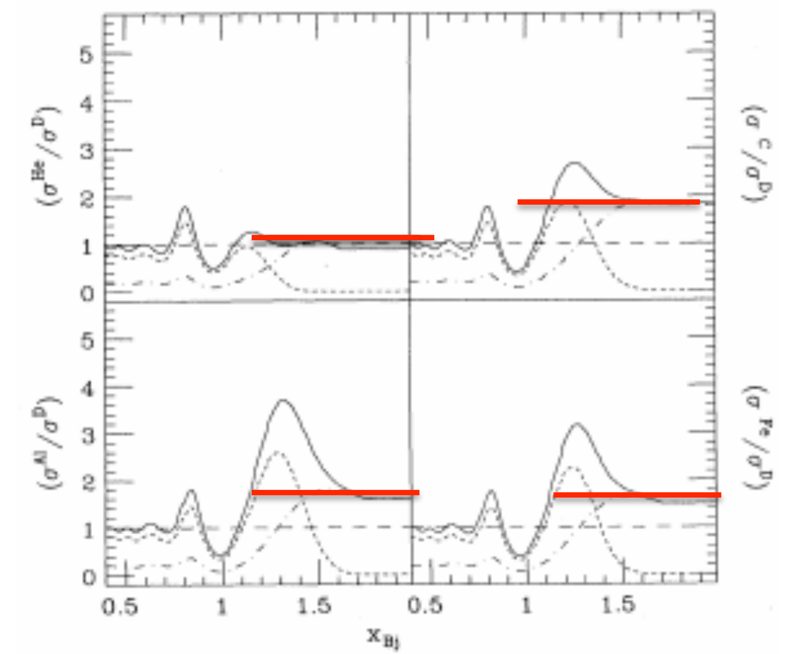
Q^2 –rescaling, "quick-fix"

… ab initio….

S. Liuti, Phys.Rev. C47 (1993): “results will depend on whether similar kinematical regions in the spectral function are integrated over”



Numerator and denominator calculated at same x_{Bj}

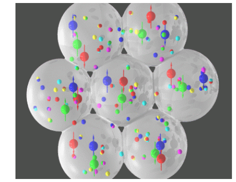


Numerator and denominator calculated at shifted x_{Bj} so as to cover the same areas in momentum and removal energy:

$$R = \sigma_A(y_A = y_D) / \sigma_D(y_A = y_D),$$

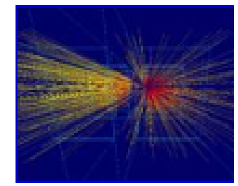
A BRIEF HISTORY…

➔ 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….



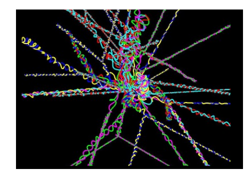
1980

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



1990

➔ 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….



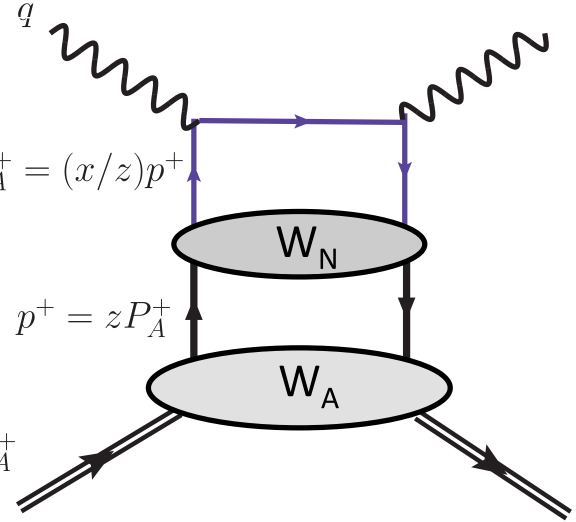
2000

➔ 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.

2010

Images from Univ. of Frankfurt + G. Miller websites

The EMC Effect: Kinematics and Definitions



Nucleon Correlator

$$W_\Lambda^{\gamma^+}(p,k) = \int \frac{d^4 z}{(2\pi)^4} e^{ikz} \langle p, \Lambda \mid \overline{\Psi}(0)\gamma^+ \mathcal{W} \Psi(z) \mid p, \Lambda \rangle$$

$$\downarrow$$

$$W_\Lambda^{\gamma^+}(p,x) = \int dk^- d^2 \vec{k}_T \, W_\Lambda^{\gamma^+}(p,k)$$

$$= \int \frac{dz^-}{2\pi} e^{ikz} \langle p, \Lambda \mid \overline{\Psi}(0)\gamma^+ \mathcal{W} \Psi(z) \mid p, \Lambda \rangle \,|_{z^+=0, z_T=0}$$

Probabilistic interpretation:

$$W_\Lambda^{\gamma^+}(p,x) = \int dz^- e^{ikz} \langle p,\Lambda \mid \overline{\phi}(0)\phi(z) \mid p,\Lambda\rangle \mid_{z^+=0, z_T=0} = f_1(x)\bar{u}(p,\Lambda)\gamma^+ u(p,\Lambda) \quad (6)$$

where $\phi = (1/2)\gamma^-\gamma^+$. Then

$$F_2(x) = \sum_\Lambda W_\Lambda^{\gamma^+}(p,x) \quad (7)$$

$$F_2(x) = \sum_X \delta(p^+ - xp^+ - p_X^+) \mid \langle X \mid \phi(0) \mid p,\Lambda\rangle \mid^2 \quad (8)$$

In a nucleus:

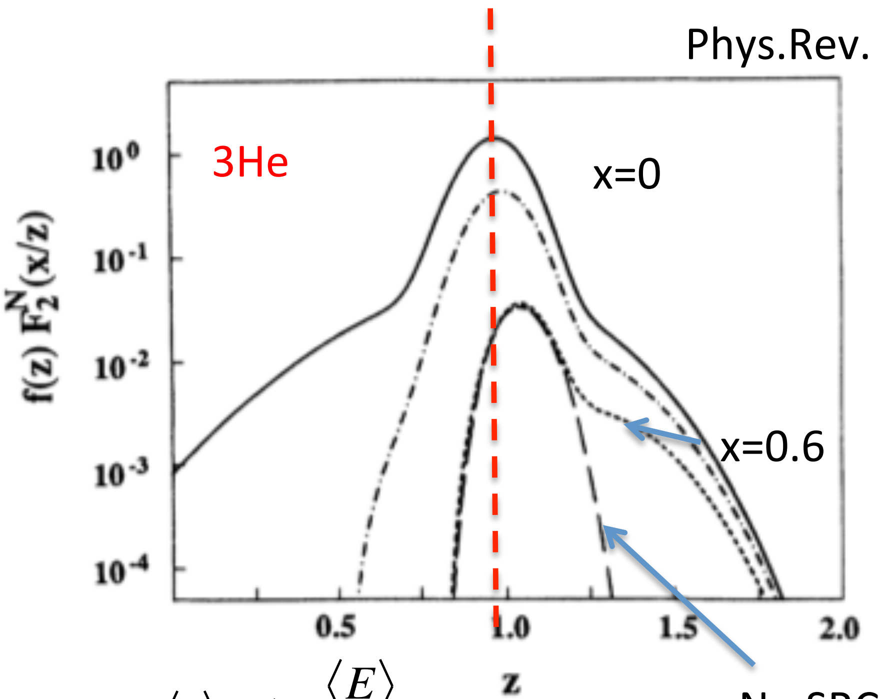
$$W_\Lambda^{\gamma^+}(P_A,k) = \int d^4p\, W(P_A,p) W_\Lambda^{\gamma^+}(P,k)$$

Naïve Convolution Formula

$$F_2(x) = \int_x^A dz\, f_A(z) F_2^N(x/z)$$

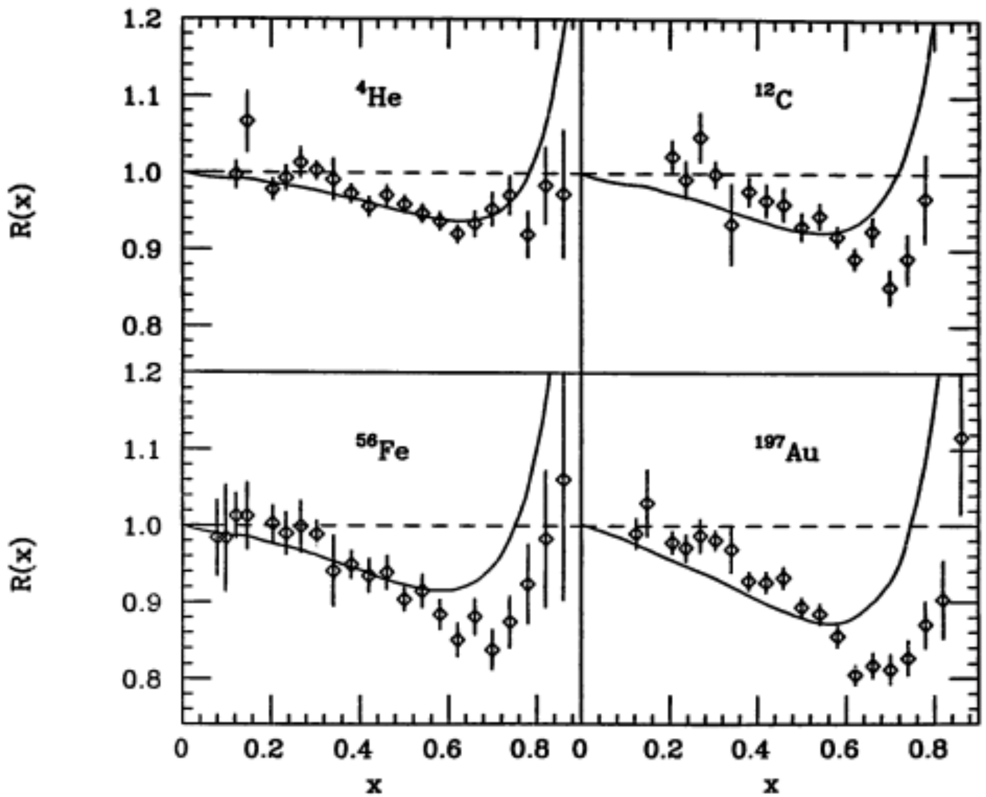
$$f_A(z) = 2\pi M \int dE \int_{k_{\min}(z,E)} dk\, k\, P_A(k,E)$$

Phys.Rev. C41 (1990) 1100-1114

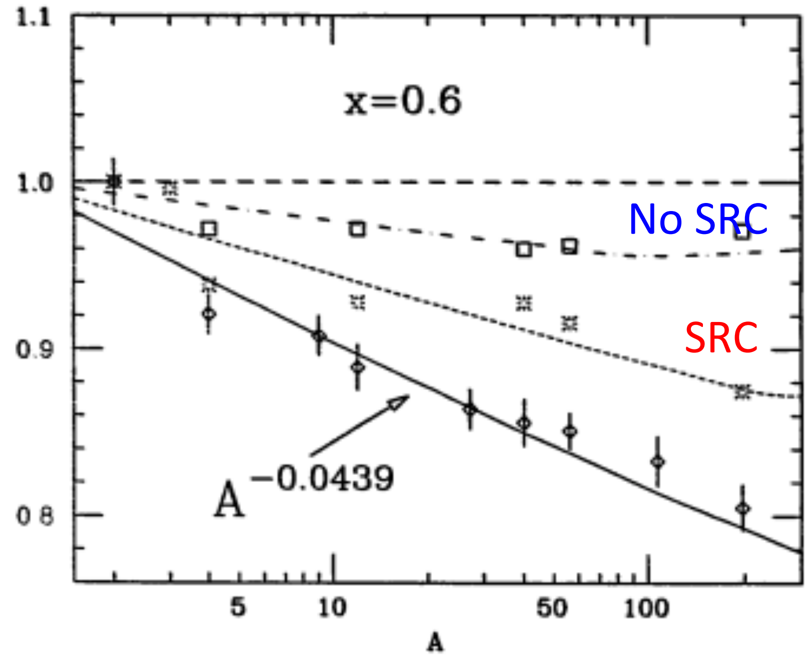


$$\langle z \rangle \approx 1 - \frac{\langle E \rangle}{M}$$

But.....

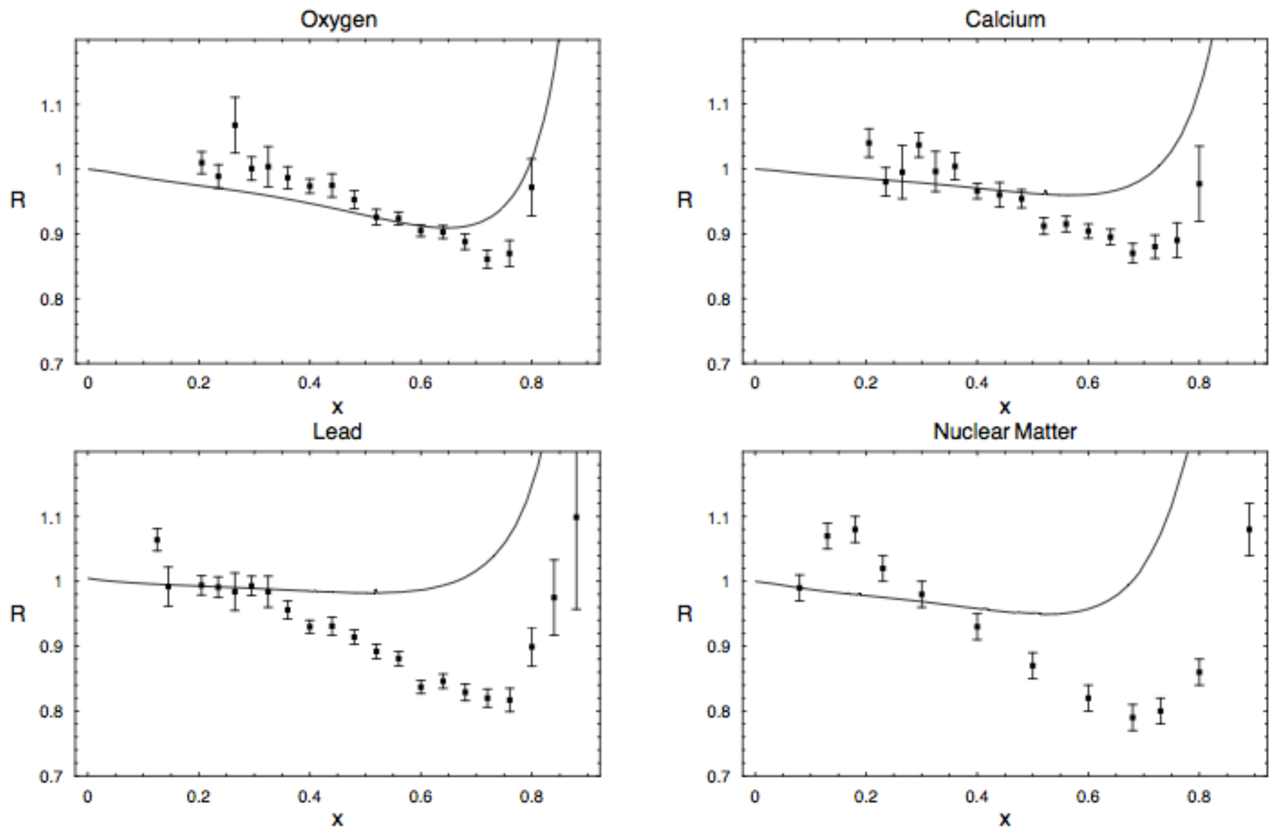


R(x)
1.2
1.1
1.0
0.9
0.8
^{4}He
^{12}C
^{56}Fe
^{197}Au
0
0.2
0.4
0.6
0.8
x



1.1
1.0
0.9
0.8
x=0.6
No SRC
SRC
$A^{-0.0439}$
5
10
50
100
A

LC extension of the Hugenholtz VanHove theorem

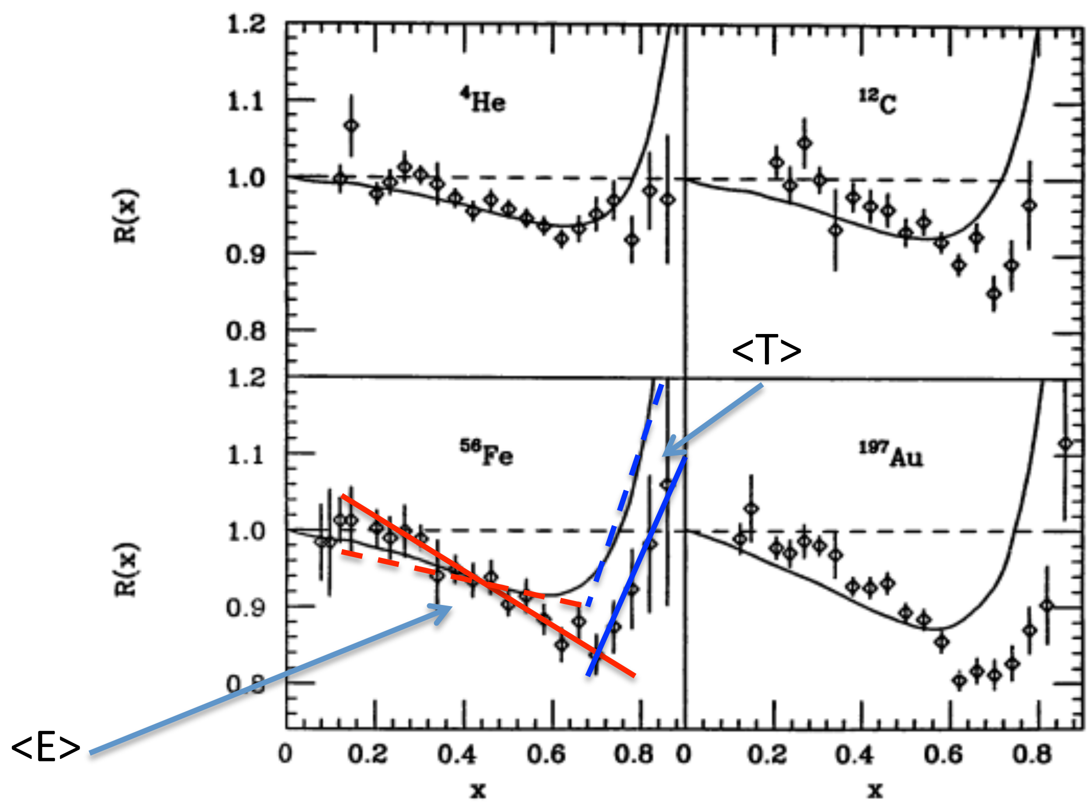


G. Miller

Because of Koltun Sum Rule

$$\langle E \rangle = 2\varepsilon_A + \frac{A-2}{A-1}\langle T \rangle - \langle V_3 \rangle$$

There is a tension between E and T, the two slopes are related, no extra d.o.f. for modeling…



Beyond naïve convolution formula In nuclei:

S.L. and S.K. Taneja, PRC (2005)

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

where:

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

The punch line: factorization is broken

$$F^A(X,\zeta,t) = \int \frac{d^4P}{(2\pi)^4} F^N_{OFF}(X_N,\zeta_N,P^2,t)\,\mathcal{M}^A(P,P_A,\Delta),$$

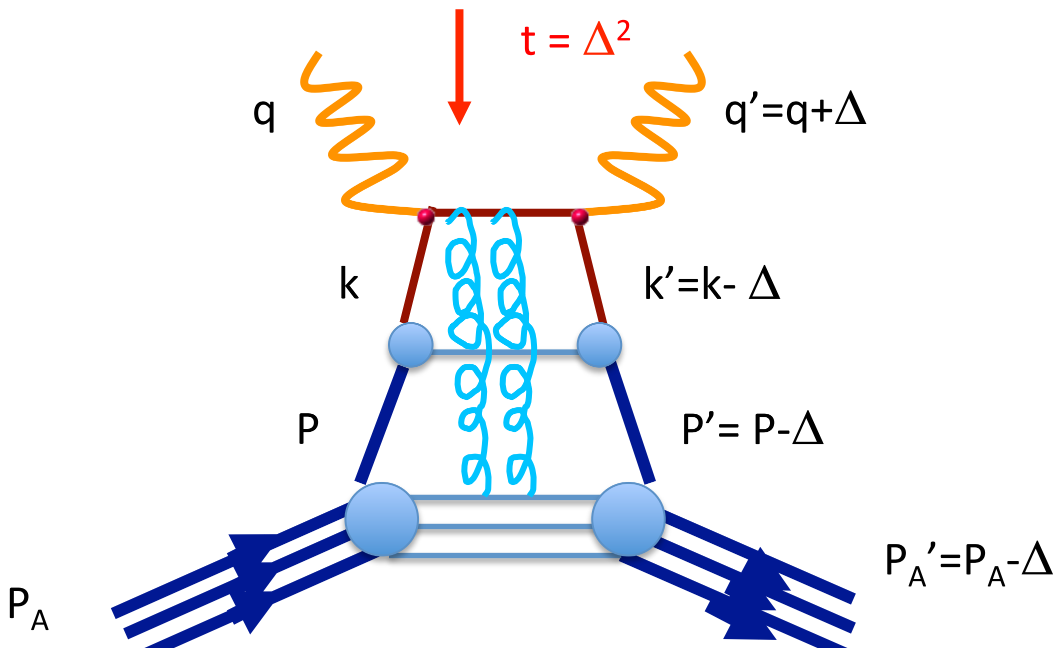
We cannot factor out the transverse degrees of freedom!

to $m_\pi^2 \cong 0.02$ GeV. Whether the distribution of quarks in a pion so far off shell is the same as the distribution on shell is anybody's guess. In any case, advocates of pion and other convolution based models ignore any p^2 dependence of the constituents' quark distributions.

The assumptions leading to a convolution model are arguable at best

R. Jaffe, 1985

A clear case where FSI dominates exists at low x_{Bj}



Brodsky, Schmidt, Yang
Brodsky, Hoyer, Peigne', Sannino

"model FSI at low x in terms of Pomeron, Reggeon, Odderon exchanges" (see S.Brodsky's talk)

Brodsky, Schmidt, Yang PRD (2004)

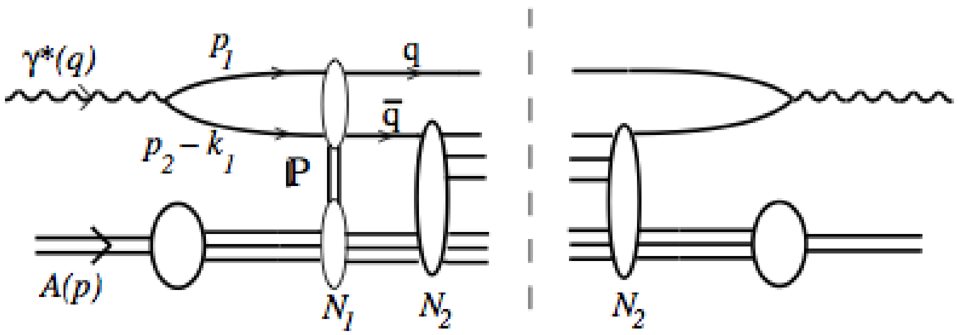
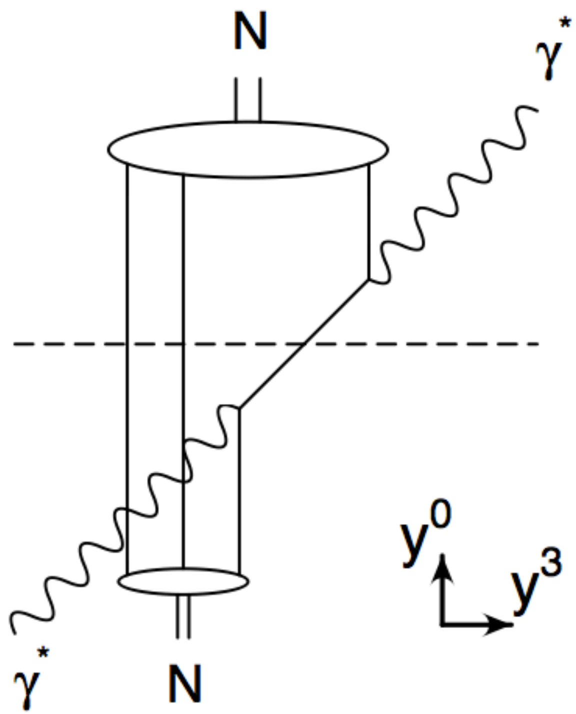


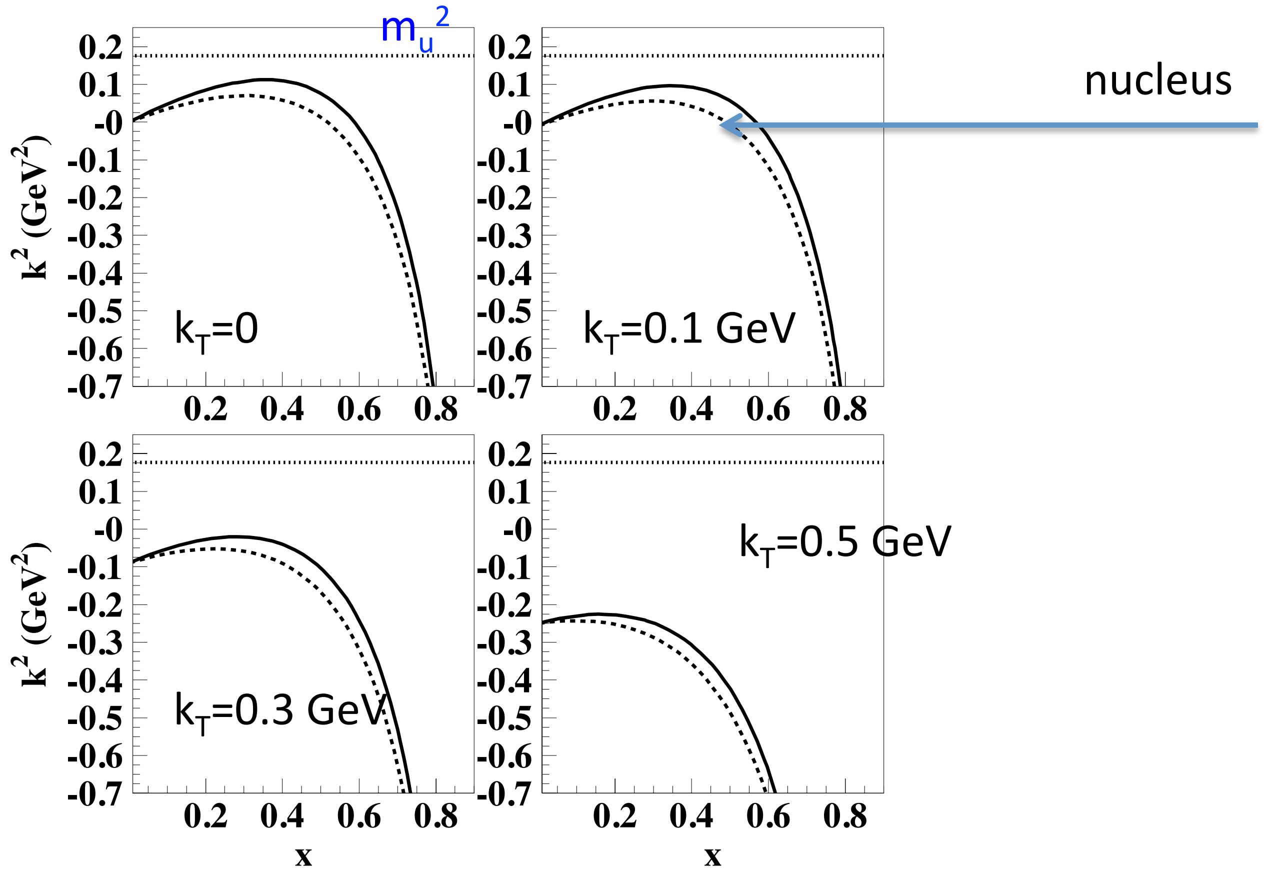
Figure 2: Glauber-Gribov shadowing involves interference between rescattering amplitudes.

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

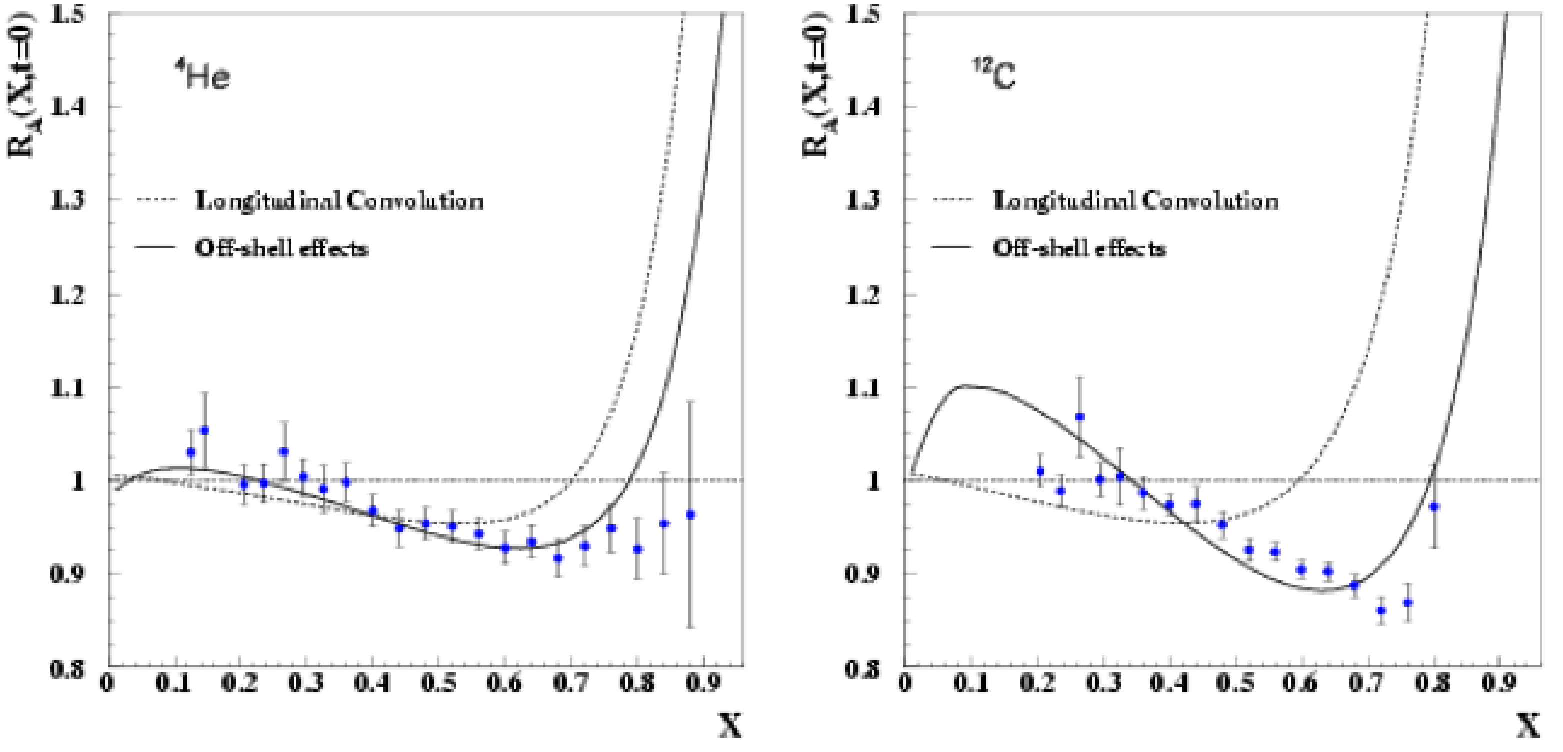
Key argument (Hoyer and Vanttinen): at low x the LC time is long enough to allow for coherent effects



Parton off-shellness for PDFs



Liuti and Taneja (2005)



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

Next using GPDs formalism, I will argue that at large x parton reinteractions in nuclei are also leading effects because of the enlarged parton offshellness

Nuclear GPDs: motivations

- Nuclear GPDs, by providing spatial distributions of partonic configurations in hadrons allow us to discern among different proposed mechanisms for the nuclear EMC effect ➔ interesting connection with TMDs (role of FSI)
- Nuclear GPDs shed light on the role of OAM in hadrons for spin ≠1/2 (S=1, deuteron), (S=0, ^{4}He).
- Moments: quarks and gluons angular momentum
- Finally, nuclear GPDs allow one to validate the onset of Color Transparency phenomena by monitoring directly in coordinate space the dominance of partonic small size configurations

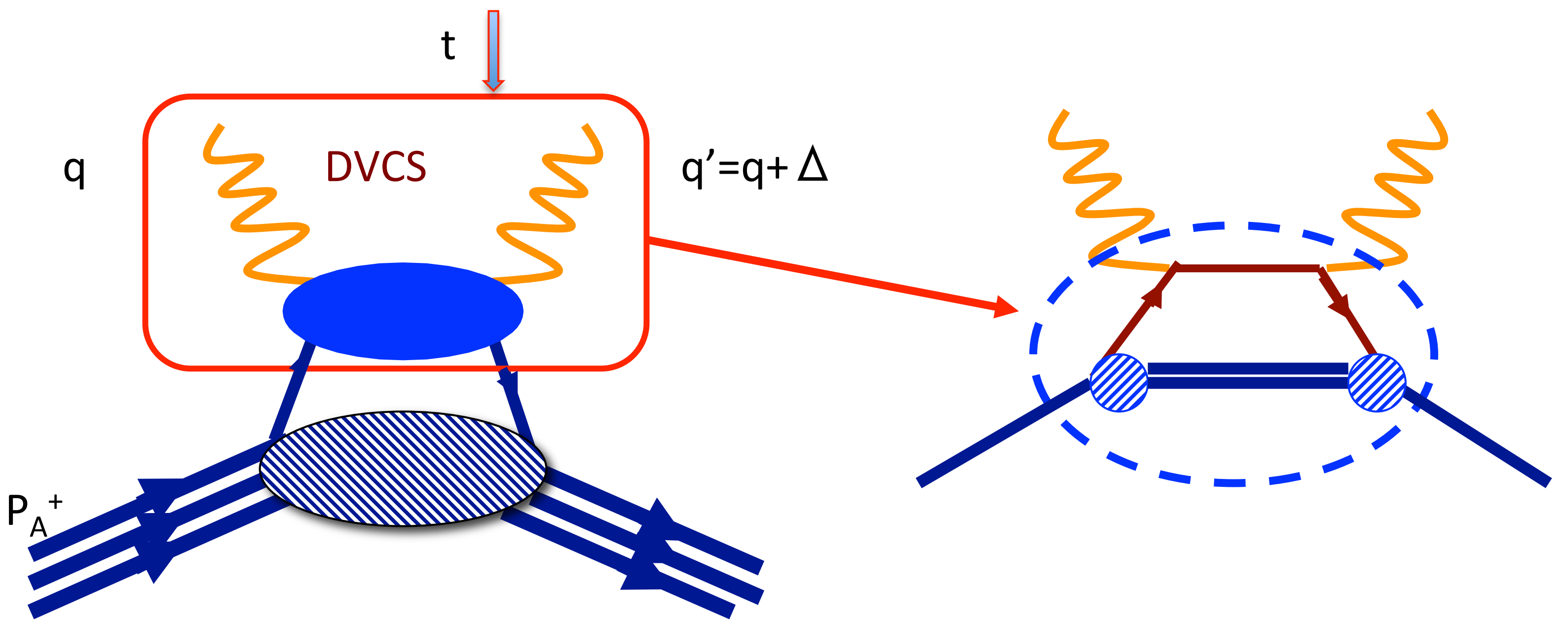
Off-forward EMC effect: Longitudinal Convolution Formula

Nuclear Hadronic Tensor

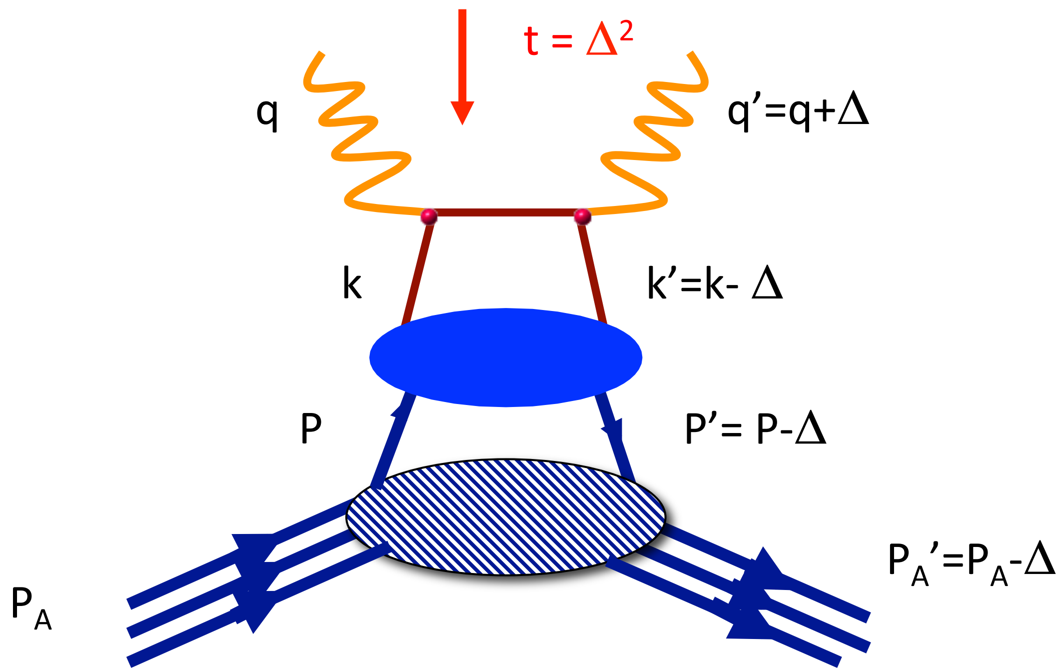
$$T^A_{\mu\nu}(P_A,\Delta) = \int \frac{d^4P}{(2\pi)^4} T^N_{\mu\nu}(k,P,\Delta)\,\mathcal{M}^A(P,P_A,\Delta),$$

Nuclear Correlator

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



Non-forward kinematics



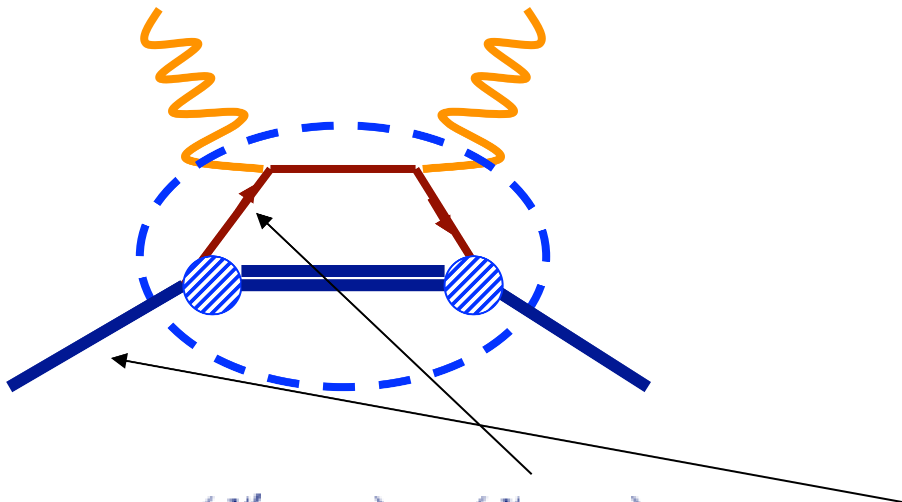
Longitudinal momentum fractions

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

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

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

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



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

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

Go To Previous Page

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

$U_{A-1} \rightarrow$ 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

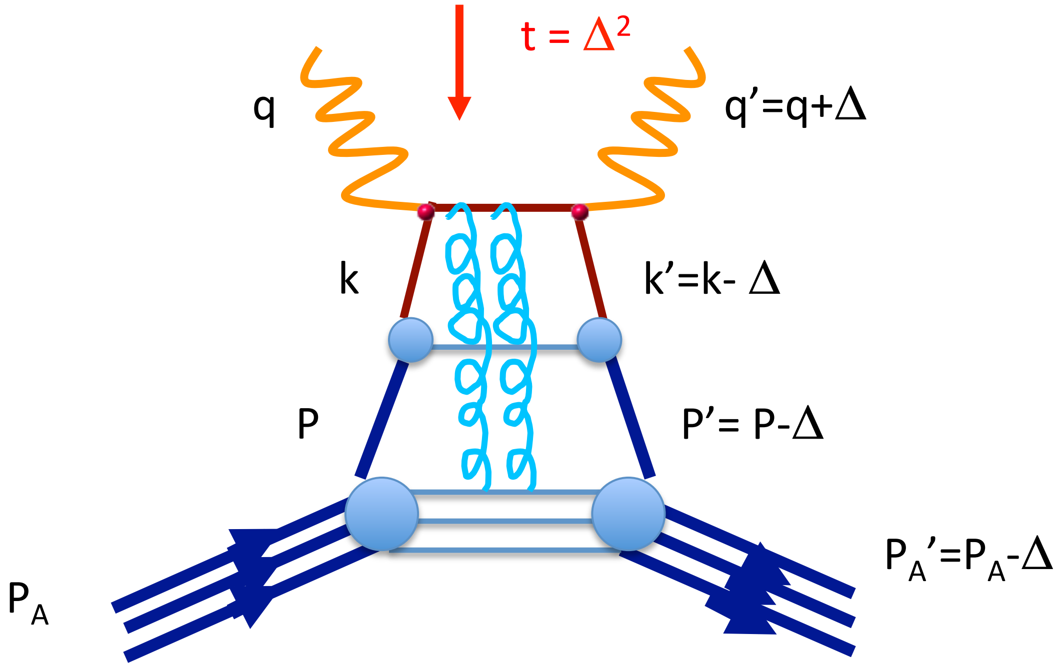
$$\begin{aligned} \rho_A(P^2, P'^2) &\approx S_A(|\,\mathbf{P}\,|, |\,\mathbf{P}'\,|, E) \\ &= \sum_f \Phi_f(|\,\mathbf{P}\,|)\Phi^*_f(|\,\mathbf{P}'\,|)\delta\left(E - (E^f_{A-1} - E_A)\right) \end{aligned}$$

With LC variables

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

Meaning of model beyond longitudinal convolution

k_T dependent nuclear structure function ≈ "Nuclear Lensing Function" × GPD

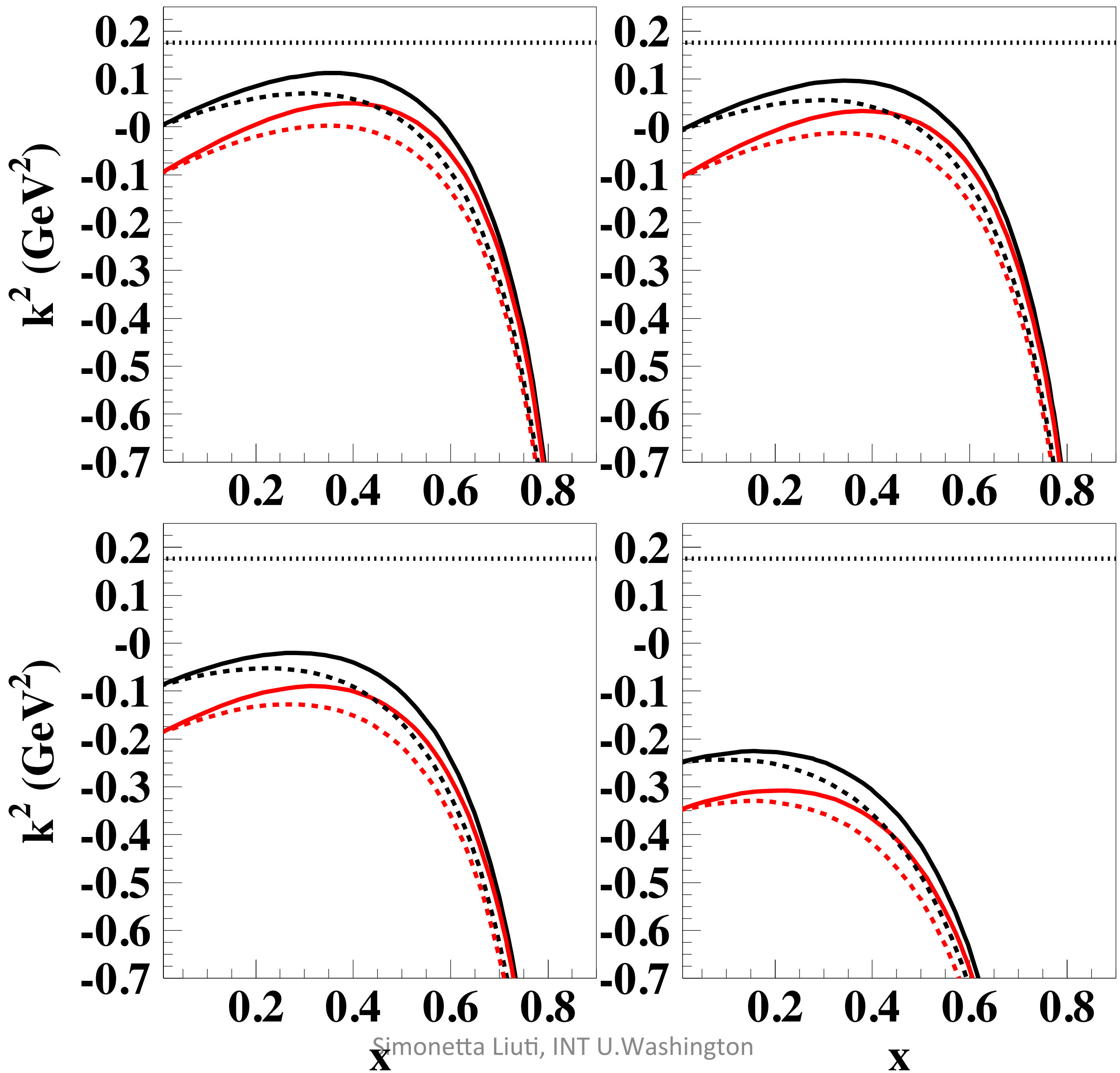


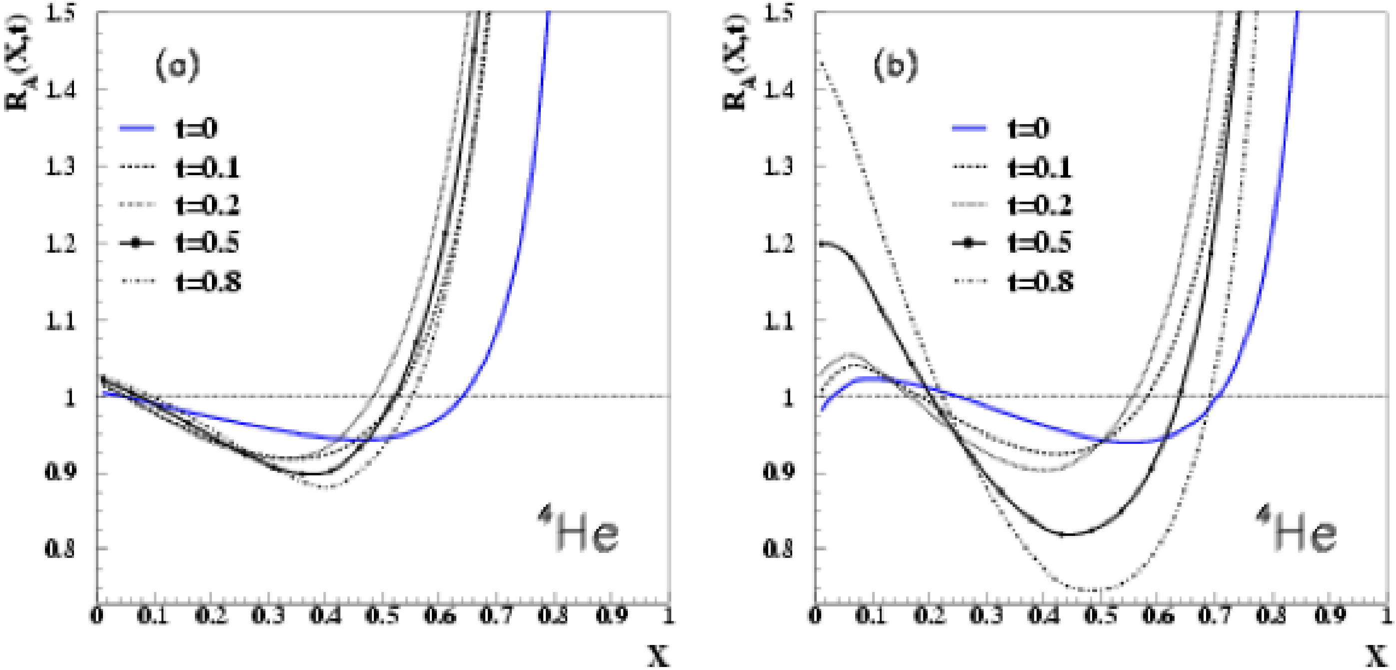
FSI are present, they affect how one goes "off the LC" in the transverse direction, this effect is larger in nuclei

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

Off-shellness

t=-0.1 GeV^2





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

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

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

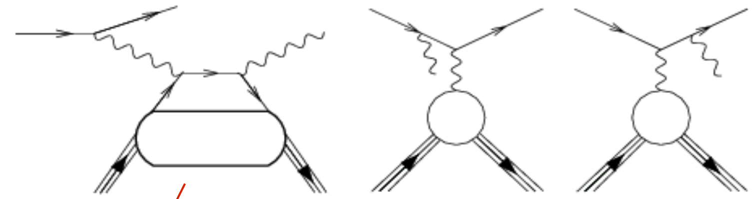
- Similarly for $k_\perp$-dependent mechanism giving anti-shadowing

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

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

Extracting GPDs from Cross Sections and Beam Spin Asymmetries

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



(a) (b)

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

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

$$\frac{d^4\Sigma}{dQ^2 dx_{Bj} dt d\phi} \equiv \frac{d^4\sigma^+}{dQ^2 dx_{Bj} dt d\phi} - \frac{d^4\sigma^-}{dQ^2 dx_{Bj} dt d\phi}$$

$$\frac{d^4\sigma}{dQ^2 dx_{Bj} dt d\phi} \equiv \frac{d^4\sigma^+}{dQ^2 dx_{Bj} dt d\phi} + \frac{d^4\sigma^-}{dQ^2 dx_{Bj} dt d\phi}$$

$\propto \Im m\mathcal{H}$

$\propto \Re e\mathcal{H}$

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

$F^q \equiv H^q, E^q$

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

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

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

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

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*

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

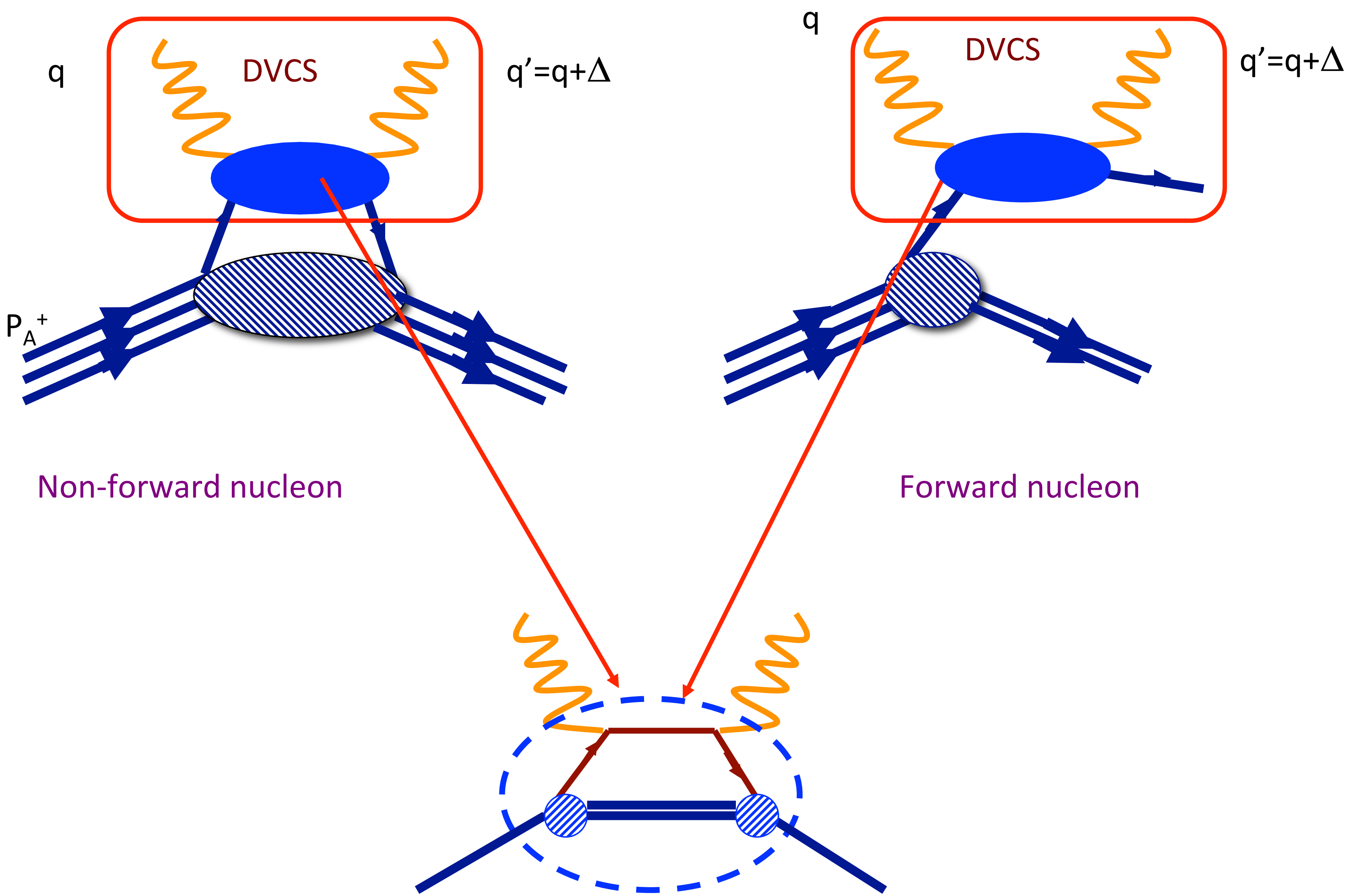
$$s_1^{\mathcal{I}} \propto \Im\mathrm{m}\, \mathcal{H}_A\, F_A(t)$$

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

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

(Kirchner and Mueller, 2004)

Coherent vs. Incoherent processes



⇒ 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

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

↑ **off-forward EMC-effect** ↑

⇒ Interference Term for Incoeherent DVCS & BH

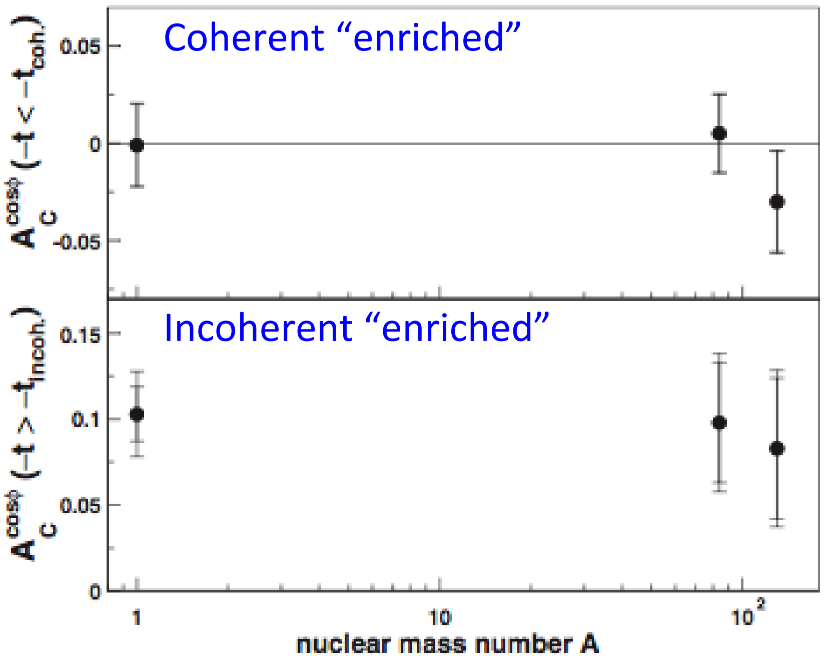
$$\mathcal{I}_{inc}(\zeta,t) = \mathcal{K} H_0^A(\zeta,t) \times Z F_1^N(t)$$

Forward spectral function

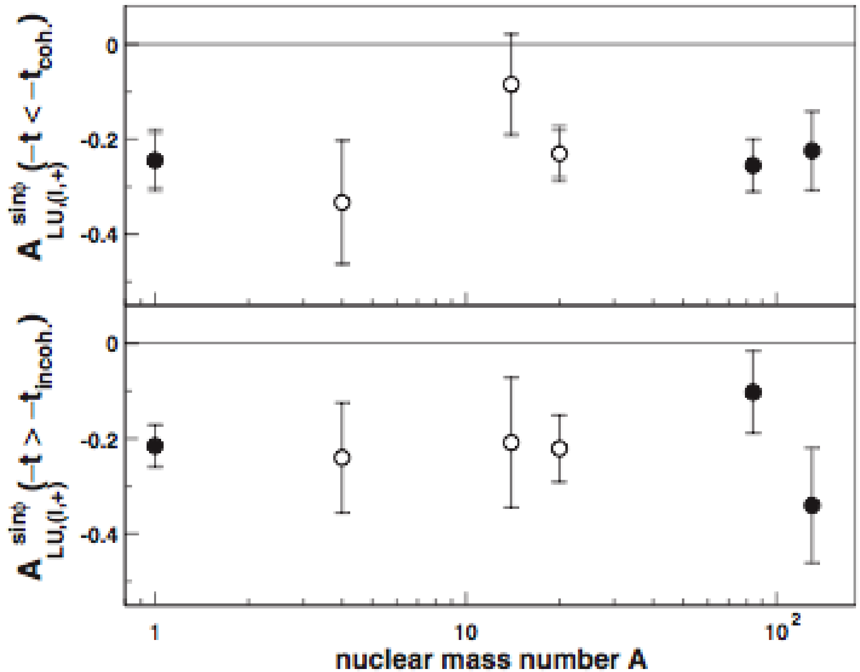
$$H_0^A(\zeta,t) = \int \frac{d^2P_\perp\, dY}{2(2\pi)^3} \mathcal{N}\, \rho_0^A(Y,P^2) H^N\left(\frac{\zeta}{Y},\frac{\zeta}{Y},t;P^2\right)$$

Hermes ⇒ first data

Phys.Rev.C81 (2010)



Beam Charge Asymmetry

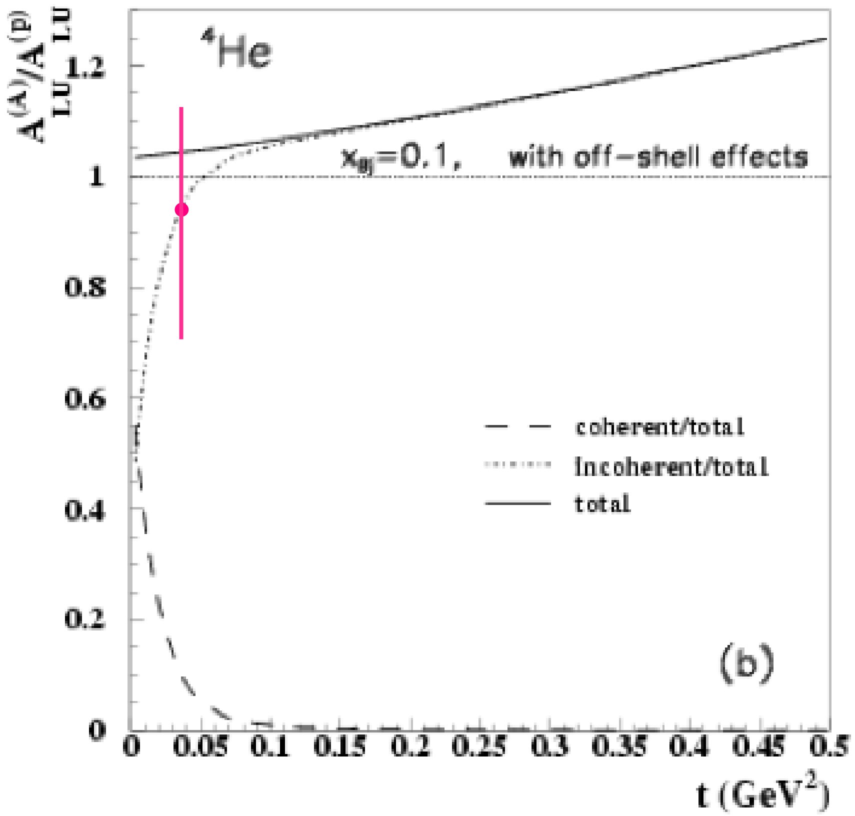


Beam Spin Asymmetry

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

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

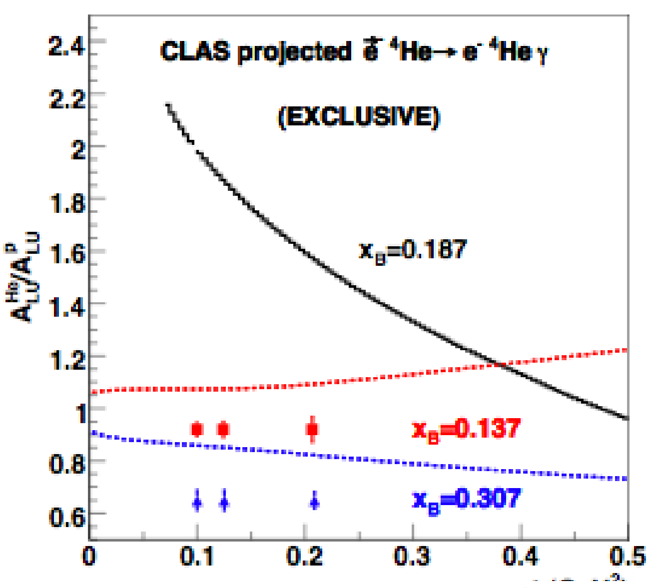
Hermes data

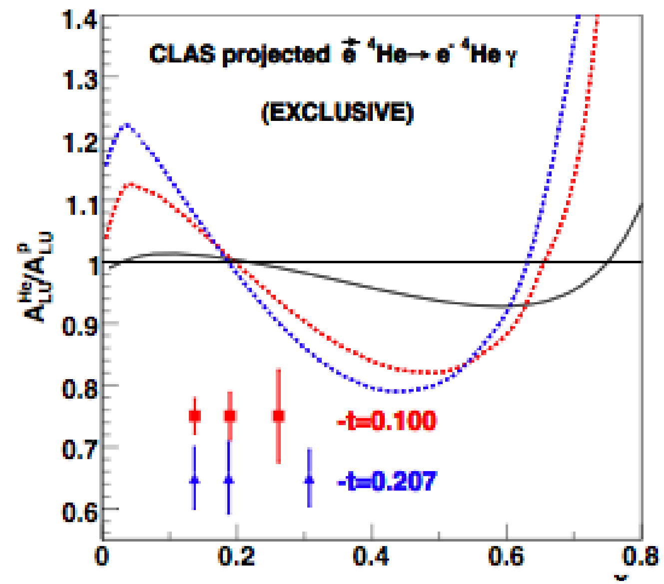


$$R_{LU}^{(A)}(\zeta,t) = A_{LU}^{A}/A_{LU}^{p} = \frac{Z^2\mathcal{I}_{coh}^{A} + Z\mathcal{I}_{incoh}^{A}}{\mathcal{F}_{DVCS}^{p}(\zeta,t)F_1(t)} \times \frac{F_1^2(t)}{Z^2F_A^2(t)+ZF_1^2(t)}$$

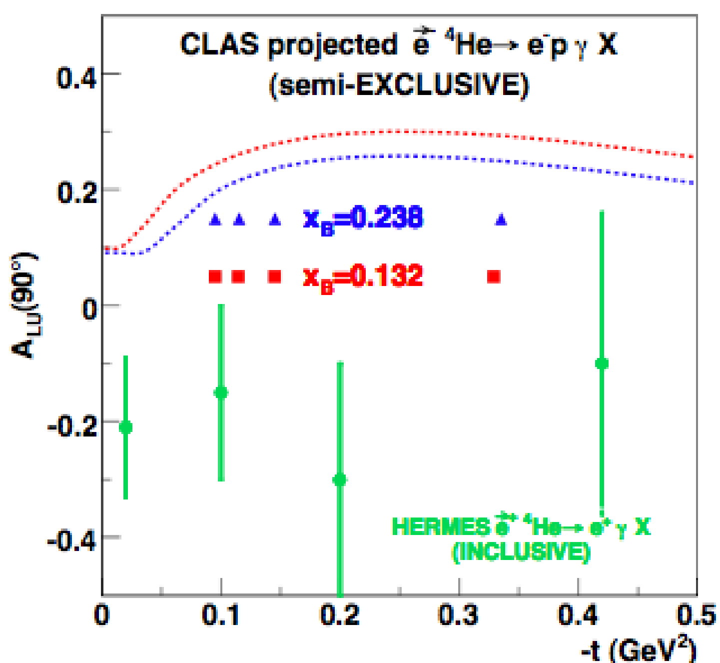
$$\mathcal{I}_{coh}^{A} = \mathcal{F}_{DVCS}^{A}(\zeta,t)F_A(t) \qquad \mathcal{I}_{incoh}^{A} = \mathcal{F}_{DVCS,0}^{A}(\zeta,t)F_1(t)$$

Jlab/Hall B analysis (K. Hafidi et al.) in progress (talk by H. Egiyan at DIS 2010)



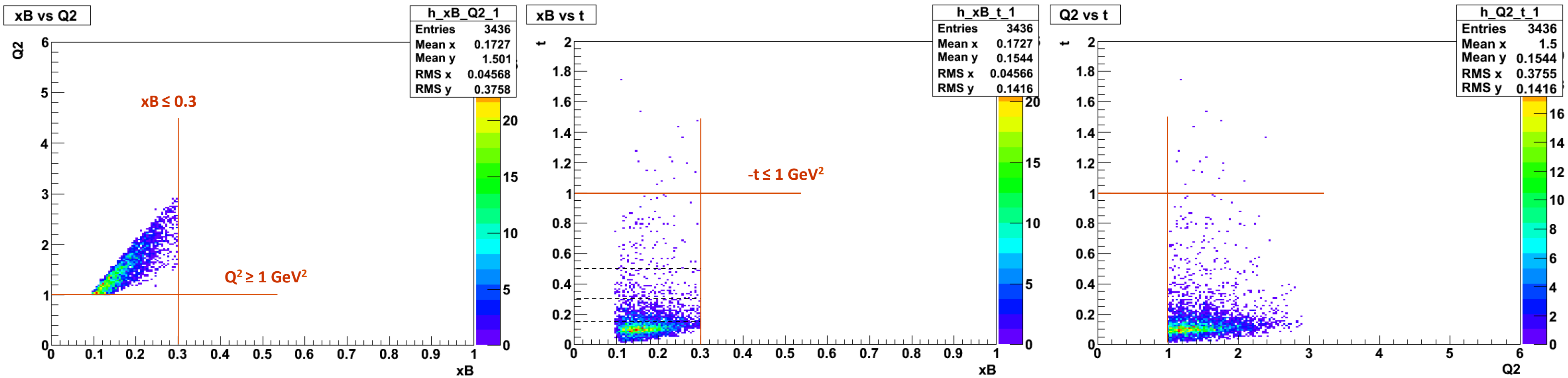


coherent



incoherent

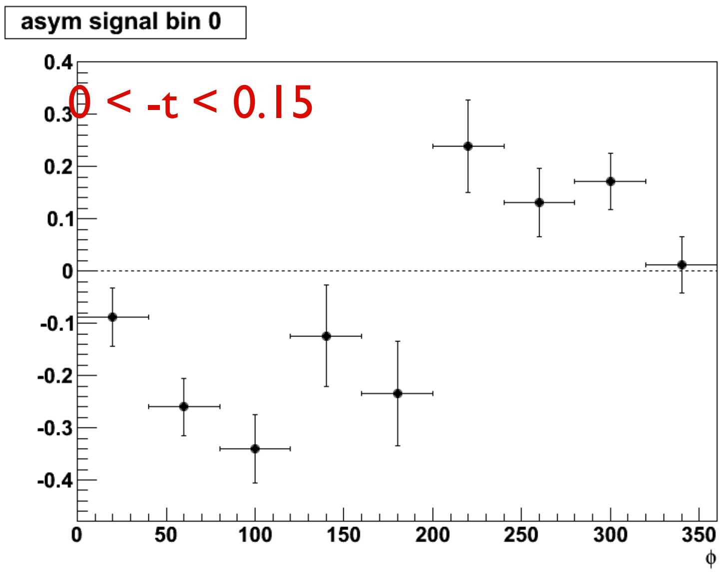
DVCS Phase Space

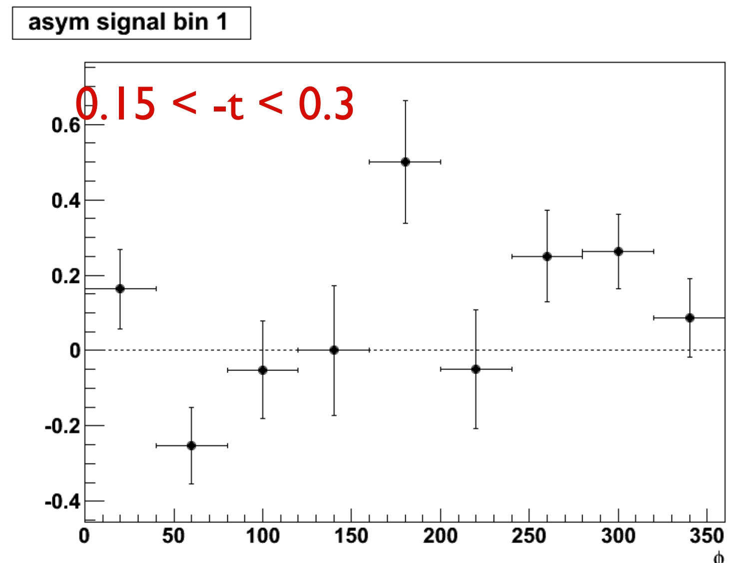


The candidate **experimental phase space** for coherent DVCS is limited and statistics **does not allow** for a **multi-dimensional analysis** as was performed in the **CLAS p-DVCS** experiment.

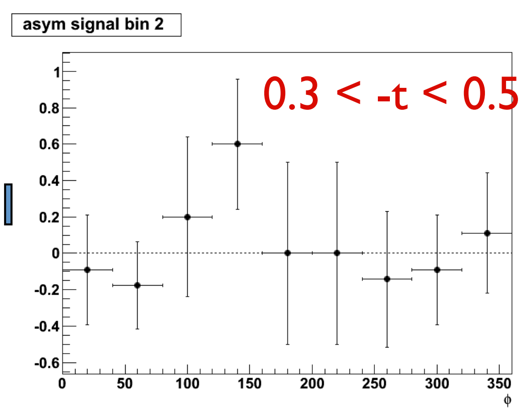
$$-t \leq 0.2\,\mathrm{GeV}^2 \qquad 0.1 \leq x_B \leq 0.3 \qquad 1\,\mathrm{GeV}^2 \leq Q^2 \leq 2.4\,\mathrm{GeV}^2$$

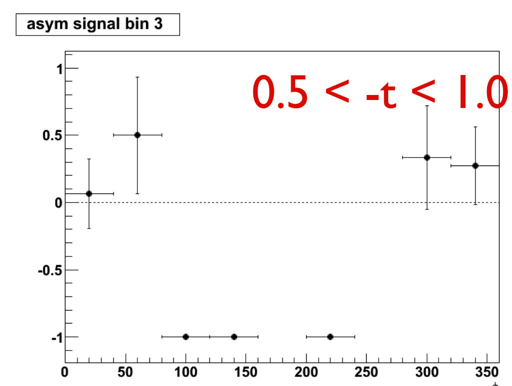
DVCS Asymmetries





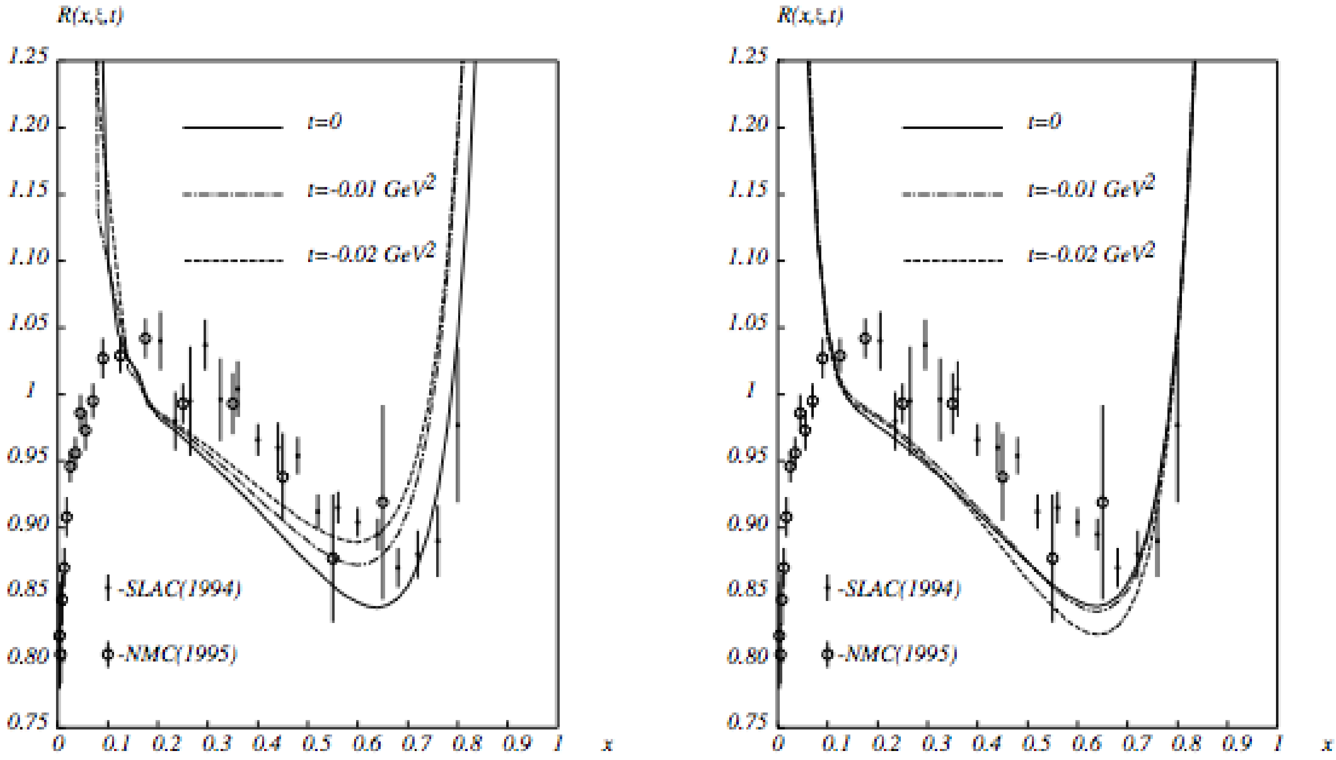
Large t data are **irrelevant**





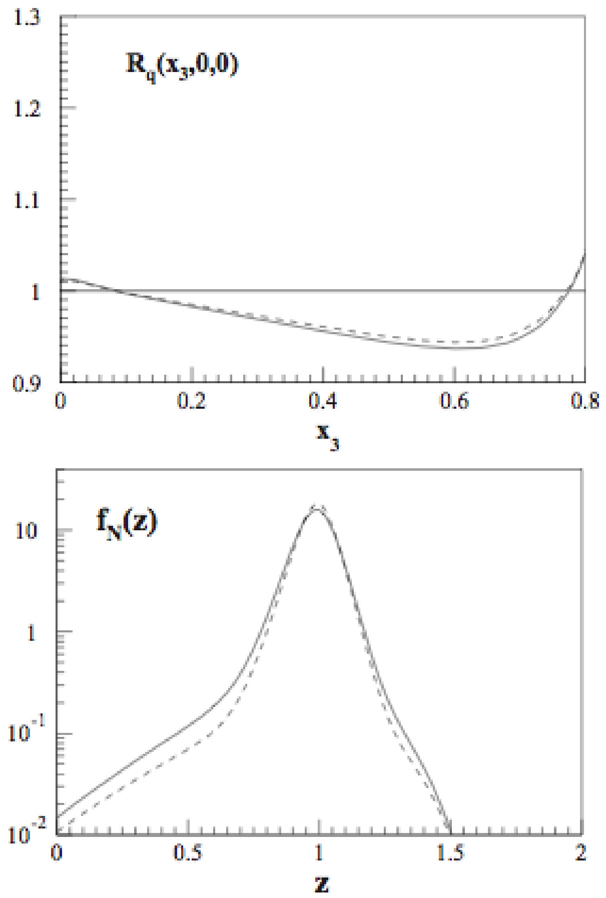
Other calculations and observables

Guzey and Siddikov (2006)



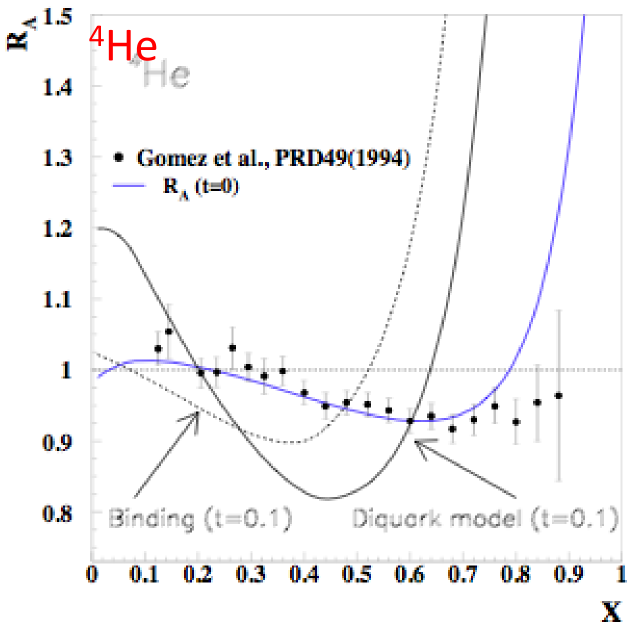
Introduce meson d.o.f. → "pion excess" model

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

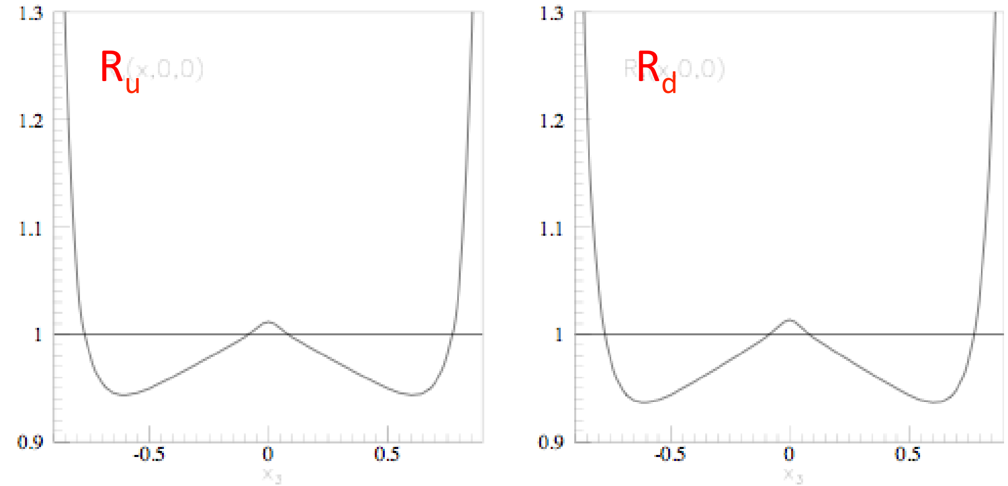


"conventional" nuclear effects

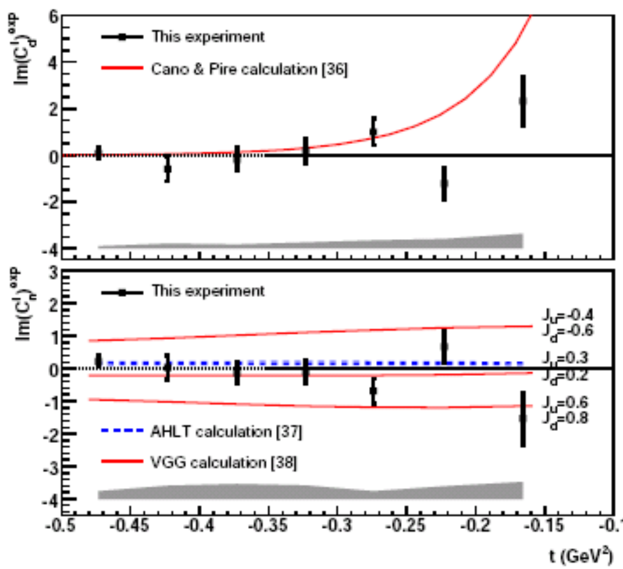
^3He



S.L. and S.Taneja



S. Scopetta



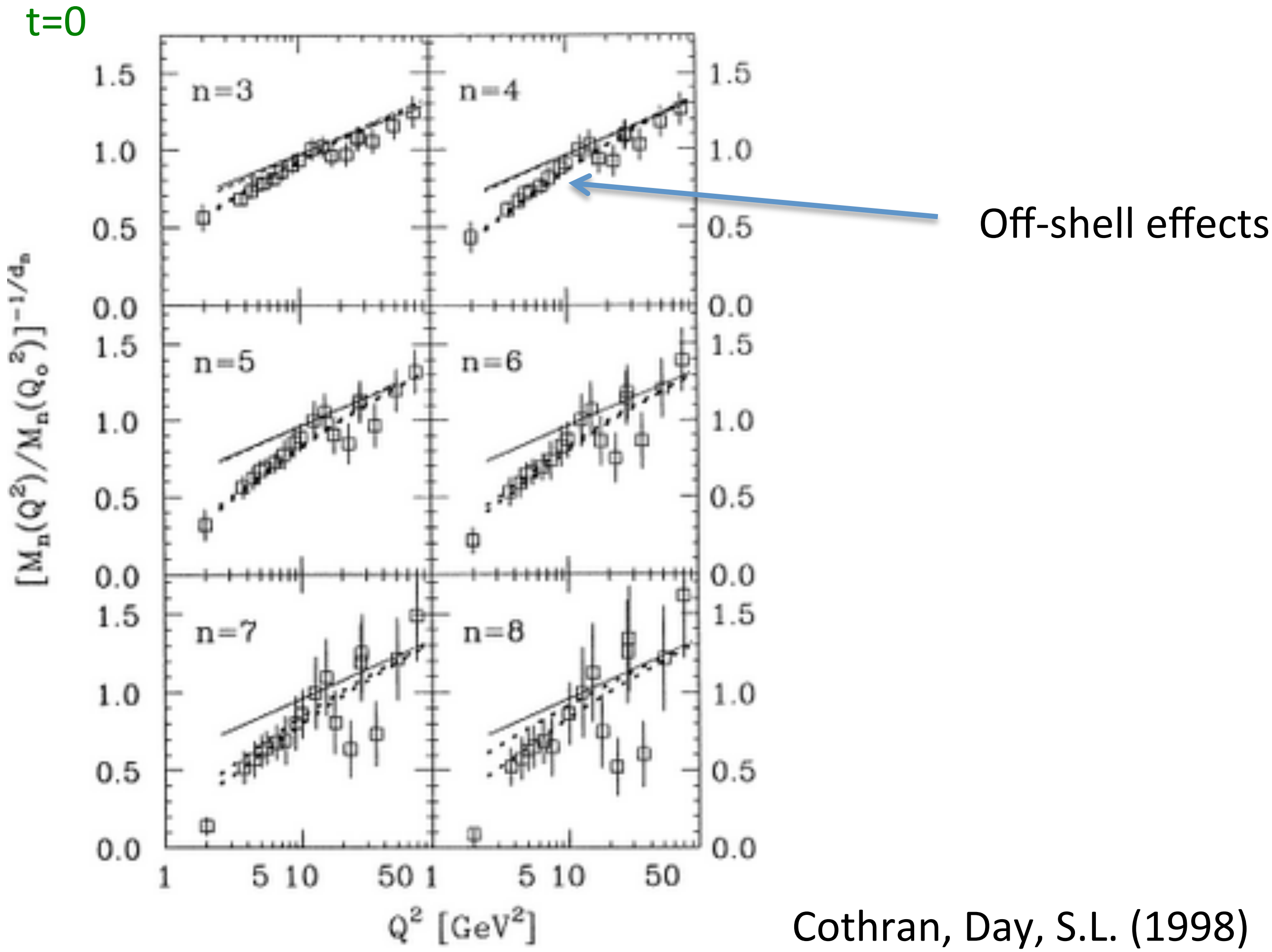
F. Cano and B.Pire

Deuteron
(data from Hall A, Mazouz et al.)

Moments: Angular Momentum Sum Rules

$$M_n^A(t) = \left(\int_0^A dy y^{n-1} f_A(y,t)\right)\left(\int_0^1 dx x^{n-2}[xH^N(x,\xi,t)]\right),$$

(e,e')



Cothran, Day, S.L. (1998)

$t \neq 0$

$$F^A(t) = F^{A,point}(t) F^N(t)$$

1st moment: form factors

$$M_2^A(\xi, t) = M_2^{A,point}(t) M_2^N(t) + M_0^{A,point}(t) \frac{4}{5} d_1^N(t) \xi^2,$$

2nd moment: momentum fraction

$$\langle x(t) \rangle_A = \frac{M_2^A(t)}{F^A(t)} = \frac{M_2^{A,point}(t)}{F^{A,point}(t)} \frac{M_2^N(t)}{F^N(t)} = \langle y(t) \rangle_A \langle x(t) \rangle_N,$$

The D-term in a nucleus reads:

$$d_1^A(t) = M_0^{A,point}(t) d_1^N(t).$$

$$d_1^A(0) \approx 1/[1 - \overline{E}/M + 2/3\langle P^2\rangle/2M^2]_A d_1^N(0)$$ ≅ A lnA

≠

$$d_1^A(0) \propto A^{7/3}$$ Polyakov – Liquid Drop Model

Nuclear Exclusive: Form Factor in Nuclei

S.L., hep-ph/0601125

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

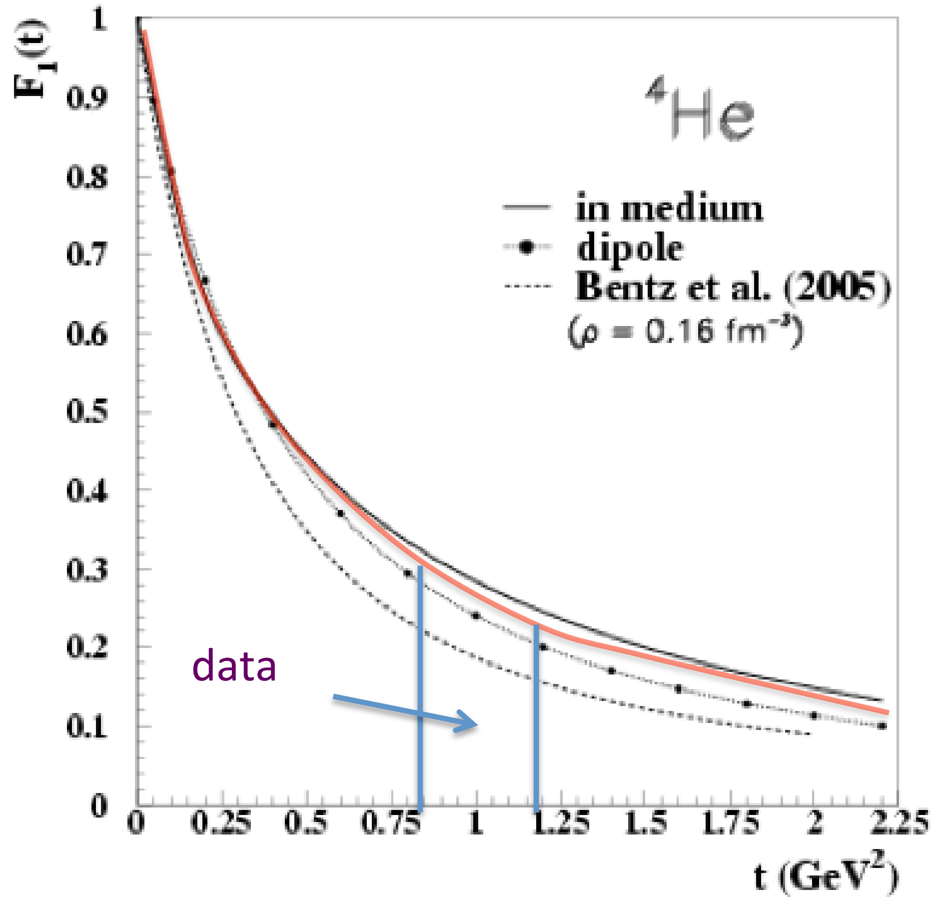
$$F_A^{LC}(t) = F_A^{point}(t) F_N(t)$$

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

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

↑ **Medium Modified Form Factor** ↑

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



Effect of shadowing on in medium form factor!

“If configurations with small radii exist, they can be isolated by performing CT and/or nuclear filtering experiments”

Define filter as

$$\Pi(b) = \begin{cases} 1 & b < b_{max}(A) \\ 0 & b \geq b_{max}(A) \end{cases}$$

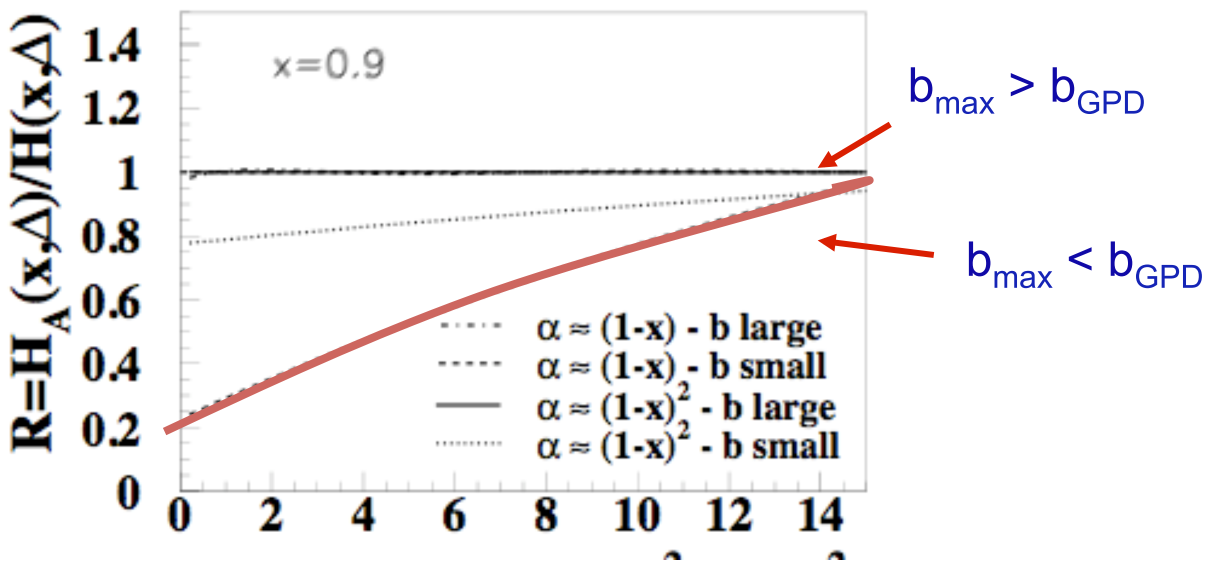
This affects the GPD as

$$H_A(x,Q^2) = \int_0^{b_{max}(A)} db\, b\, q(x,b) J_0(b\Delta),$$

Transparency ratio

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

S.L. snd S.K. Taneja (2005)



$$q(x,b) = A(x)\exp\left[-\alpha(x)\, b\right]$$

$\alpha(x) \approx (1\text{-}x)$ soft k_T, large nucleon

$\alpha(x) \approx (1\text{-}x)^2$ hard k_T, small nucleon size

$$R = 1 - \exp(-\alpha b_{\max})[\alpha b_{\max} J_0(\Delta b_{\max}) + \cos(\Delta b_{\max})].$$

DEUTERON

Physical Interpretation of the various deuteron GPDs: Form Factors

$$\int H_1(x,\xi,t)\,dx = G_1(t)$$
$$\int H_2(x,\xi,t)\,dx = G_2(t)$$
$$\int H_3(x,\xi,t)\,dx = G_3(t)$$
$$\int H_4(x,\xi,t)\,dx = 0$$
$$\int H_5(x,\xi,t)\,dx = 0$$

$$G_C(t) = G_1(t) + \frac{2}{3}\eta\, G_Q(t)$$
$$G_M(t) = G_2(t)$$
$$G_Q(t) = G_1(t) - G_2(t) + (1+\eta)\, G_3(t)$$

$$G_C(0) = 1$$
$$G_M(0) = \frac{M_D}{M_N}\mu_D = 1.714$$
$$G_Q(0) = M_D^2 Q_D = 25.83$$

$$\eta = \frac{t}{2M_D^2}$$

Physical Interpretation of the various deuteron GPDs: PDFs

$$H_1(x,0,0) = \frac{1}{3}\left(q^1(x) + q^{-1}(x) + q^0(x)\right) = f_1(x)$$

$$H_5(x,0,0) = \left(q^0(x) - \frac{q^1(x) + q^{-1}(x)}{2}\right) = b_1(x)$$

Angular Momentum Sum Rule: Taneja et al, PRD 2012

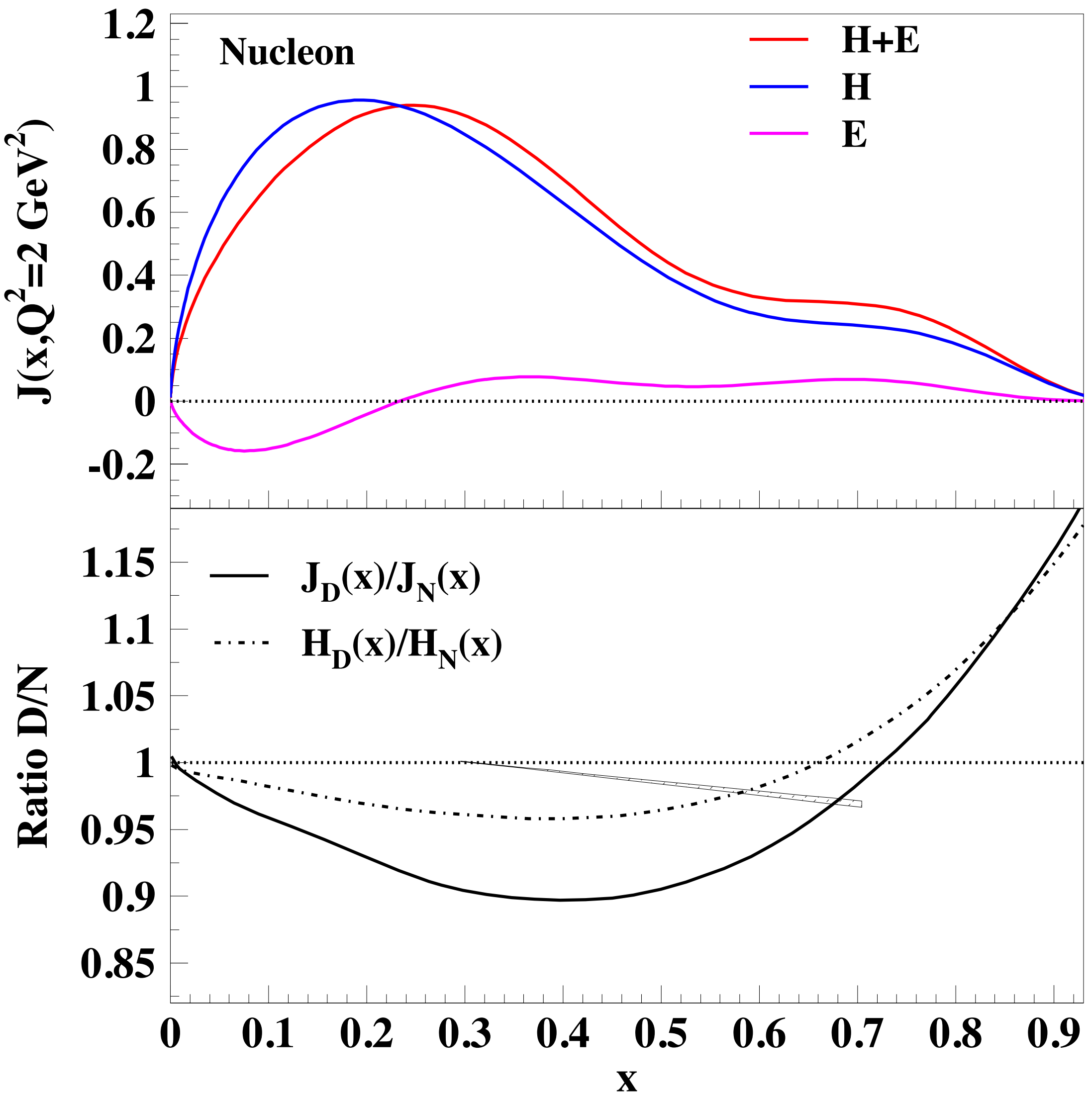
$$\frac{1}{2}\mathcal{G}_5^{q,g} = \frac{1}{2}\int dx\, x H_2(x,0,0) = J_z^{q,g}$$

$$J_q = \frac{1}{2}\int dx\, x\,[H_q(x,0,0) + E_q(x,0,0)]\,, \longrightarrow J_q = \frac{1}{2}\int dx\, x\, H_2^q(x,0,0),$$

↓ $F_1 + F_2 = G_M$

↓ G_M

Nuclear effect much larger than in unpolarized scattering



Needs to be treated systematically…

Other relations

$$\int dx x [H_1(x,\xi,t) - \frac{1}{3} H_5(x,\xi,t)] = \mathcal{G}_1(t) + \xi^2 \mathcal{G}_3(t) \quad (7)$$ Momentum

$$\int dx x H_2(x,\xi,t) = \mathcal{G}_5(t) \quad (8)$$ Angular Momentum

$$\int dx x H_3(x,\xi,t) = \mathcal{G}_2(t) + \xi^2 \mathcal{G}_4(t) \quad (9)$$ Quadrupole

$$\int dx x H_4(x,\xi,t) = \xi \mathcal{G}_6(t) \quad (10)$$

$$\int dx x H_5(x,\xi,t) = \mathcal{G}_7(t) \quad (11)$$ Connected to b_1 SR

Conclusions and Outlook

- Exclusive experiments in nuclei provide an even better laboratory to study QCD in coordinate space:
  - vast phenomenology…
  - study short LC distance structure of nuclei at the wave function level
- 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
- Comparison between GPD models and data is indeed possible...GPD extraction is possible!!!


THE GLASS FLOOR
Maybe if I just sit very, very still, nothing will happen.
R.Cht