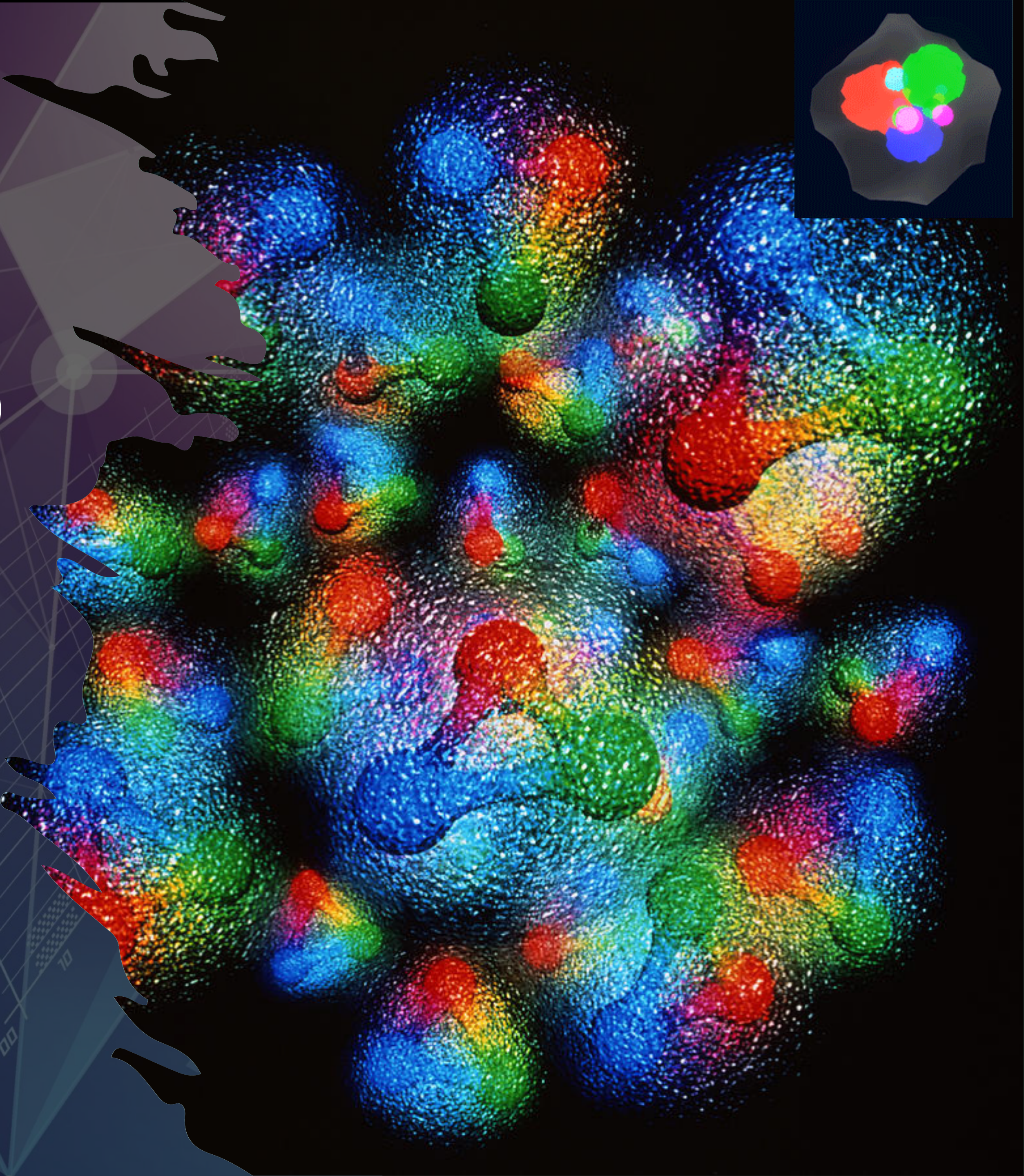
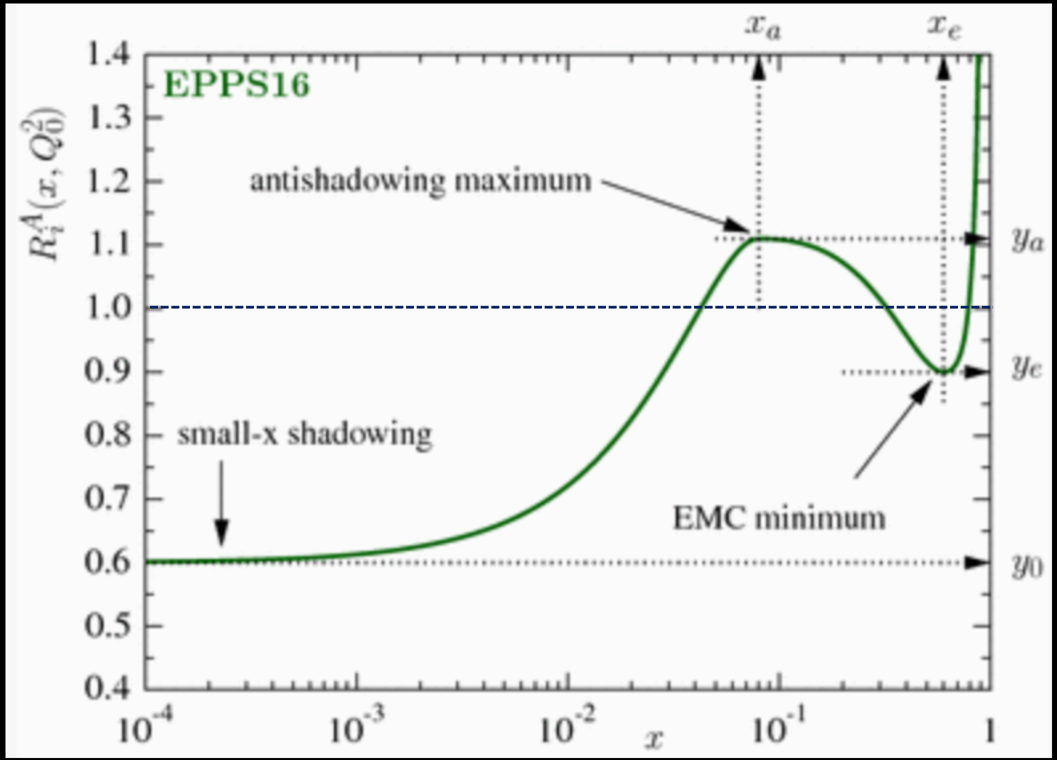
The EMC effect in QCD

Simonetta Liuti

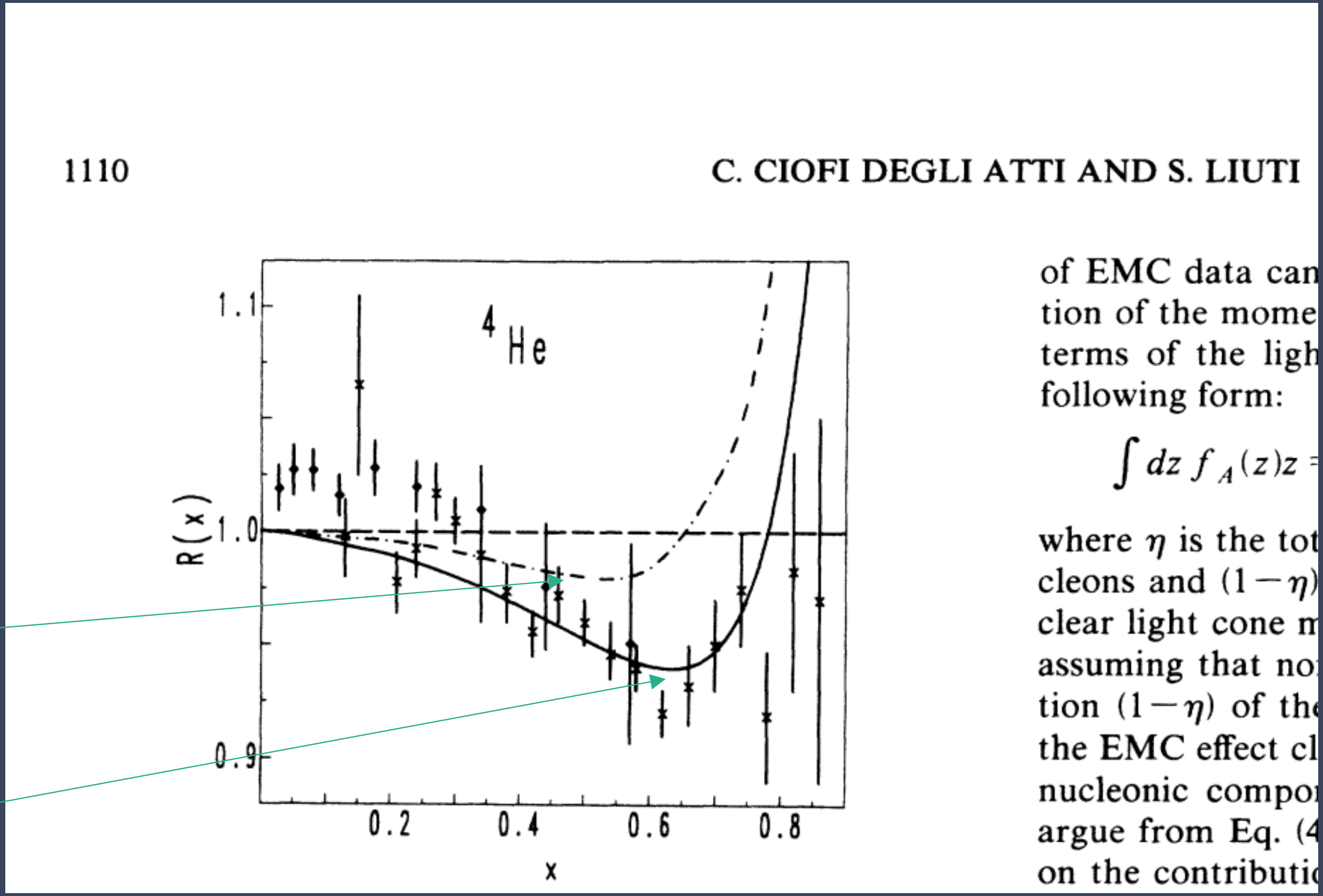


EMC Effect



EPPS16
$R_i^A(x, Q_0^2)$
antishadowing maximum
small-x shadowing
EMC minimum
x_a
x_e
y_a
y_e
y_0
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
10^{-4}
10^{-3}
10^{-2}
x
10^{-1}
1

The impact of nucleon nucleon correlations

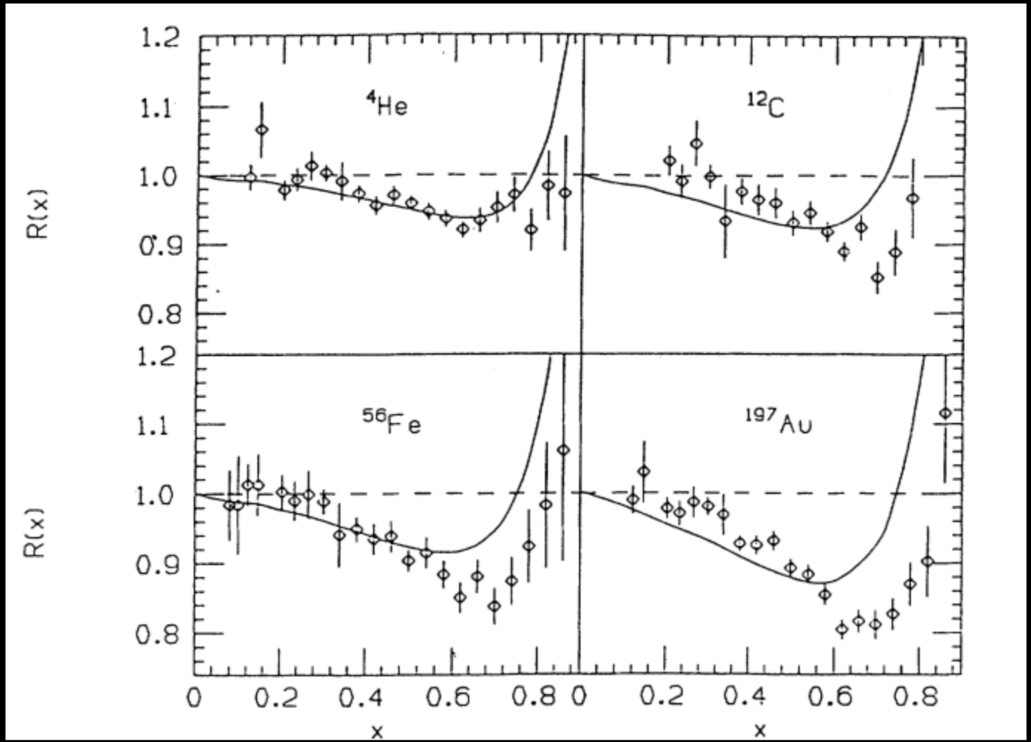


binding, no correlations

NN correlations

C. Ciofi degli Atti, S. Liuti *Phys.Rev.C* 41 (1990) 1100

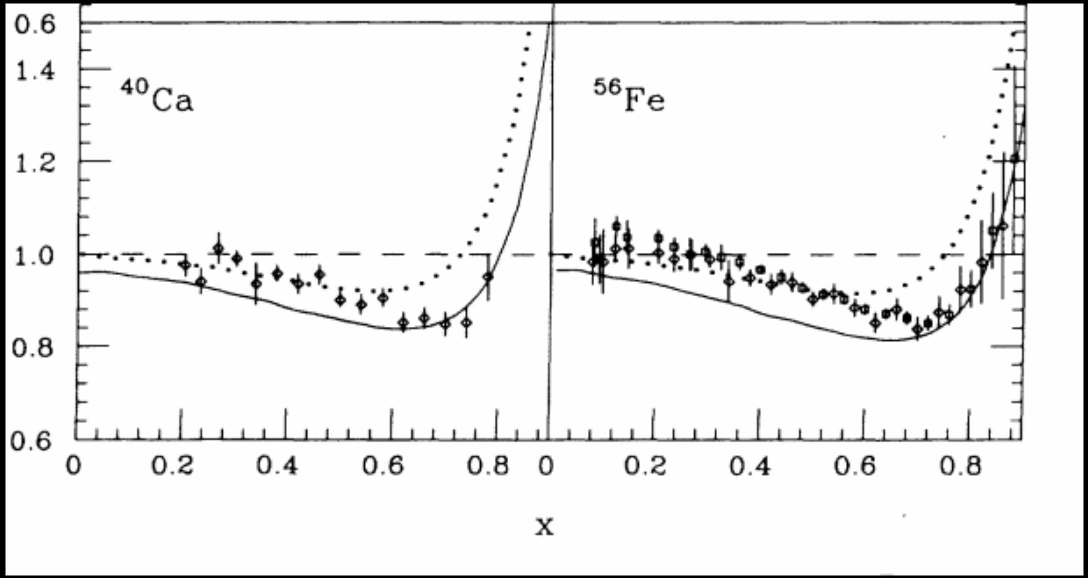
Binding alone cannot explain all of the effect



C. Ciofi degli Atti, S. Liuti *Phys.Rev.C* 44 (1991) R1269

C. Ciofi degli Atti, SL, PLB (1989)

Role of "relativistic effects" (proper LC treatment)



F. Gross, S. Liuti, PRC45 (1992)

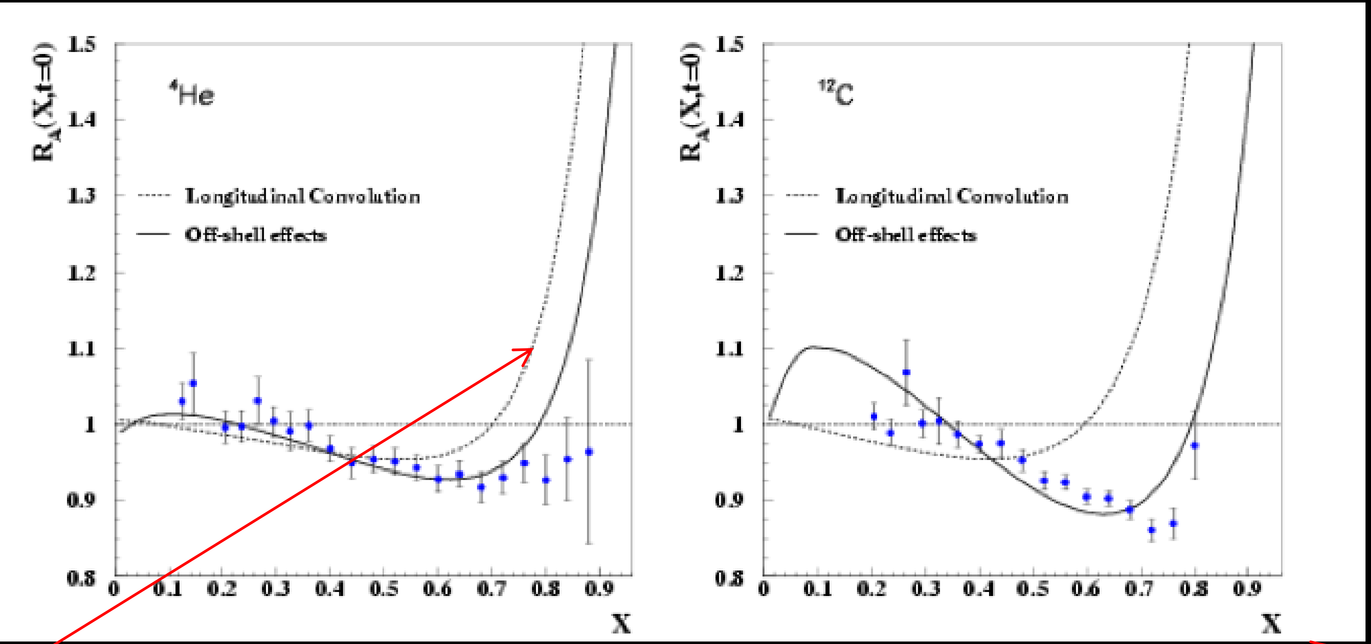
Scroll on to the new century…

Nucleon medium modifications and off-shell effects result from the combination of x-rescaling (binding) and the transverse motion of quarks

QCD correlation functions and gauge links give us the key to interpret the EMC effect

Liuti and Taneja (2005)

$R_A = F_2^A(x)/F_2^D(x)$

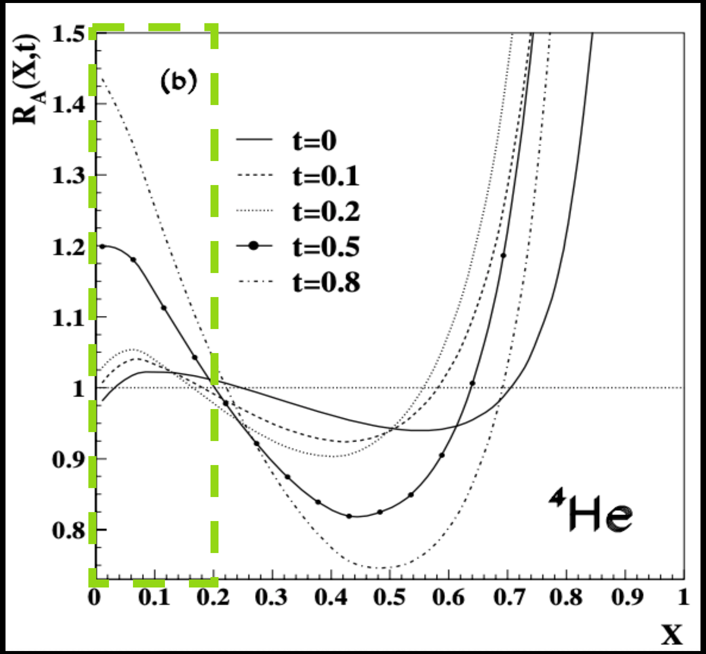


- ✓ Calculation including SRC (AV8) with unmodified nucleons
- ➔ Main constraint provided by Koltun sum rule

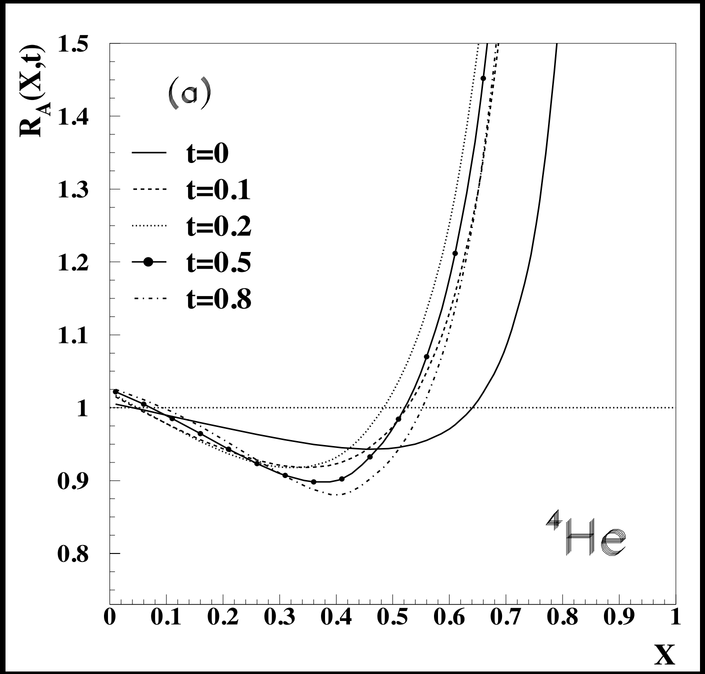
GPDs in nuclei

New observables: Deeply Virtual Compton Scattering (DVCS) and GPDs

$$R_A(x,0,t) = \frac{H_A\,(x,0,t)}{H_N(x,o,t)}$$



With off-shell effects



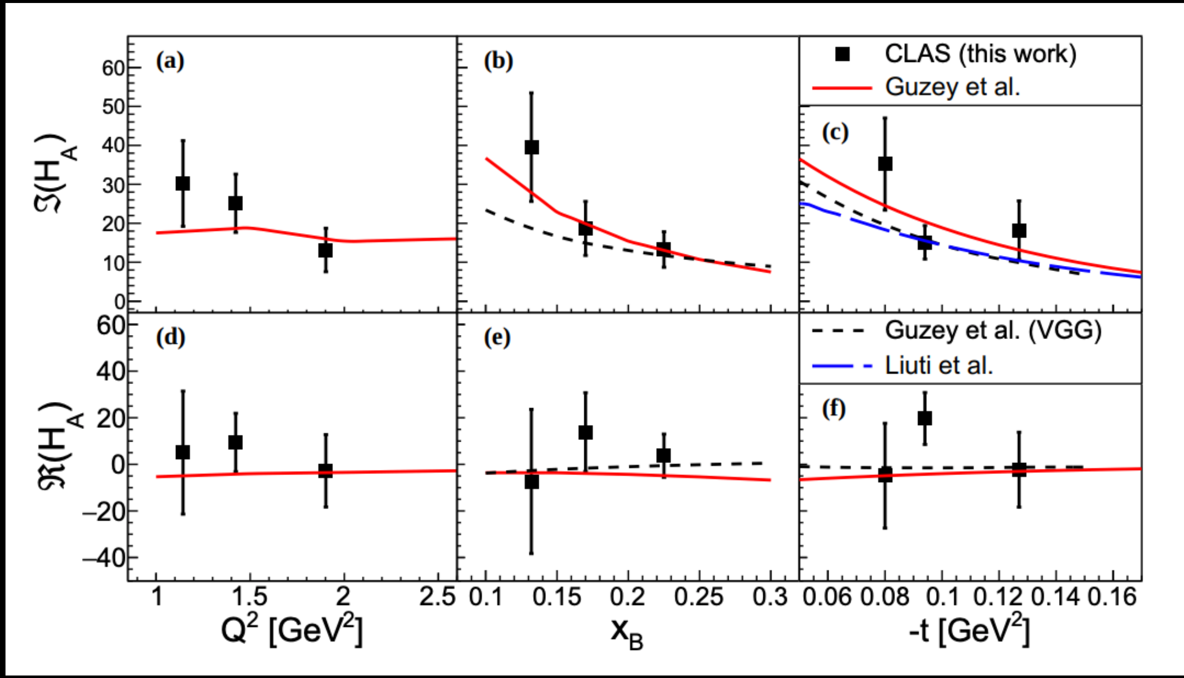
No off-shell effects

SL, SK Taneja, PRC72(2005)

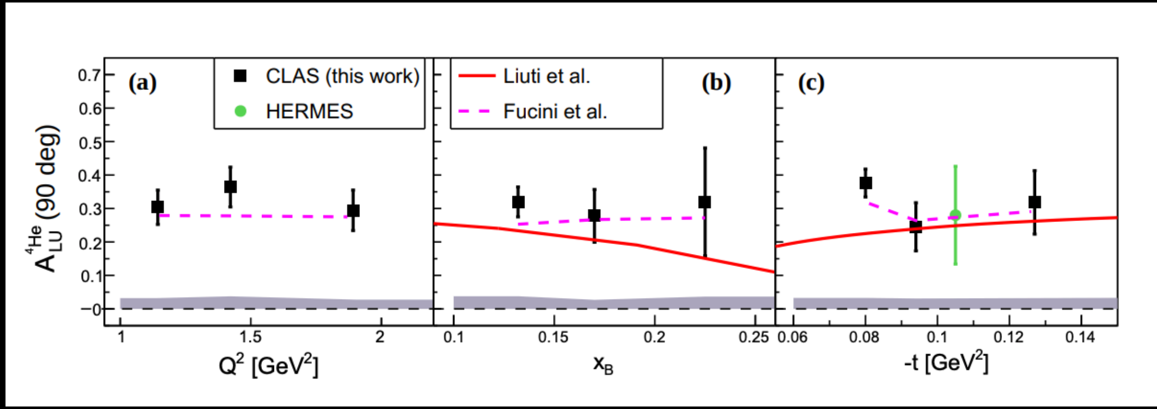
… is this trend observable…??

Measurable effect: from BSA to Compton Form Factors

e ^{4}He → e' (^{4}He)' γ



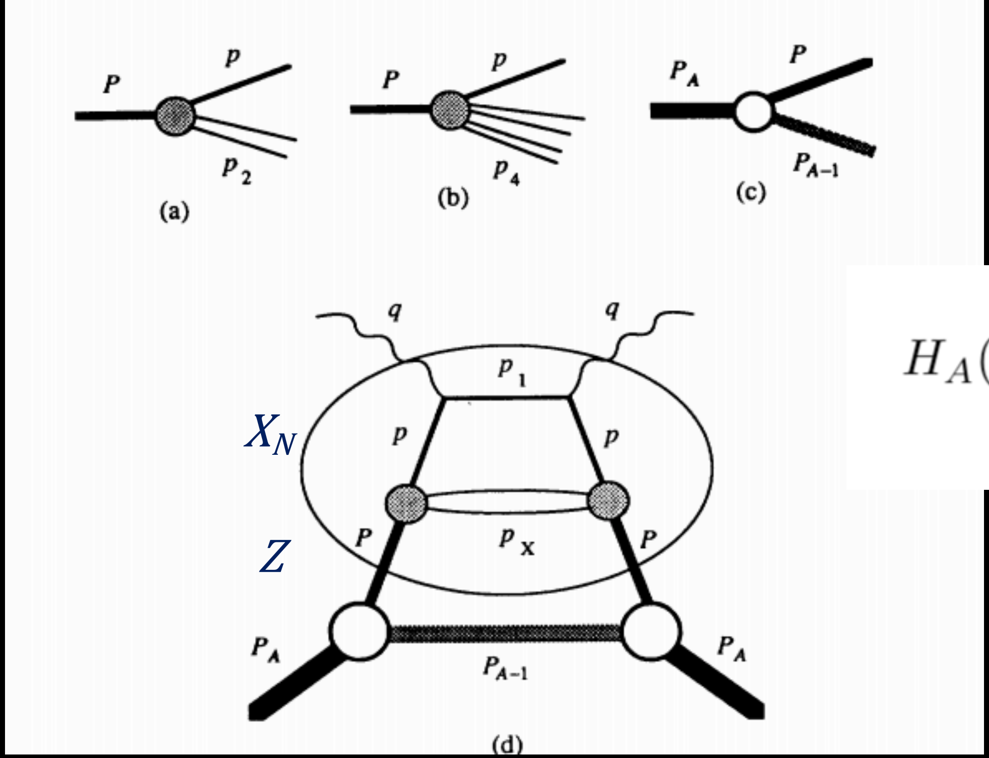
CLAS Collaboration, R. Dupré et al, *Phys.Rev.C* 104 (2021)



How does binding give an effect?

How does binding give an effect?

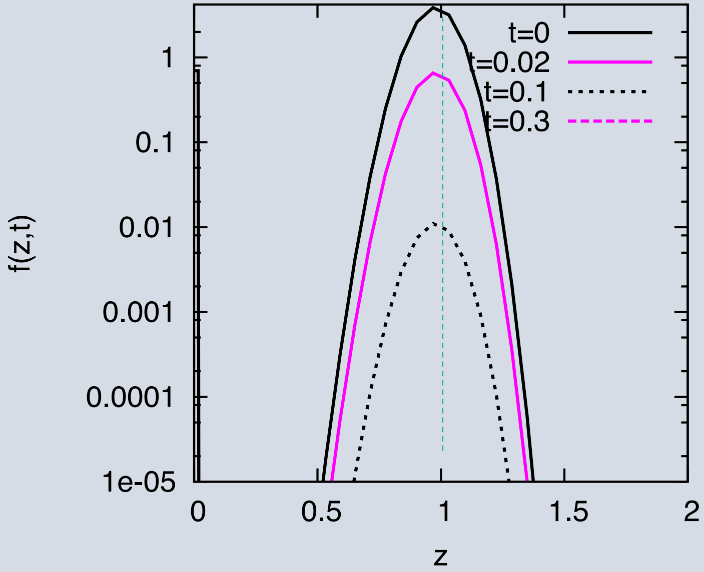
$$X = k^+/(P_A^+/A)$$
$$Z = P^+/(P_A^+/A)$$
$$X_N = X/Z \equiv k^+/P^+$$



$$H_A(X,\Delta) = \int_X^A dZ\, \rho_A(Z,\Delta) H_N(X/Z,\Delta)$$

Going from LightCone to “0” and “3” coordinates:

$$\rho_A(Z,\Delta) = 2\pi M \int dE \int_{P_{min}(Zeta,E)} dP\, P\Phi(P)\Phi^*(|\,\mathbf{P}+\mathbf{\Delta}\,|)$$

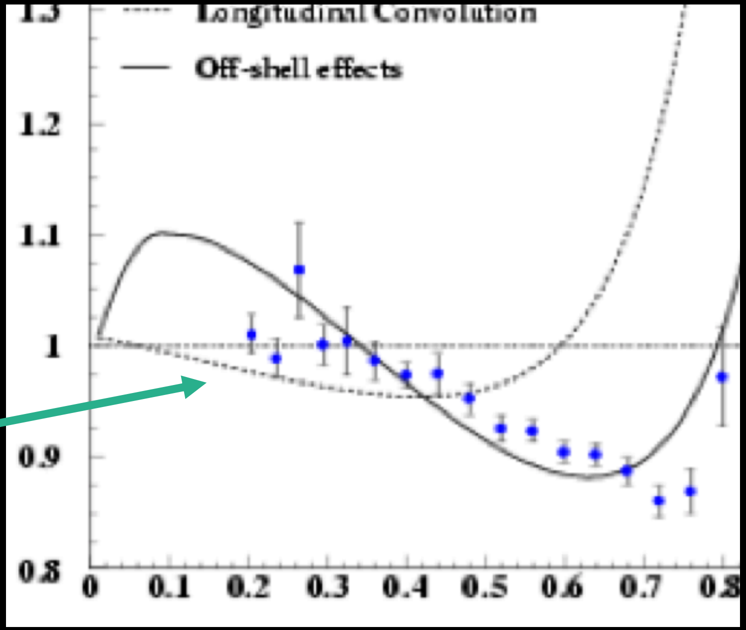


$$\delta\left(Z - \left\langle \frac{E}{M} \right\rangle\right)$$

X-Rescaling

$$H_N(X) \rightarrow H_N\left(\frac{X}{1-\left\langle\frac{E}{M}\right\rangle}\right)$$

$$R(X) \rightarrow {H_N\left(\frac{X}{1-\left\langle\frac{E}{M}\right\rangle}\right)} \Big/ {H_N(X)}$$



What are off-shell effects?

k^2

Free nucleon

$$(kp) = k^- p^+ + k^+ p^- = k^- p^+ + \frac{xM^2}{2}$$

$$k^2 = 2x(kp) - x^2 M^2 - k_T^2$$

$$p^2 = M^2$$

Nucleon is on its mass shell, quark off-mass-shell

Bound nucleon

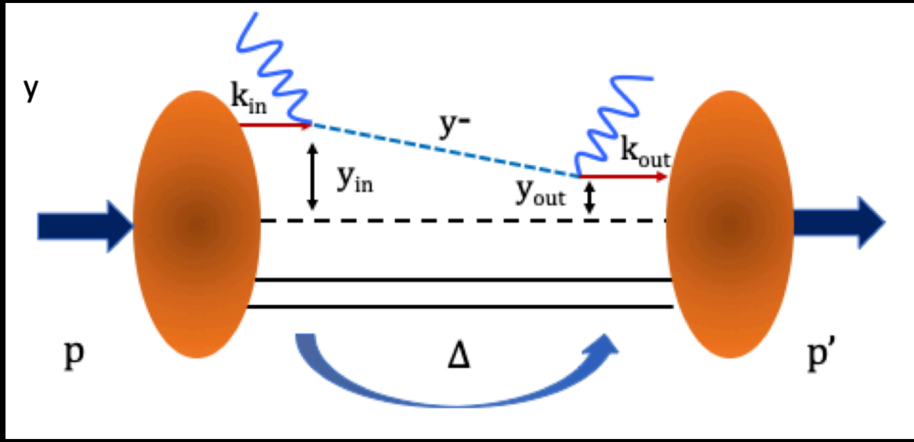
$$(kp) = k^- p^+ + \frac{x}{2}\left[M_A^2 - \frac{A}{A-z}\left(M_{A-1}^2 + \mathbf{p}_T^2\right)\right] - \mathbf{k}_T \cdot \mathbf{p}_T$$

$$k^2 = 2\left(\frac{x}{z}\right)(kp) - \left(\frac{x}{z}\right)^2 p^2 - \left(\mathbf{k}_T - \frac{x}{z}\mathbf{p}_T\right)^2$$

$$p^2 = \frac{z}{A}M_A^2 - \frac{z}{A-z}\left(M_{A-1}^*\right)^2 - \frac{A}{A-z}\mathbf{p}_T^2$$

Both nucleon and quark are off-mass-shell

QCD correlation functions



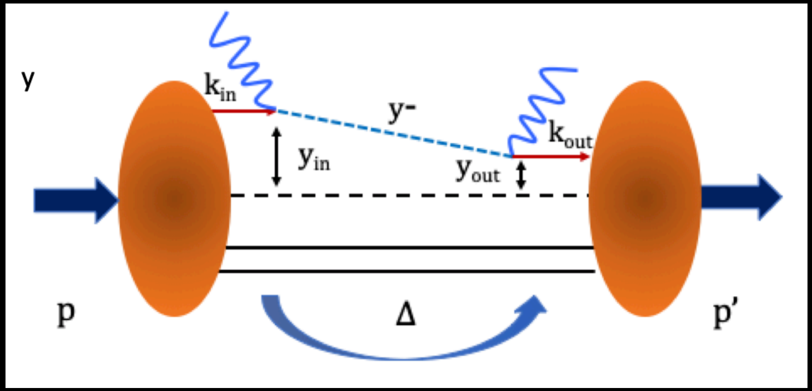
free nucleon

$$\int d^2k_T\, \Phi_\Lambda^{[\gamma^+]} = \int dz^- d^2\mathbf{z}_T\, e^{ik^+z^-}\, \delta^2(\mathbf{z}_T)\, \langle p \mid \bar{\psi}(0,0,0)\,\mathcal{U}(0,z^-,\mathbf{z}_T)\gamma^+\psi(0,z^-,\mathbf{z}_T) \mid p\rangle_{z^+=0}$$

off-shell nucleon

$$\int d^2k_T \Phi_\Lambda^{\gamma^+\,(OFF)}(x',\mathbf{k}'_T) = 2\pi \int_{\bar{k}_T(A)}^{\infty} dk_T \Phi_\Lambda^{\gamma^+\,(OFF)}(x',\mathbf{k}'_T)$$

$$= 2\pi \int dz^- d^2\mathbf{z}_T\, e^{i(x'p^+z^- - \mathbf{p}_T\cdot\mathbf{z}_T)} \int_{\bar{k}_T(A)}^{\infty} dk_T\, e^{-i\mathbf{k}_T\cdot\mathbf{z}_T} \langle p \mid \bar{\psi}(0,0,0)\,\mathcal{U}(0,z^-,\mathbf{z}_T)\,\gamma^+\psi(0,z^-,\mathbf{z}_T) \mid p\rangle_{z^+=0}$$



$$\int d^2k_T\, \Phi_\Lambda^{\gamma^+ (OFF)}(x', \mathbf{k}'_T) = 2\pi \int dz^- d^2\mathbf{z}_T\, e^{i(x'p^+z^- - \mathbf{p}_T\cdot\mathbf{z}_T)} \langle p \mid \bar\psi(0,0,0)\,\mathcal{U}(0,z)\,\gamma^+\psi(0,z^-,\mathbf{z}_T) \mid p\rangle$$

$$\times \left[\int_0^{2\pi} d\phi \int_0^\infty dk_T\; k_T\, e^{-i\mathbf{k}_T\cdot\mathbf{z}_T} - \int_0^{2\pi} d\phi \int_0^{\bar k_T^A} dk_T\; k_T\, e^{-i\mathbf{k}_T\cdot\mathbf{z}_T}\right]_{z^+=0}$$

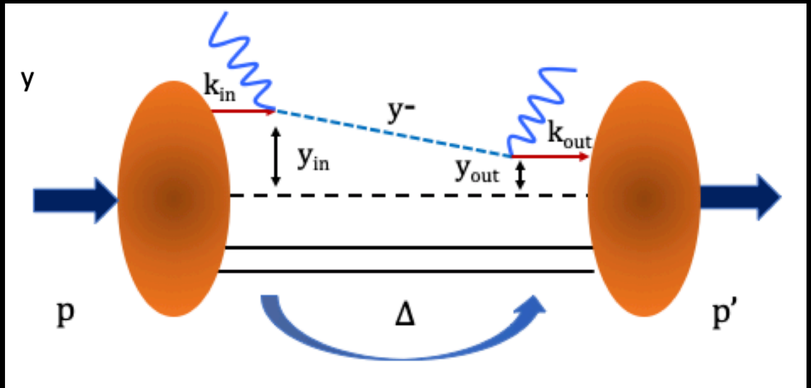
The expression in square bracket can be evaluated as,

$$[\ldots]_{z^+=0} = \delta^2(\mathbf{z}_T) - 2\pi \int_0^{\bar k_T^A} dk_T\; k_T\, J_0(k_T z_T) = \delta^2(\mathbf{z}_T) - 2\pi(\bar k_T^A)^2 \frac{J_1(\bar k_T^A z_T)}{\bar k_T^A z_T}$$

ON-SHELL PART

OFF-SHELL PART

Interpretation

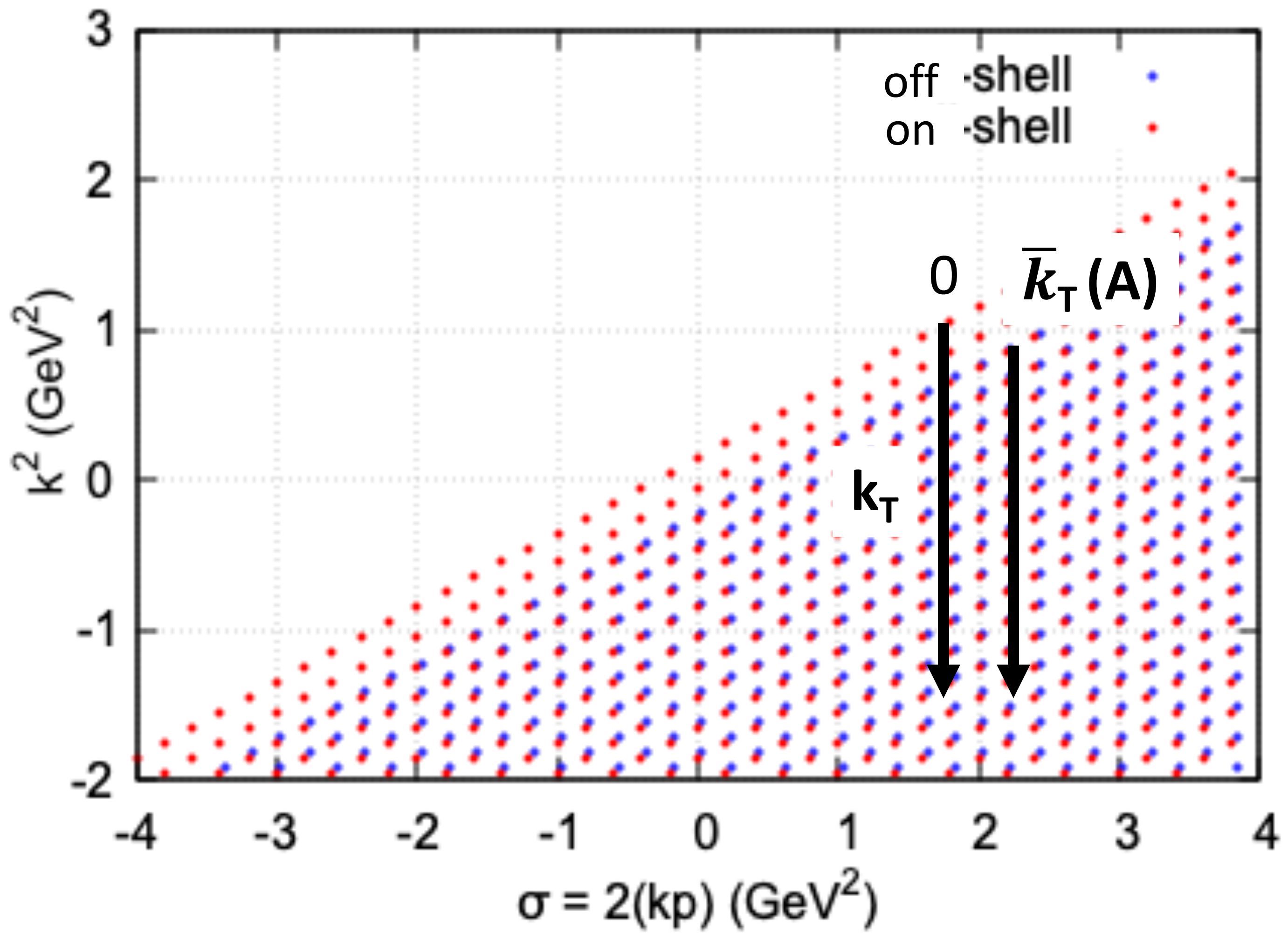


$$\delta^2(\mathbf{z}_T) - 2\pi(\bar{k}_T^A)^2 \frac{J_1(\bar{k}_T^A z_T)}{\bar{k}_T^A z_T}$$

$\delta^2(\mathbf{z}_T)$ The struck quark propagates instantaneously in the transverse direction: no Final State Interactions are allowed

$2\pi(\bar{k}_T^A)^2 \frac{J_1(\bar{k}_T^A z_T)}{\bar{k}_T^A z_T}$ A-dependent Final State Interactions are induced between the struck quark and the nucleus remnant

Off-shell effects result from FSI rather than from a nucleon size change



3
2
1
0
-1
-2
k^2 (GeV^2)
-4
-3
-2
-1
0
1
2
3
4
σ = 2(kp) (GeV^2)
off -shell
on -shell
0
$\bar{k}_T$ (A)
k_T

Conclusions and Outlook

✓ A QCD-based interpretation of off-shell effects in DIS from nuclei was presented

✓ The next step: Ca $\bar{k}_T$ (A) be determined from experiment?

✓ Role of SRC correlations and diquark configurations
(work in progress with Jennifer Rittenhouse)