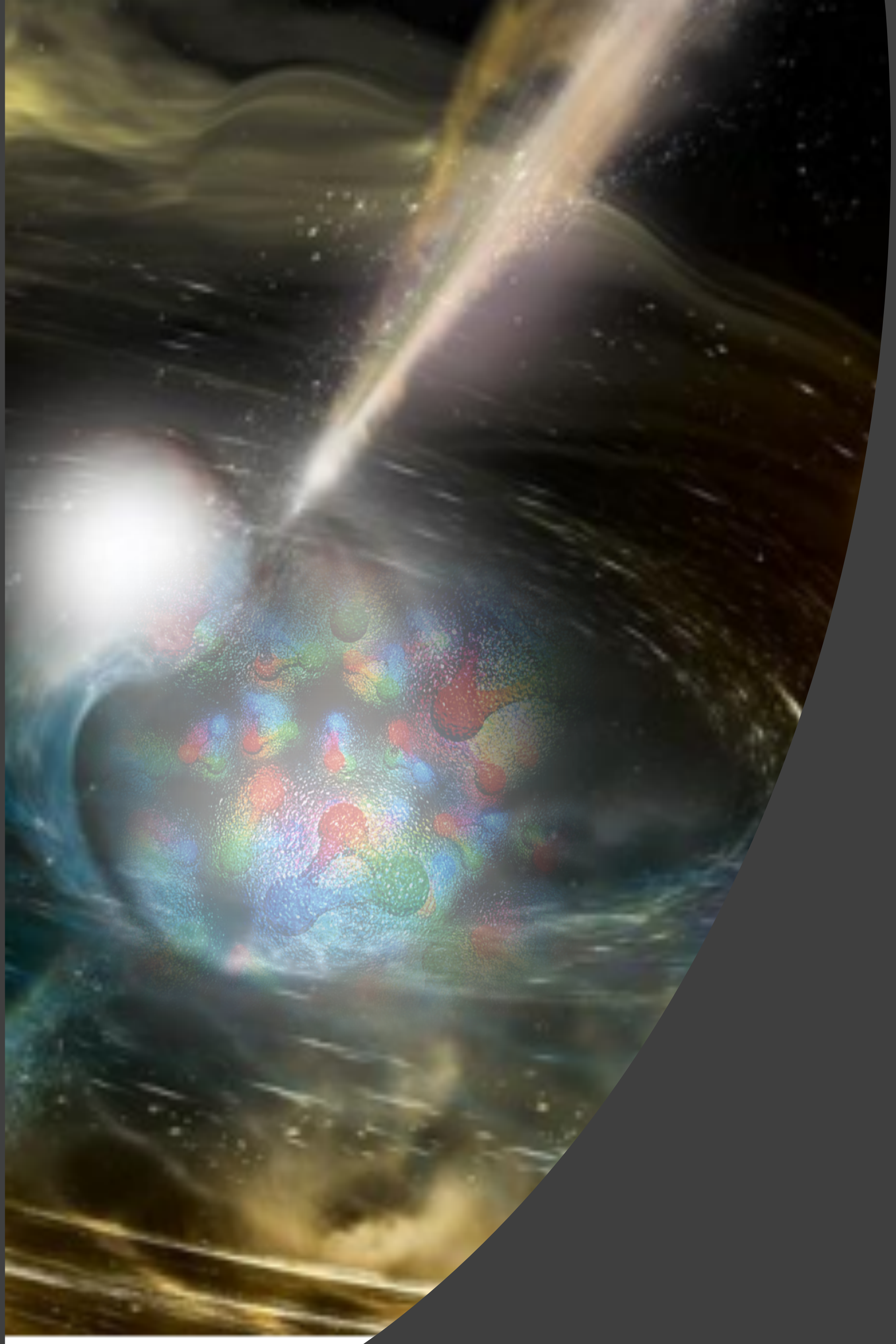
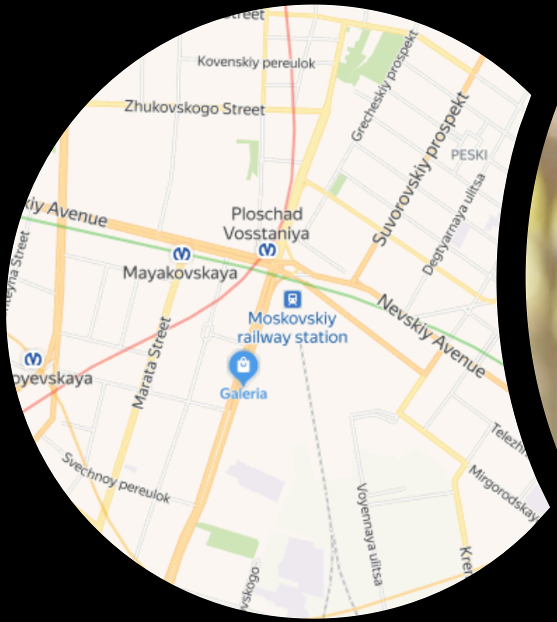


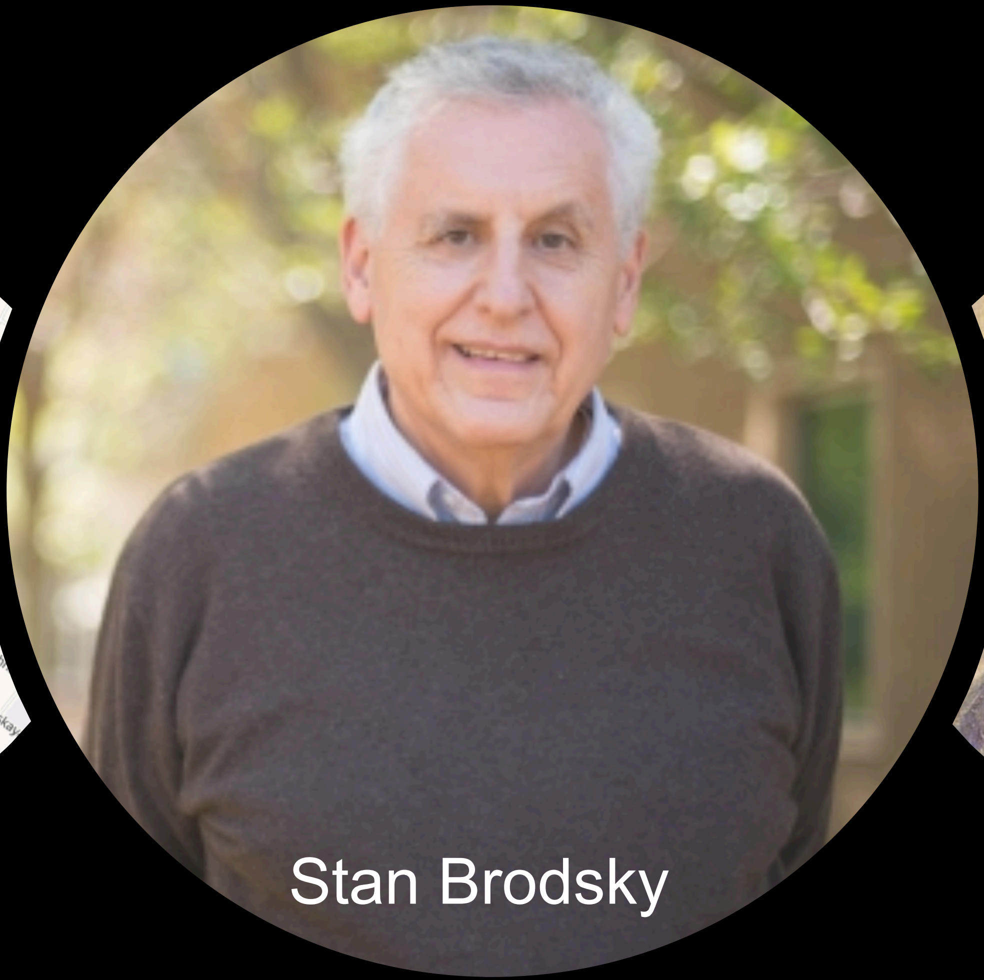
Nuclei as Laboratories for QCD

Correlations in Partonic and Hadronic Interactions
CERN
February 3-7, 2020

SIMONETTA LIUTI
UNIVERSITY OF VIRGINIA



Brodskaya Ulitza before 1991…

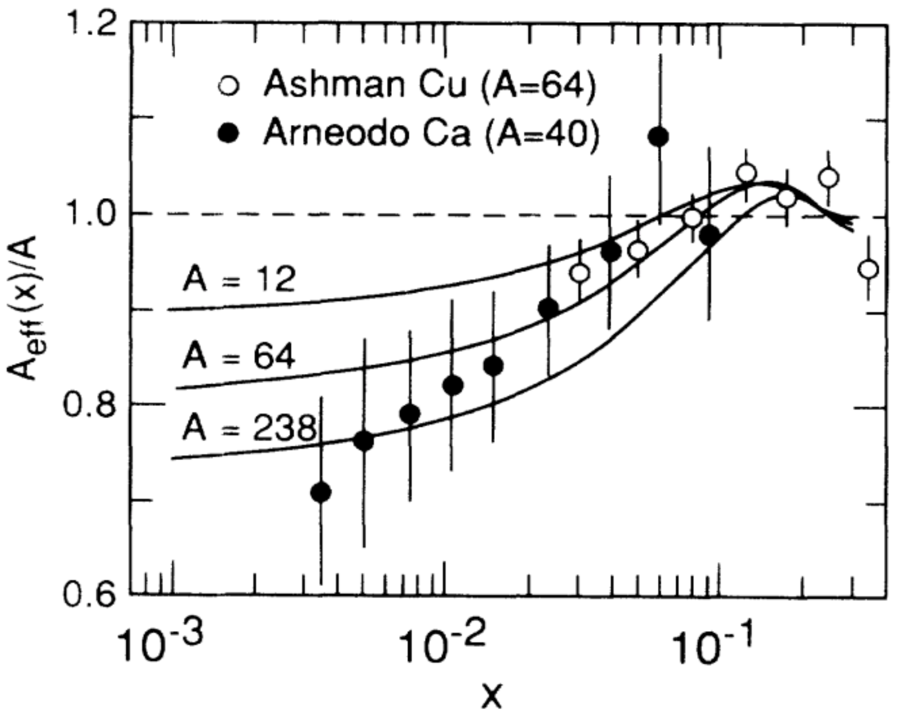


Stan Brodsky

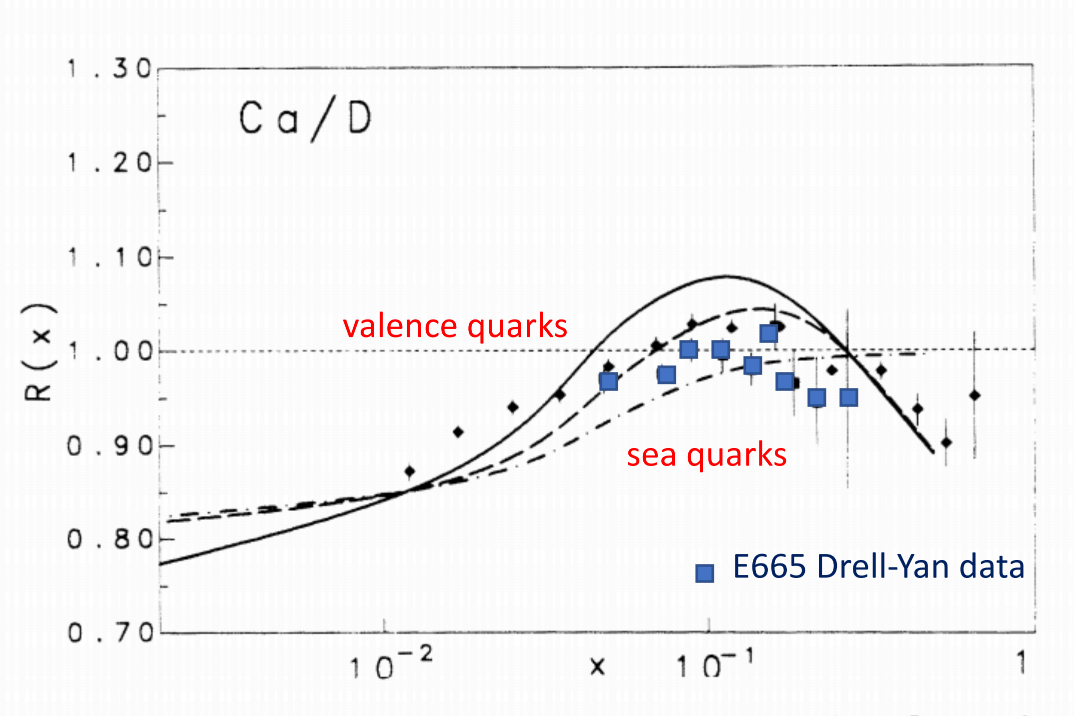
Isaak Brodsky

(1884-1939)

Nuclear shadowing/anti-shadowing



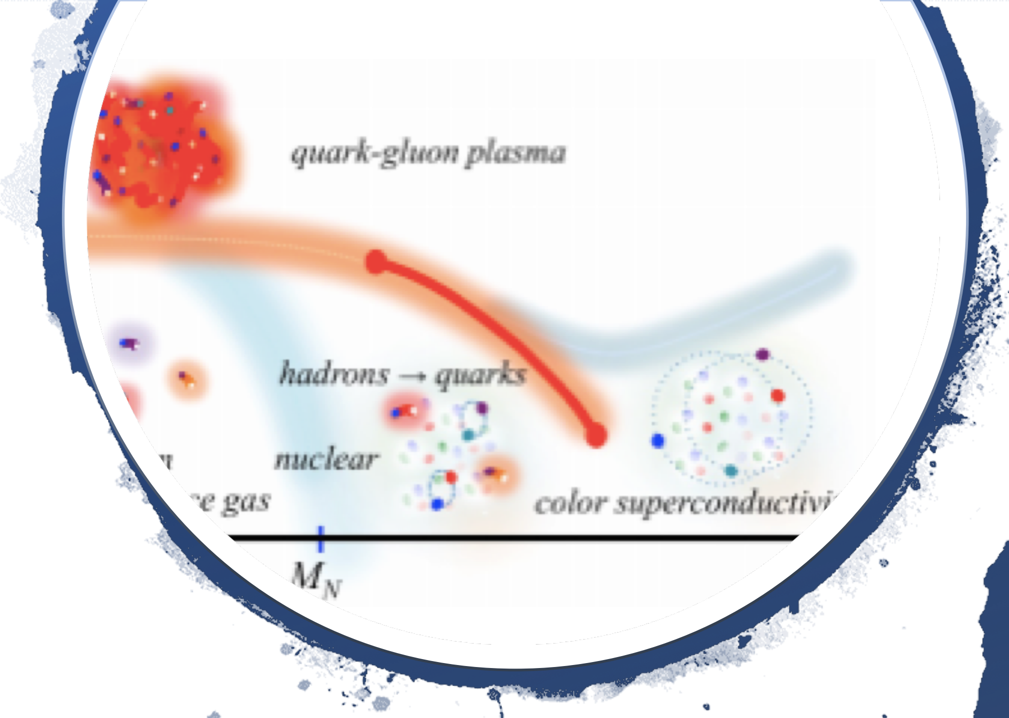
Brodsky and Lu, PRL64 (1990)



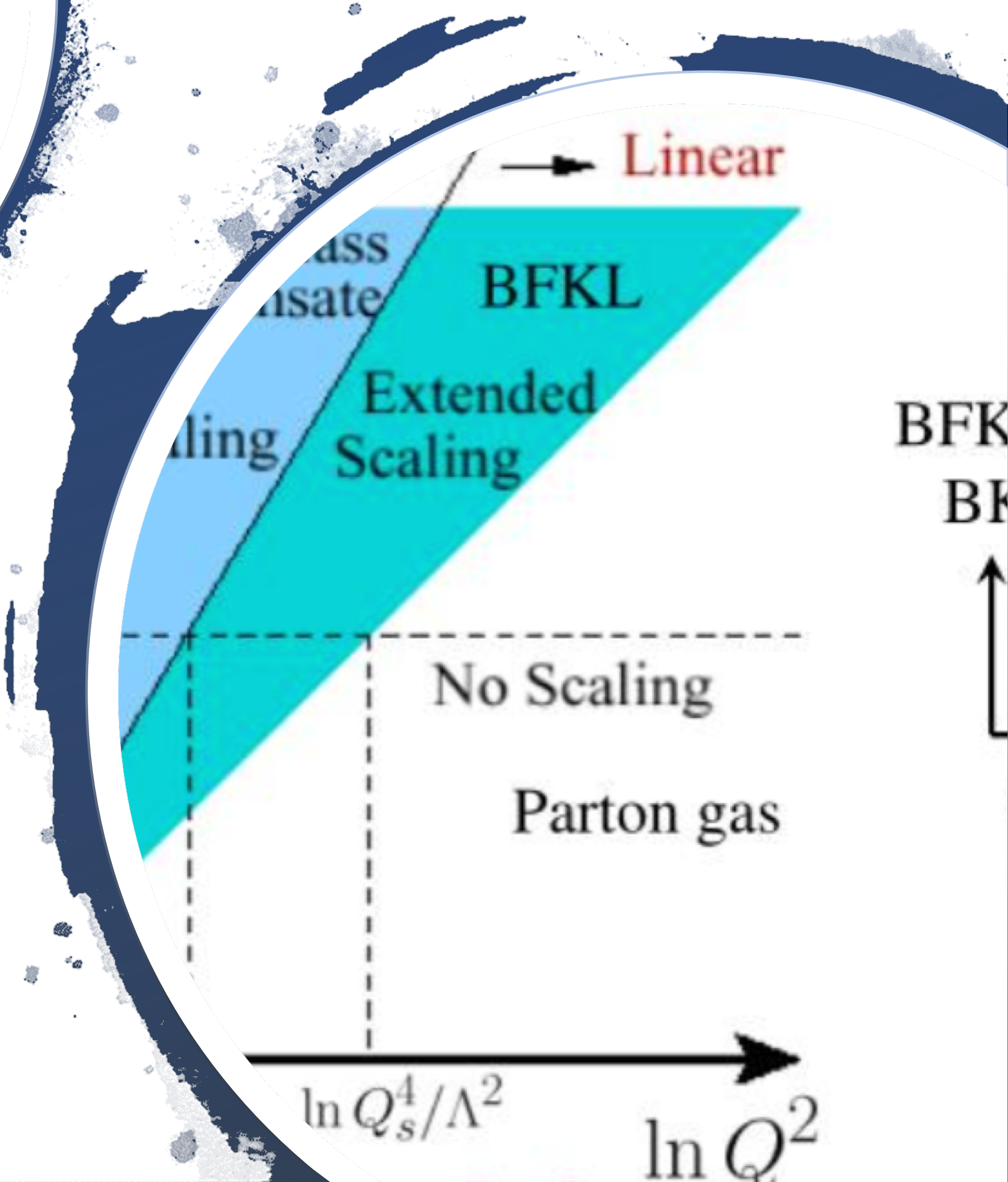
Frankfurt, Strikman, Liuti PRL65 (1990), A series of long unsolved puzzles that brought to the forefront…

…the present QCD-based picture of nuclei

➡ nuclei as testbeds for QCD



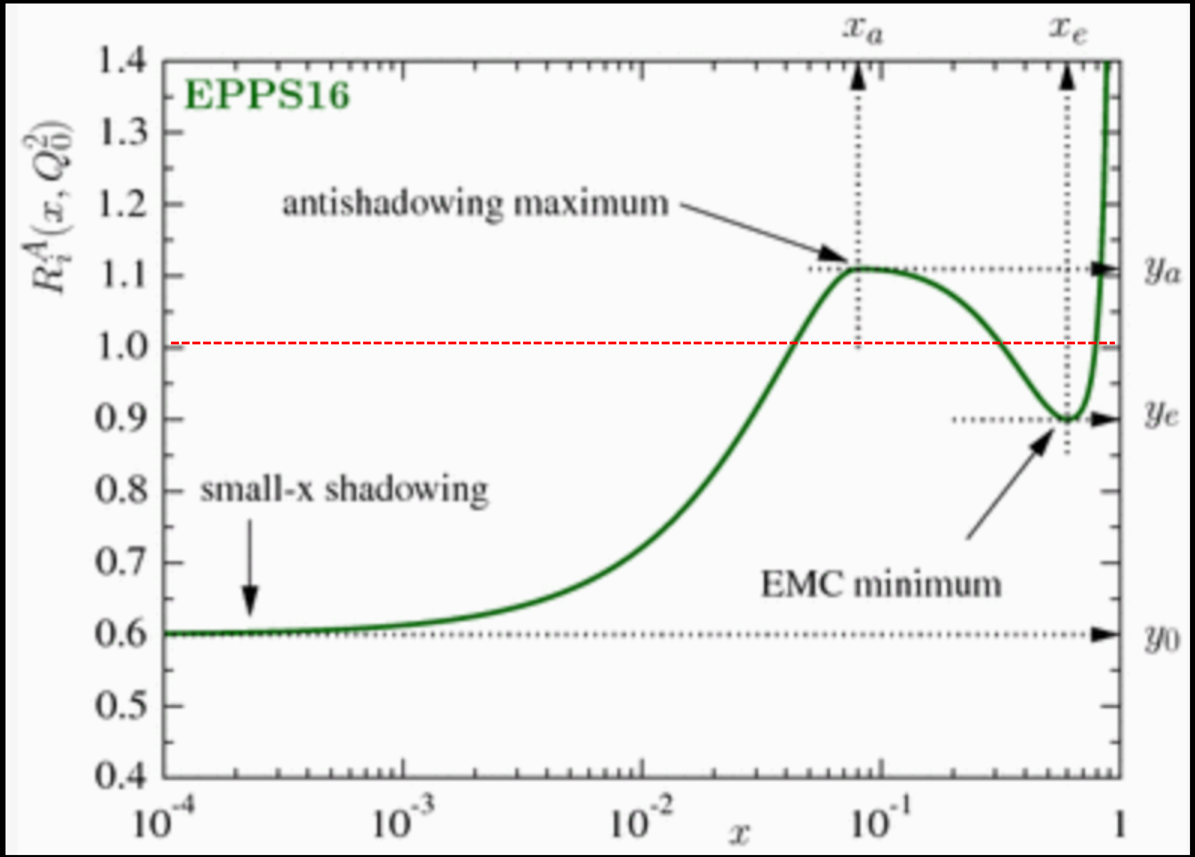
ALICE RHIC SPS



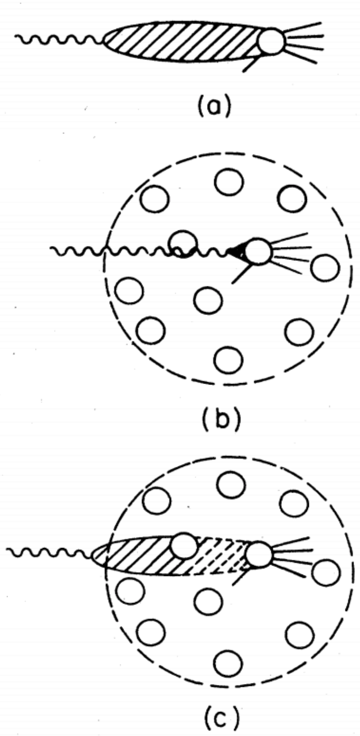
Disclaimer: not addressing High T QCD, non-linear effects…

The quark and gluon structure of nuclei

$$R_A^i = \frac{f_A^i(x, Q^2)}{f_N(x, Q^2)}$$

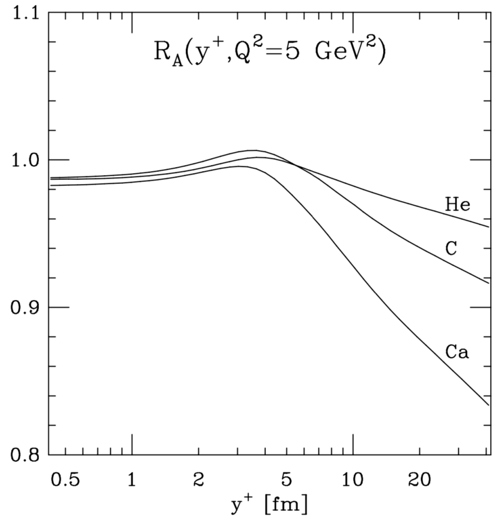


K. Eskola (2017)



$$f(x,k_T) = \int dk^- W(x,\mathbf{k}_T,k^-) = \int dy^- d^2\mathbf{y}_T\, e^{i(k^+y^- - \mathbf{k}_T\cdot\mathbf{y}_T)} \langle p \mid \bar{\psi}(0,0,0)\mathcal{U}(0,y)\gamma^+\psi(0,y^-,\mathbf{y}_T) \mid p\rangle_{y^+=0}$$

$k^+ \to 0 \Rightarrow y^- \gg 0$



P. Hoyer

Bauer, Spital, Yennie, Pipkin, RMP 51 (1979)

Shadowing and Anti-shadowing arise as coherent phenomena

Different ways to approach the problem

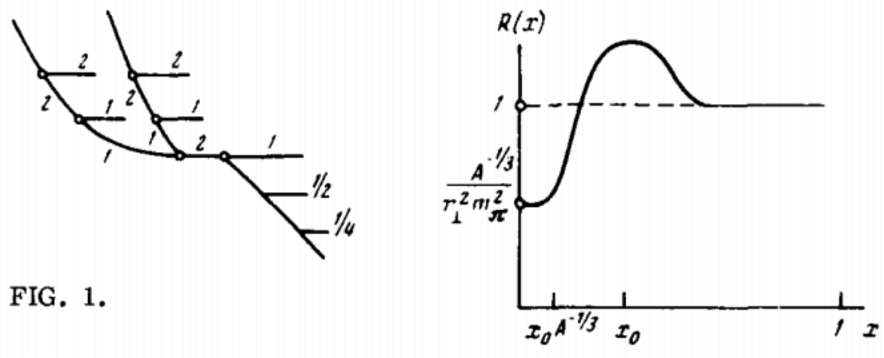


FIG. 1.

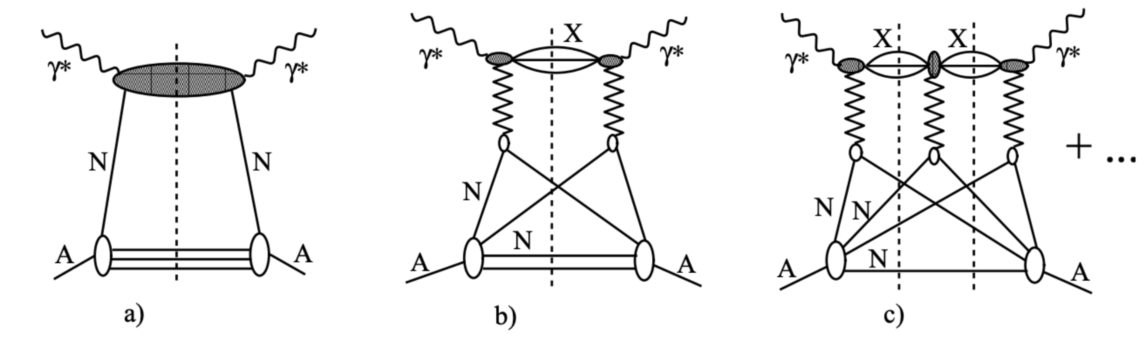
FIG. 2.

tribution. [7, 8] In the language of the perturbation-theory diagrams, this phenomenon is manifest in a coalescence of short parton ladders from different nucleons, and leads to a decrease of the parton density below the coalescence point.

Nikolaev and Zakharov, JETP Letters 20 (1974)

An important circumstance is that the coalescence does not change the total momentum of the partons. The momentum is only redistributed among partons with different values of x. On the other hand, the deep-in-

- **Shadowing** is described using a dipole—model and Glauber rescattering
- **Anti-shadowing** is **not treated as a coherent phenomenon**. It occurs in the amount necessary to satisfy the momentum sum rule



Frankfurt, Guzey, Strikman, PR 512(2012)

Glauber Rescattering in impact parameter space

$$F_{2A}^{(b)}(x,Q^2) = -8\pi A(A-1)\Re e\frac{(1-i\eta)^2}{1+\eta^2}\int_x^{0.1} dx_{I\!P} F_2^{D(4)}(x,Q^2,x_{I\!P},t_{\min})$$
$$\times \int d^2\vec{b} \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2\, \rho_A(\vec{b},z_1)\rho_A(\vec{b},z_2) e^{i(z_1-z_2)x_{I\!P} m_N} .$$

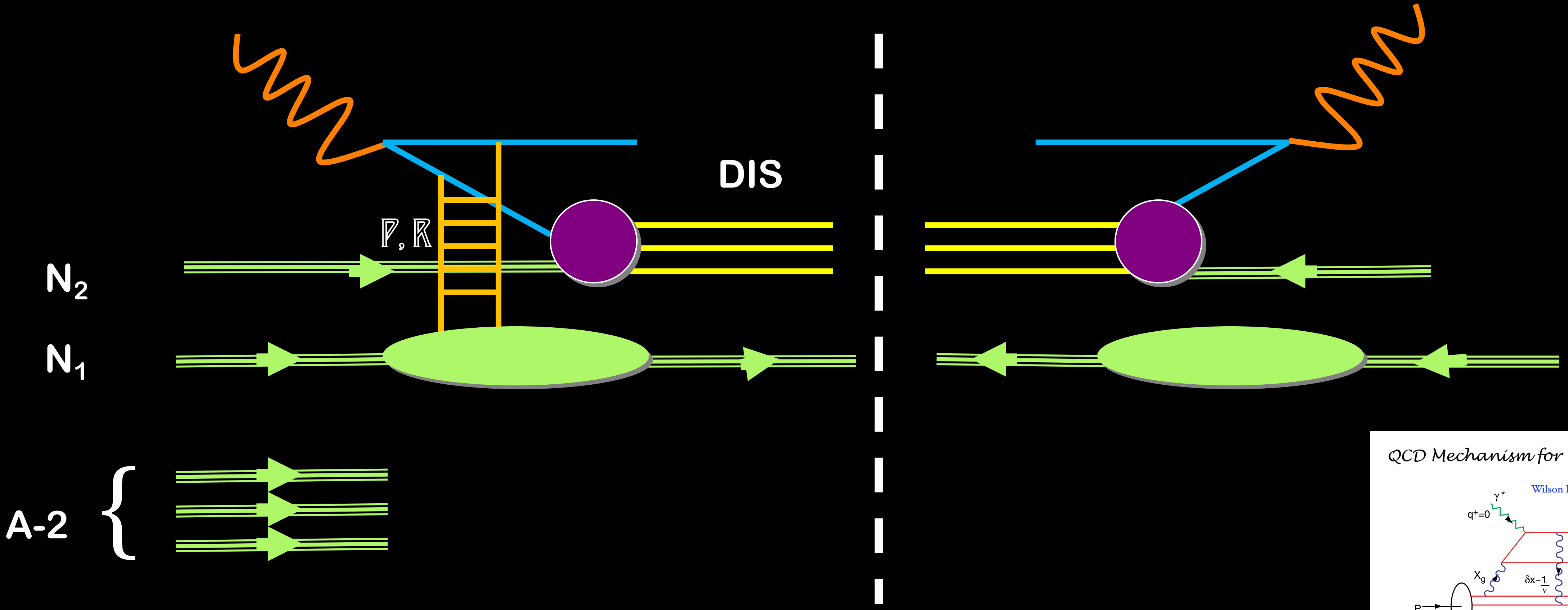
Finally, perturbative approaches: J.Qiu, Qiu and Vitev

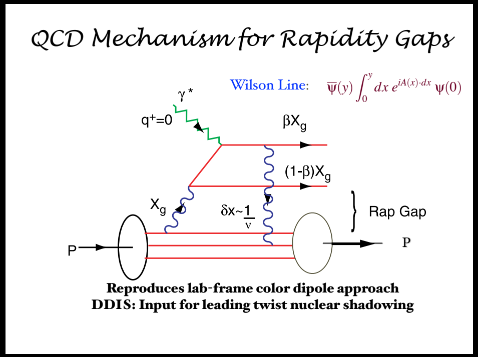
New Important Observation

- Shadowing/Anti-shadowing are coherent phenomena arising from Quantum Interference of deeply virtual scattering amplitudes with different phases

- Similar to Sivers effect but not from gauge link structure

Amplitude for Diffractive scattering (DDIS)





- DIS always come with a phase from the propagator i

- Reggeon and Pomeron exchanges phase structure:

$$T_{\bar{q}N}(s,\mu^2)=\sigma\left[is\beta_1(\mu^2)+(1-i)s^{1/2}\beta_{\frac{1}{2}}(\mu^2)+(1-i)s^{-1}\beta_{-1}(\mu^2)-\ is\beta_O(\mu^2)\right]$$

Pomeron Reggeon Reggeon Odderon

- The phase structure does not change in the Glauber type multiple scattering process

- $i\times i=(-1)\Rightarrow$ Pomeron interferes destructively **Shadowing**

- $-i\times i=1\Rightarrow$ Reggeons interfere constructively **Anti-shadowing**

- Different J^{PC} quantum numbers according to the flavor structure of the reaction

Based on…

Is the Momentum Sum Rule Valid for Nuclear Structure Functions ?

Stanley J. Brodsky

SLAC National Accelerator Laboratory, Stanford University

Simonetta Liuti*

Department of Physics, University of Virginia, Charlottesville, VA 22904, USA.

Ivan Schmidt

Departamento de Física y Centro Científico Tecnológico de Valparaíso-CCTVal Universidad Técnica Federico Santa María, Casilla 110-V, Valparaíso, Chile

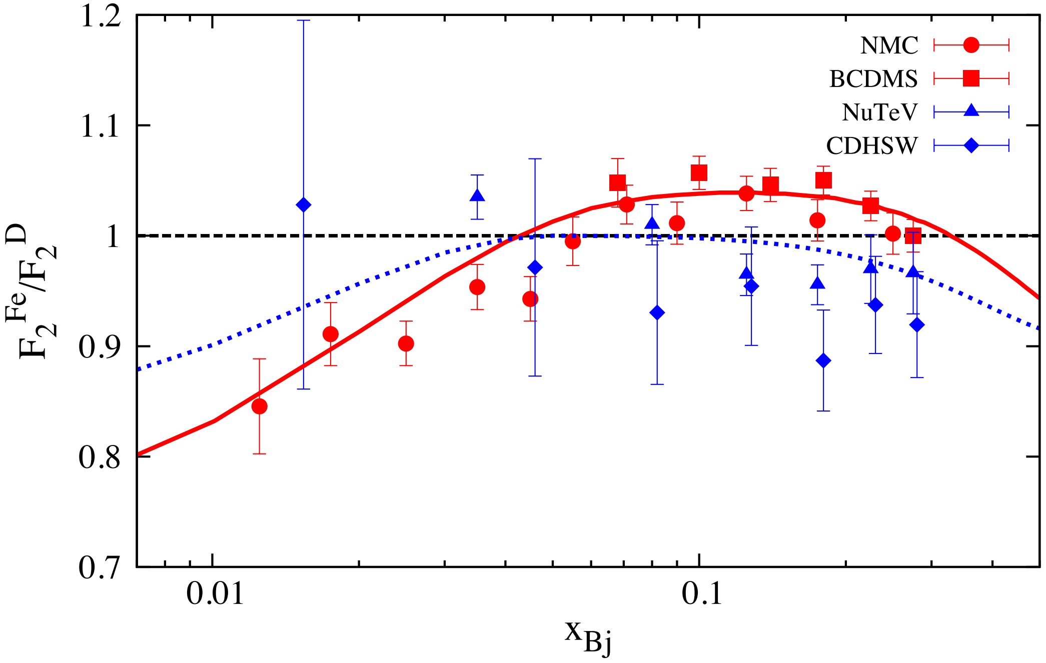
(Dated: February 4, 2020)

We address the validity of the momentum sum rule for deep inelastic nuclear structure functions.

arXiv:1908.06317

Non Universality of Nuclear PDFs

Neutrino scattering data emphasize that anti-shadowing is flavor dependent



Red: charged leptons

Blue: neutrinos

$$\frac{1}{2x}F_2^{\nu N(A)} = d_{N(A)} + s_{N(A)} + \bar{u}_{N(A)} + \bar{c}_{N(A)} \ldots \qquad \text{(1a)}$$

$$\frac{1}{x}F_2^{\ell N(A)} = \frac{4}{9}(u_{N(A)} + \bar{u}_{N(A)}) + \frac{1}{9}(d_{N(A)} + \bar{d}_{N(A)}) + \frac{1}{9}(s_{N(A)} + \bar{s}_{N(A)}) + \ldots \qquad \text{(1b)}$$

In quantum interference model this is described by t-channel exchanges with different J^{PC} quantum numbers

See e.g. I. Schienbein et al., PRD77 (2008)

N. Kalantarians et al., PRC96 (2017)

J. Mousseau et al., PRD93(2016)

Because of quantum interference the **Momentum Sum Rule** is violated in nuclei

- $\int_0^1 dx\, x\, q_A\,(x, Q^2) \neq$ A

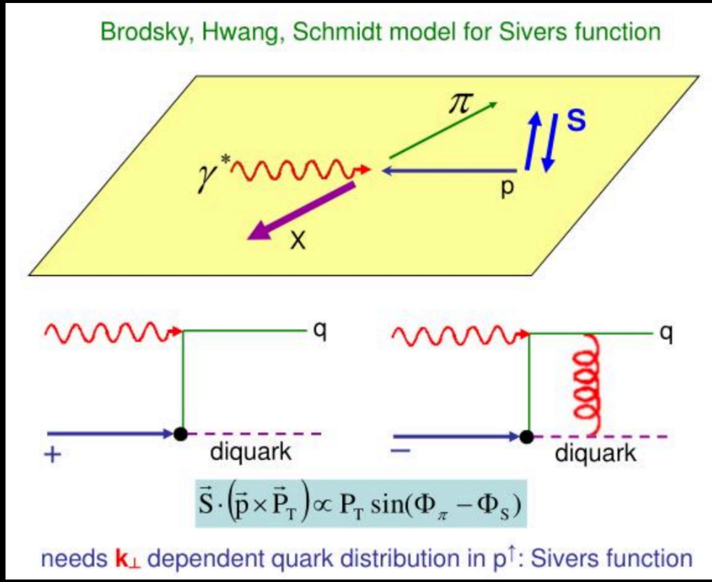
- **OPE :** $\langle p,\Lambda \mid \bar{\psi}(0) i\gamma^+ D^+ \psi(0) \mid p,\Lambda\rangle \equiv \int_0^1 dx x q_N(x)$ **does not apply**

Why…

1. One cannot evaluate local matrix elements because the quark currents act on different nucleons
1. Quarks belonging to the surface nucleons get shadowed, while interior ones do not
2. Not all propagators involved in the rescattering process are hard

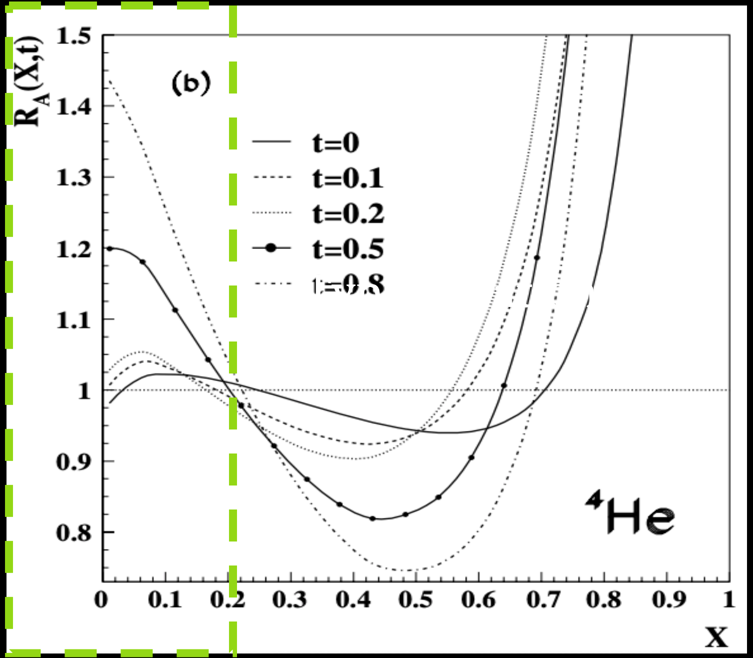
Main Takeaway: Physics of nuclear shadowing probes QCD at the amplitude level underlining the importance of quantum interference phenomena

Similarities with Sivers/Boer-Mulders effects



Similarities/Future Measurements: Deeply Virtual Compton Scattering (DVCS) and GPDs/Wigner functions

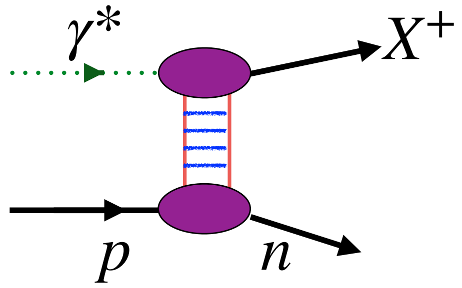
$$R_A(x,0,t) = \frac{H_A\,(x,0,t)}{H_N(x,o,t)}$$



SL, SK Taneja, PRC72(2005)

… is this trend observable…??

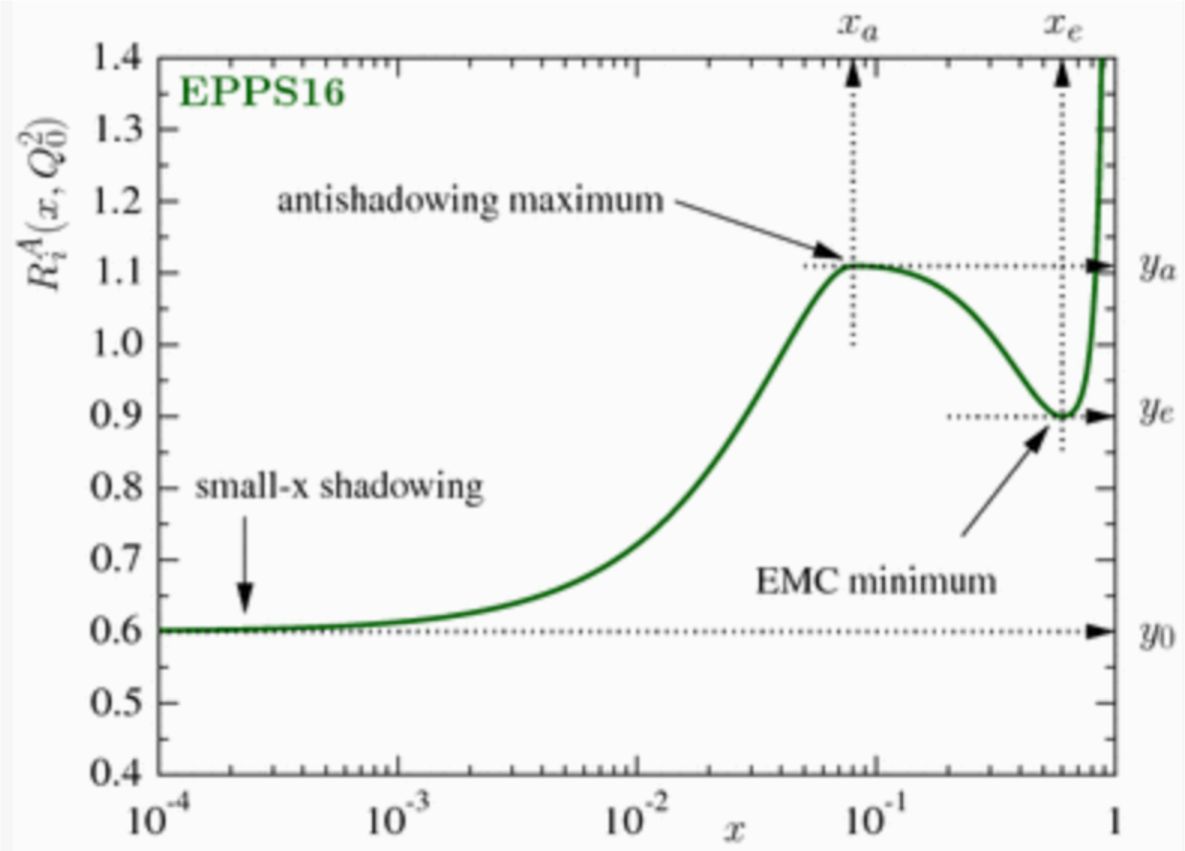
Future Measurements: Charge Exchange DDIS



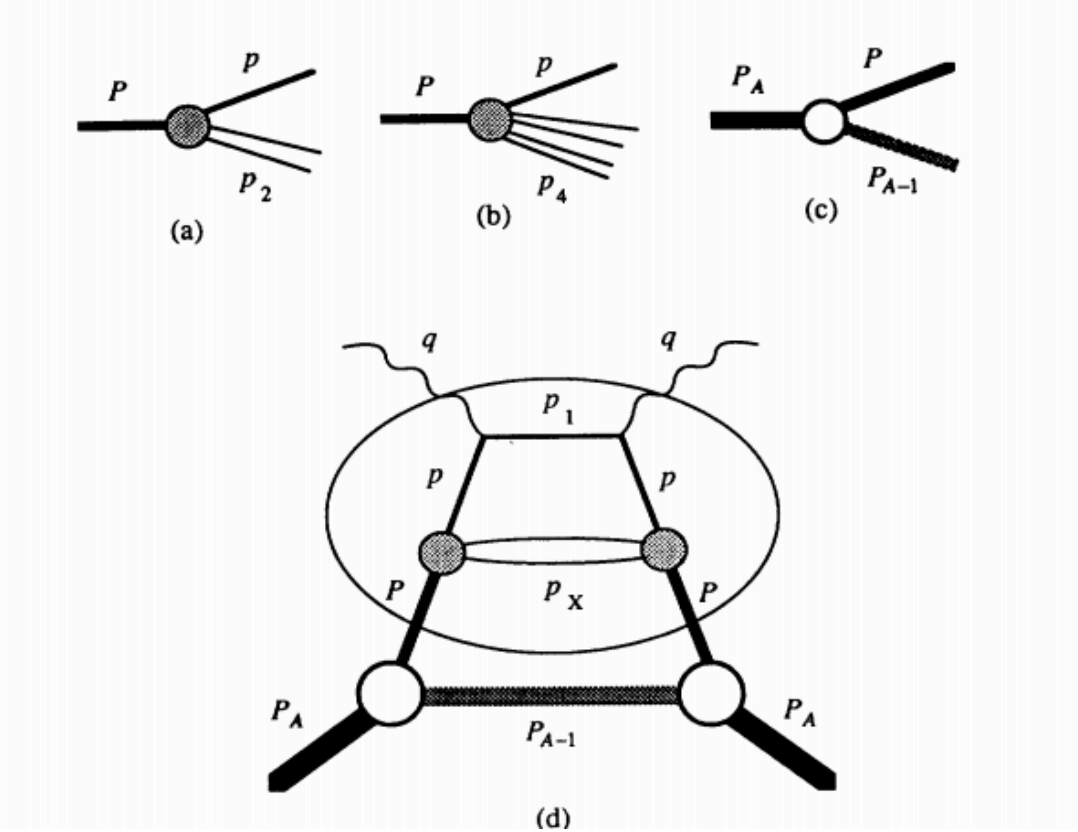
Reggeon Exchange Contribution to Charge-Exchange DDIS

- Pomeron exchange does not contribute to the charge exchange process
- This would single out Reggeon exchanges as the source of anti-shadowing

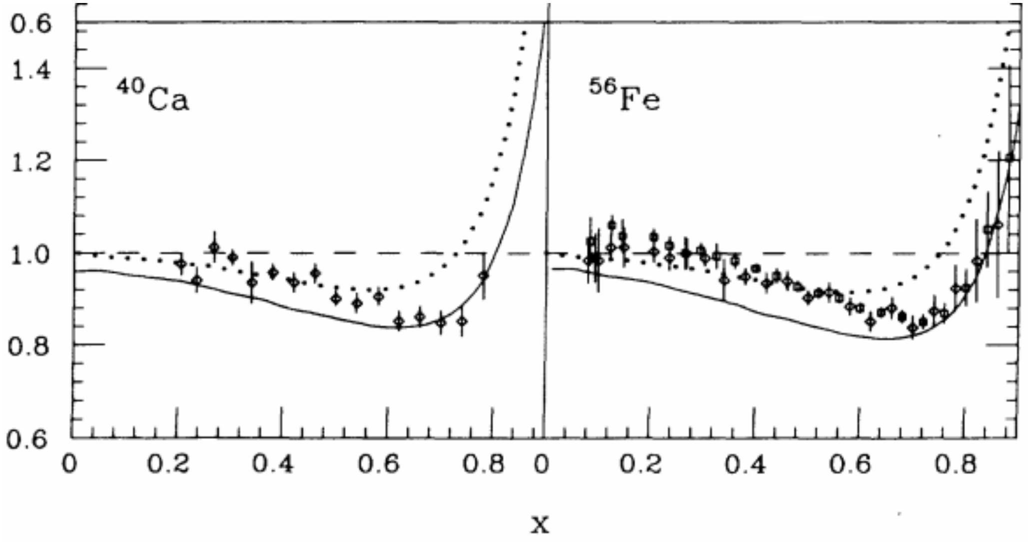
EMC Effect



EPPS16
antishadowing maximum
small-x shadowing
EMC minimum
x_a
x_e
y_a
y_e
y_0
$R_i^A(x, Q_0^2)$
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}
10^{-1}
1
x



Role of nucleon off-shellness

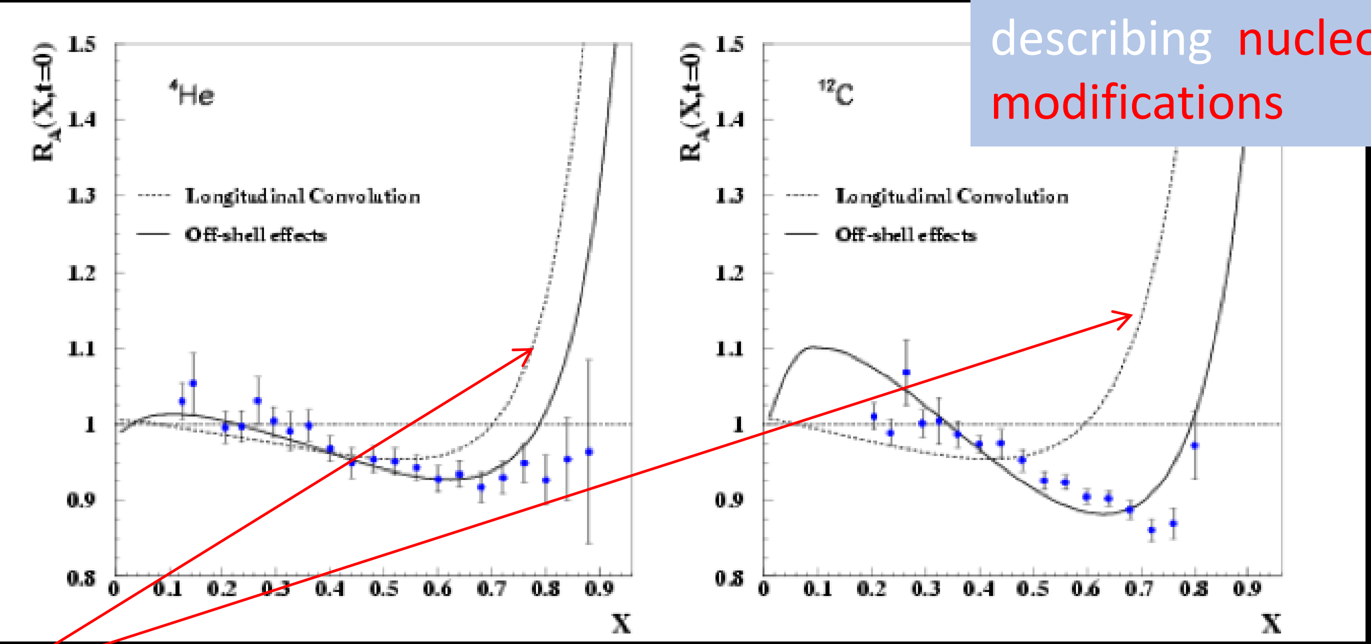


F. Gross, S. Liuti, PRC45 (1992)

f_1^q, g_1^q, h_1^q in nuclei

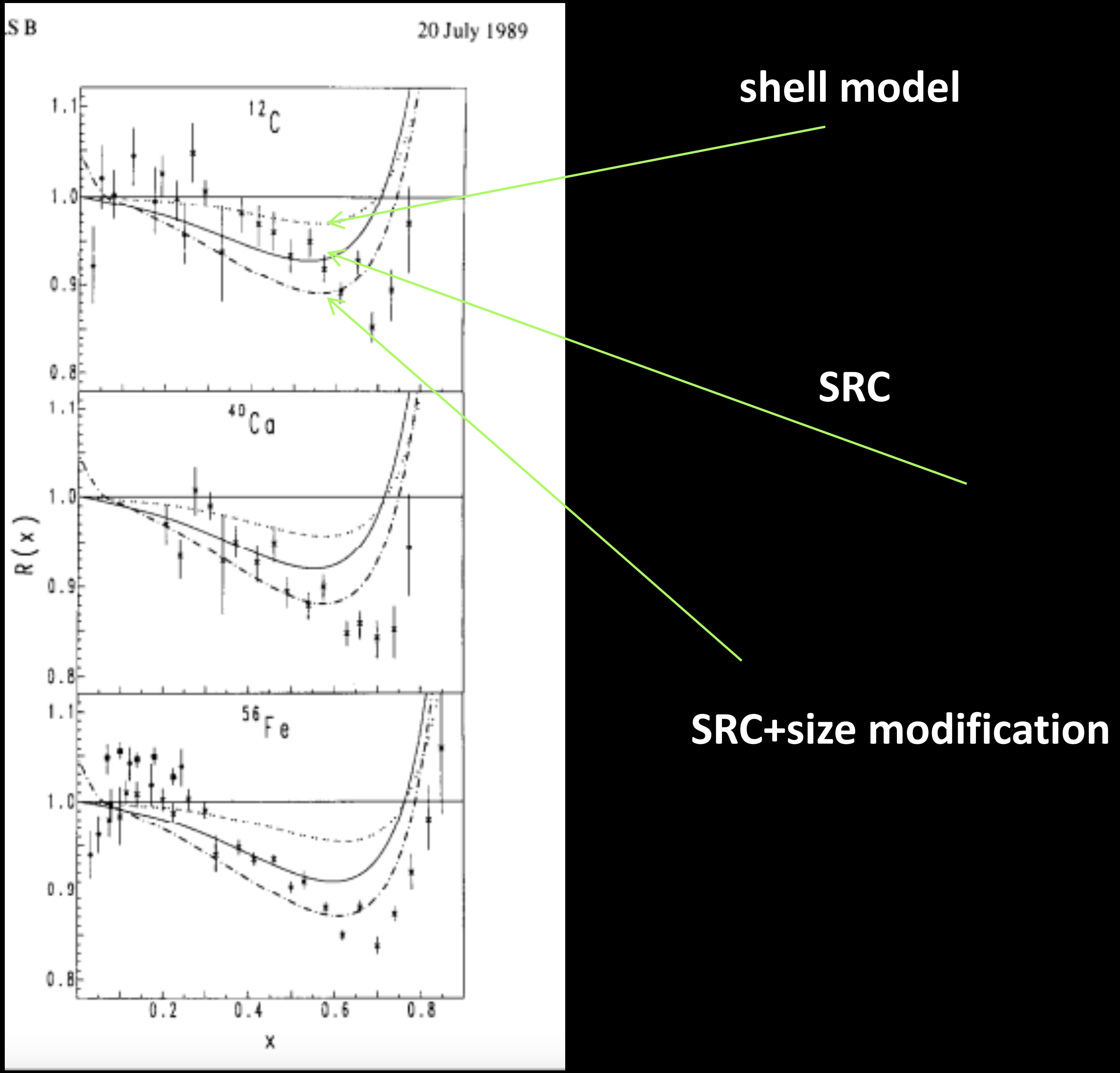
Liuti and Taneja (2005)

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



difference between dashed and full curves is due to off-shell effects related to the transverse motion of quarks an alternative way of describing nucleon medium modifications

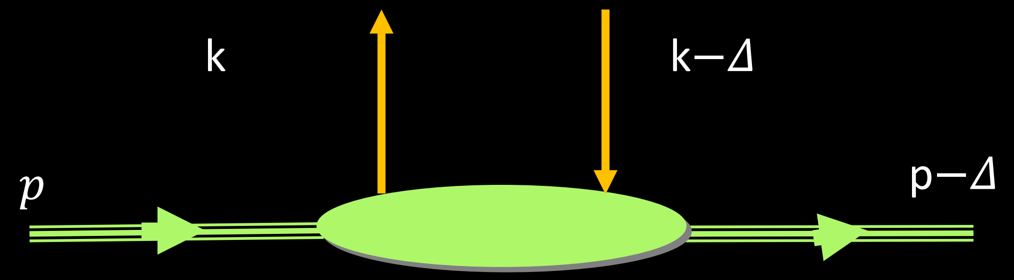
- ✓ Calculation including SRC (AV8) with unmodified nucleons
- ➔ Main constraint provided by Koltun sum rule



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

2020: correlation functions and gauge links give us the key to interpret the EMC effect

Nucleon



k_T unintegrated

$$f(x,\mathbf{k}_T) = \int dk^- W(x,\mathbf{k}_T,k^-) = \int dy^- d^2\mathbf{y}_T\, e^{i(k^+y^- - \mathbf{k}_T\cdot\mathbf{y}_T)} \langle p \mid \bar{\psi}(0,0,0)\mathcal{U}(0,y)\gamma^+\psi(0,y^-,\mathbf{y}_T) \mid p\rangle_{y^+=0}$$

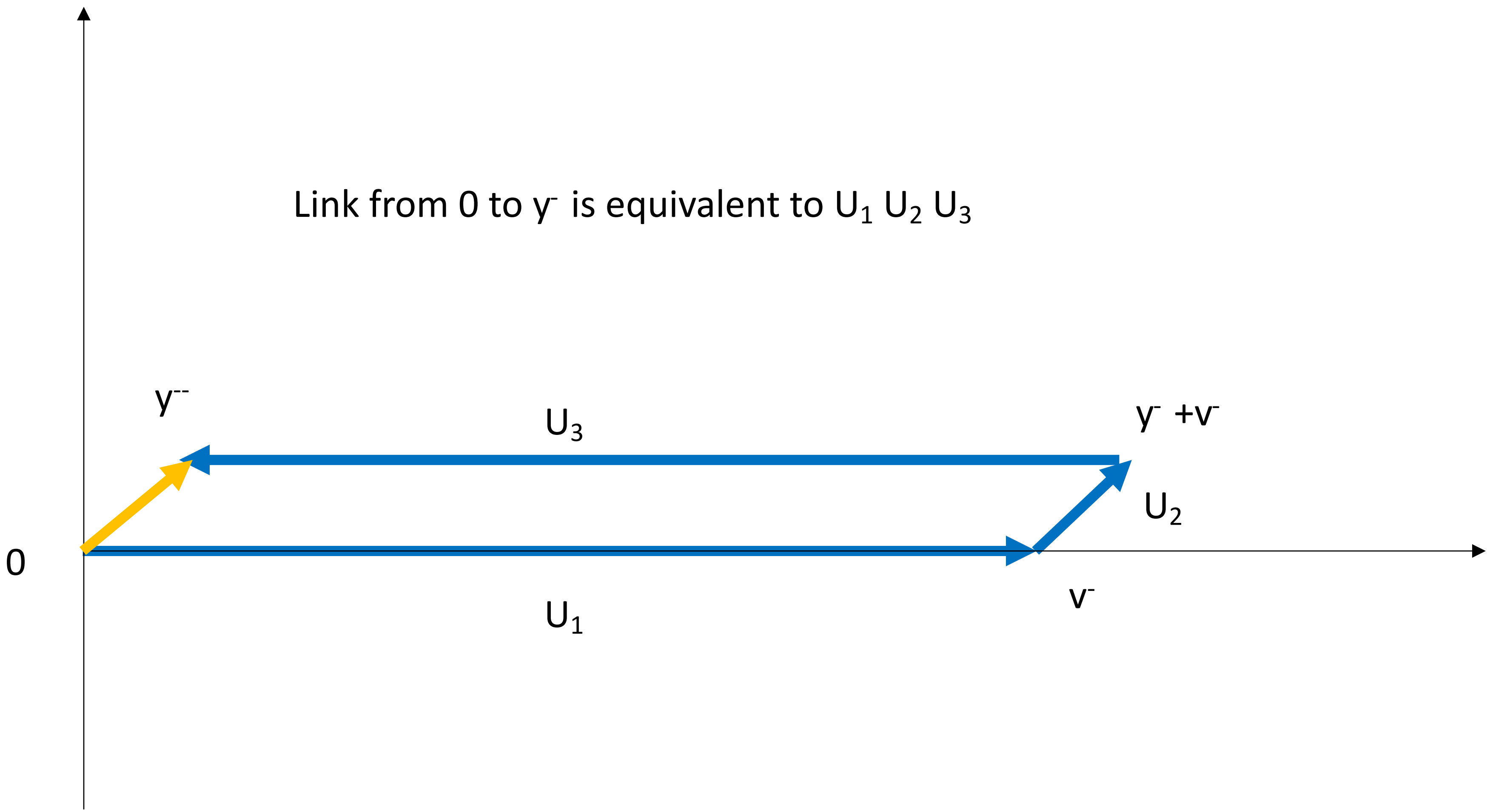
k_T integrated

$$f_N(x) \quad \int d^2k_T\, f(x,\mathbf{k}_T) = \int dy^- d^2\mathbf{y}_T\, e^{ik^+y^-}\, \delta^2(\mathbf{y}_T) \langle p \mid \bar{\psi}(0,0,0)\mathcal{U}(0,y)\gamma^+\psi(0,y^-,\mathbf{y}_T) \mid p\rangle_{y^+=0}$$

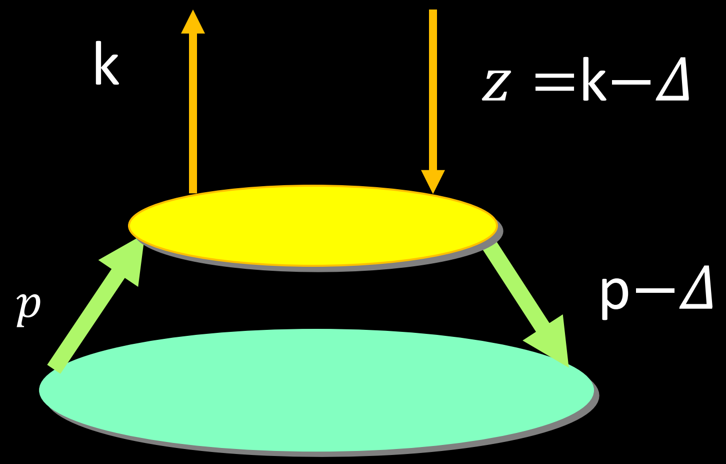
kinematical variables $\quad k^2 \qquad 2(kp) \rightarrow k^- \qquad k_T^2$

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

Link from 0 to y^{-} is equivalent to U_1 U_2 U_3



Off-shell nucleon

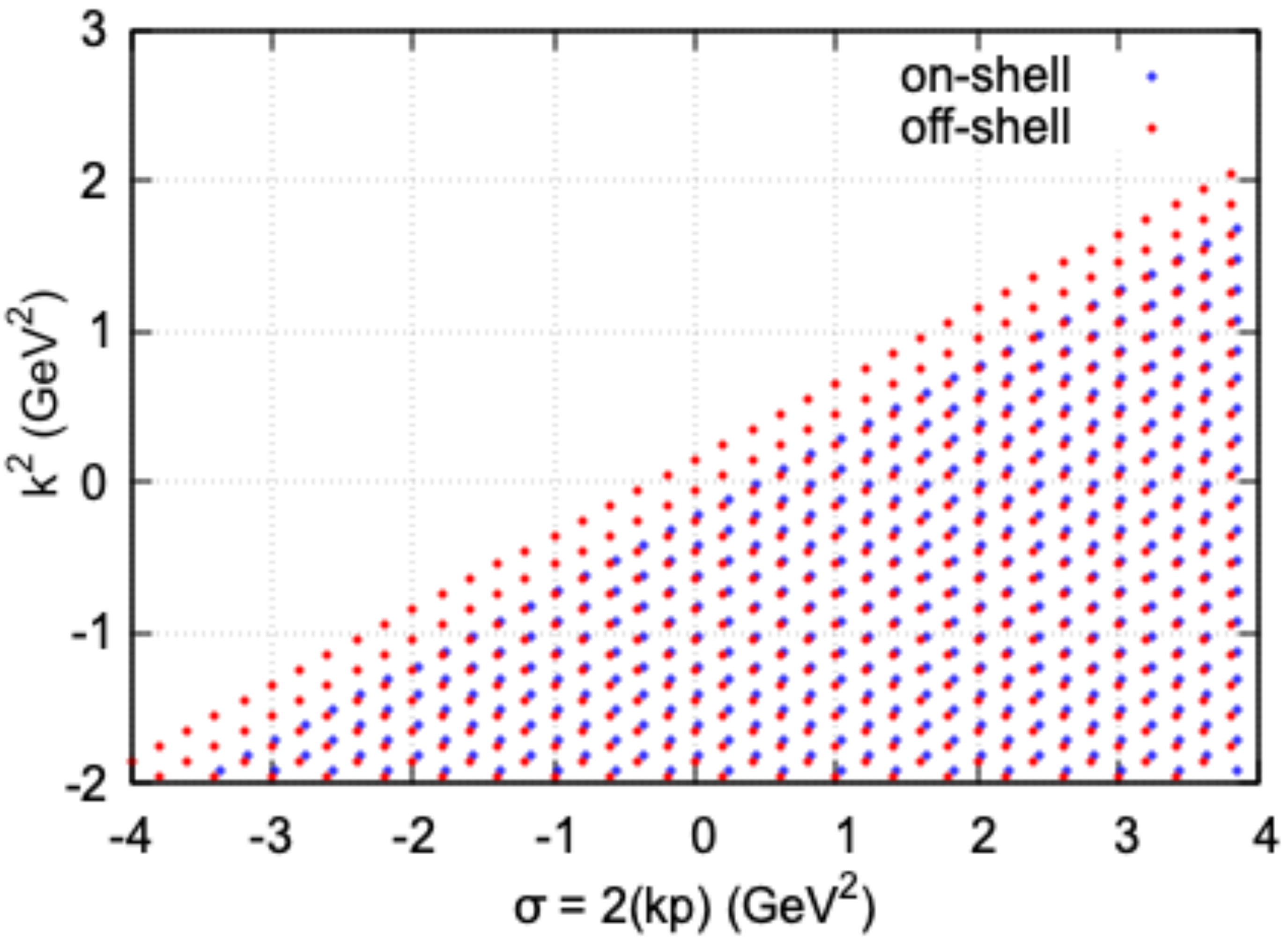


$$f_A(x)$$

$$f(x', \mathbf{k}'_T) = \int dy^- d^2\mathbf{y}_T \, e^{i(x'p^+y^- - \mathbf{k}'_T\cdot\mathbf{y}_T)} \langle p \mid \bar{\psi}(0,0,0)\mathcal{U}(0,y)\gamma^+\psi(0,y^-,\mathbf{y}_T) \mid p\rangle_{y^+=0}$$

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

$$z = p^+/AP_A^+$$



on-shell
off-shell
k^2 (GeV^2)
$\sigma = 2(kp)$ (GeV^2)
3
2
1
0
-1
-2
-4
-3
-2
-1
0
1
2
3
4

$$f(x', \mathbf{k}'_T) = \int dy^- d^2\mathbf{y}_T \, e^{i(x' p^+ y^- - \mathbf{k}'_T \cdot \mathbf{y}_T)} \langle p \mid \bar{\psi}(0,0,0)\mathcal{U}(0,y)\gamma^+ \psi(0, y^-, \mathbf{y}_T) \mid p \rangle_{y^+=0}$$

$$f_A(x) = \int d^2k_T f(x', \mathbf{k}'_T) + K_A(p^2) \int d^2k_T k_T^2 f(x', \mathbf{k}'_T)$$

Larger transverse Ioffe time in nuclei generates a non trivial gauge-link structure: FSI are present and give origin to the EMC effect

Conclusions

Stan's idea of probing QCD at the amplitude level is key to the deep inelastic structure of nuclei

- **A new approach to lepton nucleus scattering at low Bjorken x:**

- Shadowing and anti-shadowing are quantum interference phenomena between scattering amplitudes
- As a consequence of different t channel exchanges anti-shadowing is flavor dependent: non universality of charged lepton and neutrino scattering
- OPE is invalidated in nuclei: the momentum sum rule cannot be evaluated
- Similar phenomenon to Sivers effect
- Future Developments: Ioffe time description (see P. Hoyer) and pseud0-pdfs; DVCS from nuclei

- **A new approach to the EMC effect:**
- FSI due to gauge invariance cannot be disregarded, they are actually the cause of the EMC effect

"If you know when you have enough, you are wealthy,
If you carry your intentions to completion, you are resolute,
If you live a long and creative life, you will leave an eternal legacy"
– Lao Tze

Cento di questi giorni, Stan!