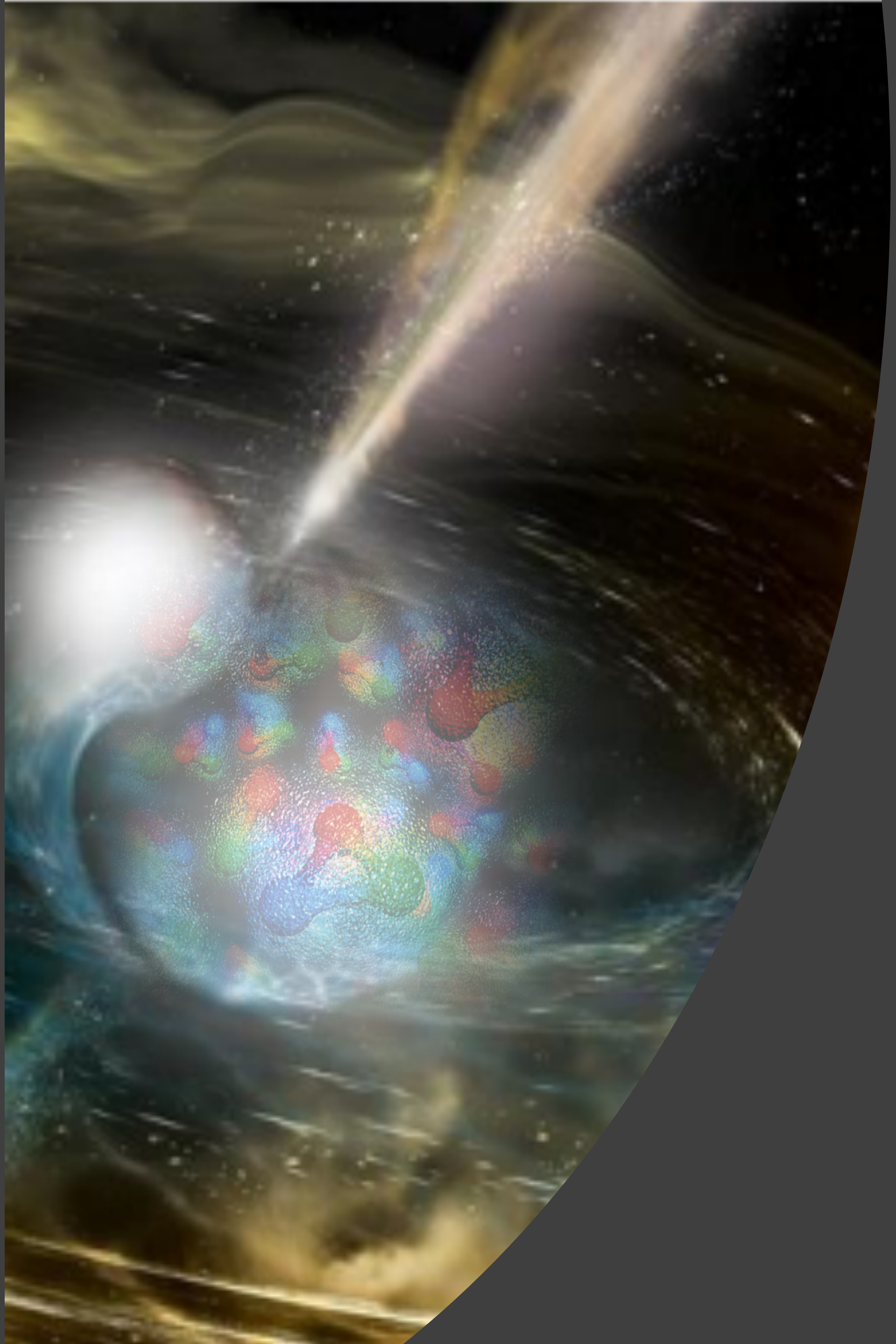


The nuclear EMC Effect as a Testing Ground for Color Forces

Quantitative Challenges in EMC and SRC Research
LNS/MIT and EIC^2/Jlab
March 22-26, 2021

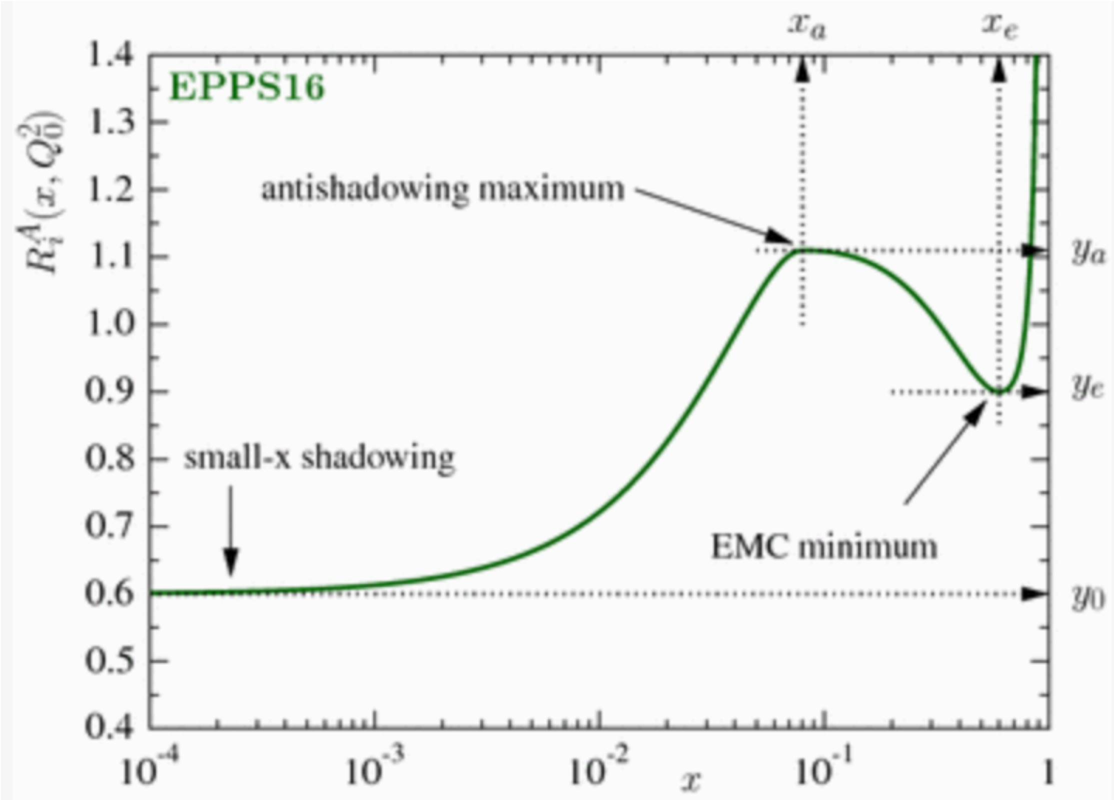
SIMONETTA LIUTI
UNIVERSITY OF VIRGINIA

Still crazy after all these years...

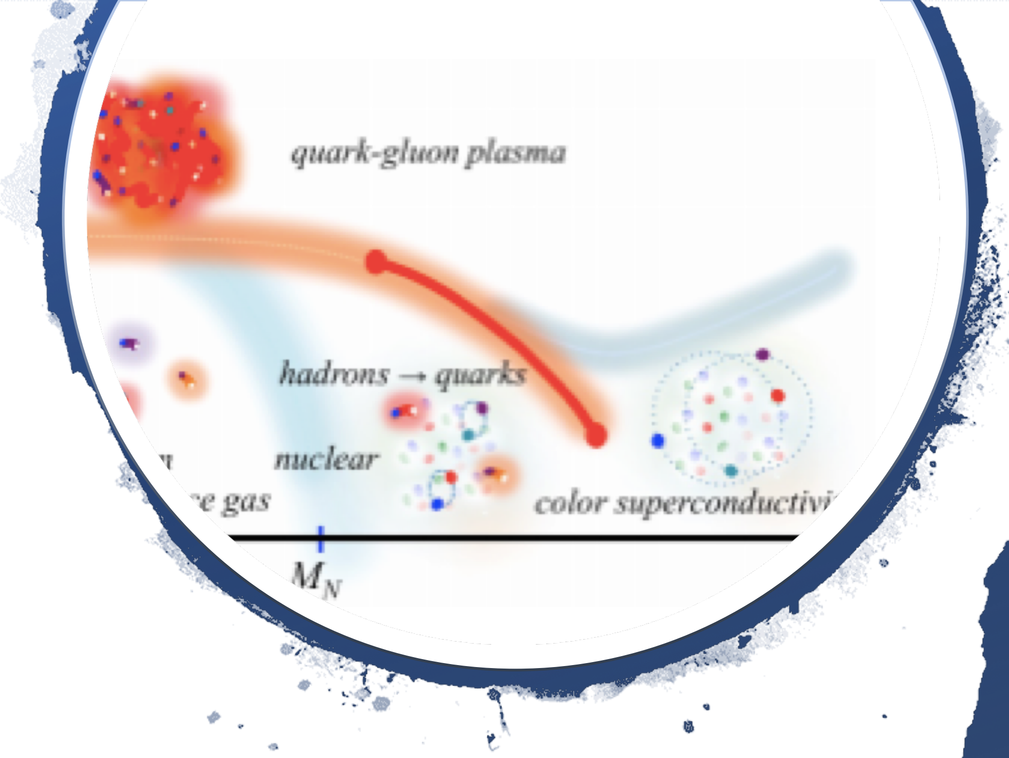
Paul Simon

A series of long unsolved puzzles is bringing to the forefront the QCD-based picture of nuclei…

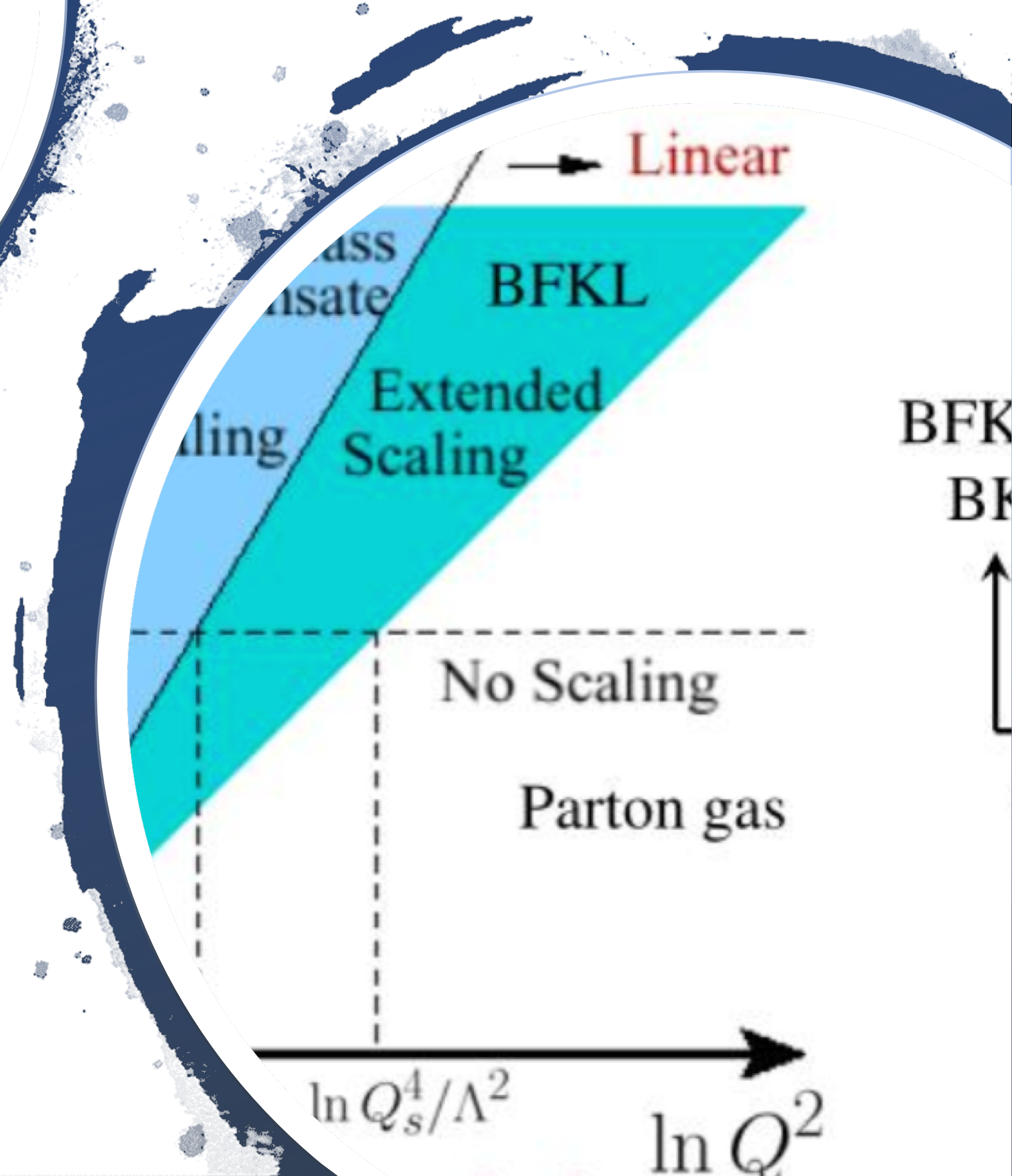
EMC Effect



K. Eskola (2017)



ALICE RHIC SPS



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

Role of Nuclear Binding and SRC

LETTERS B 20 July 1989

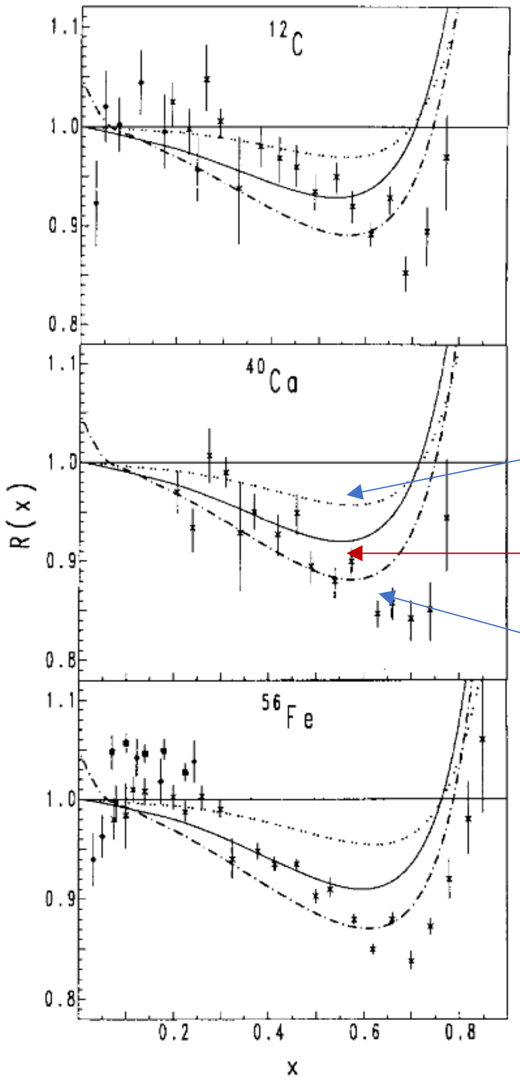
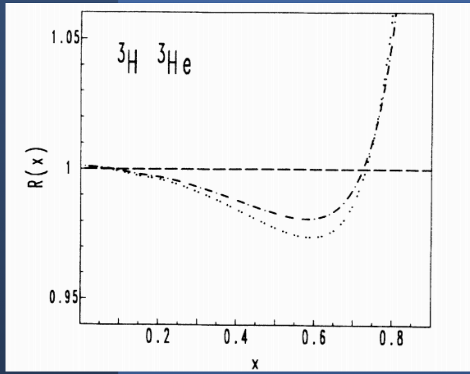


Fig. 3. The EMC effect in ^{12}C, ^{40}Ca and ^{56}Fe. Dotted lines: HF result; full lines: correlated many-body approach of the present

Independent Particle Model

SRC using Rome group spectral function

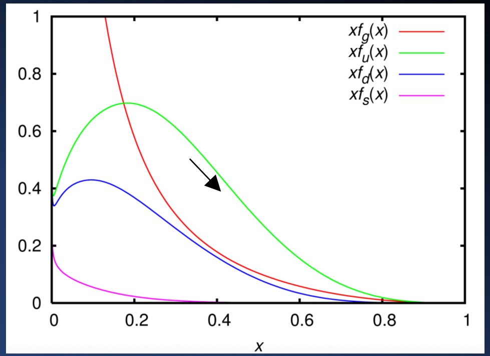
additional Q^2 rescaling

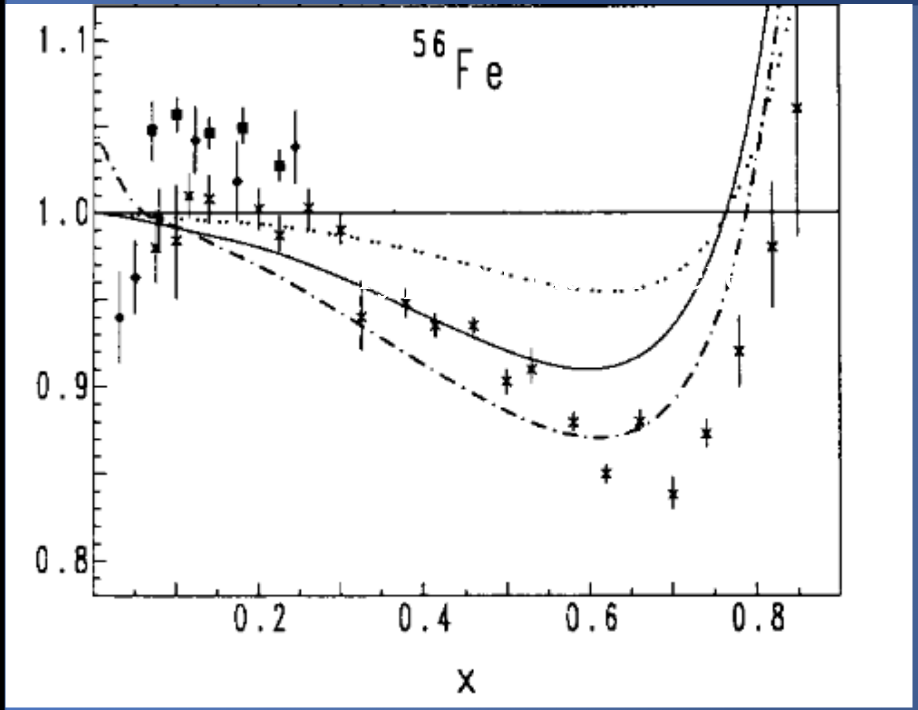


Ciofi, SL, *PLB 225* (1989)
Ciofi, SL, *Phys.Rev.C* 41 (1990)
Ciofi, SL, Simula, *Phys.Rev.C* 41 (1990)
Ciofi, *Phys.Rept.* 590 (2015)
Ciofi, Morita, *Phys.Rev.C* 96 (2017)

Explanation: x-rescaling

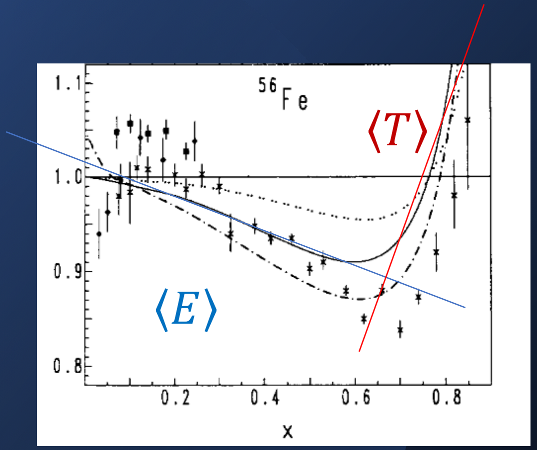
$$f_A(x, Q^2) = f_N\left(\frac{x}{1-\frac{\langle E\rangle}{M}}, Q^2\right)$$





Kinematic shift from low x to large x

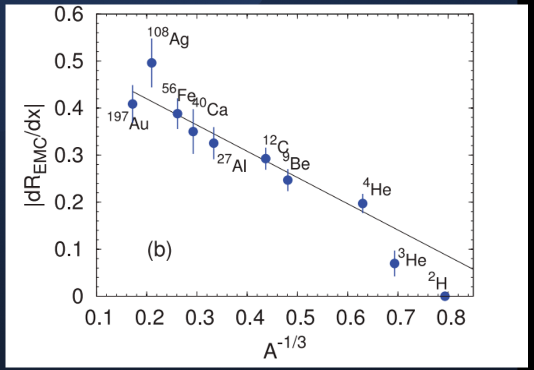
Criticism to Binding Model



1. Due to the the Koltun Sum Rule

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

As you increase the negative slope at intermediate x you also increase the positive slope at large x, and the combination does not match data!



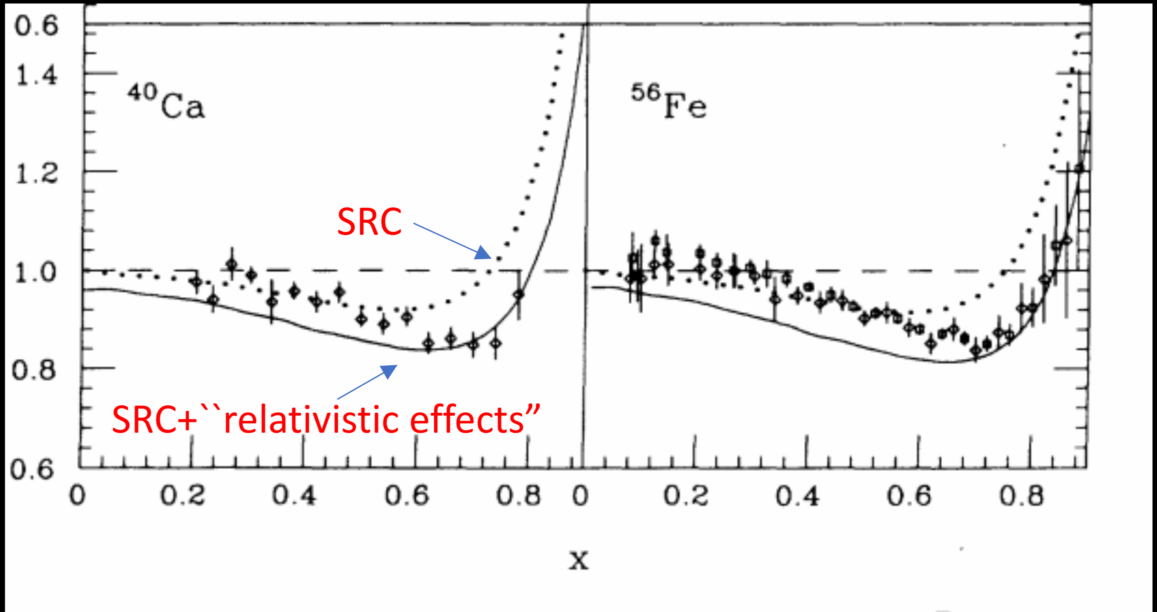
2. Hugenolz Van Hove Theorem (G. Miller)

3. From the experimental point of view cannot decscribe quantitatively the regularities in A dependent quantities

J. Arrington et al., PRC86 (2012)

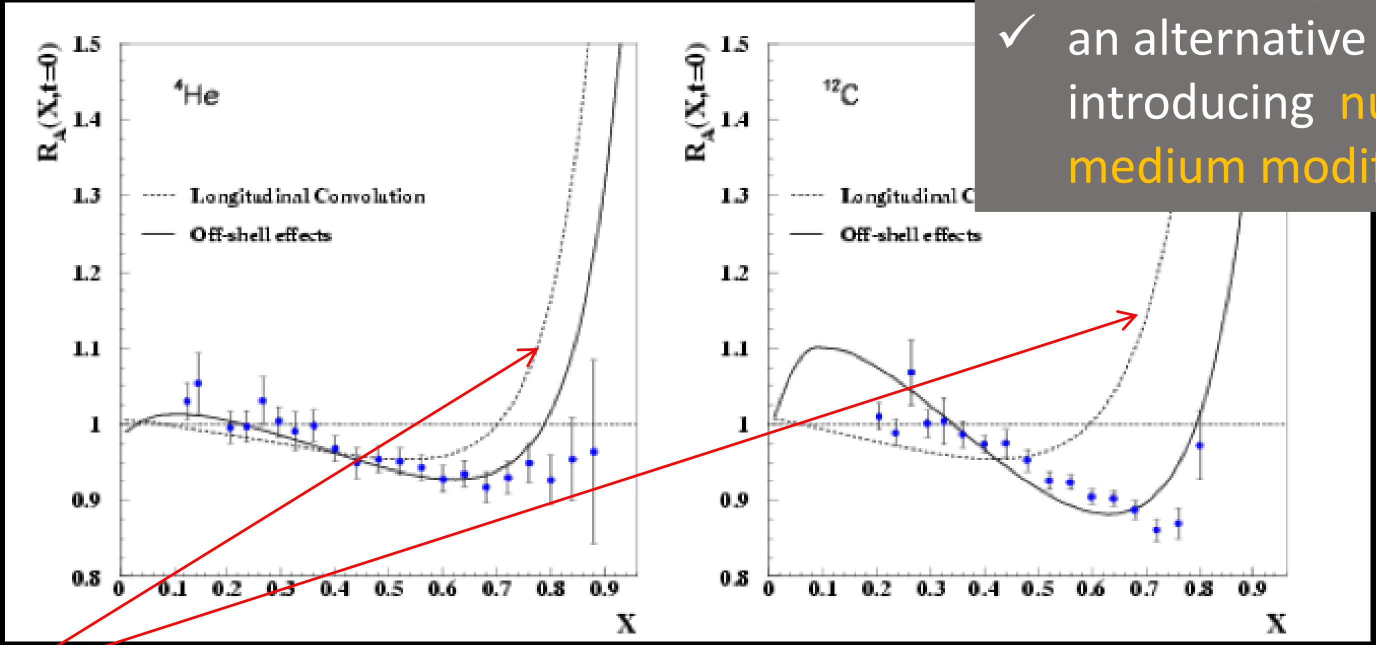
Role of nucleon off-shellness

“Relativistic Effects”



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

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



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

Liuti and Taneja PRD (2005)

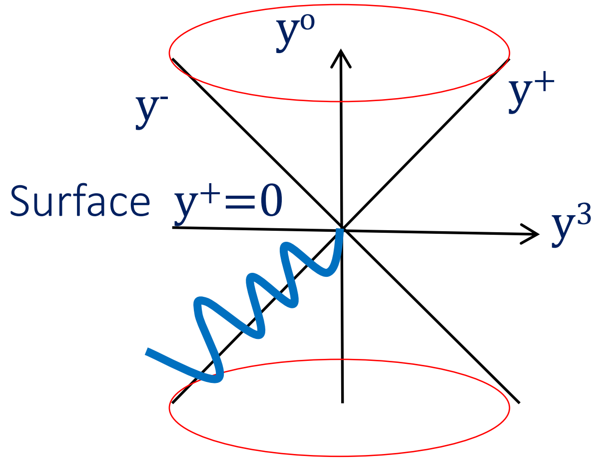
- ✓ Calculation including SRC (AV8) with unmodified nucleons

“The existence of kinematical off-shellness indirectly implies that intrinsic deformations/parton reinteractions are present. In other words, off-shell effects are an indirect manifestation of the impact of interactions among particles during the hard scattering process”

SL, S.K. Taneja, PRD72 (2005) on nuclear GPDs

What are off-shell effects ?

Momentum and Space Correlations



Fourier transform

$$\boxed{(ky) = k^+y^- + k^-y^+ - k_T \cdot y_T}$$

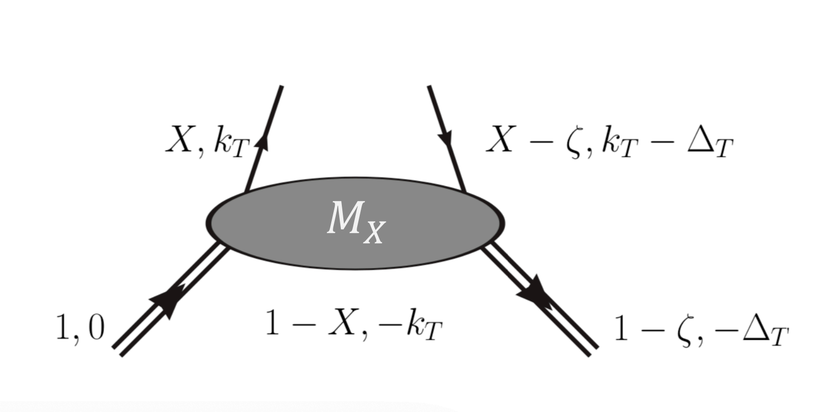
Off-shellness

$$\boxed{k^2 = 2k^+ k^- - k_T^2} \qquad \boxed{k^+ = xp^+}$$

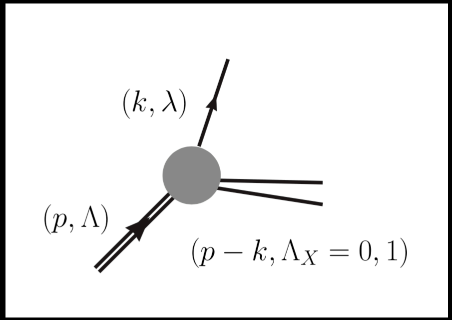
More reading in:
Kogut and Soper (1976)
Burkardt (2002)
Miller (2005)
Freese and Miller (2021)

Quark/gluon off-shellness in a partonic picture (skipping spin description)

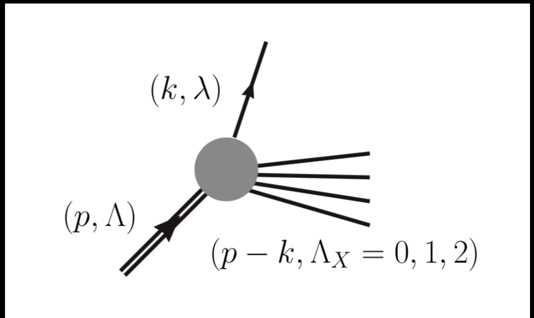
$$\boxed{k^2 = xM^2 - \frac{x}{1-x} M_X^2 - \frac{k_T^2}{1-x}}$$



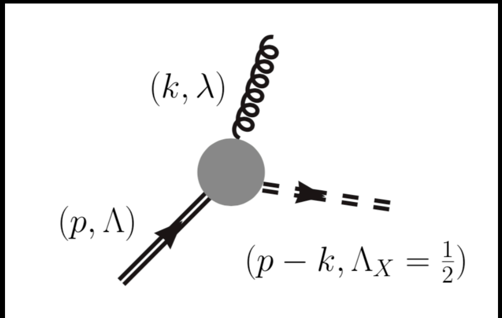
diquark



tetraquark

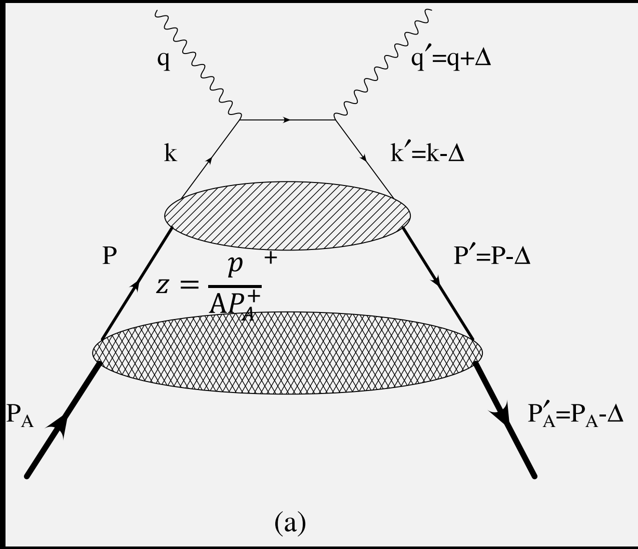


octet proton



Quark/gluon off-shellness in a Nucleus

$$k^2 = xM^2 - \frac{x}{1-x} M_X^2 - \frac{k_T^2}{1-x} \Rightarrow k^2 = x' P^2 - \frac{x'}{1-x'} M_X^2 - \frac{k_T'^2}{1-x'}$$



Longitudinal

$$x \Rightarrow x' = \frac{x}{z}$$

Transverse

$$k_T \Rightarrow k_T' = k_T - \frac{x}{z} p_T$$

Nucleon off-shellness/virtuality

$$M^2 \Rightarrow P^2$$

Quark correlation function in a nucleon

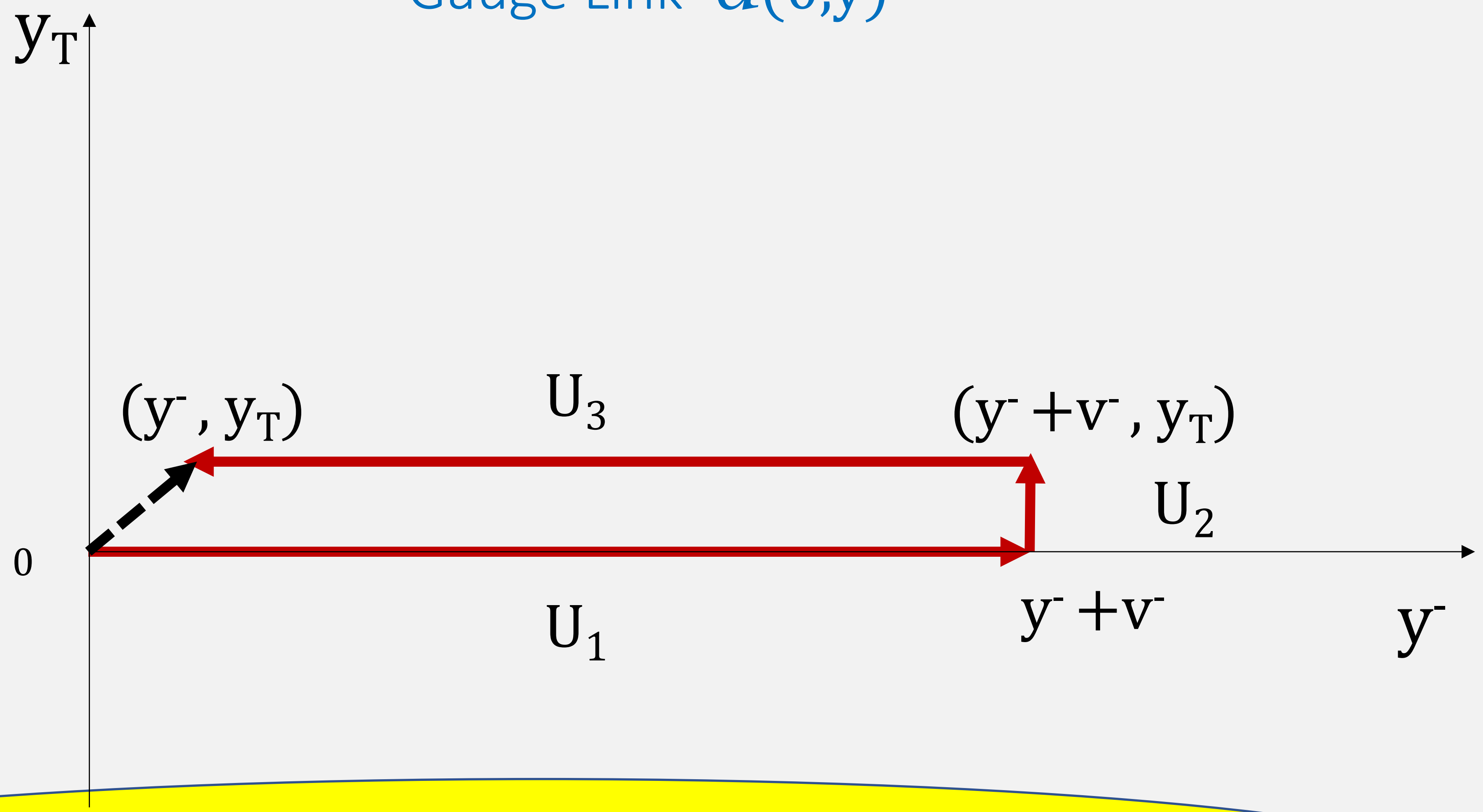
$$f(x,\mathbf{k}_T) = \int dk^- W(x,\mathbf{k}_T,k^-) = \int dy^- d^2\mathbf{y}_T\, e^{i(k^+y^- - \mathbf{k}_T\cdot\mathbf{y}_T)} \langle p \mid \bar\psi(0,0,0)\mathcal{U}(0,y)\gamma^+\psi(0,y^-,\mathbf{y}_T) \mid p\rangle_{y^+=0}$$

We integrate over k^- ⇒ off-shell effects become equivalent to “quark transverse momentum effects”

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

Disclaimer: at tree level, no pQCD yet

Gauge Link $\mathcal{U}(0,y)$



Because of the delta function, with no k_T weighting, the link from 0 to y^- (straight link) is equivalent to $U_1\, U_2\, U_3$

Quark correlation function inside a nucleus
(no off-shell effects)

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

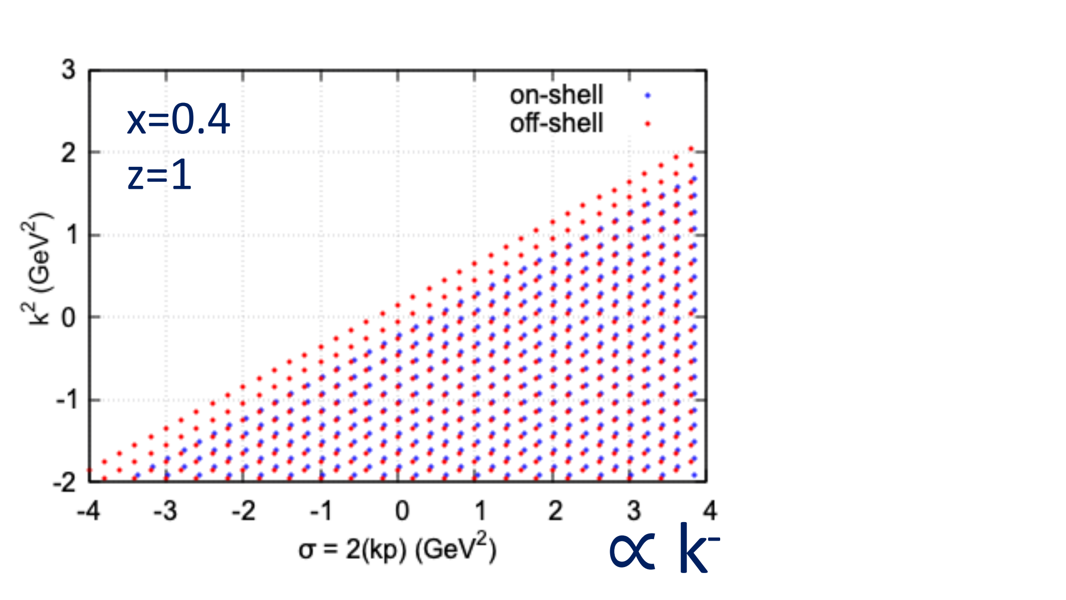
integrating

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

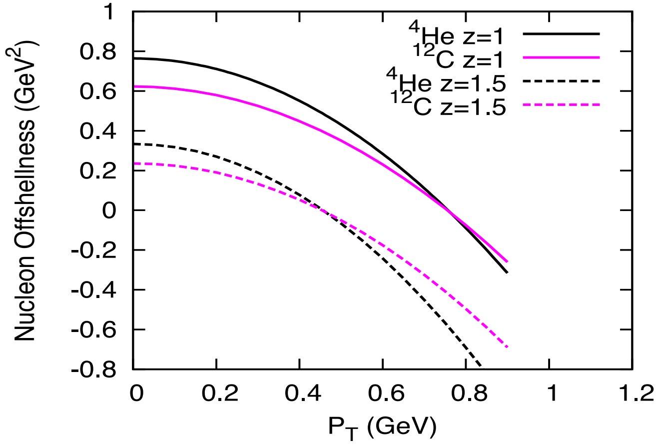
No effect from transverse d.o.f

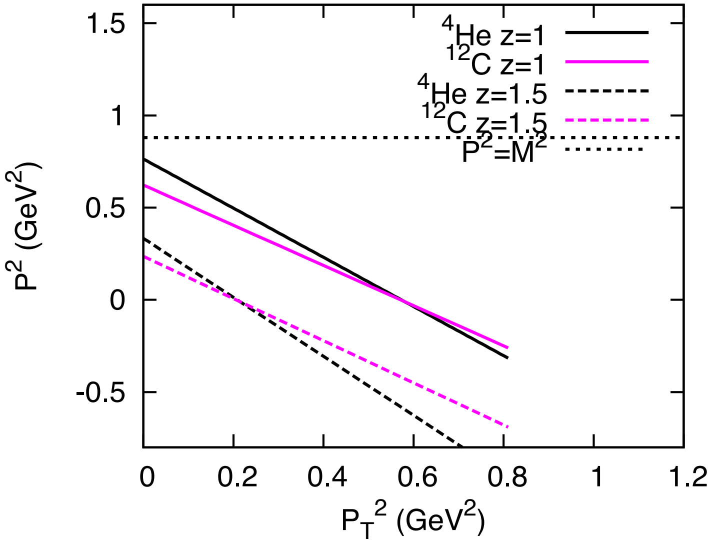
$$\int d^2k_T f(x', \mathbf{k}'_T) = \int dy^-\, e^{i(x/z)p^+y^-} \langle p \mid \bar{\psi}(0,0,0)\gamma^+\psi(0,y^-,0) \mid p\rangle_{y^+=0}$$

Collinear EMC effect or x-rescaling



But can we disregard
Off-shell effects?
(i.e. integrate over the whole range of k-
and set y+=0?)





The answer is yes, in a controlled approximation

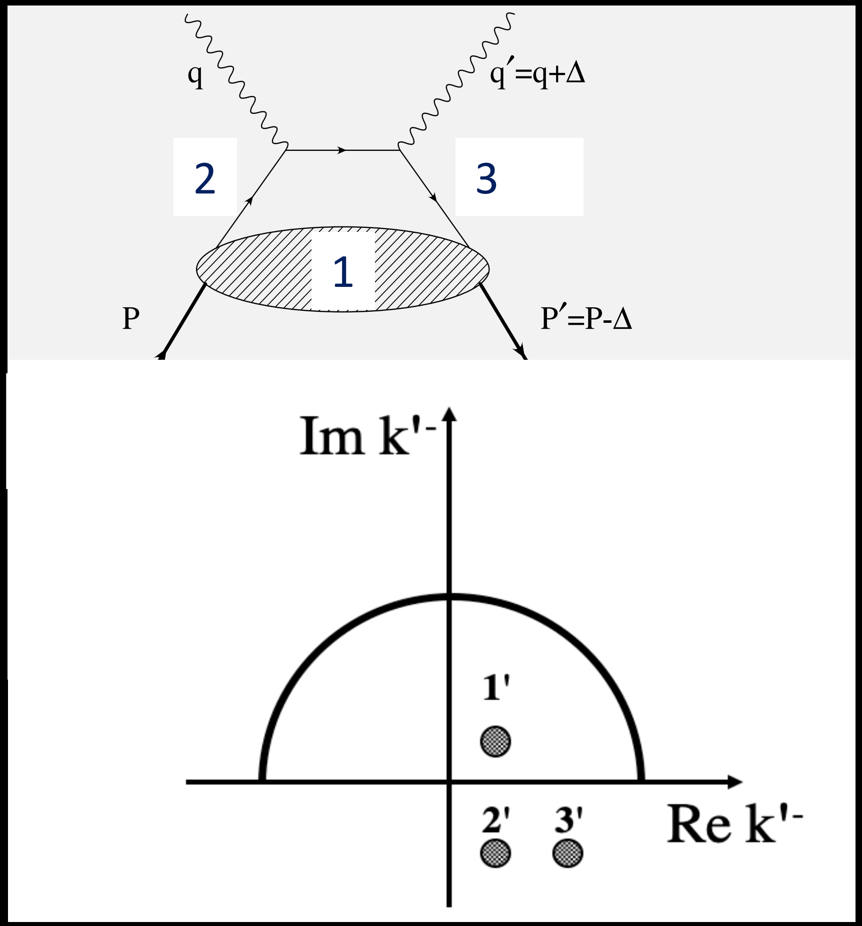
$$f_A(x) = \int d^2k_T f(x', \mathbf{k}'_T) + K_A(p^2) \int d^2k_T k_T^2 f(x', \mathbf{k}'_T)$$

Spread in y_T in nuclei generates a non trivial gauge-link structure: FSI in the nucleon and give origin to the EMC effect

Conclusions

- FSI due to gauge invariance cannot be disregarded, they are actually the cause of the EMC effect
- Envisaging a rich program where this scenario could be tested in a variety of processes, using different polarizations from inclusive to exclusive experiments including DVCS in nuclei
- Please read:
  - C. Ciofi, SL, PLB 212 (1989); C. Ciofi, SL PRC41(1990); F. Gross; SL PRC45 (1992)
  - SL, S.K. Taneja PRC72 (2005)
  - ... talk at CHPI, CERN 2020 and the upcoming paper .... and quote 

backup



In a partonic picture you have three propagators, giving three poles like in the figure you integrate over the k_X. one that means you put that particle on-shell