The EMC effect of light nuclei within the Light-Front Hamiltonian dynamics

Matteo Rinaldi

INFN section of Perugia.

in collaboration with

Emanuele Pace (“Tor Vergata”, Rome Univ.)

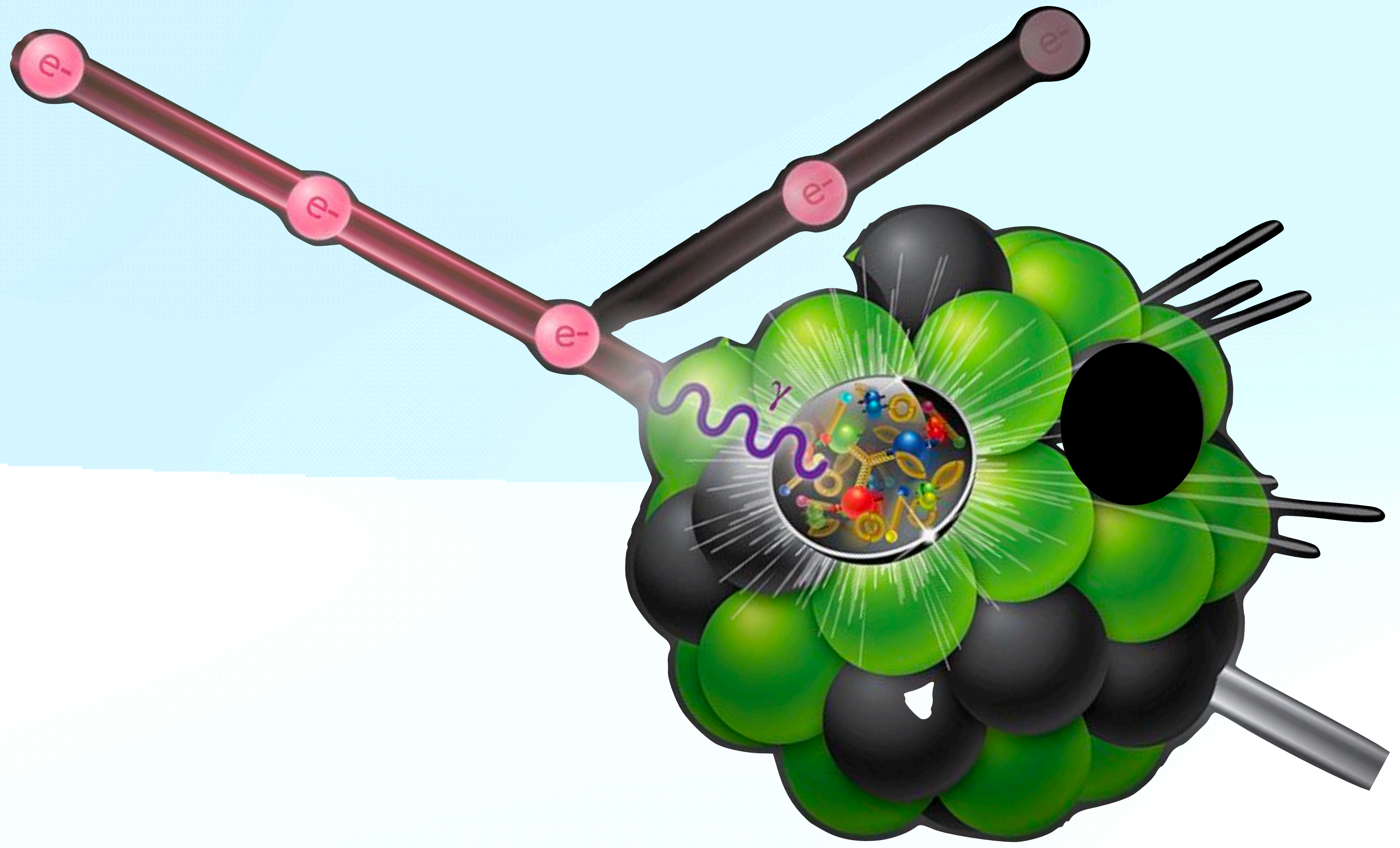
Sergio Scopetta (Perugia Univ. & INFN)

Giovanni Salmè (INFN - Rome)

Filippo Fornetti (Perugia Univ.)

Michele Viviani (INFN - Pisa)

Eleonora Proietti (Perugia Univ.; ph.d in Pisa)



STRONG 2020

INFN Istituto Nazionale di Fisica Nucleare

Based on

R. Alessandro, A. Del Dotto, E. Pace, G. Perna, G. Salmè and S. Scopetta,
Light-Front Transverse Momentum Distributions for $\mathcal{J} = 1/2$ Hadronic Systems in Valence Approximation
Phys.Rev.C 104 (2021) 6, 065204

A. Del Dotto, E. Pace, G. Salmè, and S. Scopetta,
Light-Front spin-dependent Spectral Function and Nucleon Momentum Distributions for a Three-Body System, **Phys. Rev. C 95, 014001 (2017)**

E. Pace, M. Rinaldi, G. Salmè, and S. Scopetta,
EMC effect, few-nucleon systems and Poincaré covariance,
Phys. Scr. 95, 064008 (2020)

MARATHON Coll.
Measurement of the Nucleon Fn2/Fp2 Structure Function Ratio by the Jefferson Lab MARATHON Tritium/Helium-3 Deep Inelastic Scattering Experiment,
Phys. Rev. Lett 128 (2022) 13, 132003

E. Pace, M. Rinaldi, G. Salmè, and S. Scopetta,
The European Muon Collaboration effect in Light-Front Hamiltonian Dynamics
Phys. Lett. B 839 (2023) 137810

Based on

F. Fornetti, E. Pace, M. R., G. Salmè, S. Scopetta and M. Viviani,
The EMC for few-nucleon bound systems in Light-Front Hamiltonian dynamics
arXiv:2308.15925

E. Proietti, F. Fornetti, E. Pace, M. R., G. Salmè and S. Scopetta,
^{3}He spin dependent structure functions within the relativistic Light-Front Hamiltonian dynamics
in prep. → see E. Proietti's talk

Outline

- Motivations
- The EMC effect
- The Light-Front Poincaré covariant approach
- The EMC effect within the Light-Front approach: the ^3He and ^4He cases
- Conclusions and Perspectives

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Motivations: why the ^{3}He

- Phenomenological: a reliable flavor decomposition needs the neutron parton structure (PDFs, GPDs TMDs....)

Accurate and long-lasting experimental efforts in developing effective neutron targets to carefully investigate its electromagnetic responses. ^{3}H$\vec{e}$ is SPECIAL

The polarized ^{3}He target, 90% neutron target (e.g. H. Gao et al, PR12-09-014, Chen et al, PR12-11-007,@JLab12)

- Due to the experimental energies, the accurate theoretical description (of a polarized ^{3}He) has to be relativistic

- Theoretical: a LF description of three body interacting systems! Bonus:
  Transverse-Momentum Distributions (TMDs) for addressing in a novel way the nuclear dynamics

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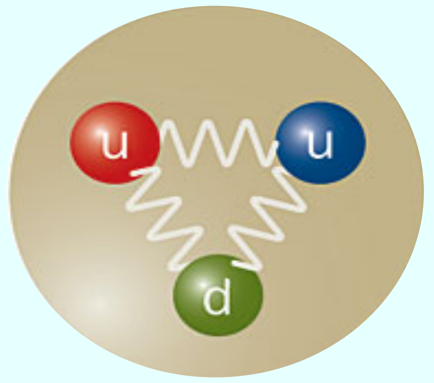

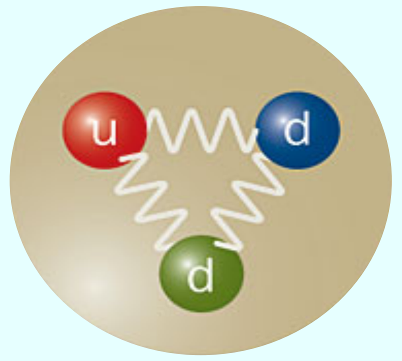

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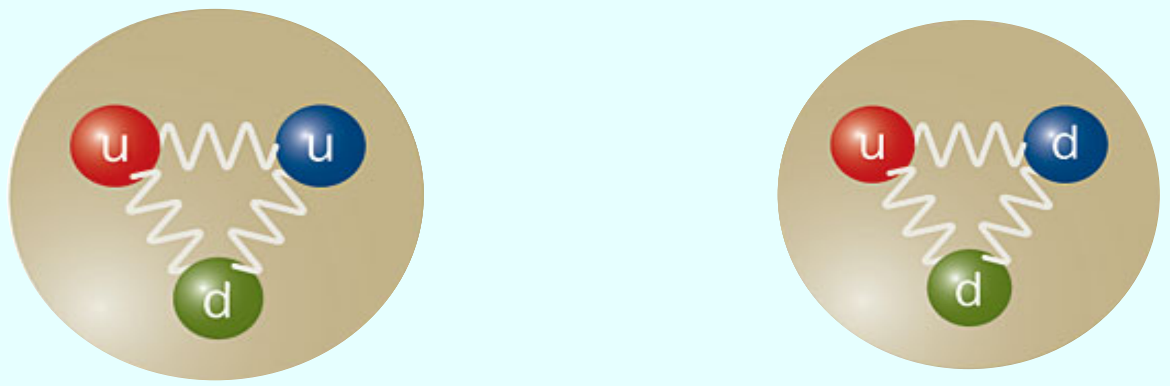

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Motivations: why the ^{4}He

- Goal: extend the approach applied for ^3He to **any nuclei** A and calculate the **EMC ratio** for ^4He and ^3H ***[E. Pace, M. Rinaldi, G. Salmè, S. Scopetta, Phys. Lett. B 839 (2023) 137810]***

- Since ^4He is a **strongly bound system** this could provide a challenging test to our approach

- Compare EMC effect for ^3He, ^4He and ^3H obtained by different **modern NN and NNN interactions** (Argonne V18+UIX, NVIa+3N, NVIb+3N)

- Compare the EMC effect for ^4He obtained by different choice of F_2^p and F_2^n **parametrization**

[R. B. Wiringa, V. G. J. Stoks, R. Schiavilla, Phys. Rev. C 51 (1995) 38–51]

[R. B. Wiringa et al., Phys. Rev. Lett. 74 (1995) 4396–4399]

[M.Viviani et al., Phys. Rev. C 107 (1) (2023) 014314]

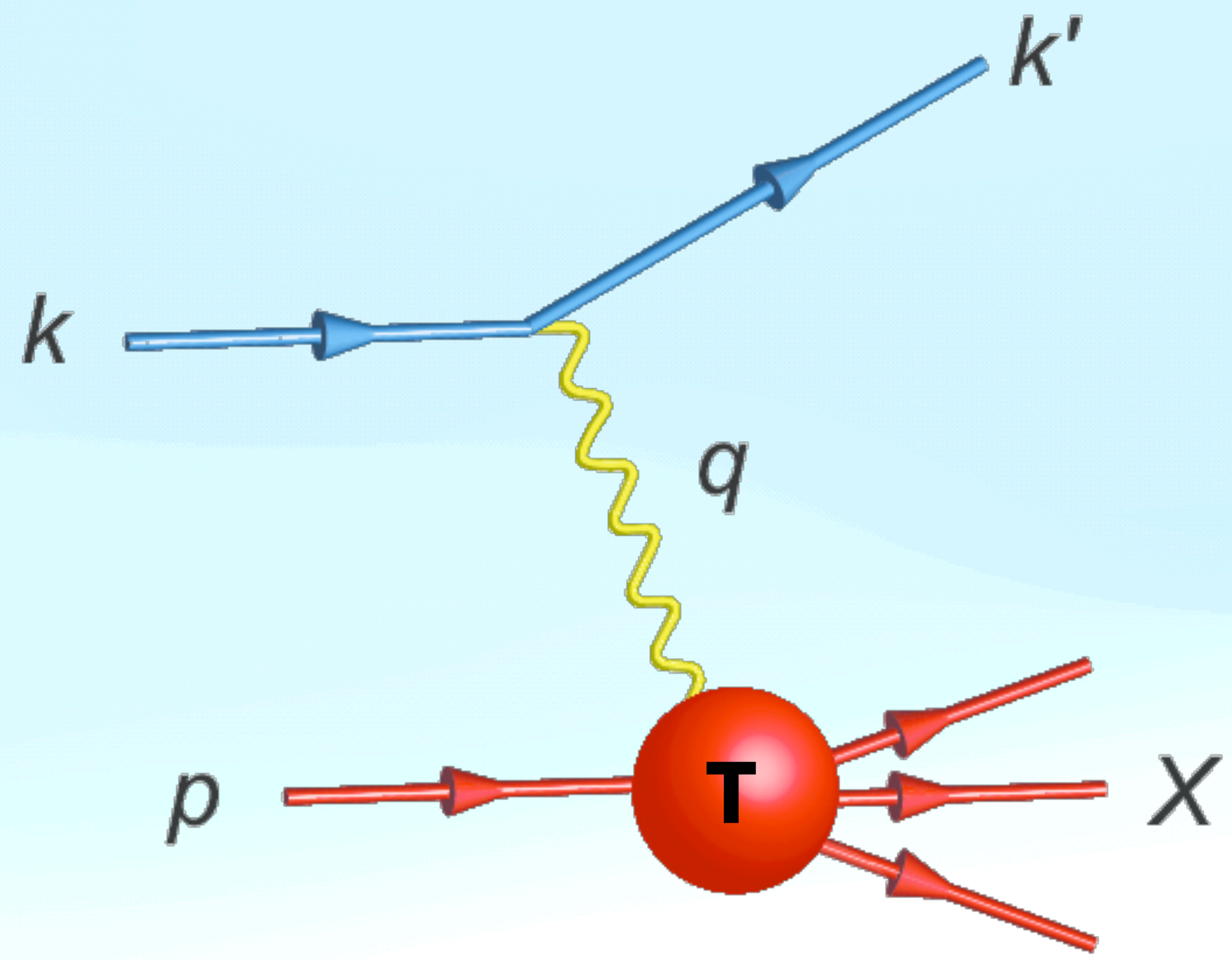
[M. Piarulli et al.,Phys. Rev. Lett. 120 (5) (2018) 052503]

[M. Piarulli, S. Pastore, R. B. Wiringa, S. Brusilow, R. Lim,Phys. Rev. C 107 (1) (2023) 014314]

*F. Fornetti's slide

The EMC effect

Almost 40 years ago, the European Muon Collaboration (**EMC**) measured in deep inelastic scattering (DIS) processes:



with T= proton/nucleus

the cross-section for different kind of targets.

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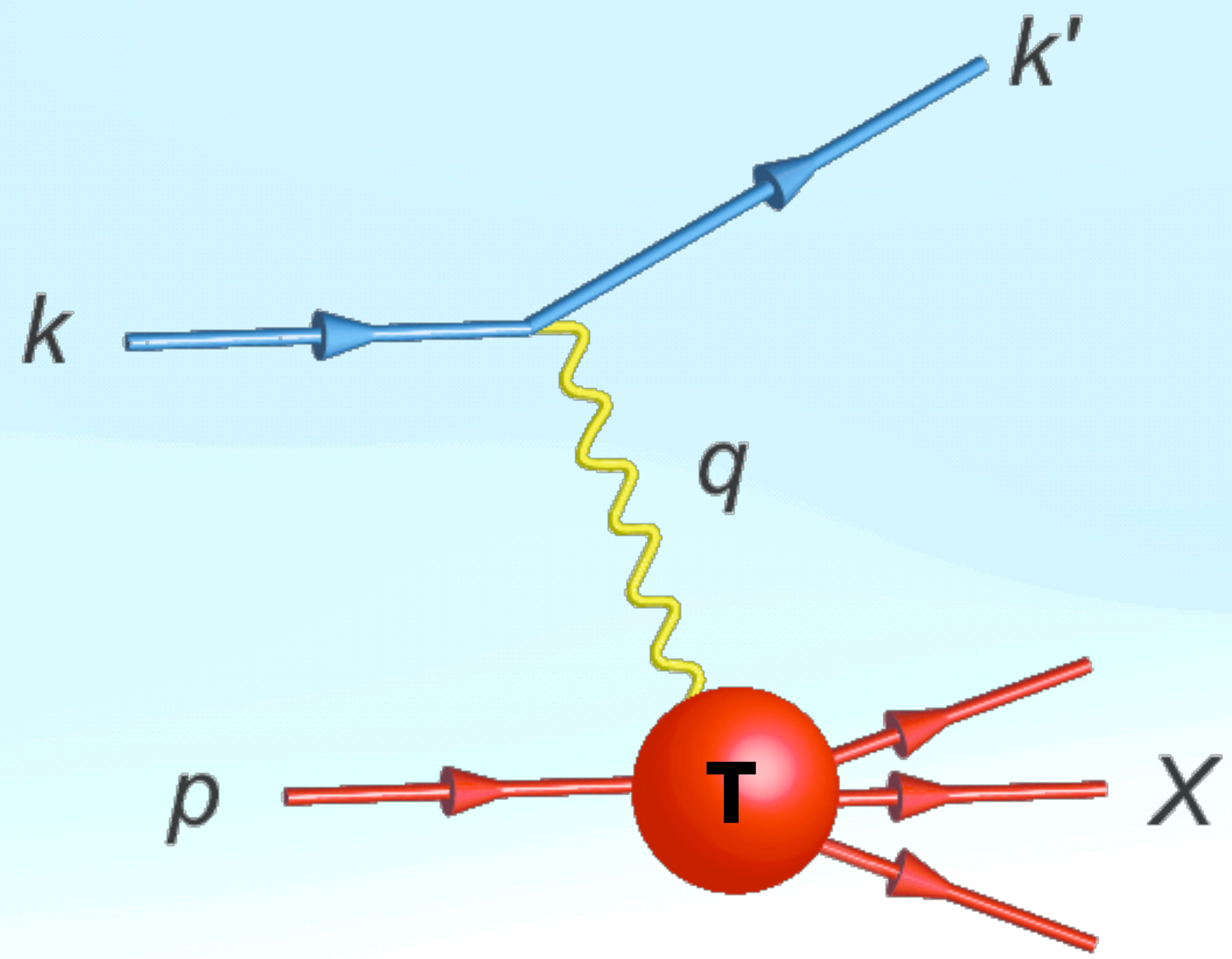

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the cross-section for different kind of targets. → they extracted the *Structure Function* of the target

$$F_2^A(x)$$

The EMC effect

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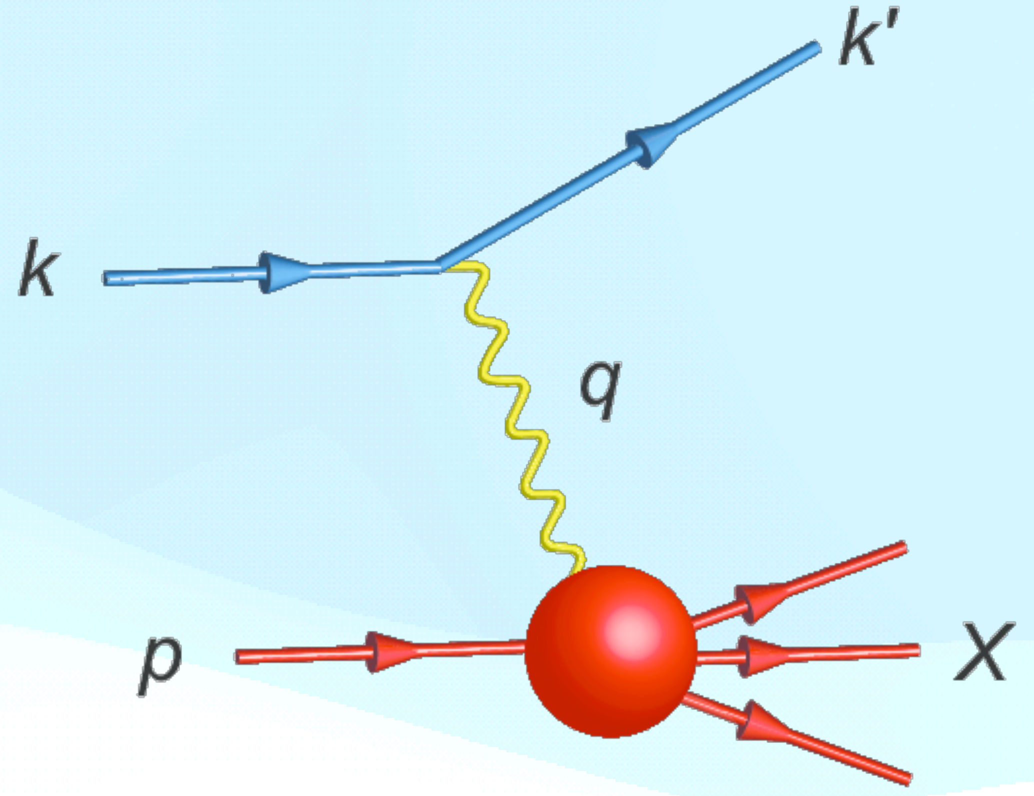

$$R(x) = F_2^{^{56}Fe}(x)/F_2^{^{2}H}(x)$$

At high energies, the expected result is $R(x) = 1$ up to corrections of the Fermi motion. **BUT**

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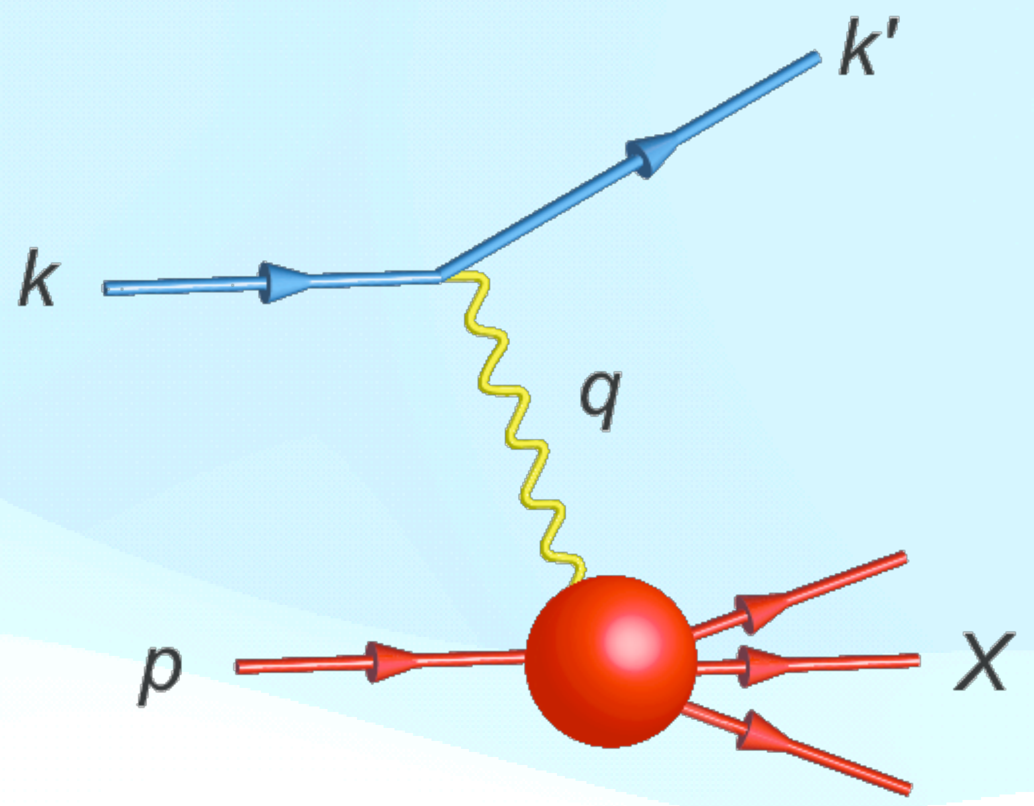

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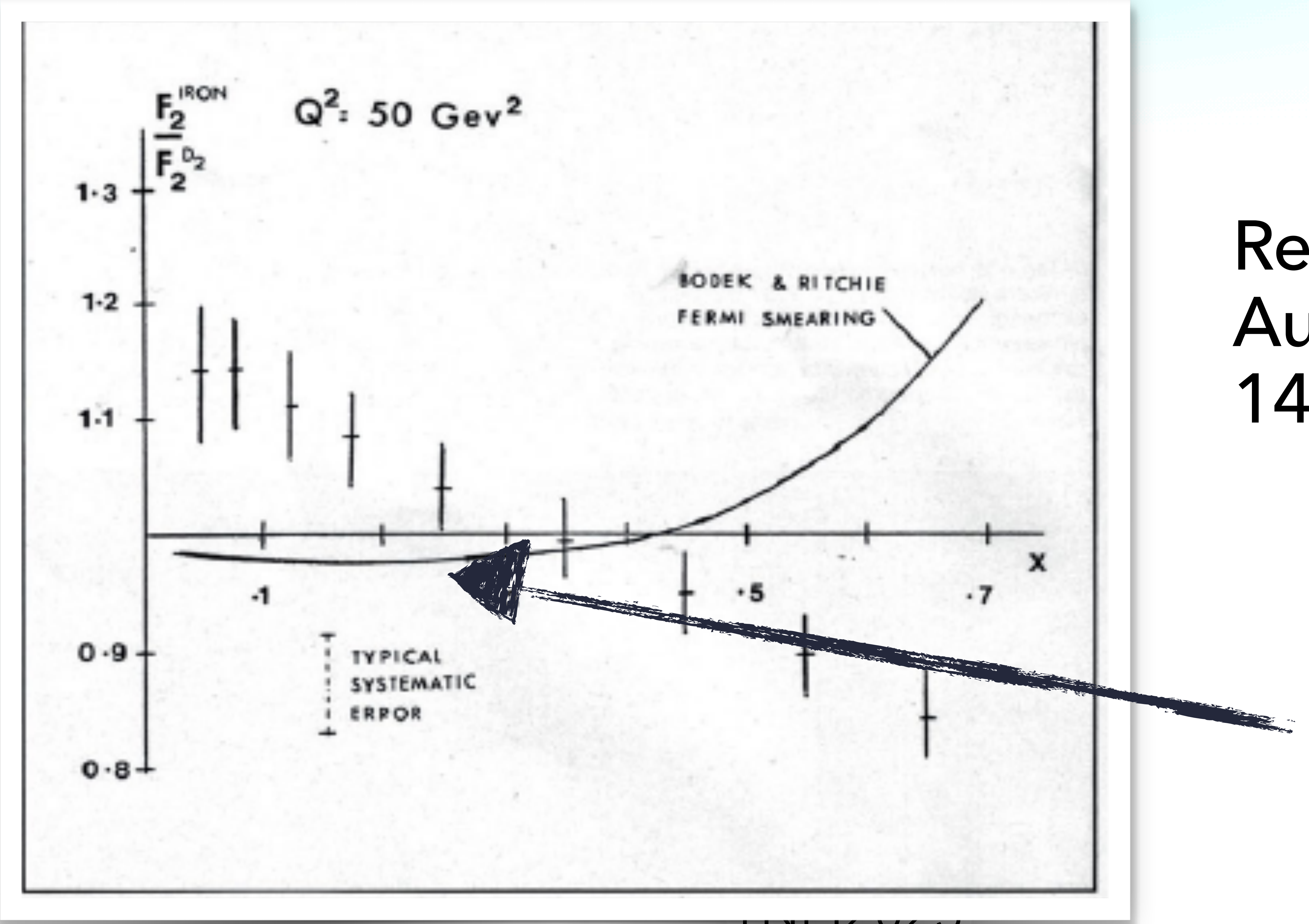

Result:
Aubert et al. Phys.Lett. B123 (1983) 275
1488 citations (inSPIRE)

Few % deviation from what expected.
WHY?

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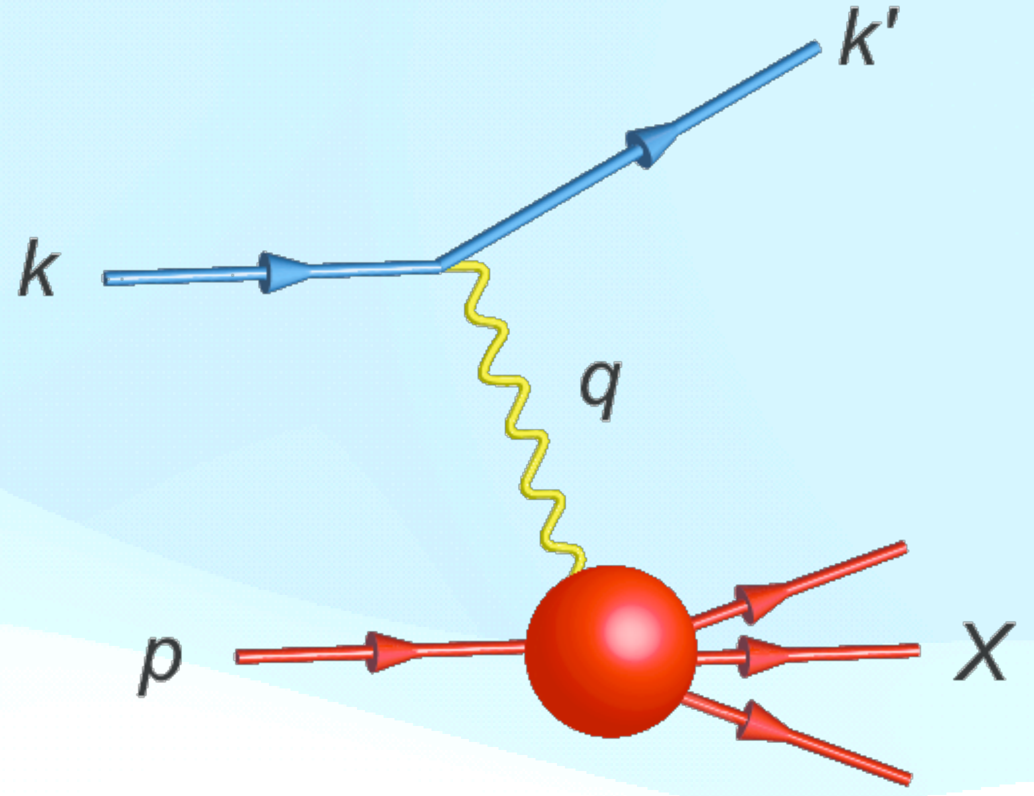

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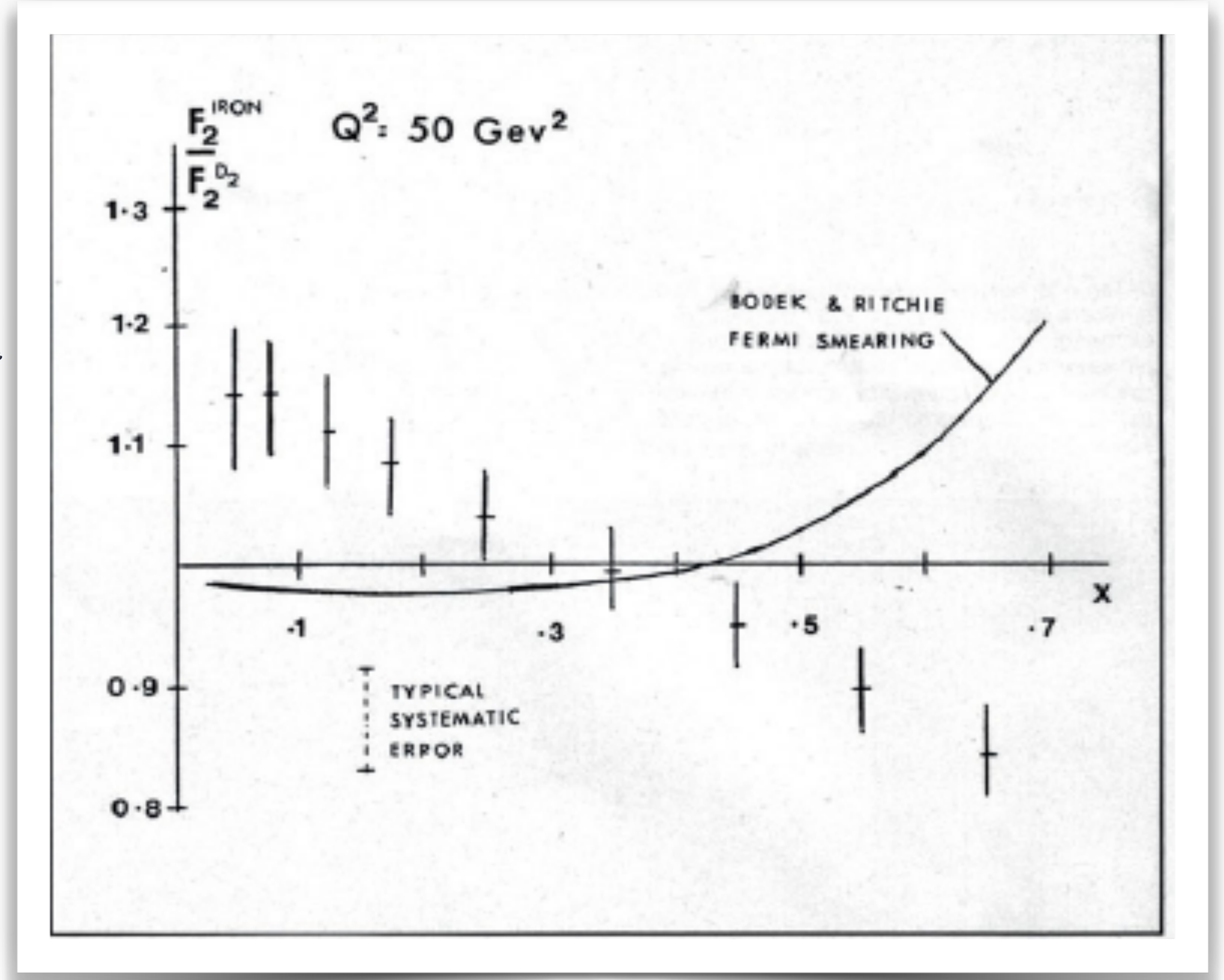
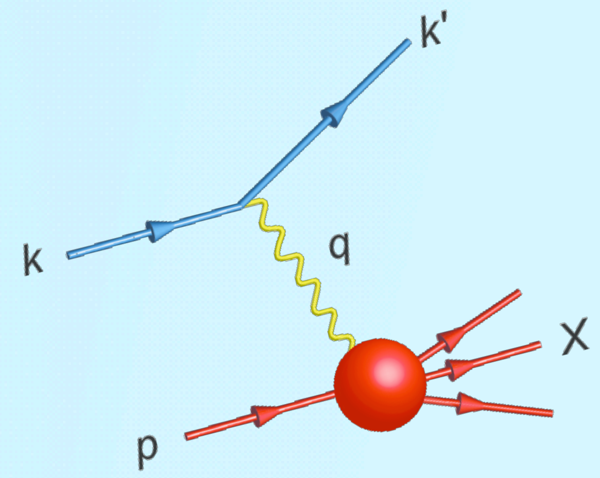
Naive parton model interpretation:
"Valence quarks, in the bound nucleon, are in average slower that in the free nucleon"



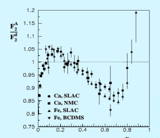
Is the bound proton bigger than the free one??

The EMC effect in details

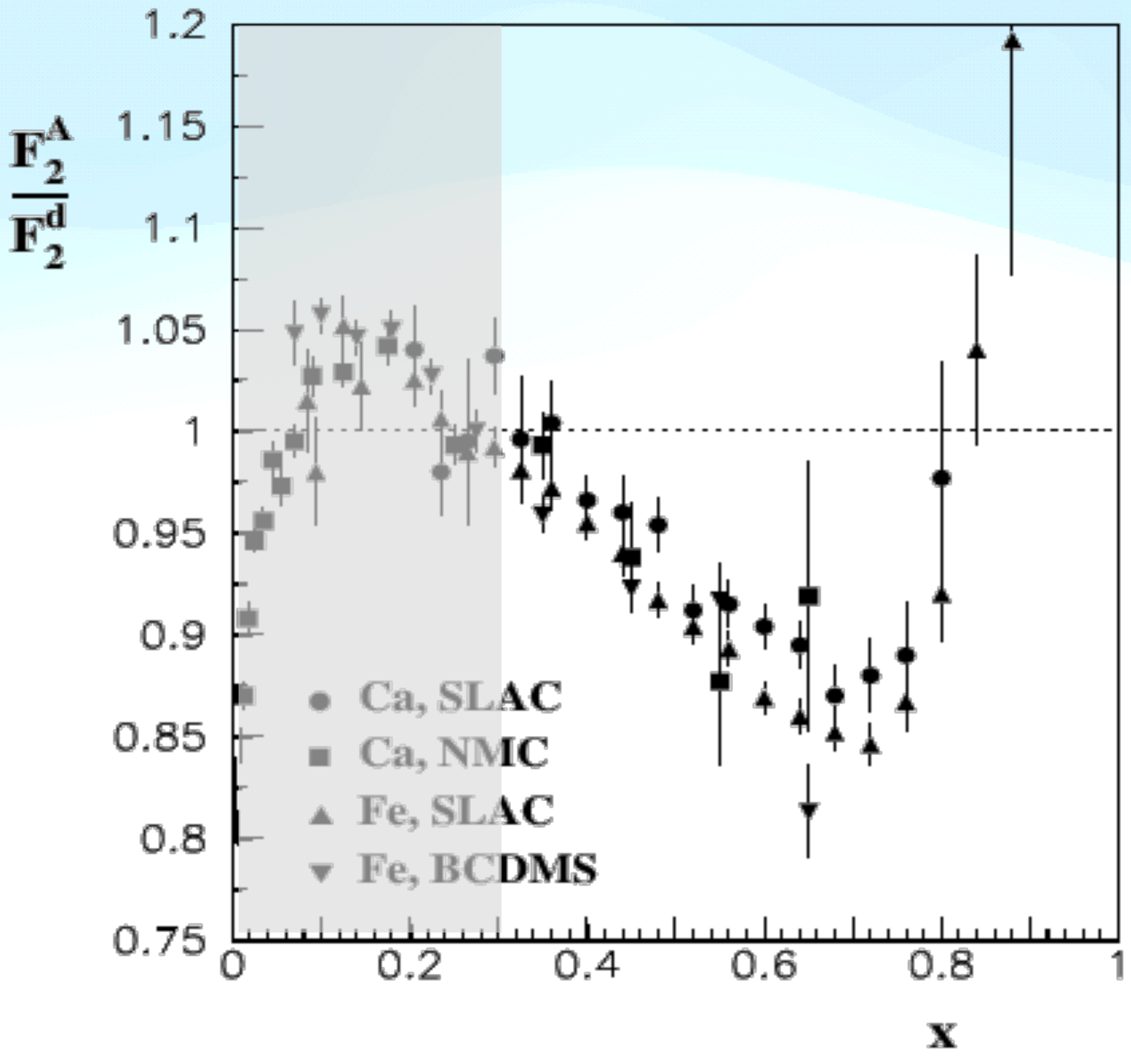


We remind that for DIS off nuclei:

$$0 \leq x = \frac{Q^2}{2M\nu} \leq \frac{M_A}{M} \simeq A$$



x ≤ 0.3 “Shadowing region”: coherence effects, the photon interacts with partons belonging to different nucleons



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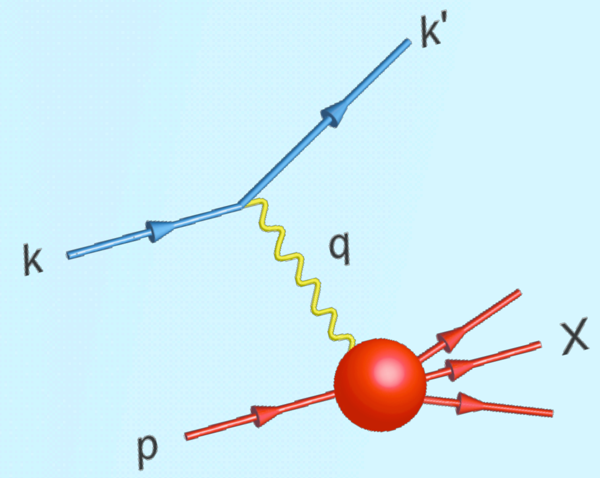

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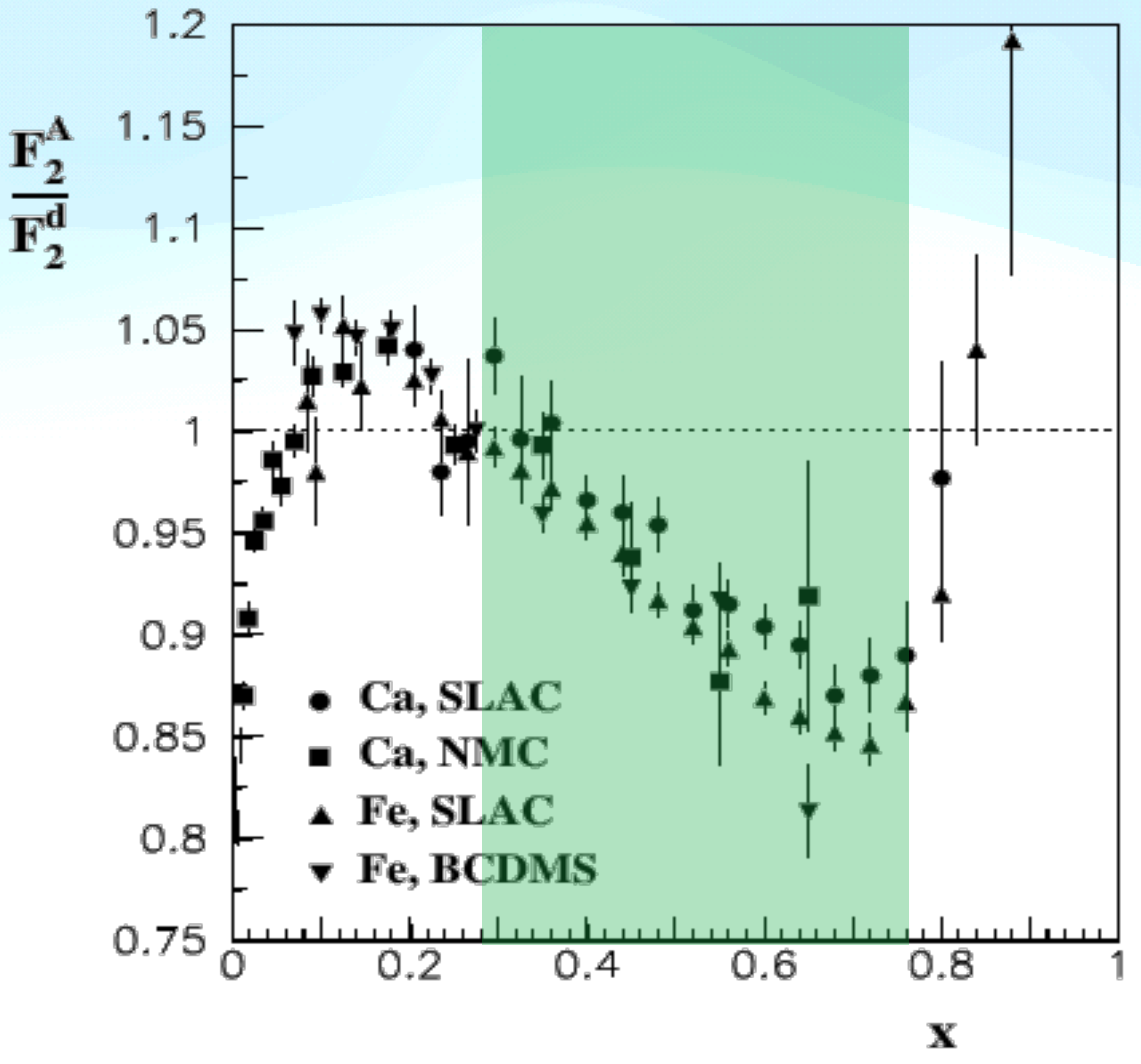
- $x \leq 0.3$ "Shadowing region": coherence effects, the photon interacts with partons belonging to different nucleons
- $0.2 \leq x \leq 0.8$ "EMC (binding) region": mainly valence quarks involved



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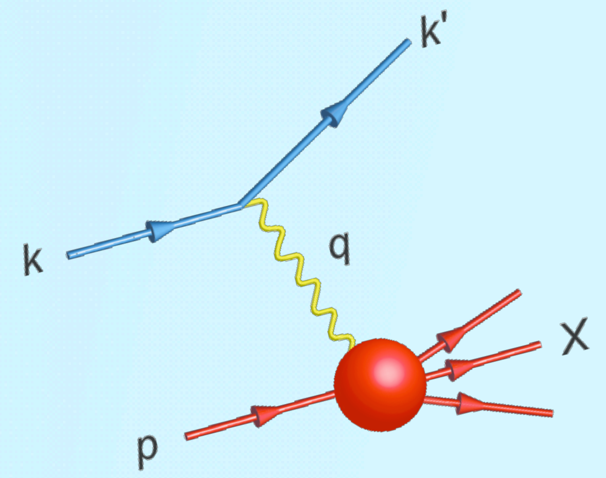

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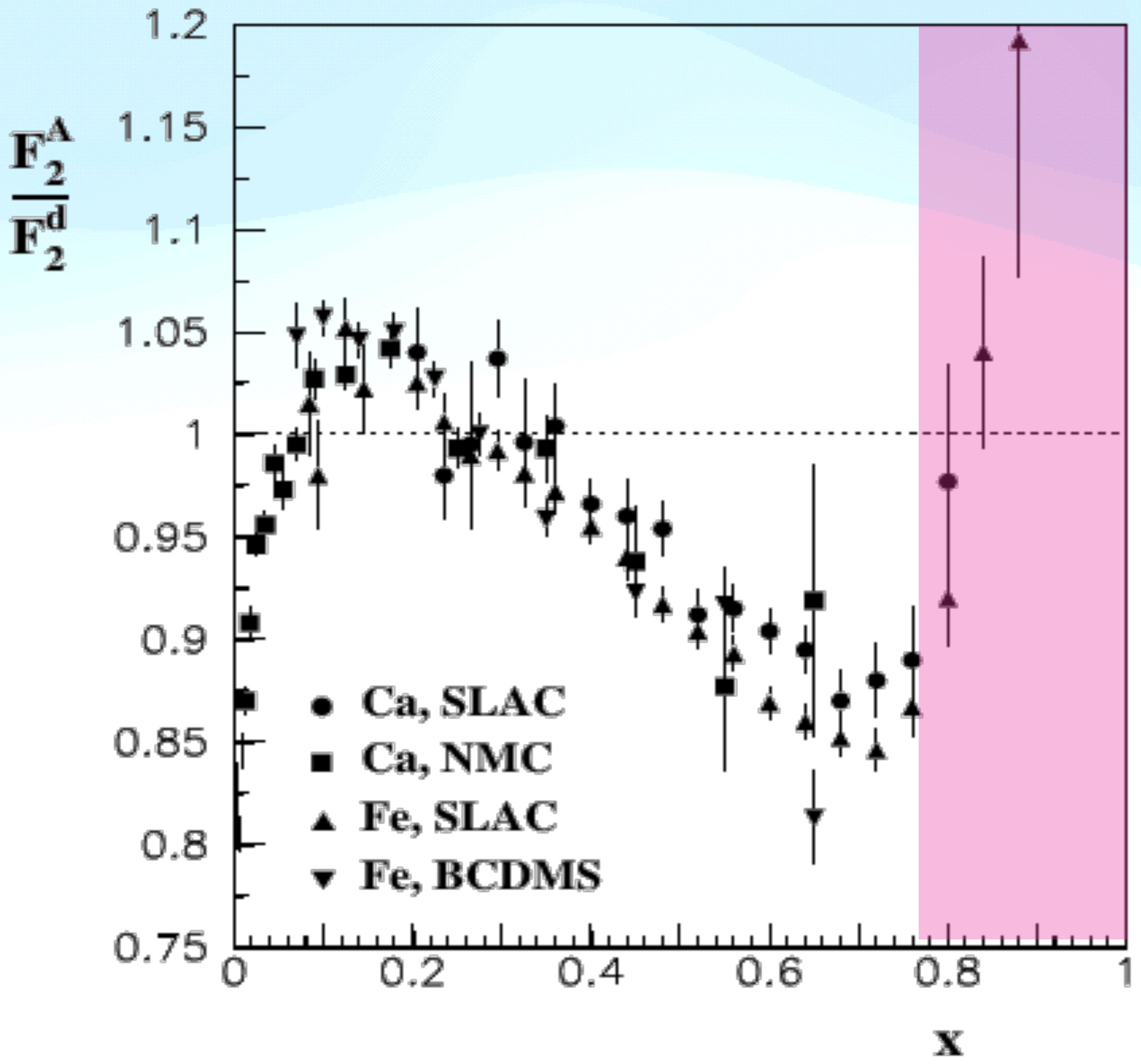
- $x \lesssim 0.3$ "Shadowing region": coherence effects, the photon interacts with partons belonging to different nucleons

- $0.2 \lesssim x \lesssim 0.8$ "EMC (binding) region": mainly valence quarks involved

- $0.8 \lesssim x \lesssim 1$ "Fermi motion region"



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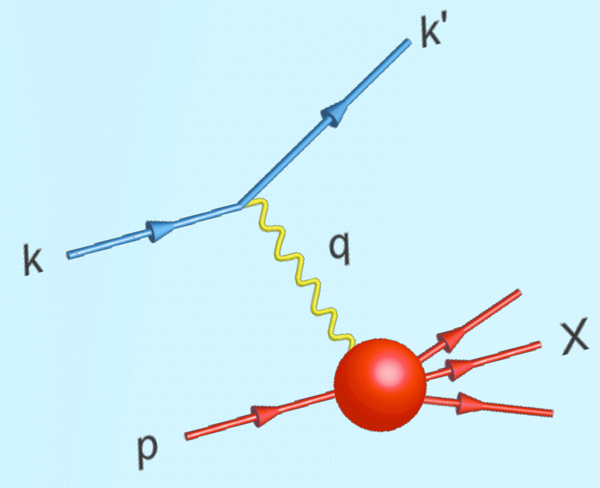

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- x ≤ 0.3 "Shadowing region": coherence effects, the photon interacts with partons belonging to different nucleons
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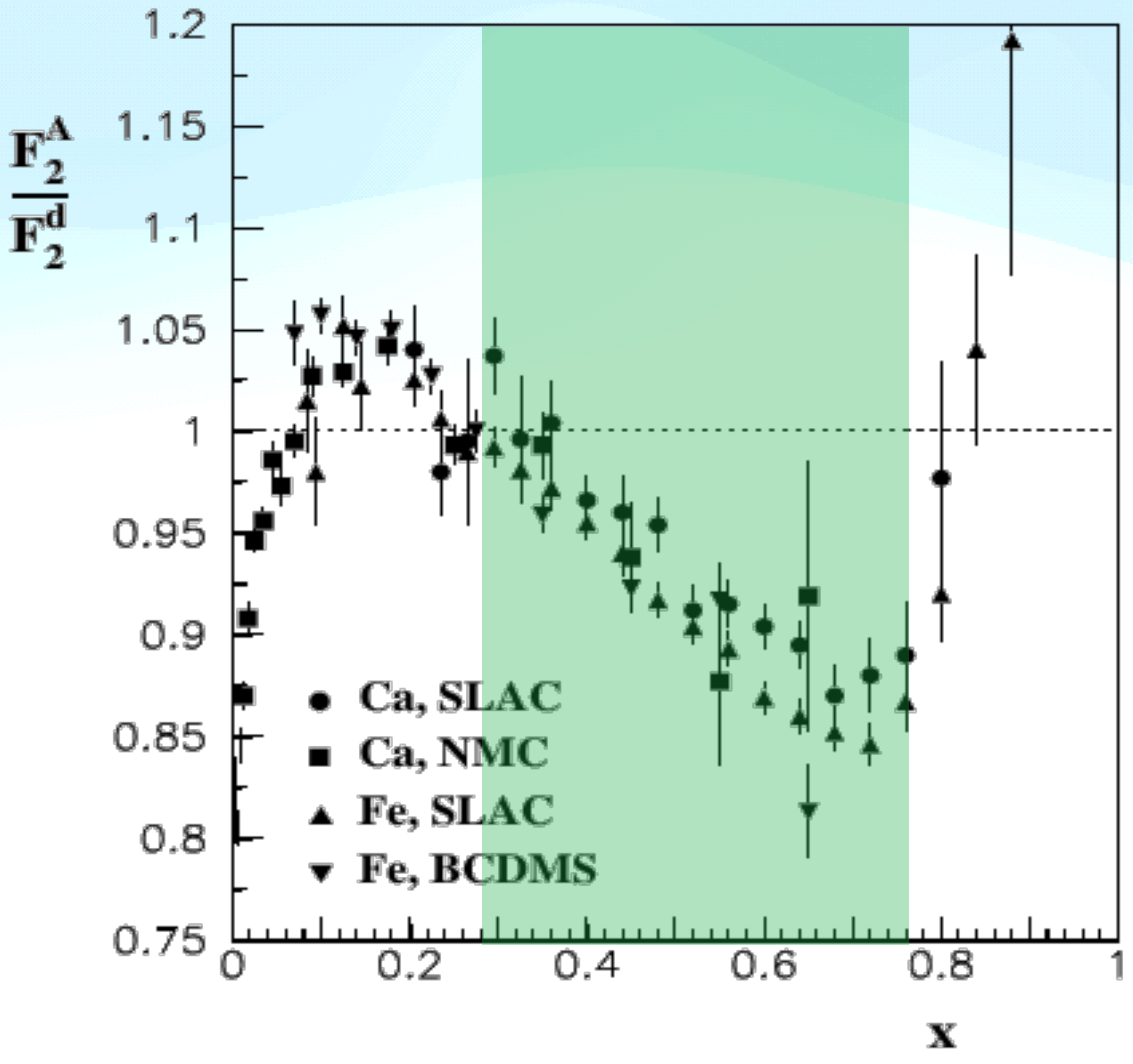

main features: universal behavior independent on Q^2 ; weakly dependent on A; scales with the density ρ → global property? Or due to correlations…Local…

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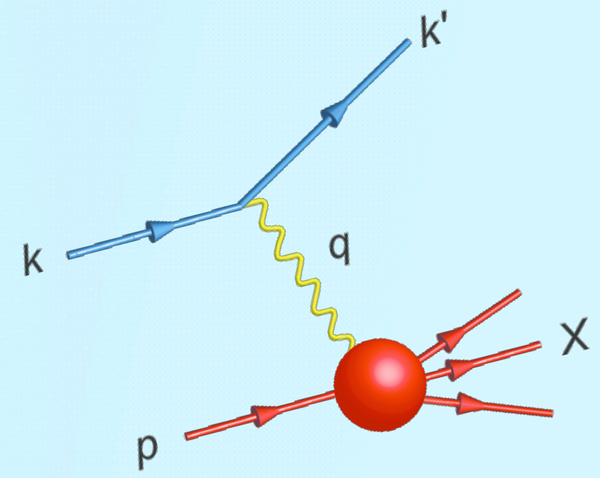

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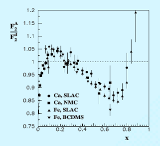

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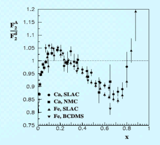

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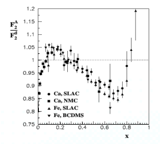

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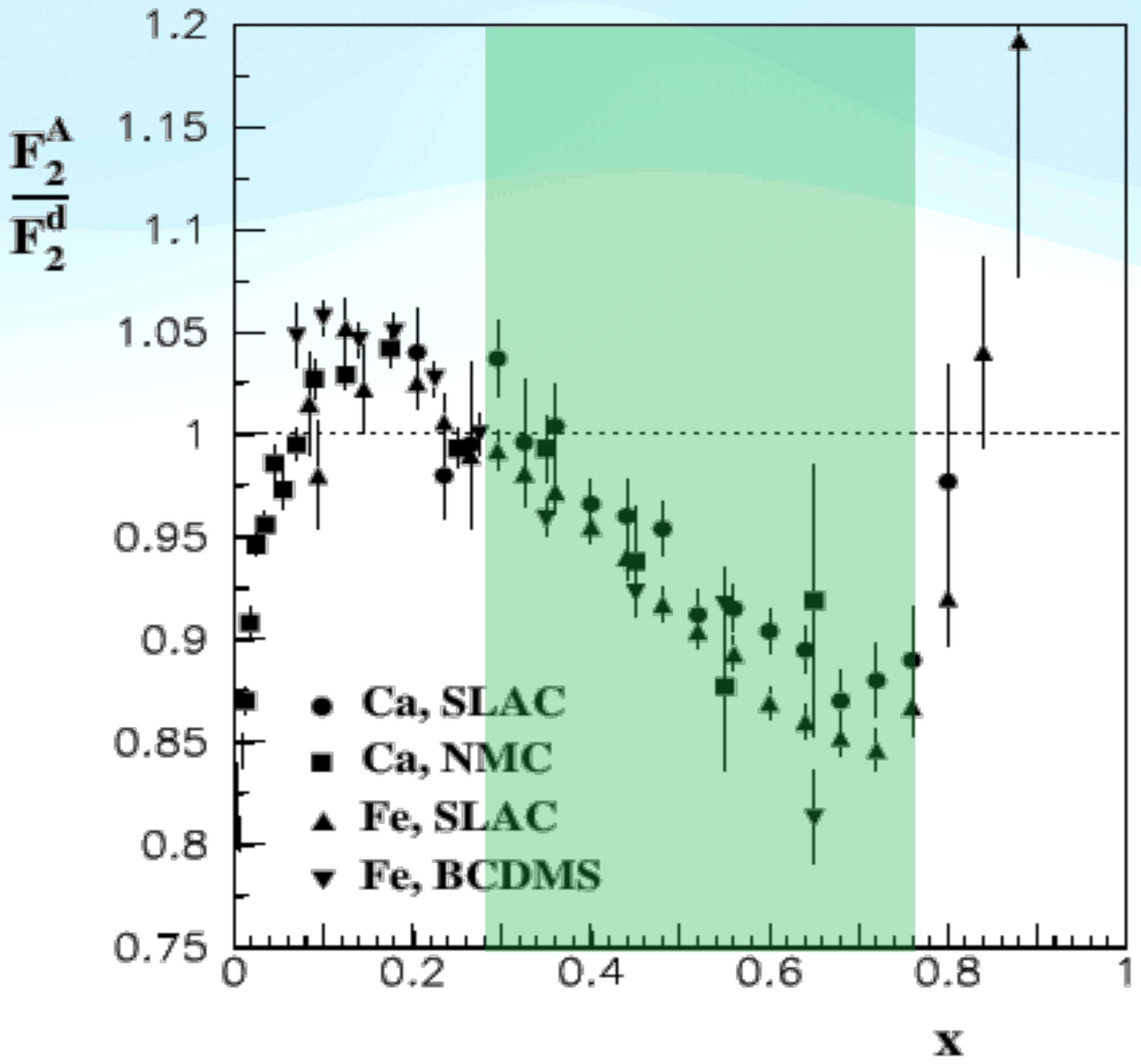
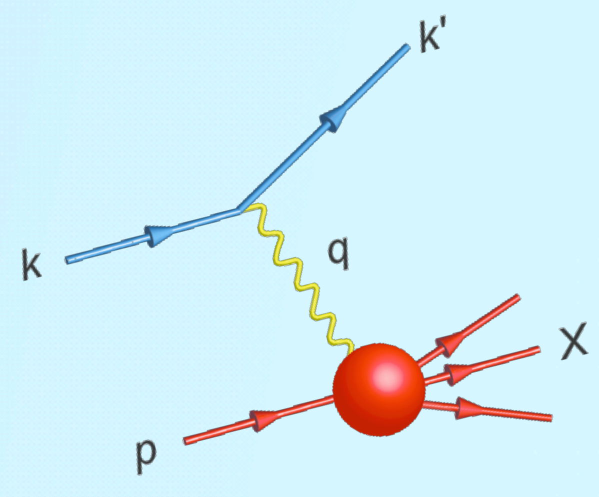


main features: universal behavior independent on Q^2 ; weakly dependent on A; scales with the density ρ → global property? Or due to correlations...Local...

Explanation (exotic) advocated: confinement radius bigger for bound nucleons, quarks in bags with 6, 9,..., 3A quark, pion cloud effects... Alone or mixed with conventional ones...

The EMC effect explanations and perspective?



Situation: basically not understood. Very unsatisfactory. We need to know the reaction mechanism of hard processes off nuclei and the degrees of freedom which are involved:

- the knowledge of nuclear PDFs is crucial for the analysis of heavy ions collisions;
- neutron parton structure measured with nuclear targets; several QCD sum rules involve the neutron information (Bjorken SR, for example): importance of Nuclear Physics for QCD

Inclusive measurements cannot distinguish between models

One has probably to go beyond (not treated here...) (R. Dupré and S.Scopetta, EPJA 52 (2016) 159)

- **Hard Exclusive Processes (GPDs)**
- **SIDIS (TMDs)**

Status of "Conventional" calculations for light nuclei:

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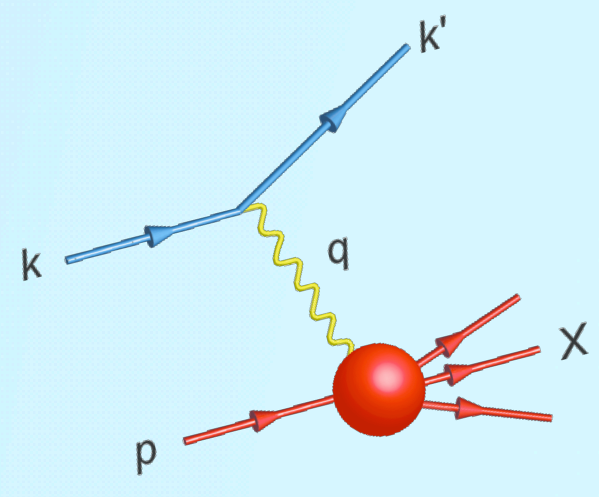

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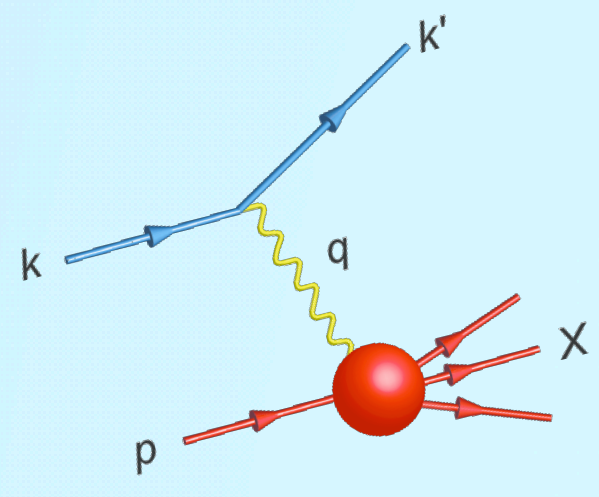

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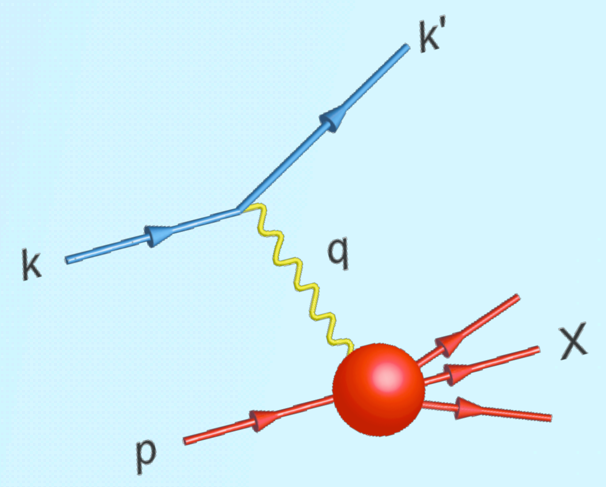

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The relativistic Hamiltonian dynamics framework

Why do we need a relativistic treatment ?

General answer: to develop an advanced scheme, appropriate for the kinematics of JLAB12 and of EIC

- The Standard Model of Few-Nucleon Systems, with nucleon and meson degrees of freedom within a non relativistic (NR) framework, has achieved high sophistication
  [e.g. the NR ^{3}He and ^{3}H Spectral Functions in Kievsky, Pace, Salmè, Viviani PRC 56, 64 (1997)].

- Covariance wrt the Poincaré Group, G_P , needed for nucleons at large 4-momenta and pointing to high precision measurements. Necessary if one studies, e.g., i) nucleon structure functions; ii) nucleon GPDs and TMDs, iii) signatures of short-range correlations; iv) exotics (e.g. 6-bag quarks in ^{2}H), etc

- At least, one should carefully treat the boosts of the nuclear states, $|\Psi_i\rangle$ and $|\Psi_f\rangle$!

Our definitely preferred framework for embedding the successful NR phenomenology:

Light-front Relativistic Hamiltonian Dynamics (RHD, fixed dof) +Bakamjian-Thomas (BT) construction of the Poincaré generators for an interacting theory.

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In RHD+BT, one can address both Poincaré covariance and locality, general principles to be implemented in presence of interaction:

- Poincaré covariance $\rightarrow$ The 10 generators, $P^\mu \rightarrow$ 4D displacements and $M^{\nu\mu} \rightarrow$ *Lorentz* transformations, have to fulfill

$$[P^\mu, P^\nu] = 0, \quad [M^{\mu\nu}, P^\rho] = -\imath(g^{\mu\rho}P^\nu - g^{\nu\rho}P^\mu),$$

$$[M^{\mu\nu}, M^{\rho\sigma}] = -\imath(g^{\mu\rho}M^{\nu\sigma} + g^{\nu\sigma}M^{\mu\rho} - g^{\mu\sigma}M^{\nu\rho} - g^{\nu\rho}M^{\mu\sigma})$$

  Also $\mathcal{P}$ and $\mathcal{T}$ have to be taken into account !

- Macroscopic locality ($\equiv$ cluster separability (relevant in nuclear physics)): i.e. observables associated to different space-time regions must commute in the limit of large spacelike separation (i.e. causally disconnected), rather than for arbitrary (microscopic-locality) spacelike separations. In this way, when a system is separated into disjoint subsystems by a sufficiently large spacelike separation, then the subsystems behave as independent systems.

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  This requires a careful choice of the intrinsic relativistic coordinates.

The relativistic Hamiltonian dynamics framework

In RHD+BT, one can address both Poincaré covariance and locality, general principles to be implemented in presence of interaction:

- Poincaré covariance → The 10 generators, P^μ → 4D displacements and $M^{\nu\mu}$ → *Lorentz* transformations, have to fulfill

$$[P^\mu, P^\nu] = 0, \quad [M^{\mu\nu}, P^\rho] = -\imath(g^{\mu\rho}P^\nu - g^{\nu\rho}P^\mu),$$

$$[M^{\mu\nu}, M^{\rho\sigma}] = -\imath(g^{\mu\rho}M^{\nu\sigma} + g^{\nu\sigma}M^{\mu\rho} - g^{\mu\sigma}M^{\nu\rho} - g^{\nu\rho}M^{\mu\sigma})$$

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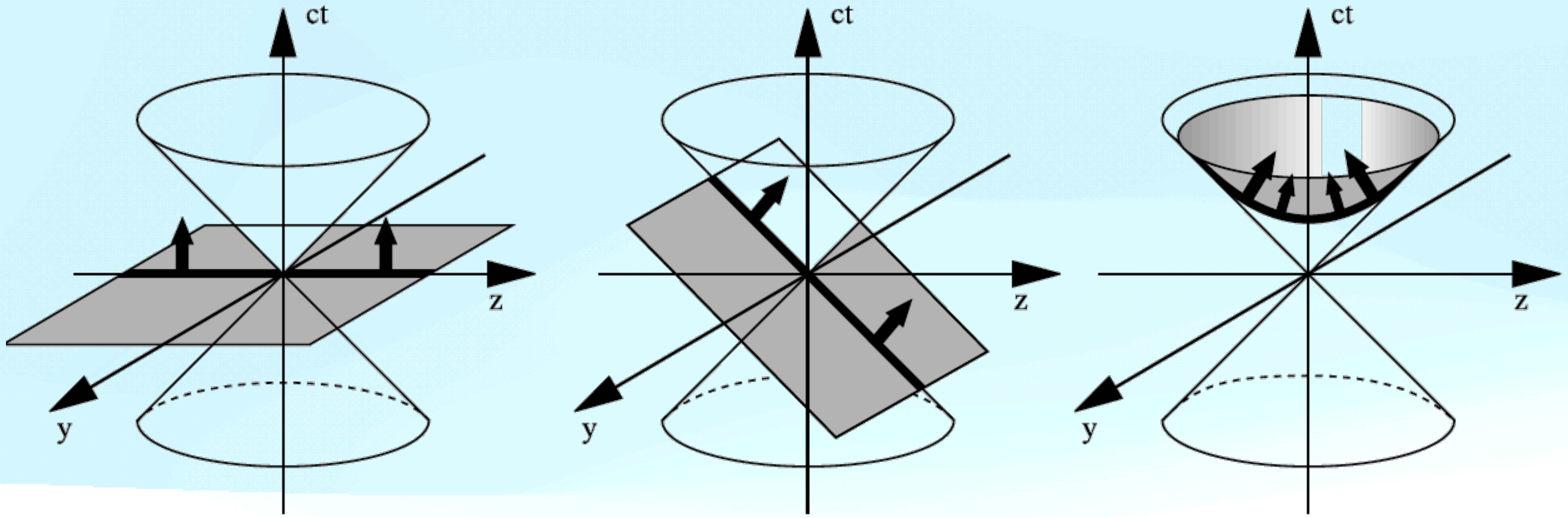
Forms of relativistic Dynamics

P.A.M. Dirac, 1949



The instant form	The front form	The point form
$\tilde{x}^0 = ct$	$\tilde{x}^0 = ct+z$	$\tilde{x}^0 = \tau \quad , \quad ct = \tau\cosh\omega$
$\tilde{x}^1 = x$	$\tilde{x}^1 = x$	$\tilde{x}^1 = \omega \quad , \quad x = \tau\sinh\omega\sin\theta\cos\phi$
$\tilde{x}^2 = y$	$\tilde{x}^2 = y$	$\tilde{x}^2 = \theta \quad , \quad y = \tau\sinh\omega\sin\theta\sin\phi$
$\tilde{x}^3 = z$	$\tilde{x}^3 = ct-z$	$\tilde{x}^3 = \phi \quad , \quad x = \tau\sinh\omega\cos\theta$

$$\tilde{g}_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$$\tilde{g}_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & \frac{1}{2} \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ \frac{1}{2} & 0 & 0 & 0 \end{pmatrix}$$

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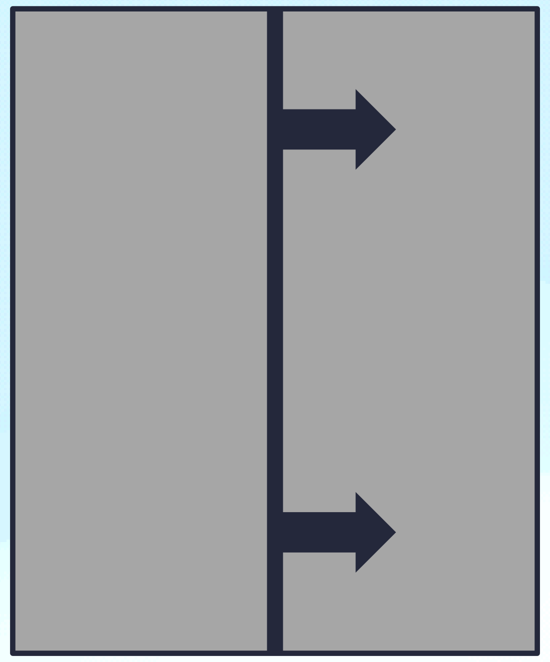
$\Sigma: \; t = 0$

$\Sigma: \; x^+ = x^0 + x^3 = 0$

$\Sigma: \; (x^0)^2 - x_i x^i = k^2$



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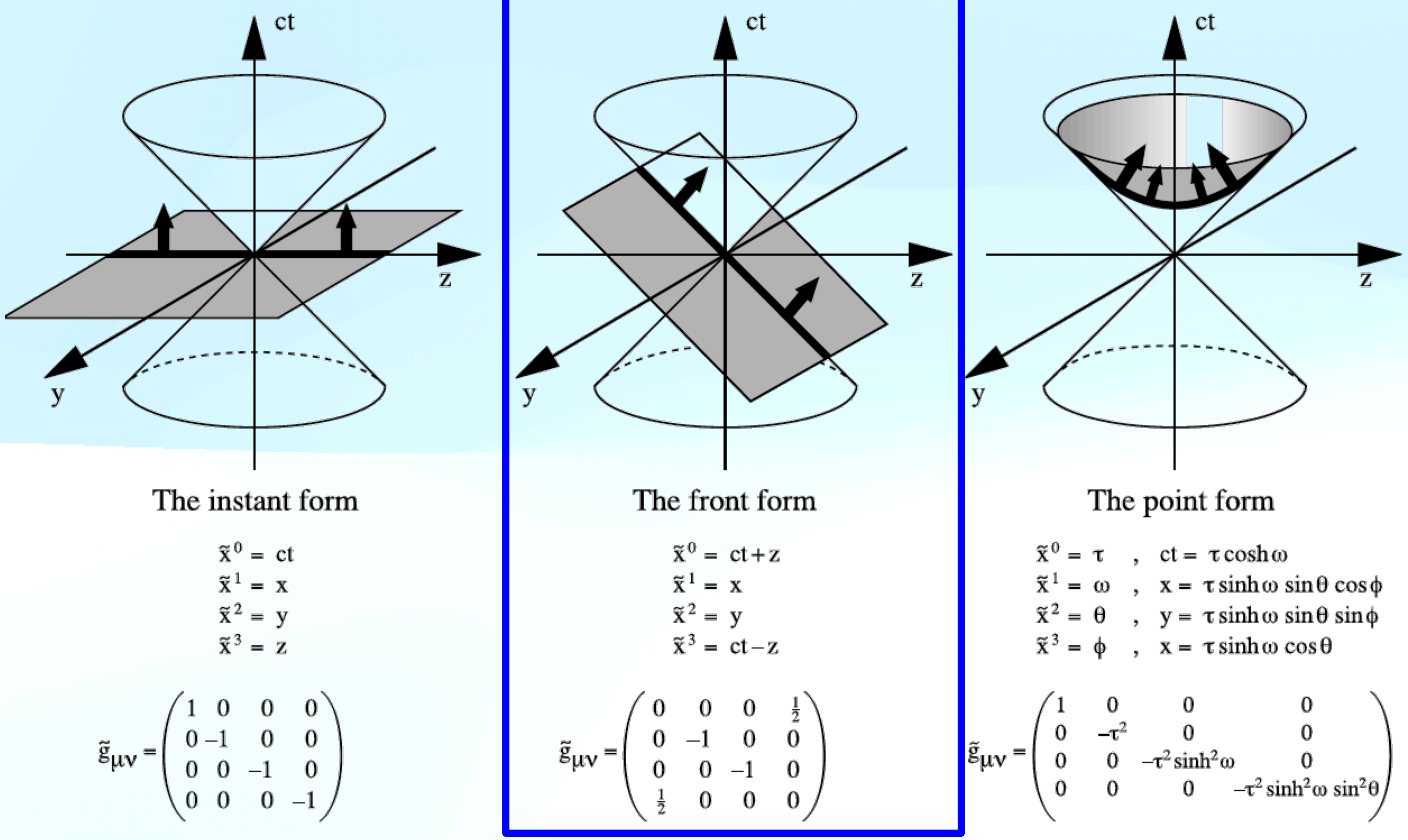

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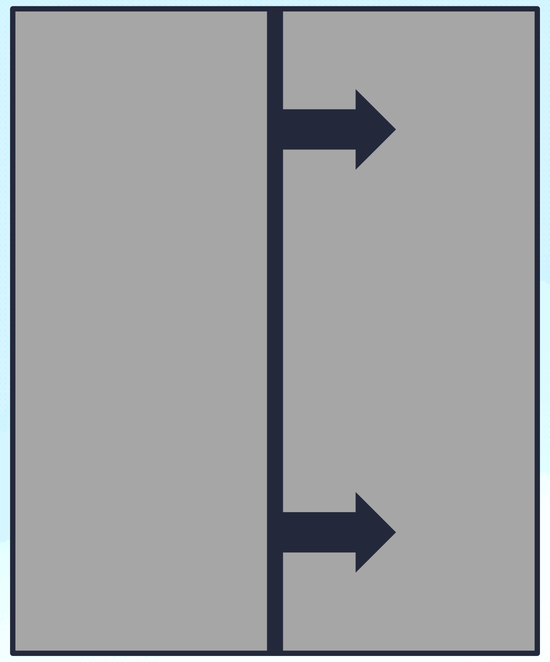

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Forms of relativistic Dynamics - The front form

The Light-Front framework has several advantages:

- 7 Kinematical generators: i) three LF boosts (In instant form they are dynamical!), ii) $\tilde{P} = (P^+ = P^0 + P^3, \mathbf{P}_\perp)$, iii) Rotation around the z-axis.
- The LF boosts have a subgroup structure : trivial Separation of intrinsic and global motion, as in the NR case. important to correctly treat the boost between initial and final states !
- $P^+ \geq 0 \longrightarrow$ meaningful Fock expansion, once massless constituents are absent
- No square root in the dynamical operator P^-, propagating the state in the LF-time.
- The infinite-momentum frame (IMF) description of DIS is easily included.

Drawback: the transverse LF-rotations are dynamical

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Bakamjian-Thomas construction and LFHD

Bakamjian and Thomas (PR 92 (1953) 1300) proposed an explicit construction of 10 Poincaré generators in presence of interactions.

- The key ingredient is the mass operator:

  i) only the mass operator M contains the interaction
  ii) it generates the dependence of the 3 dynamical generators upon the interaction

- The mass operator is given by the sum of M_0 with an interaction V, or M_0 + U. The interaction, U or V, must commute with all the kinematical generators and with the non-interacting angular momentum, as in the NR case.

In the Few-body case, one can easily embed the NR phenomenology:

i) the mass equation for, e.g. the ²H: $[M_0^2(12) + U]\,|\psi_D\rangle = \left[4m^2 + 4k^2 + U\right]\,|\psi_D\rangle = M_D^2\,|\psi_D\rangle = [2m - B_D]^2\,|\psi_D\rangle$ becomes a Schr. eq.

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- In the three-body case, the mass operator is: $M_{BT}(123) = M_0(123) + V^{BT}_{12,3} + V^{BT}_{23,1} + V^{BT}_{31,2} + V^{BT}_{123}$

  2-body forces — 3-body force

$$M_0(123) = \sum_{i=1}^{3} \sqrt{m^2 + k_i^2}$$

free mass operator — momenta in the intrinsic reference frame $\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3 = 0$

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The formalism has been extended also for ^{4}He

Reference frames

R. Alessandro, A. del Dotto, E. Pace, G. Perna, S. Scopetta and G. Salmè, PRC 104 (2021) 6, 065204
E. Pace, M. Rinaldi, S. Scopetta and G. Salmè, Phys. Scr. 95, 064008 (2020)
F. Fornetti, E. Pace, M. Rinaldi, S. Scopetta, G. Salmè and M. Viviani, arXiv:2308.15925

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- The intrinsic LF frame of the cluster, (1; 23), where $\tilde{P} = (\mathcal{M}_0(1,23), \vec{0}_\perp)$, with
  $\kappa^+(1;23) = \xi\, \mathcal{M}_0(1,23)$ and $\mathcal{M}_0(1,23) = \sqrt{m^2 + |\boldsymbol{\kappa}|^2} + \sqrt{M_S^2 + |\boldsymbol{\kappa}|^2}$

  $M_S = 2\sqrt{m^2 + m\epsilon}$

while $\mathbf{p}_\perp(lab) = \mathbf{k}_\perp(123) = \boldsymbol{\kappa}_\perp(1,23)$

The formalism has been extended also for A-nucleus

The spin-dependent LF spectral function

A. Del Dotto, E. Pace, G. Salmè, S. Scopetta, Physical Review C 95, 014001 (2017)

The Spectral Function: probability distribution to find inside a bound system a particle with a given $\tilde{\kappa}$ when the rest of the system has energy ϵ , with a polarization vector S:

$$\mathcal{P}^{\tau}_{\sigma'\sigma}(\tilde{\boldsymbol{\kappa}}, \epsilon, S) = \rho(\epsilon) \sum_{JJ_z\alpha} \sum_{Tt} {}_{LF}\langle tT; \alpha, \epsilon; JJ_z; \tau\sigma', \tilde{\boldsymbol{\kappa}} | \Psi_{\mathcal{M}}; ST_z \rangle \langle ST_z; \Psi_{\mathcal{M}} | \tilde{\boldsymbol{\kappa}}, \sigma\tau; JJ_z; \epsilon, \alpha; Tt \rangle_{LF}$$

- $|\Psi_{\mathcal{M}}; ST_z\rangle = \sum_m |\Psi_m; S_z T_z\rangle \, D^{\mathcal{J}}_{m,\mathcal{M}}(\alpha, \beta, \gamma)$ → Euler angles of rotation from the z-axis to the **polarization vector S**

  three-body bound eigenstate of $M_{BT}(123) \sim M^{NR}$

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$$\mathcal{M}_0(1,23) = \sqrt{m^2 + |\kappa|^2} + E_S \quad E_S = \sqrt{M_S^2 + |\kappa|^2} \quad M_S = 2\sqrt{m^2 + m\epsilon}$$

and fulfills the macroscopic locality (Keister, Polyzou, Adv. N. P. 20, 225 (1991)).

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The tensor product of the plane wave of the interacting particle and the state of the spectator system

In the intrinsic reference frame of the cluster $[1; 2,3,\ldots, A-1]$

The wave function of the nucleus A (i.e. the eigenstate of $M[1,2,\ldots,A] \sim M^{NR}$)

In the intrinsic frame of the system $[1,2,\ldots,A]$

We can express the **LF overlap** in terms of the **IF overlap** using **Melosh rotations** and then we can approximate the IF overlap into a NR overlap thanks to the **BT construction:**

$$\{\alpha\}; \phi >_{LF} \to \quad \{\alpha\}; \phi >_{IF} \sim \quad \{\alpha\}; \phi >_{NR}$$

The **LF spectral function** contains the determinant of the Jacobian of the transformation between the intrinsic frames $[1; 2,3,\ldots, A-1]$ and $[1,2,\ldots,A]$, connected each other by a **LF boost**

*F. Fornetti's slide

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The nuclear structure **function F_2**

The hadronic tensor, in **Impulse approximation** is found to be (Pace, M.R., Salmè and S. Scopetta, Phys. Scri. 2020)

$$W_A^{\mu\nu}(P_A, T_{Az}) = \sum_N \sum_\sigma \not\sum d\epsilon \int \frac{d\boldsymbol{\kappa}_\perp \, d\kappa^+}{(2\pi)^3 \; 2\,\kappa^+} \frac{1}{\xi} \mathcal{P}^N(\tilde{\boldsymbol{\kappa}}, \epsilon) \, w_{N,\sigma}^{\mu\nu}(p,q)$$

hadronic tensor of the bound nucleon

In the Bjorken limit the nuclear structure function can be obtained from the hadronic tensor:

$$F_2^A(x) = \sum_N \sum_\sigma \not\sum d\epsilon \int \frac{d\boldsymbol{\kappa}_\perp \, d\kappa^+}{(2\pi)^3 \; 2\,\kappa^+} \frac{1}{\xi} \mathcal{P}^N(\tilde{\boldsymbol{\kappa}}, \epsilon) \, (-x) \, g_{\mu\nu} \; w_{N,\sigma}^{\mu\nu}(p,q) = \sum_N \not\sum d\epsilon \int \frac{d\boldsymbol{\kappa}_\perp \, d\kappa^+}{(2\pi)^3 \; 2\,\kappa^+} \mathcal{P}^N(\tilde{\boldsymbol{\kappa}}, \epsilon) \frac{P_A^+}{p^+} \frac{x}{z} F_2^N(z)$$

$x = \frac{Q^2}{2P_A \cdot q}$ Bjorken variable $\quad \xi = \frac{\kappa^+}{\mathcal{M}_0(1,23)} \neq x \quad z = \frac{Q^2}{2p \cdot q}$

nucleon structure function

$F_2^N(z) = -z \, g_{\mu\nu} \sum_\sigma w_{N,\sigma}^{\mu\nu}(p,q)$

One should notice that: $\int d\epsilon \int d\kappa^+ \neq \int d\kappa^+ \int d\epsilon$ but in the BJ limit $\int d\epsilon \int d\kappa^+ = \int d\kappa^+ \int d\epsilon$

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$$F_2^A(x) = \sum_N \int_{\xi_{min}}^1 d\xi \, F_2^N\left(\frac{mx}{\xi M_A}\right) f_1^N(\xi)$$

$f_1^N(\xi)$ → Light-cone momentum distribution

$F_2^N\left(\frac{mx}{\xi M_A}\right)$ → Free nucleon structure function

With: $f_1^N(\xi) = \int d\mathbf{k}_\perp n^n(\xi, \mathbf{k}_\perp)$

LF momentum distribution:

$$n^N(\xi, \mathbf{k}_\perp) = \frac{1}{2\pi} \int \prod_{i=2}^{A-1} [d\mathbf{k}_i] \frac{\partial k_z}{\partial \xi} \mathcal{N}^N(\mathbf{k}, \mathbf{k}_2, \ldots, \mathbf{k}_{A-1})$$

$\frac{\partial k_z}{\partial \xi}$ → Determinant of the Jacobian matrix. **LF boost: effect of a Poincaré covariance approach**

$\mathcal{N}^N(\mathbf{k}, \mathbf{k}_2, \ldots, \mathbf{k}_{A-1})$ → Squared nuclear wave function. **Thanks to the BT construction, one is allowed to use the NR one**

*F. Fornetti's slide

LC momentum distributions

From the normalization of the Spectral Function one has

$$f_\tau^A(\xi) = \int d\mathbf{k}_\perp \; n^\tau(\xi, \mathbf{k}_\perp) \quad \Longrightarrow \quad \int_0^1 d\xi \; f_\tau^A(\xi) \; = \; 1$$

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We can define the essential sum rules that must be satisfied:

$$\underbrace{N_A = \int d\xi \left[Z f_p^A(\xi) + (A - Z) f_n^A(\xi) \right] = 1}_{\text{Baryon number sum rule}} \qquad \underbrace{MSR = \int d\xi \; \xi \left[Z f_p^A(\xi) + (A - Z) f_n^A(\xi) \right] = 1}_{\text{Momentum sum rule}}$$

Within the LFHD we are able to fulfill both sum rules at the same time!

E. Pace, M.R., G. Salmè and S. Scopetta, Phys. Lett. B (2023) 137810

A. Del Dotto, E. Pace, G. Perna, A. Rocco, G. Salmè and S. Scopetta, Phys.Rev.C 104 (2021) 6, 065204)

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Baryon number sum rule — Momentum sum rule

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Not possible within the IF! (Frankfurt & Strikman; Miller;....80's)

LC momentum distributions

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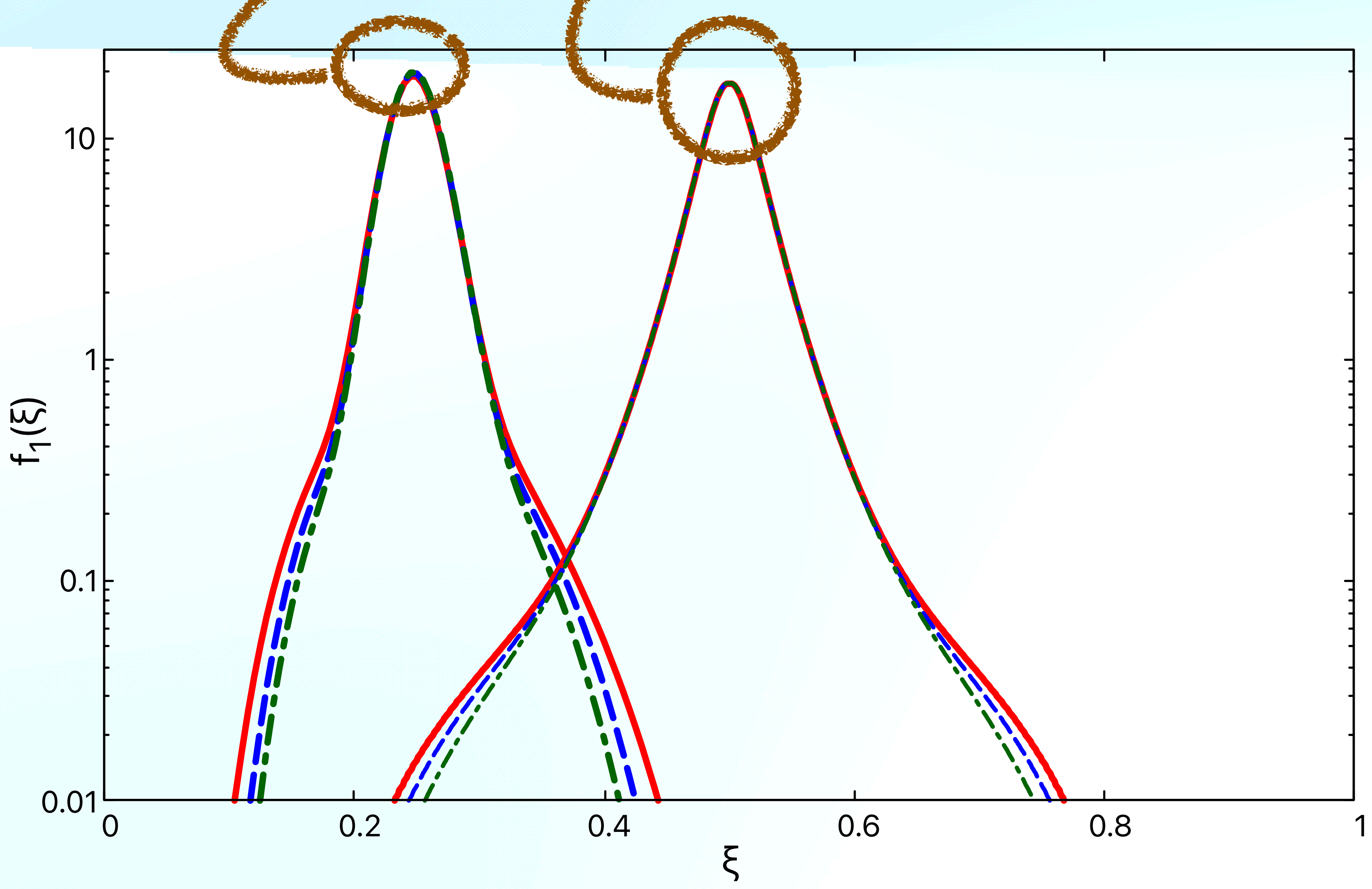
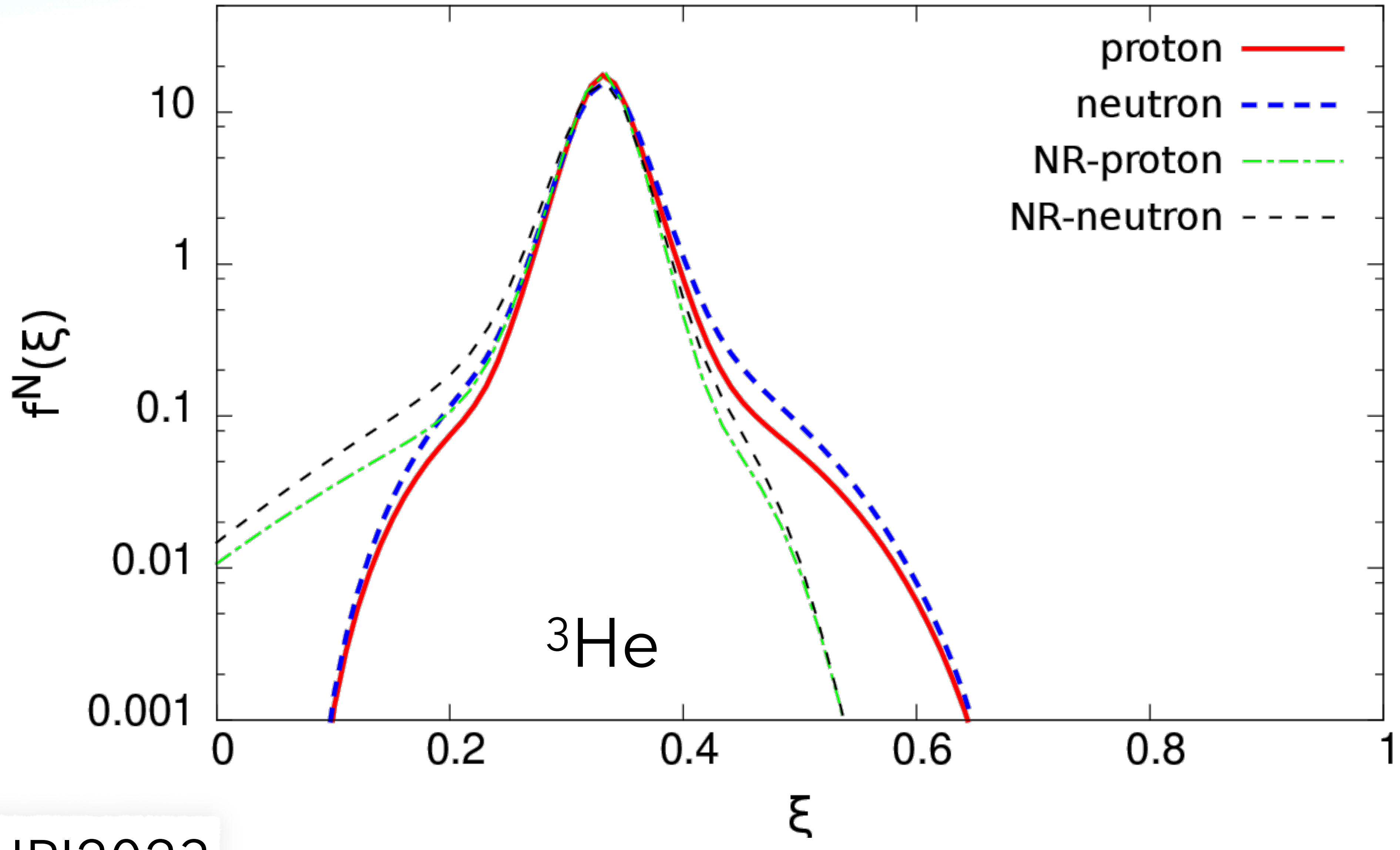
$$MSR = \int d\xi \, \xi \left[Z f_p^A(\xi) + (A-Z) f_n^A(\xi) \right] = 1$$

The distributions are peaked in 1/A with an accuracy of 1/1000:
MSR and Number of baryon sum rules are numerically satisfied



- The tails of the distributions are generated by the **short range correlations (SRC)** induced by the potentials (i.e the high-momentum content of the 1-body momentum distribution)
- The tails of the LC momentum distribution calculated by the Av18/UIX potential is larger than the ones obtained by the χEFT potentials for both ^4He and deuteron
- This difference will partially cancel out on the EMC ratio



LC momentum distributions

$$N_A = \int d\xi \left[Z f_p^A(\xi) + (A - Z) f_n^A(\xi) \right] = 1 \qquad MSR = \int d\xi \, \xi \left[Z f_p^A(\xi) + (A - Z) f_n^A(\xi) \right] = 1$$

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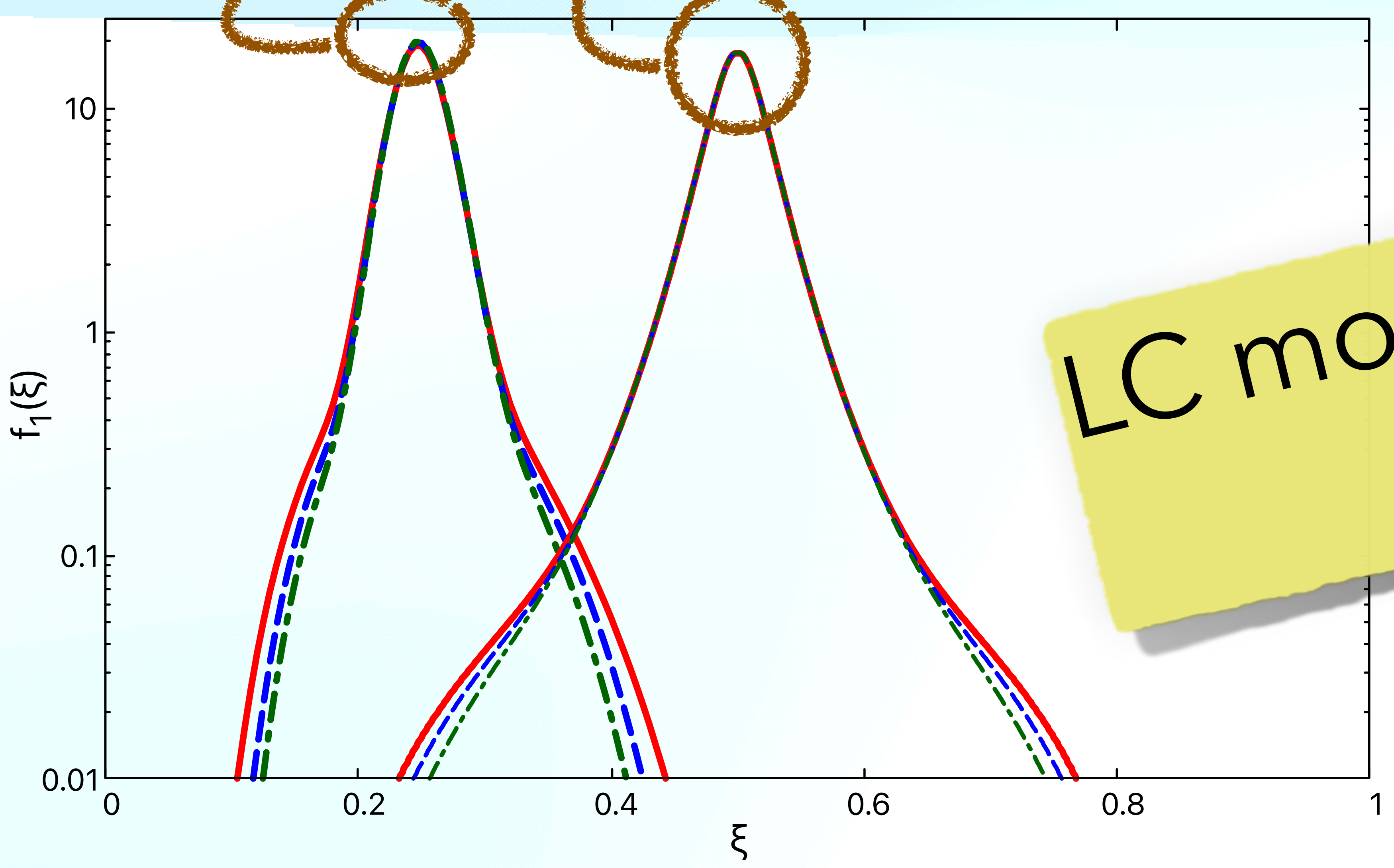
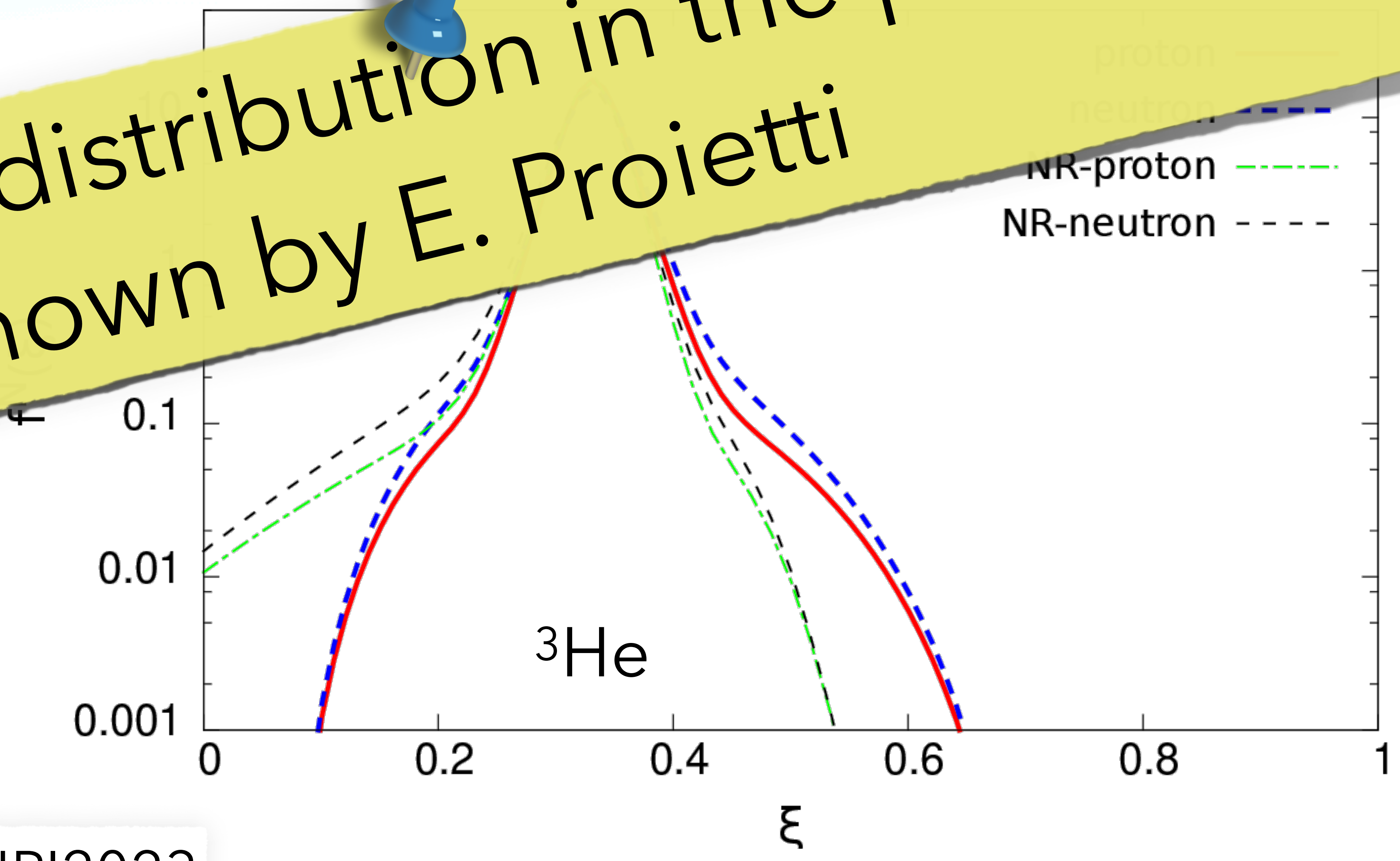
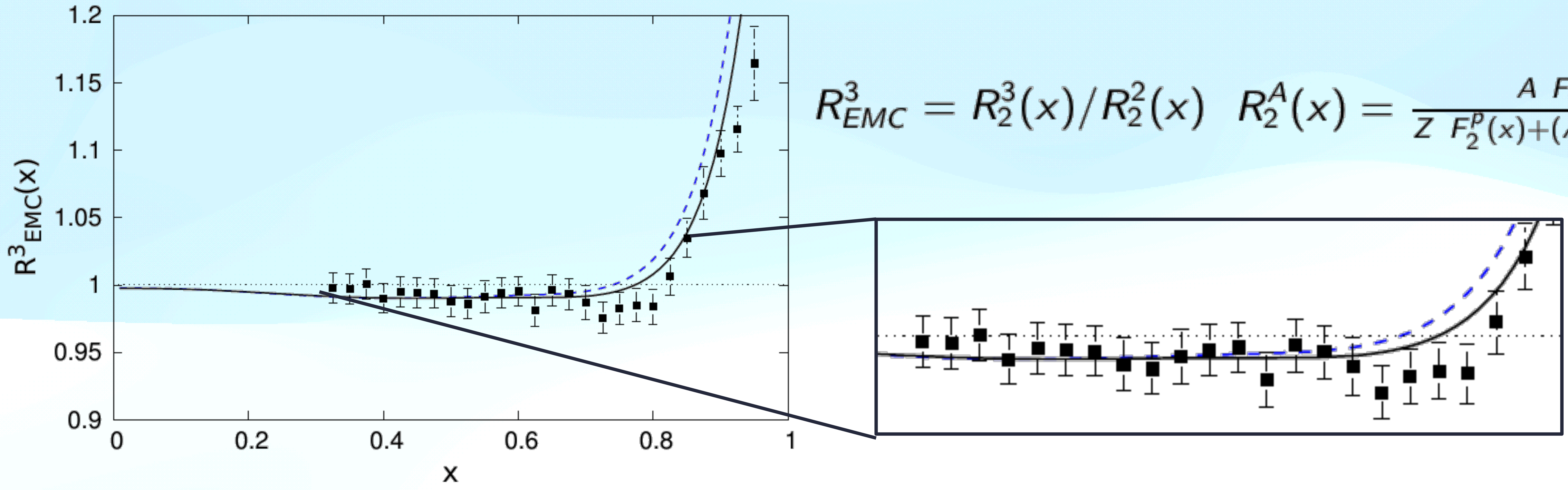




LC momentum distribution in the polarized case shown by E. Proietti

The ³He EMC effect within the LFHD

E. Pace, M.R., G. Salmè and S. Scopetta, Phys. Lett. B (2023) 137810



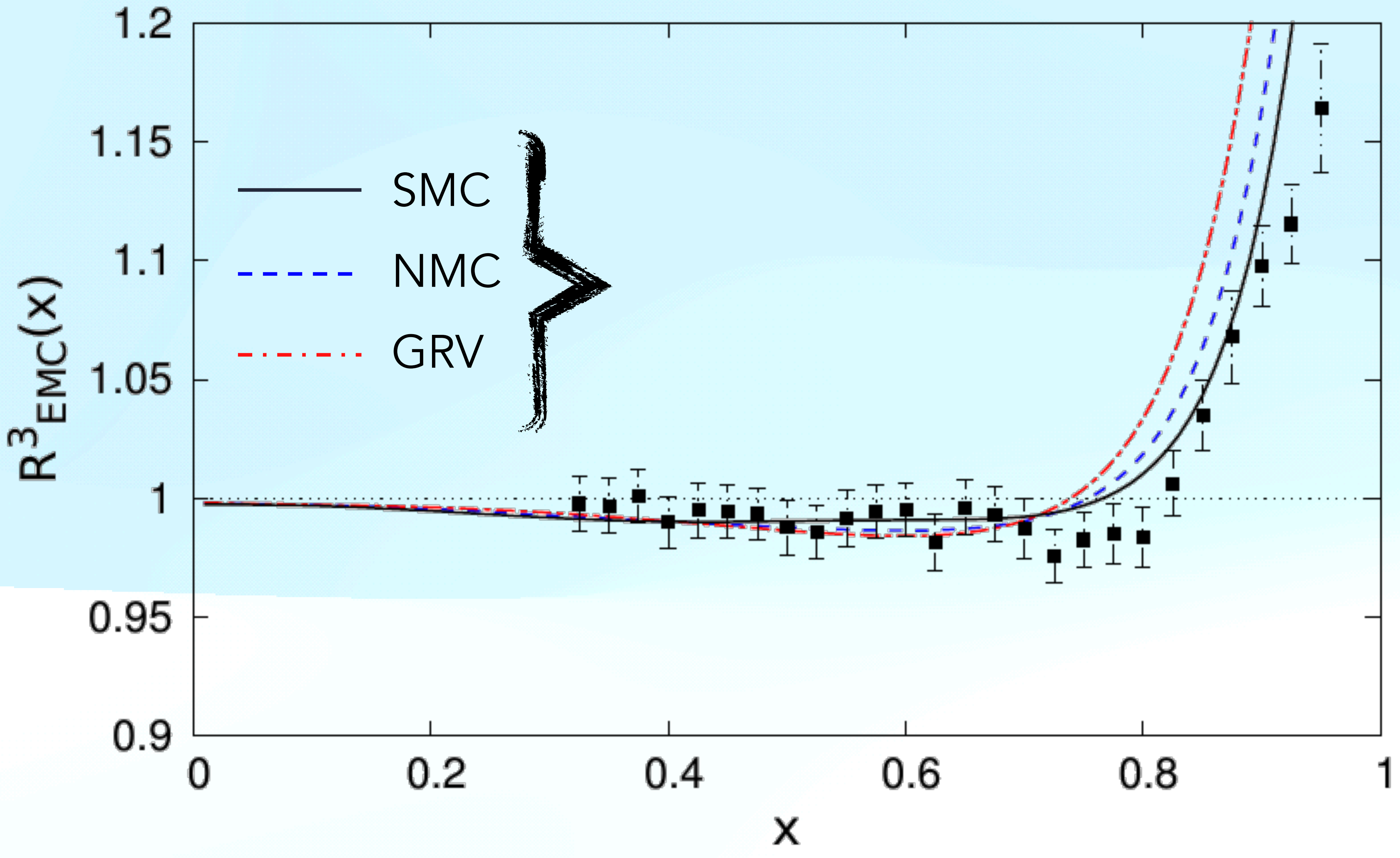
$$R^3_{EMC} = R^3_2(x)/R^2_2(x) \quad R^A_2(x) = \frac{A\ F^A_2(x)}{Z\ F^p_2(x)+(A-Z)\ F^n_2(x)}$$

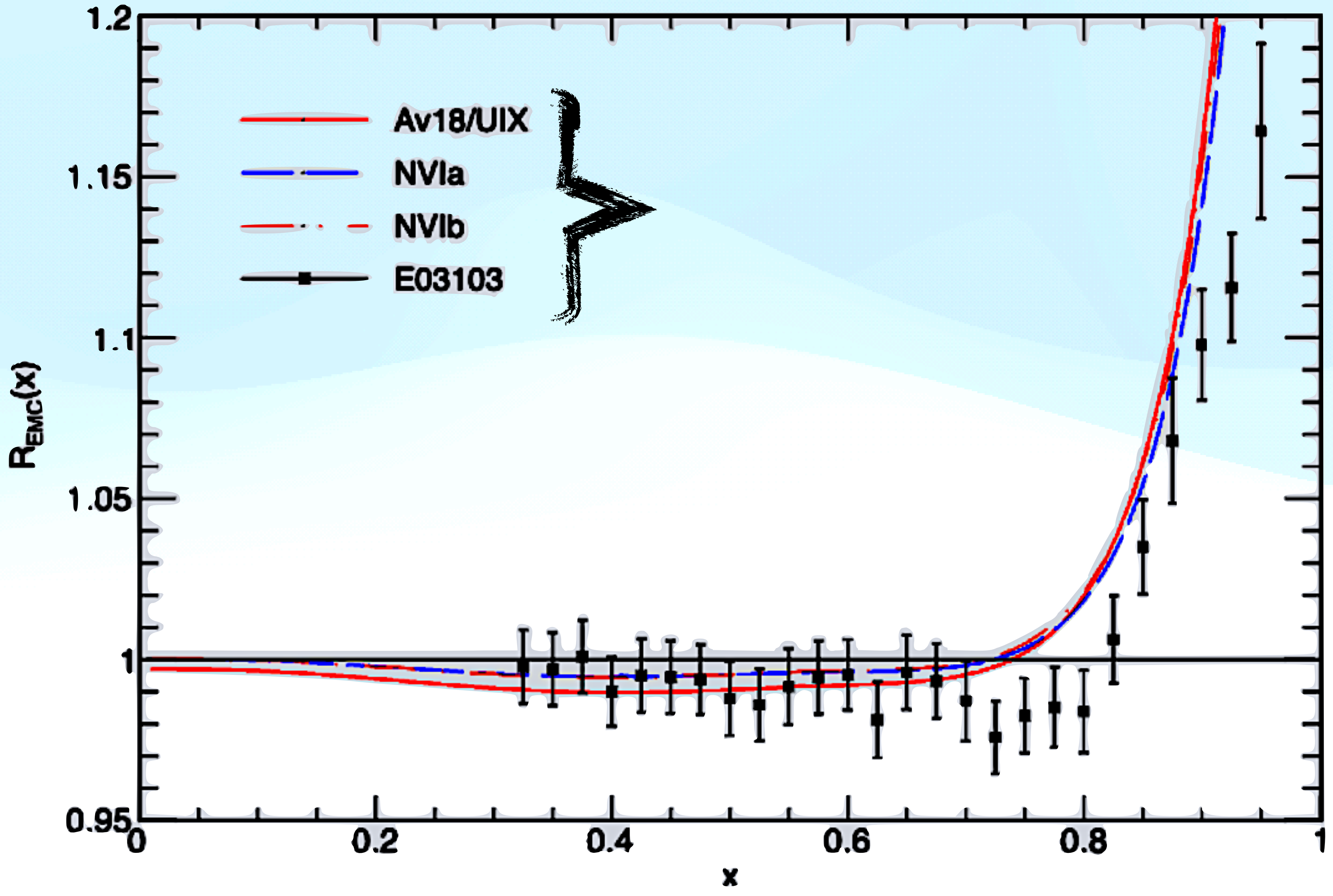
- Solid line: with Av18 description of ^{3}He, Dashed line: including three-body forces (U-IX) with "SMC" nucleon structure functions (Adeva et al PLB 412, 414 (1997)).
- Full squares: data from J. Seely et al., PRL. 103, 202301 (2009) reanalyzed by S. A. Kulagin and R. Petti, PRC 82, 054614 (2010)

The ^{3}He EMC effect within the LFHD

E. Pace, M.R., G. Salmè and S. Scopetta, Phys. Lett. B (2023) 137810

F. Fornetti, E. Pace, M. Rinaldi, S. Scopetta, G. Salmè and M. Viviani, arXiv:2308.15925



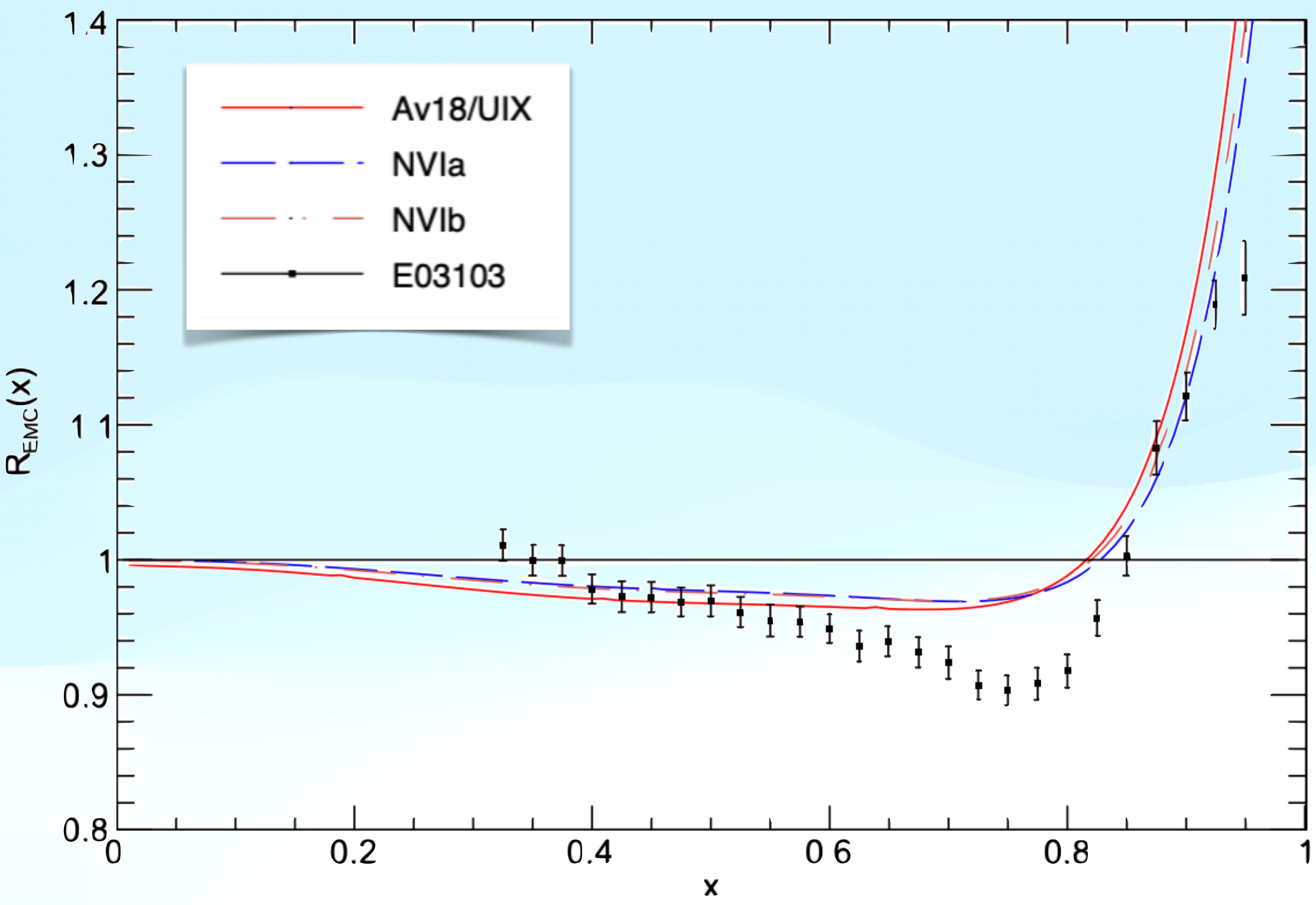


$F_2^n(x)$ extracted from the MARATHON data [MARATHON, PRL 128,132003 (2022)]

$F_2^p(x)$ SMC

The ^{4}He EMC effect within the LFHD

arXiv:2308.15925 [nucl-th]



Full squares: JLab data from experiment E03103

[J. Arrington, et al, Phys. Rev. C 104 (6) (2021) 065203]

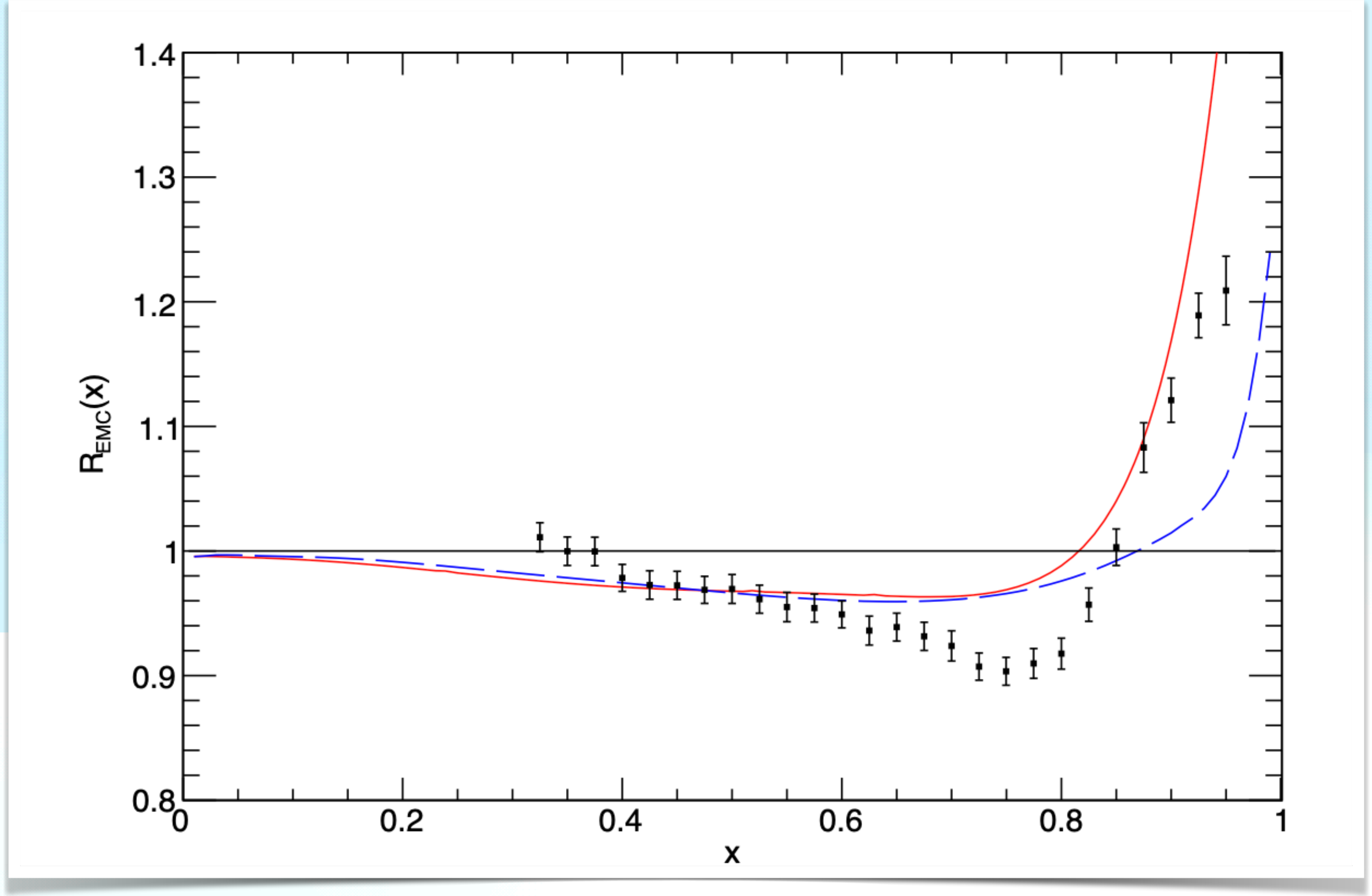
Analogous results obtained also for ^3He and ^4He

*F. Fornetti's slide

- The differences between the calculations from different potentials are of the **same order for both nuclei**
- They are definitely **smaller than the difference between data and theoretical prediction**

The ^{4}He EMC effect within the LFHD

arXiv:2308.15925 [nucl-th]



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[J. Arrington, et al, Phys. Rev. C 104 (6) (2021) 065203]

Both lines calculated with Av18/UIX
Solid line: SMC parametrization of F_2^p
Dashed line: NVIb+3N: CJ15 +TMC Parametrization of F_2^p
F_2^n extracted from MARATHON data

[B. Adeva, et al., Phys. Lett. B 412 (1997) 414–424.]

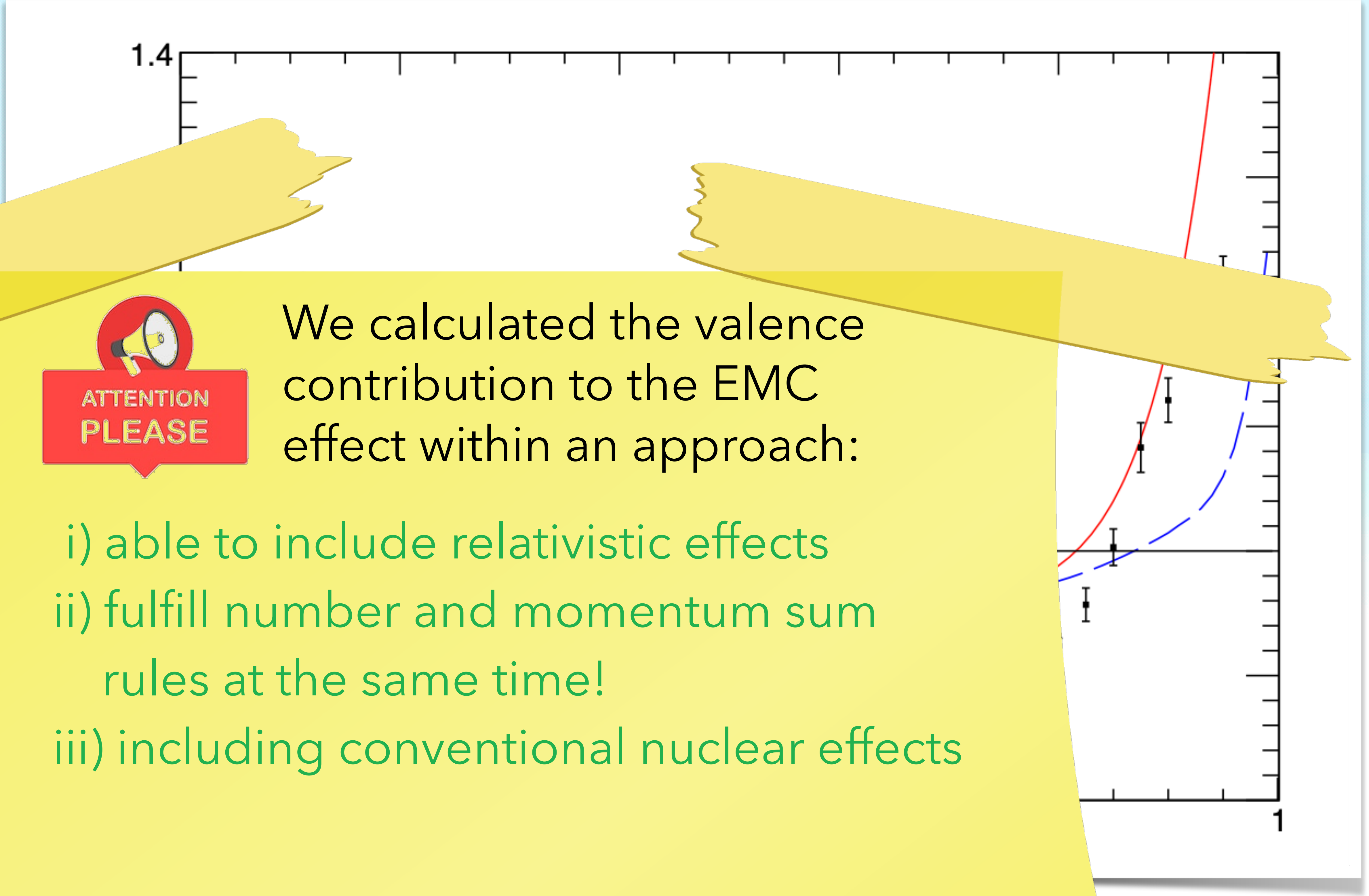
[A. Accardi, L. T. Brady, W. Melnitchouk, J. F. Owens, N. Sato, Phys. Rev. D 93 (11) (2016) 114017]

[MARATHON, PRL 128,132003 (2022)]
[E.Pace, M.Rinaldi, G.Salmè and S.Scopetta Phys. Lett. B 839(2023) 127810]

The dependance on the ratio F_2^n/F_2^p is **largely under control** as well the dependance on the parametrization of F_2^p in the properly EMC region *F. Fornetti's slide

The ^{4}He EMC effect within the LFHD

arXiv:2308.15925 [nucl-th]



ATTENTION PLEASE

We calculated the valence contribution to the EMC effect within an approach:

i) able to include relativistic effects

ii) fulfill number and momentum sum rules at the same time!

iii) including conventional nuclear effects

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*F. Fornetti's slide

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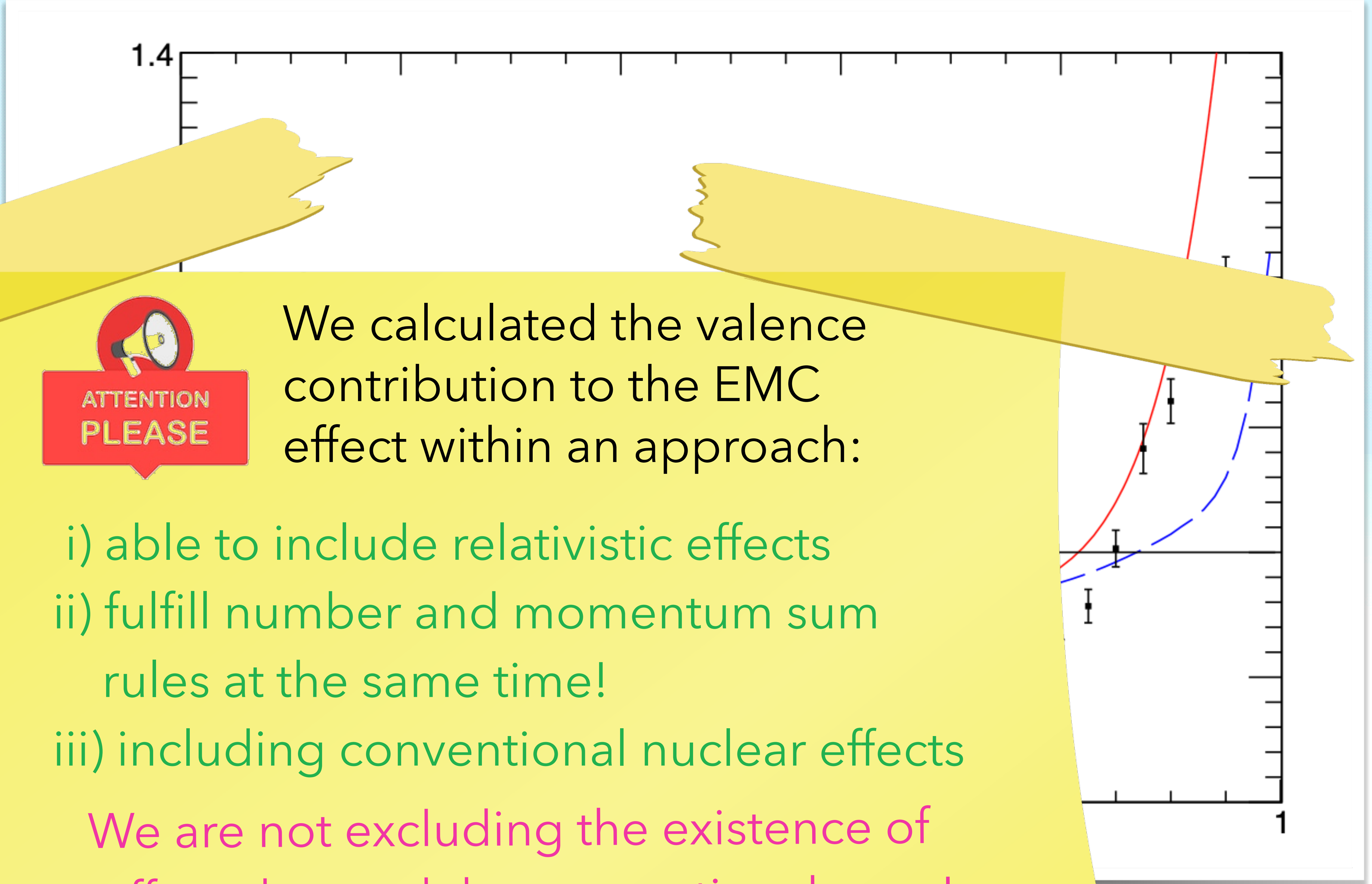

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We calculated the valence contribution to the EMC effect within an approach:

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iii) including conventional nuclear effects

We are not excluding the existence of effects beyond the conventional ones!

We need to test the approach with heavier nuclei

The dep… **…er control** as well the dependance on the parametr…

*F. Fornetti's slide

CONCLUSIONS

✓ A Poincaré covariant description of nuclei, based on the light-front Hamiltonian dynamics, has been proposed. The Bakamjian-Thomas construction of the Poincaré generators allows one to embed the successful phenomenology for few-nucleon systems in a Poincaré covariant framework.
N.B. Normalization and momentum sum rule are both automatically fulfilled.

✓ LC spin-dependent momentum distributions are available, for both longitudinal and transverse polarizations of the nucleon. (see E. Proietti's talk)

✓ Encouraging calculation of ^{3}He and ^{4}He EMC, shedding light on the role of a reliable description of the nucleus.

Analyses of A(e,e',p)X reactions, with polarized initial and final states, for accessing nuclear TMD's in ^{3}He are in progress

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Rescaling

Structure Functions for Light Nuclei

S. A. Kulagin[1,*] and R. Petti[2,†]

[1] *Institute for Nuclear Research of the Russian Academy of Sciences, 117312 Moscow, Russia*
[2] *Department of Physics and Astronomy, University of South Carolina, Columbia SC 29208, USA*

Abstract

We discuss the nuclear EMC effect with particular emphasis on recent data for light nuclei including ^{2}H, ^{3}He, ^{4}He, ^{9}Be, ^{12}C and ^{14}N. In order to verify the consistency of available data, we calculate the χ^2 deviation between different data sets. We find a good agreement between the results from the NMC, SLAC E139, and HERMES experiments. However, our analysis indicates an overall normalization offset of about 2% in the data from the recent JLab E03-103 experiment with respect to previous data for nuclei heavier than ^{3}He. We also discuss the extraction of the neutron/proton structure function ratio F_2^n/F_2^p from the nuclear ratios ^{3}He/^{2}H and ^{2}H/^{1}H. Our analysis shows that the E03-103 data on ^{3}He/^{2}H require a renormalization of about 3% in order to be consistent with the F_2^n/F_2^p ratio obtained from the NMC experiment. After such a renormalization, the ^{3}He data from the E03-103 data and HERMES experiments are in a good agreement. Finally, we present a detailed comparison between data and model calculations, which include a description of the nuclear binding, Fermi motion and off-shell corrections to the structure functions of bound proton and neutron, as well as the nuclear pion and shadowing corrections. Overall, a good agreement with the available data for all nuclei is obtained.

Backup Slides: effective polarizations

Effective polarizations

Key role in the extraction of neutron polarized structure functions and neutron Collins and Sivers single spin asymmetries, from the corresponding quantities measured for ^{3}He

Effective longitudinal polarization (axial charge for the nucleon)

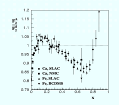
$$p_{||}^{\tau} = \int_0^1 dx \int d\mathbf{p}_\perp \; \Delta f^\tau(x, |\mathbf{p}_\perp|^2)$$

Effective transverse polarization (tensor charge for the nucleon)

$$p_{\perp}^{\tau} = \int_0^1 dx \int d\mathbf{p}_\perp \; \Delta'_T f^\tau(x, |\mathbf{p}_\perp|^2)$$

Effective polarizations	proton	neutron
LF longitudinal polarization	-0.02299	0.87261
LF transverse polarization	-0.02446	0.87314
non relativistic polarization	-0.02118	0.89337

- The difference between the LF polarizations and the non relativistic results are up to 2% in the neutron case (larger for the proton ones, but it has an overall small contribution), and should be ascribed to the intrinsic coordinates, implementing the Macro-locality, and not to the Melosh rotations involving the spins.
- N.B. Within a NR framework: $p_{||}^{\tau}(NR) = p_{\perp}^{\tau}(NR)$



Backup Slides: effective polarizations

The BT Mass operator for A=3 nuclei - II

The NR mass operator is written as

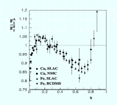
$$M^{NR} = 3m + \sum_{i=1,3} \frac{k_i^2}{2m} + V_{12}^{NR} + V_{23}^{NR} + V_{31}^{NR} + V_{123}^{NR}$$

and must obey to the commutation rules proper of the Galilean group, leading to translational invariance and independence of total 3-momentum.

Those properties are analogous to the ones in the BT construction. This allows us to consider the standard non-relativistic mass operator as a sensible BT mass operator, and embed it in a Poincaré covariant approach.

$$M_{BT}(123) = M_0(123) + V_{12,3}^{BT} + V_{23,1}^{BT} + V_{31,2}^{BT} + V_{123}^{BT} \sim M^{NR}$$

The 2-body phase-shifts contain the relativistic dynamics, and the Lippmann-Schwinger equation, like the Schrödinger one, has a suitable structure for the BT construction. Therefore what has been learned till now about the nuclear interaction, within a non-relativistic framework, can be re-used in a Poincaré covariant framework.



The eigenfuntions of M^{NR} do not fulfill the cluster separability, but we take care of Macro-locality in the spectral function.

Diagrams and infographics