The EMC effect within the light-front Hamiltonian dynamics for few-nucleon bound systems

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STRONG 2020

INFN PERUGIA Istituto Nazionale di Fisica Nucleare Sezione di Perugia

Based on

F.F, E.Pace, M.Rinaldi, G.Salmè, S.Scopetta and M.Viviani,
"The EMC effect for few-nucleon bound systems in Light-Front Hamiltonian Dynamics",
in preparation arXiv:2308.15925 [nucl-th]

E.Pace, M.Rinaldi, G.Salmè and S.Scopetta
"The European Muon Collaboration effect in Light-Front Hamiltonian Dynamics",
Phys. Lett. B 839(2023) 127810

R.Alessandro, A.Del Dotto, E.Pace, G.Perna, G.Salmè and S.Scopetta
"Light-Front Transverse Momentum Distributions for $J = 1/2$ 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 system and Poincaré covariance",
Phys. Scr. 95, 064008 (2020)

MARATHON Coll.
"Measurement of the Nucleon F_2^n/F_2^p Structure Function Ratio by the Jefferson Lab MARATHON Tritium/Helium-3 Deep Inelastic Scattering Experiment",
Phys. Rev. Lett 128 (2022) 13,132003

Outline

- **Overview**
- **The EMC effect**
- **The Light-Front Poincaré covariant approach**
- **Nuclear structure functions with Relativistic Hamiltonian Dynamics**
- **Numerical results**
- **Conclusions**

Overview

- 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]

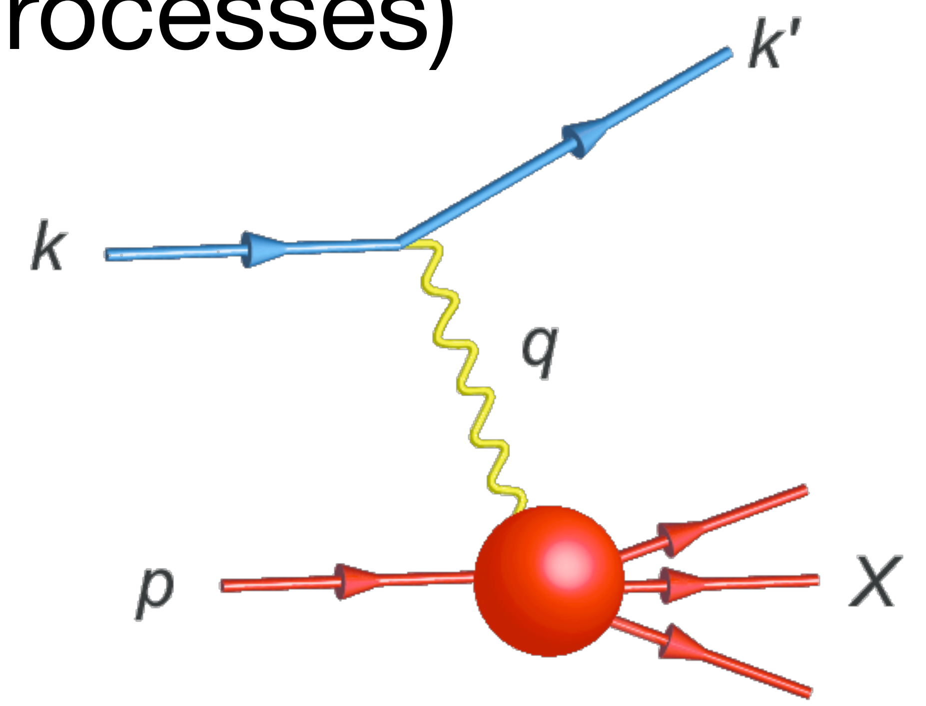
[R. B. Wiringa et al., Phys. Rev. Lett. 74 (1995) 4396–4399]

[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]

Almost 40 years ago, the European Muon Collaboration (EMC) measured (in DIS processes)

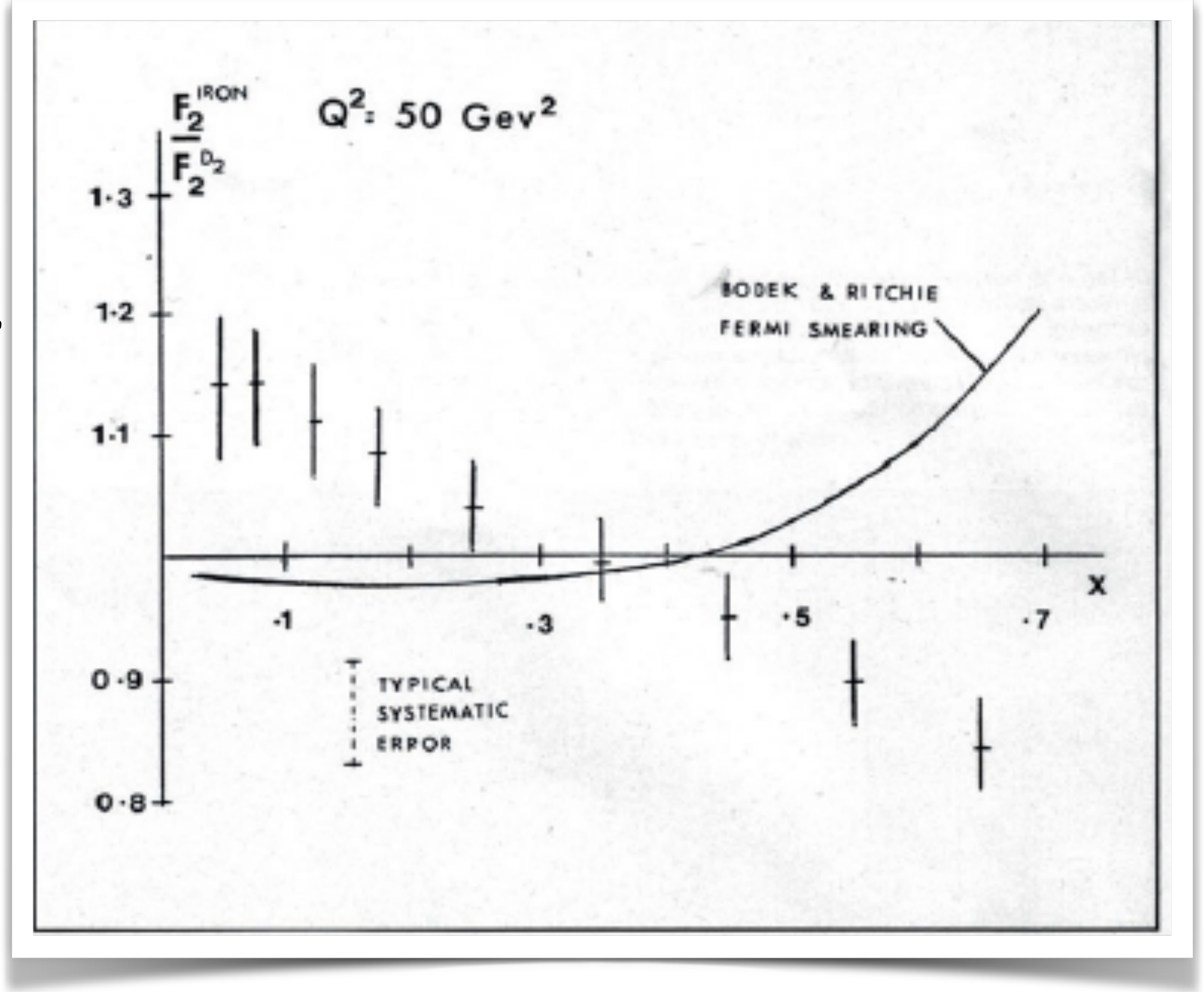


$$R(x) = F_2^{56Fe}(x)/F_2^{2H}(x)$$

Expected result: R(x) = 1 up to corrections of the Fermi motion

Result:

Aubert et al. Phys.Lett. B123 (1983) 275



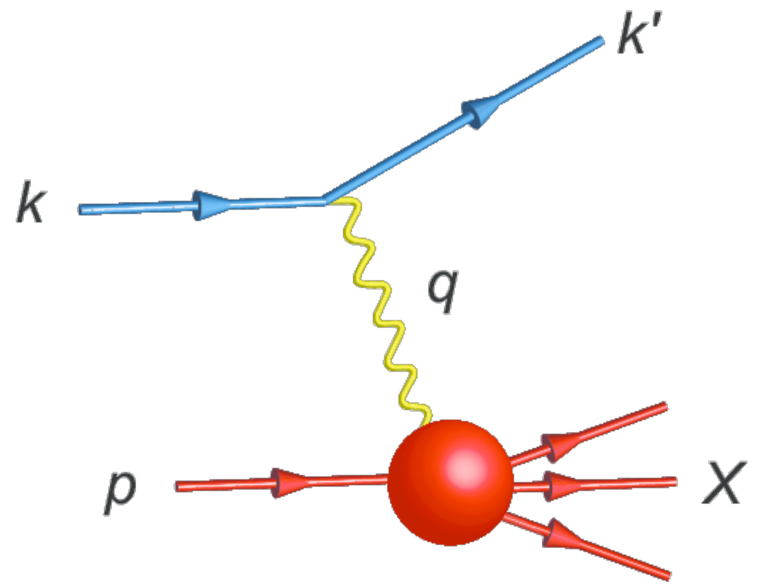
Naive parton model interpretation:

"Valence quarks, in the bound nucleon, are in average slower that in the free nucleon"

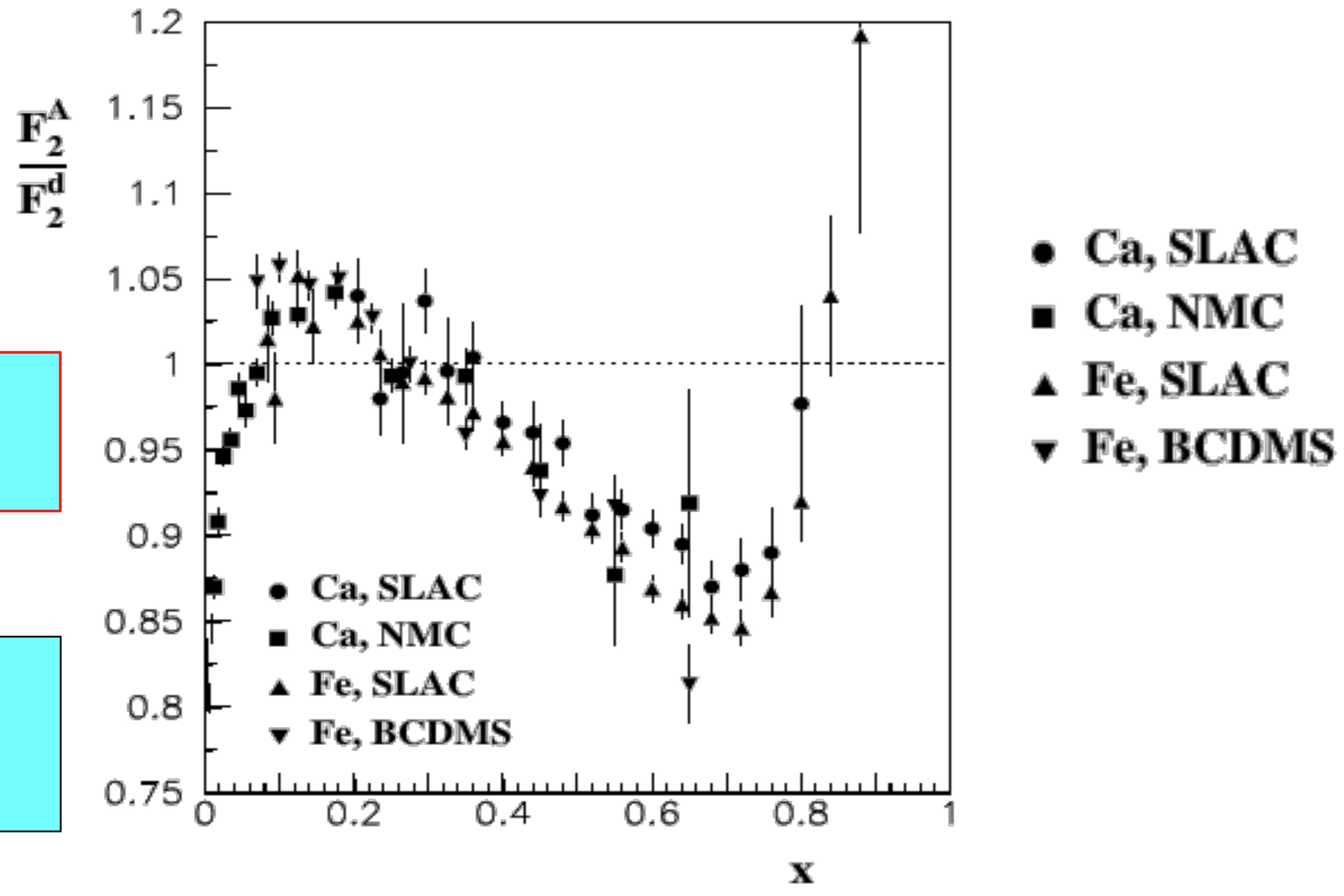
Is the bound proton bigger than the free one??

The EMC effect

We remind that for DIS off nuclei: $0 \leq x = \dfrac{Q^2}{2M\nu} \leq \dfrac{M_A}{M} \simeq A$



- **x ≲ 0.3 "Shadowing region"**: coherence effects, the photon interacts with partons belonging to different nucleons
- **0.2 ≲ x ≲ 0.8 "EMC (binding) region"**: mainly valence quarks involved
- **0.8 ≲ x ≲ 1 "Fermi motion region"**



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

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: what do we know

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:

Status of “conventional” calculations for light nuclei:

NR Calculations: qualitative agreement but no fulfillment of both particle and MSR... Not under control

Our approach is aimed to include only nucleonic dof through conventional nuclear physics in a Poincaré-covariant approach. The only way to fulfill sum rules while using realistic NR nuclear potentials is to embed relativistic effects.

A completely NR calculation of the effect due to **nucleonic dof** (conventional nuclear physics) could **overestimate** the effect due to **exotic explanations** (involving genuine QCD effects). We want to remark that because of the magnitude of the EMC effect also small **corrections due to relativistic effects** could be significant if we want to study the contribution of partonics dof

Need for a relativistic treatment

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.
- 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.

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, $P^\mu \rightarrow 4D$ displacements and $M^{\nu\mu} \rightarrow$ Lorentz transformation, have to fulfill:

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

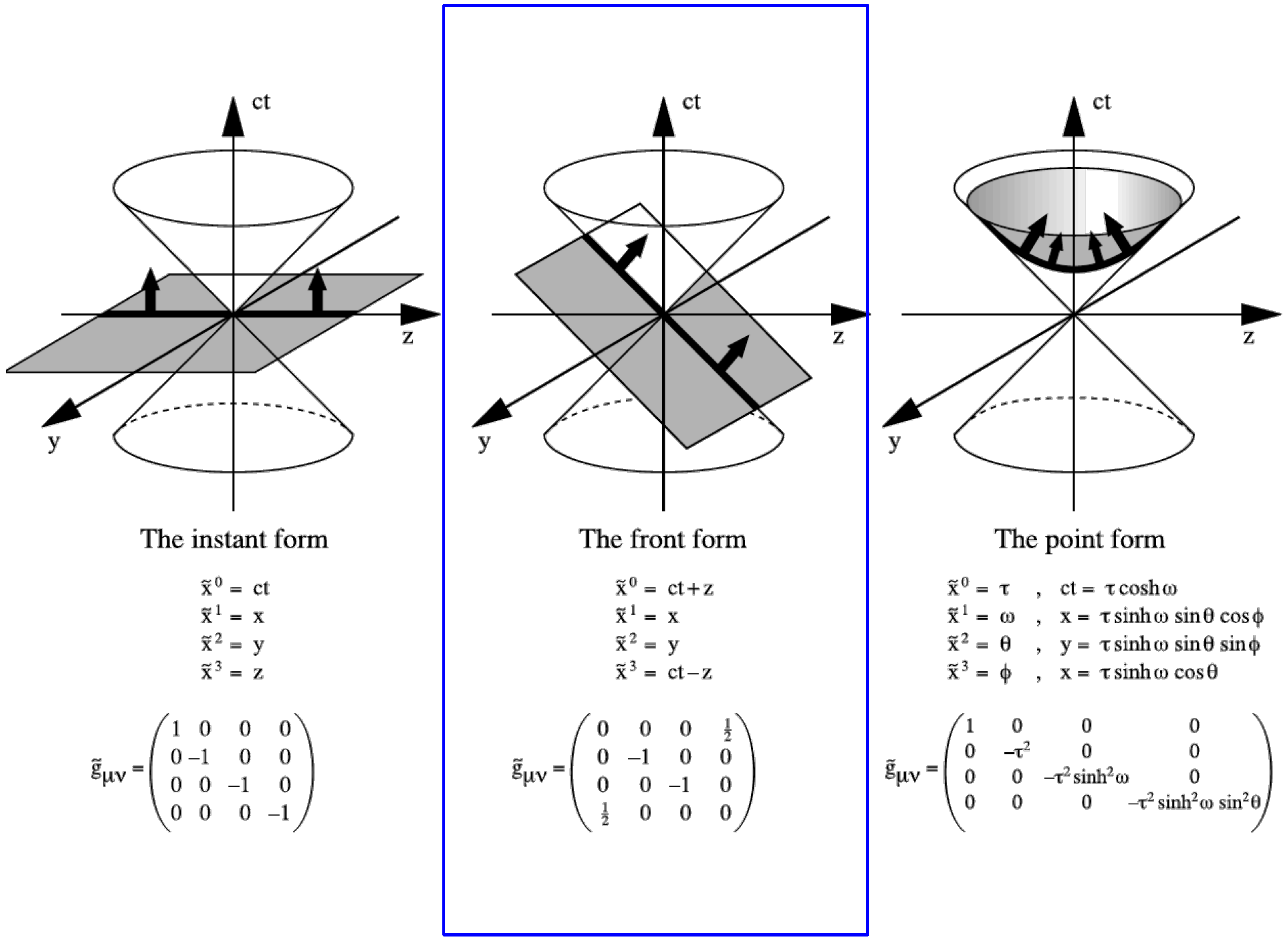
$$[M^{\mu\nu}, M^{\rho\sigma}] = -i(g^{\mu\rho}M^{\nu\sigma} + g^{\nu\sigma}M^{\mu\rho} - g^{\mu\sigma}M^{\nu\rho} - g^{\nu\sigma}M^{\mu\sigma})$$

Macroscopic locality (= cluster separability (relevant in nuclear physics)): i.e. observables associated to different space-time regions must commute in the limit of **large space like separation** (i.e. causally disconnected). In this way, when a system is separated into disjoint subsystems by a sufficiently large space like separation, then the **subsystems behave as independent systems.**

Keister, Polyzou, Adv. Null. Phys. 20,225 (1991)

This requires a careful choice of the intrinsic relativistic coordinates

Forms of relativistic Dynamics



We choose the Front Form!

Fig. from Brodsky, Pauli, Pinsky Phys.Rept. 301 (1998) 299-486

Advantages of the Light-Front framework

The Light-Front framework has several advantages:

- **7 Kinematical generators:** i) **3 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

- $P^+ = 0 \to$ **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-monentum frame (IMF)** description of DIS is easily included

Drawback: the transfers LF-rotations are dynamical!

But within the **Bakamjian-Thomas (BT)** construction of the generators in an interacting theory, one can construct an intrinsic angular momentum fully kinematical

The Bakamjian-Thomas construction

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 since $P^- = P_0^- + \frac{1}{P^+}[M^2 - M_0^2]$

ii) It generates the dependence of the **3 dynamical generators** (P^- and LF transverse rotations) upon the interaction

iii) The eigenvalue equation $M^2|\psi> = s|\psi>$ is formally equivalent to the Schrödinger equation

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.

The BT construction for a nuclear system

For a generic nucleus A, the mass operator is

$M[1,2,3,\ldots,A] = M_0[1,2,3,\ldots,A] + V(\mathbf{k}^2; \mathbf{k}\cdot\mathbf{k}_i; \mathbf{k}_j\cdot\mathbf{k}_i)$

2 and 3 body forces operator

Where the free mass operator of the system is: $M_0[1,2,3,\ldots,A] = \sum_i^A \sqrt{m^2 + \mathbf{k}_i^2}$

Momenta in the intrinsic reference frame $\sum_{i=1}^{A} \mathbf{k}_i = 0$

The **commutation rules** impose to V **invariance for translations and rotations** as well as **independence on the total momentum**, as it occurs for V^{NR}

One can assume $M[1,2,\ldots,A] \sim M^{NR}$

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**.

Reference frames

For a correct description of the structure functions, so that the Macro-locality is implemented, it is crucial to distinguish between different frames, moving with respect to each other:

- The Lab frame, where $\tilde{P} = (M, \mathbf{0}_\perp)$
- The intrinsic LF frame of the whole system, $[1,2,\ldots,A]$, where $\tilde{P} = (M_0[1,2,\ldots,A], \mathbf{0}_\perp)$ with $k_i^+ = \xi_i M_0[1,2,\ldots,A]$ and $M_0[1,2,\ldots,A] = \sum_{i=1}^{A} \sqrt{m^2 + \mathbf{k}_i^2}$
- The intrinsic LF frame of the cluster $[1;2,3,\ldots,(A-1)]$ where $\tilde{P} = (\mathcal{M}_0[1;2,3,\ldots,A-1]), \mathbf{0}_\perp)$ with $k^+ = \xi \mathcal{M}_0[1;2,3,\ldots,A-1]$ and $\mathcal{M}_0[1;2,3,\ldots,A-1] = \sqrt{m^2+\kappa^2} + \sqrt{M_s^2+\kappa^2}$

While $\mathbf{p}_\perp^{LAB} = \mathbf{k}_{1\perp} = \kappa_\perp$

$M_s = (A-1)\sqrt{m^2 + m\epsilon}$ is the mass of the spectator system

LF boost

A. Del Dotto, E.Pace, G. Salmè and S.Scopetta , **Phys. Rev. C 95,014001 (2017)**

Since we use an impulse approximation assumption (i.e. the scattering involves only a nucleon described by a plane wave), we have to define the **LF spectral function**: the probability to find a particle with a given $\tilde{\kappa} = (\kappa^+, \kappa_\perp)$ when the rest of the system has energy ϵ with a polarization S

The spectral function is written in terms of the overlap ${}_{LF} < tT; \alpha, \epsilon; JJ_z; \tau\sigma', \tilde{\kappa} | \Psi_{\mathscr{M}}; ST_z >_{LF}$

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:**

$$|\{\alpha\}; \phi >_{LF} \rightarrow |\{\alpha\}; \phi >_{IF} \sim |\{\alpha\}; \phi >_{NR}$$

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**

Hadronic tensor

In our approach the **hadronic tensor** is found to be **(E.Pace, M.Rinaldi, G.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

LF spectral function

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

$$F_2^A(x) = -\frac{1}{2} x g_{\mu\nu} W^{\mu\nu} = \sum_N \sum_\sigma \int d\epsilon \int \frac{d\kappa_\perp}{(2\pi)^3} \frac{d\kappa^+}{2\kappa^+} P^N(\tilde{\kappa}, \epsilon) F_2^N(z)$$

Free nucleon structure function

Where $x = \dfrac{Q^2}{2P_A \cdot q}$ and $\xi = \dfrac{\kappa^+}{\mathscr{M}_0[1; 2,3,\ldots, A-1]} \neq x$ with $z = \dfrac{Q^2}{2p \cdot q} = \dfrac{p}{P_A^+} \dfrac{x}{\xi}$

LC momentum distribution

$$F_2^A(x) = -\frac{1}{2} x g_{\mu\nu} W^{\mu\nu} = \sum_N \sum_\sigma \int d\epsilon \int \frac{d\kappa_\perp}{(2\pi)^3} \frac{d\kappa^+}{2\kappa^+} P^N(\tilde{\kappa}, \epsilon) F_2^N(z)$$

In the Bjorken limit $\int d\epsilon \int d\kappa^+ = \int d\kappa^+ \int d\epsilon$ so we can use the **LC momentum distribution** instead of the **LF spectral function**

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

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

Light-cone momentum distribution

Free nucleon structure function

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

LF momentum distribution:

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

Determinant of the Jacobian matrix. **LF boost: effect of a Poincaré covariance approach**

Squared nuclear wave function. **Thanks to the BT construction, one is allowed to use the NR one**

Convolution formula for the nuclear structure function

To calculate the EMC ratio $R^A_{EMC}(x) = \dfrac{F^A_2(x)}{F^d_2(x)}$ for any nucleus A, we need a **NR realistic wave function** and a **parametrization for the free-nucleon structure functions**

$$F^A_2(x) = \sum_N \int_{\xi_{min}}^1 d\xi \; F^N_2\left(\frac{mx}{\xi M_A}\right) \; f^N_1(\xi)$$

Calculated through 3 different potentials: Av18+UIX and 2 versions of the Norfolk χEFT interactions NVIa+3N and NVIb+3N

We need both F^n_2 and F^p_2

One can choice a parametrization for F^p_2 and a parametrization for the ratio $\dfrac{F^n_2}{F^p_2}$ because F^n_2 could be only extracted by nuclear DIS data. We used a parametrization extracted by MARATHON data.

MARATHON Coll., Phys. Rev. Lett 128 (2022) 13,132003

Since our approach fulfill both **macro-locality** and **Poincaré covariance** the LC momentum distribution must satisfies 2 essential **sum rules**:

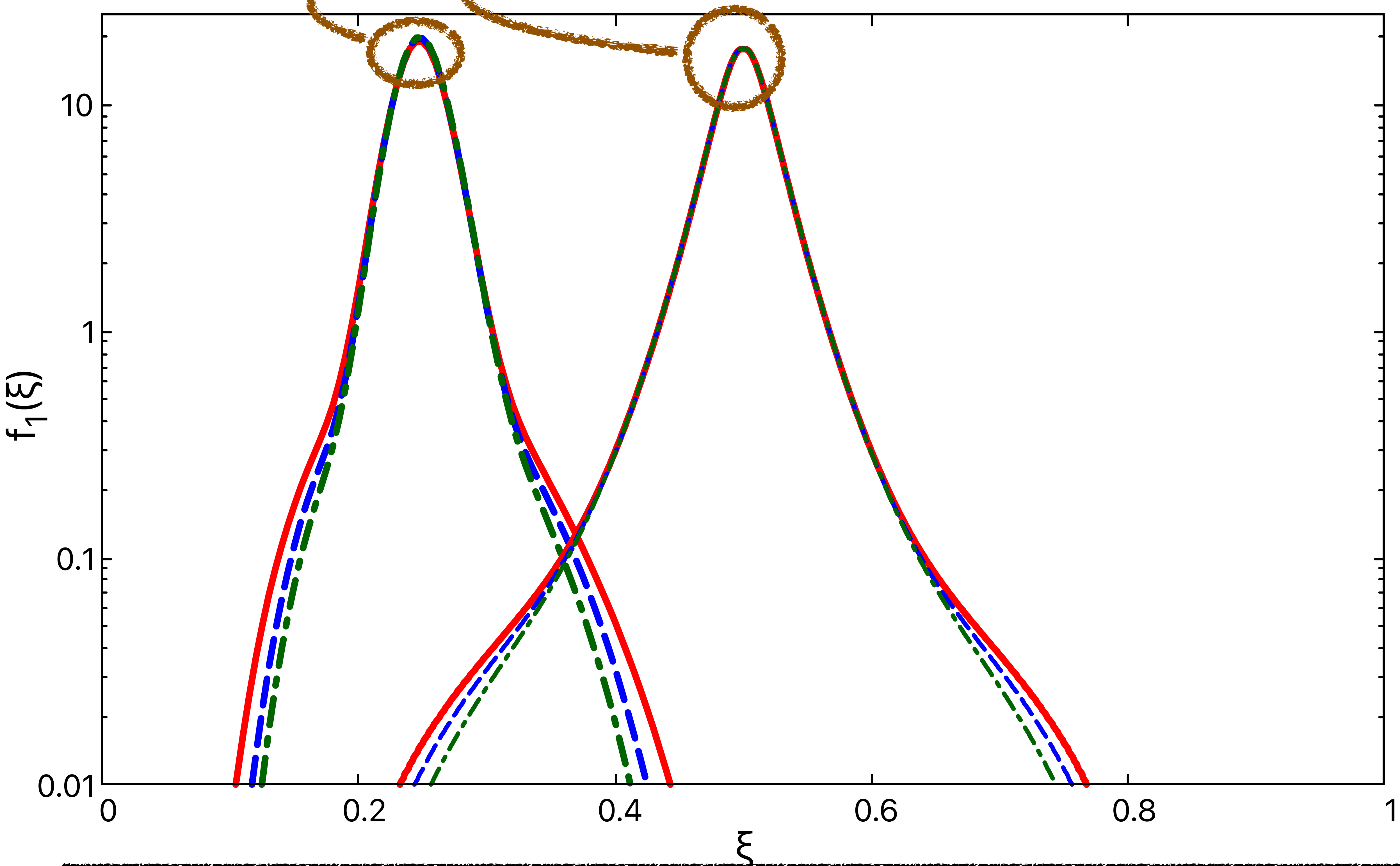
$A = \int_0^1 d\xi [Z f^p_1(\xi) + (A-Z) f^n(\xi)]$: **Baryon number sum rule;**

$1 = Z < \xi >_p + (Z-N) < \xi >_n \; ; < \xi >_N = \int_0^1 d\xi \xi f^N_1(\xi)$: **MSR**

LC momentum distribution: numerical results for ^4He

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

arXiv:2308.15925 [nucl-th]



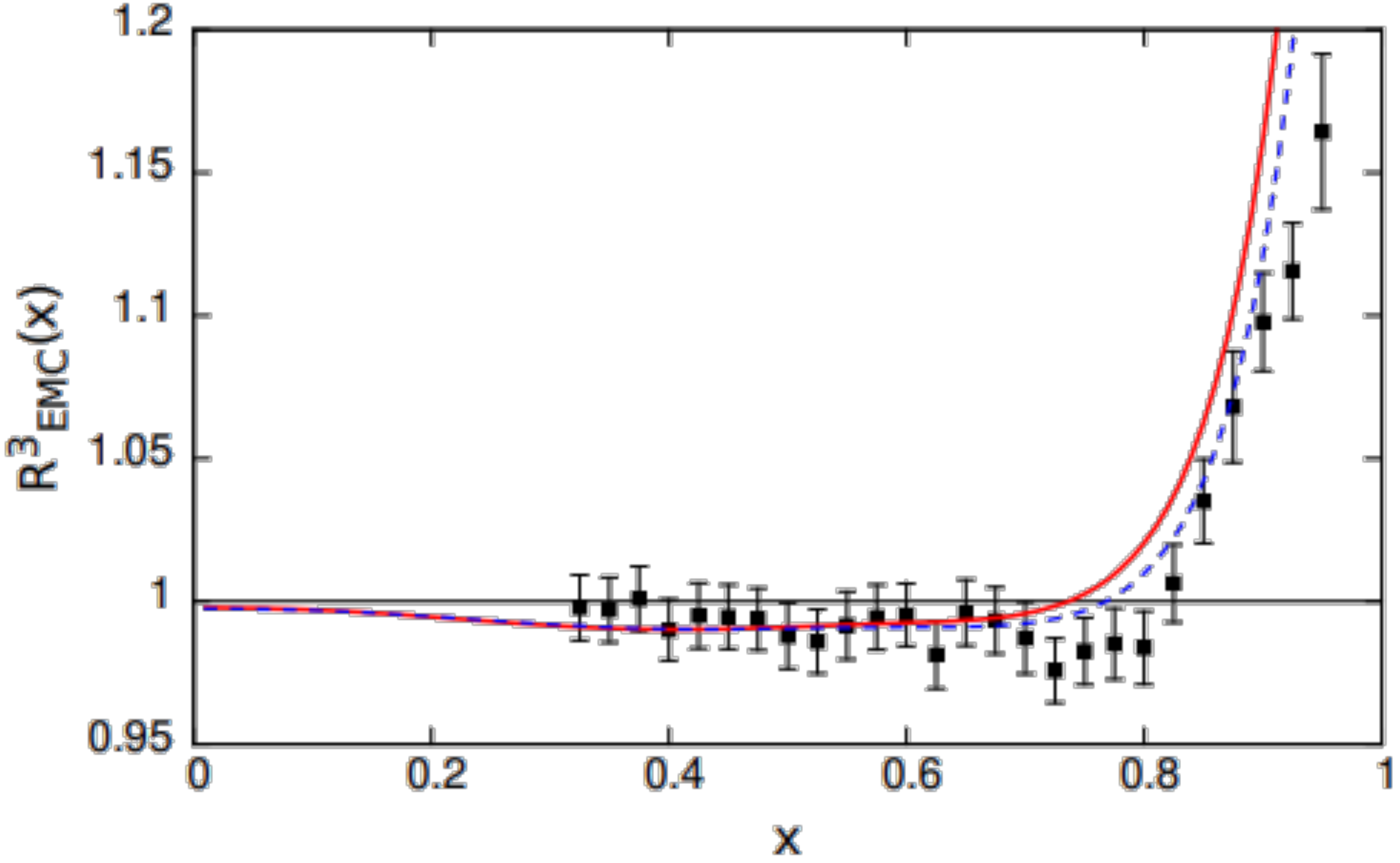
LC momentum distribution for ^4He (peaked in 0.25) and deuteron (peaked in 0.5). Remind that for symmetric nuclei $f_1^n = f_1^p$

Solid lines: Av18/UIX. Dashed lines:NVIb+3N. Dot-dashed lines: NVIa+3N

- 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

The EMC effect:results for ^3He

E.Pace, M.Rinaldi, G.Salmè and S.Scopetta Phys. Lett. B 839(2023) 127810



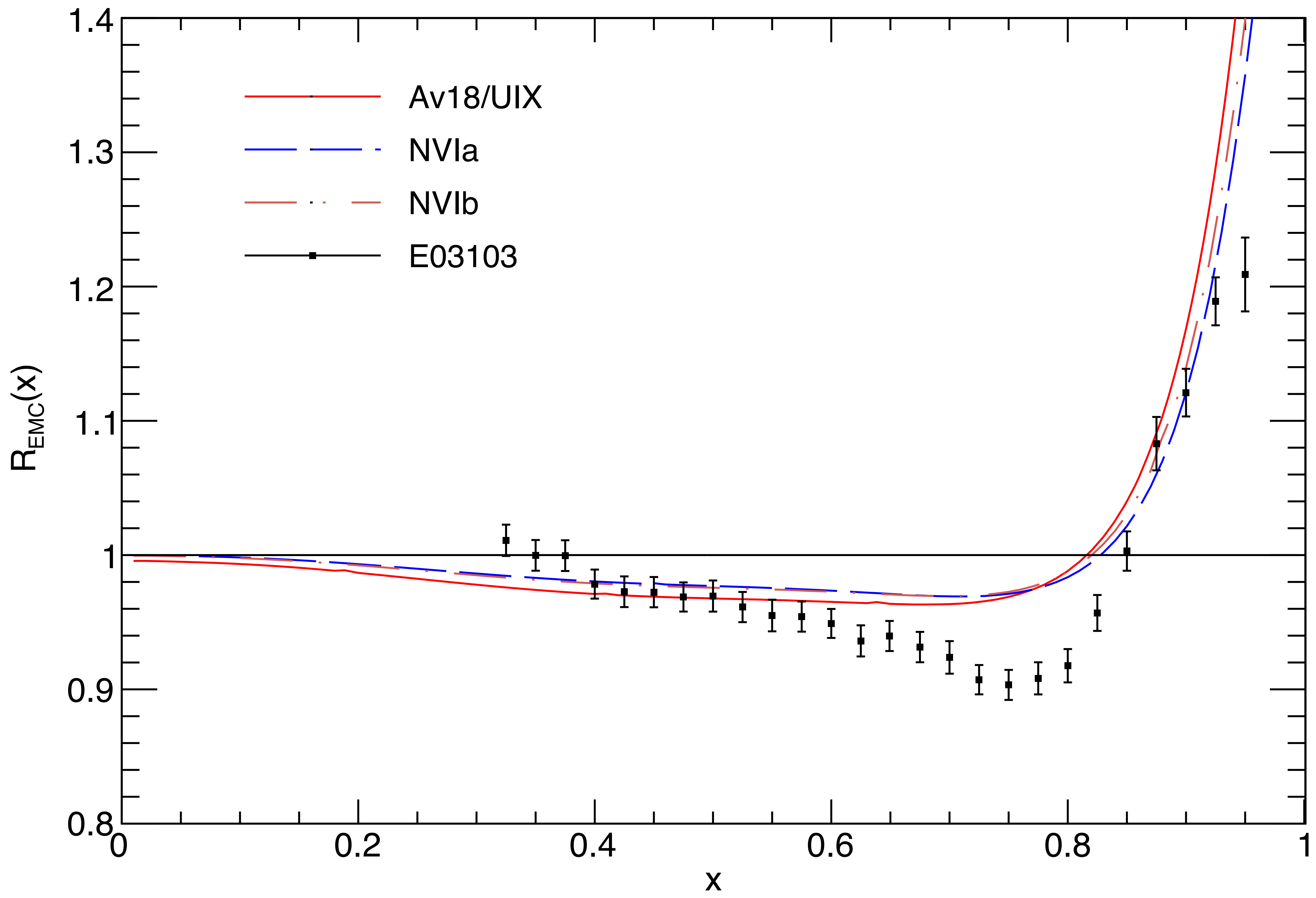
Result: small but solid effect, comparable to the experimental one

Full squares: JLab data from experiment E03103 [J. Arrington, et al, Phys. Rev. C 104 (6) (2021) 065203] **as reanalyzed in** [S. A. Kulagin and R. Petti, Phys. Rev. C 82, 054614 (2010)]

Solid lines: Av18/UIX. Dashed lines:Av18

The EMC effect: numerical results for ^4He

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

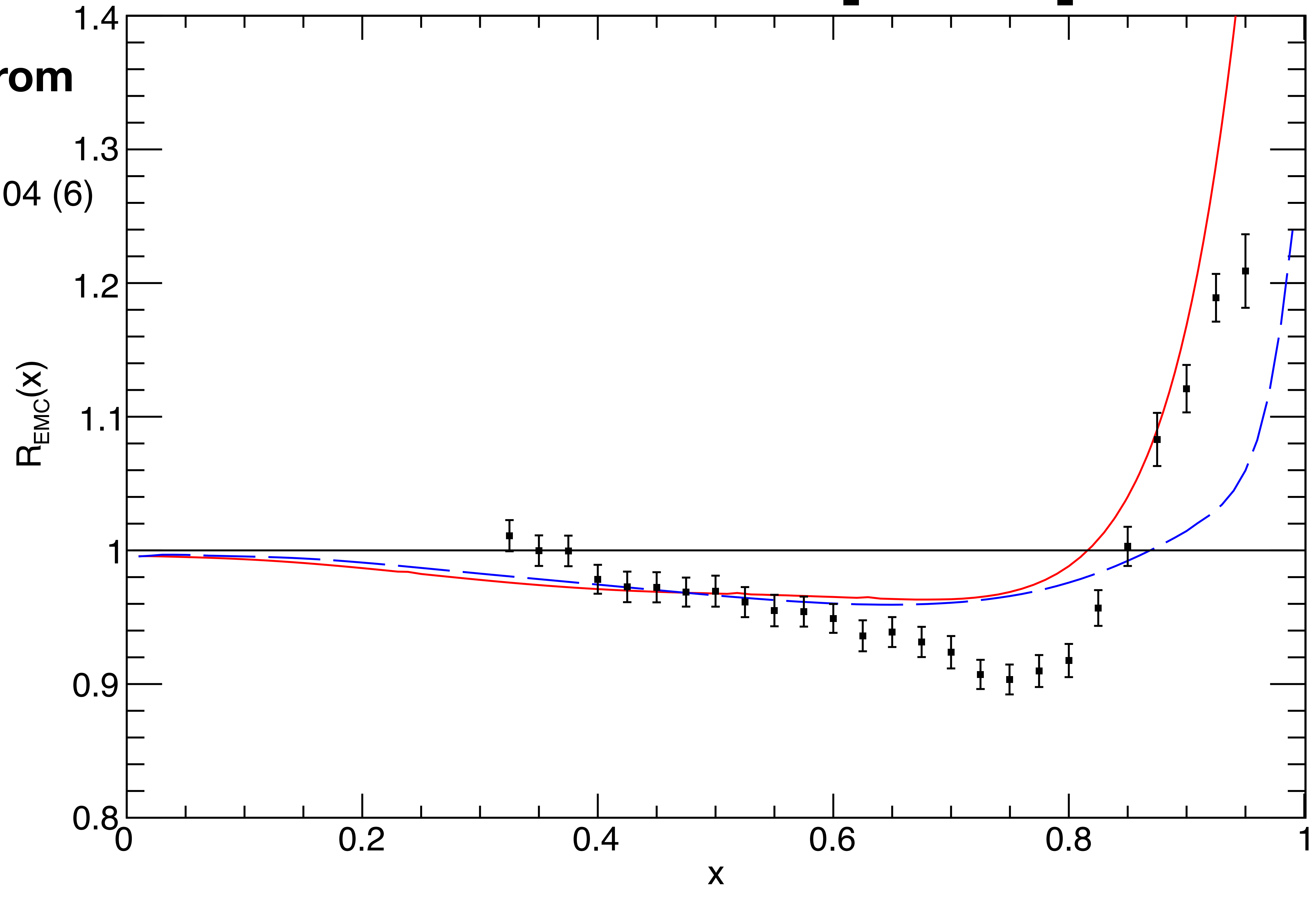
- The differences between the calculations from different potentials are of the **same order for both nuclei**
- They are definitely **smaller than the difference between data and theoretical prediction**

The EMC effect: numerical results for ^4He

Full squares: JLab data from experiment E03103

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

arXiv:2308.15925 [nucl-th]



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

Conclusions

- The results increase confidence in our **light-front approach**, which includes **only the nucleonic dof**
- The difference between the R_{EMC} generated by different **realistic nuclear potentials** is relatively **smaller than the EMC effect itself**
- The deviations from experimental data could be ascribed to **genuine QCD effects**
- Our results could provide a **reliable baseline to study exotic phenomena involving partonic dofs**

In preparation

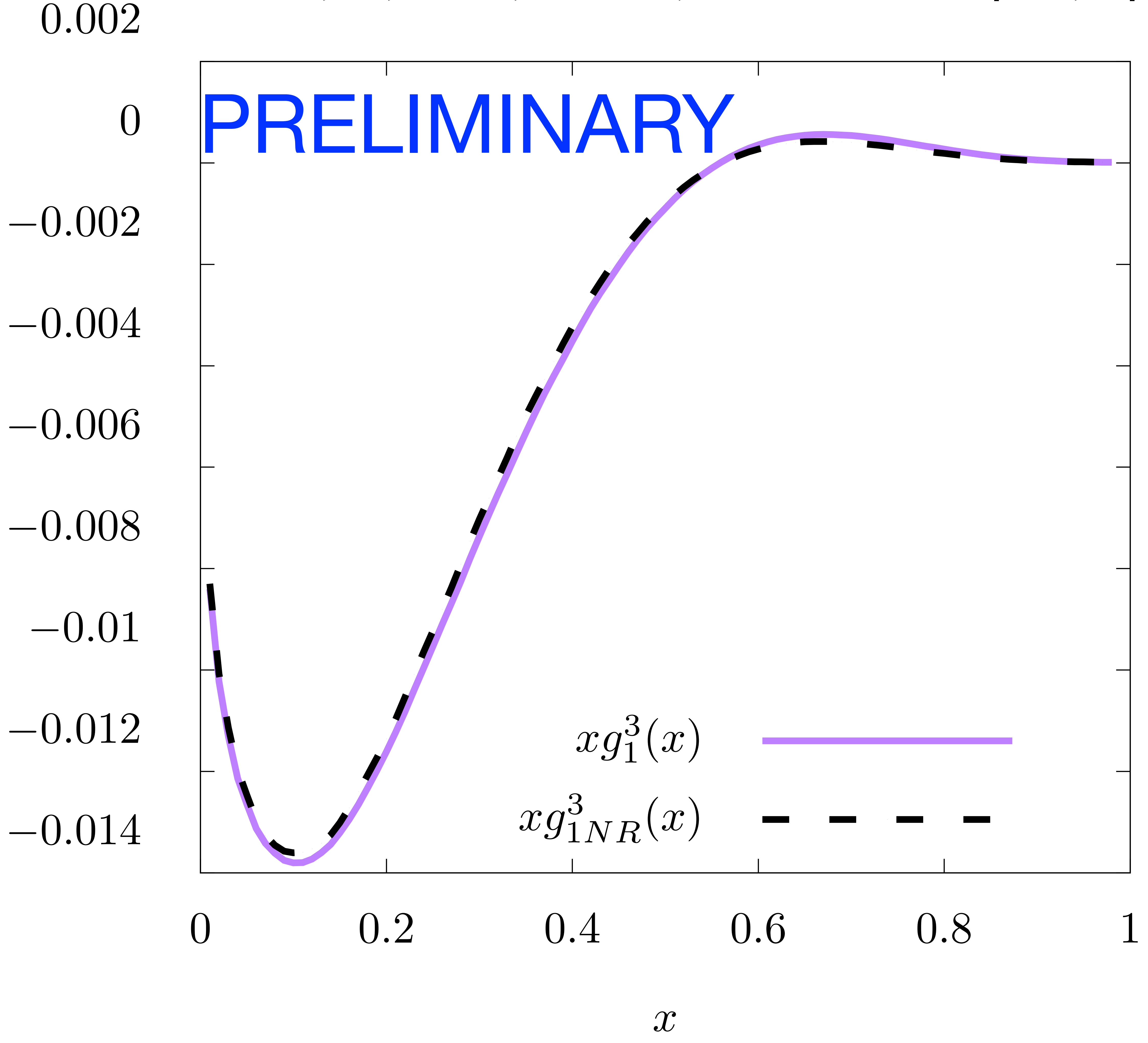
- **Spin-dependent** structure functions for ^{3}He

To do next:

- Include **off-shell** corrections to our approach
- Repeat the calculation of the EMC-effect for **heavier nuclei**

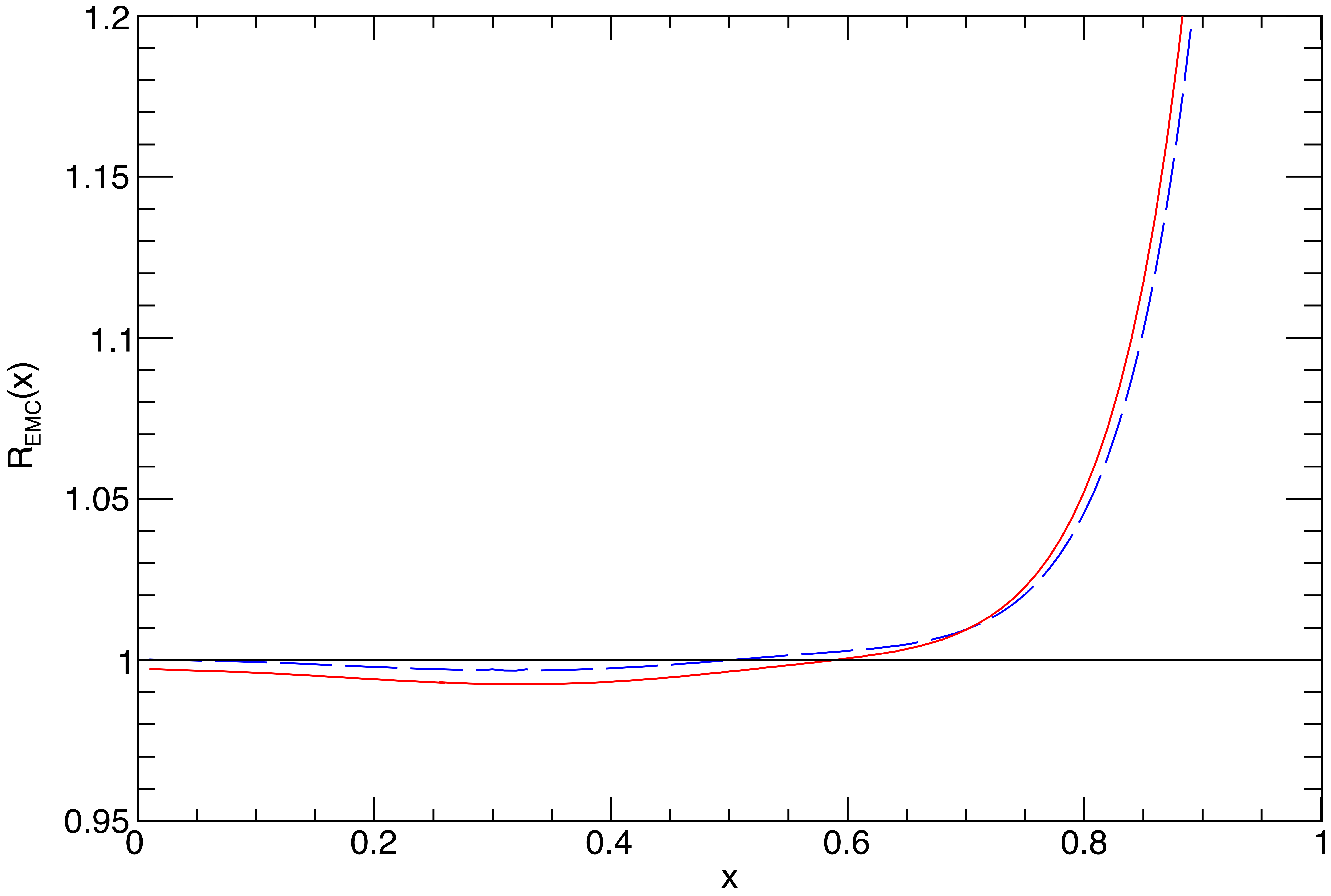
Polarized Structure Functions for ^3He

E.Proietti, F.F., E.Pace, M.Rinaldi, G.Salmè and S.Scopetta, in preparation



Comparison between the spin-dependent structure function of ^3He $g_1^3(x)$ obtained by a NR approach (dashed-line) in **[C.Ciofi degli Atti, S.Scopetta, E.Pace, G.Salme, Phys.Rev.C48:968-972(1993)]** and RHD approach (solid line)

Tritium EMC effect



Results similar to ^3He and ^4He

No experimental data

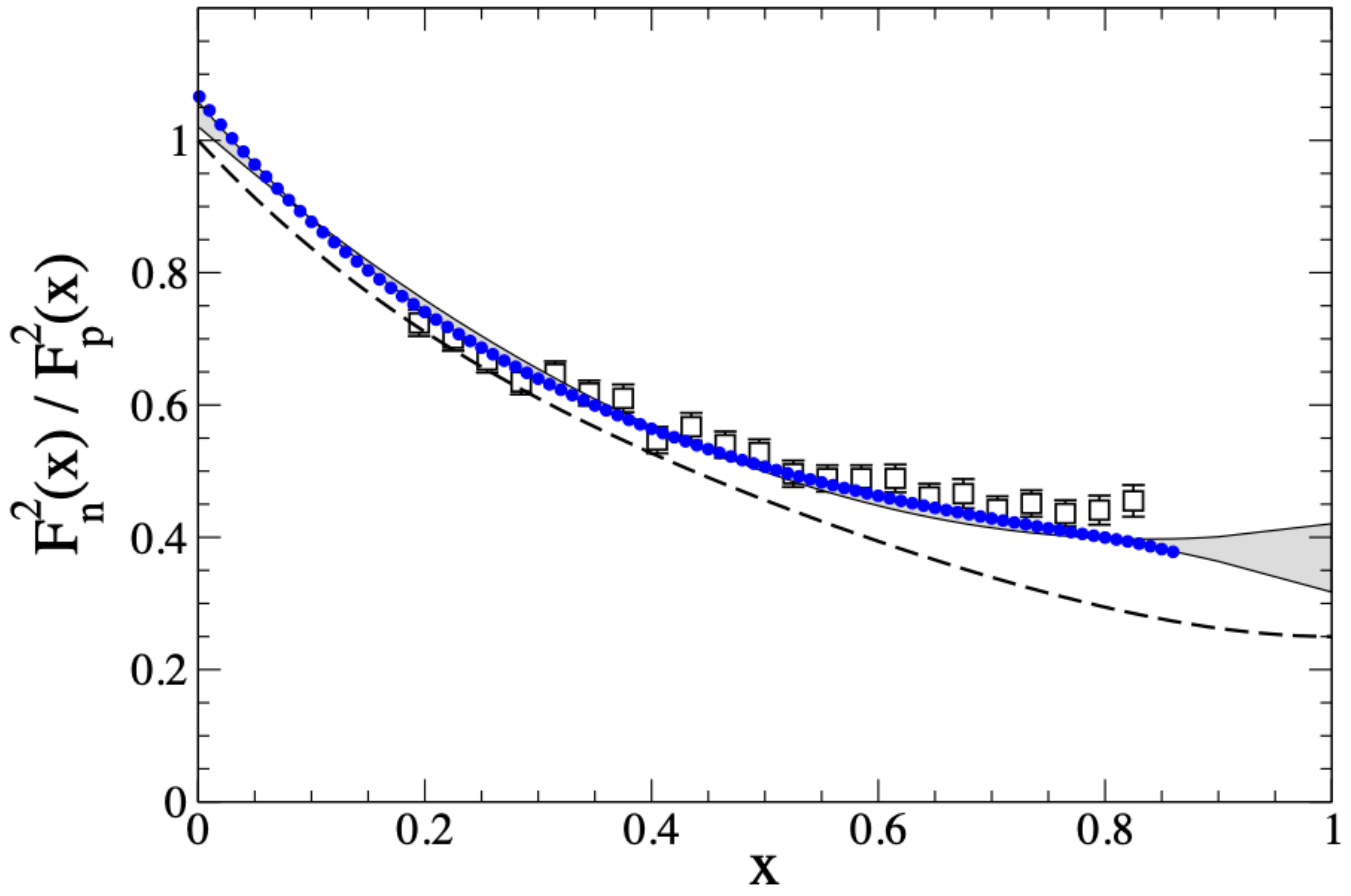
Solid line: Av18/UIX; Dashed-line: NVIb/UIX

Extraction of F_2^n/F_2^p via MARATHON data

MARATHON coll. : experimental data of the super-ratio $R^{ht}(x) = F_2^{3He}(x)/F_2^{3H}(x)$

^3He: 2p + n; ^3H: n + 2p

Is possible to extract the ratio $F_2^n(x)/F_2^p(x)$ through the super-ratio



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Dashed line: ratio from SMC collaboration
Empty squares: MARATHON extraction
Solid line: cubic and conic extractions from F_2^p SMC parametrization, fitted to MARATHON data

NR potentials

2-body case (equal mass):

$$M^2 |\psi> = s |\psi>$$

$$[4(m^2 + k^2) + U] |\psi> = s |\psi>$$

$$[\frac{k^2}{4m} + \frac{U}{4m}] |\psi> = \frac{s - 4m^2}{4m} |\psi>$$

For the states of the continuum spectrum $\frac{s - 4m^2}{2m} = T_{Lab}$, i.e. the asymptotic kinetic energy in the Lab frame when the particle 1 is at rest

The phase shifts are a given as a function of T_{Lab}

NN interaction extracted from the experimental phase shifts via the Lippmann-Schwinger equation