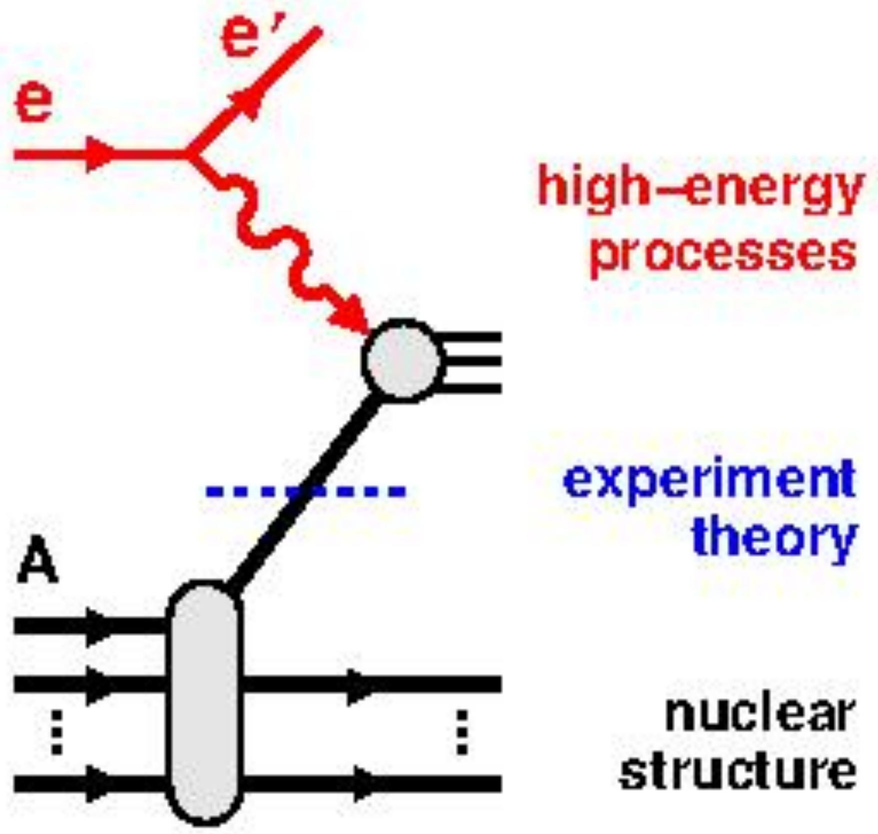
Nuclear structure functions within the light-front Hamiltonian dynamics

Filippo Fornetti (Università degli Studi di Perugia, INFN, Sezione di Perugia)

"Light-ion physics in the EIC era: From nuclear structure to high-energy processes"



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R.Alessandro, A.Del Dotto, E.Pace, G.Perna, G.Salmè and S.Scopetta
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Overview

- **Light-front formalism** for the unpolarized **Deep Inelastic Scattering (DIS) applied to the** ^3He**:** sizable **European Muon Collaboration (EMC) effect** predicted **[1]**

- Formalism **extended to any nucleus** and applied to ^4He and ^3H **[2]**

  - ^4He is a tightly bound nucleus ⇒ **Challenging** test to our approach

- The formalism is generalized for the **polarized DIS [3]** for the ^3He

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

[2] F.F, E.Pace, M.Rinaldi, G.Salmè, S.Scopetta and M.Viviani**, *Phys.Lett.B* 851 (2024) 138587**

[3] E.Proietti, F.F, E.Pace, M.Rinaldi, G.Salmè and S.Scopetta, ***Phys.Rev.C* 110 (2024) 3, L031303**

The EMC effect

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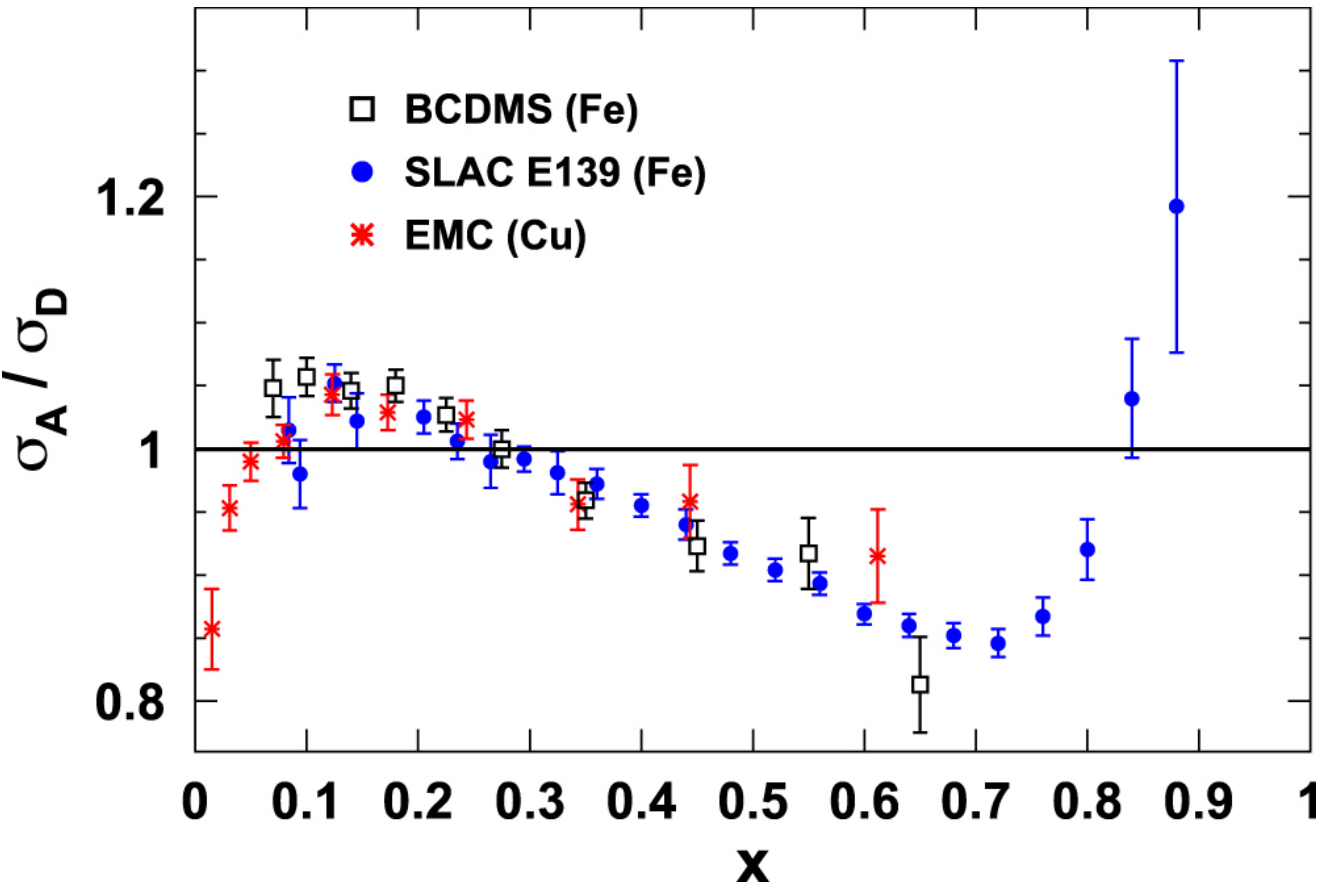

$$R_{EMC}(x) = \frac{2\sigma_A}{A\sigma_D} = \frac{2F_2^A(x)}{AF_2^d(x)} < 1$$

Naive parton model interpretation:

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

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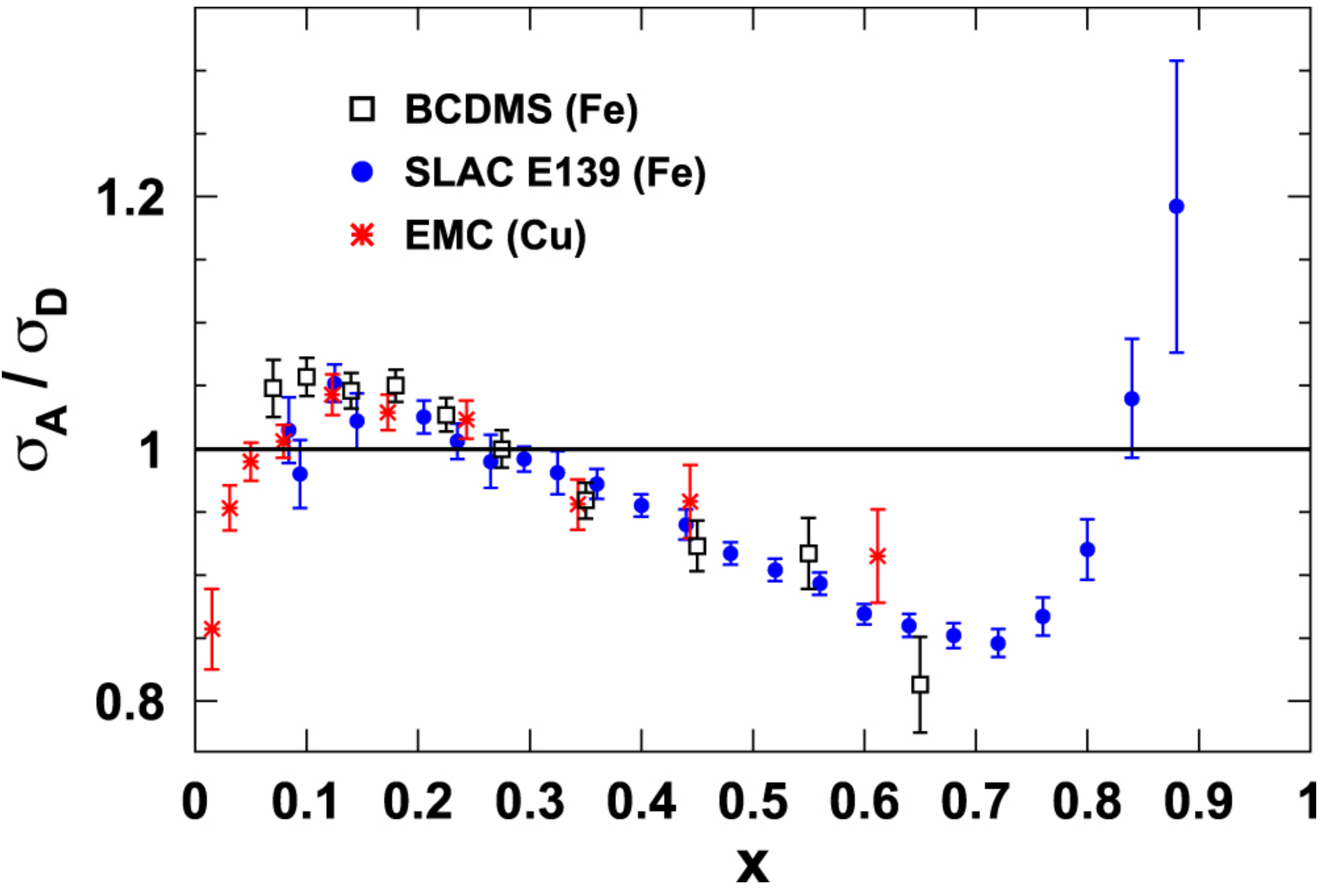

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Our approach is aimed to include **only nucleonic dof** through **conventional nuclear physics** in a **Poincaré-covariant** approach that preserves the **macroscopic locality**. The only way to **fulfill sum rules** while using **realistic NR nuclear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

The relativistic Hamiltonian dynamics framework

Our definitely preferred framework for embedding the successful **NR phenomenology:**

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

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LF Advantages

- **7 Kinematical generators**
- The **LF boosts** have a subgroup structure
- $P^+ \geq 0 \rightarrow$ **meaningful Fock expansion**
- The **infinite-monentum frame (IMF)** description of DIS is easily included

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Drawback: the transverse 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

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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**:

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i) Only the **mass operator** M contains the interaction:

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

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

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The **commutation rules** impose constraints to V fulfilled by phenomenological potentials V^{NR}, so ne can assume $M_{BT}[1,2,\ldots,A] \sim M^{NR}$

LF spectral function

With the **impulse approximation** assumption, we have to define the **spin-dependent LF spectral function** $P^{\tau}_{\sigma'\sigma}(\tilde{\kappa}, \epsilon, \mathbf{S}, M)$ to calculate the hadronic tensor $W^{\mu\nu}$

$$P^{N}_{\sigma'\sigma}(\tilde{\kappa}, \epsilon, \mathbf{S}, M) = \sum_{JJ_z} \sum_{TT_z} \rho(\epsilon)_{LF} < tT; \alpha, \epsilon; JJ_z; \tau\sigma', \tilde{\kappa} \,|\, \Psi_{JM}; \mathbf{S}, T_A T_{Az} > < \Psi_{JM}; \mathbf{S}, T_A T_{Az} \,|\,_{LF} tT; \alpha, \epsilon; JJ_z; \tau\sigma, \tilde{\kappa} >_{LF}$$

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*B.D.Keister and W.N.Polyzou, **Adv.Nucl.Phys. 20 (1991), 225-479**

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The **LF spectral function** contains the **effect** of the **LF boost connecting the intrinsic frames** $[1; 2,3, \ldots, A-1]$ and $[1,2, \ldots, A]$

*B.D.Keister and W.N.Polyzou, **Adv.Nucl.Phys. 20 (1991), 225-479**

LF spectral function

We can express the **LF overlap** in terms of the **IF overlap** using **Melosh rotations:**

$$< tT;\alpha,\epsilon;JJ_z;\tau\sigma',\tilde{\kappa}\,|\,\Psi_{JM};\mathbf{S},T_AT_{Az}>_{LF} \rightarrow \; < tT;\alpha,\epsilon;JJ_z;\tau\sigma'_c,\kappa\,|\,\Psi_{JM};\mathbf{S},T_AT_{Az}>_{IF}$$

Then we can approximate the **IF overlap** into a **NR overlap** by using the NR wave function for the nucleus, thanks to the **BT construction:**

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Poincarè covariance preserved but using the **successful NR phenomenology**

We used wave functions of $^2H, ^3H, ^3He, ^4He$ calculated through 3 different potentials: **Av18+UIX*** and 2 versions of the **Norfolk χEFT interactions NVIa+3N**** and **NVIb+3N****

*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**

Hadronic tensor

In our approach the **symmetric part** of the **hadronic tensor** is found to be *

$$W_A^{s,\mu\nu} = \sum_N \sum_\sigma \sum\!\!\!\!\!\!\int d\epsilon \int \frac{d\kappa_\perp d\kappa^+}{2(2\pi)^3\kappa^+} \frac{1}{\xi} P^N(\tilde{\kappa},\epsilon)\, w_{N,\sigma}^{s,\mu\nu}(p,q)$$

hadronic tensor of the nucleon

Unpolarized LF spectral function:

$$P^N(\tilde{\kappa},\epsilon) = \frac{1}{2j+1}\sum_{\mathcal{M}} P^N_{\sigma\sigma}(\tilde{\kappa},\epsilon,\mathbf{S},\mathcal{M})$$

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

* E.Pace, M.Rinaldi, G.Salmè and S. Scopetta, **Phys. Scr. 95, 064008 (2020)**

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$W_A^{s,\mu\nu}$ is parametrized by the SFs $F_2^A(x)$ and $F_1^A(x)$:

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

Free nucleon SF

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LC momentum distribution

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In the Bjorken limit $\int d\epsilon \int d\kappa^+ = \int d\kappa^+ \int d\epsilon$ so we can use the **light-cone momentum distribution** (LCMD) instead of the **LF spectral function** *

$$\textbf{LCMD}: f_1^N(\xi) = \sum \int d\epsilon \int \frac{d\kappa_\perp}{(2\pi)^3} \frac{1}{2\kappa^+} P^N(\tilde{\kappa}, \epsilon) \frac{E_s}{1-\xi} = \int d\mathbf{k}_\perp n^n(\xi, \mathbf{k}_\perp)$$

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LF momentum distribution:

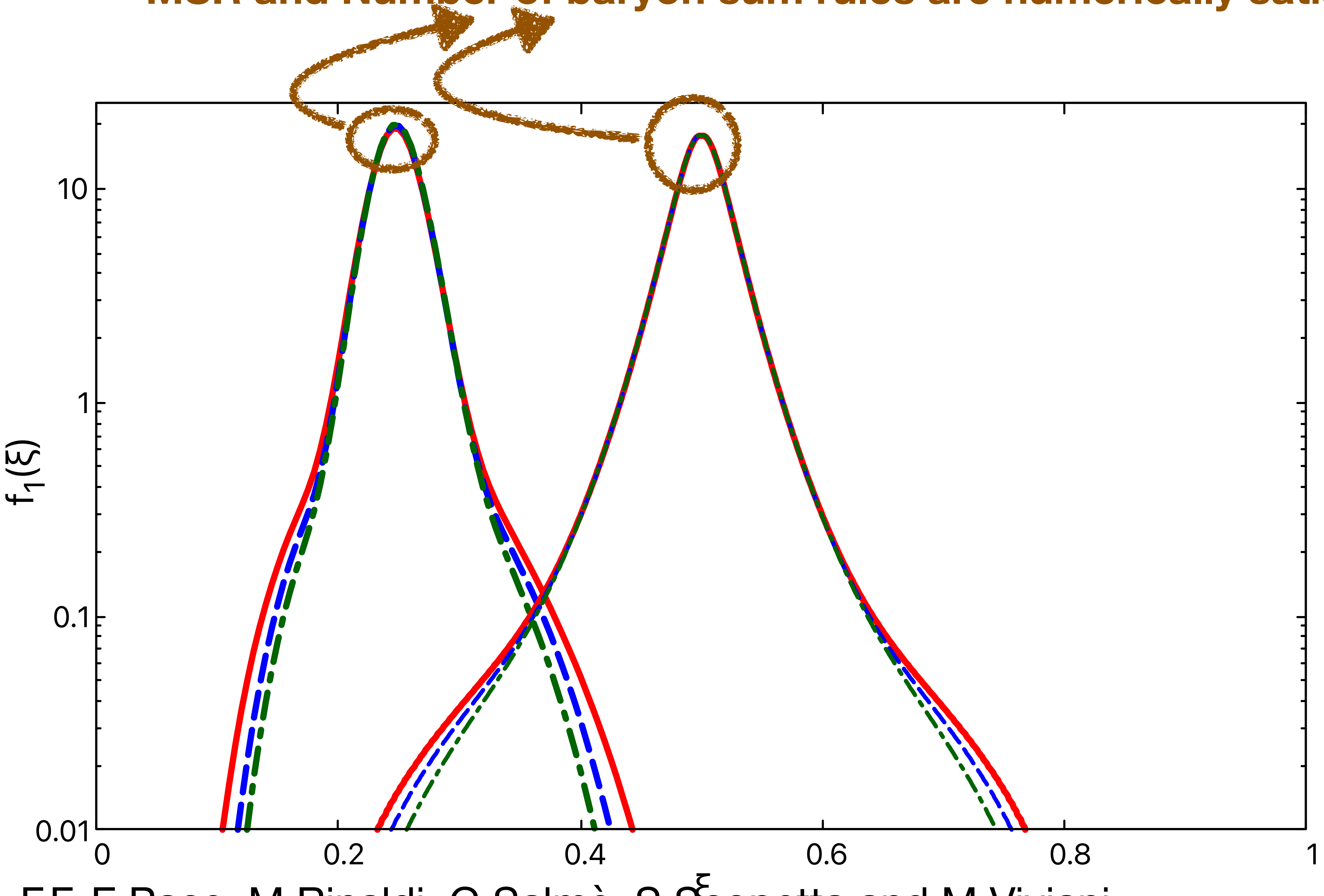
$$n^N(\xi, \mathbf{k}_\perp) = \frac{1}{2\pi} \int \prod_{i=2}^{A-1} [d\mathbf{k}_i] \quad \left| \frac{\partial k_z}{\partial \xi} \right| \quad \mathcal{N}^N(\mathbf{k}, \mathbf{k}_2, \ldots, \mathbf{k}_{A-1})$$

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

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

LC momentum distribution: numerical results for ^{4}He

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



F.F, E.Pace, M.Rinaldi, G.Salmè, S.Scopetta and M.Viviani, ***Phys.Lett.B*** **851 (2024) 138587**

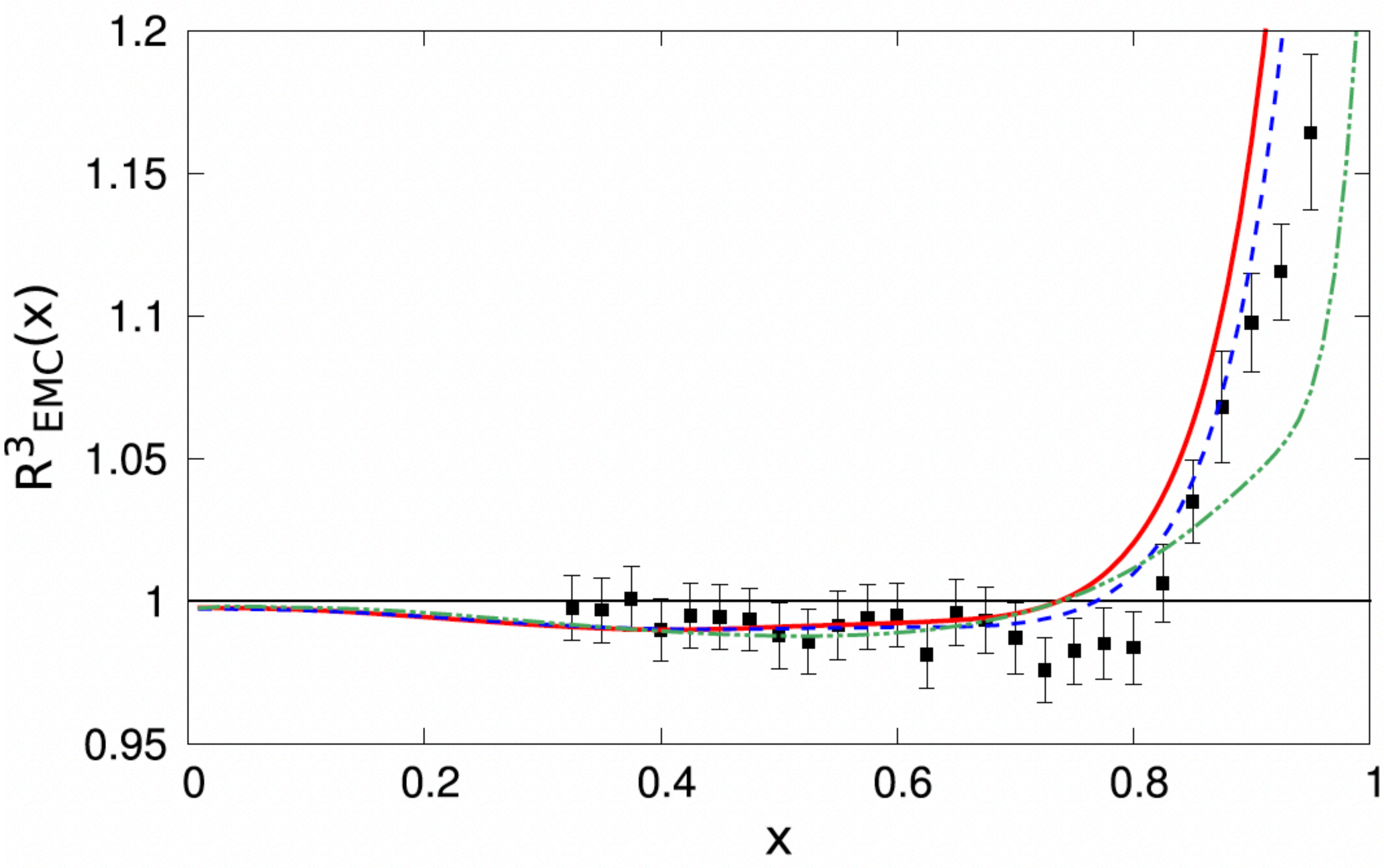
Solid lines: Av18/UIX. Dashed lines:NVIb+3N. Dot-dashed lines: NVIa+3N

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)

Since our approach fulfill both **macro-locality** and **Poincaré covariance** the LCMD satisfy both baryon and momentum SR

The EMC effect:results for ^3He

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



Solid line: Av18/UIX + SMC*
Dashed line:Av18 + SMC*
Dotted-dashed: Av18/UIX +CJ15**

[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]**

Full squares: JLab data from experiment E03103 [1] **as reanalyzed in** [2]

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

[2] S. A. Kulagin and R. Petti, **Phys. Rev. C 82, 054614 (2010)**

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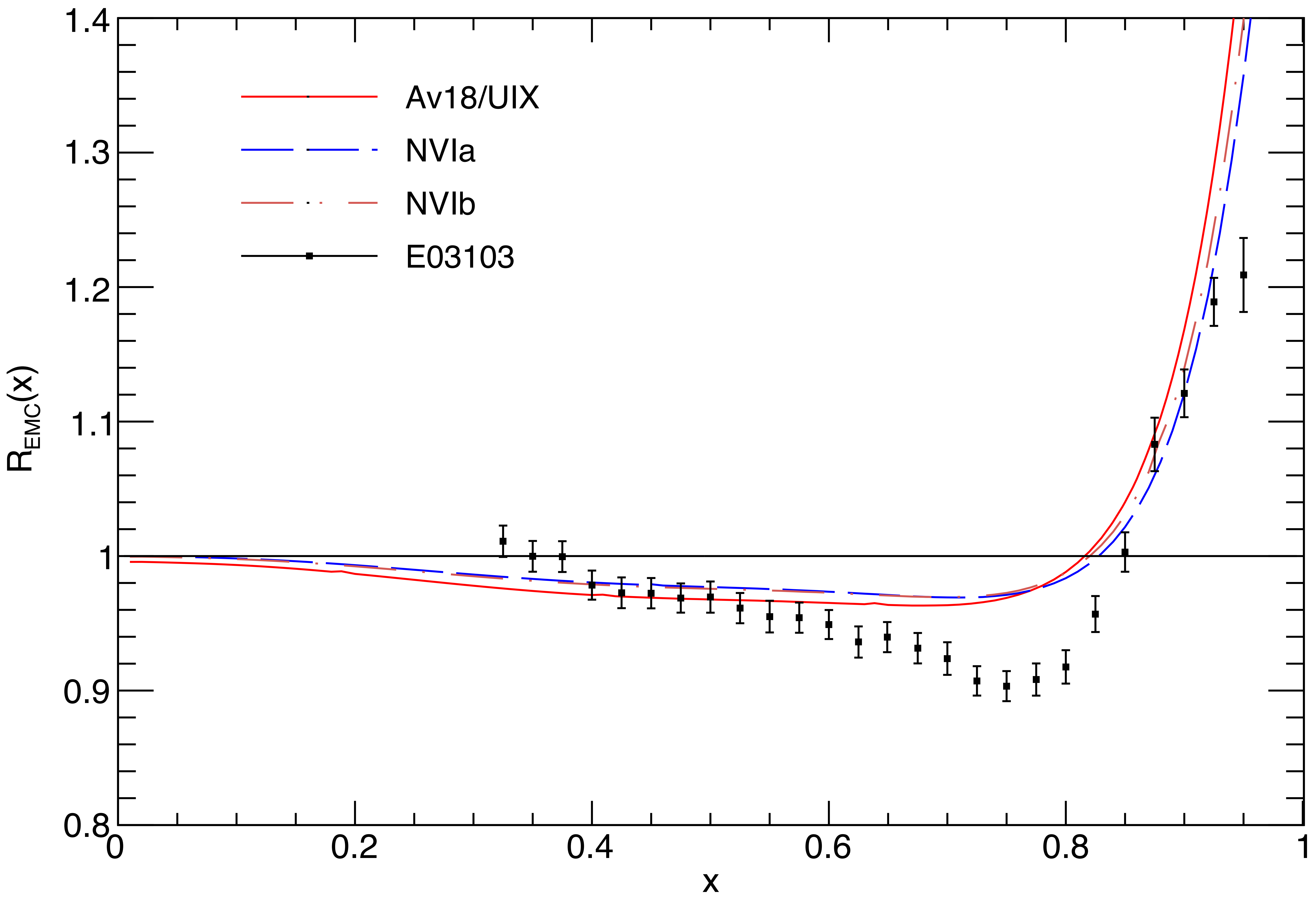

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Hadronic tensor II

For the **polarized DIS** we need to calculate the **antysimmetric** part of the **hadronic tensor**:

$$W_A^{a,\mu\nu} = \sum_N \sum_\sigma \oint d\epsilon \int \frac{d\kappa d\kappa^+}{2(2\pi)^3\kappa^+} \frac{1}{\xi} P_\sigma^N(\tilde{\kappa}, \epsilon, \mathbf{S}, \mathcal{M}) \; w_{N,\sigma}^{a,\mu\nu}(p, q)$$

hadronic tensor of the nucleon

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$W_A^{a,\mu\nu}$ is parametrized by the the **spin-dependent SFs (SSFs)** $g_1^A(x, Q^2)$ and $g_2^A(x, Q^2)$

$$g_j^A(x) = \sum_N \int_{\xi_m}^{1} d\xi \left[g_1^N(z) l_j^N(\xi) + g_2^N(z) h_j^N(\xi) \right], j = 1,2$$

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Spin-dependent LF spectral function

$W_A^{a,\mu\nu}$ is parametrized by the the **spin-dependent SFs (SSFs)** $g_1^A(x, Q^2)$ and $g_2^A(x, Q^2)$

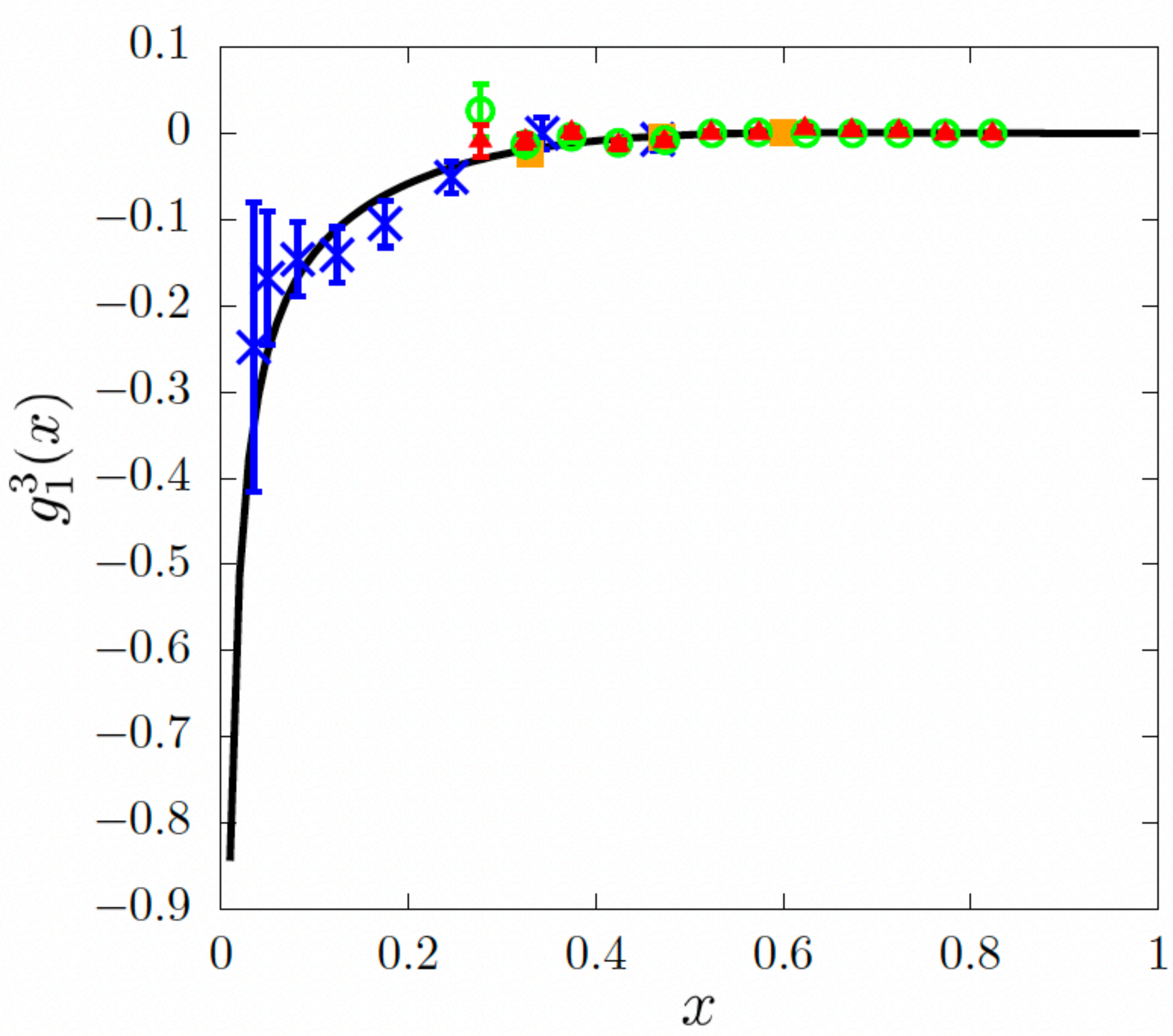
$$g_j^A(x) = \sum_N \int_{\xi_m}^1 d\xi \left[g_1^N(z) l_j^N(\xi) + g_2^N(z) h_j^N(\xi) \right], j = 1,2$$

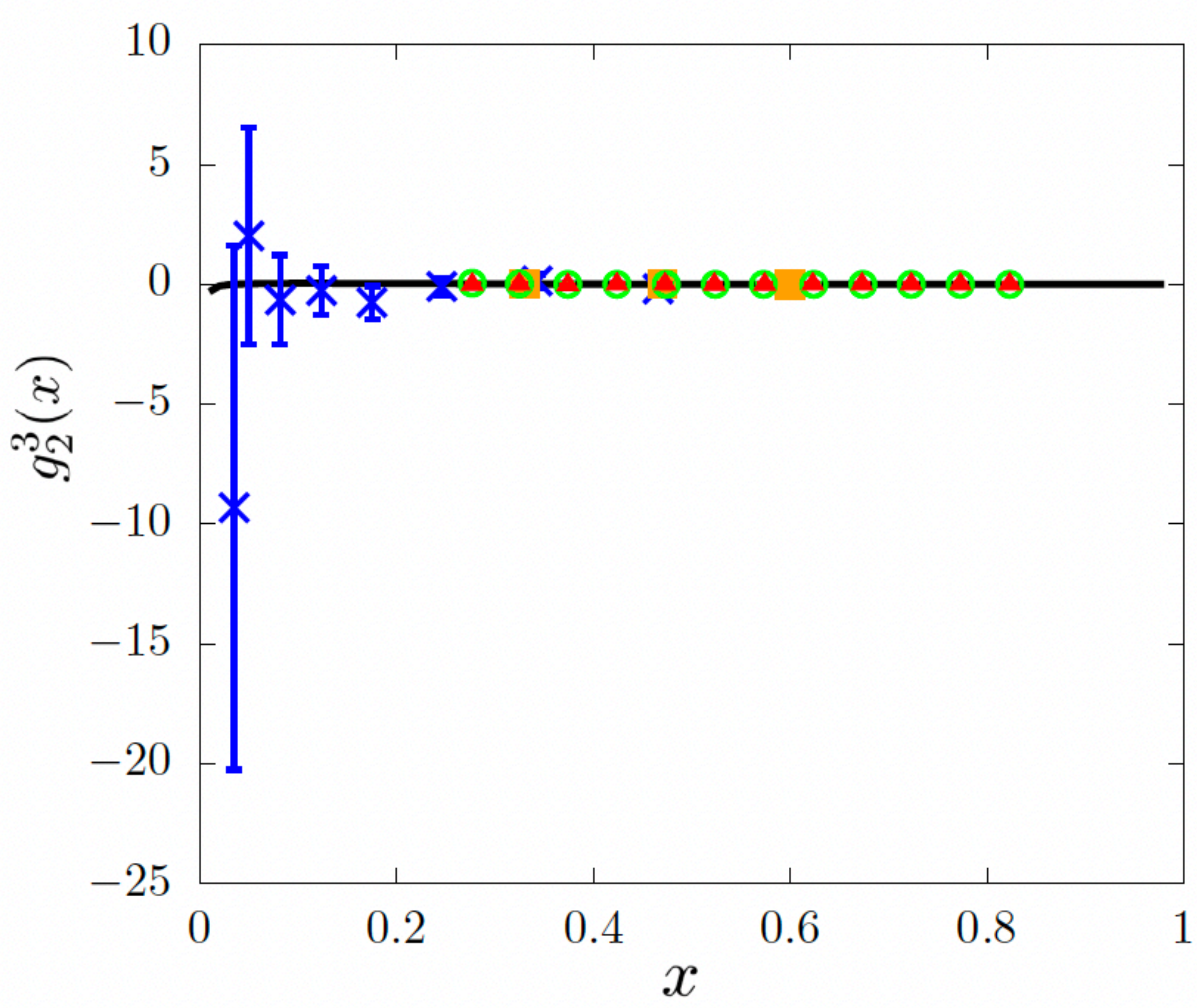
The spin-dependent **LCMD** $l_j^N(\xi)$ and $h_j^N(\xi)$ are related to the **transverse momentum-dependent distributions (TMDs)** of the nucleons $\Delta f^N, g_{1T}^N, \Delta_T' f^N, h_{1L}^N, h_{1T}^N$ calculated for ^3He with the **Av18** potential in Ref. **[1]**

[1] R.Alessandro, A.Del Dotto, E.Pace, G.Perna, G.Salmè and S.Scopetta, **Phys.Rev.C 104(2021) 6,065204**

^3He SSFs

E.Proietti, F.F, E.Pace, M.Rinaldi, G.Salmè and S.Scopetta, ***Phys.Rev.C* 110 (2024) 3, L031303**





Experimental data from **[1] (crosses)**, **[2] (squares)** and **[3] (triangles)**

[1] P. L. Anthony et al., **Phys. Rev. D 54, 6620 (1996)** [2] X. Zheng et al.,**Phys. Rev. Lett. 92, 012004 (2004)**

[3] D. Flay et al., **Phys. Rev. D 94, 052003 (2016)**

Conclusions

- **Rigorous formalism** for the calculation of **nuclear SFs and SSFs** involving only **nucleonic DOF** with the conventional nuclear physics developed

- For ^3He we obtain results in **agreement** with **experimental data** for both **EMC effect** and **SSFs.** Useful analysis for **planned experiments** in future facilities

- For ^4He the deviations from experimental data could be ascribed to **genuine QCD effects: our results provide** a **reliable baseline to study exotic phenomena**

To do next:

- Include **off-shell** corrections to our calculations

- Study the Q^2 dependence

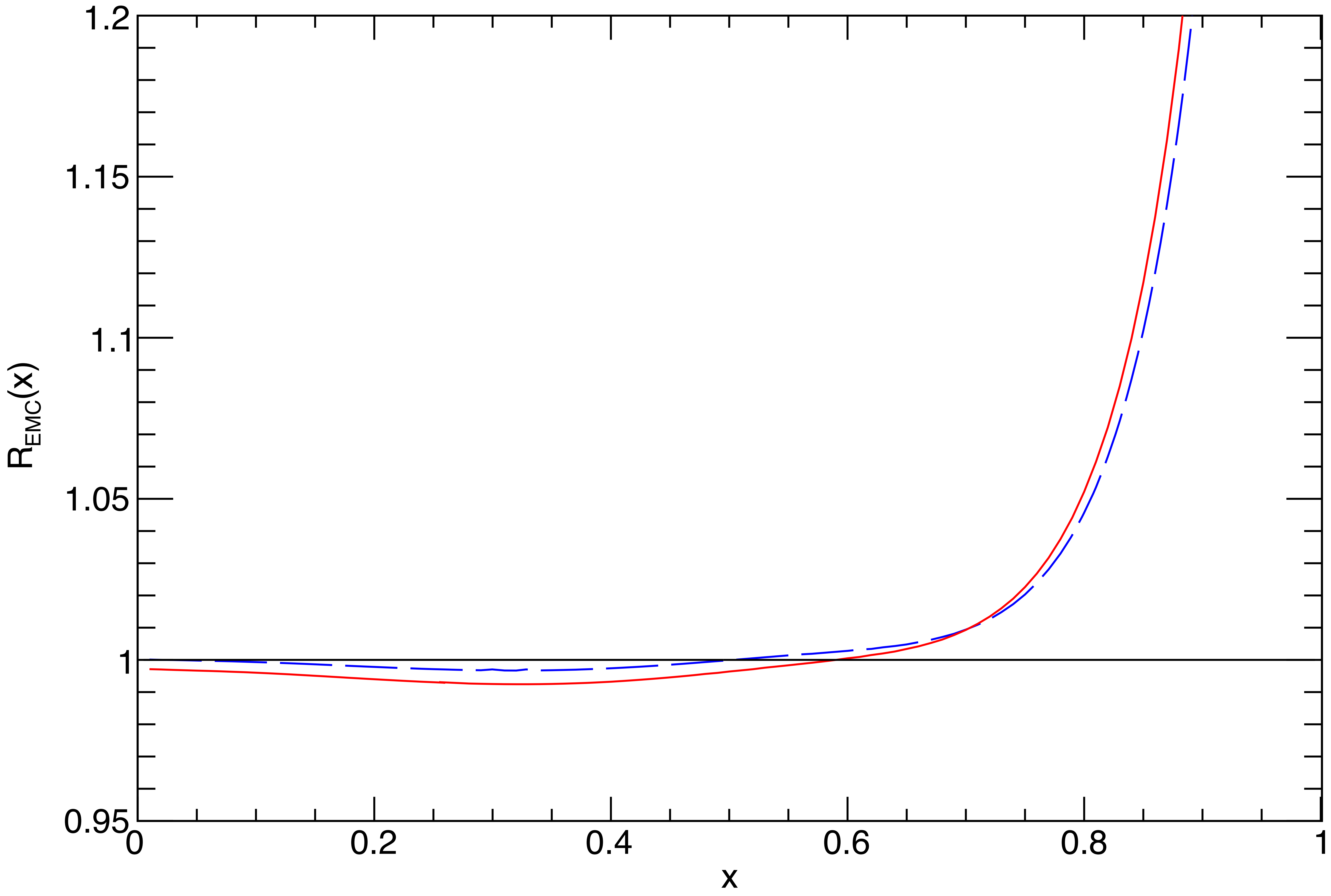
- Calculate the EMC effect for **heavier nuclei**

In preparation:

- With the s**ame approach** we are developing a new formalism for the calculation of the **nuclear Double Parton Distributions (DPDs)** for **light nuclei***

* A.Ceccopieri, F.F., N.Iles, E.Pace, M.Rinaldi and G. Salmè, **in preparation**

Tritium EMC effect



Results similar to ^3He and ^4He

No experimental data

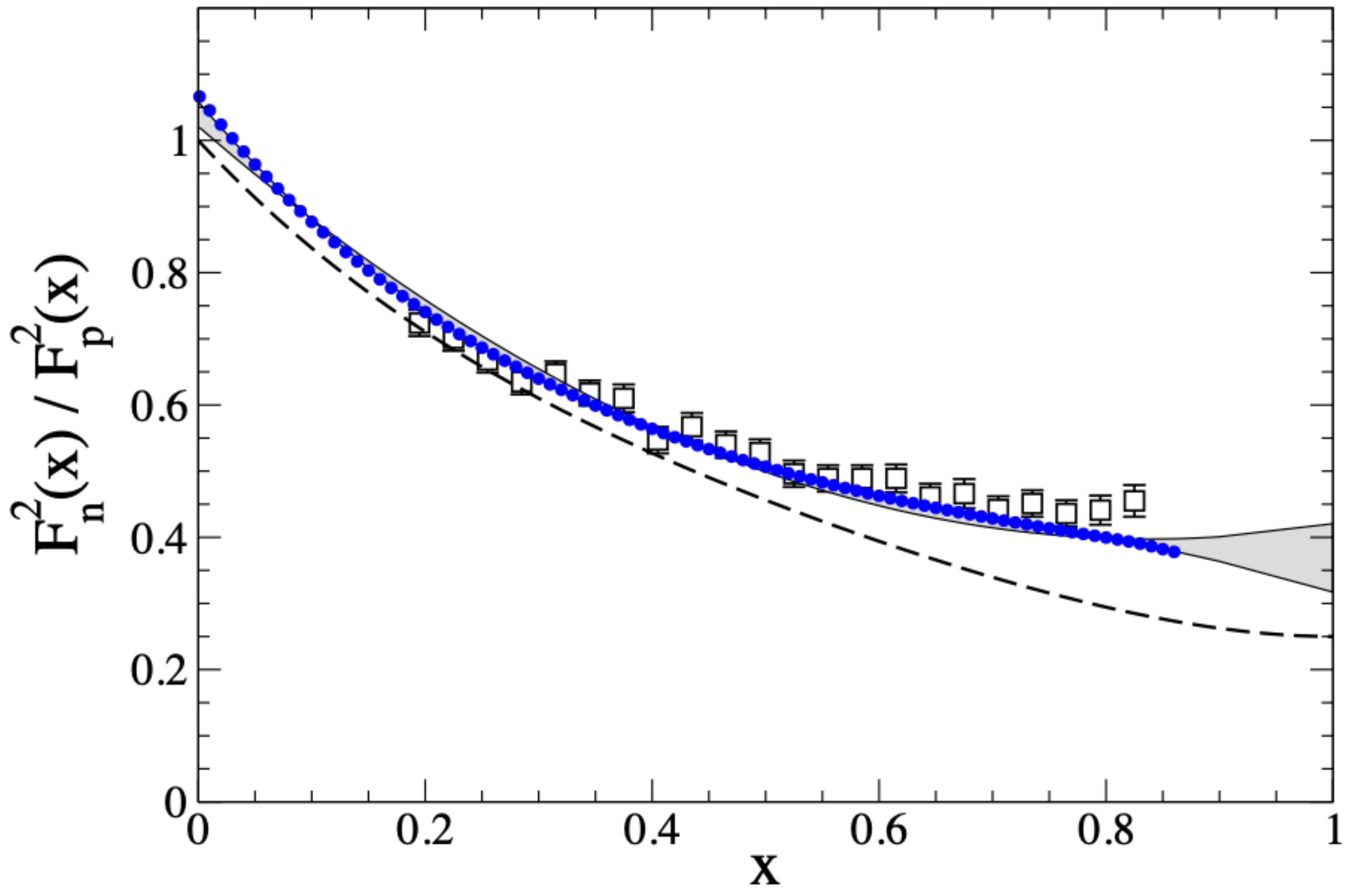
Solid line: Av18/UIX; Dashed-line: NVIb/UIX

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



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

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

Canonical and LF spin

- In Instant form (initial hyperplane t=0), one can couple spins and orbital angular momenta via Clebsch-Gordan (CG) coefficients. In this form the three rotation generators are independent of the the interaction.

- To embed the CG machinery in the LFHD one needs unitary operators, the so-called Melosh rotations that relate the LF spin wave function and the canonical one. For a particle of spin (1/2) with LF momentum

$$\tilde{\mathbf{k}} \equiv \{k^+, \vec{k}_\perp\}$$

$$|\mathbf{k}; \frac{1}{2}, \sigma\rangle_c = \sum_{\sigma'} \underbrace{D^{1/2}_{\sigma',\sigma}(R_M(\tilde{\mathbf{k}}))}_{\text{Wigner rotation for the J=1/2 case}} |\tilde{\mathbf{k}}; \frac{1}{2}, \sigma'\rangle_{LF}$$

Wigner rotation for the J=1/2 case

- $R_M(\tilde{\mathbf{k}})$ is the Melosh rotation connecting the intrinsic LF and canonical frames, reached through different boosts from a given frame where the particle is moving

$$D^{1/2}[R_M(\tilde{\mathbf{k}})]_{\sigma'\sigma} = \chi^\dagger_{\sigma'} \frac{m + k^+ - \imath\boldsymbol{\sigma} \cdot (\hat{z} \times \mathbf{k}_\perp)}{\sqrt{(m+k^+)^2 + |\mathbf{k}_\perp|^2}} \chi_\sigma = {}_{LF}\langle \tilde{\mathbf{k}}; s\sigma' | \mathbf{k}; s\sigma\rangle_c$$

χ_σ → **two-dimensional spinor**

N.B. If $|\mathbf{k}_\perp| << k^+, m \longrightarrow D_{\sigma'\sigma} \simeq I_{\sigma'\sigma}$

LF spectral function and LC Correlator

The fermion correlator in terms of the LF coordinates is [e.g., Barone, Drago, Ratcliffe, Phys. Rep. 359, 1 (2002)]

isospin

p = fermion momentum

$$\Phi^{\tau}_{\alpha,\beta}(p,P,S) = \frac{1}{2}\int d\xi^- d\xi^+ d\boldsymbol{\xi}_T \; e^{i\,p\xi} \langle P,S,A|\bar{\psi}^{\tau}_{\beta}(0)\psi^{\tau}_{\alpha}(\xi)|A,S,P\rangle$$

parent system (nucleus, nucleon..)

The particle contribution to the correlator in valence approximation, i.e. the result obtained if the antifermion contributions are disregarded, is related to the LF SF:

$$\Phi^{\tau p}(p,P,S) = \frac{(\not{p}_{on} + m)}{2m}\,\Phi^{\tau}(p,P,S)\,\frac{(\not{p}_{on} + m)}{2m} = \frac{2\pi\,(P^+)^2}{(p^+)^2\,4m}\,\frac{E_S}{\mathcal{M}_0[1,(23)]}\sum_{\sigma\sigma'}\left\{ u_\alpha(\tilde{\mathbf{p}},\sigma')\,\mathcal{P}^{\tau}_{\mathcal{M},\sigma'\sigma}(\tilde{\boldsymbol{\kappa}},\epsilon,S)\,\bar{u}_\beta(\tilde{\mathbf{p}},\sigma)\right\}$$

In deriving this expression it naturally appears the momentum $\tilde{\boldsymbol{\kappa}}$ in the intrinsic reference frame of the cluster [1,(23)], where particle 1 is free and the (23) pair is fully interacting.

TMDs and LF spectral function

14

TMDs $\xrightarrow{\text{obtained from}}$ Tr LC correlator $\xrightarrow{\text{obtained from}}$ Tr Spectral function

$$\mathrm{Tr}(\gamma^+\Phi^{\mathrm{P}}) = D\ Tr\left[\hat{\mathcal{P}}_{\mathcal{M}}(\tilde{\kappa},\epsilon,S)\right]$$

$$\mathrm{Tr}(\gamma^+\gamma_5\ \Phi^{\mathrm{P}}) = D\ Tr\left[\sigma_z\ \hat{\mathcal{P}}_{\mathcal{M}}(\tilde{\kappa},\epsilon,S)\right]$$

$$\mathrm{Tr}(\not{p}_\perp\ \gamma^+\ \gamma_5\ \Phi^{\mathrm{P}}) = D\ Tr\left[\boldsymbol{p}_\perp\cdot\boldsymbol{\sigma}\ \hat{\mathcal{P}}_{\mathcal{M}}(\tilde{\kappa},\epsilon,S)\right]$$

$$D = \frac{(P^+)^2}{p^+}\ \frac{\pi}{m}\ \frac{E_S}{\mathcal{M}_0[1,(23)]}$$

The integration $\frac{1}{2}\int\frac{dp^+dp^-}{(2\pi)^4}\ \delta[p^+ - xP^+]\ P^+$ of Tr of SF

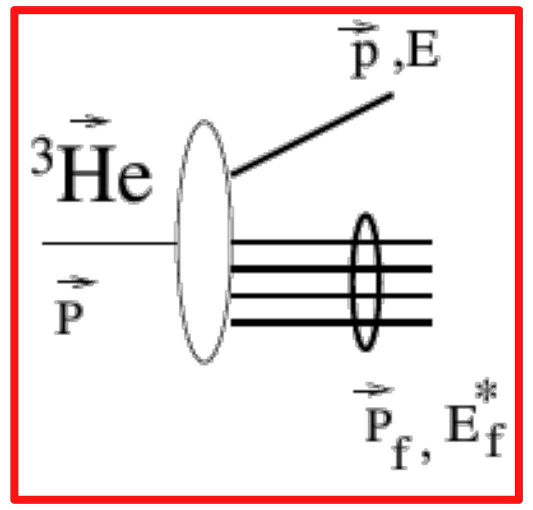
$$f(x,\mathbf{p}_\perp^2) = b_0 \quad \Delta f(x,|\mathbf{p}_\perp|^2) = b_{1,\mathcal{M}} + b_{5,\mathcal{M}} \quad g_{1T}(x,|\mathbf{p}_\perp|^2) = \frac{M}{|\mathbf{p}_\perp|}\ b_{4,\mathcal{M}}$$

$$\Delta'_T f(x,|\mathbf{p}_\perp|^2) = b_{1,\mathcal{M}} + \frac{1}{2}\ b_{2,\mathcal{M}} \quad h_{1L}^\perp(x,|\mathbf{p}_\perp|^2) = \frac{M}{|\mathbf{p}_\perp|}\ b_{3,\mathcal{M}} \quad h_{1T}^\perp(x,|\mathbf{p}_\perp|^2) = \frac{M^2}{|\mathbf{p}_\perp|^2}\ b_{2,\mathcal{M}}$$

TMDs and ^{3}He LF spectral function

The procedure works for any three-body J = 1/2 system (in valence approx!)

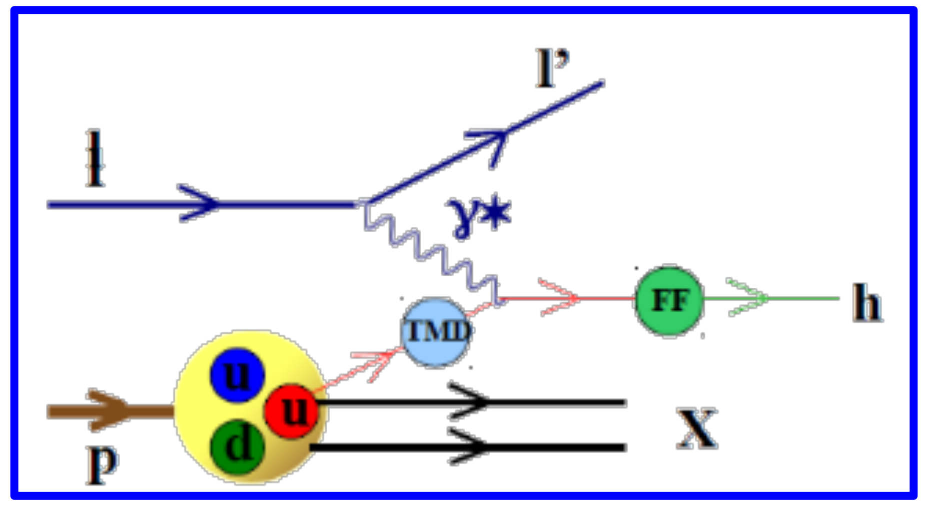
^{3}He



- p, p, n
- $(e, e'p)$ reactions
- p detection
- PW Impulse Approximation
- spin-dep response functions
- light-cone momentum distributions
- norms, effective polarizations

CORRESPONDENCE

Proton



- u_v, u_v, d_v
- SIDIS
- no q_v detection, fragmentation...
- leading twist
- TMDs
- PDFs
- charges (axial, tensor...)

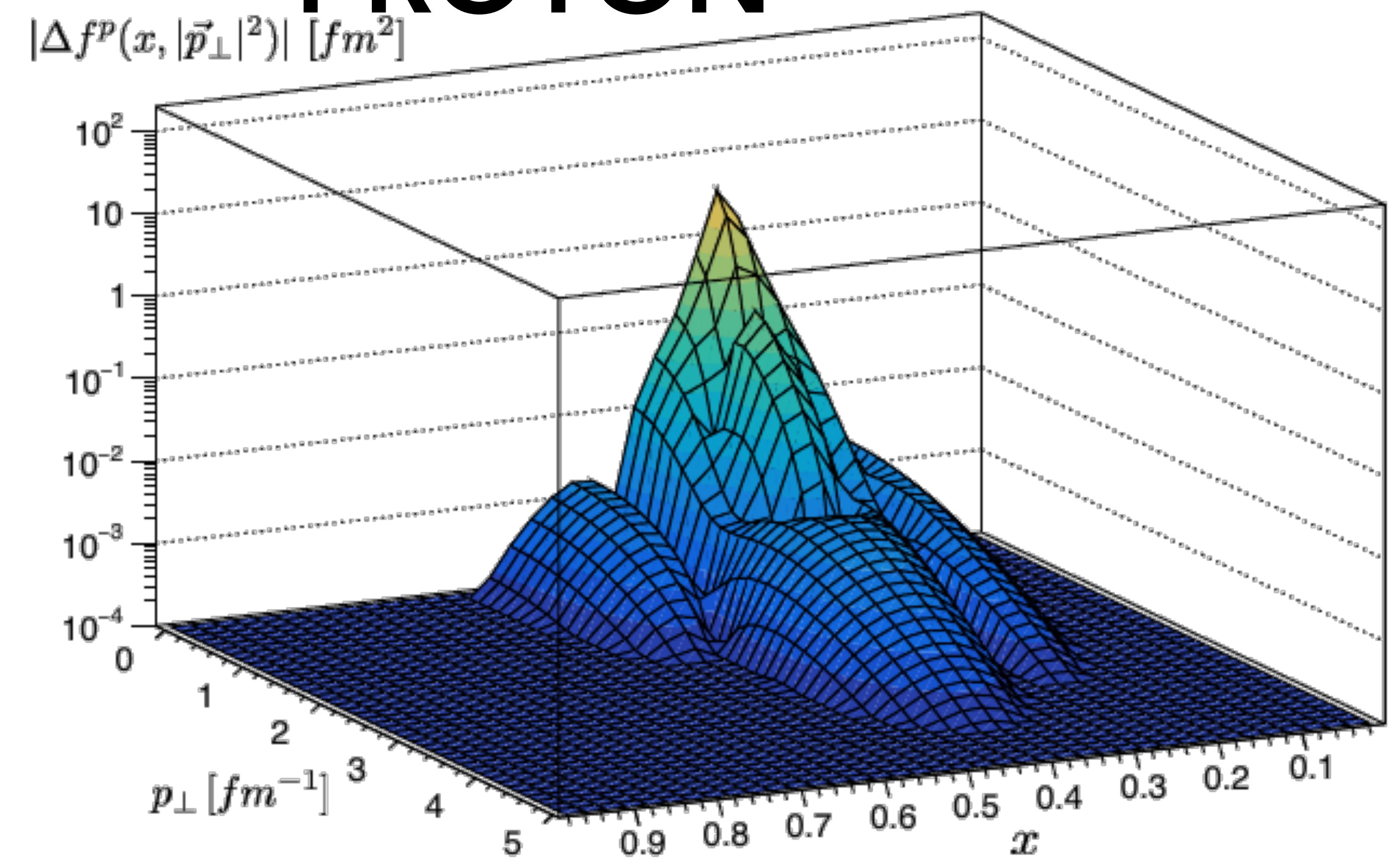
- the ^{3}He TMDs could be obtained from spin asymmetries in $^3\vec{He}(\vec{e}, e'p)$ experiments: in progress!
- We show our calculation for the TMDs of He using Av18 + UIX wfs (A. Kievsky, M. Viviani et al.)

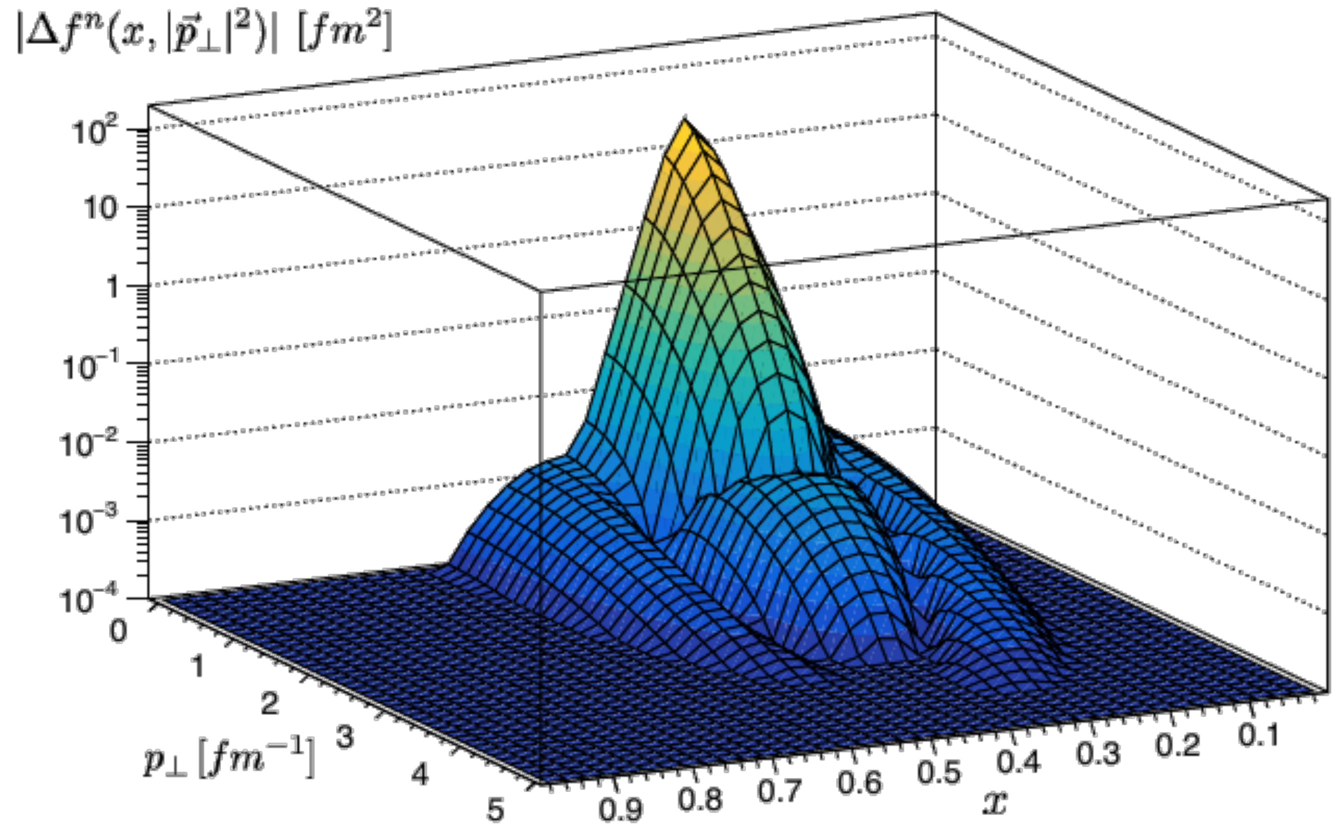
Thus testing LFRHD and of the importance of Relativity in nuclear structure.

^{3}He TMDs

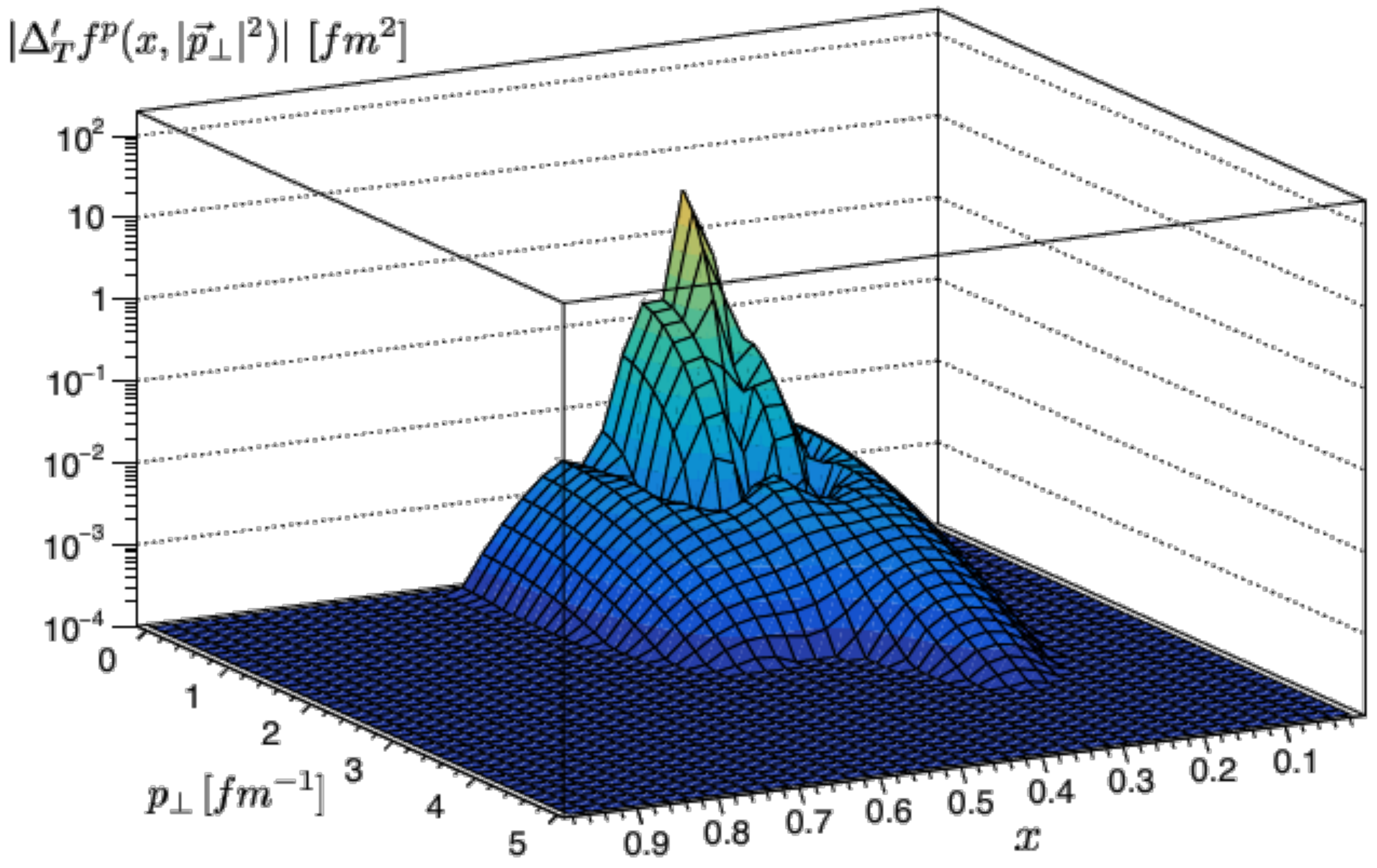
Numerical results A. Del Dotto, E. Pace, G. Perna, A. Rocco, G. Salmè and S. Scopetta, Phys.Rev.C 104 (2021) 6, 065204)

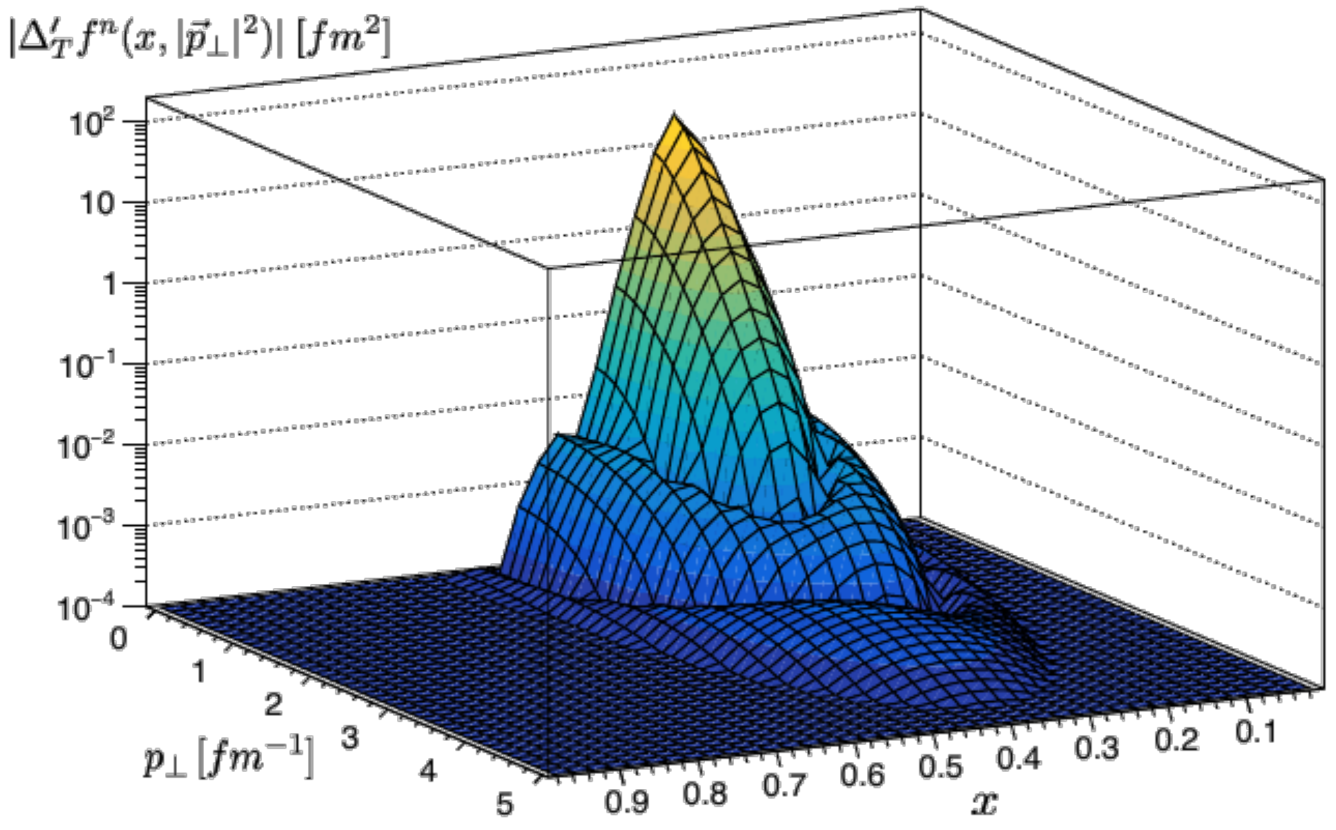
PROTON | **NEUTRON**





$\Delta f^\tau(x, |\mathbf{p}_\perp|^2)$



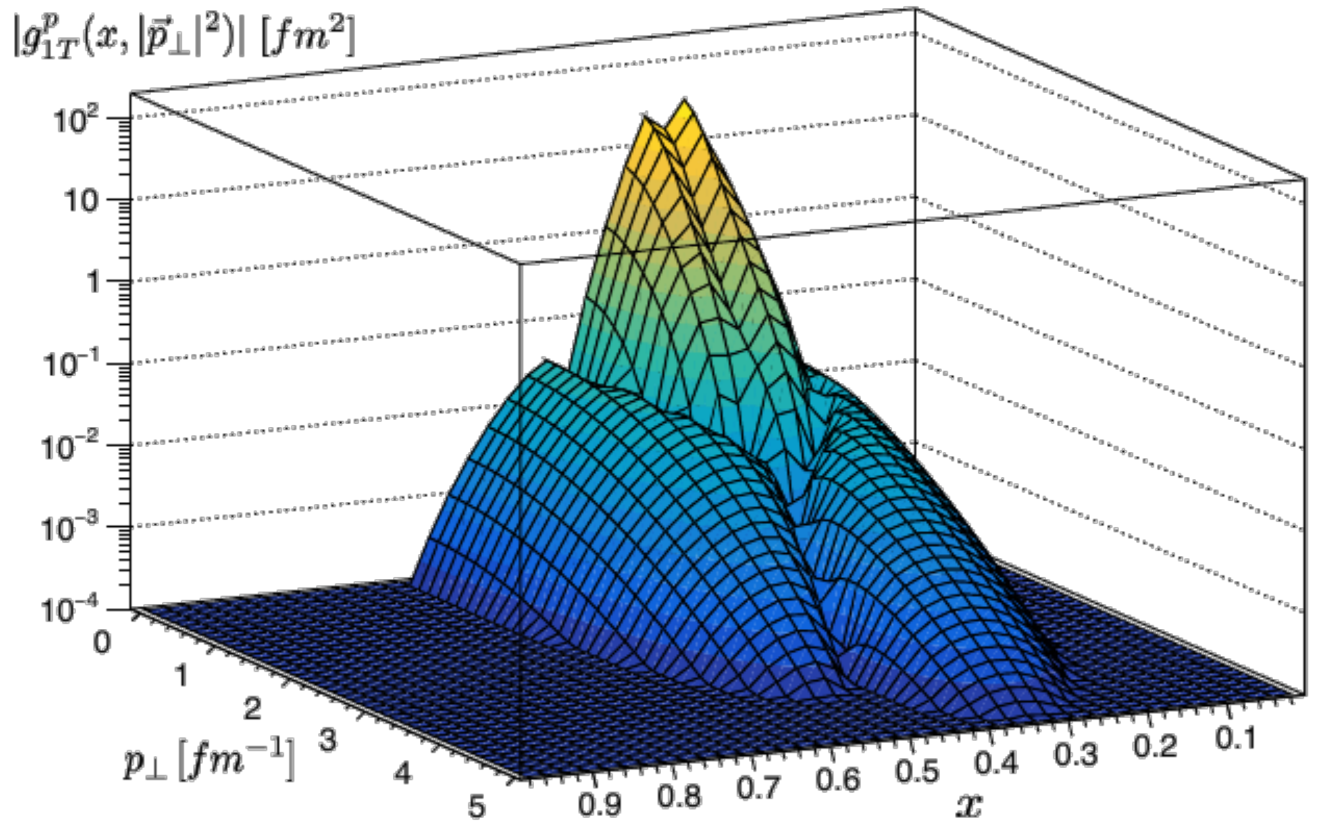


$\Delta'_T f^\tau(x, |\mathbf{p}_\perp|^2)$

^{3}He TMDs

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

PROTON



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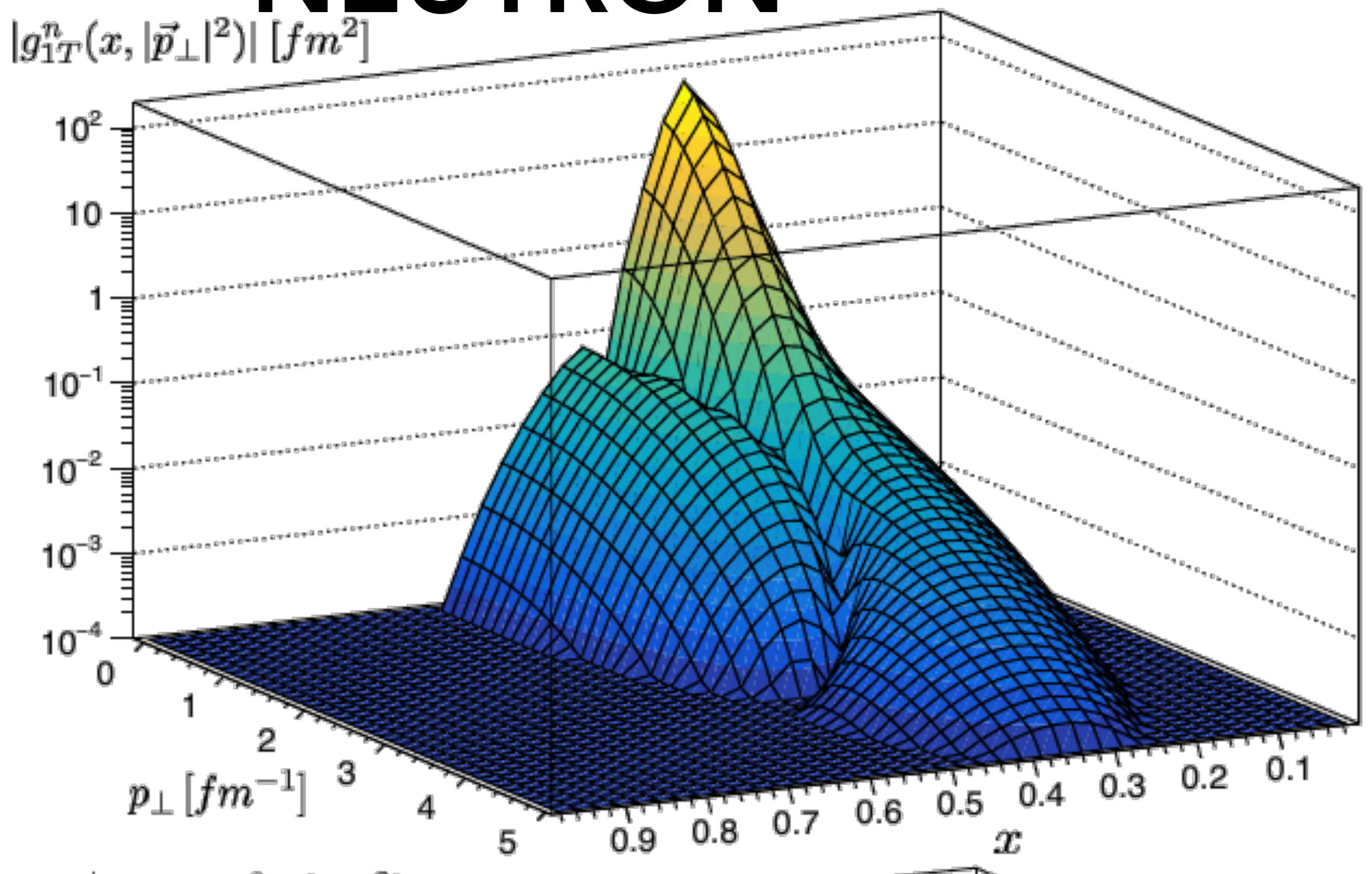
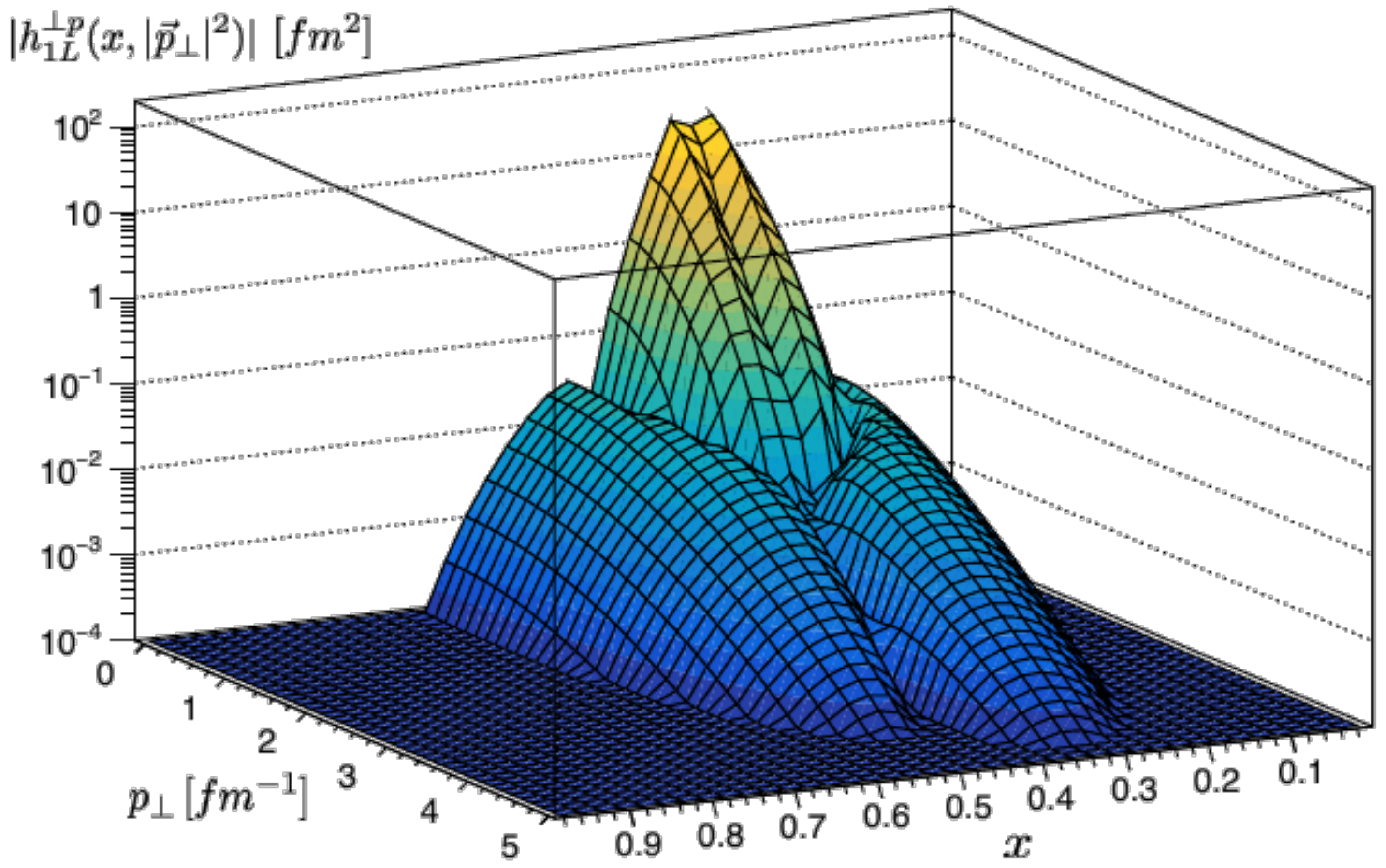
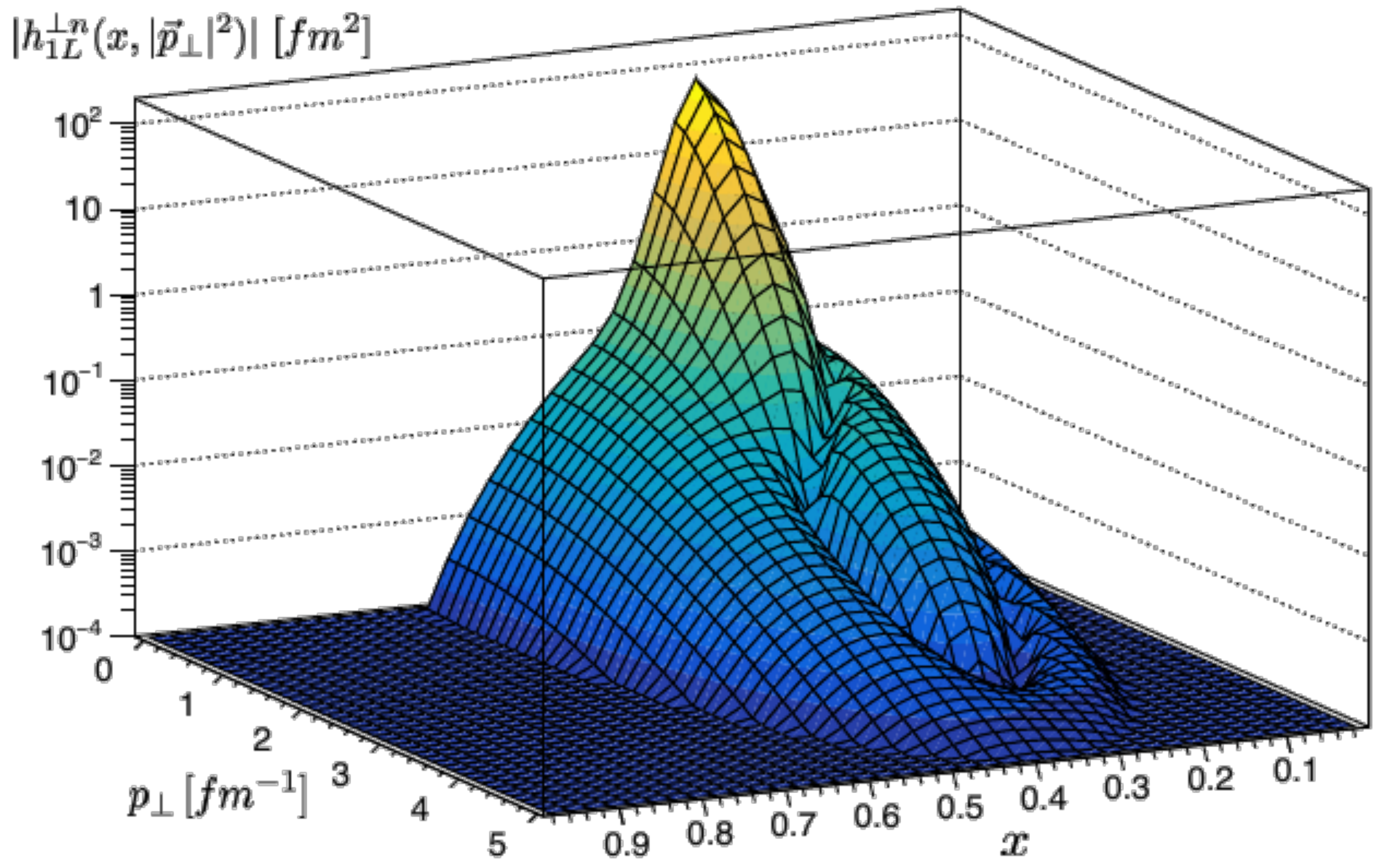


Absolute value of the nucleon longitudinal-polarization distribution, $g^{\tau}_{1T}(x, |\mathbf{p}_\perp|^2)$, in a transversely polarized ^{3}He.



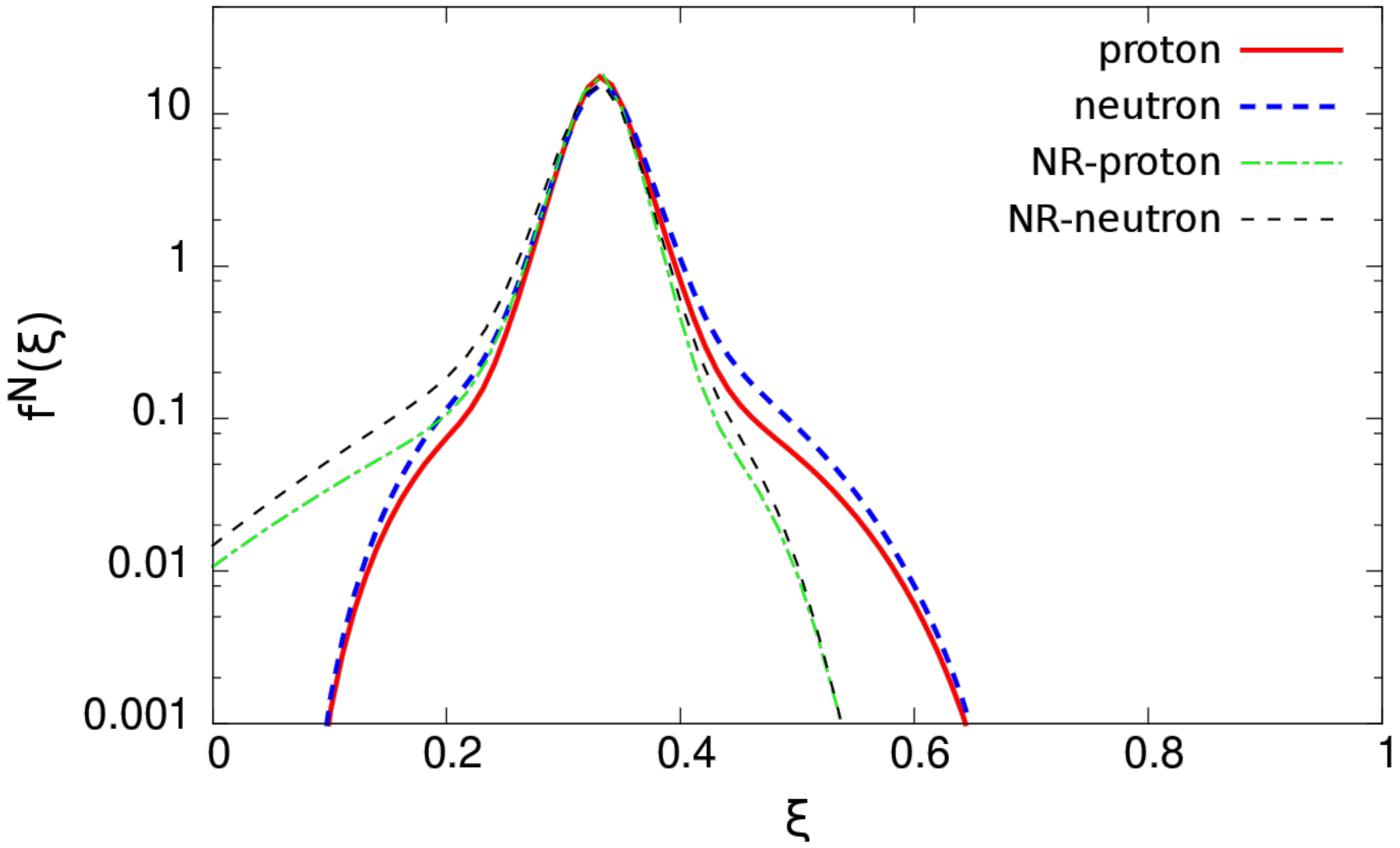


Absolute value of the nucleon transverse-polarization distribution, $h^{\perp\tau}_{1L}(x, |\mathbf{p}_\perp|^2)$ in a longitudinally polarized ^{3}He.

LC momentum distributions

From the normalization of the Spectral Function one has

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

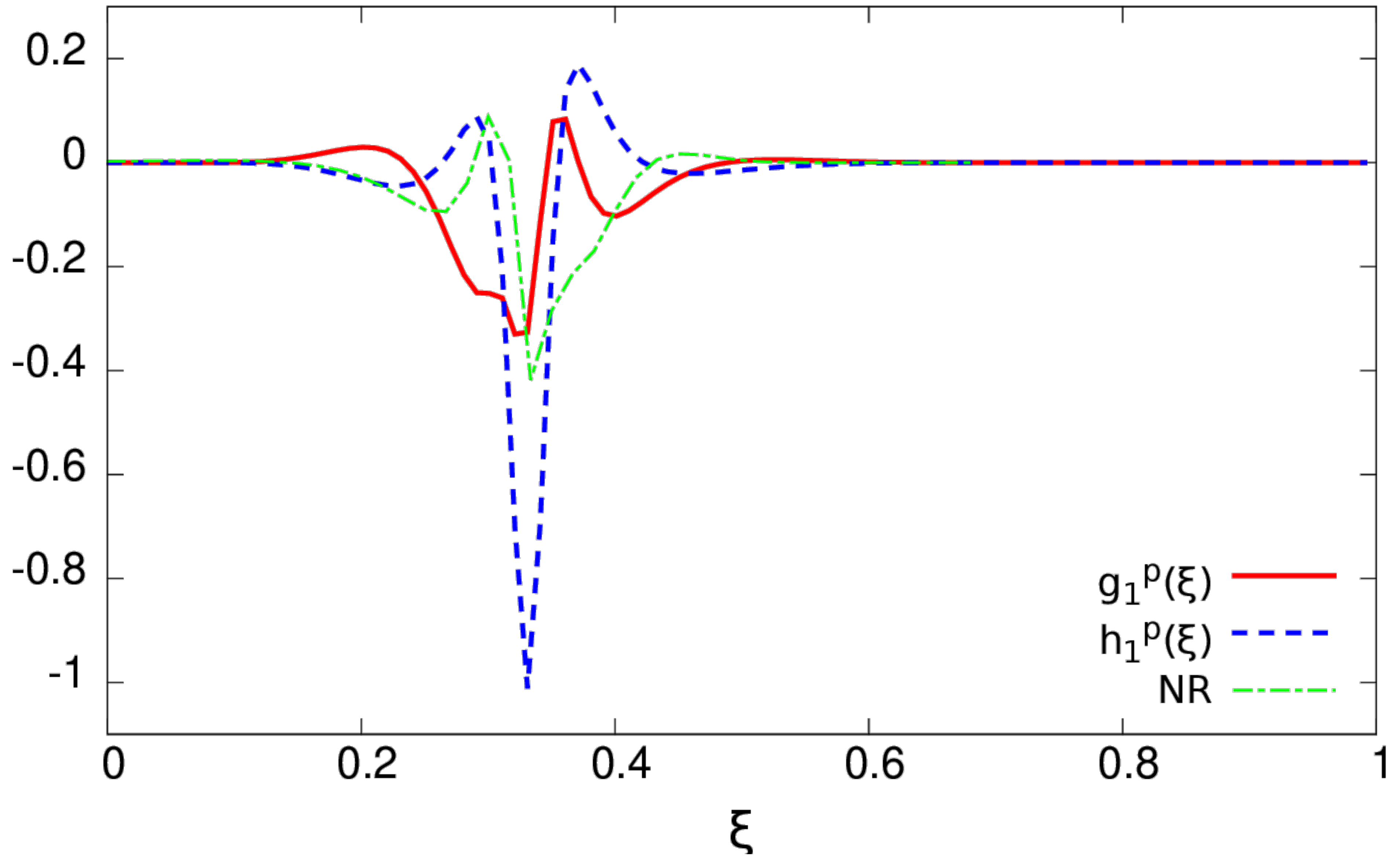


unpolarized distribution

E. Pace, M.R., G. Salmè and S. Scopetta, ArXiv:2206.05485

LC momentum distributions

PROTON



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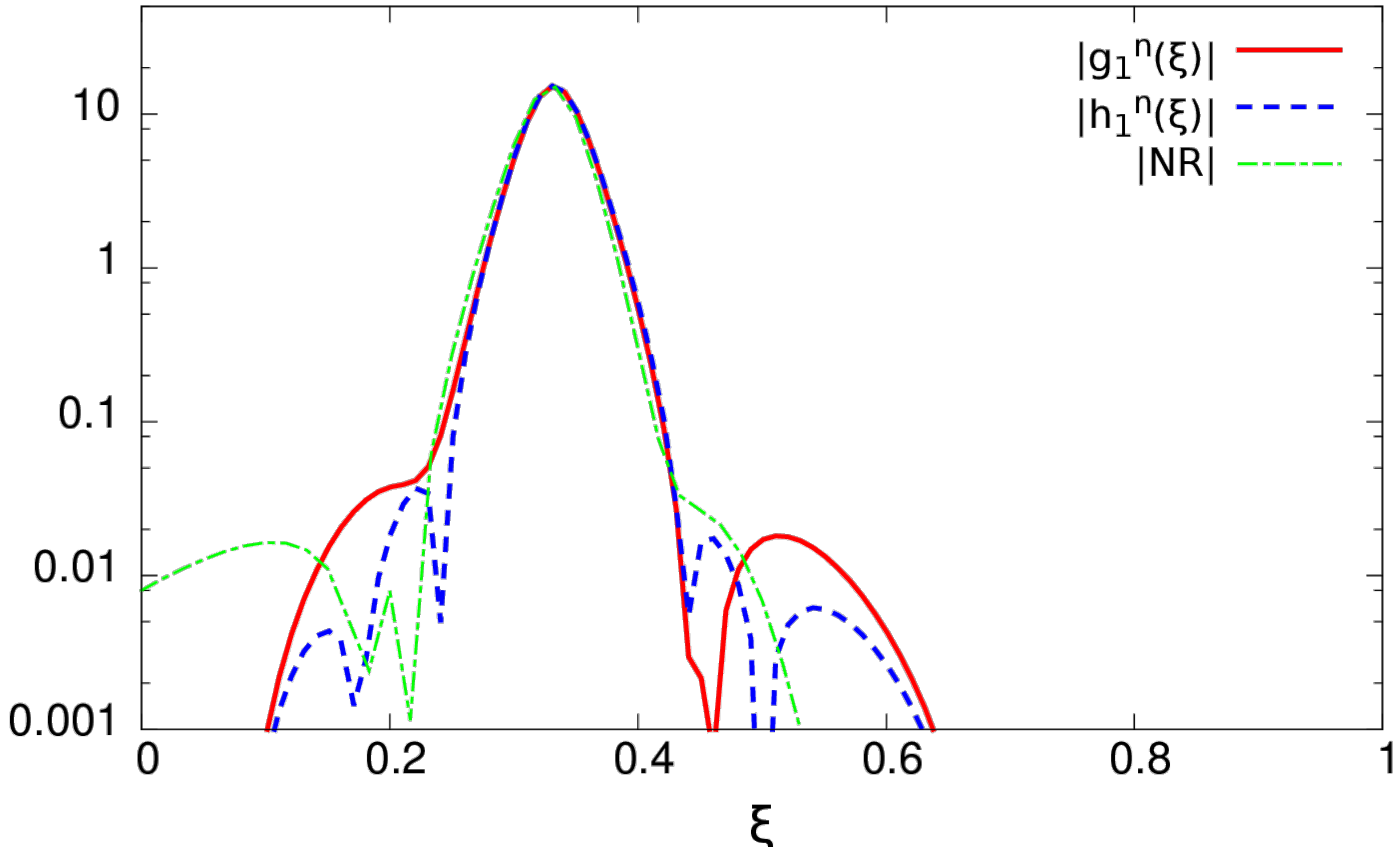


E. Pace, M.R., G. Salmè and S. Scopetta, ArXiv:2206.05485

$g_1^n(\xi)$ longitudinal-polarization distribution

$h_1^n(\xi)$ transverse-polarization distribution

- They would be the same in a NR framework;
- Crucial for the extraction of the neutron information from DIS and SIDIS off ^{3}He. Work in progress to LF update our NR results $\longrightarrow$ important for JLab12, EIC

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

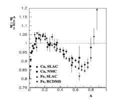
Effective longitudinal polarization (axial charge for the nucleon)

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

Effective transverse polarization (tensor charge for the nucleon)

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

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: $p^{\tau}_{||}(NR) = p^{\tau}_{\perp}(NR)$

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.

LF spectral function decomposition

The LF spin-dependent spectral function (SF), for a nucleus with polarization S, can be macroscopically decomposed in terms of the available vectors:

- the unit vector $\hat{n}$, $\perp$ to the hyperplane $n^\mu x_\mu = 0$. Our choice is $n^\mu \equiv \{1,0,0,1\} \Rightarrow \hat{n} \equiv \hat{z}$
- the polarization vector **S**
- the transverse (wrt the $\hat{z}$ axis) momentum component of the constituent, i.e. $\mathbf{k}_\perp(123) = \mathbf{p}_\perp(Lab) = \boldsymbol{\kappa}_\perp(1;23)$

$$\mathcal{P}^\tau_{\mathcal{M},\sigma'\sigma}(\tilde{\boldsymbol{\kappa}},\epsilon,S) = \frac{1}{2}\left[\mathcal{B}^\tau_{0,\mathcal{M}} + \boldsymbol{\sigma}\cdot\boldsymbol{\mathcal{F}}^\tau_{\mathcal{M}}(\tilde{\boldsymbol{\kappa}},\epsilon,\mathbf{S})\right]_{\sigma'\sigma}$$

unpolarized SF $\mathcal{B}^\tau_{0,\mathcal{M}} = Tr\left[\mathcal{P}^\tau_{\mathcal{M},\sigma'\sigma}(\tilde{\boldsymbol{\kappa}},\epsilon,S)\right]$

$\boldsymbol{\mathcal{F}}^\tau_{\mathcal{M}}(\tilde{\boldsymbol{\kappa}},\epsilon,\mathbf{S}) = Tr\left[\hat{\boldsymbol{\mathcal{P}}}^\tau_{\mathcal{M}}(\tilde{\boldsymbol{\kappa}},\epsilon,S)\ \boldsymbol{\sigma}\right]$ pseudovector

$$\boldsymbol{\mathcal{F}}^\tau_{\mathcal{M}}(x,\mathbf{k}_\perp;\epsilon,\mathbf{S}) = \mathbf{S}\mathcal{B}^\tau_{1,\mathcal{M}}(\dots) + \hat{\mathbf{k}}_\perp\ (\mathbf{S}\cdot\hat{\mathbf{k}}_\perp)\mathcal{B}^\tau_{2,\mathcal{M}}(\dots) + \hat{\mathbf{k}}_\perp\ (\mathbf{S}\cdot\hat{z})\mathcal{B}^\tau_{3,\mathcal{M}}(\dots) + \hat{z}\ (\mathbf{S}\cdot\hat{\mathbf{k}}_\perp)\mathcal{B}^\tau_{4,\mathcal{M}}(\dots) + \hat{z}\ (\mathbf{S}\cdot\hat{z})\mathcal{B}^\tau_{5,\mathcal{M}}(\dots)$$

$$x = \kappa^+(1;23)/\mathcal{M}_0(1;23)$$

The scalar functions $\mathcal{B}^\tau_{i,\mathcal{M}}(\dots)$ depend, for $\mathcal{J} = 1/2$, on $|\mathbf{k}_\perp|$, x, ϵ

LF spectral function and momentum distribution

By integrating the LF SF on κ^-, equivalent to the integration on the ϵ ≡ internal energy of the spectator system, one straightforwardly gets the LF spin-dependent momentum distribution

$$\mathcal{N}^{\tau}_{\sigma'\sigma}(x, \mathbf{k}_\perp; \mathcal{M}, \mathbf{S}) = \frac{1}{2}\left\{b_{0,\mathcal{M}}(\dots) + \boldsymbol{\sigma}\cdot\mathbf{f}_{\mathcal{M}}(x, \mathbf{k}_\perp; \mathbf{S})\right\}_{\sigma'\sigma}$$

$$\int d\epsilon \; \mathcal{B}^{\tau}_{i,\mathcal{M}}(\dots)$$

$$\int d\epsilon \; \mathcal{F}^{\tau}_{\mathcal{M}}(x, \mathbf{k}_\perp; \epsilon, \mathbf{S})$$

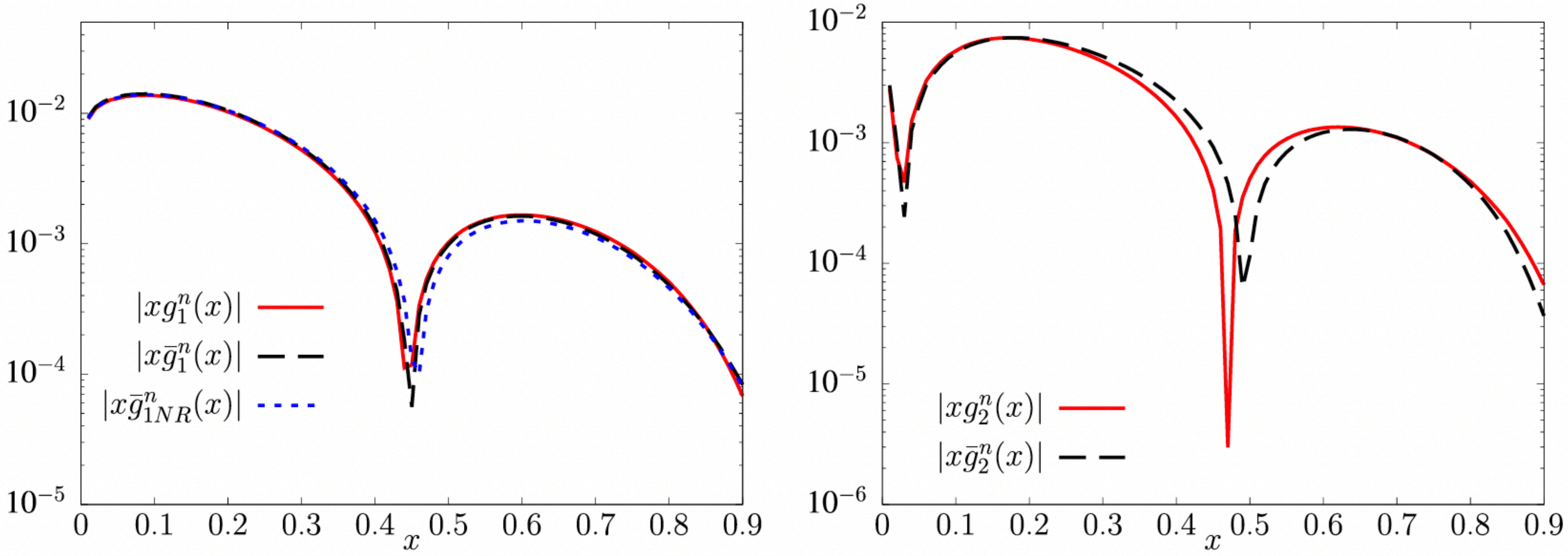
The decomposition is useful to get:

an explicit interplay between transverse momentum component and spin dofs

relations between Transverse-momentum distributions (TMDs) in the *valence sector*

Neutron SSFs

E.Proietti, F.F, E.Pace, M.Rinaldi, G.Salmè and S.Scopetta, ***Phys.Rev.C*** **110 (2024) 3, L031303**



Solide lines: GRSV parametrization of the free neutron SSFs

Dashed lines: extraction of the free neutron SSFs from **relativistic** effective polarizations

Dotted line: extraction of the free neutron SSFs from **non-relativistic** effective polarizations