The EMC effect in ^4He [F.Fornetti,E.Pace,M.Rinaldi,G.Salmè,M.Viviani, in prep.]

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SHORT-DISTANCE NUCLEAR STRUCTURE AND PDFS

Outline

1. Non symmetric intrinsic variables for a 4-body system
2. Light-cone momentum distribution for ^4He
3. Results for the R_{EMC} of ^4He
4. Preliminary results for ^3H
5. Conclusions

Motivation of this work

- Goal: extend the approach applied for ^3He to any nuclei A and calculate the EMC ratio for ^4He *[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
- Comparing the results for ^3He and ^4He obtained by different modern NN and NNN interactions (Argonne V18+UIX, NVIa+3N, NVIb+3N)
- Comparing the results 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]

EMC ratio for ^4He

- $R^{\alpha}_{EMC}(x) = \frac{1}{2}\frac{F^{\alpha}_2(x)}{F^d_2(x)}$
- Where the ^4He structure function is: $F_2^{\alpha}(x) = 2\sum_{N=p,n}\int_{\xi_m}^{1} d\xi F_2^N(\frac{mx}{M_\alpha \xi}) f_1(\xi)$
- Written in term of the light-cone momentum distribution:

$$f_1(\xi) = \int d\mathbf{k}_{1\perp}\int \mathbf{dk'_2}\int \mathbf{dk_{34}}\,\mathbf{n(k_1, k'_2, k_{34})}\frac{\mathbf{E(k_1)E_{234}}}{\mathbf{k_1^+(1-\xi_1)}}$$

$$\frac{dk_{1z}}{d\xi_1}$$

$$n(\mathbf{k_1}, \mathbf{k'_2}, \mathbf{k_{34}}) = |\psi(\mathbf{k_1}, \mathbf{k'_2}, \mathbf{k_{34}})|^{\mathbf{2}}$$

Convolution formula

- $\psi(\mathbf{k_1}, \mathbf{k'_2}, \mathbf{k_{34}})$ is the wave function of ^4He evaluated in the non symmetric intrinsic momenta
- BT construction of the Poincaré group [See M.Rinaldi's talk]

- We can use a non relativistic wave function of ^4He obtained by realistic nuclear potentials
- The wave function in momentum space becomes the Fourier-transformed of the wave function, in coordinates space, evaluated in the Jacobi vectors $\mathbf{R_1}, \mathbf{R_2}, \mathbf{R_{34}}$

Convolution formula

- $\psi(\mathbf{k}_1, \mathbf{k'}_2, \mathbf{k}_{34})$ is the wave function of ^4He evaluated in the non symmetric intrinsic momenta
- BT construction of the Poincaré group

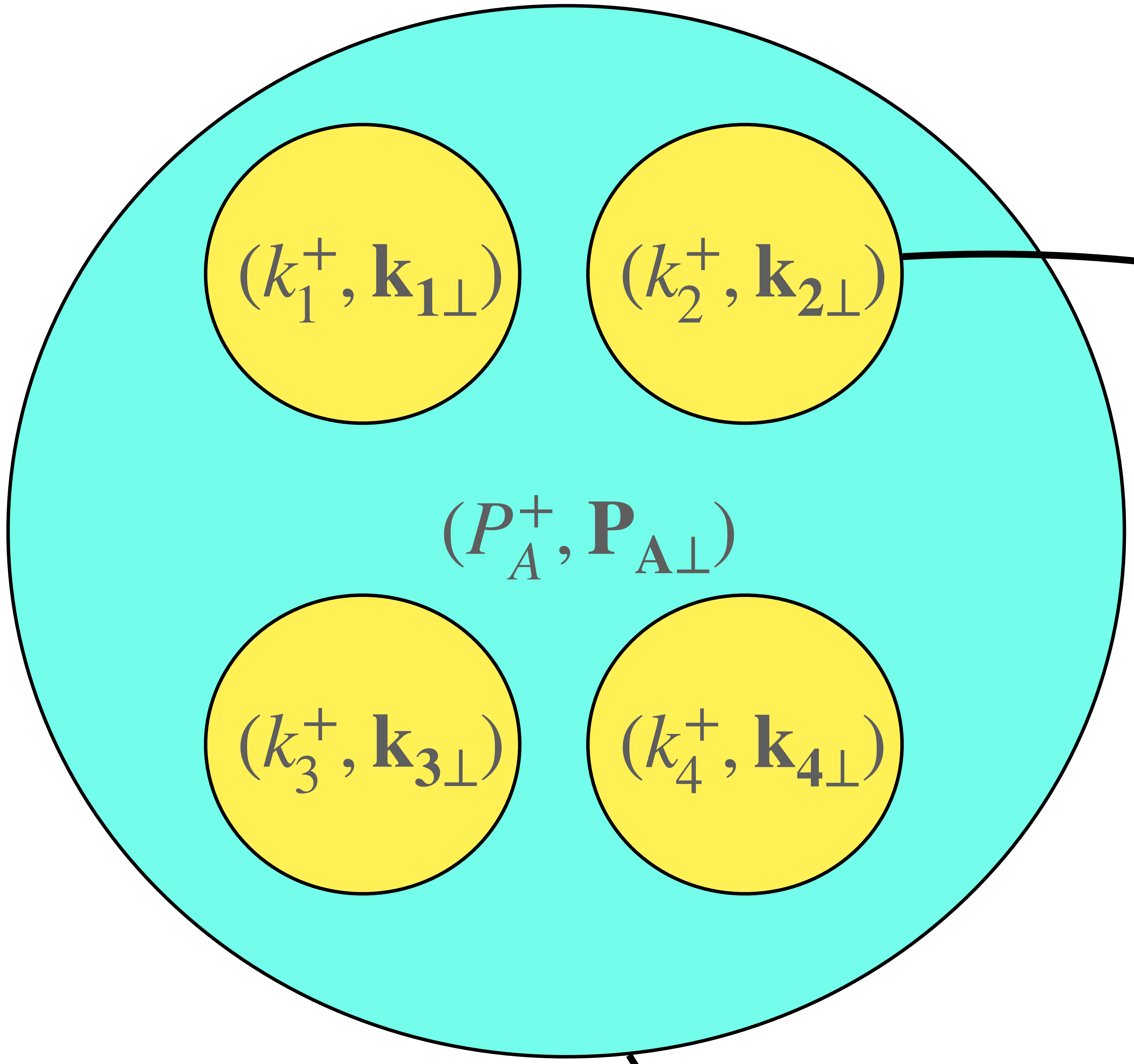
$$\mathbf{R}_1 = \mathbf{r}_1 - \frac{\mathbf{r}_2 + \mathbf{r}_3 + \mathbf{r}_4}{3}$$

$$\mathbf{R}_2 = \mathbf{r}_2 - \frac{\mathbf{r}_3 + \mathbf{r}_4}{2}$$

$$\mathbf{R}_{34} = \mathbf{r}_3 - \mathbf{r}_4$$

- We can use a non relativistic wave function of ^4He obtained by realistic nuclear potentials
- The wave function in momentum space becomes the Fourier-transformed of the wave function, in coordinates space, evaluated in the Jacobi vectors $\mathbf{R}_1, \mathbf{R}_2, \mathbf{R}_{34}$

Symmetric intrinsic variables



- 4 fully interacting particles with momenta $p_i\{i = 1,2,3,4\}$ and total momentum P_A in the lab frame

$$\xi_i = \frac{p_i^+}{P^+} \in [0, 1]$$

$$k_i^+ = M_0 \xi_i$$

$$\mathbf{k_{i\perp}} = \mathbf{p_{i\perp}} - \xi_\mathbf{i} \mathbf{P}_\perp$$

Definition of symmetric internal variables

$$P_A^+ = M_0$$

$$\mathbf{P_{A\perp}} = \mathbf{0}_\perp$$

$$M_0 = \sum_i \sqrt{m_i^2 + \mathbf{k_i}^2}$$

Choice of the intrinsic frame

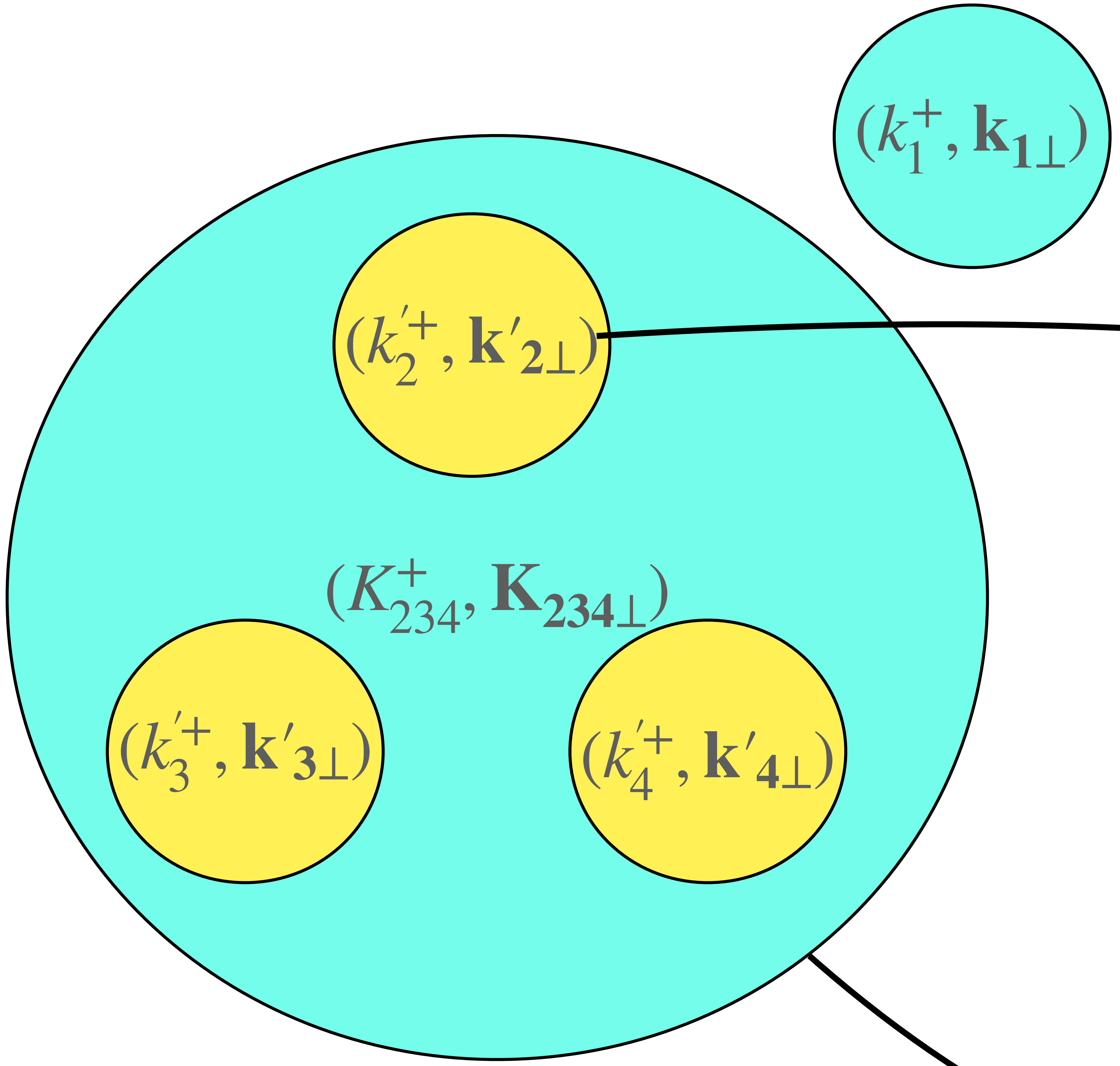
Non symmetric intrinsic variables

- We have to work in the intrinsic frame of the cluster where the free mass of the system is $M_0[1,(2,3,4)] \neq M_0$
- $\xi_1 = \dfrac{\kappa_1^+}{M_0[1,(2,3,4)]} = \dfrac{k_1^+}{M_0}$ because the frames are connected by a LF boost

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

- In the frame of the cluster [1,(2,3,4)] the intrinsic variables of the spectator nucleons (2,3,4) are not $(\xi_i, \mathbf{k}_{\perp \mathbf{i}})\{\mathbf{i} = \mathbf{2}, \mathbf{3}, \mathbf{4}\}$
- We have to define non symmetric intrinsic variables in order to fulfill the macroscopic locality

Non symmetric intrinsic variables



We have to disentangle the interacting nucleon [1] from the spectator nucleons [2,3,4]

$$\eta_l = \frac{\xi_l}{1-\xi_1}$$

$$k_l'^+ = \eta_l M_0[2,3,4]$$

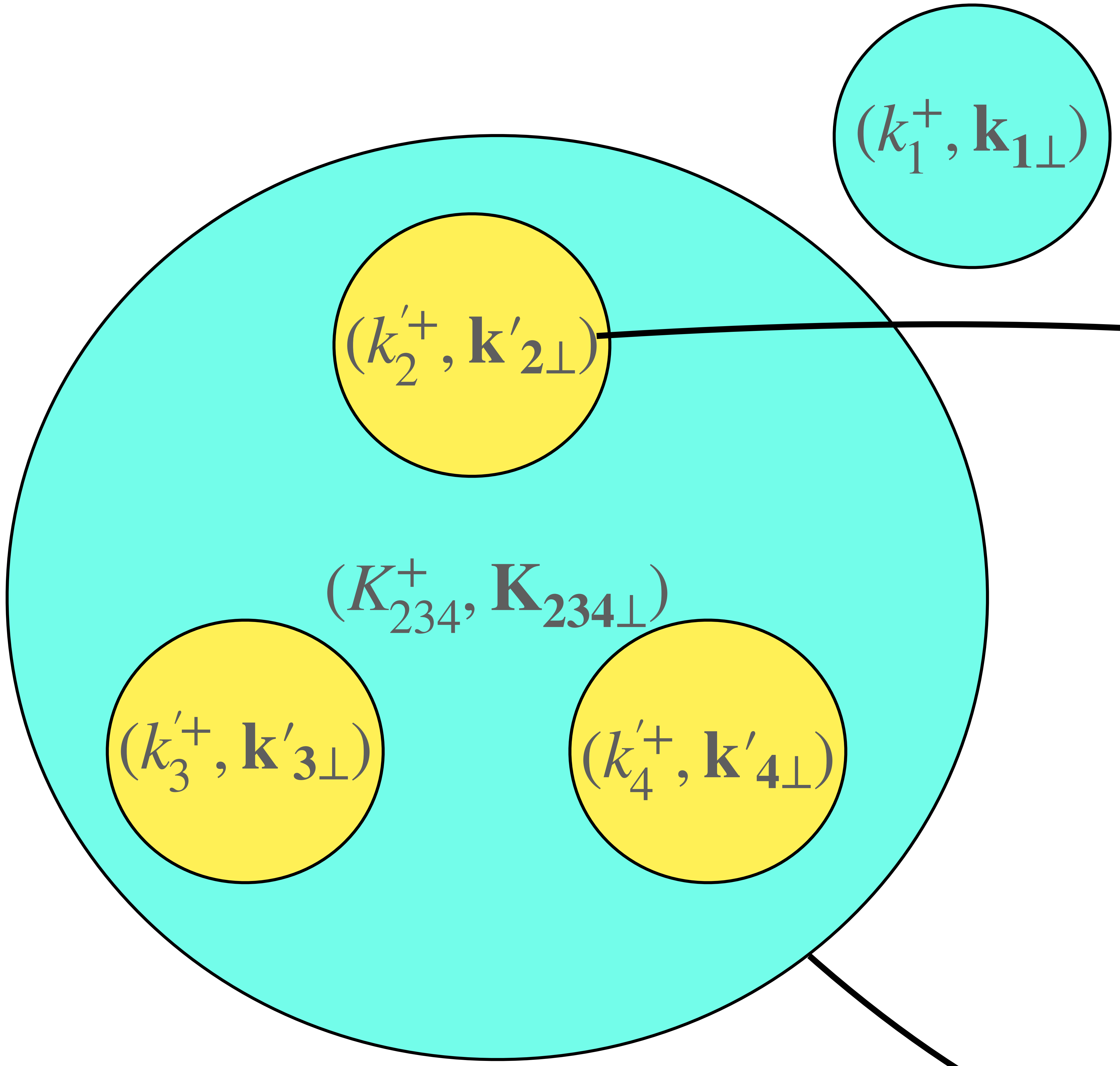
$$\mathbf{k}'_{1\perp} = \mathbf{k}_{1\perp} - \eta_l[\mathbf{k}_{2\perp} + \mathbf{k}_{3\perp} + \mathbf{k}_{4\perp}]$$

$$\mathbf{K}_{234\perp} = -\mathbf{k}_{1\perp} \quad K_{234}^+ = (1-\xi_1)M_0$$

$$M_0[2,3,4] = \sum_{l=2}^{4}\sqrt{m^2 + \mathbf{k}_l'^2}$$

$$E_{234} = K^0[2,3,4] = \sqrt{M_0^2[2,3,4] + \mathbf{k}_1^2}$$

Non symmetric intrinsic variables



We have to disentangle the interacting nucleon [1] from the spectator nucleons [2,3,4]

The non interacting subsystem [2,3,4] moves with LF momentum $(K_{234}^+, \mathbf{K}_{234\perp})$ in the intrinsic frame

$$\eta_l = \frac{\xi_l}{1-\xi_1}$$

$$k_l'^+ = \eta_l M_0[2,3,4]$$

$$\mathbf{k}'_{l\perp} = \mathbf{k}_{l\perp} - \eta_l[\mathbf{k}_{2\perp} + \mathbf{k}_{3\perp} + \mathbf{k}_{4\perp}]$$

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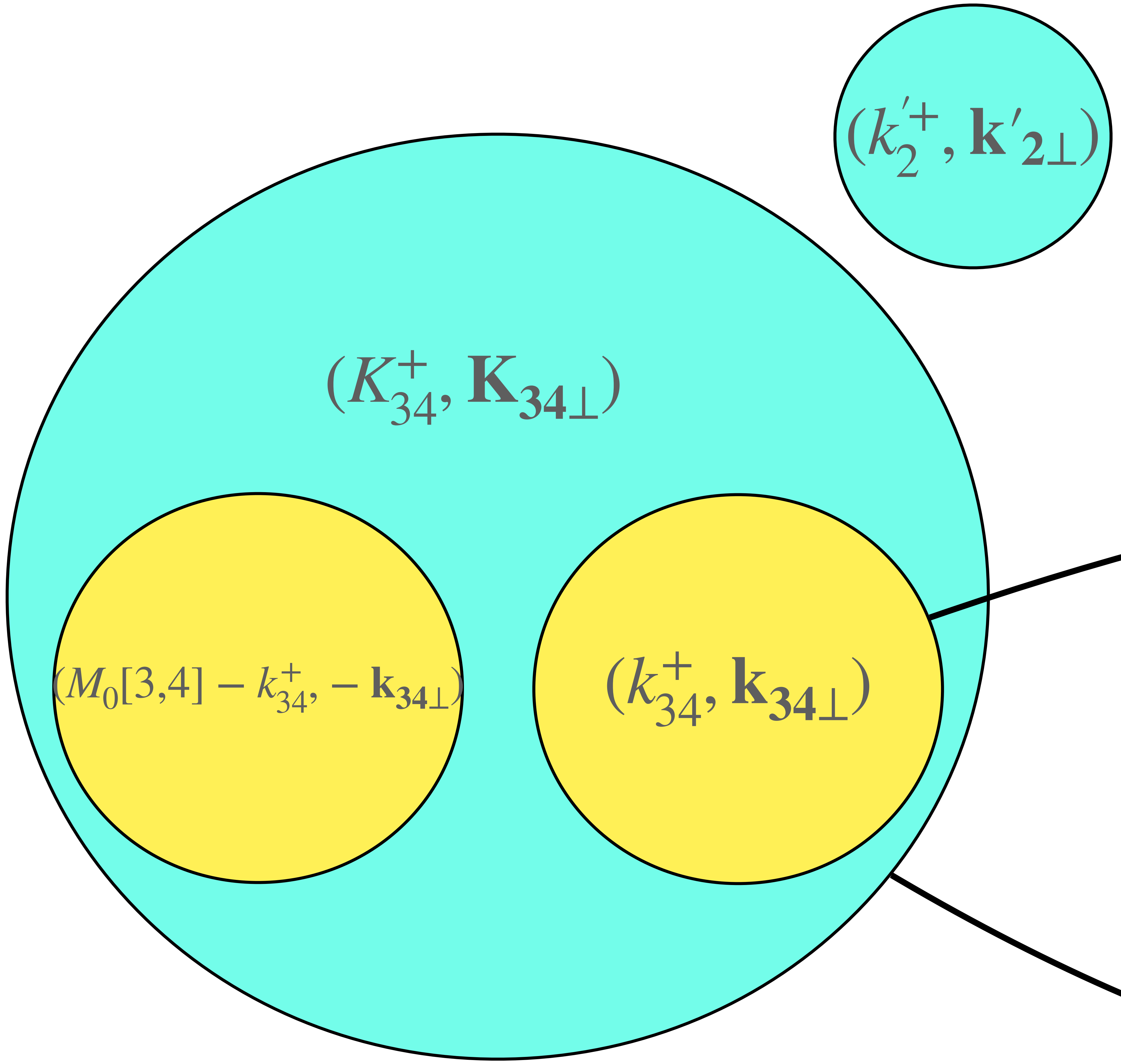
Non symmetric intrinsic variables



We have to do the same also with the [3,4] pair if we want to work with the Jacobi vectors

$$\eta = \frac{\xi_3}{\xi_3 + \xi_4}$$

$$k_{34}^+ = \eta M_0[3,4]$$

$$\mathbf{k}_{34\perp} = \mathbf{k}'_{3\perp} - \eta(\mathbf{k}'_{3\perp} + \mathbf{k}'_{4\perp})$$

$$\mathbf{K}_{34\perp} = -\mathbf{k}'_{2\perp}$$

$$M_0[3,4] = 2\sqrt{m^2 + \mathbf{k}_{34}^2}$$

Light-cone momentum distribution

$$M_0[3,4] = 2\sqrt{m^2 + \mathbf{k}_{34}^2}$$

$$M_0[2,3,4] = \sqrt{m^2 + \mathbf{k'}_2^2} + \sqrt{M_0[3,4]^2 + \mathbf{k'}_2^2}$$

$$M_0 = \sqrt{m^2 + \mathbf{k}_1^2} + \sqrt{M_0[2,3,4]^2 + \mathbf{k'}_2^2}$$

$$k_1^+ = M_0 \xi_1 \Rightarrow k^+ = k^+(\mathbf{k}_1, \mathbf{k'}_2, \mathbf{k}_{34})$$

$$E_{234} = \sqrt{M_0[2,3,4]^2 + \mathbf{k}_1^2} \Rightarrow E_{234} = E_{234}(\mathbf{k}_1, \mathbf{k'}_2, \mathbf{k}_{34})$$

Light-cone momentum distribution

$$f_1(\xi) = \int d\mathbf{k}_{1\perp} \int \mathbf{dk'_2} \int \mathbf{dk_{34}} \mathbf{n}(\mathbf{k_1}, \mathbf{k'_2}, \mathbf{k_{34}}) \frac{\mathbf{E}(\mathbf{k_1})\mathbf{E_{234}}}{\mathbf{k_1^+}(\mathbf{1} - \xi_1)}$$

We can't integrate $n(\mathbf{k_1}, \mathbf{k'_2}, \mathbf{k_{34}})$ on $\mathbf{k'_2}$ and $\mathbf{k_{34}}$

We can't use the one-body momentum distribution $n(\mathbf{k_1})$

$$k_1^+ = M_0\xi_1 \Rightarrow k^+ = k^+(\mathbf{k_1}, \mathbf{k'_2}, \mathbf{k_{34}})$$

$$E_{234} = \sqrt{M_0[2,3,4]^2 + \mathbf{k_1^2}} \Rightarrow E_{234} = E_{234}(\mathbf{k_1}, \mathbf{k'_2}, \mathbf{k_{34}})$$

Light-cone momentum distribution

$$f_1(\xi) = \int d\mathbf{k}_{1\perp} \int \mathbf{dk'_2} \int \mathbf{dk_{34}} \mathbf{n(k_1, k'_2, k_{34})} \frac{\mathbf{E(k_1)E_{234}}}{\mathbf{k_1^+(1-\xi_1)}}$$

We can't integrate $n(\mathbf{k}_1, \mathbf{k'}_2, \mathbf{k}_{34})$ on $\mathbf{k'}_2$ and $\mathbf{k}_{34}$

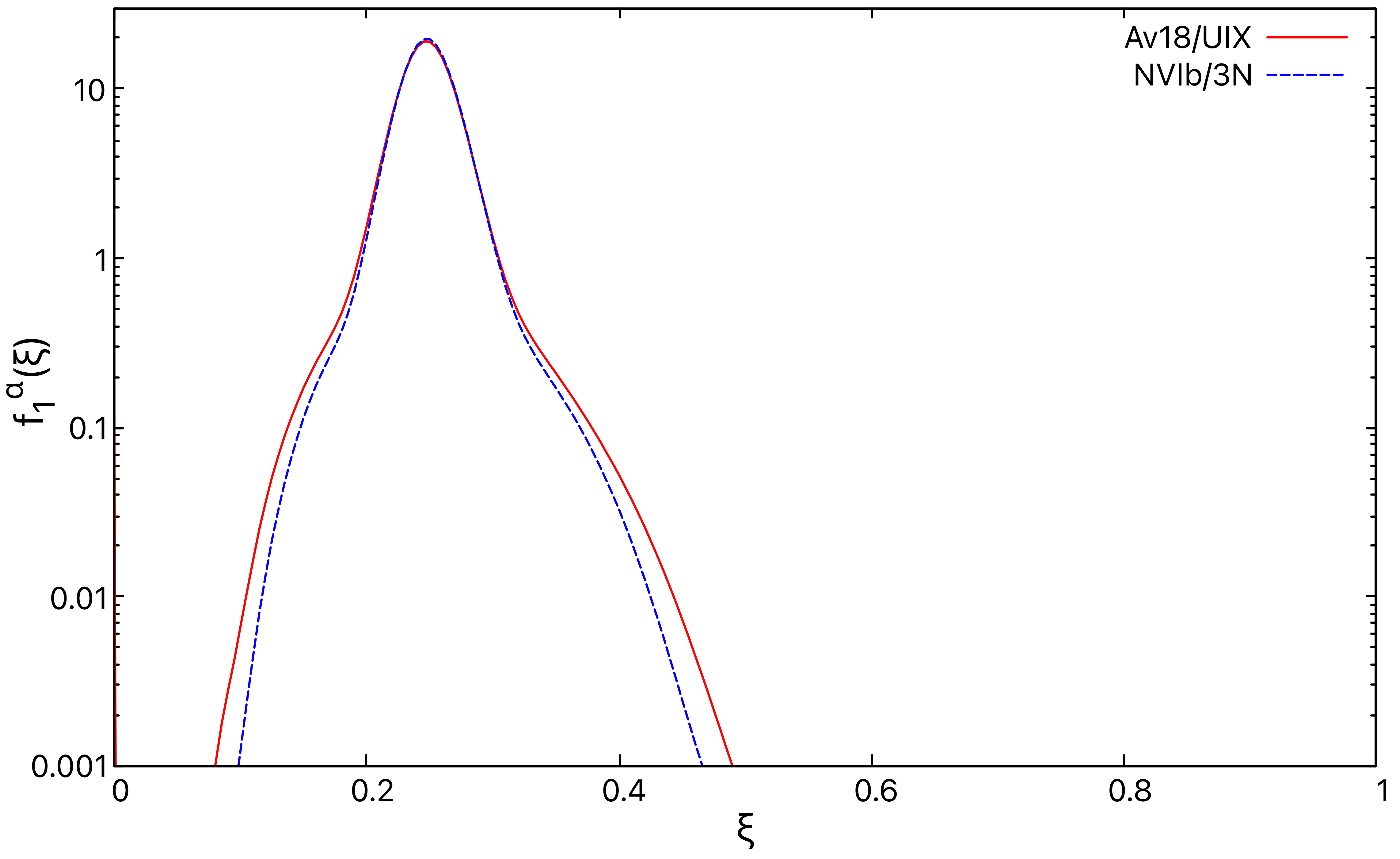
We can't use the one-body momentum distribution $n(\mathbf{k}_1)$

We need to integrate over (A-1) momenta for a generic A nucleus

$$k_1^+ = M_0\xi_1 \Rightarrow k^+ = k^+(\mathbf{k_1}, \mathbf{k'_2}, \mathbf{k_{34}})$$

$$E_{234} = \sqrt{M_0[2,3,4]^2 + \mathbf{k_1^2}} \Rightarrow E_{234} = E_{234}(\mathbf{k_1}, \mathbf{k'_2}, \mathbf{k_{34}})$$

Light-cone momentum distribution



- Three different interactions: Av18/UIX and two versions of the Norfolk χEFT interactions (NVIa+3N and NVIb+3N)
- High-momentum content of the light-cone distribution evaluated by Av18 larger than the one calculated with NVIa+3N and NVIb+3N both for ^4He and deuteron
- Small difference between NVIa+3N and NVIb+3N

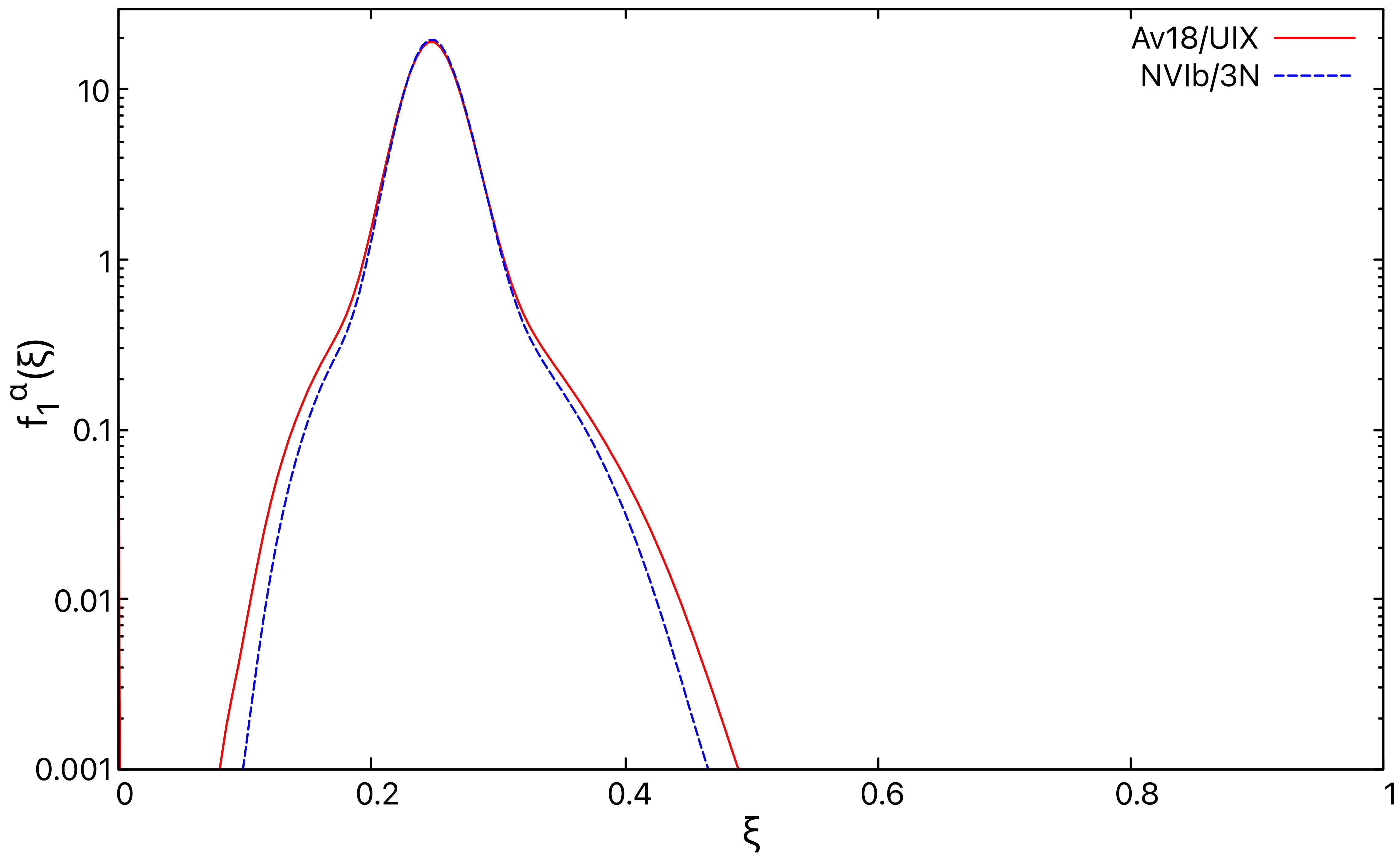
Light-cone momentum distribution

Realistic nuclear description

Poincaré covariance

Macroscopic locality

Number of particles and momentum sum rules automatically satisfied



$$N = 4\int_0^1 d\xi f_1^{\alpha}(\xi) = 4$$

$$<\xi> = \int_0^1 d\xi \xi f_1^{\alpha}(\xi) = \frac{1}{4}$$

Light-cone momentum distribution

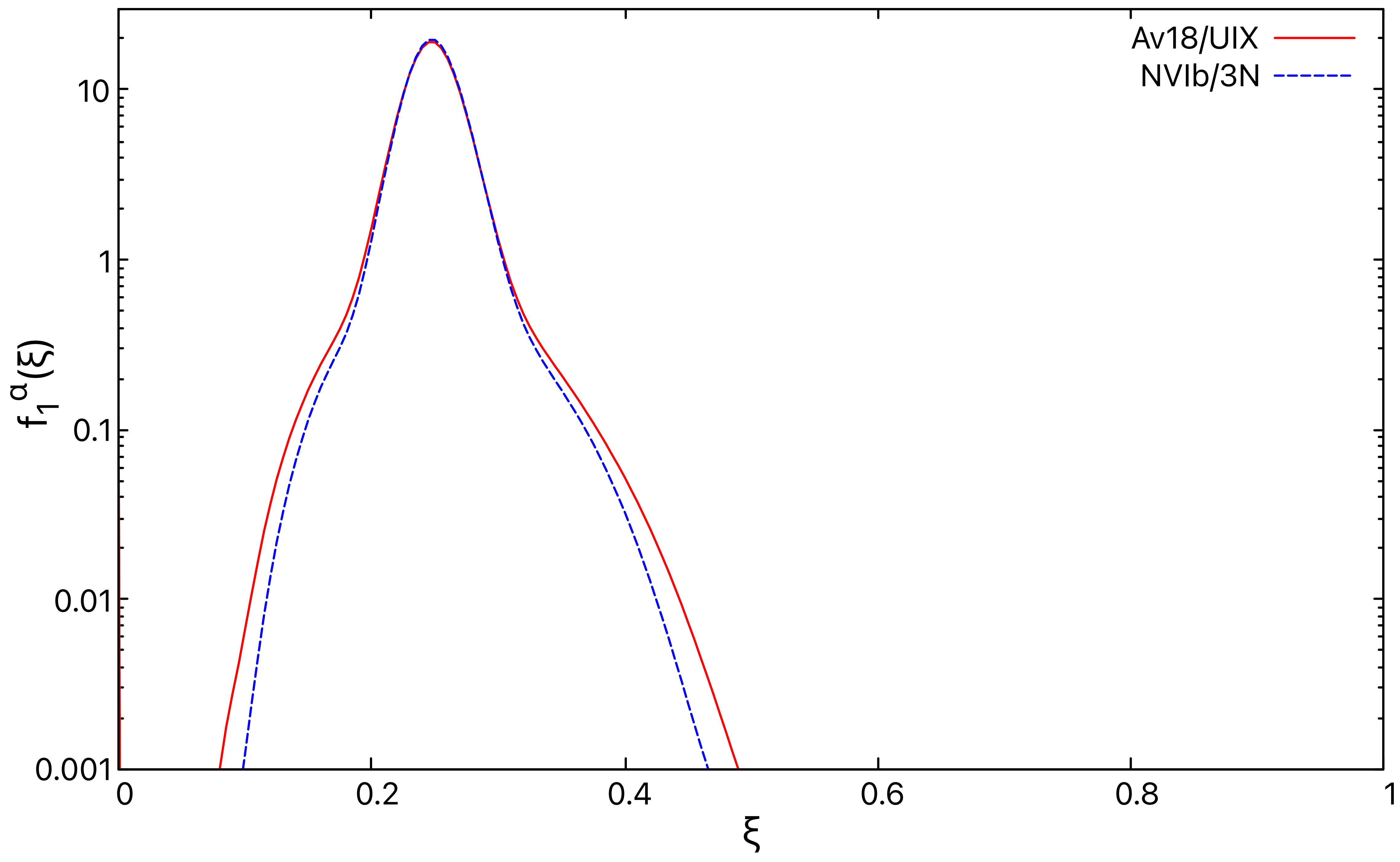
Numerically checked with an accuracy of $\simeq \dfrac{1}{1000}$

Realistic nuclear description

Poincaré covariance

Macroscopic lo

Number of particles and momentum sum rules automatically satisfied



$$N = 4\int_0^1 d\xi\, f_1^\alpha(\xi) = 4$$

$$<\xi> = \int_0^1 d\xi\,\xi\, f_1^\alpha(\xi) = \frac{1}{4}$$

Dependence on F_2^p

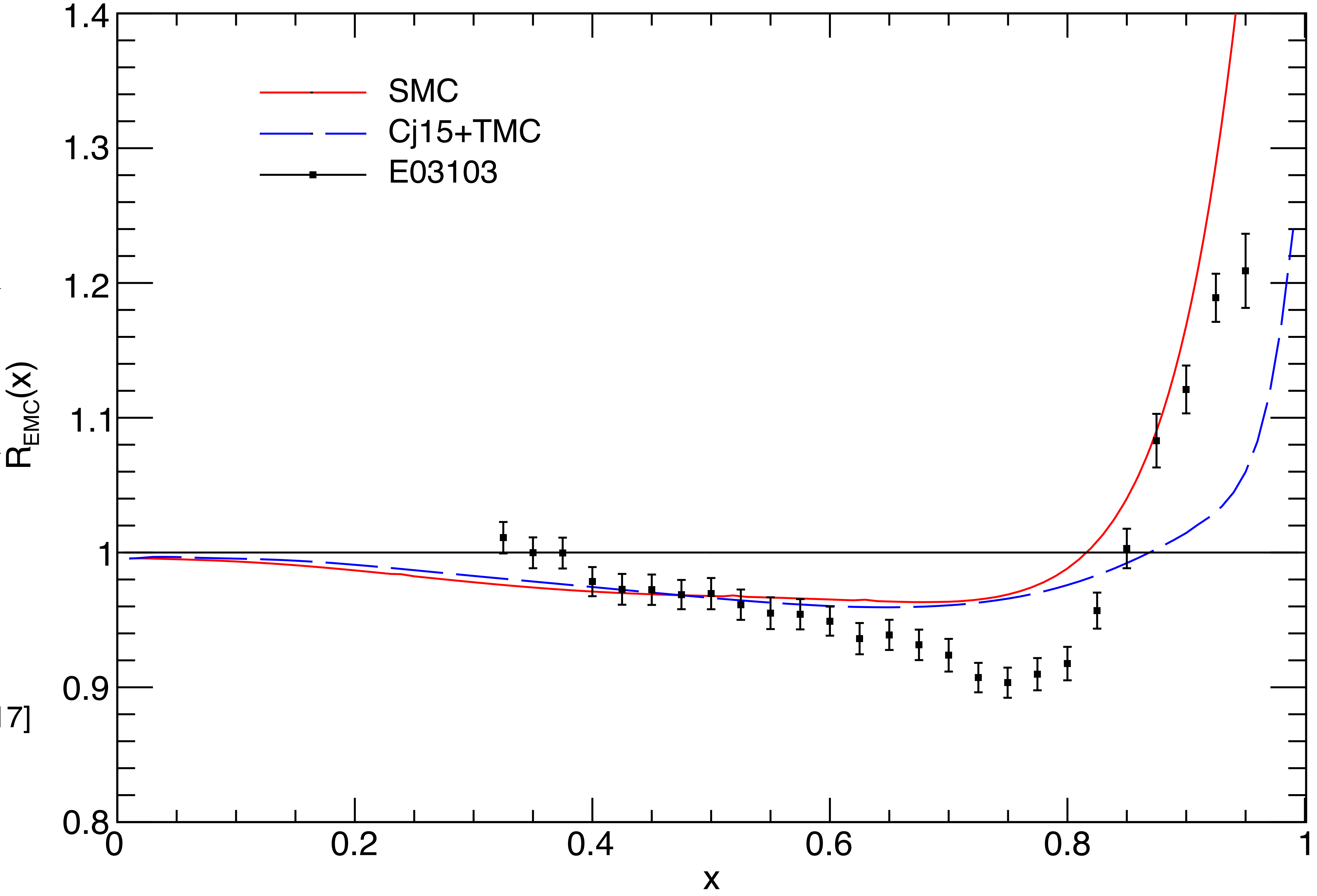
Av18/UIX

SMC parametrization of F_2^p

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

CJ15 parametrization of F_2^p

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



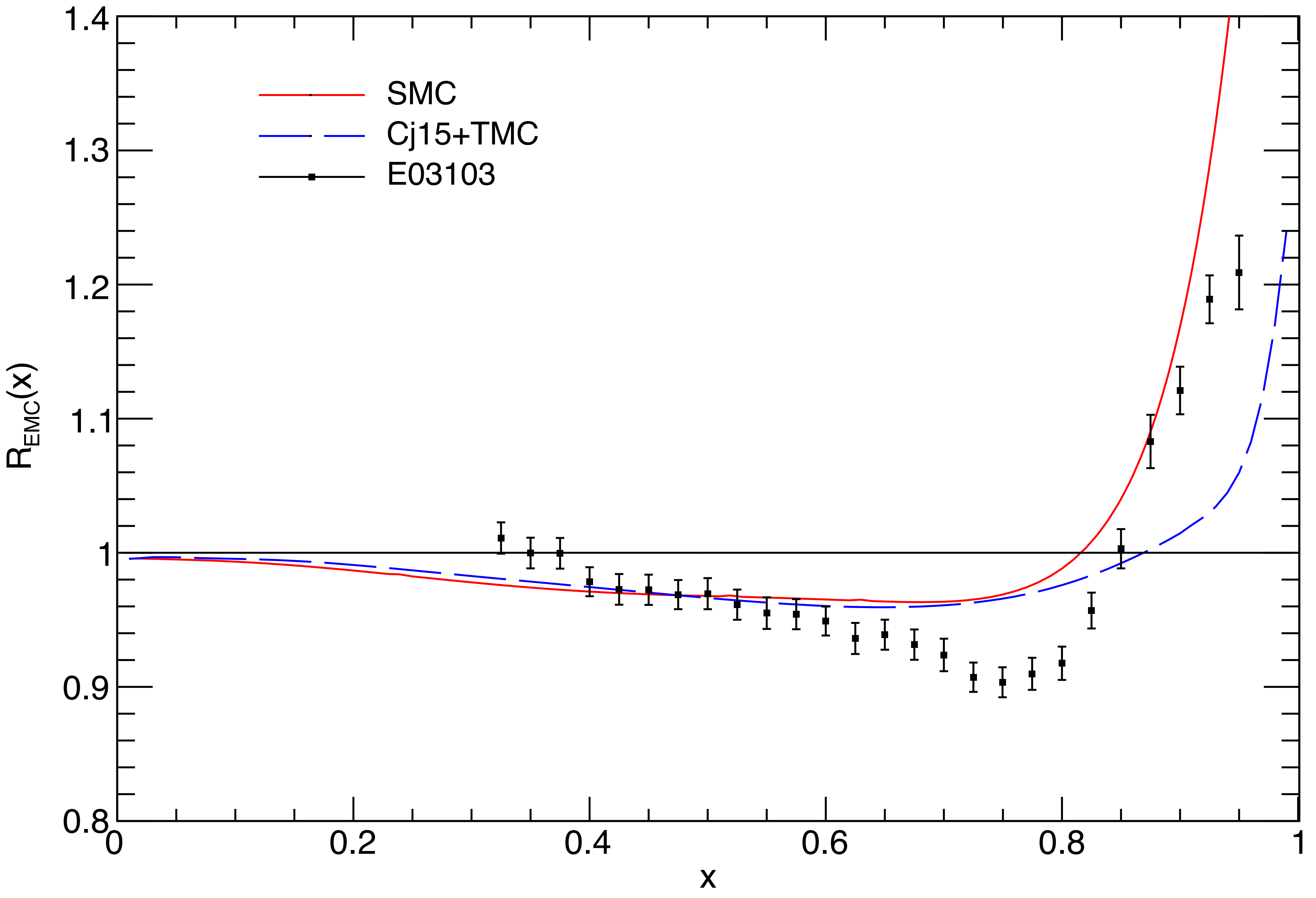
Full squares: JLab data from experiment E03103

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

Dependence on F_2^p

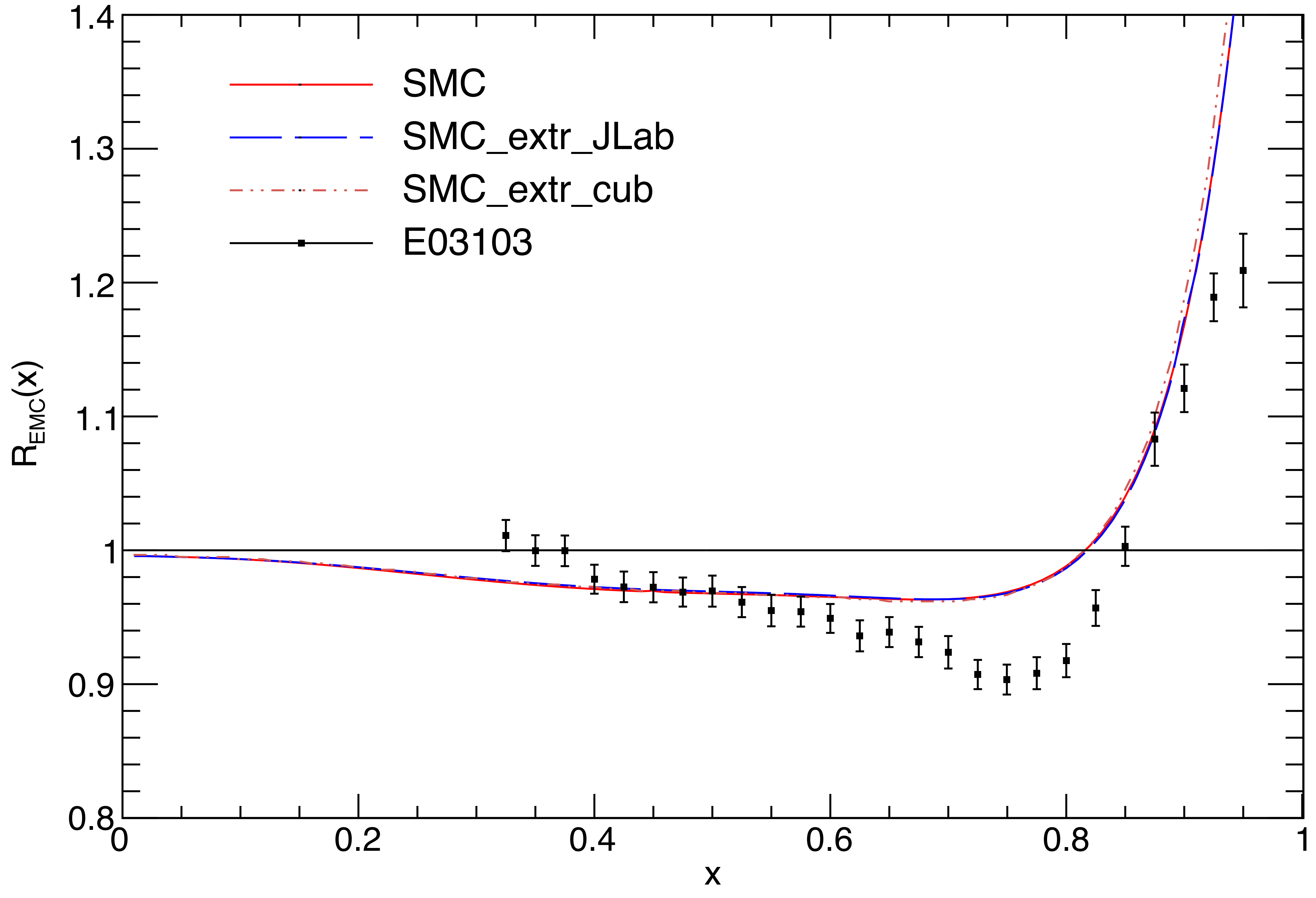
Result similar to ^3He one

- Small difference up to $x \simeq 0.75$
- Big difference for large x



- Evidence of the lack of knowledge of F_2^p for $x > 0.7$
- That does not affect the typical range of x where the EMC effect manifest

Dependence on F_2^n/F_2^p



Av18/UIX wave function

SMC parametrization of F_2^p

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

Recent extraction of F_2^n/F_2^p from MARATHON data

[H. Valenty, J. R. West, F. Benmokhtar, D. W. Higinbotham, A. Parker, E. Seroka, Phys. Rev. C 107 (6) (2023) 065203]

[D. Abrams, et al., Phys. Rev. Lett. 128 (2022) 132003]

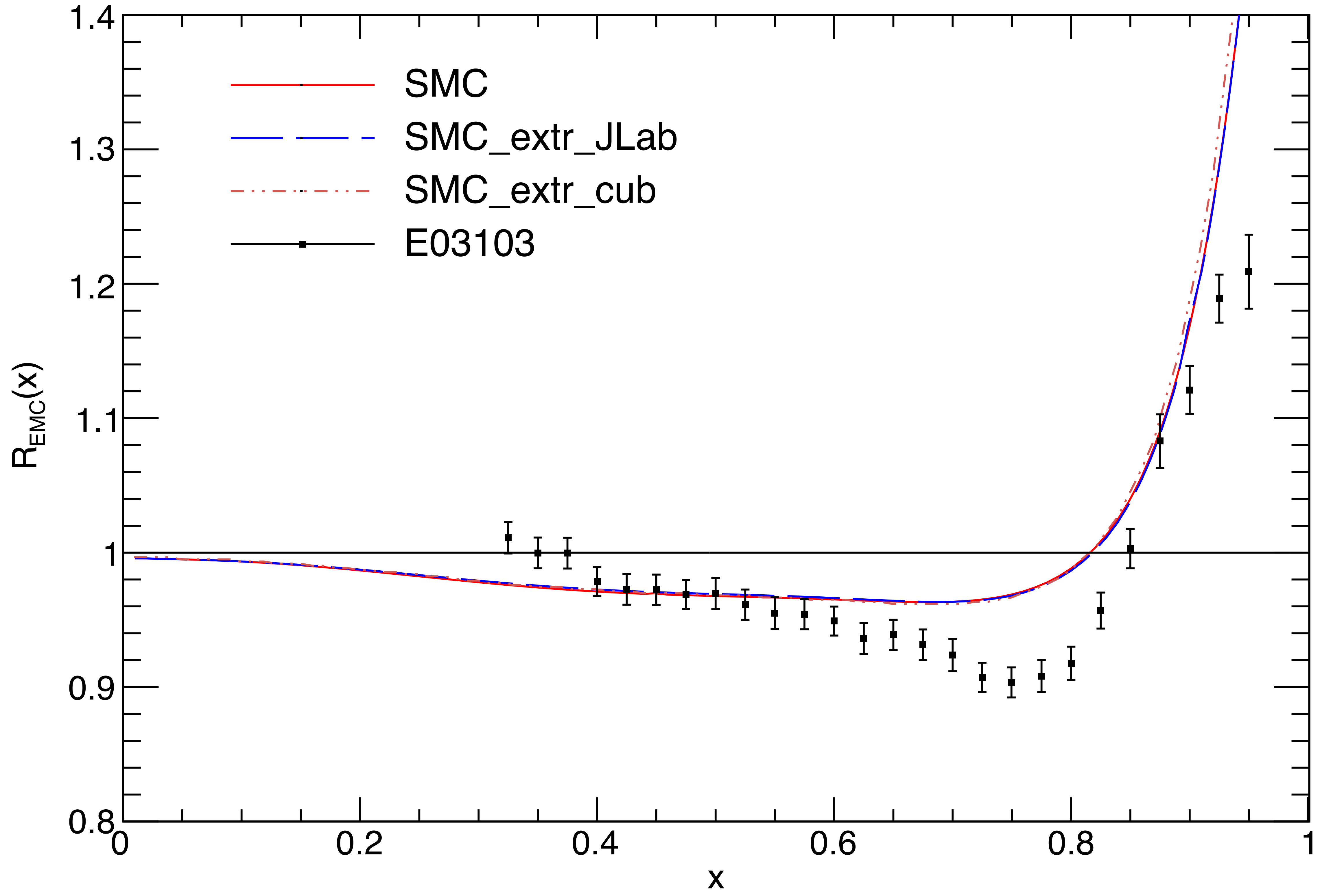
Cubic extraction of F_2^n/F_2^p from MARATHON data

[E. Pace, M. Rinaldi, G. Salmè, S. Scopetta, Phys. Lett. B 839 (2023) 137810]

[D. Abrams, et al., Phys. Rev. Lett. 128 (2022) 132003]

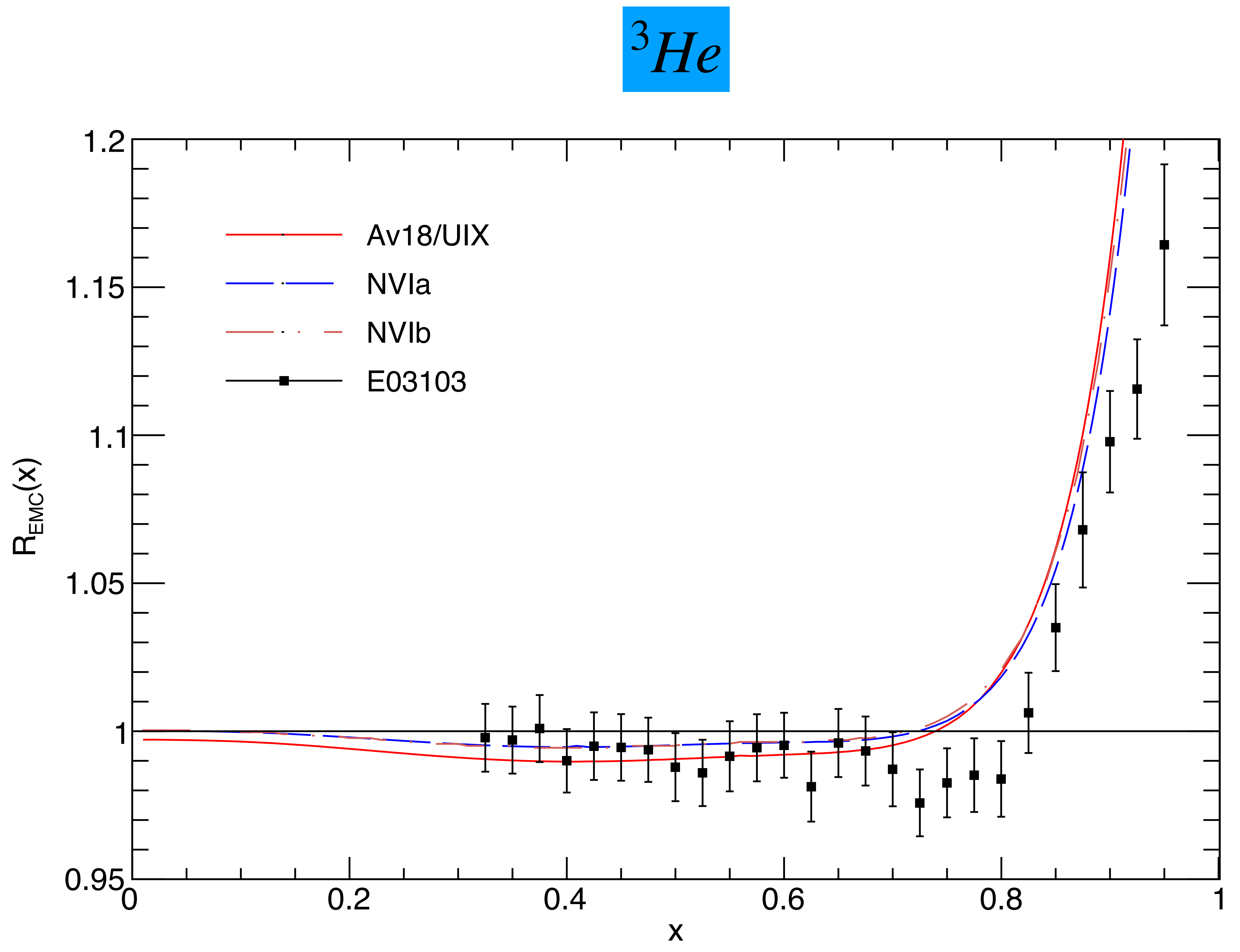
SMC parametrization of F_2^n

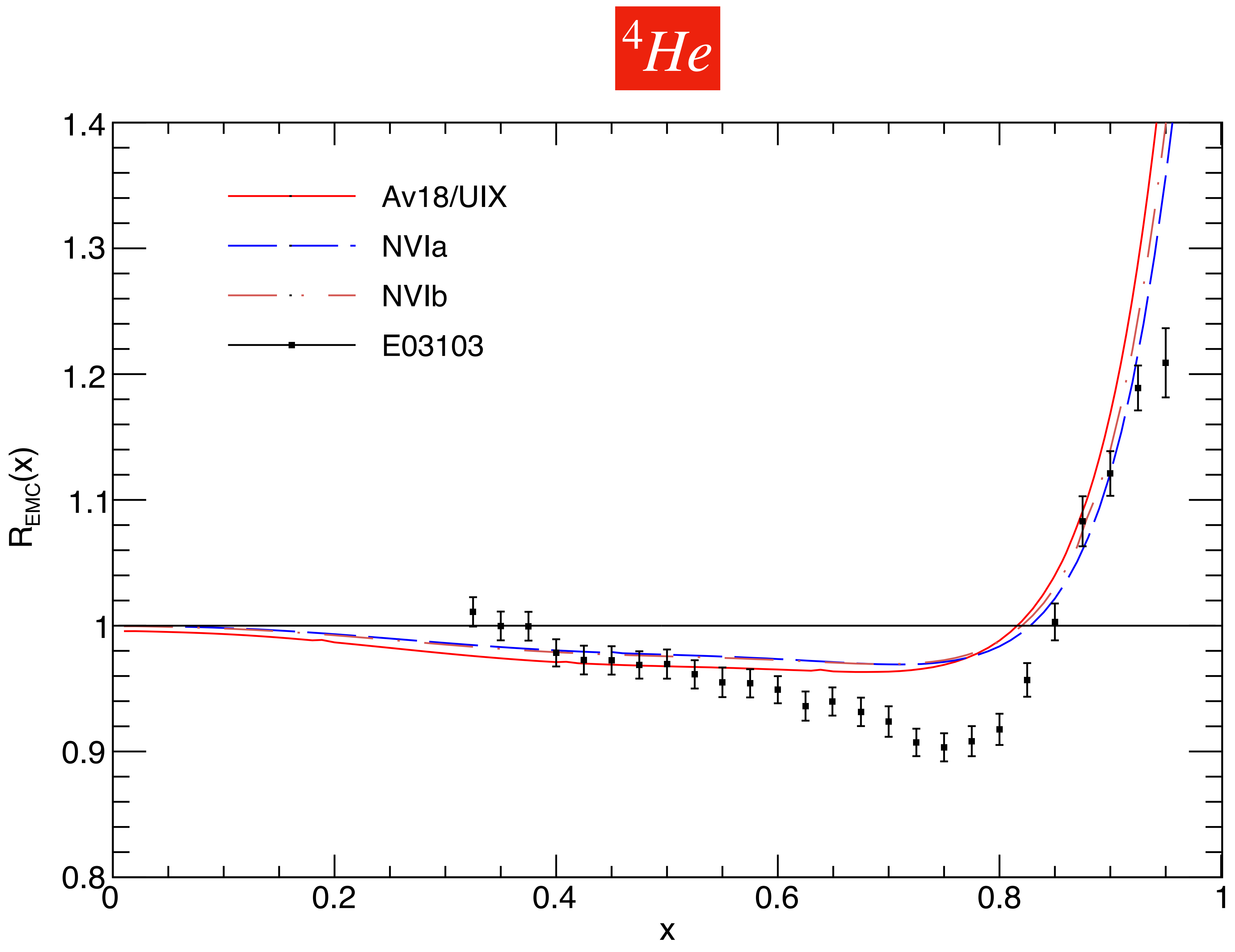
Dependence on F_2^n/F_2^p



- All the three lines are almost overlapping
- The dependence on the ratio F_2^n/F_2^p is largely under control
- The dependence on F_2^n is carried only by the dependence on F_2^p

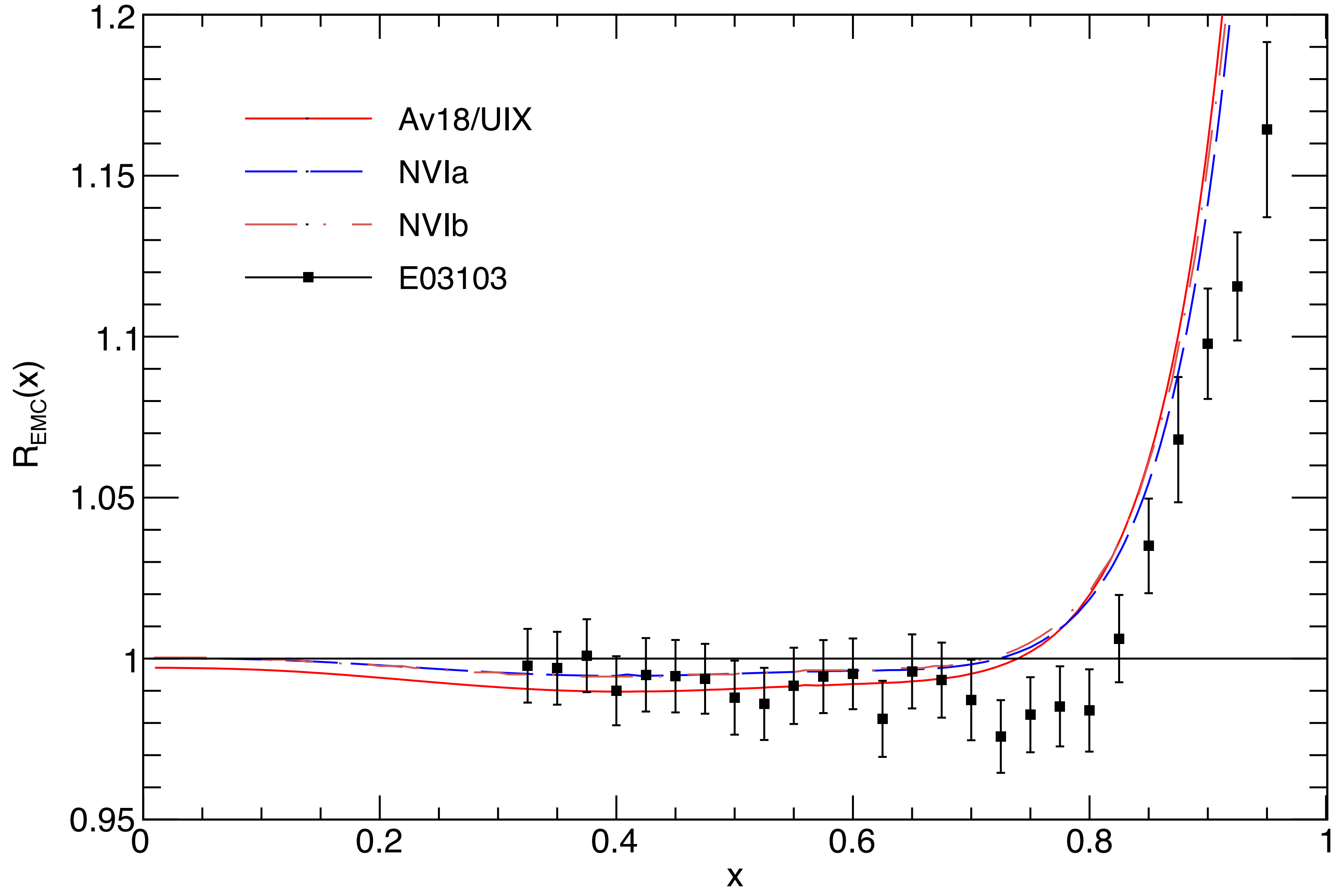
Dependence on potentials



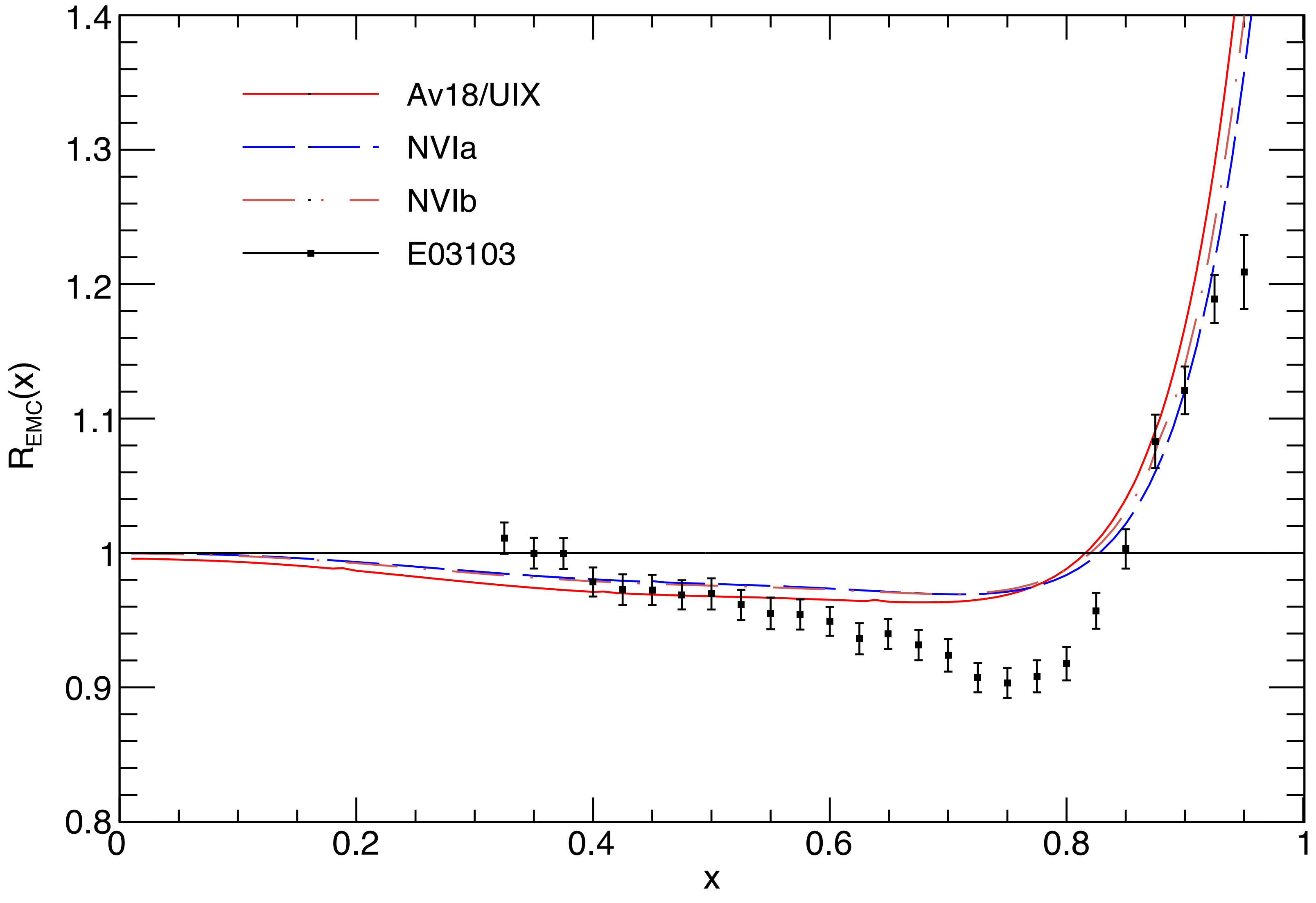


Dependence on potentials

^3He

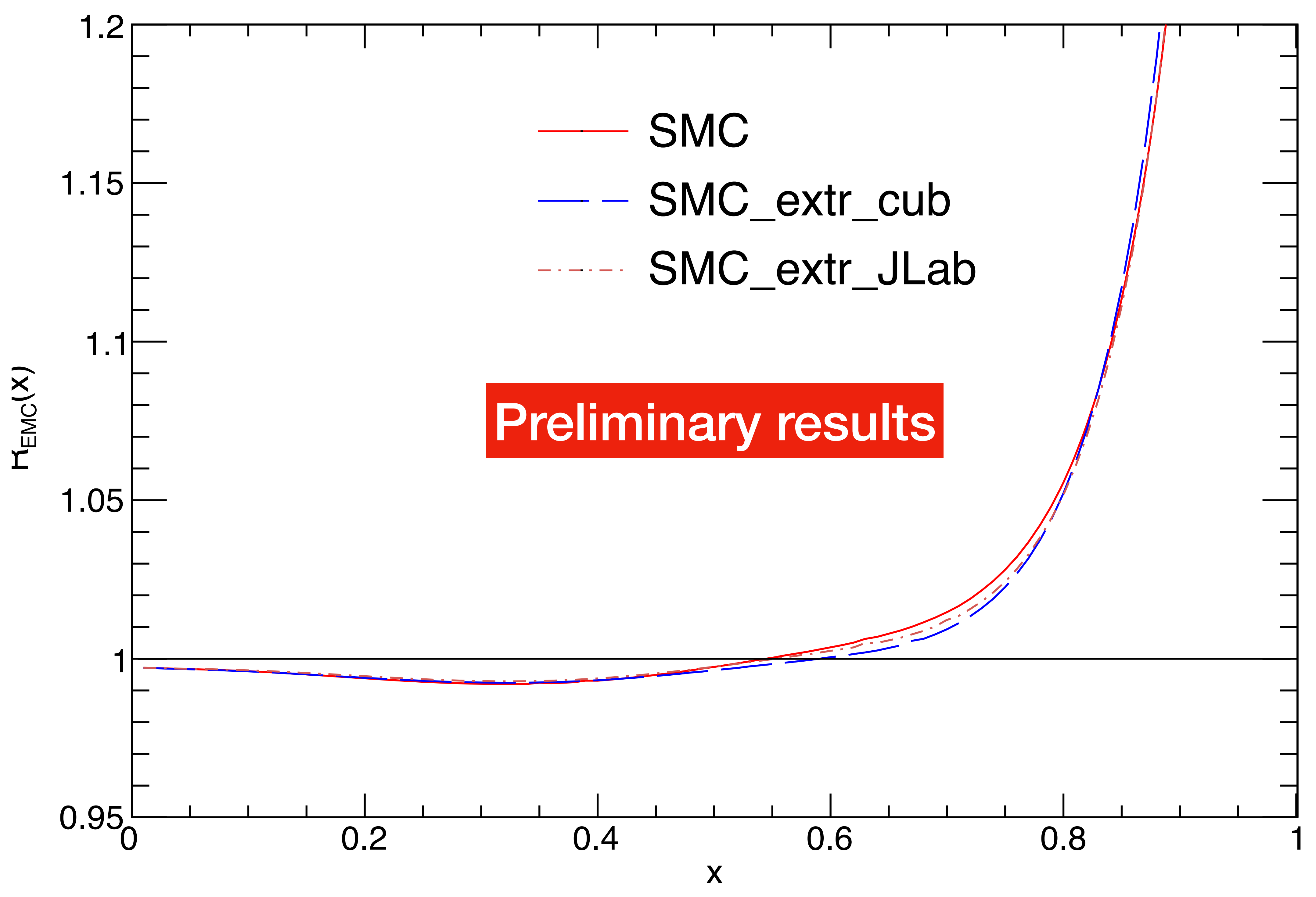


^4He



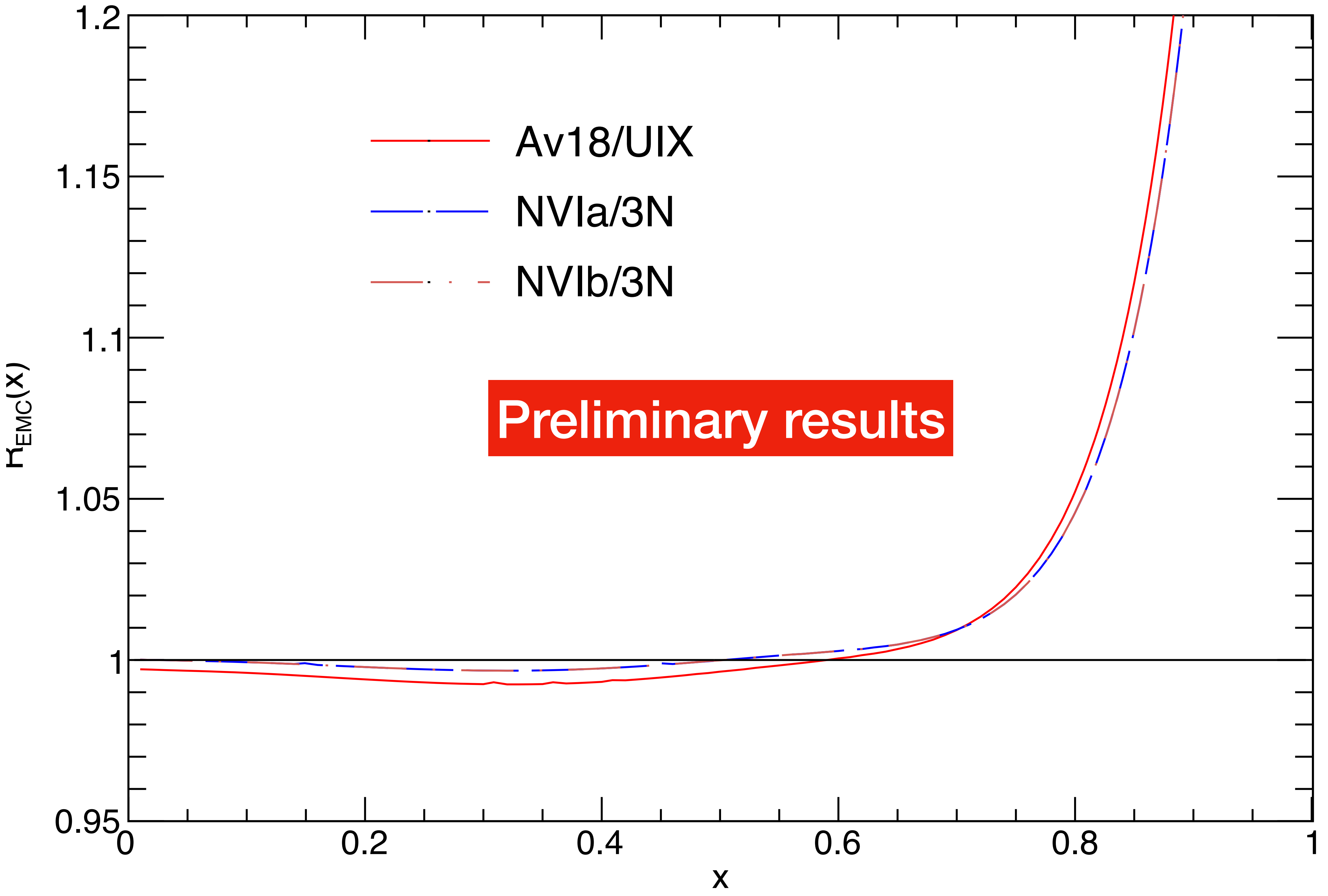
- The differences between the calculations from different potentials are of the same order for both nuclei
- They are definitely less than the difference between data and theoretical prediction

EMC for ^3H: preliminary results



- We have calculated the EMC ratio also for ^3H with the same approach adopted for ^3He and ^4He
- The difference between different $\frac{F_2^n}{F_2^p}$ parametrization is bigger than ^4He and ^3He because of the neutron abundance
- It is still small compared to the EMC ratio

EMC for ^{3}H: preliminary results



- Also the comparison between the three potentials is similar to the ones obtained for ^{3}He and ^{4}He

Conclusions

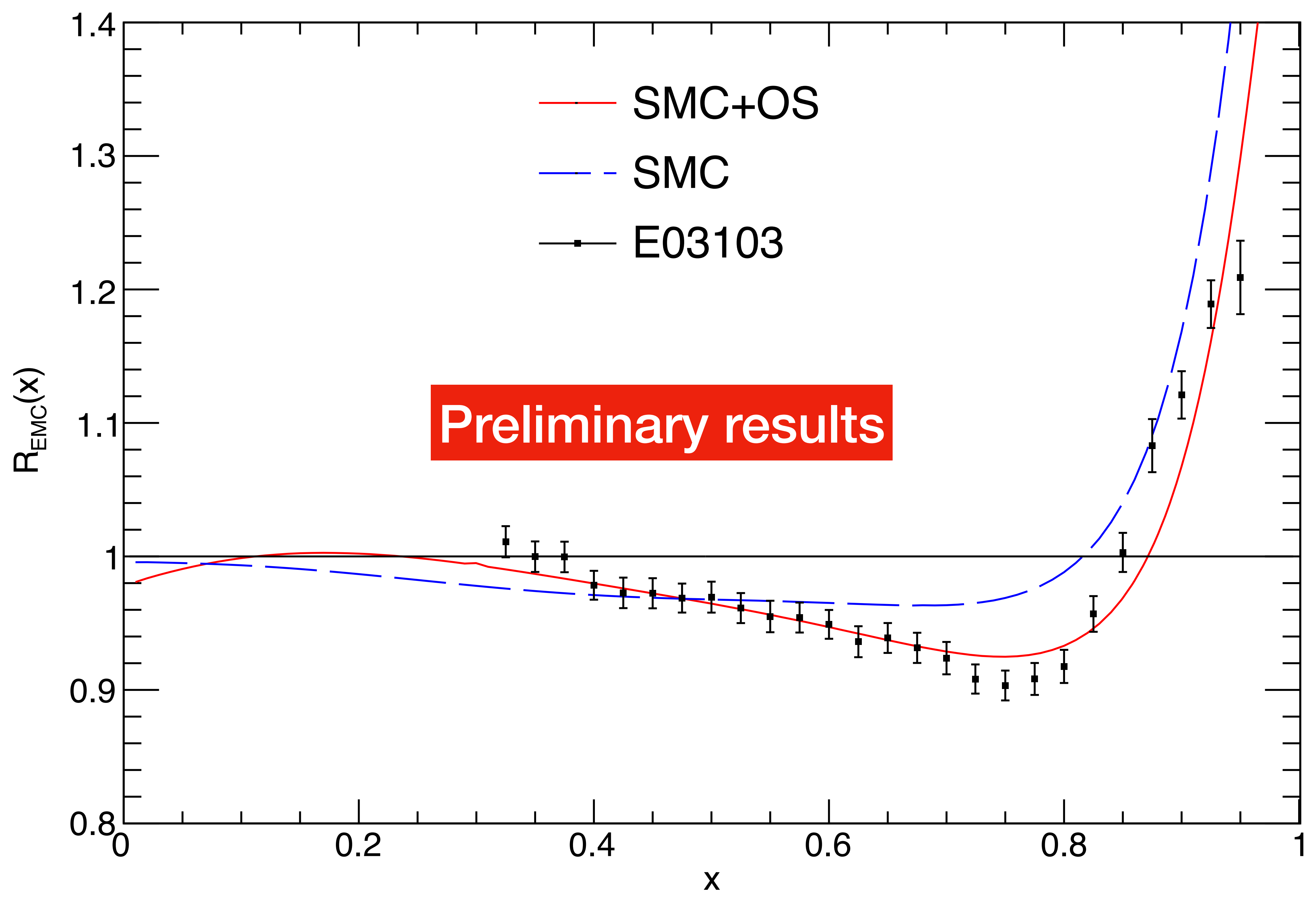
- The results for ^4He case increase confidence in our light-front approach, which includes only the nucleonic dof
- The difference between the R_{EMC} generated by different realistic nuclear potentials is relatively smaller than the EMC effect
- The deviations from experimental data could be ascribed to genuine QCD effects
- Our results could provide a reliable baseline to study exotic phenomena involving partonic dofs

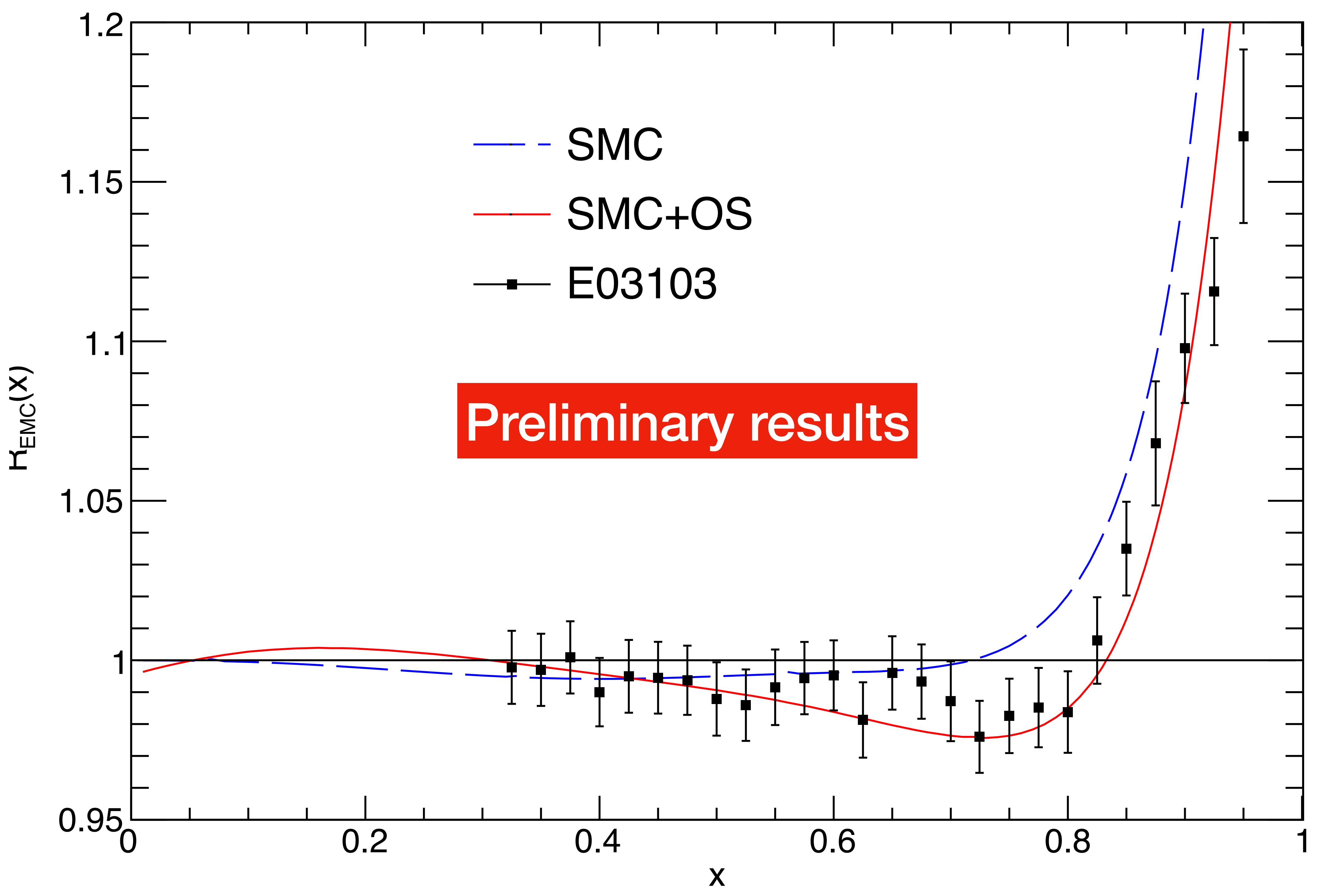
To do next:

- Try to include off-shell corrections
- Since we have extended the formalism to any nuclei: try to calculate the EMC-effect for heavier nuclei

Supplemental material

Off-shell

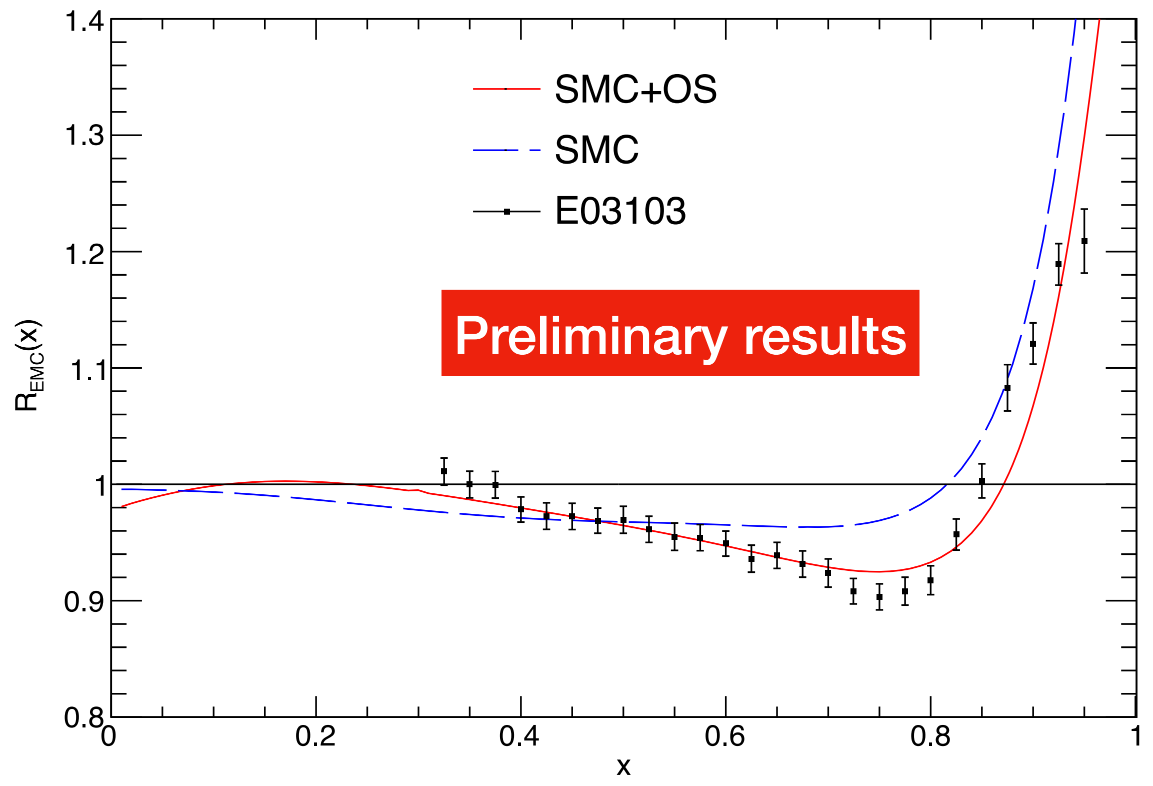


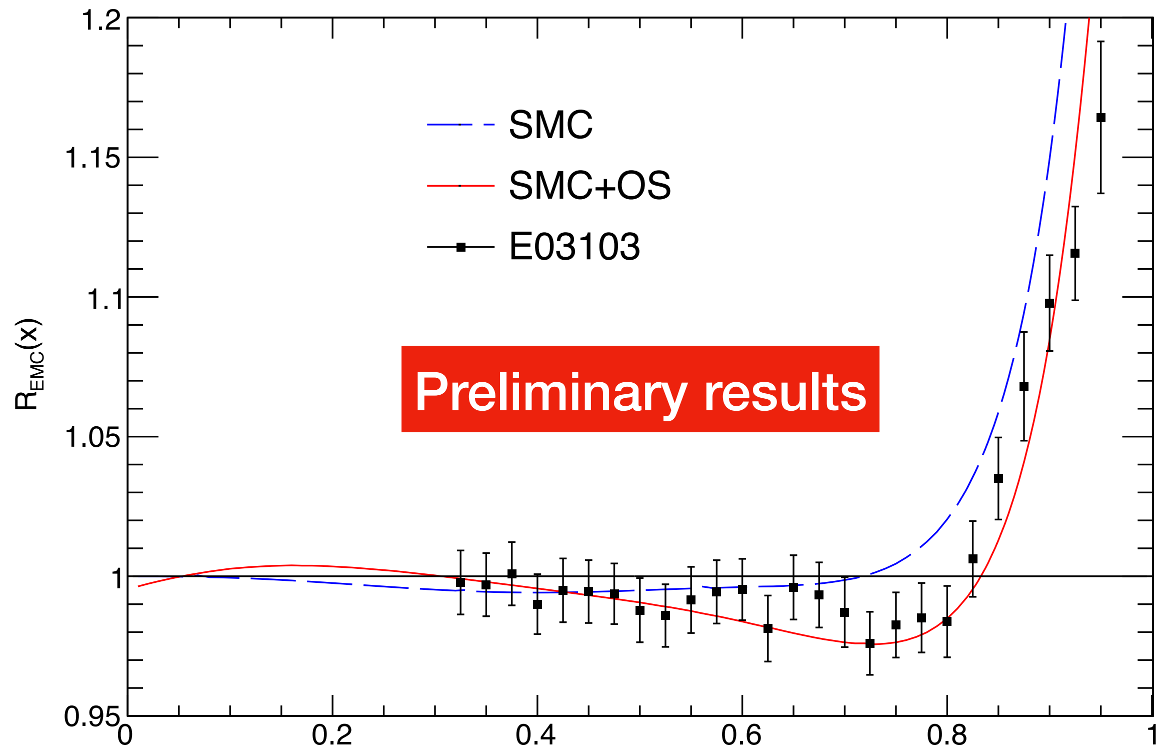


Kulagin-Petti model adapted to LF formalism

$$\delta f_2^N(x) = C_N(x - x_1)(x - x_0)(1 + x_0 - x_1)$$

Off-shell





$$\delta f_2^N(x) = C_N(x - x_1)(x - x_0)(1 + x_0 - x_1)$$

The parameters are fitted to JLab data for ^4He and we have applied the same correction to ^3He. $C_n = 3.7, x_0 = 0.45, x1 = 0.02$

We have to improve the fit and analyze the results

Study of heavier nuclei could be useful