Off-shell Effects in Bound Nucleons and Parton Distributions

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MOTIVATIONS

- *Precision studies of high-energy processes with nuclei require an understanding of nuclear effects at the parton level, which were observed to survive at $Q \gg 1$ GeV/c.*

- *The study of nuclear corrections in $^2H, ^3H, ^3He$ provides insights into the mechanisms responsible for modifications of PDFs in the nuclear environment:*
  - *Dynamics of A=2 and A=3 nuclei better understood than the dynamics of many-particle nuclei;*
  - *Effects of the momentum distribution, nuclear binding and off-shell modification of bound nucleons driven by the wave/spectral function, which is directly related to the underlying N-N interaction;*
  - *Mirror nuclei ^3H and ^3He give good sensitivity to isospin effects.*

  $\Longrightarrow$ *Compare with results obtained from heavier nuclear targets*

- *Use $^2H, ^3H, ^3He$ as "effective" neutron target in global QCD analyses:*
  - *Self-consistent determination of nuclear corrections, which strongly depend on x and Q^2 at large x;*
  - *Constrain uncertainties on d/u ratio at large x introduced by nuclear effects.*

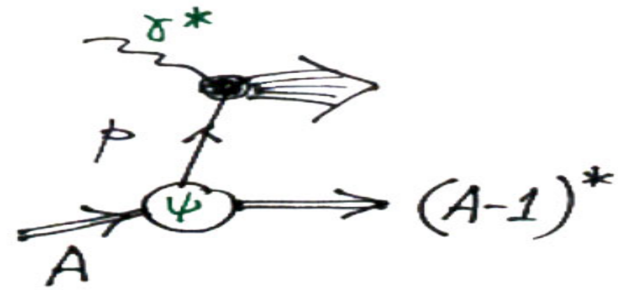
  $\Longrightarrow$ *Study interplay of nuclear effects with proton PDFs and high twist contributions*

NUCLEAR STRUCTURE FUNCTIONS AND NPDFs

Microscopic Kulagin-Petti (KP) model [NPA 765 (2006) 126, PRC 90 (2014) 045204].
At large x nuclear DIS dominated by incoherent scattering off bound nucleons:

✦ FERMI MOTION AND BINDING *effects in nuclear PDFs from the convolution of nuclear spectral function with (bound) nucleon PDFs:*

$$F_2^A = \sum_{i=p,n} \int \mathrm{d}\varepsilon \, \mathrm{d}^3\mathbf{p} \, \mathcal{P}_i(\varepsilon, \mathbf{p}) K_2 F_2^i(x', Q^2, p^2)$$



where $x' = Q^2/(2p \cdot q)$ and $p = (M+\varepsilon, \mathbf{p})$ and K_2 kinematic factor ($K_2 \approx 1 + p_z/M$ for $Q \gg M$).

✦ *Since bound nucleons are* OFF-MASS-SHELL *there appears dependence on the nucleon virtuality $p^2 = (M+\varepsilon)^2 - \mathbf{p}^2$ and expanding PDFs in the small $(p^2 - M^2)/M^2$:*

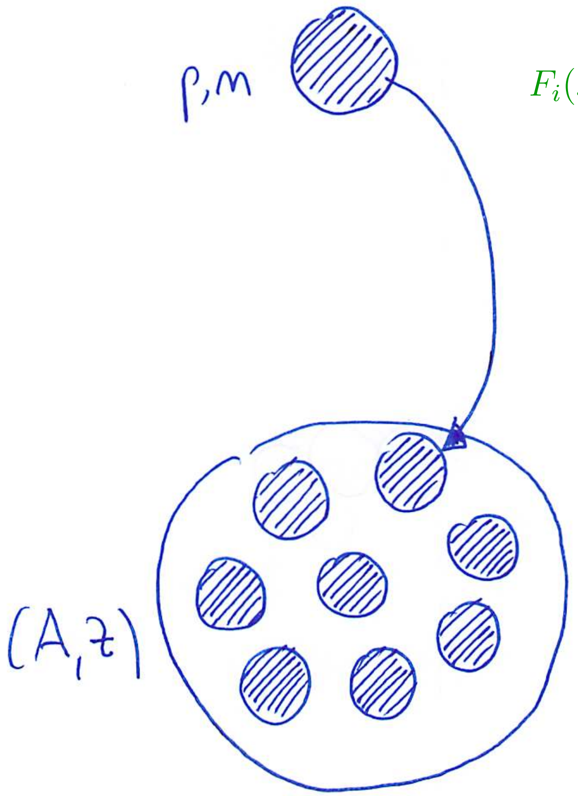
$$F_2^i(x, Q^2, p^2) \approx F_2^i(x, Q^2, p^2 = M^2) \left(1 + \delta f(x)(p^2 - M^2)/M^2\right).$$

where we introduced a universal function for the NUCLEON: $\boxed{\delta f(x)}$

$\Longrightarrow$ *Modification of bound nucleon partonic structure in the nuclear environment*

DESCRIPTION OF NUCLEON

Distribution of partons in a nucleon



STRUCTURE FUNCTIONS

$F_i(x,Q^2)$: *NNLO pQCD+TMC+HT from QCD fits*

$\boxed{\delta f(x)}$: *KP analysis of* σ^A/σ^B *DIS ratios*

DESCRIPTION OF NUCLEUS

Distribution of bound nucleons

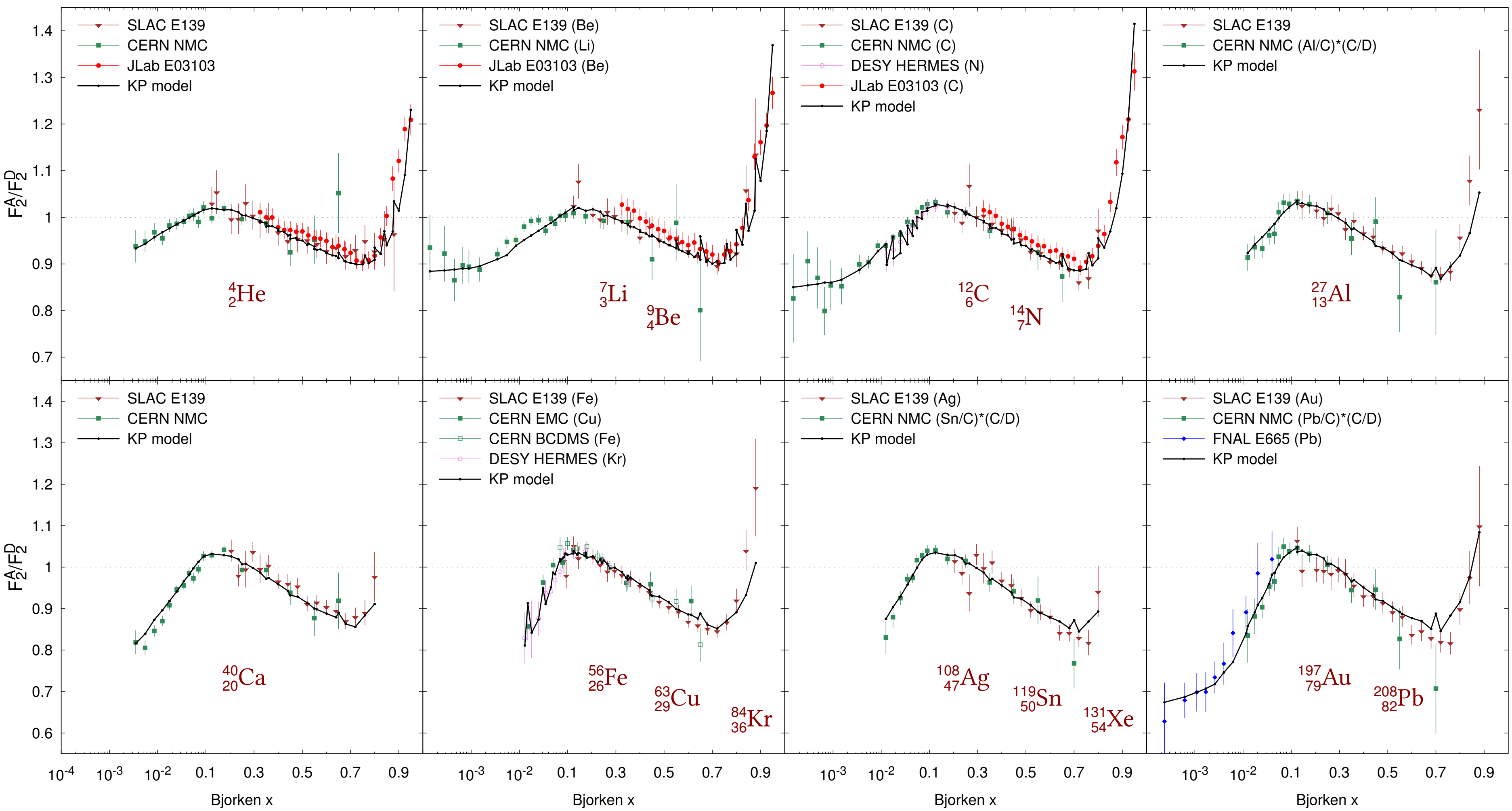
SPECTRAL FUNCTION

$\mathcal{P}(\varepsilon,\mathbf{p})$: *mean field + N-N correlated part*

Model includes meson-exchange current (MEC) correction balancing nuclear light-cone momentum and coherent multiple scattering effects responsible for nuclear shadowing

[NPA 765 (2006) 126, arXiv:hep-ph/0412425]

NPA 765 (2006) 126, PRC 82 (2010) 054614, EPJ Web. Conf. 138 (2017) 01006

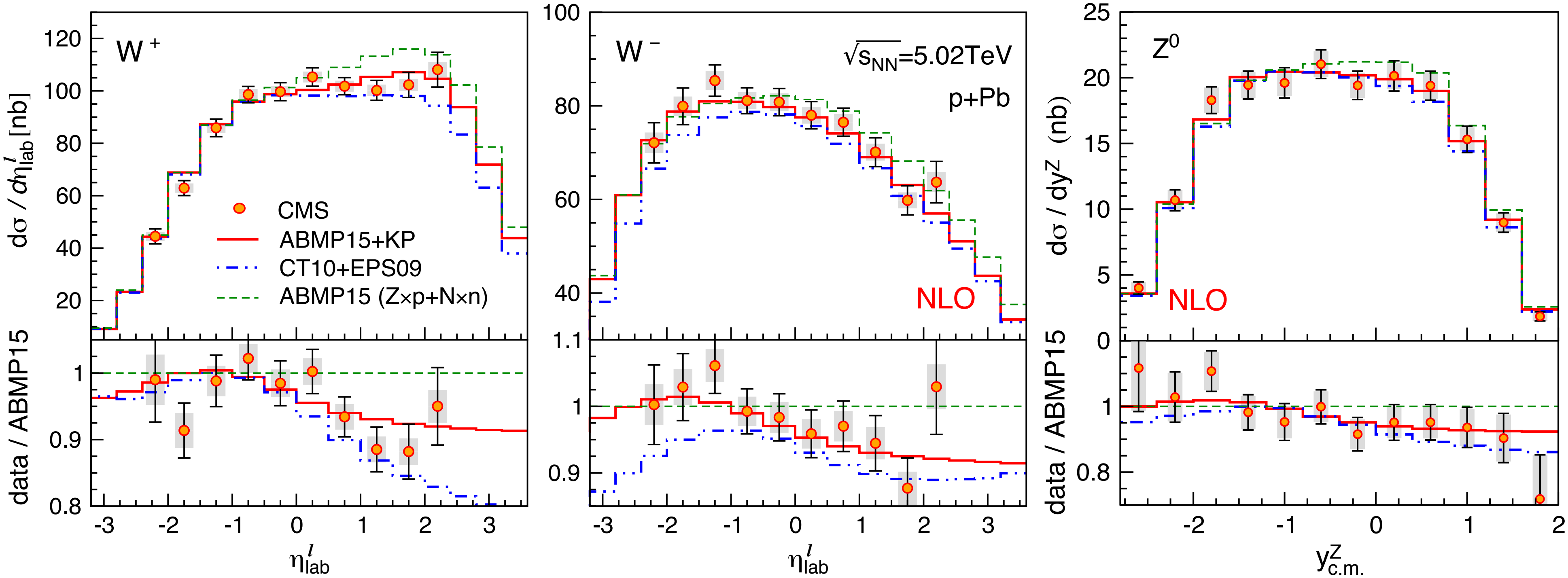


Microscopic KP model provides quantitative description of available data:

$\chi^2/N_{\text{Data}} = 466.6/586$ *for DIS data with* $Q^2 \geq 1$ *GeV*^{2}

$\Longrightarrow$ *Evidence for off-shell modification of bound nucleons from inclusive DIS*

$Q^2 = m^2_{W,Z}$



Predictions from KP model in excellent agreement with
Drell-Yan and $W^\pm/Z$ boson production in pPb collisions up to $Q^2 = m^2_{W,Z}$

(PRC 90 (2014) 045204; PRD 94 (2016) 113013)

OFF-SHELL FUNCTION FROM GLOBAL QCD ANALYSIS

✦ *Structure functions are parameterized in the NNLO QCD approximation, supplemented by two (isoscalar) High Twist (HT) corrections to F_2 and F_T:*

$$F_{2,T}(x,Q^2) = F_{2,T}^{\mathrm{LT,TMC}}(x,Q^2) + \frac{H_{2,T}^N(x)}{Q^2}$$

- *Target mass corrections (TMC) in the Leading Twist (LT) term following Georgi-Politzer;*
- *Fixed flavor number scheme (FFNS) with $n_f = 3$ and $\overline{\mathrm{MS}}$ running masses for heavy quarks;*
- *PDFs are parameterized following ABMP16 at the initial scale $Q_0^2 = 9$ GeV^2 [PRD 96 (2017) 014011];*
- *Analysis performed in the region $\boxed{Q^2 > 2.5\ GeV^2}$ and $\boxed{W^2 > 3\ GeV^2}$.*

✦ *Off-shell function parameterized as generic second order polynomial to avoid model-dependent biases related to the functional form used:*

$$\delta f(x) = a + b\,x + c\,x^2$$

- *Neglect nuclear effects related to meson exchange currents and shadowing since focus at $x > 0.1$;*
- *^{2}H wave functions: AV18 (default), Paris, CD-Bonn, WJC1, WJC2.*
- *^{3}H and ^{3}He spectral functions: Rome with AV18 NN (default), Hannover with Paris NN.*

$\Longrightarrow$ *Simultaneous extraction of $\delta f(x)$, PDFs, and HT from global QCD analysis*

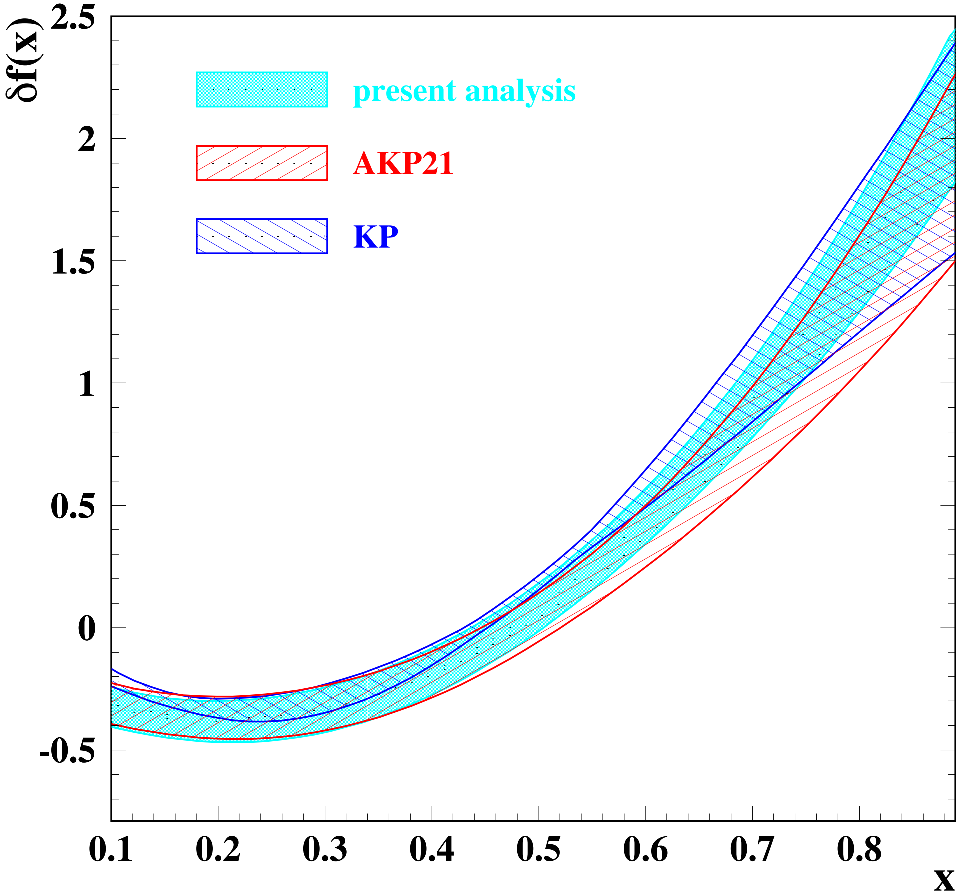
PRD 107 (2023) L051506, arXiv: 2211.09514 [hep-ph]; PRD 105 (2022) 114037; PRD 96 (2017) 054005

PRD 107 (2023) L051506, arXiv: 2211.09514 [hep-ph]

Facility	Experiment	Beam	Beam energy (GeV)	Observable	Normalization factor	Normalization error(s) (%)	$\frac{\chi^2}{\mathrm{NDP}}$
SLAC	E49a	e	$11 \div 19.5$	$\frac{\mathrm{d}^2\sigma^d}{\mathrm{d}E'\mathrm{d}\Omega}$	0.988(10)	2.1[a]	25/59
”	E49b	”	$4.5 \div 18$	”	0.996(10)	”	187/145
”	E87	”	$8.7 \div 20$	”	1.000(9)	”	114/109
”	E89b	”	$10.4 \div 19.5$	”	0.987(9)	”	52/72
”	E139	”	$8 \div 24.5$	”	1.002(9)	”	8/17
”	E140	”	$3.7 \div 19.5$	”	1	1.7	25/26
CERN	BCDMS	μ	$100 \div 280$	$\frac{\mathrm{d}^2\sigma^d}{\mathrm{d}x\mathrm{d}Q^2}$	0.989(7)	3	273/254
”	NMC	”	$90 \div 280$	F_2^d/F_2^p	1	< 0.15	155/165
DESY	HERMES	e	27.6	σ^d/σ^p	1	1.4	21/30
JLab	E00-116	e	5.5	$\frac{\mathrm{d}^2\sigma^d}{\mathrm{d}E'\mathrm{d}\Omega}$	0.981(10)	1.75	208/136
”	BONuS	”	4.2, 5.2	F_2^n/F_2^d	0.97(9)	$7 \div 10$	90/63
”	MARATHON	”	10.6	σ^d/σ^p	1	0.55	8/7
”	**MARATHON**	**”**	**10.6**	$\boldsymbol{\sigma^{^3He}/\sigma^{^3H}}$	**1**	**0.7**	**20/22**
Total							1186/1105

List of ^2H, ^3H, and ^3He data used in the global QCD analysis

RESULTS ON $\delta f(x)$



- *Different Q^2 dependence allows to disentangle off-shell correction from PDFs and HT*
- *Results on $\delta f(x)$ agree with heavy target determination $(A \geq 4)$ and our previous extraction from D data.*
- *Determination of δf from QCD fits stable against all systematics studied.*

$\Longrightarrow$ *Agreement with KP predictions based on δf universality*

MODEL VARIANTS

✦ *Multiplicative vs. additive implementation of High Twist (HT) terms:*

$$F_{2,T}(x,Q^2) = F_{2,T}^{\mathrm{LT,TMC}}(x,Q^2) + H_{2,T}^{N}(x)/Q^2$$
$$F_{2,T}(x,Q^2) = F_{2,T}^{\mathrm{LT,TMC}}(x,Q^2) + F_{2,T}^{\mathrm{LT}}(x,Q^2)h_{2,T}^{N}(x)/Q^2$$

$\Longrightarrow$ *Study impact of HT model on determination of LT and off-shell function δf*

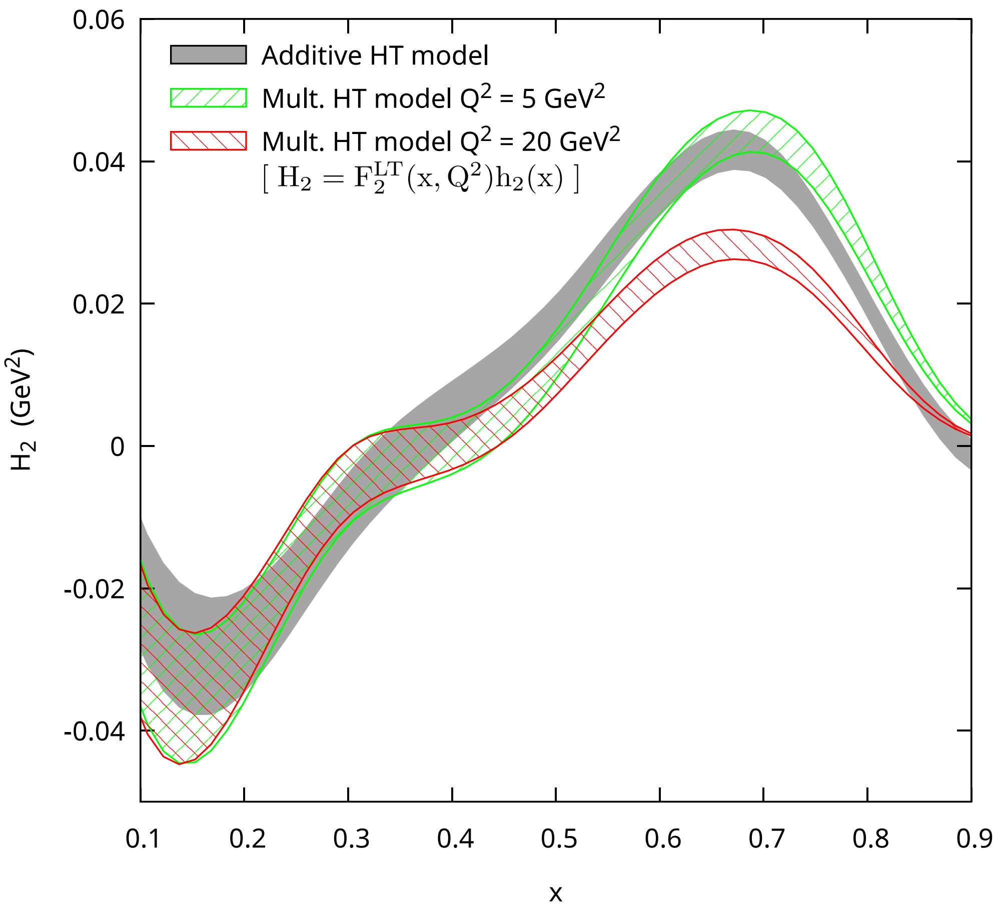
✦ *Neutron-proton asymmetry in off-shell modification of bound nucleons parameterized as generic first order polynomial:*

$$\delta f^a(x) \equiv \delta f^n(x) - \delta f^p(x) = a_1 + b_1 x$$

- *Universality of isoscalar δf for all nuclei verified with wide range of targets with A$\geq$4 [NPA 765 (2006) 126], A=3 [PRC 82 (2010) 054614, PRL 128 (2022) 132002], and A=2 [PRD 105 (2022) 114037; PRD 96 (2017) 054005];*
- *MARATHON $\sigma^{^3He}/\sigma^{^3H}$ data [PRL 128 (2022) 132003] provides good sensitivity to n-p differences.*

$\Longrightarrow$ *Test/constrain a possible isospin dependence in the off-shell function δf*

HIGH TWIST CONTRIBUTIONS



- *Different Q^2 dependence for additive and multiplicative HT due to the interplay with LT.*

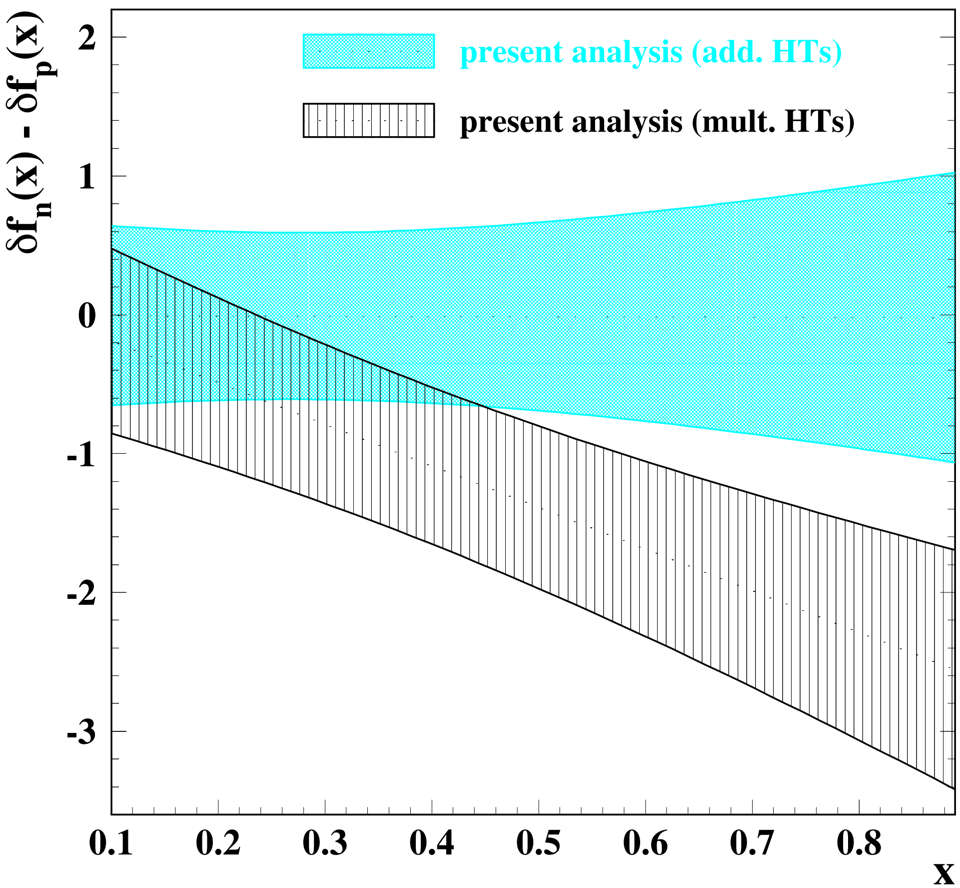
- *Consistent results from our fits with additive and multiplicative HT.*

- *Intrinsic n-p difference in HT for multiplicative HT from the LT factor with isoscalar $h_{2,T}^N$ coeffficients:*

$$F_{2,T}^n = F_{2,T}^{\mathrm{LT,n}} \left(1 + h_{2,T}^N / Q^2\right)$$
$$F_{2,T}^p = F_{2,T}^{\mathrm{LT,p}} \left(1 + h_{2,T}^N / Q^2\right)$$

$\Longrightarrow$ *Cancellation of HT terms in ratio* $F_{2,T}^n / F_{2,T}^p = F_{2,T}^{\mathrm{LT,n}} / F_{2,T}^{\mathrm{LT,p}}$

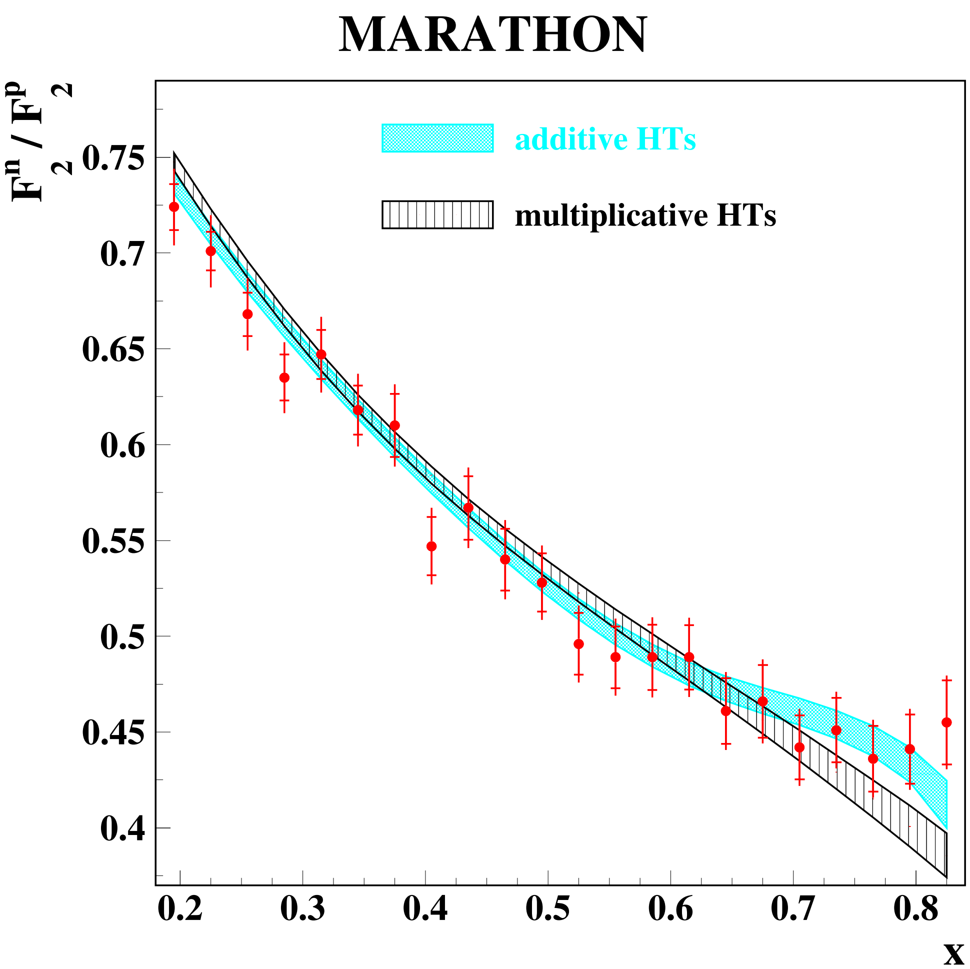
NEUTRON-PROTON ASYMMETRY δf^a



- *MARATHON* $\sigma^{^3He}/\sigma^{^3H}$ *allows an extraction of the n-p asymmetry* $\delta f^a(x)$.
- *Same* δf *obtained for protons and neutrons with additive HT model.*
- *Non-zero n-p asymmetry* δf^a *found with multiplicative HT model.*

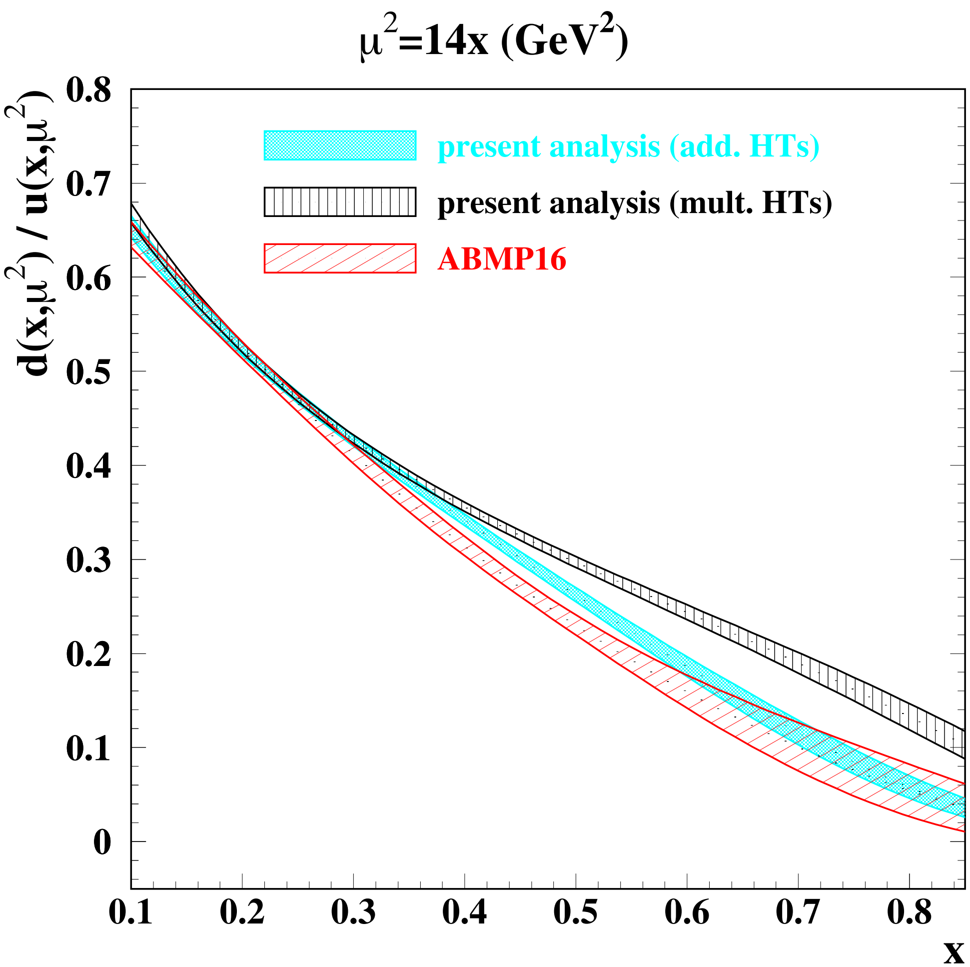
$\Longrightarrow$ *Bias introduced by LT-HT interplay in multiplicative HT model*

PREDICTIONS FOR F_2^n/F_2^p RATIO



- *Our predictions in excellent agreement with MARATHON F_2^n/F_2^p.*
- *Sensitivity of MARATHON data to HT contribution at large $x > 0.6$.*
- *MARATHON data prefers additive HT over multiplicative HT model: χ^2/NDP = 20/22 vs. 34/22.*

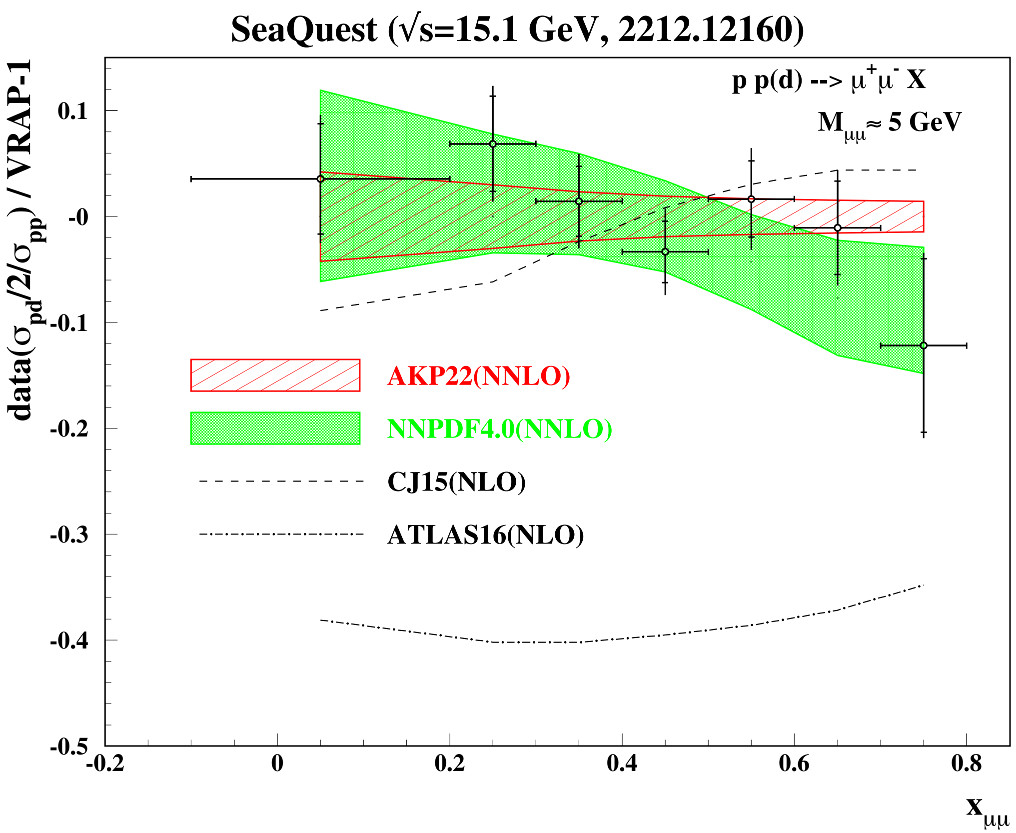
PREDICTIONS FOR d/u RATIO



- ✦ *Our predictions for d/u ratio agree with the ones from the ABMP16 QCD analysis without $^2H, ^3H, ^3He$ data.*
- ✦ *Fitting MARATHON $\sigma^{^3He}/\sigma^{^3H}$ with multiplicative HT terms results in substantial d/u enhancement at large x.*
- ✦ *Enhancement of d/u correlated with the non-zero n-p asymmetry δf^a observed with multiplicative HT.*

$\Longrightarrow$ *Could be checked with $W^{\pm}$ production from LHCb/D0 or future e & $\nu(\bar{\nu})$ CC*

COMPARISONS WITH E906 DRELL-YAN DATA



- *Our predictions in agreement with recent SeaQuest E906 data* (*not in fits*).
- *Prediction uncertainties comparable or smaller than the ones in E906 data.*
- *E906 data in clear disagreement with ATLAS16 QCD analysis.*

SUMMARY

- ✦ *The off-shell modification of bound nucleons leads to an important nuclear correction which can be described by a universal function $\delta f(x)$ for all nuclei.*

- ✦ *The δf function determined from $^2H, ^3H, ^3He$ within our global QCD analysis is consistent with the one obtained from inclusive DIS data on nuclear targets with $A \geq 4$ (Kulagin and Petti) and from our earlier QCD analyses of ^2H.*

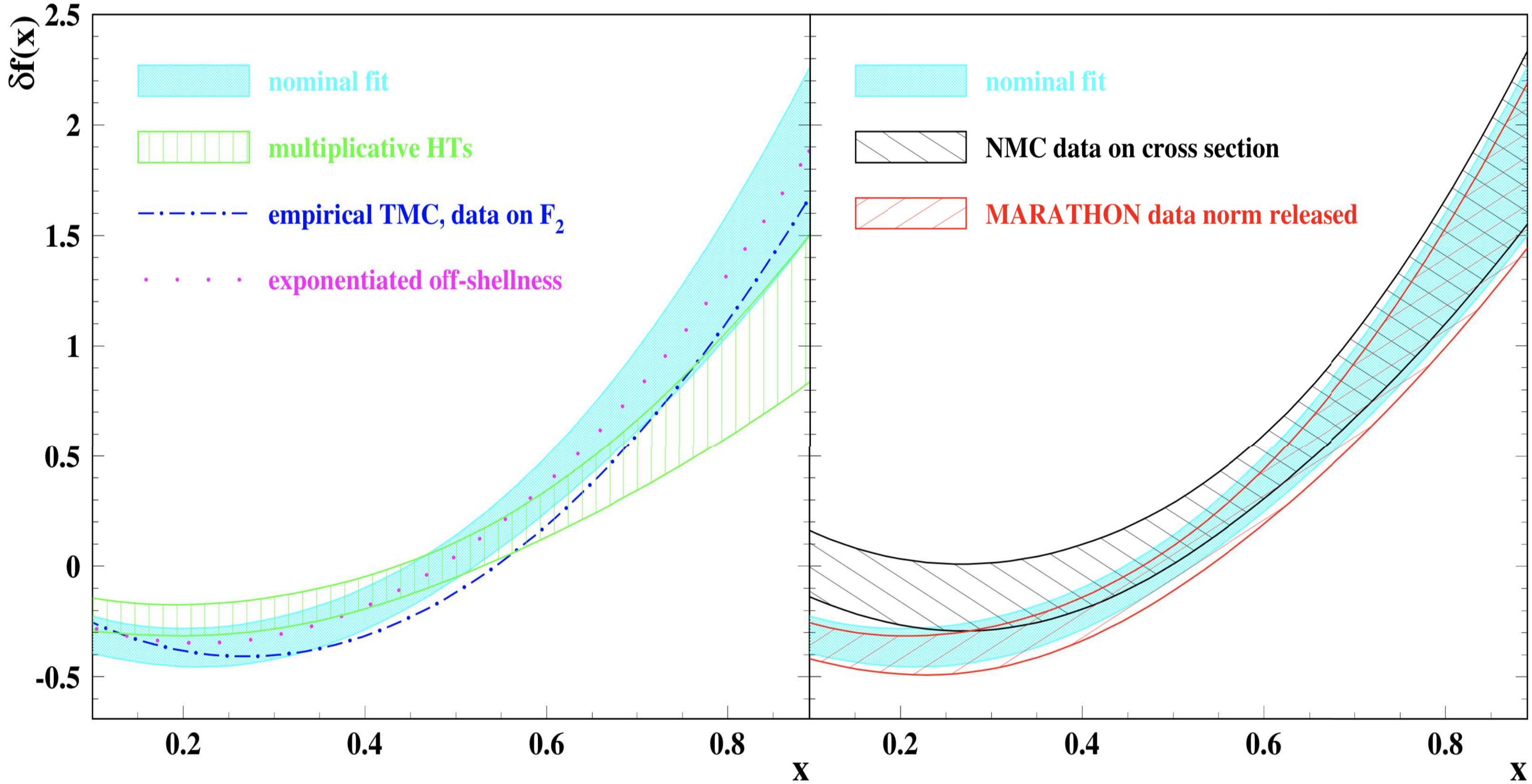
- ✦ *The results on δf are stable against systematic studies including variations of both the structure function model and the data sets used in the QCD analysis.*

- ✦ *We find no evidence for neutron-proton differences in the off-shell function δf from the QCD analysis of MARATHON $\sigma^{^3He}/\sigma^{^3H}$ data.*

  $\Longrightarrow$ *Excellent agreement with MARATHON data with isoscalar δf and additive HT*

- ✦ *Our analysis indicates that the LT-HT interplay in the multiplicative HT model can bias both the n-p asymmetry δf^a and the d/u ratio extracted from MARATHON data.*

Backup slides



✦ *Determination of δf from QCD fits stable against all systematic variations studied*

✦ *Effect of model systematics comparable with the ones from use of different data sets*

$\Longrightarrow$ *Consistency of results with nominal fit excludes model biases*

NUCLEAR SPECTRAL FUNCTION

- *Two-body ^{2}H spectral function determined by the wave function $\Psi_D(\mathbf{p})$:*

$$\mathcal{P}(\varepsilon,\mathbf{p}) = 2\pi\delta\left(\varepsilon - \varepsilon_D + \frac{\mathbf{p}^2}{2M}\right)|\Psi_D(\mathbf{p})|^2$$

where $\varepsilon_D = M_D - 2M \approx -2.2$ MeV is the binding energy.

- *Three-body ^{3}He and ^{3}H spectral functions from D bound state and continuum states:*

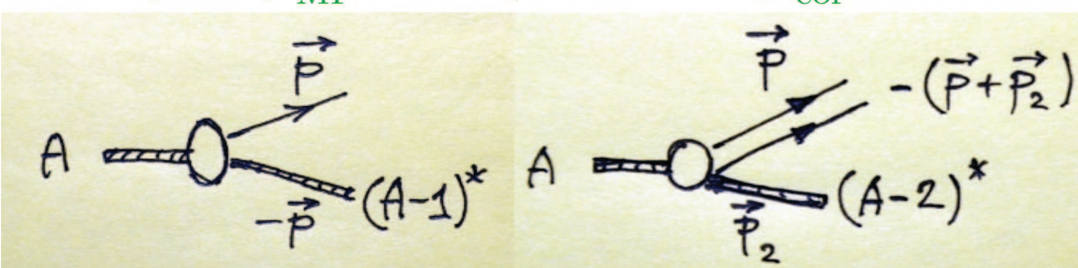
$$\mathcal{P}^p_{3He} = f^D_{3He}(\mathbf{p})\delta\left(\varepsilon + \varepsilon_{32} - \varepsilon_D + \frac{\mathbf{p}^2}{4M}\right) + f^{pn}_{3He}(\varepsilon,\mathbf{p}); \qquad \mathcal{P}^n_{3He} = f^{pp}_{3He}(\varepsilon,\mathbf{p})$$

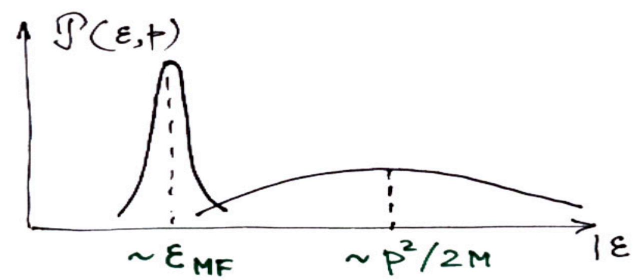
$$\mathcal{P}^n_{3H} = f^D_{3H}(\mathbf{p})\delta\left(\varepsilon + \varepsilon_{31} - \varepsilon_D + \frac{\mathbf{p}^2}{4M}\right) + f^{pn}_{3H}(\varepsilon,\mathbf{p}); \qquad \mathcal{P}^p_{3H} = f^{nn}_{3H}(\varepsilon,\mathbf{p})$$

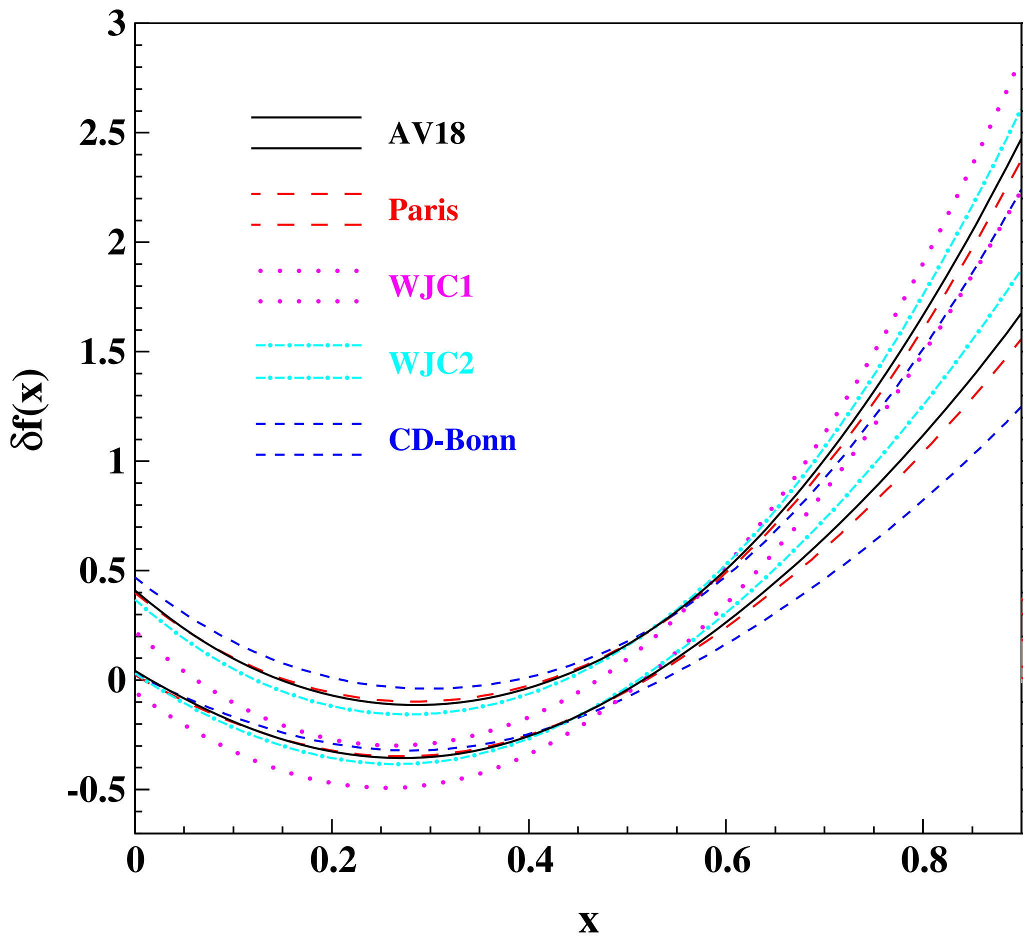
where $\varepsilon_{32} \approx -7.72$ MeV and $\varepsilon_{31} \approx -8.48$ MeV are the ^{3}He and ^{3}H binding energies.

- *Spectral function for A≥4 nuclei with mean field $\mathcal{P}_{\rm MF}$ and NN correlated $\mathcal{P}_{\rm cor}$ parts:*

$$\mathcal{P} = \mathcal{P}_{\rm MF} \qquad + \qquad \mathcal{P}_{\rm cor}$$



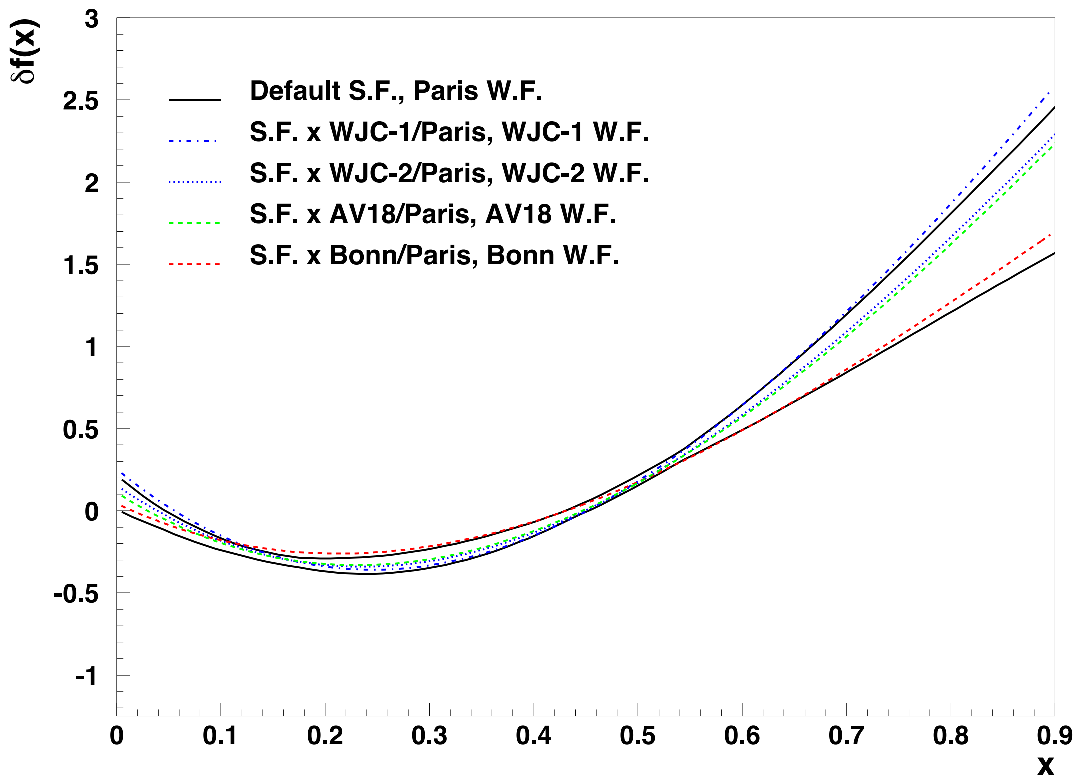




Off-shell function determined from global QCD fits with different wave function models

PRD 96 (2017) 054005

OFF-SHELL FUNCTION FROM HEAVY TARGETS ($A \geq 4$)



✦ $\delta f(x)$ *extracted phenomenologically from nuclear DIS ratios* $\mathcal{R}_2(A,B) = F_2^A/F_2^B$:

- *Electron and muon scattering from BCDMS, EMC,E139,E140,E665 and NMC*
- *Wide range of targets* ^{4}*He*,^{7}*Li*,^{9}*Be*,^{12}*C*,^{27}*Al*,^{40}*Ca*,^{56}*Fe*,^{64}*Cu*,^{108}*Ag*,^{119}*Sn*,^{197}*Au*,^{207}*Pb*
- *Systematic uncertainties including modeling, functional form and spectral/wave function variations*

$\Longrightarrow$ *Partial cancellation of systematics from spectral function in RATIOS* $\mathcal{R}_2(A,B)$

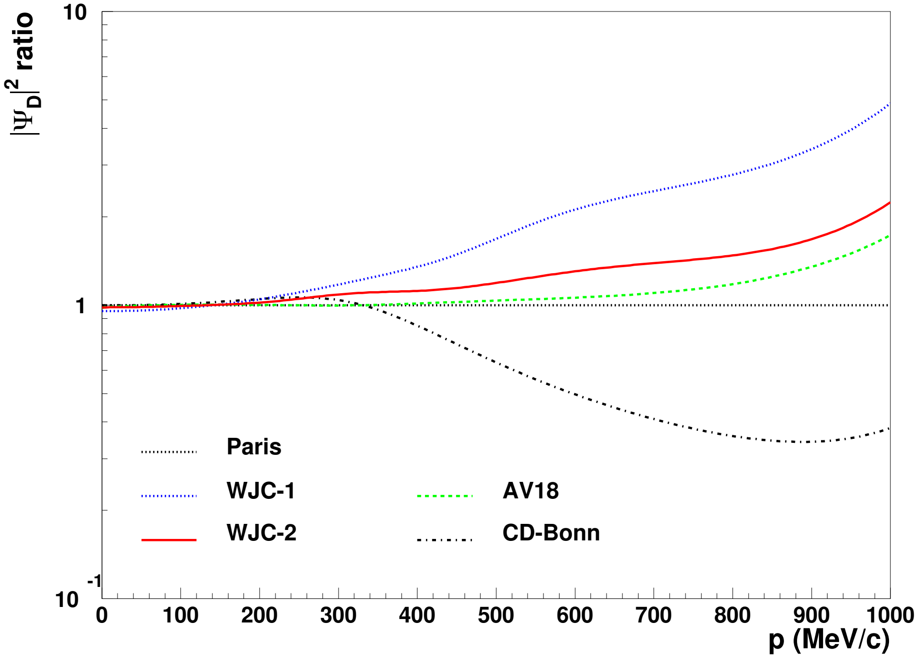
DEUTERON WAVE FUNCTION

- *Two-body nucleus whose spectral function determined by the wave function $\Psi_D(\mathbf{p})$:*

$$\mathcal{P}(\varepsilon, \mathbf{p}) = 2\pi\delta\left(\varepsilon - \varepsilon_D + \frac{\mathbf{p}^2}{2M}\right)|\Psi_D(\mathbf{p})|^2$$

where $\varepsilon_D = M_D - 2M \approx -2.2$ MeV is the binding energy.

- *The deuteron is a superposition of s- and d-wave states. Different models of $\Psi_D(\mathbf{p})$ based on the corresponding underlying N-N interaction potentials, which are constrained at low momentum ($p < 300$ MeV/c) by pp, pn and nn scattering data.*



$|\Psi_D(\mathbf{p})|^2$ gives deuteron momentum distribution

Different N-N potentials used

Paris: *PRC 21 (1980) 861*

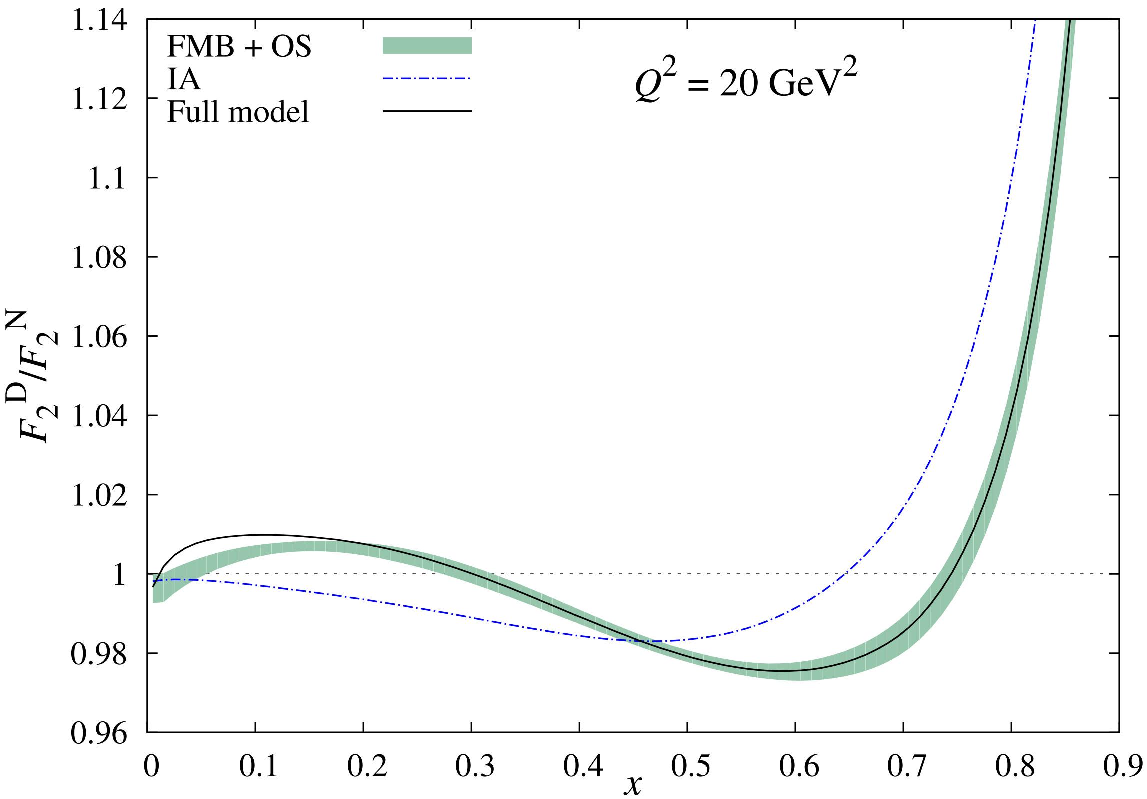
CD-Bonn: *PRC 63 (2001) 024001*

AV18: *PRC 84 (2011) 034003*

WJC-1,2: *PRC 82 (2010) 034004*

[AKP, PRD 96 (2017) 054005]

PREDICTIONS FOR THE DEUTERON



- *The full model includes nuclear Meson Exchange Currents (MEC) and coherent nuclear interactions from Nuclear Shadowing (NS)*
  (NPA 765 (2006) 126; PRC 82 (2010) 054614, PRC 90 (2014) 045204)

$\Longrightarrow$ *This study focuses on the kinematic region $x > 0.1$ dominated by FMB+OS*