Nuclear Modification of Bound Nucleons and Global QCD Analyses

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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 the deuteron provide insights into the mechanisms responsible for modifications of PDFs in the nuclear environment:*
  - *Deuteron is a weakly bound system of two nucleons whose dynamics is 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 deuteron wave function, which is directly related to the underlying N-N interaction.*
  - *Discrepancies among results reported by different groups.*

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

- *Deuterium commonly used as an "effective" neutron target in global QCD analyses:*
  - *Nuclear corrections in deuterium are non negligible and strongly depend on x and Q^2 at large x;*
  - *Nuclear effects in deuterium can introduce significant uncertainties on d/u ratio at large x.*

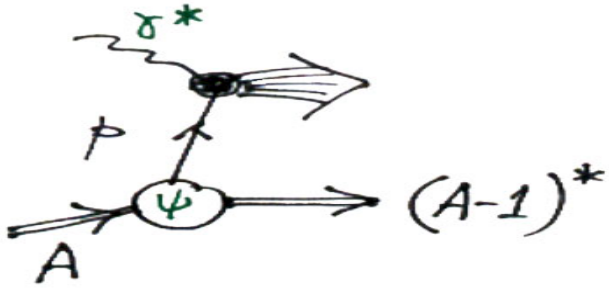
  $\Longrightarrow$ *Quantify (reduce) uncertainties on d/u ratio at large x*

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: $\delta f(x)$

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

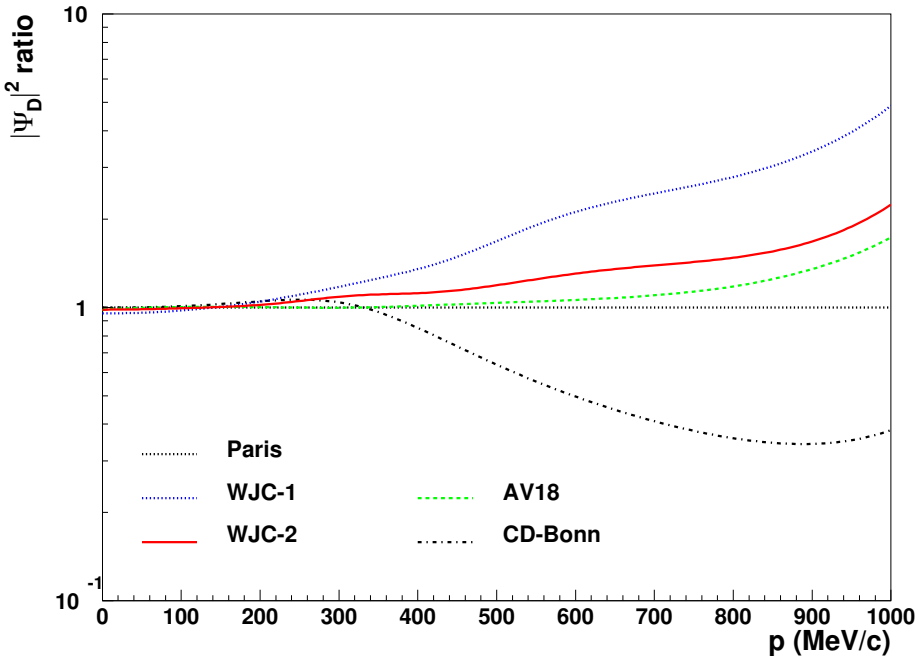
DEUTERON WAVE FUNCTION

- *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]

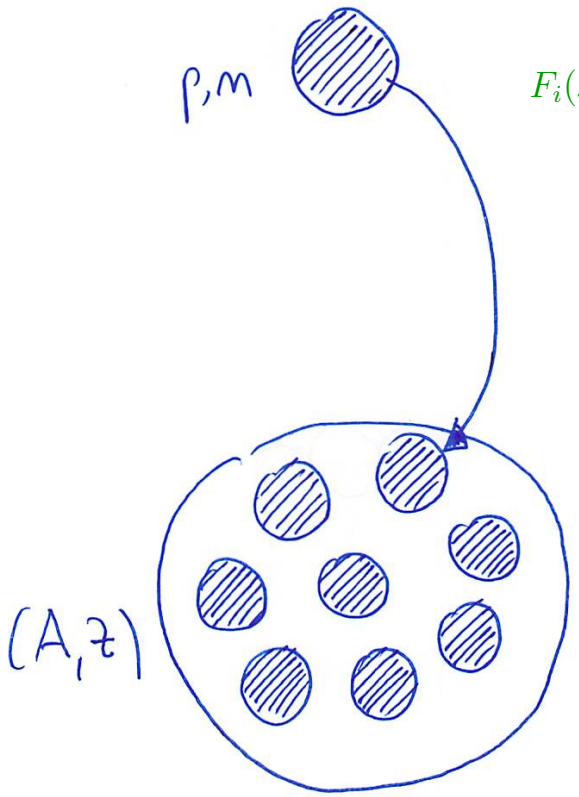
DESCRIPTION OF NUCLEON

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

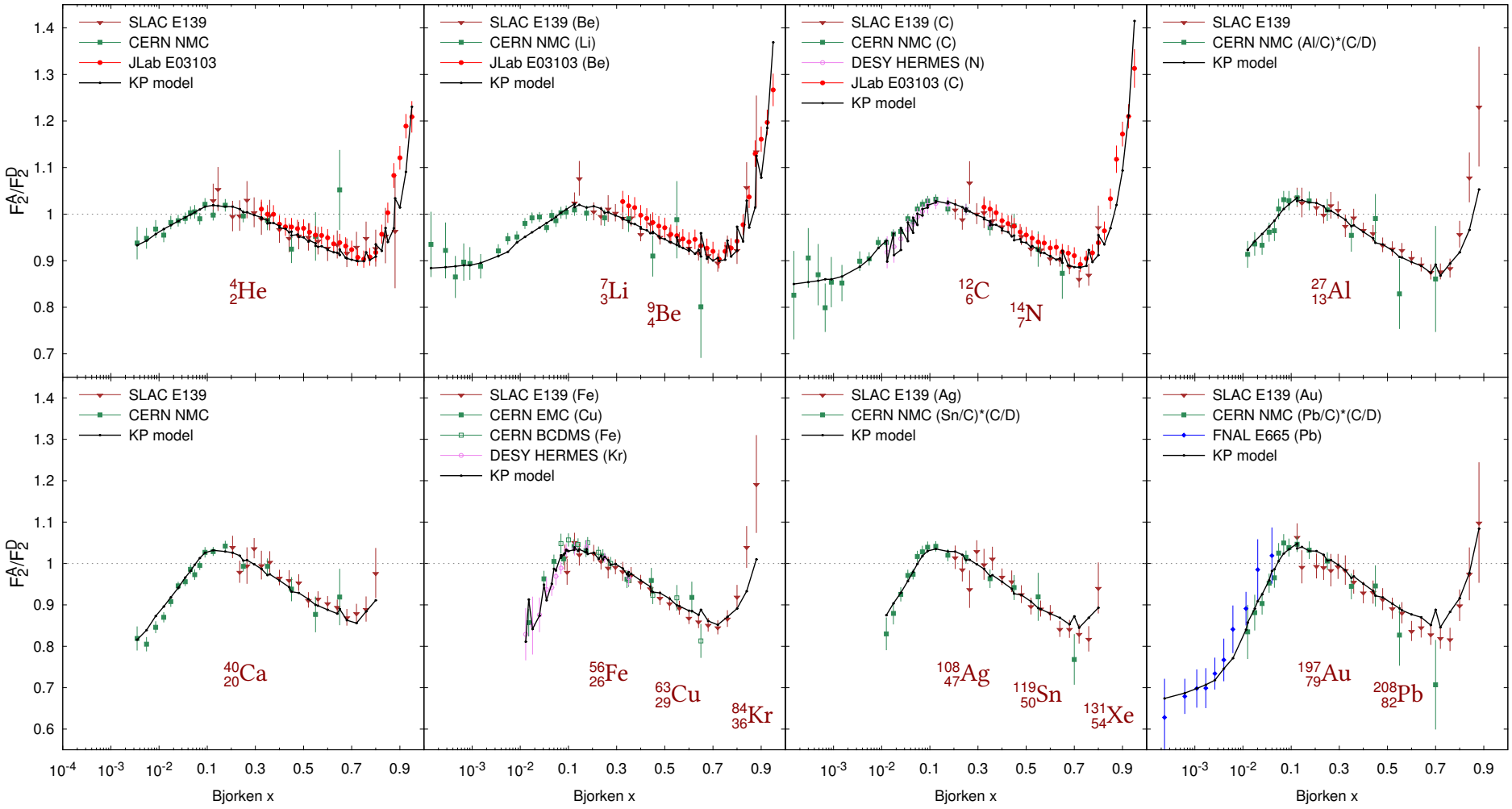
SPECTRAL FUNCTION

$\mathcal{P}(\varepsilon, \mathbf{p})$: *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

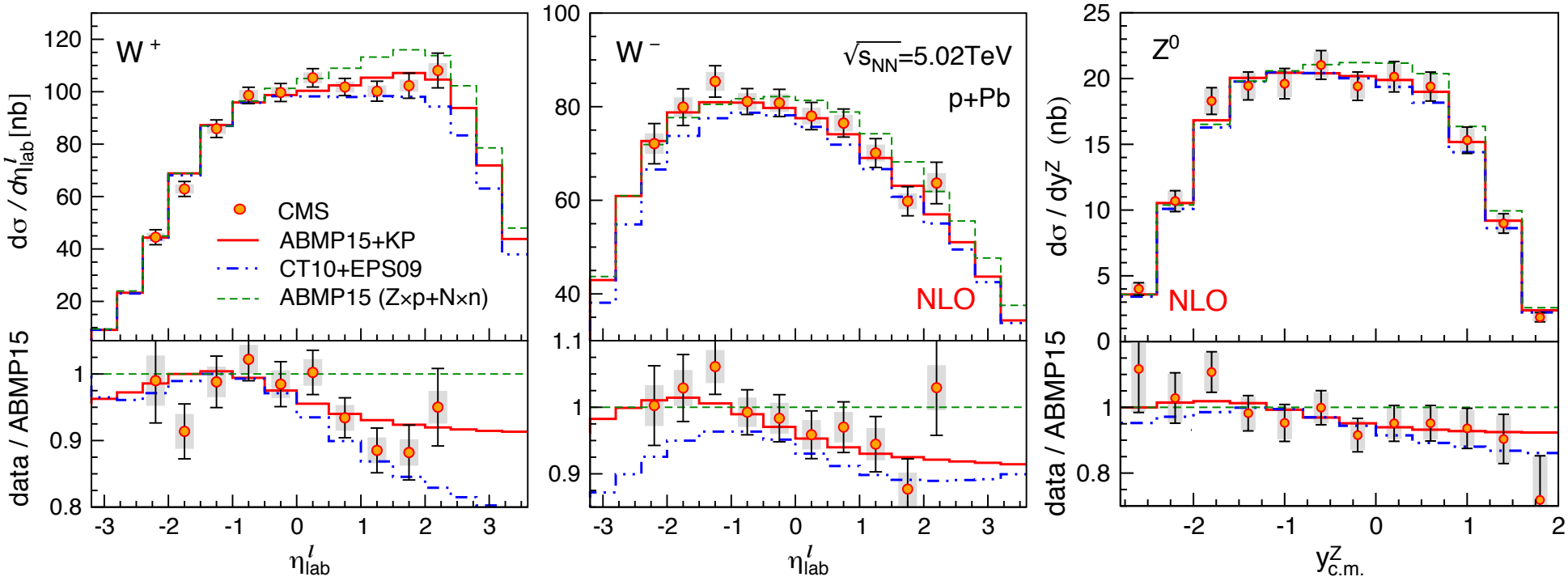


Microscopic KP model provides quantitative description of available data:

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

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

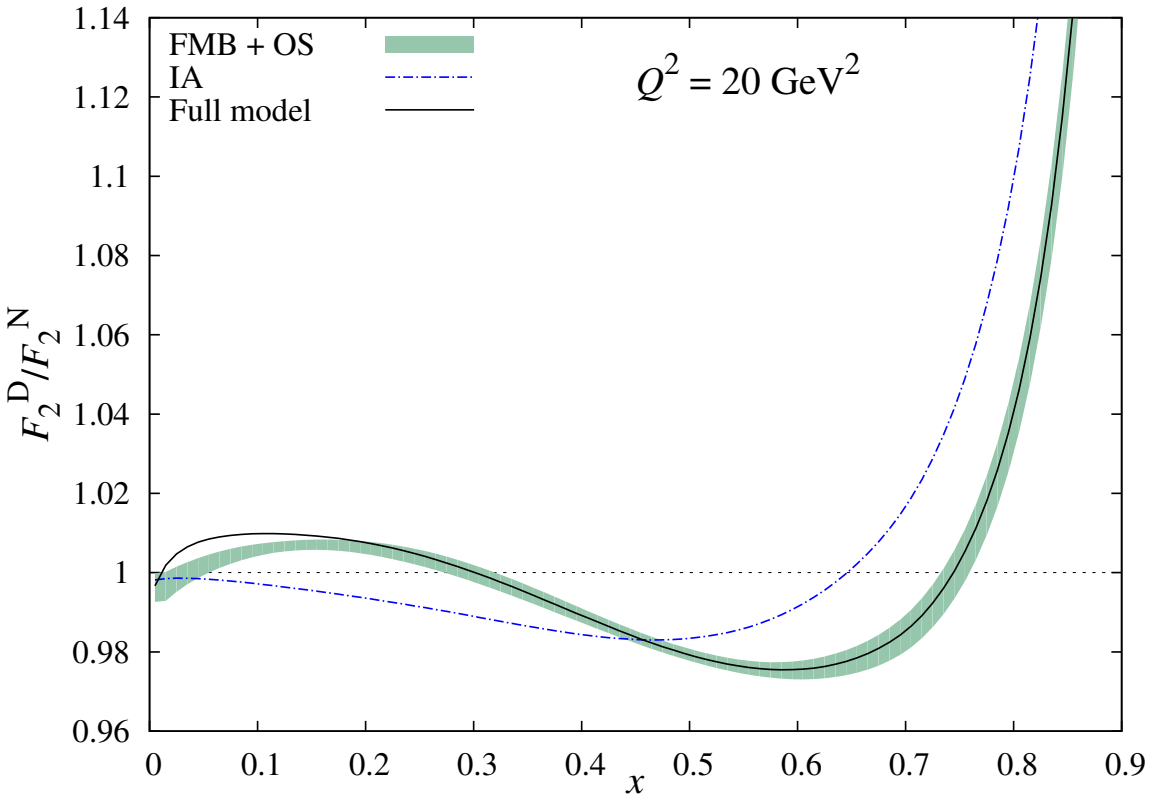
$Q^2 = m^2_{W,Z}$



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)

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*

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:*

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

- *Target mass corrections (TMC) in the Leading Twist (LT) term following Georgi-Politzer;*
- *Fixed flavor number scheme (FFNS) with $n_f = 3$ and $\overline{\rm MS}$ 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:*

$$\delta f(x) = a_0 + a_1 x + a_2 x^2$$

- *Neglect nuclear effects related to meson exchange currents and shadowing since focus on the region $x > 0.1$ dominated by Fermi motion and binding and off-shell correction;*
- *Different deuteron wave functions used: Paris, CD-Bonn, AV18 (default), WJC1, WJC2.*

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

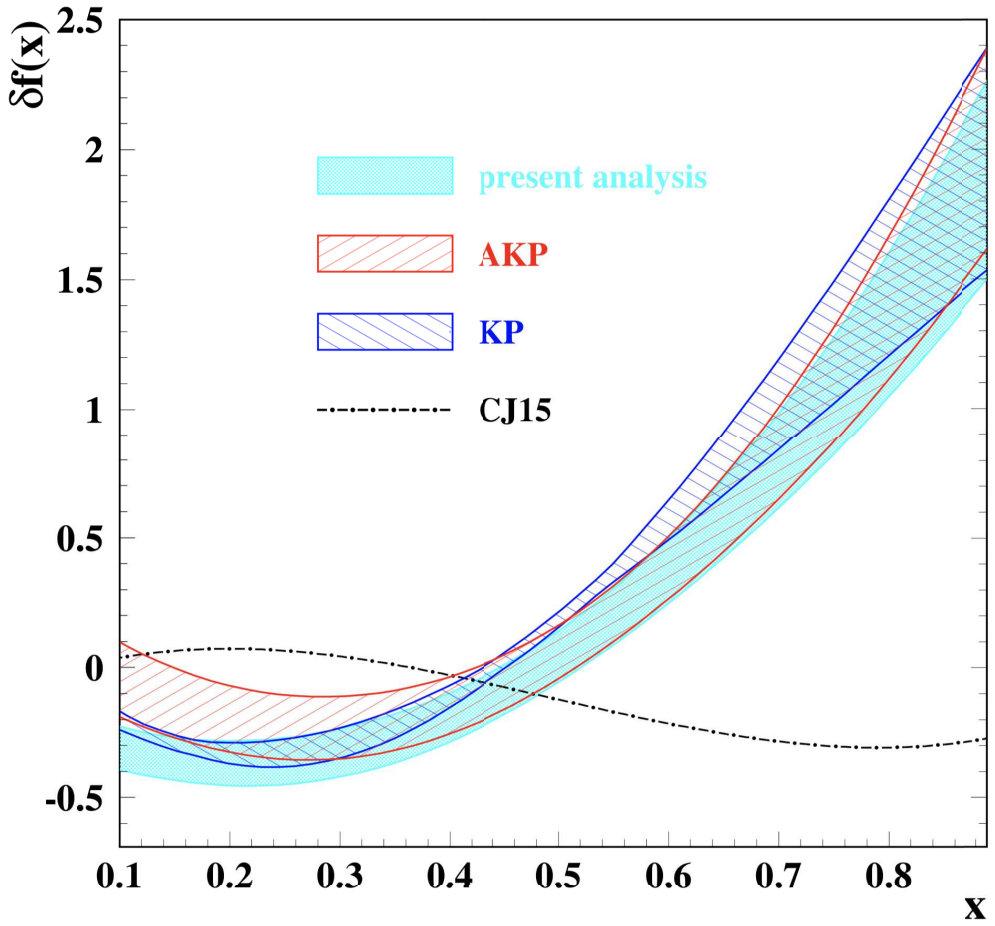
arXiv: 2203.07333 [hep-ph]; PRD 96 (2017) 054005

arXiv: 2203.07333 [hep-ph]

Facility	Experiment	Reference	Beam	Beam energy (GeV)	Observable	Normalization factor	Normalization error(s) (%)	$\frac{\chi^2}{\mathrm{NDP}}$
SLAC	E49a	[20, 21]	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	[21, 23]	”	$10.4 \div 19.5$	”	0.987(9)	”	52/72
”	E139	[21, 24]	”	$8 \div 24.5$	”	1.002(9)	”	8/17
”	E140	[21, 25]	”	$3.7 \div 19.5$	”	1	1.7	25/26
CERN	BCDMS	[26]	μ	$100 \div 280$	$\frac{\mathrm{d}^2\sigma^d}{\mathrm{d}x\mathrm{d}Q^2}$	0.989(7)	3	273/254
”	NMC	[27]	”	$90 \div 280$	F_2^d/F_2^p	1	< 0.15	155/165
DESY	HERMES	[28]	e	27.6	σ^d/σ^p	1	1.4	21/30
JLab	E00-116	[29]	e	5.5	$\frac{\mathrm{d}^2\sigma^d}{\mathrm{d}E'\mathrm{d}\Omega}$	0.981(10)	1.75	208/136
”	BONuS	[30]	”	4.2, 5.2	F_2^n/F_2^d	0.97(9)	$7 \div 10$	90/63
”	MARATHON	[14]	”	10.6	σ^d/σ^p	1	0.55	8/7
Total								1166/1083

List of deuterium 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.*
- *Clear disagreement with CJ15 results from global QCD fits.*

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

SYSTEMATIC STUDIES

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

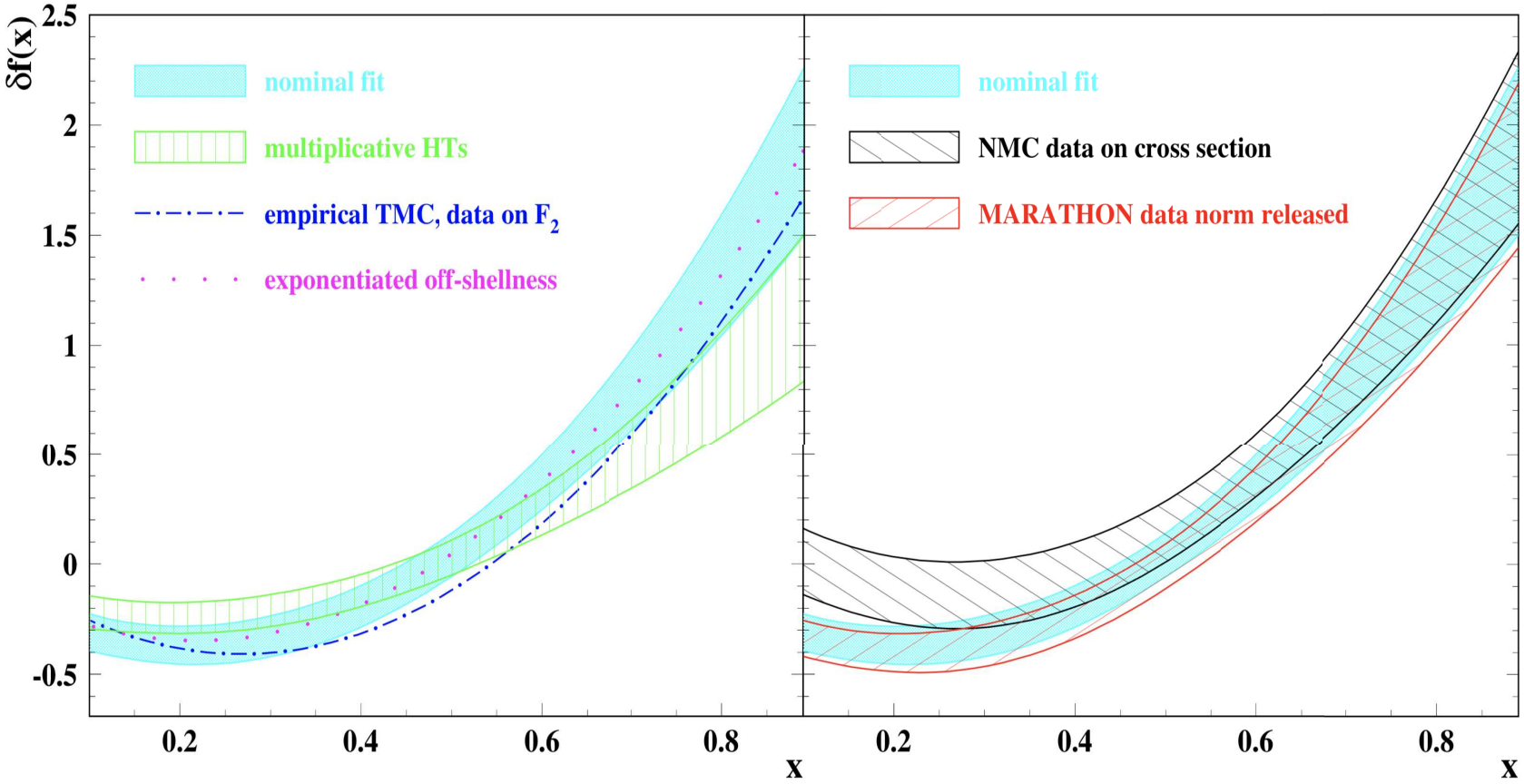
$$F_{2,T}(x,Q^2) = F_{2,T}^{\rm LT,TMC}(x,Q^2) + \frac{H_{2,T}^N(x)}{Q^2}$$
$$F_{2,T}(x,Q^2) = F_{2,T}^{\rm LT,TMC}(x,Q^2) + F_{2,T}^{\rm LT}(x,Q^2)\frac{h_{2,T}^N(x)}{Q^2}$$

- *Empirical approximation to TMC for F_2 used in CJ fits [J. Phys. G 35 (2008) 053101] vs. Georgi-Politzer original TMC implementation*

- *Exponential implementation of off-shell correction:*

$$F_{2,T}^{\rm LT}(x,Q^2,p^2) = F_{2,T}^{\rm LT}(x,Q^2)\exp[\delta f(x)(p^2-M^2)/M^2)]$$

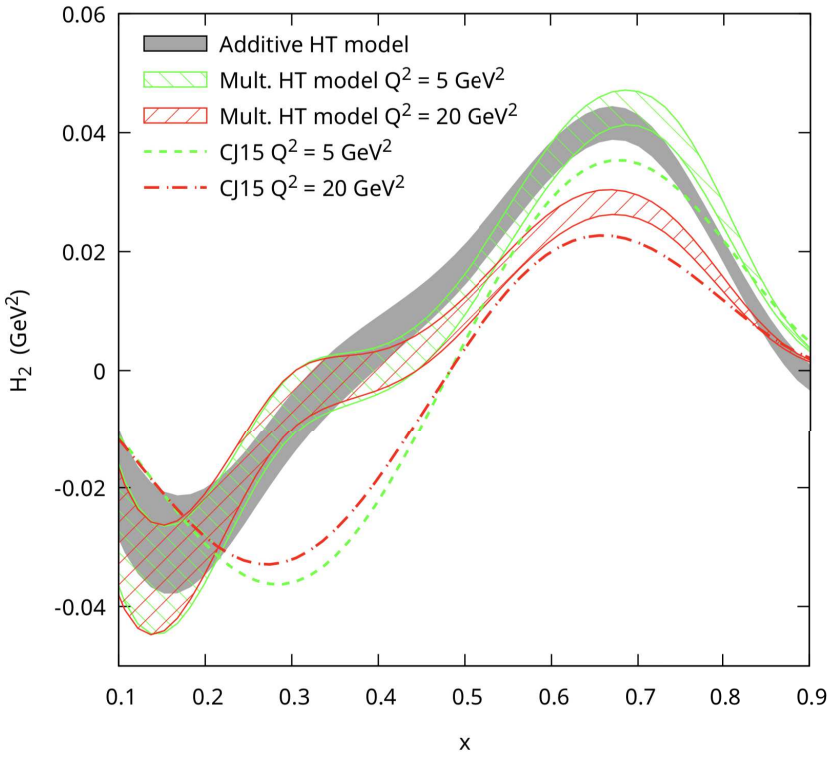
- *Impact of data sets used in QCD analysis:*
  - *Structure function F_2^D/F_2^p vs. cross-section σ^D/σ^p data from NMC experiment;*
  - *Normalization on MARATHON σ^D/σ^p data [PRL 128 (2022) 132003].*

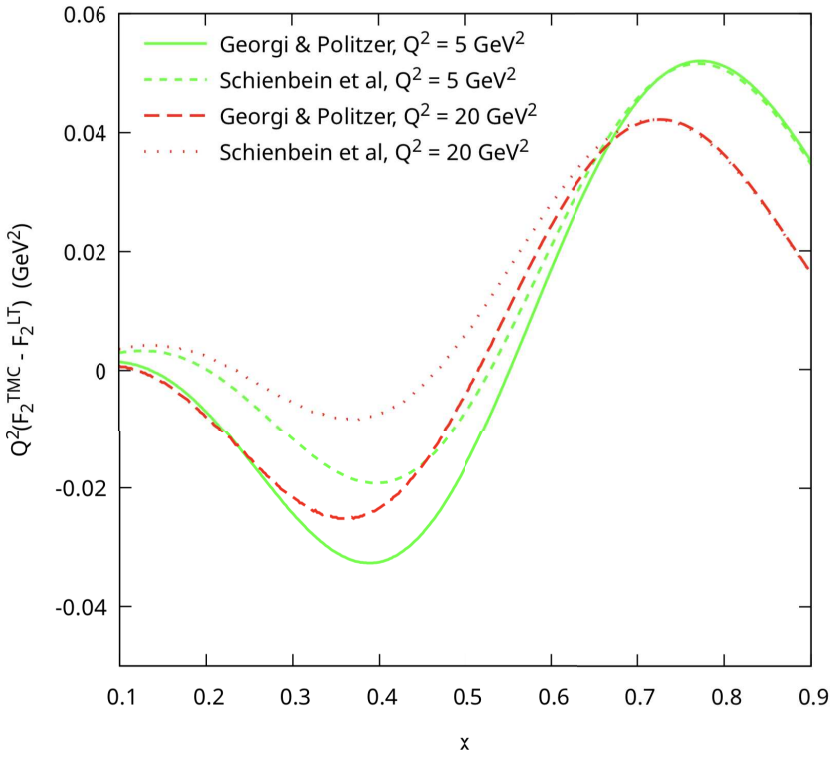


- *Determination of δf from QCD fits stable against all systematic variations studied*
- *Effect of model systematics comparable with the ones from use of different data sets*

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

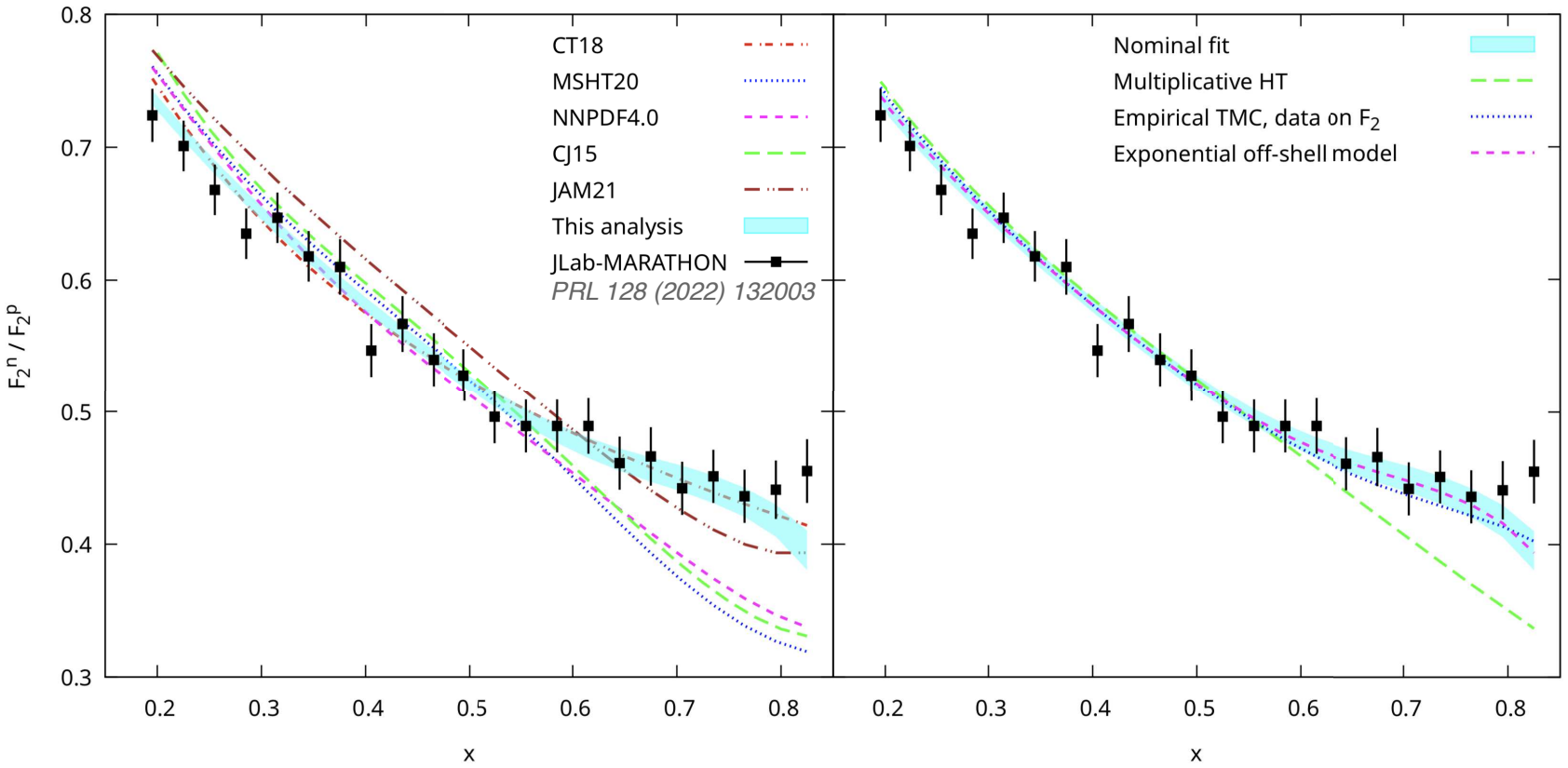
HIGH TWIST AND TMC CONTRIBUTIONS





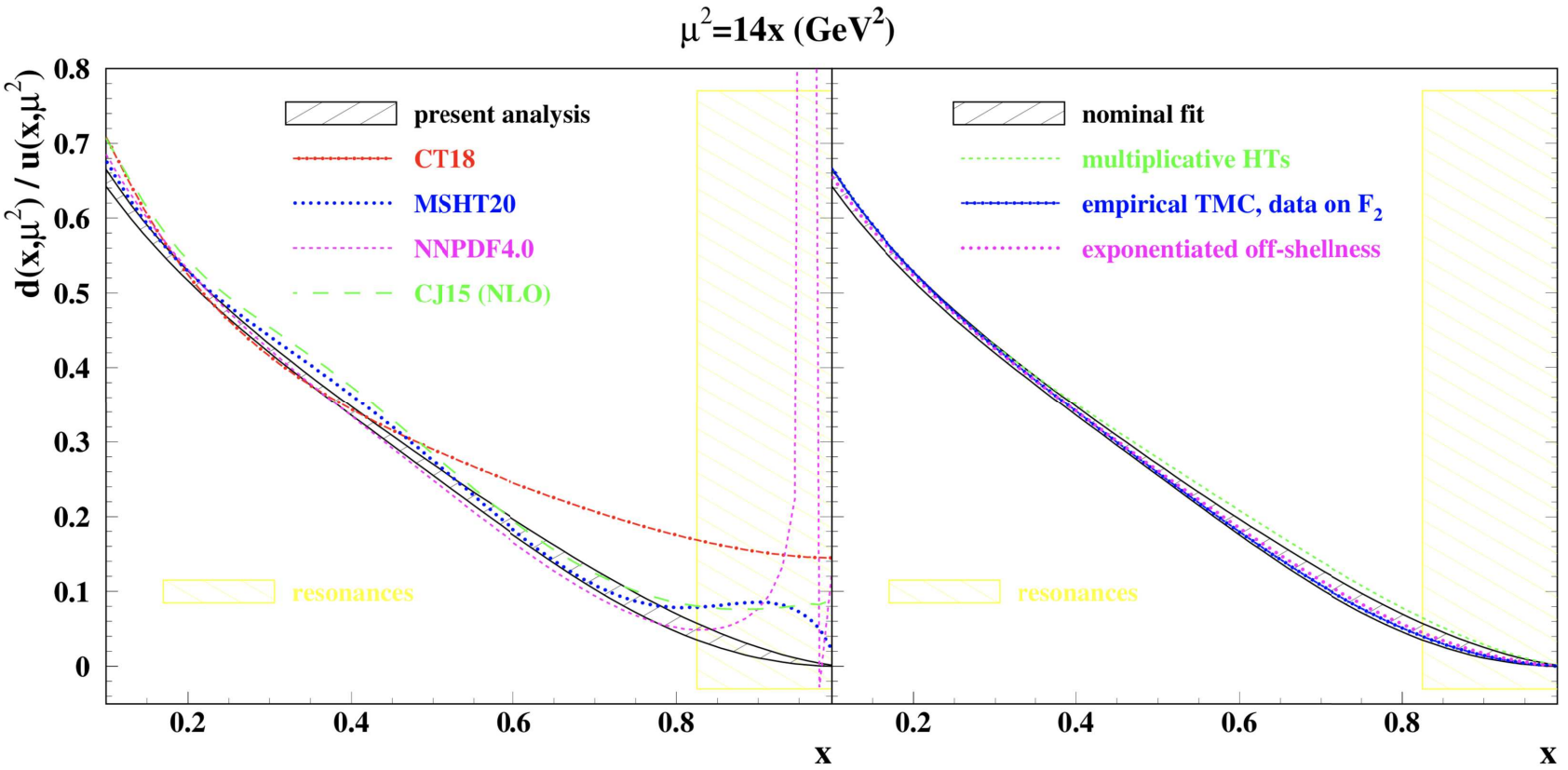
- *Different Q^2 dependence for additive and multiplicative HT due to LT contribution*
- *Consistent results obtained from our fits with additive and multiplicative HT*
- *Significant differences with CJ15 correlated between HT (multiplicative) and TMC*

PREDICTIONS FOR F_2^n/F_2^p RATIO



- *Our predictions in excellent agreement with MARATHON F_2^n/F_2^p (not used in fits)*
- *Sensitivity of MARATHON data to HT contribution at large $x > 0.6$*

PREDICTIONS FOR d/u RATIO



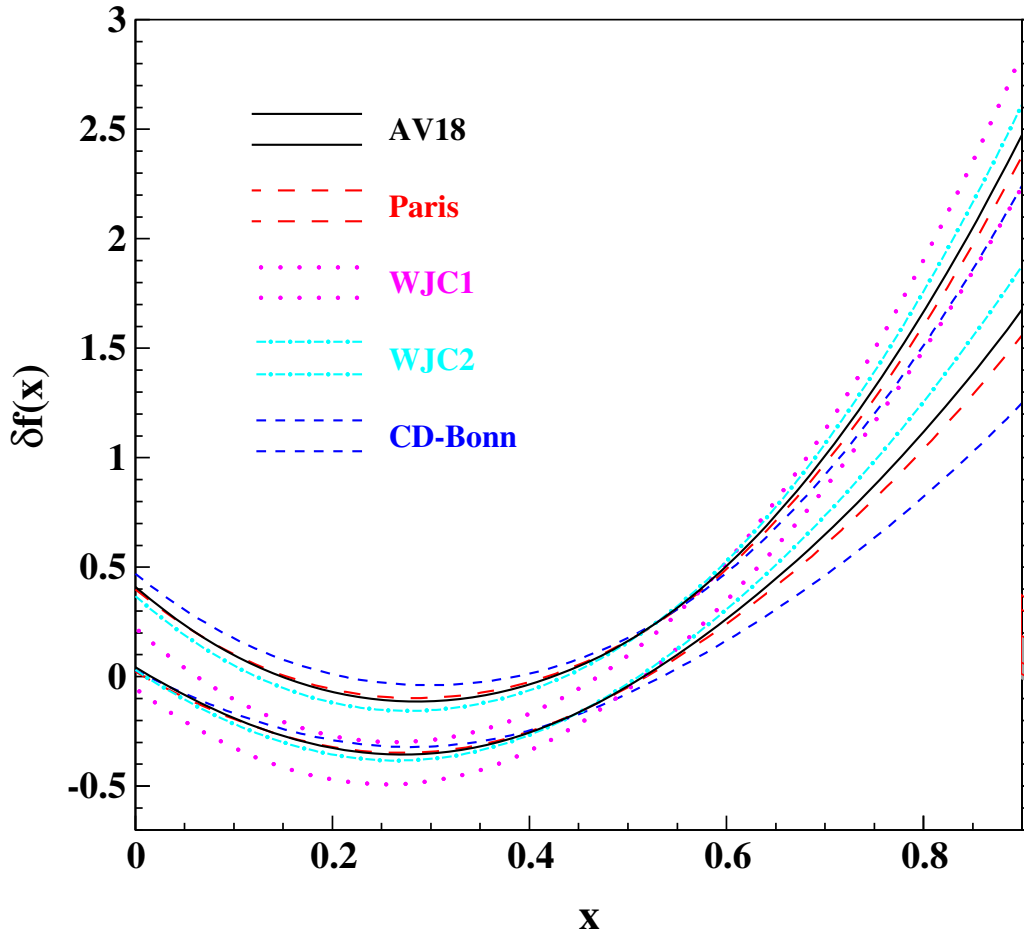
- *Similar d/u ratio from different QCD analyses at $x > 0.6$ with the exception of CT18*
- *Without additive HT terms MARATHON F_2^n/F_2^p requires substantial d/u enhancement*

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

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 deuterium data 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)*
- *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*
- *Our predictions for F_2^n/F_2^p are in excellent agreement with the recent measurement by the MARATHON experiment*
- *Our analysis indicates that the recent measurement of F_2^n/F_2^p by the MARATHON experiment is sensitive to HT effects at $x > 0.6$*

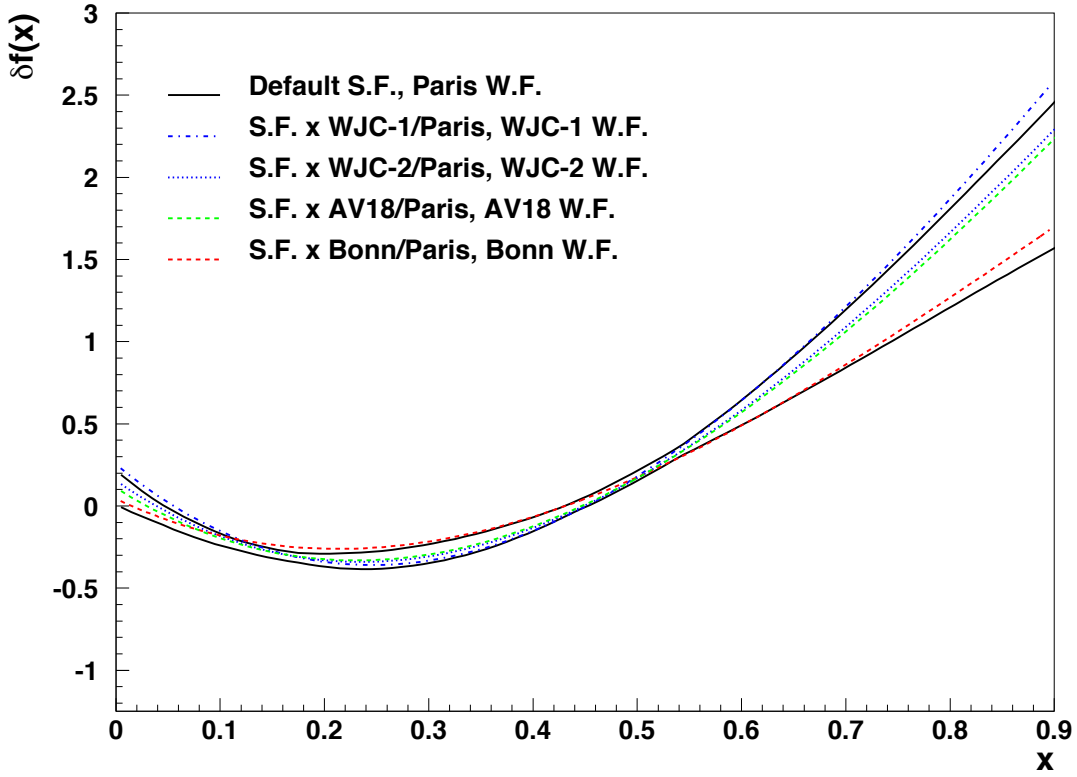
Backup slides



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 $\mathcal{R}_2(A,B)$*