Nuclear Effects in the Deuteron and Global PDF Fits

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OUTLINE

I *Nuclear Corrections in the Deuteron*

- *Incoherent nuclear Deep Inelastic Scattering;*
- *Off-shell correction $\Leftrightarrow$ in-medium modification of bound nucleons;*
- *Deuteron wave functions.*

II *Off-shell Correction from Global PDF Fits*

- *Off-shell function δf and comparisons with heavy target results;*
- *Systematic uncertainties.*

III *Application to PDF Uncertainties*

- *Determination of the d/u ratio;*
- *Determination of F_2^n/F_2^p.*

MOTIVATIONS

- *From DIS off D we have indications that nuclear corrections in the deuteron are non negligible (a few percent) and rise rapidly in the region of large Bjorken x.*

- *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-particale nuclei;*
  - *Role of Fermi motion, binding and off-shell modifications of bound nucleons;*
  - *Cannot rely upon extrapolations from heavy target based on nuclear density, atomic weight, etc.*

  $\Longrightarrow$ *Coherent description of the deuteron and heavy targets?*

- *Since D data commonly used as an "effective" neutron target, nuclear effects in D are crucial to understand uncertainties on d/u ratio extracted from global PDF fits:*
  - *Global PDF fits use only proton and deuteron data;*
  - *Main source of uncertainty correlation between d/u PDFs and nuclear correction in D;*
  - *Flavor sensitive processes (e.g. Drell-Yan and $W^{\pm}$ production) can help to disentangle correlations.*

  $\Longrightarrow$ *How to quantify and possibly reduce uncertainties on d/u ratio at large x?*

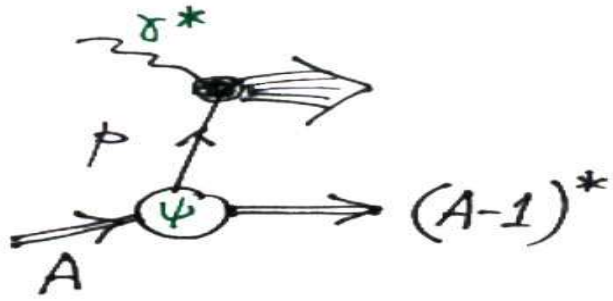
INCOHERENT NUCLEAR DIS

- FERMI MOTION AND BINDING *in nuclear PDFs can be calculated from the convolution of nuclear spectral/wave function and (bound) nucleon PDFs:*

$$q_{a/A}(x,Q^2) = q_a^{p/A} + q_a^{n/A}$$

$$x q_a^{p/A} = \int \mathrm{d}\varepsilon\, \mathrm{d}^3\mathbf{p}\, \mathcal{P}(\varepsilon,\mathbf{p}) \left(1 + \frac{p_z}{M}\right) x' q^N(x',Q^2,p^2)$$

where $x' = Q^2/(2p\cdot q)$ *and* $p = (M+\varepsilon,\mathbf{p})$ *and we dropped* $1/Q^2$ *terms for illustration purpose .*



- *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* $(p^2-M^2)/M^2$*:*

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

where we introduced a structure function of the NUCLEON: $\delta f(x)$

- *Hadronic/nuclear input:* *[S. Kulagin and R.P., NPA 765 (2006) 126]*
  - *Proton/neutron PDFs computed in NNLO pQCD + TMC + HT from global PDF fits*
  - *Deuteron wave function from nucleon-nucleon potential + constraints from low energy data*

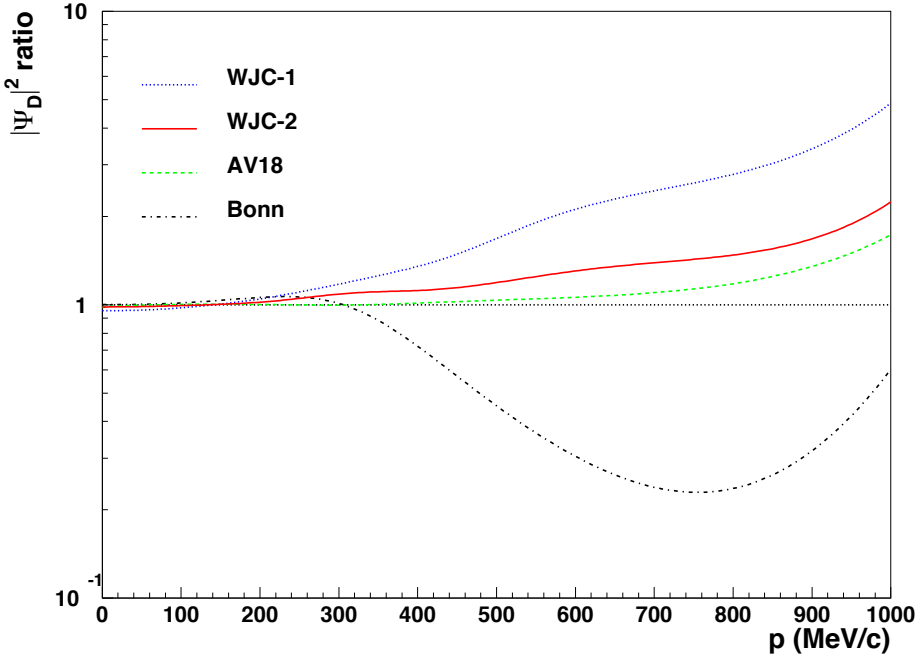
DEUTERON WAVE FUNCTION

- *For D the residual nuclear system is p or n and the spectral function becomes:*

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

where $\varepsilon_D = M_D - 2M$ *is the binding energy and* $\Psi_D(\mathbf{p})$ *is the deuteron wave function.*

- *The description of the nuclear properties is provided by the deuteron wave function, which is a superposition of* s*- and* d*-wave states in momentum space, with a a small admixture of* p*-wave in relativistic models.*



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

Different N-N potentials used

Paris: PRC 21 (1980) 861

Bonn: PR 149 (1987) 149

AV18: PRC 84 (2011) 034003

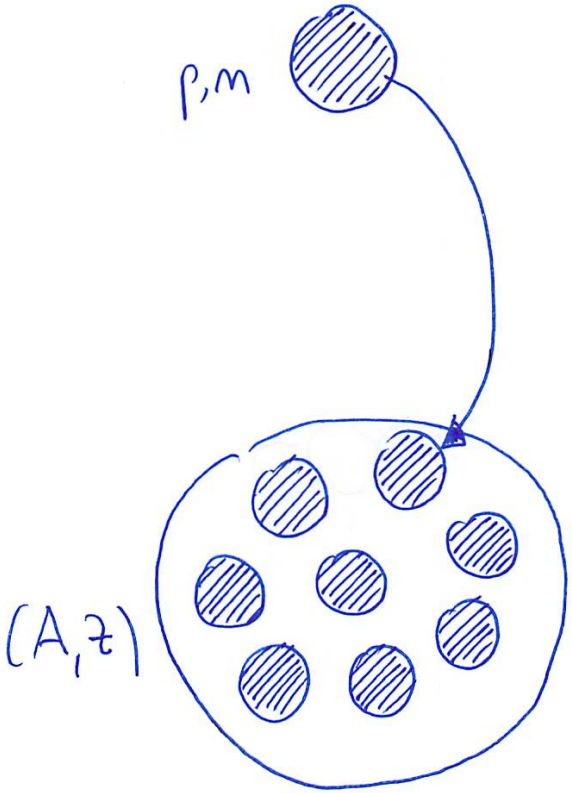
WJC-1,2: PRC 82 (2010) 034004

OFF-MASS-SHELL

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

DESCRIPTION OF NUCLEON

Distribution of partons in a nucleon



STRUCTURE FUNCTIONS

$F_1(x, Q^2), F_2(x, Q^2), xF_3(x, Q^2)$, ...

$\delta f(x)$

DESCRIPTION OF NUCLEUS

Distribution of bound nucleons

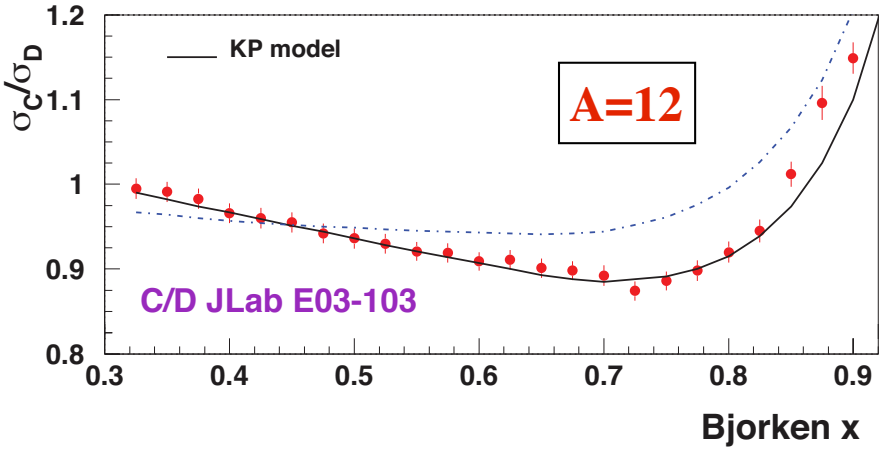
SPECTRAL/WAVE FUNCTION

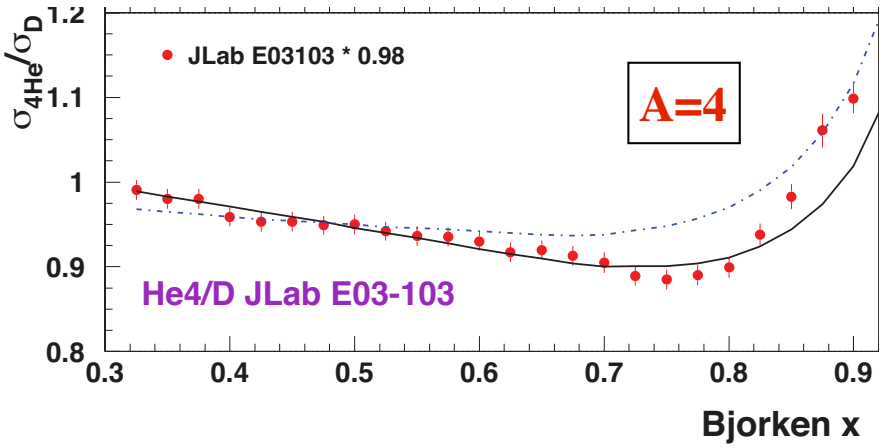
$\mathcal{P}(\varepsilon, \mathbf{p}), \mathbf{\Psi}(\mathbf{p})$

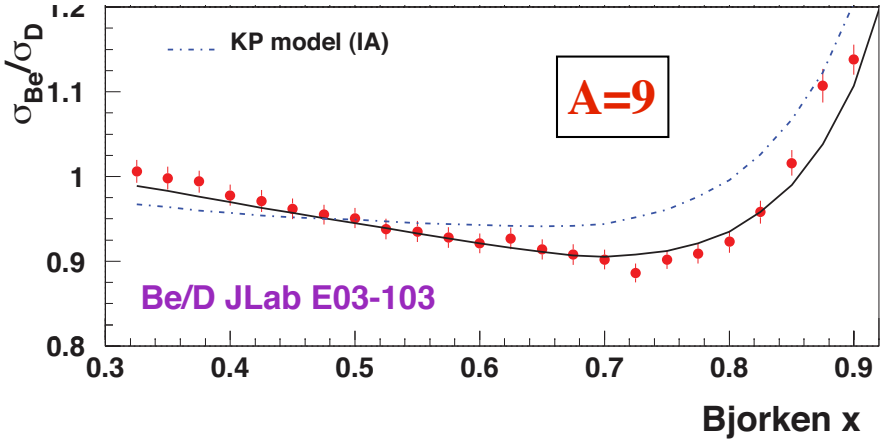
Off-shell function measures the in-medium modification of bound nucleon

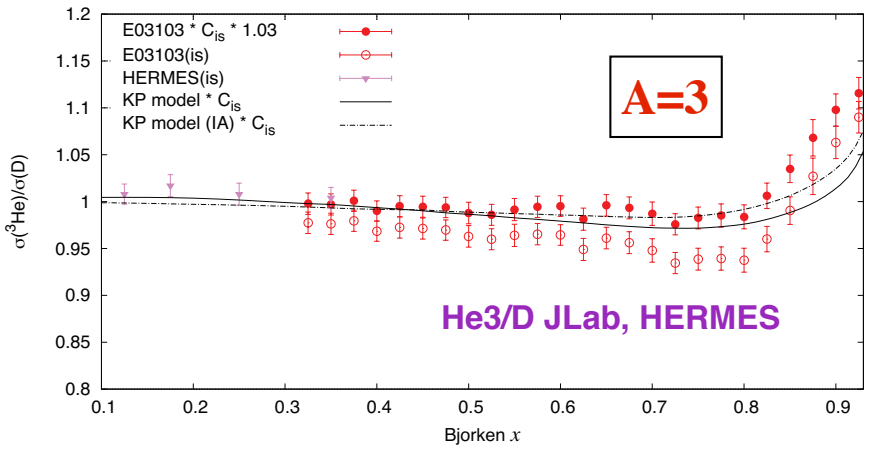
Any isospin (i.e. $\delta f_p \neq \delta f_n$) or flavor dependence ($\delta f_a$) in the off-shell function?

PREDICTIONS FOR LIGHT NUCLEI ($A \geq 3$)





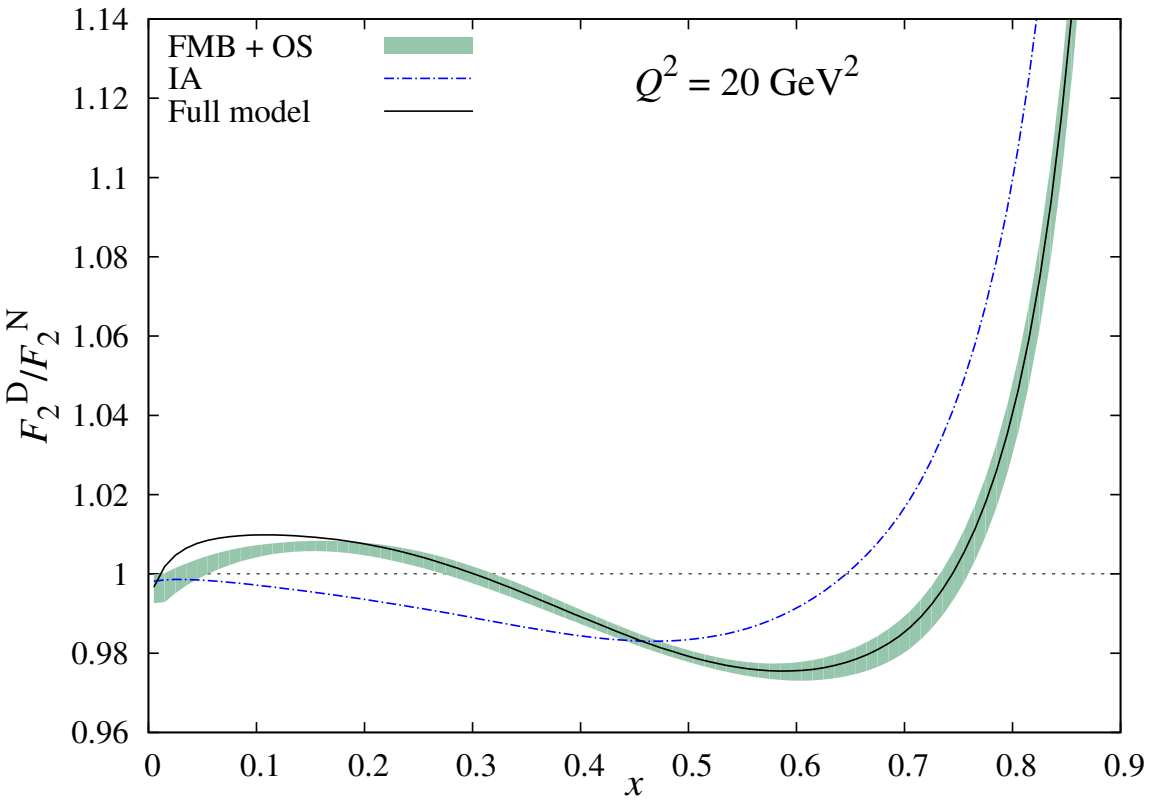




S. Kulagin and R.P., PRC 82 (2010) 054614

What about A=2 (Deuteron)?

PREDICTIONS FOR THE DEUTERON



- *The full model includes nuclear Meson Exchange Currents (MEC) and coherent nuclear interactions from Nuclear Shadowing (NS)*
  (*S. Kulagin and R.P., NPA 765 (2006) 126; PRD 76 (2007) 094023, PRC 90 (2014) 045204*)

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

OFF-SHELL FUNCTION FROM GLOBAL PDF FIT

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

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

  - Isospin asymmetry in HT set to zero to avoid biases in nuclear corrections;
  - 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 ABM fits at the initial scale $Q_0^2 = 9$ GeV^2 [PRD 89 (2014) 054028];
  - Analysis performed in the region $\boxed{Q^2 > 2.5\ GeV^2}$ and $\boxed{W > 1.8\ GeV}$.

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

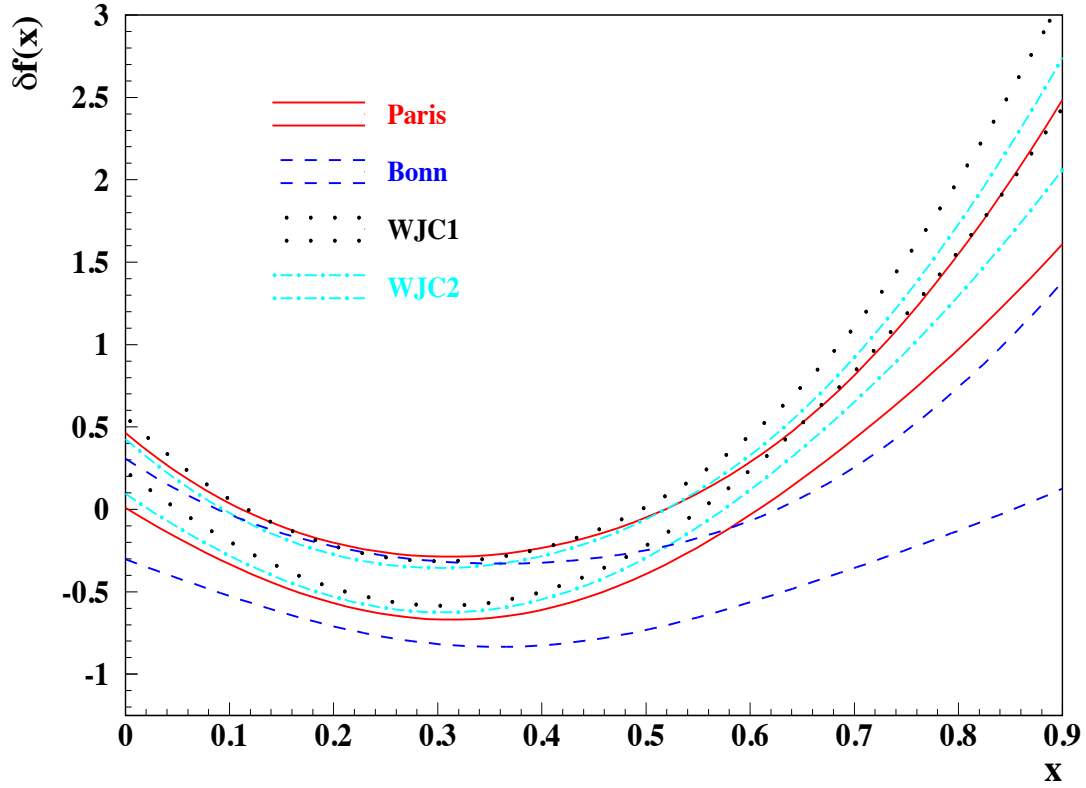
$$\delta f(x) = a_0 + a_1 x + a_2 x^2 + (a_3 x^3)$$

  - 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;
  - Study impact of different deuteron wave functions: Paris, Bonn, AV18, WJC1, WJC2;

  $\Longrightarrow$ Simultaneous extraction of $\delta f(x)$ and PDFs from global fit

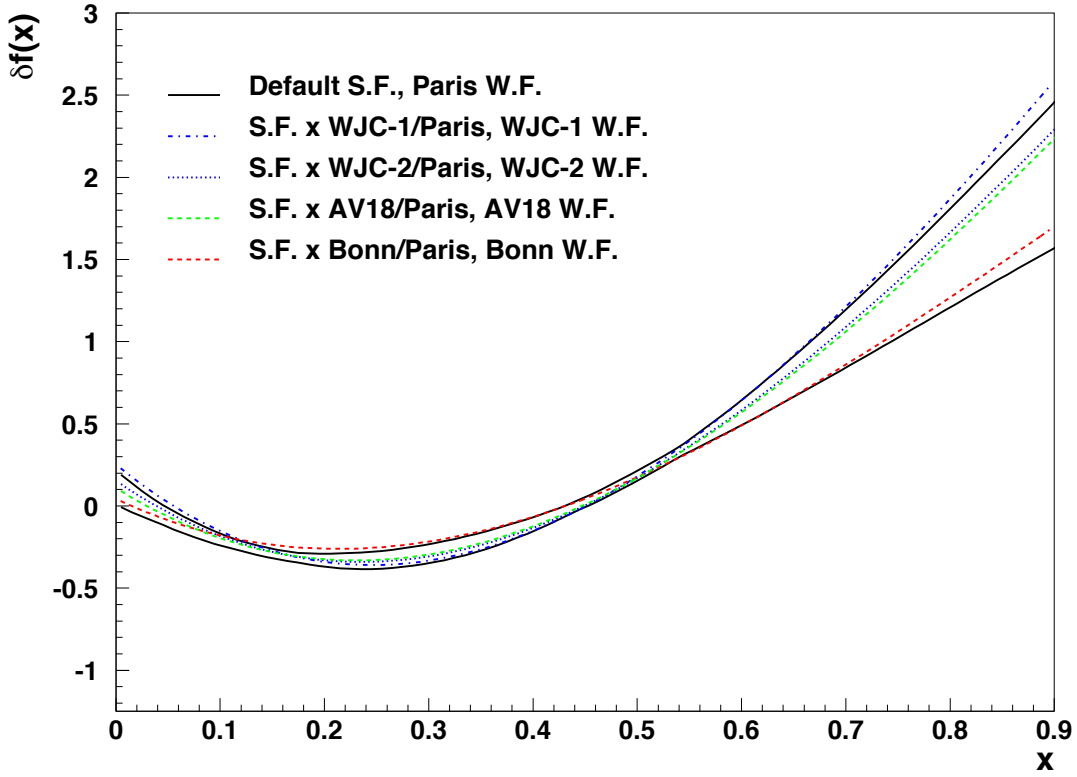
	Experiment	Reference	Beam	Target(s)	Final states	Data points
DIS collider	H1 & ZEUS	[65]	e	p	eX	486
	H1	[66]	e	p	eX	130
	H1 & ZEUS	[67]	e	p	$c\bar{c}$	130
DIS fixed target	BCDMS	[68, 69]	μ	p, D	μX	605
	NMC	[70]	μ	p	μX	245
	SLAC E49a	[71]	e	p, D	eX	118
	SLAC E49b	[71]	e	p, D	eX	299
	SLAC E87	[71]	e	p, D	eX	218
	SLAC E89b	[73]	e	p, D	eX	162
	SLAC E139	[17]	e	D	eX	17
	SLAC E140	[74]	e	D	eX	26
	NOMAD	[43]	ν	Fe	$\mu^+\mu^- X$	48
	CHORUS	[75]	ν	Emul.	$\mu c X$	6
Drell-Yan fixed target	FNAL E866	[76]	p	p, D	$\mu^+\mu^-$	39
W, Z collider	D0	[77]	p	$\bar{p}$	$W^+ \to \mu^+\nu$	10
					$W^- \to \mu^-\nu$	
	D0	[78]	p	$\bar{p}$	$W^+ \to e^+\nu$	13
					$W^- \to e^-\nu$	
	ATLAS	[79]	p	p	$W^+ \to l^+\nu$	30
					$W^- \to l^-\nu$	
					$Z \to l^+l^-$	
	CMS	[80, 81]	p	p	$W^+ \to \mu^+\nu$	33
					$W^- \to \mu^-\nu$	
	LHCb	[82, 84]	p	p	$W^+ \to \mu^+\nu$	63
					$W^- \to \mu^-\nu$	
					$Z \to \mu^+\mu^-$	
	LHCb	[83]	p	p	$Z \to e^+e^-$	17

RESULTS FROM GLOBAL PDF FITS ($A = 2$)



- *Different Q^2 dependence allows to disentangle off-shell correction from PDFs and HT*
- *Significant sensitivity to the modeling of the (high) momentum distribution of the deuteron wave function*

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

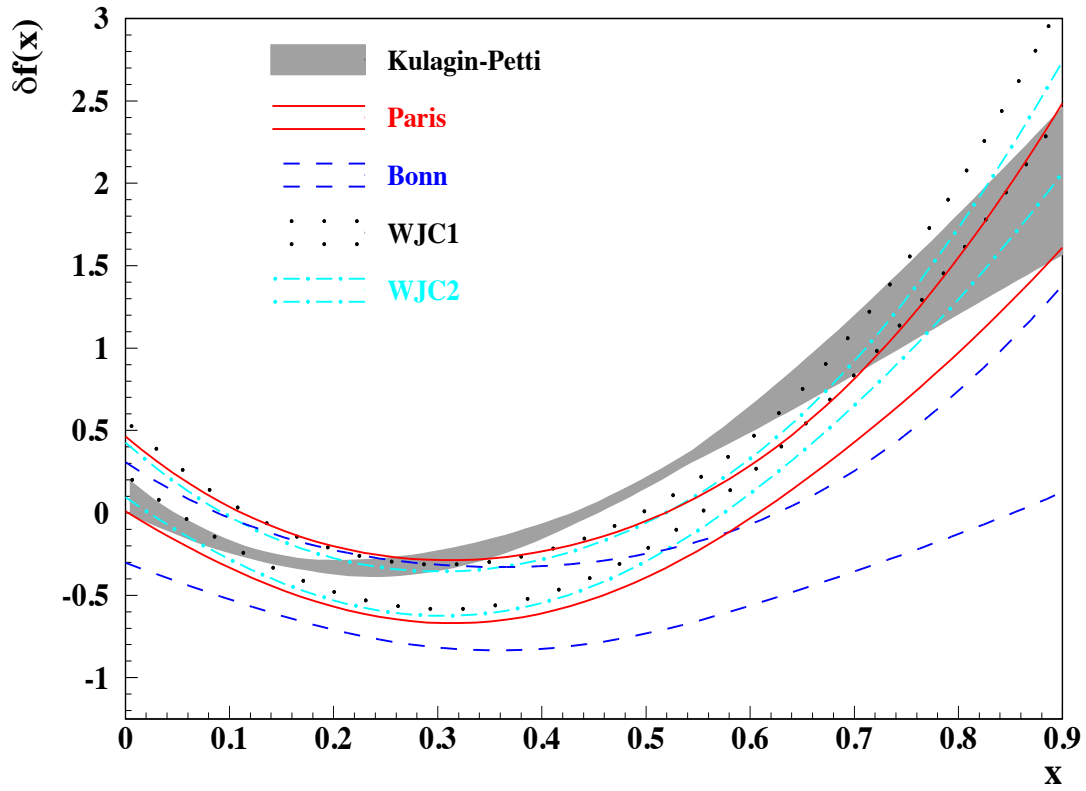


✦ *$\delta f(x)$ extracted phenomenologically from nuclear DIS ratios $\mathcal{R}_2(A,B) = F_2^A/F_2^B$:*

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

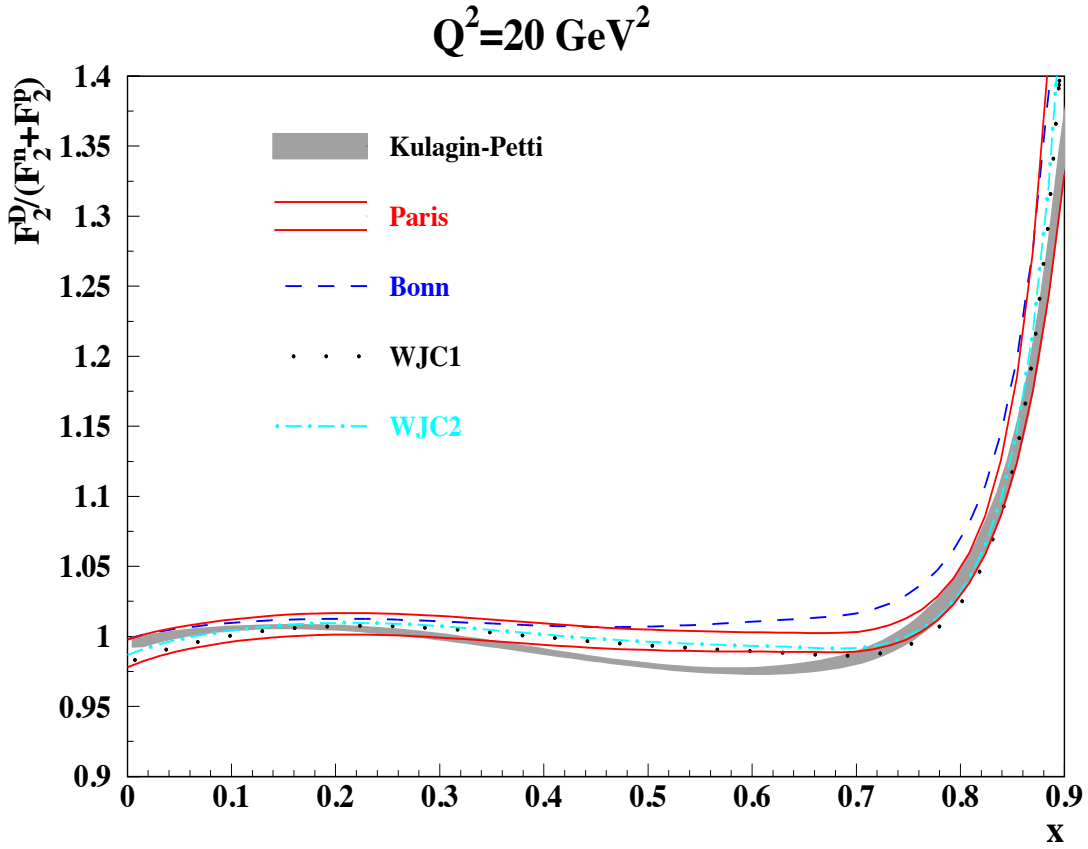
CONSISTENCY WITH HEAVY TARGETS



Larger uncertainties from global PDF fits due to correlation with PDFs (d/u ratio)

$\Longrightarrow$ *Independent extraction from D data agrees with heavy target determination*

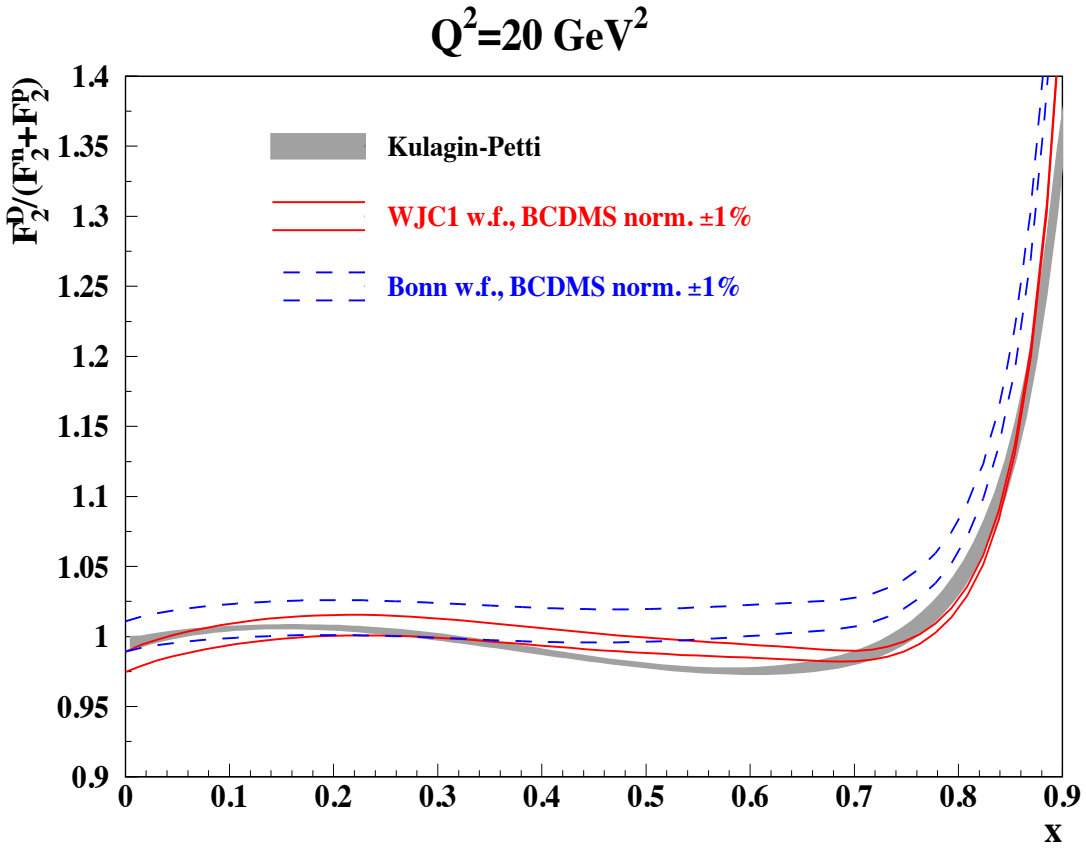
DETERMINATION OF F_2^D/F_2^N FROM GLOBAL FITS



Reduced sensitivity to deuteron wave function due to partial compensation from $\delta f(x)$

$\Longrightarrow$ *Agreement with KP predictions based upon* δf *universality (nucleon property)*

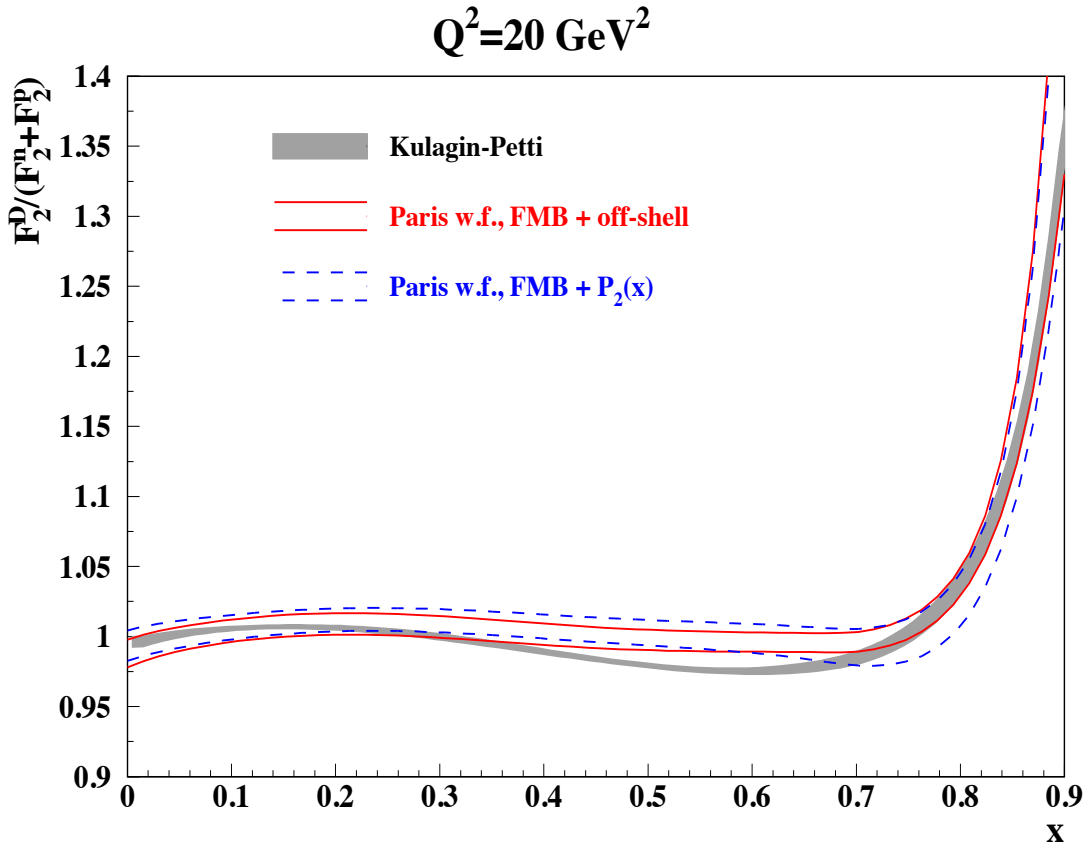
DATA NORMALIZATION UNCERTAINTY



Normalization of BCDMS deuteron data can result in a normalization offset on F_2^D/F_2^N

$\Longrightarrow$ *Define corresponding systematic uncertainty with different wave functions*

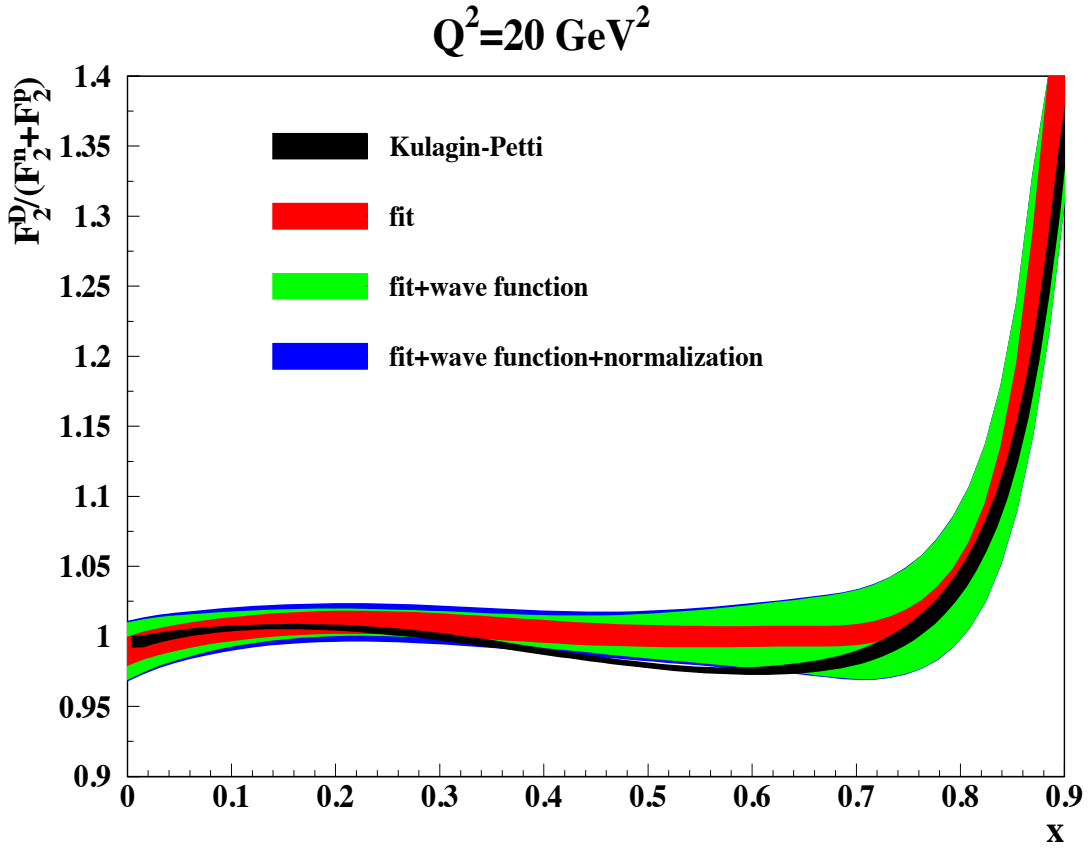
TEST OF MODEL DEPENDENCE



Perform model-independent extraction of off-shell correction to F_2^D/F_2^N
as generic polynomial without convolution with deuteron wave function

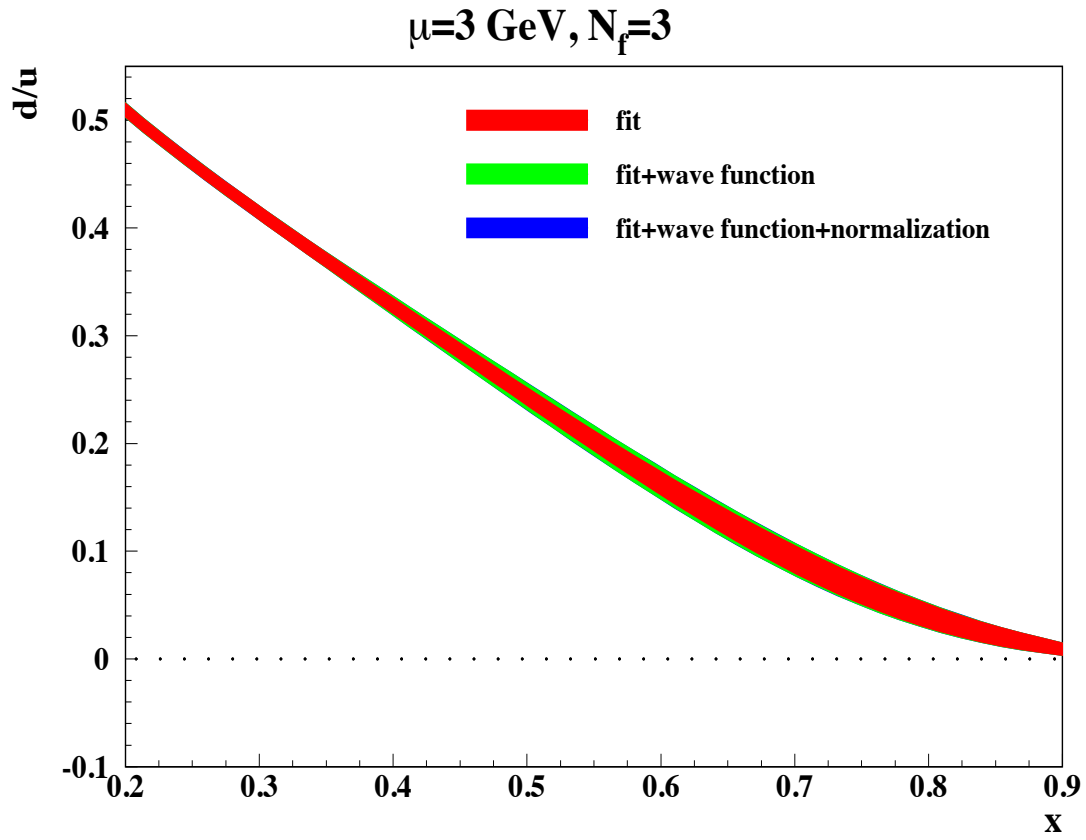
$\Longrightarrow$ *Good agreement with result based on* $\delta f(x)$ *excludes model biases*

RATIO F_2^D/F_2^N FROM GLOBAL FITS



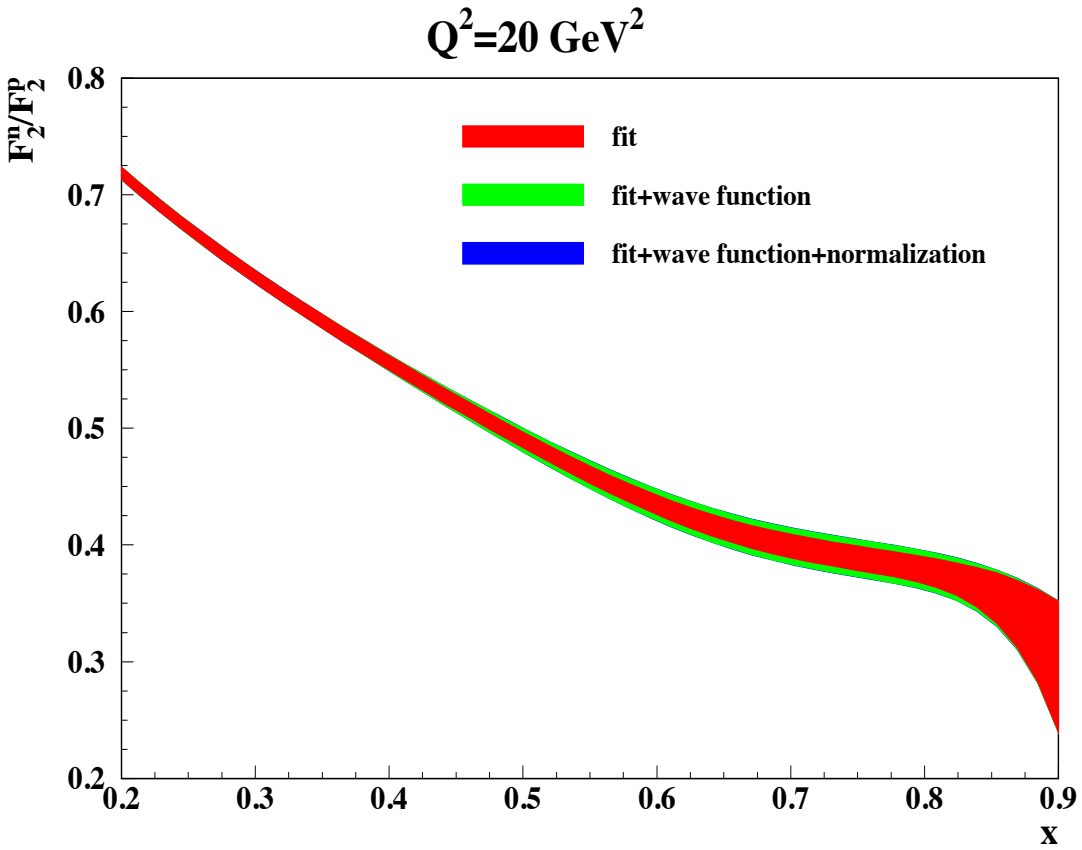
- *Experimental uncertainty from error matrix in global PDF fit;*
- *Systematic uncertainty related to the choice of the deuteron wave function;*
- *Systematic uncertainty related to the overall normalization of BCDMS D data.*

DETERMINATION OF d/u RATIO FROM GLOBAL FITS



- *Uncertainty on d/u ratio without external constraints affected by the systematics on the deuteron off-shell correction at $x > 0.4$*
- *$\delta f(x)$ universality allows to use the more precise result obtained from heavy targets*

DETERMINATION OF F_2^n/F_2^p FROM GLOBAL FITS



SUMMARY

- *The off-shell modification of bound nucleons in a nucleus can be described by a universal function $\delta f(x)$, which can be regarded as a nucleon structure function*

- *We performed an independent determination of the off-shell function $\delta f(x)$ from global PDF fits including DIS off p and D targets, Drell-Yan production from pp and pD, Z and $W^{\pm}$ production from pp at Tevatron and the LHC*

  $\Longrightarrow$ *Sensitivity to $\delta f(x)$ as well as to the deuteron wave function*

- *The off-shell function extracted from D data in global PDF fits is consistent with the one obtained from heavy targets ($A \geq 4$)*

  $\Longrightarrow$ *Validation of δf universality and of KP model for the deuteron*

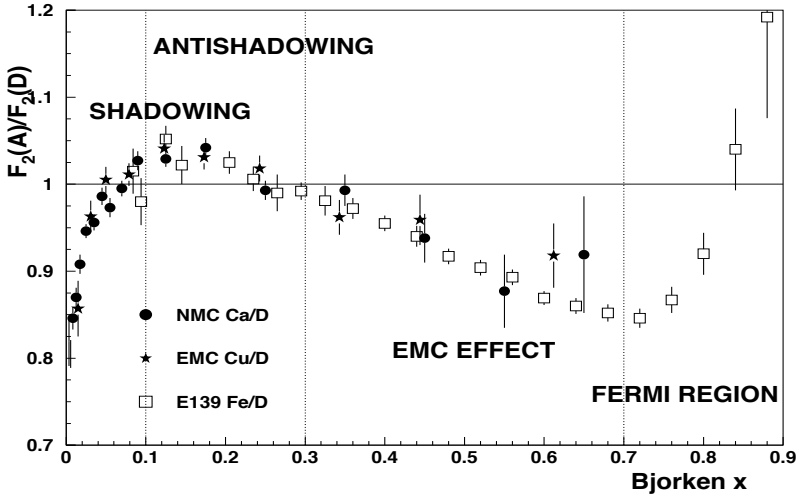
- *Our results show that we can obtain a coherent description of the deuteron and heavy targets, allowing a significant improvement of uncertainties on the d/u ratio at large x.*

Backup slides

NUCLEAR PARTON DISTRIBUTIONS

✦ **GLOBAL APPROACH** *aiming to obtain a quantitative model covering the complete range of* x *and* Q^2 *(S. Kulagin and R.P., NPA 765 (2006) 126; PRC 90 (2014) 045204):*

- *Scale of nuclear processes (target frame)* $L_I = (Mx)^{-1}$
  Distance between nucleons $d = (3/4\pi\rho)^{1/3} \sim 1.2Fm$
- $L_I < d$
  For $x > 0.2$ *nuclear DIS* $\sim$ *incoherent sum of contributions from bound nucleons*
- $L_I \gg d$
  For $x \ll 0.2$ *coherent effects of interactions with few nucleons are important*



✦ **DIFFERENT EFFECTS** *on parton distributions (PDF) are taken into account:*

$$q_{a/A} = q_a^{p/A} + q_a^{n/A} + \delta q_a^{\rm MEC} + \delta q_a^{\rm coh} \qquad a = u, d, s.....$$

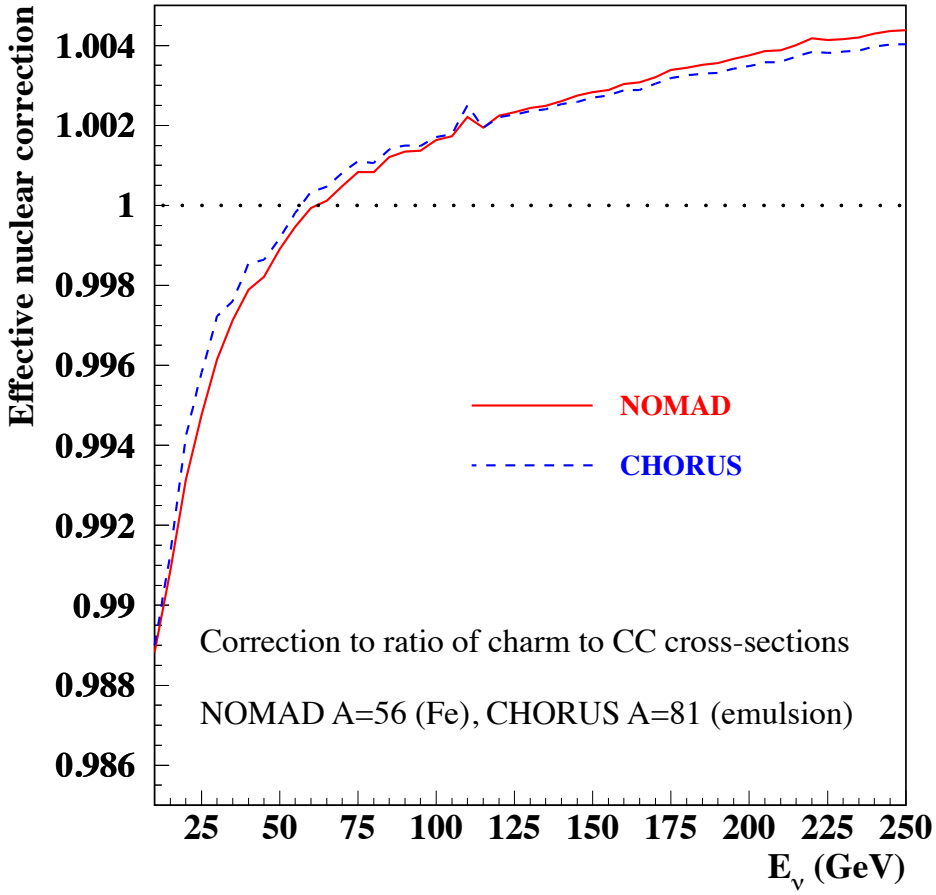
- $q_a^{p(n)/A}$ *PDF in bound p(n) with Fermi Motion, Binding (FMB) and Off-Shell effect (OS)*
- $\delta q_a^{\rm MEC}$ *nuclear Meson Exchange Current (MEC) correction*
- $\delta q_a^{\rm coh}$ *contribution from coherent nuclear interactions: Nuclear Shadowing (NS)*

PREDICTIONS FOR CHARM PRODUCTION

- *Reduced nuclear corrections on total cross-sections from phase space integration*
- *Charm production in (anti)neutrino interactions direct probe of strange sea quark distributions*
- *Consider ratio of charm to inclusive CC total cross-sections*

$$\mathcal{R}_c = \sigma_{\rm Charm}/\sigma_{\rm CC}$$

$\Longrightarrow$ *Reduction of nuclear uncertainties on strange sea determinations (cancellation to $<1\%$ on $\mathcal{R}_c$)*



NPB 876 (2013) 339; NJP 13 (2011) 093002; PRD 91 (2015) 094002