Systematics of Deuteron Smearing Corrections in Global PDF fits

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Hampton U. and Jefferson Lab

DNP meeting, Oct 31st ,2020

HAMPTON UNIVERSITY
THE STANDARD OF EXCELLENCE

Jefferson Lab

The CTEQ-JLab global analysis

- **Collaborators:**
  - **Theory:** A. Accardi, W.Melnitchouk, J.Owens, I.Fernando, J.Xiaoxian
  - **Experiment:** E.Christy, C.Keppel, P.Monaghan*, S.Li*, S.Park*

LL.02 *LL.06 11:54 am* *ML.05 2:48 pm*

- **Latest public release: CJ15**
  - A.A., Brady, Melnitchouk, Owens, Sato, PRD 93 (2016) 114017
  - www.jlab.org/cj & Included in LHAPDF
  - Working hard towards a new release
    - With JLab 6, SeaQuest, RHIC, LHC

- **All-*x* PDF global fits, focused on the "large"-*x* region**
  - Maximize use of large-*x* data (esp. DIS)
  - Large-*x* / small-Q^2 theory corrections, nuclear corrections
  - ***Quantitatively evaluate theoretical systematic errors***

35+ years of unpolarized global PDF fits

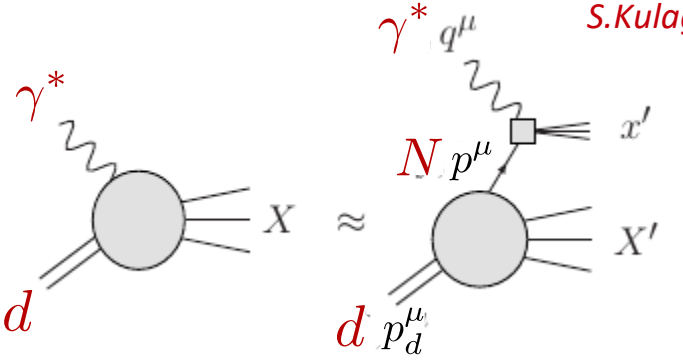
	JLab & BONUS	HER MES	HERA I+II	Tevatron W,Z	LHC, RHIC	v+A di-μ	**Large-*x* treatment** **Nucl. & offsh**	HT TMC	Flex *d*	low-W DIS
CJ15 *	✓✓	✓	✓	✓	*in prog.*	X	✓✓	✓	✓	✓
CT18			✓	✓ ¤¤	✓	✓			✓	
MMHT14			¤¤¤	✓ ¤¤	✓	✓	✓			
NNPDF3.1			✓		✓	✓		TMC only		
ABMP16/AKP				✓ ¤¤	✓	✓	✓/✓	✓	(✓)	✓
HERAPDF2.0			✓	¤						

* NLO only ** No jet data ¤ see 1503.05221 ¤¤¤ see 1508.06621 ¤¤ no reconstructed W

Deuteron target 1: Fermi motion and binding

For details: S.Kulagin, ML.06

- **Weak binding approximation:**
  - Incoherent scattering from not too fast individual nucleons
  - Neglects FSI



$$F_{2d}(x,Q^2) = \int \frac{dz}{z} dp_T^2 \, \mathcal{K}(z,p^2,\gamma) \left|\psi_{N/d}(|\vec{p}|)\right|^2 F_{2N}(x/z,Q^2,p^2)$$

kinematic and "flux" factors

Nucleon wave function

structure function of **bound, off-shell nucleon**

$$\rightarrow \quad z = \frac{p\cdot q}{p_d\cdot q} \approx 1 + \frac{p_0 + \gamma p_z}{M} \qquad \left[p_0 = M + \varepsilon, \quad \varepsilon = \varepsilon_d - \frac{\vec{p}^{\,2}}{2M}\right]$$

momentum fraction of d carried by N

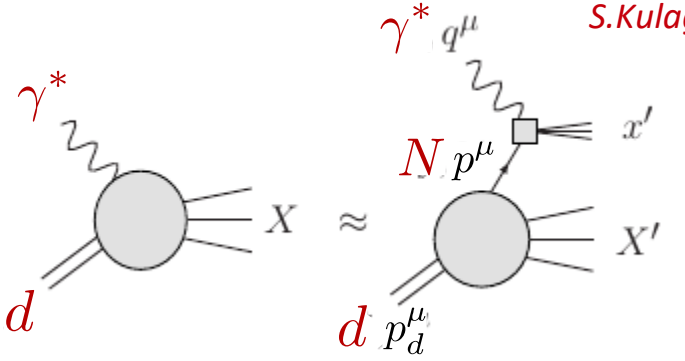
$$\rightarrow \text{ at finite } Q^2,\ \gamma = \sqrt{1 + 4x^2p^2/Q^2}$$

quantifies how far the nucleon is from the light cone ($\gamma = 1$)

Deuteron target 2: off-shell corrections

For details: S.Kulagin, ML.06

- Nucleons are bound in the deuteron:
  - $p^2 < M^2$
    (but not too much if x not too large)
  - Structure functions are deformed



- **Offshell expansion:**
  - parametrize first order coefficient

$$F_{2N}(x,Q^2,p^2) = F_{2N}^{\rm free}(x,Q^2)\left[1+\frac{p^2-M^2}{M^2}\delta f(x)\right]$$

Free proton, neutron structure function

"offshelll function"

  - In CJ15:
    - parametrization inspired by Kulagin, Petti (2007)
    - x1 fixed by valence quark sum rule

$$\delta f(x) = C(x-x_0)(x-x_1)(1+x-x_0)$$

Are we done with (nuclear) corrections?

- **Not quite!**
  - Other nuclear corrections (shadowing, pion cloud, FSI, …)
  - **Nucleon-level corrections**, compounding smearing and off-shell
    - Target Mass corrections $\sim M^2/Q^2$
    - Higher-Twists (gluon FSI) $\sim \Lambda_{QCD}{}^2/Q^2$
    - Pion threshold corrections $\sim M_\pi{}^2/Q$
    - Other power corrections $\sim \Lambda_{???}{}^2/Q^2$

    Attention: non-linear interplay of power and nuclear corrections
  - **Theoretical choices**:
    - Details of implementation, approximations
    - Wave function
    - Additive vs. multiplicative HT
    - Parametrization of off-shell function
    - ….

Are we done with (nuclear) corrections?

Theoretical choices →

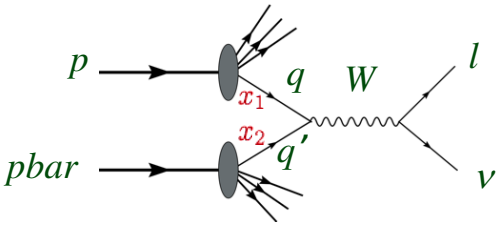
Corrections (increasing-x) ↓

	KP	AKP	CJ15	AKP-like
shadowing	yes	yes (which one?)	MST x<0.1	(same)
smearing	Paris	AV18	AV18 x>0.1	(same)
pi-cloud	yes	yes	---	---
TMC	GP O(Q4)?	GP O(Q4)??	GP approx.	(same)
HT	H (p=n ??)	H (p=n)	C (p=n)	H & C, p=n & p!=n
HT(x)	---	---	---	---
off-shell	---	---	---	---
df(x)	factorized	polyn. 2nd/3rd	factorized + sum rule	polyn. 2nd/3rd
pi thresh.	yes	yes	----	----

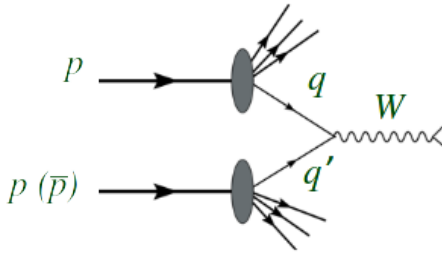
There is no "off-the-shelf" nuclear correction model:

- **Theory systematics potentially large!**
- Users need to know, pay attention to detail (yes, read the papers without rush!)

Interplay of observables



D0, CDF asymmetries



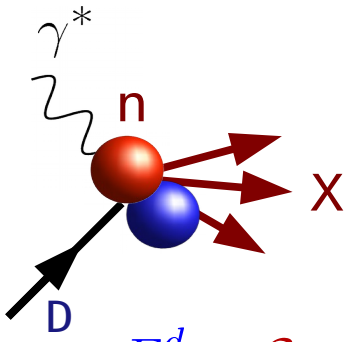
$$A_W(y) \xrightarrow{y \to y_{max}} \frac{1 - d/u(x_1)}{1 + d/u(x_1)}$$

d/u

&

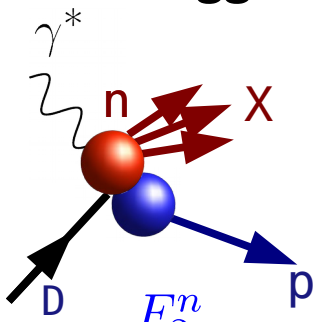
nucl. + offsh. dynamics

Deep inelastic deuterium



$$F_2^d \propto \mathcal{S}_D \otimes \left[x u_{\rm off}(x) + x d_{\rm off}(x) \right]$$

"BONuS" tagged neutron target

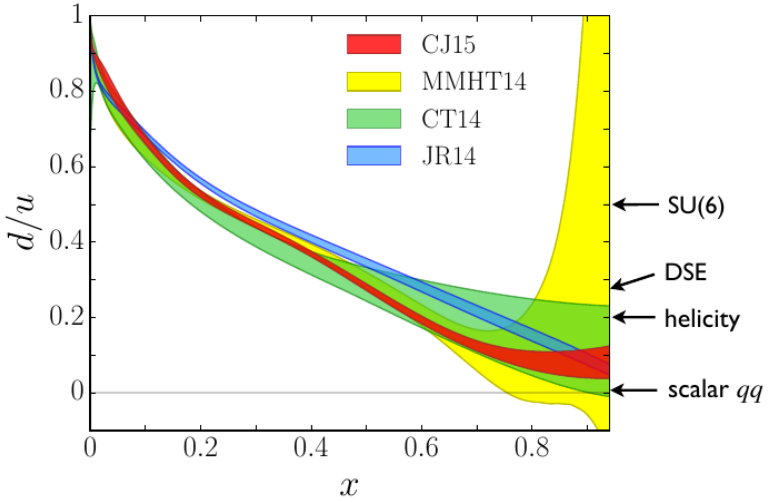


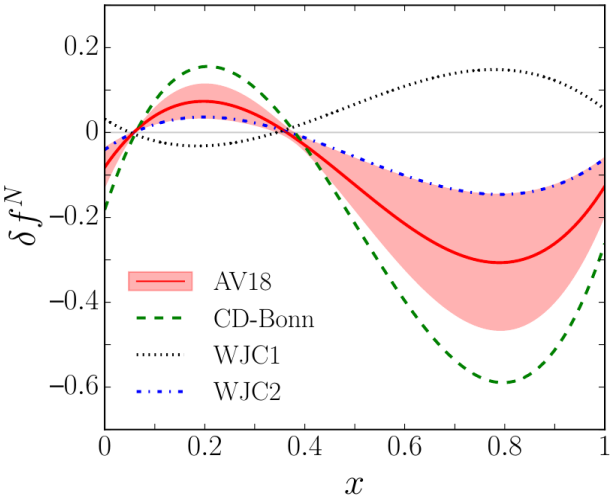
$$\frac{F_2^n}{F_2^d} \propto xu(x) + 4xd(x)$$

Universal fit: d/u and binding effects

Accardi, Brady, Melnitchouk, Owens, Sato, PRD93 (2016) 114017

- **d/u and binding at the same time**
  - → confinement at large x (using flexible large-x d-quark)
  - → bound nucleon corrections in deuteron PDFs

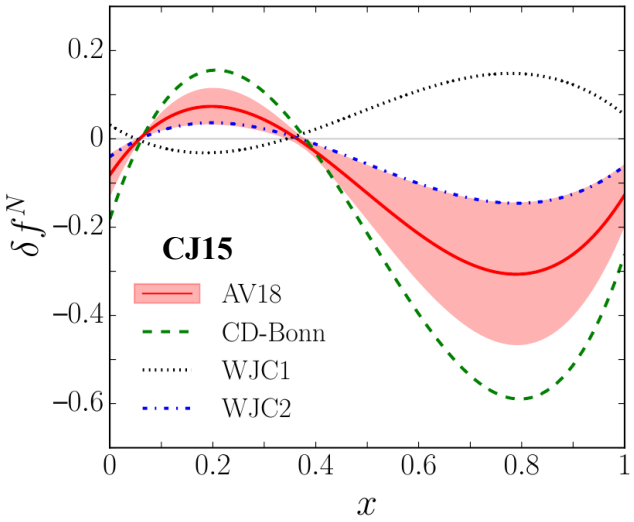


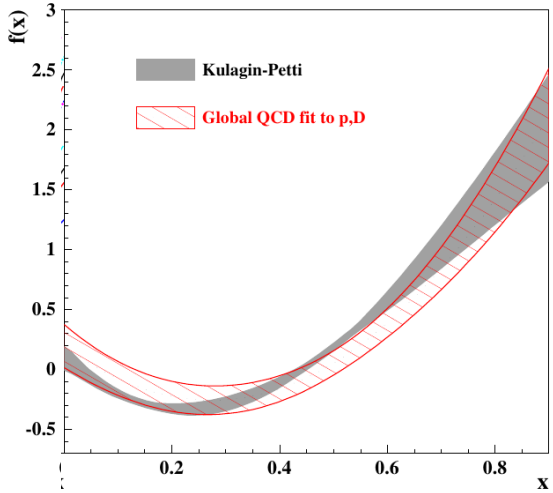


- **Opens novel possibilities**: test nuclear theory ideas against <u>other</u> data:
  - Test "EMC effect" models (of course)
  - On the lattice: "nucleon response to external color field"
  - …

The elephant in the room

- **Compare to Alekhin-Kulagin-Petti (2017)**
  - Same functional form (but different normalization)





Kulagin, Petti (e+A fits), NPA 765 (2006) 126

Alekhin + KP (e+d global fits) PRD96 (2017) 054005

CJ15: *PRD 93 (2016) 114017*

  - Different shape and size ?!?
- **But many (<u>MANY</u>) differences:**
  - Extended d-quark (CJ15) vs. conventional (AKM)
  - Fit real W asymetry vs. only decay lepton W → l + (n) asymmetry
  - **Off-shell, HT choices; WBA implementation, …**

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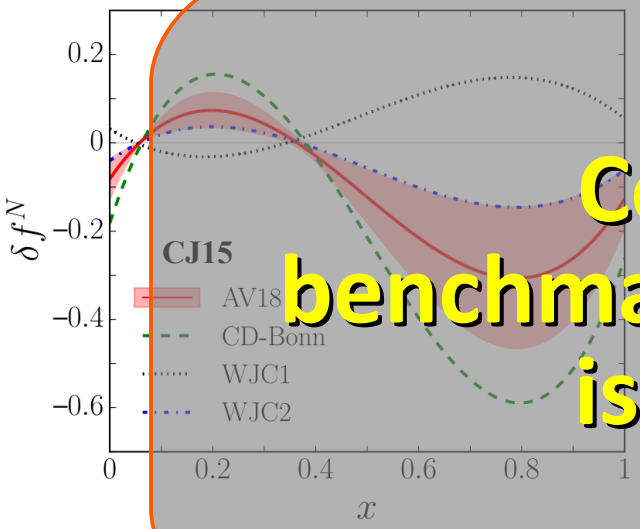
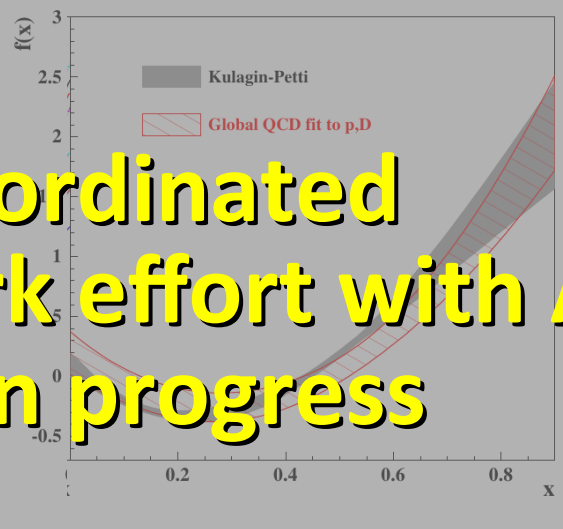




Coordinated benchmark effort with AKP is in progress

Kulagin, Petti (e+A fits), NPA 765 (2006) 126

Alekhin + KP (e+d global fits) PRD96 (2017) 054005 (Note: Paris ~ AV18 wave fn.)

CJ15: PRD 93 (2016) 114017

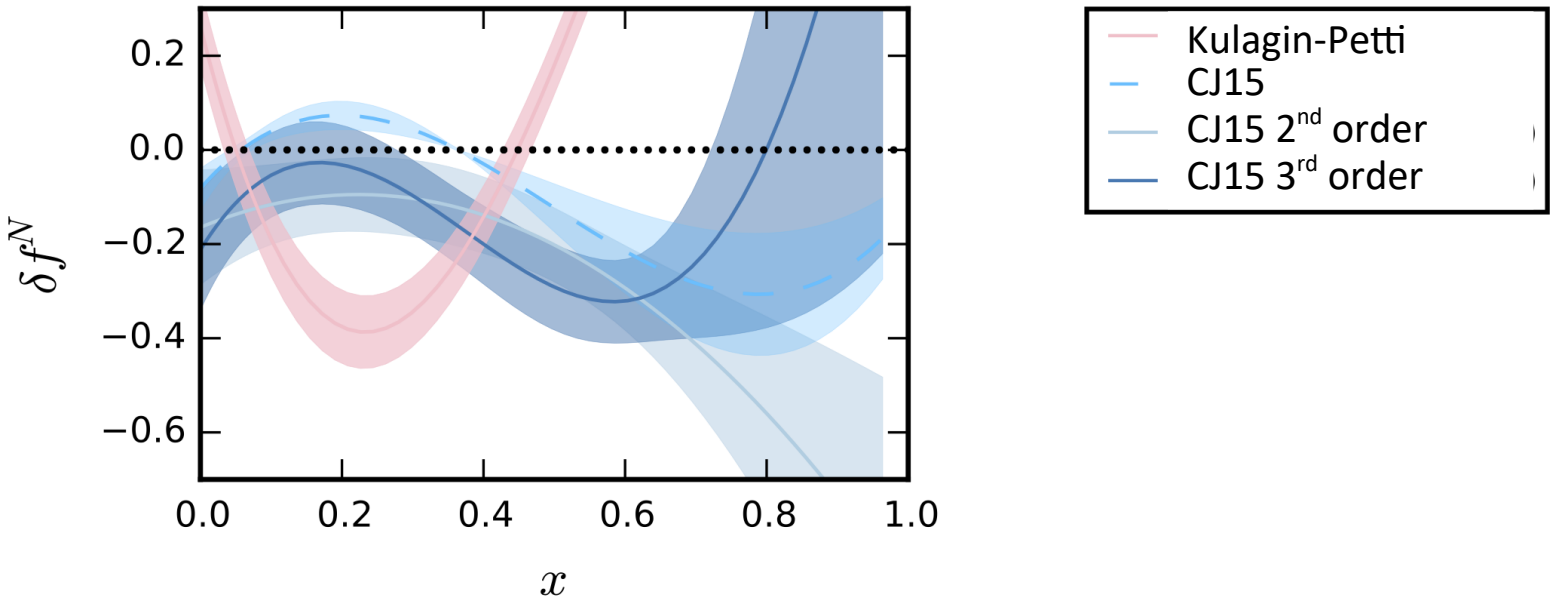
  - Different shape and size ?!?

- **But many (<u>MANY</u>) differences:**
  - Extended d-quark (CJ15) vs. conventional (AKM)
  - Fit real W asymetry vs. only decay lepton W → l + (n) asymmetry
  - **Wave function, Off-shell, HT choices, WBA implementation, …**

Parametrization of off-shell deformation

- 3 CJ variations
  - CJ15 – Factorized *à la* KP: $\delta f(x) = C(x - x_0)(x - x_1)(1 + x - x_0)$

    Fixed by baryon number sum rule
  - Generic 2nd order polynomial: $\delta f(x) = a + bx + cx^2$
  - Generic 3rd order polynomial: $\delta f(x) = a + bx + cx^2 + dx^3$



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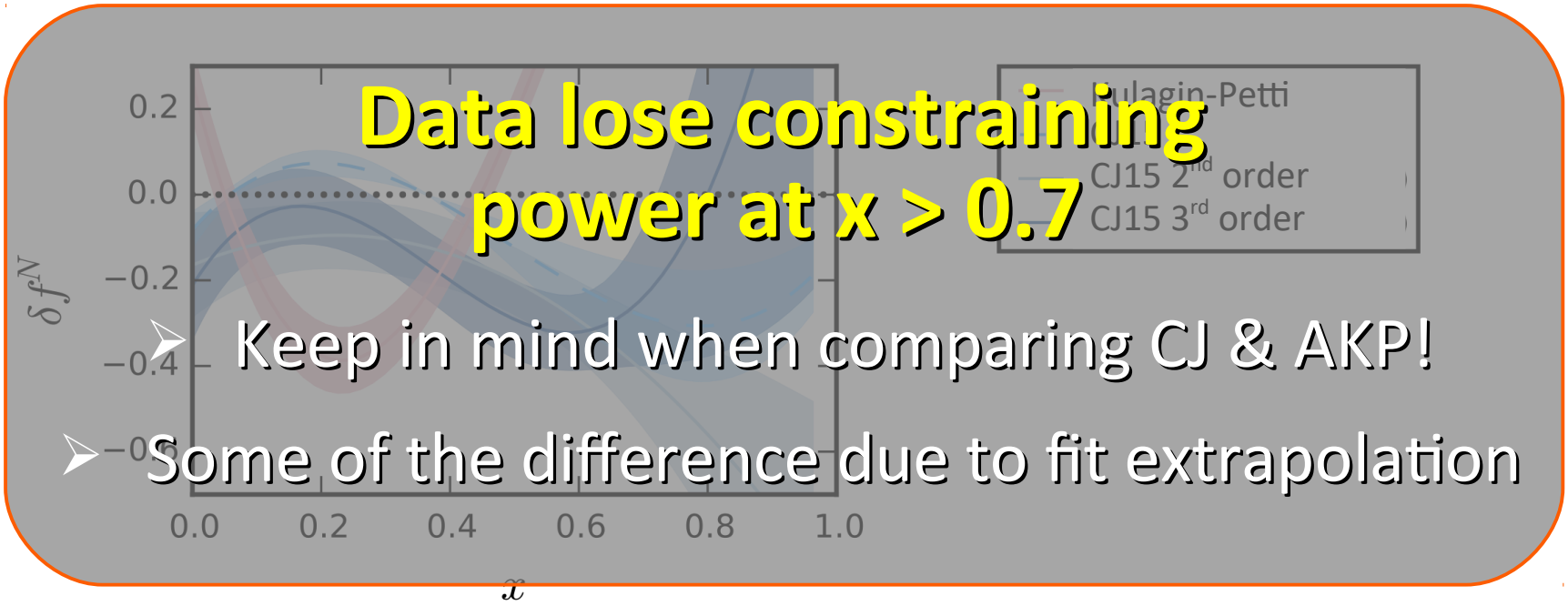


HT assumptions

- **2 sets of choices – 4 combinations:**
  - Isospin symmetric HT(p) = HT(n) vs. asymmetric HT(p) ≠ HT(n)
  - Additive vs. Multiplicative (with Q^2-independent coefficients)

$$F_2(x,Q^2) = F_2^{LT}(x,Q^2) + \frac{H(x)}{Q^2}$$

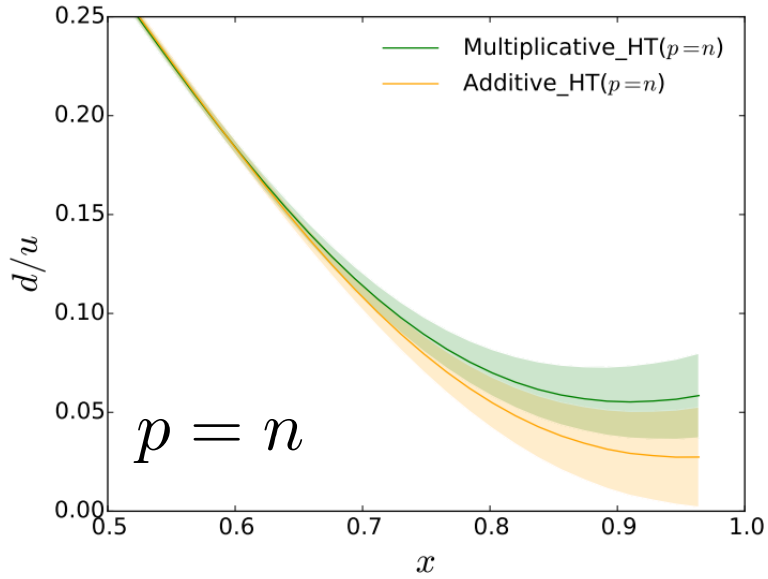
$$F_2(x,Q^2) = F_2^{LT}(x,Q^2)\left(1 + \frac{C(x)}{Q^2}\right)$$

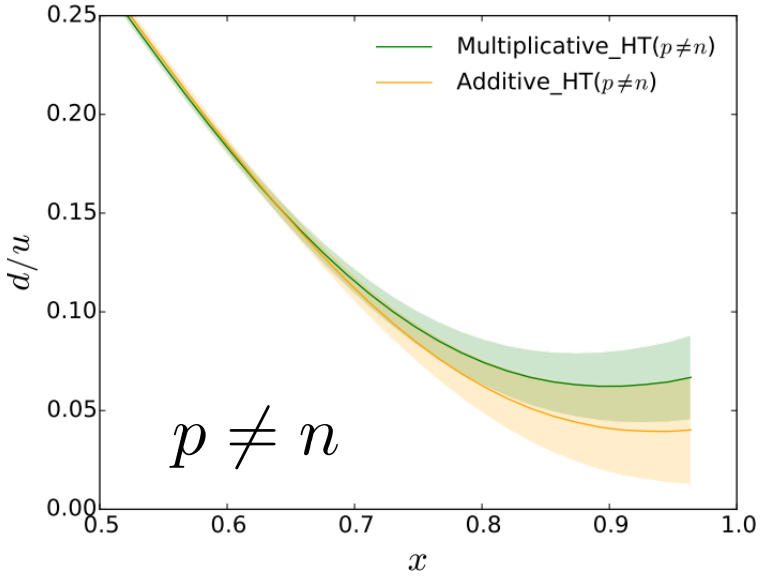
- **Note:** any given HT choice also effectively imposes isospin dependence, Q^2 evolution prescriptions!

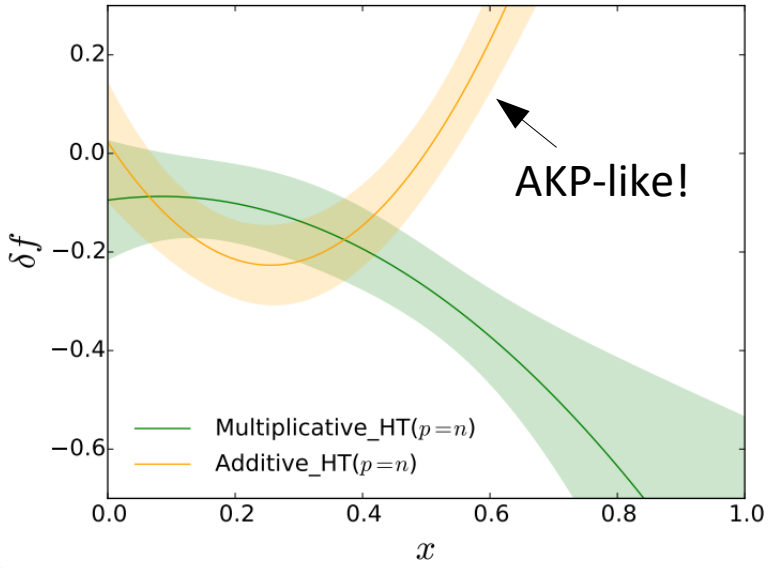
  e.g., a Q^2–independent, isospin symmetric multiplicative HT generates an equivalent additive HT that depends on both

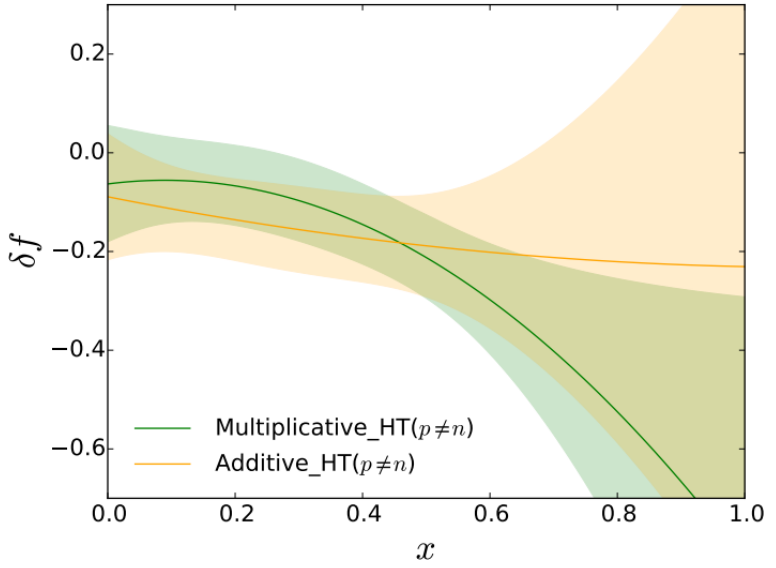
$$\widetilde{H}_{p,n}(x,Q^2) = C(x)\, F_{2p,n}^{LT}(x,Q^2)$$

HT assumptions

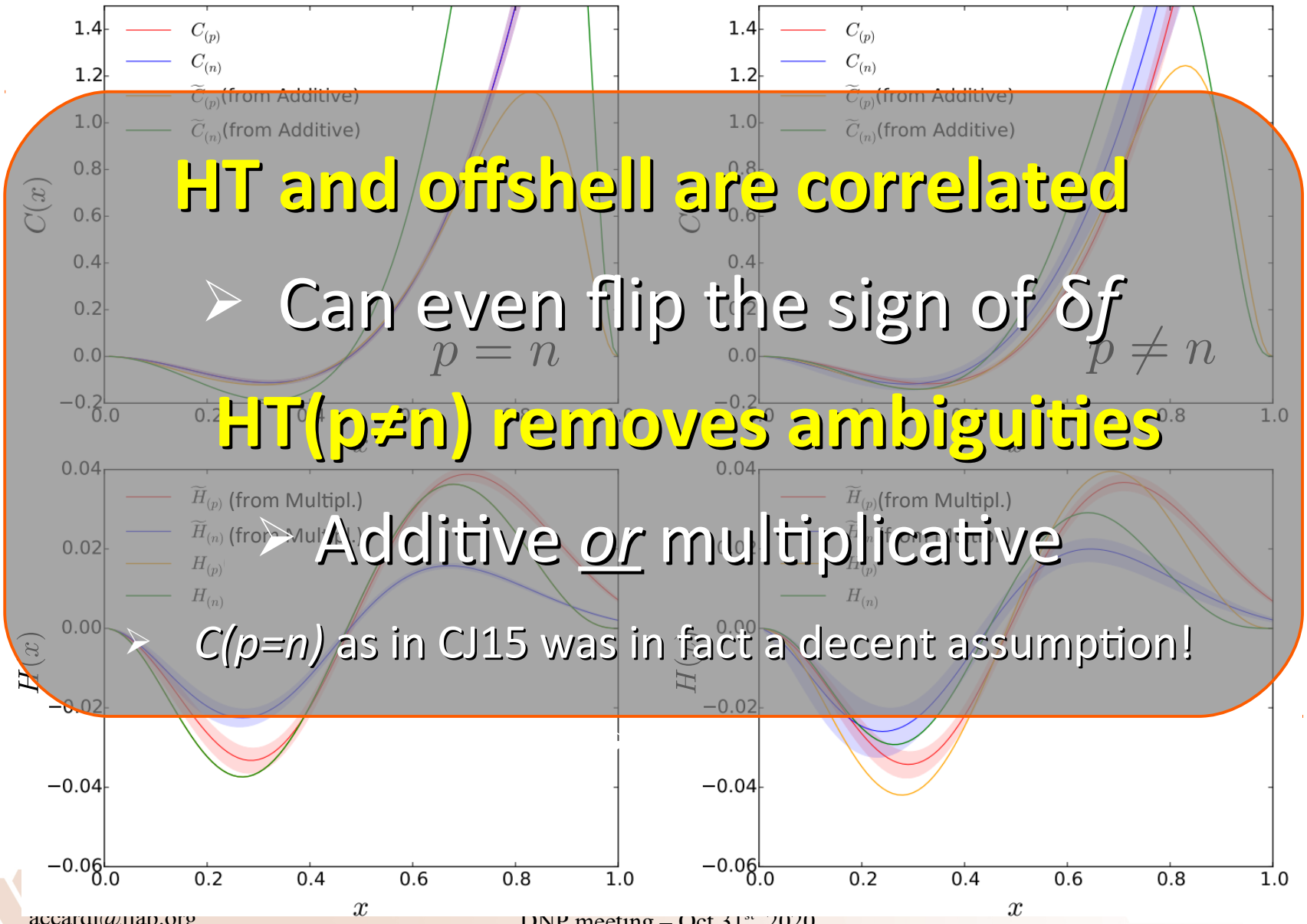








HT assumptions



HT and offshell are correlated

- Can even flip the sign of δf

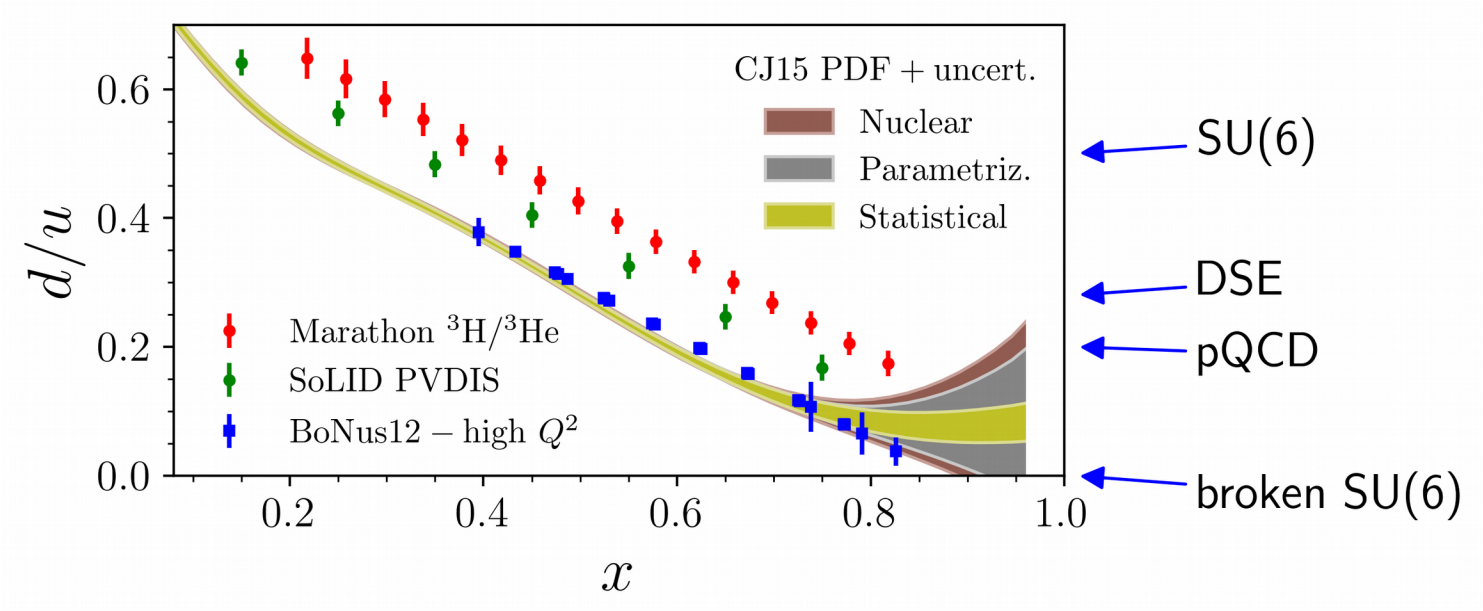
HT(p≠n) removes ambiguities

- Additive *or* multiplicative
- *C(p=n)* as in CJ15 was in fact a decent assumption!

Summary and outlook

Controlled PDFs at large x

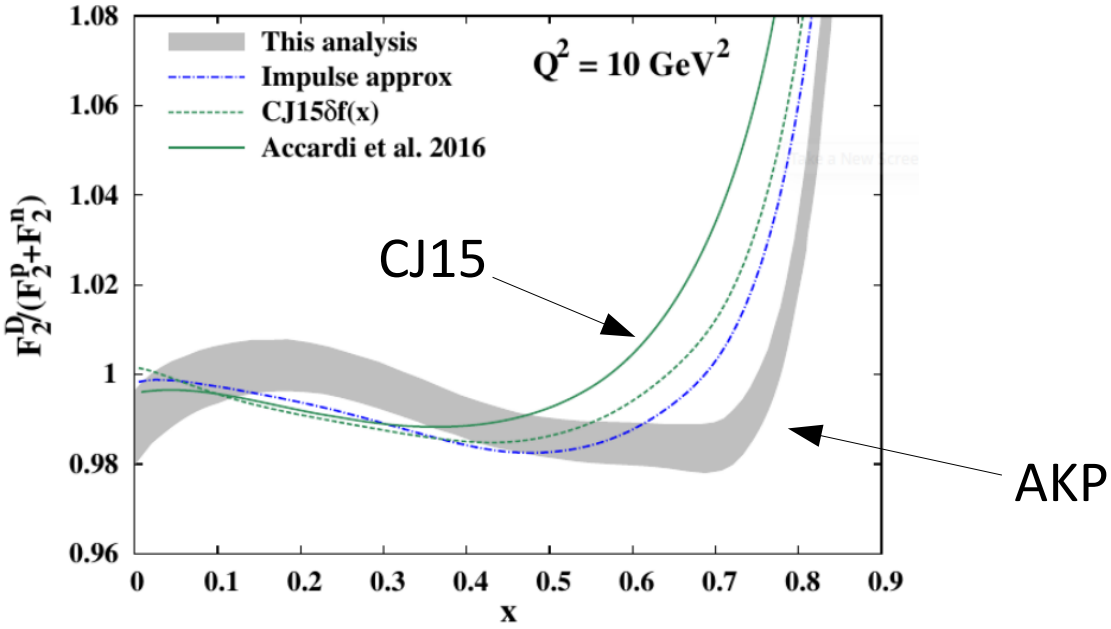
- **CJ15: well controlled large-x PDF + nuclear correction model**
  - ABPM16/AKP similar framework
    → cross-check, evaluation of systemetics



  - Nuclear uncertainty larger than indicated above
    - Only Δ(w.fn.) in the plot
    - But we have seen more sources of nuclear uncertainty

Nuclear model uncertainties

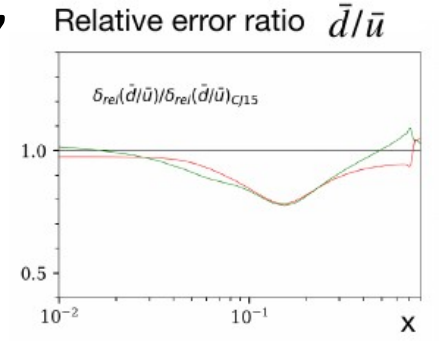
- The D/N ratio is somewhat less controlled



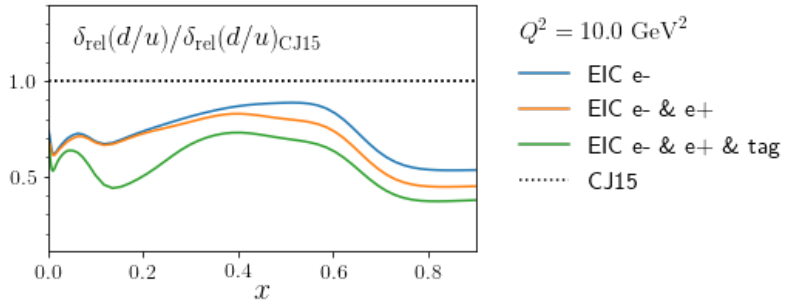
  - Lots of differences in theoretical and fitting choices
  - Take, provisionally, as magnitude of current theoretical systematics
  - **Benchmark in progress with AKP**

Outlook

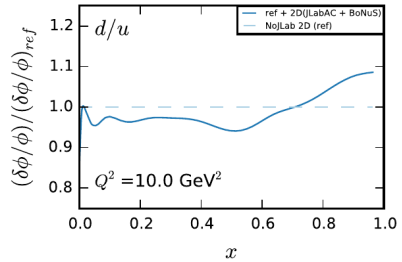
- Needs **precise nucleus-free "control observables"**
  - W, Z from RHIC & LHC(b) *M.Posik, ML.04* **– in progress!**
    … and SeaQuest *A. Tadepalli, ML.07* **w/ X.Jing, S.Li, S.Park**
  - BoNus12, Marathon*, SoLID PVDIS *E.Christy, KL.04* *M.Petratos, KL.02*
  - EIC: **w/ X.Jing, S.Li & the IRWG**
    - weak currents, tagged e+D
    - PVDIS, positron beam

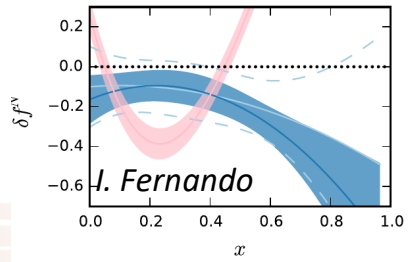


S. Park ML.05 2:48 pm



- **…plus more bread & butter p, d DIS**
  - Full JLab 6 DIS data set **– in progress!** **w/ I.Fernando, S.Li**
  - **DIS @ Jlab 12!** *Overview: S. Malace, KL.01*

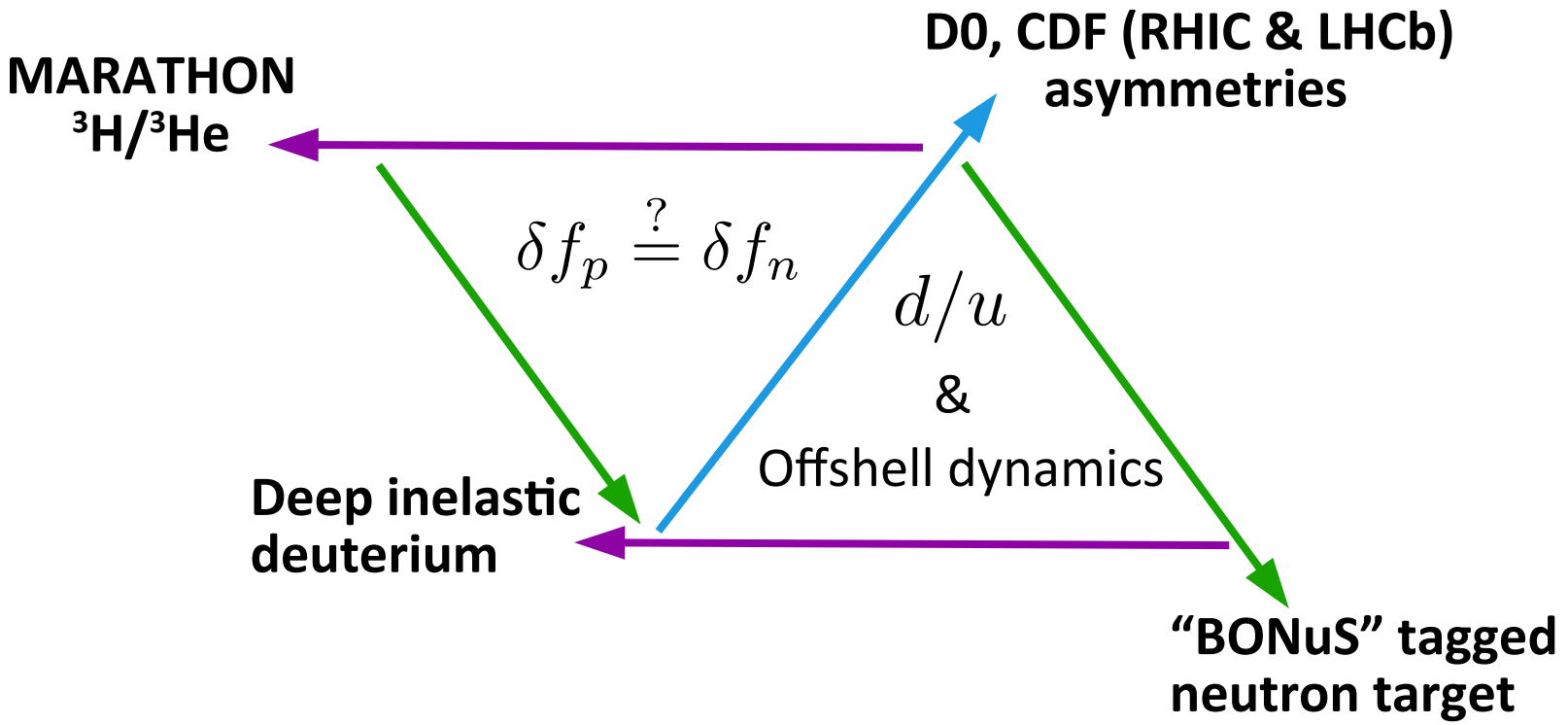




* Not quite "nuclear-free"… see Tropiano et al. PRC 99 (2019)

The Marathon parallelogram

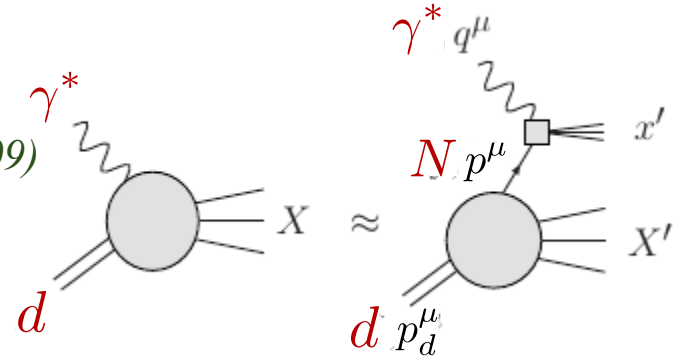
- Can extend the CJ15 triangle to a parallelogram
  - **and verify if off-shell protons ~ off-shell neutrons !!**



Backup

Deuteron target summary

- **Smearing function representation**
  → *e.g., Kahn et al., PRC 79 (2009)*
  - Precalculate the p_T^2 integral
  - Obtain a "simple" formula:



$$F_{2D}(x,Q^2) = \Big(\mathcal{S}_0 \otimes F_{2N}^{\text{free}}\Big)(x,Q^2) + \Big(\mathcal{S}_1 \otimes F_{2N}^{\text{free}}\delta f_2\Big)(x,Q^2)$$

(on-shell) smearing function

offshell smearing function

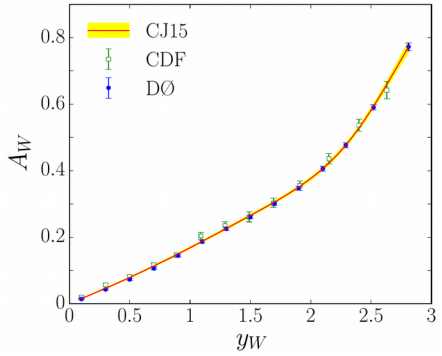
offshell deformation of the F2 str.fn.

where: $\big(\mathcal{S}\otimes F\big)(x) = \int \frac{dy}{y}\mathcal{S}(y)F(x/y)$

$$\mathcal{S}_n(y) = \int dp^2 \left(\frac{p^2-M^2}{M^2}\right)^{2n} \mathcal{K}(z,p^2,\gamma)\left|\psi_{N/d}(|\vec{p}|)\right|^2$$

Interplay of observables

D0, CDF asymmetries



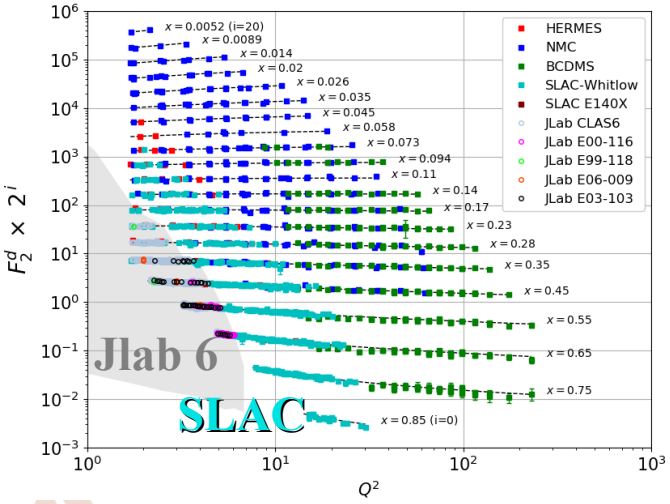
d-quark at largest x
on proton targets

d/u

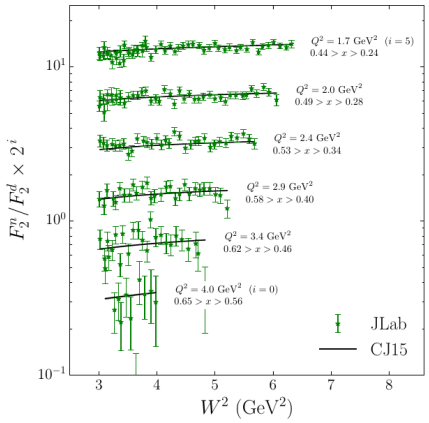
&

Offshell dynamics

Deep inelastic deuterium

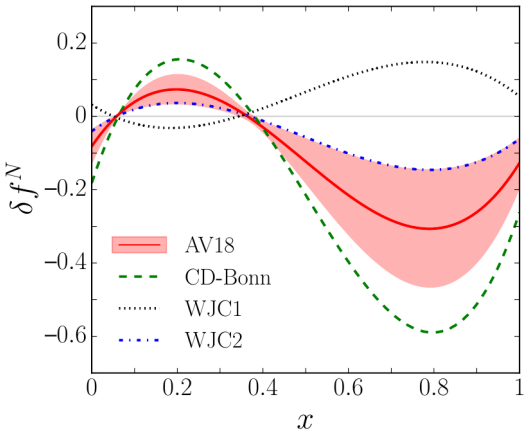


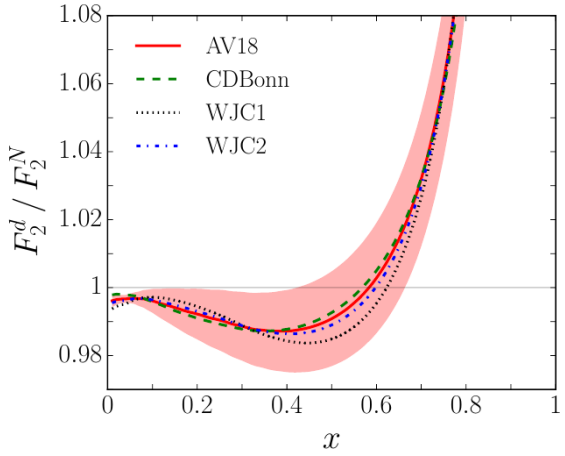
"BONuS" tagged neutron target

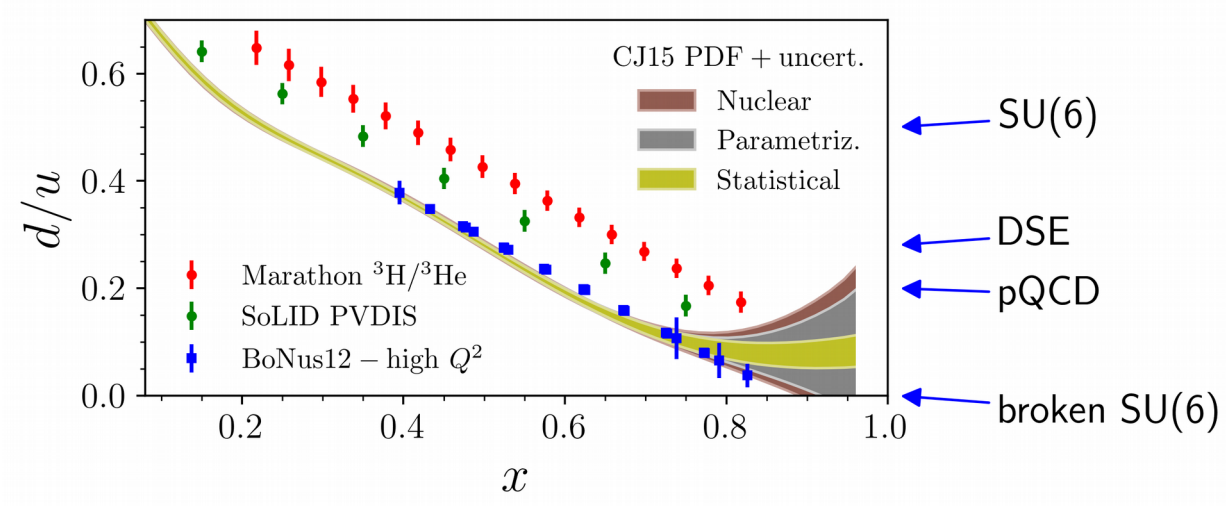


Nuclear wave function dependence

- Partly absorbed by the d-quark to give stable F2(D) fits
  - But chi^2 prefers AV18







HT assumptions