Nuclear effects in the deuteron:
model-independent constraints from QCD global analysis

Wally Melnitchouk

— Jefferson Lab —

Chris Cocuzza (Temple U), Nobuo Sato (JLab), and
JAM (Jefferson Lab Angular Momentum) Collaboration

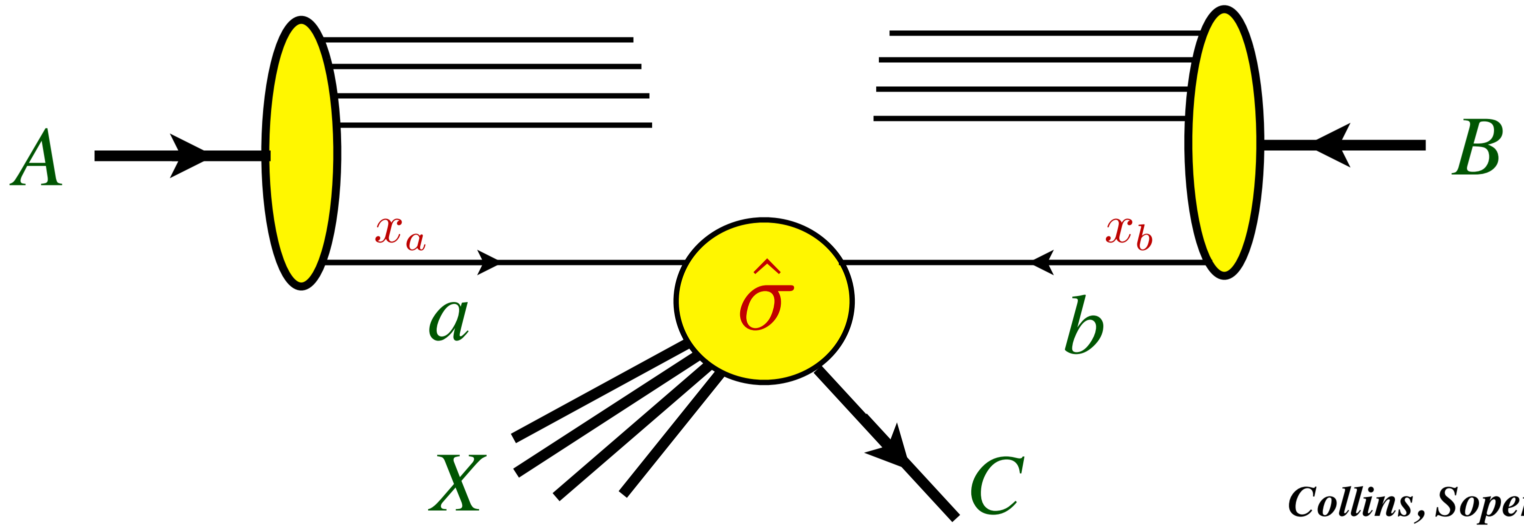
JAM https://www.jlab.org/jam

Overview

- Nucleon structure and global QCD analysis of PDFs
- Nuclear effects in DIS from the deuteron
- d/u PDF ratio at large x
- JAM Monte Carlo analysis
- Outlook

Parton distributions in the nucleon

- Inclusive high-energy particle production $A\,B \to C\,X$



Collins, Soper, Sterman (1980s)

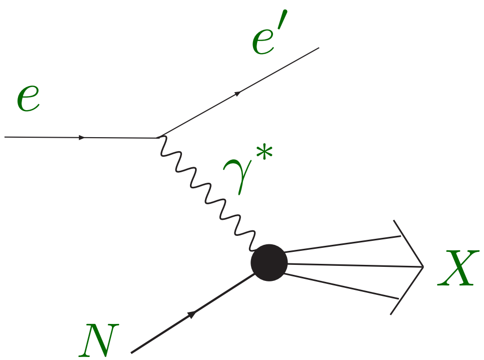
$\longrightarrow$ QCD factorization: separation of hard (perturbative, calculable) from soft (nonperturbative, parametrized) physics

$$\sigma_{AB\to CX}(p_A, p_B) = \sum_{a,b} \int dx_a\, dx_b\, f_{a/A}(x_a, \mu)\, f_{b/B}(x_b, \mu) \times \sum_n \alpha_s^n(\mu)\, \hat{\sigma}^{(n)}_{ab\to CX}(x_a p_A, x_b p_B, Q/\mu)$$

$\longrightarrow$ process-independent parton distribution functions $f_{a/A}$ characterizing structure of bound state A

Parton distributions in the nucleon

- Most information on PDFs obtained from lepton-hadron deep-inelastic scattering (DIS)



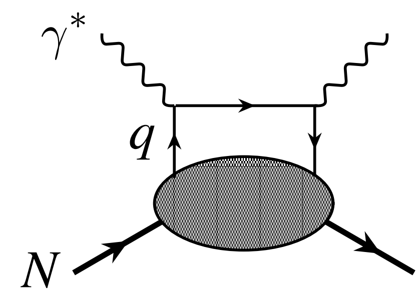
$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2\frac{\theta}{2}}{Q^4}\left(2\tan^2\frac{\theta}{2}\frac{F_1}{M} + \frac{F_2}{\nu}\right)$$

$$x_B = \frac{Q^2}{2M\nu} \qquad Q^2 = \vec{q}^{\,2} - \nu^2 \qquad \nu = E - E'$$

$\longrightarrow$ structure function given as convolution of hard Wilson coefficient with PDF

$$F_2(x_B, Q^2) = x_B \sum_q e_q^2 \int_{x_B}^1 \frac{dx}{x} C_q\left(\frac{x_B}{x}, \alpha_s\right) q(x, Q^2)$$

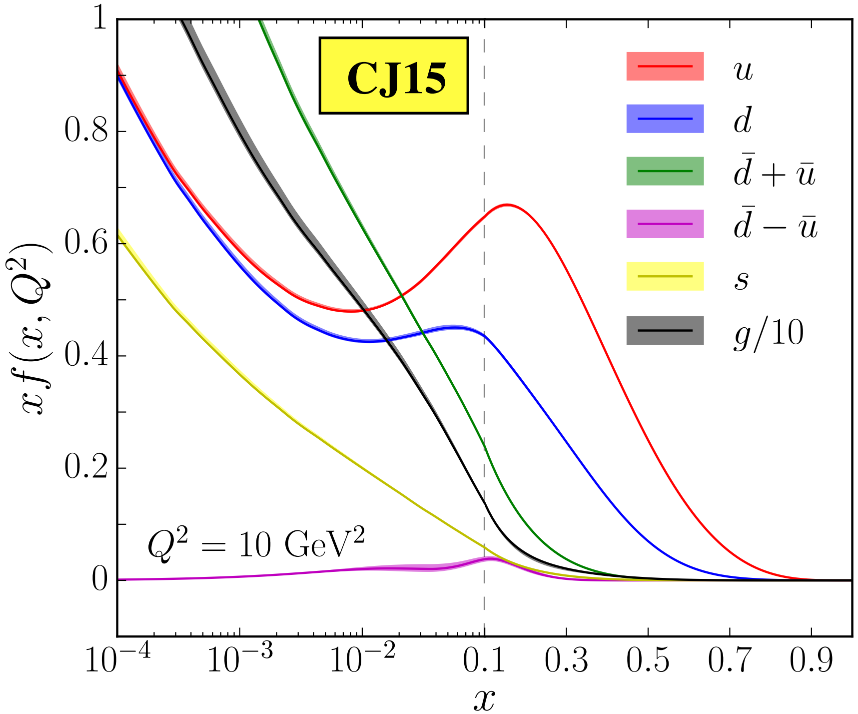
$$\longrightarrow x_B \sum_q e_q^2\, q(x_B, Q^2)$$



for leading order approximation $C_q \longrightarrow \delta\left(1 - \frac{x_B}{x}\right)$

Parton distributions in the nucleon

- Ubiquity of proton F_2 data (SLAC, EMC, NMC, BCDMS, HERA, JLab, …) provides strong constraints on u-quark PDF over large x range



$$F_2^p \sim \frac{4}{9} xu + \frac{1}{9} xd + \cdots$$

- Absence of free-neutron data and smaller $|e_q|$ of d quarks limit precision of d-quark PDF, especially at high x

$\longrightarrow$ nuclear effects in deuteron obscure free-neutron structure

Nuclear effects in DIS

- Approximate scattering from weakly-bound nuclei at $x \gg 0$ in terms of incoherent scattering from bound nucleons

$\longrightarrow$ generalized convolution in "weak binding approximation" (WBA)

$$F_2^A(x,Q^2) = \sum_N \int \frac{d^4p}{(2\pi)^4} \mathcal{F}_0^N(\varepsilon,\mathbf{p}) \left(1 + \frac{\gamma p_z}{M}\right) \mathcal{C}_{22}\, \widetilde{F}_2^N(x/y,Q^2,p^2)$$

nuclear spectral function

bound nucleon momentum $p = (p_0;\mathbf{p}) = (M+\varepsilon;\ \mathbf{p}_\perp,\ p_z)$

kinematic factor $\mathcal{C}_{22} = \frac{1}{\gamma^2}\left[1 + \frac{(\gamma^2-1)}{2y^2M^2}(2p^2 + 3\mathbf{p}_\perp^2)\right]$ $\qquad \gamma^2 = 1 + \frac{4M^2x^2}{Q^2}$

nuclear momentum fraction $y = \frac{M_A}{M}\frac{p\cdot q}{P\cdot q} = \frac{p_0 + \gamma p_z}{M}$

$\longrightarrow$ factorized formula valid up to $\mathcal{O}(\mathbf{p}^2/M^2)$ corrections

WM, Schreiber, Thomas (1994)
Kulagin et al. (1994)

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off-shell nucleon structure function

$\longrightarrow$ expand to lowest order in nucleon virtuality $(p^2 - M^2)$

$$\widetilde{F}_2^N(x,Q^2,p^2) = F_2^N(x,Q^2) \left(1 + \frac{p^2 - M^2}{M^2} \delta f^N(x)\right)$$

on-shell structure function

off-shell correction

$$\delta f^N = \left. \frac{\partial \log \widetilde{F}_2^N}{\partial \log(p^2/M^2)} \right|_{p^2=M^2}$$

Nuclear effects in DIS

- Write total nuclear structure function as a sum of nucleon on-shell and off-shell contributions

$$F_2^A(x,Q^2) = F_2^{A(\text{on})}(x,Q^2) + F_2^{A(\text{off})}(x,Q^2)$$

where

$$F_2^{A(\text{on})}(x,Q^2) = \sum_N \int dy\, f^{N/A}(y,\gamma)\, F_2^N(x/y,Q^2)$$

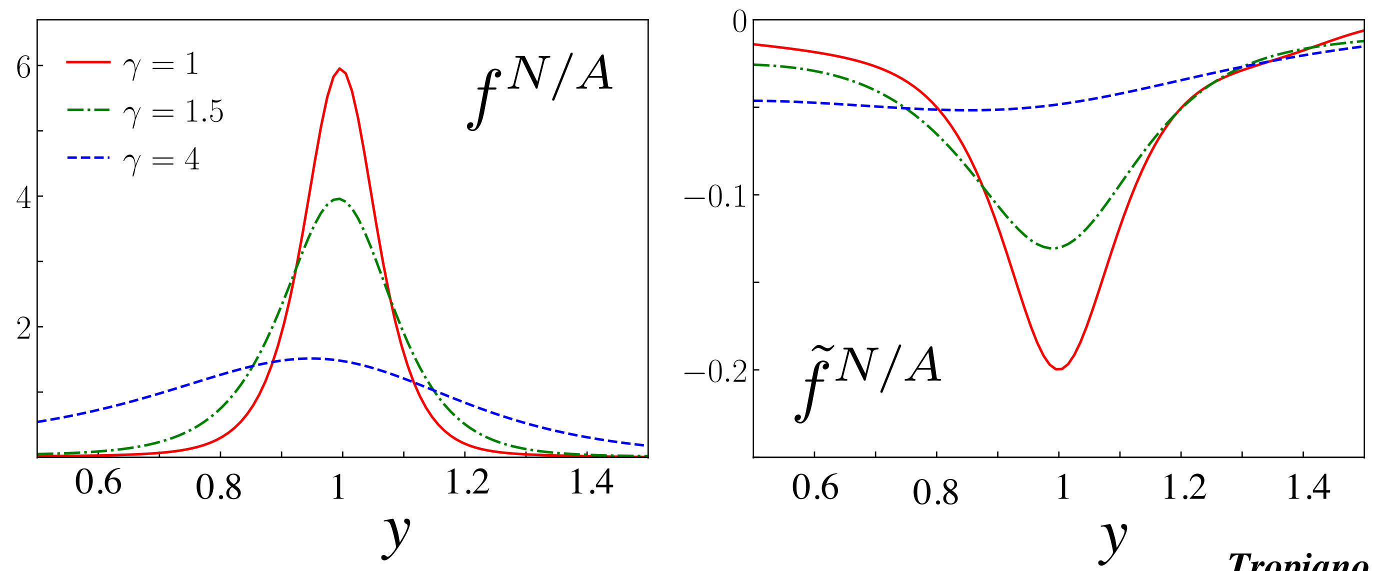
$$F_2^{A(\text{off})}(x,Q^2) = \sum_N \int dy \left[\tilde{f}^{N/A}(y,\gamma)\, F_2^N(x/y,Q^2)\right] \delta f^N(x/y)$$

- Nucleon "smearing functions" (light-cone momentum distributions)

on-shell $$f^{N/A}(y,\gamma) = \int \frac{d^4p}{(2\pi)^4} \mathcal{F}_0^N(\varepsilon,\mathbf{p}) \left(1 + \frac{\gamma p_z}{M}\right) \mathcal{C}_{22}\, \delta\left(y - 1 - \frac{\varepsilon + \gamma p_z}{M}\right)$$

off-shell $$\tilde{f}^{N/A}(y,\gamma) = \int \frac{d^4p}{(2\pi)^4} \mathcal{F}_0^N(\varepsilon,\mathbf{p}) \left(1 + \frac{\gamma p_z}{M}\right) \mathcal{C}_{22}\, \frac{(p^2 - M^2)}{M^2} \delta\left(y - 1 - \frac{\varepsilon + \gamma p_z}{M}\right)$$

Nuclear effects in DIS



Tropiano et al. (2019)

→ off-shell smearing functions $\ll$ on-shell smearing functions for most kinematics of interest, strongly peaked around $y = 1$, opposite sign

→ for deuteron, $f^{p/D}(y) = f^{n/D}(y) \equiv f^{N/D}(y)$

Nuclear effects in DIS

- For $A = D$ off-shell part of structure function can be written

$$F_2^{D(\mathrm{off})}(x,Q^2) = \int dy\, \tilde{f}^{N/D}(y)\, F_2^{p+n}(x/y,Q^2)\, \delta f^D(x/y)$$

where

$$\delta f^D(x) \equiv \delta f^0(x) = \frac{\delta f^{p/D}(x) F_2^p(x) + \delta f^{n/D}(x) F_2^n(x)}{F_2^p(x) + F_2^n(x)}$$

$\longrightarrow$ deuteron not sensitive to possible differences $\delta f^{p/D} \stackrel{?}{\neq} \delta f^{n/D}$

- To ensure conservation of valence quark (baryon) number in the deuteron, off-shell function is normalized

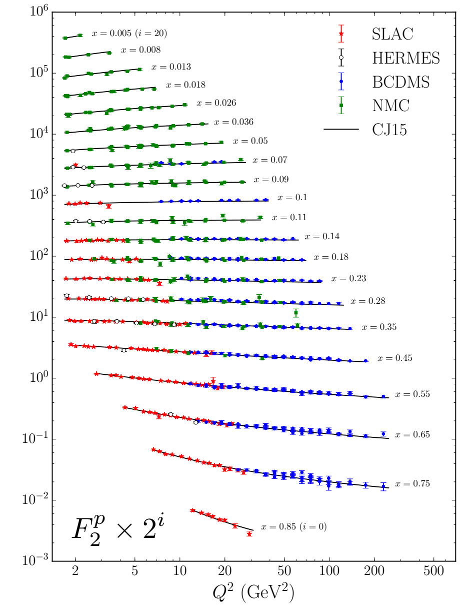
$$\int_0^1 dx\, q_v(x)\, \delta f^{N/D}(x) = 0$$

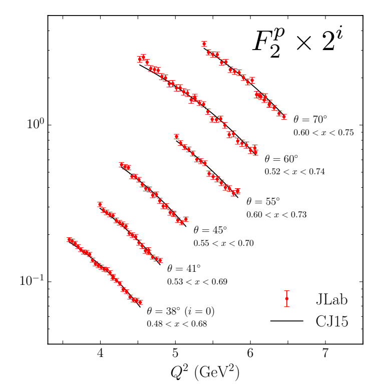
for $q = u, d$ and $N = p, n$

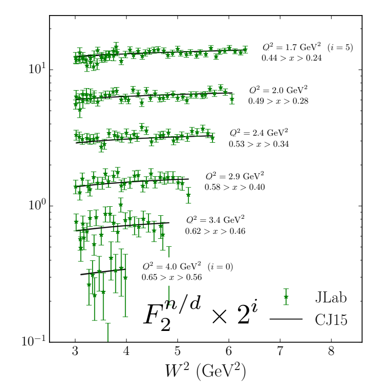
Previous analyses — CJ15

- CJ (CTEQ-JLab) Collaboration has performed global QCD studies focusing in particular on the high-x, low-W region, to better constrain PDFs at large x

Observable	Experiment	# points	χ^2				
			LO	NLO	NLO (OCS)	NLO (no nucl)	NLO (no nucl/D0)
DIS F_2	BCDMS (p) [81]	351	426	**438**	436	440	427
	BCDMS (d) [81]	254	292	**292**	289	301	301
	SLAC (p) [82]	564	480	**434**	435	441	440
	SLAC (d) [82]	582	415	**376**	380	507	466
	NMC (p) [83]	275	416	**405**	404	405	403
	NMC (d/p) [84]	189	181	**172**	173	174	173
	HERMES (p) [86]	37	57	**42**	43	44	44
	HERMES (d) [86]	37	52	**37**	38	36	37
	Jefferson Lab (p) [87]	136	172	**166**	167	177	166
	Jefferson Lab (d) [87]	136	131	**123**	124	126	130
DIS F_2 tagged	Jefferson Lab (n/d) [21]	191	216	**214**	213	219	219
DIS σ	HERA (NC e^-p) [85]	159	315	**241**	240	247	244
	HERA (NC e^+p 1) [85]	402	952	**580**	579	588	585
	HERA (NC e^+p 2) [85]	75	177	**94**	94	94	93
	HERA (NC e^+p 3) [85]	259	311	**249**	249	248	248
	HERA (NC e^+p 4) [85]	209	352	**228**	228	228	228
	HERA (CC e^-p) [85]	42	42	**48**	48	45	49
	HERA (CC e^+p) [85]	39	53	**50**	50	51	51
Drell-Yan	E866 (pp) [29]	121	148	**139**	139	145	143
	E866 (pd) [29]	129	202	**145**	143	158	157
W/charge asymmetry	CDF (e) [88]	11	11	**12**	12	13	14
	DØ (μ) [17]	10	18	**20**	19	29	28
	DØ (e) [18]	13	49	**29**	29	14	14
	CDF (W) [89]	13	16	**16**	16	14	14
	DØ (W) [19]	14	35	**14**	15	82	—
Z rapidity	CDF (Z) [90]	28	108	**27**	27	26	26
	DØ (Z) [91]	28	26	**16**	16	16	16
jet	CDF (run 2) [92]	72	29	**15**	15	23	25
	DØ (run 2) [93]	110	87	**21**	21	14	14
γ + jet	DØ 1 [94]	16	16	**7**	7	7	7
	DØ 2 [94]	16	34	**16**	16	17	17
	DØ 3 [94]	12	35	**25**	25	24	25
	DØ 4 [94]	12	79	**13**	13	13	13
total		4542	5935	**4700**	4702	4964	4817
total + norm			6058	**4708**	4710	4972	4826
χ^2/datum			1.33	**1.04**	1.04	1.09	1.07







Accardi, Brady, WM, Owens, Sato (2016)

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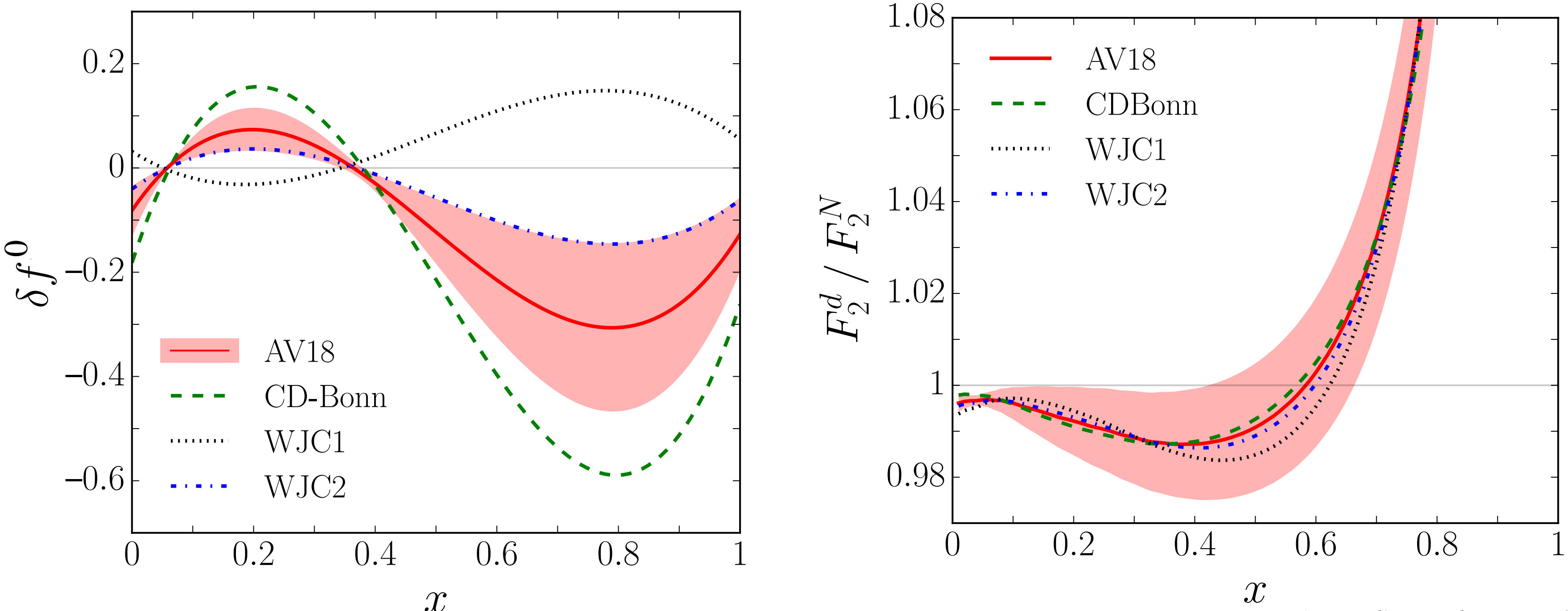


Accardi, Brady, WM, Owens, Sato (2016)

$\longrightarrow$ off-shell effects are correlated with nuclear wave function, but best fit is for AV18 model

$\longrightarrow$ gives small negative (positive) shift in d/N at low x (high x)

Previous analyses — CJ15

- Valence d/u ratio at high x of particular interest

  → testing ground for nucleon models in $x \to 1$ limit

  - $d/u \to 1/2$

    SU(6) symmetry

  - $d/u \to 0$

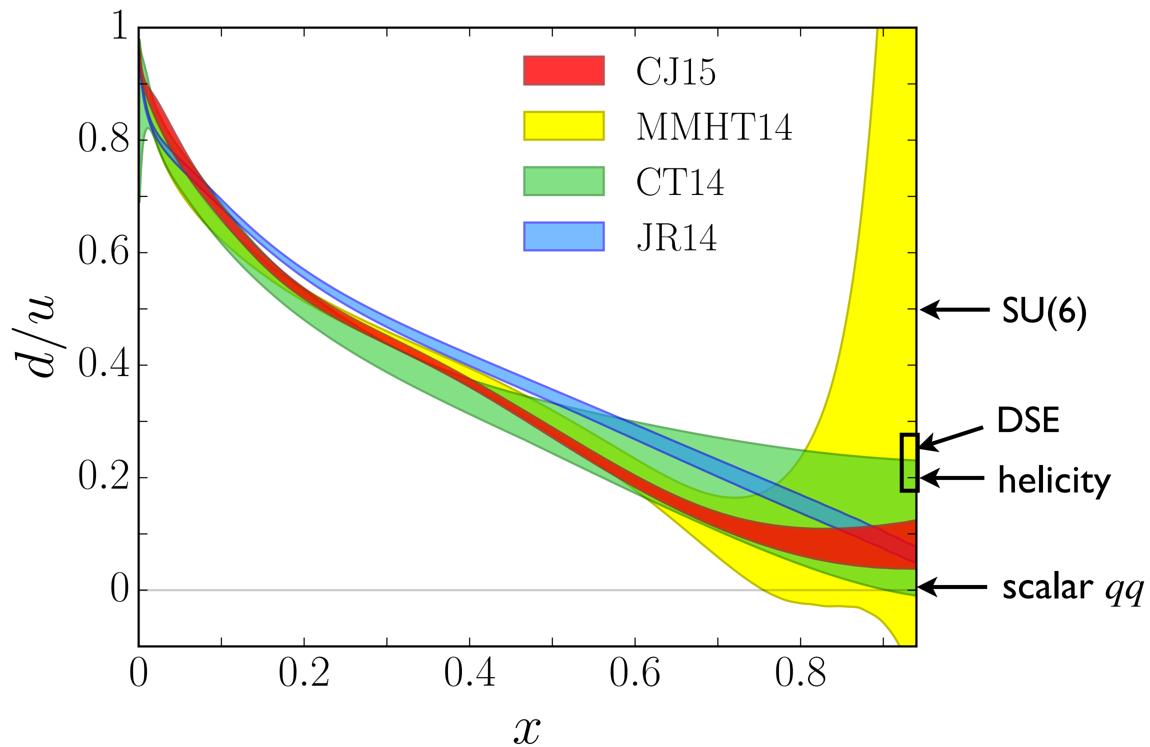
    $S = 0$ qq dominance
    (color-hyperfine interaction)

  - $d/u \to 1/5$

    $S_z = 0$ qq dominance
    (perturbative gluon exchange)

  - $d/u \to 0.18 - 0.28$

    DSE with qq correlations



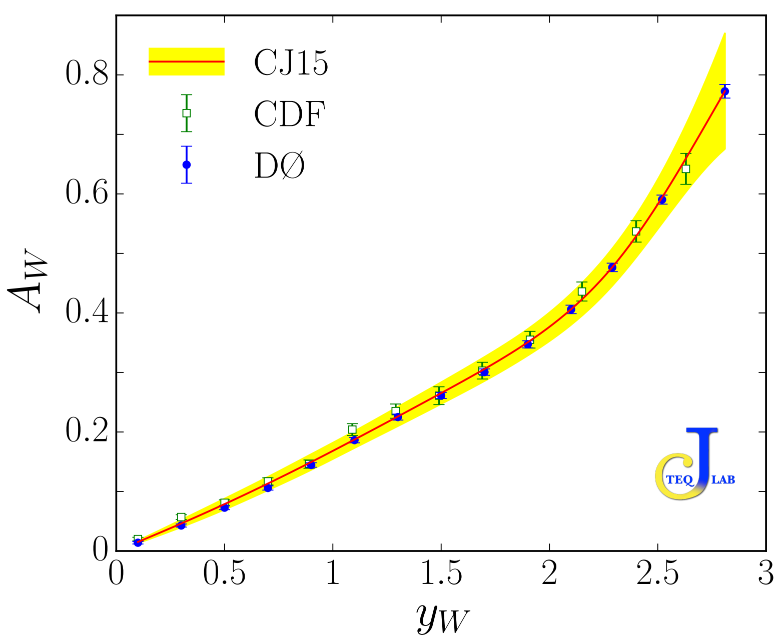
→ considerable uncertainty at high x from deuterium corrections

Previous analyses — CJ15

- Valence d/u ratio at high x of particular interest

  → significant reduction of PDF errors with new JLab tagged neutron & FNAL W-asymmetry data

$$d + \bar{u} \to W^- \to \ell^- + \bar{\nu}$$



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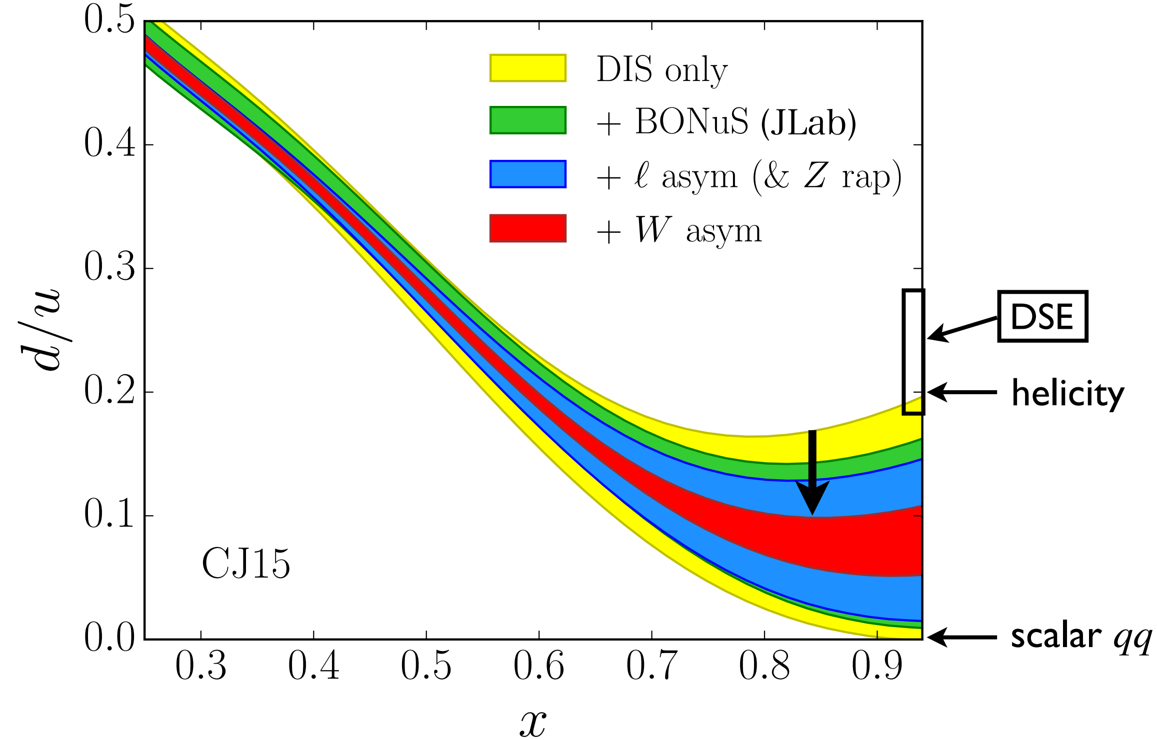


→ extrapolated ratio at $x = 1$

$$d/u \;\to\; 0.09 \pm 0.03$$

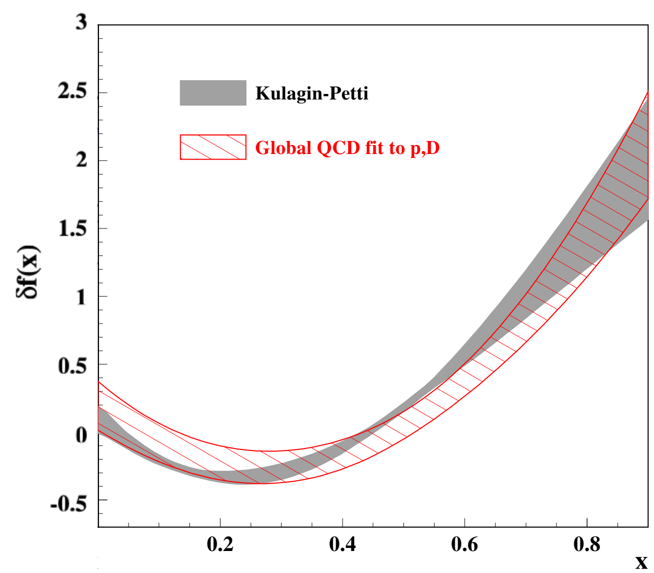
does not match any model…

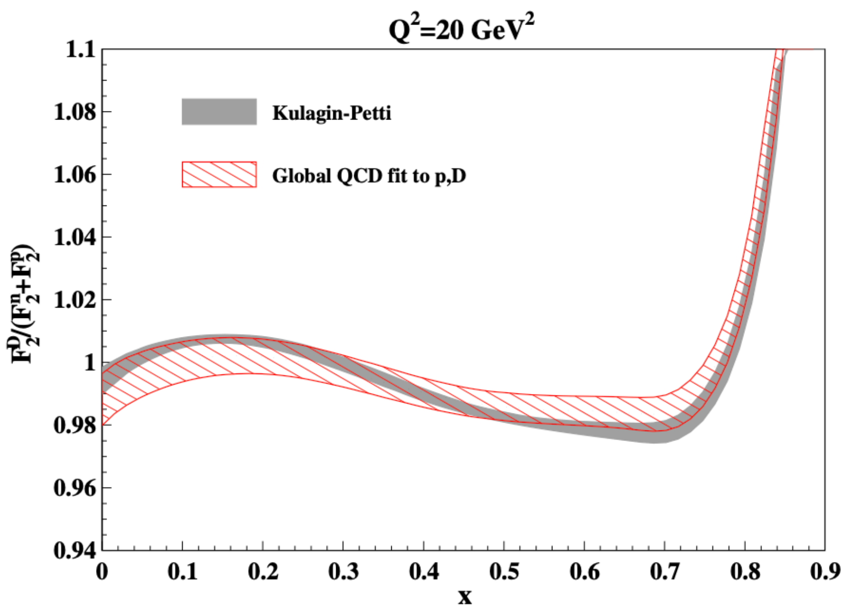
→ experiments at JLab (MARATHON, BONuS, SoLID) will determine d/u up to $x \sim 0.8$-0.85

Previous analyses — AKP17

- Similar global analysis was performed by Alekhin, Kulagin, Petti (AKP17) — similar data sets & cuts (earlier analyses used data on heavy nuclei), similar nuclear theory…

→ find qualitatively different behavior for off-shell function, and EMC ratio shape that resembles ratio for heavy nuclei!





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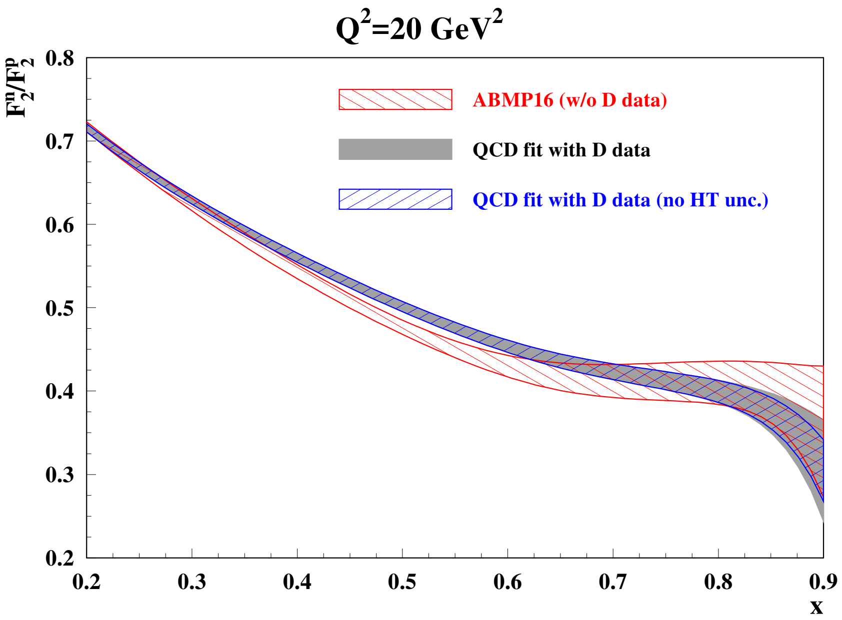
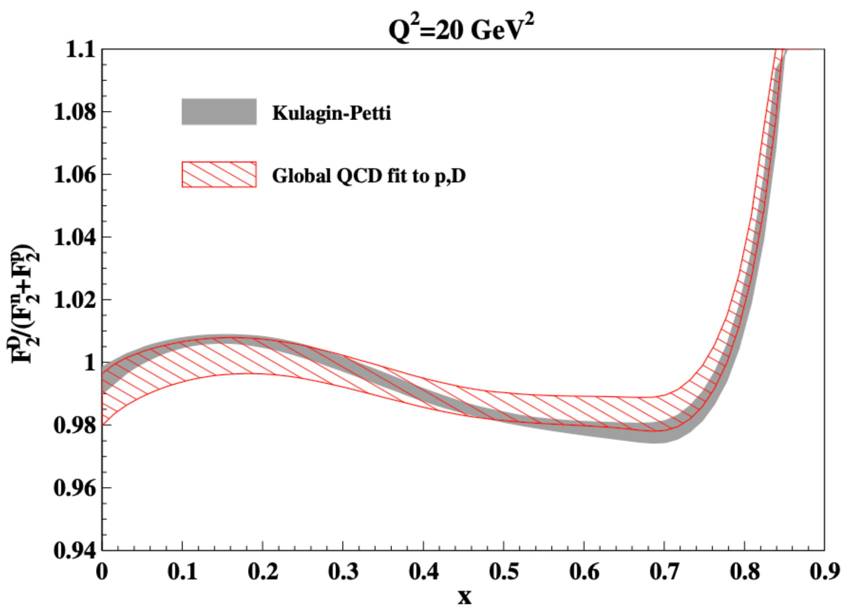
→ correspondingly larger n/p ratio at large x





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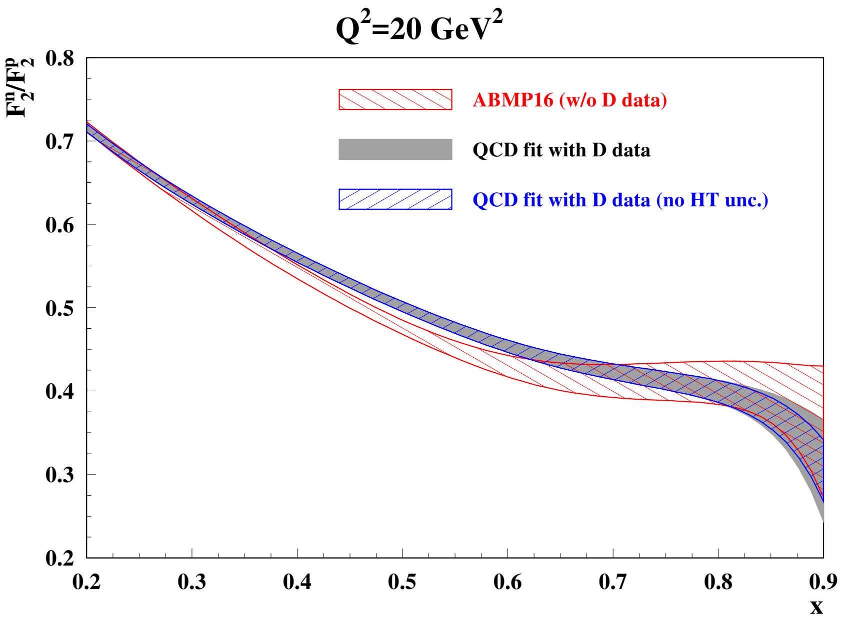
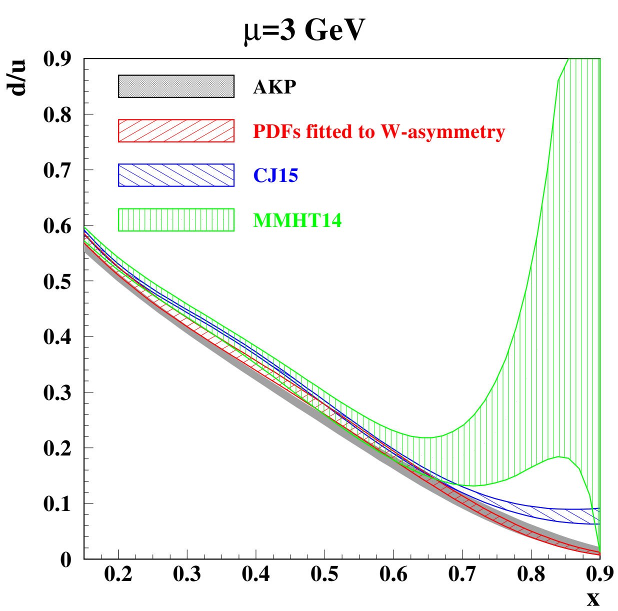


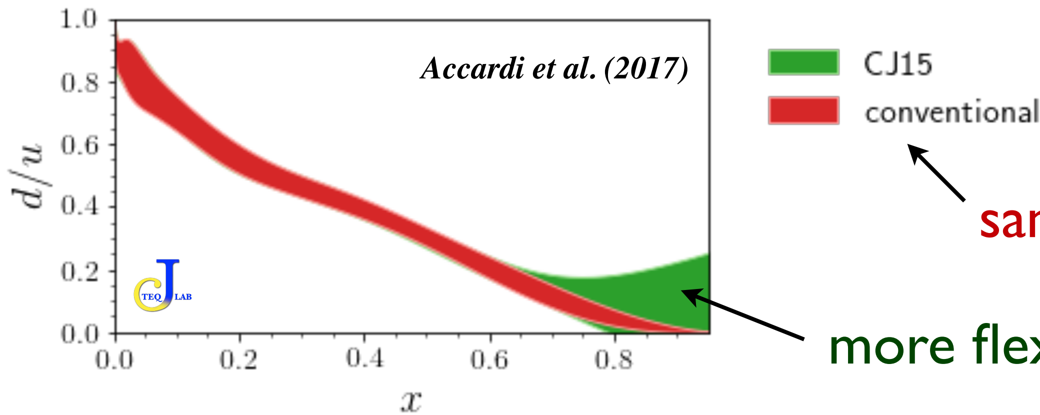


→ … but curiously smaller d/u at $x \gtrsim 0.75$

Previous analyses — AKP17 vs. CJ15

- Which (if any) is correct?

  $\longrightarrow$ benchmarking efforts by Accardi & Alekhin/Kulagin…

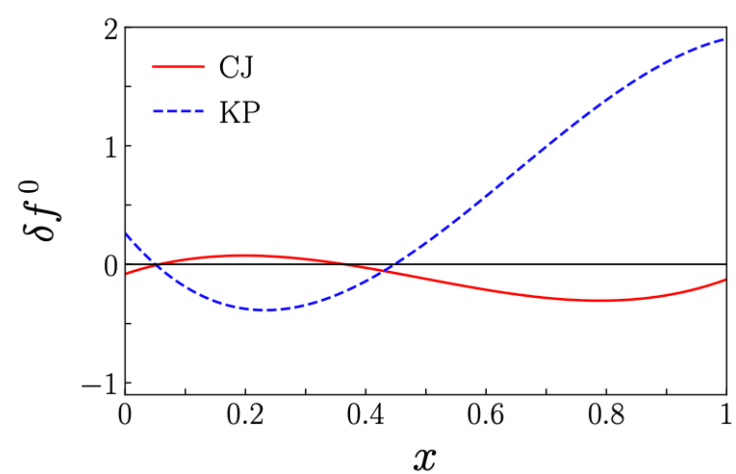


same functional form for u & d $\sim (1-x)^\beta$

more flexible form $d \;\rightarrow\; d + a\,x^b\,u$

- Both use a lot of data, have a lot of phenomenological experience, but rely on single-fit technology, which can sometimes be problematic…

  … is there a more robust analysis?



JAM global QCD analysis

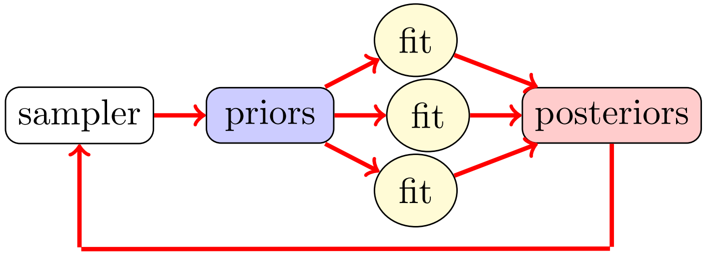
- JAM — iterative, multi-step Monte Carlo

→ traditional functional form for distributions

polynomial, neural net, …

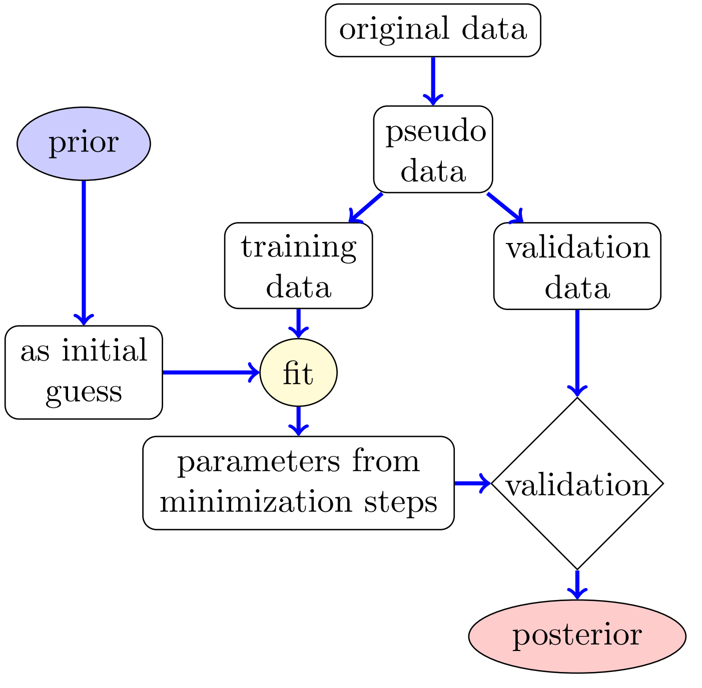
$$f(x) = N\, x^{\alpha} (1-x)^{\beta}\, P(x)$$

but sample large parameter space



→ iterate until convergence
(posteriors = priors)

→ robust determination of
PDF uncertainties



N. Sato et al. (2015 –)

JAM global QCD analysis

- Analysis of data requires estimating expectation values E and variances V of "observables" $\mathcal{O}$ (functions of PDFs) which are functions of parameters

$$E[\mathcal{O}] = \int d^n a \, \mathcal{P}(\vec{a}|\mathrm{data}) \, \mathcal{O}(\vec{a})$$

$$V[\mathcal{O}] = \int d^n a \, \mathcal{P}(\vec{a}|\mathrm{data}) \, \big[\mathcal{O}(\vec{a}) - E[\mathcal{O}]\big]^2$$

"Bayesian master formulas"

- Using Bayes' theorem, probability distribution $\mathcal{P}$ given by

$$\mathcal{P}(\vec{a}|\mathrm{data}) = \frac{1}{Z} \mathcal{L}(\mathrm{data}|\vec{a}) \, \pi(\vec{a})$$

in terms of the likelihood function $\mathcal{L}$ and priors π

JAM global QCD analysis

- Likelihood function

$$\mathcal{L}(\mathrm{data}|\vec{a}) = \exp\left(-\frac{1}{2}\chi^2(\vec{a})\right)$$

is a Gaussian form in the data, with χ^2 function

$$\chi^2(\vec{a}) = \sum_i \left(\frac{\mathrm{data}_i - \mathrm{theory}_i(\vec{a})}{\delta(\mathrm{data})}\right)^2$$

with priors $\pi(\vec{a})$ and evidence Z

$$Z = \int d^n a\, \mathcal{L}(\mathrm{data}|\vec{a})\, \pi(\vec{a})$$

$\longrightarrow$ Z tests if $e.g.$ an n-parameter fit is statistically different from $(n+1)$-parameter fit

JAM global QCD analysis

X2 Table

		Step:	01 (Start)	02 (+HERA)	03 (W2 cut -> 4)	04 (+JLab) (+test nuc. smearing)					05 (+TMCs)		06 (+DY)	09(OS++)
		W2 cut :	10	10	4	4	4	4	4	4	4	4	4	4
		TMCs:									GP	AOT	AOT	AOT
		Power Corrections:												
		Offshell Corrections:												
		Deuteron Smearing:	Paris	Paris	Paris	Paris	AV18	CD-Bonn	WJC-1	WJC-2	Paris	Paris	Paris	Paris
		# Data Points/# Runs:	50	50	50	50	50	50	50	50	50	50	50	50
DIS	BCDMS (p)	351	1.11	1.10	1.70	1.72	1.73	1.74	1.73	1.73	1.24	1.15	1.08	1.18
	BCDMS (d)	254	1.03	1.12	1.73	1.74	1.73	1.78	1.71	1.73	1.26	1.13	1.09	1.11
	NMC (p)	275	1.32	1.77	1.75	1.72	1.72	1.76	1.71	1.72	1.78	1.76	1.90	1.65
	NMC (d/p)	189	0.94	0.95	0.90	0.91	0.91	0.93	0.91	0.91	0.96	0.94	1.04	0.89
	SLAC (p)	564	0.85	1.20	1.67	1.66	1.66	1.70	1.67	1.66	1.19	1.07	1.28	0.97
	SLAC (d)	582	0.61	0.88	1.42	1.42	1.42	1.48	1.45	1.43	0.88	0.81	1.00	0.77
	HERA (NC e+p 1)	402		1.57	1.75	1.83	1.83	1.78	1.82	1.82	1.64	1.60	1.64	1.47
	HERA (NC e+p 2)	75		1.20	1.23	1.25	1.24	1.21	1.24	1.24	1.21	1.21	1.22	1.50
	HERA (NC e+p 3)	259		1.02	1.04	1.05	1.06	1.04	1.06	1.06	1.03	1.02	1.03	1.00
	HERA (NC e+p 4)	209		1.11	1.13	1.15	1.15	1.13	1.15	1.15	1.11	1.10	1.10	1.09
	HERA (NC e-p)	159		1.77	2.13	2.14	2.14	2.14	2.13	2.13	1.82	1.73	1.68	1.62
	HERA (CC e-p)	39		1.48	1.44	1.32	1.30	1.59	1.30	1.30	1.66	1.62	1.29	1.33
	HERA (CC e-p)	42		1.17	1.07	1.10	1.09	1.08	1.09	1.10	1.13	1.19	1.25	1.06
	JLab (d)	136				0.66	0.66	0.58	0.68	0.67	0.55	0.59	0.60	0.57
	JLab (p)	136				1.12	1.12	1.13	1.12	1.11	0.93	0.94	0.95	0.94
	BONUS (n/d)	191				0.99	0.99	1.02	0.98	0.99	0.98	0.98	1.00	1.00
DY	E866 (pp)	121											1.49	1.16
	E866 (pd)	129											2.99	1.06
Z	CDF (Z)	28												
	D0 (Z)	28												
W	CDF (W)	13												
	D0 (W)	14												
Lepton	D0 (e)	13												
	CDF (e)	11												
	D0 (μ)	10												
	ATLAS (2012)	22												
	ATLAS (2011)	22												
	ATLAS (2010)	22												
	CMS (sig)	22												
	CMS (μ) (2011)	11												
	CMS (e) (2011)	11												
	CMS (e) (2010)	6												
	CMS (μ) (2010)	6												
Jets	D0	110												
	CDF	76												
	STAR MB	2												
	STAR HT	8												
		Total:	**1.002**	**1.265**	**1.530**	**1.505**	**1.505**	**1.523**	**1.509**	**1.506**	**1.241**	**1.183**	**1.323**	**1.123**

		Step:	10 (+Z)	11 (+W)	12 (+PCs)		13 (+Tevatron)	14 (+LHC)	15 (+offshell)	16 (PCs p≠n)	17 (+mix par.)	18 (+par. range)	19 (W2 cut -> 3)	22 (+Jets)	CJ15
		W2 cut :	4	4	4	4	4	3.5	3.5	3.5	3.5	3.5	3	3	3
		TMCs:	AOT	AOT	AOT	AOT	AOT	AOT	AOT	AOT	AOT	AOT	AOT	AOT	GP
		Power Corrections:			Mult. (p=n)	Add. (p=n)	Mult. (p=n)	Mult. (p=n)	Mult. (p=n)	Mult. (p≠n)	Mult. (p≠n)	Mult. (p≠n)	Mult. (p≠n)	Mult. (p≠n)	Mult. (p=n)
		Offshell Corrections:							Yes	Yes	Yes	Yes	Yes	Yes	Yes
		Deuteron Smearing:	Paris	Paris	Paris	Paris	Paris	Paris	Paris	Paris	Paris	Paris	Paris	Paris	AV18
		# Data Points/# Runs:	50	50	50	50	50	50	50	50	50	50	50	176	1
DIS	BCDMS (p)	351	1.18	1.20	1.15	1.16	1.20	1.18	1.17	1.17	1.17	1.13	1.13	1.14	1.25
	BCDMS (d)	254	1.10	1.10	1.05	1.05	1.07	1.09	1.08	1.08	1.07	1.06	1.06	1.06	1.15
	NMC (p)	275	1.65	1.66	1.64	1.62	1.64	1.64	1.64	1.64	1.64	1.63	1.63	1.64	1.47
	NMC (d/p)	189	0.89	0.88	0.88	0.87	0.89	0.93	0.93	0.91	0.91	0.90	0.90	0.90	0.91
	SLAC (p)	564	0.97	0.95	0.78	0.80	0.76	0.78	0.78	0.79	0.79	0.80	0.80	0.78	0.77
	SLAC (d)	582	0.77	0.78	0.62	0.61	0.61	0.64	0.63	0.63	0.63	0.64	0.65	0.65	0.65
	HERA (NC e+p 1)	402	1.48	1.48	1.46	1.44	1.46	1.49	1.48	1.48	1.48	1.48	1.47	1.51	1.44
	HERA (NC e+p 2)	75	1.15	1.14	1.14	1.13	1.14	1.12	1.12	1.13	1.13	1.11	1.11	1.11	1.25
	HERA (NC e+p 3)	259	1.01	1.01	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.02	0.96
	HERA (NC e+p 4)	209	1.09	1.09	1.09	1.09	1.09	1.09	1.10	1.09	1.09	1.09	1.09	1.09	1.09
	HERA (NC e-p)	159	1.62	1.63	1.54	1.54	1.57	1.61	1.60	1.61	1.60	1.59	1.59	1.55	1.52
	HERA (CC e-p)	39	1.32	1.34	1.32	1.32	1.46	1.63	1.63	1.65	1.65	1.48	1.46	1.53	1.28
	HERA (CC e-p)	42	1.05	1.01	1.04	1.04	1.23	1.16	1.16	1.16	1.15	1.16	1.16	1.08	1.14
	JLab (d)	136	0.57	0.57	0.75	0.68	0.73	0.89	0.91	0.95	0.94	0.93	0.92	0.89	0.90
	JLab (p)	136	0.94	0.94	1.08	1.02	1.09	1.24	1.25	1.21	1.21	1.22	1.79	1.79	1.22
	BONUS (n/d)	191	1.00	1.00	1.00	0.90	1.01	1.12	1.13	1.10	1.10	1.09	1.13	1.13	1.12
DY	E866 (pp)	121	1.16	1.17	1.14	1.15	1.20	1.24	1.24	1.25	1.24	1.25	1.23	1.24	1.15
	E866 (pd)	129	1.00	1.12	0.95	0.92	0.91	0.95	0.94	0.92	0.91	0.92	0.93	0.98	1.12
Z	CDF (Z)	28	1.18	1.19	1.15	1.22	1.23	1.13	1.12	1.10	1.09	1.32	1.35	1.07	0.96
	D0 (Z)	28	0.58	0.58	0.58	0.59	0.61	0.59	0.59	0.59	0.59	0.60	0.60	0.58	0.57
W	CDF (W)	13		1.04	0.98	1.08	0.53	0.56	0.55	0.54	0.55	1.18	1.28	1.21	1.23
	D0 (W)	14		0.84	0.68	0.59	3.32	3.15	3.23	3.23	3.21	1.29	1.24	1.65	1.00
Lepton	D0 (e)	13					1.59	1.65	1.72	1.85	1.94	1.88	1.89	2.29	2.23
	CDF (e)	11					1.03	1.01	1.01	1.00	1.01	1.06	1.05	1.04	1.09
	D0 (μ)	10					3.57	4.68	4.52	4.62	4.39	3.02	2.99	3.26	2.00
	ATLAS (2012)	22						0.56	0.56	0.59	0.59	0.49	0.50	0.43	
	ATLAS (2011)	22						2.04	2.08	2.55	2.54	1.93	1.92	1.98	
	ATLAS (2010)	22						1.92	1.93	1.99	1.98	1.90	1.95	1.87	
	CMS (sig)	22						0.37	0.35	0.35	0.36	0.40	0.41	0.38	
	CMS (μ) (2011)	11						4.10	3.92	3.65	3.69	3.97	4.02	4.11	
	CMS (e) (2011)	11						1.37	1.37	1.29	1.30	1.59	1.65	1.59	
	CMS (e) (2010)	6						0.74	0.73	0.71	0.71	0.58	0.56	0.62	
	CMS (μ) (2010)	6						0.10	0.10	0.09	0.09	0.07	0.07	0.08	
Jets	D0	110												0.92	0.19
	CDF	76												1.34	0.21
	STAR MB	2												0.02	
	STAR HT	8												1.59	
		Total:	**1.116**	**1.121**	**1.059**	**1.054**	**1.084**	**1.109**	**1.108**	**1.108**	**1.107**	**1.093**	**1.106**	**1.109**	**1.070**

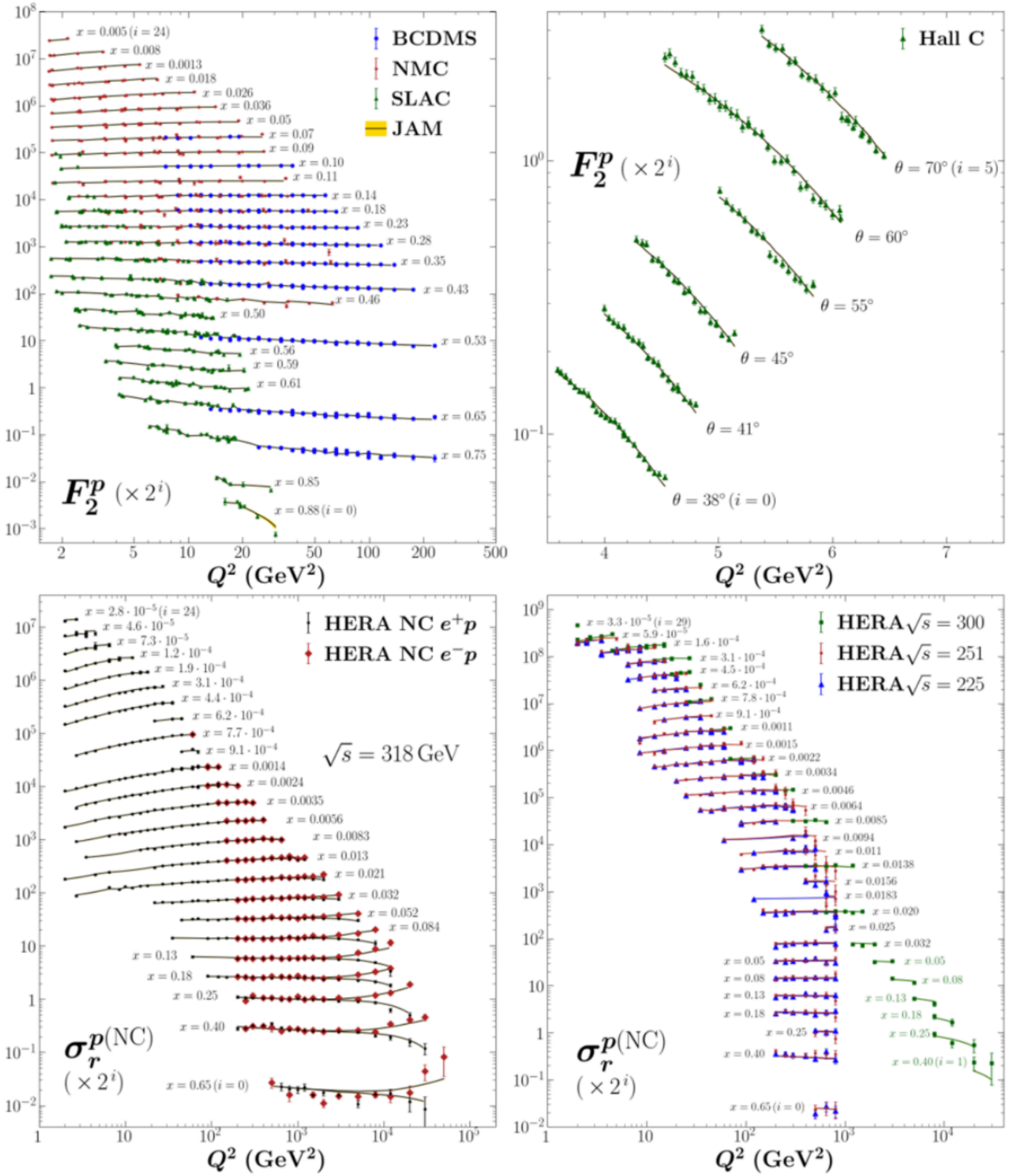
Cocuzza et al. (2021)

→ multi-step procedure to localize solutions in parameter space

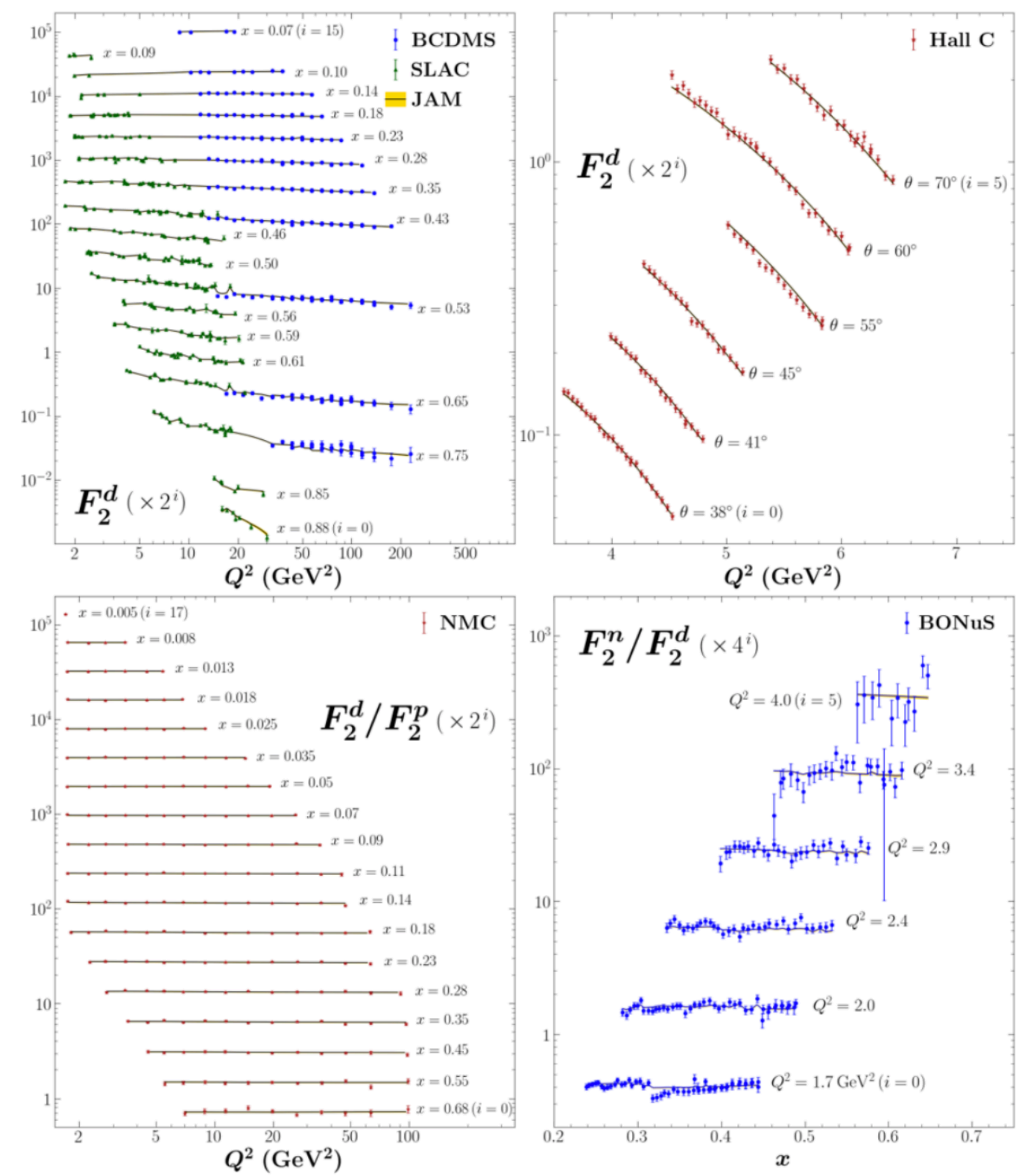
→ data randomized at each step

JAM global QCD analysis

proton DIS data

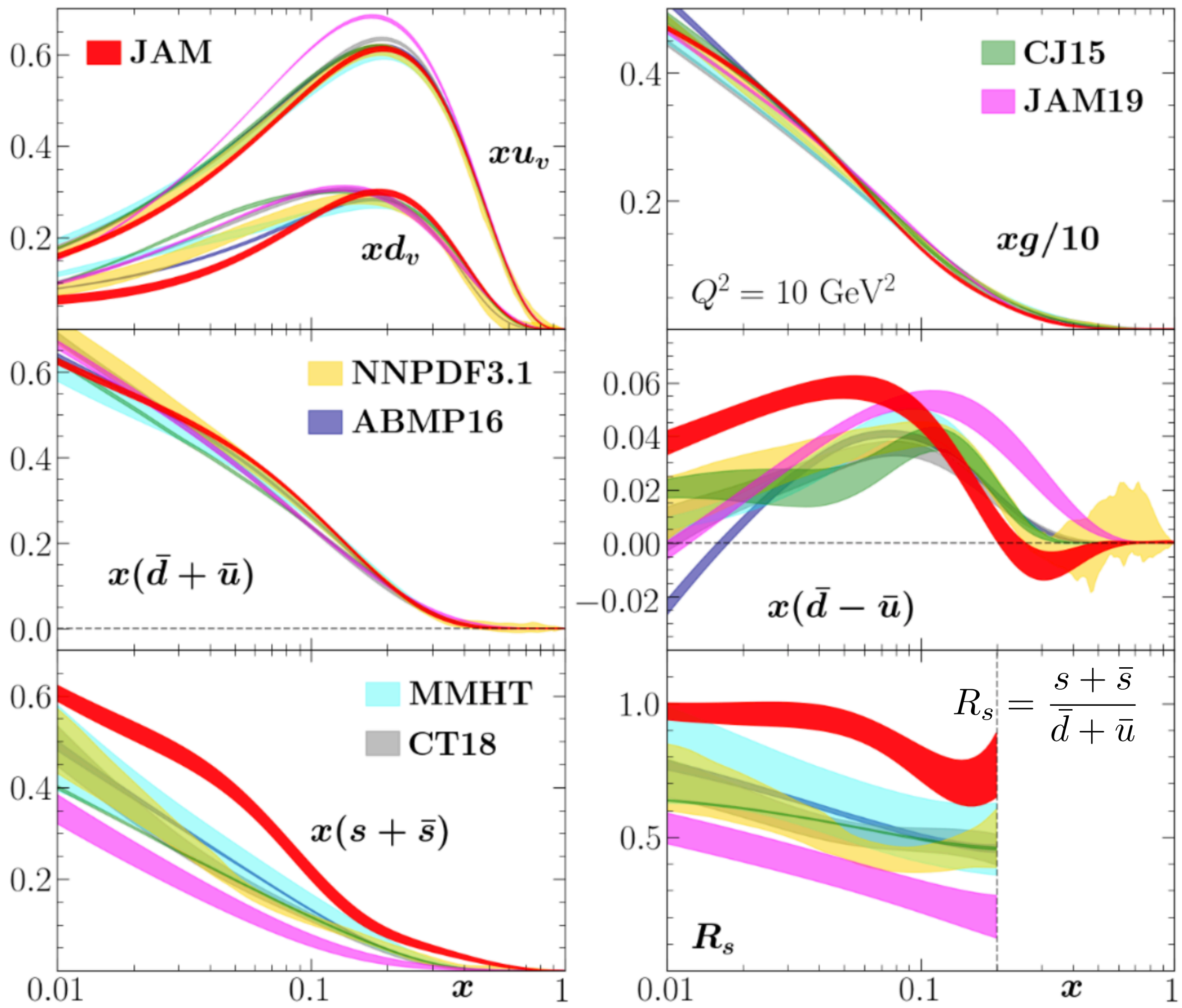


deuteron DIS data



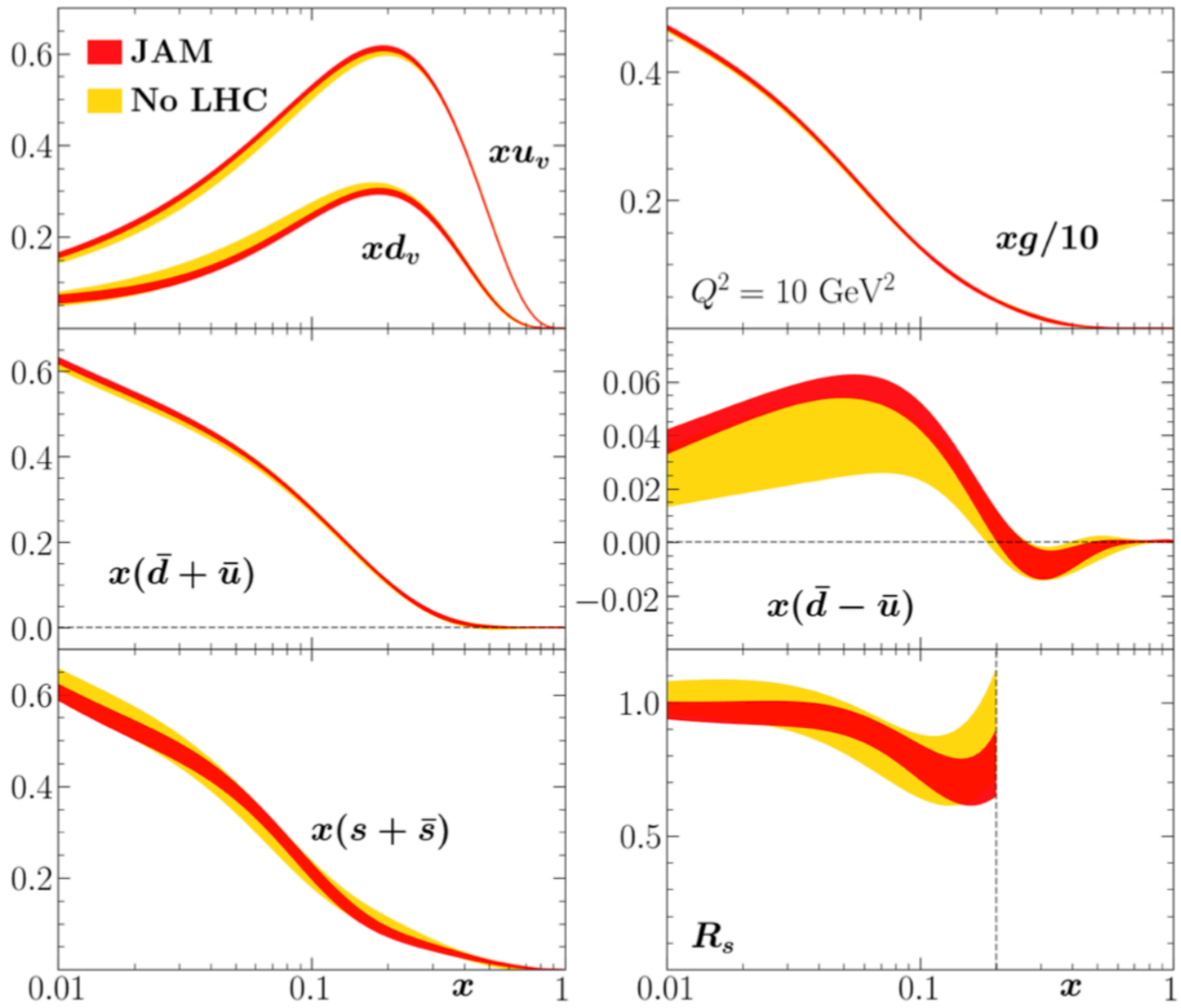
Cocuzza et al. (2021)

JAM global QCD analysis



Cocuzza et al. (2021)

JAM global QCD analysis

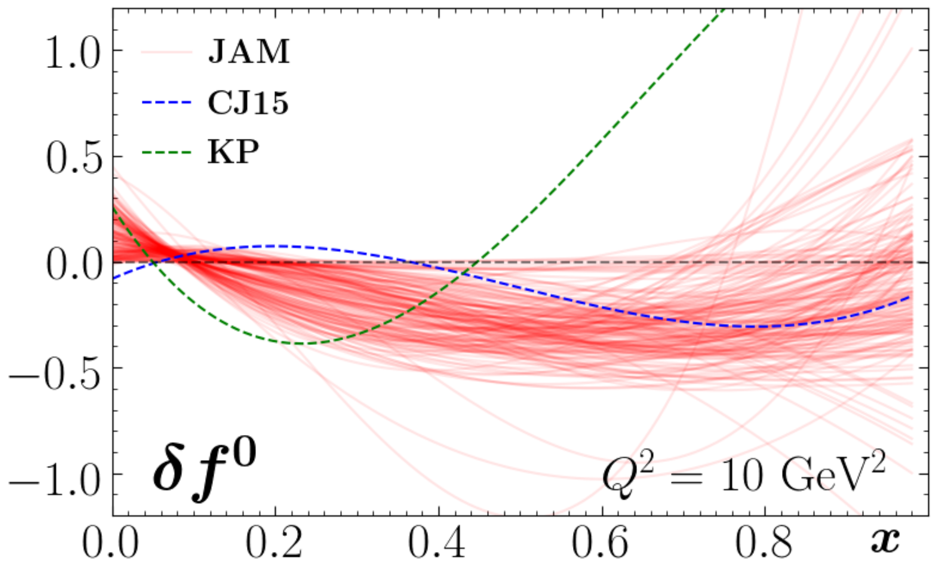


Cocuzza et al. (2021)

⟶ impact of LHC data mostly on sea-quark PDFs

JAM global QCD analysis

- Monte Carlo analysis tells a different story…



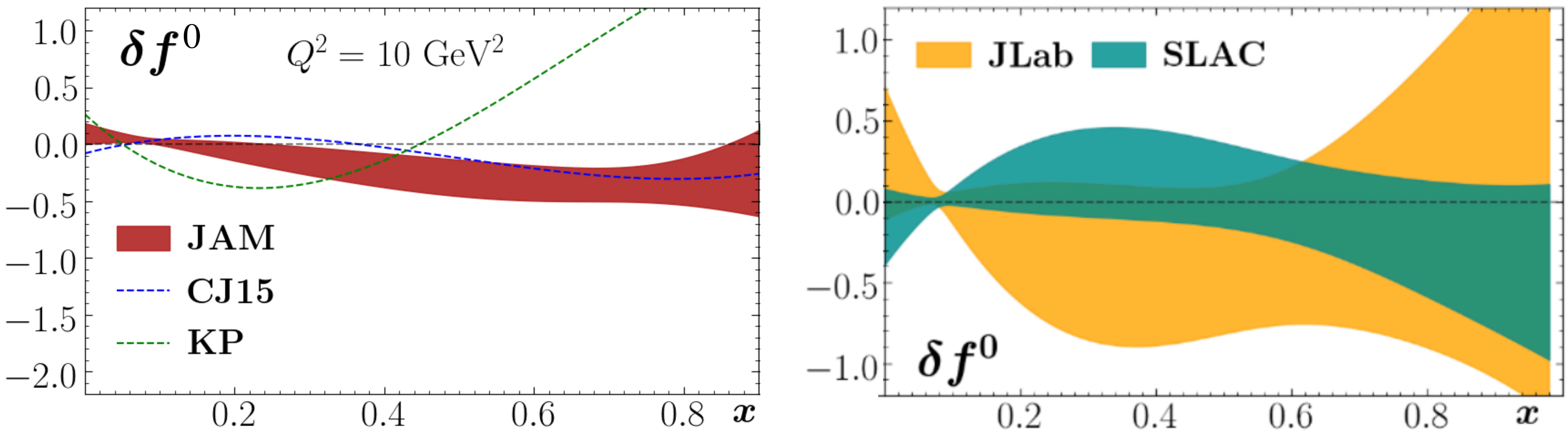
→ effect very small!

→ sits between KP and CJ15 at small x ($\sim 0.1 - 0.3$)

→ more consistent with CJ15 at large x ($\sim 0.5 - 0.8$)

JAM global QCD analysis

- Monte Carlo analysis tells a different story…

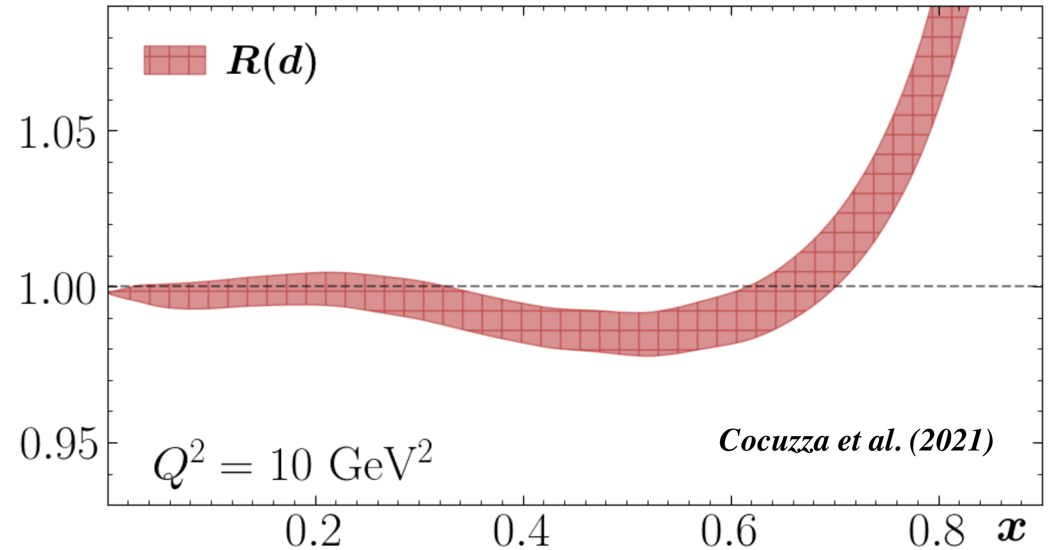


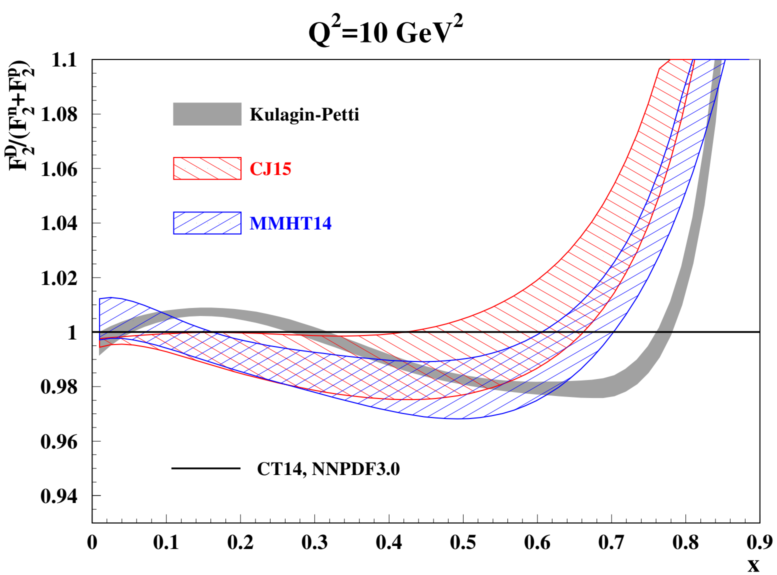
→ fitted result fairly robust

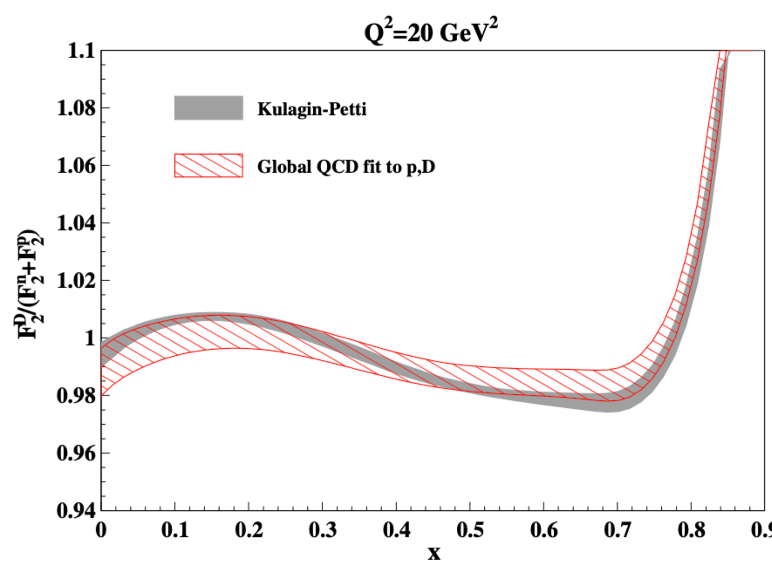
→ reveals some tension between different data sets
(e.g. SLAC vs. JLab)

JAM global QCD analysis

- Fitted deuteron EMC ratio has small, $< 2\%$ deviations from unity for $x < 0.6$



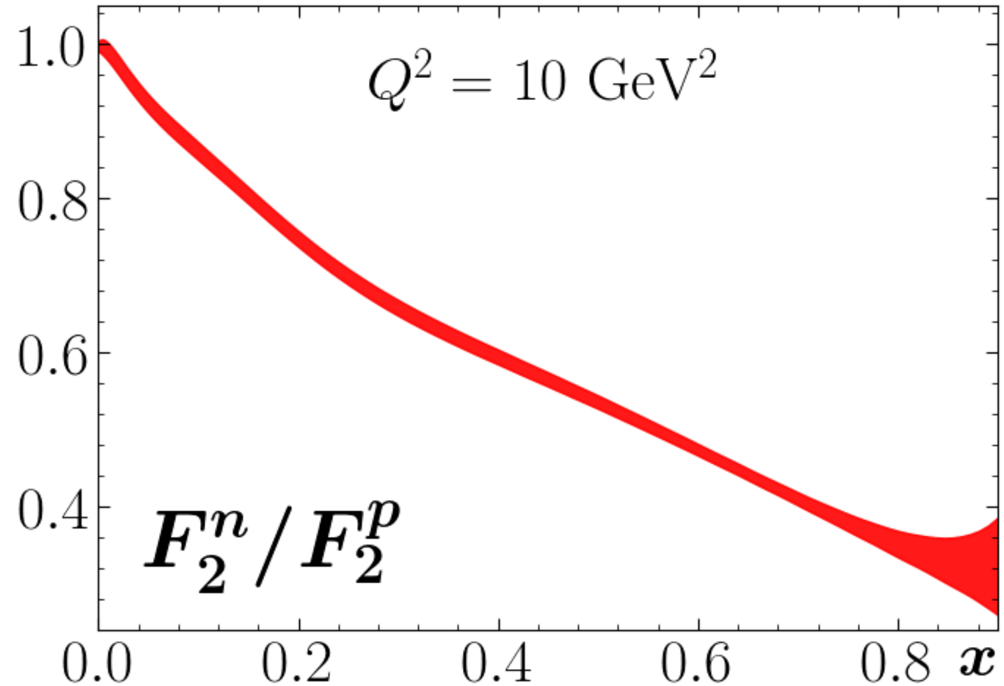




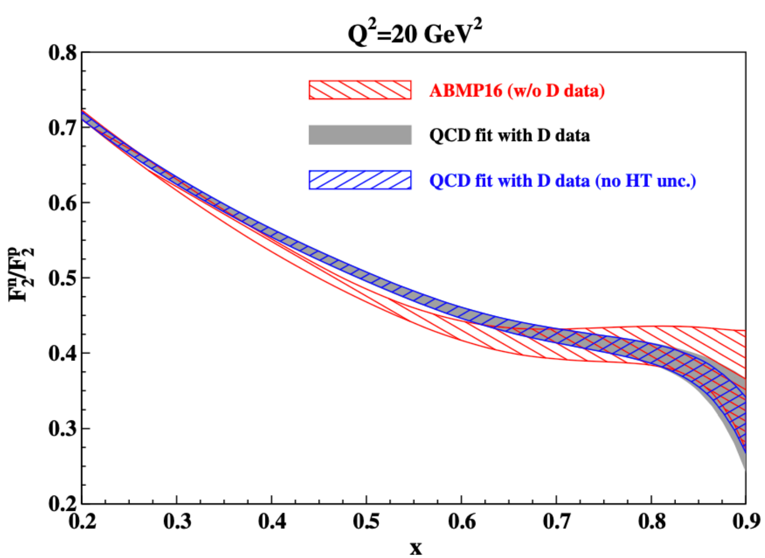
Alekhin et al. (2017)

JAM global QCD analysis

- Resulting neutron structure function is <u>smaller</u> at large x



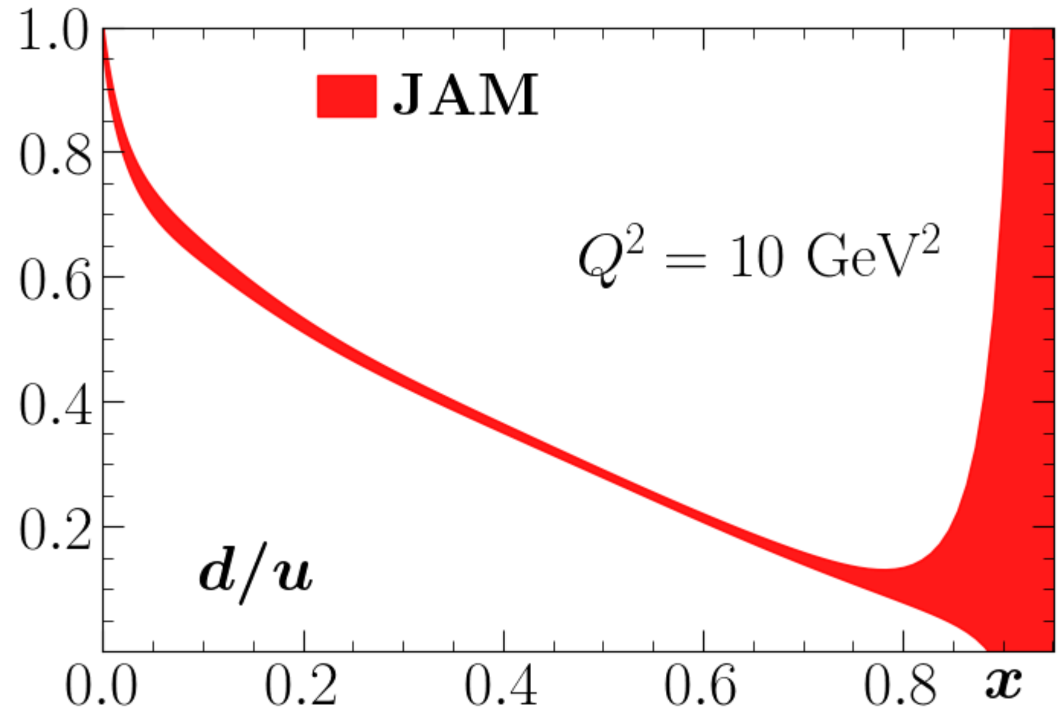
Cocuzza et al. (2021)



Alekhin et al. (2017)

JAM global QCD analysis

- d/u PDF ratio from global fit to all data is well constrained up to $x \sim 0.8$
  (mostly by W-asymmetry data)



Cocuzza et al. (2021)

$\longrightarrow$ DIS measurements on deuteron (& other light nuclei) may be more sensitive to nuclear physics than to d/u ratio!

Outlook

- Most reliable information on nucleon PDFs requires Monte Carlo analysis and modern Bayesian analysis tools

  $\longrightarrow$ upcoming JAM21 global QCD analysis *Cocuzza et al. (2021)*

- Data on $A = 3$ nuclei may shed light on isospin dependence of nuclear (including off-shell) effects

  $\longrightarrow$ upcoming results from MARATHON experiment